Title
Overview of heavy-ion fusion focus on computer simulation aspect

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Overview of Heavy-Ion Fusion Focus on computer simulation aspect*

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Computer Engineering Science seminar
University of California at Berkeley

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The U.S. Heavy Ion Fusion Program - Participation

Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
Princeton Plasma Physics Laboratory
Naval Research Laboratory
Los Alamos National Laboratory
Sandia National Laboratory
University of Maryland
University of Missouri
Stanford Linear Accelerator Center
Advanced Magnet Laboratory
Idaho National Environmental and Engineering Lab
University of California
  a. Berkeley
  b. Los Angeles
  c. San Diego

MIT
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Allied Signal
National Arnold
Hitachi
Mission Research
Georgia Tech
General Atomic
MRTI

Employees of LBNL, LLNL, and PPPL form the U.S. Virtual National Laboratory for Heavy Ion Fusion

Outline

Fusion energy
- Principles, advantages/disadvantages
- Basic requirements
- Paths to fusion

Basic plasma computer models
- Particle-In-Cell
- Fluid

Heavy Ion Inertial Fusion
- The target
- The chamber
- The accelerator

Conclusion

FUSION ENERGY

FUSION ENERGY: principles

Equivalence of mass and energy

Einstein's equation

$$E = mc^2$$

- m = mass of particle
- c = speed of light ~ 3.10^8 m/sec

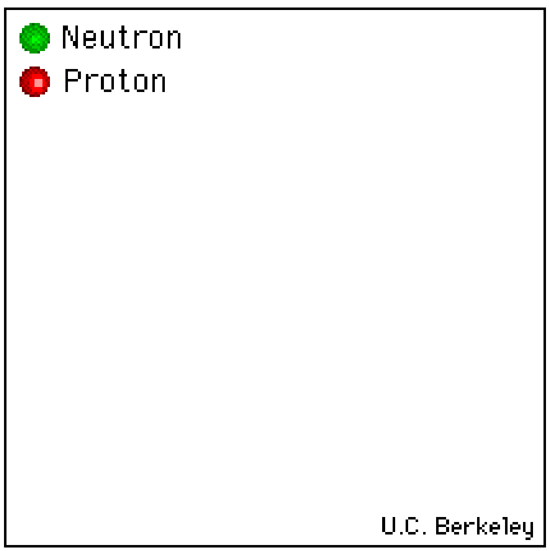
Example:

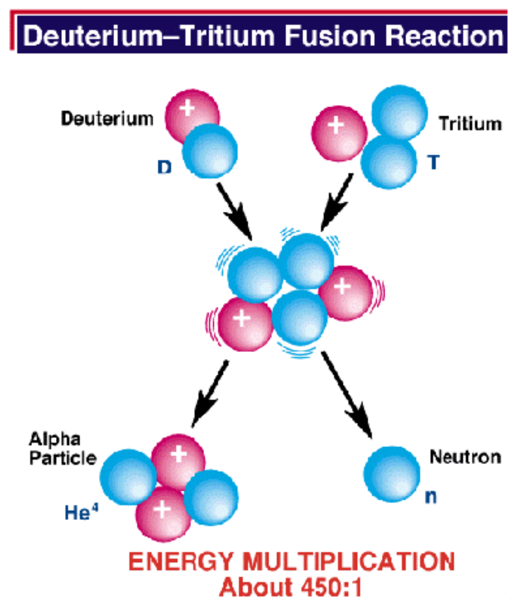
if a 1 gram raisin was converted completely into energy

E = 1 gram x c^2
= (10^{-3}kg) x (3.10^8 m/sec)^2
= 9.10^{13} Joules
~ 10,000 tons of TNT!

⇨ **huge amount of energy can be extracted from mass conversion.**

Fusion





Advantages of fusion

Virtually inexhaustible resources of fuel (water)

Clean (no CO_2 emission, almost no radioactive waste)

Fusion reactors are inherently safe. They cannot explode or overheat.

Byproducts or fuel cannot be used to build mass destruction weapons

The fuel is accessible worldwide

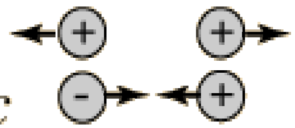
Disadvantages of fusion

Complex, still at conceptual stage

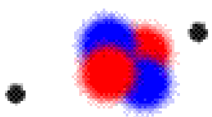
Centralization of power sources

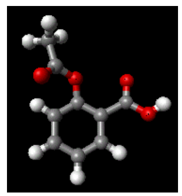
FUSION ENERGY: Basic requirements

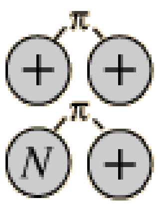
Fundamental forces (some)

		Strength	Range (m)	Particle
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1

Holds





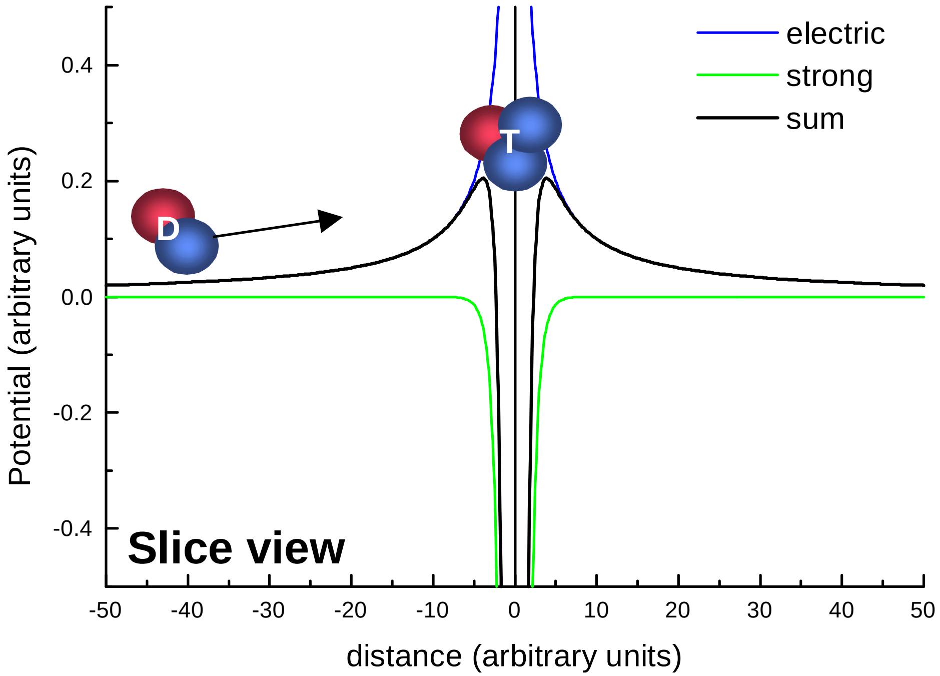
		Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	π, others mass > 0.1 GeV

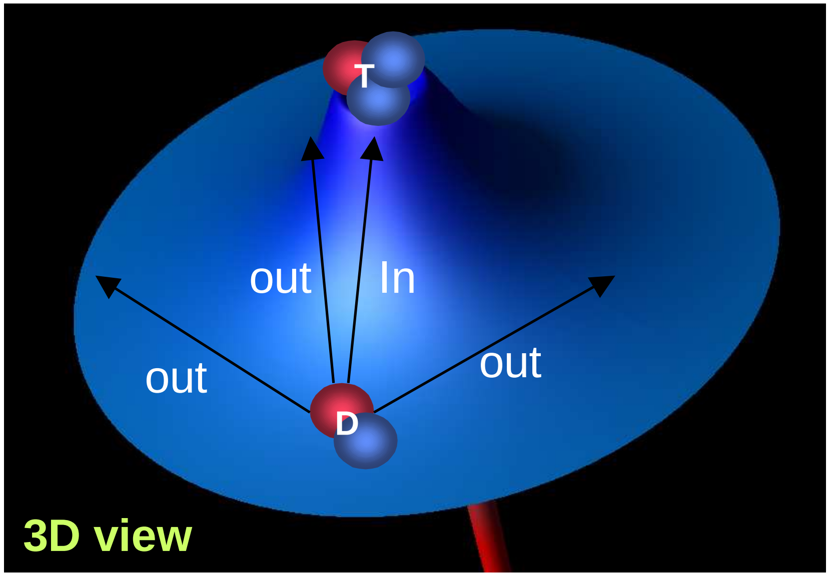
Holds

Potential barrier

In order to fuse, the nuclei have to

overcome electrostatic barrier **go into right direction**



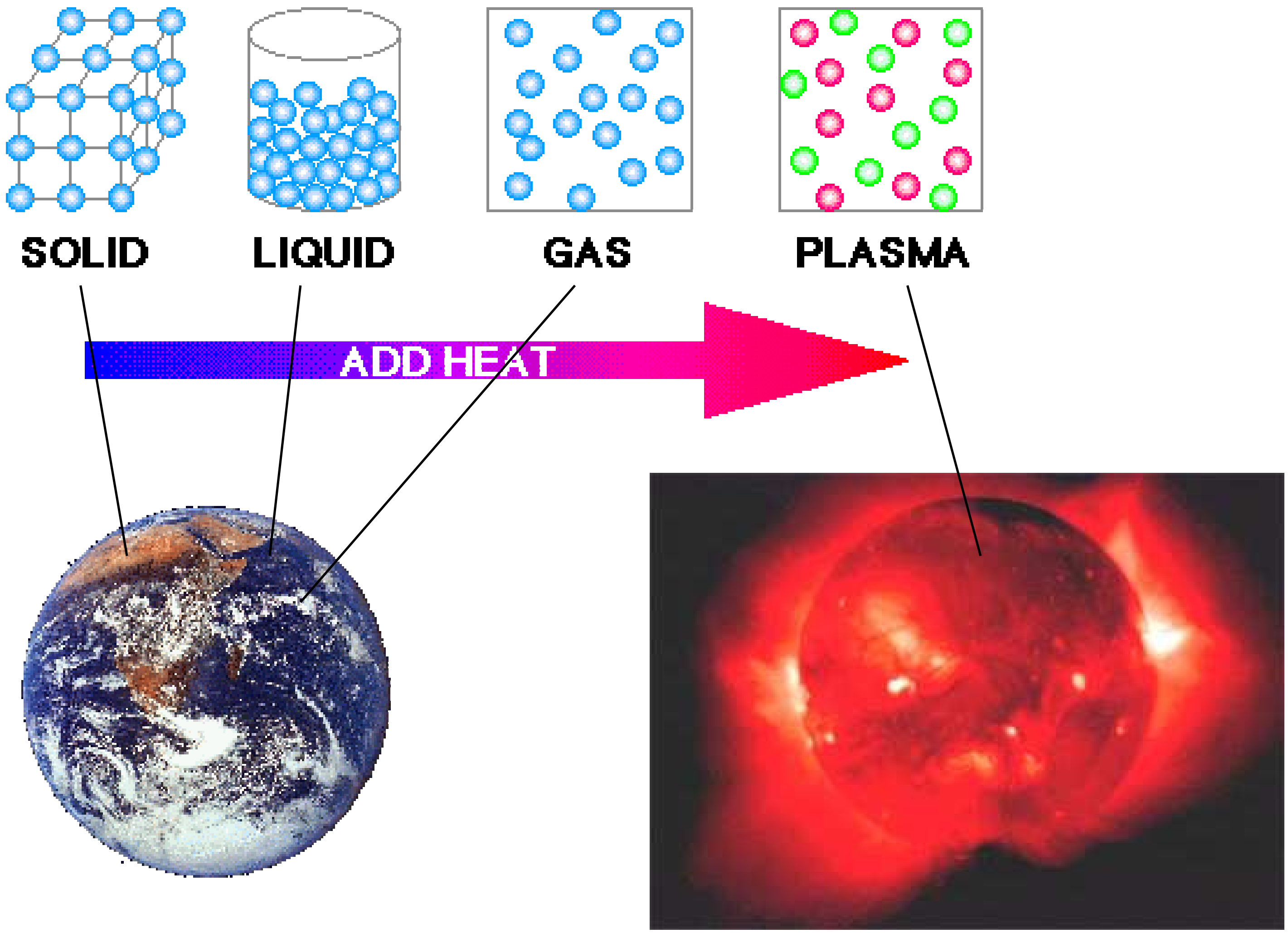


need energy (millions of degrees)

need many events (many particles)

Find these conditions in “PLASMAS”

States of matter



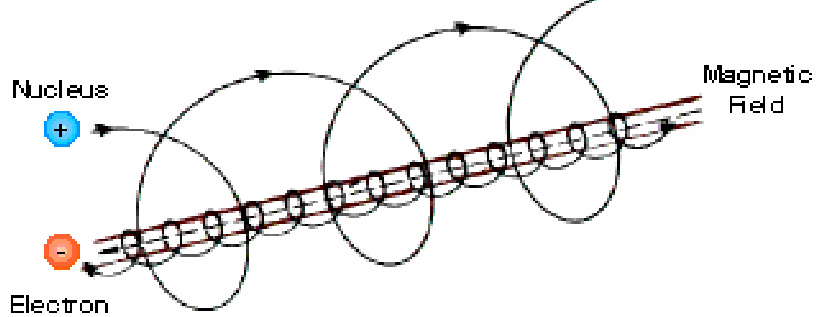
FUSION ENERGY: Paths

The different paths to fusion energy

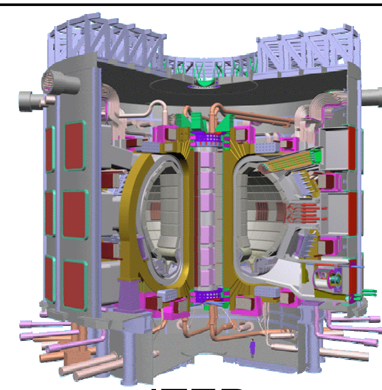
Gravitational Confinement

Far too big!

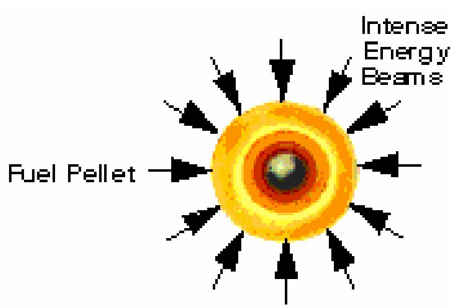
Magnetic Confinement



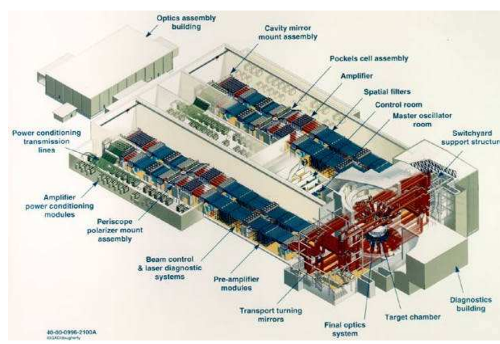
Tokamaks



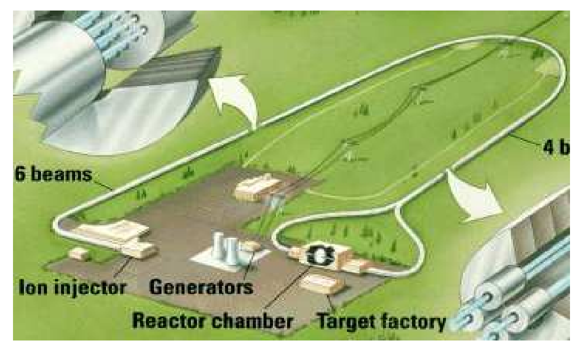
ITER



Inertial Confinement



Lasers (NIF)



Particle accelerators

BASIC PLASMA COMPUTER MODELS

Computer simulation of plasmas

We compute on various platforms: pc (Pentium, Athlon), Pentium clusters, IBM-SP

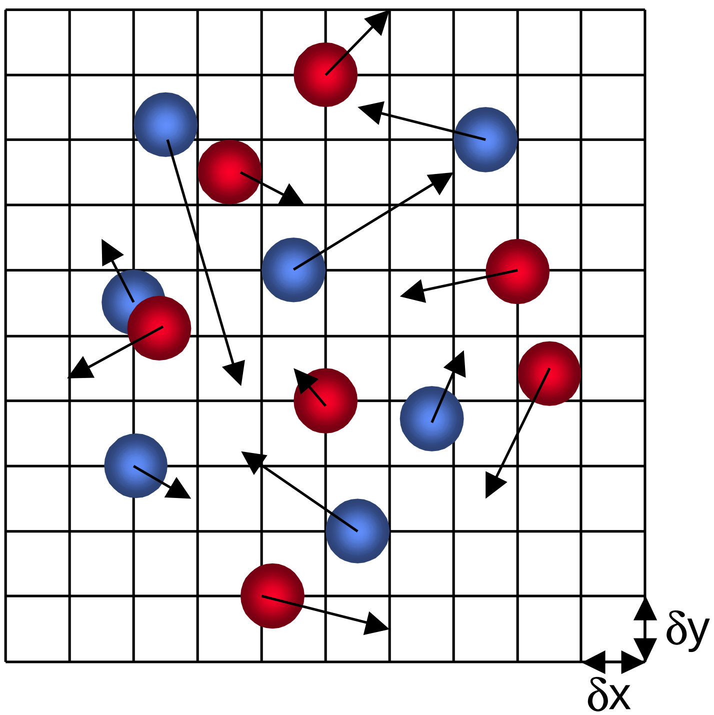
IBM-SP very powerful parallel computer but need to simulate systems that contains at least 1000 billions of real particles

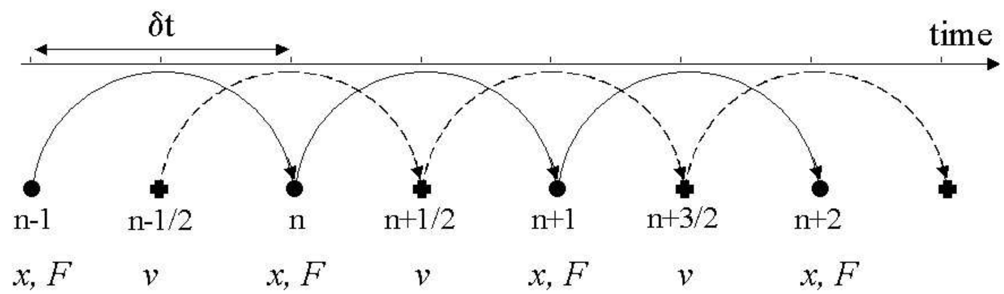
Even on the NERSC IBM-SP, the simulation of all the real particles is usually unfeasible

We have to make approximations!

Computer simulation of plasma as collection of particles

- We use macroparticles (1 macroparticle = many real particles)
- We compute the force (field) on a grid
- We advance particle and fields by finite time steps



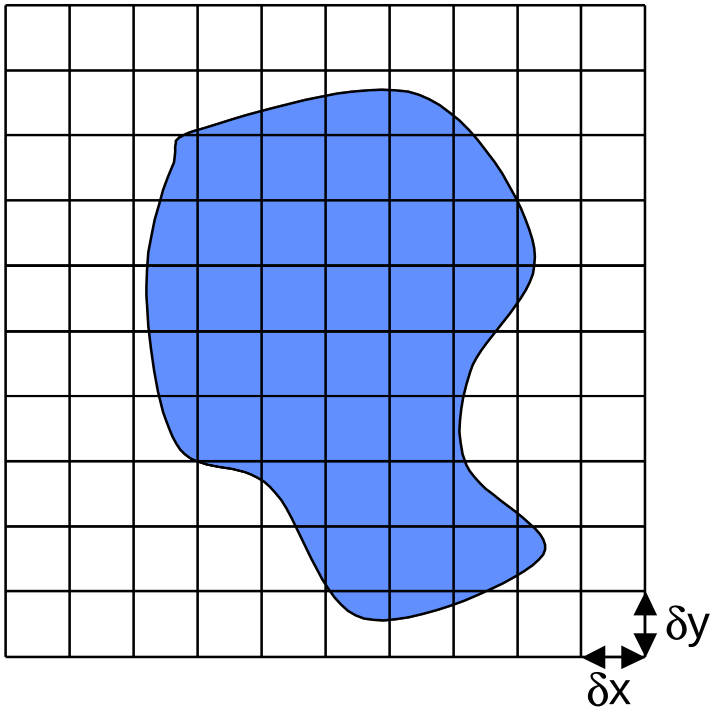


Computer simulation of plasma as fluid

– **A system containing many particles may (under certain conditions) be modeled as a fluid**

  Example: air is made of molecules but is often described as a fluid

– **Restriction: one location = one velocity**

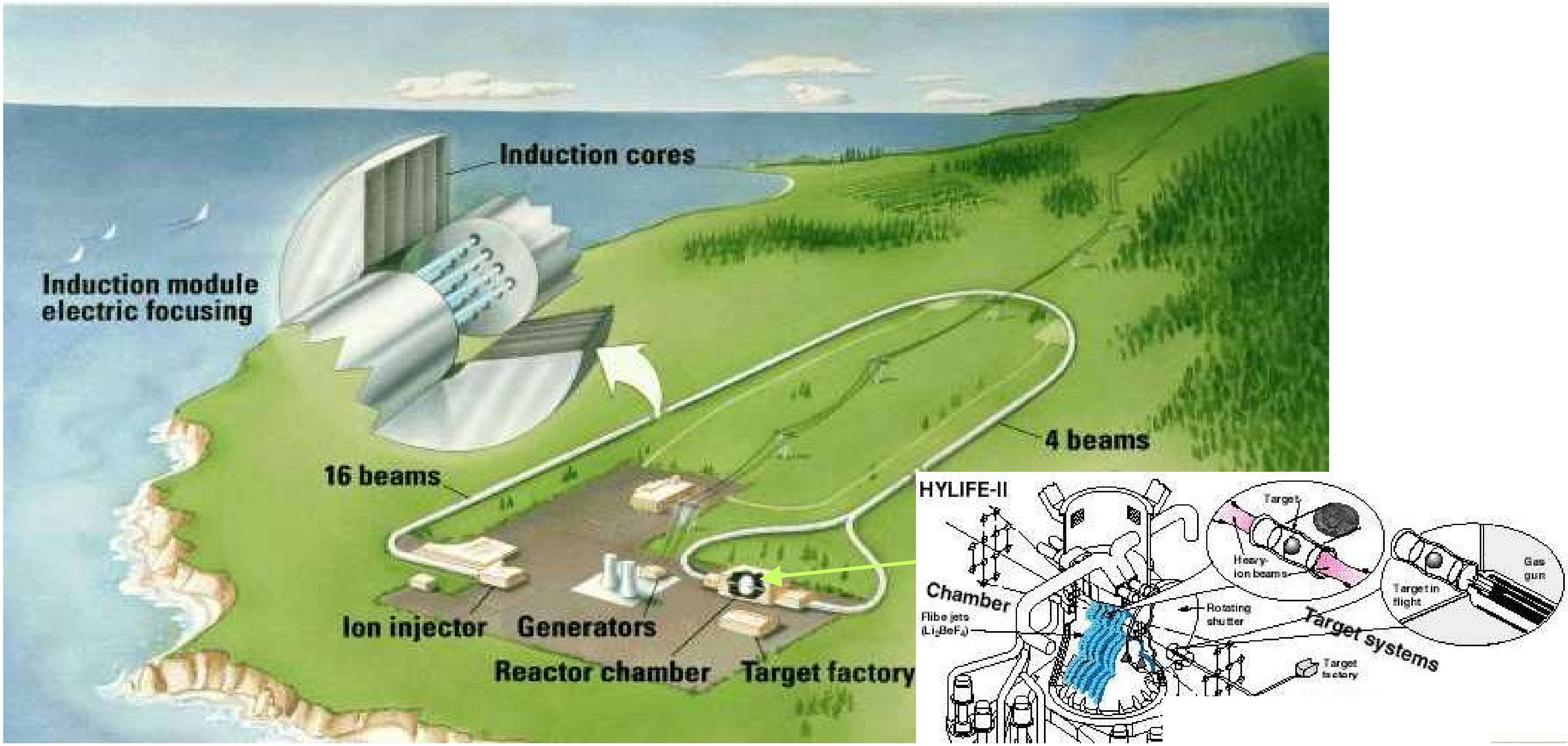


– **We compute the fluid equation on a grid**

– **The temporal evolution of the fluid is computed using finite time steps**

HEAVY ION INERTIAL FUSION

An Artist's Conception of a Heavy Ion Fusion Power Plant

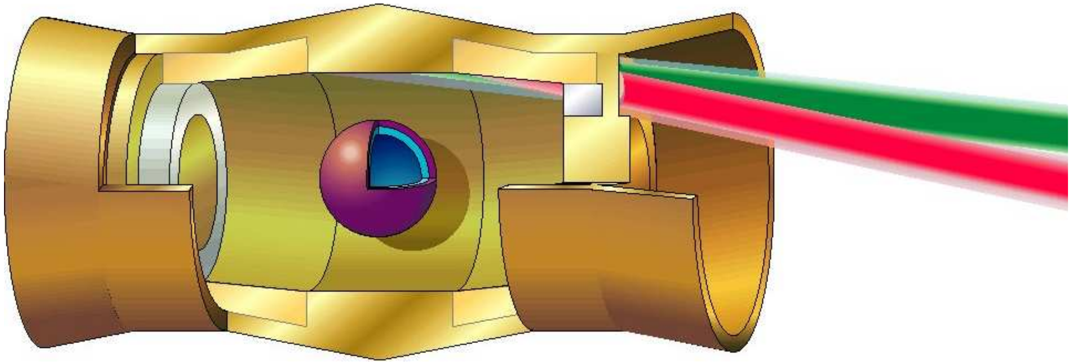


From the overall system, we identify several parts and study them <u>separately</u> using theory, experiments and computer simulations.

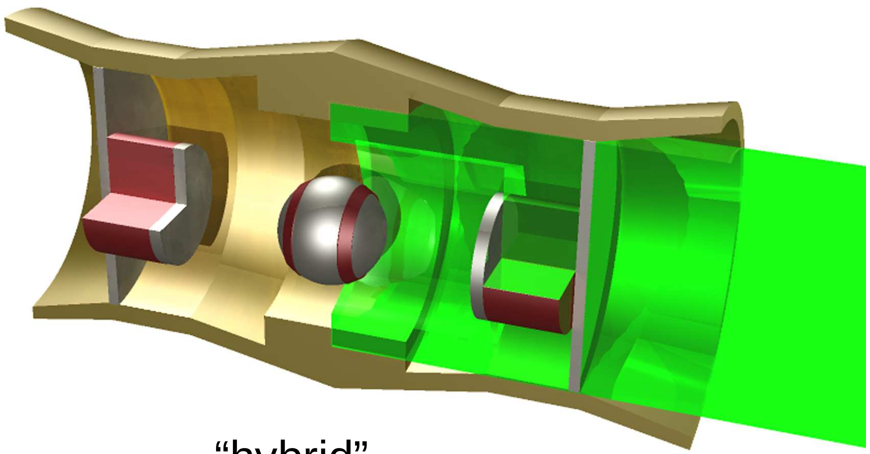
HEAVY ION INERTIAL FUSION: the target

For symmetric illumination, the target is enclosed into a capsule

Examples of capsule

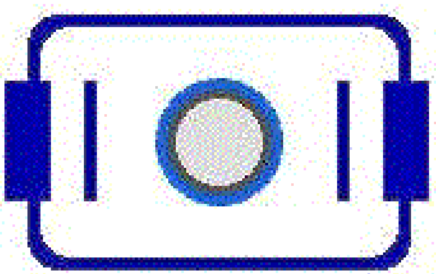


“close coupled”

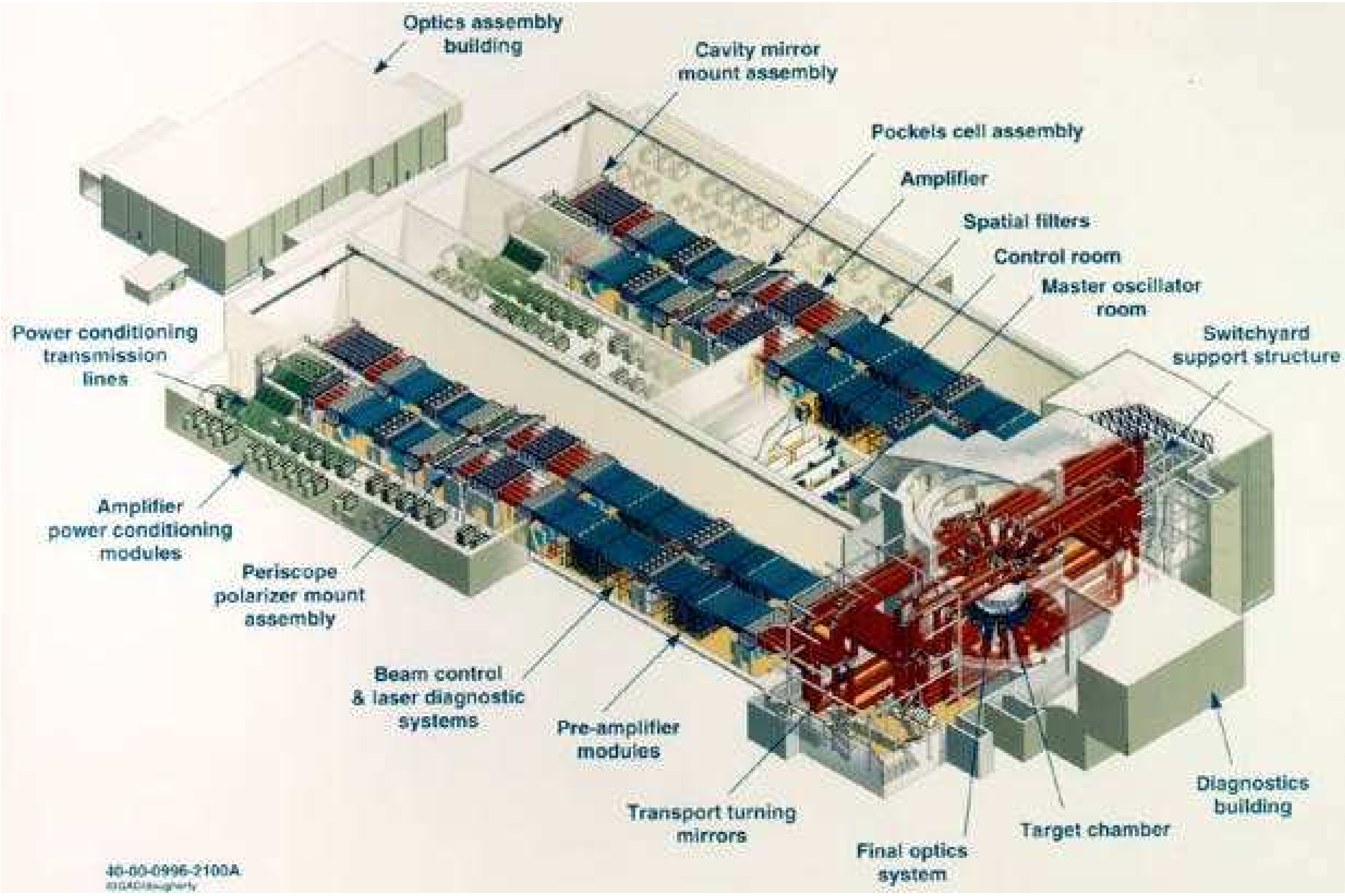


“hybrid”

Hydrodynamic simulation of target implosion and capsule expansion (Lasnex)

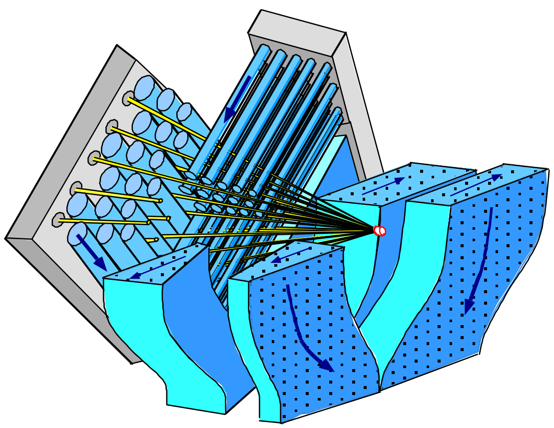


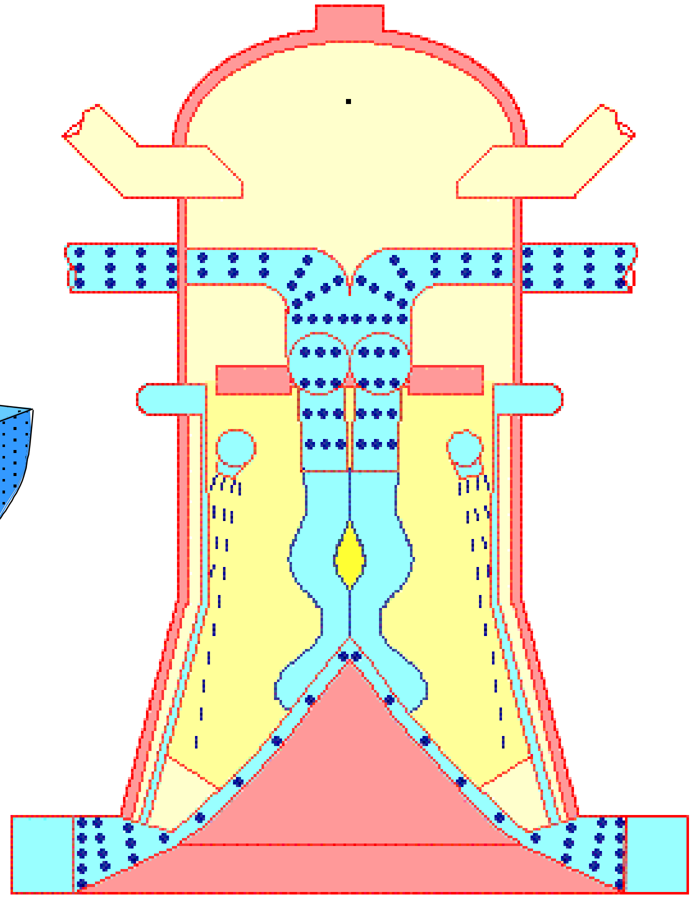
LASNEX is validated against Laser fusion experiments



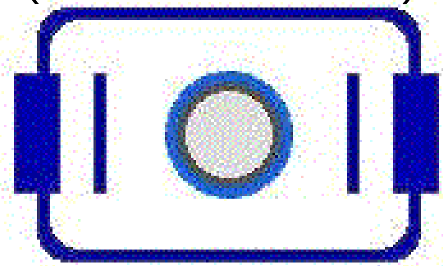
HEAVY ION INERTIAL FUSION: the chamber

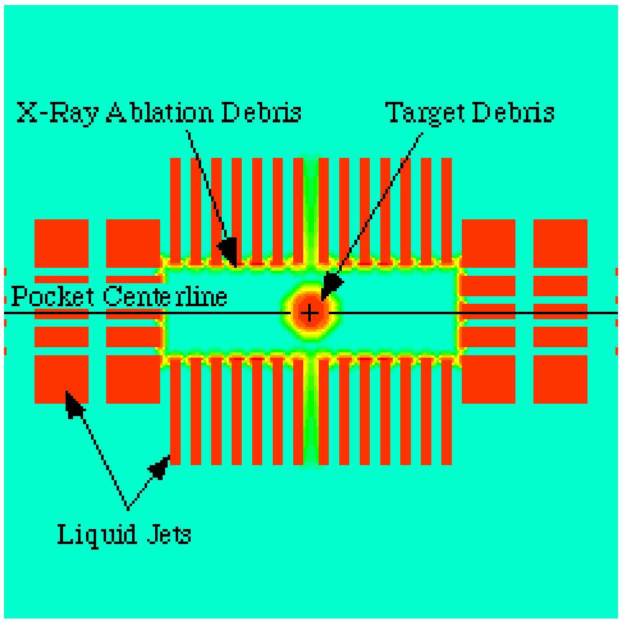
Inside the chamber





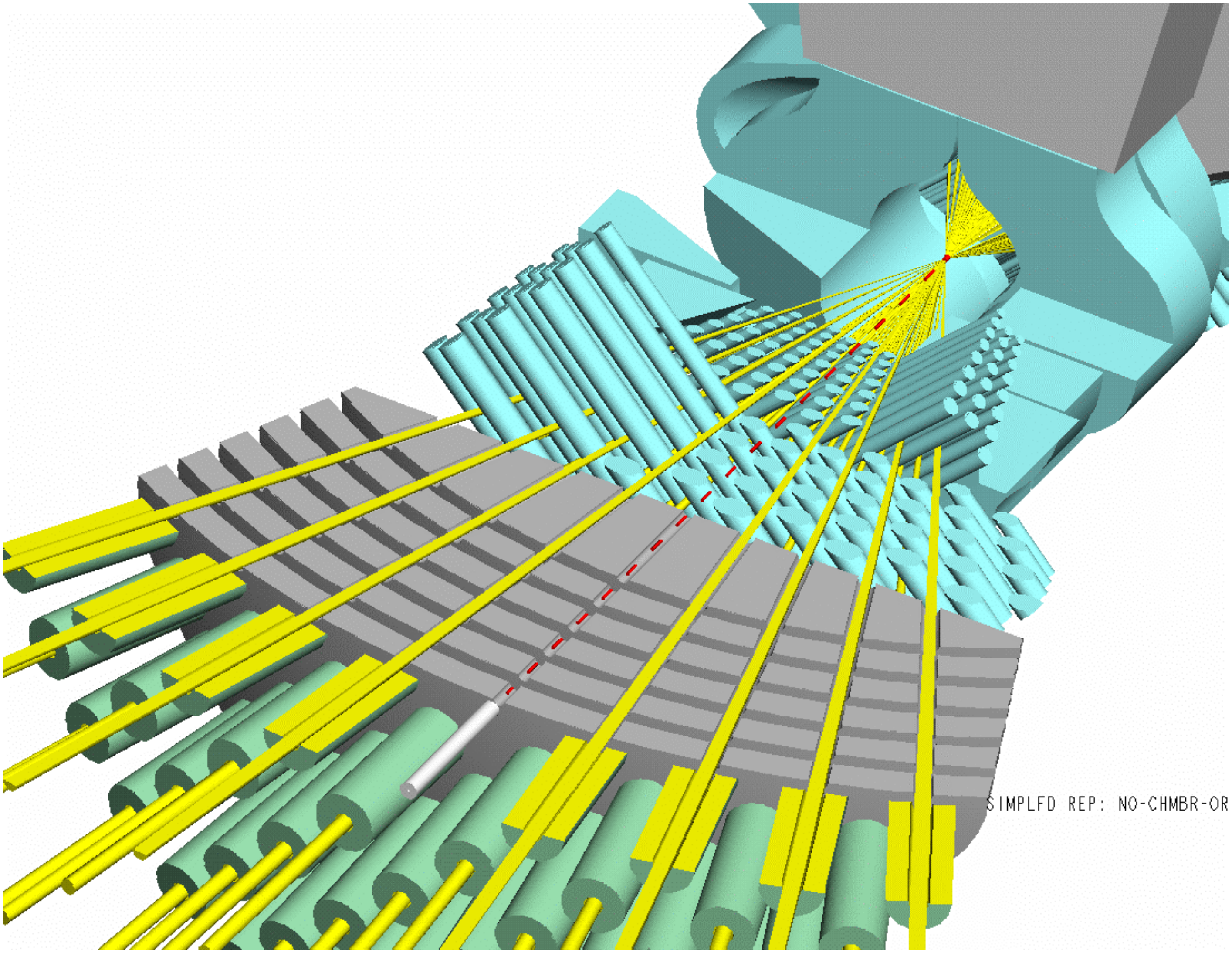
(Lasnex simulation)



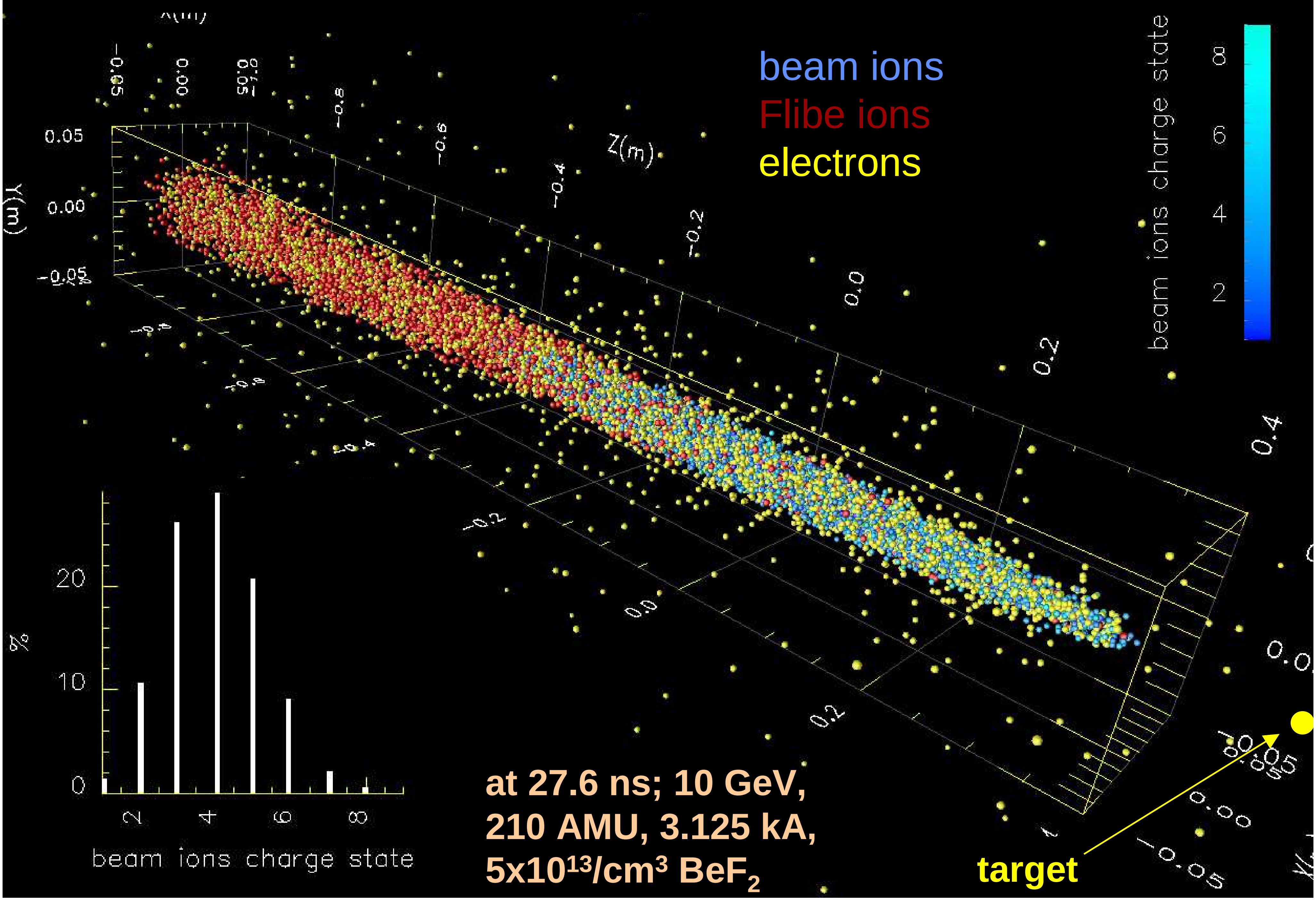


(Tsunami simulation)

Cut-away view shows beam and target injection paths for an example thick-liquid chamber

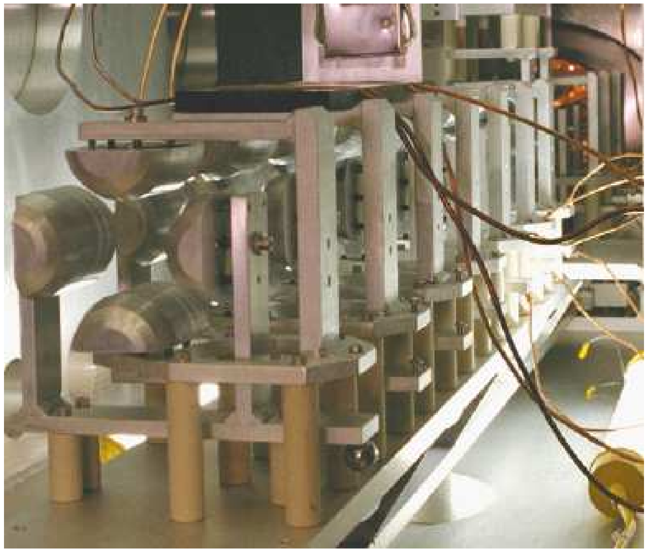


3-D BPIC simulation of beam propagating through Flibe



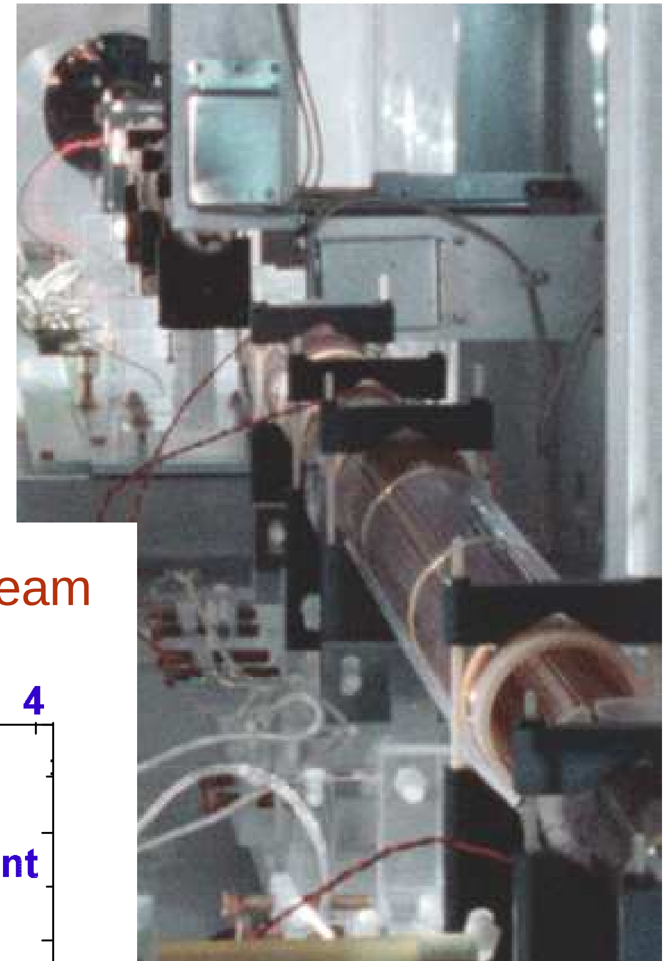
at 27.6 ns; 10 GeV, 210 AMU, 3.125 kA, $5\times10^{13}/cm^3$ BeF_2

Final-Focus Scaled Experiment studied effect of neutralizing electrons (from a hot filament) on focal spot size



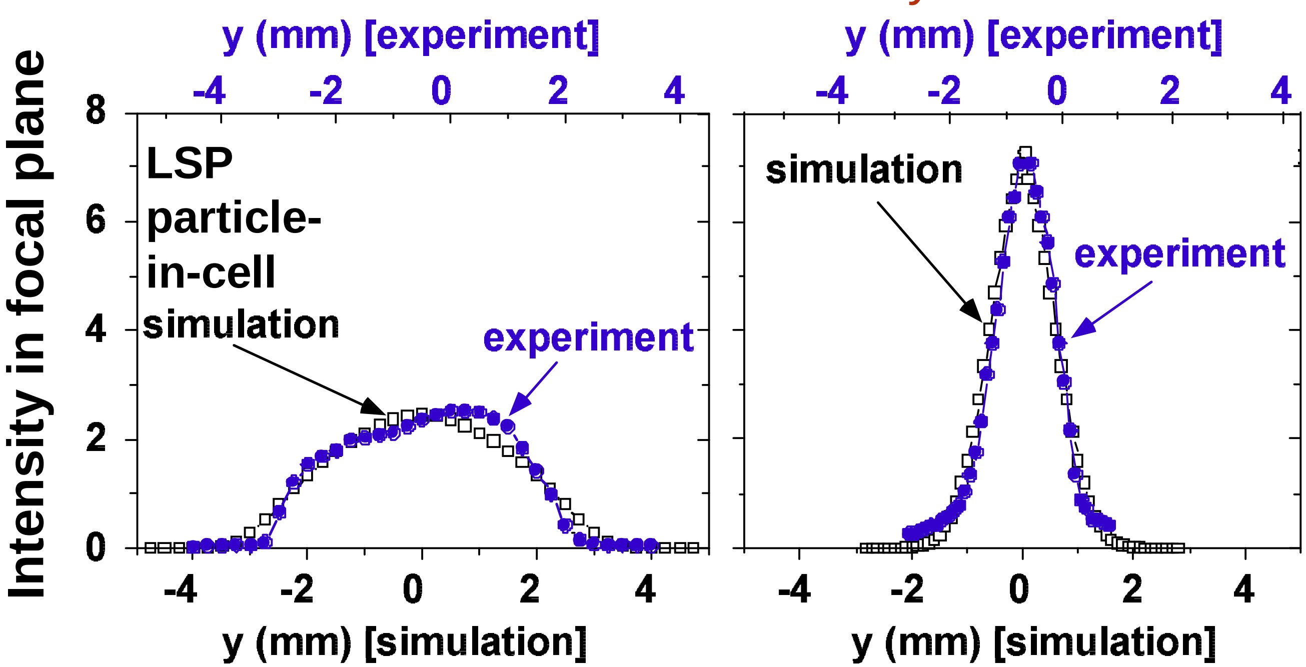
Electrostatic quadrupole lenses for beam set-up

Magnetic quadrupoles for final focusing



Unneutralized beam

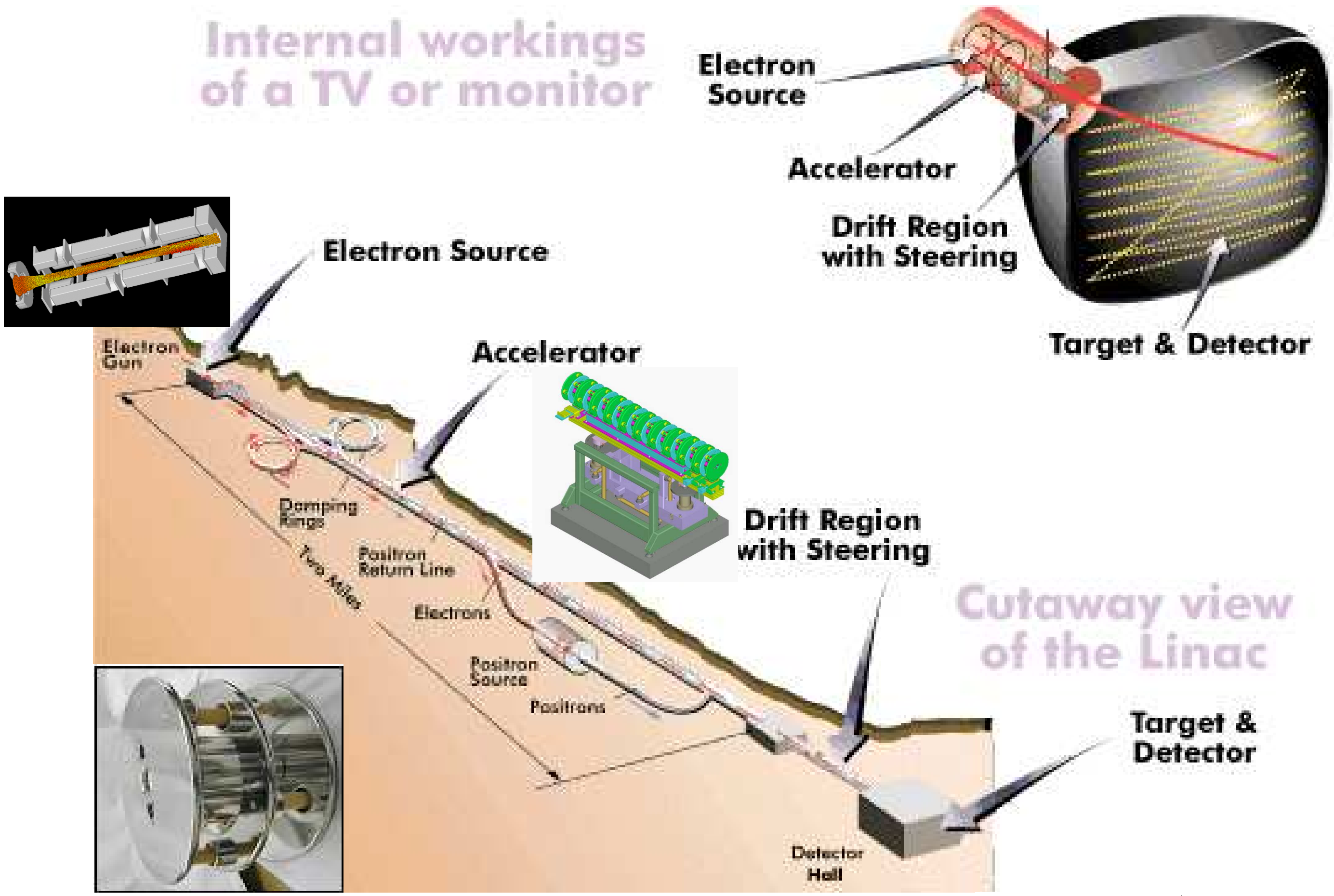
Partially neutralized beam



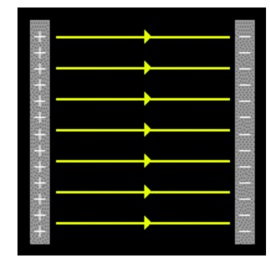
400μA, 160 keV, Cs^+

HEAVY ION INERTIAL FUSION: the accelerator

Principles of particle accelerator (similar TV tube)

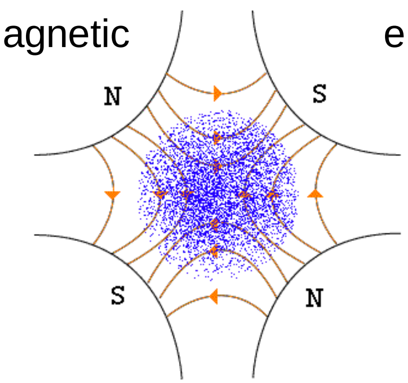


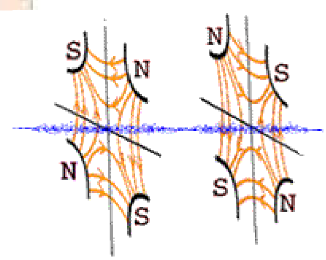
Acceleration



Transverse confinement

Magnetic electric





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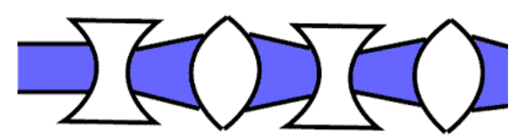
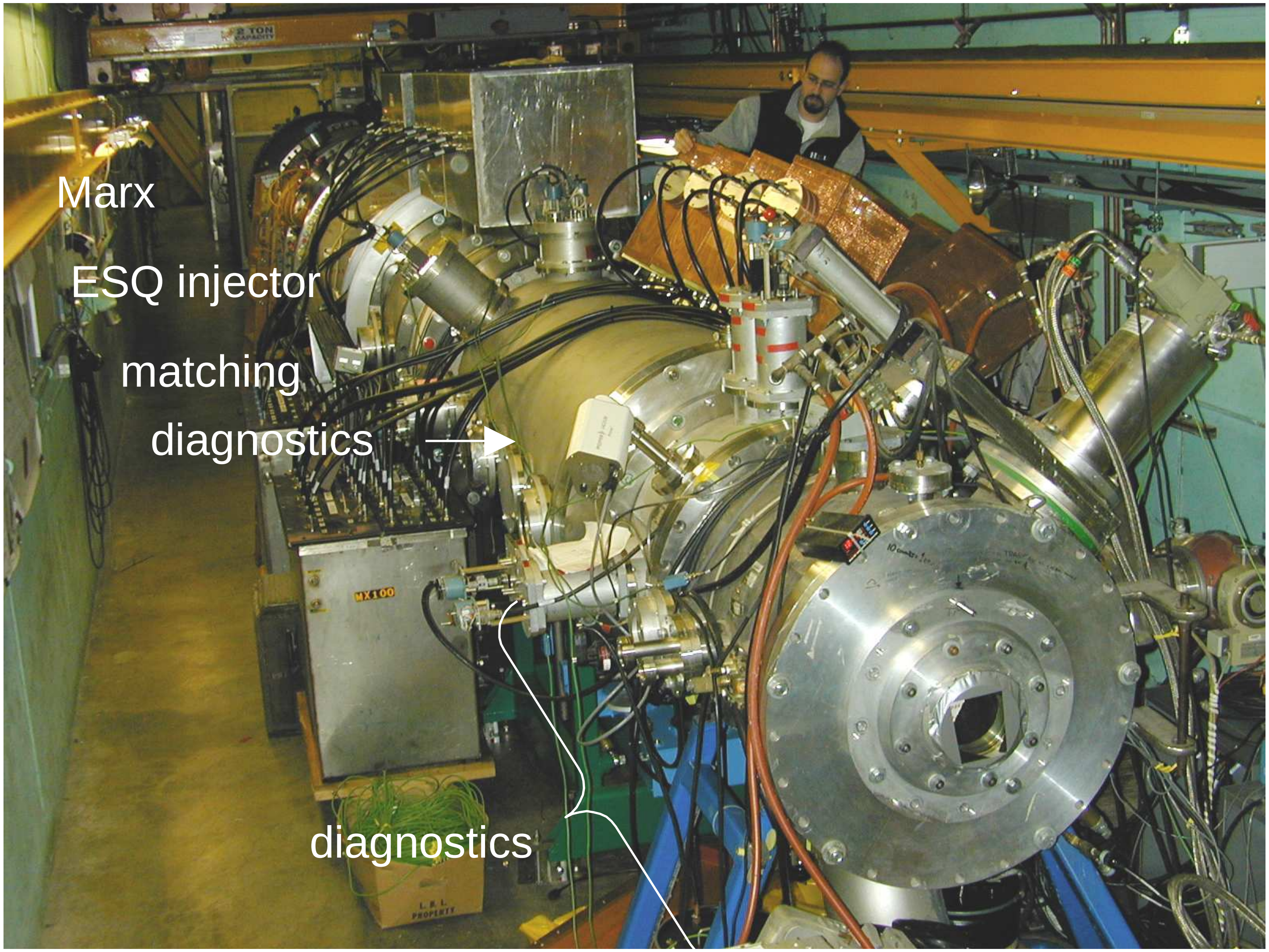


High Current Experiment (HCX) began operation January 11, 2002.

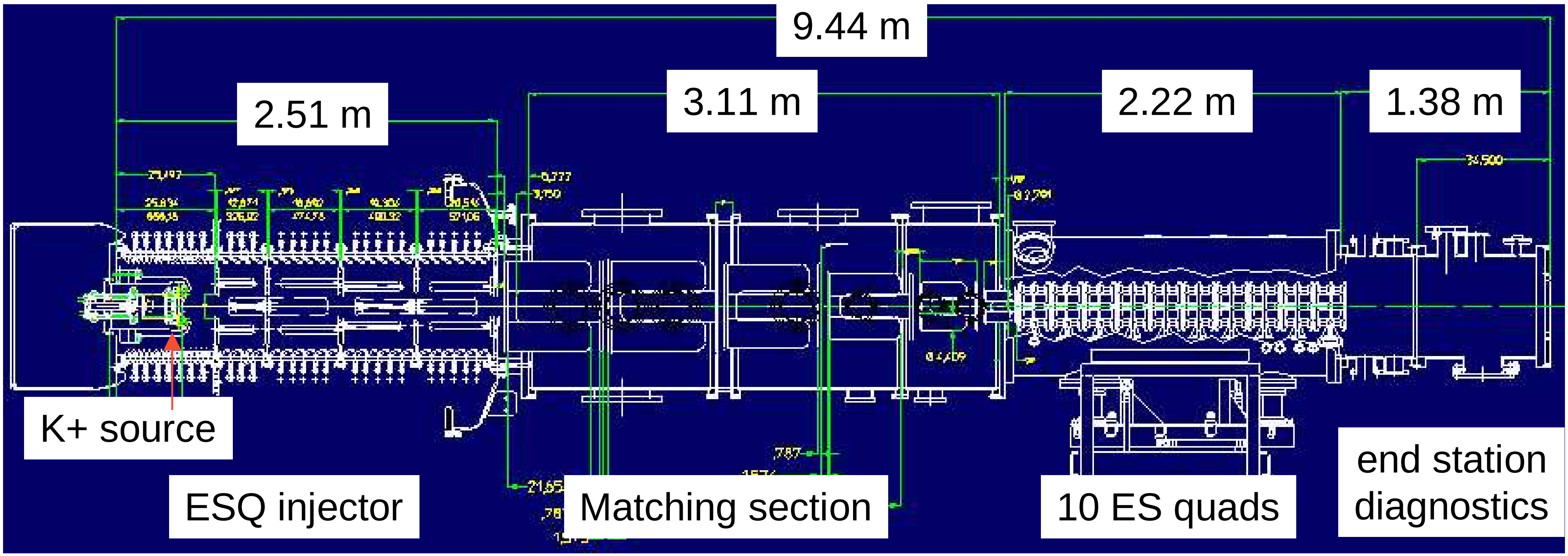


High-Current Experiment (HCX): first transport experiment using a driver-scale heavy-ion beam

K^+, 1 - 1.8 MeV, 0.2 - 0.6 A, 4 - 10 μs, 10 - 40 ES quads

HCX is to address four principal issues:

- **Aperture limits ("fill factor")?**
- **How maximum transportable current affected by misalignment, beam manipulations, and field nonlinearities**
- **beam halo?**
- **effects of gas and stray electrons?**

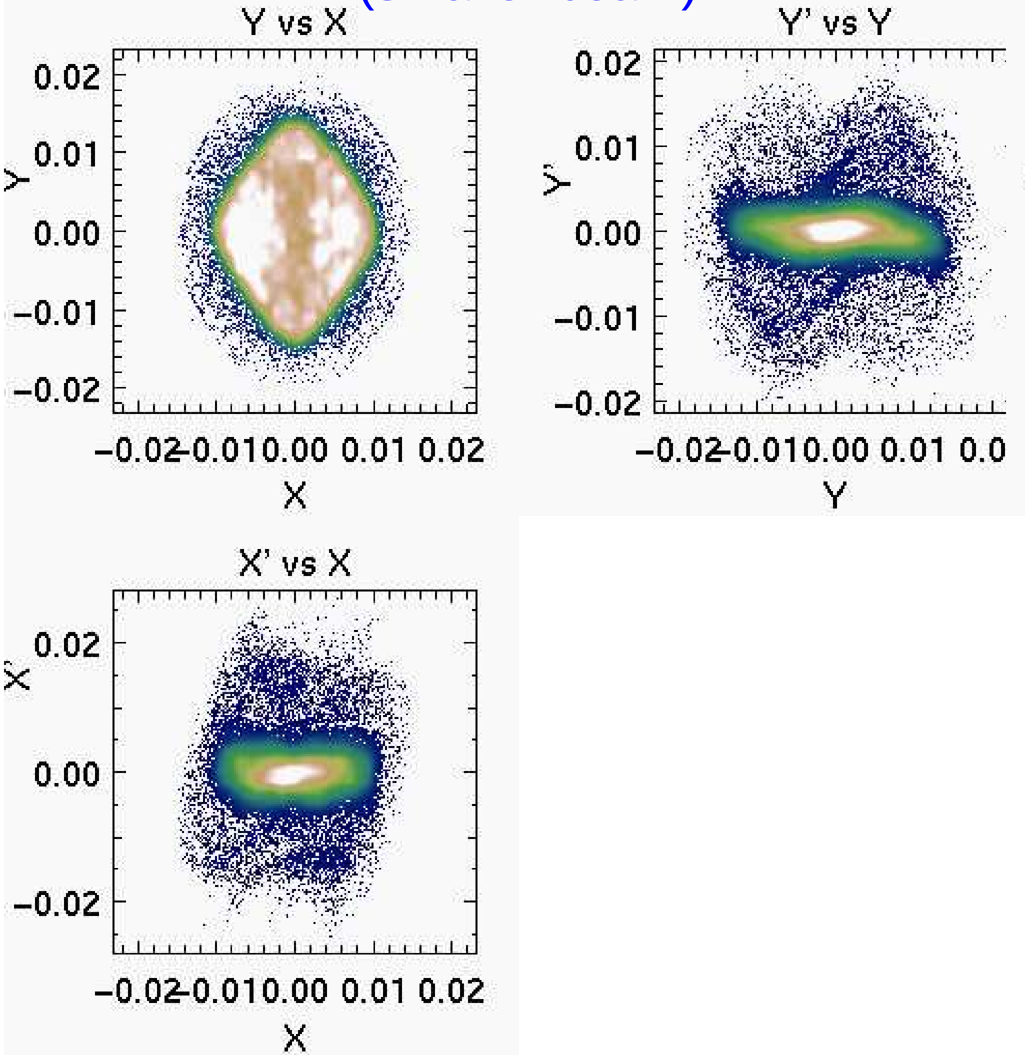


HCX Transport: Transverse slice simulations with 3D applied fields and initial distributions from linked 3D injector simulations

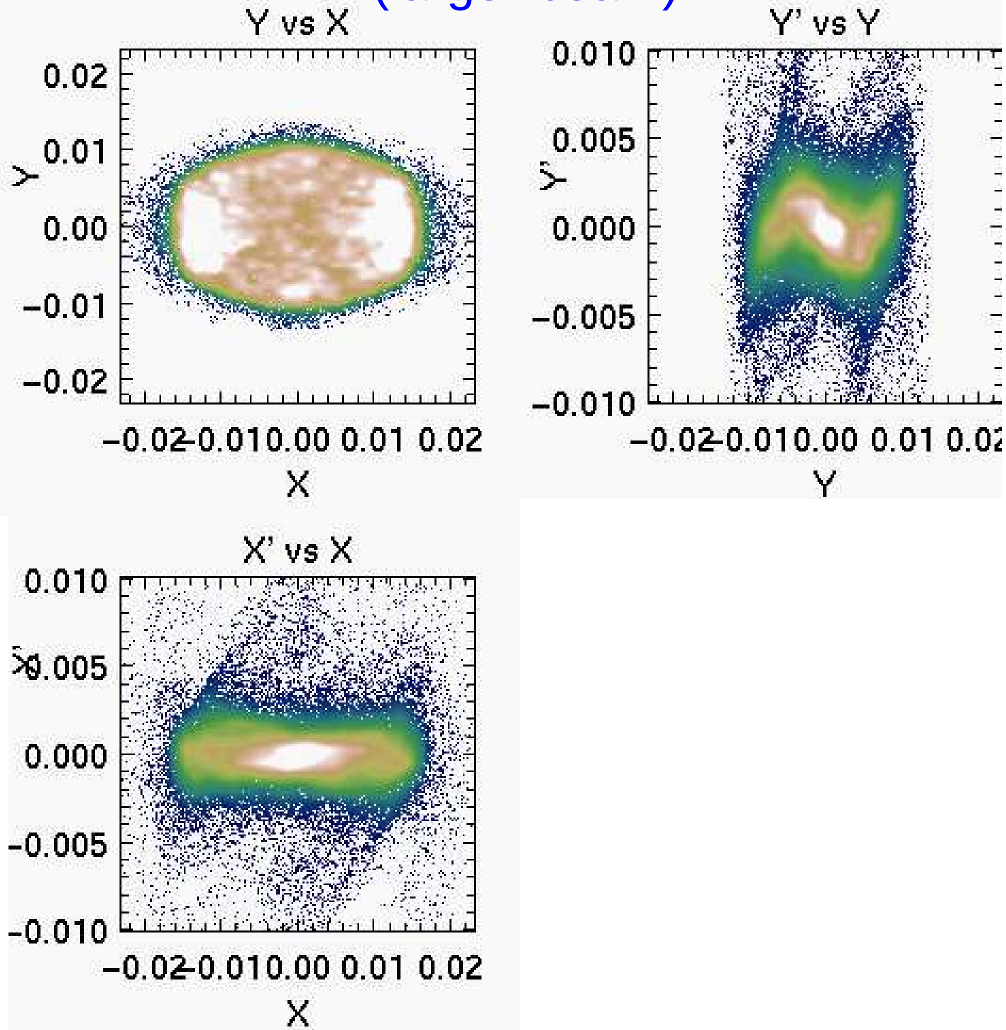
Goal: explore acceptable aperture fill factor

At the end of the HCX Transport Channel

$\sigma_0 = 80^o$ (smaller beam)



$\sigma_0 = 60^o$ (larger beam)

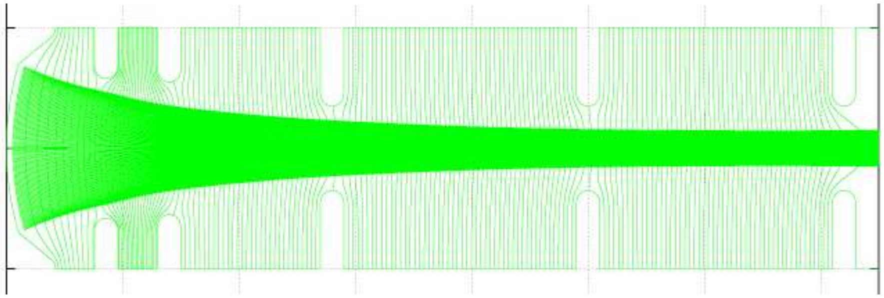


HEAVY ION INERTIAL FUSION: looking to the future

Near future - advanced multi-beam injector

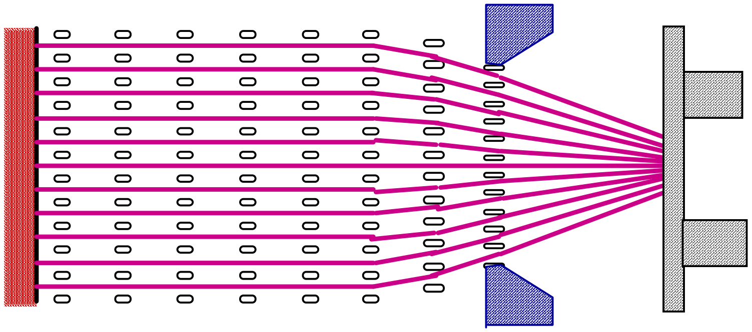
Two possible ion source approaches

Use a large diameter but low current density single-aperture ion source. This is the traditional HIF approach.



4 mA/cm^2

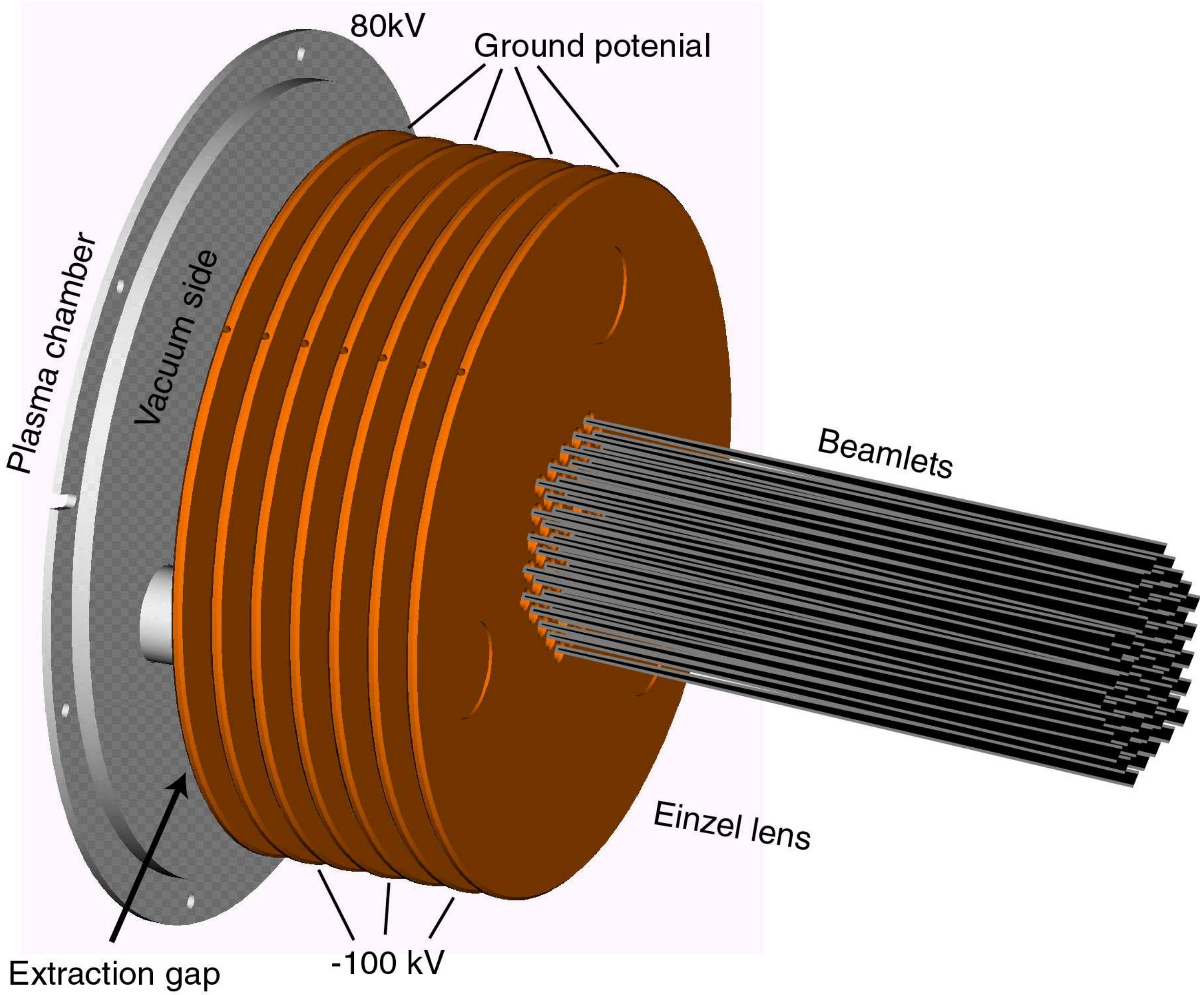
Extract hundreds of mm-scale high current density beamlets, from a multiple-aperture ion source.



100 mA/cm^2/beamlet

Theory → Simulation → Experiment

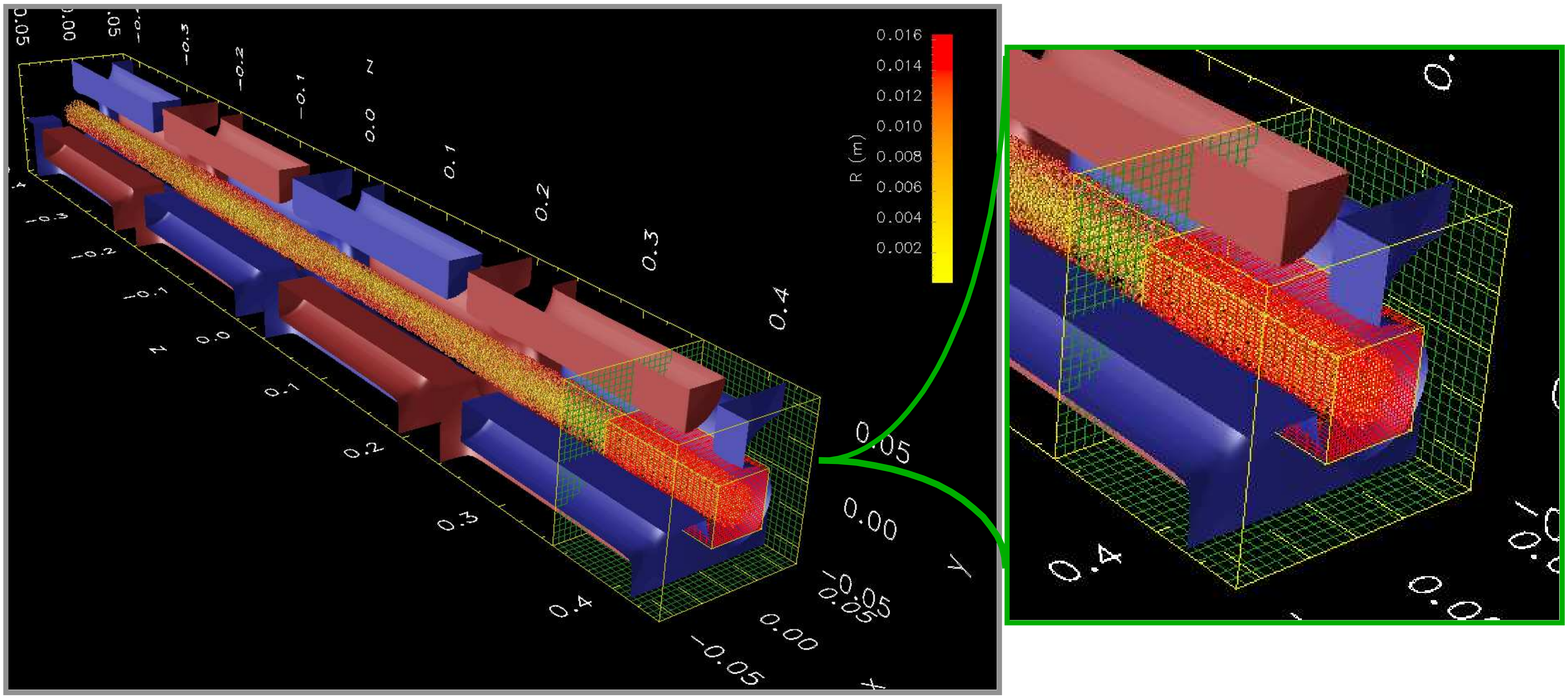
Advanced multi-beam injector – planning first experiment



The future: Adaptive mesh refinement in WARP

Must resolve Debye length (fundamental plasma parameter) in beam

– **mesh refinement offers a “better, cheaper, faster” field solution**

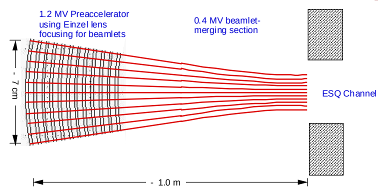


Our next-step vision

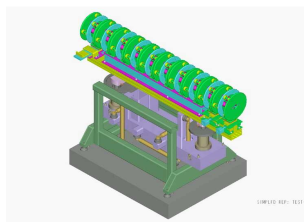
Beam Science → Inertial Fusion Energy

NOW (next three years) → **NEXT STEP**

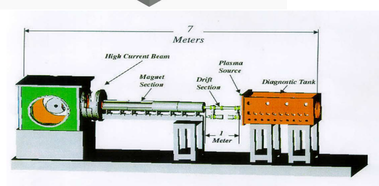
Brighter sources/ injector



Maximum <J >, B_n Transport

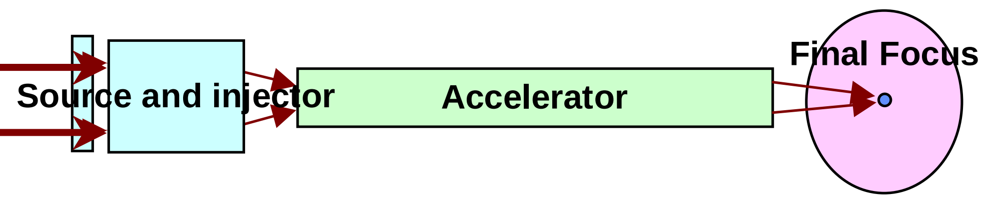


Beam neutralization



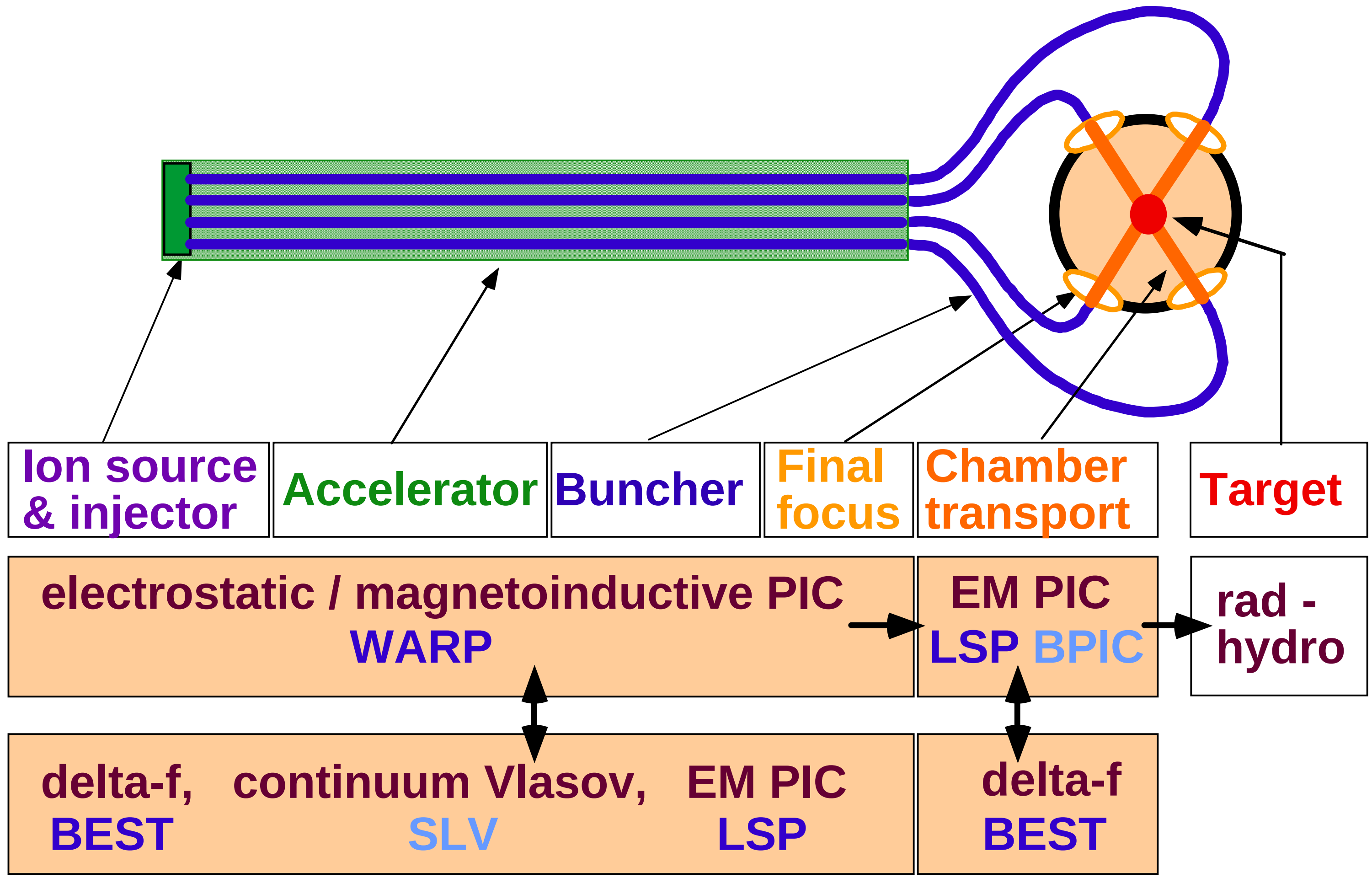
Theory/simulations

integrated beam experiment (IBX)



...to test source-to-target-integrated modeling

We will develop an *integrated*, *detailed*, and *benchmarked* source-to-target beam simulation capability



CONCLUSION

Fusion is a very attractive source of energy

- Would solve many problems
- But hard to achieve

Still far: there is lot of exciting science to study and technologies to develop

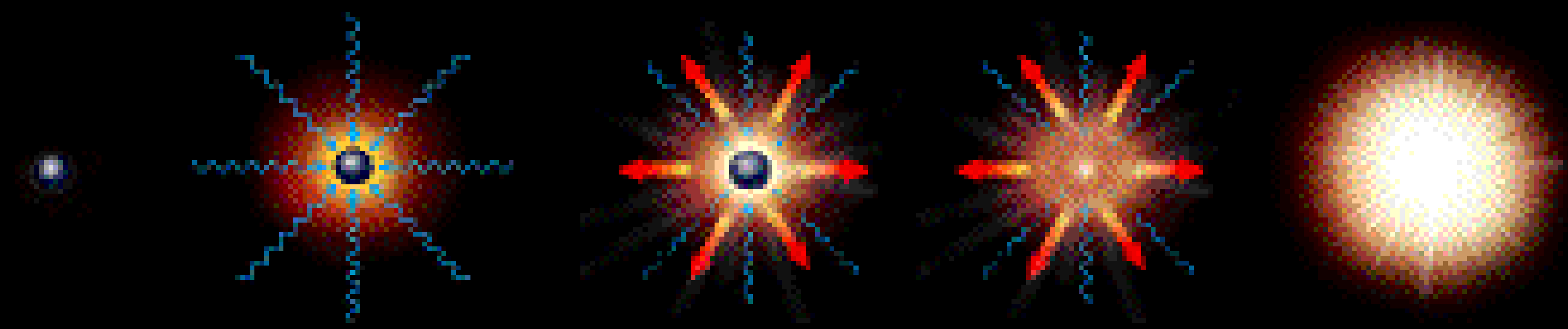
Computer simulation plays a crucial role in studying science, planning and analyzing experiments

The design of a full scale driver will rely heavily on integrated simulation from end-to-end

For more, visit our home page at http://hif.lbl.gov

MORE

Inertial Confinement Fusion Concept



Fuel Capsule

A small metal or plastic capsule (about the size of a pea) contains fusion fuel

Target Heating

Radiation (light, X-rays, ions, or electrons) rapidly heats the surface of the fuel capsule

Compression

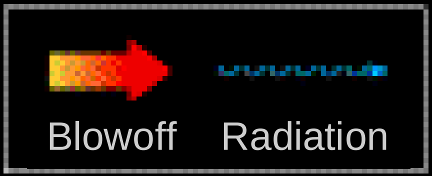
Fuel is compressed (imploded) by rocket-like blowoff (ablation) of the surface material

Ignition

With the final driver pulse, the fuel core reaches about 1000 times liquid density and ignites at 100,000,000 degrees

Burn

Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the imput energy

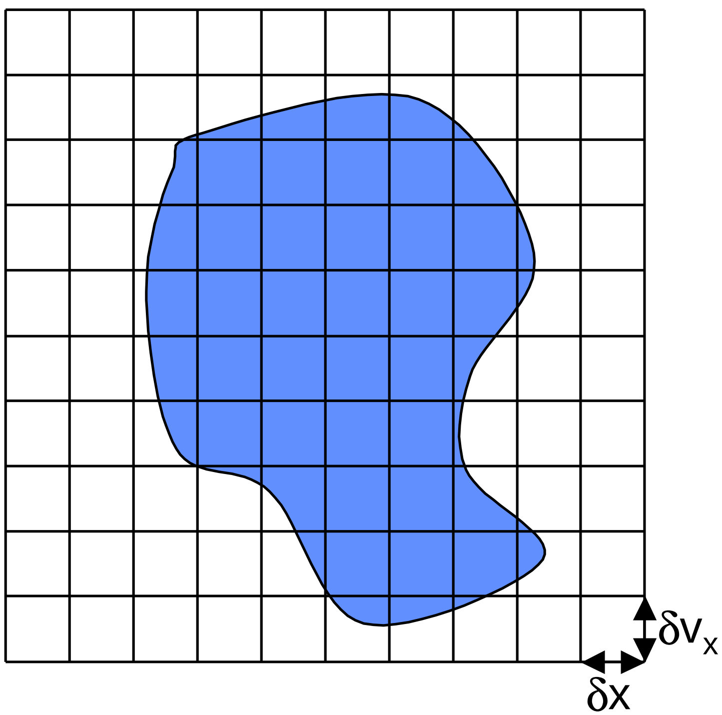


Computer simulation of plasma: methods (3)

Vlasov

- **Mathematically, the motion of a large collection of particles is equivalent to the motion of a fluid-like in a 6-D space (3-D space + 3-D velocities)**

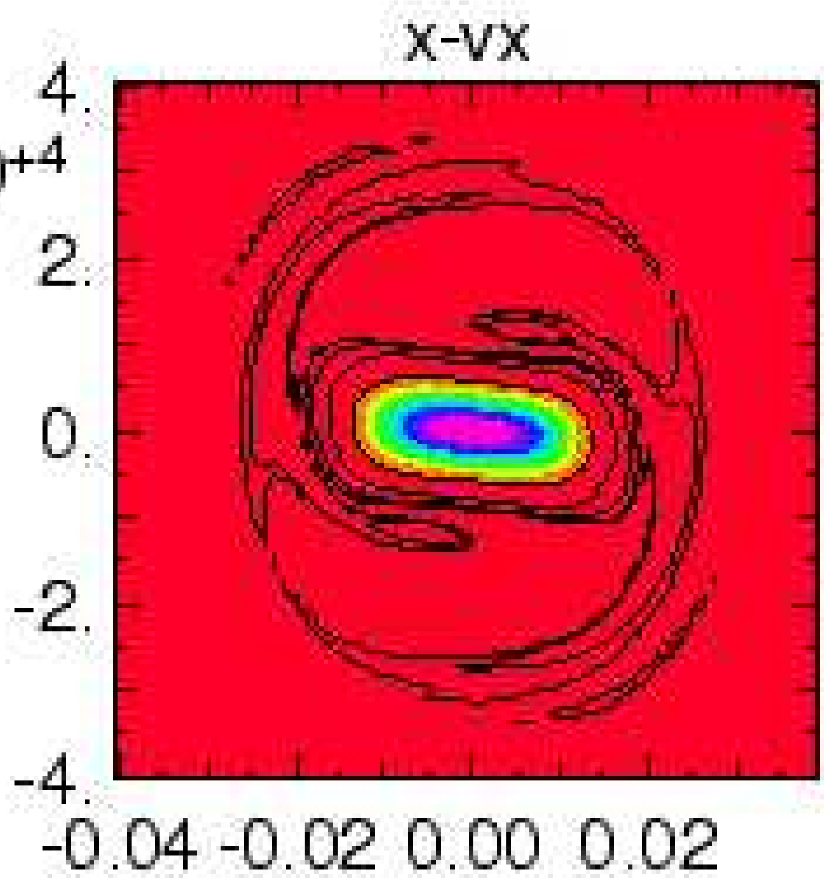
  ⟹ **we can solve using fluid representations**



- **The fluid is "discretized" on a 6-D grid**
- **The temporal evolution of the fluid is computed using finite time steps**
- **A lot less noisy than PIC but very expensive (interesting when very high accuracy is needed)**

SLV (Semi-Lagrangian Vlasov) simulation of beam in an anharmonic uniform focusing channel

Keep $f(\underline{x},\underline{v})$ at nodes of 4-D mesh; look back along orbits to obtain f



v_x

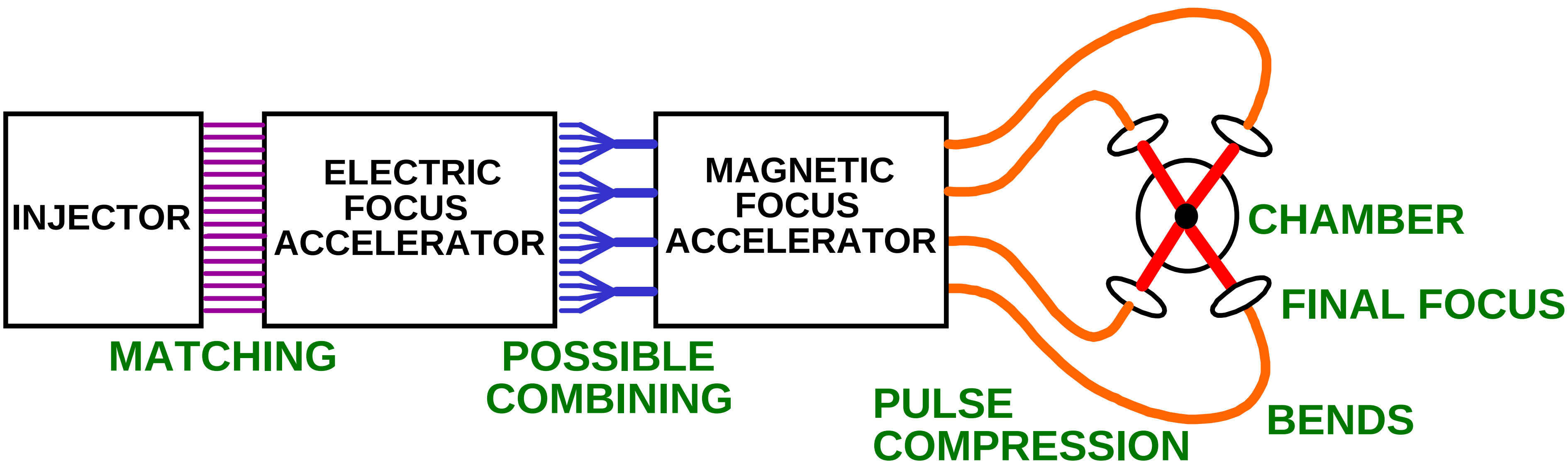
x

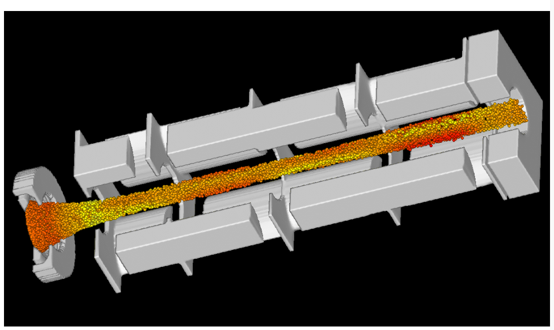
Low-density and high-density regions of phase space are tracked equally well

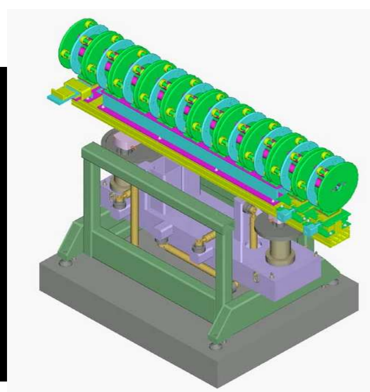
Black contour lines are 0.1, 0.01, 0.001, 0.0001, and 0.00001 of peak

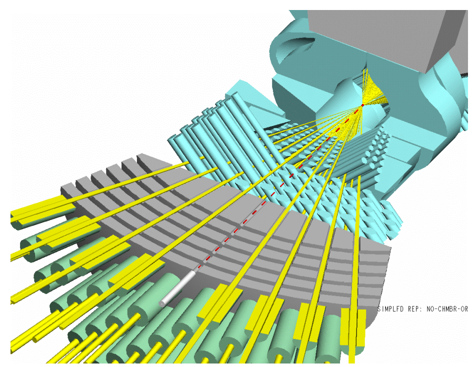
Plan: generalize to alternating-gradient via sequential transforms

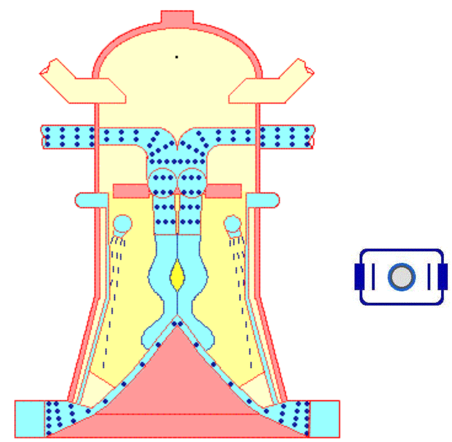
Heavy Ion Fusion scheme diagram



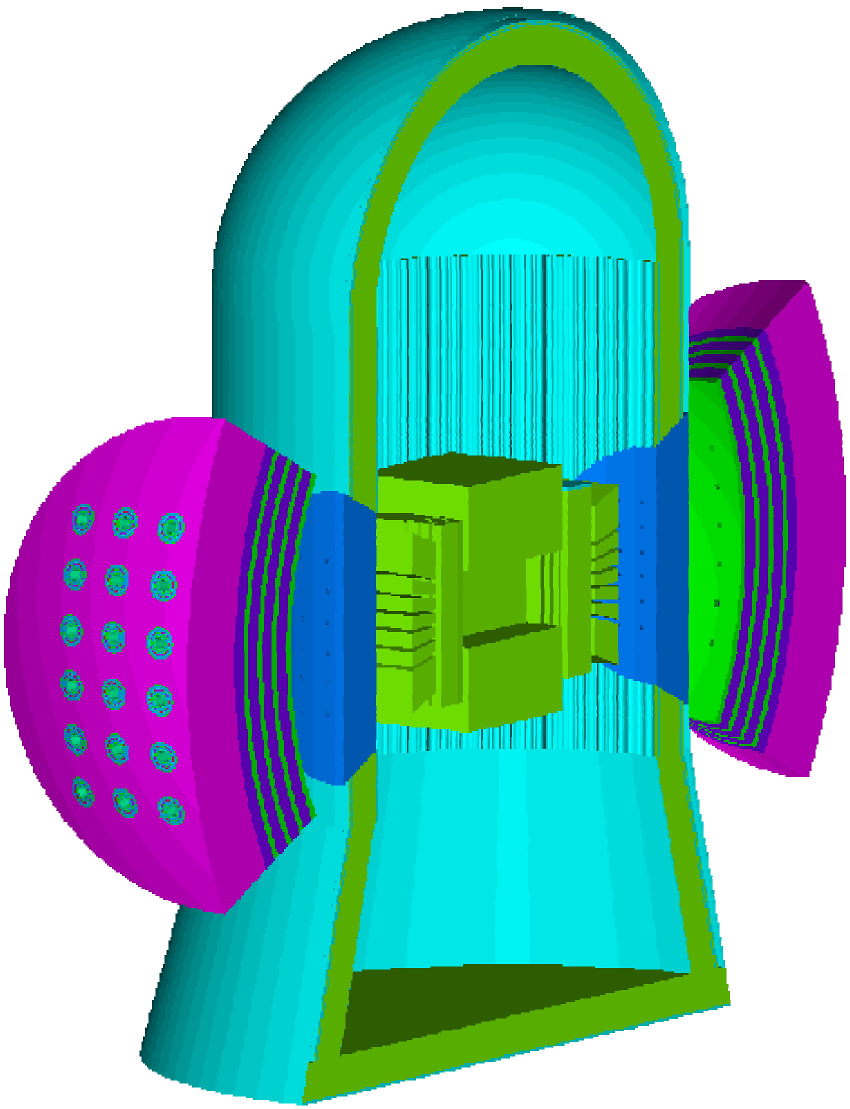








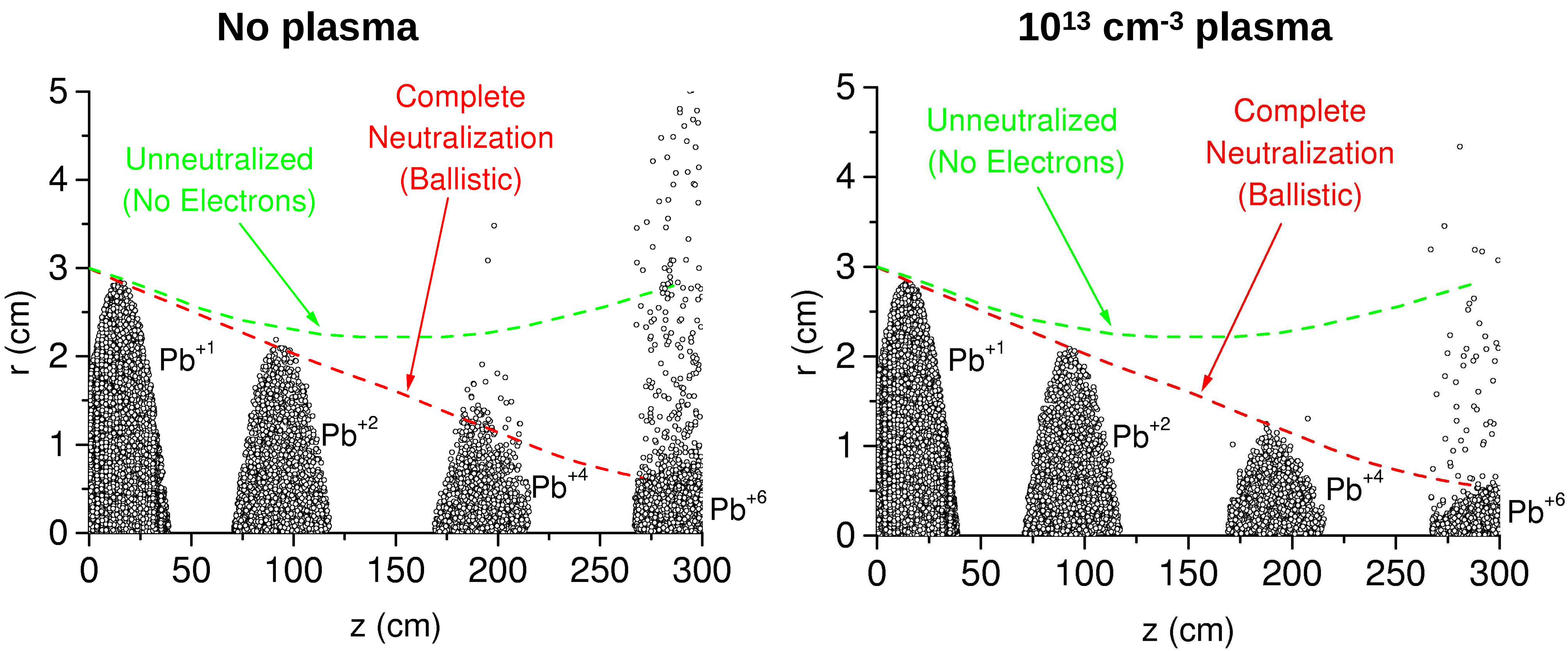
LLNL is conducting neutronics analyses of final focus magnet shielding



- Magnet shielding calculations use 3-D representations of the chamber, flibe pocket, and magnet arrays

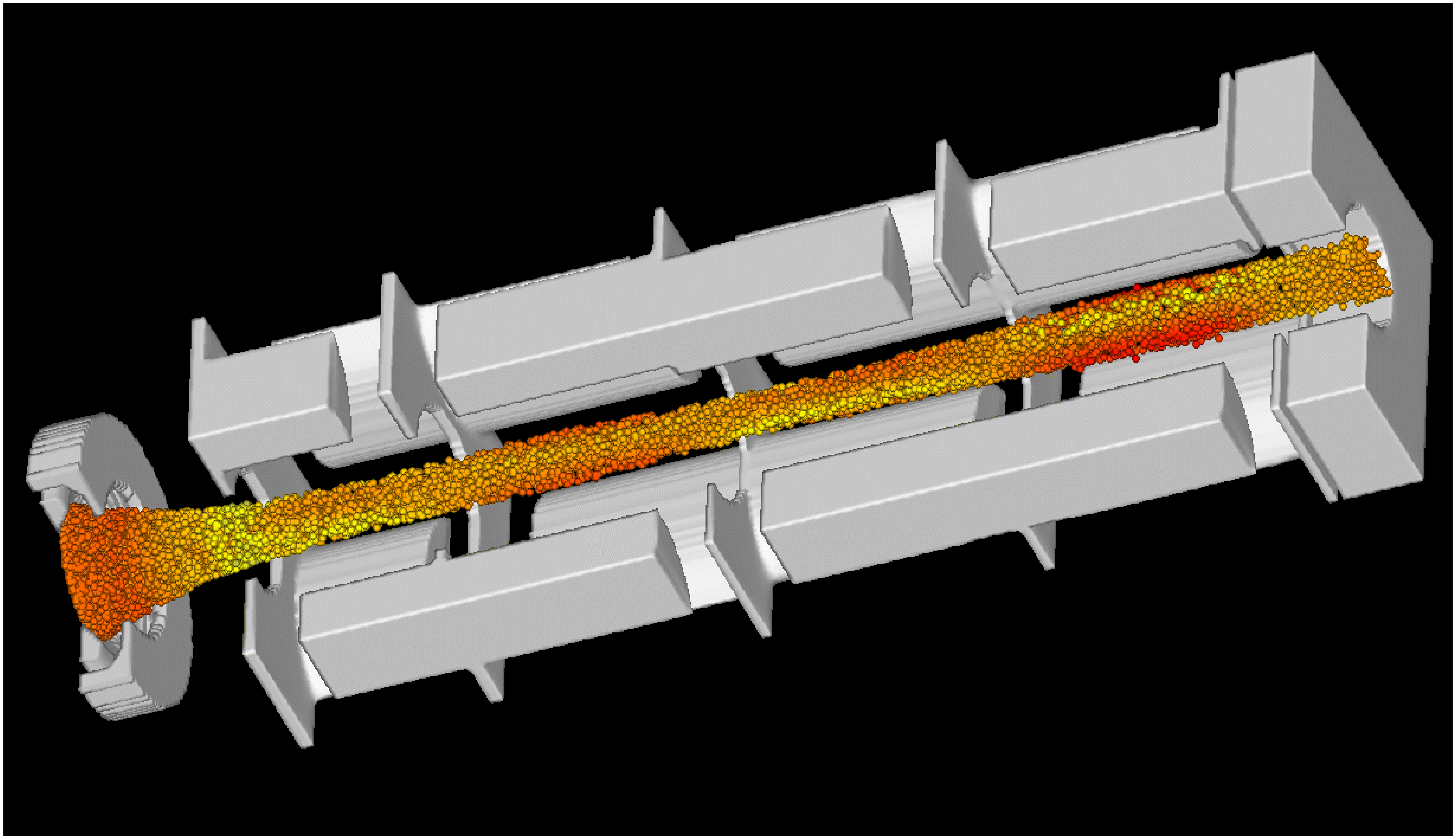
- Magnets are expected to last for over 30 years with adequate shielding

Chamber Transport Simulation (BIC)

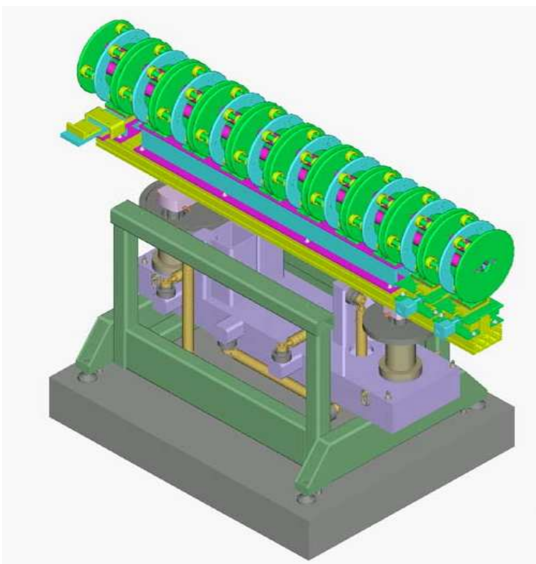


Plasma prevents beam deflection until z=200 cm where $n_b/n_p = 1$

WARP3d simulation of 2 MV, 0.8 A electrostatic quadrupole injector

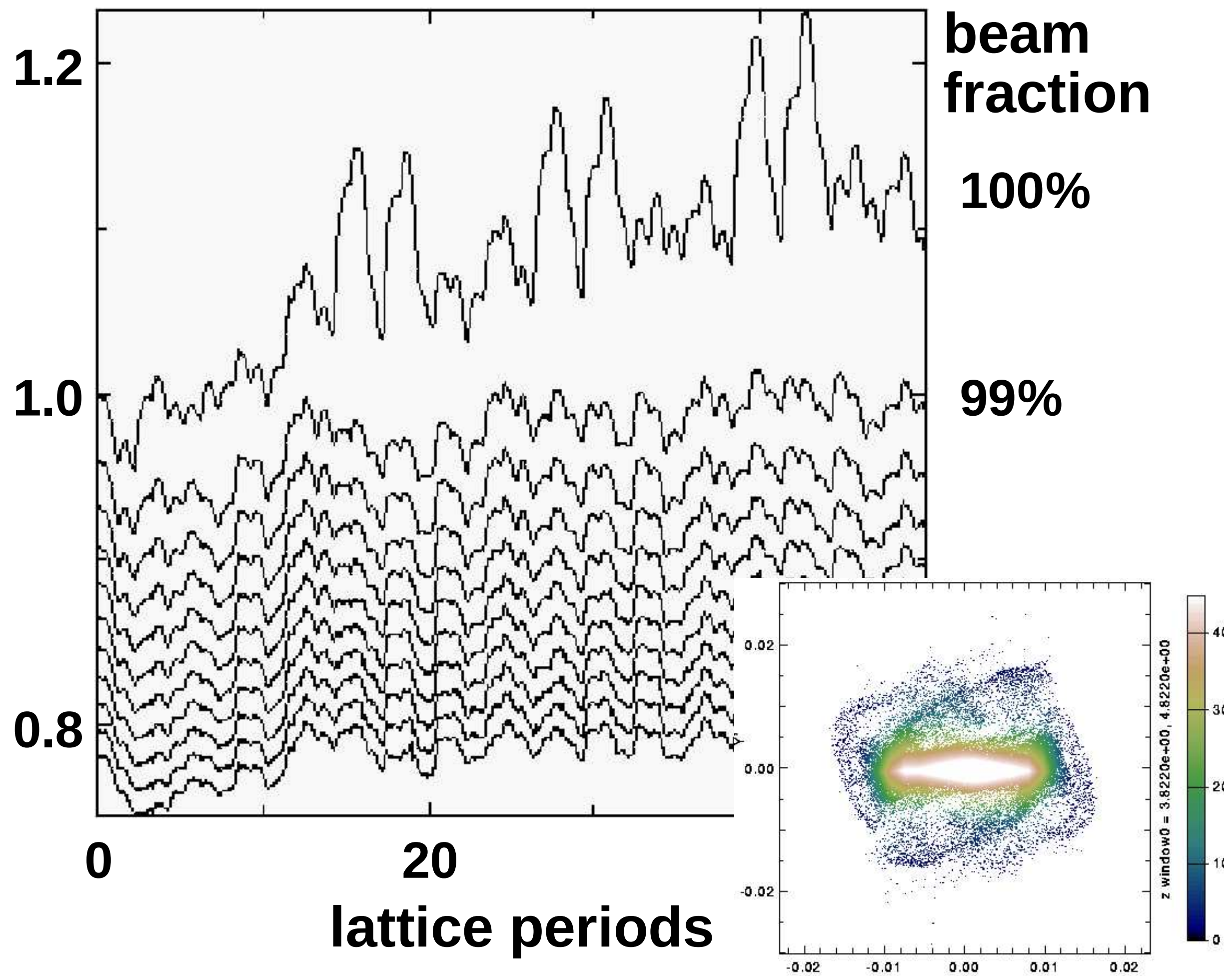


HCX effort is guided by simulations; here, we show a study of halo induced by beam envelope mismatch



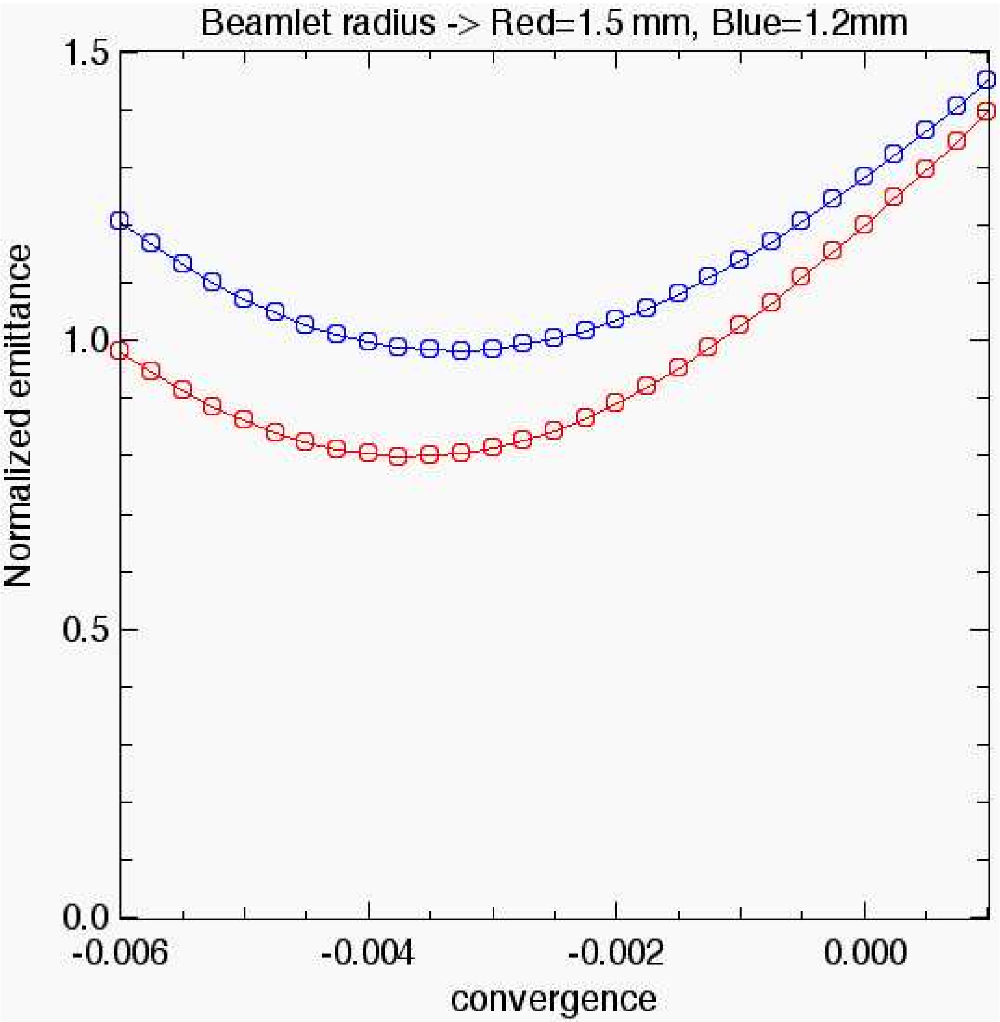
This work established a 10% acceptable mismatch amplitude for HCX

RMS emittance evolution $\mathcal{E}_x/\mathcal{E}_{x,initial}$ vs. beam fraction (32% mismatch amplitude)



Electrostatic Quadrupole

Simulation of multi-beamlet injector matching section



0.006 A, 91 beams, 1.200 MeV, 0.003 pi-mm-mrad S-G, 1024x1024, 1 cm/step, ratio of areas 0.070, beam size 0.800 mm