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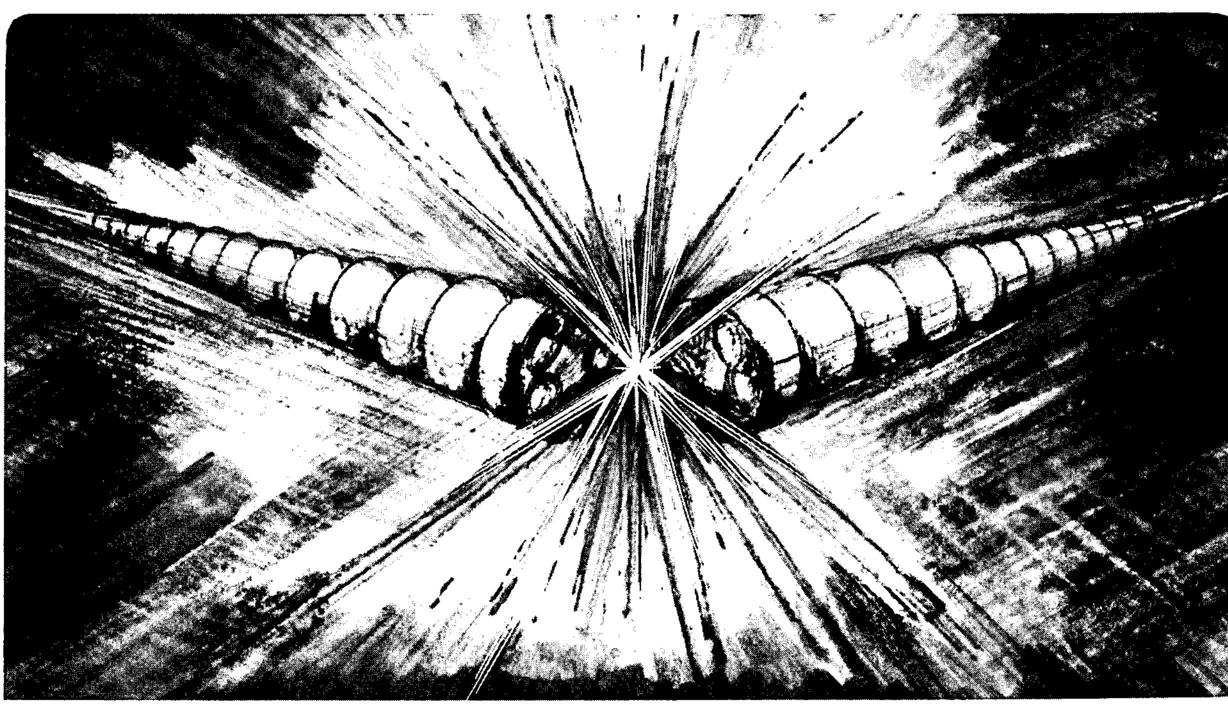

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CHALLENGES ON THE HIGH LUMINOSITY FRONTIER OF $e^+ e^-$ FACTORIES

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ABSTRACT:
For phi factories, tau-charm factories, and B factories to meet their respective luminosity goals, the circulating currents that typify $e^+ e^-$ colliders must be raised an order of magnitude. At the same time the beam size at the interaction point must be decreased. The approaches to realizing these conditions include increasing the charge per bunch, increasing the number of bunches in the collider, increasing the crossing angle for rapid bunch separation, tilting the bunch with respect to the direction of motion at the interaction point ("crab-crossing"), and minimizing the β function at the interaction point. The technological challenges implied by such strategies include the development of 1) novel rf-cavity designs to suppress higher order modes and to provide large rf-voltages for longitudinal focusing, 2) a new generation of powerful feedback electronics to control multi-bunch instabilities, and 3) vacuum chambers and pumping schemes suitable for operation with very high levels of synchrotron radiation. In high current colliders the design of the interaction region poses special problems of allowing rapid beam separation and avoiding excessive scattering of background radiation into the detector.

I. GENERAL CONSIDERATIONS

In recent years most accelerator laboratories throughout the world have conducted detailed studies of the design of high luminosity electron-positron colliders at a variety of center of mass energies. Commonly referred to as "factories", these machines generally have been considered to be storage ring colliders, although the low energy end of linear colliders has been studied as top and Higgs factories. Of all such studies only one, the Frascati phi factory DAΦNE, is an approved construction project. Other efforts – most notably the B-factory efforts at SLAC/LBL/LLNL, at Cornell, and at KEK – are still restricted to the R&D phase. While designs of tau-charm, Z, and top factories have been focused on equal beam energies, proposals for phi factories have also considered the use of unequal beam energies [1]. Indeed all recent conceptual design studies of B factories (at CERN, DESY, KEK, Cornell, and SLAC) are based on the use of unequal beam energies (asymmetric B factories). This paper reviews the accelerator physics and technology issues that are central to the design of high luminosity lepton colliders with particular attention paid to the interaction region, vacuum and rf-systems.

The common features of all factory designs follow from the basic scaling of luminosity with beam energy, E, average current I, tune shift, ξ, aspect ratio, r, and β-function at the interaction point. With equal tune shifts for both beams, the peak luminosity is

$$\mathcal{L} = 1.3\times10^{33}\left(\frac{\xi(E)}{0.03}\right)\left(\frac{I}{2\,A}\right)\left(\frac{1\text{ cm}}{\beta_y^*(E)}\right)\left(\frac{E}{1\text{ GeV}}\right)(1+r)\,\text{cm}^{-2}\,\text{s}^{-1}$$

This scaling equation along with required ranges of time-average luminosity is illustrated in Figure 1. The dark gray curve assumes that β^* scales with $\sqrt{E}$ and $\beta^* \approx 1$ cm at 5 GeV. To take advantage of the small β^* possible at low beam energy requires operating the collider with very short bunches, as has been proposed for a quasi-isochronous phi factory at UCLA. [2] If the minimum practical value of β^* is limited to 1 cm, then the scaling of luminosity with energy is follows the bottom of the gray band.

There is no strong evidence that the maximum achievable tune shift has any strong dependence on the beam energy. Though there has been theoretical speculation that the maximum head-on tune shift may be as large as 0.1 for round beams, there is no experimental evidence for this assumption, especially in the case of colliders with many, closely spaced bunches, for which the long-range tune spread is non-negligible. Consequently, most factory designs have assumed a "conservative" value of $\xi = 0.3$.

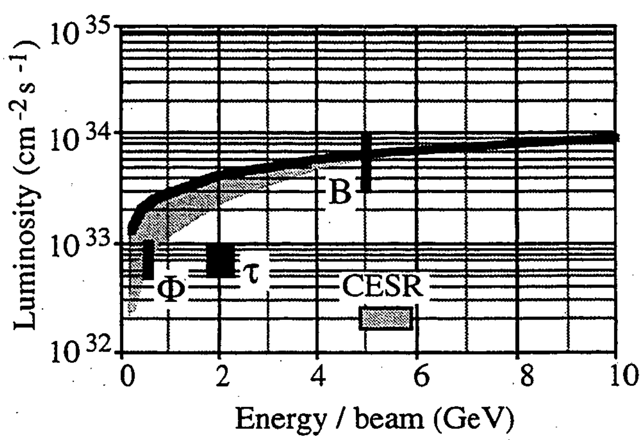

Figure 1. Luminosity scaling with beam energy and the requirements for flavor factories.

Especially for B-factories, the control of synchrotron radiation generated by the beam separation process seems to preclude the use of round beams; all B factory designs now have adopted flat beam scenarios. Moreover, studies of IR optics indicate that the minimum practical β^* is larger for round beam designs than flat beam designs.

As the physics goals of the flavor factory determines the range of operating energies, the only quantities available for adjustment by the designer are the average current and β^*. With the exception of Φ–factory designs by UCLA (SMC) and Novosibirsk, all of the e^+e^- factories have assumed the following common characteristics: 1) two rings with one or more common interaction regions (IR); 2) an average beam current in each ring of ~ 2 Amp, 3) a number of bunches ~10^3 to keep the single bunch current well within existing practice, 4) flat beams - the apparent gain with round beams cannot be realized due to background problems and optics design practicalities. In contrast, both the UCLA and Novosibirsk Φ–factory designs rely on single, compact rings with 4 - 6 T dipoles and few, very short bunches.

II. INTERACTION REGION DESIGN

The large number of bunches in e^+e^- factories requires rapid separation of the beams outside interaction region to avoid the deleterious effects of parasitic, near-collisions. In the case of asymmetric colliders the separation need not rely on the beams crossing at a finite angle. Indeed, the separation can be accomplished by purely magnetic means as typified by the PEP-II design [3], which employs a S-shape, magnetic separation scheme. Such configurations with head-on collisions have the advantage of maximizing the beam-beam tune shift without risking the excitation of synchro-betatron resonances and without the introduction of additional rf-cavities for beam manipulation. The price of purely magnetic separation is the use of several shared optical components, some of which are of unusual design. The septum quadrupole of PEP-II exemplifies a difficult, specialty magnet for the IR. In the design of the shared optics, special attention must be paid to the minimization of the synchrotron radiation fans that can lead to detector backgrounds and excessive operating pressure near the IR.

For the tau-charm factory and symmetric Φ-factory, the typical approach is to consider a first phase design based on proven beam separation approaches; in the second phase the effective luminosity is increased by modifying the IR (and ring lattice) to include crab-crossing, monchromatization, or longitudinal polarization of the beams. In phase 1, beam separation is performed via a shallow crossing angle or by electrostatic separators. Consequently, the bunch spacing cannot be as close as is possible with an energy asymmetry or with crab-crossing. Achieving sufficient luminosity during phase one depends, therefore, on maximizing the single bunch luminosity; i.e., by maximizing the single bunch peak current and minimizing β^*.

A further challenge for the design of the tau-charm factories is the exceedingly narrow width of the J/ψ at 3.1 GeV. For the collider to access this state with high efficiency Zohlents [4] has proposed a monchromatization scheme. In this scheme the dispersion at the IR is non-zero in the horizontal plane. The sign of the dispersion is opposite for the two beams so that electrons of slightly higher energy collide with positrons of slightly lower than average energy and vice versa. The center of mass energy is then always 2E. The emittance is made small so that the beam size (and tune shift) is set by the energy spread and the dispersion. In that case luminosity scaling equation above does not apply. An example of a two stage approach including monochromatization [5] is given in Table 1.

Table 1. Characteristics of tau-charm factory with Phase 2 optimized for J/ψ production

Characteristic	Phase 1	Phase 2
Energy (GeV)	2	1.5
β at IP, (β^*_x, β^*_y) (m)	(0.2,0.01)	(0.01, 0.15)
Energy spread in CM	4×10^{-4}	6×10^{-5}
Emittance, ε_x, ε_x (nm)	110, 2.6	10, 2
Number of bunches	30	30
Bunch spacing (m)	12	12
Particles/bunch	1.4×10^{11}	8×10^{10}
Tune shift	0.039	0.015
Long. impedance (Ω)	≈0.13	≈1
Luminosity ($cm^{-2}s^{-1}$)	10^{33}	4×10^{32}

Including radio frequency deflecting cavities located at a betatron phase angle of (n + 1/2)π on each side of the collision point allows rapid separation of the beams via the crab-crossing scheme [6], [7]. The crab-cavities introduce a time-dependent transverse kick that tilts the bunches with respect to the beam trajectories so that the collisions take place head-on. The crossing angle of the beam trajectories can then be large enough to reduce the number of magnets common to both beams to a single quadrupole. This approach, adopted for CESR-B and for the second phase of DAFNE, allows for greater flexibility in the choice of beam energy and greater ease in suppressing the generation synchrotron radiation near the IR. The voltage in the crab cavity is related to the "crab angle", rf-wavelength, and the magnitude of the beta function at the cavity by

$$V_{\perp\,crab} = \frac{\theta_{crab}\,\lambda_{rf\text{-}crab}\,(E/e)}{4\pi\sqrt{\beta^*\,\beta_{crab}}} .$$

Typical peak voltages in the crab cavities are 1 - 4 MV.

The "crab-crossing" scheme has never been tried in practice. Considerable effort in designing and testing super-conducting crab-cavities [8] has been conducted at Cornell in collaboration with KEK. Foreseen difficulties include the maintenance of tight tolerances on the phase and voltage of the rf in the cavities; another disadvantage of crab crossing is that the cavities add to ring impedance. Both the voltage and phase tolerances are proportional to the beam radius at the interaction point; the voltage tolerance also varies with the square root of the damping decrement. Hence, crab-crossing provides an additional reason for the use of wigglers or wiggler lattices in low energy rings.

III. RF CHALLENGES

The rf-systems challenges of flavor factories derive from two considerations: 1) maintaining a short bunch length through strong longitudinal focusing, 2) restoring the large amount of energy lost through higher order modes and copious synchrotron radiation. Both these requirements imply that the cavity must have as large a shunt impedance as possible at the fundamental. As the circulating current in all factories range from ≈1 to 5 Amps, coupled bunch instabilities will be excessively strong unless the shunt impedance is low at all other frequencies.

Unless the bunch length, σ_z, is appreciably less than β^* (the depth of focus), the actual luminosity will be reduced due to the "hourglass" shape of the bunch at the interaction point and due to synchrobetatron coupling effects. Consequently factory designs generally have required that $0.2<\sigma_z<1.5$ cm. As the bunch length scales as

$$\sigma_z \propto \left(\frac{\alpha_1}{V_{RF} f_{RF}} \right)^{1/2}$$

where α_1 is the first order momentum compaction, flavor factories generally require a large rf-voltage, even at low beam energies for which the radiated power is not large. As high power tubes are readily available at ≈500 MHz, all proposed projects have opted for frequencies in this range, leaving V_{RF} as the only free parameter. Despite the broad range of RF-voltages for the various projects (see Table 2), the simultaneous need to minimize the higher order mode impedances has led almost all the projects to adopt designs with a large voltage per cavity (1.5 - 2 MV).

Table 2. RF parameters for various flavor factories

Project	$\mathcal{L}$ (10^{33})	Type	V_{RF} (MV)	f_{RF} (MHz)	σ (cm)	P_{SR} (MW)
SMC	1	NC	0.1	486	0.1	0.1
DAΦNE	0.2 -1	NC	0.25	≈357	3.0	0.05
INP	>1	NC		≈700	0.5	0.05
SτCF	1	SC	12	400	0.8	0.06
JINR	1	?	3.1	257.5	0.8	0.06
BFI	1	SC	13	498	2	3.1
CESR-B	3	SC	35	500	1	4.5
DESY	3	NC	17	500	1	2.4
INP	5	NC/SC	15.4	500	0.7	3.8
KEK	2	NC/SC	48	508	0.5	4.6
PEP-II	3	NC	19	476	1	5.3

Especially in small rings such as CESR where space is at tight, high voltage operation makes superconducting cavities an attractive option, despite the lack of any experience with operating such cavities at high fields under heavy beam loading. A further practical difficulty is protecting the superconducting cavities from virtually all the synchrotron radiation generated in the dipole arcs. For superconducting cavities, widening the beam pipe so that the cavity supports only the fundamental accelerating mode can reduce HOMs. The Cornell design extends this concept by adding a specially designed fluted wave-guide tube [9] to transmit the two lowest frequency modes (TM_{111} and TM_{110}) outside the cavity to ferrite rf-absorbers located outside the cryostat. A problem peculiar to crab-cavities is the need to attenuate fundamental mode which is at a lower frequency than the desired deflecting mode.

Room temperature cavities can satisfy all requirements by extending the nose cone to increase the gradient to 4 MV/m. The price is increased power dissipation in the cavity walls (up to ≈150 kW in PEP-II) and large Q for the superior modes. SLAC/LBL, LNF, and KEK have been studying the suppression of the superior modes through the addition of waveguides attached to the sides of the cavities. The waveguides must be positioned carefully to couple to all the unwanted modes without strong suppression of the fundamental accelerating mode. Calculations and low power tests confirm the validity of this approach for reducing the Q of the most dangerous modes below 100. At this level, coupled bunch instabilities can be controlled by a suitable feedback system. Indeed for Q_{HOM} >>100 the growth can be more rapid than change in beam phase, thus precluding efficient feedback control. The design of a high power cavity is complicated by the frequency shifts (≈130 MHz) caused by the deformation of the copper cavity under the high thermal and mechanical loads. Both approaches to supplying rf-power require the development of high power klystrons and windows that can pass ≈500 kW reliably.

An alternative to using large RF-voltages is to design the lattice to have a very small value of α_1. As the maximum current to avoid the single bunch microwave instability is also proportional to α_1, this approach will decrease the luminosity unless the second order momentum compaction and the damping time are simultaneously made small enough that radiation damping prevents the bunch-lengthening. This approach has been analyzed by Pellegrini and Robin [10], [11] as the basis of a quasi-isochronous design for the proposed UCLA Φ factory.

IV. FEEDBACK CONTROL OF INSTABILITIES

Despite the suppression of the Q of the superior modes to values <100, the large number of bunches and high average current make factories susceptible to virulent multi-bunch instabilities. Those modes with growth times shorter than a radiation damping time must be controlled with active feedback system.

The heavy beam loading combined with a sizable gap in the bunch pattern (to avoid ion trapping) requires detuning the cavity by so that the beam presents a matched load to the rf-drive. The shift,

$$\Delta f/f \sim I\,(R/Q) N_{cell}\,;$$

hence, the detuning can lead to driving the first (m=1, n=1) longitudinal, coupled-bunch mode. For room temperature cavities the dipole oscillation must be controlled by a feedback loop on the low-level rf-drive. The use of superconducting cavities can avoid this difficulty as Q is very large and the number of cells can be minimized; hence the detuning frequency can be much smaller.

Other longitudinal, coupled-bunch modes can be controlled via a digital, bunch-by-bunch feedback system. A down-sampling technique of updating the correction signal every n^{th} revolution allows the feedback to operate closer to the Nyquist limit and reduces the number of computations by n^{-2}. A prototype for PEP-II [11] that employs commercially available signal processors has been tested at SLAC and will be installed on the Advanced Light Source at LBL. A similar system will be used in DAΦNE. Such bunch-by-bunch feedback systems are also essential to preserve the emittance in the SSC and LHC.

Digital feedback systems are also envisioned to control transverse, coupled bunch modes, including the transverse resistive wall instability. Even with feedback, the resistive wall mode grows so rapidly in the low energy rings that the beam tube must have a conductivity much higher than that of stainless steel.

IV. VACUUM IMPLICATIONS

While currents >1 Amp are not unprecedented in rings, they are much larger than found in existing e^+e^- colliders. Hence, factories will be characterized by large thermal loads on the vacuum chamber walls and large dynamic gas loads. Moreover, factories require operating pressures <10 nTorr in the dipole arcs. To meet these unprecedented demands, the characteristics of vacuum systems of colliders at the luminosity frontier must evolve markedly from those of existing rings. Thermal loads due to synchrotron radiation, which were typically in the range of 1 - 5 kW/m, have been pushed to 10 – 40 kW/m, introducing both cooling and thermal fatigue difficulties. Whereas the material of choice for vacuum chambers was commonly stainless steel , it is now Al (with an outer Pb cladding) or Cu (or a Cu alloy). Thus, the vacuum engineer faces new and unfamiliar fabrication and cost issues. The are summarized in Table 3.

Table 3. Materials for e^+e^- factory vacuum chambers

	Al	Cu	SS
Photo-desorption	+	++	++
Self-shielding	-	++	++
Thermal conductivity	+	+ to ++	-
Strength	+	- to +	++
Ease of fabrication	++	+	++
Experience	++	+	++
Cost	$	$$	$$

Whereas typical photon fluxes have been 5×10^{17} photons/s/m, B factories will generate $\approx 10^{19}$ photons/s/m. Hence, the vacuum chamber must be characterized by a low design value of the photo-desorption efficiency, η_F, $\approx 10^{-6}$. As the scrubbing of the vacuum chamber by the radiation is the principal means of reaching very low η_F, the initial value of η_F must be small and the clean-up rate rapid to keep the commissioning time less than hundreds of hours.

Pumping speeds in the dipole arcs, S_d, which are 100 - 300 L/s/m in existing storage rings, will be increased to values as large as 3000 L/s/m for CESR-B and SMC. Providing so much distributed pumping strongly affects the choice of the type of pumps and the chamber design. For S_d >1000 L/s/m, the chamber will not have the traditional oval shape. Rather, a complex shape including an antechambers is likely to be adopted despite the adverse impact on ease of fabrication, on costs, and on magnet designs.

The complexity of the vacuum system design is exemplified by the arcs of the low energy ring (LER) of CESR-B. The arcs are a wiggler lattice composed of dipoles with a 20 m bend radius interleaved with -98 m reverse bends. The arrangement of the magnets, the relative distribution of synchrotron power, the relative η_F, and the relative distributed gas load are displayed in Fig. 2. Because of the strong variation in power loading, the desorption coefficient suffers equally strong fluctuations. The gas load, which is proportional to the product of these two functions, is much smoother; hence, the phrase "eta-leveling". [13]

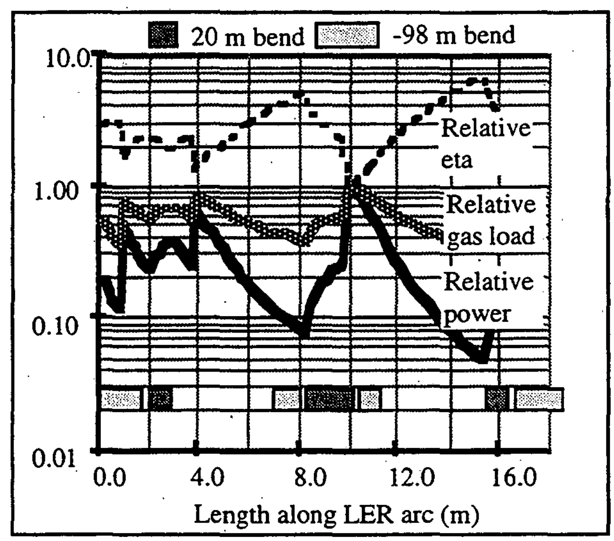

Figure 2. Relative desorption characteristics in dipole arcs of the CESR-B LER. 1.0 corresponds to $\eta = 1.7 \times 10^{-6}$, $Q = 2.3 \times 10^{-6}$ Torr-l/s/m and $P = 10.4$ kW/m.

The arc is pumped with a combination of TiSPs and NEGs, each of which require regeneration at differing intervals. The system requirement is formulated in terms of the average pressure along the arc. Figure 3 illustrates the degree to which the requirement is met as the pumps approach their capacity and require regeneration. From such curves, one calculates an appropriate regeneration scenario.

The vacuum system in the interaction region of e^+e^- factories poses a confluence of conflicting physics and engineering difficulties. Space is at a premium because the beams must be separated rapidly into their respective rings, because detector components are desirable where one might wish to locate pumps, and because beam-pipe conductance can be expected to be small. The rapid beam separation can produce several tens of kilowatts of radiation which must be deposited on photon dumps near the IR, generating a moderately large distributed gas load. Handling the gas load would be routine were it not that the background pressure especially in the incoming beamlines must be <<1 nTorr. The desorbed gas is a direct source of backgrounds because the electrons that scatter from the beam can readily be transported into the detector. Controlling this lost particle background is an extremely difficult and important problem for all high luminosity electron-positron colliders.

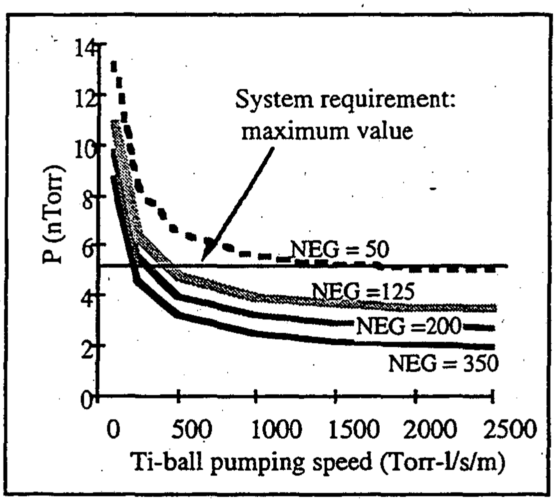

Figure 3. Variation of <P> in the CESR-B LER

One approach that minimizes pumping would employ a differentially-pumped ante-chamber to house the photon dump. In such a design, illustrated schematically in Fig. 4, most of the gas is removed by TiSPs. The gas that leaks through the low conductance duct into the beam chamber is pumped by two rows of NEG modules. The regeneration intervals for the NEGs and TiSPs in the interaction region of PEP-II are ≈ 2 months and ≈ 1 week respectively.

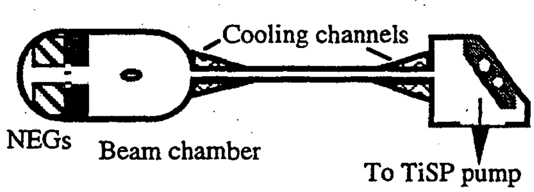

Fig. 4. Differentially-pumped chamber in the PEP-II HER beamline of upstream of IR. The duct is 11×300 mm

V. CONCLUDING COMMENTS

To meet the electromagnetic impedance budget, factory designs will require beamline components to have a $(Z/n)_{eff} \approx 1\ \Omega$ – lower than typically found in storage rings. In the case of the tau-charm or Φ factory, in which the single bunch luminosity must be maximized, $(Z/n)_{eff} \sim 0.1\ \Omega$. The compact Φ factory designs of UCLA and Novosibirsk have the additional difficulty that the ring impedance will be dominated by the vacuum impedance, because of the very small radius of the machine. Coherent synchrotron radiation may therefore be a substantial component of the total beam losses, even exceeding the incoherent synchrotron radiation. Large losses are especially trouble-some in miniaturized rings as the interaction region may absorb as much as 1 kW/m of the coherent radiation.

Most factory designs include specialized components such as wigglers to decrease the damping time and increase the natural beam emittance. Given the high currents, such wigglers can generate enormous, localized thermal and/or gas loads. Although such specialized beamline components do not appear to produce insurmountable problems, engineering the practical realizations can be costly.

Proposed e^+e^- factories present a challenging task to the accelerator designer. As the single bunch physics of most designs is similar to that in existing colliders, the major challenges derive from the large number of bunches that yield a high average current. Most major sub-systems will be pushed to unprecedented levels of performance and of reliability. The benefits of accelerator development for high luminosity will be realized not only in flavor factories, but also in hadron supercolliders.

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