Heavy Ion Driver Systems Modeling

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ARIES IFE Meeting
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PPPL

We have developed and continue to update / improve a heavy ion driver systems model

- Model is quite detailed and rather lengthy (>120 pages of Mathcad)
- Currently working on several improvements
  - Transverse and longitudinal emittance growth
  - Improved injector and quad models
  - Improved final focus and drift compression models
- Would not recommend that ARIES attempt to replicate
- Aries should focus on ways to improve cost basis and normalization to other MFE/IFE costing
  - Unit costs for materials (superconductor, steel, aluminum, etc.)
  - Costs for energy storage, pulsed power, cyro systems
  - Fabrication and assemble cost factors
  - Apply Boeing's manufacturing cost-reduction techniques developed for ARIES
- Use driver systems code output as input to power plant systems model that will include target gain scaling, chamber models, power conversion, conventional plant systems, etc.

Previously presented as:

A 3.3 MJ, Rb^{+1} Driver Design Based on an Integrated Systems Analysis

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Heavy Ion Fusion
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Conclusions

- The primary goal of our driver systems analyses is to find research areas with high payoff (e.g., target improvements, high acceleration gradients, core performance and cost, etc.)

- In this work, an integrated systems model has been used to investigate a driver design for HIF based on the closed-couple target design

- All magnetic transport is used with a maximun acceleration gradient of 2 MV/m giving a total accelerator length less than 1 km

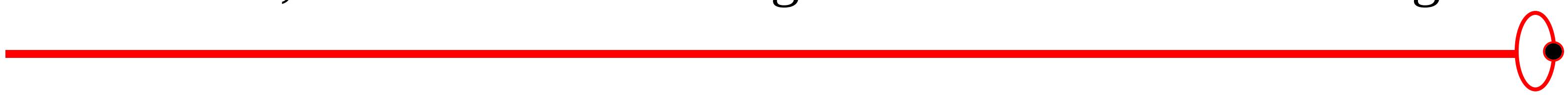
- This 3.3 MJ, Rb^+ driver has estimated direct capital cost of ~$0.7 B assuming success in component cost reduction R&D

- Better models are needed for emittance growth in the accelerator and for the beam transport through the chamber – both important for determining if the spot size requirement can be met

Recent driver designs are much shorter than past designs

Early designs:

10 GeV Pb^+, 1 MV/m maximum gradient → ~10 km length

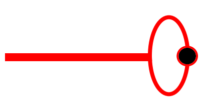


Heidelberg HIF Symposium:

4 GeV Pb^+, 1 MV/m maximum gradient → ~ 4 km length

Most recent design:

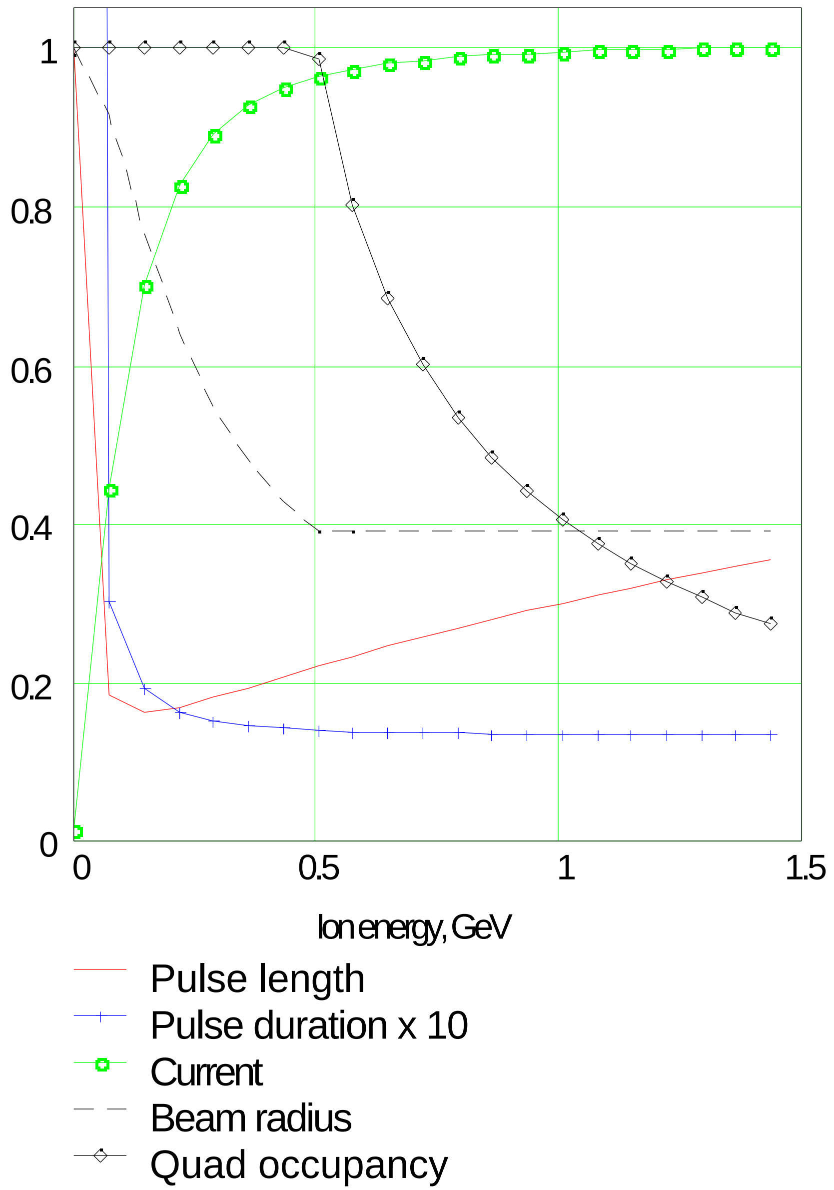
1.4 GeV Rb^+, 2 MV/m maximum gradient → ~1 km length



Key design parameters for reference case

Number of beams (Foot / Main / Total)	36 / 124 / 160
Initial pulse duration	15 μs
End radial compression of beam	500 MeV
Accelerator quadrupole field at winding	3.5 T
Final focus length	5.5 m
Beam focus half angle	6 mrad

Beam parameter variations vs. ion energy



Initial values:
Pulse length = 32 m
Pulse duration = 15 μs
Avg. beam radius = 2.0 cm
Quad occupancy = 75%

Current is fraction of final current = 78 A per beam

- Pulse length decreases due to ion acceleration and bunch compression.

- Pulse duration reaches a minimum of 200 ns.

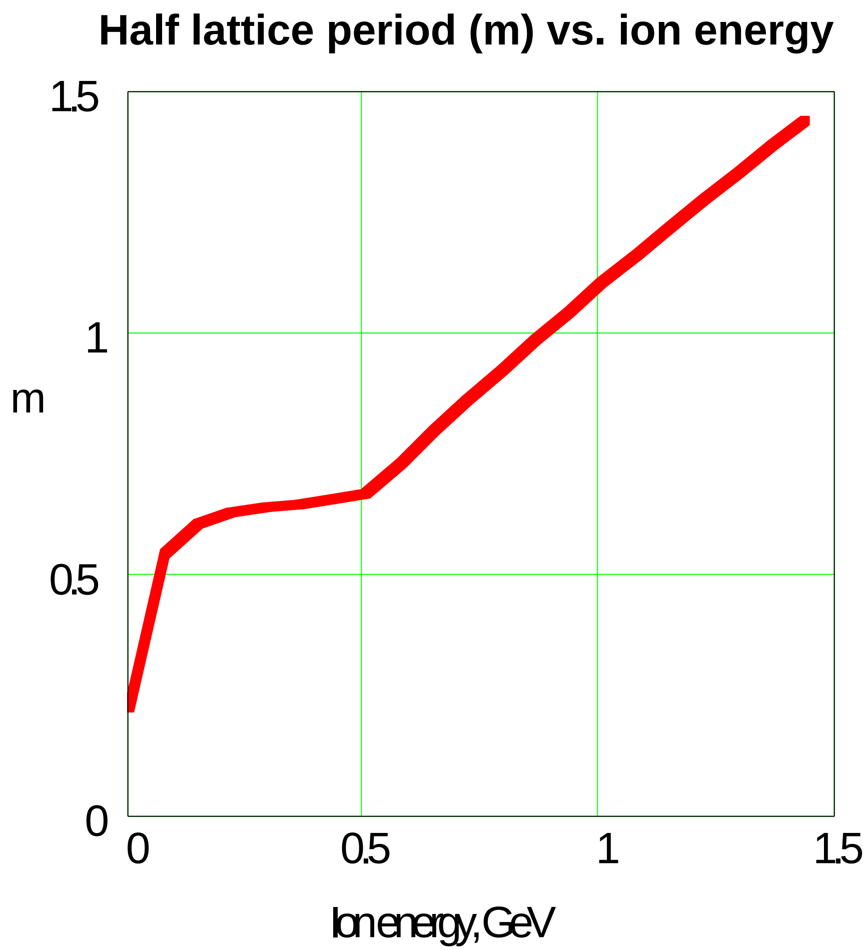
- Beam radius is reduced from 2.0 to 0.8 cm, then held fixed.

- Once beam radius is fixed, quad occupancy drops from 75% to ~ 20%.

Key parameters along accelerator

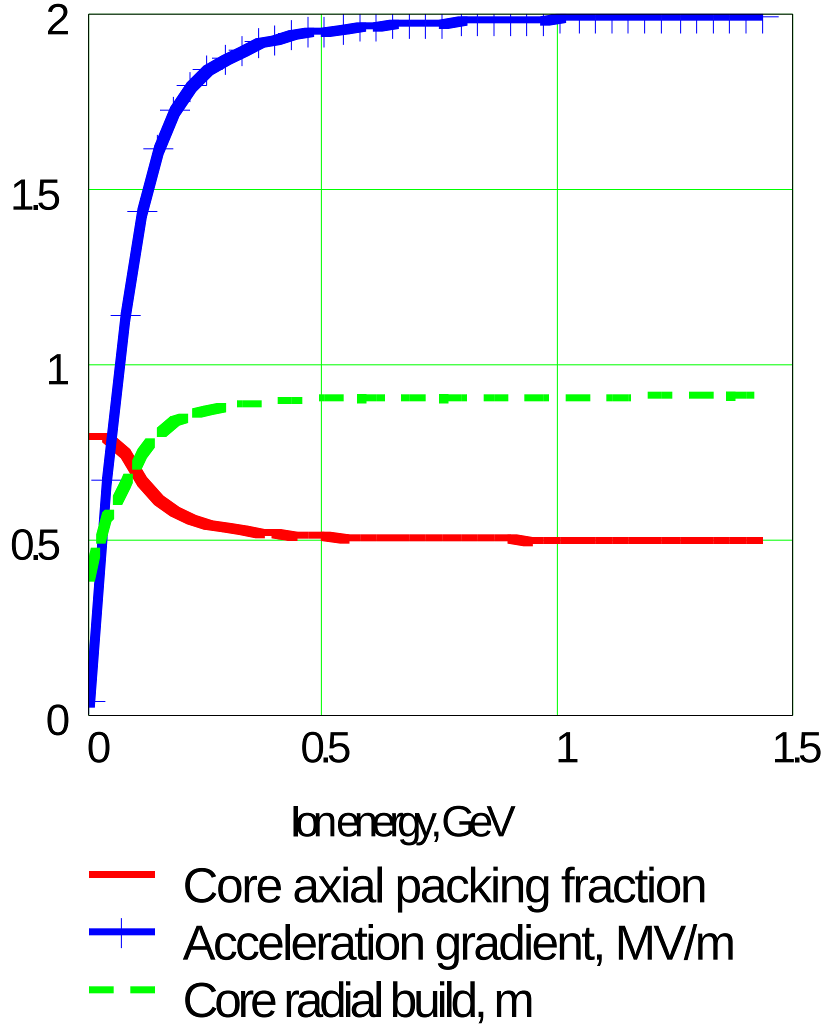
	Injector Exit	Foot Pulse 0.8 MJ	Main Pulse 2.5 MJ
Ion energy, GeV	0.002	0.90	1.44
Pulse duration, μs	15	0.20	0.20
Beta	0.007	0.15	0.19
Pulse length, m	32.0	9.1	11.3
Beam current, A	1.0	77	78
Beam radius (avg.), cm	1.96	0.77	0.77
Bore radius, cm	3.66	1.73	1.73
Winding radius, cm	4.52	2.40	2.40
Field gradient, T/m	78	146	146
Core inner radius, m	1.02	0.57	0.51
Core build, m	0.40	0.91	0.91
Quad Occupancy, %	75	45	20.5
Half lattice period, m	0.23	1.02	1.45
Accelerator gradient, MV/m	0.038	2.0	2.0
Distance from injector, km	0	0.64	0.91

Half lattice period increases with increasing ion energy



The half lattice period increases from 0.23 m to 1.45 m over the length of the accelerator.

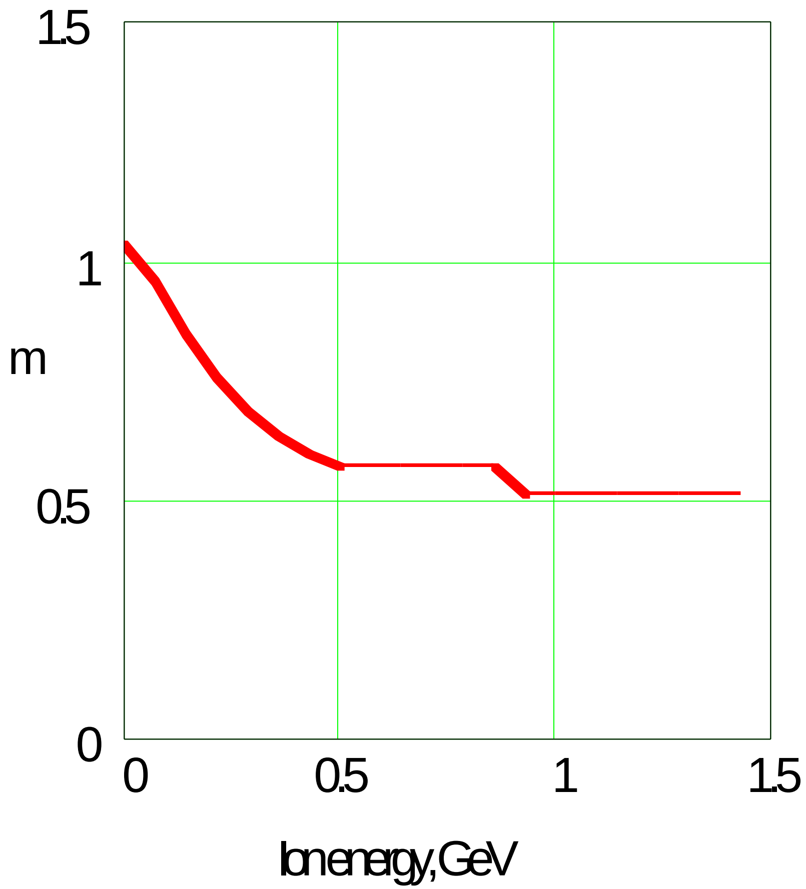
Core axial packing fraction, acceleration gradient, and core radial build vs. ion energy



As the acceleration gradient approaches the assumed 2 MV/m limit, the core axial packing fraction decreases to 50%, and the core radial build increases to ~ 0.9 m.

Core inner radius decreases with increasing ion energy

Core inner radius (m) vs. ion energy (GeV)

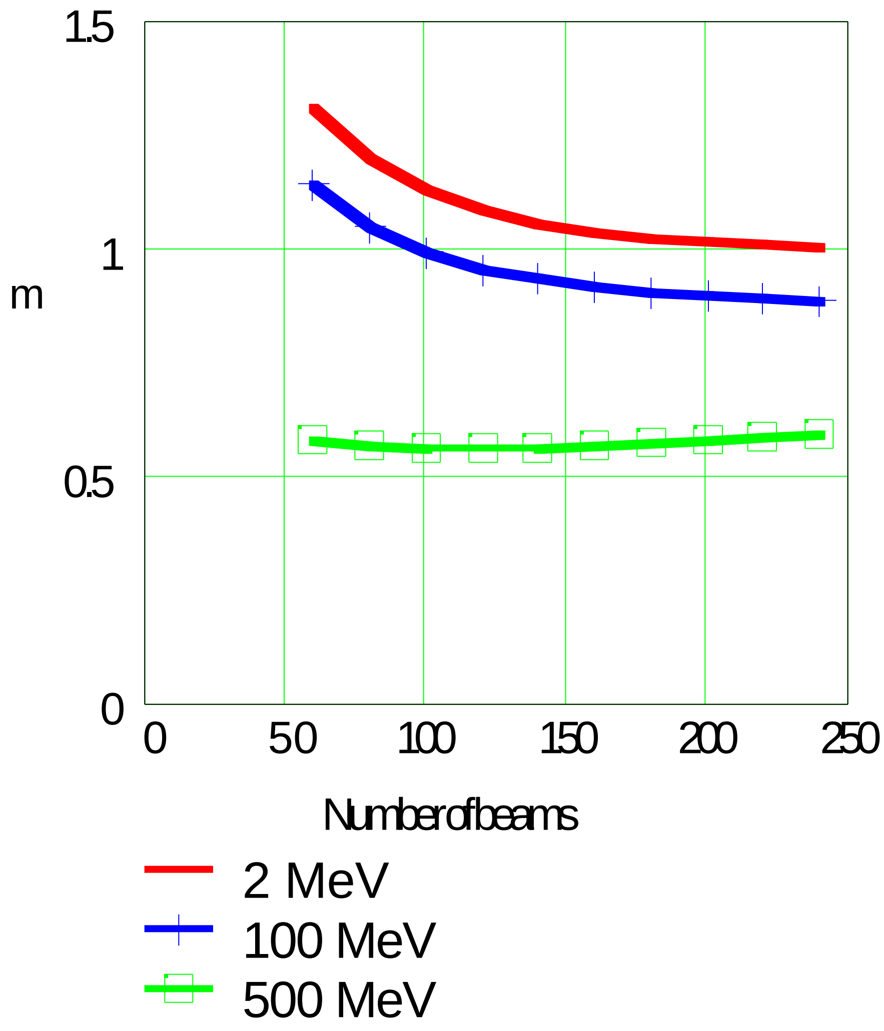


With 160 beams, the core inner radius ranges from ~1 m at 2 MeV to ~ 0.6 m at 0.5 GeV.

Beyond 0.9 GeV (the foot pulse energy), the core radius drops to ~ 0.5 m since only main pulse beams continue to be accelerated.

Core inner radius decreases with increasing number of beams, especially at the low energy end

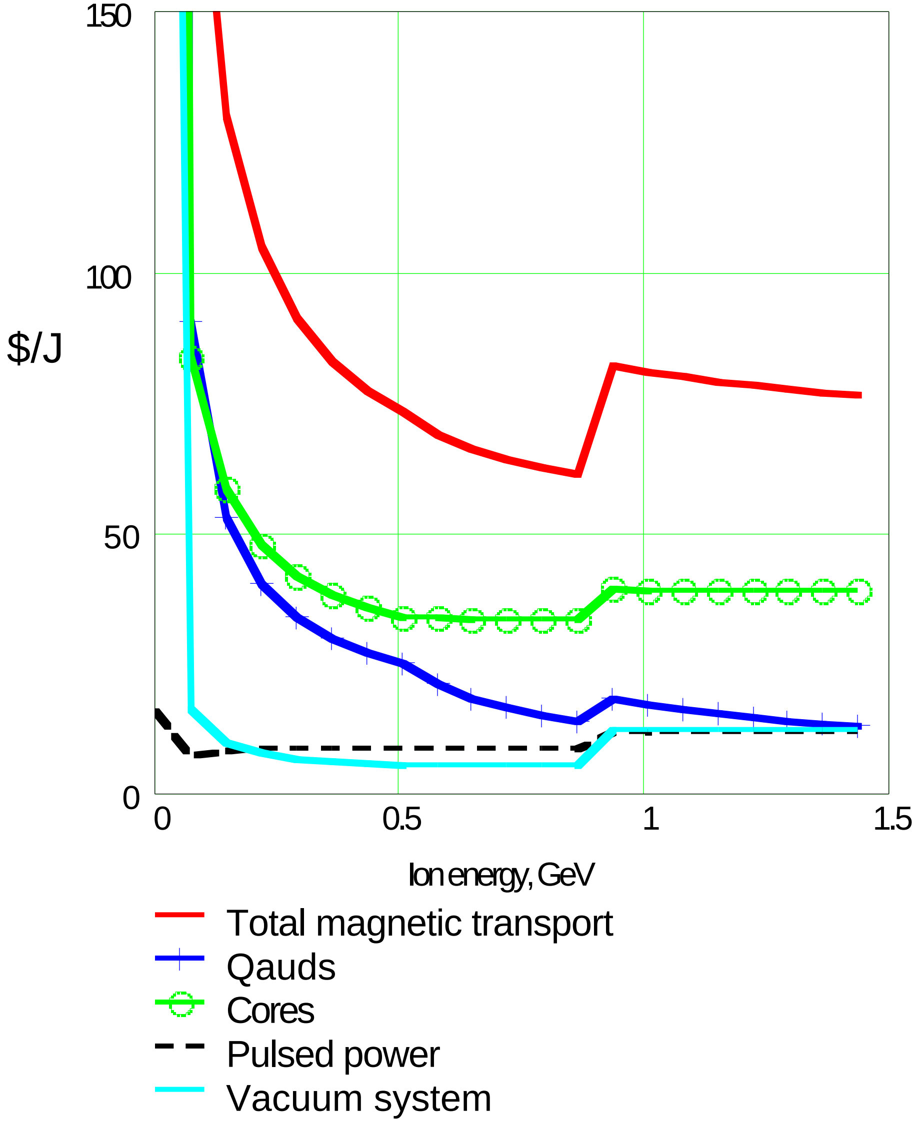
Inner radius of core (m) vs. number of beams



In terms of decreasing the core inner radius, there is little benefit to use more than ~ 100 beams.

Transport unit costs ($/J) decrease with increasing ion energy

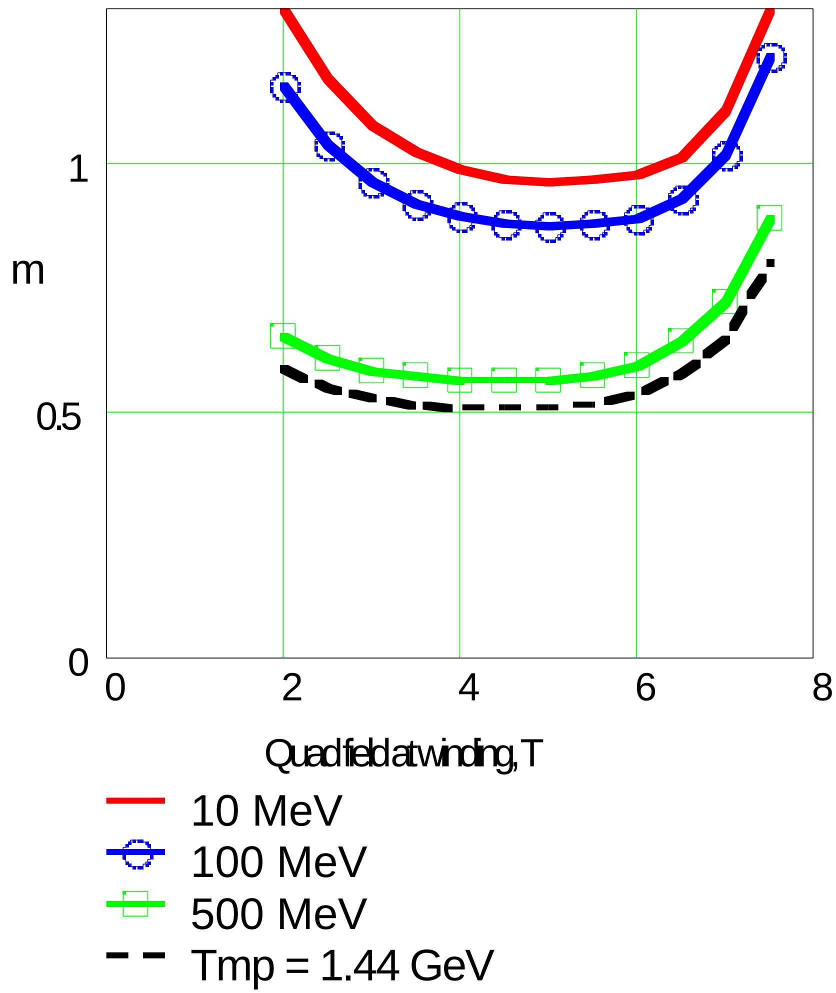
Cost per unit beam energy ($/J) vs. ion energy



The jump in $/J at 0.9 GeV is due to continued transport of foot pulse beams while only adding energy to main pulse beams.

Inner radius of core is minimized by using quad field of 4-5 T

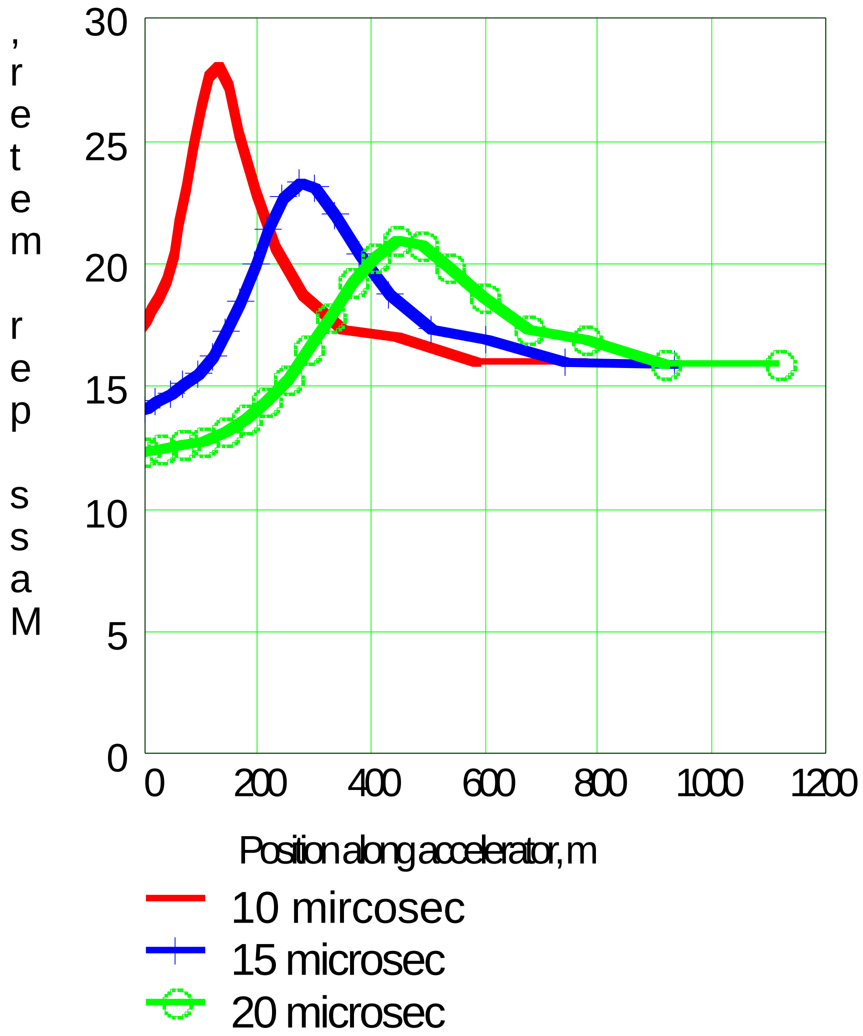
Inner radius of core (m) vs. quad field at winding (T)
(shown at different points along accelerator)



While core radius is minimized with B_q = 4 - 5 T, the driver cost is minimized using B_q of ~ 3 T (see cost sensitivity graph).

The peak core mass per meter (along accelerator) is higher for shorter initial pulse durations

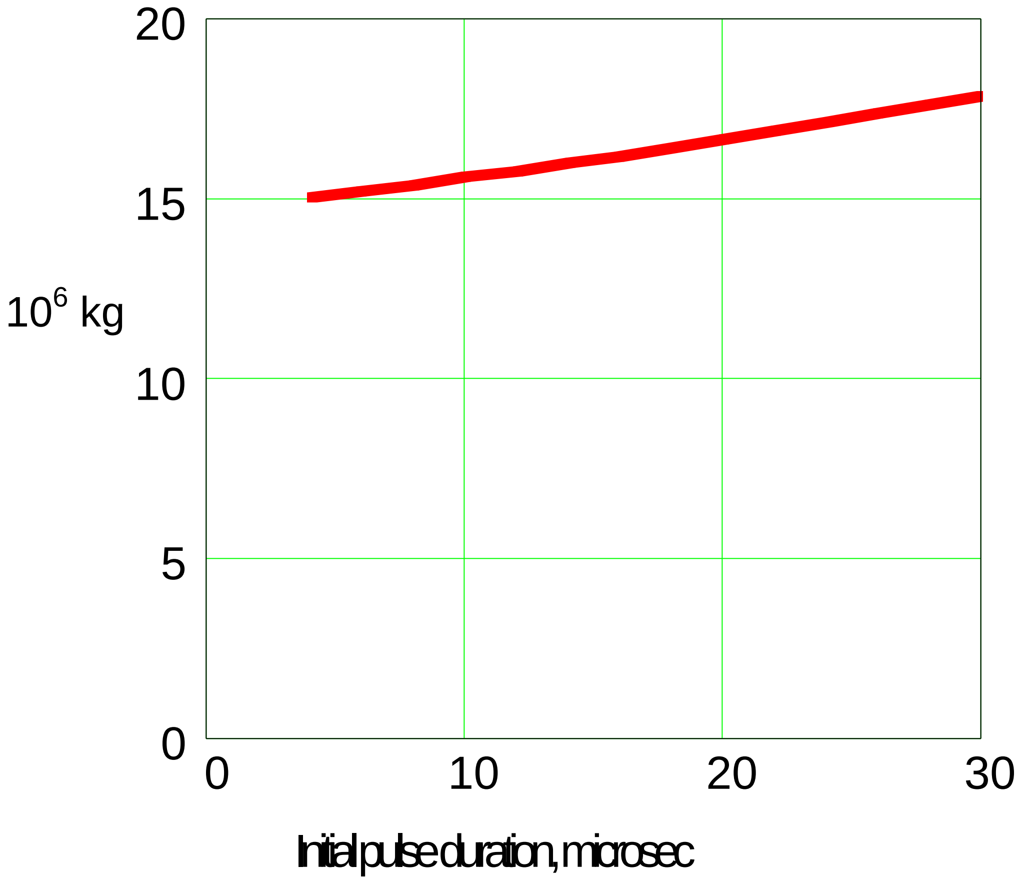
Core mass per unit length (kg/m) vs. position along accelerator



A shorter initial pulse duration, τ_o, gives a higher peak kg/m but also results in a shorter accelerator. This is because we limit the maximum velocity tilt, hence the initial acceleration gradient increases with decreasing τ_o.

The total mass of ferromagnetic material increases slightly with increasing initial pulse duration

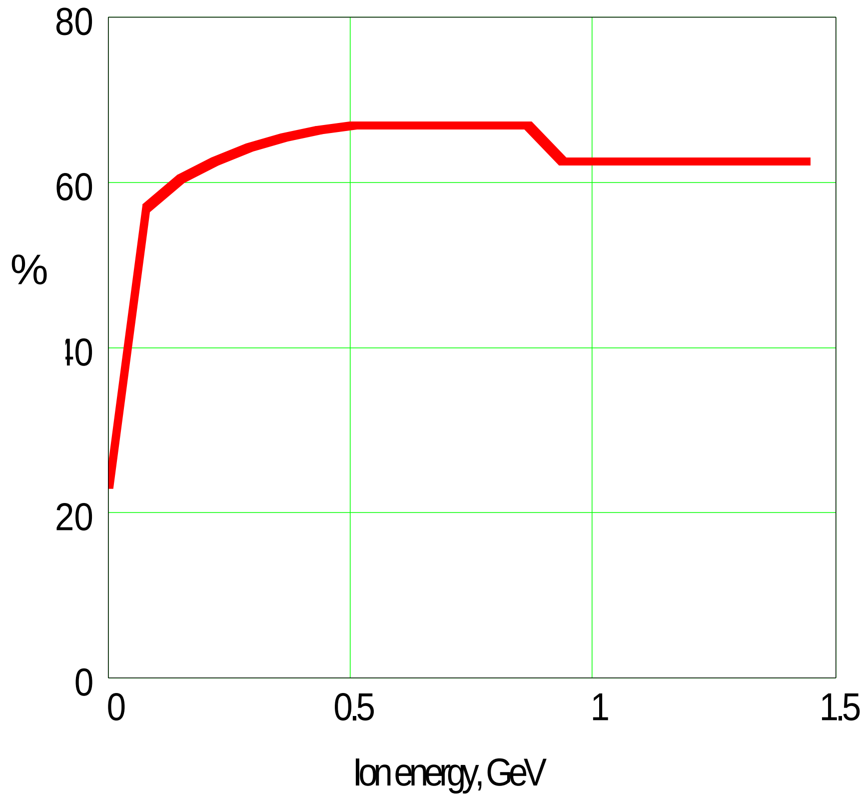
Mass of core material (10^6 kg) vs. initial pulse duration (μs)



The reference case design with τ_o = 15 μs, uses 1.6 x 10^7 kg of ferromagnetic material

Local core efficiency exceeds 60% for much of the accelerator

Core efficiency (%) vs. ion energy (GeV)



Assuming a pulsed power system efficiency of 75%, an auxiliary power load of 5 MWe (primarily for cryo-cooling), and 5 Hz operation gives:

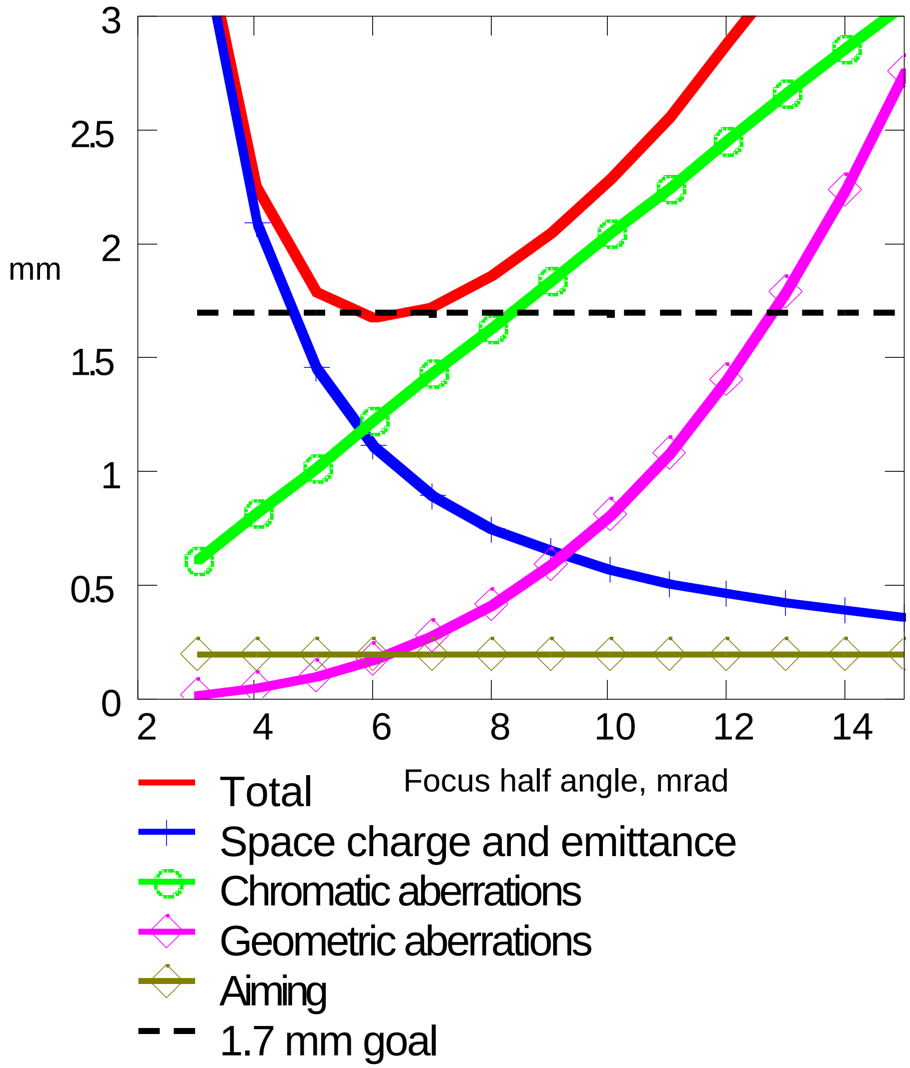
Driver efficiency = 42%

Parameters at final focus magnet

	Foot Pulse	Main Pulse
Pulse duration, ns	30	8
Pulse length, m	1.35	0.45
Beam current, kA	0.52	1.95
Beam radius, cm	3.3	3.3
Bore radius, cm	5.9	5.9
Norm. emittance, mm-mrad	1.0	1.0
Focus half-angle, mrad	6	6

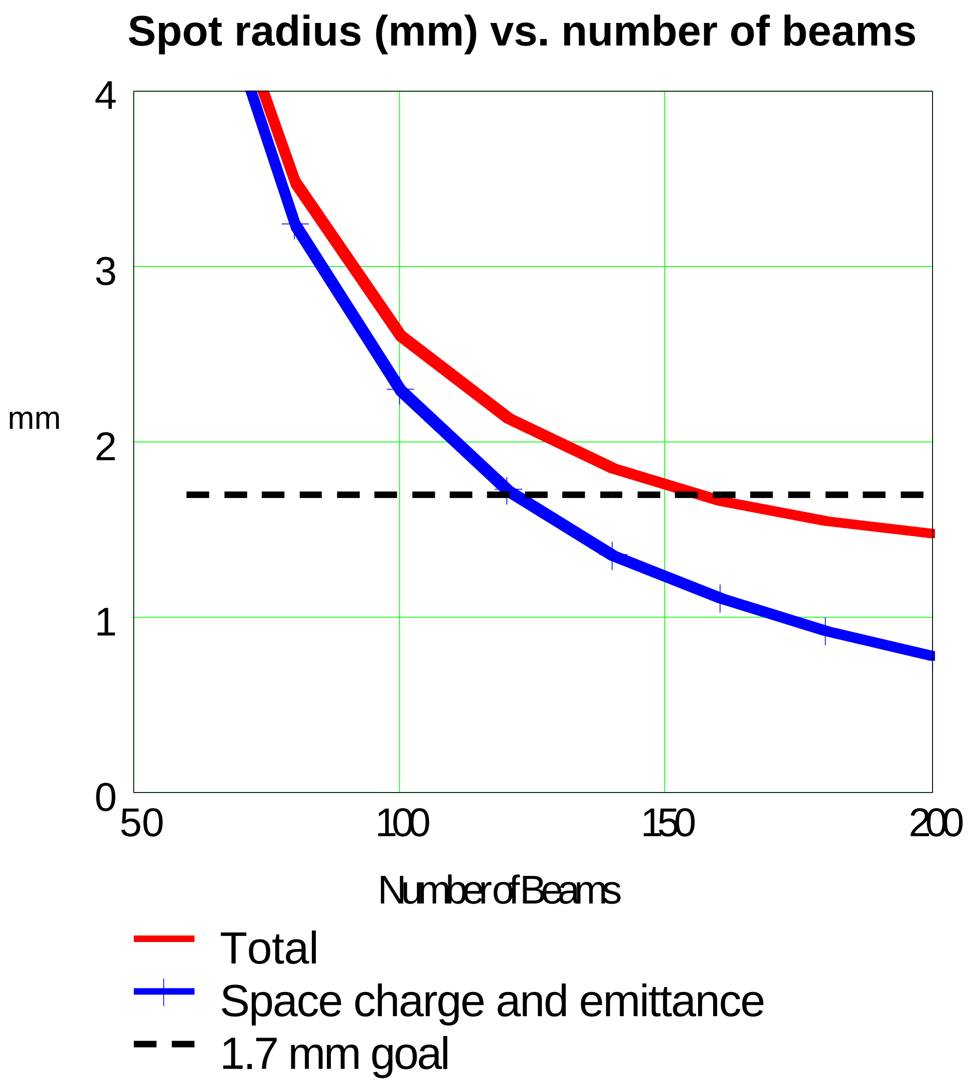
Total spot size on target varies with the focus half angle of the beam

Spot radius (mm) vs. focus half angle (mrad)



Rb^+ (A = 85 amu)
Final focus length = 5.5 m
99% space charge neutralized
Normalize emittance = 1 mm-mrad
$\Delta V/V = 10^{-3}$ initially, 4.6x growth

A minimum of about 160 beams is needed to meet the spot size requirement

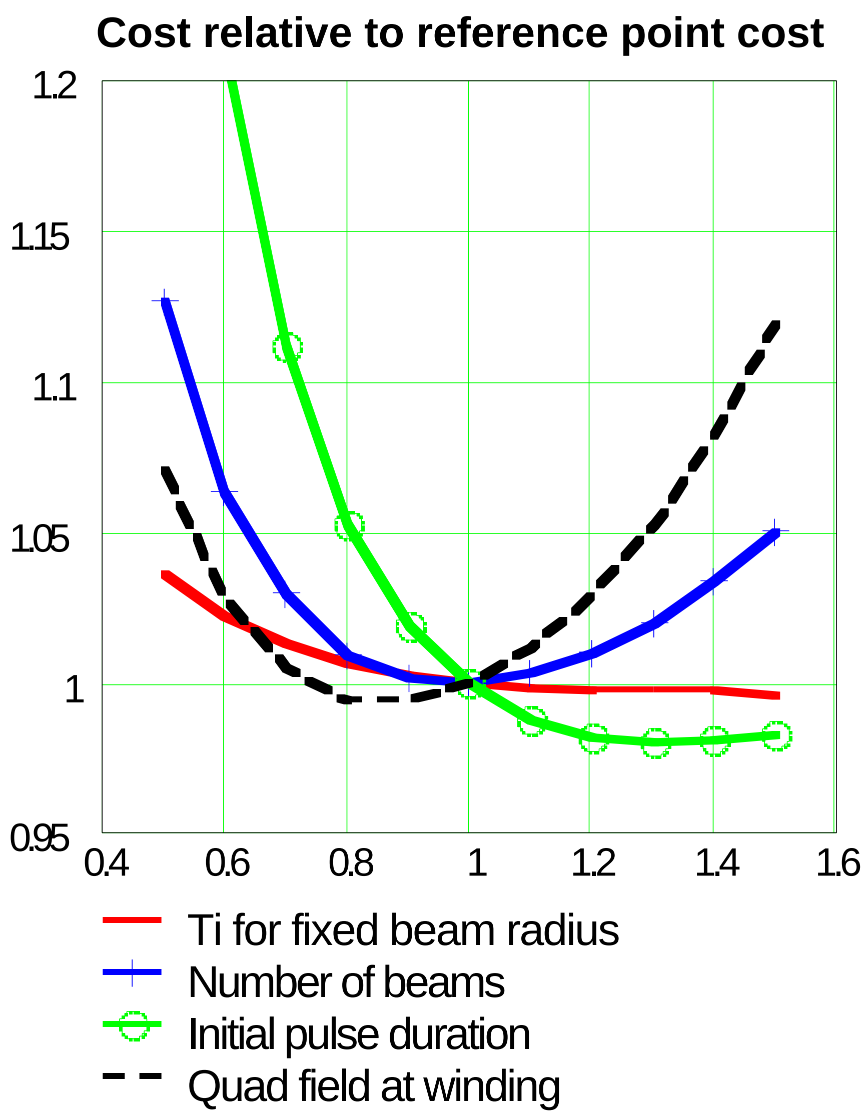


Combined space charge and emittance contribution is compared to total.

The estimated direct capital cost is ~ $0.7 B

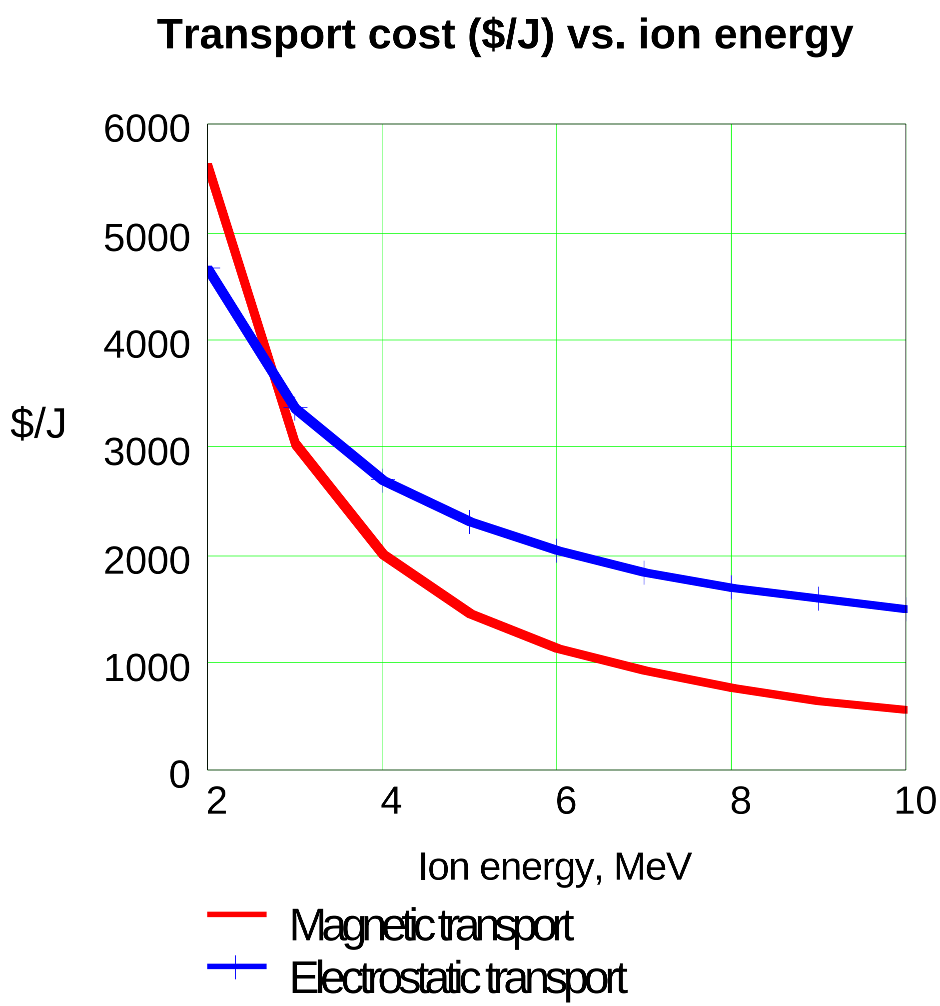
Subsystem	Direct Cost, $M		
1. Injector			**47**
2. Magnetic Focus Section			**363**
2.1 Quad Transport		137	
Magnets	*70*		
Cyrostats	*32*		
Refrigeration	*36*		
2.2 Accelerator Modules		157	
Metglas	*81*		
Structures	*49*		
Insulators	*27*		
2.3 Accel. Power Supplies		32	
Pulsers (switches)	*17*		
Storage and PFN	*15*		
2.4 Vacuum systems		37	
3. Final Transport			**65**
3.1 Quad magnetic		6	
3.2 Dipole Magnetic		17	
3.3 Cryostat		12	
3.4 Refrigeration		17	
3.5 Vacuum System		14	
4. Final Focus Magnets			**2**
Driver Equipment Subtotal			**477**
Allowance for I&C			**57**
Allowance for Installation			**160**
Total Direct Cost			**694**

Driver cost varies by less than 10% for design point variations of 30% or more



Reference case:
T for fixed beam radius = 500 MeV
Number of beams = 160
Initial pulse duration = 15 μs
Quad field at winding = 3.5 T
Direct cost = $0.7 B

Electrostatic transport would be less expense up to an ion energy of ~ 3 MeV



Because of the small benefit, the reference case design uses all magnetic transport.

Conclusions

- The primary goal of our driver systems analyses is to find research areas with high payoff (e.g., target improvements, high acceleration gradients, core performance and cost, etc.)

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