

Neutralized Drift Compression

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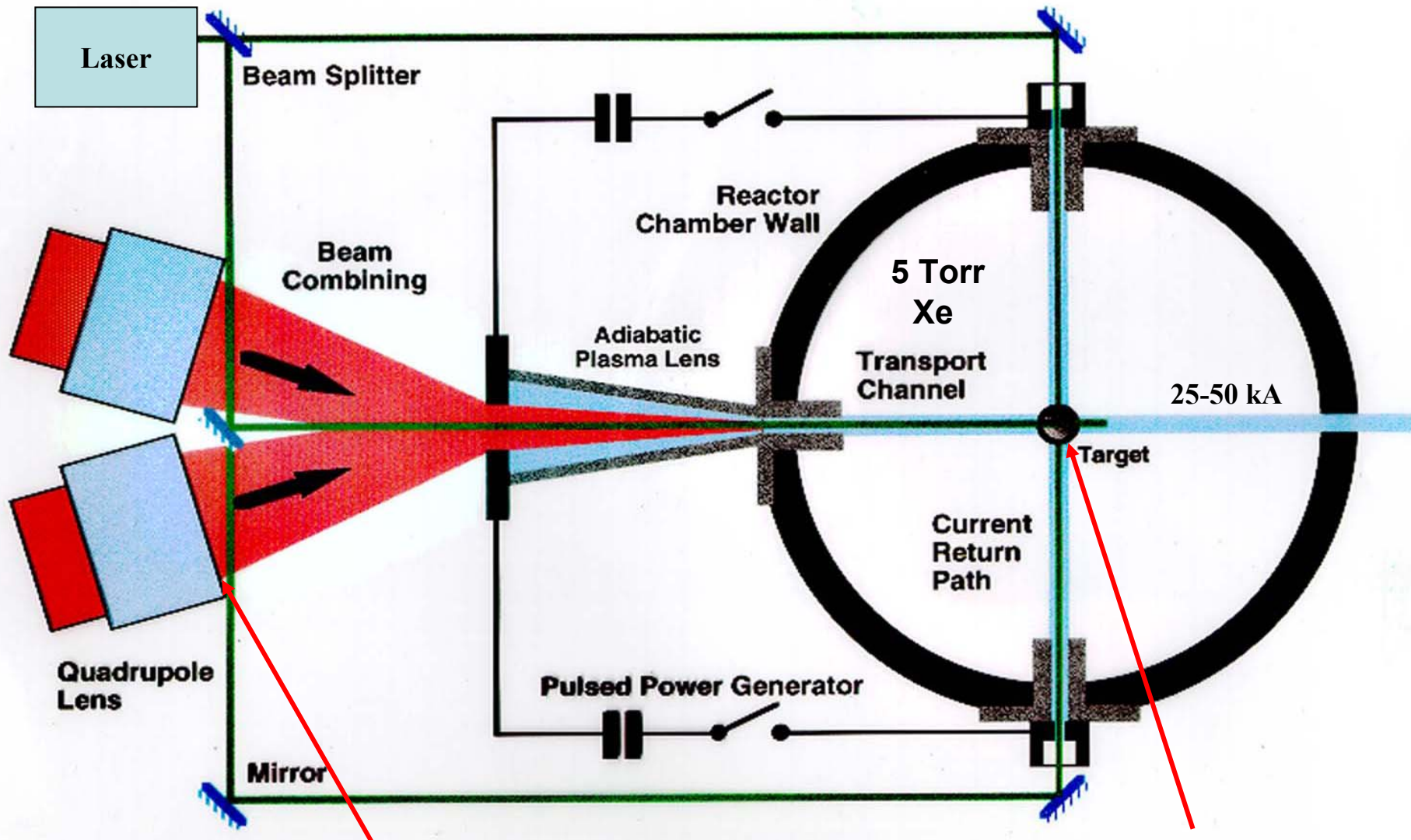
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Presented at the ARIES Project meeting
At LLNL, May 6, 2003

Beams must combine in all HIF transport scenarios

- For mainline Neutralized Ballistic Transport (NBT), the beams combine right at the target within a 2-3 mm radius
- For Assisted Pinched Transport (APT) and Self Pinched Transport, the beams combine at the Adiabatic Discharge Channel within a 1-cm radius
- 10-100's m neutralized drift compression envisioned for modular solenoidal transport

Assisted Pinched Transport can reduce chamber focus requirements and reduce driver costs - Back up to NBT

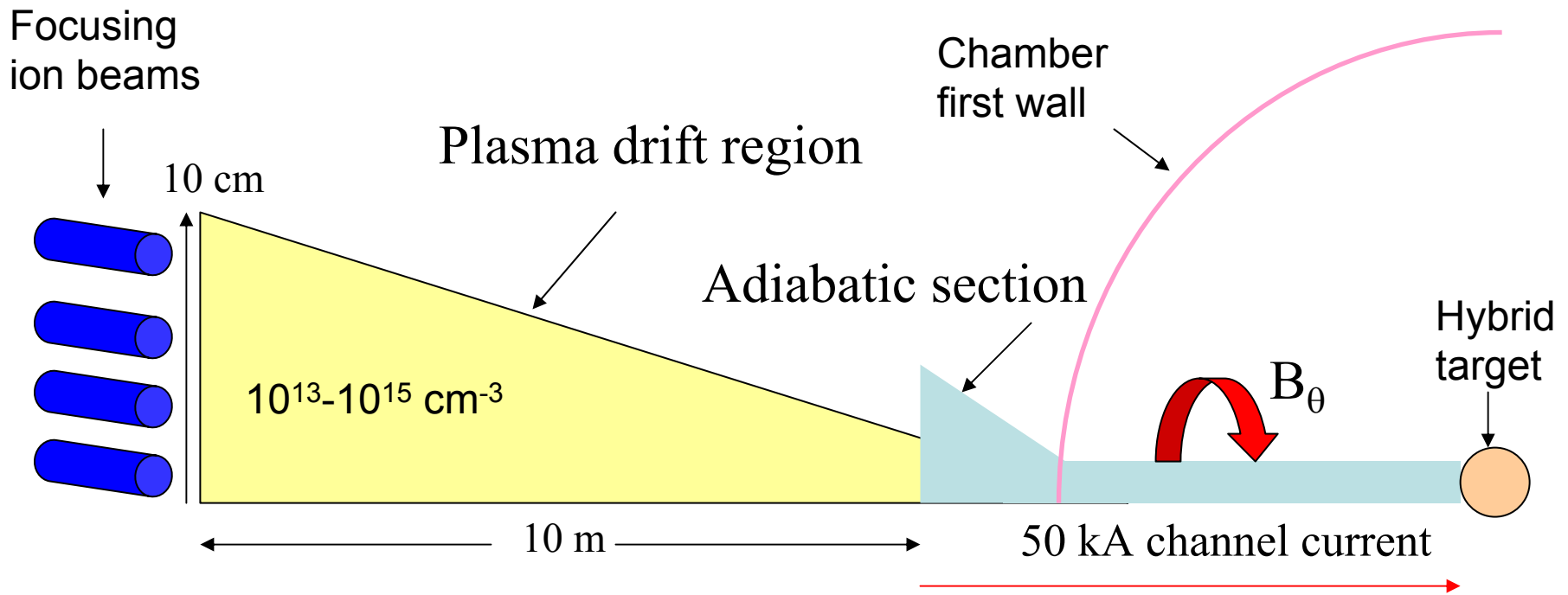


LSP simulation starts

Hybrid Target

Beams drift, combine and possibly compress in plasma drift region

- 10-80 beams per side
- Combined beams must focus to a 1-cm spot at the adiabatic discharge channel to couple to hybrid target (0.5-cm radiator - D. A. Callahan, M. C. Herrmann, M. Tabak, Laser and Particle Beams, **20**, 405-410 (2002).)



Goal is determine transport characteristics and stability regimes of compressing/combining beams in neutralizing plasma

Final focusing limits beam velocity tilt for compression to a few %

- For reasonable length simulations, we use large tilts and shorter drift lengths
- 2D calculations examine the two extremes in beam current
 - low current and longer drift length (30 m)
 - high-current but shorter drift length (10 m)
- 3D calculations look at high current beam combining
- A beam frame calculations would greatly speed these calculations

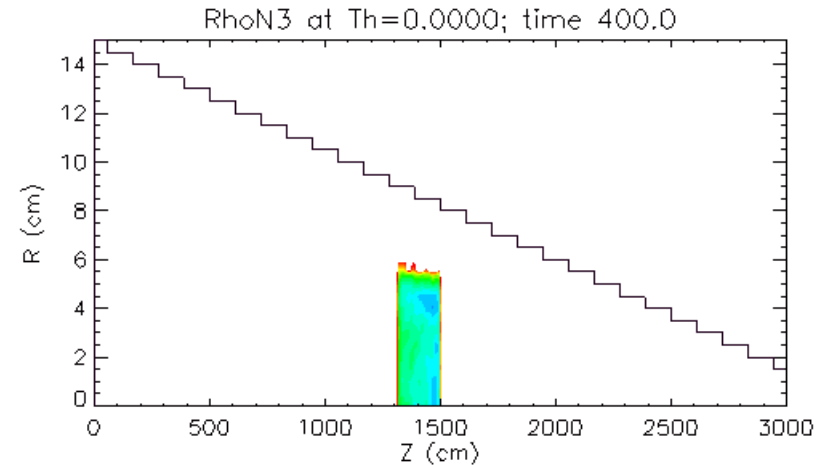
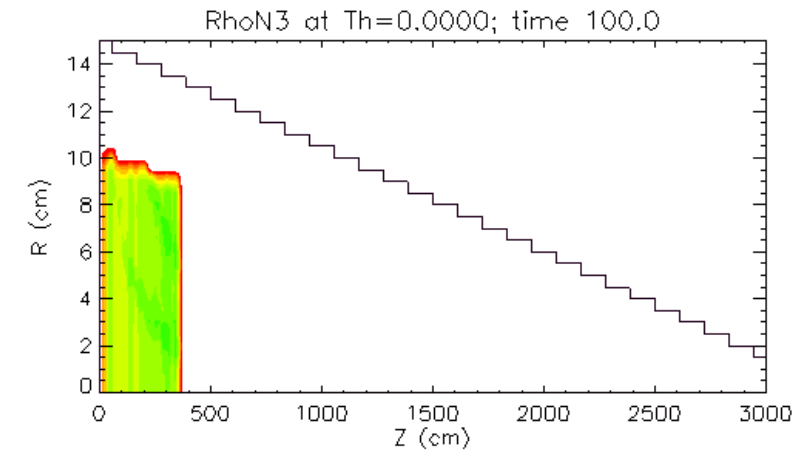
2D LSP Low-Current Parameters

- Ne⁺ ions
 - 100 ns pulse length at injection
 - 2 kA current, rising to 12 kA after 600 ns transport
 - 210 MeV Ne⁺ 2.5×10^{-3} perveance
 - injected in $r=10$ cm radius with 4π -mm-mrad emittance
 - v tilt: beta = .125-.145 in 100 ns (20 ns pulse after 600 ns drift)
- Uniform plasma fill of 4×10^{12} cm⁻³ density in conical drift tube
- LSP* used in direct-implicit mode
 - Constraints on simulation timesteps and cell sizes are greatly relaxed
 - Scattering and stripping is ignored

* T. P. Hughes, S. S. Yu, and R. E. Clark, Phys. Rev. ST-AB **2**, 110401 (1999); D. R. Welch, D. V. Rose, B. V. Oliver, and R. E. Clark, Nucl. Instrum. Meth. Phys. Res. A **464**, 134 (2001).

Simulation shows good transport

- Resolution becomes coarse for the beam at >600 ns
- Beam density begins lose sharp edge

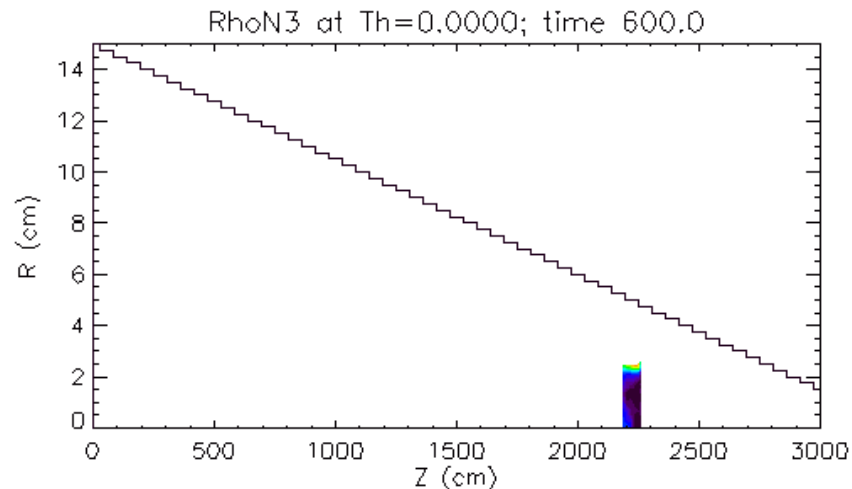


-527.8, 21.58, 0.00000

Legend

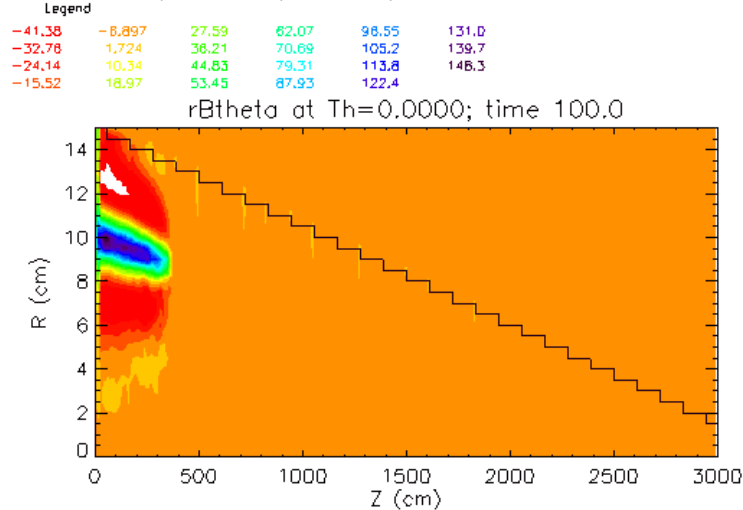
9.000	9.444	9.889	10.33	10.78	11.22	11.67
9.111	9.556	10.00	10.44	10.89	11.33	11.78
9.222	9.667	10.11	10.56	11.00	11.44	11.89
9.333	9.778	10.22	10.67	11.11	11.56	12.00

-243.1, 22.24, 0.00000



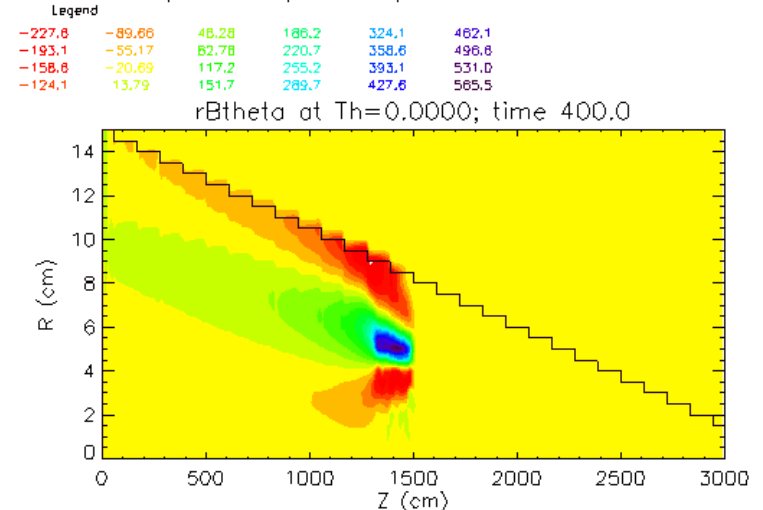
Net currents increase with distance

APT Plasma Transport: drift.jsp - Wed Apr 30 08:24:32 2003

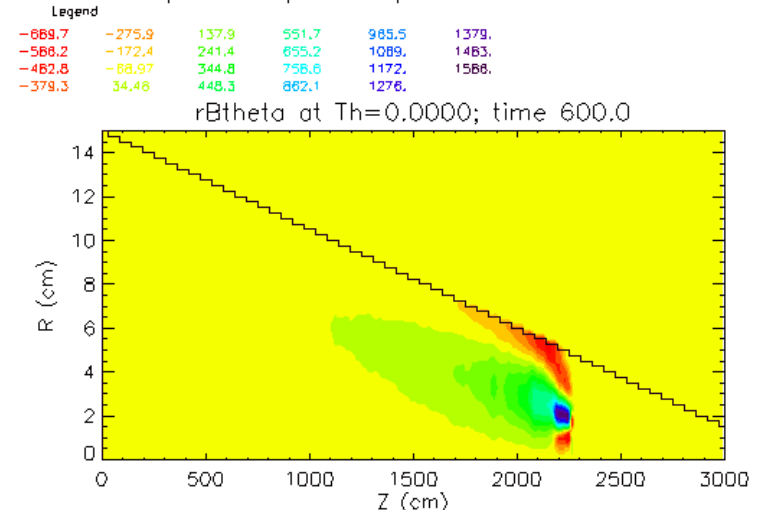


1132. 21.45 -2.2784E-008

APT Plasma Transport: drift.jsp - Wed Apr 30 09:07:03 2003



APT Plasma Transport: drift.jsp - Wed Apr 30 18:08:02 2003



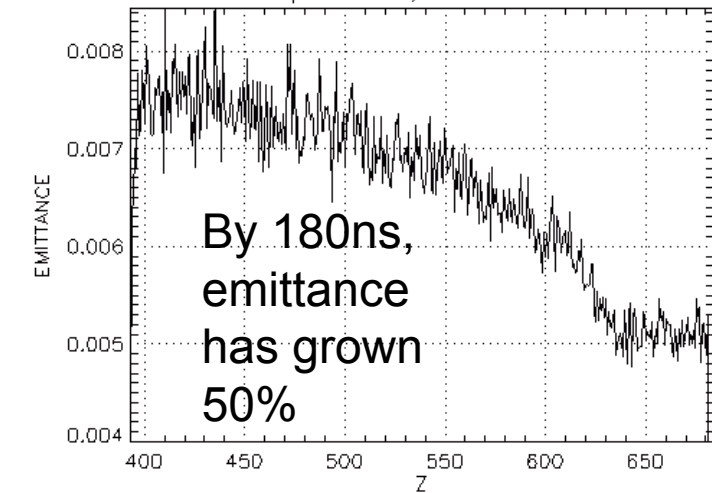
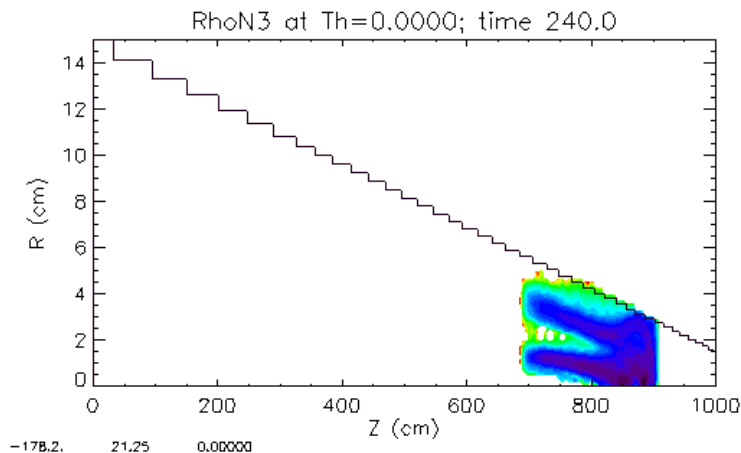
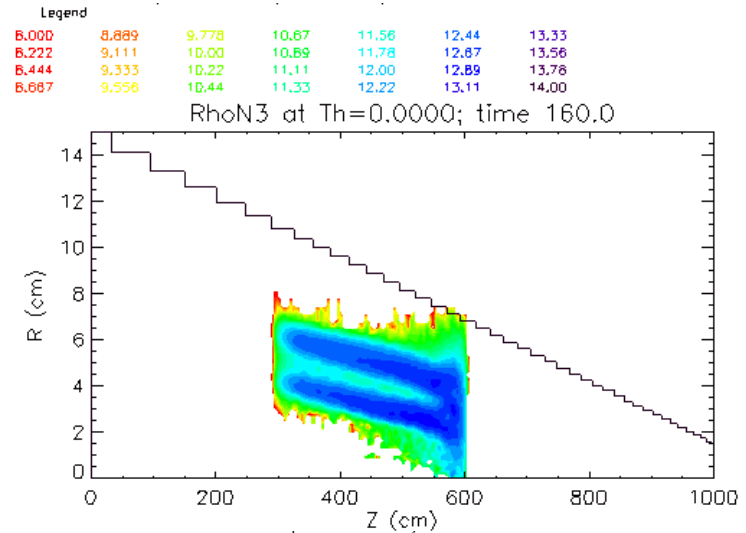
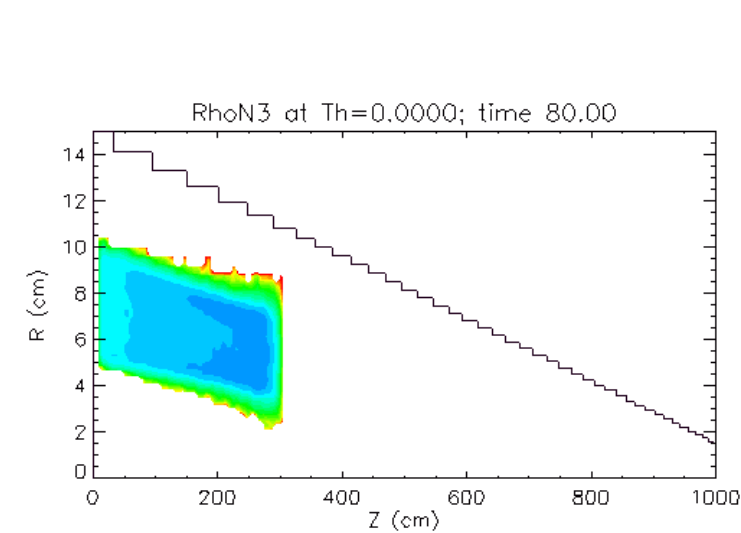
- Simple theory predicts 100 amp net current for 2 kA beam 1% of plasma density
- Beam emittance roughly doubles to 8π -mm-mrad by 600 ns
- No surprises

2D LSP High-Current Parameters

- Used several ions Ne^+ , K^+ , Xe^+ , Pb^+
- Uniform plasma fill with density roughly that of beam peak
- Solenoidal field 0-4 kG (uniform over simulation region)
- For Ne^+ :
 - 100 ns pulse length at injection
 - 150 kA current (combining 10 beams of 15 kA)
 - 210 MeV Ne^+ 0.1 perveance (3 MJ total energy)
 - injected in $r=5\text{-}10$ cm annulus
 - v tilt: $\beta = .125\text{-.}165$ in 100 ns (8 ns pulse after 14.5 m drift)
- Scaling of heavier mass ion simulation
 - Same velocity, m x more energy, $1/m$ x less current
 - Beam emittance was decreased with mass

10 x 15 kA Ne⁺ beams without B_z

- Ensemble given a 50- π -mm-mrad emittance (2 cm ballistic spot)
- Uniform 4x10¹⁴ cm⁻³ plasma density
- Charge neutralization is excellent – 99.99% neutralized at 160 ns
- Beam magnetically filaments radially, emittance increases 75- π -mm-mrad



Legend

6.000	8.889	9.778	10.67	11.56	12.44	13.33
6.222	9.111	10.00	10.89	11.78	12.67	13.56
6.444	9.333	10.22	11.11	12.00	12.89	13.76
6.667	9.556	10.44	11.33	12.22	13.11	14.00

10 x 15 kA Ne⁺ beams with B_z=1kG

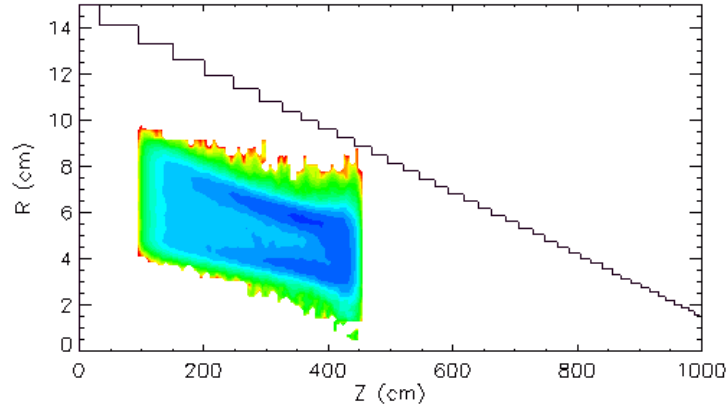
- Filamentation is reduced slightly with applied field
- Beam density from 120-280 ns

APT Plasma Transport: drift.jsp - Mon Apr 7 13:16:29 2003

Legend

6.000	8.889	9.778	10.67	11.56	12.44	13.33
6.222	9.111	10.00	10.89	11.78	12.67	13.56
6.444	9.333	10.22	11.11	12.00	12.89	13.78
6.667	9.556	10.44	11.33	12.22	13.11	14.00

RhoN3 at Th=0.0000; time 120.0

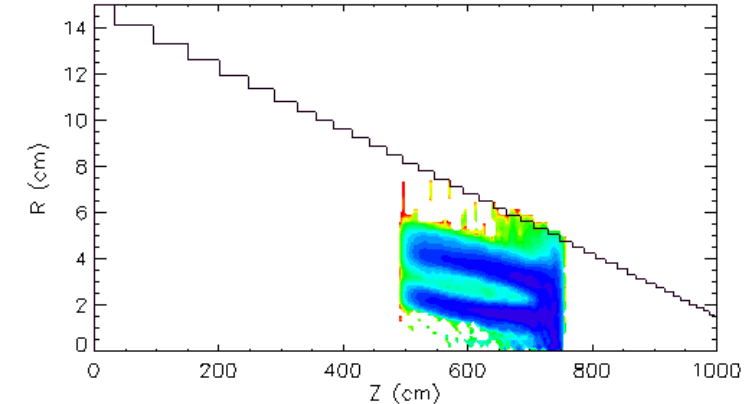


APT Plasma Transport: drift.jsp - Mon Apr 7 13:16:29 2003

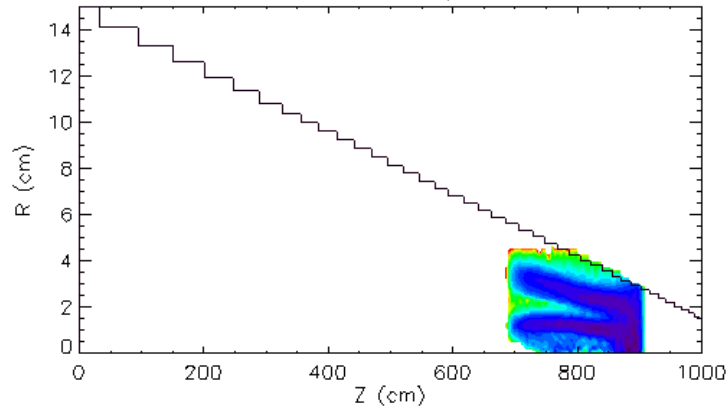
Legend

6.000	8.889	9.778	10.67	11.56	12.44	13.33
6.222	9.111	10.00	10.89	11.78	12.67	13.56
6.444	9.333	10.22	11.11	12.00	12.89	13.78
6.667	9.556	10.44	11.33	12.22	13.11	14.00

RhoN3 at Th=0.0000; time 200.0

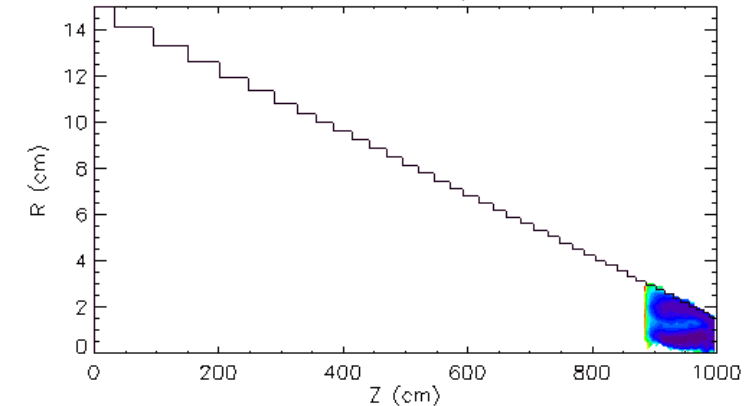


502.3, 20.50, 0.00000
RhoN3 at Th=0.0000; time 240.0



159.7, 21.81, 0.00000

-34.72, 21.94, 0.00000
RhoN3 at Th=0.0000; time 280.0



606.5, 20.06, 0.00000

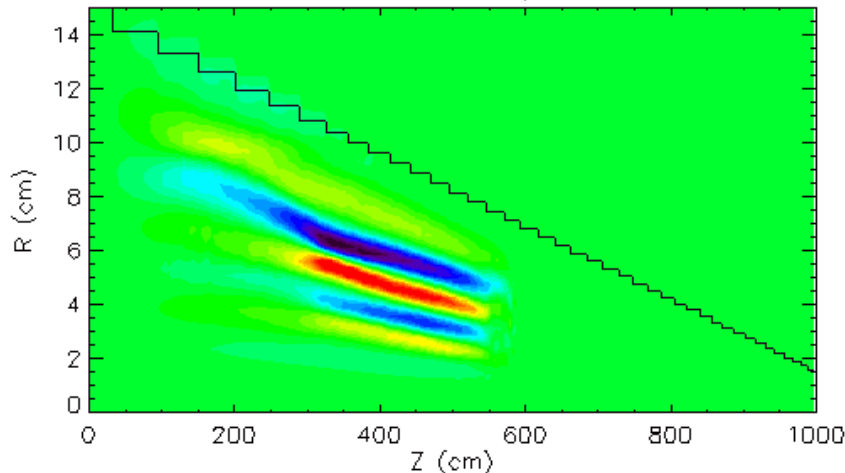
Significant net current at beam edges produce annulii

APT Plasma Transport: drift.lsp - Mon Apr 7 13:16:29 2003

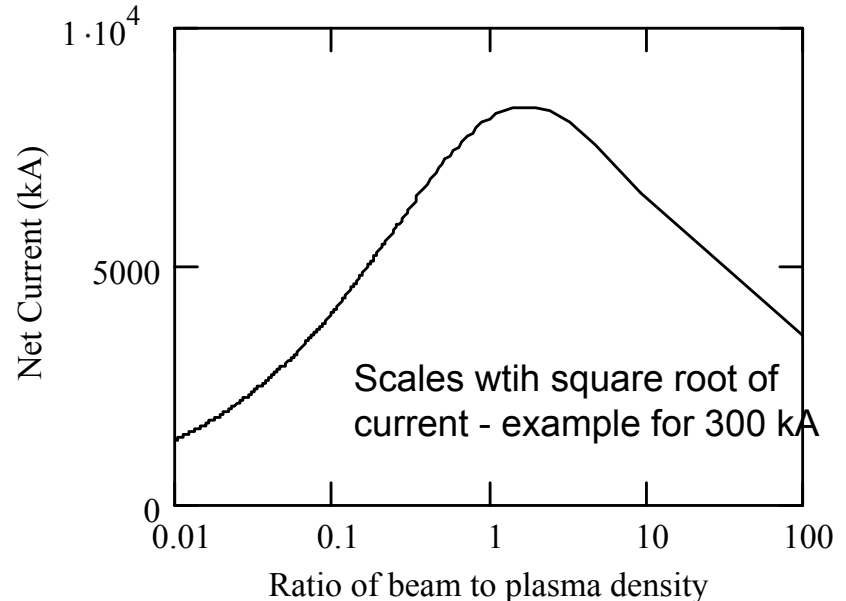
Legend

-2.000E+004	1.407E+004	-8148.	-2222.	3704.	9630.	1.558E+004
-1.852E+004	1.259E+004	-6887.	-740.7	5185.	1.111E+004	1.704E+004
-1.704E+004	1.111E+004	-5185.	740.7	6887.	1.259E+004	1.852E+004
-1.558E+004	9630.	-3704.	2222.	8148.	1.407E+004	2.000E+004

rBtheta at Th=0.0000; time 160.0



886.8. 20.56 4.6281E-005

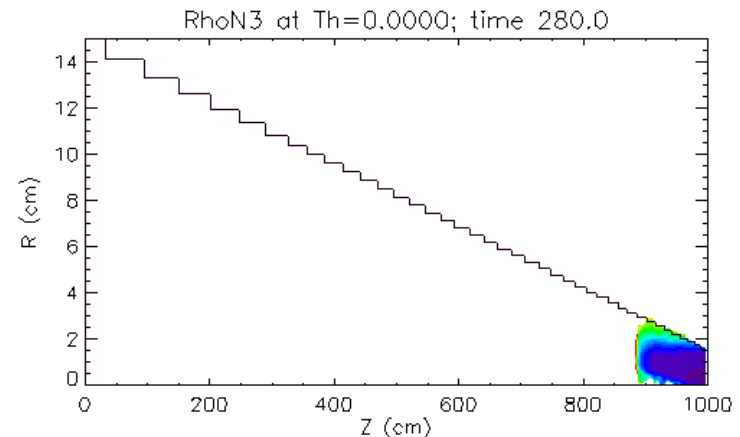
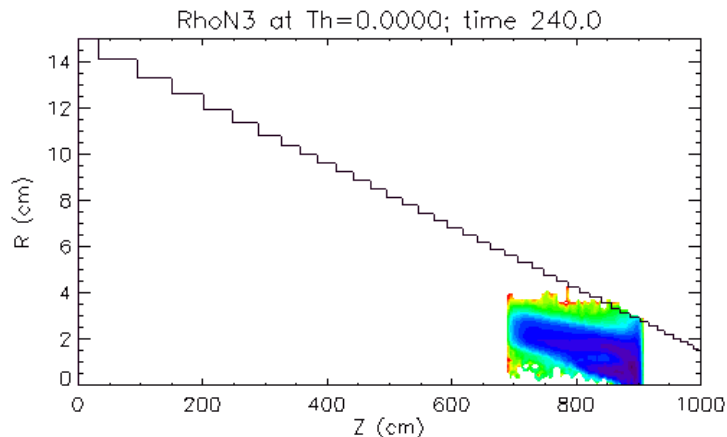
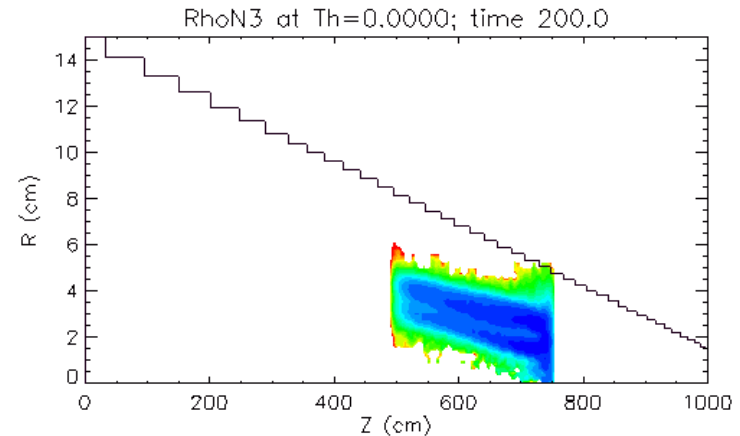
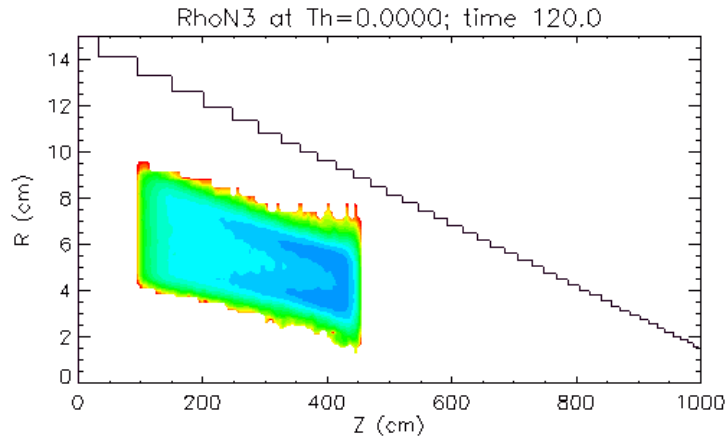
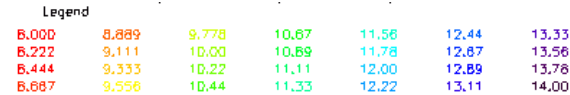


- No applied B field case
- Roughly 10-20 kA net currents (Amps) force concentric beam annulii to form - consistent with theory - D. R. Welch, D. V. Rose, B. V. Oliver, T. C. Genoni, R. E. Clark, C. L. Olson and S. S. Yu, Phys. Plasmas **9**, 2344 (2002).

Lower perveance beams should be less susceptible

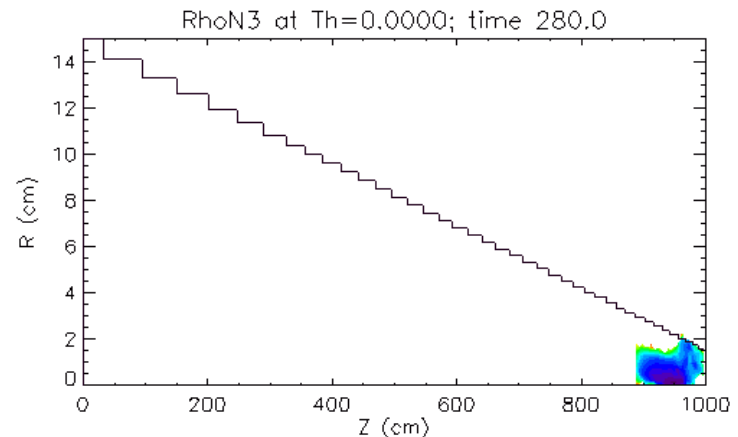
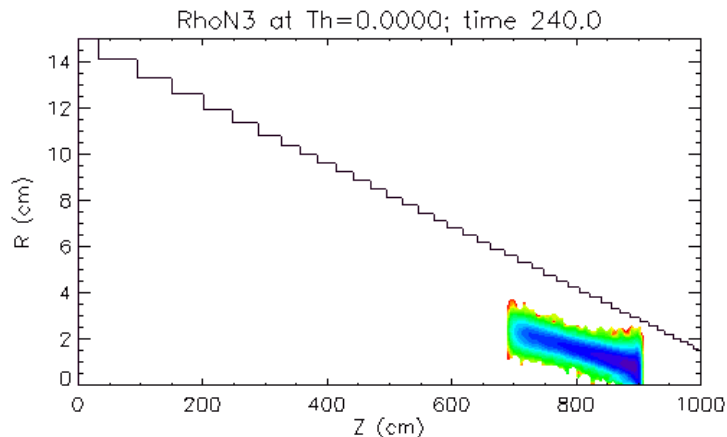
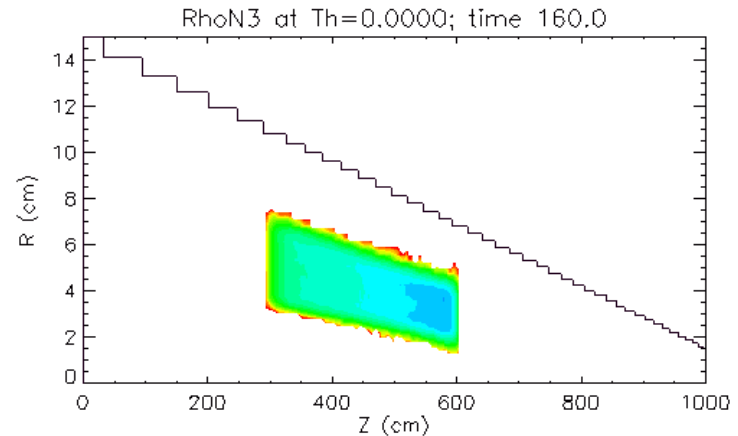
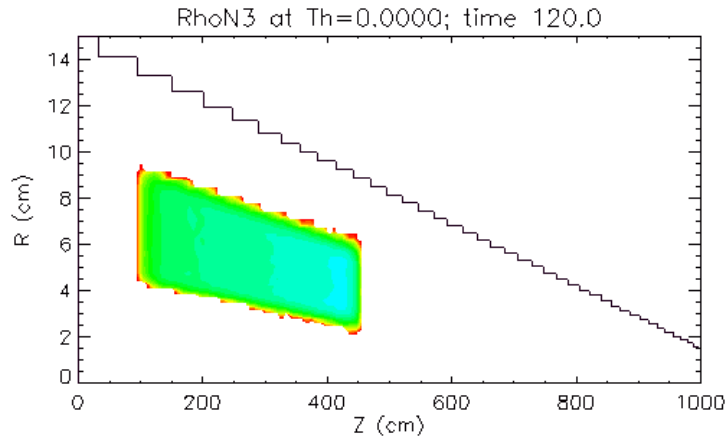
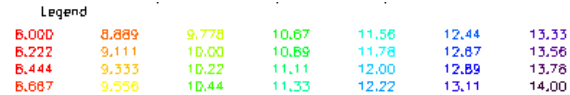
10 x 7.5 kA K⁺ beams show improved transport

- 32- π -mm-mrad beam emittance for a 1.4 cm ballistic spot (K = 0.025)
- $2 \times 10^{14} \text{cm}^{-3}$ plasma density
- K filamentation looks tolerable, emittance grows to 42 π -mm-mrad
- Beam density from 120-280 ns



10 x 2.3 kA Xe⁺ beams

- Beam emittance 13π -mm-mrad for a 0.6 cm ballistic spot, grows to 17.5
 - $K = 2.4 \times 10^{-3}$
- $6 \times 10^{13} \text{ cm}^{-3}$ plasma density
- Coupling to adiabatic discharge channel looks feasible
- Beam density from 120-280 ns

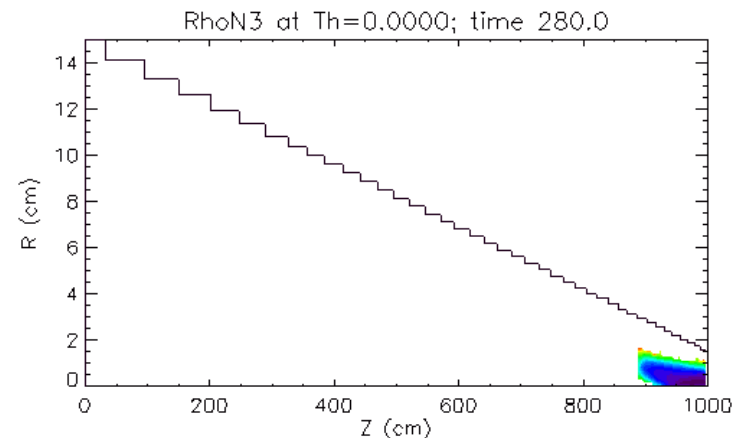
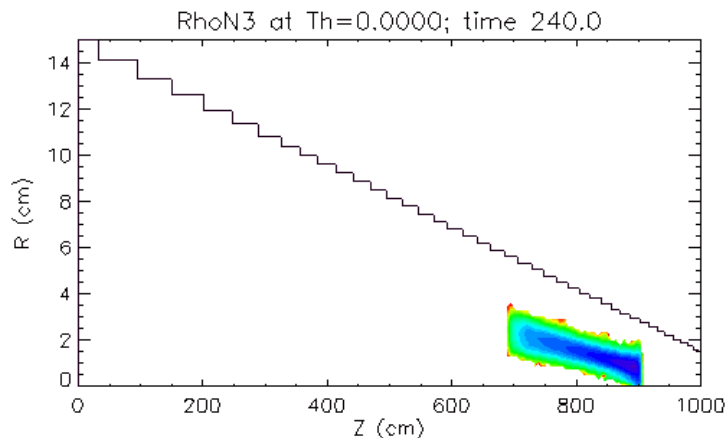
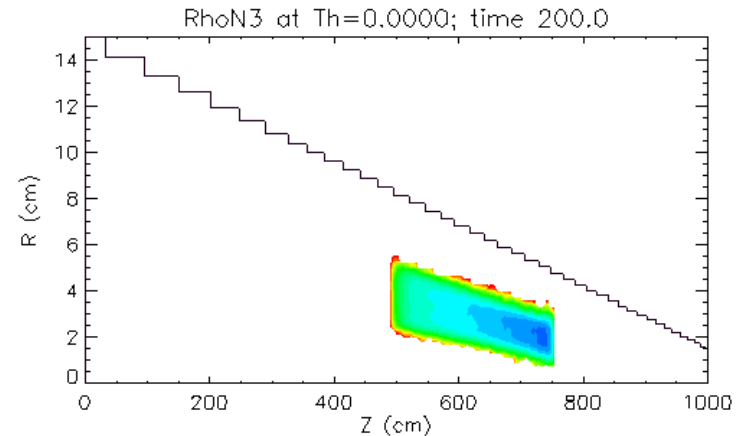
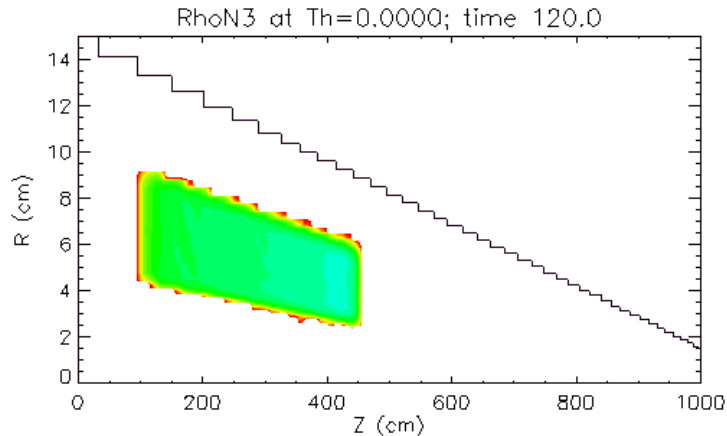


10 x 1.45 kA Pb⁺ beams

- Beam emittance 9.5π -mm-mrad for a 0.4-cm ballistic spot, grows to 10.7
– $K = 9.2 \times 10^{-4}$
- $4 \times 10^{13} \text{ cm}^{-3}$ plasma density
- Stiffer beam shows little filamentation, excellent spot
- Beam density from 120-280 ns

Legend

6.000	8.889	9.778	10.67	11.56	12.44	13.33
6.222	9.111	10.00	10.89	11.78	12.67	13.56
6.444	9.333	10.22	11.11	12.00	12.89	13.78
6.667	9.556	10.44	11.33	12.22	13.11	14.00

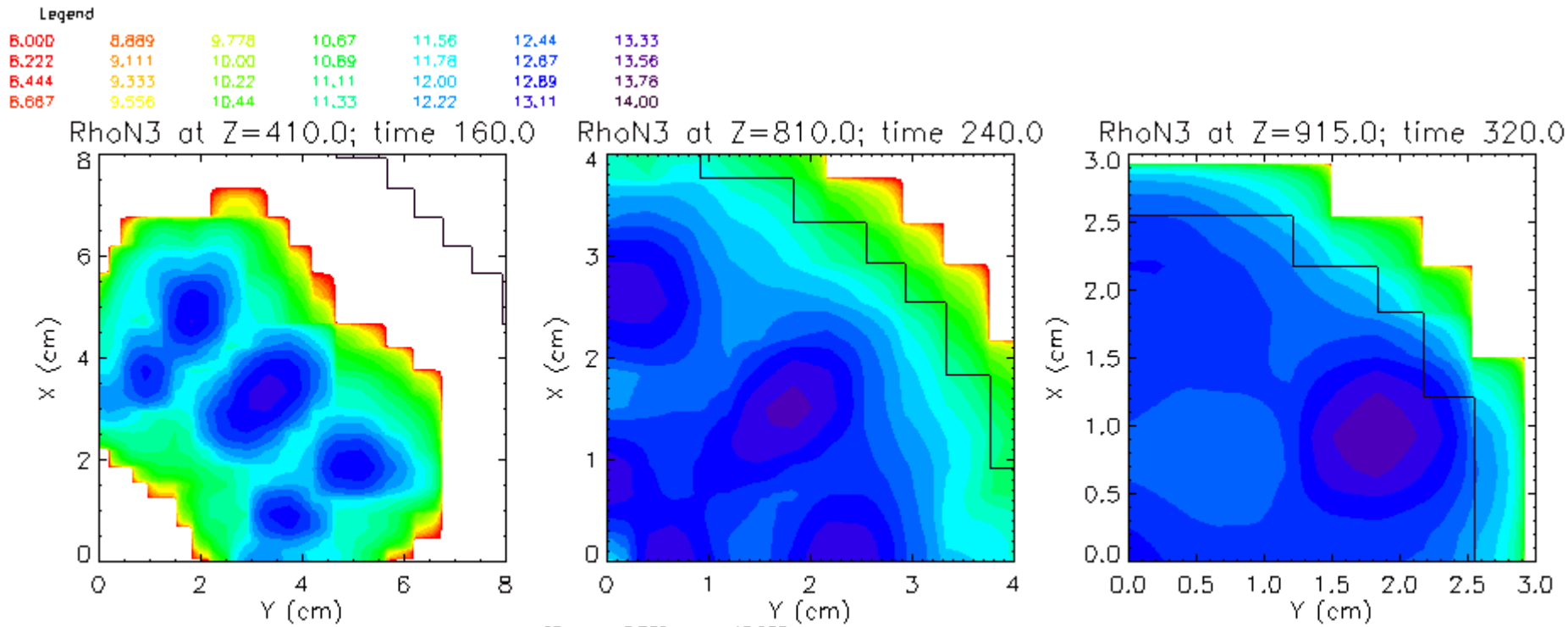


3D Lsp simulations with $\frac{1}{4}$ volume

- Direct-Implicit cartesian electromagnetic simulations
- Symmetry boundaries at $y=0$ and $x=0$
- 2 uniform density ion beams of 3-cm radii with edges just touching (slightly asymmetric in azimuth) – models 8 beams in full volume

Combined Ne⁺ beam filament

- 4×10^{14} cm⁻³ plasma density
- 5π -mrad-mm emittance
- Combined beam emittance grows to 86π -mrad-mm
- Filaments wash out near focus ($z > 800$ cm)



Beam density z=410 cm at 160 ns

z=810 cm at 240 ns

z=915 cm at 320 ns

K⁺ beams show 2d and 3d filamentation

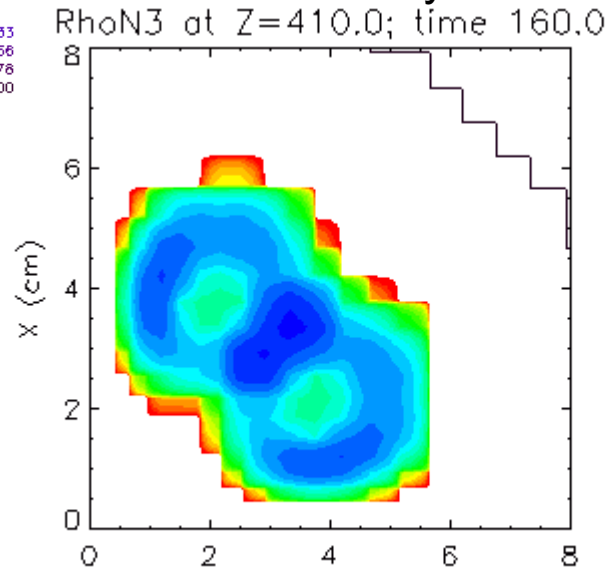
Legend

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6.222	9.111	10.00	10.89	11.78	12.67	13.56
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6.667	9.556	10.44	11.33	12.22	13.11	14.00

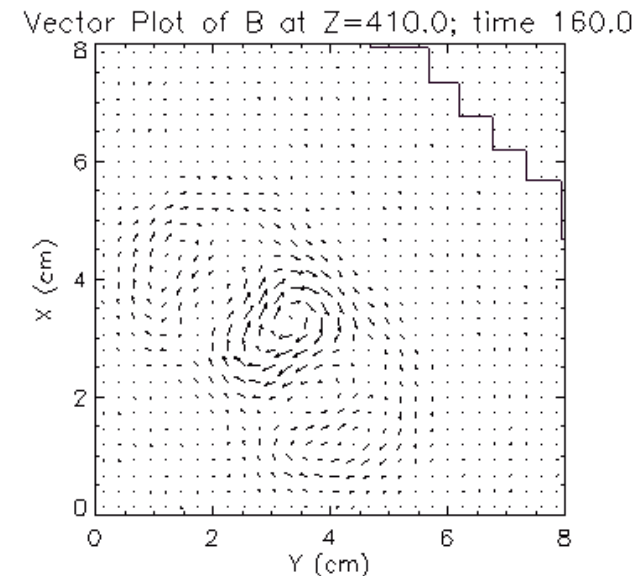
- 2×10^{14} cm⁻³ plasma
- Beamlets have 3 π -mrad-mm emittance
- 4.4 kG self B fields by 240 ns
- Combined beam emittance grows to 15 π -mrad-mm

Beamlets first radially filament, then the combined beams show m=8 azimuthal mode structure

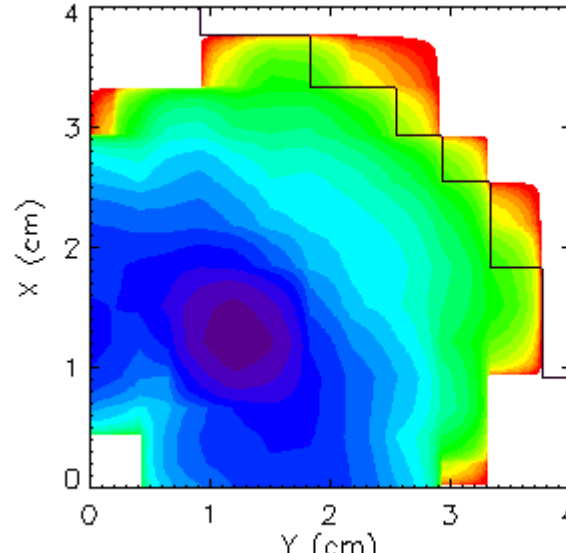
Beam Density



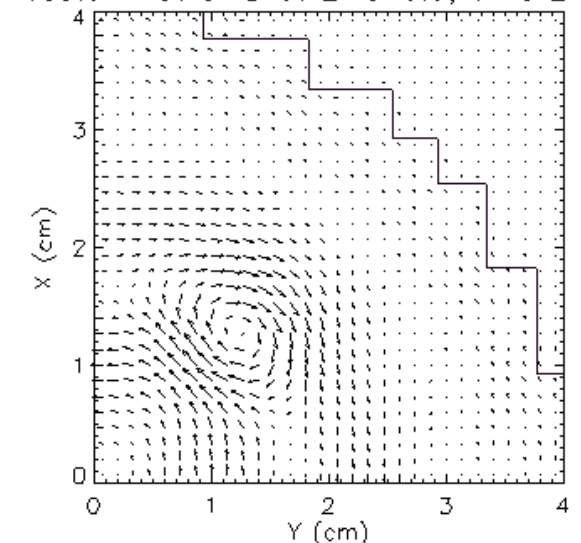
B field Vectors



RhoN3 at Z=810.0; time 240.0



9,571 Max. magnitude (3.333,2.800) : 1352.97

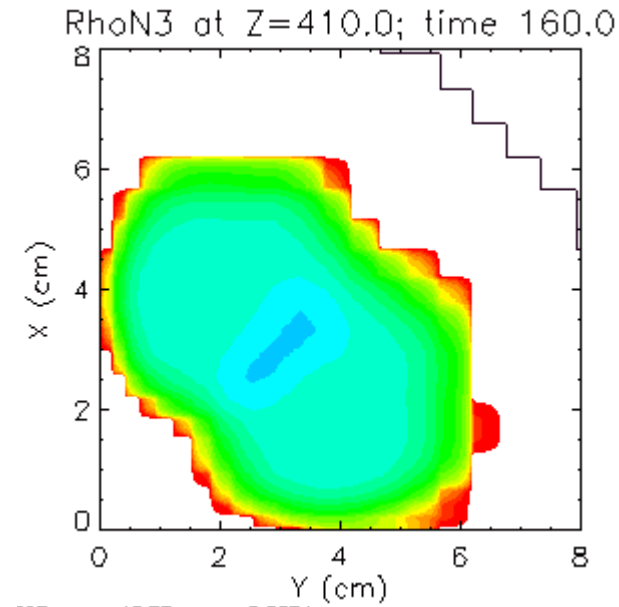
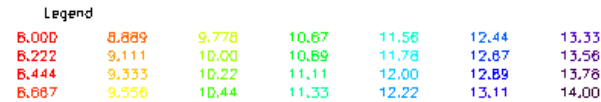


7.183. -0.2887 0.00000

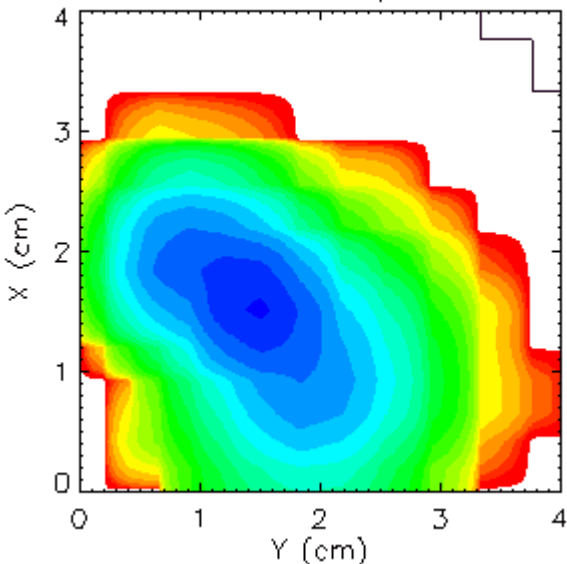
4,729 Max. magnitude (0.8667,1.000) : 4420.84

Xe beams combine quiescently

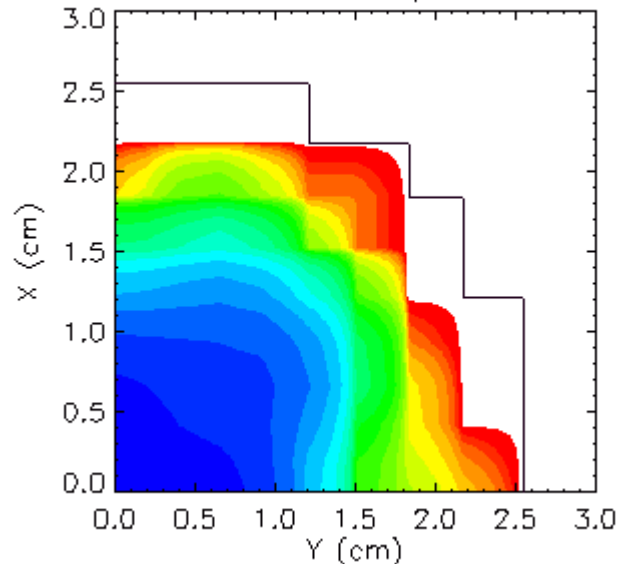
- Symmetry boundaries at $y=0$ and $x=0$
- 2 Xe⁺ beams of 3-cm radii
- 1.7 π -mrad-mm emittance
- 6×10^{13} cm⁻³ plasma density
- Combined beams reach desired 1-cm spot at 1000 cm
- Combined emittance grows to 15 π -mrad-mm



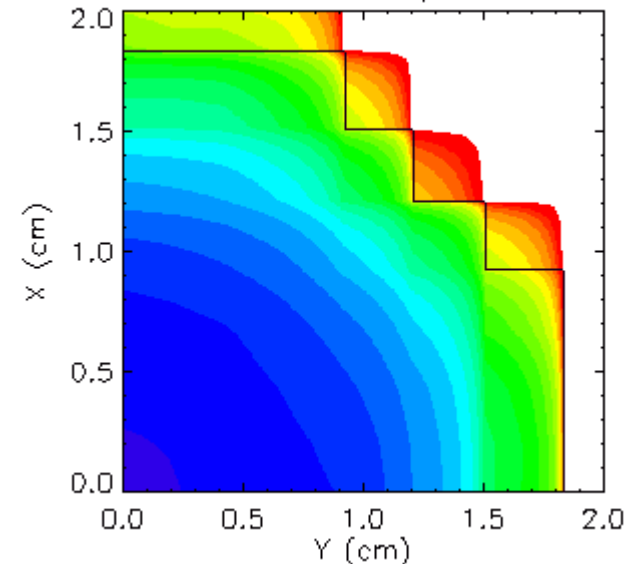
RhoN3 at Z=720.0; time 240.0



RhoN3 at Z=915.0; time 320.0



RhoN3 at Z=970.0; time 340.0



Beam frame option under development for LSP should allow longer transport simulations

- 1-cm, 10-kA beam in a $4 \times 10^{12} \text{ cm}^{-3}$ plasma example propagated 32 ns in the beam frame

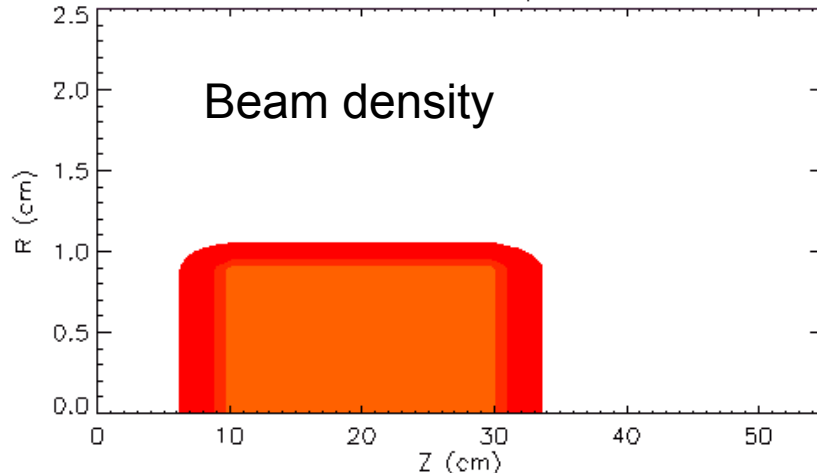
Mesh velocity, $0.2 c$ \longrightarrow

sim4 - moving: sim4.lsp - Thu Apr 24 19:33:53 2003

Legend

1.000E+012 3.815E+012 6.630E+012 9.444E+012 1.228E+013 1.507E+013 1.789E+013
 1.704E+012 4.519E+012 7.333E+012 1.015E+013 1.298E+013 1.578E+013 1.859E+013
 2.407E+012 5.222E+012 8.037E+012 1.085E+013 1.367E+013 1.648E+013 1.930E+013
 3.111E+012 5.928E+012 8.741E+012 1.156E+013 1.437E+013 1.719E+013 2.000E+013

RhoN3 at Th=0.0000; time 32.69



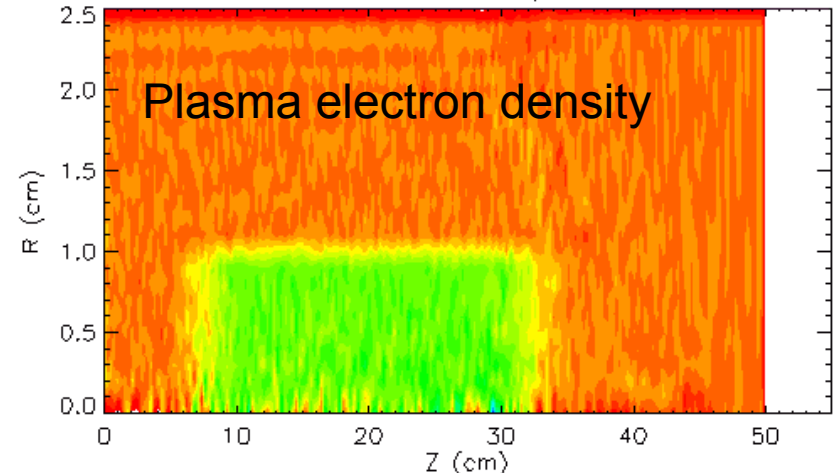
50.50, 3.552, 0.00000

sim4 - moving: sim4.lsp - Thu Apr 24 19:33:53 2003

Legend

1.000E+012 3.815E+012 6.630E+012 9.444E+012 1.228E+013 1.507E+013 1.789E+013
 1.704E+012 4.519E+012 7.333E+012 1.015E+013 1.298E+013 1.578E+013 1.859E+013
 2.407E+012 5.222E+012 8.037E+012 1.085E+013 1.367E+013 1.648E+013 1.930E+013
 3.111E+012 5.928E+012 8.741E+012 1.156E+013 1.437E+013 1.719E+013 2.000E+013

RhoN4 at Th=0.0000; time 32.69



19.43, 3.856, 1.0529E+013

Neutralized Drift Compression Summary

- Larger mass ions (eg. Xe^+ , Pb^+) exhibit good transport
 - should couple to APT transport channels
- “Low-current” drift compression of Ne^+ over 25 meters shows good transport with 6x compression
- Filamentation heats high perveance (low mass) ion beams to higher beam temperatures and larger spots
- Solenoidal field reduces filamentation – needs further study
- First look at neutralized drift compression for modular solenoidal transport encouraging