HIF Driver Requirements*

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Driver requirements for HIF have to be integrated with chambers and targets to have a consistent design.

☞ **Competitive cost-of-electricity < 5 cents per kWehr with acceptable environmental/safety characteristics, requires:**

- **Multiple heavy-ion beams with range ~ 0.03 g/cm2 capable of delivering a total ion beam power ~0.5 PW for ~10 ns into r < 2 mm spots at ~ 5 Hz pulse rate for > 10^9 shots, with efficiencies > 20%, and direct capital cost < 1 B$.**

- **Manufacture of 500,000 heavy ion targets per day with gain > 50 at < 30 cents/target cost using materials that meet accident dose, waste management, and recyclability criteria.**

- **Long life chambers and final focusing magnets (> 3 x 10^8 shots) with low T inventory (<15 g for <1 rem worst case accident dose), and < 0.1 m^3 of long-term radioactive waste disposal per year.**

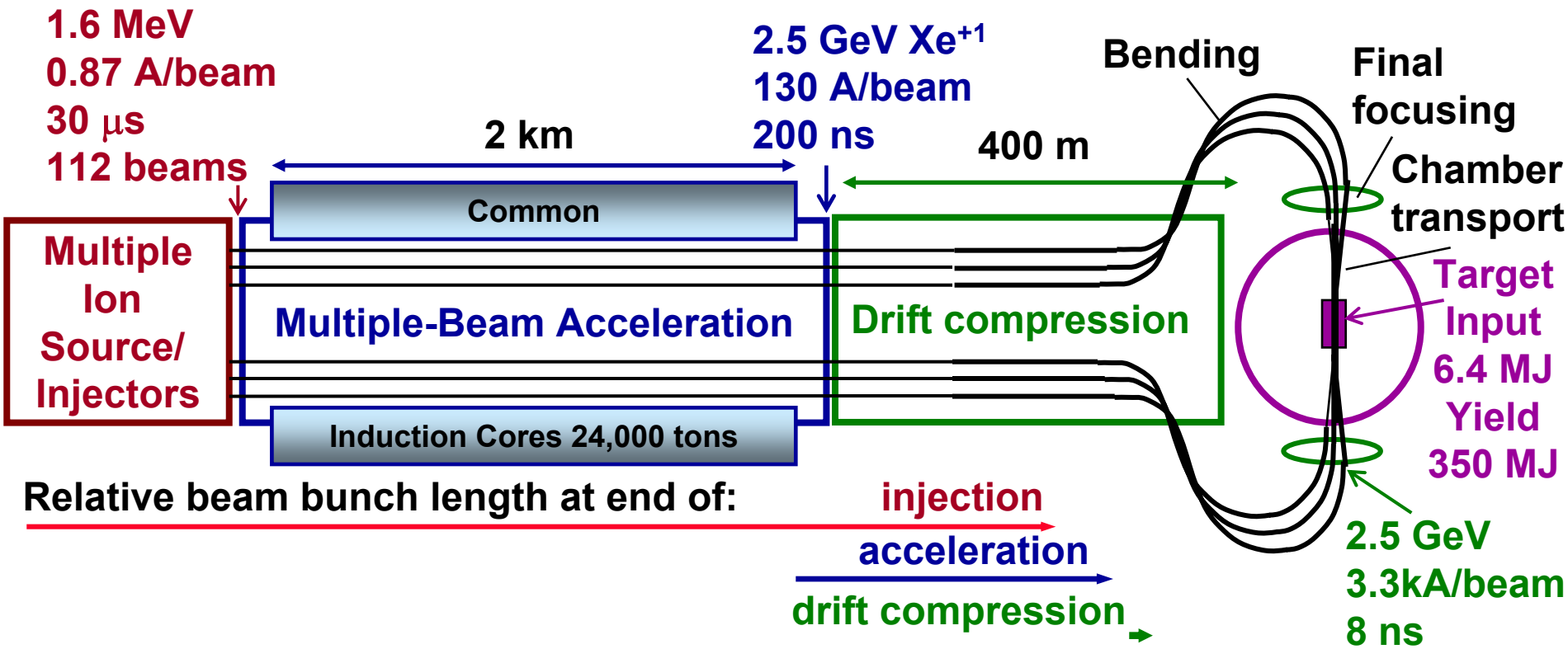
The HIF final focus/chamber interface and target requirements have posed a significant challenge.

- **HIF driver Issues are more economic than basic feasibility: e.g. halo ion losses may be reduced with larger gaps between beam and pipe wall, at expense of larger focusing magnets and induction cores.**

- ***Most uncertain current issue is achievable focal spot size consistent with bunch compression, focal length, target gain, chamber gas, ion stripping, and plasma neutralization. (From the Monday plenary talk)***

→The VNL and VLT have been working hard as a team to realize a self-consistent heavy-ion driver, chamber and target design baseline, taking into account relatively new chamber transport physics gained through extensive analytic theory and particle simulations. NTX will play a key role in testing this new physics.

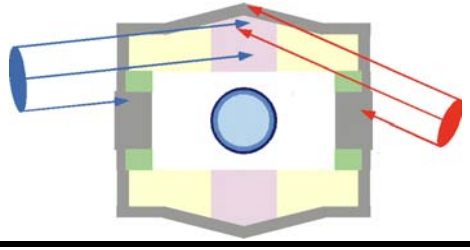
Reference 112-beam quad-focused driver: 6.4 MJ, 2.5 GeV Xe^{+1}, 24,000 tons induction cores, $720M hardware, $1 B direct,$2.1 B tot capital cost



Bunch length compression is integral part of HIF concept

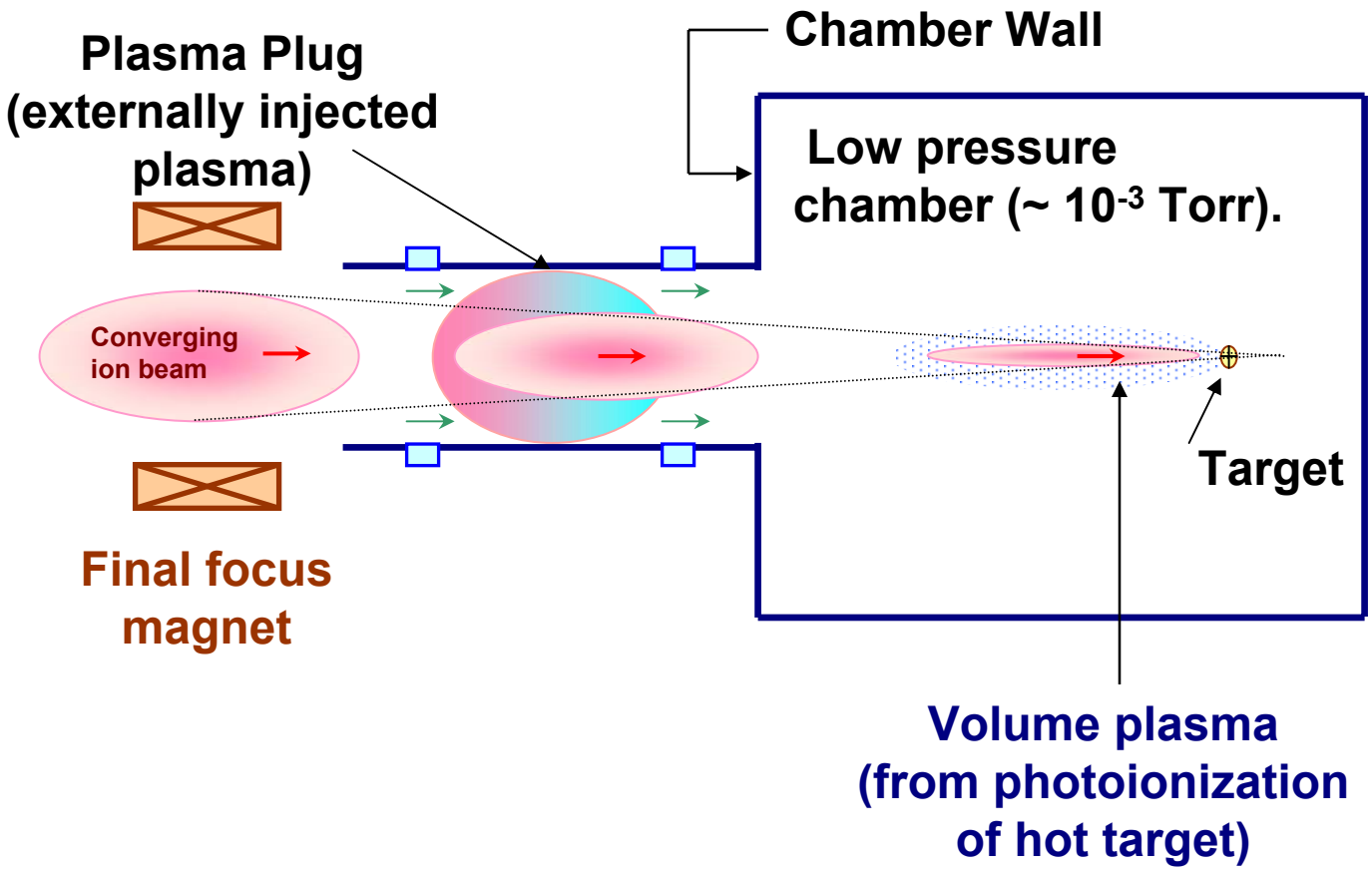
Within accelerator, average induction pulse ~300 ns
Target requires pulse duration of ~10 ns

Reference HIF target requirements (Debra Callahan)



Requirement	Range
Total ion beam input energy	5 to 8 MJ (can vary size/ion range, 6.4 for ref design)
Ion range	0.035 g/cm2 (2.5 GeV Xe or equiv. for main pulse)
Number of beams	> 8 per end per angle (for azimuthal symmetry)
Pulse shape/symmetry- pre-pulse beams	25 to 45 % energy @ 75% range , 6-12 degrees, 30 ns
Pulse-shape/symmetry-main pulse beams	75 to 55 % energy @ full range, 12 to 24 degrees, 8 ns
Spot radius	2.3 mm for pre-pulse, 1.8 for main-pulse
In-flight aspect ratio	36
Capsule finish (nm RMS)	50-200
DT ice layer roughness (microns RMS)	1-5
Minimum fusion yield and target gain	> 200 MJ @ gain >25 for $\eta G>10$ @ calculated driver η of 48%, >350 MJ @ gain >50 for minimum CoE
Hohlraum material/density	Recyclable, cocktail, 1-100 % of solid density
Cost per target	~25 cents/target for acceptable CoE

Neutralization is essential for focusing heavy ion beams onto target



Reference case HIF driver requirements

Driver requirement	Range
Ion mass	131 amu (for lower cost) to 238 (only if more margin needed on focusing spot)
Ion kinetic energy	2.5 to 5 GeV for mass 131 to 238
Number of beams	> 50 (to avoid excessive electric fields in final focus to ~ 100 for minimum cost based on SC quad transport
Beam energy to target	5 to 7 MJ total depending on desired yield/rep rate, ~ 30-40% of beams @ 75% full energy for pre-pulse,70-60% of beams @ full energy for main pulse
Ion source current/emittance/pulse	> 0.5 A/beam, < 2 π mm-mr normalized /, > 10 μsec
Transverse emittance growth at focus	< 5 p mm-mr normalized to meet focal spot size
Parallel momentum spread at focus	delta p /p < 5 x 10-3 to meet focal spot size
Electric-to-beam efficiency @ >5 Hz	> 20% for ηG > 10, > 40% for minimum CoE
Ferritic core material cost	< 5 $ /kg
Switching cost for >109 shot life	<10-5 $/Watt
Insulator cost	< 0.01 $ Volt @ meter diameter
Durability/reliability	> 10^9 shots between maintenance periods, sufficient for >75% overall plant availability

Reference HIF Chamber Requirements

Requirement	Range
Geometry compatible with reference target	One or two sided illumination with > 100 beams
Pulse rate	~ 5 to 7.5 Hz for CoE minimum depending on target gain and driver energy range
Lifetime for focus magnets and chamber	> 109 shots for overall availability > 75 %
Ballistic neutralized focus	Chamber pressure < 1 millitorr, maximum standoff for final focus < 6-8 meters
Focus array size	< 24 degrees for array half-angle
Beam focusing angle	~ 12 -15 mr
Coolant temperature	550 to 650 C for thermal conversion efficiency
Tritium inventory in chamber	< 150 g mobilizable T for safety
Annual waste production	< 1 m3/yr for class C and <0.01 m3/yr for above Class-C-level, assuming recycle
Maximum credible accident dose	< 10 mSv (1 rem)

Term for emittance growth in chamber has been added

$$\varepsilon_x^2 = \varepsilon_{x0}^2 + \alpha_x^2 d^2 \left(\frac{\Delta p}{p}\right)^2 \theta_x^4$$

← Previous version (similarly for ε_y)

$$\varepsilon_x^2 = \varepsilon_{x0}^2 + \alpha_x^2 d^2 \left(\frac{\Delta p}{p}\right)^2 \theta_x^4 + \left(\lambda Q_c d\right)^2$$

← New version with added term

λ = dimensionless "shape" parameter ~ ½
Q_c = "net" perveance in chamber
d = focus length

Emittance growth in chamber (cont.)

$$Q_c = \alpha q \frac{m_e}{m_i} = \alpha q \cdot \frac{5.49 \cdot 10^{-4}}{A}$$

αq =1 to 2 when gas effects are small
A = ion mass, amu

For flibe simulations at n = $7 \cdot 10^{12}$ cm^{-3}, αq = 2 is a good fit.

Example: for A = 131, d = 6 m $\longrightarrow$ $\lambda Q_c d$ = 25 mm·mrad
This will lead to significant spot size contribution:
$R_{spot} > 25(\text{mm})/\theta(\text{mrad})$
where θ = focus half angle (typically 10-20mrad)

Factor for photo-ionization gives smaller main pulse beams

$$\theta_x^2 \approx \frac{\varepsilon_x^2}{r_x^2} + 2Q_f \ln\left[\frac{d(\theta_x + \theta_y)}{r_x + r_y}\right]$$

$$Q_f = \alpha q \frac{m_e}{m_i}$$ For pre-pulse beams

$$Q_f = -q \frac{m_e}{m_i}$$ For main-pulse beams

These relationship are preliminary and require more simulations

What code is used for chamber simulations?

LSP (Large Scale Plasma) is a versatile 1D / 2D / 3D PIC code developed by Mission Research Corporation

features

- parallelized C coding using standard MPI message passing
- energy-conserving electromagnetic and electrostatic algorithms
- implicit field and particle advance for long time step
- multi-species and multi-region capability for flexibility
- hybrid fluid/particle electron model for high plasma densities
- Monte Carlo particle interactions including ionization, scattering, energy transfer, and charge exchange
- Child-Langmuir emission from metal surfaces
- and now photoionization

Liabilities: Cartesian or cylindrical mesh with rectilinear boundaries, evolving source

LSP is an advanced, flexible, portable code with few shortcomings

What parameters are used in driver simulations?

all cases here use a single Xe^{+1} beam (131 amu)

- 2.8 kA main pulse at 2.5 GeV, giving 1.75 x 10^{-4} perveance
- 0.9 kA foot pulse at 1.95 GeV, giving 0.88 x 10^{-4} perveance
- 3 m conical beam pipe plus chamber with 3 m radius
- 9 mm-mrad unnormalized edge emittance
- 10 and 16 mrad convergence angle
- 7 x 10^{12} cm^{-3} BeF_2 density in chamber (~0.4 mTorr), falling off in port
- 3 x 10^{11} cm^{-3} hydrogen plasma layer near each end of port
- Child-Langmuir emission from port and chamber walls

Infelicities

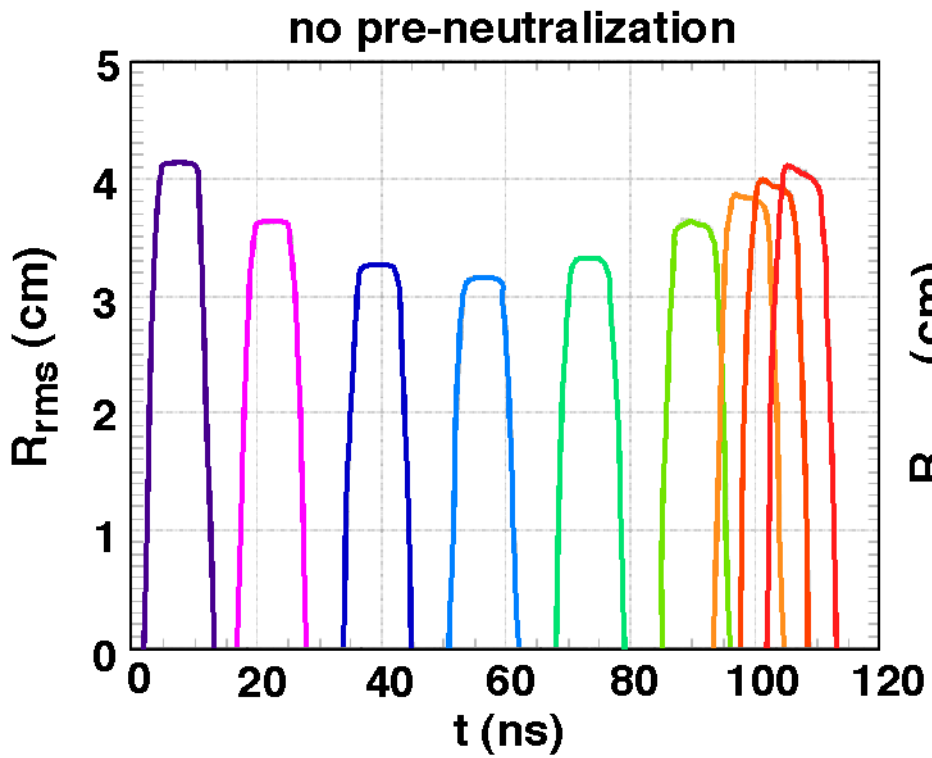
- stair-stepped beam port
- idealized initial conditions
- no multiple-electron ionization
- no molten-salt jets or target charge-up

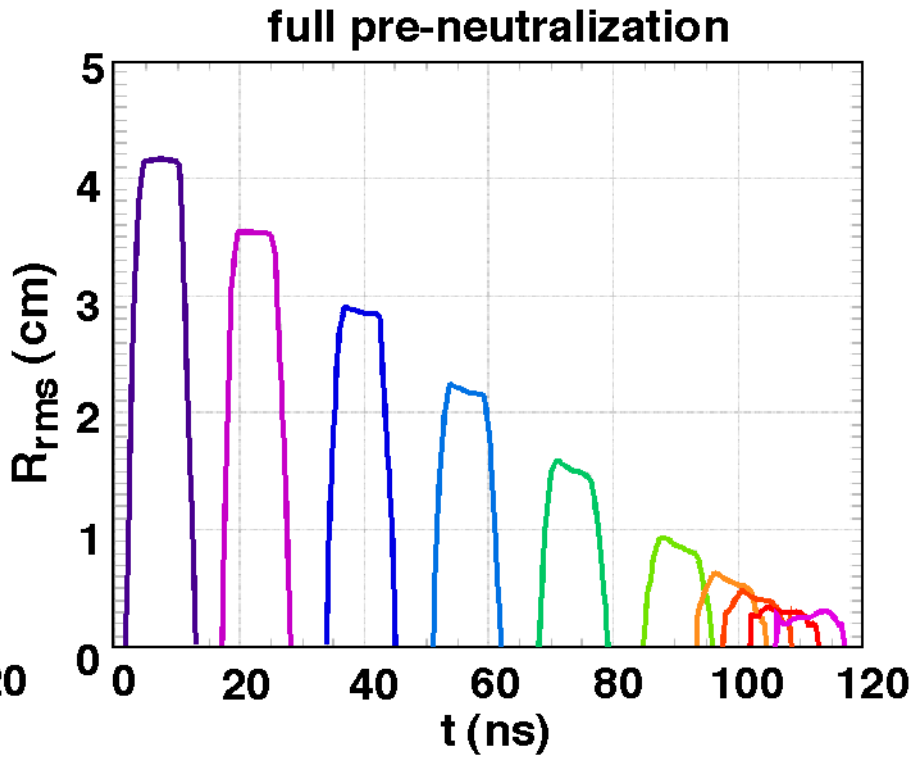
Parameters here describe one of many possible driver designs

Does pre-neutralization really work?

results for standard Xe main pulse

- **time histories of rms radius at selected axial positions**
- **plasma is electrically connected to wall by images and emission**



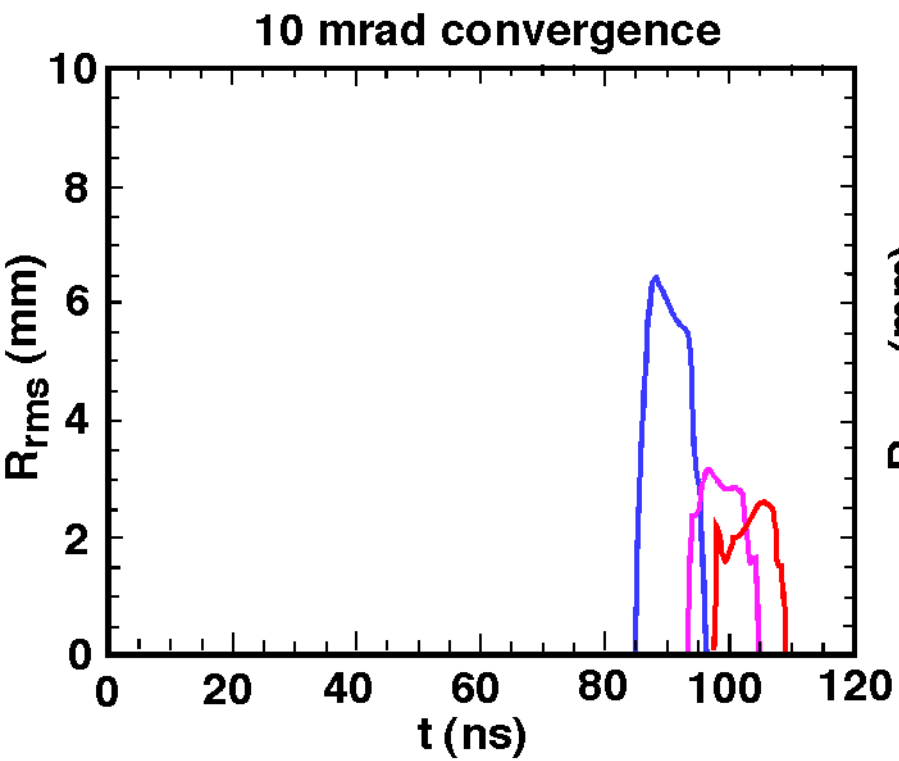


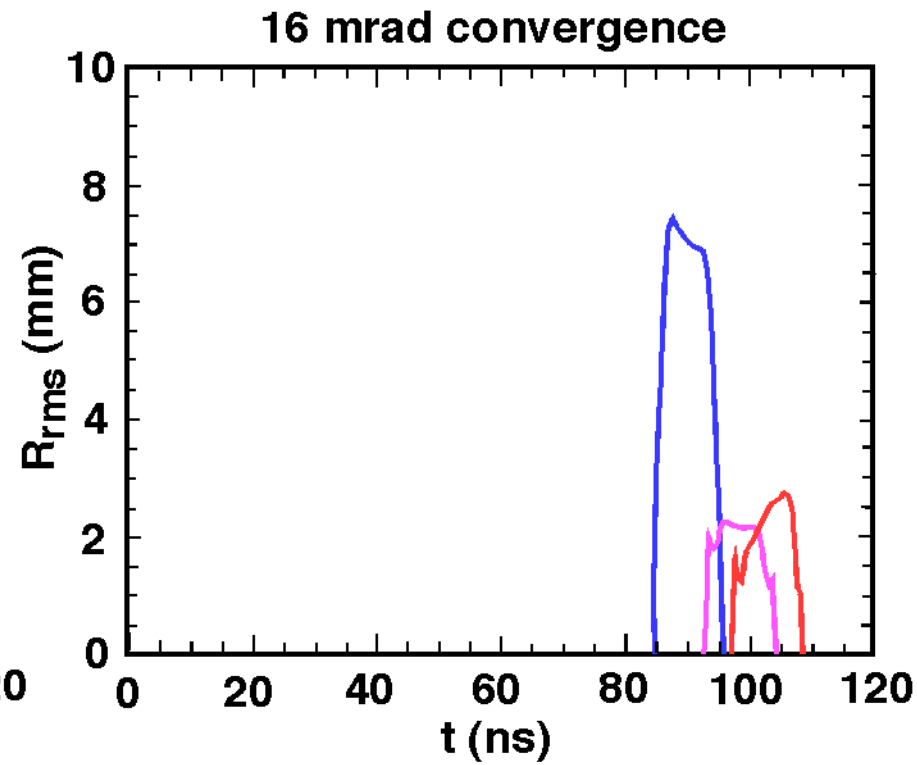
2.5 mm waist is close to value needed by distributed-radiator target

Does a larger convergence angle help?

time histories of rms radius for standard Xe main pulse

- initial convergence angles are 10 and 16 mrad. no photoionization.
- rms radius at waist is about 2 mm for larger angle
- larger angle complicates neutronics and layout problems



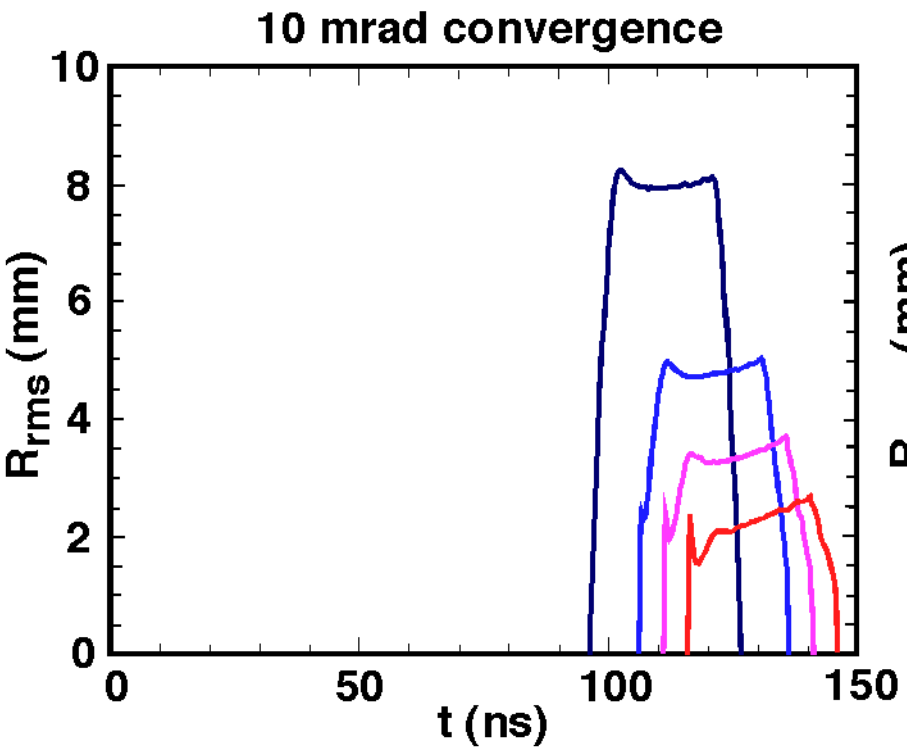


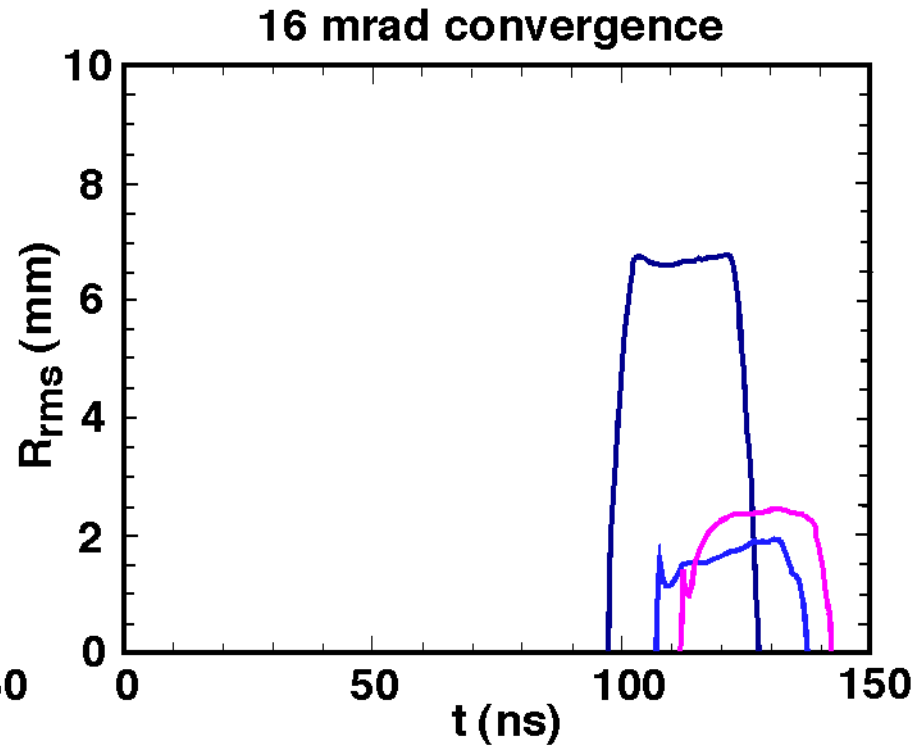
if practicable, a larger convergence angle would improve focus

Does a larger convergence angle also help foot pulses?

time histories of rms radius for standard Xe foot pulse

- initial convergence angles are 10 and 16 mrad
- rms radius at waist is less than 2 mm for larger angle



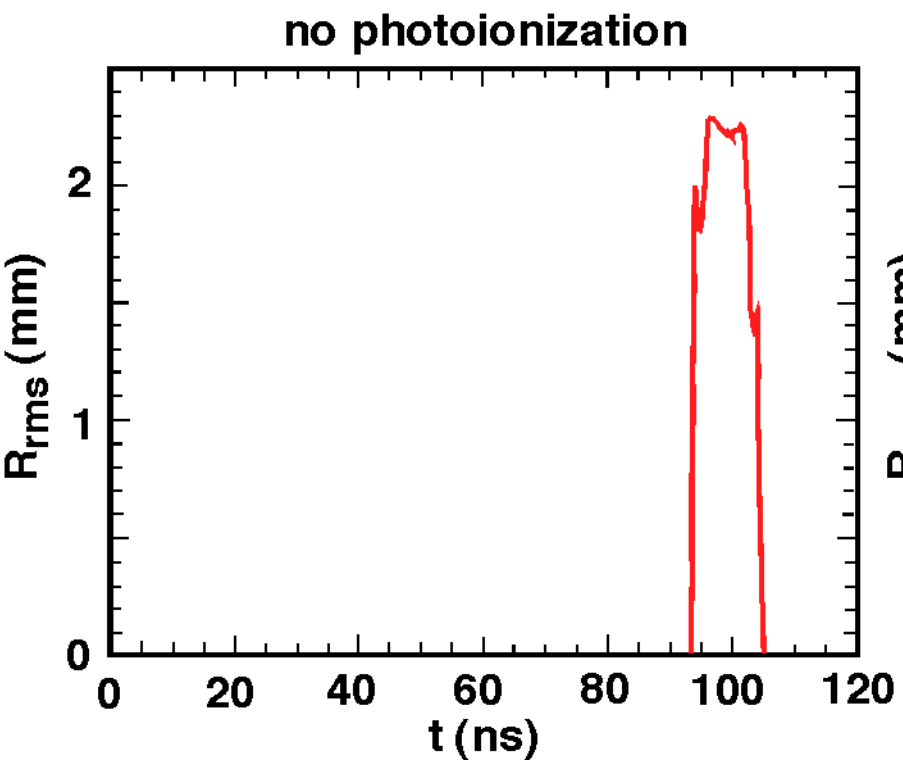


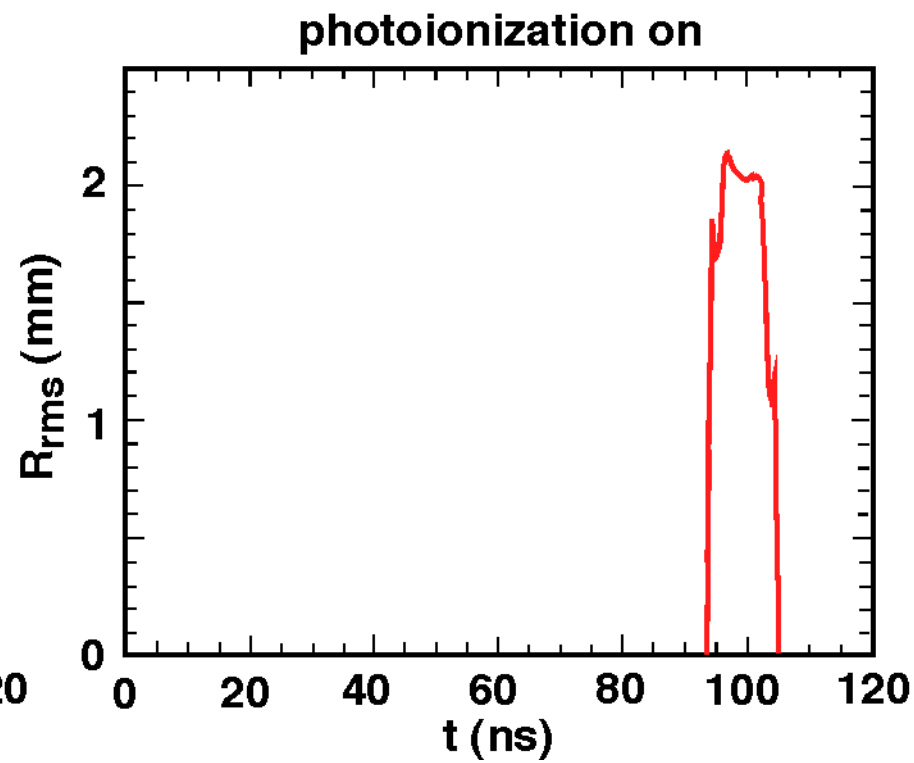
wider angle gives usable focal spot for both main and foot pulses

How does photoionization affect the focal spot?

time histories of rms radius for standard Xe main pulse

- target heating by 30-ns foot pulses in other entry ports
- photoionization reduces focal spot by about 10%
- larger effect expected from multiple ionization of background gas





beam neutralization is limited by low density of photoionized plasma

Conclusions

Additional neutralization is crucial for practical chamber transport

- modern targets and accelerators need high current and low energy
- ballistic transport only works for low current or high energy

An upstream plasma can effectively pre-neutralize a beam

- fully ionized hydrogen somewhat denser than beam is optimum
- background-gas density less than 10^{-13} cm^{-3} is necessary
- larger convergence angle reduces the waist radius
- photoionization by target X rays makes further improvement
- pre-neutralization reduces sensitivity to beam parameters
- calculated waist meets requirements of distributed-radiator target

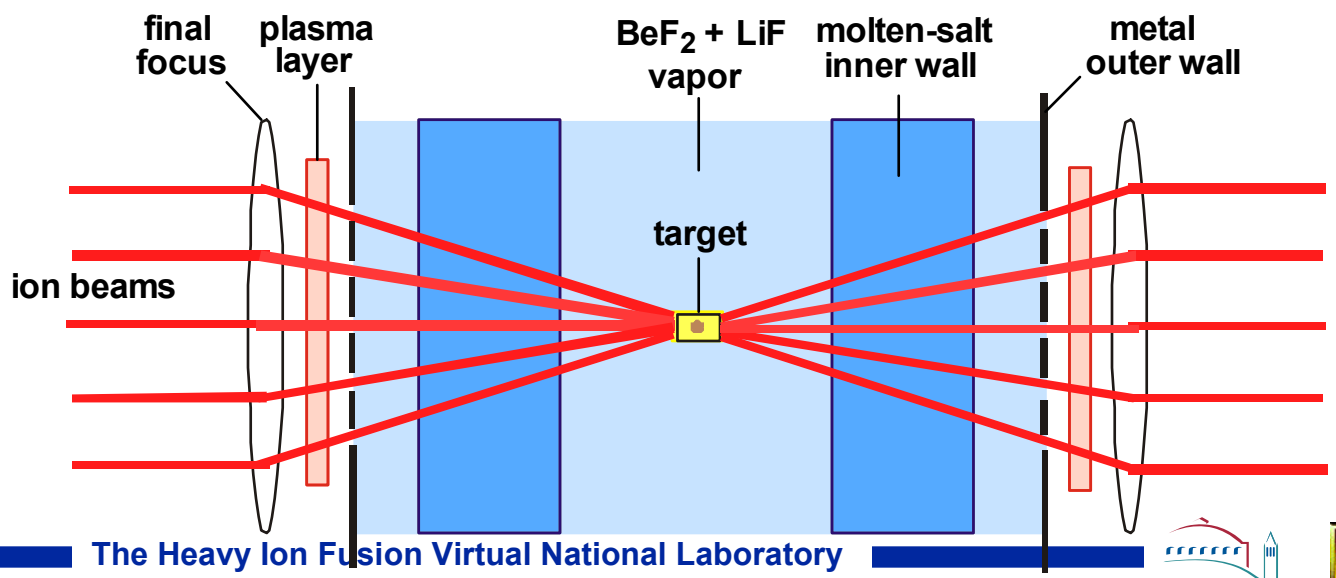
More-detailed physics modeling is needed

- inclusion of molten-salt jets
- realistic target model
- 3-D simulations to model instabilities and non-axisymmetries
- multiple-beam simulations to study interaction between pulses

What's going on in the chamber?

chamber physics poses several modeling challenges

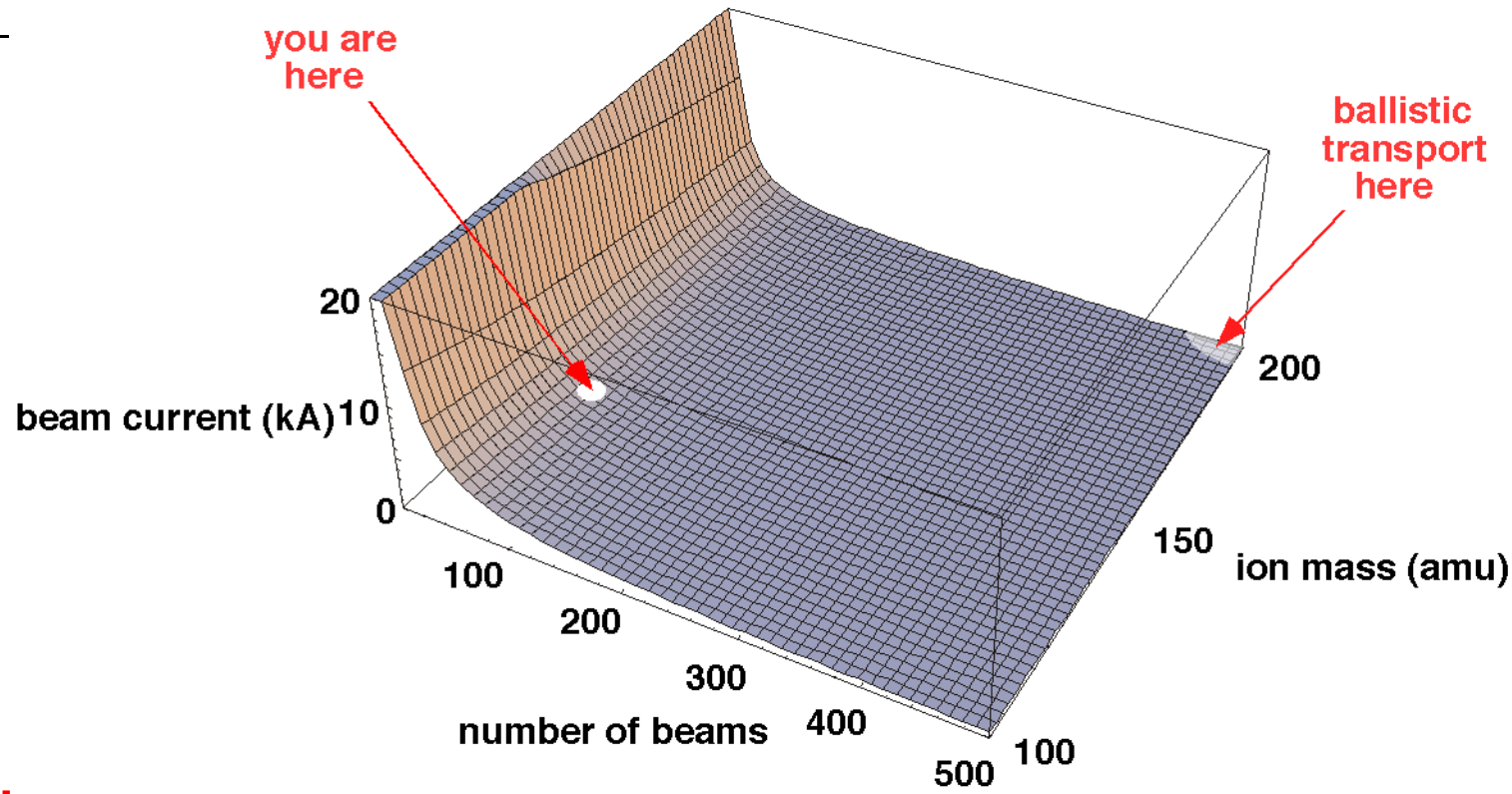
- space-charge-dominated beam dynamics
- radial compression due to beam focusing
- pre-neutralization of beams by hydrogen plasma in beam ports
- electron emission from walls and from heated target
- complicated boundary conditions due to molten-salt inner walls
- scattering and collisional ionization by vapor from liquid walls
- photoionization by soft X rays from heated target
- overlapping fields from neighboring beams near the target



Is beam neutralization necessary?

perveance κ must be less than 1.6 x 10^{-5} for ballistic transport

- **for distributed-radiator target,** $N\, M_{amu}\, I_{kA} \sim 3 \times 10^4$
- **perveance definition gives** $\kappa \sim 10^{-2}\, I_{kA} / M_{amu}$
-



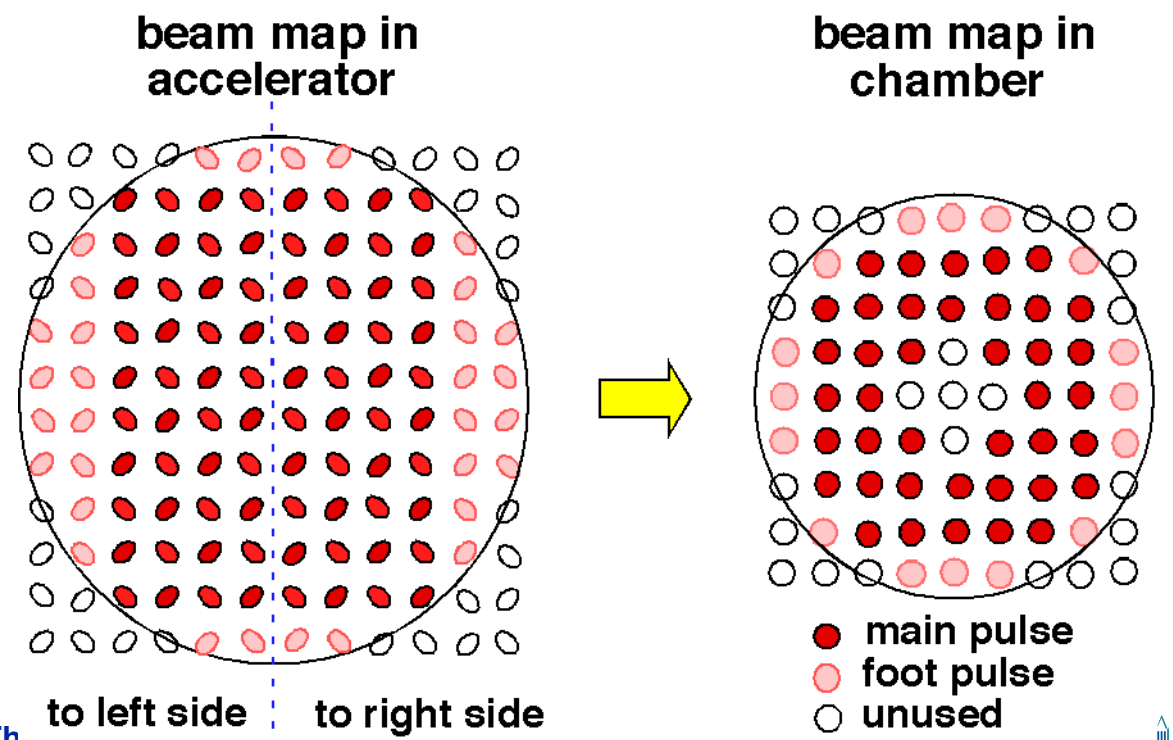
an upstream plasma is used here to pre-neutralized the beam

How are the beams laid out?

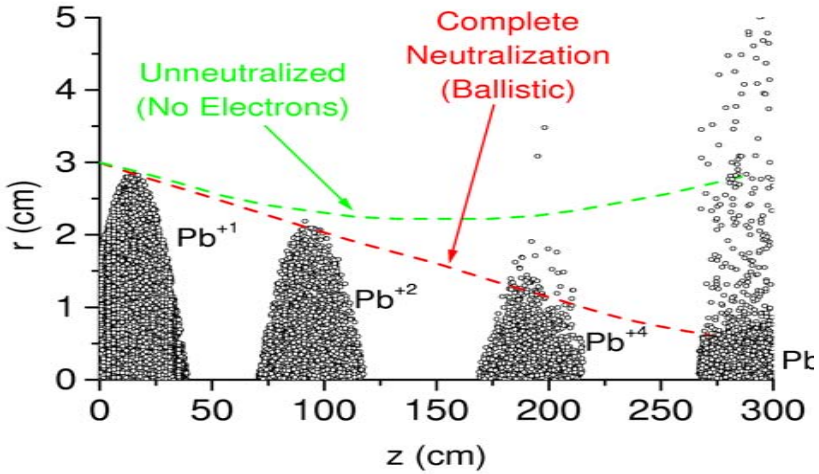
symmetry requirements limit possible layouts

- **accelerator layout needs an even number of rows to allow splitting**
- **chamber layout needs odd number to allow target injection at center**
- **ratio of foot and main pulses should match target energy needs**

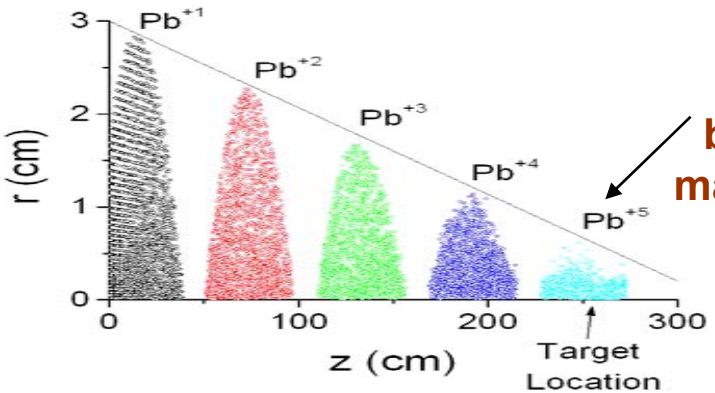
nominal case here has 80 main and 32 foot pulses



Chamber plasma reduces focal spots compared to vacuum, but nonlinear residual fields can dominate emittance growth in foot pulses

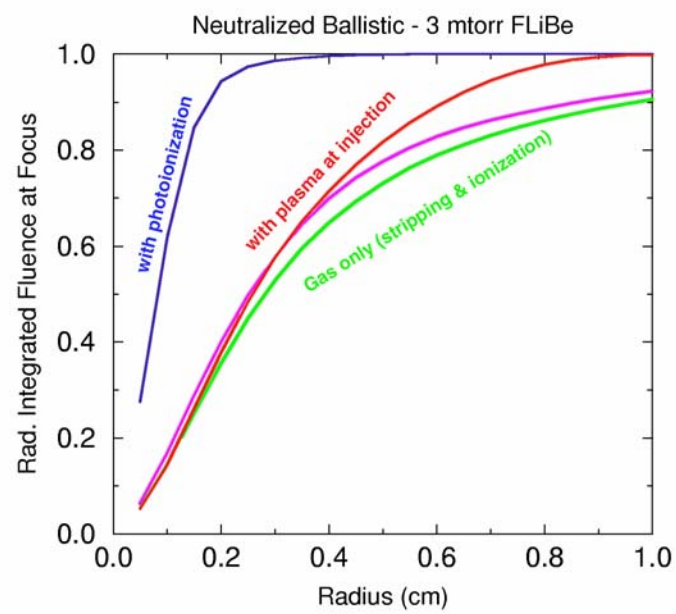


Stripping & ionization only for foot pulse



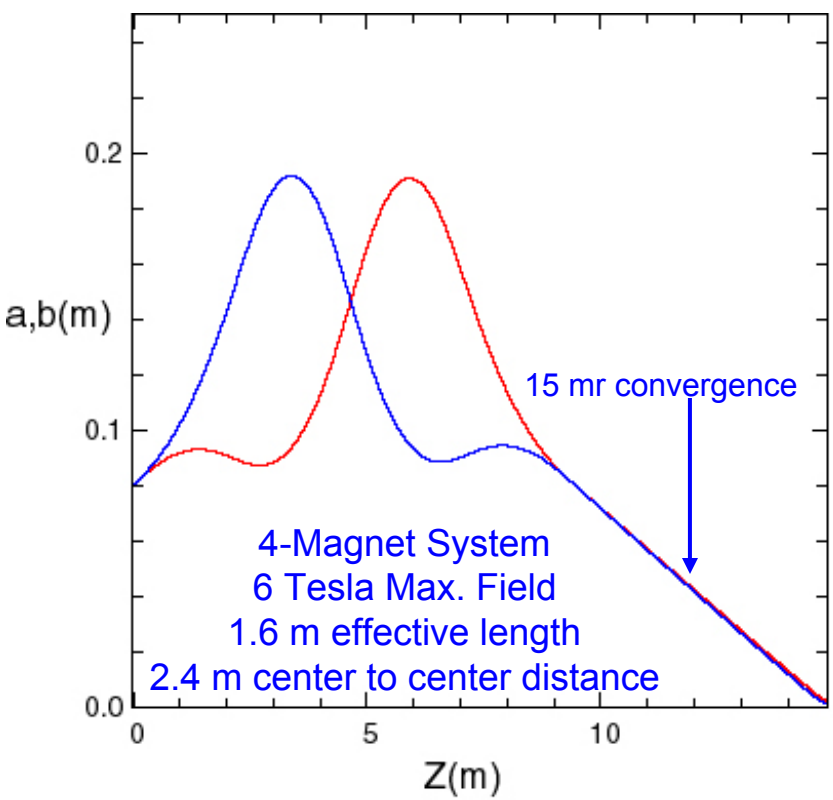
Magnetic pinch effect benefits main pulse

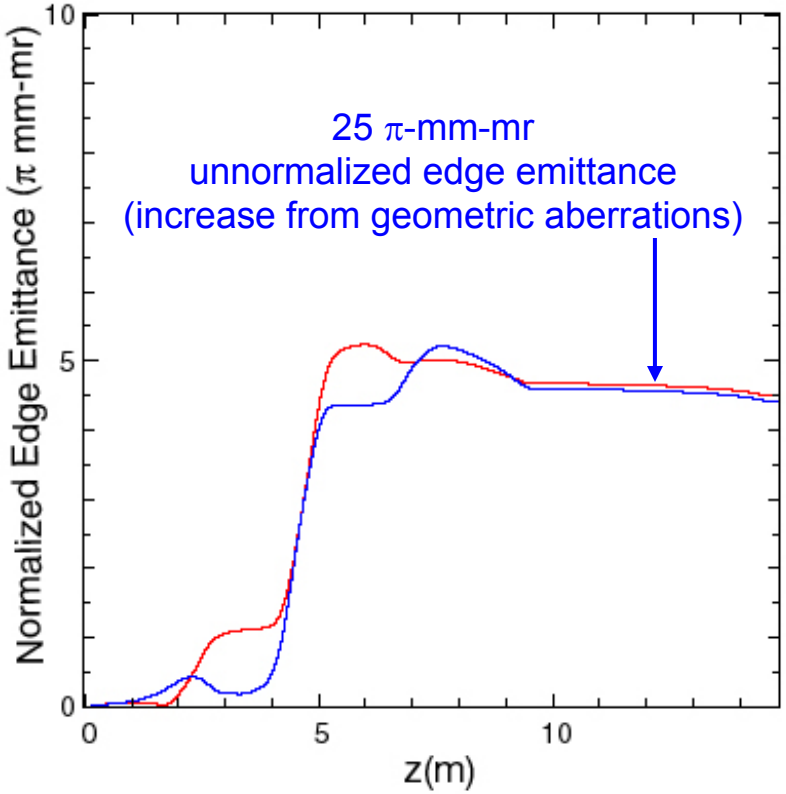
Main pulse benefits from photo-ionized plasma



- 4-kA, 4-GeV, 8-ns Pb^+ beam
- 3-cm "parabolic" profile (constant J_b)
- 30 πmm-mrad un-normalized emittance
- SCL emission from injection plane
- R. Olson stripping X-sections for all states (Bi)
- 5×10^{13} cm^{-3} FLiBe ambient gas
- Photo-ionized $FliBe^+$ plasma has 5×10^{13} cm^{-3} maximum density

Final Focus System for Driver Scenario (2.5 GeV,2.8 kA Xe, NTX Type Magnets)





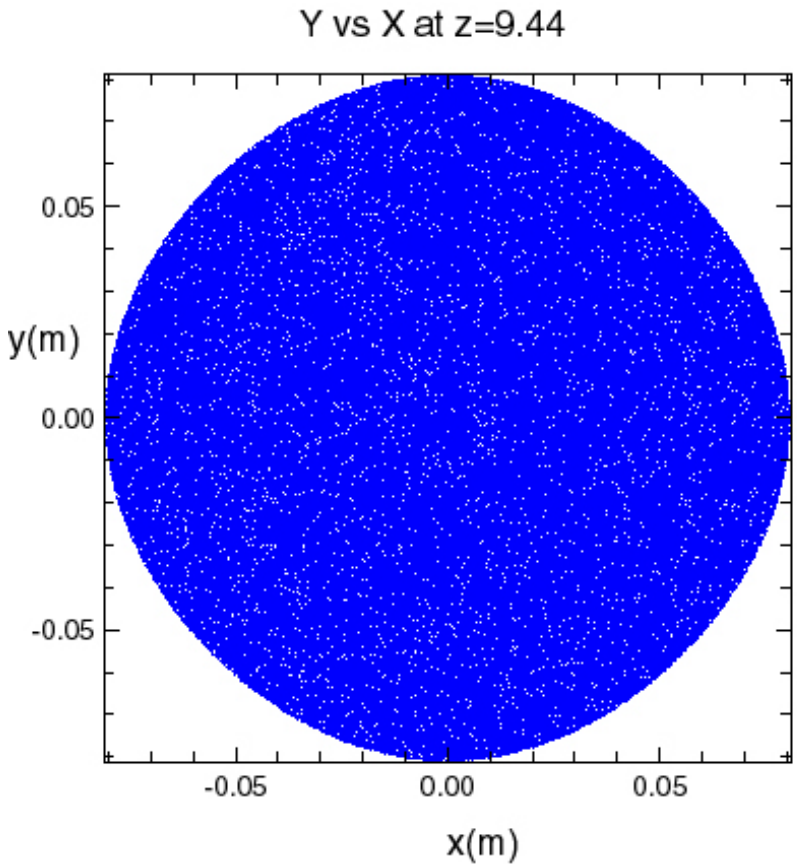
Step 1483, T = 0.2465e-6 s, Zbeam = 14.8200 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDO$_{OCT+12}$POLE

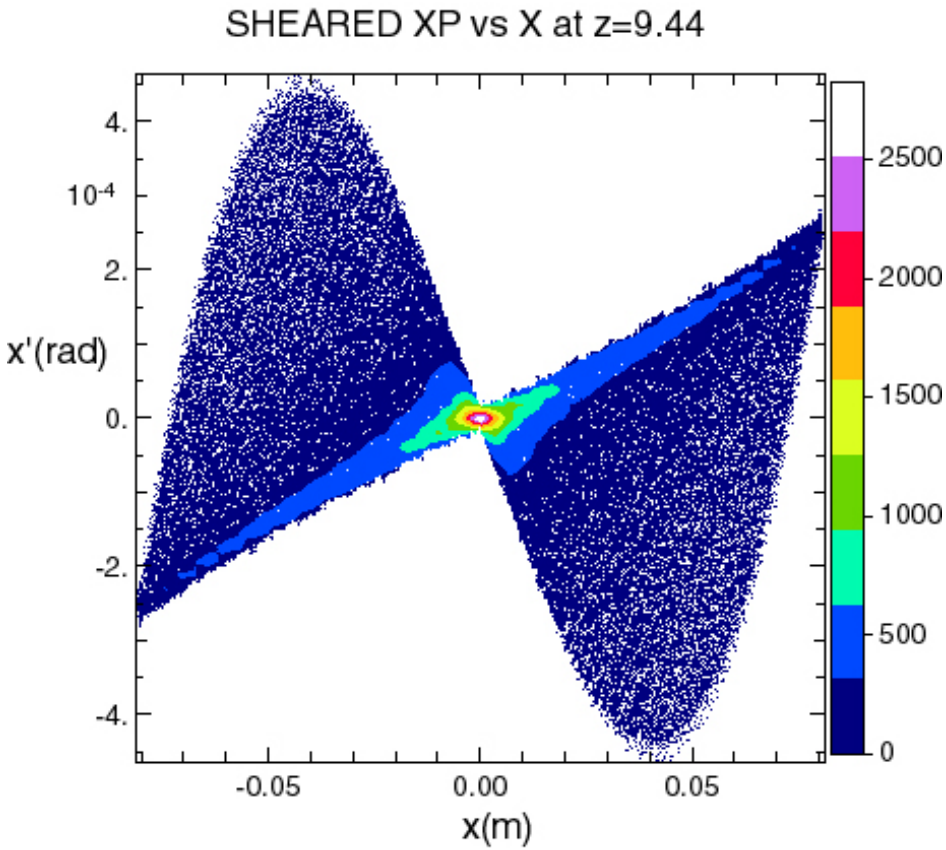
Enrique Henestroza warp r2 drNO

Step 1483, T = 0.2465e-6 s, Zbeam = 14.8200 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDO$_{OCT+12}$POLE

Enrique Henestroza warp r2 drNO

Final Focus System for Driver Scenario (phase space at entrance to neutralization region)





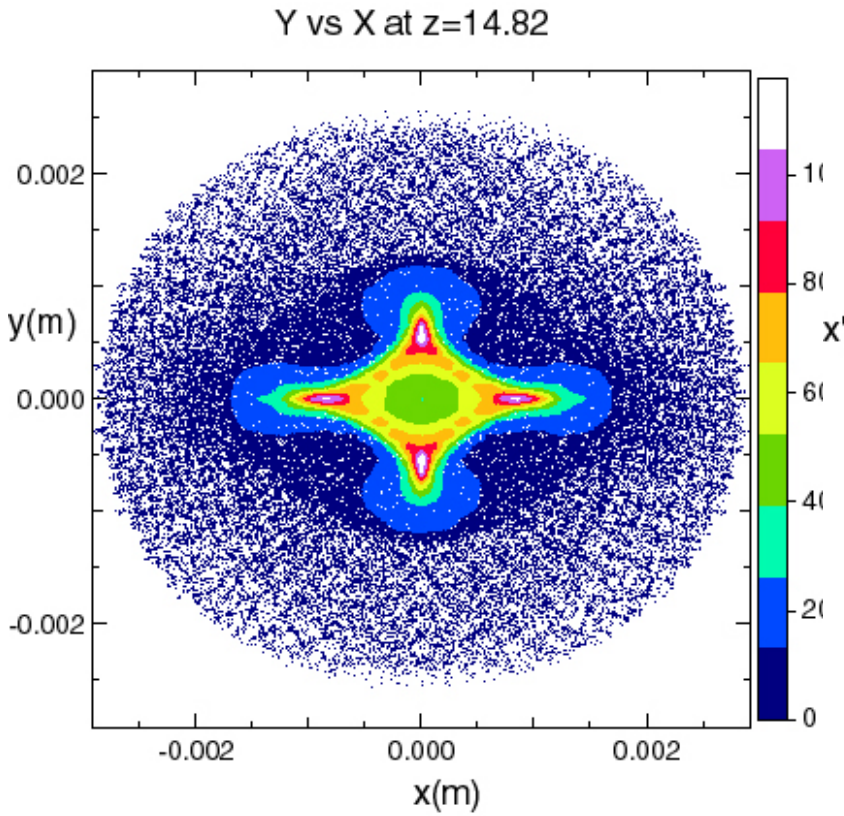
Step 945, T = 0.1570e-6 s, Zbeam = 9.4400 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDO$_{OCT+12}$POLE

Enrique Henestroza warp r2 drNO

Step 945, T = 0.1570e-6 s, Zbeam = 9.4400 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDO$_{OCT+12}$POLE

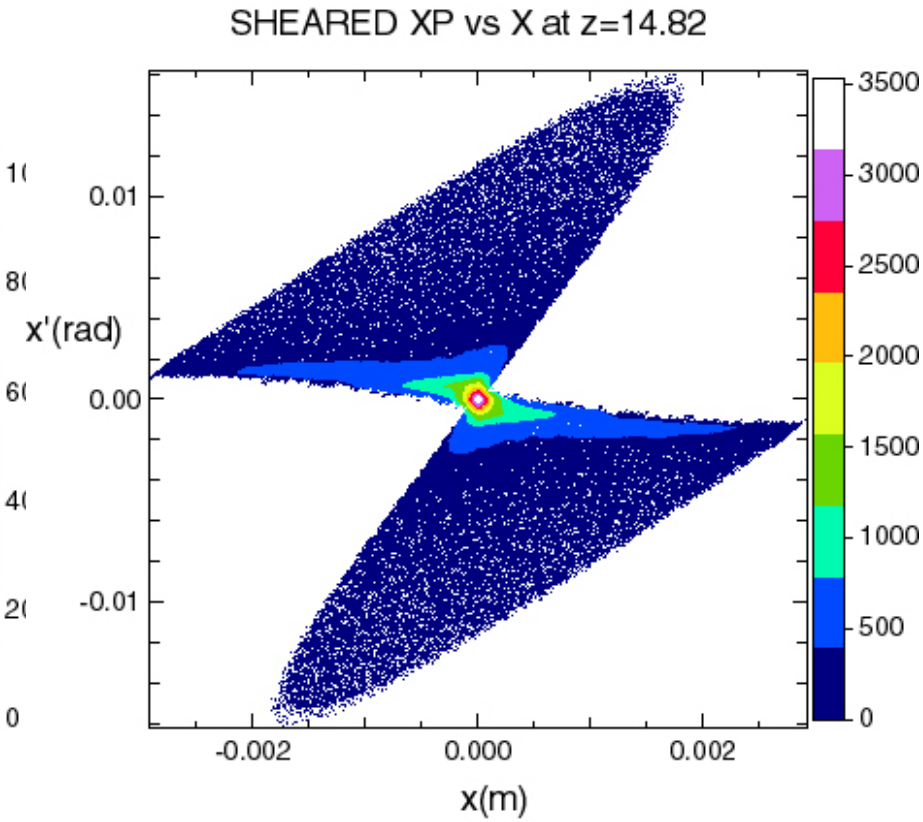
Enrique Henestroza warp r2 drNO

Final Focus System for Driver Scenario (phase space at focal point without neutralization plasma dynamics)



Step 1483, T = 0.2465e-6 s, Zbeam = 14.8200 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDOOCT+12POLE

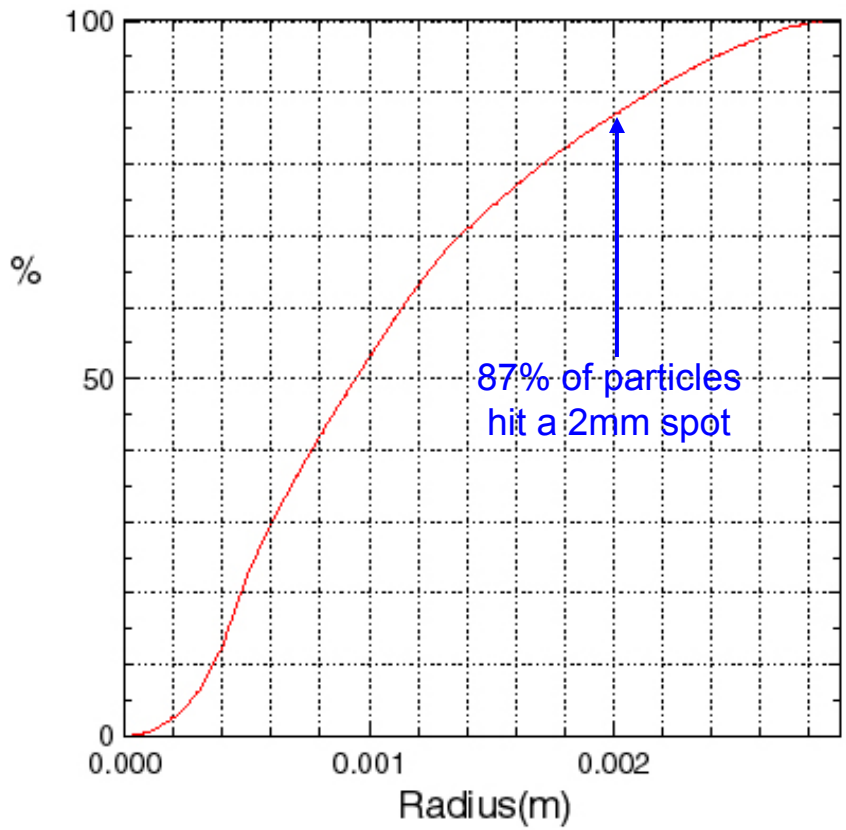
Enrique Henestroza warp r2 drNO



Step 1483, T = 0.2465e-6 s, Zbeam = 14.8200 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDOOCT+12POLE

Enrique Henestroza warp r2 drNO

Final Focus System for Driver Scenario
(Percent of particles as function of radius at focal point)



Step 1483, T = 0.2465e-6 s, Zbeam = 14.8200 m
NTX Final Focus System (20mm,-20mr)
2D Slice, QUAD+PSEUDO$_{OCT+12}$POLE

Enrique Henestroza warp r2 drNO

Interface Issues

Thermal

- 4 K magnets must be insulated from 400^0 C Flinabe in a few mm of space.

Vacuum

- 10^{-6} target chamber needs to be isolated from 10^{-9} beam lines.
- Debris from target must be kept out of beam lines.

Electromagnetic Loads

- Forces between quadrupole magnets must be reacted by strutures between the magnets.
- Adequate preload on the magnets must be provided to avoid quenching,

Radiation

- Magnets must be shielded for 30 yr. life.
- Nuclear heating of the superconducting magnets must be as low as possible.

Alignment

- Beam alignment must be maintained within TBD dimensions.

Maintenance & Assembly

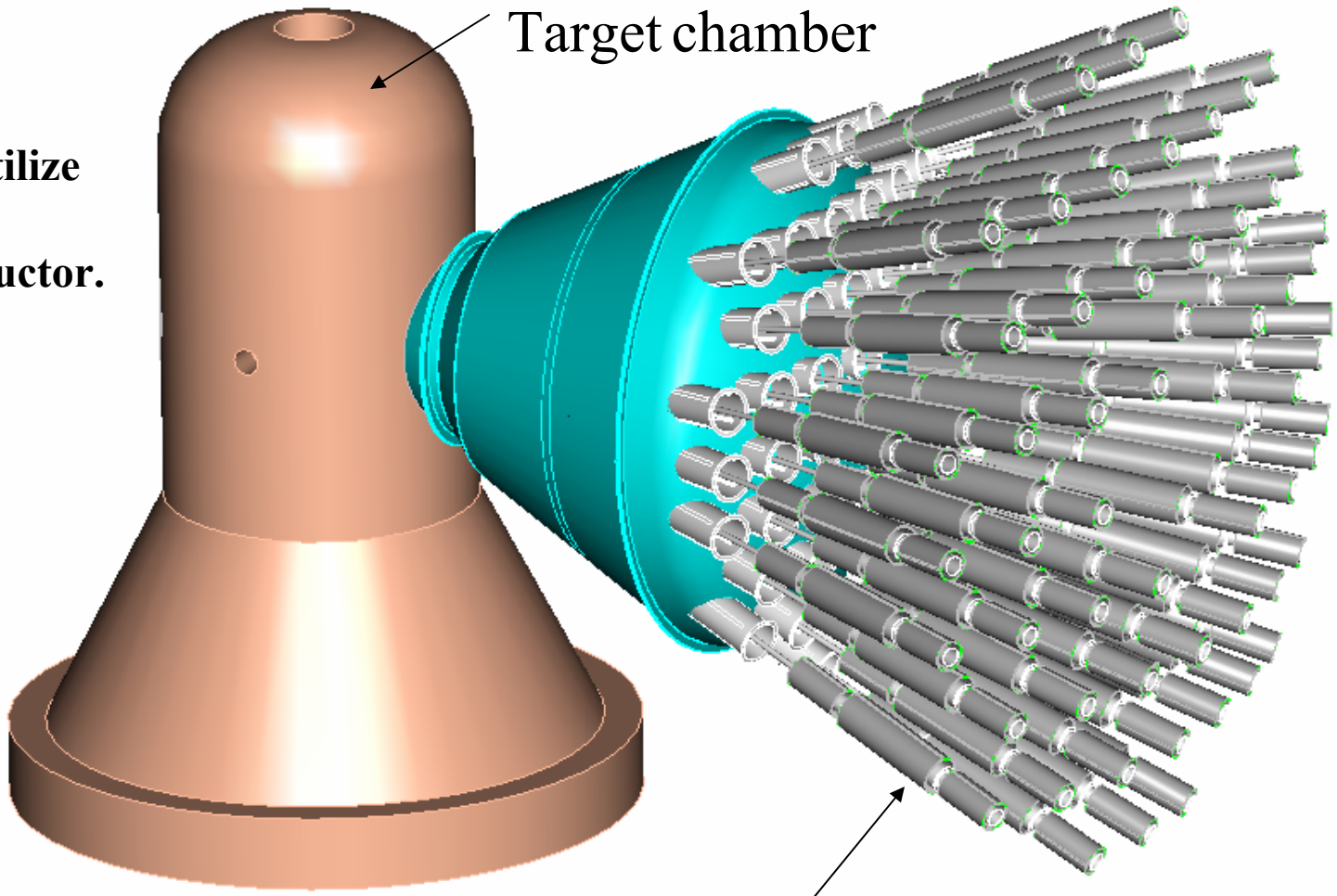
- Array should be capable of tolerating the loss of a few beam lines (symmetric side to side).
- Goal: to be able to replace failed beam lines in <6 mos.
- Array assembly must be practical from the field construction point of view.

Utility Feeds

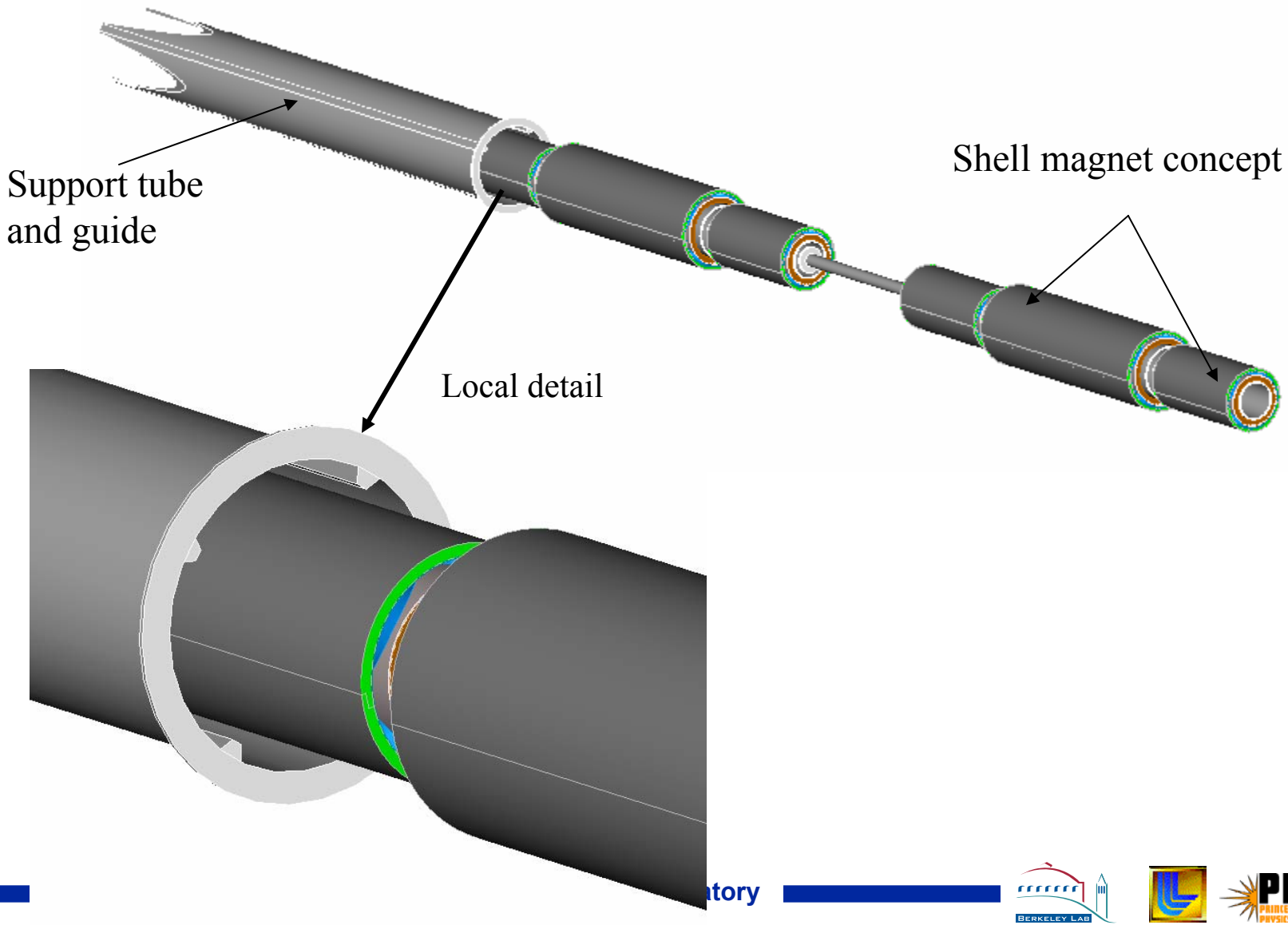
Cryogenic feed lines, power lines, instrumentation lines, Flinabe lines from all of the 104 beam lines must all be accommodated.

Preliminary Concept

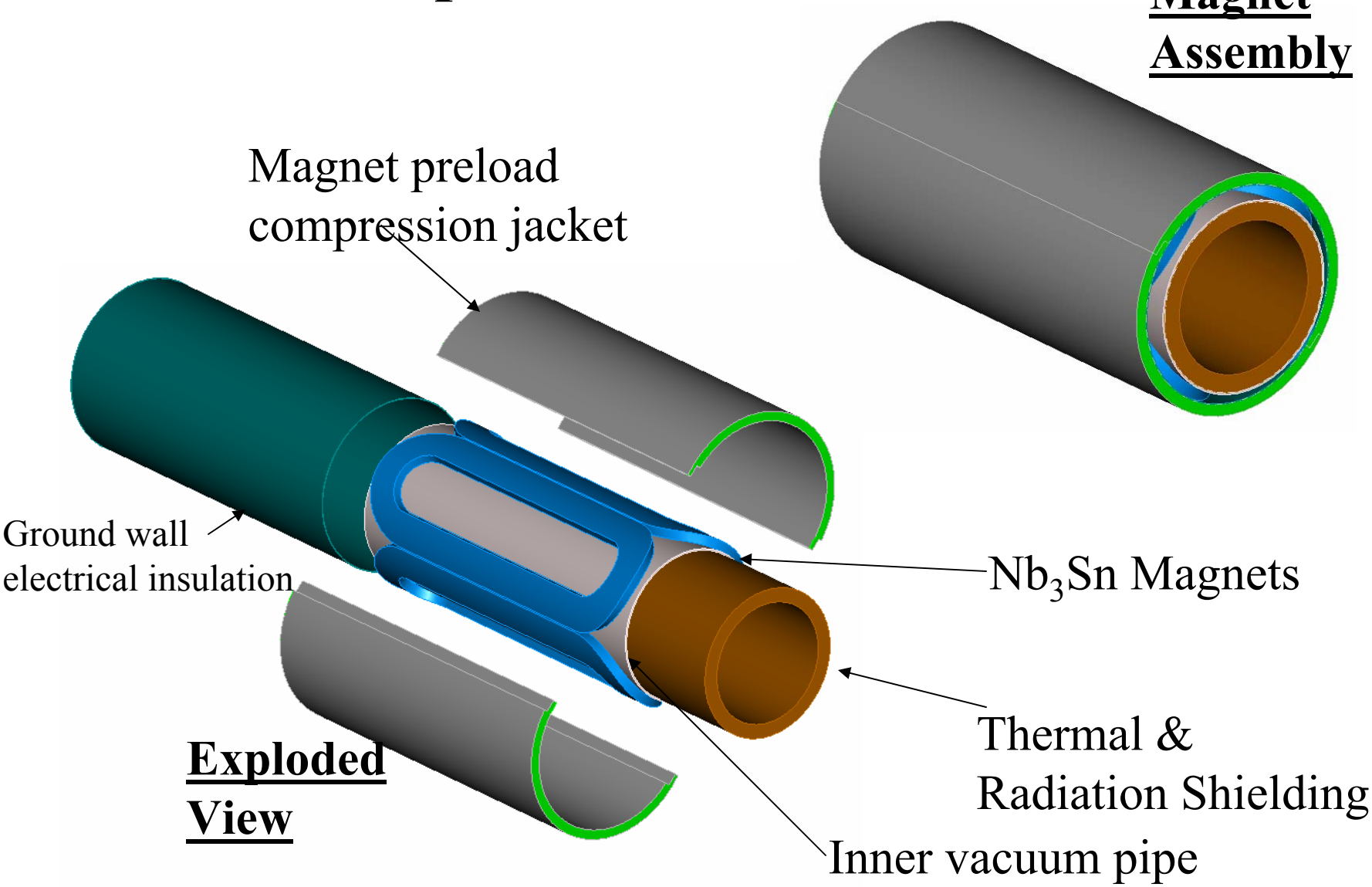
- **52 Beam Lines / side**
- **Focusing magnets utilize Nb_3Sn superconductor.**



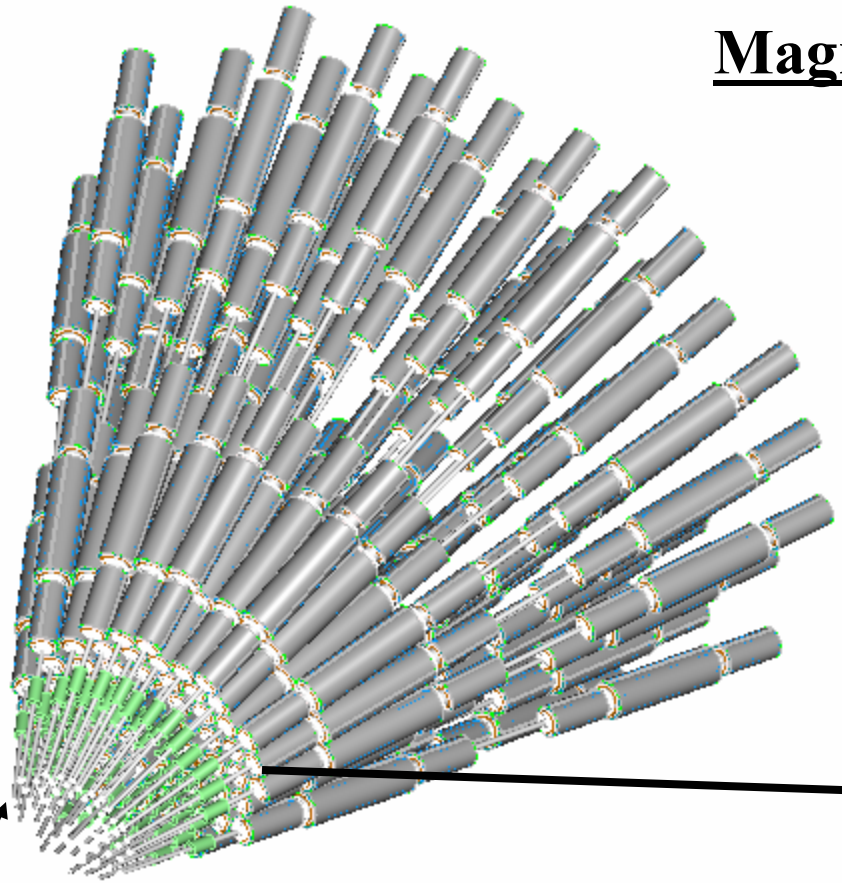
Configuration based on the Shell magnet arrangement.

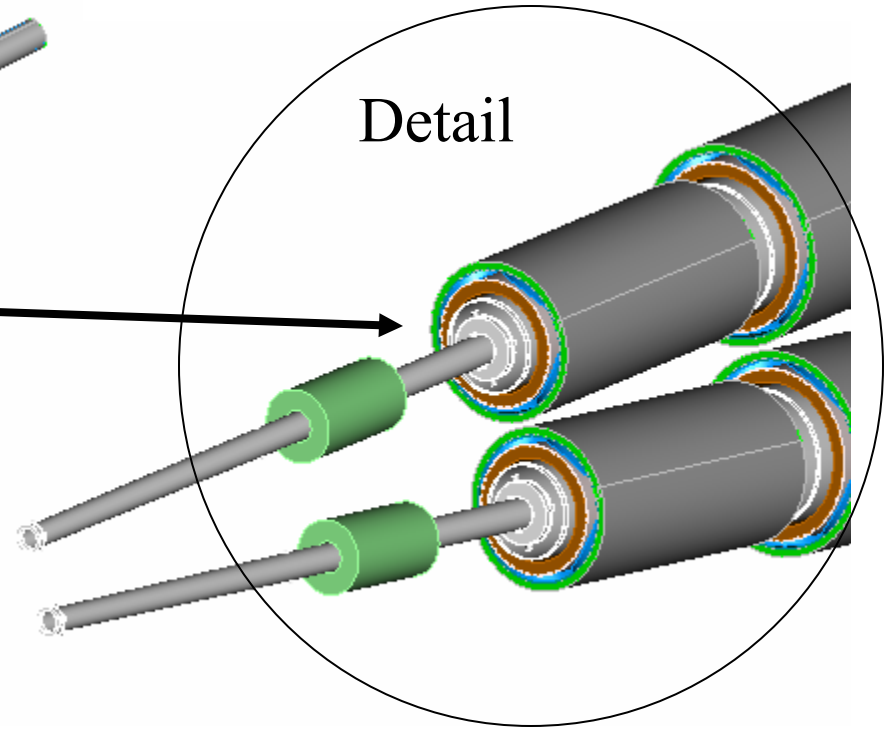


Quadrupole Details



Magnets Installed in Guide Tubes





The "nose" is the difficult area. There is insufficient space for the guide tubes. The dipoles here will be supported by the vacuum pipes. Bulk shielding is a problem!