



# Scientific Issues in Future Induction Linac Accelerators for Heavy Ion Fusion

**C.M. Celata**

**Lawrence Berkeley National Laboratory  
and the  
Heavy Ion Fusion Virtual National Laboratory**





# In 2011 a national HIF workshop identified issues ...

## APPENDIX B

### COMPILED LIST OF HEAVY ION FUSION SCIENCE AND ENGINEERING ISSUES

**Source**

What are the viable ion source options (large surface induction source? plasma manifold? higher charge state?)? Must have acceptable rise time, neutrality, emittance, current density, current, purity, charge, spot purity, lifetime, reliability, pulse length, stability of current with time, and be usable in an array.

Do there adequate sources for the multi-beamlet injector concept (acceptable rise time and neutral drift)?

How reproducible are the beams from the on-axis laser sources?

What causes non-on-axis emittance in our ion sources?

How short rise time can we get from a plasma ion source?

What is the neutral emittance from the various ion source options, and what is the limit on how much we can correct?

Can we use continuous or fast ion sources in an array?

What is the effect of the radius of curvature of the source on beam quality?

How realistic can we make the beams?

**Injector**

What causes beam emittance growth in the injector?

Can we use a single master of a side, and how much does that improve beam quality?

Should we use large ion sources or merge an array of "mini-beamlets" in the injector?

How does the production of neutrals and secondary electrons near the source affect the beam quality?

How do we handle resistively stored energy via a large array of injectors to limit damage from voltage breakdown?

What is the distribution function that comes out of the injector—the pre-injector, and the last injector to emanate?

What is the best way to "ramp" the beam, longitudinally and transversely, as it exits the injector? How: Important to look at neutral, realistic distribution function.

What is the longitudinal distribution function coming out of the injector?

What is the minimum limit to injector pulse length, with a finite number of beams?

What is the effect of the time dependence of the voltage rise on the distribution function at the beam head, and therefore the beam head mismatch?

What happens to the beam head at the injector exit, given the mismatch? Can we make the voltage rise time that we need, and can we make it as necessary we need it?

How reproducible are the beams exiting the injector?

What physics would limit the pulse length produced by the injector, and what is the limit?

Can we remove the beam at the end of the injector without harm to the beam from electron or gas production?

Can we use new high-gain laser amplifiers, or is our pulse length too long?

At what energy should we transition from injector to accelerator?

What are acceptable limits for emittance and spot size of the pulse exiting the injector?

What are the voltage breakdown limits for appropriate gap lengths and pulse shapes? How is this affected by a full scale simulation?

Are the observations inherent in the ESD acceptable? Is the energy effect the limit?

Can we use a laser amplifier to blow electrons and eliminate the ESD?

How do the observations of the electron in the ESD affect the injector?

How realistic can we make the beams?

**Accelerator Dynamics**

**Steering**

How well do we need to measure beam offset? How often? How often do we need to steer, and with what precision? (TV, IR, laser for electrostatic and magnetic focusing). Can we keep the beam aligned during its flight? How well can we measure it with non-intercepting diagnostics?

Is there a scenario to do real-time beam deflection to compensate for errors in target injection?

What are the beam loss reflections in the accelerator? Are there needed in the target to control dose? Do the various dose high recovery modes in the cavity? Are there mid-beam collector movements of the beam? Are they needed? How does one correct for systematic differences in mid-beam intersections at head, middle, and tail of the beam?

**Matching Structures**

Should we use a matching system, or a hybrid matching?

What is the optimum number of lenses in a matching section to minimize transverse envelope rise and beam heating?

What is the optimal aperture in the matching section, where the beam radius can be very large, transverse temperature cold, and therefore nonlinearities very effective at increasing emittance?

How should we match from the electrostatic to the magnetic lattice, given the 3D mismatch?

What happens to the beam head at the injector exit, given the mismatch? What frequency do we need to match the beams?

**Beam-Beam**

How reproducible are beam dynamics in the final focus?

Does the magnetic return of periodic time-dependent focusing when the beam pulse is brief (<100 ns) and the velocity is fully relativistic with longitudinal injection flow or to increase the acceptable velocity through the final focus section? How is the optimum point to provide for time-dependent focusing?

How does one have to be driven, shielding matters? If reactor distance in the range of 50-100 mm have important effects, how much do beam-to-beam differences in the shielding matter?

What is the positioning precision required for the final focus magnets?

What are the primary beam-to-beam constraints on transverse and plasma sheet transport in the region near the focus magnets? What neutron shielding is required for the final focus magnets, and knowing that, what is the minimum number period of the beam array as a function of beam energy and stand-off from the target?

What physics would limit the pulse length in the accelerator, and what is the limit?

Can we keep the electron from downstream out of the final focus?

What is the 3D distribution function to be expected for a real beam exiting the final focus system?

Can plasma lenses be used for final focus system?

Can we do the location where a beam pulse is measured during chamber operation, so that we can correct the pointing error it provides?

**Alternate Focusing Methods (Sub-Finch, Assisted Finch [Channel Transport], Helical Lens)**

What distribution function can be focused onto the axially-transported by each approach? Are the beam distribution functions consistent with target requirements?

What is the equilibrium amount of charge and current neutralization for each method?

How are the chamber perturbations, and how big are they, for the different methods?

**Sub-Finch**

Is self-matched propagation viable to base, filamentation, and two-wave instability?

What is the effect on the beam distribution function, radius, and longitudinal profile?

Is a gap to feed for wavebreaking, is the pressure consistent with chamber design?

Is a plasma used, what will be the pre-ionization, and is it uniform enough?

What plasma composition mixture of hydrogen and neutral He/2? Is it possible, and optimal?

For the self-match, can a lens-chamber be produced and sustained?

**Assisted Finch [Channel Transport]**

What controls are needed for a degree of stability in our experiments? (Mostly) Transverse Dynamics

What happens in phase space distribution once for realistic distribution functions over long lengths on the accelerator?

What is the dynamic aperture in the electrostatic section? In the magnetic section? The limits for the following: energy? Have the rate of emittance and halo growth from injector and schematics for specified aperture fill? We need to give information that are qualitatively understood and comparable to driver and ESD-scale systems.

When is halo formed?

How does the dynamic aperture change if the beam is mismatched—what are the rates of emittance growth based on a function of aperture fill or varying degree of mismatch?

Can we increase the dynamic aperture by using a non-minimal heliostatic for other nonlinearities? Is this feasible to understand the effects of images?

What are the mechanisms and rate of reduction of electron transverse modes due to phenomena and thermalization, and what are the best emittance and halo growth? How does this depend on mismatch and the nonlinearities that are present?

Why does the optimum heliostatic at about 80 degrees almost, when theory says it should occur at higher sigmas?

What are the realistic limits to the acceleration gradient and velocity tilt for long-time launch compression and beam dynamic aperture? Do we have a ceiling on electron limit under acceleration and heating?

What is the beam loss in the accelerator, where does it take place, and what is the mechanism involved in the process?

What is the transverse dynamics of the beam end in the accelerator? (Mostly) Longitudinal Dynamics

How does the beam loading impact the pulse shape?

How does the longitudinal mode structure, especially in the head and tail of the beam, give a longitudinal wobble effect?

Give minimum matching between an eye ray injection mode and a quadrupole lattice, what are the constraints and derived with or without of laser gain that allow maximum smooth acceleration relative without bunching behavior? Longitudinal space-charge effects? What is the dependence of longitudinal electron growth on velocity errors?

What is the best method between modes in resonance and off-resonance? How do we implement feedback for longitudinal wave feedback control?

How does the presence of multiple beam affect beam-end dynamics?

**3D Dynamics** or both transverse and longitudinal

Can the distribution function remain steady state? How does it do that, and how does the electron do it? How is the 3D? What are the dynamic mechanisms for transverse and longitudinal waves? Does the beam ever lose the "character" of the initial laser injection? Is there an "equilibrium" state with the periodicity of the laser? Is it relevant to the HIF parameter regime?

What is the parameterization of equilibrium rate and saturation level of the transverse and longitudinal mismatches due to transverse-longitudinal coupling with a realistic distribution function? What do we measure to measure transverse-longitudinal coupling?

On the effect of electron in the magnetic-focused section. What are the sources of electron and how many are produced? Given the electron source rate, what is the electron density as a function of time? What is the distribution function? How much is the electron source rate? How much is the electron steering control? Will electron effects limit the pulse length? Are instabilities important in electron beam stream, possible electron modulation of wave instability? How much pulse length is reproducibly do it occur even? What can be done to reduce the source function via materials, vacuum, halo removal, etc? What effect do acceleration may have on uncorrelated electron transport? What is the magnetic focusing section? What is important on a laser dose to determine the answer to these questions? What happens if we have more?

What is the effect of mismatch on transverse and longitudinal emittance?

What is the effect of pulse correlation on both the transverse and longitudinal emittance, especially given the likely coupling between transverse and longitudinal dynamics at the beam end?

What limits are there to acceleration gradient given by effect on beam dynamics?

What is the distribution function and profile of the beam end in real experiments?

How is the dynamic aperture affected by electron? Splitting and Combining

What is the impact to beam quality of splitting beams at the high energy end of the accelerator? Can nonlinear fields be used to control the space charge nonlinearities for the beam end?

How much halo is produced by combining?

Other Overall

What gives the lower limit on beam radius? Is it laser slice alignment and vacuum, or the electron source? How do we correct for halo, source of halo, or other, or something else?

How do we correct for halo, source of halo, or other, or something else?

Are there limits on the number of beam ends than beam-beam interactions and resonances?

How reproducible are the beams exiting the accelerator?

What will be the reliability of the accelerator?

How realistic will the beams be when they exit the accelerator?

Can we alter the beam distribution function in a controlled way in our experiments, so as to be able to explore the dependence of the physics on distribution function?

What is the detectability of diameter to implement the beam shaker goal for ESD and lower experiments? What of these cause difficulties or are to implement?

How can we measure longitudinal emittance?

How often do we have to measure, with what diagnostics, and with what precision, to measure mismatch?

**Accelerator Technology**

What are the expected errors for electron optics, focusing and bending components, 10% risk of them of 10-100 micrometers and charge field error, 10% for electron optics, and 100-200 micrometers for 100-200 micrometers error (10% for the error, and 10% for the error of error)?

Will induction electron linacs reach the 10% error range?

Can we use new high gradient insulators, or is our pulse length too long?

Can we relax the requirement of having insulators from beam, without degrading the performance of other?

How do we minimize the cost of superconducting quadrupoles? How small can we make them?

Can we use higher efficiency induction cores, and still be able to achieve pulse fidelity with beam loading?

Can we get higher efficiency cores, or cover with a higher surface in B in order to minimize core material and power requirements?

Will we be able to get affordable solid state pulser?

What are the limitations of acceleration and error waveform accuracy and control for various DT approaches?

**Drift Compression**

What is the sensitivity of the beam distribution function to current variations and velocity (or longitudinal) variations as a function of compression rate (beam length) and of accelerator length (length structure) and final pressure?

What is the sensitivity of the drift compression mismatch?

What is the effect of transverse-longitudinal coupling on the drift compression?

What are the constraints on the drift compression?

What is the sensitivity of the stagnation point to distribution function error?

What is a method for setting up drift compression lattice? How does one estimate variations in rise times, pulse tail fall, stray, vacuum, and laser pulse as a function of it?

Should we use alpha or beta or gamma beams? Is this necessary?

What is the level for multiple beams to achieve simultaneous target? In general, how do the time-correlated character of beams to ensure correct arrival of foot-pulse and main pulse?

**Diagnostics**

What mechanisms limit the lifetime of chamber and shielding materials (corrosion, erosion, and thermal stress) and how can these mechanisms be avoided and controlled?

How mechanistic of mechanical stress?

How can we use of various of forms and electron probes on the beam when they are in the chamber and control, during normal operation and during pulse operation?

**Target Physics**

How do we control symmetry in hollow core and the effect of asymmetries on emitter? Do radiation limits work to take out low order asymmetries like we think?

Can we design targets that are not just lower phase density?

Can we design targets that are less sensitive to beam pointing?

What is the effect of non-ideal thermal vacuum equilibrium shifter on operation? On photon path of target?

What is the effect of nuclear preheat target?

Can we design a system that can target get plumes before a reactor driver is available on DT, DT, DT, DT?

Can we get adequate symmetry control without using two ion kinetic energy?

How do radiation limit effect DT ions? Can we test the experimentally? Does the hydrodynamic motion or both of them? Do the components below the simulation predict both pressure balance and motion in liquid target?

For the different target types, how reproducible do the beam size and distribution (HWHM and velocity) can be?

Do we understand the trade-off between DT and DT?

What are the beam pointing (target position accuracy) required? Can we make the target less sensitive?

What is the required power balance from the target?

What is the expected power balance from the accelerator? What happens if we lose a fraction of a beam? A whole beam?

How sensitive to the target to pulse shape error? Are there advantages to the accelerator?

How accurate do we know the ion stopping in the target? How accurately do we need to know it? Are there any DT ion beam loss mechanisms (non-linear, self-ionization, etc.) that are important to the ion beam in the target?

Can we design a target that is illuminated from only one side? What is the allowable beam core angle?

How does the DT growth rate in 3-D or 2-D for our emitter?

What is the effect of all of the low order asymmetries in 3-D to change like a finite number of beams, power imbalance, beam pointing/target position error?

Does the "hot" lining of the hollow core have any effect on the performance?

Can we tolerate the DT growth due to a seam or a plug in the oxygen (which might be a different situation and/or filling)?

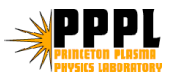
How much can we relax accelerator requirements if we design a fast ignition system using heavy ions to compress the fuel and a short pulse laser to ignite? In the case of the laser source, is it a high laser energy (high laser energy temperature)?

How much can we relax driver direct drive target? What are the requirements on the heavy ion beams? What is the limit?

Can we design direct drive targets with beams coming from just two sides?

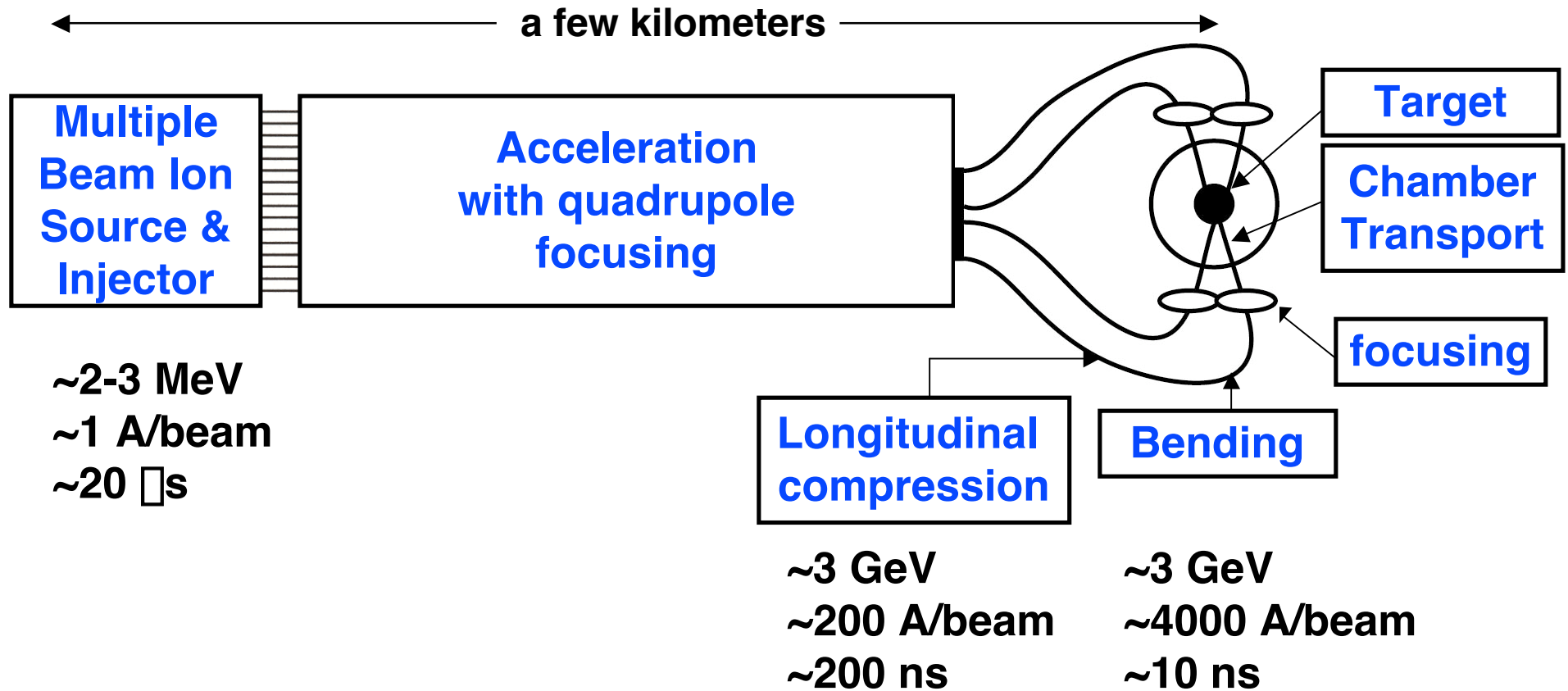
Can we improve the target materials for the blast, given a low concentration in the DT?

## The Heavy Ion Fusion Virtual National Laboratory





# A Multibeam Induction Linac Driver





# Sources/Injectors -- Many issues, but encouraging progress

## Priority 1 Injector Issues:

- Merging beamlet injector or large-aperture diode?

**Merging beamlet experiment by end of March**

- Will high gradient insulators work for long pulses?

**Experiment imminent**

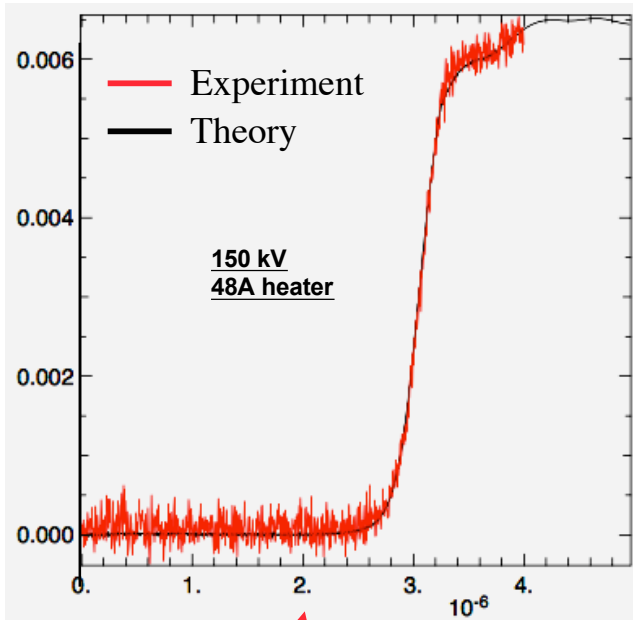
- Understand diode current risetime requirements
- Understanding phase space changes in injector



# STS-500 is also investigating large-aperture diode dynamics

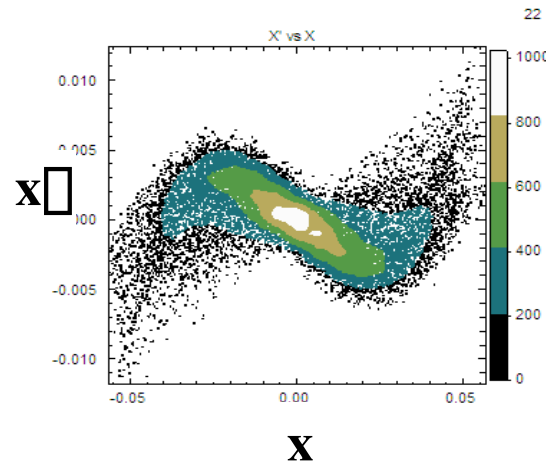
## Risetime

Current at Faraday cup

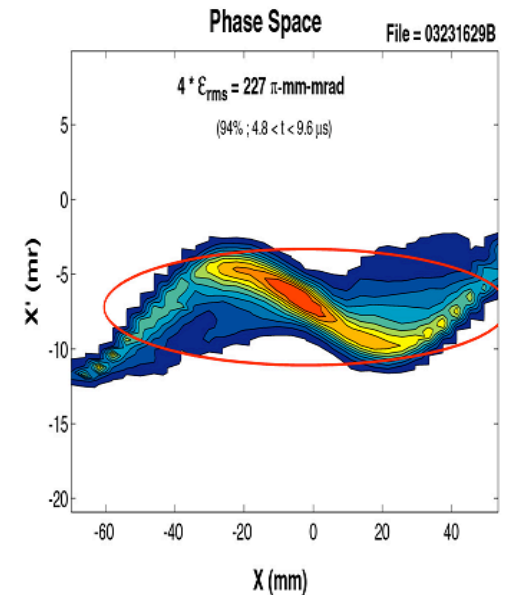


## Phase Space at End of Diode

Warp simulations



Experimental results



r-z time-dependent PIC

10-cm-diameter K<sup>+</sup>  
Alumino-silicate source

This result depends critically on new computer technique (Adaptive Mesh Refinement), that has moved the state-of-the-art.



## Priority 1 issues continued:

- Is beam aperturing workable?  
STS-500, NTX, HCX -- seems good. More to do.
- Which sources suitable? plasma, aluminosilicate, laser, ...  
STS-100 plasma source qualification
- Understand nonuniform source emission  
plasma source experiments - now  
New uniform aluminosilicate sources  
STS-500 experiments on nonuniform emission & source temperature
- How much neutral emission from source is acceptable?  
Plasma source, aluminosilicate – OK





# Source/Injector - Conclusions and Future

## ***Multibeamlet Approach:***

Have workable source (plasma)  
If viable, need engineering design

## ***Large-aperture diode:***

Aluminosilicate sources OK for nearterm. Need long-life driver source.

Better diode optics highly desirable - 3D simulation design!  
Need good multibeamlet engineering design

## ***Both:***

Longitudinal phase space measurements & theory beginning



# “Priority 1” Accelerator Issues - Multibeam Quadrupole Driver

## Dynamic aperture issues

steering  
mismatch  
electrons & gas (halo)  
nonlinear fields

**~50% impact on  
driver cost**

**HCX  
&  
NTX**

## Longitudinal physics

wave production, growth, emittance growth  
measurements of distribution function

## 3D dynamics

temperature anisotropy instability  
beam end evolution, waves

## Multiple Beam effects

longitudinal instability  
electrostatic normal modes





# Resolution of these issues requires investment in experimental equipment

## Lengthscales are long

### Longitudinal

With no module capacitance:

$$c_s = (gK/2)^{1/2} v_b$$

$g$ = $g$  factor  $\sim 1-2$

$K$  = perveance  $\sim 10^{-5}-10^{-3}$

wave travels: 2 mm - 3 cm as beam moves 1 m  
6 cm - 90 cm as beam moves 30 m

Want to see wave produced, travel, reflect, turn around  $\square$

**$\sim 30$  m ( $\sim 50$  lattice periods)**

**Note:** length scale for instability growth  $\sim 100$ 's of  $l_p$ 's



## Many transverse phenomena also require tens of meters of lattice

**50 lattice periods**, with  $\alpha_0=72^\circ$  is

- ~ 15 plasma periods
- ~ 10 centroid oscillation or internal mode periods
- ~ 10, 14 mismatch periods (2 modes)

and simulations of electron dynamics, space charge waves, & many other problems show good data and “resolution” of dynamics over this length.

**but**

- ~ 1.4 depressed betatron periods
- ~ 5% of number of driver lattice periods  
miss low-level slow emittance growth



## We are doing valuable initial experiments on accessible physics. (HCX = a few lattice periods)

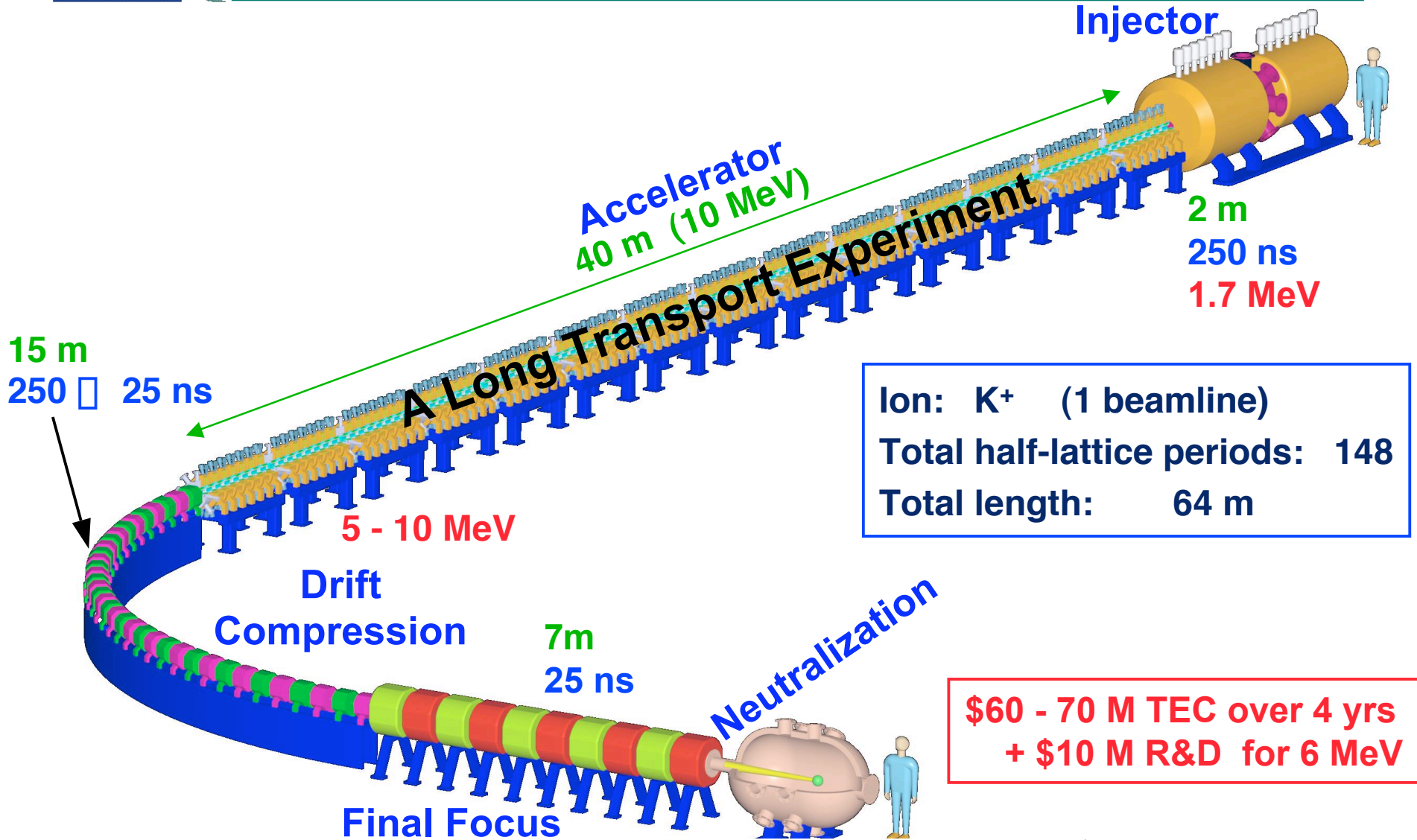
- Electron and gas production coefficients
- Electron orbits in magnets & acceleration gaps
- Steering
- Short longitudinal wave dynamics experiments
- Short dynamic aperture experiments

**then we need an experiment with ~ 50 lattice periods, to see**

- Dynamic aperture
- Effect of electrons on ion transport
- Mismatch producing halo & halo scraping
- Longitudinal wave propagation  
etc.



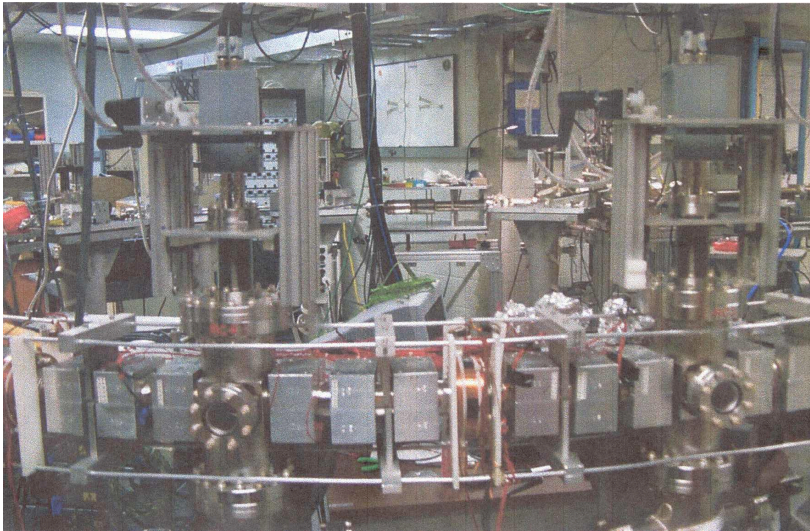
# Part of our Integrated Beam Experiment mission is to do longer-length-scale physics







# UMER & PTSX are designed to test long-length-scale dynamics



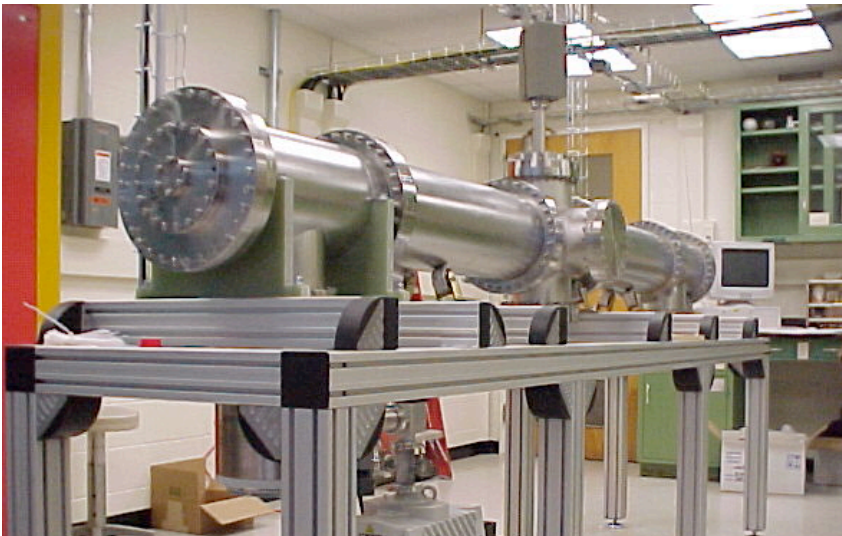
## University of Maryland Electron Ring

10 keV

100 mA,  $\beta/\beta_0 > 0.12$

Parameters variable over a wide range

Long Path (~ 110 m)



## Paul Trap Simulator Experiment

Ion column length            2 m

Wall electrode radius        10 cm

Ion column radius            1 cm

Voltage oscill. freq.        100 kHz

Effective path length        7.5 km (100 ms)



# What can't be seen in ~50 lattice periods needs an IRE-scale experiment

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## Inductive Effects require high energy + multiple beams

$N\alpha^2 \sim 0.1$  for 10 beams of  $K^+$   $\square$  190 MeV  
120 beams of  $Bi^+$   $\square$  78 MeV

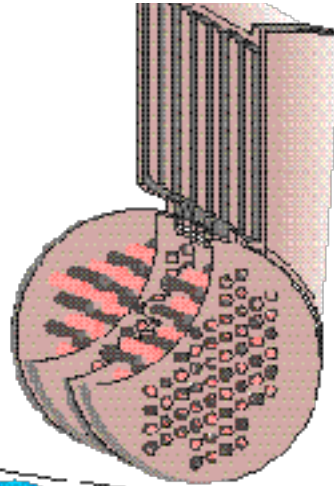
## Multiple Beams



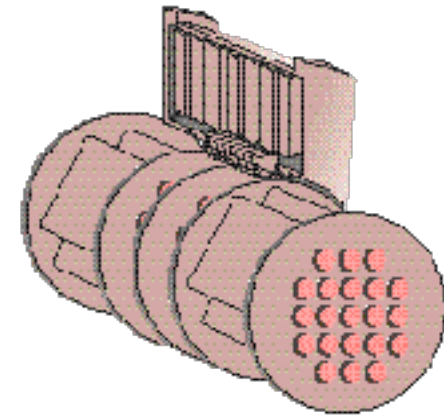
# The Integrated Research Experiment (IRE) will test long length scale, higher energy, multiple beams

400 - 800 MeV  
~ 30-200 kJ on target  
~ 300 - 500 m  
~ \$150 - 300 M

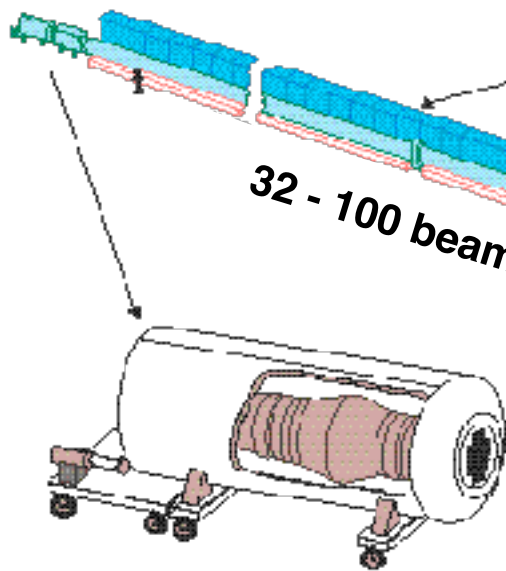
Acceleration & Electrostatic Focusing



Acceleration & Magnetic Transport

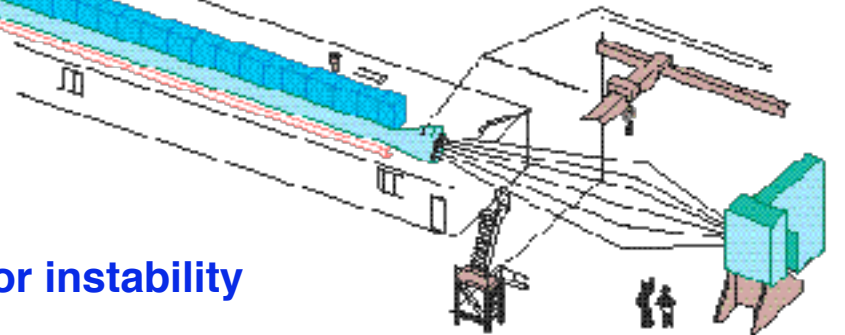


32 - 100 beams



Injector Source

Target physics:  
Rayleigh-Taylor instability  
 $dE/dx$



Target Chamber





# Important post-accelerator issues-- progress, but lots to do

## A sampling (most) of Priority 1 issues:

### Drift Compression (unneutralized)

- dependence on initial distribution function
- dependence on current, compression schedule
- optimization of lattice
- emittance growth (  $\parallel$  and  $\perp$  )
- sensitivity to errors

**Neutralization seems workable & robust !**

### Final Focus (quadrupole)

- dependence on initial conditions  **NTX**
- aberration control & correction  **identify - NTX**
- neutralization  **NTX**
- chamber transport
- alternatives-- assisted pinch, plasma lens, solenoid

**LSP Simulations**





# Unneutralized drift compression is important and relatively unexplored

## Simulation is difficult:

- 3D
- initial distribution function not known  $\Rightarrow$  big parameter space
- optimum I vs. z unknown  $\Rightarrow$  big parameter space
- simulate shaping & tilt imposition & compression sections

## Experiments are expensive:

Compressing a parabolic pulse **to stagnation:**

For  $C \gg 1$ ,

$$d \approx \frac{l_a}{\sqrt{8K_a g C}} \quad \frac{\Delta v}{v} \approx \frac{l_a}{d} \approx \sqrt{8K_a g C}$$

$d$  = length to stagnation  
 $C$  = compression factor  
 $K_a$  = initial perveance  
 $l_a$  = initial pulse length

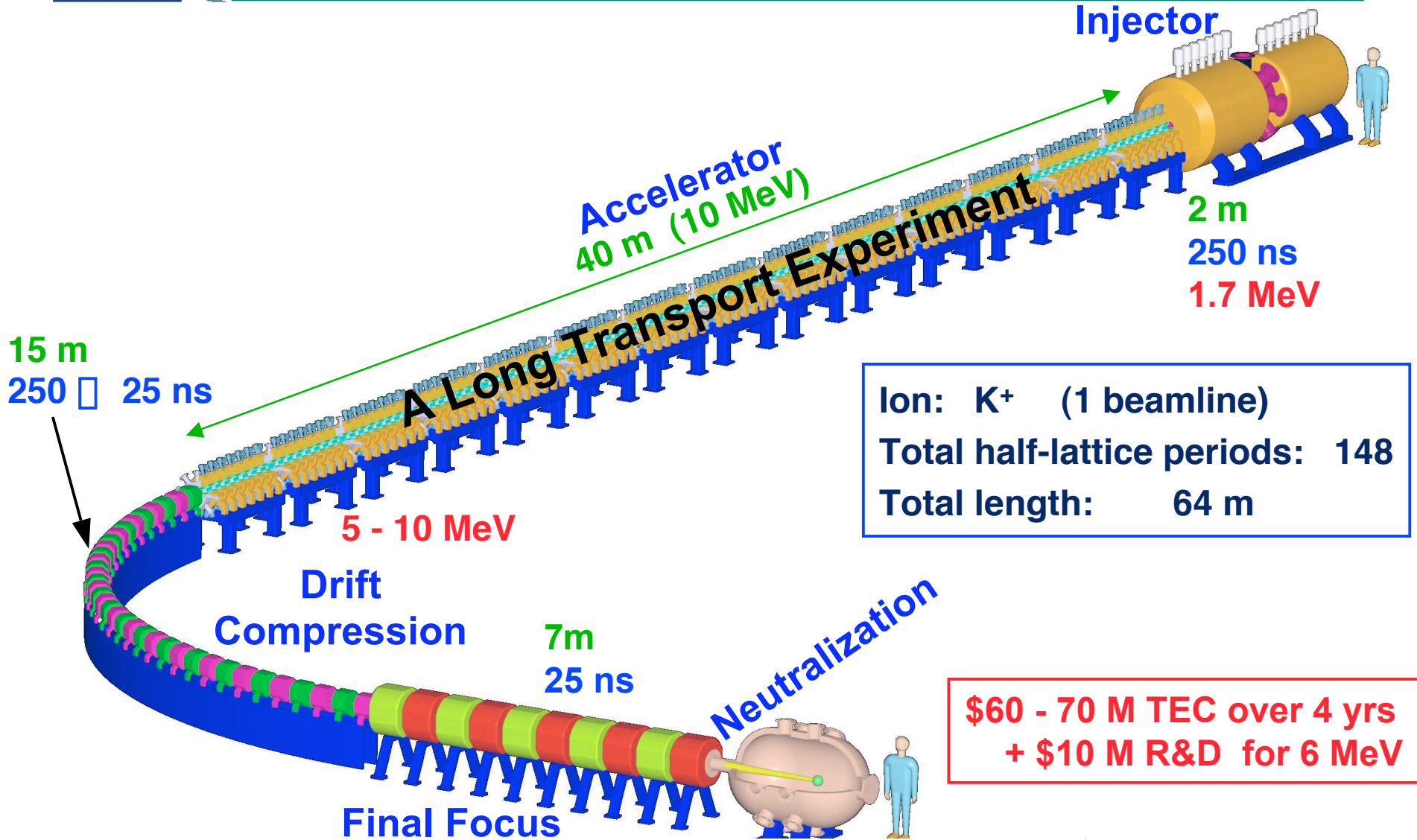
**Even with 200 ns, reasonable  $K$ ,  $C \Rightarrow$  tens of meters necessary.**







# The IBX would also do the first drift compression, and final focus (integrated!)





# What are the concept feasibility issues?

These can stop the beam or prevent focusing on target:

- **Long lengthscale emittance growth**
- **Drift compression**
- **Effect of electrons on beam**
- **Gas desorption instability?**

Wait

Long  
Transport  
Expt

Mitigate

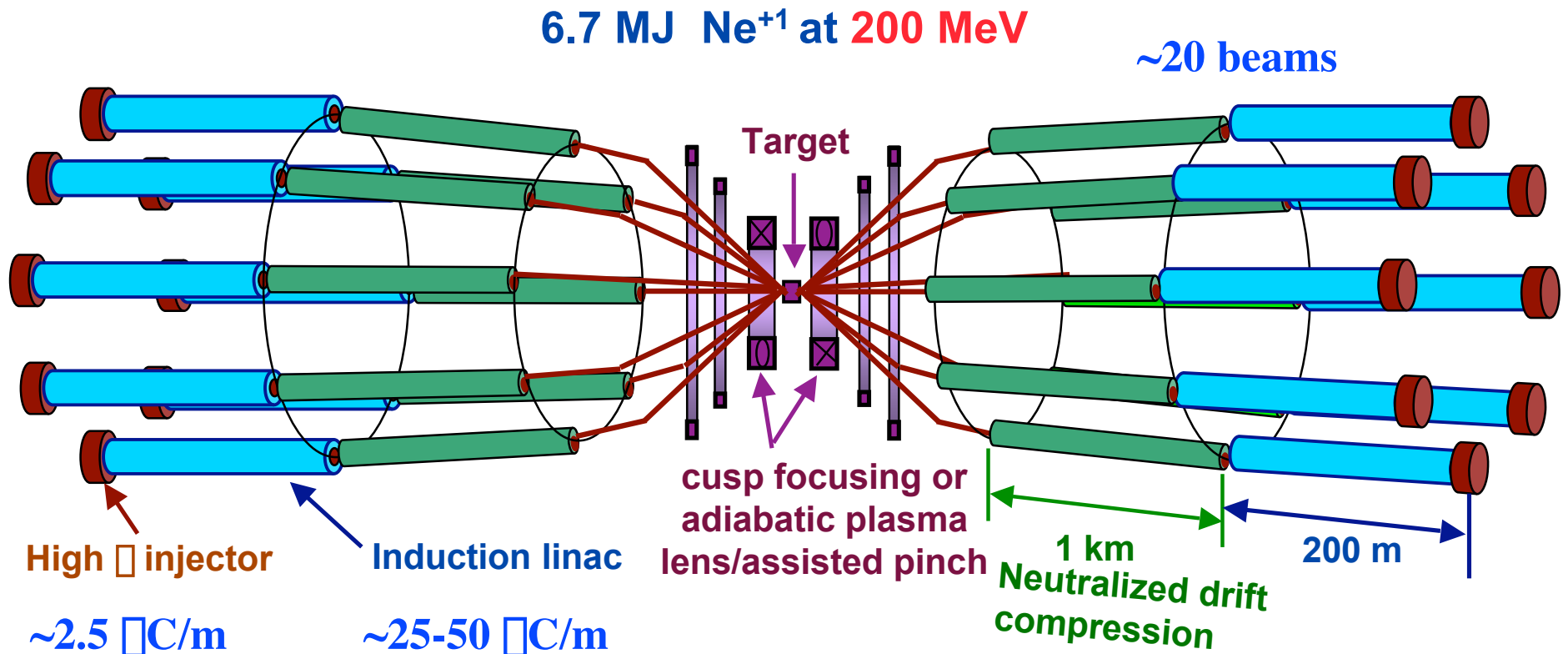
And maybe:

Effect of charging of FLiBe jets?

Multiple beam effect? (nothing suspected)

**It's a short list!**

# A new solenoid-focused modular driver concept has been suggested-- with its own issues ...







# HEDP/Modular Solenoid Drivers have a new set of injector issues

Line charge densities ~ **50 nC/m** desirable in the accelerator.

## Decel + Load-and-Fire

Decel – compression x ~**10**

Compression in accelerator x ~**10-30**

## Issues:

focusing / control-- decelerating beam  
time-dependent parameters

emittance growth

transition to accelerator



# And many accelerator & final transport issues

**Transport** (Line charge density ~ 100x quad driver  
final perveance ~ 1500x quad driver value)

- electron effects
- departures from Brillouin flow
- beam breakup, longitudinal instability
- transitions
- sensitivity to errors, mismatch
- $\rho_{\perp}$  buildup



See talk by Ed Lee

**Drift compression** (must be long & neutralized)

- instabilities
- bending neutralized beams
- stripping

See talk by Dale Welch

**Final focus** (plasma lens, assisted pinch, solenoid, etc.)

neutralized, with extreme perveance, tilt, maybe large  $\rho_{\perp}$





## Conclusions

- **Lots of progress has been made in the past 3 years, all aimed at high priority issues**
- The possible feasibility issues for the multibeam standard driver are **long-length-scale emittance growth, drift compression, and electron/gas effects** on the beam.
- The next step : **~ 30 m lattice (~50 lattice periods)** for transport & drift compression expts, then an **IBX**, a **longer 1-beam expt (?)**, then a multibeam **IRE**
- The investigation of the modular solenoid driver has just begun. This has lots of interesting, challenging physics. Ideas for a **high-current injector, neutralized drift compression, and new final focus methods** will be tested.





# Acknowledgements

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