Scientific Issues in Future Induction Linac Accelerators for Heavy Ion Fusion

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In 2001 a national HIF workshop identified issues …

APPENDIX B

COMPILED LIST OF HEAVY ION FUSION SCIENCE AND ENGINEERING ISSUES

Source

Injector

Accelerator Dynamics

Steering

Matching Sections

Mismatch

(Mostly) Transverse Dynamics

(Mostly) Longitudinal Dynamics

3D Dynamics, or both transverse and longitudinal

Splitting and Combining

Other/Overall

Diagnostics

Accelerator Technology

Drift Compression

Final Focus

Alternate Focusing Methods (Self-Pinch, Assisted Pinch (Channel Transport), Minifocus)

Self-Pinch

Assisted Pinch (Channel Transport)

Minifocus

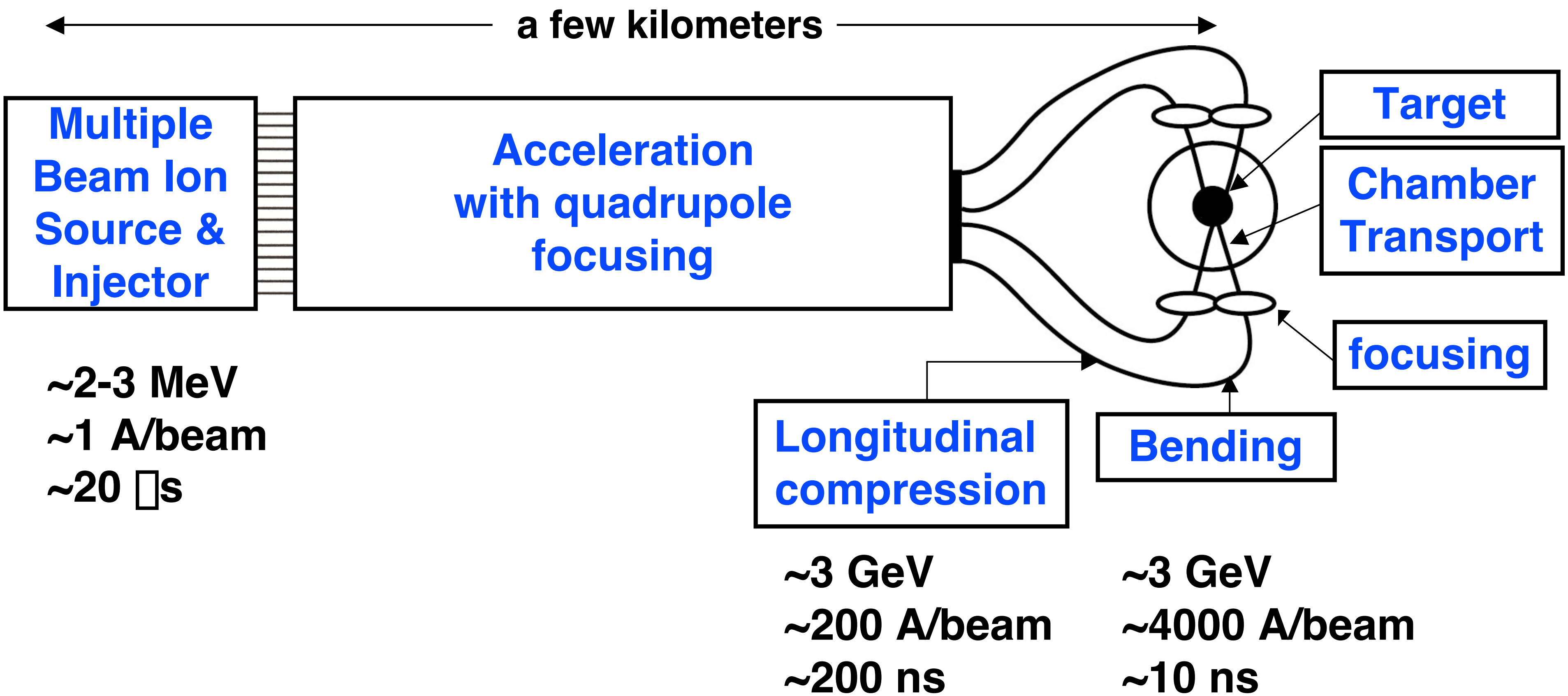
Chamber Dynamics

Beam Physics

Chamber design, safety, reliability

Target Physics

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?

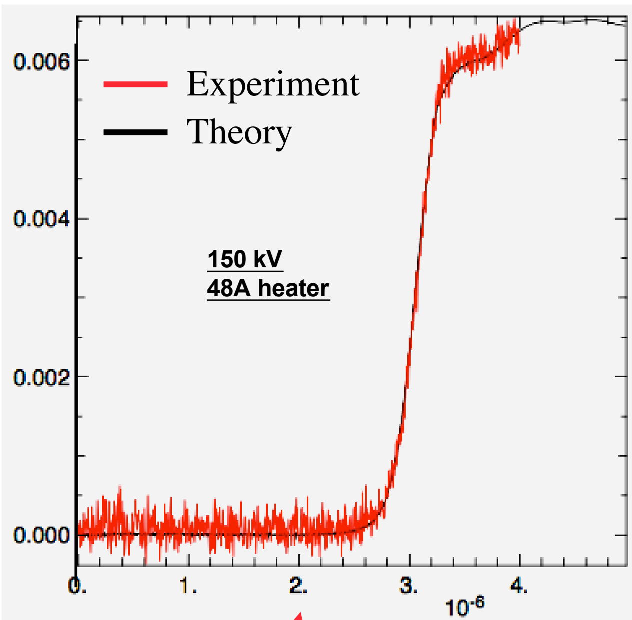
  Experiment imminent

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

STS-500 is also investigating large-aperture diode dynamics

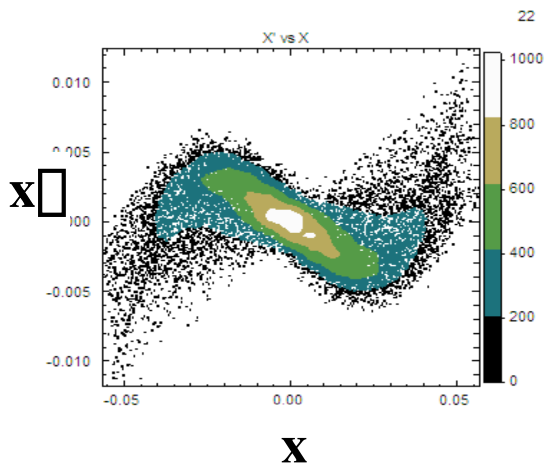
Risetime

Current at Faraday cup

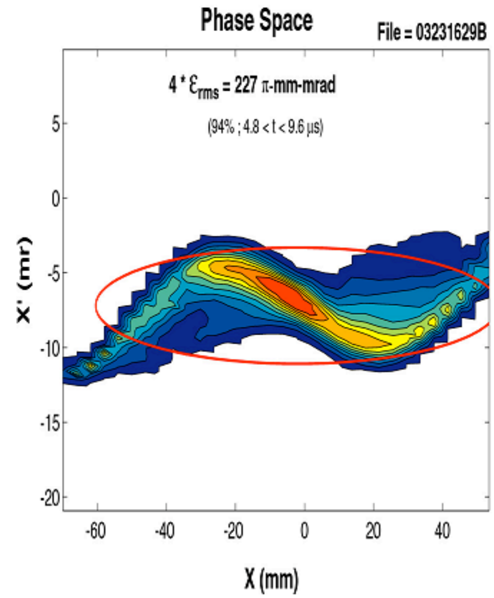


Phase Space at End of Diode

Warp simulations



Experimental results



10-cm-diameter K^+
Alumino-silicate source

r-z time-dependent PIC

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

~50% impact on driver cost

HCX & NTX

Dynamic aperture issues

steering
mismatch
electrons & gas (halo)
nonlinear fields

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 ~ 1-2
K = perveance ~ 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

~30 m (~ 50 lattice periods)

Note: length scale for <u>instability growth</u> ~ 100's of lp's

Many transverse phenomena also require tens of meters of lattice

50 lattice periods, with σ_0=72° 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)

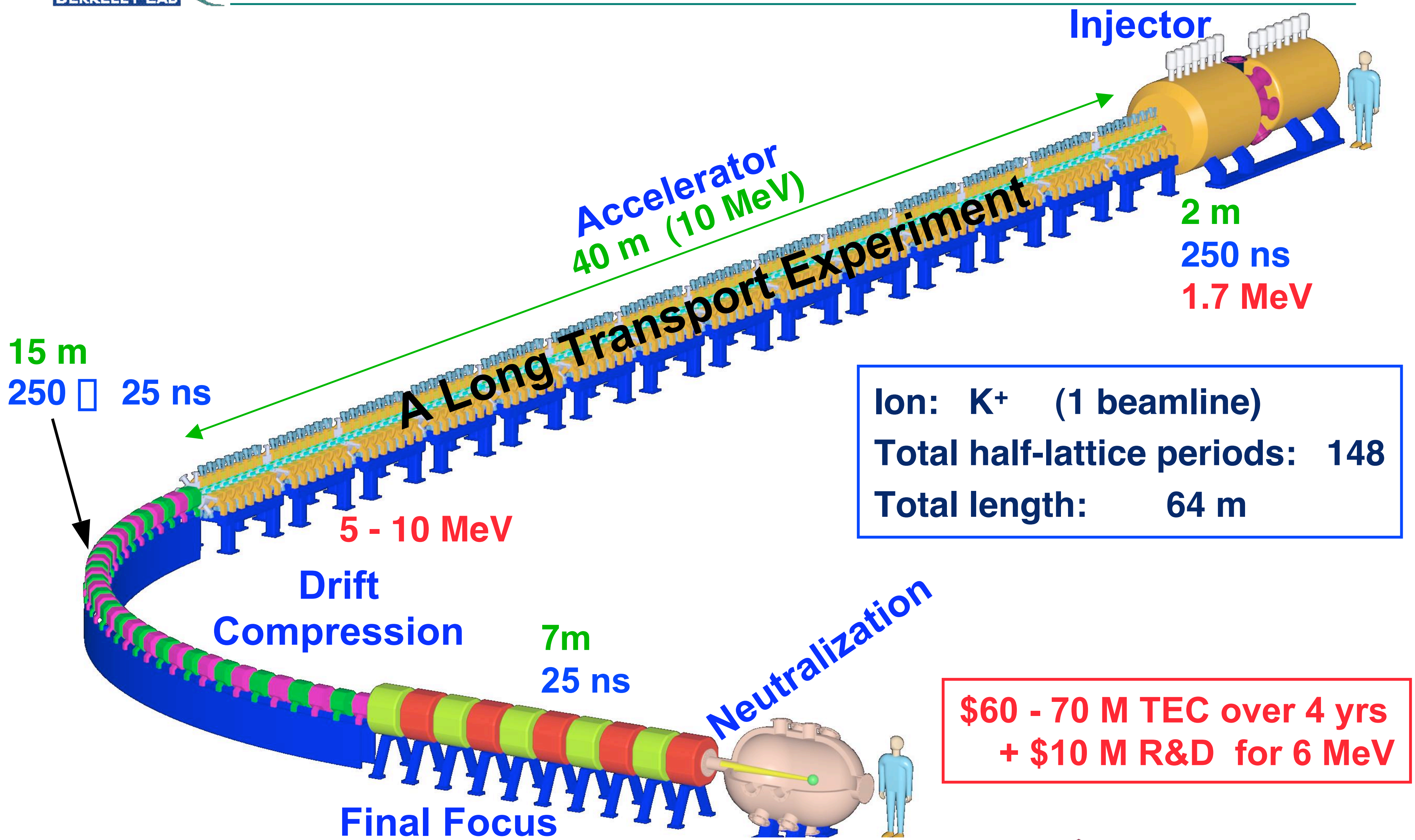
- Electron and gas production coefficients
- Electron orbits in magnets & acceleration gaps
- Steering
- Short longitudinal wave dynamics experiments
- Short dynamic aperture experiments

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

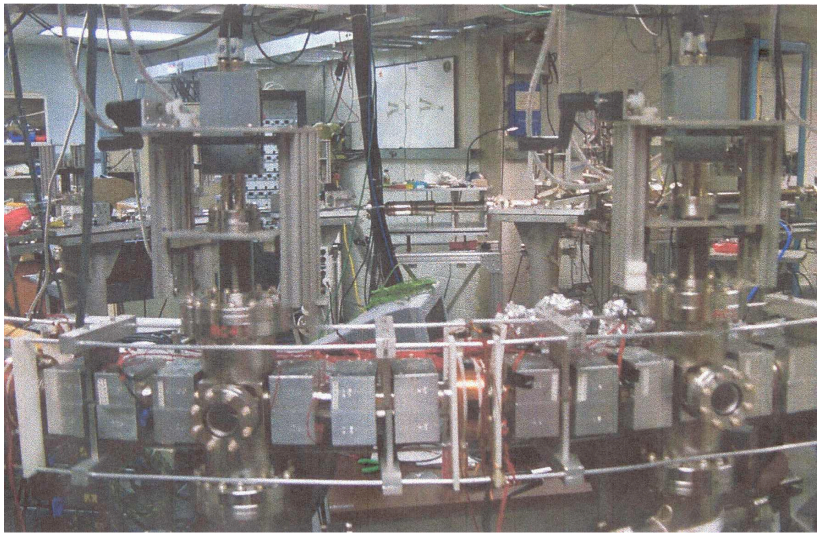
- Dynamic aperture
- Effect of electrons on ion transport
- Mismatch producing halo & halo scraping
- Longitudinal wave propagation

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



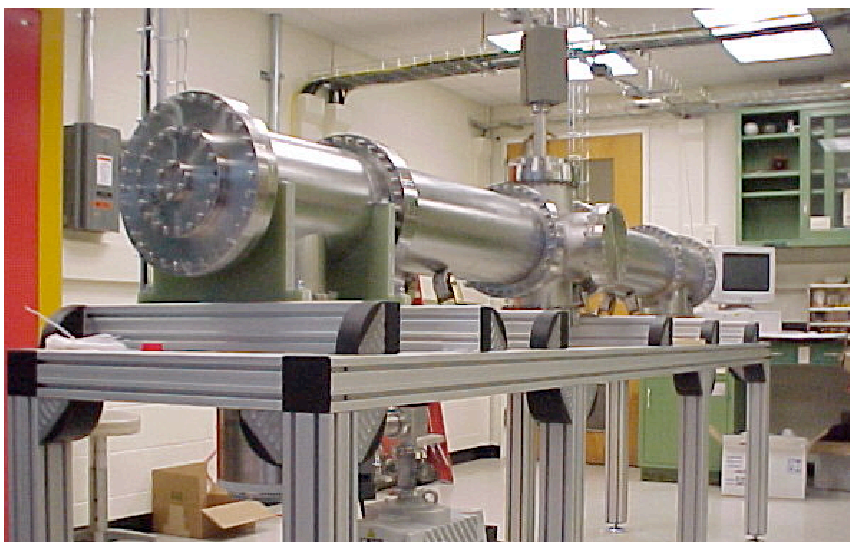
University of Maryland Electron Ring

10 keV

100 mA, $\square/\square_0 > 0.12$

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

Inductive Effects require high energy + multiple beams

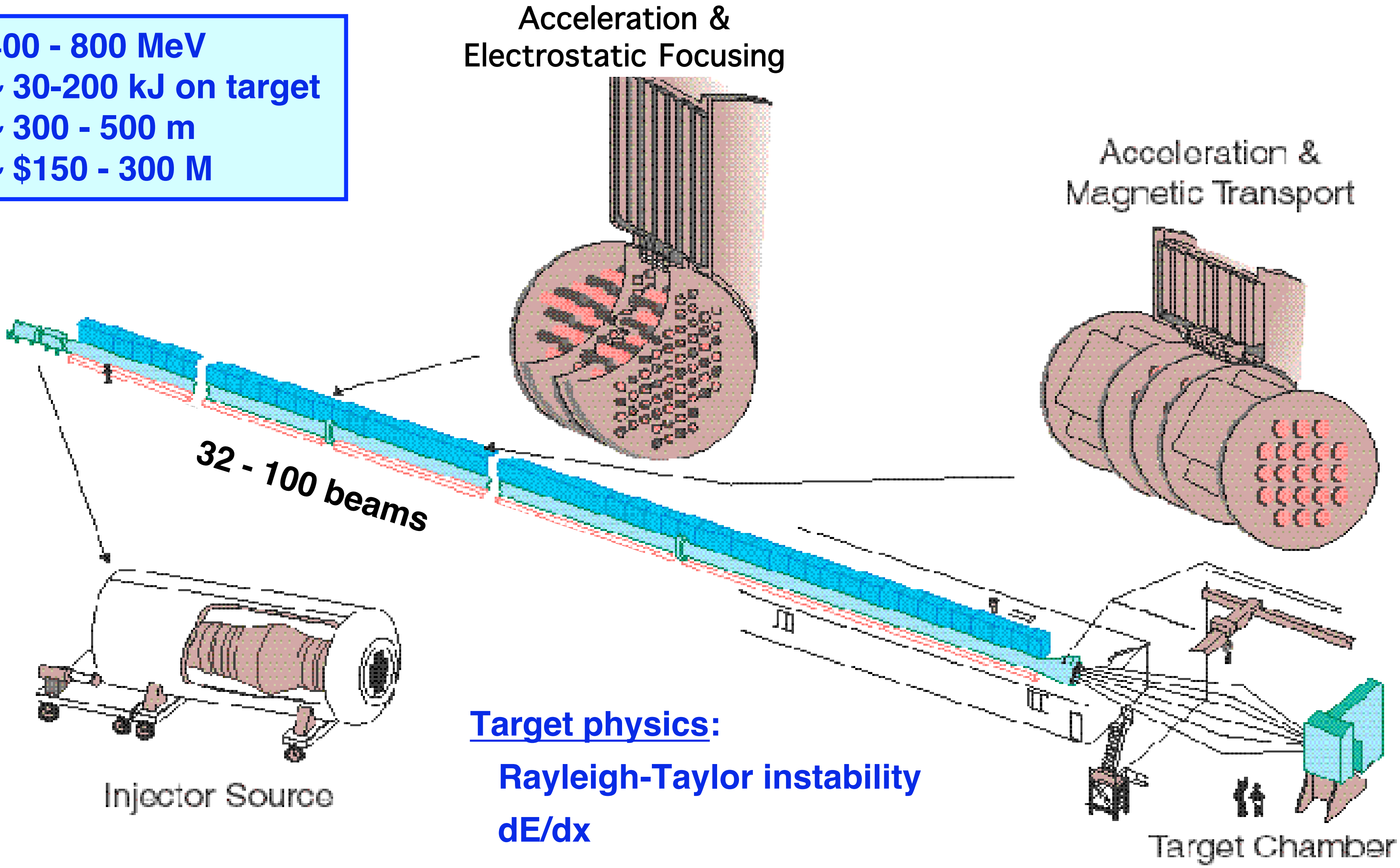
$N\beta^2 \sim 0.1$ for 10 beams of K^+ $\Rightarrow$ **190 MeV**

120 beams of Bi^+ $\Rightarrow$ **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



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

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 (|| and ⊥)
- 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

(chamber transport; alternatives) } **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:

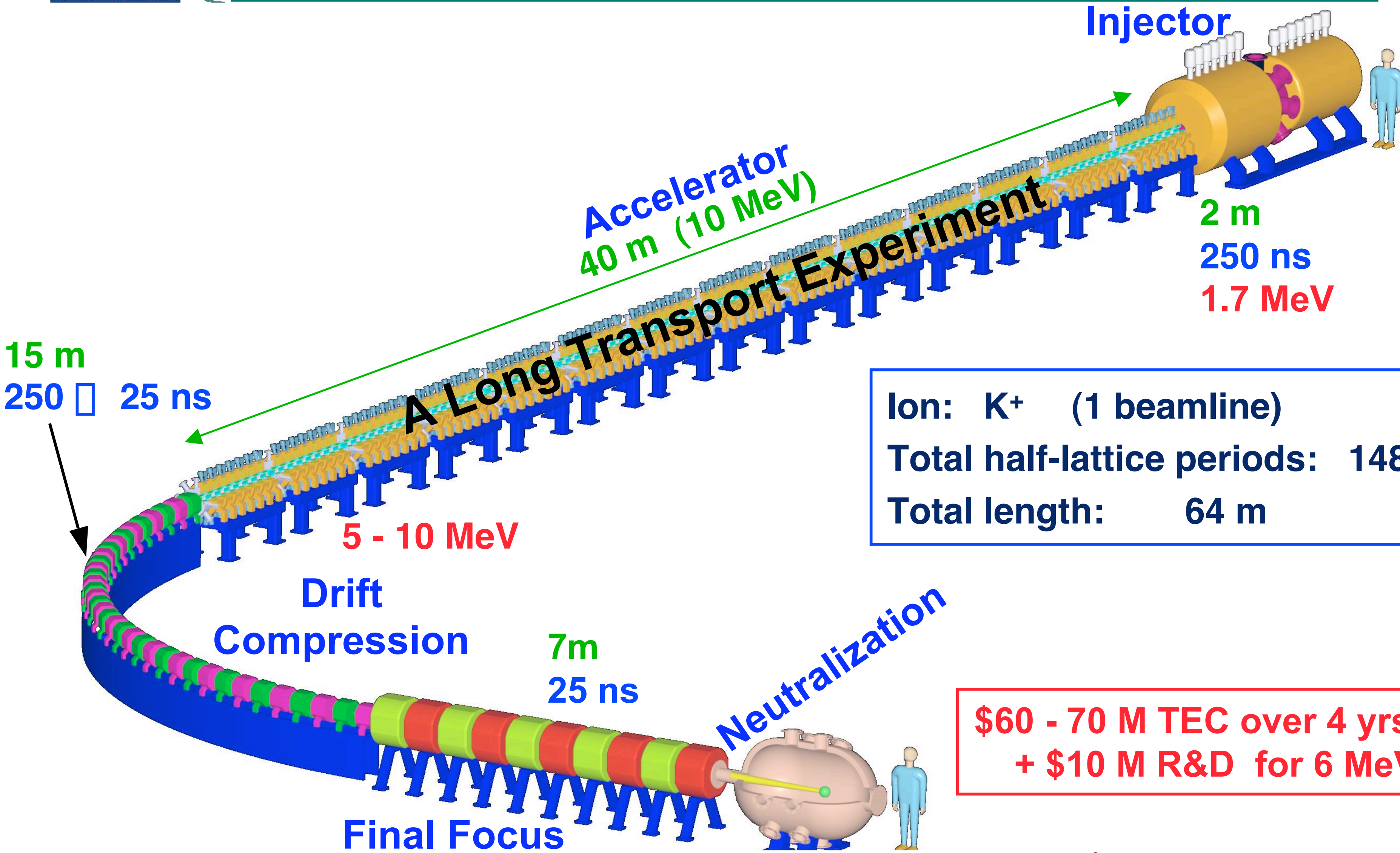
For C >> 1,

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

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!)



Ion: K+ (1 beamline)
Total half-lattice periods: 148
Total length: 64 m

$60 - 70 M TEC over 4 yrs
+ $10 M R&D for 6 MeV

What are the concept feasibility issues?

These can stop the beam or prevent focusing on target:

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

(Drift compression and Effect of electrons on beam: **Long Transport Expt**)

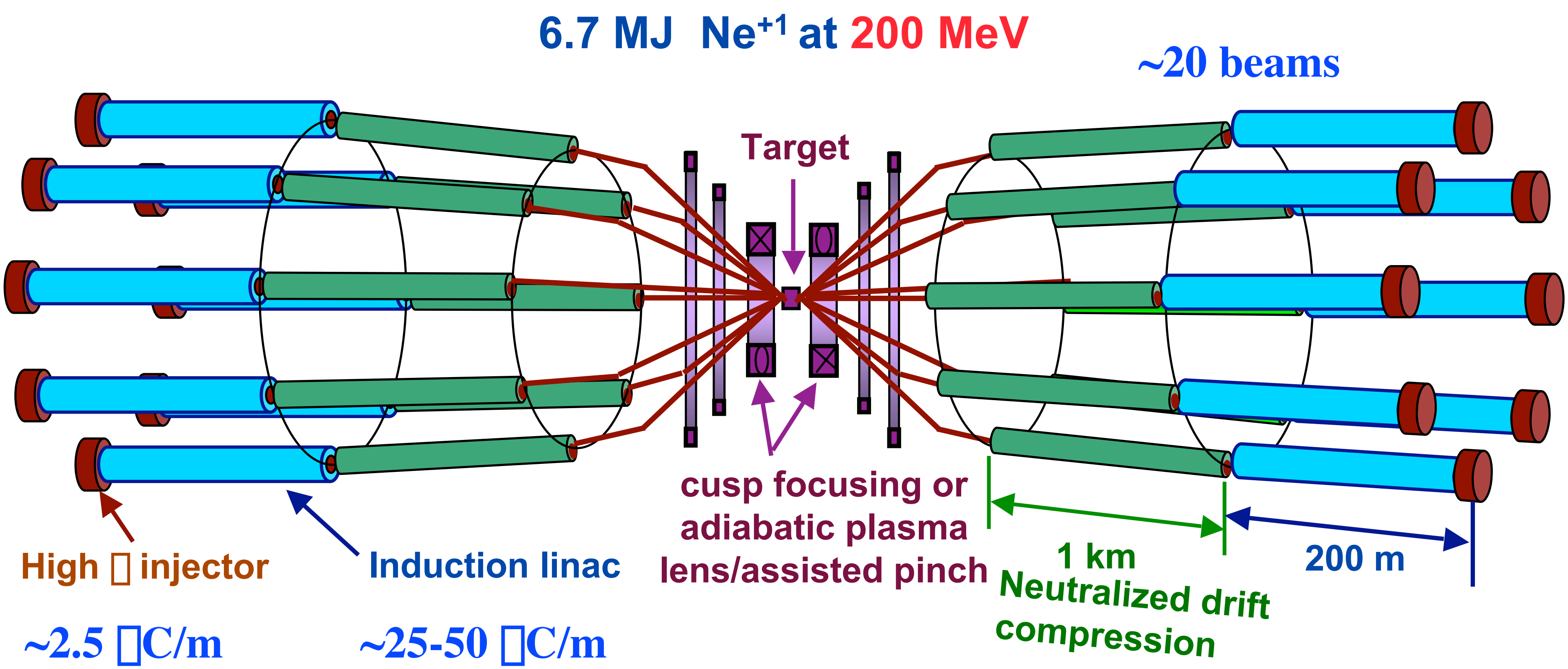
And maybe:

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 μC/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
$p_{\square}$ 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 $\square_l$

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.

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