# Self-Pinched Transport Modeling

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ARIES Project Meeting
Georgia Tech Conference Center
Atlanta, GA
September 3-5, 2003

# Outline

Self-pinched transport concept and research areas

Status of self-pinched transport at low pressures (trumpet)

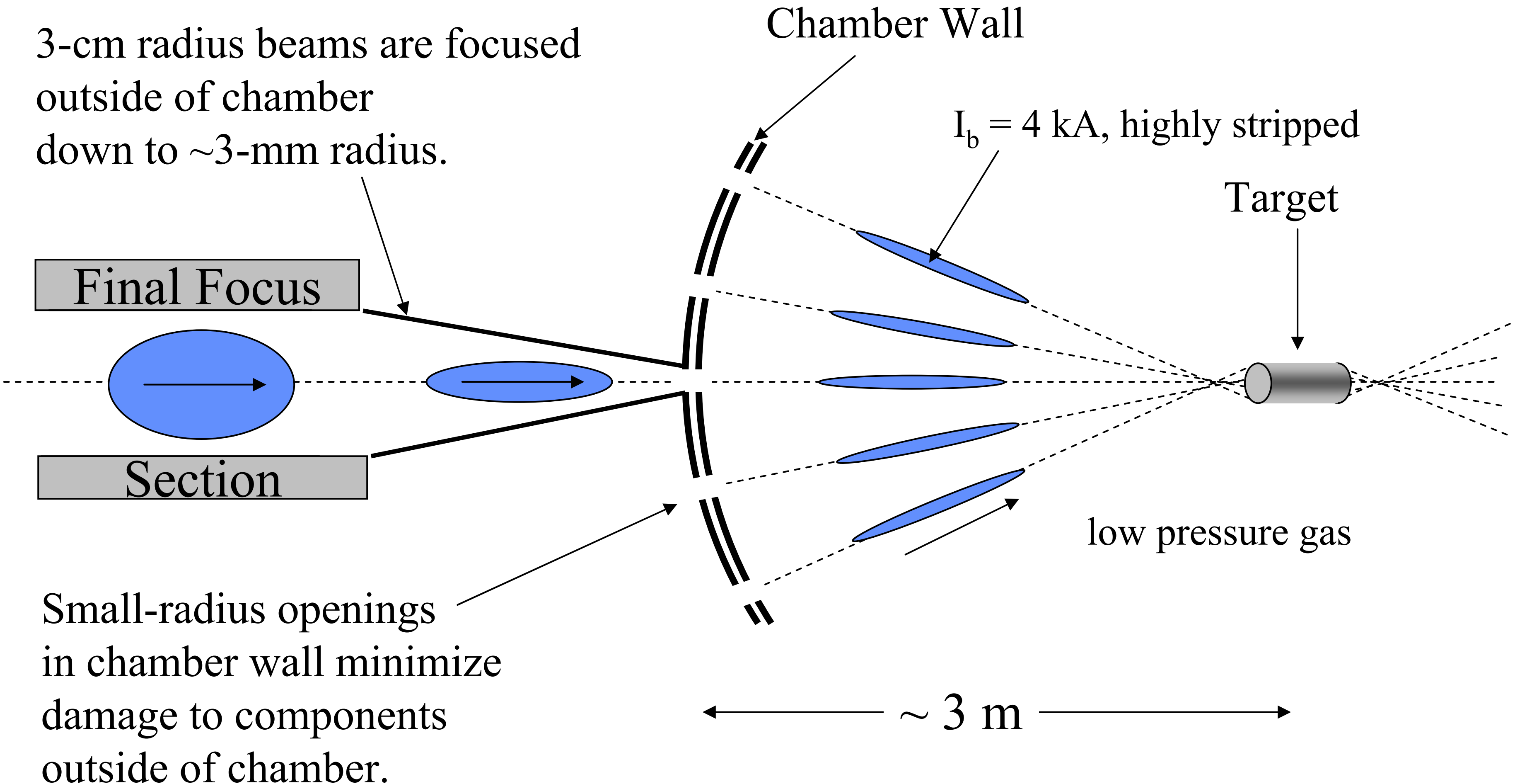
New analytical modeling of trumpet equilibria

Issues and research areas for future work

# Self-Pinched Transport Concept and Research Areas

Sandia National Laboratories   Mission Research Corporation

# Self-Pinched Transport should lead to the simplest, most attractive, least expensive chamber option for HIF



Chamber Wall

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

$I_b$ = 4 kA, highly stripped

Target

Final Focus Section

low pressure gas

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

# SPT can be used with all chamber concepts

## ARIES-IFE Study of HIF

| Transport Mode<br>Chamber Concept | Ballistic Transport<br>*chamber holes ~ 5 cm radius*<br>*most studied* | | Pinch Transport<br>*chamber holes ~ 0.5 cm radius*<br>*higher risk, higher payoff* | |
|---|---|---|---|---|
| | **Vacuum-ballistic**<br>*vacuum* | **Neutralized-ballistic**<br>*plasma generators* | **Preformed channel**<br>**("assisted pinch")**<br>*laser + z-discharge* | **Self-pinched**<br>*only gas* |
| **Dry-wall**<br>*~6 meters to wall* | **Not considered now:**<br>**Requires ~500 or more beams** | ARIES-IFE (2002)<br>**Possible option: but tighter constraints on vacuum and beam emittance** | ARIES-IFE (2001)<br>**Option: uses 1-10 Torr**<br>***2 beams*** | ARIES-IFE (2001)<br>**Option: uses 1-100 mTorr**<br>**~2-100 beams** |
| **Wetted-wall**<br>*~ 4-5 meters to wall* | HIBALL (1981)<br>**Not considered:**<br>**Needs ≤ 0.1 mTorr leads to ⇦** | OSIRIS-HIB (1992)<br>ARIES-IFE (2002)<br>**Possible option: but tighter constraints on vacuum and beam emittance** | ARIES-IFE (2001)<br>**Option: uses 1-10 Torr**<br>***2 beams*** | PROMETHEUS-H (1992)<br>ARIES-IFE (2001)<br>**Option: uses 1-100 mTorr**<br>**~2-100 beams** |
| **Thick-liquid wall**<br>*~ 3 meters to wall* | **Not considered:**<br>**Needs ≤ 0.1 mTorr leads to ⇧** | HYLIFE II (1992-now)<br>ARIES-IFE (2002)<br>**Main-line approach: uses pre-formed plasma and 1 mTorr for 3 meters**<br>***~50-200 beams*** | ARIES-IFE (2002)<br>**Option: uses 1-10 Torr**<br>***2 beams*** | ARIES-IFE (2002)<br>**Option: uses 1-100 mTorr**<br>**~2-100 beams** |

# Self-Pinched Transport Research Areas

All aspects of self-pinched transport (SPT) were examined at the Workshop on Final Transport of Heavy Ion Beams, San Damiano Retreat, Danville, CA, February 13-15, 2001 (HIFAR-513, LBNL-47686, 599 pages).

The four main areas of SPT research are:

## (1) self-pinched radial equilibria (once beam is in self-pinched mode):

balance between beam emittance and net current

$I_{net} \sim \theta^2 I_A$ will confine beam, where $\theta$ is the injection angle and

$I_A$ is the Alfven current for the ion beam

$I_A = \beta\gamma m_p(A/Z)c^3/e$

*[C.L.Olson, J. Fusion Energy 1 , 309 (1982);*
*P.F.Ottinger, D.V.Rose, B.V. Oliver, Phys. Plasmas 6, 3717 (1999)]*

need complete charge neutralization and only 1% net current for HIF driver scenarios

*[C.L.Olson et al., 16th IAEA Fusion Energy Conf., Montreal, Canada, Oct. 7-11, 1996]*

# Self-Pinched Transport Research Areas (cont'd)

## (2) beam into gas

**"1 Torr" case: early codes predicted near perfect charge and current neutralization, with a net current too small for SPT. BUT, codes included only local ionization. The need for inclusion of non-local ionization led to the hybrid codes IPROP and LSP.**

*Possibility of 1% net current for HIF driver parameters should still be assessed for this regime. Recent interest has centered on the following case:*

**"10-100 mTorr" case ("Trumpet"):**
**low pressure regime, where beam becomes near charge neutralized with large net currents**

*[D.R. Welch and C.L. Olson, Fusion Eng. And Des. 32-33, 477 (1996);*
*D.R. Welch, M.E. Cuneo, C.L.Olson,T.A.Mehlhorn, Phys. Plasmas3, 2113 (1996);*
*D.V. Rose, P.F. Ottinger, D.R. Welch, B.V. Oliver, C.L. Olson, Phys. Plasmas 6, 4094 (1999)]*
*P.F. Ottinger, F.C. Young, S.J. Stephanakis, D.V..Rose, J.M. Neri, B.V. Weber, M.C. Meyers, D.D. Hinshelwood, D. Mosher, C.L. Olson, D.R. Welch, Phys. Plasmas 7, 346 (2000)]*

**further analysis in this talk**

# Self-Pinched Transport Research Areas (cont'd)

## (3) beam into preformed plasma:

**models rigid beam injected into preformed plasma**
**actual chamber schemes not proposed**

*B.V. Oliver (San Damiano)*
*I. Kagonovich (San Damiano)*

## (4)  plasmoid equilibira

**concept is to create an isolated self-consistent plasmoid equilibria**
**actual chamber schemes not proposed**

*M. Rosenbluth (San Damiano)*
*R. Briggs (San Damiano)*

# Status of Self-Pinched Transport at Low Pressures

## (Trumpet)

# Status of Self-Pinched Transport Experiments

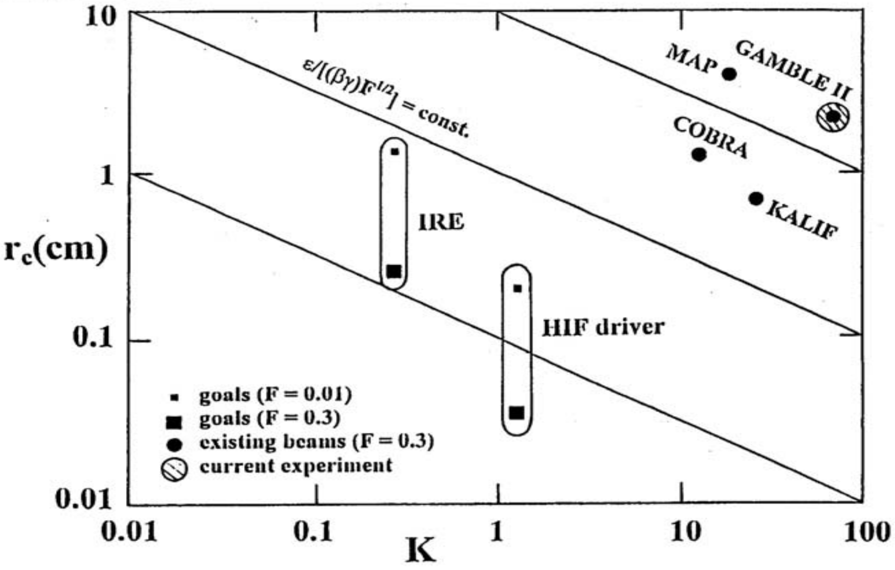
- First SPT experiment was on GAMBLE II at NRL, and demonstrated onset of pinching in agreement with IPROP simulations

  *P.F. Ottinger, F.C. Young, S.J. Stephanakis, D.V. Rose, J. M. Neri, B.V. Weber, M.C. Meyers, D.D. Hinshelwood, D. Mosher, C. L. Olson, D.R. Welch, Phys. Plasmas 7, 346-358 (2000)*

- SPT experiments require high current (> 1 kA)

  HCX - NTX - IBX currents are too small to test SPT
  SPT experiments can be done on the IRE
  Possible nearer-term experiments:
    - Mercury (Kalif-Helia at NRL)
    - PW laser (but short pulse, high energy spread)
    - Develop high-impedance, low-emittance, low-efficiency diode

# Small equilibrium beam radius for channel-like transport requires high current (high K) and small emittance (ε)



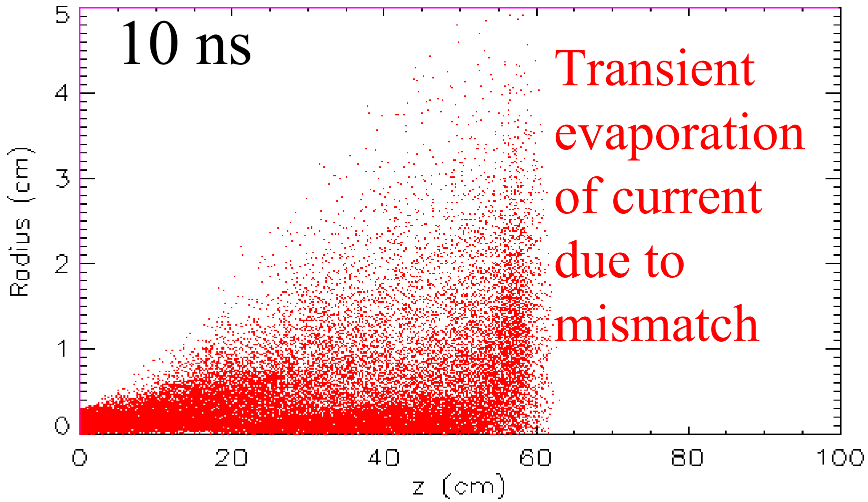
$$\boxed{r_c = [\varepsilon/(\beta\gamma)]\,[FK]^{-1/2}}$$

$\varepsilon$ = unnormalized emittance
$F = I_c / (qI_p)$ for channel
$F = I_{net} / (qI_p)$ for self-pinched
$K$ = perveance

**Currents ≥ 1 kA needed to study pinch modes**

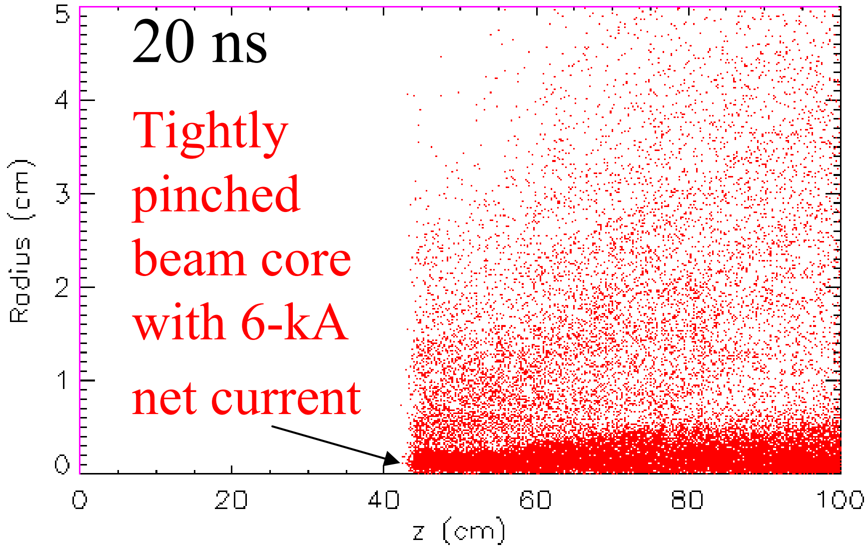
*C.L. Olson, Nuclear Inst. & Methods 464, 118 (2001)*

# Driver Scale Simulations demonstrate self-pinched transport equilibrium



10 ns

Transient evaporation of current due to mismatch



20 ns

Tightly pinched beam core with 6-kA net current

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

8-ns pulse

$\tau = 0.5$ ns, 7-3.5 mm radius

50-mTorr Xe gas fill

Only 61% transport within 6 mm radius after 1-m (but better matching does reduce evaporation)

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

# New Analytical Modeling of Trumpet Equilibria

# Neutralization desired for self-pinched transport

**Radial force on an edge ion in ion beam is:**

$$dr^2/dt^2 = [(2I_eZe)/(\beta_i c r_b \gamma_i m_p A)][(1 - f_e) - \beta_i^2(1 - f_m)]$$

$$= - [(2I_eZe)/(\beta_i c r_b \gamma_i m_p A)][f_e - \gamma_i^{-2} - \beta_i^2 f_m]$$

**where $f_e$ is charge neutralization factor**

**$f_m$ is current neutralization factor**

**Some possible cases:**

| | | | |
|---|---|---|---|
| $0 < f_e < \gamma_i^{-2}$ | and | $f_m = 0$ | beam blow up |
| $f_e < \gamma_i^{-2}$ | and | $f_m = 0$ | radial force neutrality |
| $\gamma_i^{-2} < f_e < 1$ | and | $f_m = 0$ | pinching |

**In general, need:** $f_e > \gamma_i^{-2} + \beta_i^2 f_m$ **for pinching**

**HIF Example:** $\beta_i = 0.2$, $\gamma_i = 1.02$, $\gamma_i^{-2} = 0.96$

**need** $f_e > [(0.96) + (0.04)f_m]$ **for pinching**

# Neutralization mechanisms for self-pinched transport

recall, for $\beta_i = 0.2$, really want $f_e > \gamma^{-2} = 0.96$ and $f_m = 0$

## (1) space charge E always dominates initially

e.g., no ExB drift can occur until $E < B$

at beam edge, $E = [2I_e/(\beta_i c r_b)](1 - f_e)$

$B = [2I_e/(c r_b)](1 - f_m)$

for $f_m = 0$, E dominates until $(1 - f_e) = \beta_i$ , which is $f_e = 0.8$ for $\beta_i = 0.2$

so $f_e \approx 0.8$ occurs by brute force E

## (2) axial trapping of electrons born in beam front potential well

electrons available by impact ionization, and at chamber entrance

lowers well potential to $e\phi_{min} \approx 1/2\ m_e V_i^2$

effective neutralization is $f_e = \phi_{min}/\phi_o = [1/2\ m_e V_i^2]/[I_e/(\beta_i c)]$

for $\beta_i = 0.2$ and $I_e = 4$ kA, this is $f_e = 0.98$ (but also makes $f_m > 0$)

## (3) trumpet - shape of beam envelop at beam front

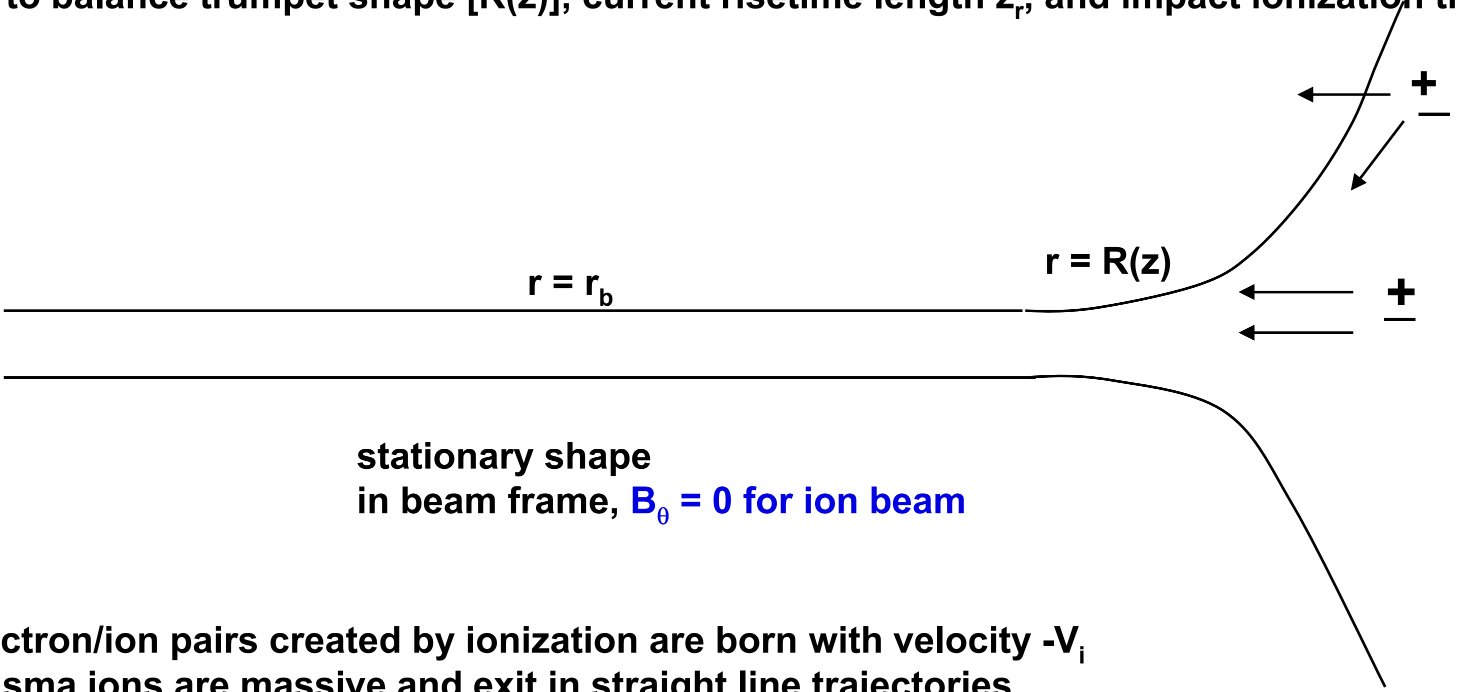
leads to pulling electrons into beam channel at radius $r_b$

possible to have $f_e \rightarrow 1$ and $f_m \approx 0$

# Trumpet in beam frame

**assume ion beam has fixed trumpet shape (to be specified)**

**need to balance trumpet shape [R(z)], current risetime length $z_r$, and impact ionization time $\tau$**



**stationary shape**
**in beam frame, $B_\theta = 0$ for ion beam**

**electron/ion pairs created by ionization are born with velocity $-V_i$**
**plasma ions are massive and exit in straight line trajectories**
**plasma electrons respond to net fields (E and B) and may be drawn in**
**want plasma electrons from $r > r_b$ to be drawn into $r < r_b$ and keep axial velocity $-V_i$**
**will provide charge neutralization, and create an electron current in this frame**

# Trumpet in beam frame (possible cases)

$I_{e,NET}$ = net electron current in ion beam frame
$I_{e,A}$ = Alfven electron current = $\beta_e \gamma_e m_e c^3/e$
$I_{e,A}$ = 3.4 kA for $\beta_i = \beta_e = 0.2$

**$I_{e,NET} < I_{e,A}$** $r_{ce} > r_b$

**(new case)** electrons NOT attached to field lines

electron beam "has own $B_\theta$" and betatron trajectories

can provide $f_e \rightarrow 1$ and $f_m \approx 0$ (if trumpet shape is right)

but limited to $I_{e,NET} < I_{e,A}$, so limited to $I_i <$ 3.4 kA for $\beta_i = 0.2$

**$I_{e,NET} > I_{e,A}$** $r_{ce} < r_b$

core electron current ( $\approx I_{e,A}$ ) at beam center provides core $B_\theta$

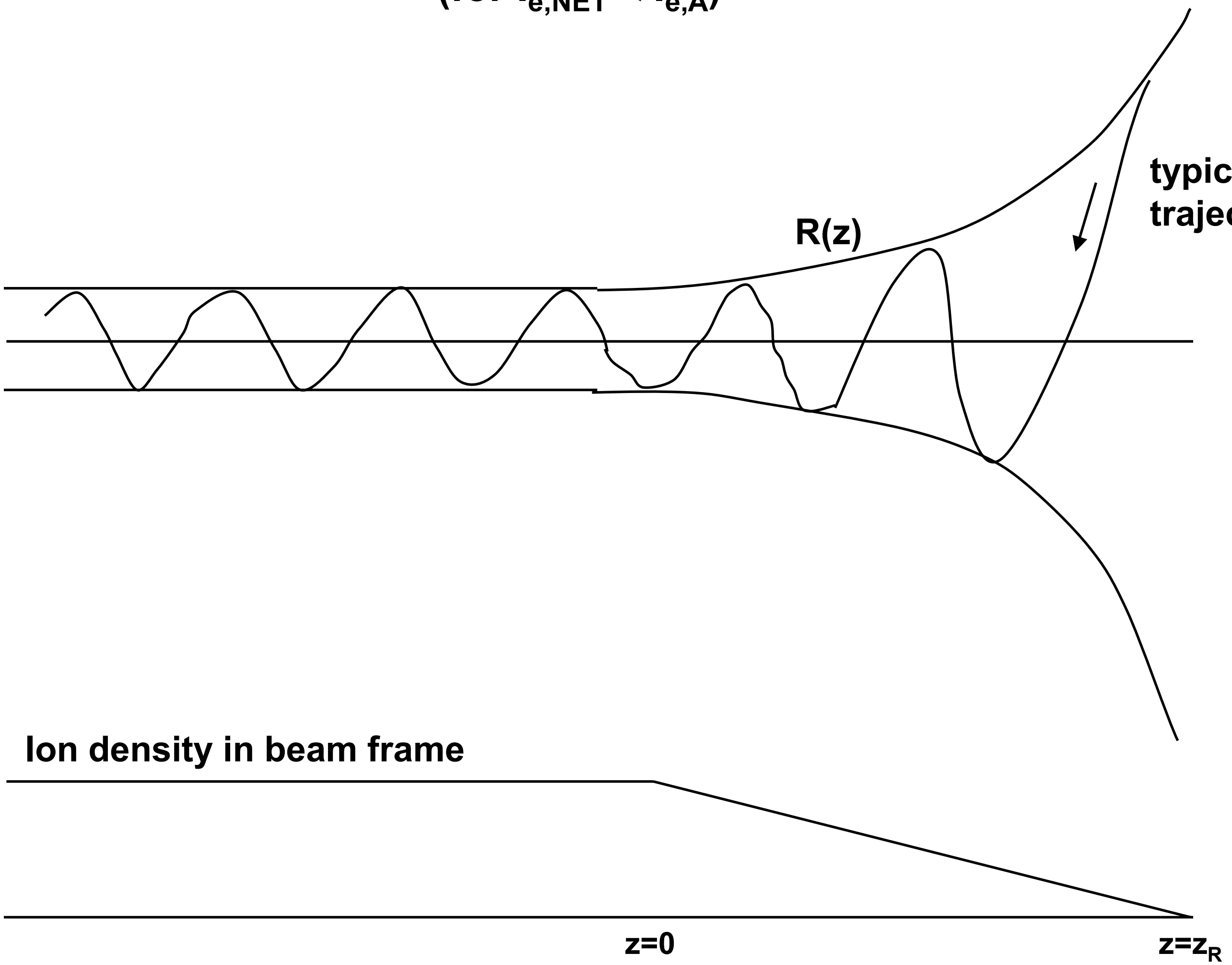
outer electrons drift (ExB and Bx∇B) backwards: these contribute to some current neutralization in beam frame

electron drift velocity is now a function of r

leads to $f_e \rightarrow 1$, but with $f_m > 0$, resulting in $I_{i,NET} > I_{e,A}$, but complicated electron trajectories (LSP)

# Trumpet shape in beam frame

(for $I_{e,NET} < I_{e,A}$)



# Trumpet shape in beam frame

(for $I_{e,NET} < I_{e,A}$)

chose risetime = trumpet length
assume paraxial trajectories
radial force for a border electron is

$$F(z) = -(r/r_b)[(2I_eZe)/(\beta_i c r_b \gamma_i m_p A)][f_e - \gamma^{-2} - \beta_i^2 f_m] \underbrace{[1 - (z/z_r)]}_{\textit{risetime}} \underbrace{[r_b/R(z)]^2}_{\textit{trumpet}}$$

assume final equilibrium has fixed values of $f_e$ and $f_m$
then trajectories are described by adiabatic harmonic oscillator equations*
solution for border trajectories envelop is

$$R(z) \sim [F(z)]^{-1/4}$$

combine equations, and solve for trumpet shape, gives

$$\boxed{R(z) = r_b\,[1-(z/z_r)]^{-1/2}}$$

this is the self-consistent shape that brings in all electrons and keeps them inside R(z)

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* *C.L. Olson, Phys. Fluids 16, 529 (1973); Phys. Fluids 16, 539 (1973)*

# Trumpet in beam frame (summary)

**$I_{e,NET} < I_{e,A}$** (new case)

adjust $\tau$ relative to $z_r$ to provide $f_e = 1$ and $f_m \approx 0$ in the laboratory frame

electron beam "has own $B_\theta$" and betatron trajectories

"ideal case" but limited to $I_{e,NET} < I_{e,A}$, so limited to $I_i <$ 3.4 kA for $\beta_i = 0.2$

trumpet shape is $R(z) = r_b\,[1-(z/z_r)]^{-1/2}$

$\approx r_b\,[\,1 + (1/2)(z/z_r) + (3/8)(z/z_r)^2 + (5/16)(z/z_r)^3 + \ldots]$

(similar to trial shapes that worked on LSP)

**$I_{e,NET} > I_{e,A}$**

core electron current ( $\approx I_{e,A}$ ) at beam center provides core $B_\theta$

outer electrons drift (ExB and Bx∇B) backwards: these contribute to some current neutralization in beam frame

electron drift velocity is now a function of r

complicated trajectories & crossings & velocity shear in r

but can lead to net currents above $I_{e,A}$

# Future Work and Conclusions

# Issues and Research Areas for Self-Pinched Transport

## (future work)

- analytical equilibria (extend new results)
- computer simulations (compare to new results)
- total transport efficiency
- head erosion mechanisms *[minimum erosion rates assessed in D.V. Rose, T.C.Genoni, D.R. Welch, Phys. Plasmas 9, 1053 (2002)]*
- stability
- tracking
- high-brightness issues (e.g., hydro expansion)
- experimental demonstration

# Conclusions for ARIES-IFE Study

- Self-pinched transport should lead to the simplest, most attractive, least expensive chamber option for HIF

- Self-pinched transport can be used for all chamber concepts
  (dry-wall, wetted-wall, thick-liquid wall)
  pressure window for propagation identified (ARIES special issue)

- Self-pinched transport for beam into gas (trumpet)
  - first experiment was on GAMBLE II at NRL
  - small pinch radius requires high net current and small emittance
  - LSP simulations show self-pinched transport for HIF driver parameters

- New analytical modeling of trumpet equilibria:
  - analysis in beam frame
  - $I_{net} < I_A$(for electrons at $\beta_i$) leads to electron betatron trajectories
    with $f_e \sim 1$ and $f_m \approx 0$ (analytic trumpet shape)
  - $I_{net} > I_A$(for electrons at $\beta_i$) leads to core electrons + ExB & $B \times \nabla B$
    with $f_e \sim 1$ and $0 < f_m < 1$

- Continuing work should refine self-pinched transport options

# Possible Collaborative Areas for HIF and Z-Pinch IFE

- Targets: double-ended hohlraum on Z ⇔ HIF targets
  fast ignition on Z ⇔ HIF fast ignition
- Chambers: thick liquid walls
  materials testing on Z and RHEPP (Flibe, etc.)
- Pulsed Power: magnetic switching technology (RHEPP)
  linear transformer technology (LTD)

# Possible near-term, small-scale experiments for HIF

- Ion source - cryogenic diode on RHEPP at SNL
- Multiple beamlet experiment on RHEPP at SNL