Beam Chamber Transport Requirements for Flibe Vapor Pressure and Aerosol Conditions

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Outline

Motivation

- transport modes
- effects of increasing line charge density

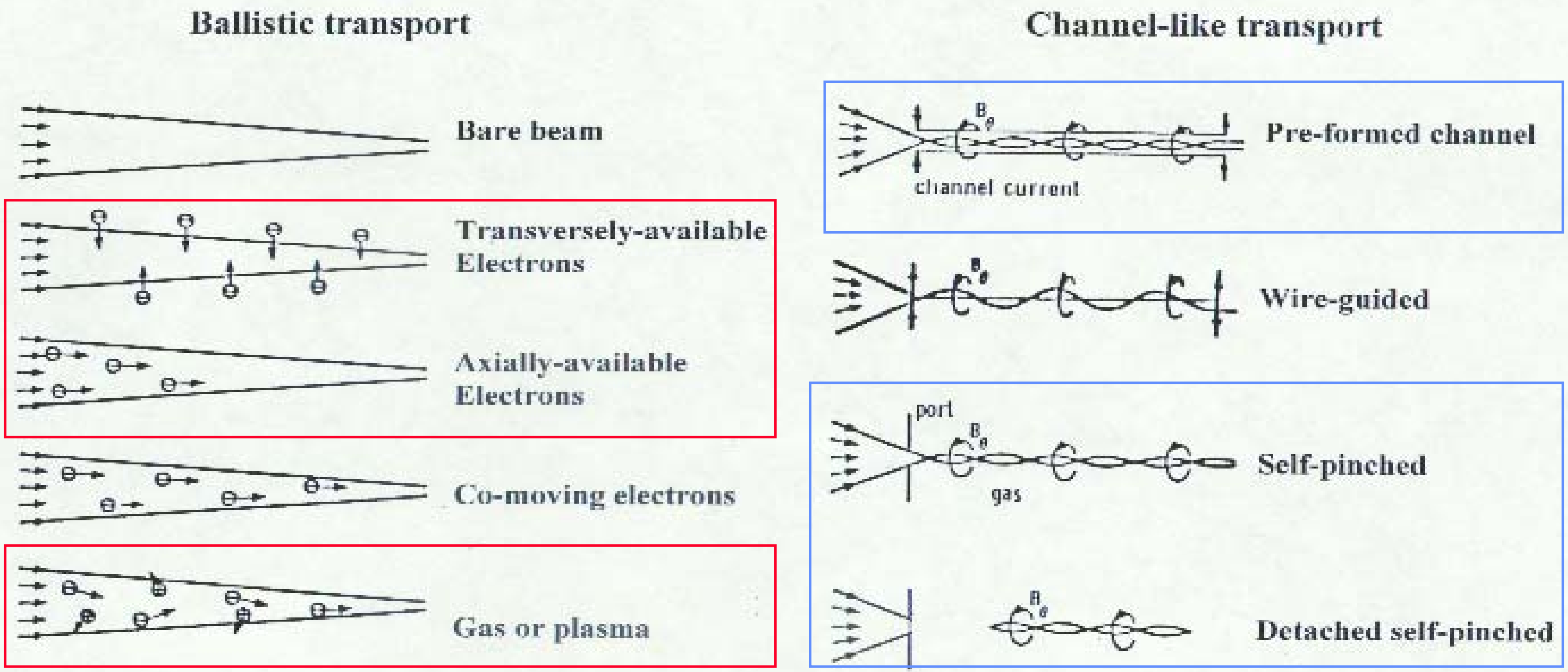
Aerosol effects on ballistic transport

- ∂E/∂x
- scattering
- stripping
- charged droplet effects
- micro-breakdown
- plasma-like effects

Net effect of aerosols

- integrated line density
- effects on ballistic, channel, self-pinched transport

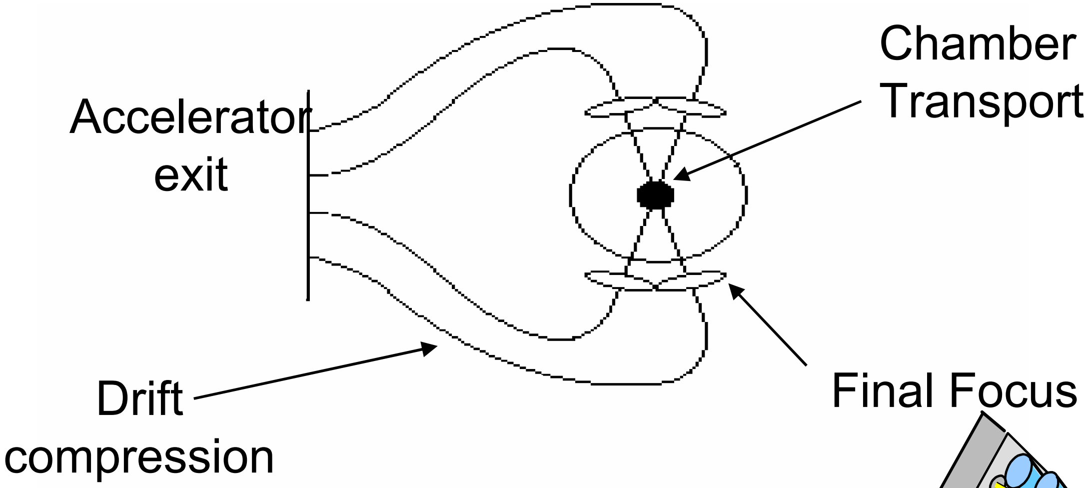
Ion Beam Transport Modes

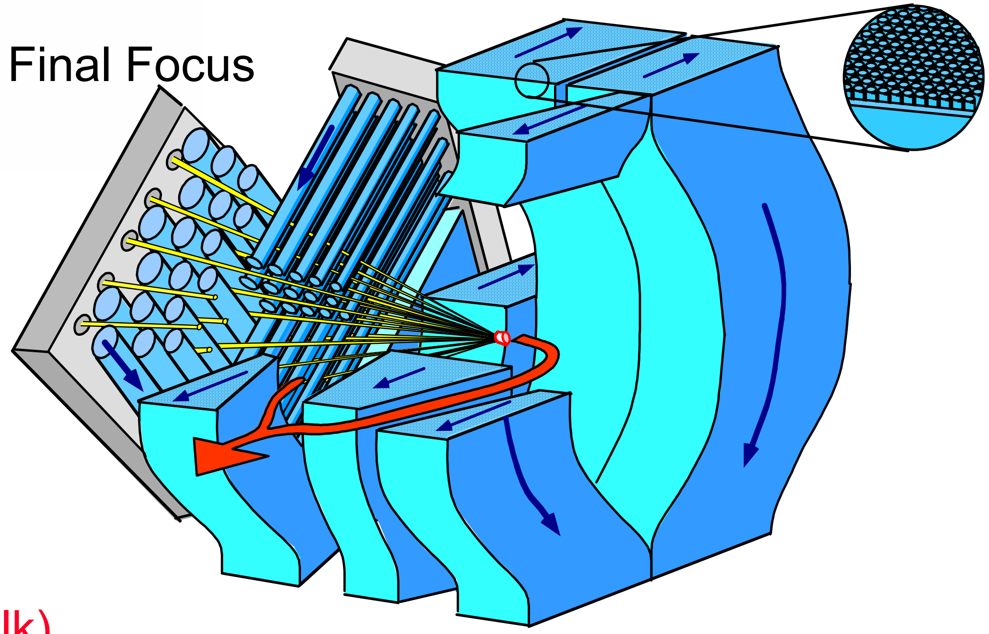


Neutralized Ballistic (mainline)

Pinch modes (backup)

Aerosols may affect neutralized ballistic transport with thick liquid walls (the mainline approach for HIF)





Multiple beams converge onto one side of target, and Flibe jets for thick liquid wall chamber

(Per Peterson HIF2002 Invited Talk)

ARIES-IFE Study of HIF - Aerosol Effects (●)

Transport Mode	Ballistic Transport *chamber holes ~ 5 cm radius* *most studied*		Pinch Transport *chamber holes ~ 0.5 cm radius* *higher risk, higher payoff*	
Chamber Concept	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	ARIES-IFE (2002) Possible option: but tighter constraints on vacuum and beam emittance	ARIES-IFE (2001) Option: uses 1-10 Torr *2 beams*	ARIES-IFE (2001) 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) ARIES-IFE (2002) Possible option: but tighter constraints on vacuum and beam emittance ●	ARIES-IFE (2001) Option: uses 1-10 Torr *2 beams* ●	PROMETHEUS-H (1992) ARIES-IFE (2001) 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) ARIES-IFE (2002) Main-line approach: uses pre-formed plasma and 1 mTorr for 3 meters *~50-200 beams* ●	ARIES-IFE (2002) Option: uses 1-10 Torr *2 beams* ●	ARIES-IFE (2002) Option: uses 1-100 mTorr ~2-100 beams ●

A Series of Scaled Experiments at LBNL will address science issues of HIF

Concept: keep perveance K at driver-scale, and progressively increase λ

FFSE (Final Focus Scaled Experiment) *electron neutralization* **Completed**

160 keV Cs^+, 95 - 400 μA, K = 1-4 x 10^{-5}, λ = 2-8 x 10^{-4} μC/m

NTX (Neutralized Transport Experiment) *neutralized ballistic transport* **Being set up**

400 keV K^+, 75 mA, K $\approx 10^{-3}$, $\lambda \approx 0.05$ μC/m

HCX (High Current Experiment) *quadrupole transport in accelerator* **Underway**

1.8 MeV K^+, 0.8 A K $\approx 10^{-3}$, $\lambda \approx 0.2$ μC/m

IBX (Integrated Beam Experiment) *first integrated system/bunching* **Proposed**

10-20 MeV K^+, 10 A (final) K $\approx 10^{-3}$, $\lambda_{final} \approx$ 1-2 μC/m

IRE (Integrated Research Experiment) *integrated system/heat matter* **Future**

200 MeV K^+, 500A (final) K $\approx$ 7.5 x 10^{-4}, $\lambda_{final} \approx 17$ μC/m

Several quantities scale with the line charge density λ

Beam potential: $\varphi_0 = qI_p/(\beta c) = \lambda$

Electric field at beam edge: $E_0 = 2\varphi_0/r_b = 2\lambda/r_b$

Current (electric): $I_e = \lambda\beta c$

Magnetic field at beam edge: $B_0 = 2I_e/(cr_b) = 2\lambda\beta/r_b$

Time scale for electron motion: $\tau = 2R/(\beta_e c)$ where $(1/2)m_e\beta_e^2c^2 = e\varphi_0$, so $\tau \sim \lambda^{-1/2}$

Beam density: $n_b = \lambda/(\pi r_b^2 qe)$

Beam plasma frequency: $\omega_{bi} = [4\pi n_b qe^2/(AM_p)]^{1/2} \sim \lambda^{1/2}$

Beam cyclotron frequency: $\omega_{ci} = qB/(AM_pc) \sim \lambda$

Example: FFSE, $\lambda \approx 8\text{x}10^{-4}$ μC/m, $e\varphi_0 \approx 8$ eV, $E_0 \approx 16$ V/cm (for $r_b = 1$ cm)

Driver, $\lambda \approx 80$ μC/m, $e\varphi_0 \approx 0.8$ MeV, $E_0 \approx 1.6$ MV/cm (for $r_b = 1$ cm)

Electron motion, non-local ionization, beam pinching, ω_{bi}, ω_{ci}, etc., increase with λ

Need to study possible aerosol effects as λ increases toward driver scale

Aerosol effects for neutralized ballistic transport

- $\partial E/\partial x$ find aerosol limit for 10% energy loss
- Scattering assume emittance dominated spot
  find limit for 10% increase in spot area (5% in radius)
- Stripping find limit for onset

- Charged droplets charging processes
  role of ion beam in charging
  max ϕ that droplet can attain
  simple deflection due to E

- Micro-breakdown fine mist, beam E leads to breakdown
  beam induced ionization of aerosol

- Plasma-like effects of "charged aerosol"

  Debye -like effects
  dusty plasma effects
  plasma waves, etc.

Fill fraction for droplets

Assume droplets are liquid spheres of radius r (all one size)
Assume packed like cubes, so $(2r)^3 = (1/n_{aerosol})f$ where f = fill fraction
$n_{aerosol}$ = aerosol density

So

$$\boxed{n_{aerosol} r^3 = (1/8) f}$$

	r(microns) for			:
$n_{aerosol}(cm^{-3})$	f=1	$f=10^{-3}$	$f=10^{-6}$	$f=10^{-9}$
10^{12}	0.5	0.05	0.005	0.0005
10^{9}	5	0.5	0.05	0.005
10^{6}	50	5	0.5	0.05
10^{3}	500	50	5	0.5
1	5000	500	50	5

Limits to $n_{aerosol}r^3$ in terms of equivalent density

For effects that depend only on integrated line density,

(e.g., $\partial E/\partial x$, scattering, stripping, …), use equivalent density:

$$n_{aerosol}\,N = n_{equivalent}$$

where N = #atoms/droplet = $(4/3)\pi r^3 n_{liquid}$

Therefore,

$$\boxed{n_{aerosol}\,r^3 = [3/(4\pi)]\,n_{equivalent}\,/\,n_{liquid}}$$

Now, calculate $n_{equivalant}$ for each effect

$\partial E/\partial x$ limit

Classical stopping (non-rel.):

$$-\partial E/\partial x = [(4\pi n Z q^2 e^4)/(m_e v^2)] \ln [m_e v^3/(\langle \nu \rangle Z e^2)]$$

incident beam ion: $+qe$, v
background medium: n(atom density), Z electrons/atom

Limit when $[-\partial E/\partial x]\, L = \eta\, E_0$ where η = fractional energy loss allowed

Therefore:

$$\boxed{n_{\text{equivalent}} = m_e v^2 \eta E_0/(4\pi Z q^2 e^4 L\, \mathit{ln}[\ ])}$$

For: 4 GeV Pb, $L = 500$ cm, $\eta = 0.1$, $Z = 3$, $\mathit{ln}[\ ] = 5$;

$n_{\text{equivalent}} = 4.2 \times 10^{21}\ \text{cm}^{-3}$ for $q = +1$
$4.2 \times 10^{19}\ \text{cm}^{-3}$ for $q = +10$
$6.2 \times 10^{17}\ \text{cm}^{-3}$ for $q = +82$

Scattering limit

Multiple small-angle scattering:

$\Theta_{rms} = [\langle\Theta^2\rangle]^{1/2}$ **where** $\langle\Theta^2\rangle = 2\pi nL[2qZe^2/(Mv^2]^2 \ln[b_{max}/b_{min}]$

incident beam ion: +qe, M, v
background medium: n(atom density), Z charge on nucleus

Limit when $\Theta_{rms} = [(1/2)\eta r_s]/[(1/2)L]$ **where** r_x **= spot radius**

Therefore:

$$\boxed{n_{equivalent} = [(\eta r_s Mv^2)/(L2qZe^2)]^2(2\pi L\, \mathit{ln}[\ \ ])^{-1}}$$

For: 4 GeV Pb, L = 500 cm, $\eta = 0.1$**, Z = 3,** $\mathit{ln}[\ \ ] = 5$**,** $r_s = 0.2$ **cm ;**

$n_{equivalent}$ = 1.06×10^{18} cm^{-3} for q = +1
1.06×10^{16} cm^{-3} for q = +10
1.58×10^{14} cm^{-3} for q = +82

Stripping limit

Use a pressure of 1mTorr to represent onset of damaging stripping effects

(based on LSP simulations of Welch and Rose)

Then:

$$\boxed{n_{\text{equivalent}} = 3.6 \times 10^{13}\ \text{cm}^{-3}}$$

Charges on aerosol droplets (“initial conditions”)

Example: H.E. Hesketh, Fine Particles in Gaseous Media (Lewis Pub., 1986) p.10, p.74.

“As aerosols, fine particles can have no charge, a positive charge, or a negative charge”

“Most particles larger than 1 μm in diameter have charge +1 as a result of diffusion charging”

Maximum possible charge (limited by air breakdown) is about +5 for a 0.1 μm particle (i.e., $Q/M < 10^{-7}\ e/M_p$)

Example: E.C. Whipple, “Potentials of Surfaces in Space,” Rep. Prog. Phys. 44, 1197-1250 (1981).

“Potentials of some tens of kV occur on objects in the solar system”

“Lack of hard data on charging of natural objects”

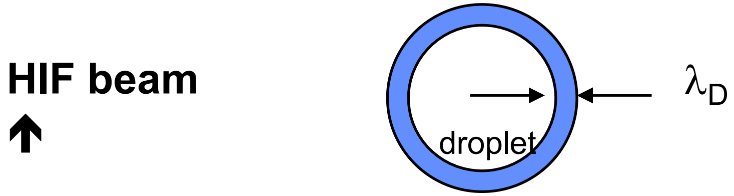
Example: V.W. Chow, D.A. Mendis, M. Rosenberg, “Role of Grain Size and Particle Velocity Distribution in Secondary Electron Emission in Space Plasmas,” J.G.R. 98, 19,065-19076 (1993).

“By virtue of being generally immersed in a plasma environment, cosmic dust is necessarily charged”

“We find that for thermal energies that are expected in several cosmic regions, grains of different sizes can have opposite charge, the smaller ones being positive while the larger ones are negative”

Charge may be + or -
Net charge to mass ratio is very small
Net potential is very small

HIF beam injection through charged aerosol droplet
LSP simulation results (see following talk by Rose et al.)



Net $e\phi \sim kT_e \sim 10$ eV

aerosol droplet may be initially charged, radius used is 1 μm
ion beam ionizes droplet and quickly forms plasma ($\sim 10^{16}/cm^3$, $\sim$ 10 eV)
plasma shields charged droplet and limits net potential to $e\phi \sim kT_e \sim 10$ eV
Debye sheath: $\lambda_D \sim v_e/\omega_{pe} \sim 0.2\ \mu m$
$E \sim \phi/\lambda_D \sim (10\ V)/(0.2\ \mu m) \sim 5x10^5$ V/cm, but only over 0.2 μm
maximum deflection of ion in sheath is negligible compared to r_s/L
$\lambda_D \ll r_{droplet}$

therefore, HIF beam deflection effects by "charged droplet deflection" are negligible

Droplet causes usual losses by $\partial E/\partial x$, scattering, and stripping

Integrated line density of aerosol droplets determines net effects

Possibility of micro-breakdown of fine aerosol mist

droplets inside the HIF beam quickly form plasmas
droplets outside the HIF beam could be subject to net beam fields

beam must be well-neutralized to hit target ($f_e \sim 0.98$),
so net potential and E_r of beam must be ~ (0.02)(bare beam values)

net value for an HIF driver beam would be $e\phi \sim 16$ keV
net minimum potential is given by $(1/2)m_e V_i^2 \sim 10$ keV

are these potential large enough to cause mist breakdown to nearby
surfaces?
if this could occur, it would try to draw in electrons radially, but would
not reduce the potential substantially
only potential damaging effect might be if nearby boundary is not

Effects appear to be negligible

Plasma-like effects of charged aerosol particles

behaves as a separate plasma species

charge/mass ratio is very low, so plasma frequency is very low

Debye shielding could occur (e.g., outside beam envelope) but
with little effect on the beam

plasma waves and instabilities could occur, but the time scale
would be very long compared to the beam pulse length

Example: M. Rosenberg, “Ion-Dust Streaming Instability in Processing Plasmas,” J. Vac. Soc. Technol. A 14, 631 (1996);
nominal parameters - dust radius 0.3 μm, density

Plasma-like effects of aerosols appear to be negligible for HIF

Examples of $n_{aerosol}r^3$ for ballistic transport

Recall: $n_{aerosol}\,r^3 = [3/(4\pi)]\, n_{equivalent} / n_{liquid}$

Use: $n_{liquid} = 10^{22}\ \mathrm{cm}^{-3}$

Then:
$n_{aerosol}\,r^3 = 1.0 \times 10^{-3}$ for $\partial E/\partial x$ limit for $q = +10$
$n_{aerosol}\,r^3 = 0.25 \times 10^{-6}$ for scattering limit for $q = +10$
$n_{aerosol}\,r^3 = 0.86 \times 10^{-9}$ for stripping

aerosol charge effects, micro-breakdown effects, plasma effects negligible

Worst case is for stripping

Example (use $n_{aerosol}\,r^3 = 1 \times 10^{-9}$):

$n_{aerosol}$ (cm^{-3})	r (micron)
10^{12}	0.001
10^{9}	0.01
10^{6}	0.1
10^{3}	1
1	10

Aerosol effects on neutralized ballistic transport

$$n_{aerosol}\, r_{aerosol}^{3} = 1\times10^{-9}$$

Stripping is dominant limit

Integrated line density equivalent to 1 mTorr

Aerosol effects on channel transport

Start with 1-10 Torr, and fully stripped beam

$\partial E/\partial x$ limit is $n_{equivalent} = 6.2 \times 10^{17}\ cm^{-3}$

scattering limit (for $\theta \sim 0.1$) is $n_{equivalent} = 3.95 \times 10^{16}\ cm^{-3}$

$n_{aerosol}\, r_{aerosol}^3 \approx 1 \times 10^{-6}$

Scattering is dominant limit

Integrated line density equivalent to ~ 1 Torr

Aerosol effects on self-pinched transport

Start with 1-100 mTorr, and fully stripped beam

$\partial E/\partial x$ limit is $n_{\text{equivalent}} = 6.2 \times 10^{17}$ cm^{-3}

scattering limit (for $\theta \sim 0.1$) is $n_{\text{equivalent}} = 3.95 \times 10^{16}$ cm^{-3}

BUT, self-pinched process will require $n_{\text{equivalent}} \approx 3.6 \times 10^{15}$ cm^{-3}

$$n_{\text{aerosol}}\, r_{\text{aerosol}}^{3} \approx 1 \times 10^{-7}$$

Self-pinched process is dominant limit

Integrated line density equivalent to ~ 100 mTorr

ARIES-IFE Study of HIF - Aerosol Effects Summary

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*	**N/A**	**N/A**	**N/A**	**N/A**
Wetted-wall *~ 4-5 meters to wall*	**N/A**	$nr^3 \leq 1x10^{-9}$ **integrated line n ~ 1 mTorr**	$nr^3 \leq 1x10^{-6}$ **integrated line n ~ 1 Torr**	$nr^3 \leq 1 \text{ x } 10^{-7}$ **Integrated line n ~ 100 mTorr**
Thick-liquid wall *~ 3 meters to wall*	**N/A**	$nr^3 \leq 1x10^{-9}$ **integrated line n ~ 1 mTorr**	$nr^3 \leq 1 \text{ x } 10^{-6}$ **Integrated line n ~ 1 Torr**	$nr^3 \leq 1 \text{ x } 10^{-7}$ **Integrated line n ~ 100 mTorr**

Conclusions for Aerosol Effects on HIF Transport

neutralized ballistic: most stringent
stripping sets limit
integrated line density
equivalent to 1 mTorr

channel transport: most forgiving
scattering sets limit
integrated line density
equivalent to 1 Torr

self-pinched transport: in between
self-pinch sets limit
integrated line density
equivalent to 100 mTorr

What needs to be done

1. **What needs to be done to complete this work?**
   Write up
   Determine if expected aerosol distribution is good enough
   Fix it if necessary

2. **What can be done by the ARIES team (or you) to address these issues?**
   Self-pinched transport theory (analytic envelope, LSP)
   Determine expected aerosol distribution

3. **What modeling/experimental work can be done to resolve these issues?**
   Ballistic transport experiments: NTX + metal arc source to make Al micro-particles
   IBX + aerosols
   Pinched mode transport experiments: Need high current!
   Not planned until IRE
   BUT, maybe high-Z ion diode or Mercury at NRL