Simulation of Heavy Ion Beam Propagation

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Outline of Talk

- Assisted-Pinch Transport
  - concept
  - self field evolution
  - transport efficiency
  - stability

- Self-Pinched Transport
  - concept
  - pinch force mechanism
  - propagation window
  - status of 3d modeling

- Transport Issues
IPROP Modeling of Assisted Pinch Transport
Channel transport could ease chamber focus requirements and reduce driver costs.
Key physics issues involve the evolution of self fields

- Beam must first be captured at small radius by 50 kA discharge current - adiabatic lens
- 6-MA electrical beam current has potential for huge self fields given finite plasma conductivity
- Strong plasma return current can drive “hose” instability
IPROP* simulates HIF beam interaction with discharge channel in 2 and 3D

- IPROP is a quasi 3D EM hybrid code
- 2 fluid model for the plasma, PIC beam ions
- Extensive models for xenon gas breakdown physics

Simulation beam and gas conditions

- 4-GeV, 6 MA Pb\(^{+72}\) ions
- 15-cm radius beam is first transported ballistically 10 meters to the discharge. Micro-divergence nominally 1 mrad.
- Discharge initial parameters:
  - 50-kA current
  - 5-Torr, 3-eV ambient Xe
  - Axial position-dependent radius, reduced density (to 0.5 Torr minimum), ionization fraction (0.9 peak). Current density, reduced gas density and ionization fraction have square profiles
Effective current - sum of discharge and self currents - reaches 80 kA

- Results for nominal parameters
- 6 snapshots of effective current
- 2-4 s plasma return current decay time permits self field growth
Plasma heats ohmicly and from beam impact - decay time increases

- Red contour is 3.3 keV, beam head at 375 cm
- Enhanced sigma reduces magnitude of B oscillation

Enhanced heating at beam waists
Beam oscillations imprinted on self magnetic fields
Beam halo growth from interaction with varying $B_2(z)$

- 87% of beam transported over 4.5-m length
- 3.5-mm RMS radius
Finite conductivity results in some self field growth, beam loss

- Plasma current decay time scales as $F r^2$, reaches 2-4 $\mu$s (enough to permit 20-30 kA self field for 8 ns beam)
- Inductive fields rise with net current, reducing beam energy
- Oscillating beam imprints oscillating magnetic well
- Ions interact with changing B fields and heat
- Despite above effects, 87% beam energy transported, 3.5-mm RMS radius.
IPROP simulations of assisted-pincho hose instability

- IPROP is run with 2 azimuthal Fourier modes, m=0,1
- Beam is injected offset from channel 0.5 mm
- Conductivity profile is held fixed by initializing a singly ionized plasma with a gaussian radial profile

- **Run91** - 100 eV plasma and 50 kA discharge
- **Run92** - 10 eV plasma and 50 kA discharge
- **Run93** - 30 eV plasma and 12.5 kA discharge
Nominal conductivity simulation shows no evidence of hose

- Fixed 5 microsecond decay time - consistent with 2D breakdown calculations
- 100 eV plasma temperature
- 50 kA discharge
- Offsets damp
Highly resistive case - less than an e-fold growth

- 10-eV temperature,
- 50 kA discharge
- Large net currents, beam pinches
- Weak hose growth that damps rapidly
Low discharge current, medium conductivity case

- 30 eV temperature, 12.5-kA channel
- Hose again is very weak
Simulations suggest weak assisted pinch hose

\[ \frac{I_d}{I_b} > I^* \]

* Ed Lee’s stability condition from Pinch Transport Workshop, 2001

- Hose instability does not appear to be an issue for assisted pinch
- Neglected effects of beam scattering, ionization should be stabilizing

**IPROP result**

<table>
<thead>
<tr>
<th>run</th>
<th>( I_d/I_b )</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>run91</td>
<td>5</td>
<td>rock stable</td>
</tr>
<tr>
<td>run92</td>
<td>0.4</td>
<td>weak instability</td>
</tr>
<tr>
<td>run93</td>
<td>0.26</td>
<td>weak instability</td>
</tr>
</tbody>
</table>
Optimization of beam transport - work in progress

- Self-field strength limits energy transport efficiency and spot size
- 87% transport and 3.5 mm RMS spot size calculated over 4.5-m transport
- Weak self-hose instability calculated
- Need to develop technique for hollowing beam profile to better match recent target designs
LSP Modeling of Self-Pinched Transport

Enclosed Net Current (Amps); 14 ns

Propagation of pinched beam
2 possible scenarios for self pinched transport

- Beams combined into 2 as in assisted pinch
  - large currents have potential for instability without discharge channel

- Use 100-200 beams with 1-4 kA per beam (as in Neutralized Ballistic Transport)
  - requires more beam ports, beams overlap near target
Self-pinched transport relies on limited beam impact ionization in a low pressure gas

- Ionization electrons provide good charge but imperfect current neutralization

\[ I_{net} = \theta^2 I_A \quad \text{where} \quad I_A = \frac{m_b c^3}{e Z} \beta \gamma \quad \text{and} \quad \theta = \frac{v_{b\perp}}{v_{bz}} \]
Self-pinched transport is predicted to occur at an intermediate gas pressure

- Maximum pinch force occurs when beam-impact ionizes a plasma density roughly that of the beam on time-scale of beam density rise time, $/v_b$
- Optimized for:
  \[ R = n_g / 4Z = 1^* \]
- Trumpet shape and non-local secondary ionization help supply neutralization without $v_e = v_b$

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

Consistent with results observed in SPT experiment on Gamble II at NRL (Ottinger et al., Phys. of Plasmas 7, 346, 2000)
Identify pinched transport gas/plasma constraints for HIF chamber transport

- New LSP* code calculations
- 10-kA, 4-GeV Pb\(^+\) beam, 2-ns rise in current
- \( \mathbf{J} = 2 \) ns trumpet-shaped beam envelope:
  - 1-cm max radius falling to .5 cm in 2 ns
- 3-300-mtorr FLiBe pressure (\( R = .1-10 \))
- Normalized plasma density \( N = n_p/n_b = 0-1 \)
  - \( n_b = 1.3 \times 10^{13} \) cm\(^{-3}\)
- Beam impact ionization only (ignore avalanche)

Weak net force for pencil beam in gas

- Significant fields limited to beam edge (skin depth effect)

Constant enclosed net current

Electric fields, 918 kV/cm max
Trumpet beam shape enlarges net-current sheath

- Large net current with trumpet
- Sheath thickness defined in low density beam front

Constant enclosed net current
Electric fields, 529 kV/cm max
Electron density follows trumpet shape

- Ion density indicates ionization position

Log plasma ion density
Log beam density
Log electron density
Log plasma ion density
LSP calculates strength of pinch force sensitive to gas, plasma densities

- Normalized gas density, \( R = \frac{J_F n_g}{4Z} \)
- Normalized plasma density (R=1), \( N = \frac{n_p}{n_b} \)

Pinch force optimized near \( R = 1-2 \), constrains chamber pressure
Falls off \( N > 0.1 \), pinch may weaken near target due to photo-ionization
Beam maintains pinch after detaching from wall

Beam Density contours (cm⁻³)
30-mtorr flibe  R = 1, F = 0
Pinch force stabilizes at 3 kA in meter long simulation

- Pinch force is still sufficient for confinement
- Electric fields are small, < 100 kV/cm
Two-beam interaction in 3-D LSP simulation geometry

$\text{Pb}^{+5}$, 4 kA (electrical) current, $n_p = 5 \times 10^{13} \text{ cm}^{-3}$, $n_b = 1 \times 10^{12} \text{ cm}^{-3}$
No observed deflection for these 2 weak beams in N=10 plasma

- Need to examine higher currents, ionization and lower plasma densities
Research in self-pinched transport for HIF beams has just begun

- Confirmed the SPT mechanism for HIF beams
  - constraints of gas pressure and plasma density
- Pinch is sustained after detachment from wall
- Simulation of 3d beam-beam interaction underway
- Many issues remain:
  - Detailed beam-gas interaction (such as beam stripping)
  - Beam losses from inductive fields, trumpet formation
  - m=1 (hose) stability, beam-beam interactions
  - Steering and capturing beam
  - Channel expansion from $J \times B$ force