LSP Neutralized Ballistic Transport Calculations

D. R. Welch, D. V. Rose, B. V. Oliver

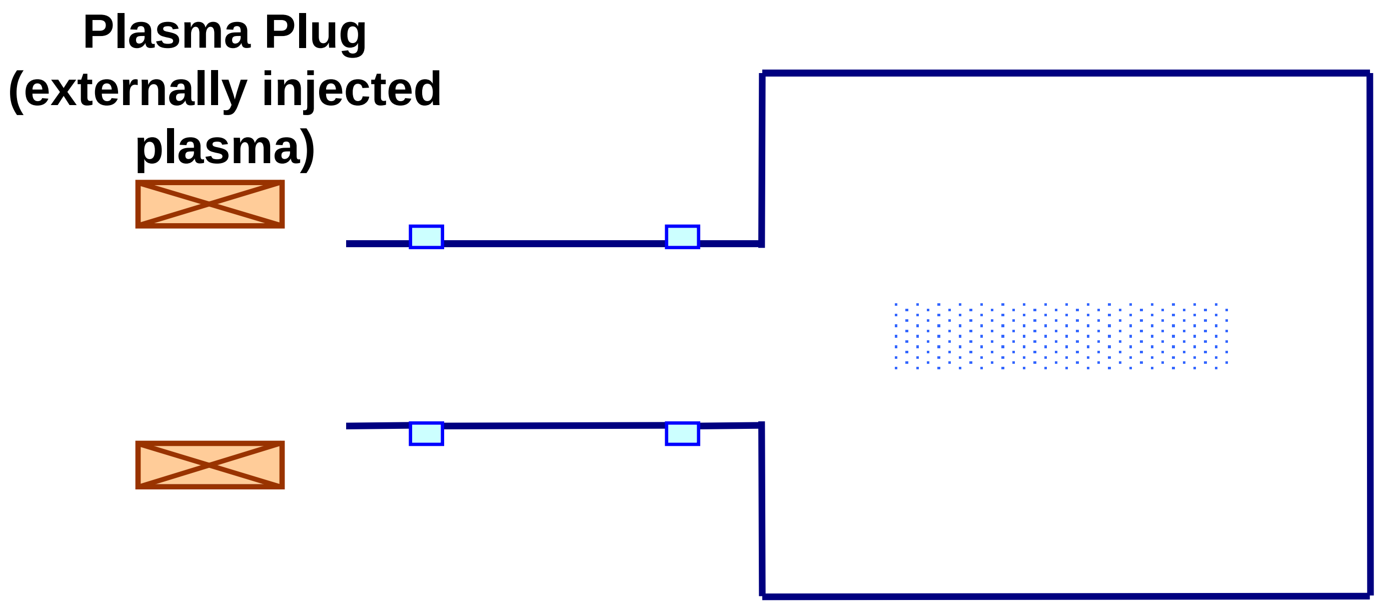
S. S. Yu and W. Sharp

Presented at the ARIES Project Meeting

January 10-11, 2002

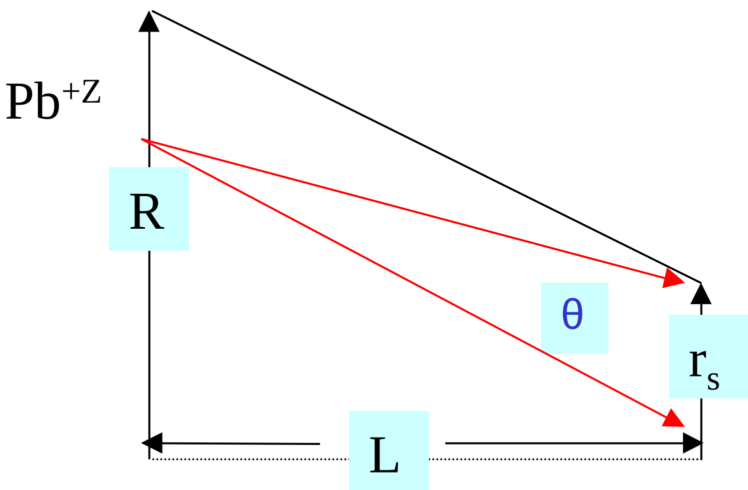
Research supported by the DOE through PPPL and the HIF VNL

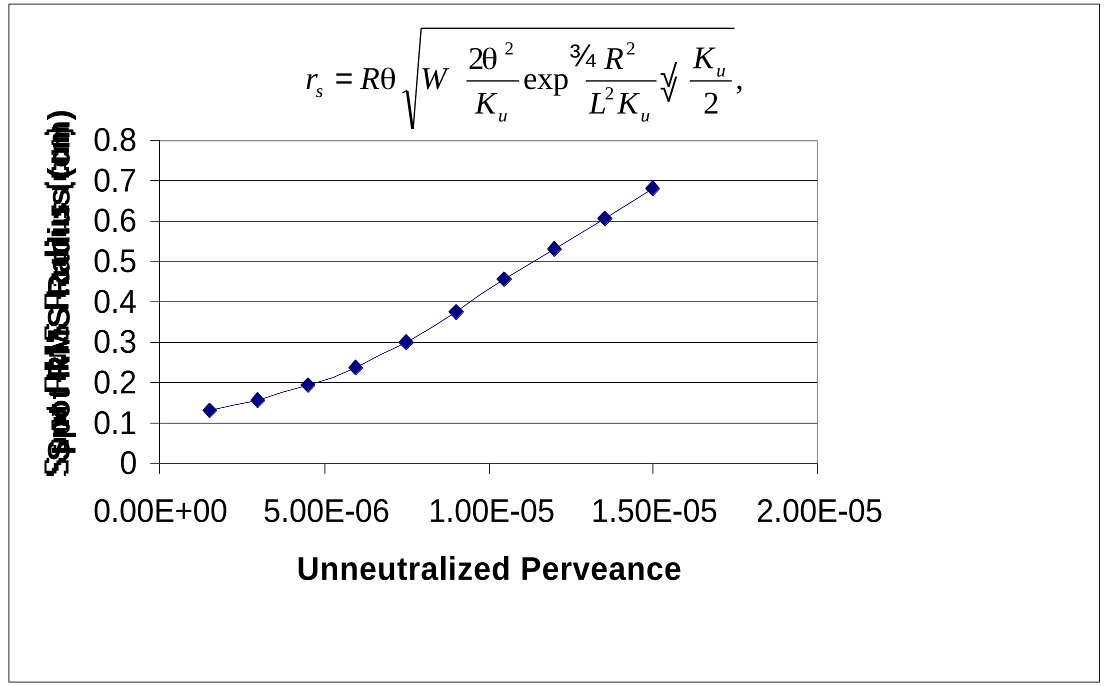
Neutralized Ballistic Transport



- We are characterizing NBT and attempting to distill physics for systems code

Spot size on target is a function of neutralization *f* and beam charge state Z



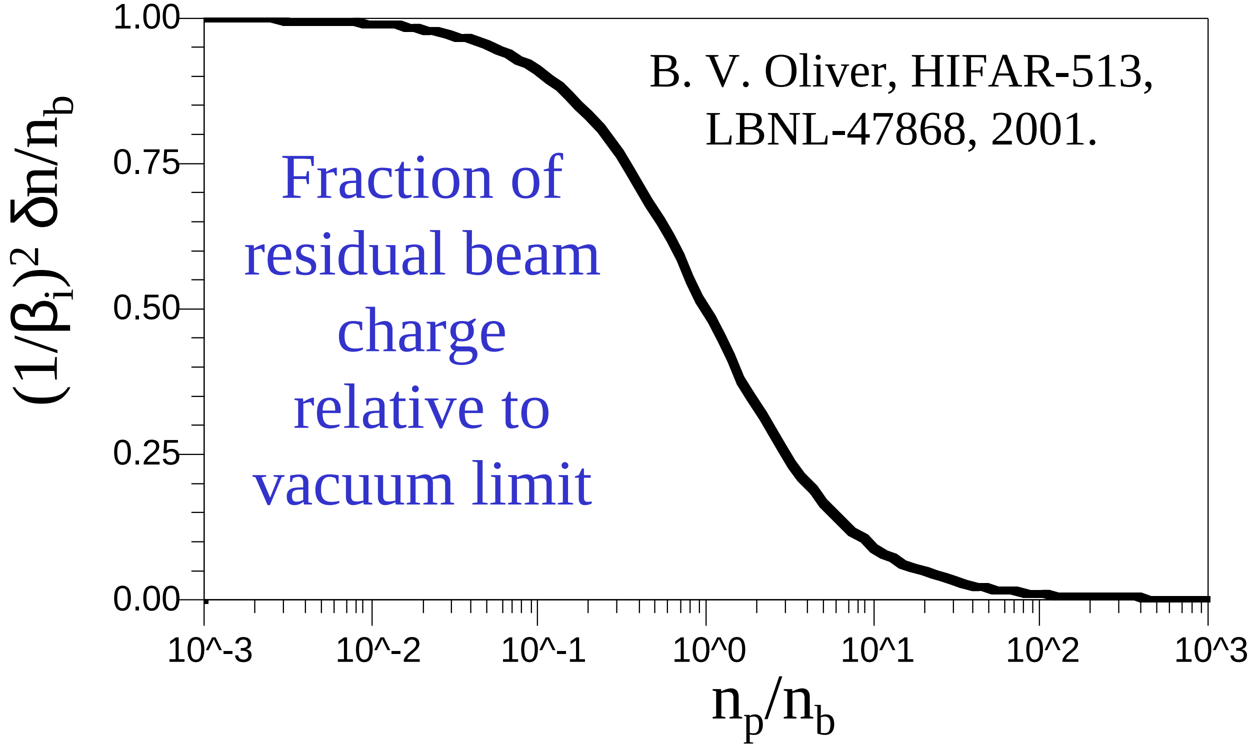


- Initial beam radius R=2 cm, focal length L=300 cm and θ=0.5 mrad
- Unneutralized perveance $K_u = 2I_b/I_A\beta_i^{\,2}\,(1\text{-}f)$, $I_A = \beta_i\gamma_i m_i c^3/eZ$
- Axial neutralization limit* $K_u \sim Zm_e/m_i$ or $3\text{x}10^{-6}$Z for Pb^{+Z}

*C. L. Olson, AIP Conf. Proc. 152, “Heavy Ion Inertial Fusion,” M. Reiser, T. Godlove, and R. Bangerter, eds. (AIP, NY, 1986), p. 215.

Charge neutralization can be enhanced by a dense plasma

- Without plasma neutralization for driver scale beam with β_i =0.2, vacuum limit *1-f* is limited to $(1/\beta_i^2) = 0.04$



LSP code* simulates both NBT and SPT including dense plasmas

- 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).

LSP setup for driver-scale beam simulations

Pb^{+1} ion beam, K = 1.5e-4
4-kA, 4 GeV, β_l = 0.2
30 mm-mrad emittance
3 mTorr neutral Flibe

With and without photo-ionized plasma (peak $5x10^{13}$ cm^{-3}) from target radiation.*
n_p/n_b = 10 at z=0

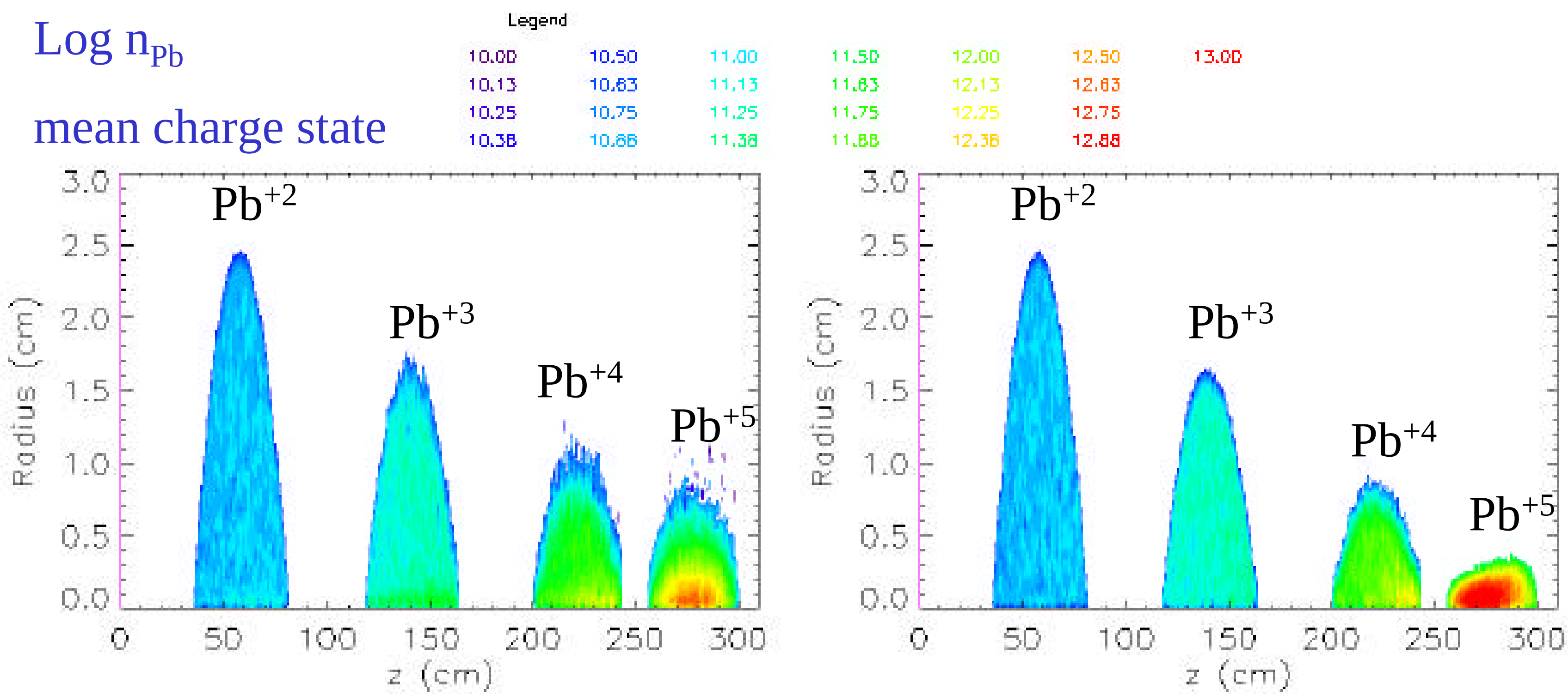
Plasma neutralization crucial to good spot

Stripped ions deflected by un-neutralized charge at beam edge*

Plasma provides > 99% neutralization, focus at 265 cm

Log n_{Pb}

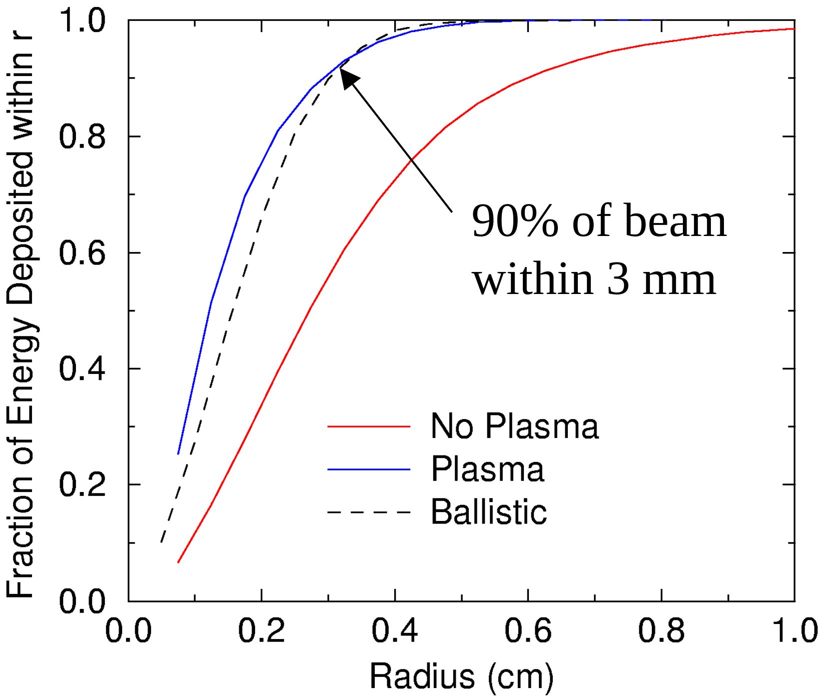
mean charge state



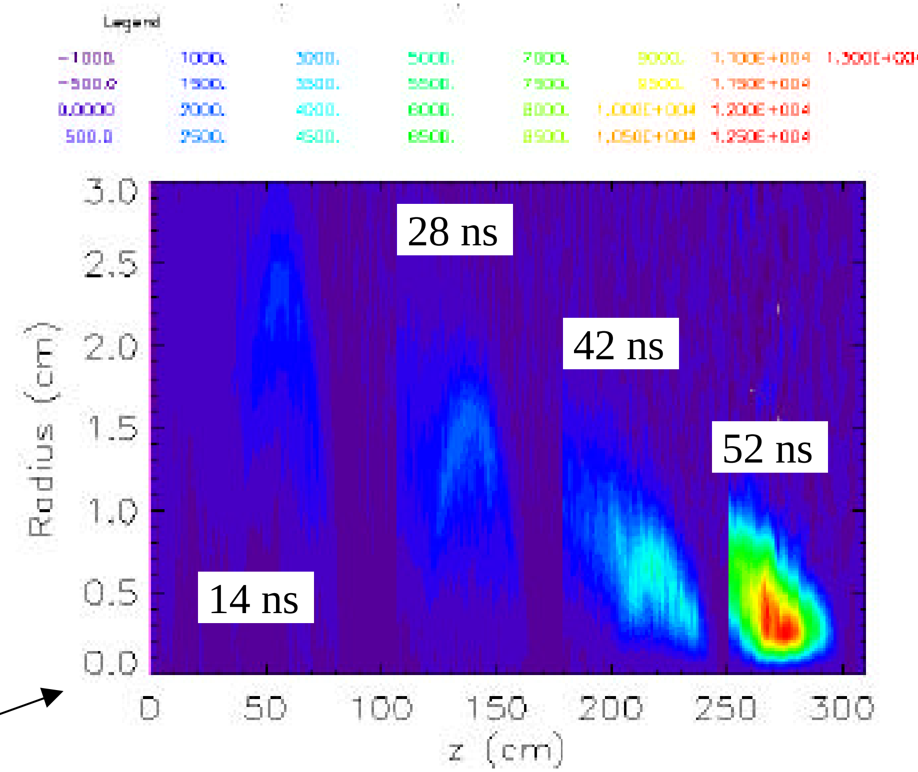
No Plasma   Plasma

*D. A. Callahan, Fusion Eng. Design **32-33**, 441 (1996)

Plasma simulation spot slightly better than ballistic case



Net Current (A) within r



Residual net current results in premature but tight focus

Net current rise from 1 kA at 14 ns to 12 kA at 52 ns

The foot-pulse beams do not have the benefit of photo ionization

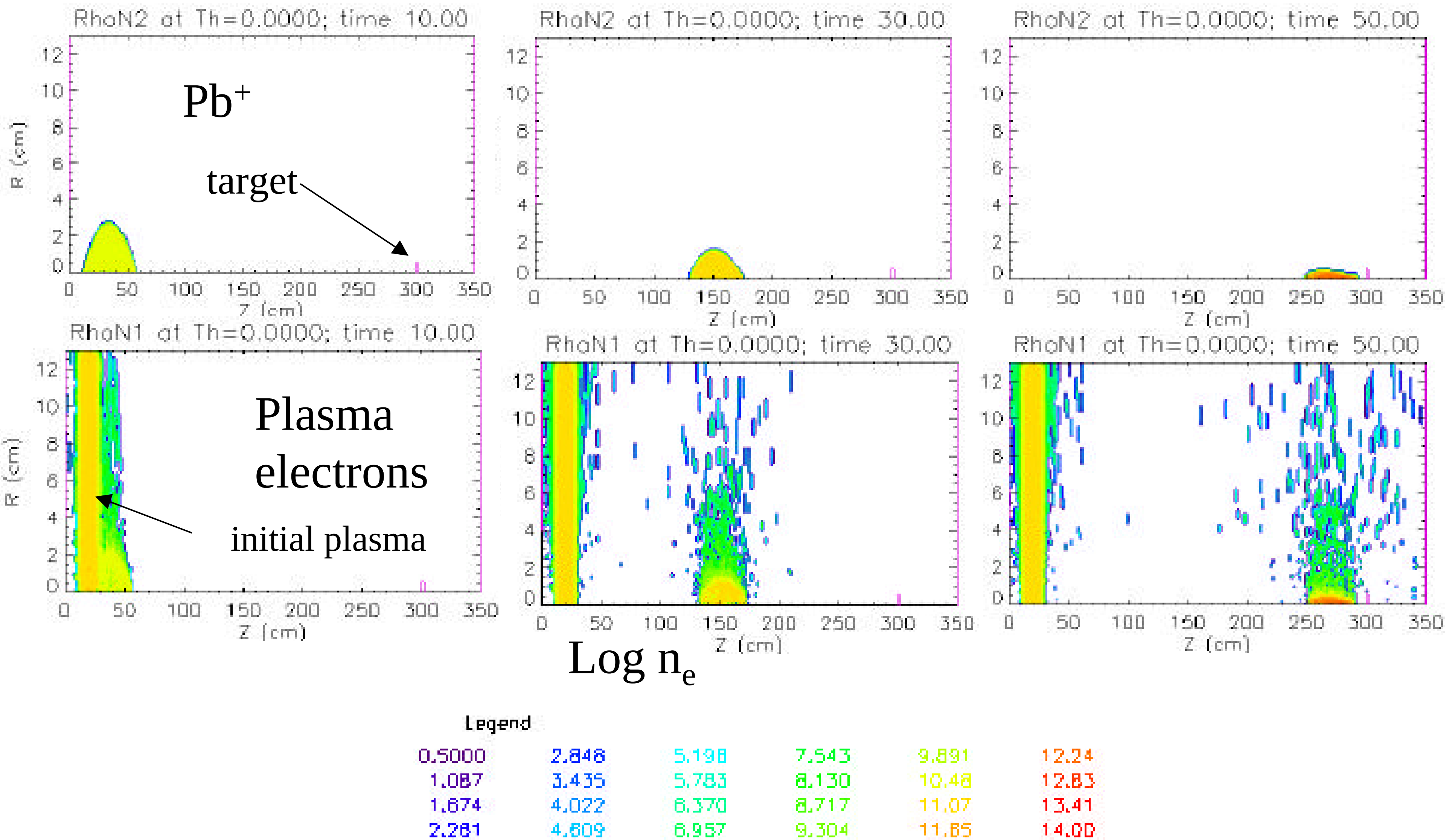
- Even though these beams are typically low current, W. Sharp has shown that without a plasma, these foot-pulse beams are poorly neutralized and the focal spot is big
- Neutralization must come from a localized plasma intentionally produced near the chamber wall

Beam/Vacuum Chamber Simulations with localized plasma

- 4 GeV, 0.25-4 kA, ($K=1\text{-}16\times10^{-5}$)
- 8 ns parabolic profile
- 1.1 pi-mm-mrad normalized emittance
- zero chamber pressure
- With an emitting target at 3 m
- With a plasma near injection into chamber
  - with 3×10^{11} cm^{-3} density (n_p/n_b = 10 for 1 kA)

What can we expect in an idealized situation without beam stripping?

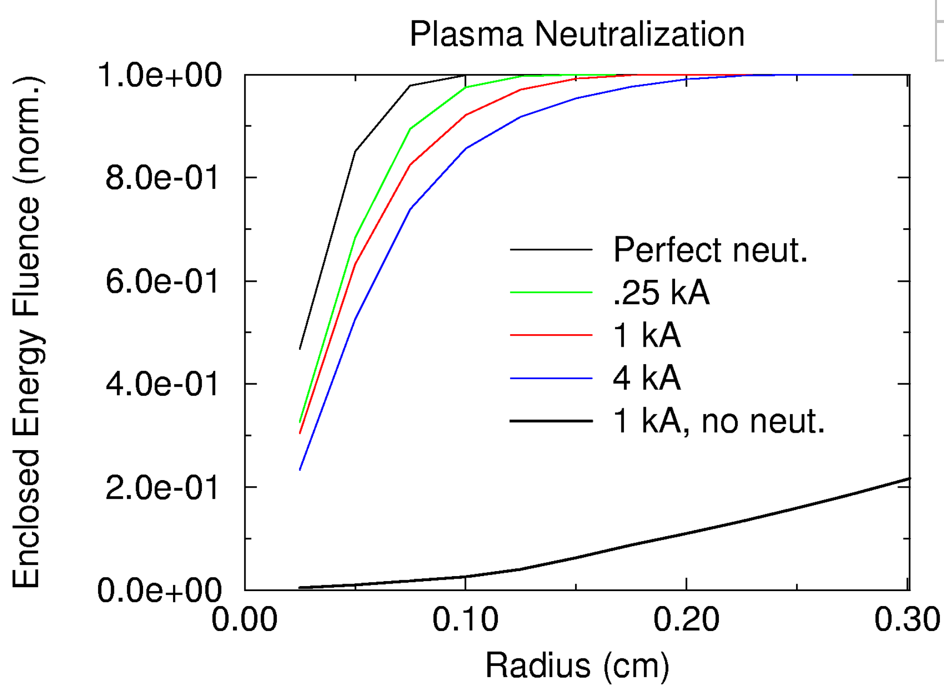
1-kA Beam picks up neutralizing electrons from plasma and carries them to the target



Neutralization in vacuum with plasma at injection produces small spot

- 13-cm plasma with wall emission
- $\alpha\ \beta_i^2$ residual charge fraction with an $\alpha = 1$ fits spot adequately but α decreases somewhat with decreasing beam current
- beam spot < 1 mm for all currents
- K_u is unneutralized perveance

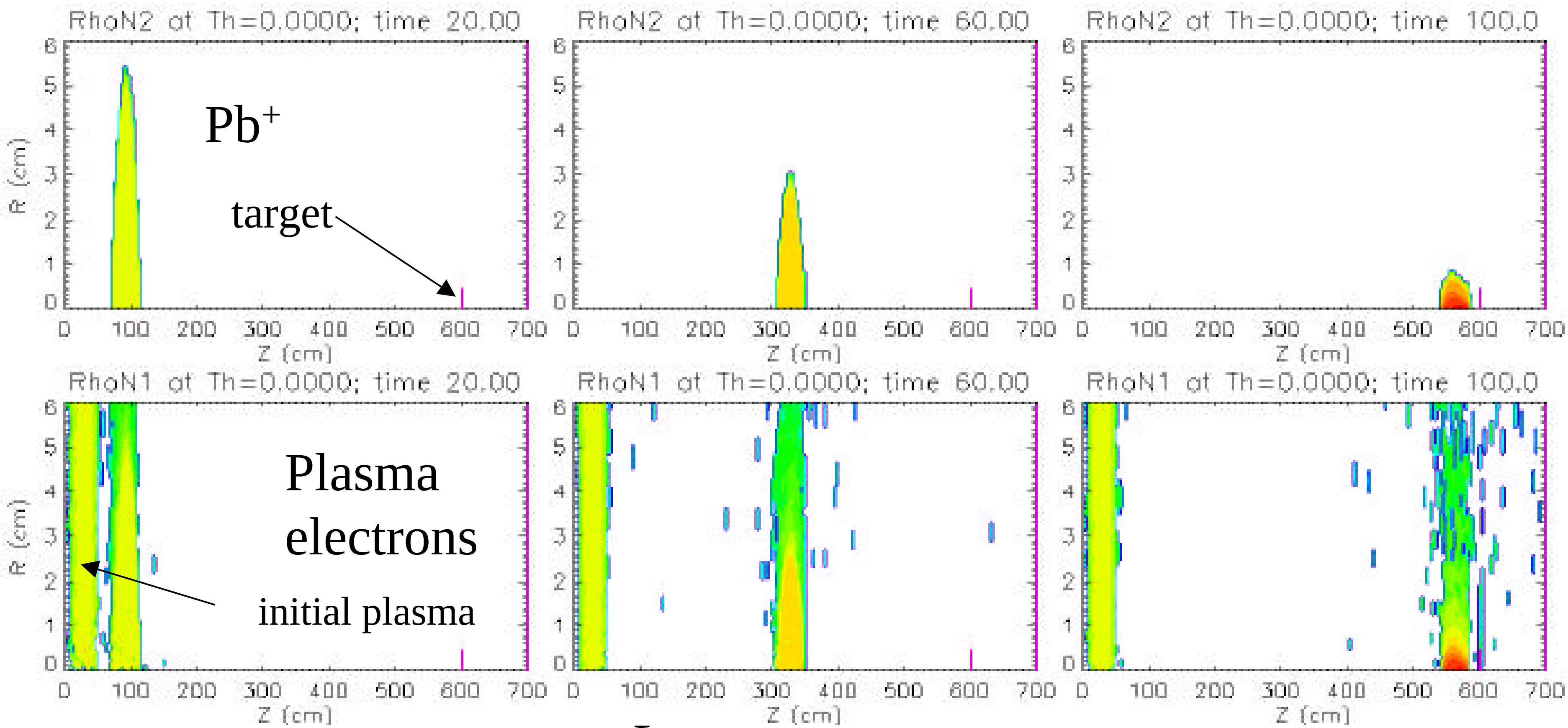
run	I (kA)	RMS Rad(cm)	f_eff	f(alpha=1)	Ku
neut0	0	0.044			0
neut2	0.25	0.058	0.68	0.49	3.00E-06
neut1	1	0.0662	0.89	0.87	4.40E-06
neut3	4	0.0813	0.96	0.96	6.40E-06
neut4	1	0.52	0		3.80E-05



Possibility of NBT for a Dry Wall Chamber Design

- We assume the same emittance as the earlier runs but with a 1 and 4-kA, 6-cm beam at injection into a 6-m transport chamber with a plasma near the injection plane - no stripping or ionization
- For perfect neutralization, we expect the same spot size
- However, neutralizing plasma electrons are carried twice as far and are compressed to half the radius - neutralization should degrade somewhat

Neutralizing electrons mostly remain with 4-kA beam but increasingly uncover the beam edge



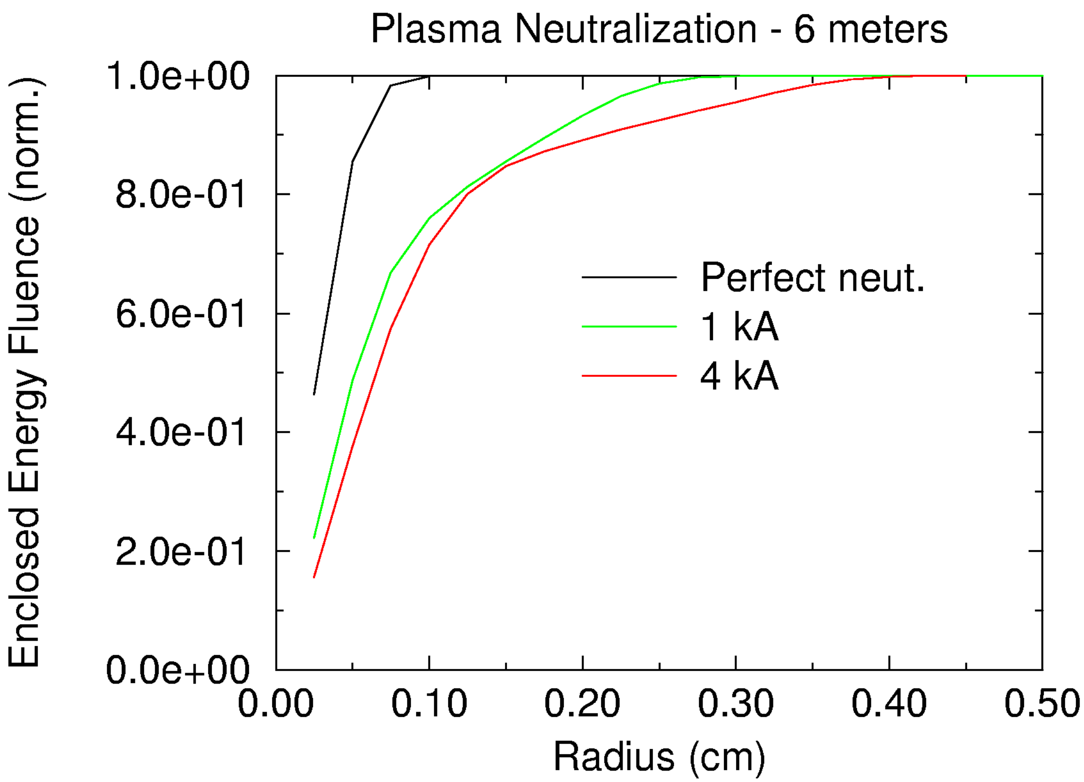
Log n_e

Legend

0.5000	2.848	5.196	7.543	9.891	12.24
1.087	3.435	5.783	8.130	10.48	12.83
1.674	4.022	6.370	8.717	11.07	13.41
2.261	4.609	6.957	9.304	11.65	14.00

Spot size is not much worse than the 3-m transport

run	I (kA)	RMS Rad(cm)	f_eff	f(alpha=1)	Ku
neut12	0	0.043	1		0
neut11	1	0.106	0.86	0.87	5.40E-06
neut10	4	0.131	0.95	0.96	6.50E-06



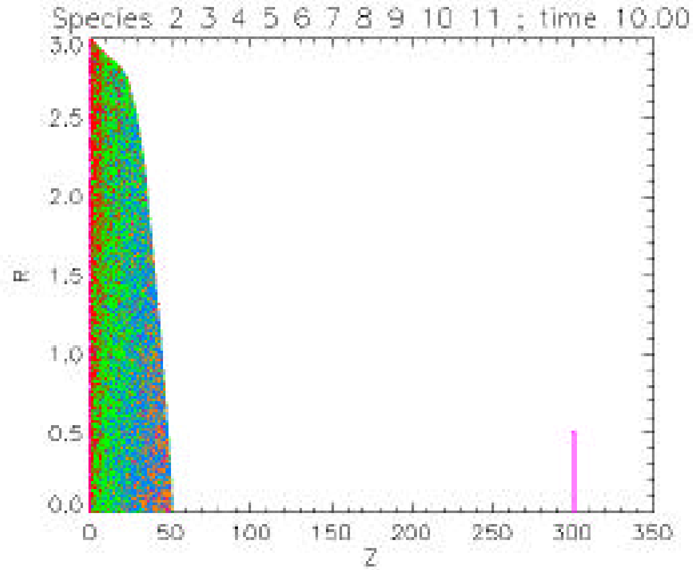
The beam develops a pronounced halo containing 10% of the energy at 4 kA, but overall transport is encouraging for a dry wall chamber

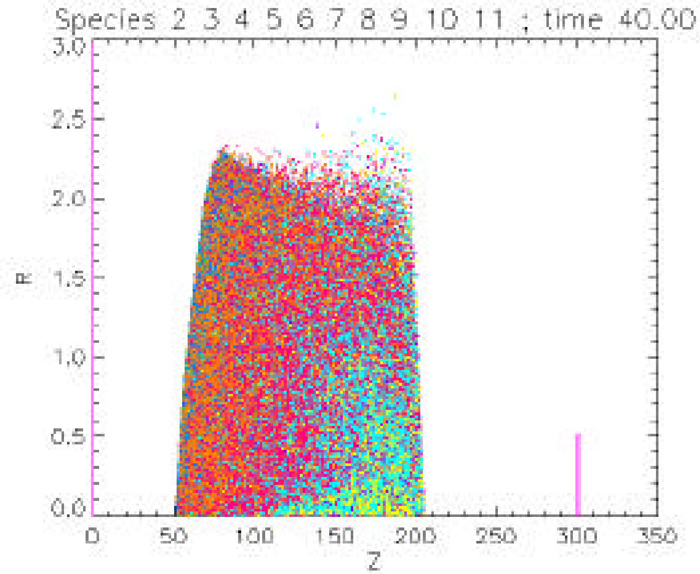
Foot Pulse Beam/Chamber Parameters

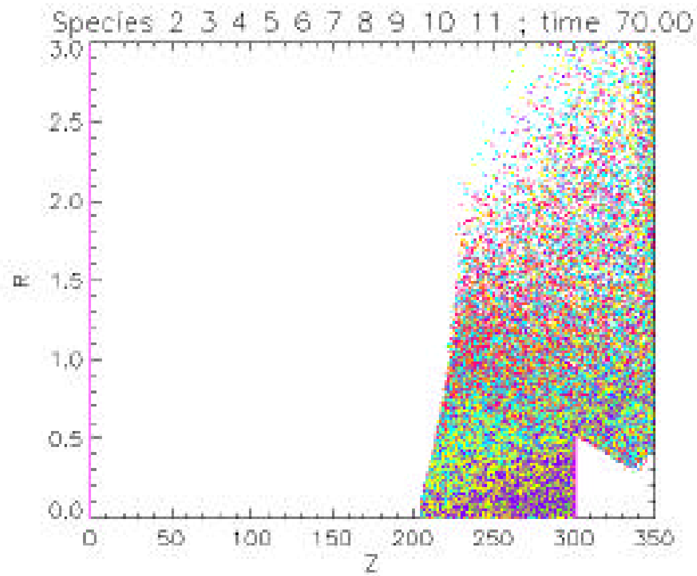
- 3 GeV, 1 kA, ($K=6x10^{-5}$) 30-ns parabolic ends
- 1.1 pi-mm-mrad normalized emittance
- 3 mTorr Flibe in chamber (ionization and stripping)
- With and without an emitting target at 3 meters
- With and without axial neutralization at chamber wall

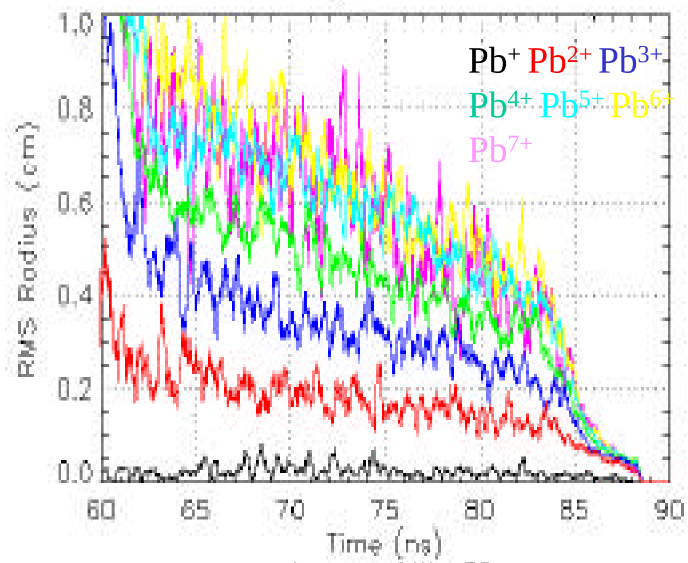
Do the benefits of a local plasma extend to the realistic case with beam stripping?

No plasma case: higher charge state ions expand in head, neutralized by ionization only

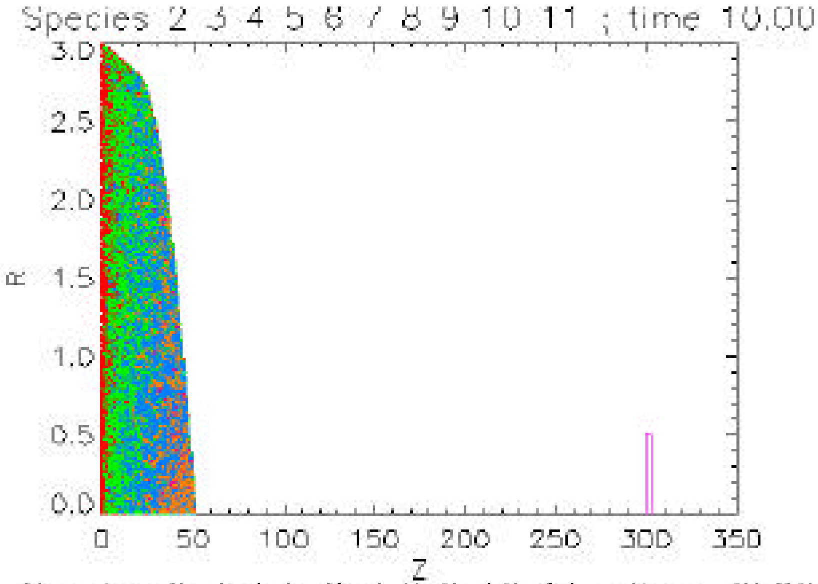


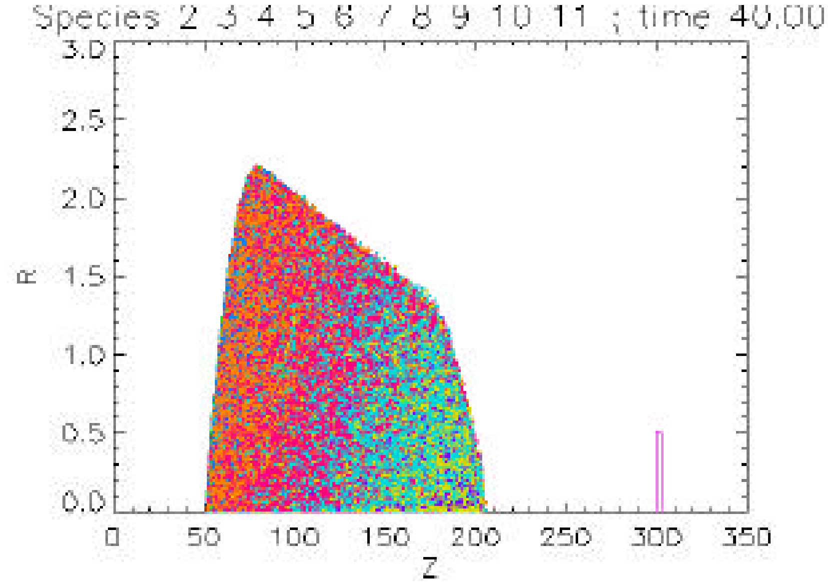


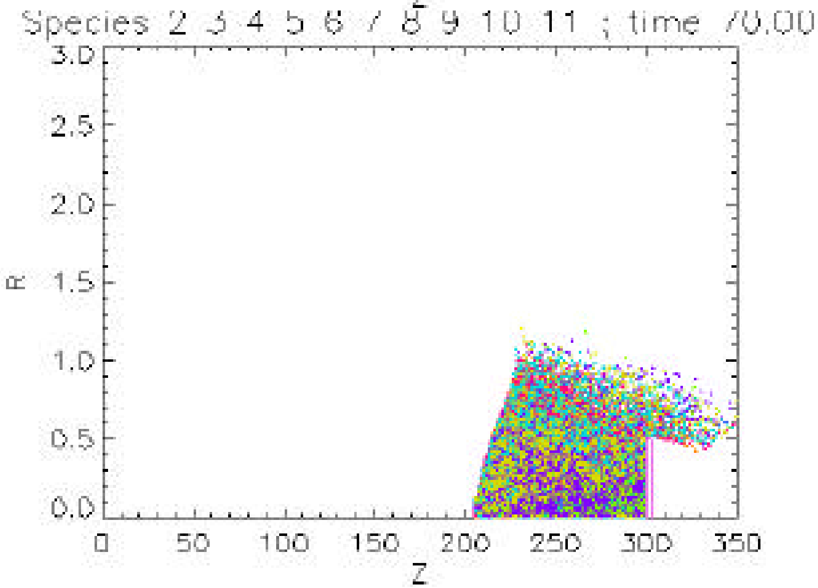


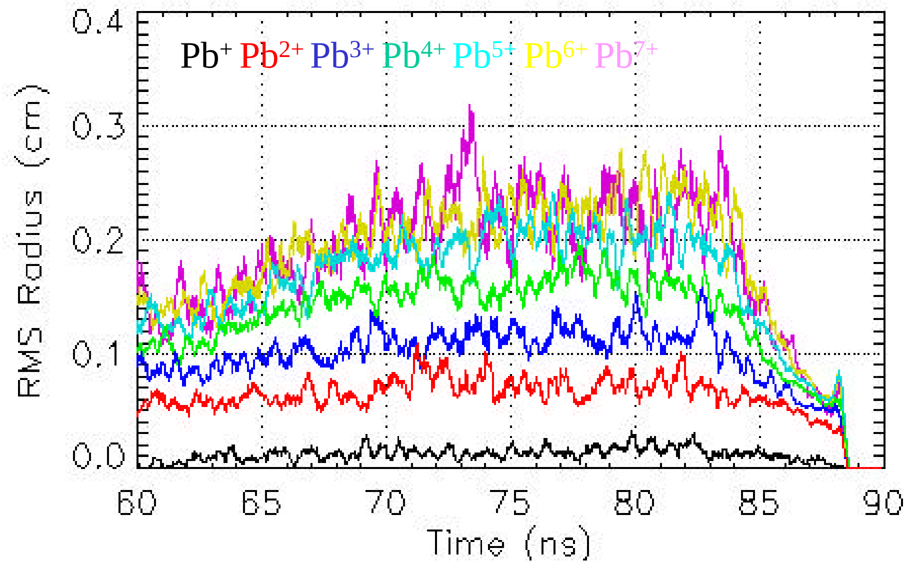


Plasma reduces expansion



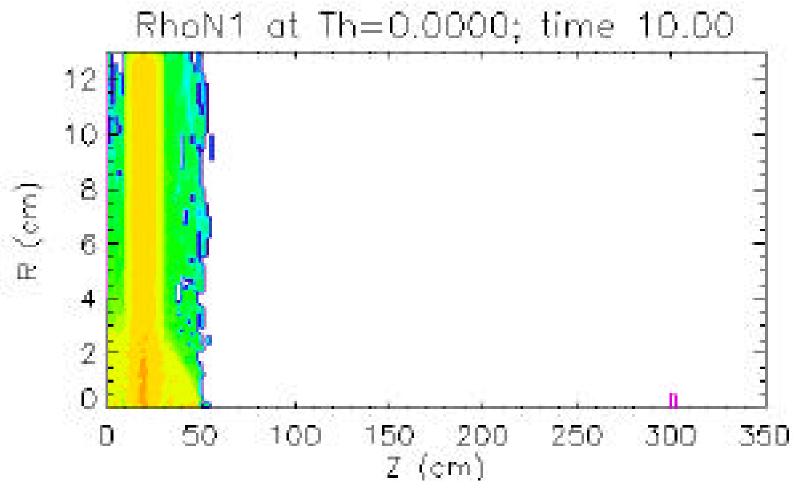


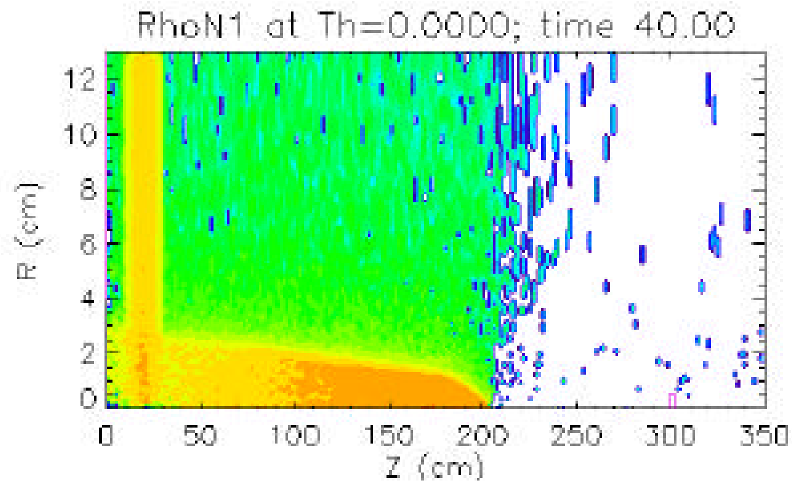


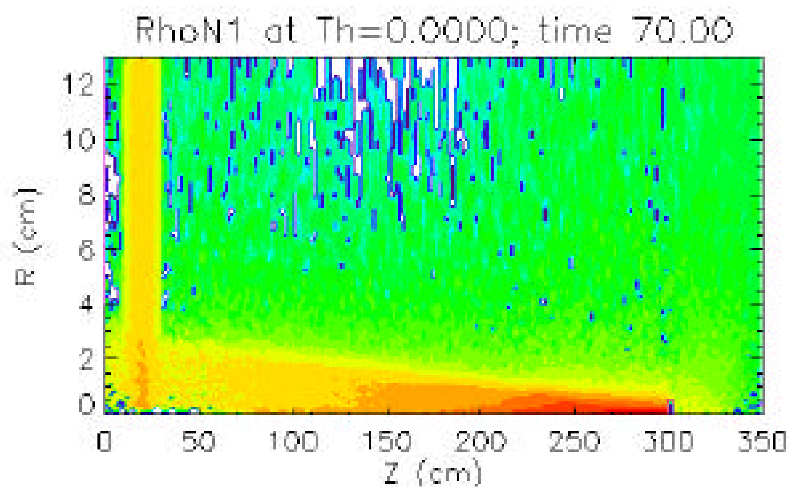


- 13-cm plasma with wall emission (foot12)

Plasma electrons are effective neutralizers even with ion stripping







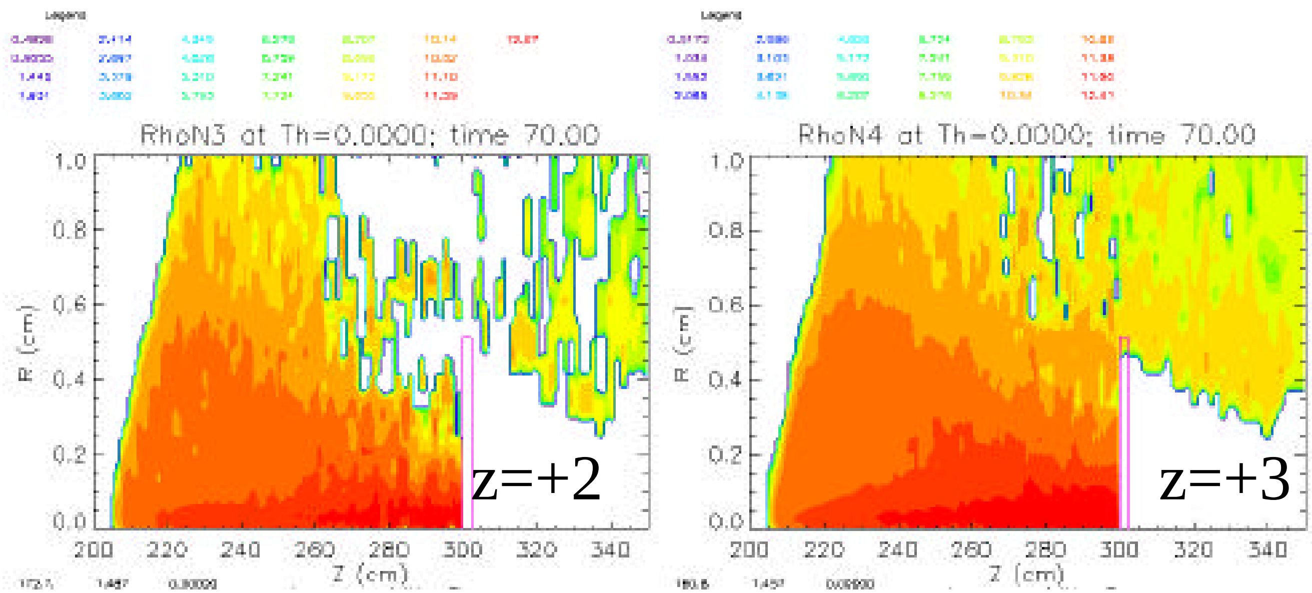
Log n_e

Legend

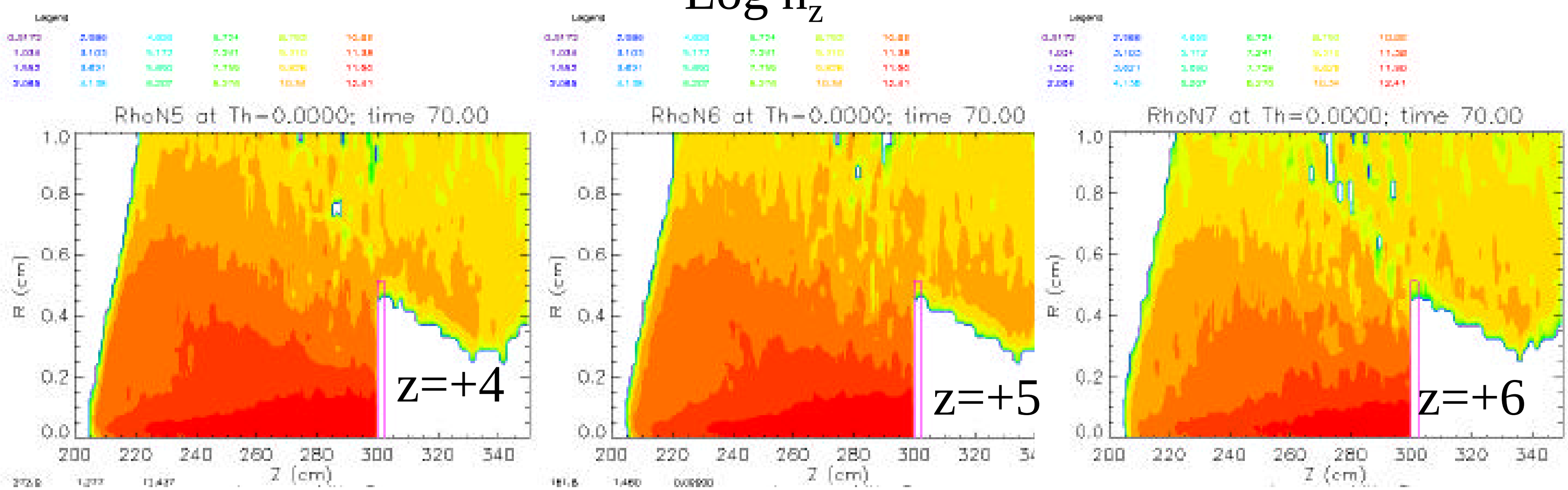
0.5000	2.848	5.198	7.543	9.891	12.24
1.087	3.435	5.783	8.130	10.48	12.83
1.674	4.022	6.370	8.717	11.07	13.41
2.261	4.609	6.957	9.304	11.65	14.00

- Foot12 - 13-cm plasma

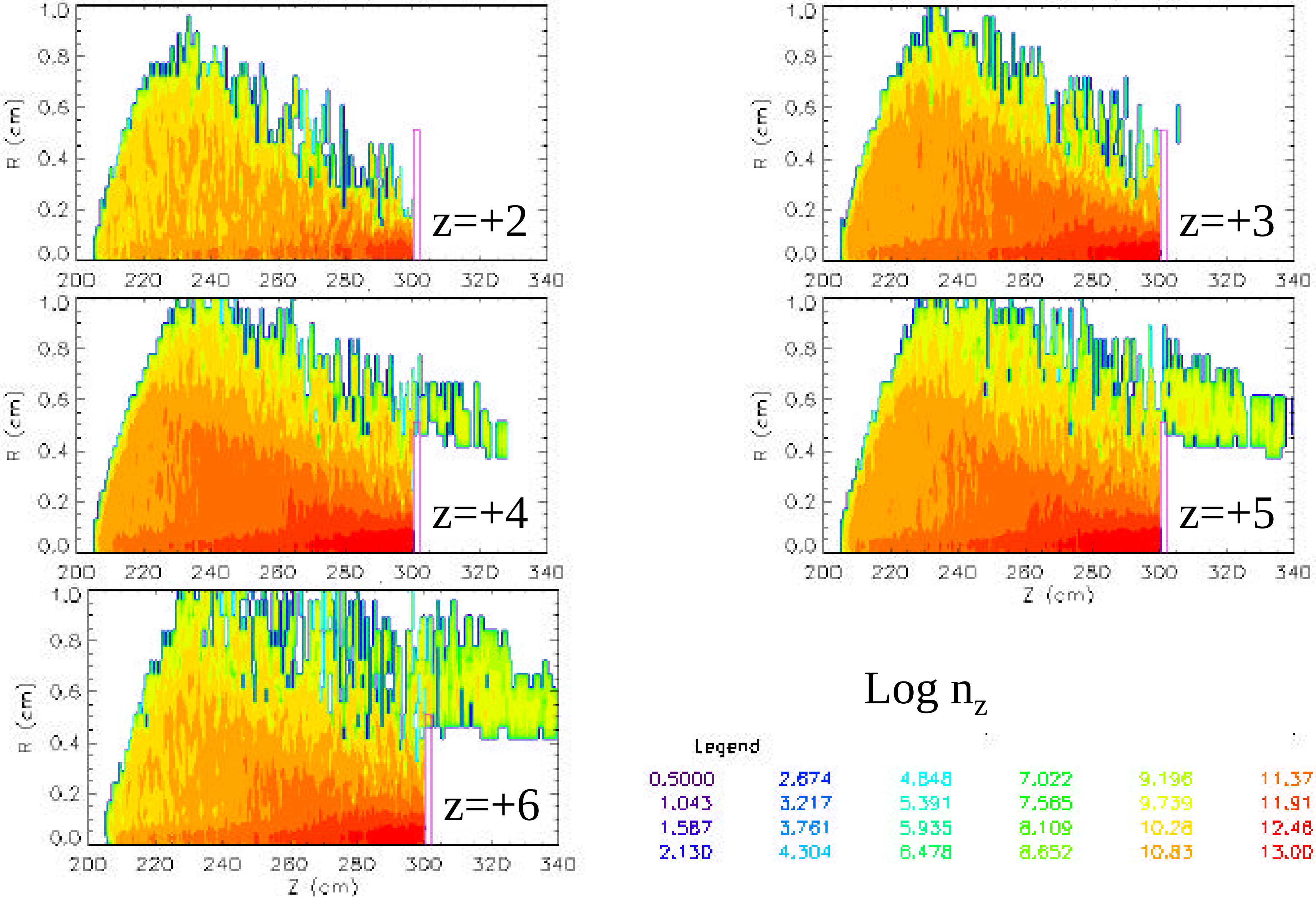
Charge states at 70 ns without plasma neutralization



Log n_z

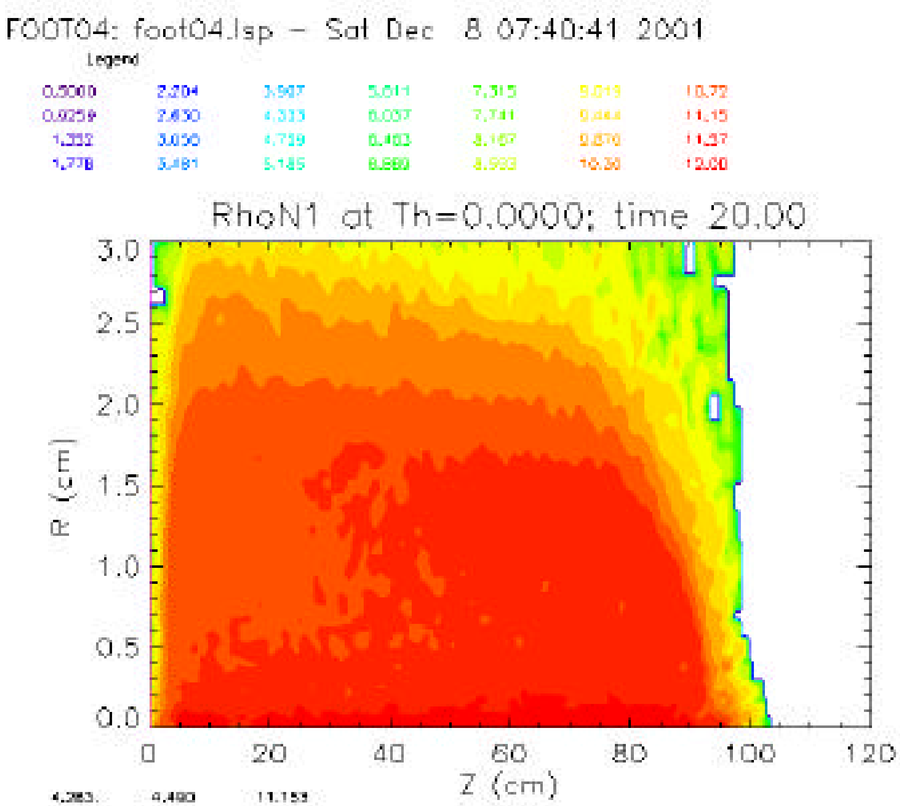


Charge states at 70 ns with plasma neutralization

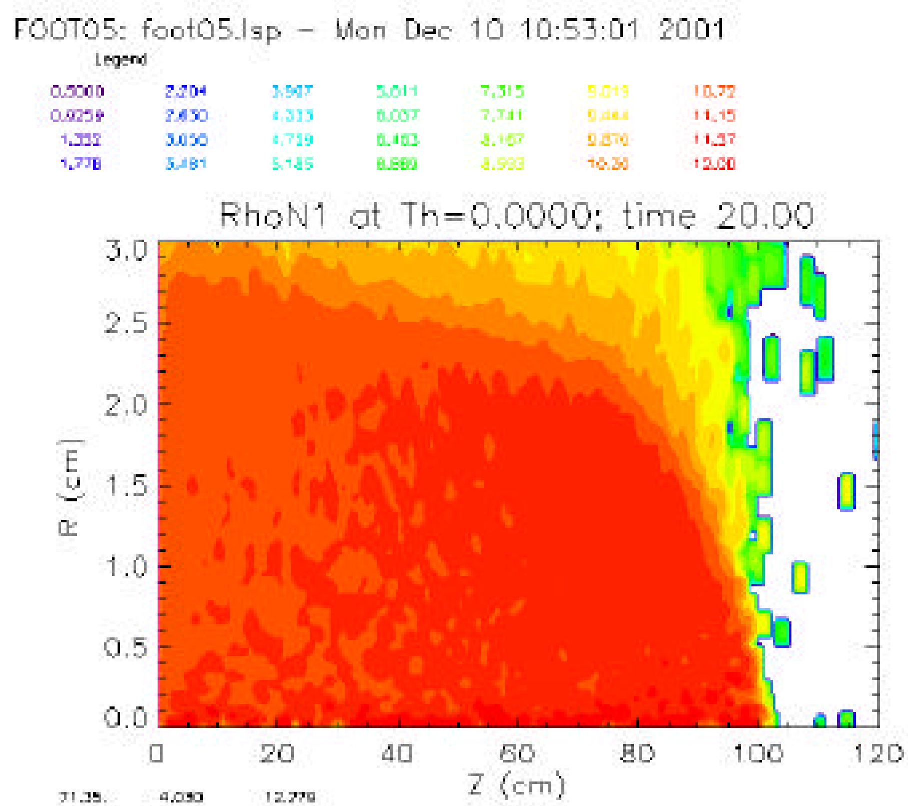


Improved neutralization near wall at larger radii

- Axially available electrons neutralize beam edge effectively, benefits extend well into chamber
- plot of Log n_e for identical beam parameters



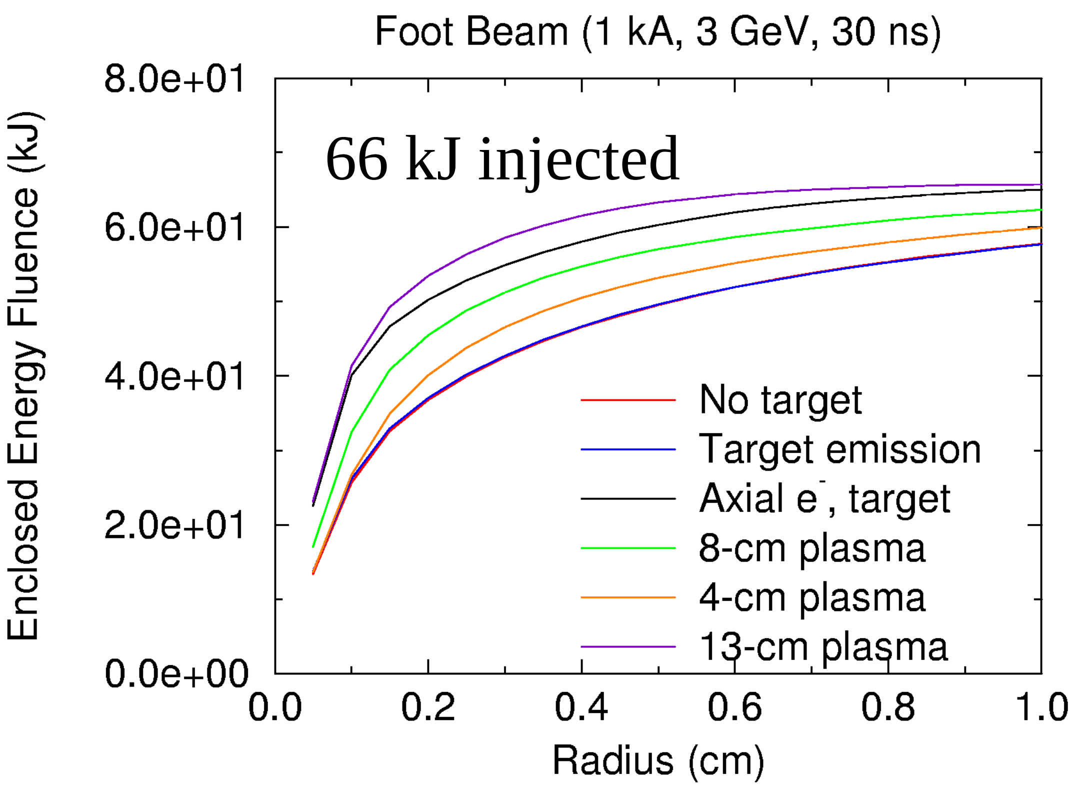
No axial e^-



Axial e^- source

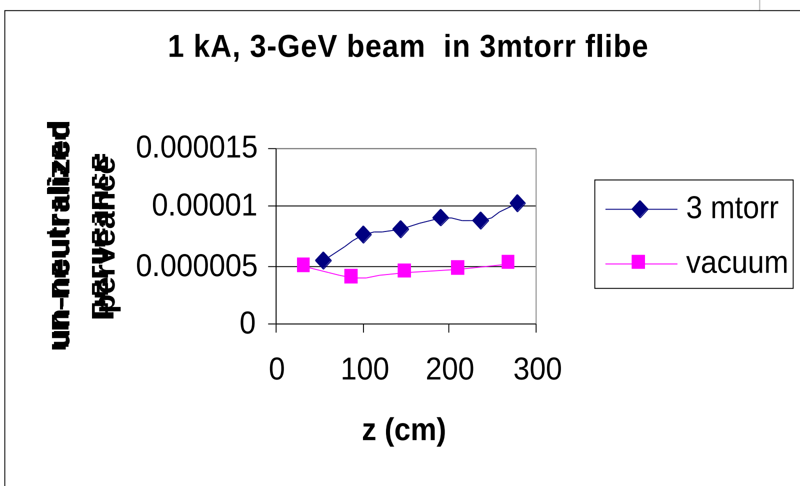
Integrated Energy Deposition

- Electron emission from target doesn't improve focus appreciably
- axial or plasma neutralization does help (< 3 mm spot)



We are characterizing beam and electron evolution for systems code

- Results from foot12, neut1 runs with 13-cm plasma
- C. Olson's and B. Oliver's α $m_e v_i^2$ residual charge with α ranging from 1-2 with 3 mtorr FLiBe to 0.75-1 for vacuum case
- K_u , unneutralized perveance, increases with Z due to stripping
- Beam emittance grows by > factor of 2 in 3 mtorr flibe



Run foot12		1-kA, 3-GeV Pb				Neutralization at beam edge			
		bms		electrons			1/2mv2=	7.7	
	z (cm)	radius(cm)	emit	radius(cm)	emit	radius	Er(kV/cm)	Phi(kV)	Ku
	20	2.12	1.15E-04	2.7	0.15				
	55	1.72	1.17E-04	1.9	0.22	2.5	12.7	15.875	5.47E-06
	100	1.41	1.33E-04	1.5	0.23	2	22.2	22.2	7.66E-06
	145	1.1	1.83E-04	1.24	0.22	1.61	29.4	23.667	8.16E-06
	190	0.77	2.60E-04	0.95	0.2	1.3	41	26.65	9.19E-06
	235	0.5	3.43E-04	0.8	0.21	1	52	26	8.97E-06
	280	0.27	3.90E-04	0.82	0.33	0.58	104	30.16	1.04E-05
neut1		1 kA, 4-GeV Pb				Neutralization at beam edge			
		bms	(pi-rad-cm)	electrons	(pi-rad-cm)		1/2mv2=	10.22	
	z (cm)	radius(cm)	emit	radius(cm)	emit	radius	Er(kV/cm)	Phi(kV)	Ku
	34	1.85	1.13E-04	2.2	0.25	2.7	14.1	19.035	4.95E-06
	90	1.44	1.14E-04	1.65	0.24	2.13	14.2	15.123	3.93E-06
	150	1.05	1.21E-04	1.19	0.2	1.56	22.1	17.238	4.48E-06
	210	0.63	1.35E-04	0.9	0.18	0.973	37.72	18.35078	4.77E-06
	270	0.23	1.46E-04	0.79	0.21	0.4	99.7	19.94	5.18E-06

Conclusions

- Photo ionization plasma assists main pulse transport - but not available for foot pulse
- Without local plasma at chamber, beam transport efficiency is < 50% within 2 mm for "foot" pulse
- Electron neutralization from plasma improves efficiency to 85% - plasma plug greatly improves foot pulse transport
- Lower chamber pressure should help beam transport for both foot and main pulses given plasma at chamber wall
- 6-m NBT transport with good vacuum looks feasible for dry wall chamber design
- System code: "Alpha" factor for neutralization roughly 1 in vacuum, increases with increasing pressure and propagation distance