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Transverse Stability In Dielectric Wakefield Accelerators

A dissertation submitted in partial satisfaction
of the requirements for the degree
Doctor of Philosophy in Physics

by

Walter J. Lynn

2025

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ABSTRACT OF THE DISSERTATION

Transverse Stability In Dielectric Wakefield Accelerators

by

Walter J. Lynn

Doctor of Philosophy in Physics

University of California, Los Angeles, 2025

Professor James Rosenzweig, Chair

Dielectric Wakefield Accelerators (DWA) can provide accelerating gradients far in excess of those accessible to conventional radio-frequency powered machines. This carries the potential to drastically shrink the footprint of future accelerators and simultaneously expand the accessible energy range, reducing costs and increasing capability. A longstanding obstacle to the realization of this promise is the presence of wakefield-driven beam instabilities. This dissertation experimentally examines the transverse short-range wakefields generated in planar symmetric structures due to various electron beams. It first studies the effect of misalignment between flat beams and the structure geometry and the resulting novel skew-quadrupole component to the transverse wakefields. It then discusses how the inherent quadrupole-like nature of the planar geometry can be exploited with the alternating dielectric wakefield structure to achieve transverse focusing and suppress the effect of the dipole-mode transverse wakefield. These results help clear the way towards realizing an operational dielectric wakefield accelerator.

The dissertation of Walter J. Lynn is approved.

Troy Carter

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James Rosenzweig, Committee Chair

University of California, Los Angeles

2025

To my parents

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When I first committed to attending UCLA for graduate school I was still completely undecided on the question of what I wanted to actually do when I got there. When browsing through the lists of faculty members on the department website I came across Jamie's blurb and I was somewhat shocked. I hadn't even realized that accelerator physics was a distinct field and that it was something I could study here at UCLA. After a quick email exchange I was enlisted as a zeroth-year student and upon arrival in LA, was promptly hooked. From that point on Jamie has been a constant source of support, from the early days as a fledgling graduate student until now, he has unfailingly provided direction, advice, and last but not least funding. This support has facilitated a thoroughly enjoyable experience in graduate school which I will look back on fondly.

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CHAPTER 1

Accelerator History and Basics

Particle accelerators have a long and rich history as essential tools in various fields of Physics. Starting with Wideroe's 50 keV linear accelerator [1] in 1928, followed shortly by Lawrence and Edlefsens 80 keV cyclotron [2] and Cockcroft and Walton's 400 keV electrostatic design [3] accelerators have undergone a shockingly rapid course of development and innovation. Initially experiments using accelerators were focused on nuclear physics such as Cockcroft and Walton's splitting of lithium nuclei [4] or the discovery of new isotopes, the number of which exploded after the invention of the particle accelerator [5]. As accelerators continued to increase in energy and complexity, effort began to transition to the emerging field of particle physics with the work of Veksler [6] and McMillan [7] and the subsequent development of the Synchrotron. Synchrotrons such as the Bevatron (6 GeV) began to make discoveries such as the antiproton [8] and the antineutron [9]. Eventually, in order to boost the center of mass energy, the field began constructing colliders such as AdA, the first e^+e^- collider which operated at a beam energy of 250 MeV [10] and ISR, the first proton-proton collider (60 GeV center of mass) [11]. This led to a new explosion of colliders and commensurate discoveries along the way such as the first linear collider, the SLC (90 GeV center of mass) [12] which was an e^+e^- machine, and p-p machines such as the Tevatron (1.96 TeV center of mass) which discovered the top quark [13] and the Super Proton Synchrotron (900 GeV center of mass) which discovered the W boson [14] and the Z boson [15]. Ultimately this process led to the construction of the Large Hadron Collider (LHC) which operates at a center of mass energy of 13.6 TeV [16] and culminating in the discovery of the Higgs boson [17]. To this day the LHC remains the world's largest and highest energy collider and while

there is some discussion [18] of creating larger, higher energy machines there are none under construction or funded.

As the field has reached for larger and higher energy machines, it has also continuously branched off into other applications. Some of the most common being light sources based on synchrotrons [19, 20] which have proliferated across the scientific community [21]. Another is the Free Electron Laser [22], a device in which interest has exploded in relatively recent years [23]. These light sources then contribute to many other fields of science such as Chemistry and Biology. Medical uses include radioisotope production [24] and proton therapy for cancer treatment [25]. Industrial accelerators are quite common as well for applications such as sterilization of medical supplies [26] and food [27] or even as a welding technique [28]. The indirect impact extends even further afield such as potentially playing a role in the leading hypothesis for the extinction of the dinosaurs [29].

Across all of these applications a reduction in the size of accelerators is a highly desirable outcome, either for convenience or for cost savings. The primary driver for the size of an accelerator is the accessible accelerating gradient, with the current radio-frequency (RF) driven technology typically capable of 10-20 MeV/m [30, 31] before breakdown [32]. Some advancements in the field promise to increase this limit through innovations in the cavity structure as well as cryogenic cooling [33] to reach 150 MeV/m. Other techniques involve multi-beam acceleration schemes [30, 34] that can reach up to 100-400 MeV/m of gradient. These are promising results but given that cost estimates for future colliders are optimistically in the realm of 30 billion USD [35], even a 10-fold increase in gradient only goes so far. To address this desire to reach even higher gradients another type of accelerator was developed, the wakefield accelerator [36]. These accelerators operate on the principle of an exciting beam generating an electromagnetic wake in a medium which transfers that energy into a trailing “witness” beam. The Tajima & Dawson scheme used a laser pulse as the excitation and plasma as the medium but later experiments showed that it was possible to use a beam as the driver instead [37]. It is also possible to swap the plasma for another medium such

as a dielectric-lined waveguide [38]. These wakefield accelerators are valuable directions of research because they can support accelerating gradients far in excess of even the most optimistic RF-based designs. The focus of the rest of this work is on this last type of wakefield driven accelerator, the dielectric wakefield accelerator or DWA.

CHAPTER 2

Dielectric Wakefield Accelerators

A dielectric wakefield accelerator is fundamentally an object that transfers energy from a “drive” beam to a “witness” beam using a dielectric material. Historically, this has taken the form of a dielectric tube with the outer surface coated in metal through which the two beams traveled. The “drive” beam excites electromagnetic wakefields in the form of Cerenkov radiation which then form an accelerating region behind the “drive” beam which the “witness” beam can reside in and be accelerated by. Figure 2.1 shows a cartoon of this interaction, complete with wakefields. In this geometry the longitudinal electric field is given by

$$E_z = \frac{2Ne}{\epsilon b} \sum_{\lambda} \left(\frac{J_0(s_{\lambda}b)N_0(s_{\lambda}a) - N_0((s_{\lambda}b)J_0(s_{\lambda}a))}{\frac{d}{ds}(J_1(sb)N_0(sa) - J_0(sa)N_1(sb))|_{s=s_{\lambda}}} \right) \cos\left(\frac{\omega_{\lambda}}{v}z_0\right) \exp\left(-\frac{(\omega_{\lambda}\sigma_z)^2}{2c^2}\right) \quad (2.1)$$

where N is the number of particles in the gaussian drive bunch of length σ_z , z_0 is the distance behind the drive beam, J_n and N_n are the n th order Bessel functions of the first and second kinds respectively, s_{λ} is the wave number given by the root of

$$J_1(s_{\lambda}b)N_0(s_{\lambda}a) - J_0(s_{\lambda}b)N_1(s_{\lambda}a) = 0, \quad (2.2)$$

ω_{λ} is given by

$$\omega_{\lambda} = \frac{s_{\lambda}c}{\sqrt{\epsilon - 1}}, \quad (2.3)$$

a is the inner radius of the dielectric tube, b is the outer radius, and ϵ is the dielectric constant [38]. These types of structures can survive peak surface fields of up to 13.8 ± 0.7 GV/m before breakdown [39] and have experimentally demonstrated accelerating gradients of 320 ± 17 MeV/m [40], clearly demonstrating their attractiveness as the basis for future

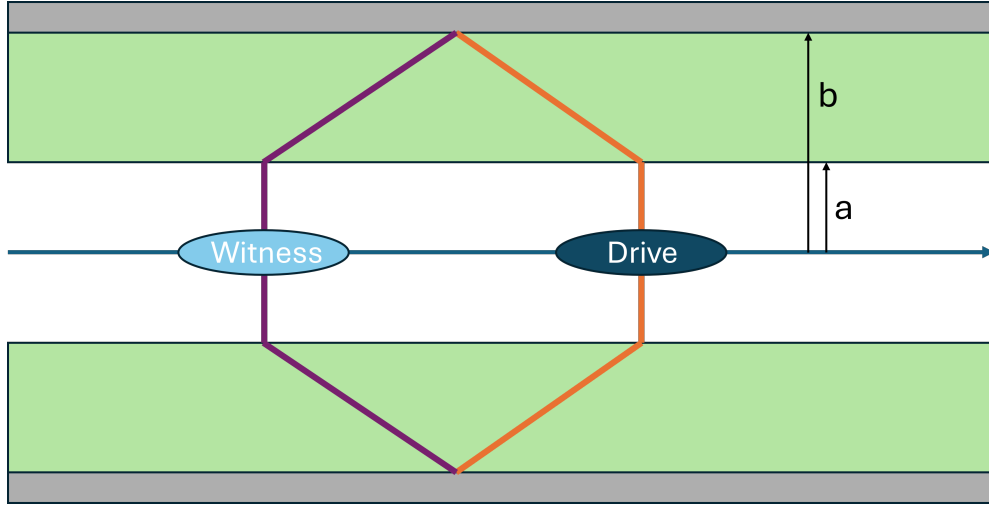


Figure 2.1: A cartoon of a typical dielectric wakefield acceleration scheme. The green material is the dielectric material and the gray is the metallic coating that forms the waveguide. The beam axis is the blue arrow on which the two beams are traveling. The orange and purple lines represent the wakefields, the color representing the direction of E_z with orange a decelerating field and purple, accelerating.

potential accelerators. In addition to the high gradient, dielectric wakefield accelerators have been shown to be conducive to antimatter operation without adjustment making them highly attractive as a choice for any future e^+e^- collider [41].

CHAPTER 3

Instabilities and Beam Breakup

Unfortunately, while the longitudinal characteristics of DWAs are quite nice, the transverse field structure is where the difficulty lies [42]. As with wakefields in traditional linacs [43], DWAs are highly susceptible to coherent instabilities leading to beam breakup. In cylindrical structures, longitudinal and transverse wakefields are coupled such that longitudinal wakefields strong enough to be interesting are accompanied by transverse wakefields strong enough to cause single bunch beam breakup (SBBU) [44]. One way to understand this is through the Panofsky-Wenzel theorem which can be expressed as

$$\nabla_{\perp} W_z = \frac{\partial W_{\perp}}{\partial \zeta} \quad (3.1)$$

where W is the wake potential and $\zeta = ct - z$ is a measure of distance from the head of the beam [45]. Clearly a finite beam generating a large W_z will not be constant transversely leading to a significant $W_{\perp}$. In general the longitudinal wakefields scale with $E_z \propto Q/a^2$ while the transverse wakefields scale with $E_{\perp} \propto Q/a^3$ [46]. This imposes a near-fatal constraint on DWA-based acceleration schemes because any accelerator that does not produce a beam is not a very useful thing. One solution is to apply the principle of BNS damping [47] to suppress resonant oscillations in the beam and thereby prevent SBBU. This approach is limited however by the strength of available quadrupoles and a maximal accelerating gradient can be constructed based on this approach as shown in [46]. This maximal gradient is much lower than the breakdown limit for accessible beam charges and so we search for another method to combat SBBU.

Another approach is to fundamentally change the geometry of the entire interaction. The

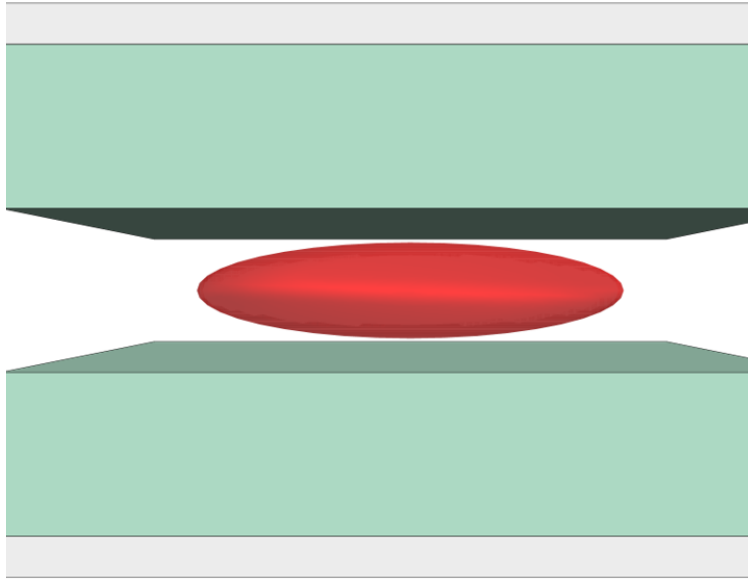


Figure 3.1: A cartoon of the flat beam and planar symmetric structure configuration. The red ellipsoid is the beam moving into the page. The green shaded objects are the dielectric slabs and the grey caps are the metallic waveguide.

old dielectric tubes become planar-symmetric dielectric slabs and the previously round beams become flat in both their transverse size but also in their emittances [48]. That is to say for the new beams, $\sigma_y \ll \sigma_x$ and $\epsilon_y \ll \epsilon_x$. This is necessary to fit the beam into the structure in the first place and to maintain the requisite aspect ratio. Figure 3.1 shows a cartoon of a flat beam traversing a planar-symmetric structure. The previous field structure and limitations thereof were the product of a round beam in a cylindrical structure. Employing this new beam and dielectric structure geometry results in significant suppression of the net dipole transverse wakefield. In fact, in the case of an infinitely wide beam in such a structure, the transverse wakefields vanish entirely [45]. For a given charge, as σ_x increases the longitudinal wakefields scale with $W_z \propto 1/\sigma_x$ while the transverse wakefields scale with $W_\perp \propto 1/\sigma_x^3$ [49]. This flat beam in a planar structure configuration has been tested experimentally [50] as have the σ_x scalings of the wakefields [51]. If we are to employ these beams ourselves we need to understand them in more depth.

CHAPTER 4

Flat Beams

In addition to the previously mentioned effect on SBBU, the field at large is also interested in flat beams for an additional reason. At the interaction point of a collider flat beams reduce the effects of “beamstrahlung,” the beam-beam forces, without compromising on luminosity, one of the key figures of merit for a collider. We are interested in reducing “beamstrahlung” because it increases the energy spread of the colliding beams leading to a loss of precision. The impact on the energy spread δ_E due to “beamstrahlung” is given by

$$\delta_E = \frac{R}{(1 + R)^2} \quad (4.1)$$

where R is the ratio σ_x/σ_y . Luminosity $\mathcal{L}$ in a collider is the proportionality factor between the interaction cross section σ_p and the number of collisions per second $\dot{R}$ or

$$\dot{R} = \mathcal{L} \sigma_p. \quad (4.2)$$

For two identical Gaussian beams colliding head-on, the luminosity is given by

$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} \quad (4.3)$$

where N is the number of particles in the beam and $\sigma_{x,y}$ are the transverse standard deviations. From this we can see that preserving the product $\sigma_x\sigma_y$ while increasing the ratio σ_x/σ_y means that the luminosity can remain unaffected while the effect of “beamstrahlung” is reduced [52, 53]. Based on this we can conclude that understanding the interactions flat beams have with their environment is of critical interest beyond just the DWA application.

Now that we’ve established why we’re interested in flat beams we must discuss how to create them. The basic concept is described in [48, 52, 54, 55], the first step is to generate the

beam in a magnetic field by adjusting the focusing solenoid so that the field on the cathode is non-zero. This means that the beam has a non-zero canonical angular momentum due to the vector potential $\vec{A}$ with transverse components

$$\vec{A} = -\frac{B_c}{2}y\hat{x} + \frac{B_c}{2}x\hat{y} \quad (4.4)$$

where B_c is the magnitude of the longitudinal magnetic field on the cathode. This results in an angular momentum $\vec{L}$ of

$$\vec{L} = \vec{r} \times e\vec{A} \quad (4.5)$$

$$\vec{L} = \frac{eB_c}{2}r^2\hat{z}. \quad (4.6)$$

The ensemble-average of this is

$$\langle L \rangle = eB_c\sigma_c^2 \quad (4.7)$$

where σ_c is the transverse rms size of the laser spot on the photocathode. With this we can define the “magnetization” of the beam as $\mathcal{L}$ given by

$$\mathcal{L} = \frac{\langle L \rangle}{2p_z} \quad (4.8)$$

where p_z is the mean longitudinal momentum of the beam. Now that we have a magnetized beam, the next step is to run the beam through a triplet of skew quadrupoles such that the off-diagonal blocks in the beam covariance matrix, Σ , vanish. Σ is given by

$$\Sigma = \begin{bmatrix} \langle XX^T \rangle & \langle XY^T \rangle \\ \langle YX^T \rangle & \langle YY^T \rangle \end{bmatrix} \quad (4.9)$$

$$\Sigma = M\Sigma_0M^T \quad (4.10)$$

where Σ_0 is the incoming beam covariance matrix and M is the skew triplet transport matrix. In an unmagnetized beam the off-diagonal elements of Σ_0 are zero but in this case $\langle XY^T \rangle = -\langle YX^T \rangle = \mathcal{L}J$ where J is given by

$$J = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}. \quad (4.11)$$

The components of M are found via algorithmic optimization which results in the following emittances

$$\epsilon_n^\pm = \sqrt{(\epsilon_n^u)^2 + (\beta\gamma\mathcal{L})^2} \pm \beta\gamma\mathcal{L} \quad (4.12)$$

where ϵ_n^u is the original uncorrelated normalized emittance and β and γ are the normal special-relativistic variables. Applying the approximation $\beta\gamma\mathcal{L} \gg \epsilon_n^u$ we get

$$\epsilon_n^+ = 2\beta\gamma\mathcal{L} \quad (4.13)$$

$$\epsilon_n^- = \frac{(\epsilon_n^u)^2}{2\beta\gamma\mathcal{L}}. \quad (4.14)$$

For large $\mathcal{L}$ this results in a clearly flat beam with a tunable aspect ratio selected by the strength of the magnetic field on the cathode and the laser spot size.

CHAPTER 5

Skew Wake Experiment

Given that we have already established the interest in flat beams generally and in our case, their interaction with dielectric structures we must better understand them. One known issue is that while the transverse mode is suppressed due to the geometry it is not eliminated entirely and so this mode itself must be studied further. In this experiment we seek to do exactly that by examining the effect of a slight angular misalignment between the long axis of the beam and the dielectric surface. These canted beams can result from errors in the flat beam generation process or structural misalignment. Fully understanding this interaction is crucial if these types of structure are ever to be used for an application with tolerances as demanding as a collider.

The material in the following chapters regarding the skew wake experiment is adapted from [56] in accordance with the UCLA Dissertation Requirements section “ALTERNATE VERSIONS OF PUBLISHED ARTICLES”

CHAPTER 6

Skew Beam-Structure Interaction

The central idea guiding this experiment was to understand what happens when a flat beam is injected into a structure with an angular mismatch. That is to say, when the sem-major transverse axis of the beam is not parallel to the dielectric surface as seen in Fig 6.1. To understand this we began with a simple two-particle model based on the methods described in [49, 57]. We begin with one of the main results of [57] which states

$$F_{\perp}(\omega, \omega_0) = \frac{4qQ\theta(\zeta)\zeta}{a^2} f''(\omega, \omega_0)^* f'(\omega_0, \omega_0) \quad (6.1)$$

where q is the charge of a test particle located at $\omega = x + iy$, Q is the charge of a source particle located at ω_0 , ζ is the co-moving longitudinal coordinate $\zeta = ct - z$, θ is the heavyside step function, and a is half of the vacuum gap. The function $f(\omega, \omega_0)$ is a conformal map from a circle with the source particle located at its center to the intended geometry, $*$ is complex conjugation, and $'$ represent differentiation with respect to ω . We considered two different cases, a double sided structure and a single sided structure where the lower dielectric slab is missing as seen in Fig 6.1. The map from a horizontal strip of height $2a$ centered at zero to a disk of radius a centered at the origin is

$$\chi(\omega) = a \tanh\left(\frac{\pi\omega}{4a}\right) \quad (6.2)$$

and the map from the upper half of the complex plane to the same disk is

$$\chi(\omega) = a \frac{\omega - i}{\omega + i}. \quad (6.3)$$

Once mapped to the disk, we employ the additional mapping

$$g(\chi, \chi_0) = a^2 \frac{\chi - \chi_0}{a^2 - \chi\chi_0^*} \quad (6.4)$$

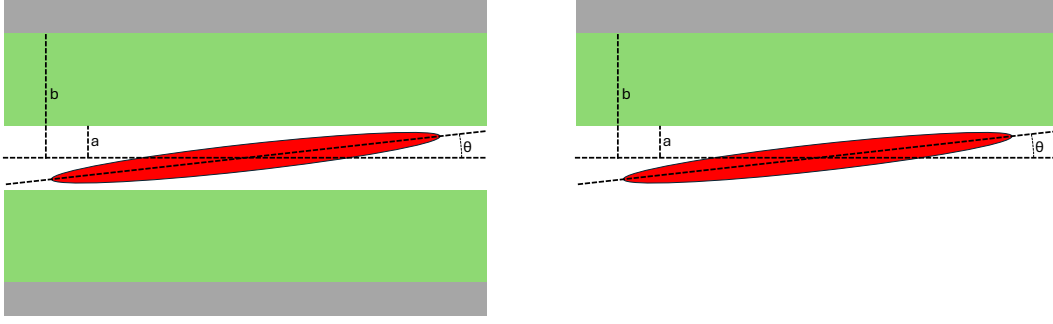


Figure 6.1: A cartoon of the two beam-structure configurations. The beam is represented by the red oval and is traveling away from the viewer. The green rectangles represent the dielectric material and have a thickness of $b - a$. The grey is the metallic coating that forms the containing waveguide. The beam is rotated in the transverse direction by an angle θ with respect to the surface of the dielectric material. The beam is not rotated in any other direction.

where $\chi_0 = \chi(\omega_0)$ which sets the location of the source to be at the center of the disk. Now we compute the total map

$$f(\omega, \omega_0) = (g \circ \chi)(\omega, \omega_0). \quad (6.5)$$

This gives us

$$f(\omega, \omega_0) = a \frac{\tanh\left(\frac{\pi\omega}{4a}\right) - \tanh\left(\frac{\pi\omega_0}{4a}\right)}{1 - \tanh\left(\frac{\pi\omega}{4a}\right) \tanh\left(\frac{\pi\omega_0^*}{4a}\right)} \quad (6.6)$$

for the double slab structure and

$$f(\omega, \omega_0) = a \frac{(\omega - i) - \frac{\omega_0 - i}{\omega_0 + i}(\omega + i)}{(\omega + i) - a \frac{\omega_0^* + i}{\omega_0^* - i}(\omega - i)} \quad (6.7)$$

in the case of the single slab structure. Now we can put these back into Eq 6.1 with the additional clarification that $\omega = x + iy$ and $\omega_0 = x_0 + iy_0$ to get

$$F_{\perp}(\omega, \omega_0) = \frac{\pi^3 q Q \theta(\zeta) \zeta}{8a^3} \text{sech}^2\left(\frac{\pi}{4a}(-(x - x_0) + i(y + y_0))\right) \tanh\left(\frac{\pi}{4a}(-(x - x_0) + i(y + y_0))\right) \quad (6.8)$$

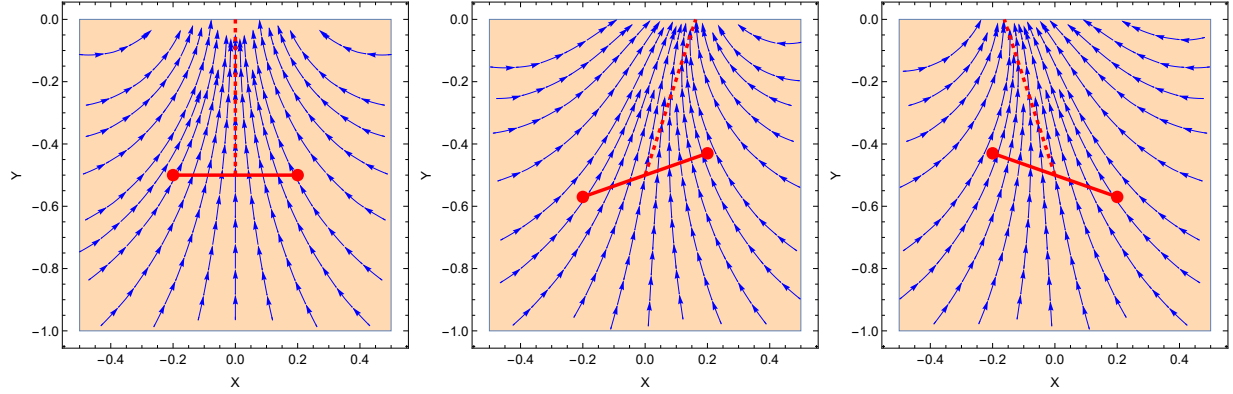


Figure 6.2: Stream plots of $F_{\perp}$ according to Eq 6.9 generated by two particles represented by red disks below a single dielectric slab located at $y = 0$. The solid red line illustrates the transverse beam axis and the dashed red line connects the center of the beam to the point on the dielectric surface with zero transverse force. The three figures show an un-rotated beam and two beams with identical in magnitude positive and negative rotations.

for the two-slab case, and

$$F_{\perp}(\omega, \omega_0) = \frac{32qQ\theta(\zeta)\zeta}{a^2} \frac{8a^2x_0(1-a) + i(1+a+y_0(1-a))}{(a(x-i(y-1))(x_0+i(y_0-1)) - (x-i(y+1))(x_0+i(y_0+1)))^3} \quad (6.9)$$

for the single slab.

We can understand these results graphically by examining Figs 6.2 and 6.3. The figures clearly show that tilting the beam introduces a skew component into the field structure. The apparent effect is stronger in the single-slab case, as measured by the deflection of the zero-transverse force point on the dielectric surface. The difference being a skew effect is more evident in the double-slab case where the quadrupole-like fields simply rotate counter to the beam. This indicates that the single slab results may be easier to analyze.

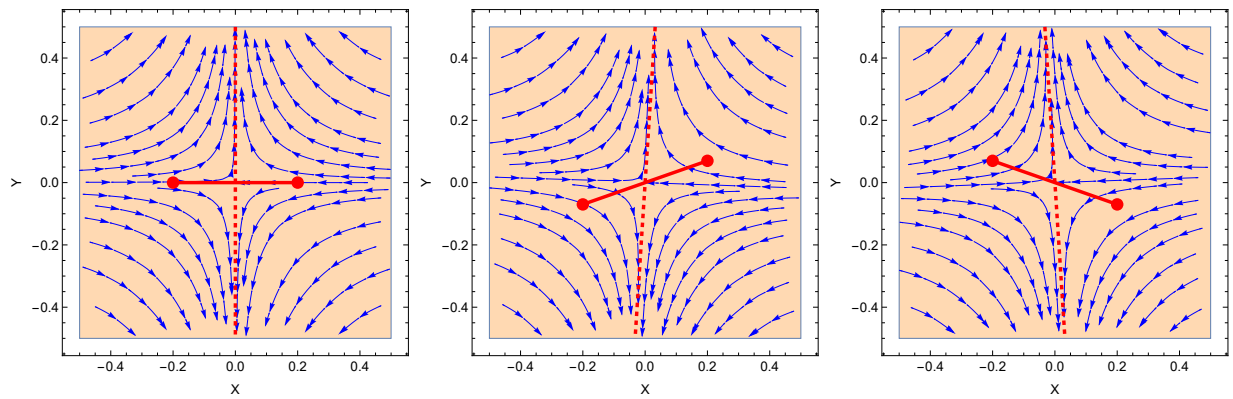


Figure 6.3: Stream plots of $F_{\perp}$ according to 6.8 generated by two particles represented by red disks between two dielectric slabs located at $y = \pm 0.5$. The solid red line illustrates the transverse beam axis and the dashed red line connects the center of the beam to the points on the dielectric surface with zero transverse force. The three figures show an un-rotated beam and then two beams with identical in magnitude positive and negative rotations.

CHAPTER 7

Simulation

We used simulations extensively, both as a guide when designing the experiment and after the fact to help understand our results. The primary simulation tools used in this experiment were CST Studio Suite [58] and WARP [59]. CST is a broad multiphysics set of tools published commercially by Dassault Systemes, but for the purposes of this experiment we primarily used the Particle In Cell (PIC) and Wakefield solvers. Warp is a PIC solver written and distributed by LBNL that we used to benchmark and verify the initial CST simulations. The overall workflow for both PIC solvers is to generate a particle distribution with the desired parameters externally and then allow the solvers to simulate the beam-structure interaction. At the exit of the structure the changed beam is extracted and analyzed by additional tools. The primary external tool used to both generate the input beams and analyze the results was Mathematica [60].

Initial simulations guided the experimental design, helping set parameters such as the structure gap and manufacturing details such as whether to electroplate the dielectric slabs. The beam used in those initial simulations was generated with a Mathematica notebook that allowed us to easily set beam parameters arbitrarily. A useful detail of this method of beam generation is that it allowed us to independently tune features such as the beam emittance, separate from the rest of the parameters. This allowed us to probe the beam-structure interaction very cleanly before reintroducing the reality of a warmer beam. An example of this is in Fig 7.1 where we can easily see the effect of turning the beam emittance on and off. The effects of the transverse wakefields on the beam are very clear without the blurring

Parameter (Symbol)	Value	Unit
Charge (Q)	2	nC
Energy (U)	40	MeV
rms size in x (σ_x)	0.9	mm
rms size in y (σ_y)	0.13	mm
rms size in z (σ_z)	0.64	mm
Normalized horizontal emittance (ϵ_{Nx})	160	$\mu\text{m}\cdot\text{Rad}$
Normalized vertical emittance (ϵ_{Ny})	3	$\mu\text{m}\cdot\text{Rad}$
Tilt angle w.r.t. x-axis (θ)	1-10	deg

Table 7.1: Beam parameters for initial simulations to set dielectric structure parameters. Values are loosely derived from previous experimental work at AWA to maintain physical plausibility.

introduced with a warmer beam. This allowed us to cleanly simulate the beam-structure interaction before subsequently introducing more realistic parameters to simulate an actual experiment. One helpful tip that we learned was that it was better to rotate the beam and keep the structure aligned with the simulation coordinate system. This maintained agreement between the structure edges and the cell walls and prevented staircasing of the dielectric surface.

Prior to the experiment we simulated both single and double slab configurations as seen in Fig 7.2. We began with CST’s PIC solver because we were primarily interested in the beam dynamics within the structure. Detailed instructions for running a PIC simulation in CST are available in Appendix A. The three questions we sought to answer were “What angle relative to the structure should the beam be set to?”, “How long should the structure be?”, and “what should the structure gap be?” All three of these questions are interdependent and so must be addressed in concert. The beam angle is bounded by the gap if we’re to prevent beam losses and the desire to see a signal. Too much tilt and the edges are clipped

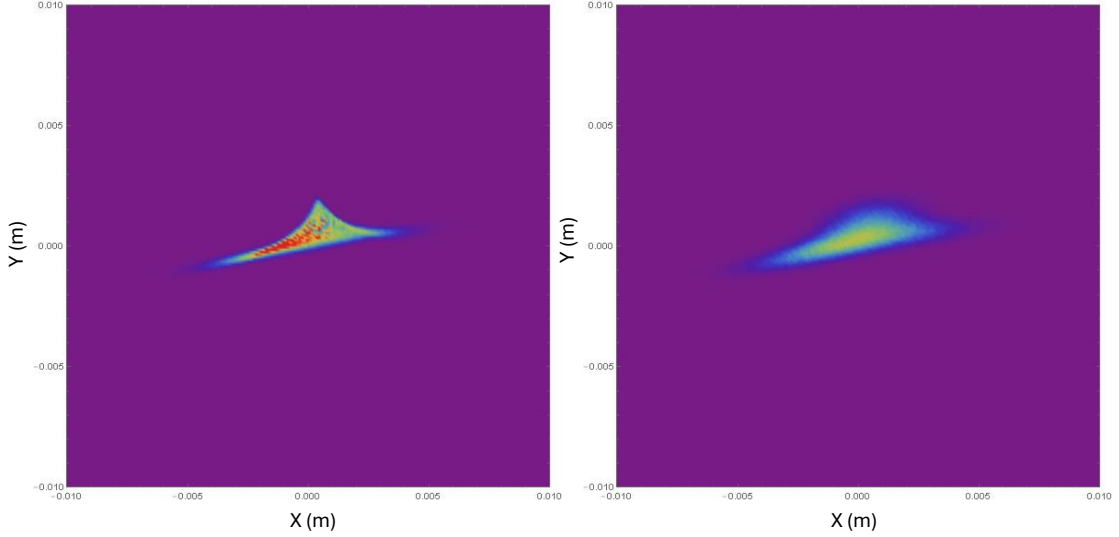


Figure 7.1: Two simulations of a flat beam with a 10° tilt relative to a single dielectric slab 0.8 mm above the beam centroid. The beam on the left had no initial transverse momentum and the beam on the right had a realistic transverse momentum distribution.

by the dielectric surface and too little tilt and we don't see any effect. The gap is bounded below by the beam emittance and the magnetic quadrupole field gradient of the focusing magnets and above by the fact that transverse wakefield strength scales with a^{-3} . Too small of gap and the beam can't fit through and too large of gap and we see no effect. Finally, the structure length is constrained by available vacuum chamber space and the strength of the transverse fields and therefore the gap. If the gap is larger, we can increase the interaction length to generate more effect until the structure won't fit in the vacuum chamber. If the gap is smaller, then we must reduce the structure length otherwise the transverse fields induce beam breakup and beam losses. The goal was to locate an angle with clear signal that did not also overly distort the beam. The initial beam parameters are described in Table 7.1 and are derived from previous experimental work at AWA to ensure a future experiment could replicate them.

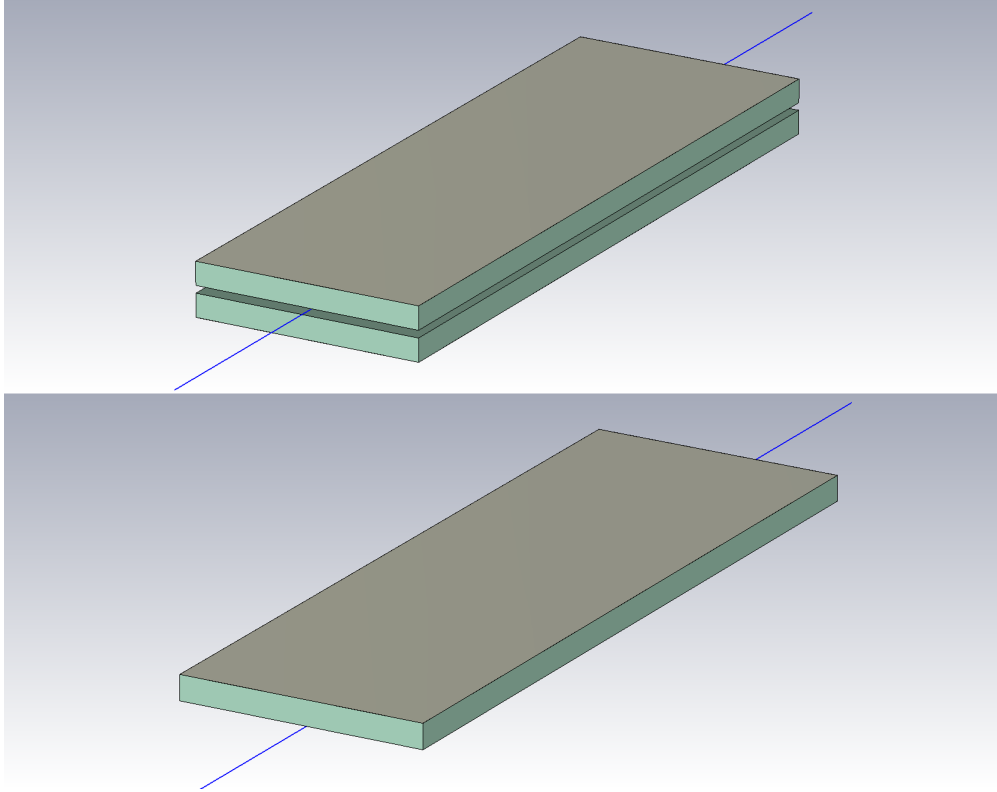


Figure 7.2: The two configurations of the dielectric structure used in the experiment as represented in CST. The green material is the dielectric, the grey is the metallic coating, and the blue line is the beam path.

Ultimately, after a series of simulations we concluded that our maximum acceptable angle was $\theta = 10^\circ$. After incorporating the results of the optimizations described in Section 4 to establish the round-to-flat transformation, we settled on examining two different angles, $\theta = 2^\circ$ and $\theta = 7^\circ$. With this angle and the anticipated emittance of the beam we arrived at a nominal gap of $a = 0.5$ mm. Based on these two parameters we then arrived at a total structure length $L = 15$ cm. We then repeated our final simulations in WARP to double check our results. CST and WARP showed good agreement on the general beam-structure interaction and it's effect on the beam.

The next step after establishing the basic stucture parameters was to examine the frequency response using the wakefield solver in CST. Detailed instructions for setting up a wakefield simulation in CST are available in Appendix B. The reason to use the wakefield solver instead of the PIC solver is that the fields are much cleaner. The frequency response is important because it determines the length-scale of the wakefields and the necessary thickness of the external metallic coating. Skin depth can be calculated with the standard formula [61]

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_0\mu_r}} \quad (7.1)$$

where ρ is the material resistivity, ω is the frequency of the field, μ_0 is the vacuum permeability, and μ_r is the relative permeability. The frequency response of the structure is determined by the beam length, σ_z , the dielectric constant, ϵ , and the dielectric thickness, $b - a$. Given the beam length mentioned in Table 7.1 and a dielectric thickness of 5 mm, and a dielectric constant $\epsilon = 9.9$, we found that the fundamental frequency was ~ 700 MHz. This gives us a skin depth of only $2.46 \mu\text{m}$ assuming a resistivity of $\rho = 1.678 \times 10^{-8} \Omega\text{m}$. This is a very convenient result because the maximum thickness of copper that can be deposited on to the dielectric surface using physical vapor deposition is roughly $3 \mu\text{m}$ due to the buildup of internal stresses in the material [62].

CHAPTER 8

Experimental Design

8.1 The Argonne Wakefield Accelerator Facility

To test the skew-wake concept, we conducted an experiment at the Argonne Wakefield Accelerator (AWA) facility located at Argonne National Laboratory [63]. AWA is home to several radio-frequency powered accelerators and can deliver beams ranging from 1 pC to 100 nC at energies from 8-68 MeV. The AWA layout can be found in Fig 8.1, we used the 70 MeV drive linac for this experiment although we operated at ~ 42 MeV. Conceptually, an electron bunch in the drive linac begins as a pulse in the master laser oscillator. From there it passes through a regenerative amplifier and two Ti:Sapphire amplifiers resulting in a 1.5 mJ pulse with a pulse length of 2-8 ps at 248 nm with a repetition rate of 10 Hz. The laser pulse is transported to the photoinjector where it strikes a Cs₂Te cathode and generates the actual electron bunch via photoemission. The electron bunch is accelerated by the RF cavity in the photoinjector which is powered by 12 MW at 1.3 GHz. This produces an 80 MV/m field on the photocathode surface which brings the bunch up to 8 MeV as it passes through the matching magnetic solenoid and into the first of six seven-cell standing wave accelerating cavities. Each cavity boosts the bunch energy by ~ 10 MeV resulting in a maximum final energy of just shy of 70 MeV. After exiting the final cavity the bunch passes through a series of magnetic quadrupoles that refocus the beam as it's transported downstream. At various points along the beampipe there are Ce:YAG screens on pop-in actuators that allow operators to image the beam for various diagnostics. About 13m after exiting the final accelerating cavity there is another magnetic quadrupole triplet that provides final focusing

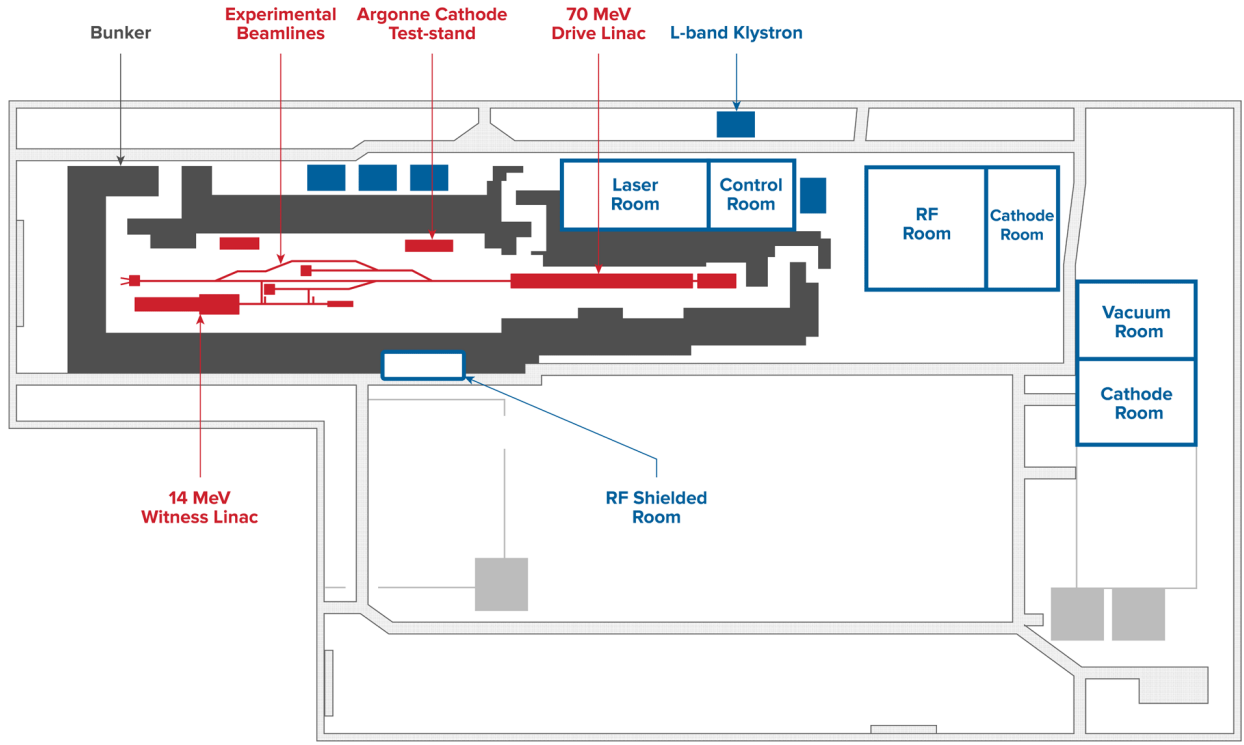


Figure 8.1: The Argonne Wakefield Accelerator Facility layout [64].

into the experimental area. After the experimental area the bunch passes through another set of magnetic quadrupoles and then a transverse deflecting cavity. Finally there is an optional dipole magnet for energy measurements.

8.2 The Experimental Structure

With AWA providing the beam, we still needed an actual experimental structure for the beam to interact with. The structure can be divided into two distinct sections, the dielectric material and the supporting structure that holds, aligns, and moves it. The dielectric material was prepared at UCLA using the resources of the UCLA Nanolab and Center for High Frequency Electronics (CHFE). We initially were able to procure two polished slabs of alumina that were $100 \times 100 \times 5$ mm. We brought the slabs to the CHFE shop where they

were diced into four 49×100 mm sections using a high speed diamond blade saw. Alumina is typically somewhat challenging to machine so we opted to use a saw designed to dice silicon wafers, both for the precision afforded and because the saw is abrasive which is ideal for the material. The missing mm is the kerf of the saw blade. One of the four sections was split again into two 49×49 mm pieces.

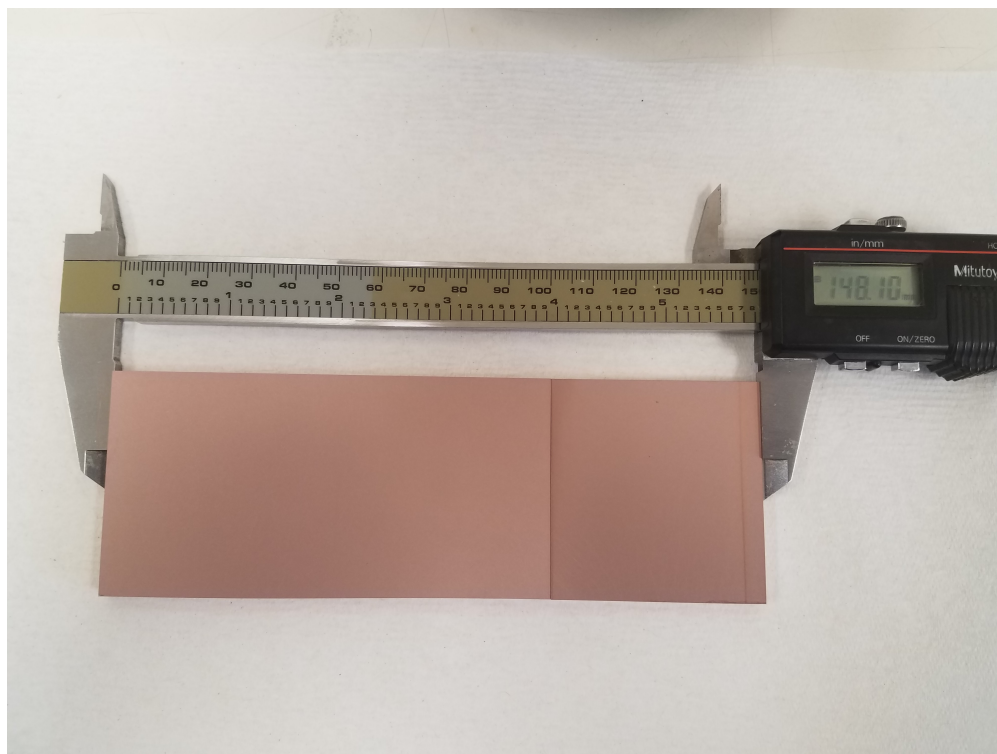


Figure 8.2: One half of the coated and cut alumina slabs, ready to be installed in the supporting structure. The coating is $3 \mu\text{m}$ of copper on top of a few nm of titanium. There are two sections because we were not able to obtain a monolithic section of dielectric with the requisite length. The boundary between the two dielectric sections is nearly seamless. The total length is, as shown, 148.1 mm, the width is 4.9 mm, and the thickness is 5 mm.

After dicing, the dielectric slabs were brought to the Nanolab for coating. There, $3 \mu\text{m}$ of copper was deposited using physical vapor deposition. A bonding layer of several nm of titanium was used to ensure good adherence of the copper to the alumina surface. An issue

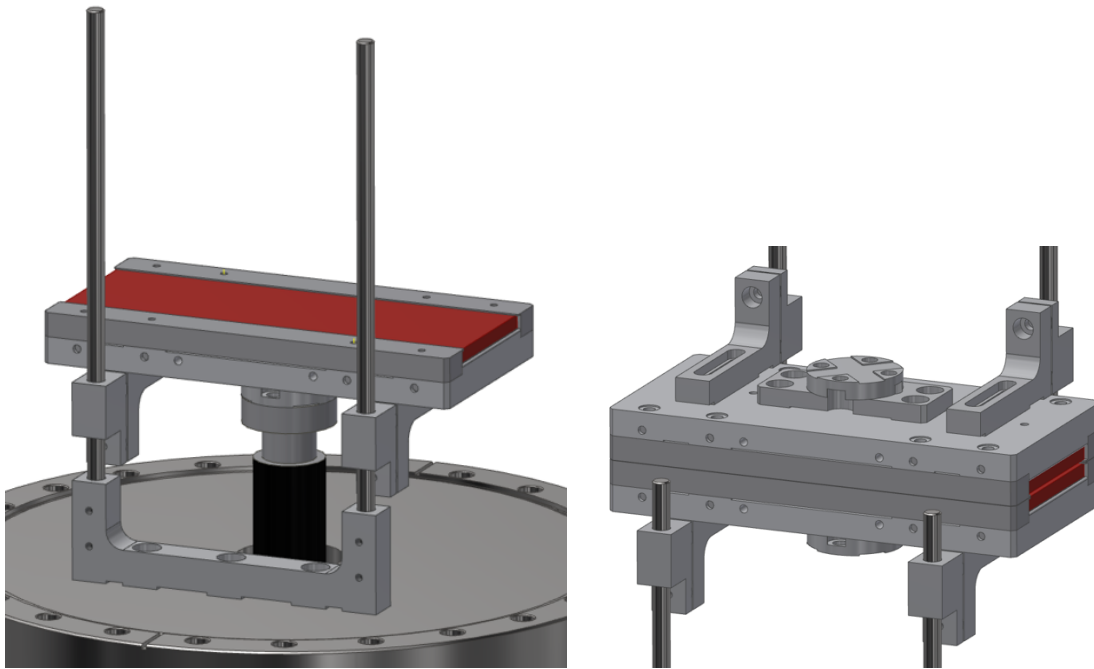


Figure 8.3: The support structure that retained, aligned, and moved the dielectric slabs. The red material represents the dielectric slabs. They're retained by small lips that protrude on the two aluminum pieces that immediately abut the sides of the slabs. These lips also serve as shims to set the minimum gap between the slabs. Rails mounted perpendicular to the flange face help to maintain alignment and correct wobble from the linear actuator. Dielectric face-to-face parallelism is initially set by the vacuum chamber and corrected with shims under the alignment rod collar.

occurred when we failed to mask the edges of the alumina before deposition which resulted in a copper coating along the 5 mm high sides. After some discussion we determined that a copper break “within” the dielectric was undesirable so we returned to the CHFE shop and removed one edge of each of the coated slabs. This additional operation is what caused the final 1 mm loss in total structure length. The finished slabs can be seen in Fig 8.2, the line in the slab is the joint between the two different sections.

The support structure was constructed at AWA using ANLs indigenous capabilities. It's purpose was to hold the dielectric sections such that the two surfaces were parallel and

separated by a known gap. That gap was to sufficiently adjustable such that each set of slabs could be independently retracted out of the beam path entirely and a YAG screen inserted from the side. To achieve this, each set of dielectric slabs was retained by independent, symmetric structures. CAD models of the structures sans the vacuum chamber are shown in Fig 8.3 and the full structure assembly is visible in Fig 8.4. Since each set of dielectric material is actually two pieces, they must first be aligned to each other. This is accomplished by pressing them against a monolithic strong-back creating a single uniform plane of reference. The components retaining the slabs to the strong-back are aluminum shoulders that have lips that protrude slightly in front of the dielectric surface. As the shoulders are tightened to the strong-back the lips press down on the dielectric, holding it in place. The aluminum lips flex slightly as the shoulders are tightened, this is important because the dielectric material is very rigid and will shatter if compressed. The lip thickness also functions to set the minimum gap between the slabs which serves as a reference point during operation of the structure and a safety feature to prevent collision between dielectric pieces. Motion is provided by two linear vacuum feedthroughs coupled to the strong-backs. Alignment between the two sets of slabs during motion is maintained by machined rods held perpendicular to the mounting flange faces. This greatly reduces the effect of the wobble induced by the linear actuator's motion. The direction of the alignment rods is coarsely set by the parallelism of the vacuum chamber and the flanges on which they're mounted. Finer alignment is achieved by shimming the mounting bracket to ensure the opposing dielectric components are parallel at all gap sizes.

After assembly, the experimental chamber is installed in the beamline as shown in Fig 8.5. In addition to the main chamber, the experiment makes use of other diagnostics already present in the AWA beam line. There are up- and downstream Ce:YAG screens, in conjunction with the one that can be inserted from the side of the experimental chamber, allow us to perform a three-screen measurement to extract the full set of Twiss parameters at the structure location [65]. YAG screens allow us to measure the transverse beam profile [66].

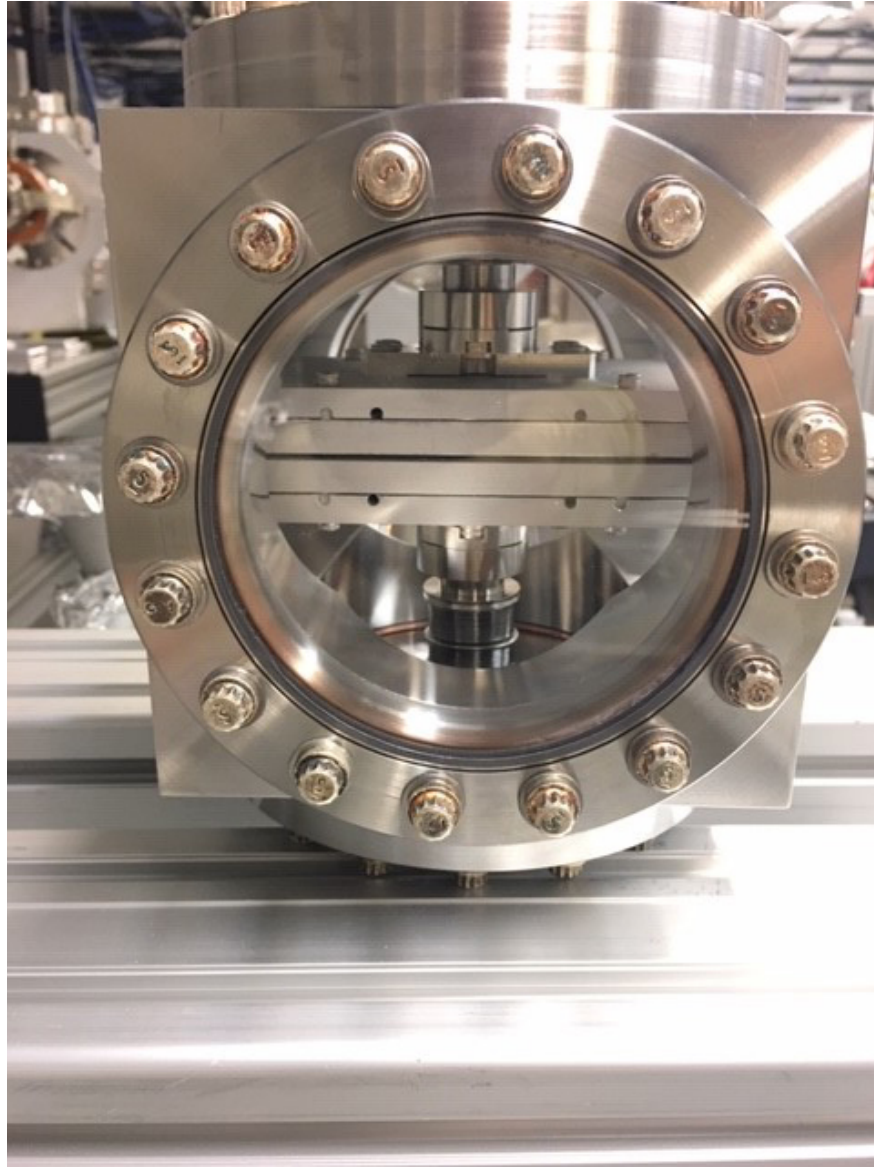


Figure 8.4: The full experimental assembly, mounted and installed in the vacuum chamber. The structure is currently in a nearly closed position given the visible gap on the edge. The dielectric material is not visible, the two visible pieces extending from the strong-back are the aluminum shoulders that retain the alumina. The in-vacuum portions of the linear actuators are visible above and below the strong-backs.

The YAG screens are read with CCD cameras placed as far off the beam axis as possible so as to avoid radiation damage. A series of mirrors are used to allow the cameras to view the back of the screen, including a mirror integrated into the screen holder at a 45° angle so as to allow viewing from the side. Next to the additional YAGs there are also Integrated Current Transformers (ICT) that allow us to measure the charge of the beam [67]. Positioning them on either side of the structure allows us to measure the transmission of the beam through the structure. This gives us a worst-case measure of any beam-breakup that causes beam loss. Immediately upstream of the ICT is a pair of steering magnets used for final beam alignment. Finally, several meters downstream of the experimental chamber is a dipole magnet used as an energy spectrometer.

Alignment of the structure to the beam axis was performed by adjusting the vacuum chamber housing the structure. This is necessary since the support structure has only one degree of freedom to reduce error during operation. The vacuum chamber was adjusted so that the structure, while set to the minimum gap setting, was aligned with a HeNe laser. This laser was previously aligned to a different HeNe that runs the length of the beam pipe. This two step process ensured that a beam traveling along the nominal beam axis sees a constant distance to the dielectric above and below. Some degree of skew in the x-z plane is permitted but this ultimately does not affect the interaction as long as it's small given that the structure is very wide relative to the beam. During operation the primary alignment laser can be toggled to show the location of the nominal beam axis on the YAG screens. The beam can then be aligned to these locations to ensure rough centering. Finer alignment leverages the transverse wakefields and their effect on the beam. Symmetrizing the transverse distortion of the beam ensures that the beam is “seeing” a symmetric structure.

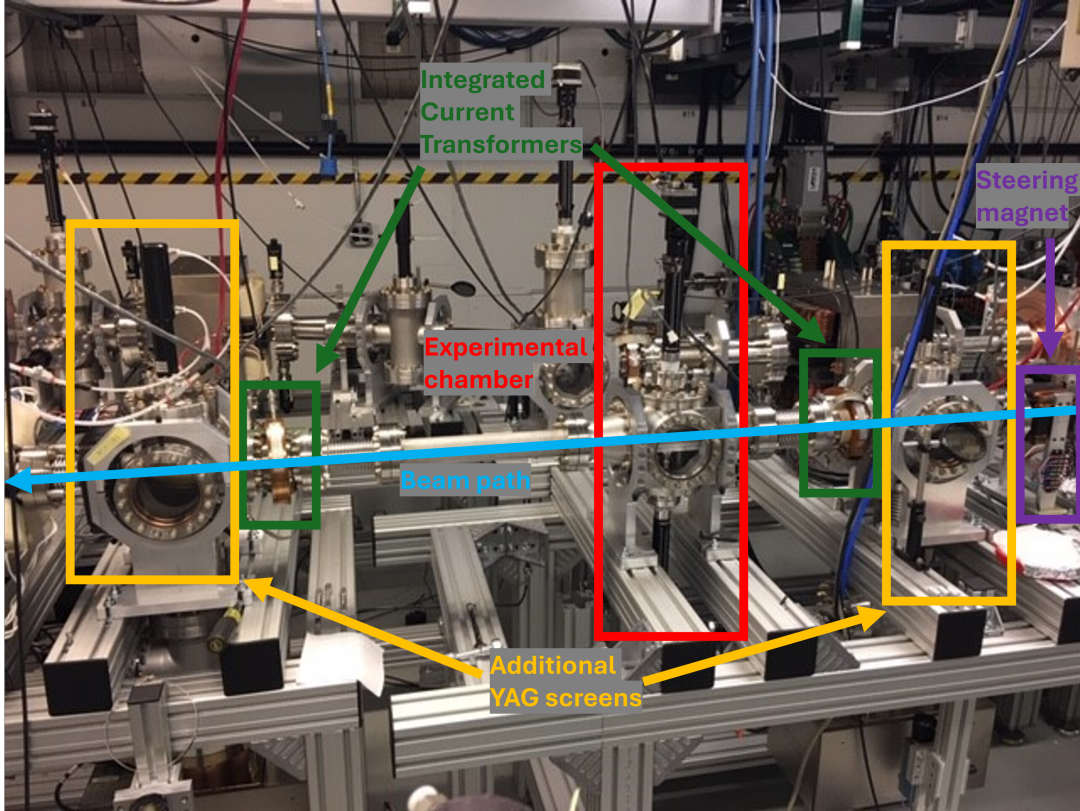


Figure 8.5: The assembled experimental structure installed in it's vacuum chamber and installed in place in the AWA beamline. The integrated current transformers allow us to measure transmission of the beam through the structure and the YAG screens before and after the structure help us to measure the beam parameters before inserting the structure. The experimental chamber contains an additional YAG screen that can be inserted from the side opposite the camera when the slabs are fully retracted. Furthest upstream is a steering magnet for aligning the beam with the structure.

CHAPTER 9

Results

9.1 Data

In this experiment we ran a flat electron beam at two different angles (θ) w.r.t. the x-axis through three different configurations of the dielectric structure. The three configurations can be identified by the number of dielectric slabs that the beam interacted with. The first configuration featured both slabs retracted and the beam propagating in free space. The second configuration had a single slab inserted, the top one, and so the beam experienced the structure asymmetrically such as the image on the right in Fig 6.1. The third configuration had both slabs inserted such as the image on the left in the same figure. We recorded the transverse distribution of the beam, projected in z, on a YAG screen downstream of the structure for every combination of θ and structure configuration. We also recorded the mean energy of the beam without the structure using a magnetic spectrometer. Further, by including the results of a screen that could be inserted in lieu of the structure and a third one upstream, we were able to compute the transverse emittance of the input beam. The measured input beam parameters are described in Table 9.1.

We computed the beam angles by applying a machine vision technique based on the Hough transform [68] to the YAG images of the beam with no structure interaction. The transform was originally designed to detect lines in images but has since been modified to include significant generalization [69]. Algorithmically the transform works by mapping every pixel in the image from x-y space to the set of lines intersecting that pixel as expressed

Table 9.1: Beam parameters measured and computed at the structure location.

Parameter (Symbol)	Value		Unit
Charge (Q)	2.0 ± 0.3		nC
Energy (U)	42 ± 0.2		MeV
Horizontal emittance (ϵ_x)	196 ± 19		μm Rad
Vertical emittance (ϵ_y)	2.5 ± 0.25		μm Rad
rms bunch length (σ_z)	610 ± 70		μm
Tilt angle w.r.t. x-axis (θ)	2.19	7.17	deg
rms horizontal size (σ_x)	1.70 ± 0.01	1.77 ± 0.01	mm
rms vertical size (σ_y)	0.22 ± 0.02	0.26 ± 0.01	mm

in polar coordinates. Often the image has been pre-processed depending on the application such as applying an edge finding algorithm. In our case we omitted pre-processing and simply used the intensity at each pixel as an additional weight. This means that in the transform space, the highest value pixel corresponds to the line that passes through the most “charge” shown on the screen.

Screen images of the single-slab results the two different measured values of θ are shown in Fig 9.1. Here the beam is passing 0.91 mm below the dielectric surface and there is no dielectric below the beam. The two rows correspond to the two θ values described in Table 9.1. In the first row, a) transforms into b) in the absence of the dielectric structure and into c) with the dielectric inserted. The difference between b) and c) is then due to the effect of the transverse wakefields. Similarly in the second row d) transforms into e) in free space, and into f) when interacting with the structure. From these results we can clearly see a confirmation of the model described in 6. First, a strong quadrupole-like transverse effect in general is evident. Second, as θ is increased, the skewing of the effect becomes pronounced

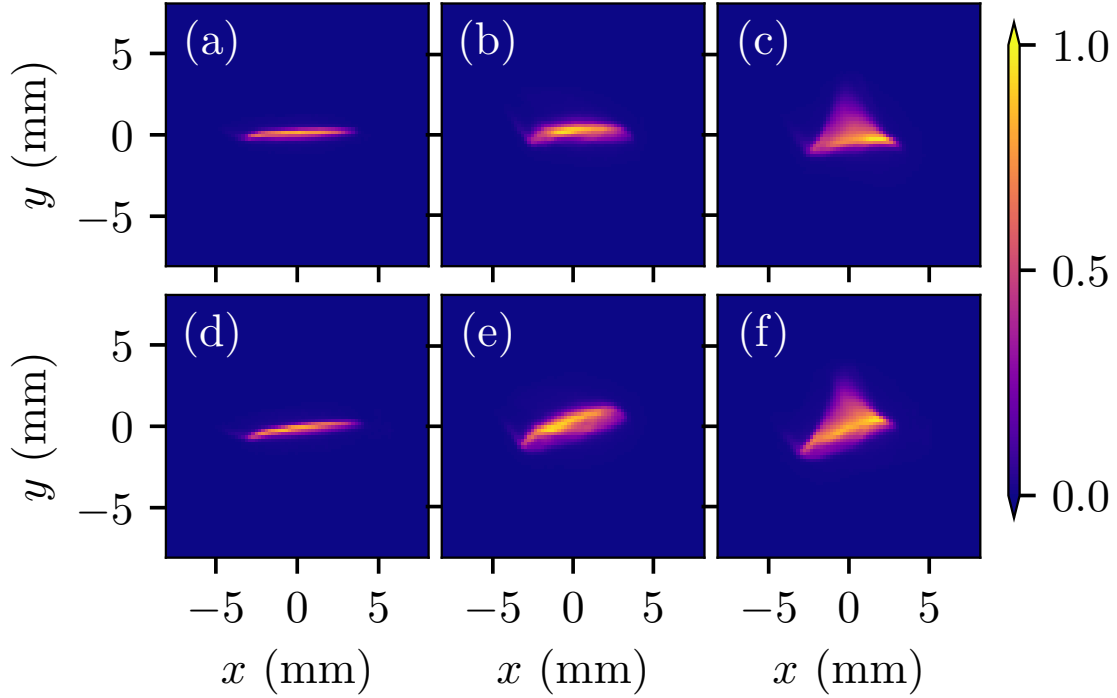


Figure 9.1: YAG screen images of the beam for the single-slab configuration. The first row (a-c) corresponds to a beam angle θ of 2.19° and the second row (d-f) corresponds to a θ of 7.17° . The first column (a, d) shows the beam at the structure location with the dielectric retracted. The second column (b, e) shows the beam at the downstream YAG, also with the dielectric retracted. The third column (c, f) shows the beam at the downstream YAG with the dielectric inserted. The color map is uniform across images and normalized to the peak value in a).

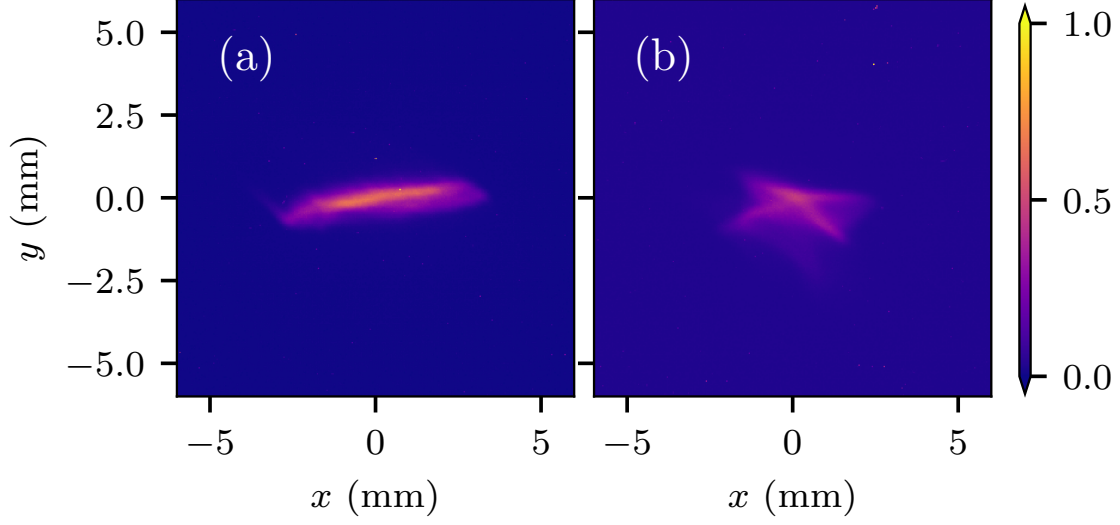


Figure 9.2: YAG screen images of the beam at an angle θ of 7.17° with the dielectric in the double-slab configuration. Both images are of the downstream YAG. Image a) is when the dielectric slabs are retracted. Image b) is when the slabs are both inserted creating a gap of 1.83 mm.

as demonstrated by the two-particle model in Fig 6.2. Finally, we can see that a portion of the beam is unchanged indicating that the visible effect is occurring in the tail of the beam as predicted.

Screen images of the double-slab results for $\theta = 7^\circ$ are shown in Fig 9.2. The image of the beam at the structure location is omitted as it's identical to d) in Fig. 9.1. These images indicate a highly complex interaction as evidenced by the rotation of tail particles in the beam. One potential source of this effect could be a chromatic error in the flat-beam transformation leading to significant correlations in the tail of the beam. A full understanding

of these results would require disproportionate investment and so they have been tabled for future study.

9.2 Simulation

In order to better understand and validate the results we performed additional simulations with updated beam and structure parameters to better match the experimental conditions. Using the same tools described in Ch 7 we re-ran the simulations with the beam parameters in Table 9.1. These simulations are valuable because in addition to verifying our understanding of the experiment, they provide additional insight into the intra-beam dynamics that cannot be observed due to the inherent longitudinal integration that occurs during measurements with the YAG screens. Figure 9.3 shows a simulated recreation of the measurements in Fig 9.1 which accurately reproduces the key skew effects depicted in the latter. When the beam is nearly parallel to the surface, the resultant effect is a composite of the dipole and quadrupole fields. When the beam is tilted significantly the quadrupole fields acquire an additional skew component.

9.3 Wake Reconstruction

The material in this section is adapted from [70] in accordance with the UCLA Dissertation Requirements section “ALTERNATE VERSIONS OF PUBLISHED ARTICLES”

In order to better understand the nature of the skew beam-structure interaction and attempt to quantify it, we deployed a newly developed reconstruction technique as described in detail in [70]. In general, the technique attempts to reconstruct the transverse wakefields based on YAG images of the beam at the same location, with and without structure interaction. It does this by first turning the images into Probability Density Functions (PDF) and then generating particle distributions from those PDFs. The distribution generated from the

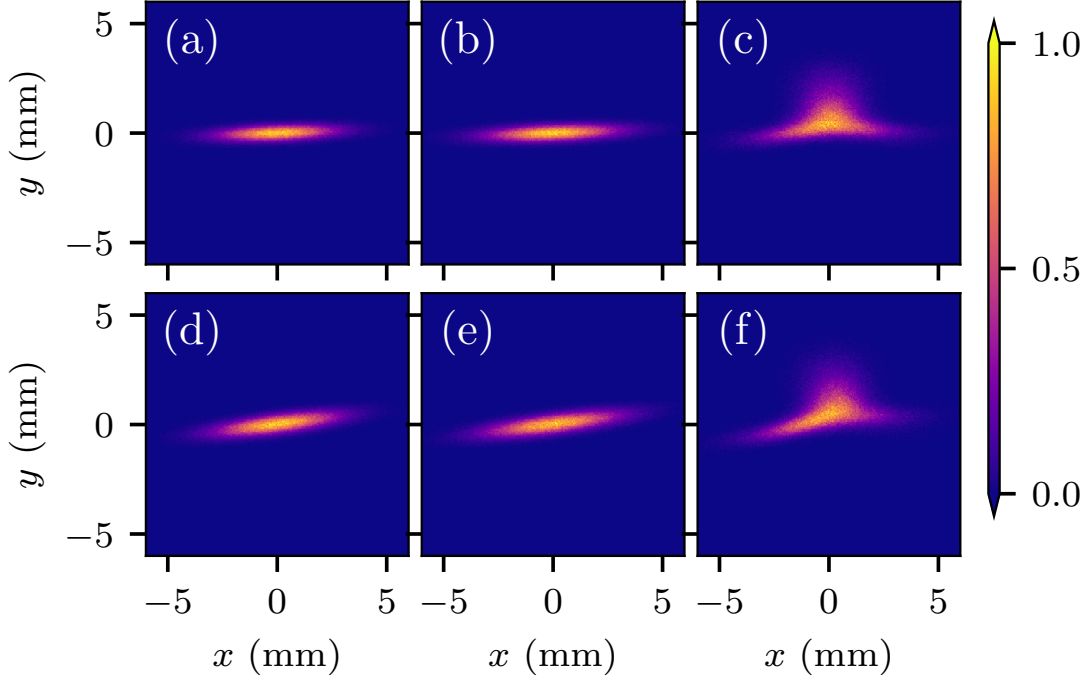


Figure 9.3: Simulated screen images corresponding to Fig 9.1. The beam-structure interaction used WARP and downstream transport to the YAG screen used a simple matrix formalism when appropriate. The color map shows normalized charge density in arbitrary units.

beams without structure interaction is then subjected to kicks of the form

$$p = p_0 + p_c + \frac{\kappa \vec{W} L}{p_z} \quad (9.1)$$

where p is the new location of the particle, p_0 is the old location, p_c is a constant across the entire population to account for drift, κ is a scaling factor, $\vec{W}$ is the transverse field map, L is the distance between the structure and the screen, and p_z is the mean longitudinal momentum of the beam. The field map $\vec{W}$ can be decomposed into a multipole form

$$\vec{W} = -(a_1 + b_1) - 2a_2(x + y) - 2b_2(x - y) - a_3(3x^2 + 6xy - y^2) - b_3(\dots) \dots \quad (9.2)$$

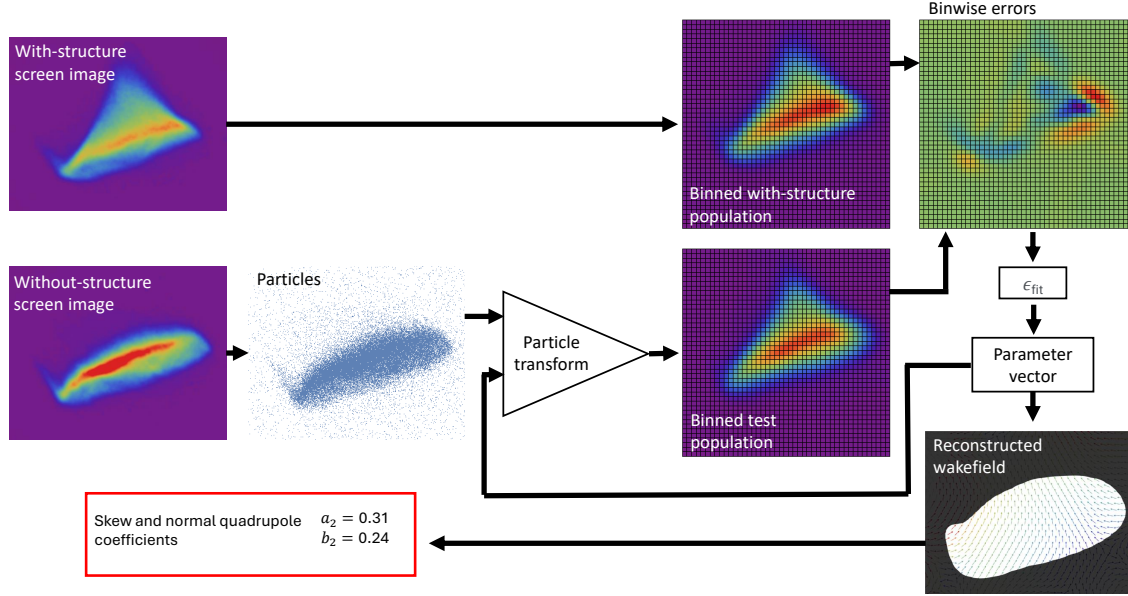


Figure 9.4: The fitting process flow chart. The “without-structure” image is converted into a particle distribution which is then kicked by a field map. The kicked distribution is compared to the “with-structure” distribution to compute an error. A numerical optimizer minimizes this error to produce a final kick map which can then be queried.

Here, a_n and b_n are the n th order skew and normal multipole coefficients respectively. The with-structure distribution and the post-kick distribution are both then binned and an error is computed. A numerical optimizer is then applied to modify the kick map coefficients a_n and b_n , p_c , and $\mathcal{K}$, the PDF that κ is drawn from. The process is repeated until the solution converges. Fig 9.4 is a diagrammatic overview of this process. Further details of this process are described in [70]. After reconstruction we can then simply read off the coefficients of the multipole decomposition of the transverse kicks.

We applied this reconstruction process to our data as seen in Fig 9.5. The incoming no-structure beam is depicted in (a) which also defines the region of interest in the kick-map (b). Visually, comparing the final reconstructed beam (d) to the experimental result (c) we can see that the result is quite reasonable although there are some minor differences. Further,

comparing the reconstructed kick map in the region of interest (b) to the two-particle model in Fig 6.2 we continue to see agreement. Numerically, this process resulted in skew and normal quadrupole coefficients in the kick map of 0.31 and 0.24 respectively. This further supports the conclusion that the shape of the beam after interacting with the structure at an angle is due, in part, to a skew quadrupole-like field.

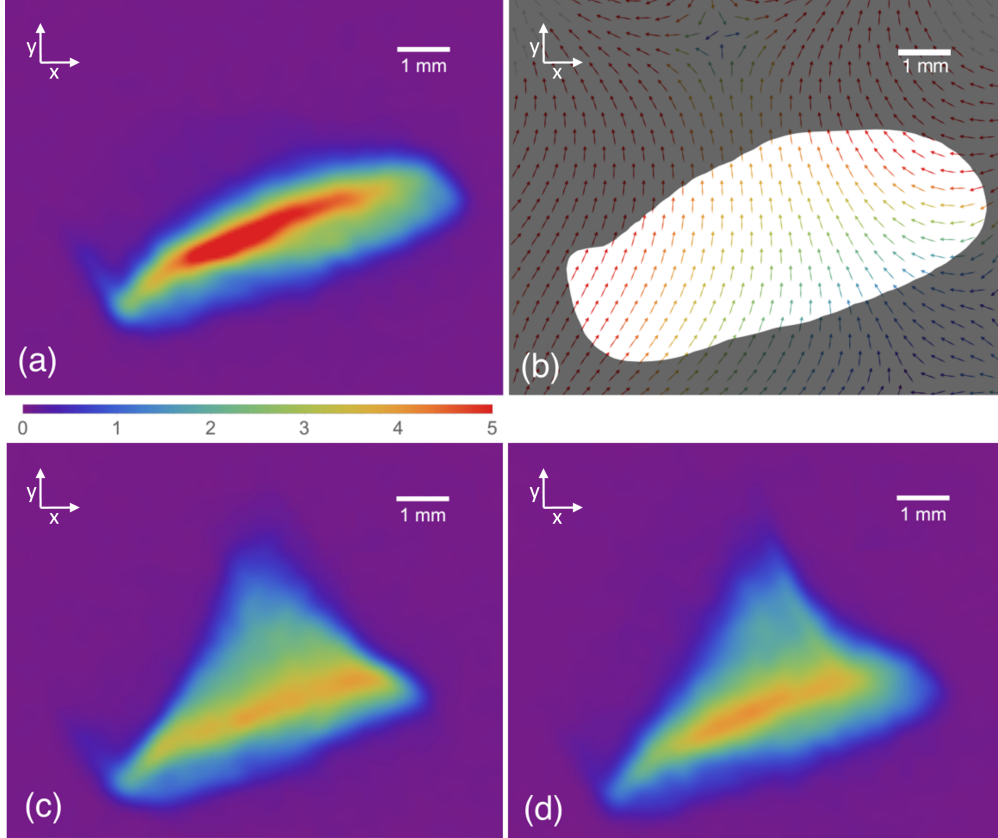


Figure 9.5: The results of the wakefield reconstruction technique. Image (a) is the beam without structure interaction and image (c) is the beam with structure interaction. The reconstruction technique generates a kick-map (b) which is intended to transform (a) into (c). Image (d) is the actual result of applying (b) to (a), by comparing it to (c) we can speak to the effectiveness of the reconstruction.

To close the loop, we used simulation to generate a kick map in an entirely different manner. Since we can access the beam at any point in time during a simulation, we're able

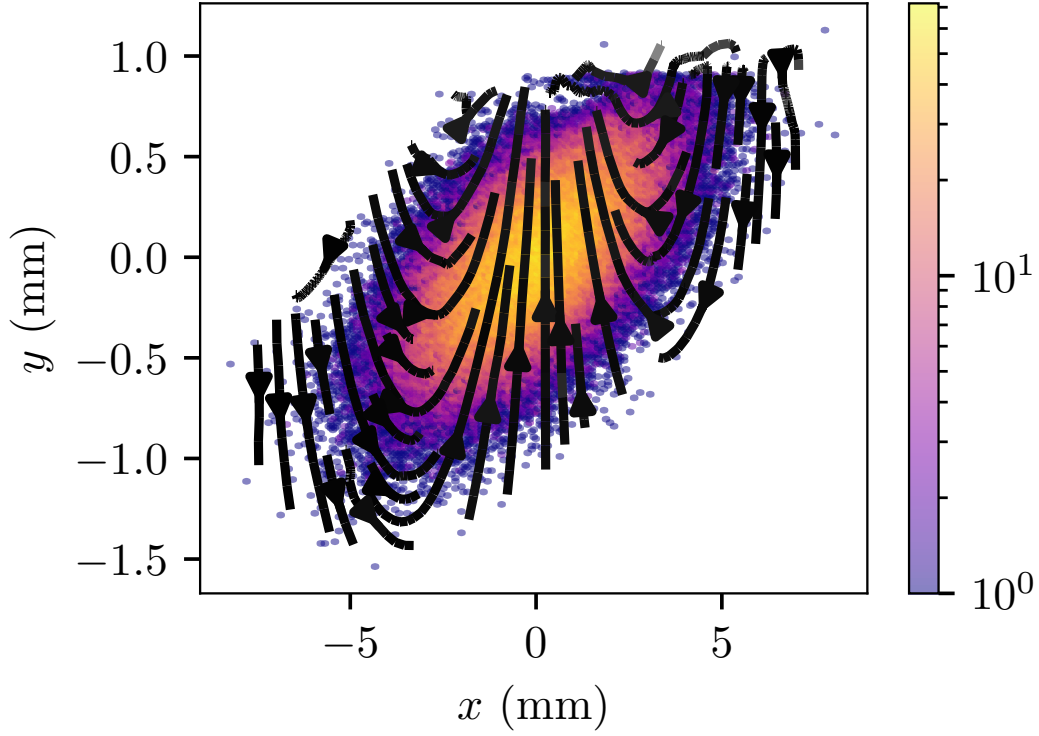


Figure 9.6: The kick map experienced by the shown beam in a simulation. The map is generated by fitting the numerically integrated change in transverse momentum of the beam to the multipole expansion.

to directly integrate the forces on the beam as it interacts with the structure. The result of this is visible in Fig 9.6 which is directly comparable to Fig 9.5 (b). With this we have dual agreement, the reconstructed kick map matches the theoretical model and simulated kicks. Ultimately these results efficiently demonstrate the fundamental nature of the skew wakefields produced by tilted beams.

CHAPTER 10

The Alternating Dielectric Wakefield Accelerator

The premise of this experiment is to find a way to regain control from the instabilities that drive beam breakup. This experiment was borne out of the frustration inflicted by the quadrupole-like mode of planar-symmetric dielectric structures. We found via simulation that even flat beams were eventually destroyed by this mode and so sought to do something about it. Eventually we came to the conclusion that suppressing the instabilities directly was unsustainable but perhaps manipulating them might be more fruitful.

The first step is to instigate an instability ourselves instead of letting it develop spontaneously. We accomplish this by using a planar symmetric dielectric structure similar to the one used in the skew wake experiment. This structure has an inherent quadrupole-like response, even to perfectly on-axis particles. The nature of that quadrupole response is largely dictated by the orientation of the structure which means that we can externally control the stable and unstable directions of the beam by controlling the orientation of the dielectric structure. The result of this is a structure such as the one depicted in Fig 10.1. As a beam proceeds through this structure, at any one instant in time it sees a simple planar structure and begins to destabilize accordingly. When the beam passes to a rotated section of the structure, the orientation of the transverse wakes suddenly rotates as well. Integrated along the length of the structure, the cumulative effect of the transverse wakes can be programmed via the length of the various dielectric sections. This programming must take into account the beam parameters and other structure parameters, such as the vacuum gap described by a , the dielectric thickness $b - a$, and the dielectric permeability ϵ . If the periodicity of the

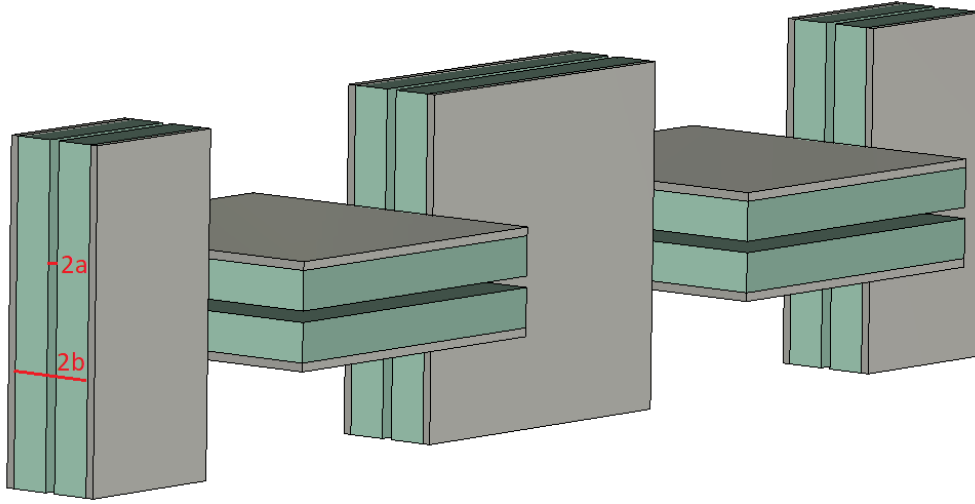


Figure 10.1: The Alternating Dielectric Wakefield Accelerator concept. Planar sections of dielectric structure are periodically rotated about the beam axis. The beam passes through the slab sections and at any one point in time sees a planar cross section but, integrating longitudinally, the aperture is actually square.

structure is quite short, such that the driving beam does not spend enough time within one orientation to experience significant transverse particle motion, then the alternating structure simply results in a cancellation of the transverse momentum. An example of this cancellation approach can be seen in various dechirper modules such as [71] at Brookhaven National Laboratory and [72] at Stanford National Laboratory, which used a corrugated waveguide as the slow-wave structure instead of dielectric, but the principles remain the same. On the other side of things, the structure periodicity can be so long that the transverse forces cause the tail of the beam to strike the structure edges. In this case, the head of the beam and some core regions of the tail may survive, but the overall result is obviously undesirable. In this experiment, we attempt to strike the middle ground, where the structure period is long enough to permit non-negligible transverse motion, but not so long as to induce beam loss. Permitting this transverse motion allows us to leverage second-order effects to actually focus the beam rather than simply canceling momentum. There is significant historical interest in

dielectric structures with similar geometries [73, 74, 75, 76, 77] but these examinations have not proceeded beyond the simulation stage. To gain a deeper understanding of the system we elected to perform a full experimental test of this dielectric structure with and at the Argonne Wakefield Accelerator facility.

CHAPTER 11

Simulation

This chapter was adapted in part from [78] in accordance with the UCLA Dissertation Requirements section “ALTERNATE VERSIONS OF PUBLISHED ARTICLES”

The ADWA experiment was preceded by a significant simulation campaign, first to verify the plausibility of the basic concept and second to establish the experimental parameters. We began this experiment with only the notional idea that we could somehow exploit the inherently quadrupole-like response of the planar-symmetric dielectric structure. We had no existing theoretical framework to analyze a dielectric wakefield acceleration structure that incorporated a longitudinal geometric variation. As a result we turned to simulation tools to check our intuitive expected results and to build understanding of the system in question. We actually began by examining continuously varying dielectric structures such as in Fig 11.1. The initial idea was simply to disrupt the instability caused by the quadrupole-like wakefields. We thought that by constantly varying the orientation the instability would not have time to develop. This intuition was actually correct, the quadrupole-induced breakup was gone, but instead it was replaced by a rather severe corkscrew instability. Additionally, we determined that manufacturing such a structure would be prohibitively difficult and costly. This led to our decision to switch to a piecewise-alternating structure as seen in Fig 10.1.

Initial simulations with the piecewise structure were highly exploratory, we were attempting to understand the system rather than test specific parameters. The test beam parameters are shown in Table 11.1 and are a combination of experimentally achievable

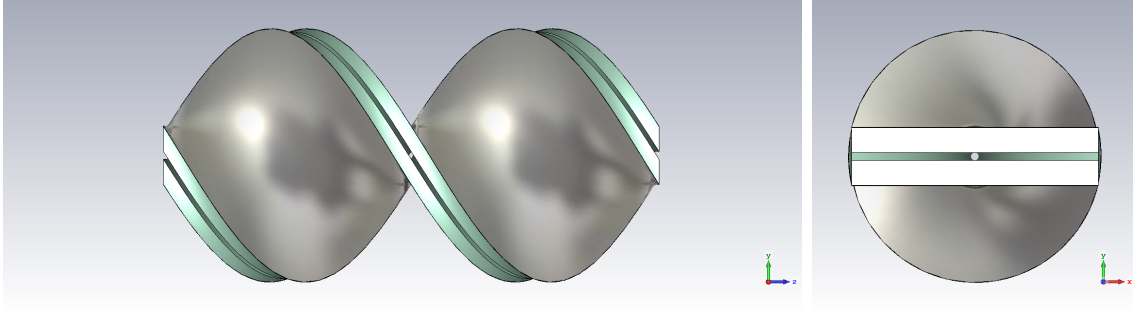


Figure 11.1: A single period of a continuously varying dielectric structure. Any single cross-sectional slice is identical to a planar configuration. The image on the left shows the structure from the side with the beam passing from left to right. The image on the right shows the beam’s perspective with the only clear aperture being the smaller circle in the center of the gap despite the planar-symmetric cross sections.

Beam Parameters	
Energy	40 MeV
Charge	1 nC
σ_x	10 μm
σ_y	10 μm
σ_z	600 μm
ϵ_{Nx}	0.05 μm Rad
ϵ_{Ny}	0.05 μm Rad

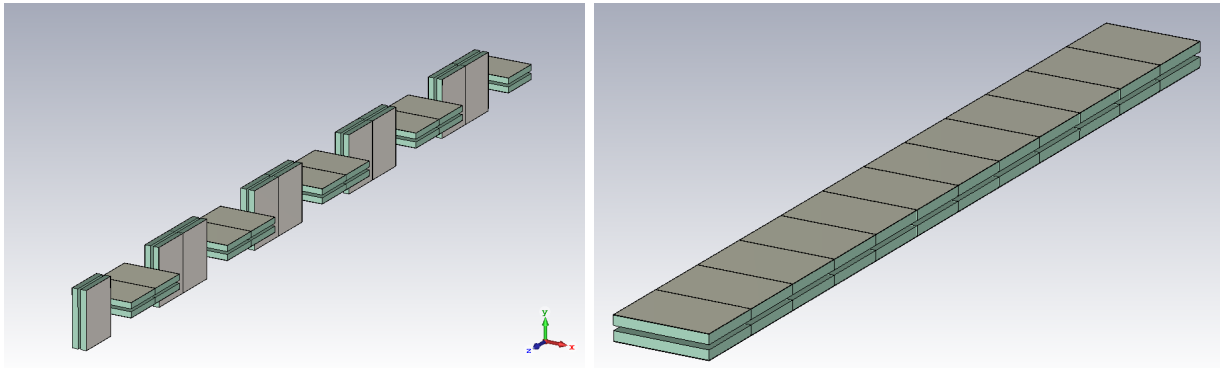
Table 11.1: The beam parameters used during simulations of the early dielectric structures. The values are loosely based on experimentally predicted parameters at SLAC’s FACET-II facility [79] except the energy and beam length are scaled to values accessible at AWA. The emittance is artificially reduced to provide clarity when examining the short range wakefields. The beam is mono-energetic.

Structure Parameters	
Gap	1 mm
Period length	30 mm
Slab thickness	2 mm
Dielectric constant	3.75
Number of periods	9

Table 11.2: The relevant geometric parameters of the alternating structure used for our initial simulations. The structure itself is shown in image (a) of Fig 11.2

values at both FACET-II and AWA. We artificially reduced the emittance to more clearly show the beam-structure interaction as with the skew wake experiment. We conducted simultaneous simulations in two different structures, a “test” structure and a non-alternating “control” structure as seen in Fig 11.2 with the relevant geometric parameters in Tab 11.2. This allowed us to directly see the impact that the alternating geometry had on the beam, in contrast to a non-alternating case. The “control” structure also served as a readily available demonstration of the existence of a strong transverse wakefield effect. Further, the non-alternating structure allowed us to understand how quickly the quadrupole-induced deformation of the beam occurred which informed future decision making on matters such as the structure period and gap. We can see example results of these simulations in Fig 11.3, the non-alternating structure demonstrates extreme deformation of the beam. These images are essentially simulated YAG measurements of the XY distribution of the beam at the exit of the structure.

Additionally, since this is a simulated environment, we’re able to examine other perspectives that may be difficult to view experimentally. One such perspective is the beam’s YZ distribution, as seen in Fig 11.4, which is valuable to examine since we can see the ζ -dependence of the transverse wakefields through the deformation of the tail. This gives us



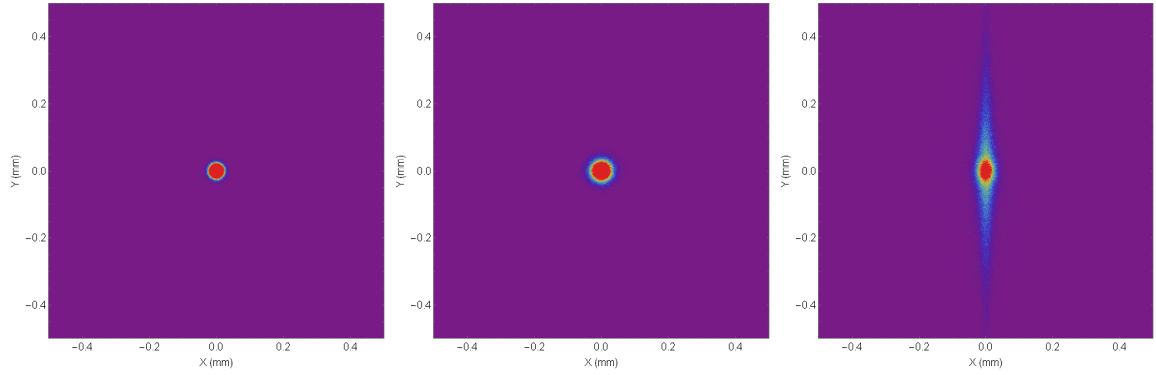
(a) An early concept for the ADWA structure.

(b) The control geometry.

Figure 11.2: The two simulated structures. Structure (a) tests the ADWA concept and (b) verifies that there are strong transverse wakefields with significant effects on the beam if unaddressed. The ADWA structure attempts to counteract the adverse effects of the transverse wakefields through the periodic manipulation of the structure geometry.

a time-dependent view of the wakefields, not just the projected result. As the results in Fig 11.4 show, for these parameters the transverse wakefields don't have a significant effect until about halfway down the beam at which point their effect rapidly becomes quite pronounced, thoroughly smearing the beam out in the vertical direction. Further back, this effect is so strong that scant few particles remain near their original location with the rest having been spread across the available space. Upon close examination, we can see evidence of beam loss starting at approximately $Z = 0$ mm and continuing further back. We can see this by noticing that the beam distribution in this region appears to sharply stop at $Y = \pm 0.5$ mm which is consistent with a structure gap of 1 mm.

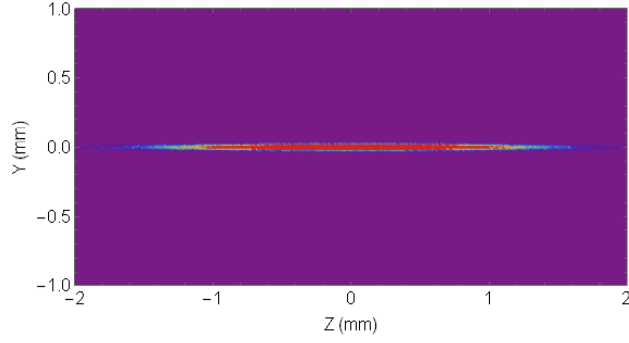
One very early issue we encountered was the fact that the structure geometry varied longitudinally which breaks the built-in assumptions of many simulation codes. CST, which we used in the skew wake experiment, handled this condition well enough but WARP did not. This was problematic because early designs featured dielectric structures of significant length such as shown in Fig 11.2. Computationally, one of the biggest differences between



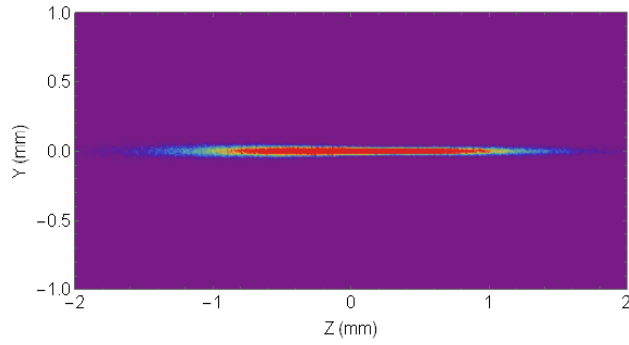
(a) At the entrance to the structures. (b) At the exit of the alternating symmetry structure. (c) At the exit of the “control” structure.

Figure 11.3: XY trace spaces of the beam at the start of the structures and at the end of both the alternating symmetry structure and control structure. Contrasting (b) and (c) we can clearly see the effect of the transverse wakefields focusing in the x-direction and de-focusing in the y-direction in the distortion of the beam core and the significant vertical spreading of the beam. The color map indicates the charge density.

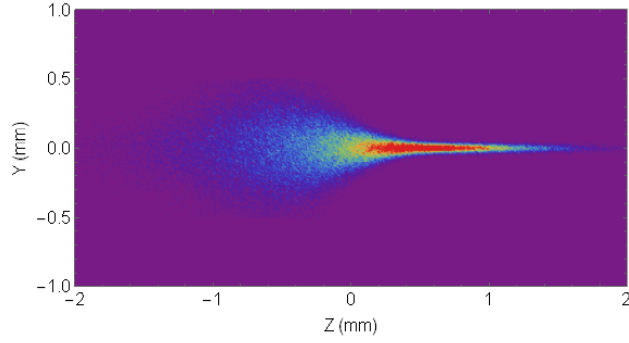
CST and WARP is the ability of WARP to use a moving window to conduct the simulation. What this means is that WARP can simulate a co-moving window that contains the beam and as much trailing structure as desired to show the field structure. Since the length of this window is typically much shorter than the structure length this drastically reduces the computational load of the simulation, both in terms of time and memory required. For our longer designs, CST which does not possess a moving window feature, was unable to hold the entire structure in memory on the available hardware. This required us to reduce the mesh frequency, and correspondingly, the accuracy of the simulation. Unfortunately the moving window feature in WARP is incompatible with the longitudinal geometric variation of the structure. Significant effort was devoted to circumventing this issue until it was deemed futile. A successor code to WARP, WarpX, has rectified the issue however [80]. Ultimately we were forced to reduce the simulation accuracy enough to actually run the simulations in CST. Other codes, like WARP, were unable to handle the longitudinal geometric variation.



(a) At the entrance to the structures.



(b) At the end of the alternating structure.



(c) At the end of the “control” structure.

Figure 11.4: The YZ distributions of the same beams as Fig 11.3. The beams are traveling in the z -direction and so the head of the beam is on the right. Image (c) clearly shows the effect of the transverse wakefields, demonstrating not only the quadrupole-like vertical de-focusing but also beam loss in the tail. The beams have all been rescaled to be centered at $Z = 0$ and the color map describes the charge density.

The initial course of simulations clearly validated the basic concept of the Alternating Dielectric Wakefield Accelerator concept but there was clearly much more work to be done. All aspects of the simulations were iterated upon to bring them more in line with basic reality. First, we settled on conducting the experiment at the Argonne Wakefield Accelerator Facility as opposed to FACET-II which had also been under consideration at the time. This meant that the beam parameters had to be updated to reflect the hardware. Second, we began designing the actual experimental structure and quickly came to the conclusion that even the most basic conception required significant mechanical complexity and so we needed to simplify the design as much as possible. A detailed description of the design of the physical structure and supporting apparatus is in Ch 13. The biggest change that resulted from this simplification is that we abandoned the idea of embedding the structure within a magnetic lattice which meant that the overall length was capped by the expansion of the head of the beam in a drift. The decision to conduct the experiment at AWA meant that we could nail down the beam parameters much more accurately. Using the OPAL accelerator code [81] we conducted start-to-end simulations of the AWA beamline, ending at the dielectric structure. Using OPAL we also attempted to optimize the AWA lattice in order to produce the lowest emittance beam possible with the desired charge. Table 11.3 contains the parameters of the beam that resulted from the OPAL optimization which we used for the next round of simulations.

The new beam parameters necessitated a change to a new structure geometry. All of the same tradeoffs involved in the design of the Skew Wake structure apply here as well. The beam size and emittance set bounds on the structure gap and the total length while the beam energy and gap affect the period length for the alternating sections. A smaller, low emittance beam will fit through a smaller gap and a smaller gap will drive stronger wakefields which necessitate shorter periods. Through an iterative process we arrived at the structure shown in Fig 11.5 with the parameters listed in Table 11.3. In addition to the previously mentioned change in length, the period was increased to 80 mm, the slab thickness

Beam Parameters	
Energy (U)	60.9 MeV
Charge (Q)	1 nC
Length (σ_z)	639.8 μm
Width (σ_x)	69.2 μm
Height (σ_y)	76.5 μm
Horizontal Emittance (ϵ_x)	2.82 μm Rad
Vertical Emittance (ϵ_y)	3.37 μm Rad

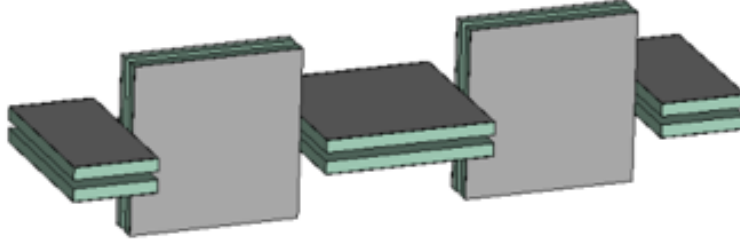
Table 11.3: The beam parameters for the second iteration of simulations for the ADWA structure. These were generated based on start-to-end simulations and optimizations of the AWA beamline conducted in OPAL.

Structure Parameters	
Vacuum Gap	0.8 mm
Period	80 mm
Width	20 mm
Total Length	160 mm
Slab Thickness	5 mm
Dielectric Constant	9.4

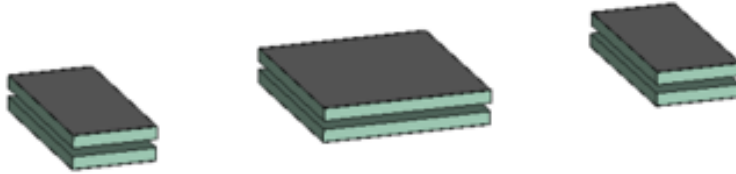
Table 11.4: Dielectric structure parameters that resulted from our OPAL-optimized beam informed simulations.

increased to 5 mm, and the dielectric material changed resulting in a new constant of 9.4. The period was increased because, as the goal of the experiment was clarified, we began to focus more on demonstrating second-order focusing with the quadrupole-like wakefields. In order to achieve this, each orientation of the structure needs to be long enough for the beam to evolve transversely before the orientation is changed again. We increased the slab thickness, both for ease of handling and machining but also to increase the fundamental wavelength of the structure to keep the accelerating region away from the beam. The change in dielectric constant represents a change from fused quartz to alumina and was done for reasons similar to the increase in slab thickness. We have significant experience working with alumina, especially at AWA and so it was a safe choice of material. A final change was to the layout of the structure rather than its other parameters. We rearranged the order of the slabs to ensure that the structure began with a quarter period length of dielectric and ended on an identical quarter period length to help match the beam into the structure, this is similar to alternating gradient undulators present in free electron lasers [82, 83].

Simulations of this new beam-structure combination showed clearly that the concept still held. Transverse distributions in the form of simulated YAG measurements can be seen in Fig 11.6 and YZ distributions can be seen in Fig 11.7. The simulated YAG measurements show only slight distortion of the beam in the ADWA case and the expected prominent quadrupole-like effect in the non-alternating case. It's important to note the change in geometry of the non-alternating structure, now the sections in the “wrong” direction are removed instead of rotated to better represent anticipated experimental reality. This means that the beam passing through the non-alternating structure only experiences half the beam-dielectric interaction of the full-structure case. Overall however, the transverse results are in-line with the previous simulations shown in Fig 11.3. The YZ distributions show much more variation compared to Fig 11.4. First we notice that the beam inherently has some outward fanning of the tail, even in the no-structure case. When looking at the non-alternating result we see that the biggest area of transverse deformation is now around the center of the



(a) The updated ADWA dielectric structure geometry. This structure is based on updated beam parameters listed in Table 11.3.



(b) The updated ADWA “control” structure geometry. This geometry better represents the anticipated experimental configuration. Dielectric sections in the wrong orientation cannot be physically rotated, only retracted. This retraction is represented in the simulation by simply deleting them.

Figure 11.5: The updated test and “control” dielectric structures as a result of new beam parameters.

beam, not the tail. The degree of transverse deformation is not quite as extreme as well, with the new beam not exhibiting beam loss. The longitudinal dependence of the transverse deformation is also quite interesting, showing us that the periodicity of the transverse wake-fields has changed significantly due to the change in structure parameters. This manifests in the alternating structure result as well, the most significant effect there is that not only does the beam not exhibit significant transverse deflection or adverse deformation but there appears to actually be transverse focusing near the center of the beam. The location of this apparent transverse focusing lines up well with the region of greatest transverse de-focusing in the non-alternating case which is expected in the event of successful second-order focusing. This is very promising given the goals of the experiment.

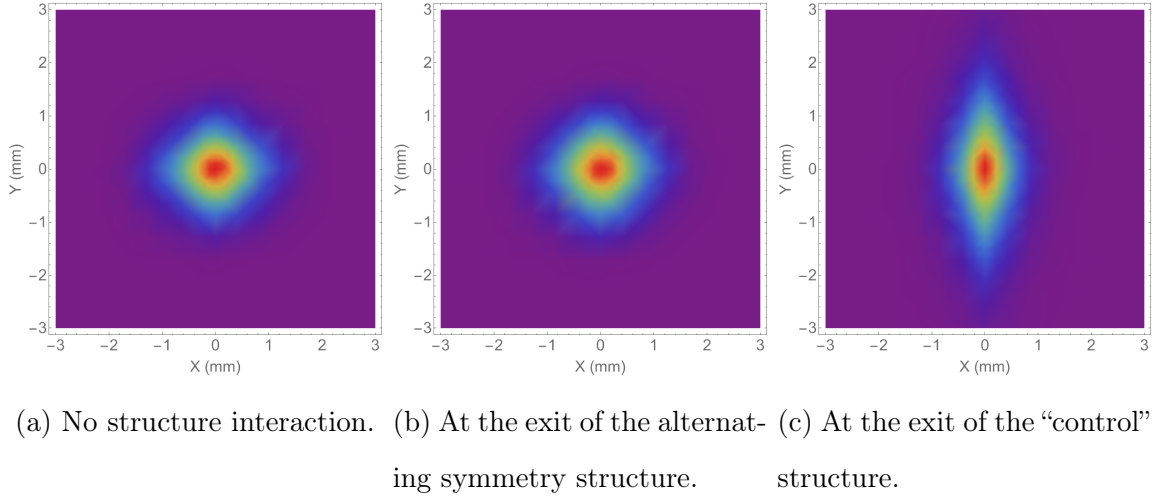
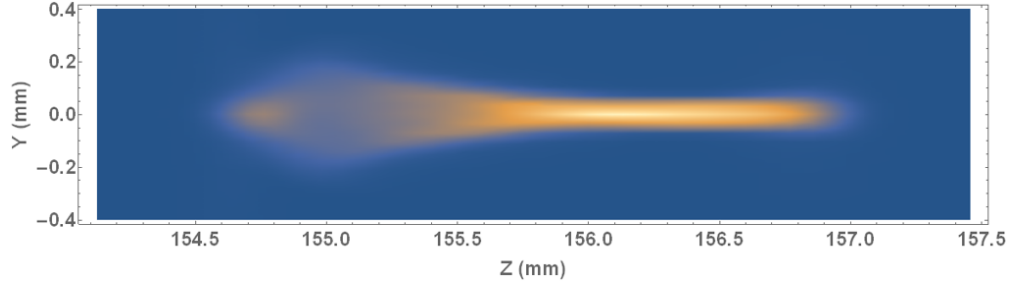
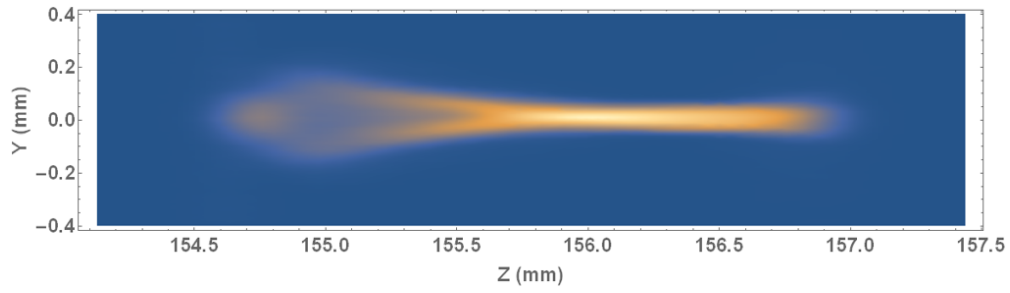


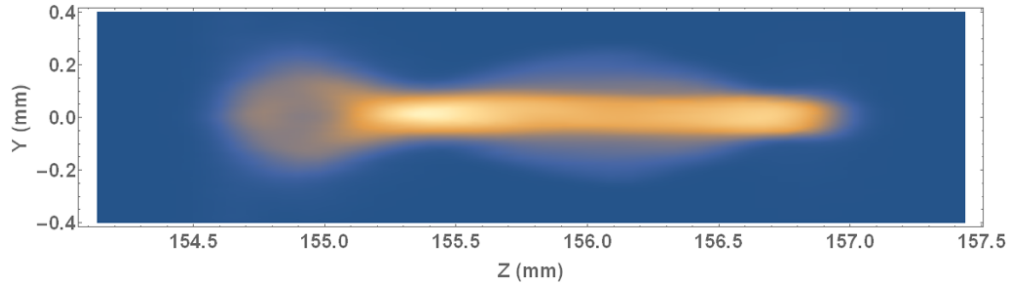
Figure 11.6: Simulated YAG screen measurements of the updated beam described in Table 11.3 interacting with the updated structures seen in Fig 11.5. In contrast to previous simulations, (a) shows the result of simulating the beam passing through simple vacuum of equivalent length to the structure. This provides a better comparison than showing the beam at the beginning of the structure.



(a) No structure interaction.



(b) At the exit of the alternating symmetry structure.



(c) At the exit of the "control" structure.

Figure 11.7: Simulated YZ distributions of the updated beam described in Table 11.3 interacting with the updated structures seen in Fig 11.5. In contrast to previous simulations, (a) shows the result of simulating the beam passing through simple vacuum of equivalent length to the structure. This provides a better comparison than showing the beam at the beginning of the structure.

CHAPTER 12

Theory

Theoretical analysis of the alternating gradient structure is fundamentally an extension of the analysis of the two-slab configuration used in the skew wake experiment. We begin by considering Eq 6.8, reproduced here, as it gives us our instantaneous transverse field map.

$$F_{\perp}(\omega, \omega_0) = \frac{\pi^3 q Q \theta(\zeta) \zeta}{8a^3} \text{sech}^2 \left(\frac{\pi}{4a} (-(x - x_0) + i(y + y_0)) \right) \tanh \left(\frac{\pi}{4a} (-(x - x_0) + i(y + y_0)) \right) \quad (12.1)$$

Numerically convolved with a gaussian particle distribution, this equation generates maps such as those in Fig 12.1. Analytically, for an on-axis source, to first order this becomes

$$F_x = -\frac{\pi^4 q Q \theta(\zeta)}{32a^3} \zeta x \quad (12.2)$$

$$F_y = \frac{\pi^4 q Q \theta(\zeta)}{32a^3} \zeta y. \quad (12.3)$$

If we assume that the head of the beam is frozen within a dielectric section and that the head is primarily the region driving the transverse wakes then we can treat these forces as piecewise constant. We can then follow the analysis in [84, 85], beginning with the equations of motion

$$x'' - kx = 0 \quad (12.4)$$

$$y'' + ky = 0 \quad (12.5)$$

where k is given by

$$k = \frac{\pi^4 q Q \theta(\zeta)}{32a^3} \zeta. \quad (12.6)$$

From this we get the matrices

$$m_{focusing} = \begin{pmatrix} \cos(\sqrt{k}L_s) & \frac{1}{\sqrt{k}} \sin(\sqrt{k}L_s) \\ -\sqrt{k} \sin(\sqrt{k}L_s) & \cos(\sqrt{k}L_s) \end{pmatrix} \quad (12.7)$$

$$m_{defocusing} = \begin{pmatrix} \cosh(\sqrt{k}L_s) & \frac{1}{\sqrt{k}} \sinh(\sqrt{k}L_s) \\ -\sqrt{k} \sinh(\sqrt{k}L_s) & \cosh(\sqrt{k}L_s) \end{pmatrix} \quad (12.8)$$

where L_s is the length of a dielectric slab and half the period, L_p . Since there are no drifts we do not take any thin lens approximations. We can then determine the phase advance using

$$\cos \mu = \frac{1}{2} \text{Tr}(M) \quad (12.9)$$

$$\cos \mu = \cos(\sqrt{k}L_s) \cosh(\sqrt{k}L_s) \quad (12.10)$$

where $M = m_{focusing} \cdot m_{defocusing}$, Tr means to take the trace of a matrix, and μ is the phase advance per period. If we expand this equation we get

$$1 - \frac{\mu^2}{2} \simeq (1 - kL_s^2) (1 + kL_s^2) \quad (12.11)$$

$$\mu \simeq \sqrt{2k}L_s^2. \quad (12.12)$$

Next we can use

$$k_{sec} = \frac{\mu}{L_p} \quad (12.13)$$

to derive the average focusing strength k_{sec}^2 and we arrive at

$$k_{sec}^2 \simeq \frac{1}{2} (kL_s)^2. \quad (12.14)$$

Finally, substituting back in for k gives

$$k_{sec}^2 \simeq \frac{1}{2} \left(\frac{\pi^4 q Q L_s \theta(\zeta)}{32a^3} \zeta \right)^2. \quad (12.15)$$

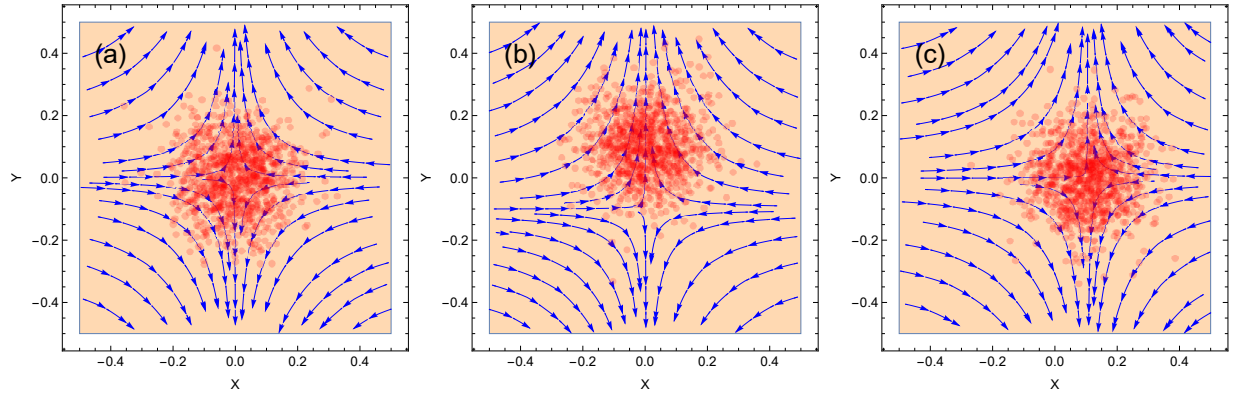


Figure 12.1: Stream plots of the transverse forces generated by a bi-gaussian distribution of particles according to Eq 6.8. (a) shows the map when the distribution is centered at the origin. (b) shows the map when the distribution is offset in the Y-direction by 0.1 (arb units). (c) shows the map when the distribution is offset in the X-direction. The opaque red circles represent the particles in the distribution and the blue arrows the direction of the force at those points but not the magnitude.

CHAPTER 13

Experimental Design

13.1 Manufacturing and Assembly

Now that we've verified the basic idea of the alternating dielectric structure we need to actually conduct the experiment to test it. The first element of that experimental program is to design and construct the mechanical structure that retains and maneuvers the dielectric elements. The dielectric structure, as seen in Fig 10.1, can be broken down into four discrete arrangements of dielectric material. Those four can be grouped into two opposing pairs described by the longer transverse dimension of the dielectric slabs comprising the pairs. The two different pairings are the vertical and horizontal sets of slabs. The first goal of the dielectric support structure is to hold each arrangement of slabs such that they are self-consistently aligned to each other. To make this more concrete, consider just the horizontally oriented pair of slabs then consider just the collection of slabs on the bottom. That collection must be retained such that the beam-facing surface of the dielectric of every slab is co-planar with the equivalent surfaces of every other slab in the collection. Our solution to the alignment aspect of the problem can be seen in Fig 13.1 which shows an image of one of the strongbacks used in the experiment. The strongback is machined so that the two locations that seat the dielectric slabs were originally part of a single surface that was machined flat before the notch was machined into it, creating the separation. This ensures that the two sites are entirely co-planar then when the dielectric slabs are added their inward-facing sides will also be aligned, assuming the slabs are the same thickness.

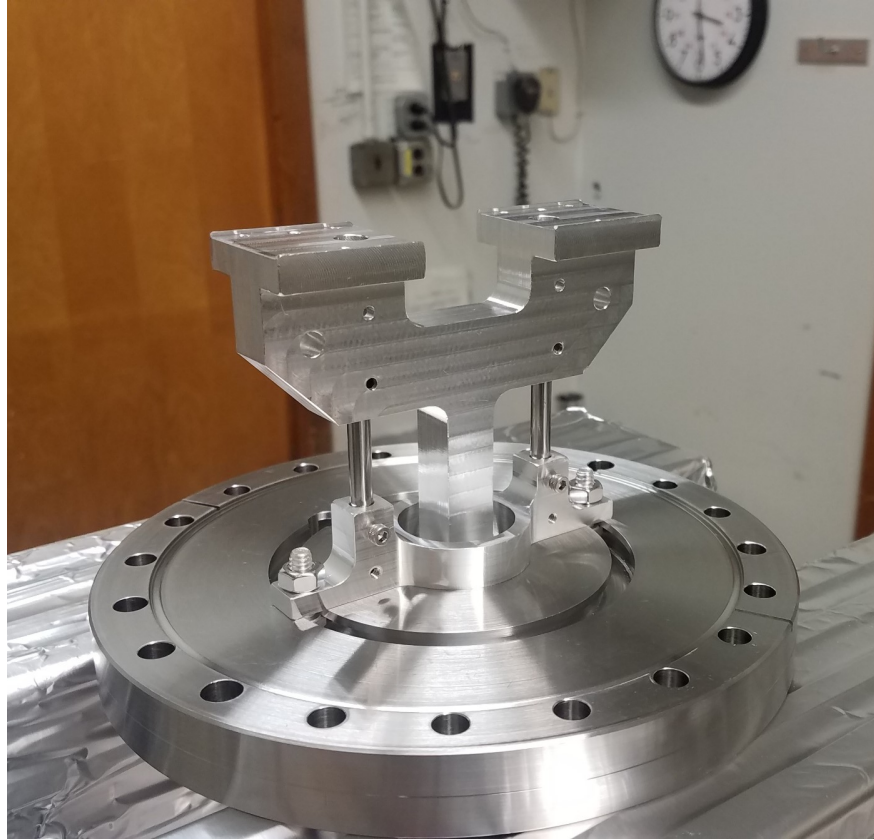


Figure 13.1: One of the strongbacks used to mount the dielectric slabs and its supporting alignment structure. The Y-shaped piece is the strongback which moves along two alignment rods that protrude from the collar mounted to the flange face. Ceramic bushings within the strongback reduce friction during motion.

The other issue that this design must resolve is that of retaining the dielectric slabs to the strongback. The retaining mechanism must securely hold the slabs but not protrude overmuch beyond the dielectric surface as this would set a hard lower bound on the accessible gaps. To accomplish this we begin with the design of the dielectric slabs themselves. During fabrication we machined the slabs so that the inward-facing sides had chamfered edges on two sides as shown in Fig 13.2. Complementary to this, the support structure features aluminum wedges that screw into the strongback and press on the chamfered edges of the dielectric to hold it in place. This indirect method of applying force to the dielectric is important because the dielectric, while strong, is also brittle and can crack or shatter if successfully compressed. A rendering of the full retention mechanism can be seen in Fig 13.3. For the safety of the dielectric material during operation the structure contains hard stops that set an adjustable minimum gap between opposing dielectric arrays. These are composed of a mounting on the side of the strongback containing a screw and nut with the screw extending beyond the face of the dielectric surface. Opposing the screw is an angle-bracket of aluminum, also mounted to the strongback. The face of the bracket is flush or slightly recessed relative to the dielectric surface. By adjusting the length of the screw we can set the minimum gap between the two strongbacks and consequently between the dielectric material. This is a necessary safety precaution because if the dielectric material collides with anything during operation it may chip or even shatter. The hard stops in operation are visible in Fig 13.7.

Now that we have a unified arrangement of dielectric slabs the next step is to combine two opposing arrangements to create a single unified pairing that aligns the two strongbacks to each other and maintains that alignment under motion. To accomplish this we need some sort of driving force and tunable constraining structure to ensure that the strongback moves but only in the desired direction and not in any other. The alignment structure can be seen quite clearly if we refer back to Fig 13.1. The alignment collar mounted to the groove machined in the flange face provides our constraint, specifically the two machined rods that extend from the collar into holes machined in the strongback. More precisely the

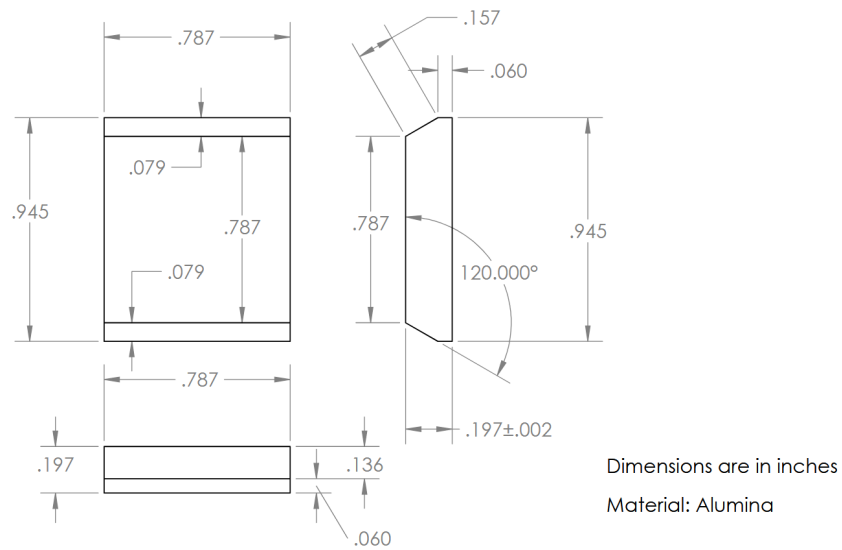


Figure 13.2: The technical drawing for the shorter dielectric slabs.

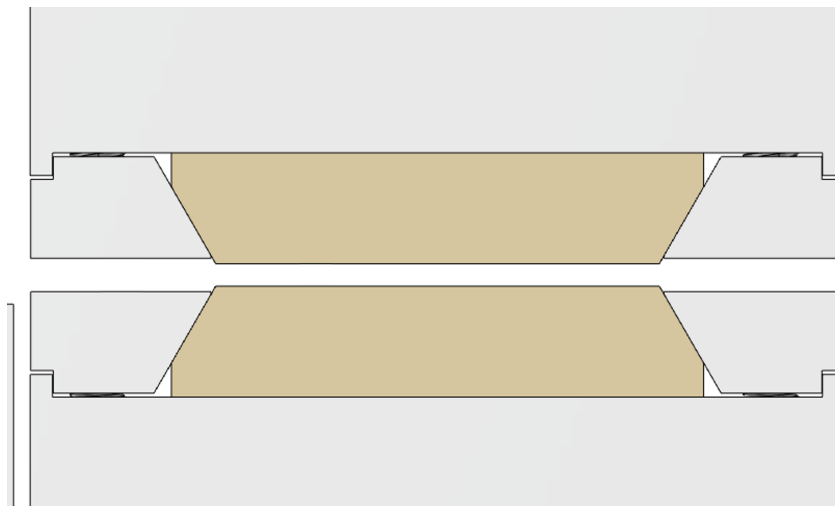


Figure 13.3: A rendering of the dielectric slab retention mechanism. The two tan pieces are the dielectric slabs and the angled pieces on either side are the retention wedges. The larger pieces above and below the dielectric slabs are the strongback. The wedges are attached to the strongback via screws and a small lip on the strongback helps prevent rotation.

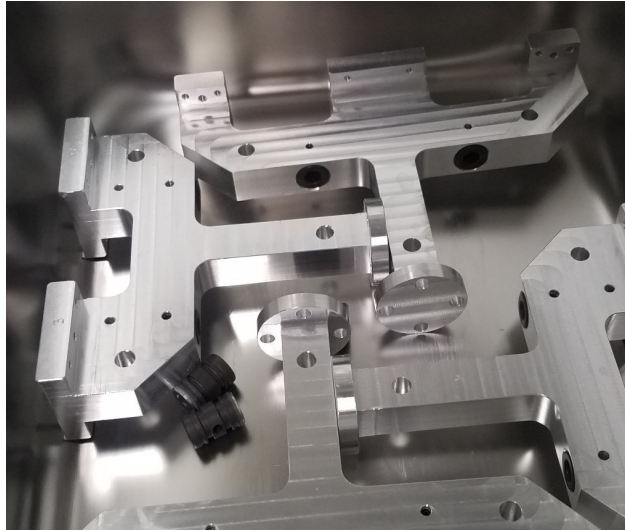


Figure 13.4: The strongbacks and ceramic bushings after cleaning. The strongbacks are the aluminum pieces and the bushings are the black cylinders inset into the strongbacks. Two bushings have come loose during the cleaning process and are lying loose in the bottom left of the image.

rods are captured by ceramic bushings that are inset into the strongbacks. These bushings are necessary to reduce friction between the rod and the aligned structure, an issue that has proven to be quite problematic in previous experiments. The bushings are visible in Fig 13.4, both in their installed position and loose. The rods are mounted in the collar, perpendicular to the flange face. The mounting has two set screws which can be used to trim the exact angle of the rods to provide some element of roll to the structure. The collar itself can also rotate about the axis of motion of the structure providing a yaw adjustment to the dielectric. Motion is provided by stepper motor-powered linear motion vacuum feedthroughs. These are mounted on reducing nipples connected to the flanges that mount the alignment collar. They connect to the shaft of the strongback that passes through the collar. The linear motion feedthroughs can be remotely controlled in the control room to allow adjustments to the structure during operation.

Now that we have a full assembly supporting a single array of slabs we need to combine

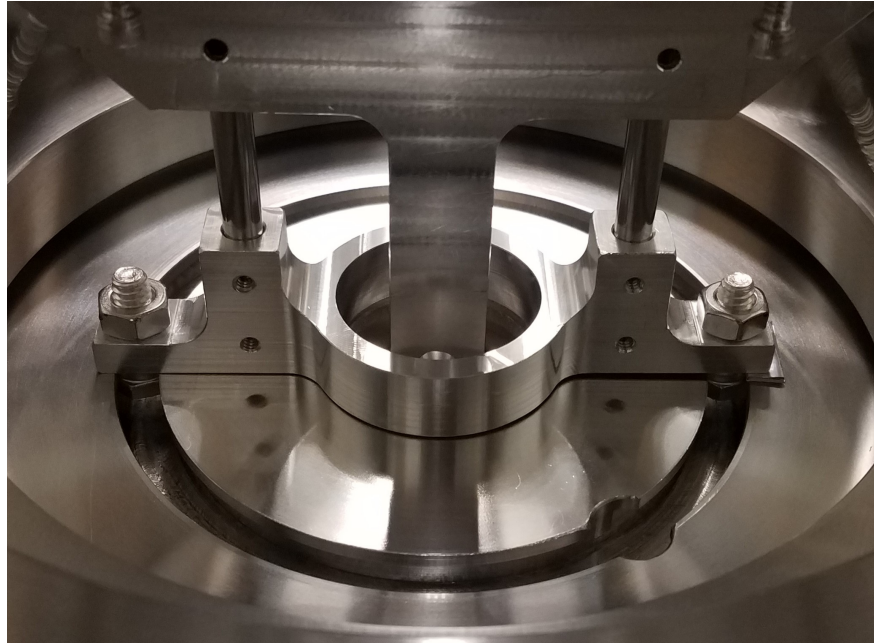


Figure 13.5: Shims were used to tilt the structure longitudinally in order to ensure that the gap was consistent across the entire length. Folded aluminum foil was used as a shim which was convenient due to it's ready availability and consistent thickness.

it with it's opposing array to create one of the pairings. We do this on the vacuum chamber which is an 8" cube, conveniently just large enough for the longest strongback to fit through one of the openings with some care involved. Custom-machined shoulder bolts are used in pairs on each flange to provide a repeatable reference during alignment. The alignment procedure is to install the pair of opposing support assemblies and then move both arrays inward until the gap is fairly small. At this point, coarse adjustments are first entered by eye, noting that the two opposing arrays were either skewed with respect to each other or that the gap on one end was larger than the other. The two flanges were then removed and the alignment structures adjusted according to the noted errors. The assemblies were then reinstalled with the repeatability of the structure positions ensured by the shoulder bolts.

It's important to note that the alignment error that the experiment was most sensitive to was the gap between the dielectric slabs. After coarse alignment we focused on this error

alone, using an iterative process with a precision shim to measure the gap. The shim was inserted in the gap on one end of the structure and both sets of slabs moved towards each other until the shim began to catch. The shim was then moved to the other side to check the relative gap. After noting a relative tilt between the arrays, one assembly was removed and the tilt adjusted by folding aluminum foil and using it to lift up one end of the alignment collar as seen in Fig 13.5. This was necessary because the alignment structure did not contain an in-built method to adjust this variable, something to correct in future experiments. After one pair of arrays was aligned relative to each other the entire process was repeated with the second pair. The tolerances between the two pairs were loose enough to accept these adjustments without issue. The fully assembled structure is visible in an open configuration in Fig 13.6 and in the minimum gap configuration in Fig 13.7. These images illustrate how the entire assembly comes together to create the full dielectric structure and also provide a sense of scale for the working area of the structure during operation.

The details of the fabrication of various components depended on the material involved. The metal pieces were either purchased as-is in the case of much of the vacuum hardware or machined in various ANL shops using standard tools. They were then cleaned using standard UHV cleaning procedures such as ultrasonic baths [86, 87]. The alumina however could not be machined in this manner due to its material properties. Instead it had to be processed by ANLs x-ray optics shop which was capable of working with the material. Figure 13.8 shows the drawing we used to compute the number of dielectric slabs of both lengths that our block of alumina would yield. We intentionally overproduced slabs of both sizes in the event of breakage during cleaning, installation, or operation.

A key process during the machining at the x-ray shop was grinding the alumina to ensure that it had a consistent thickness and to chamfer the edges. A necessary element of this grinding process is to “block” or secure the piece so that it does not move during work. As previously mentioned, alumina is prone to breaking when subjected to compressive force and so blocking methods that may work on metals are inadvisable. Instead the x-ray optics shop

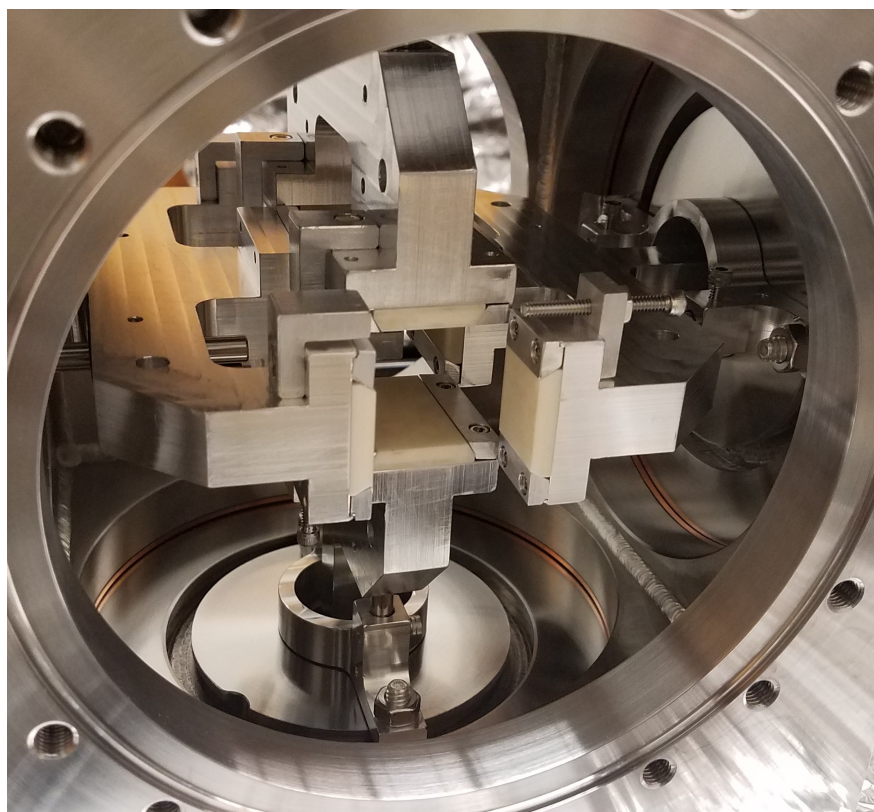


Figure 13.6: The fully assembled experimental structure in the “open” gap configuration. The off-white pieces are the alumina that serves as our dielectric material. We can clearly see how the two opposing pairs of dielectric arrays interleave to create the full structure as well as how the dielectric material is retained to the strongbacks.



Figure 13.7: The fully closed and aligned experimental structure in the minimum gap configuration. The small square in the center of the image is the beam axis. The dielectric slabs are the lighter components immediately adjacent to the gap and retained by the wedges of aluminum holding them to the strongbacks. The visible screw and nut are the hard-stop system with the screw impacting the angle bracket on the opposing strongback to set the minimum gap.



Figure 13.9: The alumina slabs immediately after the machining process. The black substance and staining is from the blocking material used to secure the slabs during work.

used standard optical blocking techniques which utilized a mixture of wax and pitch [88]. As a result, the alumina slabs were quite dirty after manufacturing, as seen in Fig 13.9, and required significant cleaning before admission to the beamline. The cleaning process began with mechanical removal of the contaminants with scotch-brite after soaking the slabs in acetone. This soaking and scrubbing process was repeated until there was no more visible improvement with iteration. The slabs were then sonicated in acetone several times and then again using standard detergents as shown in Fig 13.10. Finally the slabs were baked in a vacuum oven to remove excess moisture. There were some residual stains from the blocking material but residual gas analysis prior to installation in the beamline showed no off-gassing [89].

13.2 Installation and Beamline Layout

After the experimental structure is cleaned and assembled it must then be installed in the beamline for the experiment. The first step is to perform an RGA analysis of the fully



Figure 13.10: The alumina slabs during the cleaning process. In the image they are depicted undergoing an ultrasonic bath. The aluminum foil is used as a cushion to prevent contact between the slabs and the tub wall. It is also folded to prevent contact between the slabs themselves.

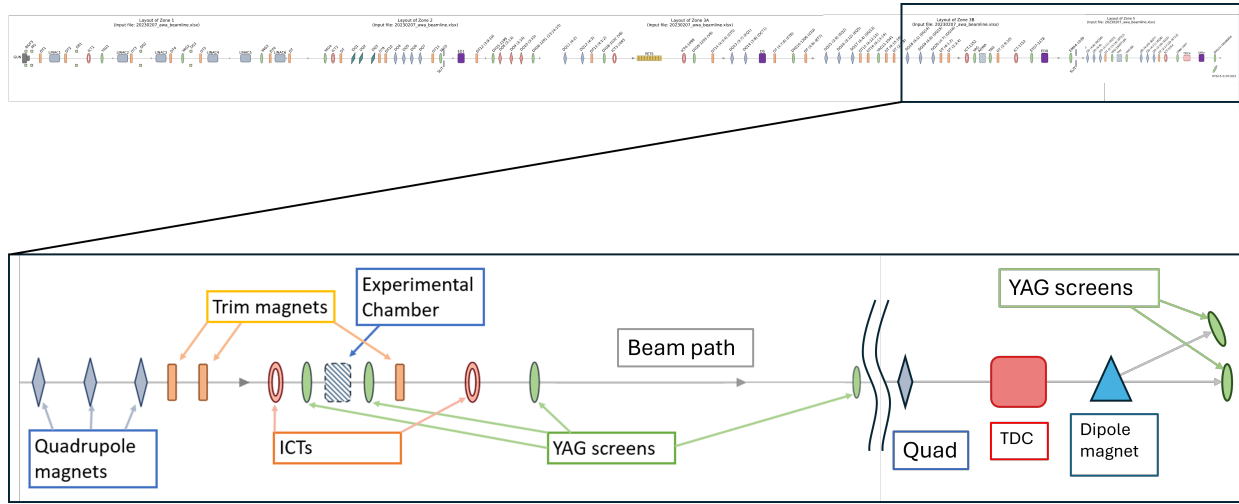


Figure 13.11: A simplified cartoon layout of the relevant components in the experimental zone of the AWA beamline. The full beamline layout is provided for context, a larger version is available in Appendix C. The beam is moving from left to right along the gray line. The parallel squiggly lines indicate omitted distance for clarity.

assembled chamber to make sure it can hold vacuum and that it won't offgass something that can spoil the cathode. The AWA cathode is made of cesium telluride and the quantum efficiency is highly susceptible to contamination [63, 90]. After the RGA analysis the chamber is brought into the bunker placed into the beamline at the location indicated in Fig 13.11 after removing the local beampipe. The chamber is mounted on the left and right flanges which allow it to be pitched up and down easily.

After the chamber is set roughly in place it must be aligned to the nominal beam path. To do this we use two different HeNe lasers, one that travels the length of the beam pipe starting just after the linacs and one in the experimental zone. First the longer-distance laser is adjusted so that it is traveling nearly the full length of the accelerator and striking the rough center of a sticky note taped to a window at the far end of the pipe. The location the laser strikes is noted on the sticky note. Then a mirror is inserted at the end of the experimental zone to image the laser on a second reference. Next we turn on the experimental zone HeNe

and pop in a mirror to shine it down the pipe instead, the other HeNe is turned off at this point. We align the experimental zone laser to the two reference points from the longer laser, ensuring they are now aligned. We now align the structure with the experimental zone laser as shown in Fig 13.12. Image (b) illustrates exactly why we use the second laser, the large oval is the spot of the first laser and the black dot is the spot of the second beam. The central beam shown in the figure is even smaller due to the structure clipping most of it out. Aligning the structure to the laser involves manipulating the entire vacuum chamber since the structure itself is already self-aligned and we don't want to disturb that. First we ensure that the beam is passing through the structure, then angular corrections are made to symmetrize the diffraction pattern on the reference target.

After aligning the structure to the laser we installed the rest of the diagnostics. For this experiment, in addition to the structure chamber, we added YAG screens immediately up and downstream of the structure. We also connected the linear actuators that drove the structure motion to controllers so that they could be operated from the control room and set their limit switches. Most of the newly installed hardware can be seen in Fig 13.13 which shows the experimental chamber and YAG chambers in their installed location, albeit without the YAG screens and associated actuators. Finally after everything is closed up we pumped down this section of the beamline to perform leak checks and ultimately begin the experiment.

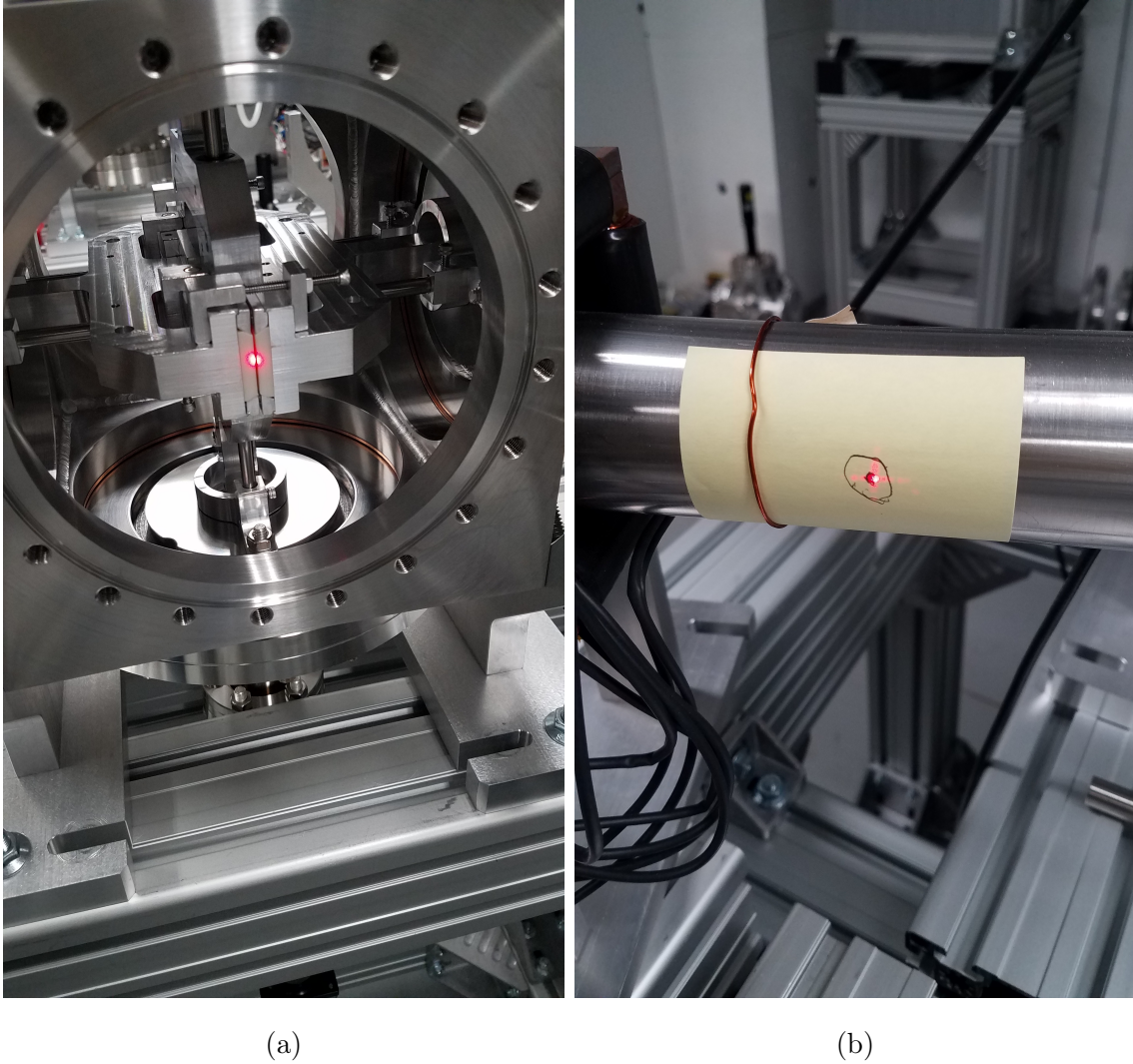


Figure 13.12: Aligning the structure to the nominal beam path. The laser represents the beam path and the structure is manipulated so that the laser can pass through, even when the structure is in the minimum gap configuration. Image (a) shows the laser on the upstream side of the structure, the laser spot is larger than the gap. Image (b) shows the laser on the reference target downstream of the structure. The diffraction pattern can be used to help with the structure alignment.

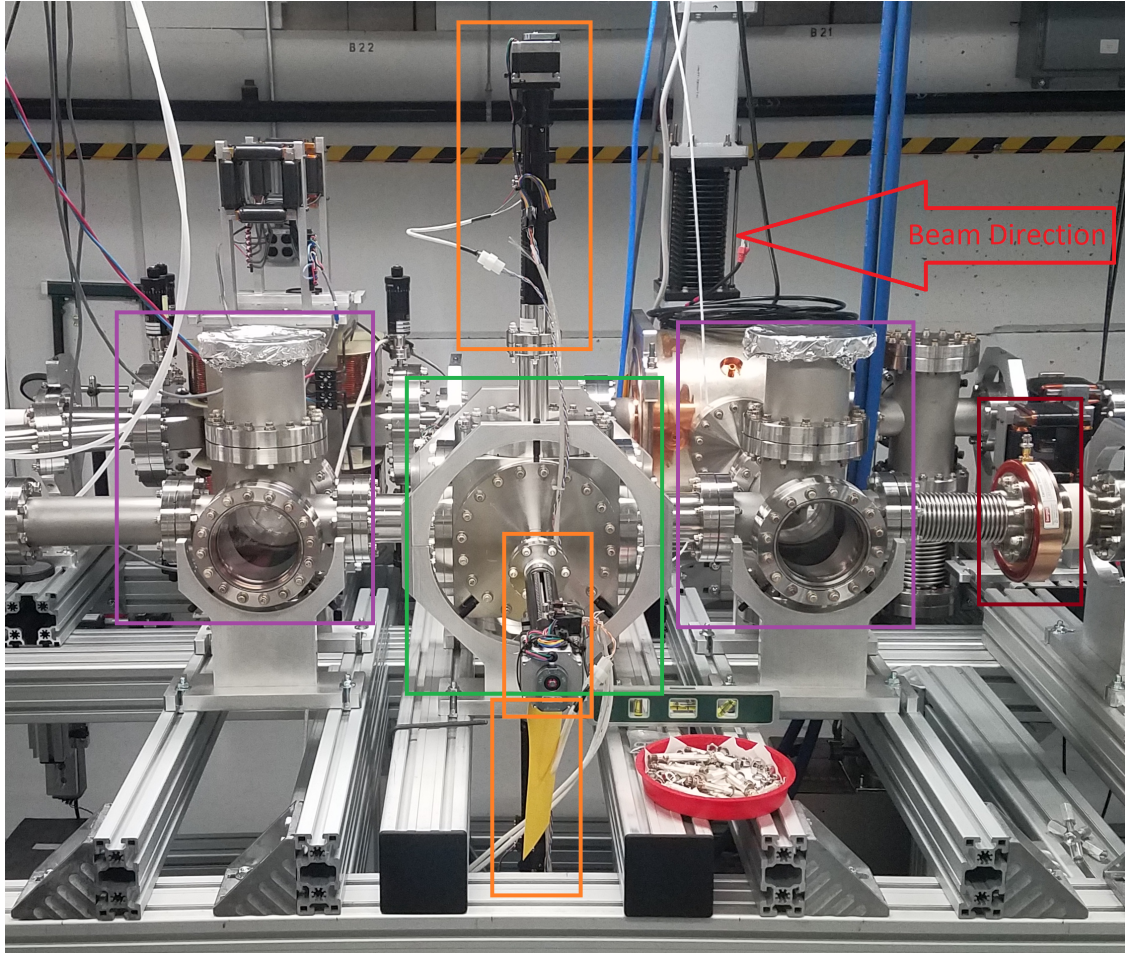


Figure 13.13: The experimental chamber mid-install. The green box denotes the experimental chamber itself held up by the support structure. The orange boxes are the linear actuators. The purple boxes show the location of the fore and aft YAG screens although the screens and associated actuators are yet to be installed. The rust colored box is the upstream ICT.

CHAPTER 14

Operation and Results

14.1 Running

During the experimental run, significant effort was devoted to obtaining a beam with the desired parameters. This effort is not the subject of the experiment however and so further discussion will be omitted. After we obtained a beam with the best parameters that we could we began the process of aligning it with the structure. Luckily, since the dielectric structure is entirely passive, we did not need to perform any additional temporal synchronization. To align the beam with the structure we once again employed the alignment laser used to position the structure during installation. This time however instead of aligning the structure to the laser, we're aligning the electron beam to the laser instead. We do this using the YAG screens immediately up- and downstream of the structure, see Fig 13.11 for the layout. We record the position of the laser spot at both locations and then align the beam so that it passes through those locations meaning the laser and electron beams are collinear. Unfortunately we learned mid-experiment that the laser spot does not show up well on the YAG screen making this process quite difficult. Luckily the YAG screens immediately up and downstream of the structure were stacked with calibration targets meaning that setting the linear actuator to a different position allowed us to insert the target instead of the screen. The targets, being pieces of metal, showed the laser spot splendidly on our camera. Fig 14.1 shows the laser spot on the target and the beam on the YAG. This was an iterative process because the two trim magnets used to steer the beam were not ideally located due to the constraints imposed by the vacuum hardware. The general process we used was to

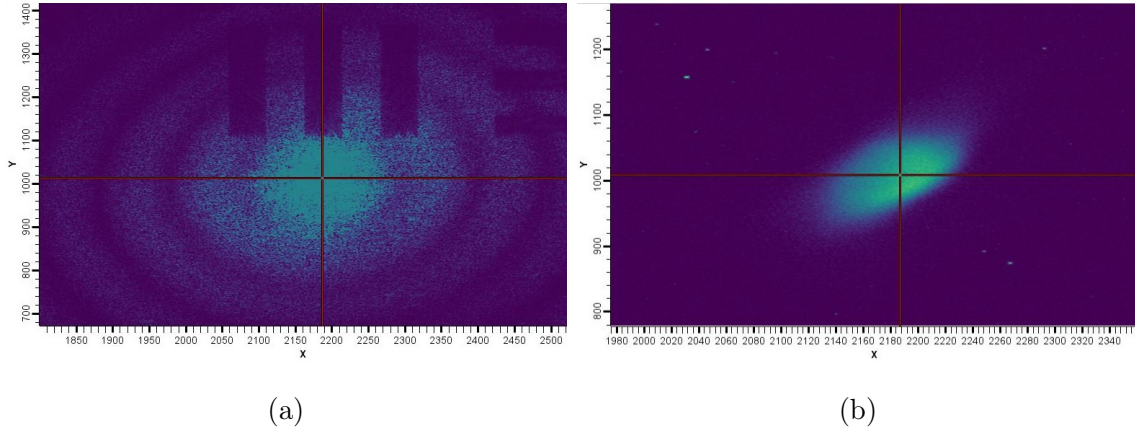


Figure 14.1: Screen images from the location of the YAG immediately downstream of the structure. Image (a) depicts the alignment laser spot on a calibration target loaded in-line with the YAG screen on the same actuator stack. Image (b) shows the beam image on the YAG screen. The crosshair is courtesy of the software used to view the camera feed and was used to mark the laser location as a reference when aligning the electron beam.

use the rearward magnet to set the beam position on the upstream screen and the second magnet to adjust the beam angle so that it struck the correct position on the second screen. Unfortunately the second magnet, being set away from the first screen by some distance, also adjusted it's position there and so we iterated.

After aligning the beam to the laser we then reduced the gap in one dimension and watched the effect it had on the beam on multiple downstream YAGs. As the gap narrowed, the effect on the beam became more pronounced and we looked for net deflections of the beam given that the expected result for a centered beam was a symmetric deformation. Once the desired gap was reached we switched to the other set of slabs and repeated the process, essentially centering the structure on the beam. After both sets of slabs were closed we repeated the process of adjusting the original set of slabs because with a largely symmetric structure the deformation was greatly reduced giving us a better understanding of the effect on the beam. Even though we were adjusting the structure to the beam, the initial alignment of the structure to the laser and the beam to the laser was necessary to

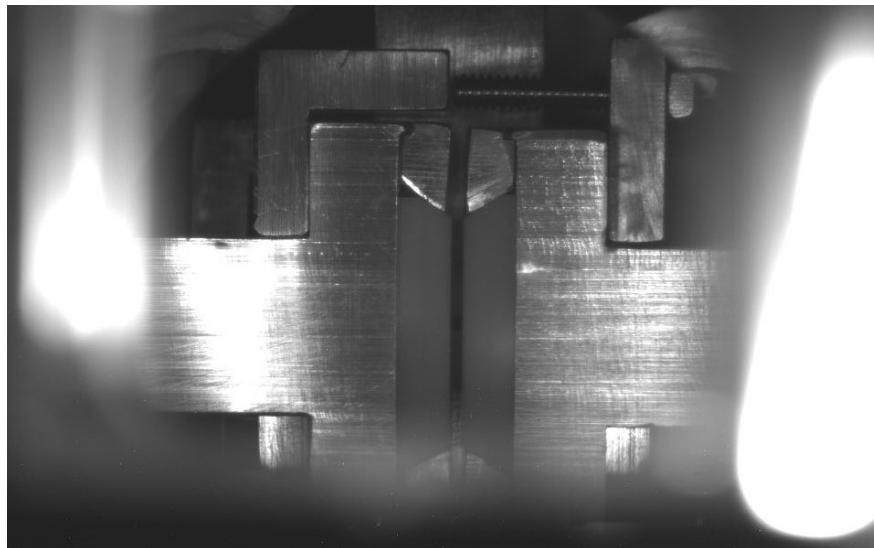


Figure 14.2: A picture of the front of the experimental structure in the minimum gap configuration in both dimensions after it was installed in the beamline. The image was taken by pointing a camera at the back of the mirror used to image the upstream YAG. The white blotches are glare from the lamp used to illuminate the structure.

ensure that the beam and structure have no significant angular deviation which is something that the linear actuators could not adjust for.

Conveniently, after this alignment process was complete we were perfectly positioned to begin taking data. We recorded the XY distribution of the beam on three different YAG screens downstream of the structure. For every shot we also recorded the charge passing through the ICTs before and after the structure. We recorded approximately 300 shots at every screen to ensure that we had sufficient data within the target charge window. After recording the XY data we used a quadrupole to focus the beam vertically, attempting to minimize the vertical size on another YAG screen at the very end of the beamline. At this point we turned on the Transverse Deflecting Cavity (TDC) which provides a phase-dependent transverse kick to the beam [91]. When configured correctly this allows us to create a ZY correlation in the beam and so when we image the beam, the Y-axis of the image actually contains information about the Z-axis of the beam. After scanning the TDC

to find the right phase, the zero crossing, we recorded XZ beam distribution data and charge data. Next we introduced a vertical slit, which eliminated all information in the X-direction, and turned on the magnetic dipole. The dipole acts as a spectrometer by creating an energy dependent bend in the beam which converts into an energy dependent distribution in the X-direction [84, 85]. Combined, the TDC and dipole allow us to measure the beams Longitudinal Phase Space (LPS) which is the slicewise energy of the beam. Again we took about 300 shots including charge data. After recording data for this structure configuration we used the linear actuators to slightly adjust the gap and rechecked the beam-structure alignment in case the actuator backlash was uneven. For every structure configuration we imaged the structure as seen in Fig 14.2 to verify the geometry was as expected. Once we were satisfied that the structure was in the correct new configuration we re-ran the data collecting procedure, repeating this entire process until the scan was complete.

14.2 XY Results

The reason we recorded the XY distribution of the beam at three different YAG screens downstream of the structure is two-fold. The first is simply to record the changes in that distribution as we changed the aspect ratio or ratio of the gaps in each direction. This is to verify that as simulations predict, we can functionally tune the net quadrupole effect of a single orientation of slabs. The second reason is also the reason why we need three screens instead of just one, and that's to perform a three-screen measurement [65]. By measuring the transverse beam size at three different locations along a drift we can fit the equation

$$w^2 = \beta\epsilon - 2L\alpha\epsilon + L^2\gamma\epsilon \quad (14.1)$$

to obtain β , γ , α , and ϵ . These are the twiss parameters and the beam emittance. We can also rewrite this equation around a waist where $\alpha = 0$ to get

$$w^2 = \epsilon \left(\beta^* + \frac{(z - z^*)^2}{\beta^*} \right) \quad (14.2)$$

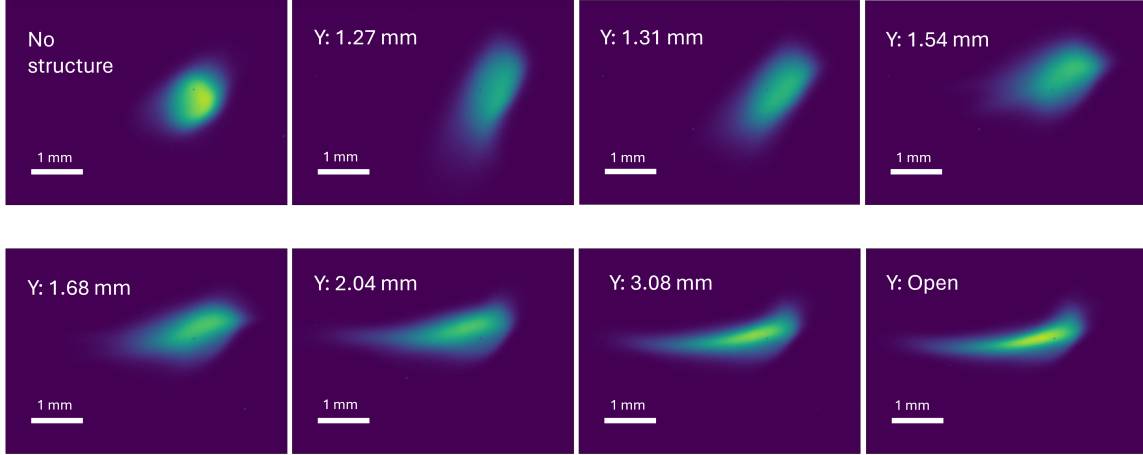


Figure 14.3: The average XY beam distribution captured at the YAG screen closest to the structure exit, 23 cm downstream. This sequence shows the result of scanning the vertical gap while the horizontal gap is held constant at $a_x = 1.31$ mm. The first image shows the beam with both sets of slabs removed as a comparison.

where $*$ denotes the value of the parameter at the beam waist [92]. These are equivalent formalisms but occasionally the latter is preferable when fitting if it allows you to avoid constraints.

Figures 14.3 and 14.4 show the results corresponding to the first reason. Figure 14.3 shows the average screen image on the closest downstream YAG screen for every structure configuration in the scan. The average image is computed by first filtering the data collected at the screen for that configuration by the ICT data to ensure that we're only keeping beams that are within 5 % of the target charge of 1 nC. After filtering for charge we digitally processed the image to reduce noise. The first step of this processing is to subtract a background image captured with the laser shutter closed, meaning there was no electron beam. This background subtraction removes constant errors such as burned out pixels in the camera. The next step is to compute a threshold intensity and set every pixel less than

that threshold to zero. This thresholding step removes low intensity noise such as some of the effect of x-rays impacting the camera as well as the beam image diffusely reflecting off of the inside of the vacuum chamber and within the screen itself. The goal of this step is to break the image into easily identifiable but disparate high-intensity regions analogous to islands in a sea of below-threshold background. This disconnection allows us to easily pick out just the beam and exclude noise that is spatially separate from the beam profile, regardless of intensity. At this point we can compute values such as the standard deviation of the transverse beam distribution. Finally, after repeating this filtering process on every collected beam image within the charge window, we simply stack all of the filtered images and normalize the result. This causes some blurring due to charge and pointing jitter of the beam but, especially at the YAG closest to the structure, the resultant images are still quite clear, as seen in the figure.

Figure 14.3 clearly shows that the prediction that we can functionally tune the net effect of the quadrupole-like transverse mode by adjusting the structure geometry is correct. This quadrupole-like response is shown clearly in Fig 12.1 and if one were to imagine the evolution of a beam according to the stream plot show in (a) it would look quite similar to the last image in Fig 14.3 after accounting for the fact that the geometry in the two images are orthogonal. As we open the gap in the vertical direction we affect the wakes from those slabs by a factor of $(\Delta a_y)^{-3}$. Since the other set of slabs is unchanged, the net result is to transition from a symmetric effect to a quadrupole-like effect. We clearly see this progression in the images as a_y transitions from 1.27 mm to the “Open” position, functionally this was about 5 cm. This is also clear numerically in Fig 14.4 which shows σ_x and σ_y of the same scan as Fig 14.3. These results can be compared to simulation as shown in Fig 11.6 where image (a) corresponds to the No structure image in 14.3, (b) corresponds to the Y: 1.31 mm image, and (c) corresponds to the “Open” image. Again it must be noted that the simulation geometry and experimental geometry are rotated 90° with respect to each other.

For the three screen measurements we extract the measurements taken at the end of the

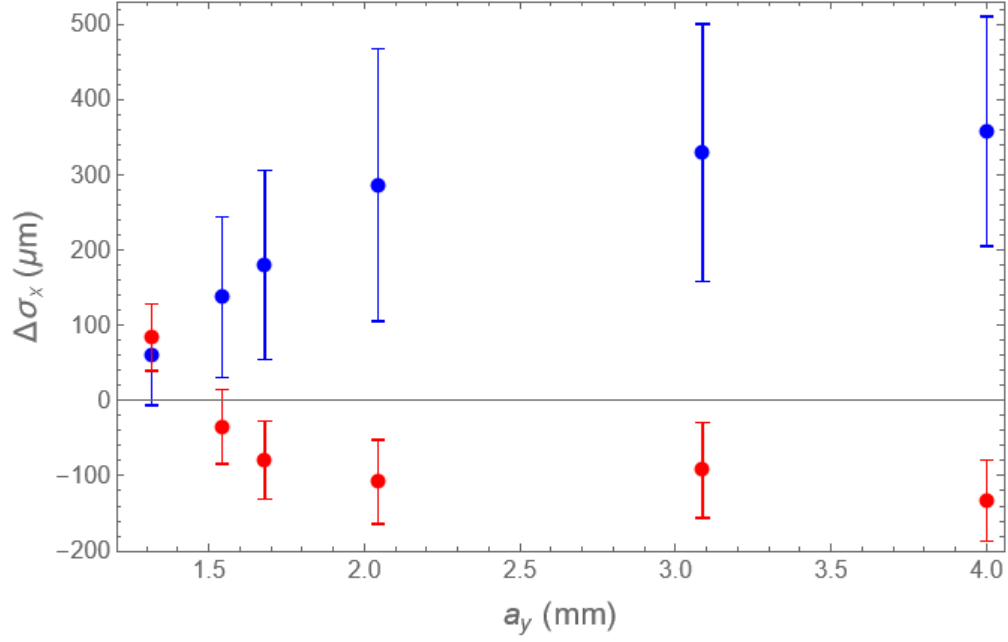


Figure 14.4: A plot of the change in the transverse beam size with respect to the beam with no structure interaction as a function of the vertical gap while the horizontal gap is held constant at 1.3mm. The first data points are the symmetric gap configuration. The error bars represent one σ deviation. The red color indicates the y direction and blue the x direction.

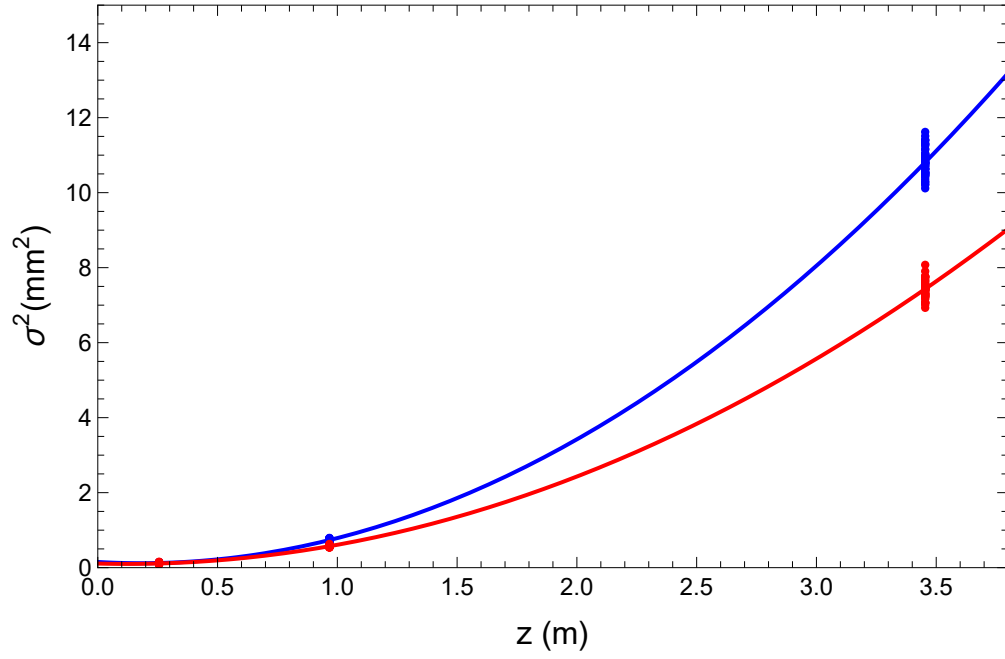


Figure 14.5: The three-screen fit for the no structure configuration. The red line and points are measurements in the y-direction and blue in the x-direction. The three sets of points per color are the measurements at the corresponding screen locations. The lines are the fits to those points according to Eq 14.2.

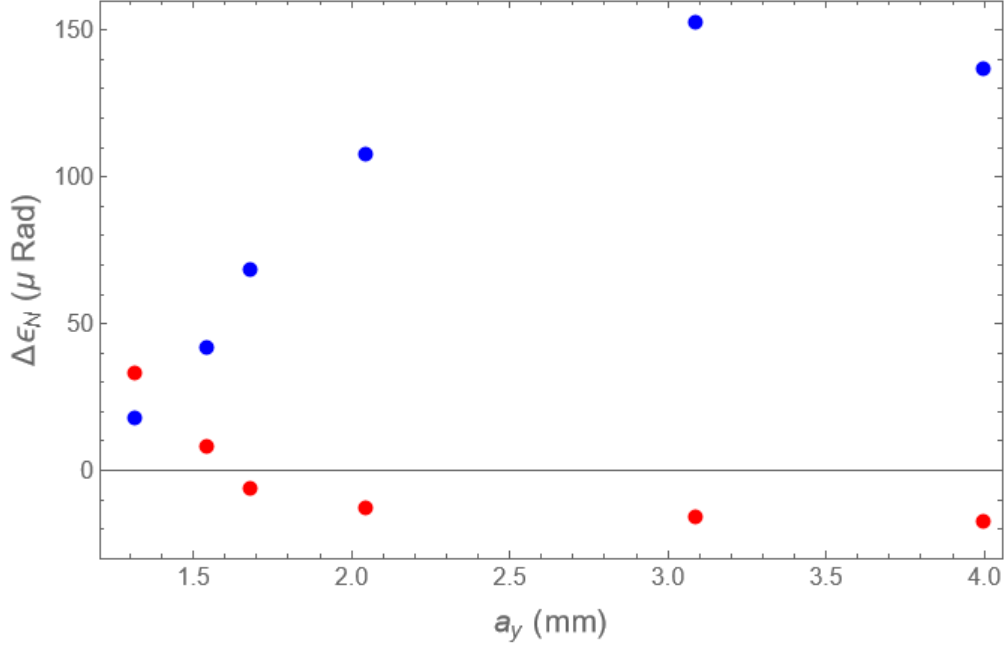


Figure 14.6: A plot of the change in emittance from the no structure configuration as the slabs in the horizontal direction are opened while the slabs in the vertical direction are held constant with a gap a_x of 1.31 mm. The no structure beam emittances are $\epsilon_{Nx} = 40 \pm 5 \mu\text{m}$ rad and $\epsilon_{Ny} = 30 \pm 3 \mu\text{m}$ rad. Blue corresponds to the emittance in the x direction and red in the y direction.

image processing sequence and save them as distinct measurements with no averaging. We then repeat the process for the other two screens so that for each structure configuration there is a set of beam measurements at each screen location. We then fit the data with Eq 14.2 as shown in Fig 14.5. This fit gives us the beam's waist beta function, waist position, and emittance. We can extract error in the fit to generate uncertainty for the fit parameters. Repeating this analysis for every structure configuration gives us Fig 14.6 which depicts the change in the beam emittance from the no structure case as we change the structure parameters. The scan starts with the symmetric structure and progresses as the slabs in the horizontal direction are opened. Each set of points at a given a_y corresponds to an image in Fig 14.3 for context.

These results are particularly notable for two main reasons, the first is that even with a fully symmetric structure the beam emittance increases in both dimensions and the second is that the emittance in the x and y directions split as the structure becomes more asymmetric. The first result can be explained by examining the time dependence of the structure’s transverse wakes whose structure we will explore in more detail later. In short however, due to the time dependence of the transverse wakefields each slice of the beam experiences a different net focusing force causing a correlated spread in beta functions. This results in an increase in the projected emittance of the beam but this increase is reversible due to the correlation. The second result can be understood by going back to the Skew Wake experiment. If we understand our incoming beam to be “magnetized” in the same way that the beam used in the skew wake experiment was prior to passing through the round-to-flat transformer then it’s plausible that the structure interaction is acting analogously to the transformer via the skew effect described in that experiment. The conclusion that the input beam was magnetized is supported first by the very large emittances of the no structure beam, $\epsilon_{Nx} = 40 \pm 5 \mu\text{m rad}$ and $\epsilon_{Ny} = 30 \pm 3 \mu\text{m rad}$, and second by the fact that after passing through regular quadrupoles in order to focus it down into the structure the beam exhibits a visible x-y correlation as seen in Fig 14.3. AWA is typically capable of producing beams of significantly higher quality and so an initial emittance of this magnitude is quite surprising. Preliminary machine studies prior to this experiment generated a beam with transverse emittances of approximately $5 \mu\text{m rad}$ which is much more in line with expectation. Further, log entries recorded during the experiment speculated that the beam may have been magnetized due to the apparent rotation of the x-y correlation of the beam as the normal quadrupole fields were changed. The increase in the emittance in the x direction can further be explained by a time-dependent dipole component of the transverse wakefield in the x direction that operated similarly to the time-dependent focusing except with an effect contained to only that dimension. We can see evidence of this kick graphically by examining Fig 14.3 where we can clearly see that unlike in a pure quadrupole, where we’d expect the horizontal defocusing

to extend the beam in both directions, we see the beam only being extruded to the left side of the image.

This magnetized beam explanation for the emittance splitting can be checked with simple matrix models in order to verify the basic premise. If we begin with a round unmagnetized beam with $5\text{ }\mu\text{m rad}$ transverse emittances and add in $x\text{-}p_y$ and $y\text{-}p_x$ correlations, effectively magnetizing it, we can bring the projected transverse emittances up to $30\text{ }\mu\text{m rad}$. We can then either apply a linearly ζ -dependent normal quadrupole kick that brings the emittances up to just over $55\text{ }\mu\text{m rad}$ or a combination of normal and skew quadrupoles that instead give us $\epsilon_x = 46\text{ }\mu\text{m rad}$ and $\epsilon_y = 18\text{ }\mu\text{m rad}$. In the second case we can also apply a ζ -dependent dipole resulting in $\epsilon_x = 170\text{ }\mu\text{m rad}$ and $\epsilon_y = 18\text{ }\mu\text{m rad}$. From this simple exercise we can clearly demonstrate how the skew quadrupole effect observed in the first experiment is the key to understanding our results in this one.

14.3 XZ Results

We recorded the beams XZ distribution in order to understand the temporal structure of the transverse wakefields. This is valuable because the field structure changes dramatically along the length of the beam so certain conditions may exist at a given ζ that do not elsewhere. Figure 14.7 example images of the XZ distributions for three different structure configurations. These three images correspond to the first, third, and last images in Fig 14.3. We can see quite clearly how this perspective provides additional information in contrast to the projected images. As you look from the head to the tail of the beam, the transverse location and spread of the beam can be radically different and so we processed these images to extract that information. We performed the same basic noise filtering process as with the XY distributions but the analysis diverged at this point. After extracting the beam image from the background we computed a line-by-line mean and standard deviation weighted by the beam intensity. We then averaged these values over every beam within the charge

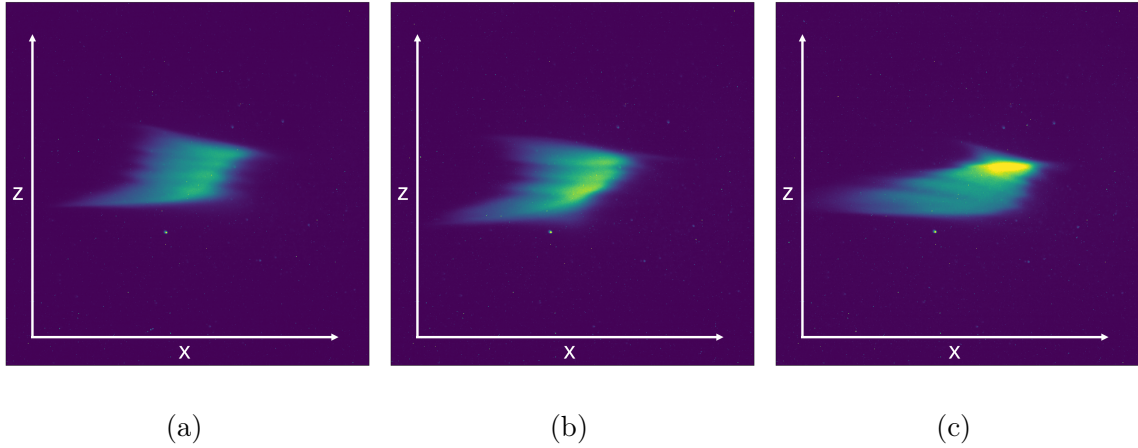


Figure 14.7: Example images of the XZ distribution of the beam for three different configurations. Image (a) shows the beam after no interaction with the structure. Image (b) shows the beam after passing through the fully symmetric structure with a gap of 1.31 mm. Image (c) shows the beam after passing through the fully asymmetric structure with the same gap as (b) in the horizontal direction. The horizontal banding in the distribution is due to the temporal structure of the laser pulse used to generate the beam.

window of that configuration to get statistics for the two values.

The two calculations we perform on the beam distributions represent measurements of two different physical quantities. The slicewise measurement of the transverse mean allows us to measure net deflections of the beam which correspond to dipole-mode transverse wakefields. We're interested in this because these net deflections are one of the primary causes of beam breakup and the corresponding beam loss. Figure 14.8 shows these results overlaid upon the footprint of the no structure beam to provide context. The red line and shading corresponds to the no structure beam and we can clearly see that the green line and shading, representing the fully symmetric structure, is quite well aligned indicating that there is little net dipole. The green shading is much wider than the red indicating that even if on average there is very little deflection, there exist shots that include net dipole in both directions. The overall lack of a net dipole is brought into stark relief when we include the asymmetric or non-

alternating structure represented by the blue line and shading. This structure configuration clearly exhibits a strong net dipole mode which is suppressed in the alternating structure configuration. It should be emphasized that these are not different structures, only different configurations. The physical dielectric slabs that are creating the asymmetric structure that generated the results in blue are in the same slabs in the exact same place when the structure is in the symmetric configuration that results in the green line. Therefore only the added presence of the alternate orientation of dielectric slabs can be responsible for the suppression of the net dipole effect.

The other calculation, that of the slicewise standard deviation, is essentially a measure of the net focusing experienced by the beam at each ζ . Figure 14.9 shows that data with no processing in addition to that used to generate the slicewise mean data. The solid lines represent the slicewise mean of σ_x and the shaded regions represent the slicewise standard deviation. Immediately we can see the clear effect of the transverse de-focusing that occurs due to the asymmetric structure by looking at the blue line and shaded region. The last nearly two-thirds of the asymmetric beam are clearly de-focused with respect to the no structure beam although the clear inflection that occurs in the last quarter or so of the beam is interesting. Similarly we can see that in the same region, roughly half of the beams that pass through the symmetric structure actually experience transverse focusing. Already this is arguably a major win for the symmetric structure, it demonstrates dipole suppression and transverse focusing, at least for some ζ . Now though, if we turn our attention to the head of the beam we notice that there is significant asymmetry between the three configurations at the head of the beam. This can be attributed to the different quadrupole settings used to focus the beam vertically prior to running it through the TDC.

To adjust for the different quadrupole settings we can rescale the symmetric and asymmetric results to the no structure beam under the theory that the head of the beams are unaffected by the transverse wakefields and as a result should be the same across structure configurations. We selected the head of the beam by examining Fig 14.8 and selecting the

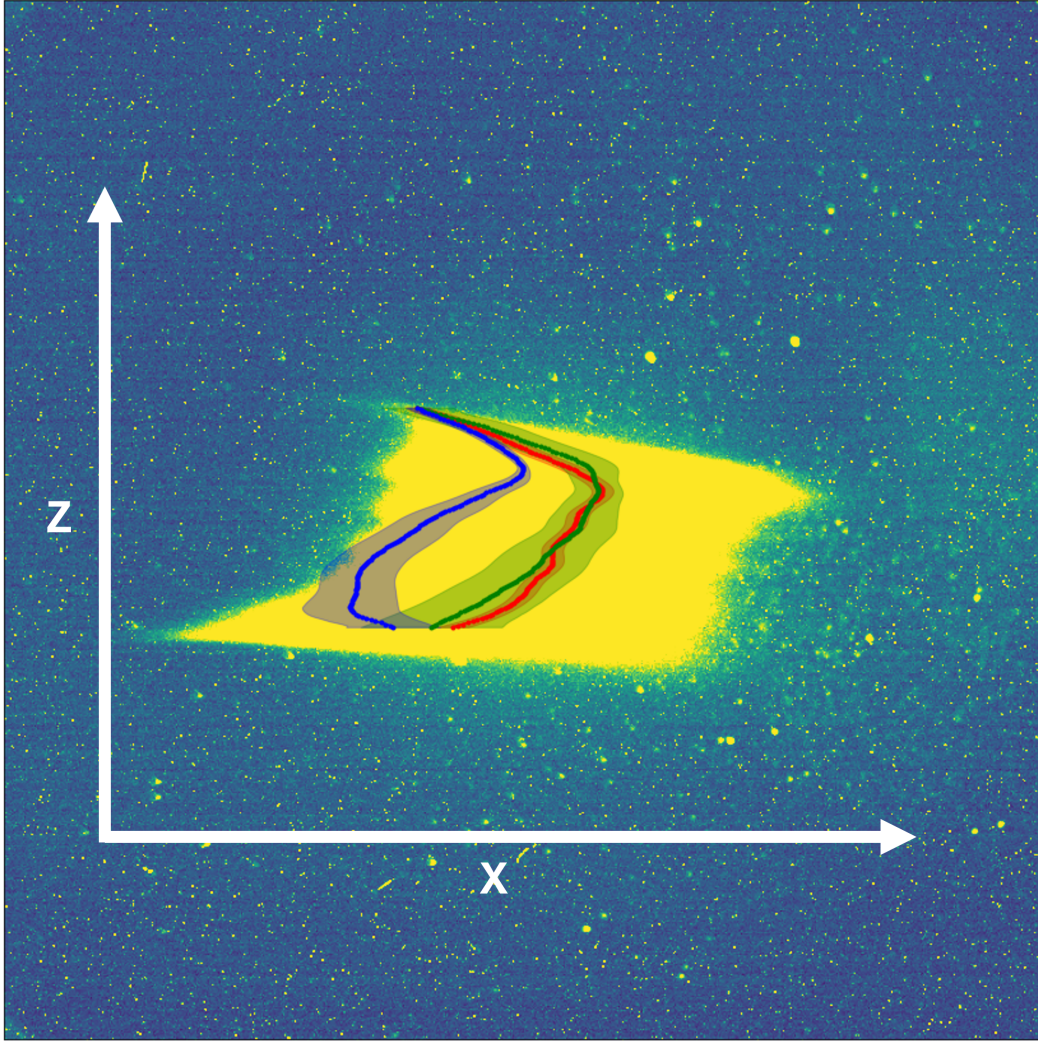


Figure 14.8: A plot of the average slicewise mean x position of the beam after interacting with three different structure configurations. The background is a representative image of the X - Z distribution of the beam without structure interaction with the contrast increased to show the beam footprint. The red line shows the mean x position of the beam as a function of z averaged across all beams for the no structure configuration. The correspondingly colored shaded region shows one standard deviation of the mean on either side. The green line and shaded region show the equivalent information for the symmetric gap structure configuration. The blue line and shaded region show the equivalent information for the asymmetric structure configuration where the slabs oriented in the horizontal direction have been fully retracted.

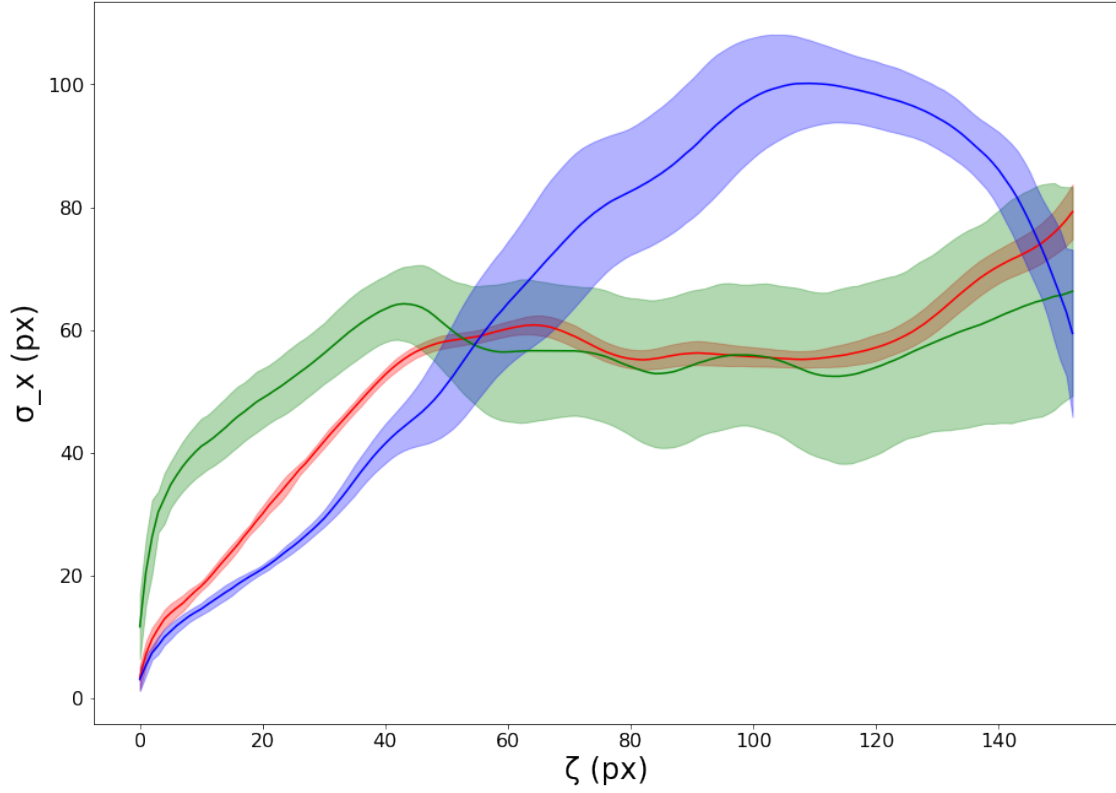


Figure 14.9: A plot of the mean standard deviation of the x distribution as a function of ζ . The shaded region shows the standard deviation of the standard deviation of the x distribution across all beams of the configuration. The red color corresponds to the no structure configuration, green corresponds to the symmetric gap configuration, and blue corresponds to the fully asymmetric configuration where the slabs oriented in the horizontal direction have been fully retracted.

point where the blue and red lines no longer overlapped as the end of the “head” region under the assumption that ζ dependence of the dipole and quadrupole-like wakes was the same. Figure 14.10 shows the result of this analysis and brings the true difference between the structure configurations into stark relief. The symmetric structure is now clearly focusing transversely while the asymmetric structure is revealed to de-focuses even more strongly.

14.4 Energy Results

The final measurement we made was of the longitudinal phase space of the beam. This measurement allows us to map the longitudinal wakefields which is a valuable comparison to the maps of the transverse wakefields generated from the XZ distributions. Since the longitudinal effect is independent of the structure orientation, the only relevant parameter is some effective structure length which is the actual structure length weighted by the change in gap to the inverse cubic power. From this perspective the extreme configurations are the no structure beam and the symmetric structure since they have zero and the maximum effective lengths respectively, all other configurations are intermediate values. For this reason we only examine the LPS of these two configurations, as seen in Fig 14.11 which shows representative measurements of each. Visually we can already identify the main feature, that there is clear deceleration of most of the beam and even some acceleration of the tail. Further, in the full structure case, the majority of the correlated energy spread has been removed from the beam.

To understand the LPS results numerically, we can essentially subtract the full structure case from the no structure beam to generate the longitudinal field structure. To do this we apply essentially the exact same processing that we used to generate the slicewise mean data for the XZ distributions. Once we’ve converted the image into a numerical result we can quite literally subtract the two. To convert the result from pixels to energy we use the

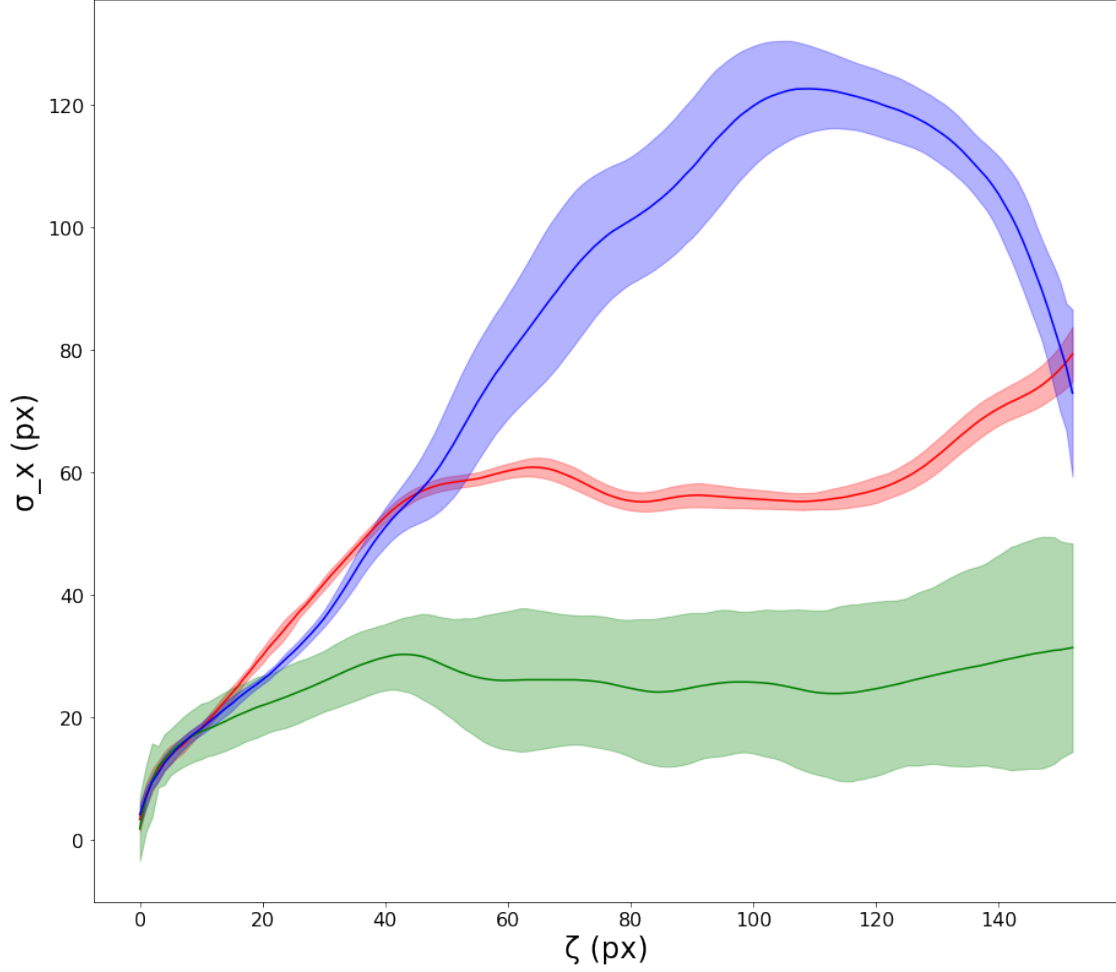


Figure 14.10: Re-plotting the same data as Fig 14.9 except the full structure and asymmetric structure results have been translated and then linearly scaled along the y-axis. Each configuration has a separate scaling factor based on the difference between it and the no structure configuration for $\zeta < 10$ pixels. This scaling factor accounts for the different quadrupole settings used when recording data.

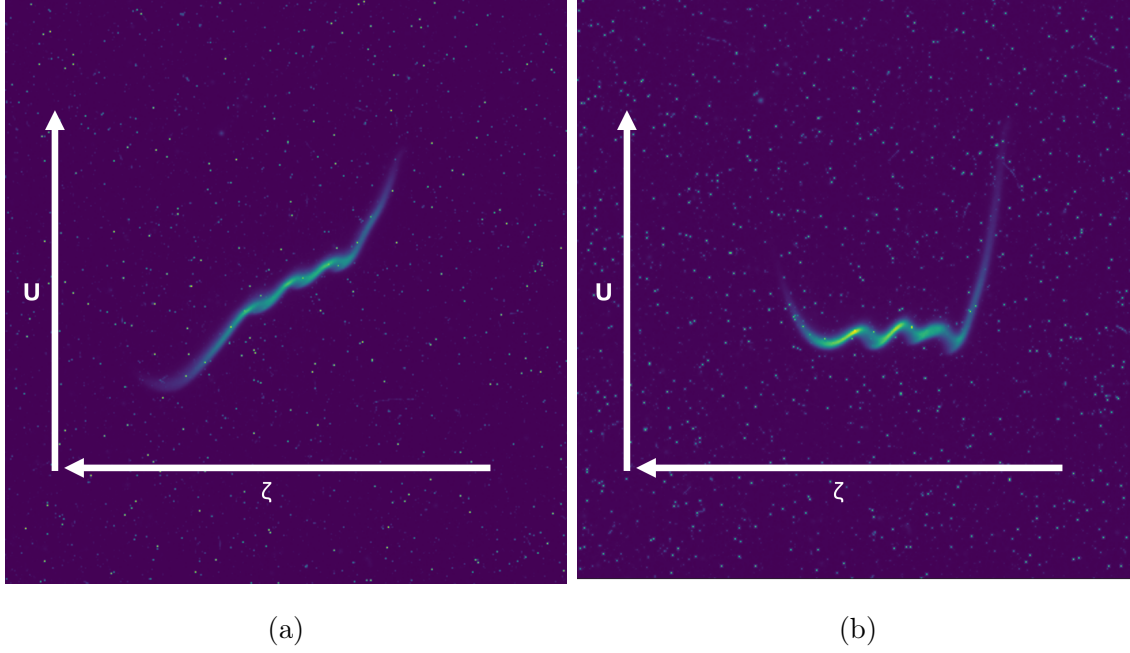


Figure 14.11: Beam images depicting the beam's longitudinal phase space (LPS). Image (a) shows the LPS of the beam with no structure interaction. Image (b) shows the LPS of the beam after interacting with the structure in the symmetric gap configuration. The central energy is 63 MeV. The speckled background is due to x-rays emitted when the beam passes through the spectrometer dipole.

equation

$$U_{ref} = 0.115344 I_{dipole(counts)} - 0.116 \quad (14.3)$$

to get the reference energy for a given dipole current. This equation uses empirical values specific to the AWA spectrometer dipole. After obtaining the reference energy we can combine it with the dispersion of the magnet which is 0.3093 m and the image resolution of 37 $\mu\text{m}/\text{px}$ to get the results shown in Fig 14.12. We can see that the decelerating field turns on extremely quickly, reaching a peak at about 1/6th of the way back from the head and then is largely linearly decreasing for the middle 2/3 of the beam before suddenly reversing sign and actually accelerating the tail of the beam. Some slight ripples in the field persist due to slight longitudinal density variations caused by the laser structure on the cathode. Given the total length of the structure is 16 cm, we obtain a peak decelerating field of 4.25 MeV/m. We can use the longitudinal field structure to cross-check the XZ results as well via Panofsky-Wenzel, reproduced here

$$\nabla_{\perp} W_z = \frac{\partial W_{\perp}}{\partial \zeta}. \quad (14.4)$$

If we assume that the ζ dependence of W_z is strictly independent of its transverse position then integrating W_z with respect to ζ gives us the ζ dependence of $W_{\perp}$. Figure 14.13 shows a comparison between this result and a measure of $W_{\perp}$ obtained by taking the difference in σ_x between the asymmetric structure and the no structure configurations up to a sign flip. While the agreement isn't perfect we can see that the functional form for the two results is essentially the same and from this conclude that we have successfully checked our previous results. Examining these plots shows that the linearity of the ζ dependence assumed in the matrix model used to interpret the emittance results was a valid choice as well.

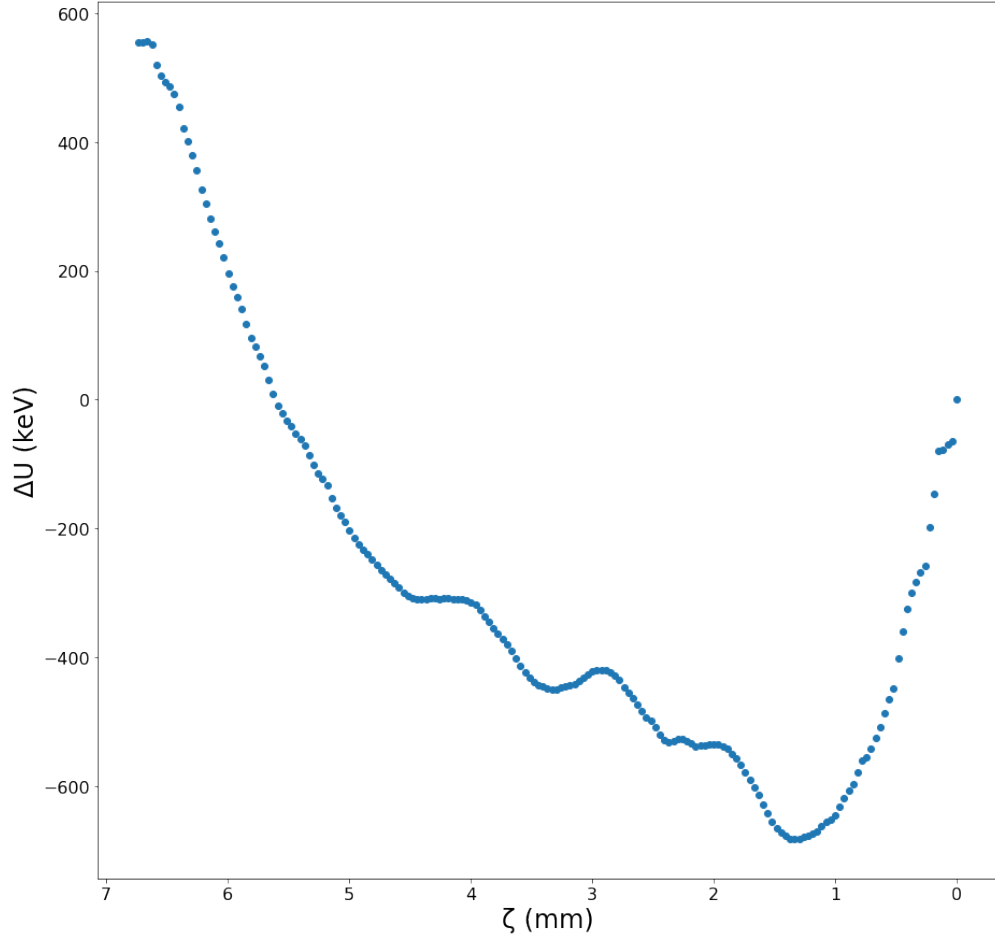
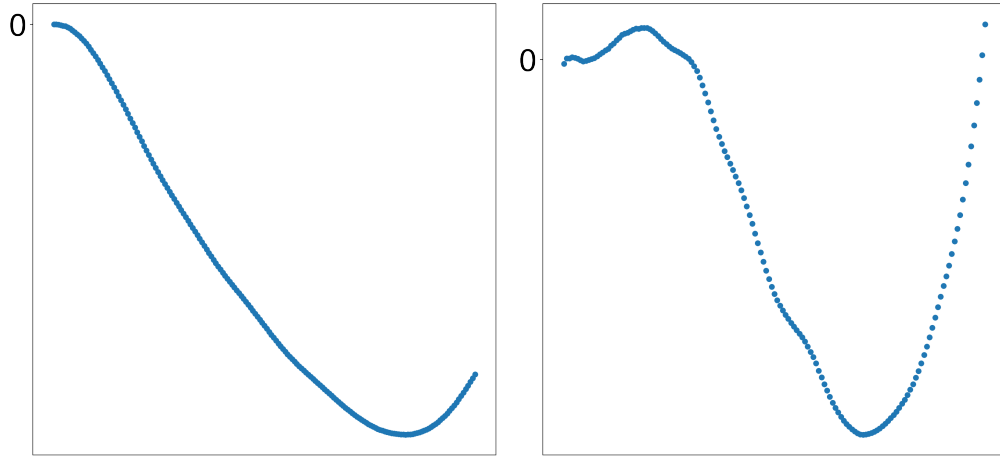


Figure 14.12: The measured change in energy between the two longitudinal phase spaces shown in Fig 14.11. The peak loss in energy is -681 keV which corresponds to a peak decelerating field of 4.25 MeV/m. The tail of the beam is accelerated to 556 keV due to the frequency of the structure.



(a) The integral of the difference in (b) The difference in σ_x between the longitudinal phase spaces shown in Fig asymmetric structure and the no struc-
 14.12. ture configurations up to a sign flip.

Figure 14.13: The functional form for the longitudinal dependence of the transverse wakefields as computed with two different techniques.

CHAPTER 15

Conclusion

Through these two experiments, we have shown that dielectric wakefield accelerators are a fruitful area of research with a depth belied by their apparent simplicity. In the skew wake experiment we showed that even seemingly well-understood problems must be studied carefully and in depth less essential details should be overlooked. The observation of the skew component of the quadrupole-like wakefields is an essential piece of understanding for any attempts to employ flat beams at scale. In the alternating dielectric wakefield experiment we experimentally demonstrated a new method for addressing the fundamental problem in dielectric wakefield accelerators, single bunch beam breakup. We showed that by controlling the geometry of the structure we could exert control over the field structure of the transverse wakefields and, as a result, achieve transverse focusing and suppress the effect of the dipole mode. We also showed the interconnection between these two experiments through the skew-quadrupole interaction and the asymmetric structure's effect on the beam emittance in the ADWA experiment.

Further work extends naturally from the experiments described here. Continued exploration of new transverse geometries such as elliptical, parabolic, or even more complex profiles carry unknown promise but a better understanding and control of the transverse field structure is always something to be welcomed. Complementary to this effort is an exploration in the longitudinal direction as well. In these experiments the longitudinal variation was quite simple, in no small part due to the limitations of constructing and assembling a more complex structure. Future experiments could take advantage of advances in manufac-

turing techniques such as the constant improvements in additive manufacturing. Finally, more consideration could be given to the longitudinal fields and how they could be manipulated and employed. There is already some work [\[93\]](#) in this direction but the geometries considered are comparatively simple and perhaps greater effect could be realized by further exploitation of our ability to shape the dielectric structure.

APPENDIX A

CST PIC Instructions

Begin by opening a new CST project and selecting the Particle Dynamics section, followed by Accelerator Components, Cavities, Particle Analysis, and finally the Particle in Cell solver. Next the relevant simulation units are described, the only relevant ones for this work are Dimensions, Frequency, and Time. We then pick a file name and start the project. The first step upon opening a new project is to set the background material to vacuum. This setting can be found under the Simulation option in the menu ribbon. Next set the boundaries to “open (add space)” right next to the background setting. At this point we’re ready to define the structure geometry, for simple structures such as two dielectric slabs we can go straight to the modeling tab and click on “Curves”. For a dielectric slab we select “Rectangle” and can then either define the rectangle by hand or parametrically. Parametric definitions are highly encouraged, to do so press escape to open the dialogue box where the bounds can be defined. Variables can be used to define the shape by simply typing them into the boxes. New variables will issue a prompt for a value. After the profile of the dielectric is defined, repeat the process for the metallic coating, this need not have significant height if planning to assume the metal to be perfectly conducting.

Now to extrude the dielectric by picking “Extrude Curve” in the “Shapes” section. Now select the rectangle defining the dielectric profile, either by clicking it directly or clicking on it’s name in the navigation tree on the left. Next define the material and thickness, in our case the thickness is the length of the structure and can also be defined with a variable. After creating a dielectric slab, repeat the process for the metallic coating. If this is to be a double-

slab simulation, we can either repeat all of this for the bottom slabs or select the slab and associated metal coating and under "Transform" in the tools section, select "Mirror". Select the axis you want the slab to be mirrored on, the axis normal to the dielectric surface, and make sure the "Copy" checkbox is ticked. Now that the structure is defined we navigate to the "Simulation" tab and select "Particle Import Interface" under "Particle Sources". Import the desired input beam and translate so that it begins fully outside of the structure if desired.

Now select the desired monitors, the "PIC Position Monitor" will allow you to examine the full 6-D phase space of the beam at a given timestep. The "Field Monitor" can allow you to extract the electric and magnetic fields both temporally and in frequency space. The "Phase Space" monitor allows you to quickly see the beam phase and trace spaces without performing post-processing on the position monitor results. Next check the "Mesh View" to make sure that the beam area is sufficiently meshed, if it is not then increase the project frequency in the "Settings" section. Finally, select "Set Up Solver" in the solver section and define the simulation time, which is how long the simulation will run, for then click start.

Once the simulation has concluded you can view the measurements made by the monitors in the navigation tree. Results can then be exported by selecting "Import/Export" under "Post-Processing" in the ribbon.

APPENDIX B

CST Wakefield Instructions

Follow the PIC instructions in Appendix A until you reach the step to import the beam. Instead of importing an external beam change the solver type by navigating to the Home section of the ribbon. There, under the “Simulation” section click the drop-down menu for “Setup Solver” and select “Wakefield Solver”. Navigate back to the “Simulation” section on the ribbon and under “Sources and Loads” select “Particle Beam”. Input the desired beam parameters, namely charge and σ_z . Next, select your field monitors, select the desired quantities to be measured. Finally, click “Setup Solver” and pick your wake length, this can be somewhat arbitrary so don’t worry about it. Once the simulation has concluded you can view the measured fields in the navigation tree and, when viewing them, export them for further analysis by clicking on “Post-Processing” in the ribbon and then selecting “Import/Export”.

APPENDIX C

AWA Beamline Layout

Figure C.1: The full AWA beamline layout. It is broken into three parts to fit on the page, the curved gray arrows indicate continuity. The gun, linacs, and ICTs are labeled with their names. The thin orange rectangles with the “DT” label are trim magnets. The green ovals are insertable YAG screens. The upright blue diamonds are magnetic quadrupoles and the skewed blue diamonds are skew magnetic quadrupoles. The green pairs of squares on either side of the beam path are solenoids. The purple rectangles are magnetic dipoles.

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