Self Pinch Transport Design Considerations

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Transport for several chamber concepts currently being studied

ARIES-IFE Study of HIF

Transport Mode / Chamber Concept	Ballistic Transport *chamber holes ~ 5 cm radius* *most studied*		Pinch Transport *chamber holes ~ 0.5 cm radius* *higher risk, higher payoff*	
	Vacuum-ballistic ***vacuum***	**Neutralized-ballistic** ***plasma generators***	**Preformed channel ("assisted pinch")** ***laser + z-discharge***	**Self-pinched** ***only gas***
Dry-wall ***~6 meters to wall***	**Not considered now: Requires ~500 or more beams**	**Not considered: insufficient neutralization for 6 meters**	**Option: uses 1-10 Torr** ***2 beams***	**Option: uses 1-100 mTorr** **~2-100 beams**
Wetted-wall ***~ 4-5 meters to wall***	HIBALL (1981) **Not considered: Needs ≤ 0.1 mTorr leads to □**	OSIRIS-HIB (1992) **Possible option: but tighter constraints on vacuum and beam emittance**	**Option: uses 1-10 Torr** ***2 beams***	PROMETHEUS-H (1992) **Option: uses 1-100 mTorr** **~2-100 beams**
Thick-liquid wall ***~ 3 meters to wall***	**Not considered: Needs ≤ 0.1 mTorr leads to □**	HYLIFE II (1992-now) **Main-line approach: uses pre-formed plasma and 1 mTorr for 3 meters** ***~50-200 beams***	**Option: uses 1-10 Torr** ***2 beams***	**Option: uses 1-100 mTorr** **~2-100 beams**

LSP code* used for simulation of self-pinched ion beams

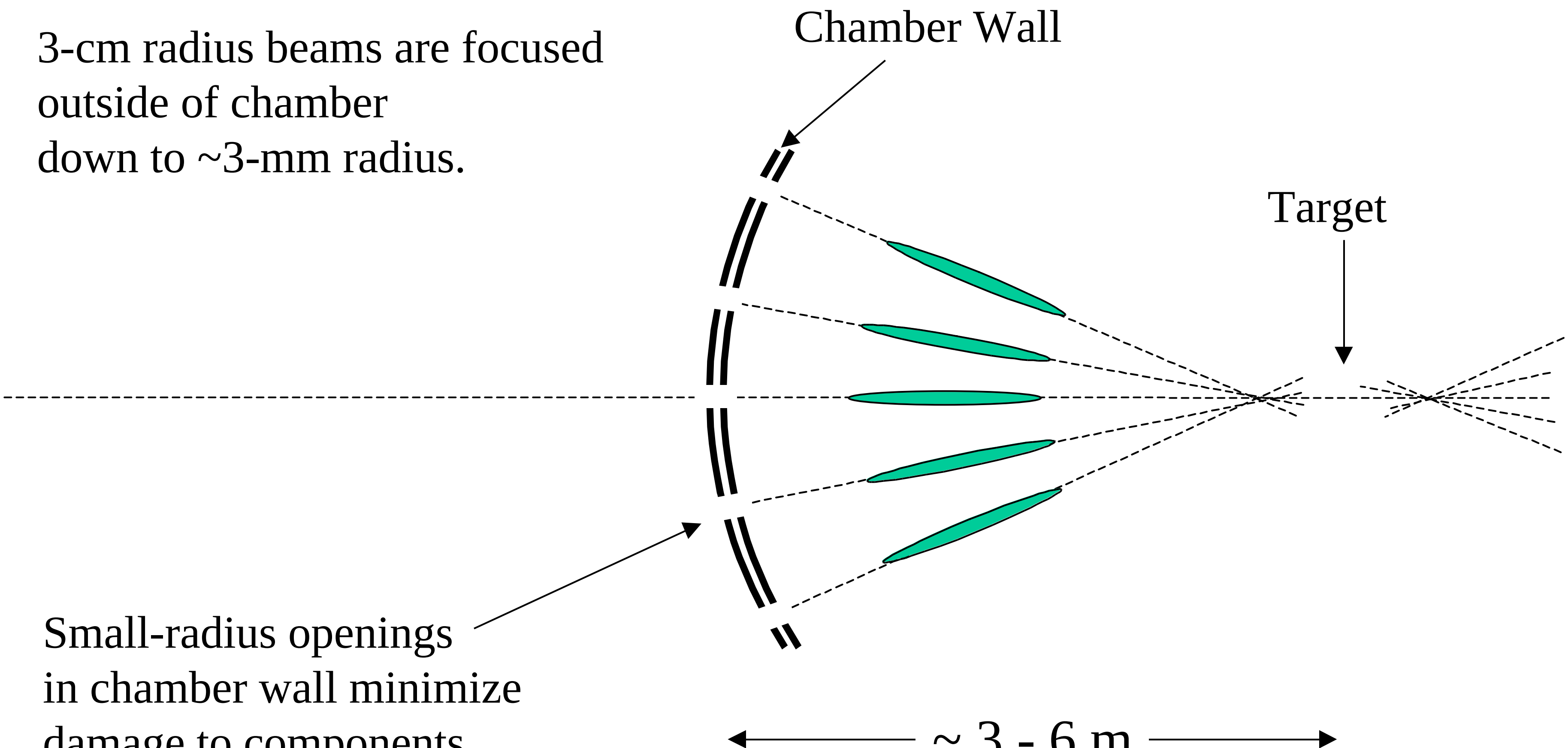
- 1D, 2D and 3D particle-in-cell and cloud-in-cell
- Energy-conserving electromagnetic and electrostatic algorithms
- Hybrid fluid-kinetic descriptions for electrons with dynamic reallocation
- Particle interactions include: scattering, energy transfer, ionization, stripping and charge-exchange
- Cold plasma initialization, target-photon ionization/stripping
- Surface physics includes Child-Langmuir emission, surface heating, neutral thermal/simulated desorption

*See D. R. Welch, *et al.*, Nucl. Instrum. Meth. Phys. Res. A **464**, 134 (2001).

Self-pinched chamber transport scheme

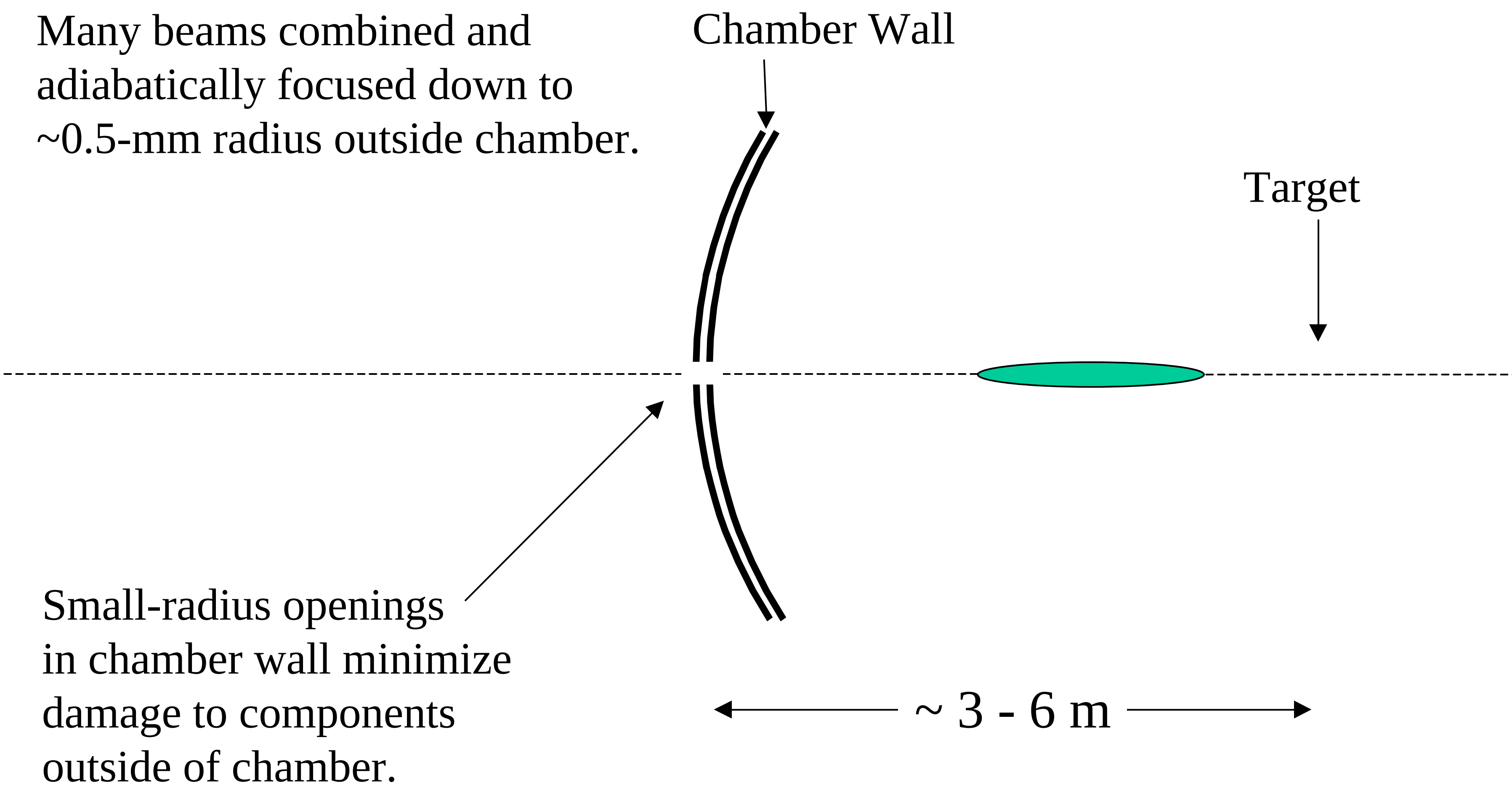
Charge and partial current neutralization provided by impact ionization of highly stripped ion beam in 10’s mTorr gas

3-cm radius beams are focused outside of chamber down to ~3-mm radius.



Small-radius openings in chamber wall minimize damage to components outside of chamber.

SPT schemes continued…



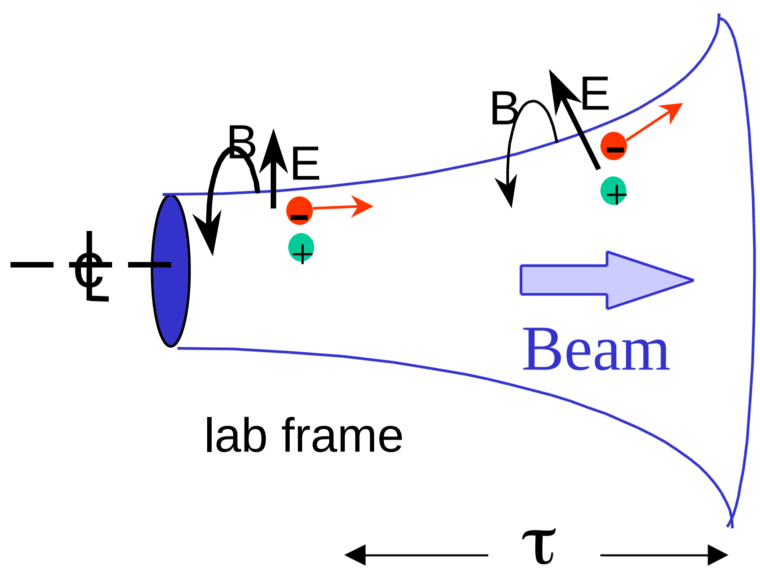
Self-pinched transport is predicted to occur within a gas pressure window:

- Maximum pinch force occurs when beam-impact ionizes a plasma density roughly that of the beam on time-scale of beam density rise length, τ
- Optimized for normalized trumpet length*:

  $$R = \tau\, \sigma\, n_g/4Z = 1$$

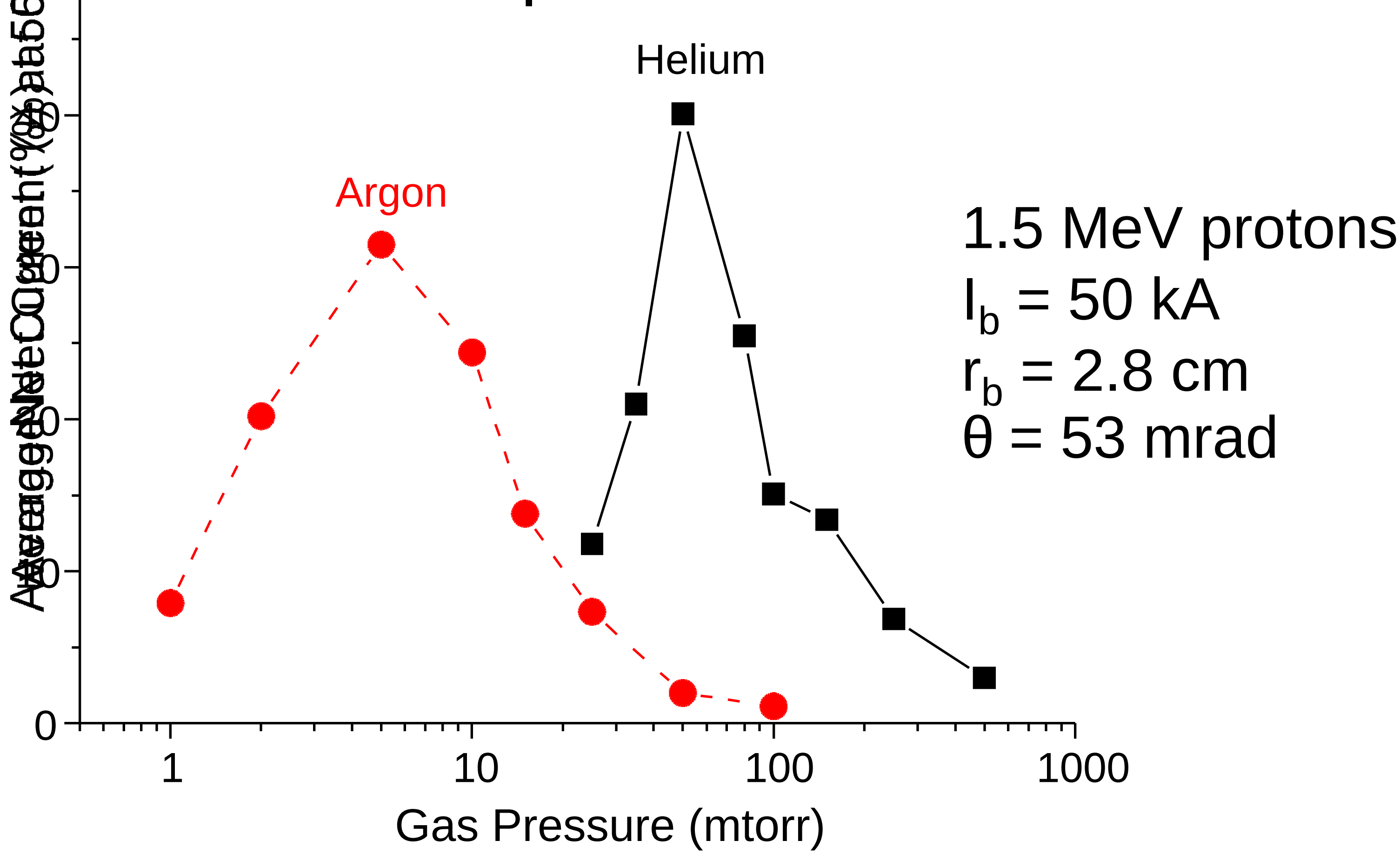
- Trumpet shape and non-local secondary ionization supply neutralization without $v_e = v_b$

Electron orbits are mainly E×B



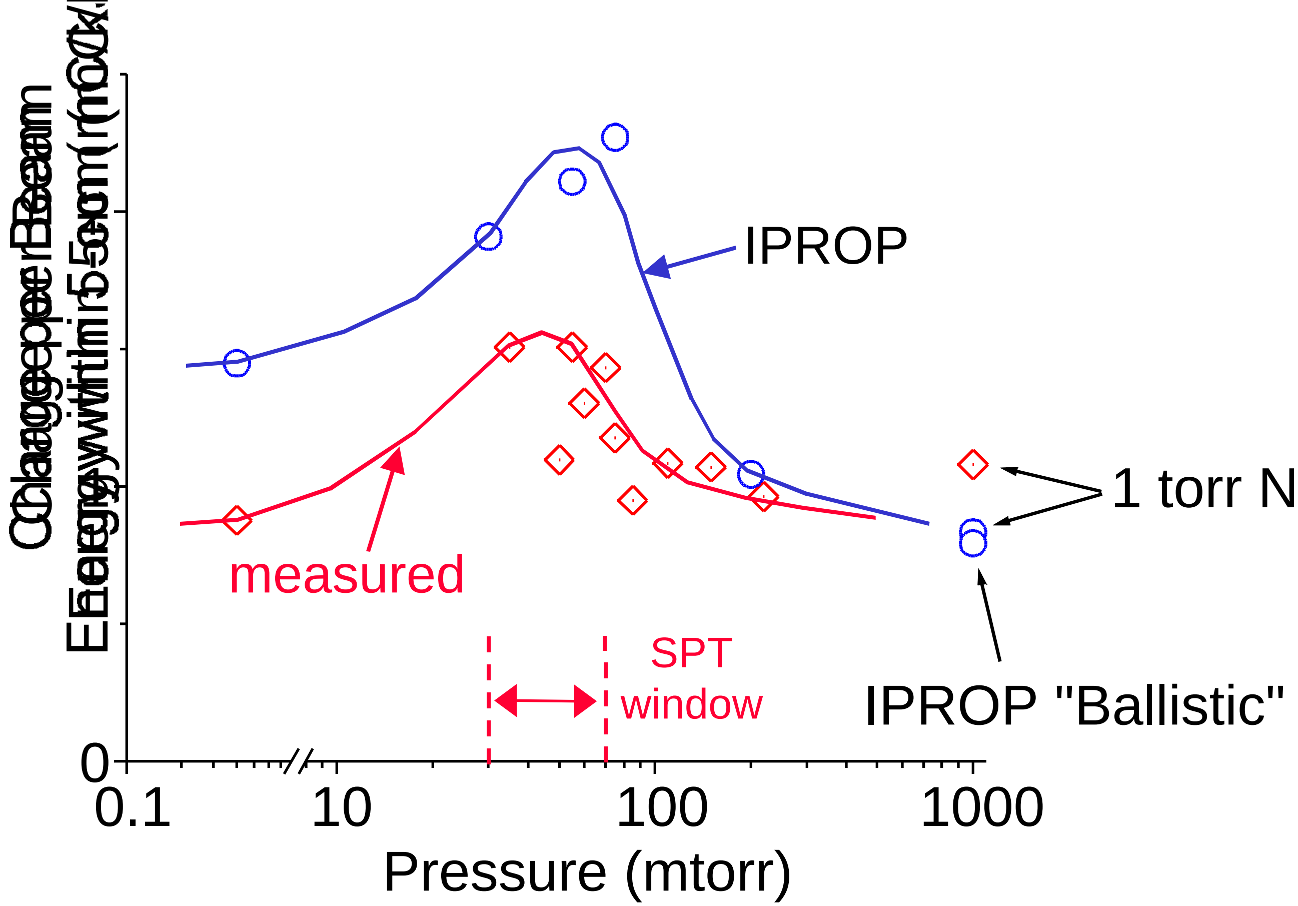
* D.R. Welch and C.L. Olson, Fusion Eng. and Des. **32-33**, 477, 1996.

Simulations indicated that a large net current fraction can be generated for SPT of a 1.5-MeV, 50-kA proton beam*



*D. V. Rose, *et al.*, Phys. Plasmas **6**, 4094 (1999).

Comparison of measured [with Li(Cu) nuclear activation] and predicted proton charge collected on a 5-cm-radius target at 50 cm into the transport region shows the same SPT pressure window.*

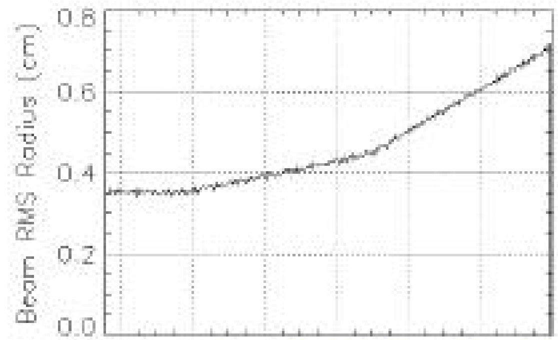


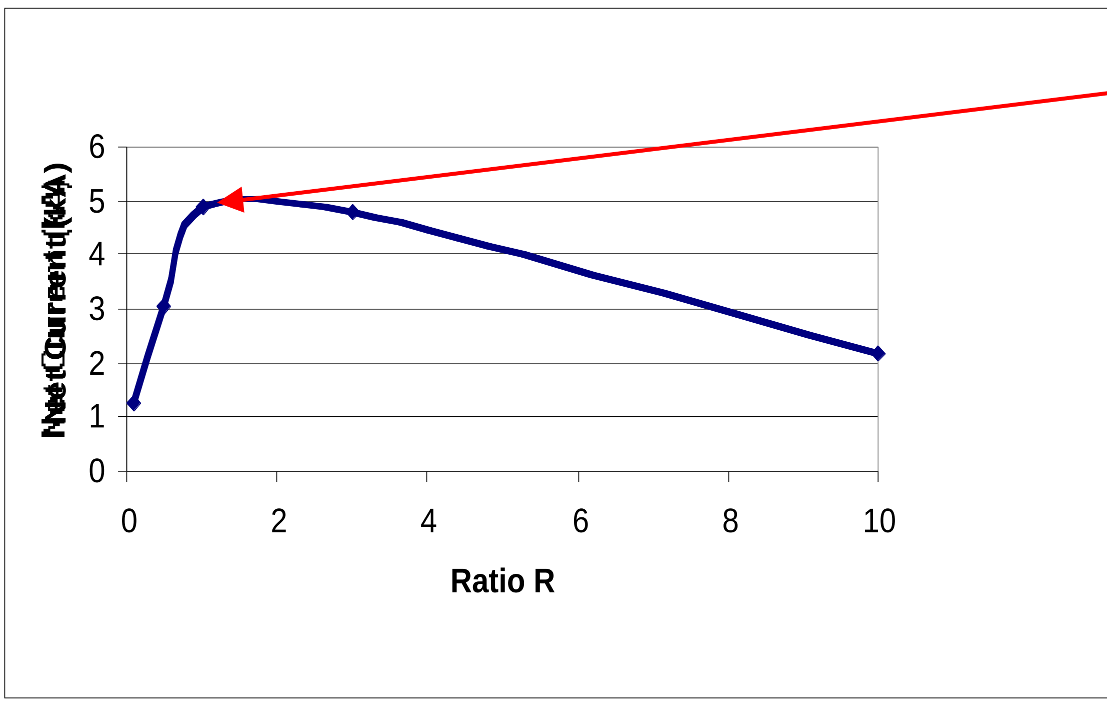
Results from SPT experiment on Gamble II at NRL

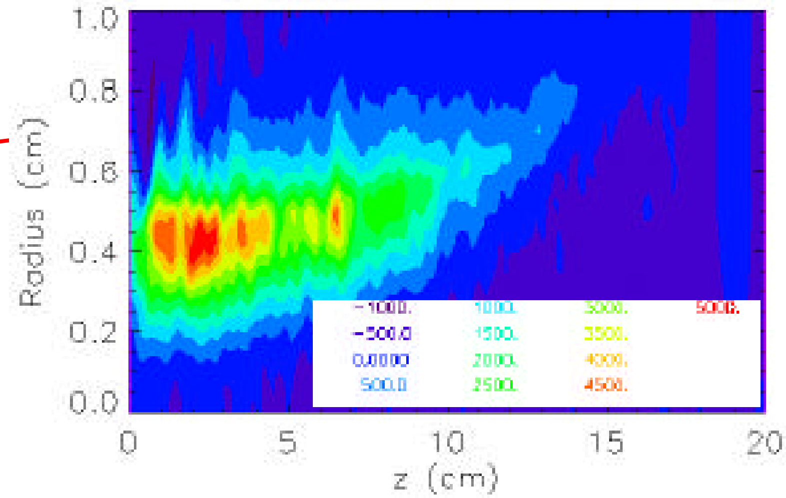
[*P. F. Ottinger, *et al.*, Phys. of Plasmas **7**, 346 (2000)]

LSP calculates maximum I_{net} near normalized trumpet length of unity

- LSP simulations of 10-kA, 4-GeV Pb^{+1} beam
- Beam trumpet 7 mm to 0.35 mm in 12 cm







Net current (A) for R=1

Cross-sections…

- Equilibrium charge-state for Lead beam assumed to be +65.
- Cross-section for 4 GeV Pb^{+65} impacting neutral Xenon (ionization potential U = 12.13 eV) calculated from limiting case Gryzinski [*] model [#] ($m_e E_b >> M_b U$) of 7.2e-15 cm^2.
- Expected gas pressure for SPT is then

$$n_g \sim \frac{Z}{\tau\sigma_b}$$

which is then approximately 50 mTorr for $\tau/v_b \sim 1$ ns.

[*] M. Gryzinski, Phys. Rev. A **138**, A322 (1964).

[#] B. V. Oliver, P. F. Ottinger, and D. V. Rose, Phys. Plasmas **3**, 3267 (1996).

Pinched transport [both assisted pinch (APT) and SPT] is feasible for net current chosen to match the beam divergence.

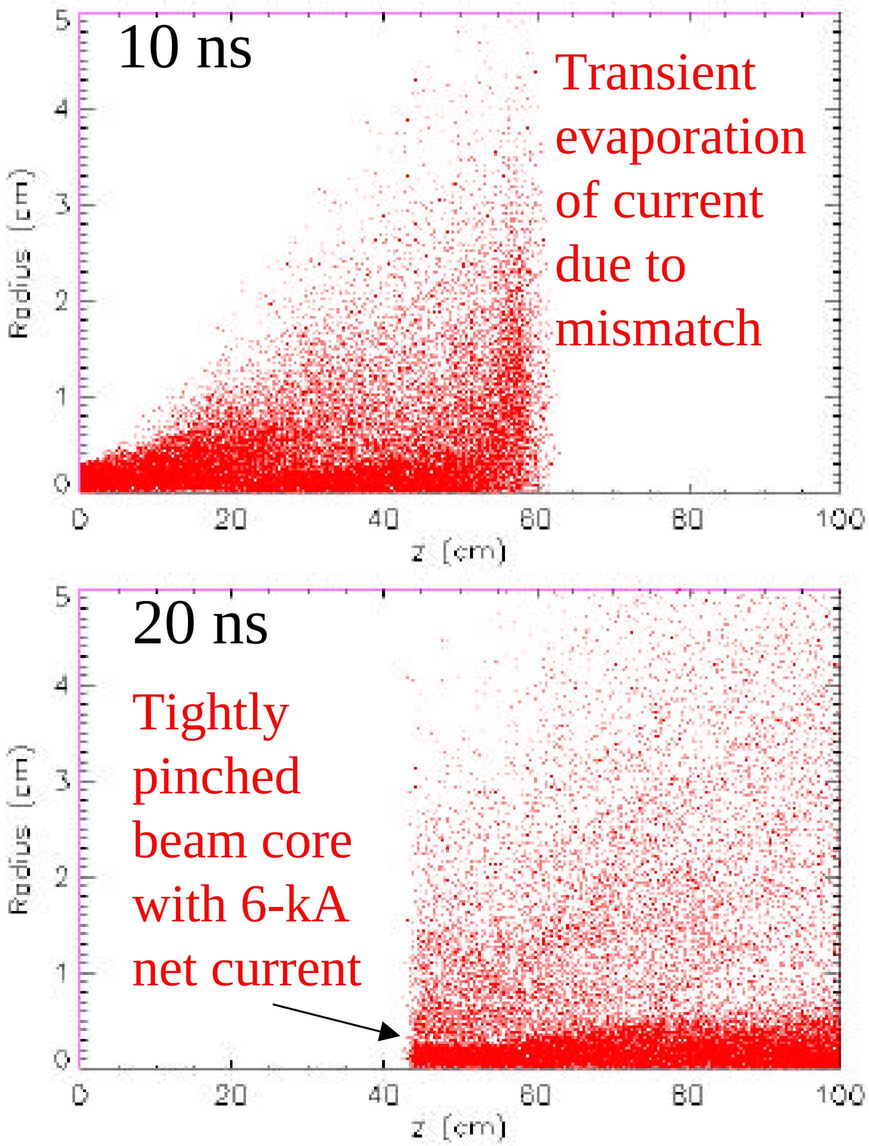
Sample parameters assuming an average charge state for lead ions (Z= +65), 1 kA beam particle current, and beam radius of 3 mm…

Beta =	0.2								
rb =	0.3	(cm)							
Beam Ion Mass	Beam Charge State	Beam Particle Current (kA)	**Postulated Net Current Fraction**	Beam Number Density (cm-3)	Beam Plasma Freq (s-1)	I_A Alfen Current (MA)	beta_perp from Inet> I_A*(theta)^2	beam-cyclotron freq. (s-1)	Betatron Wave-length (cm)
207	65	1	**0.01**	3.68E+12	7.04E+12	19.94	0.0011	1.30E+06	233.48
207	65	1	**0.05**	3.68E+12	7.04E+12	19.94	0.0026	6.52E+06	104.42
207	65	1	**0.1**	3.68E+12	7.04E+12	19.94	0.0036	1.30E+07	73.83
207	65	1	**0.15**	3.68E+12	7.04E+12	19.94	0.0044	1.96E+07	60.28
207	65	1	**0.2**	3.68E+12	7.04E+12	19.94	0.0051	2.61E+07	52.21
207	65	1	**0.25**	3.68E+12	7.04E+12	19.94	0.0057	3.26E+07	46.70

Bennett pinch condition: $I_n = \theta^2 I_A.$

2-D Simulation Geometry

1-m propagation demonstrates pinched equilibrium for R = 0.14



65-kA, 4-GeV Pb^{+65} beam

8-ns pulse

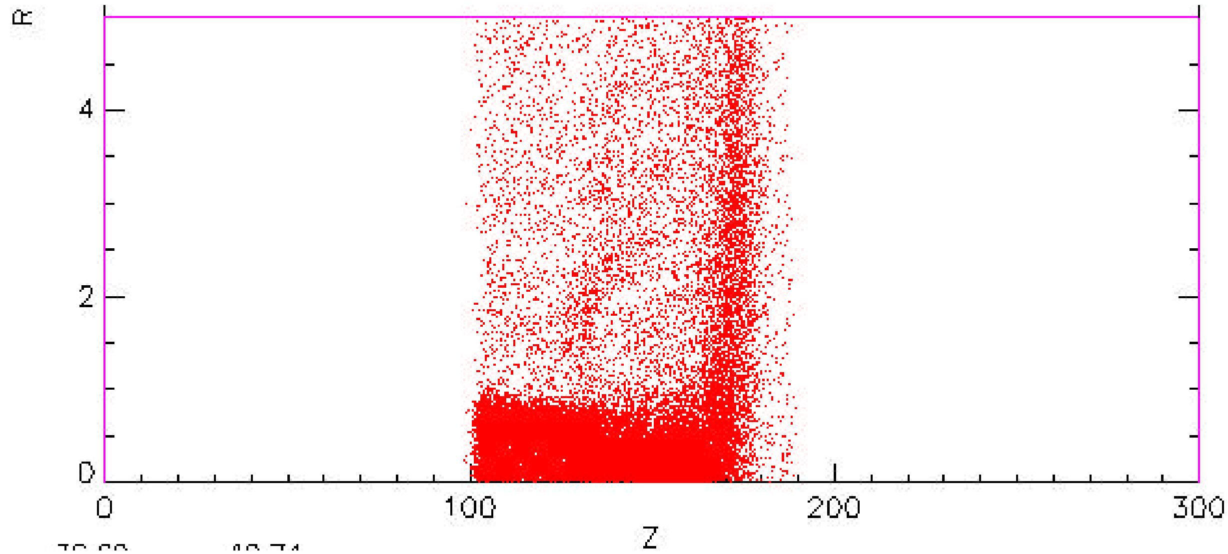
τ = 0.5 ns, 7-3.5 mm radius

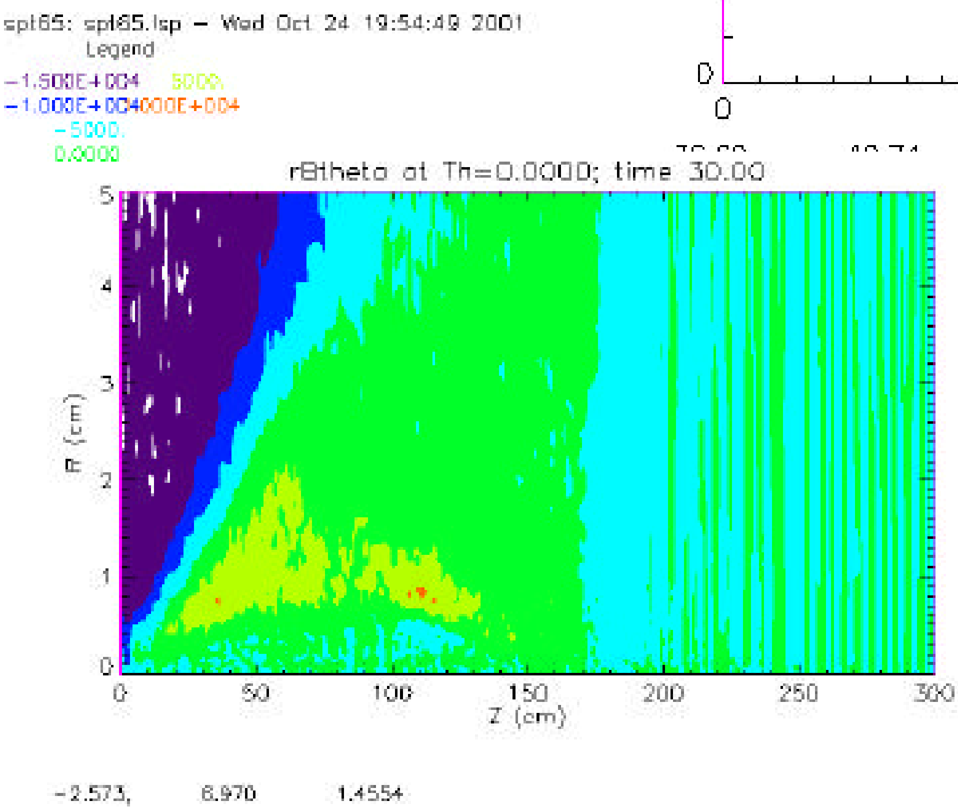
50-mTorr Xe gas fill

Only 61% transport within 6 mm radius after 1-m

Tolerable steady-state erosion rate 10^{-3}

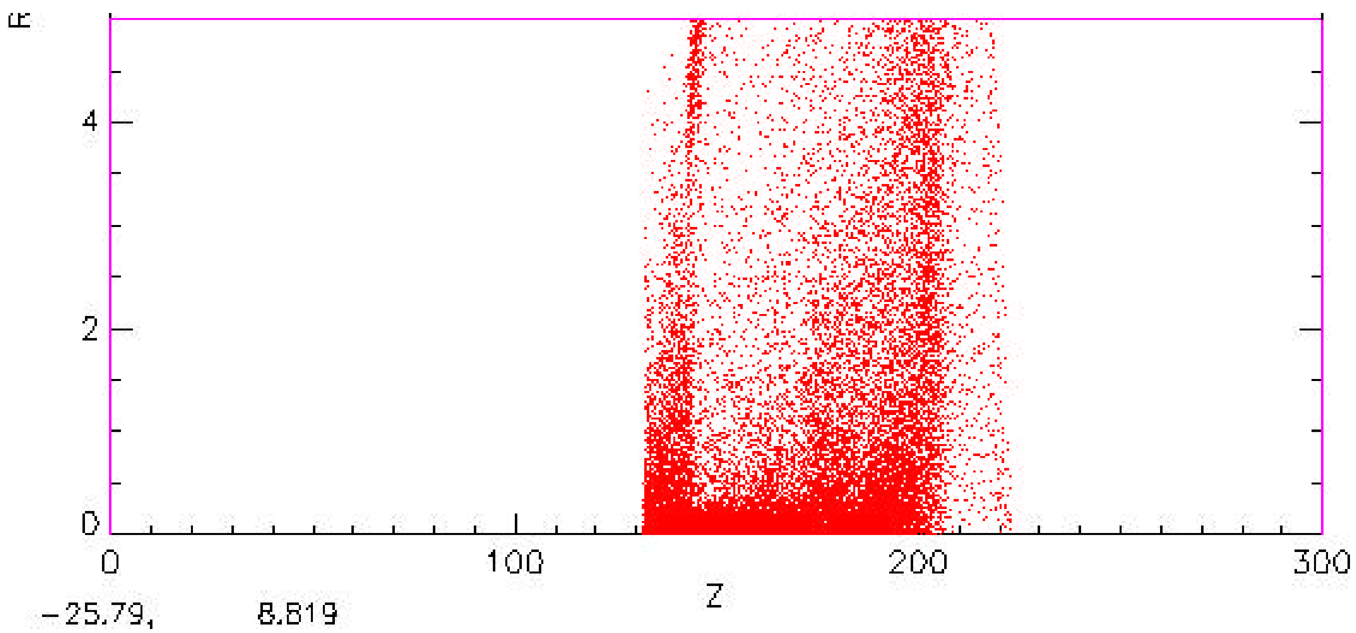
At 65 mtorr, beam develops an equilibrium half-current radius of 0.5 cm





~5 kA of net current

For the special case of no beam emittance, the beam body develops a 1-mm (!) half-current radius, but the head and tail are not confined…



Net Current of ~ 20 kA, 65 mtorr Xe

Steady-State Erosion Model For Propagating Ion Beams[*]

- Model accounts for non-zero beam erosion front velocities and the finite energies of beam particles radially exiting the beam through a single parameter α.
- Model in very good agreement of earlier simulations for a single value of the parameter α [*] and previous analyses for relativistic electron beams [+,#].

[*] D. V. Rose, T. C. Genoni and D. R. Welch, to appear in Phys. Plasmas (2002).
[+] W. M. Sharp and M. Lampe, Phys. Fluids **23**, 2383 (1980).
[#] M. Mostrom, D. Mitrovich, D. R. Welch, and M. M. Campbell, Phys. Plasmas **3**, 3469 (1996).

Erosion Rate:

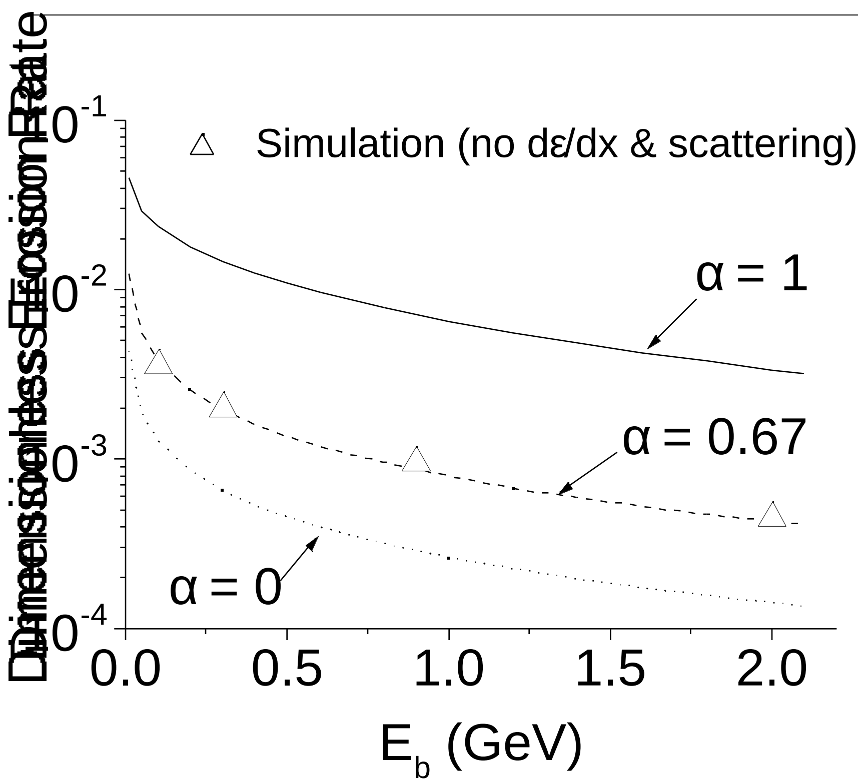
- Dimensionless erosion rate from model is determined by solution of:

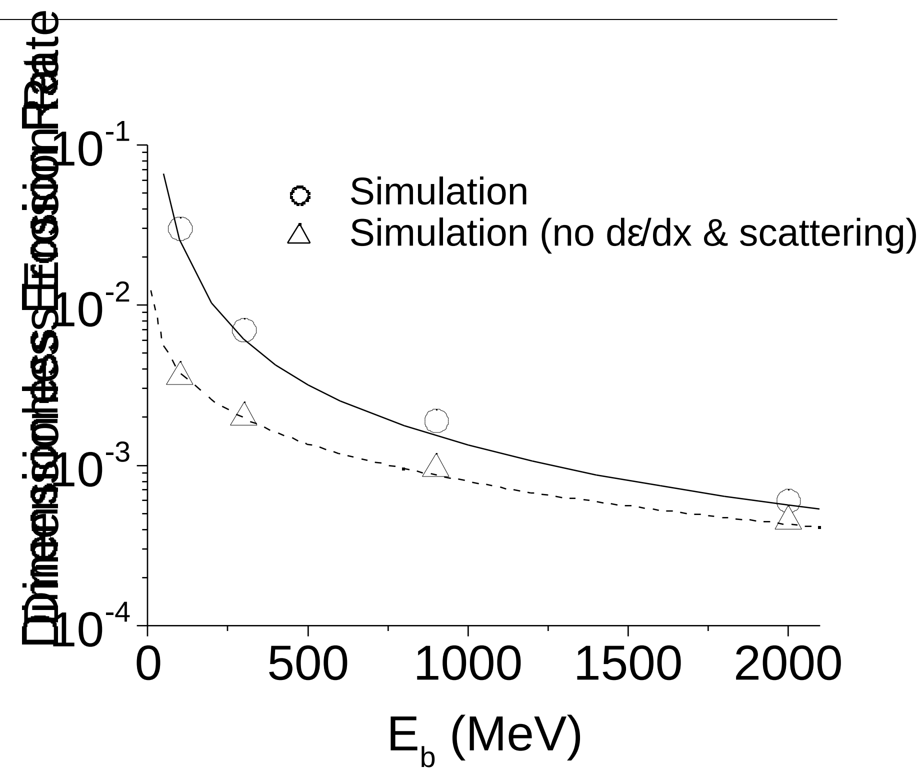
$$\left(1-\frac{\beta_F}{\beta}\right)=\frac{\beta_F X}{(\gamma-1)-\alpha(\gamma_F-1)}$$

$$X=\frac{I_n^2(\mathrm{kA})L}{17MI_b(\mathrm{kA})}$$

Subscript "F" denotes the front velocity, α is a dimensionless parameter, I_n is the net current, I_b is the beam current, L is a dimensionless inductance, and $M = Am_p/Zm_e$.

Simulations of self-pinched proton beams in dense (760 Torr) gas are in good agreement with the model for a fixed value of α[ ]:





I_b = 10 kA, I_n ~ 5 kA, L ~ 4

* D. V. Rose, T. C. Genoni, and D. R. Welch, to appear in Phys. Plasmas (2002).

Status

- Self-pinched transport is an attractive chamber propagation scheme; small entrance holes in the chamber wall, no hardware (sacrificial structures) in chamber.
- LSP simulations have identified a propagation window in 10-150 mTorr Xe.
- Efficiency of energy transport is presently being studied.
  - Simulations so far have shown evaporation at early stages of transport can result in ~30% losses.
  - Steady-state erosion rates are predicted to be small.

Planned Activities for FY02

- Generic scaling of three modes for chamber transport (neutralized ballistic, preformed channel, self-pinched) and participation in the HIF point design using neutralized ballistic transport.
- LSP simulations of self-pinched transport, including a pressure scan of I_{net} vs. pressure for Xe gas. Study of erosion and evaporation, equilibrium transport, and transport efficiency of self-pinched ion beams.
- For preformed channels, study of fundamental limits to channel radius using LSP for breakdown and proposed use of Alegra or other MHD code for radiation/MHD evolution of channel.
- Work with Sandia National Laboratories on power plant scenario using self-pinched ion beam transport.