Physics of the Current Injection Process in Localized Helicity Injection

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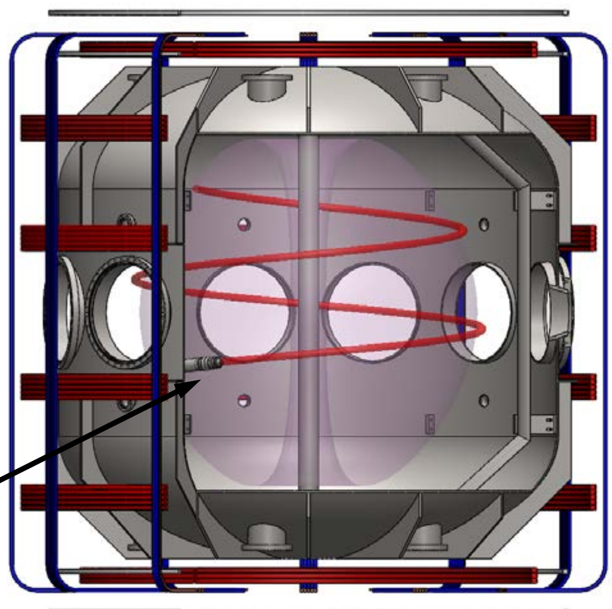
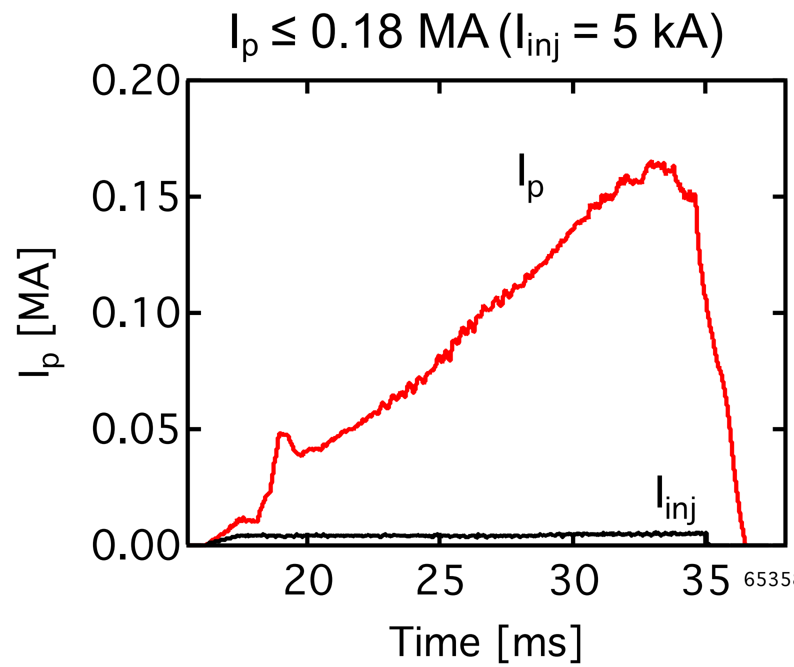
PEGASUS Toroidal Experiment

Local Helicity Injection (LHI) is a Promising Non-Solenoidal Tokamak Startup Technique

Current injected in plasma edge region → Plasma startup and current growth



Local Helicity Injectors



- Unstable current streams form tokamak-like state via Taylor relaxation
- Appears scalable to MA-class startup

Injector Impedance Relates Key Figures of Merit

- The simple model for helicity injection posits two I_p limits related to the injector circuit
  - Helicity balance limit depends on injector voltage V_{inj}:

$$I_p \le \frac{A_p}{2\pi R_0 \langle \eta \rangle} \left(V_{ind} + \frac{A_{INJ} B_{\phi,inj}}{\Psi_T} V_{inj} \right)$$

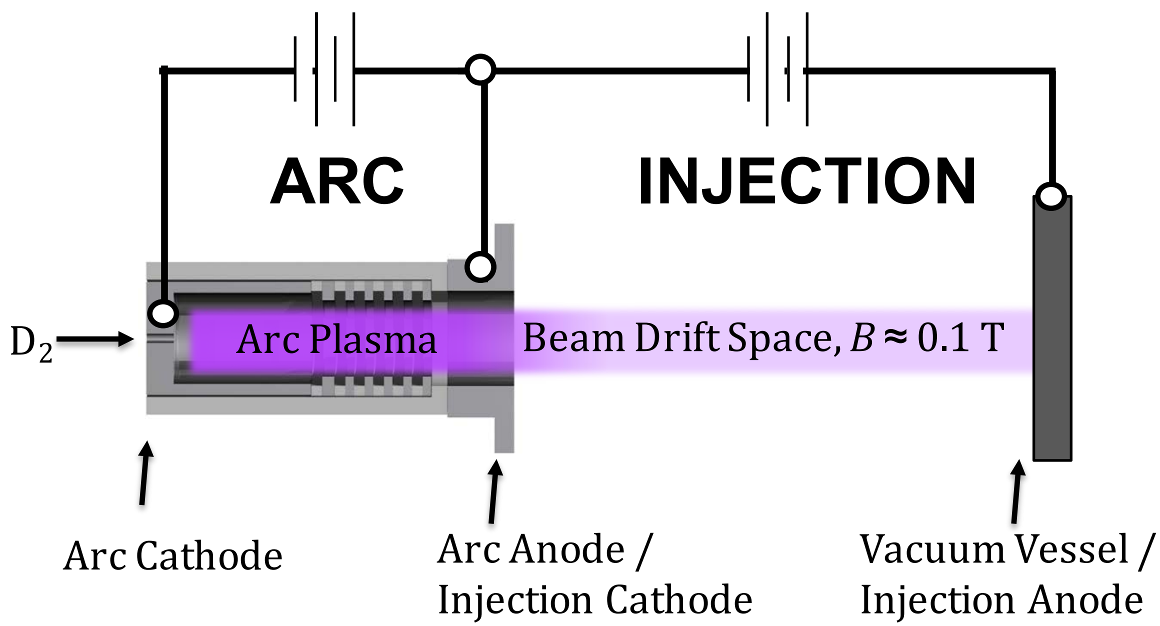
  - Taylor relaxation limit depends on current I_{inj}:

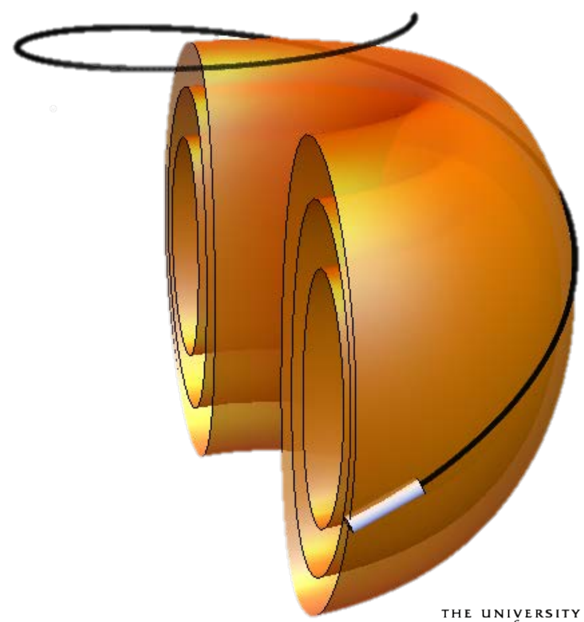
$$I_p \le f\left(\varepsilon, \delta, \kappa\right) \sqrt{\frac{\kappa A_p I_{TF} I_{inj}}{2\pi R_0 w}}$$

- Injector impedance describes relationship b/w I_{inj} and V_{inj}
  - Determined by plasma physics
  - Determines feasibility and power requirements for scaling up LHI

Edge Current Injection is Straightforward Conceptually

- Injection in Pegasus accomplished with arc plasma guns
- 2-stage circuit: bias and arc circuits “daisy chained”
- Voltage (~1 kV) is determined by plasma physics





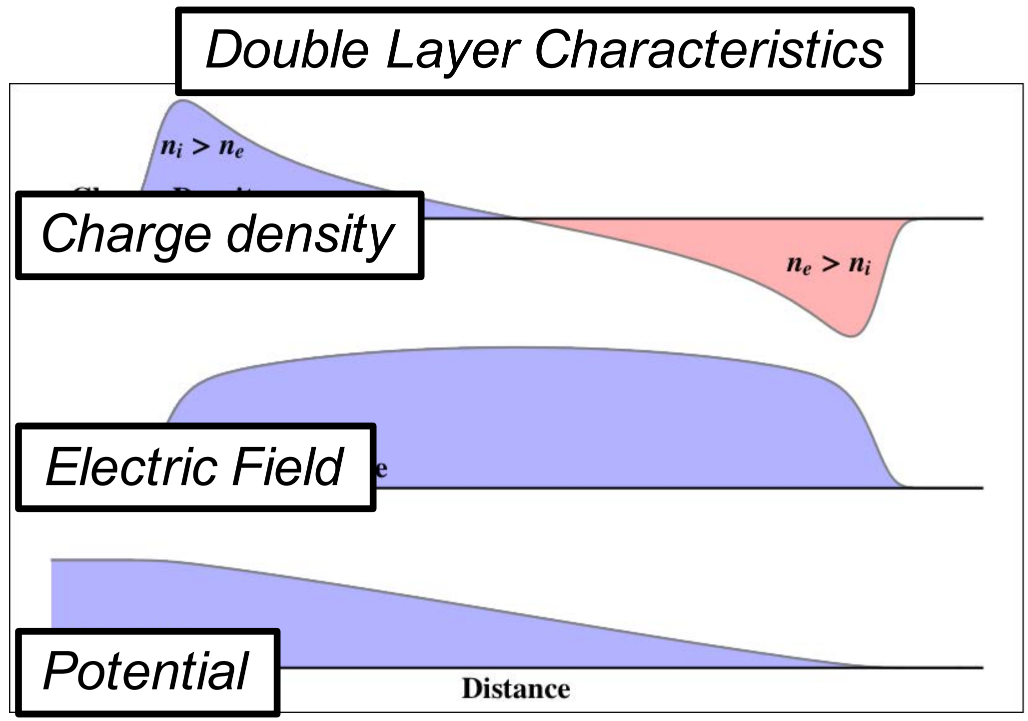
Double Layer Sheath: A Promising Framework for Understanding Injector Impedance

- Two space-charged layers "sandwiched" to each other

- Width of space charge set by plasma, order λ_{De}

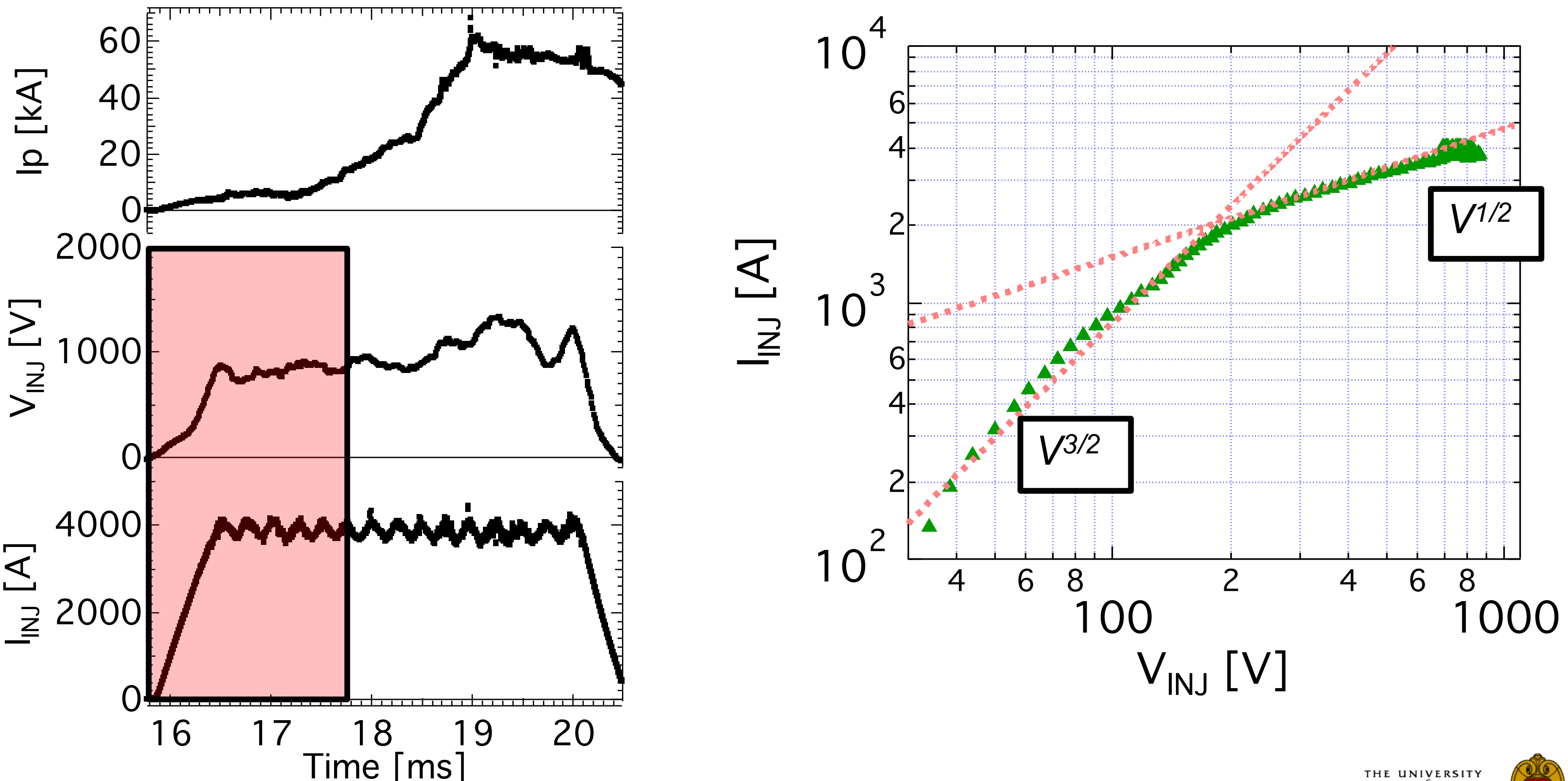
$$J = \frac{4}{9} 1.865 \varepsilon_0 \left(1 + \sqrt{\frac{m_e}{m_i}}\right) \left(\frac{2e}{m_e}\right)^{\frac{1}{2}} \frac{V^{\frac{3}{2}}}{\ell_{DL}^2}$$

$$\ell_{DL}^2 = \left(\lambda_{De} \cdot \chi\right)^2 \Rightarrow \boxed{I \sim n_{DL} V^{\frac{3}{2}}}$$



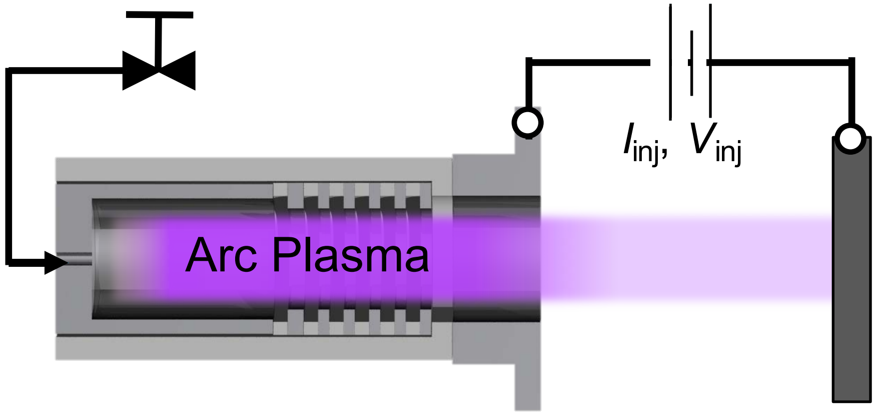
I-V Characteristics Show 2 Regimes

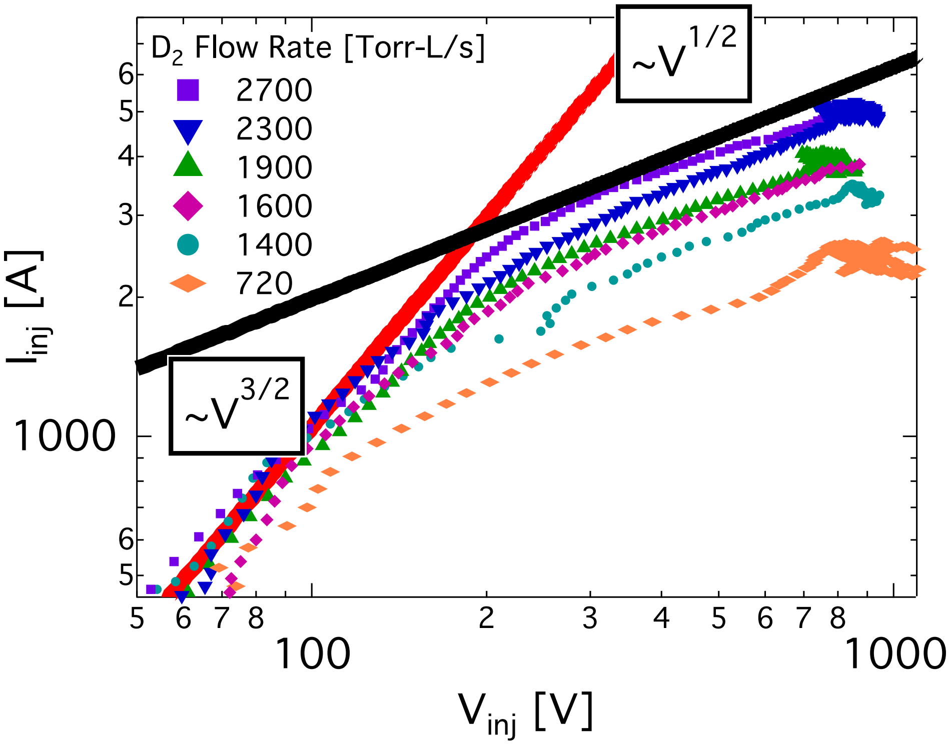
- Typical I-V relationship shows two power law regimes, $I_{inj} \sim V_{inj}^{3/2}$, $V_{inj}^{1/2}$

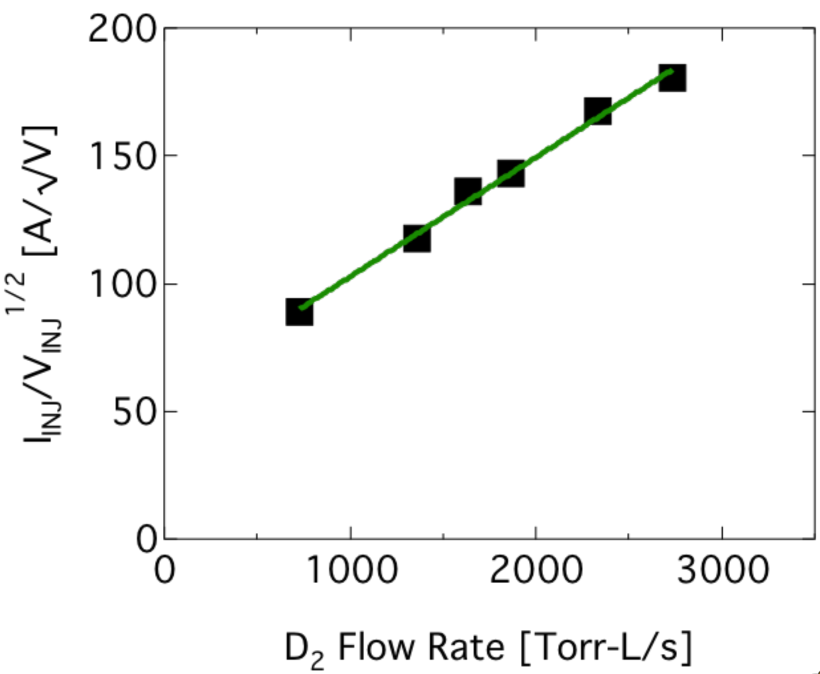


Injector Impedance Has Fueling Dependence

- Deuterium gas flow rate into the source plasma scanned
- $I_{inj}/V^{1/2}$ increases with gas flow







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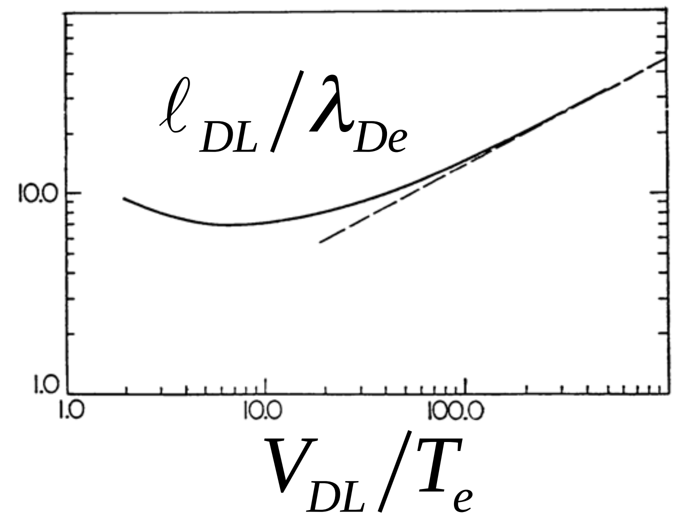
- Simulations* find when $V_{DL}/T_e >> 1$:

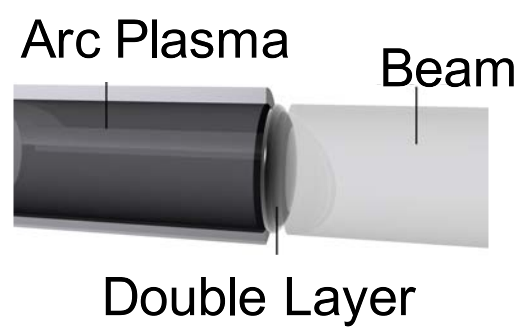
$$\ell_{DL} \sim \lambda_{De}\sqrt{V_{DL}/T_e}$$



Expected I-V relation is:

$$I_{inj} \sim n_{arc}\sqrt{V_{inj}}$$

$$n_{arc} \sim n_{DL}$$



*Hershkowitz 1985, Goertz 1975,1978, Benilov 2009,
R. A. Smith, Physica Scripta, 1982

2: Beam Neutralization Yields $I_{inj} \sim n_{edge} V_{inj}^{1/2}$

- Electron beam propagation requires drift space ions neutralize electrons: $n_b \leq n_i$
- Typical beam values imply beam density $n_b \sim 10^{18} m^{-3}$ - comparable to edge density n_{edge}!
- Assume drift space has same density as edge: $n_i \approx n_{edge}$

$$I_{inj} = n_b e v_e A_{inj} \leq n_i e \sqrt{\frac{2eV_{inj}}{m_e}} A_{inj} \sim n_{edge} \sqrt{V_{inj}}$$

$$\boxed{I_{inj} \sim n_{edge} \sqrt{V_{inj}}}$$

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Impedance Model Based on Density Limits Created

Minimum of both limits is applicable:

Sheath expansion:

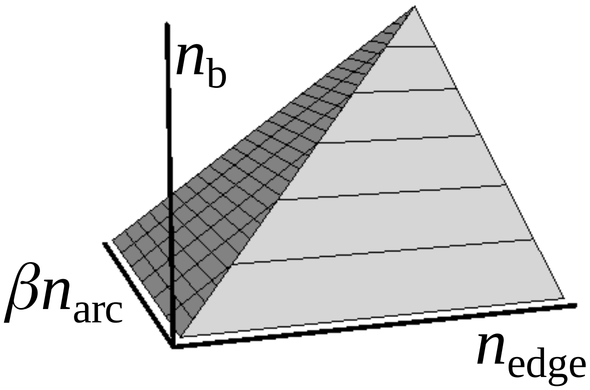
$$I_{inj} \sim n_{arc}\sqrt{V_{inj}}$$

Quasineutrality:

$$I_{inj} \sim n_{edge}\sqrt{V_{inj}}$$

Impedance Model:

$$I_{inj} = \mathrm{Min}[n_{edge}, \beta n_{arc}]e\sqrt{\frac{2eV_{inj}}{m_e}}A_{inj}$$



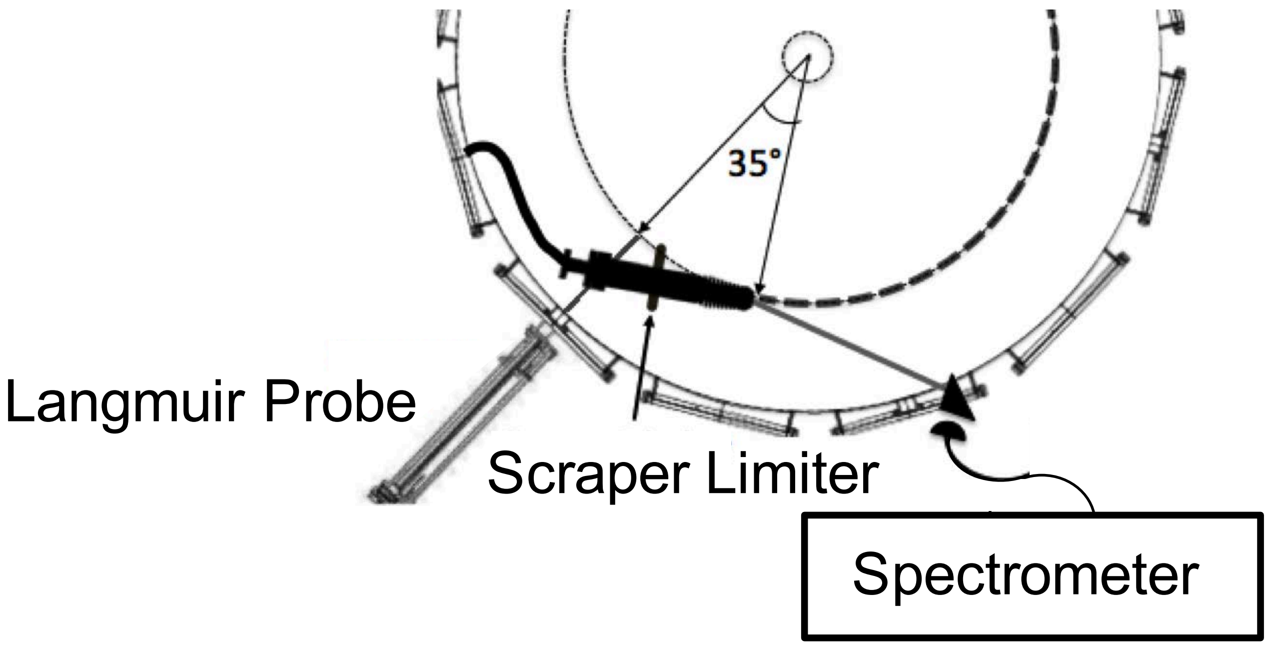
Ohmic Plasmas Created to Test Model via Measured n_{edge}, n_{arc}

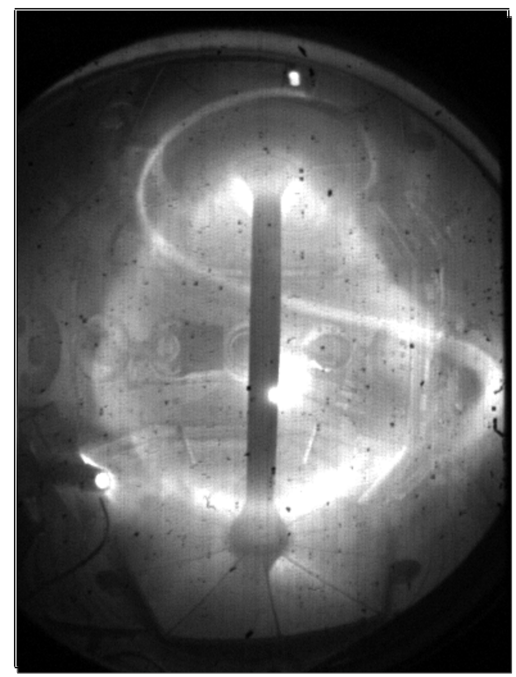
n_{edge}:

- Measured with Langmuir probe behind injector limiter
- Controlled with edge fueling

n_{arc}:

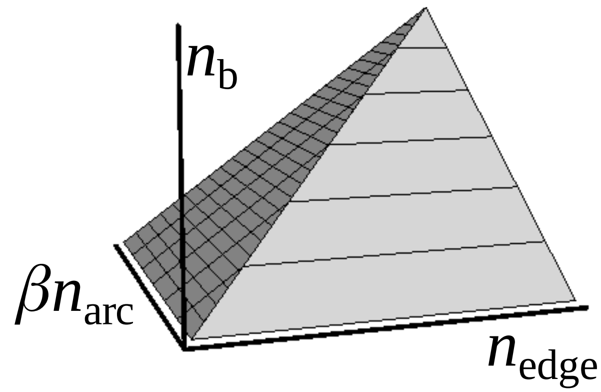
- Measured via Stark broadening of H-δ in arc channel
- Controlled with injector fueling

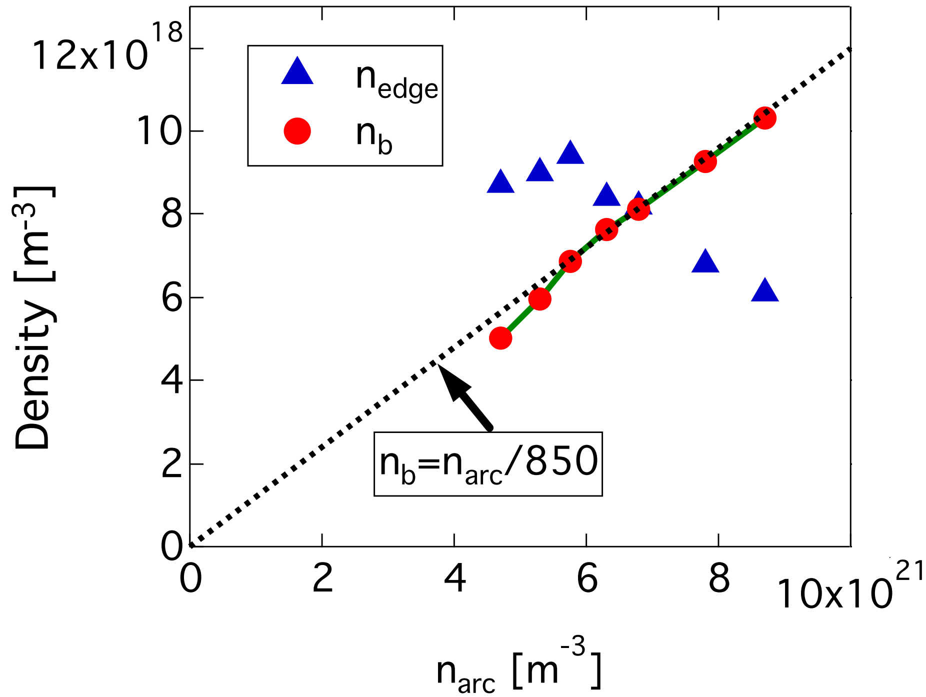




n_{arc} Scanned

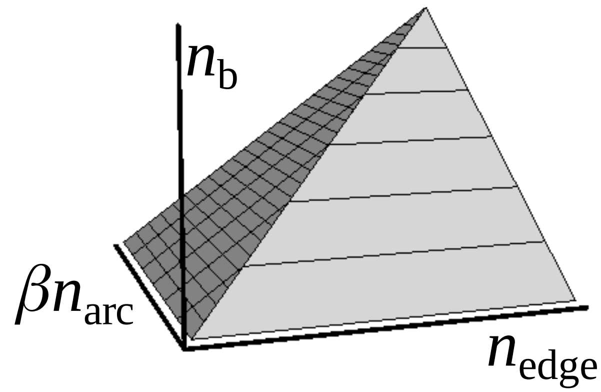
- Arc density n_{arc} scanned
- Entire scan consistent with sheath expansion: $n_b \sim \beta n_{arc}$ where $\beta = 1/850$

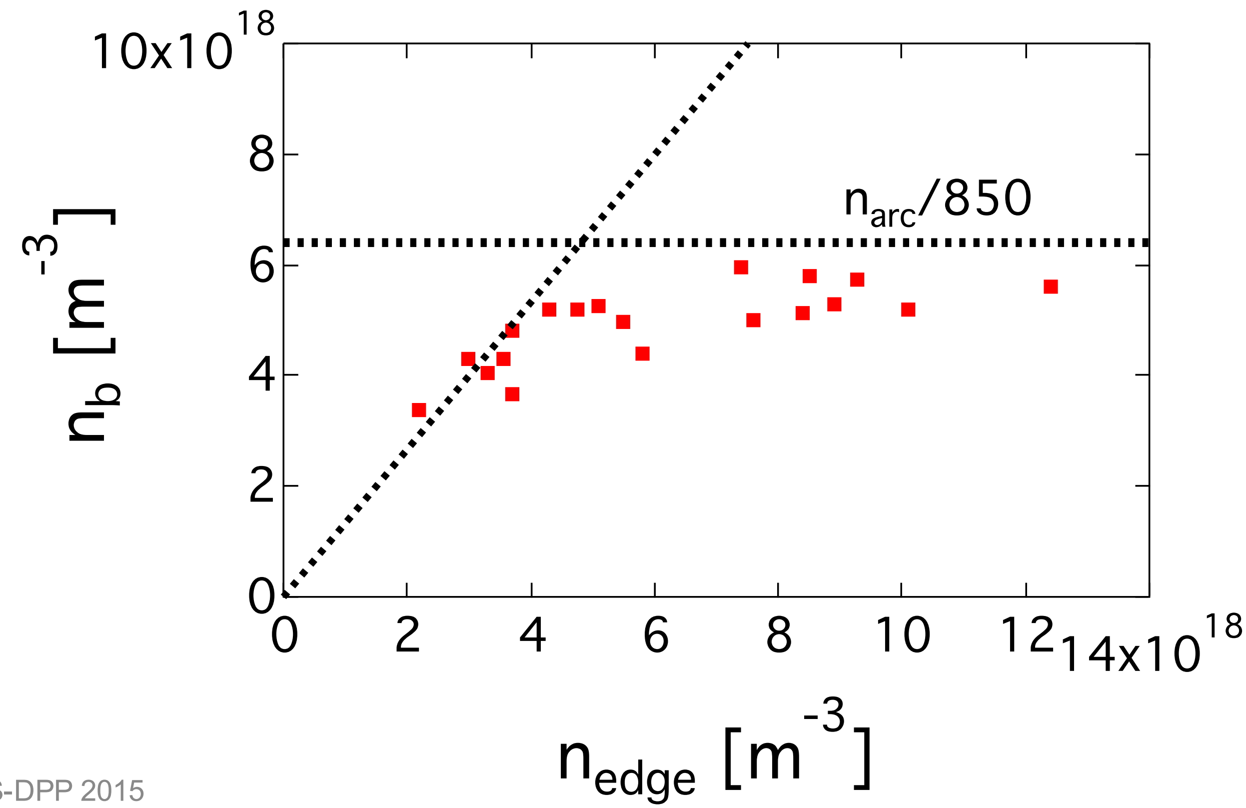




n_{edge} Scanned at constant n_{arc}

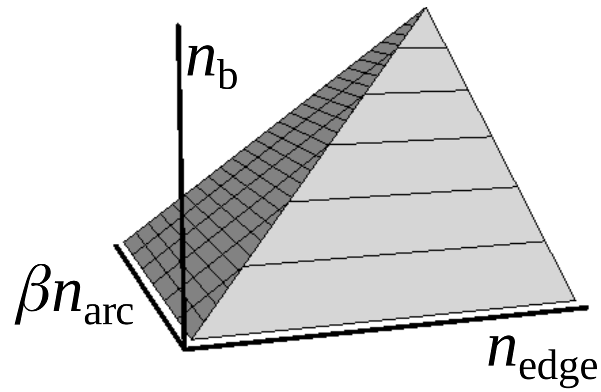
- Increasing n_b at low n_{edge}
- Saturation at $n_b = n_{arc}/850$

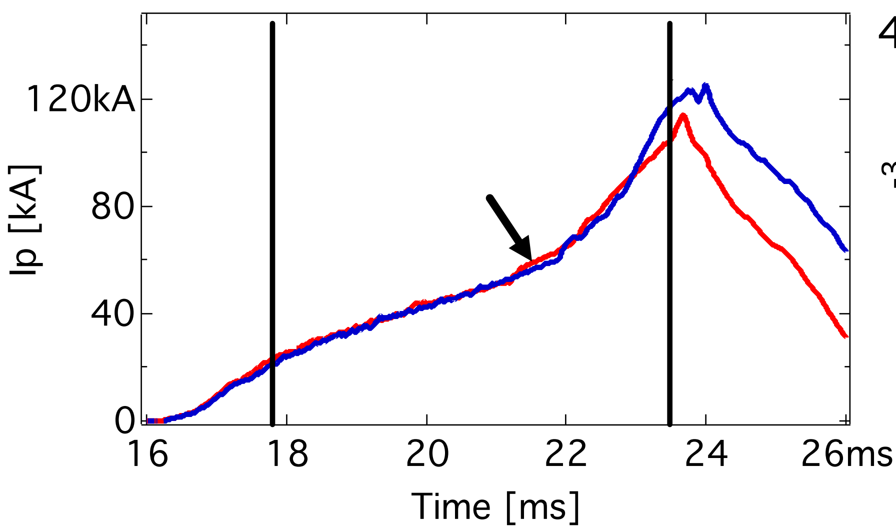


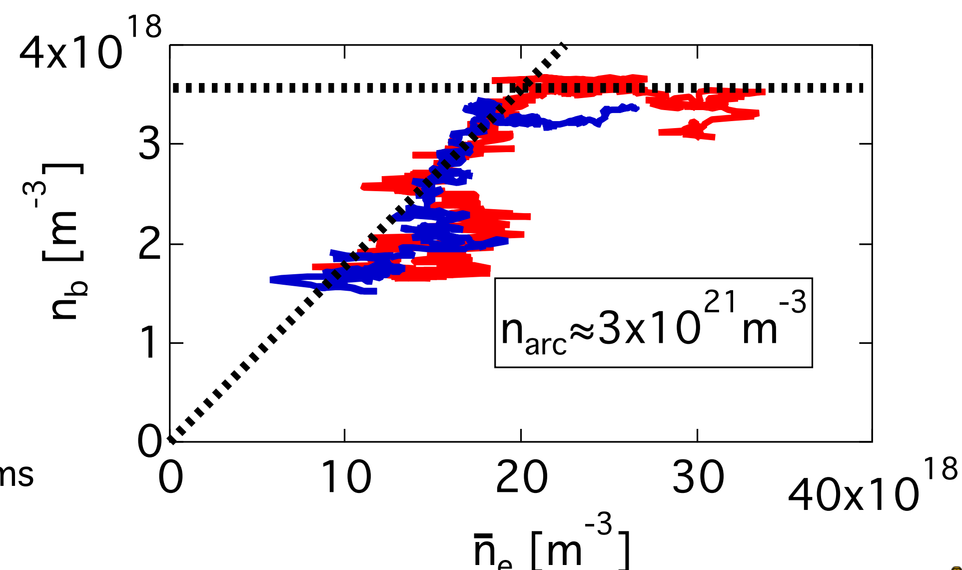


Interferometer Line-Averaged Density Expected to Trend with n_{edge}

- Interferometer captures linear behavior at low n_{edge}
- Saturation at $n_b = n_{arc}/850$



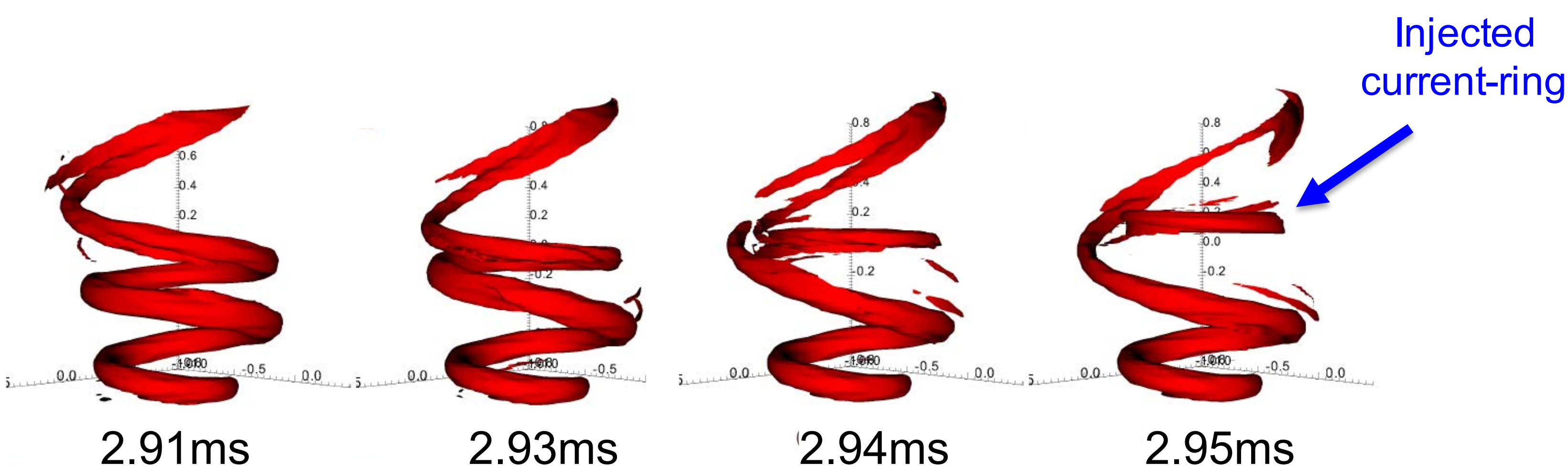




NIMROD Simulations Show Reconnecting Streams in Edge

- NIMROD shows* I_p growth via intermittent reconnection
  - Coherent current streams exist in edge throughout discharge
  - Adjacent passes reconnect to inject rings into core

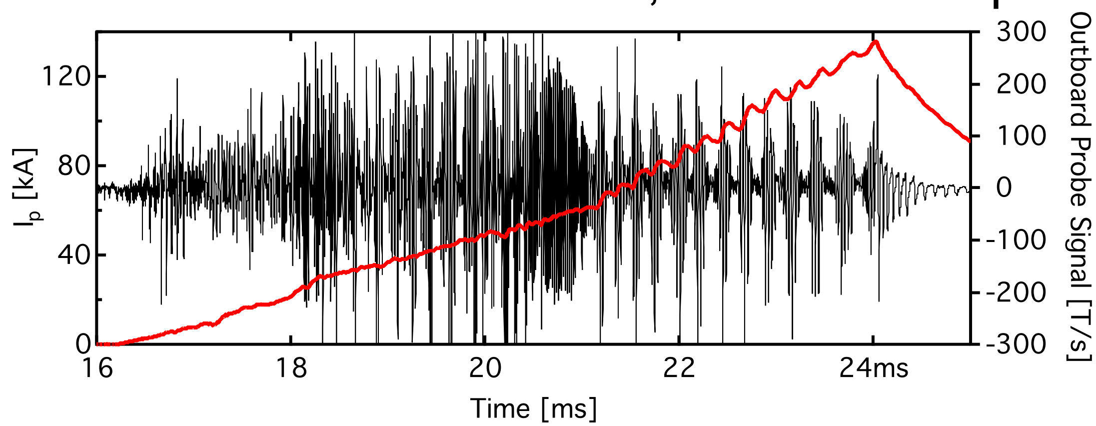
- Poloidal flux buildup and I_p multiplication results



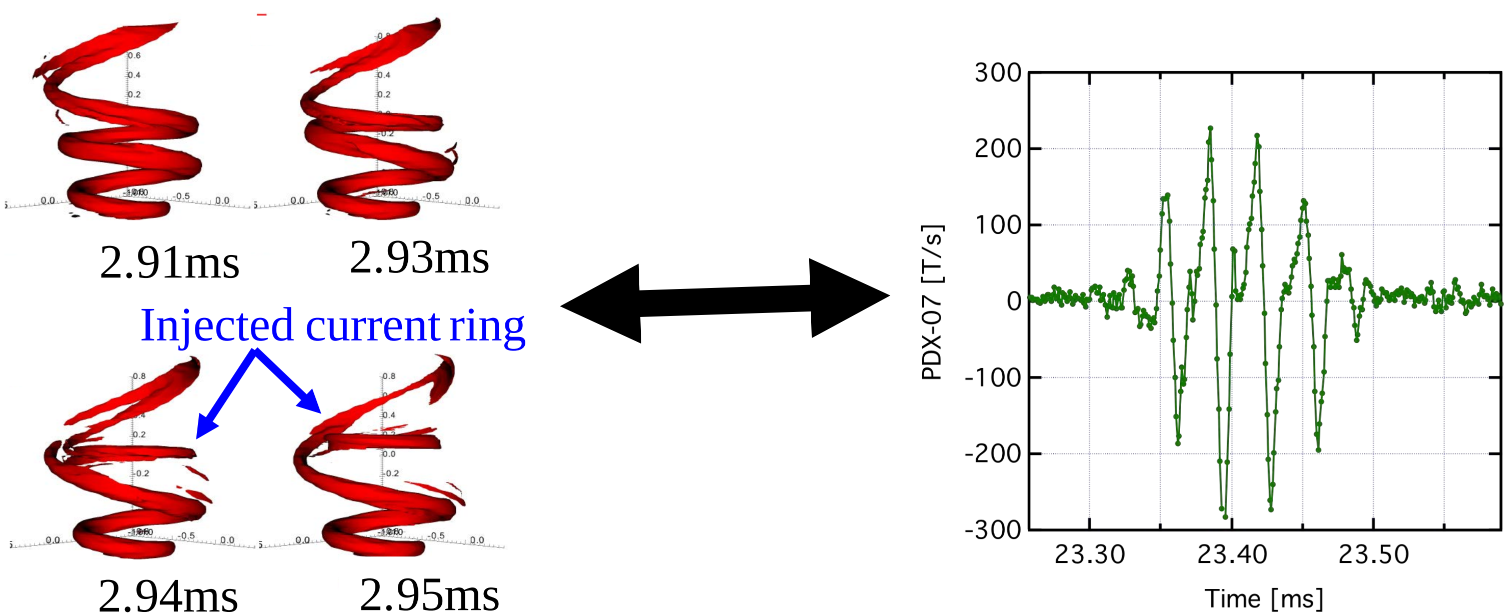
*J. O'Bryan, PhD Thesis, UW Madison 2014

Connection between Loop Creation, Bursts

- Bursts associated with coherent stream, current buildup



- What could MHD say about existence of beam in edge?



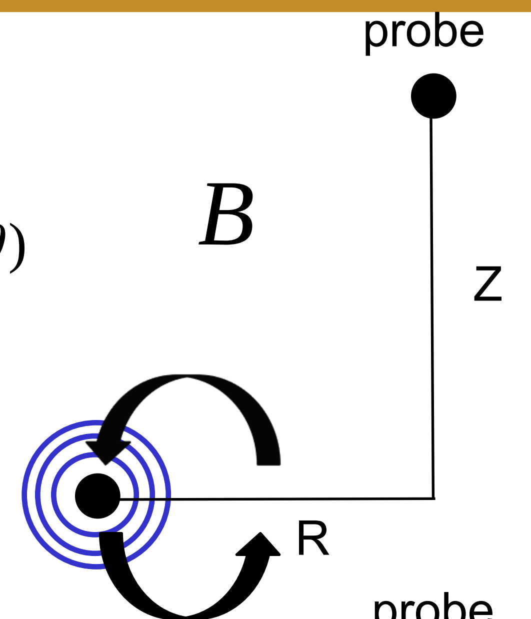
Hypothesis: dB/dt on PDXs Comes from ‘Whirling’ (Infinite) Line Source

- Assume remote, circular stream rotation

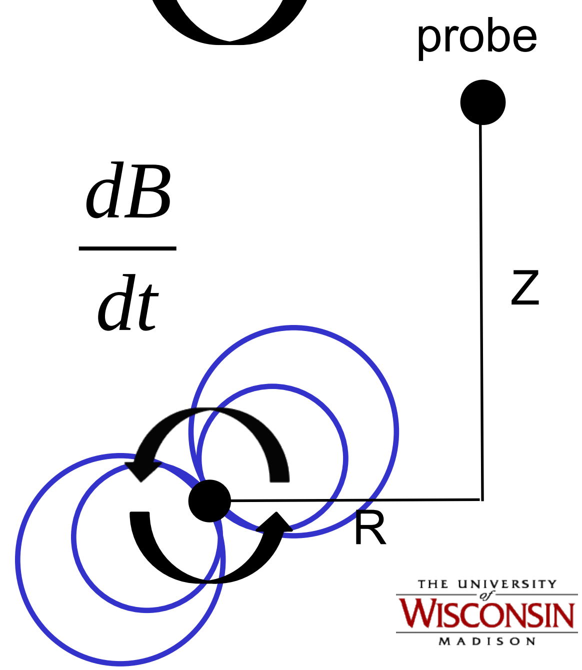
$$\Delta B = \frac{\mu_0 I}{2\pi r_1} - \frac{\mu_0 I}{2\pi r_2} = \frac{\mu_0 I}{2\pi r_1 r_2}\left(\vec{r}_1 - \vec{r}_2\right) \approx \frac{\mu_0 I}{2\pi r^2}\left(r_1 - r_2\right)\cos(\theta)$$

$$\frac{dB}{dt} \approx \frac{\mu_0 I}{2\pi}\frac{\left(r_1 - r_2\right)}{dt}\frac{\cos(\theta)}{r^2}$$

$$\frac{dB}{dt} \approx \frac{\mu_0 I}{2\pi} 2\pi r f \frac{\cos(2\pi f t - \arctan(Z/R))}{R^2 + Z^2}$$



- dB/dt structure looks like ‘tumbling’ dipole

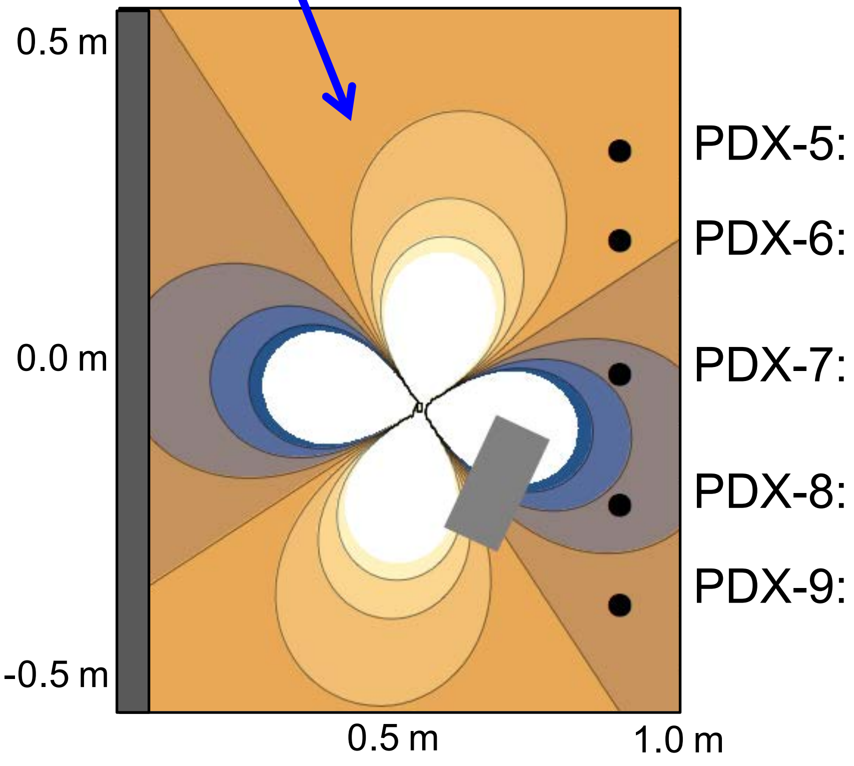


- However, probes measure d(B_z)/dt, not total dB/dt

Hypothesis: dB/dt on PDXs Comes from 'Whirling' (Infinite) Line Source

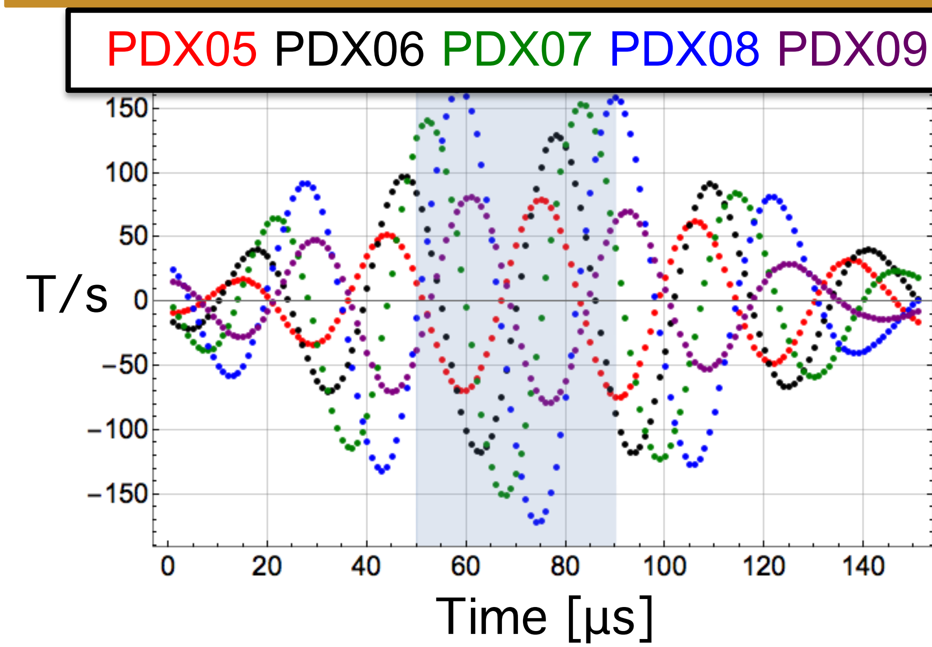
- Hypothesized dB_z/dt:

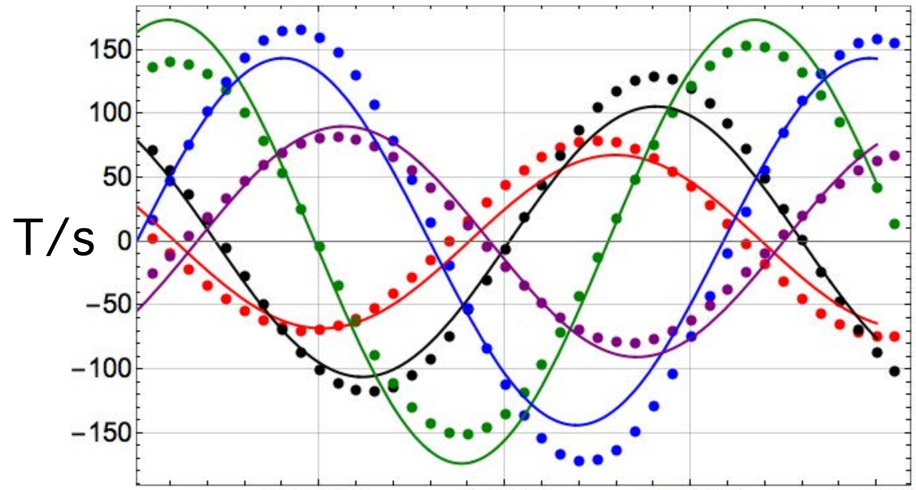
$$\frac{dB_{z,probe}}{dt} = \frac{\mu_0 I r_{motion} f \cos[2\pi ft - 2\arctan[\frac{z_{probe} - Z_{stream}}{r_{probe} - R_{stream}}]]}{\left(z_{probe} - Z_{stream}\right)^2 + \left(r_{probe} - R_{stream}\right)^2}$$



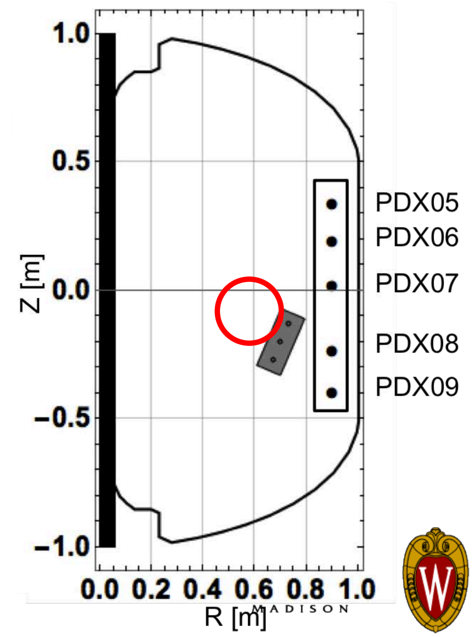
- 4-lobed, fall-off is $\frac{1}{r^2}$

Fit to Data Looks Promising





$$\frac{dB_{z,probe}}{dt} = \frac{\mu_0 I r_{motion} f \cos[2\pi f t - 2\arctan[\frac{z_{probe}-Z_{stream}}{r_{probe}-R_{stream}}]]}{\left(z_{probe}-Z_{stream}\right)^2+\left(r_{probe}-R_{stream}\right)^2}$$



R_{stream}	Z_{stream}	r_{motion}
0.58m	-0.08m	10cm

Model Inverts for R(t), Z(t)

- Phase difference of 2 signals is

$$\Delta\varphi = 2\arctan[\frac{z_{probe1} - Z_{stream}}{r_{probe1} - R_{stream}}] - 2\arctan[\frac{z_{probe2} - Z_{stream}}{r_{probe2} - R_{stream}}]$$

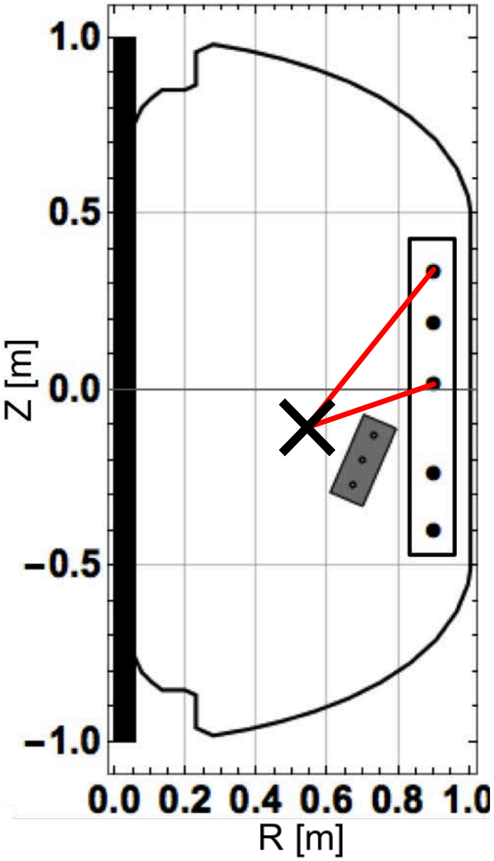
- The ratio of amplitudes of 2 signals

$$T = \frac{\left(z_{probe2} - Z_{stream}\right)^2 + \left(r_{probe2} - R_{stream}\right)^2}{\left(z_{probe1} - Z_{stream}\right)^2 + \left(r_{probe1} - R_{stream}\right)^2}$$

- 2 equations, 2 unknown R, Z of stream:

$$R_{stream} = r_p \pm \frac{\sqrt{T}\,\Delta z \sin\left(\Delta\varphi/2\right)}{T \pm 2\cos\left(\Delta\varphi/2\right)\sqrt{T} + 1}$$

$$Z_{stream} = \frac{z_2 - T\cos\left(\Delta\varphi\right)\left(z_1 + z_2\right) + z_1 T^2 \pm \sqrt{T}\left(T-1\right)\Delta z \cos\left(\Delta\varphi/2\right)}{T^2 - 2\cos\left(\Delta\varphi\right)T + 1}$$



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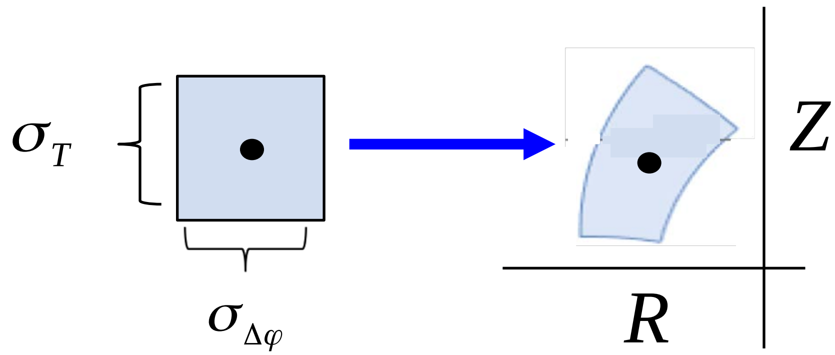
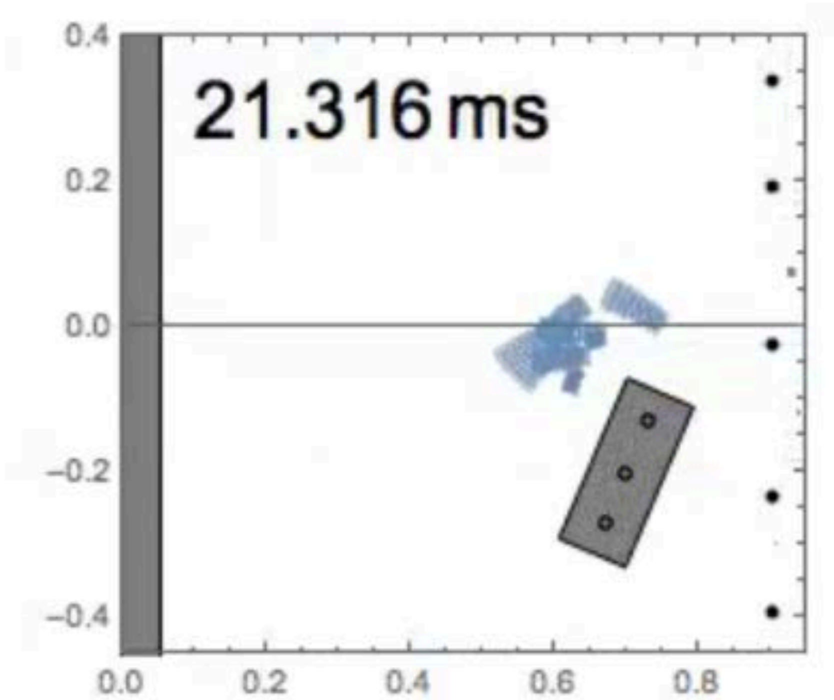
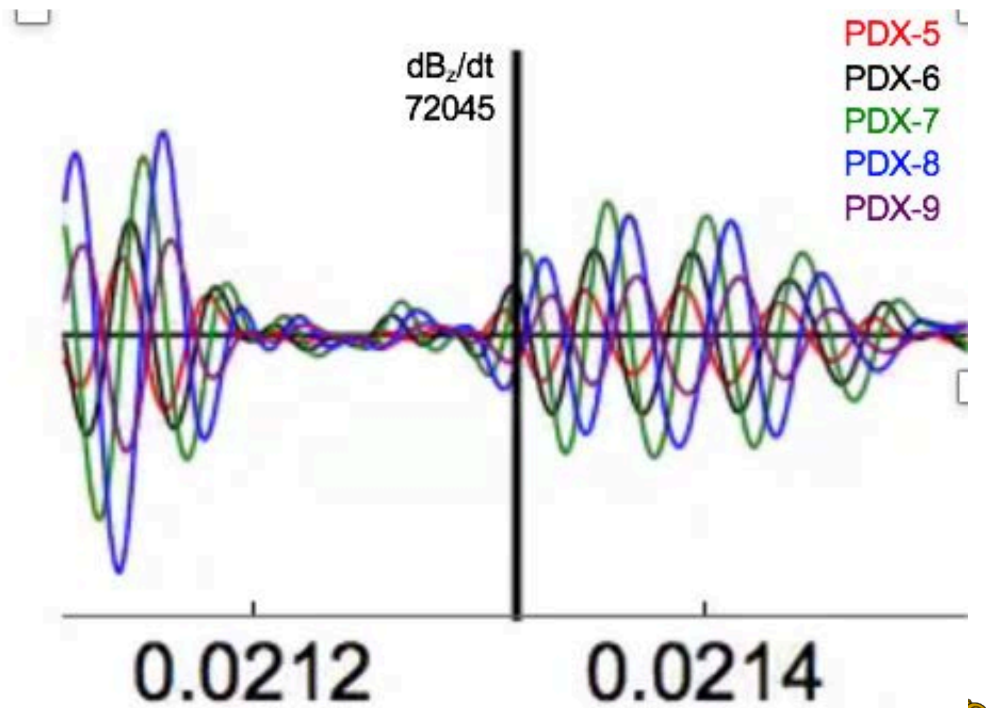
$R_{stream}(t)$, $Z_{stream}(t)$ is Output

- Combine with uncertainty to yield small R,Z region
- Signal origin appears localized







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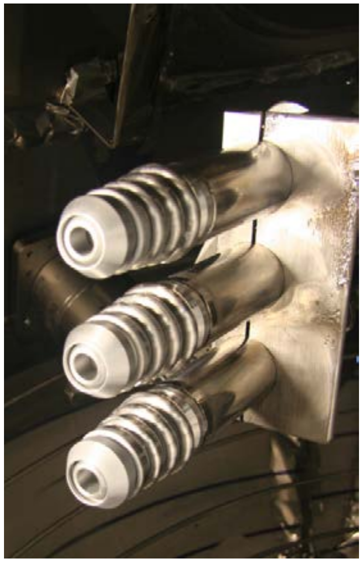
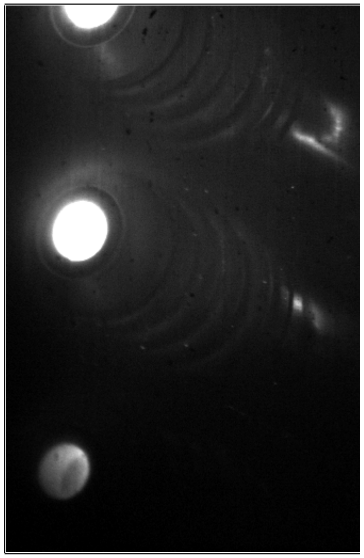
Managing Plasma-Material Interaction is a Formidable Challenge

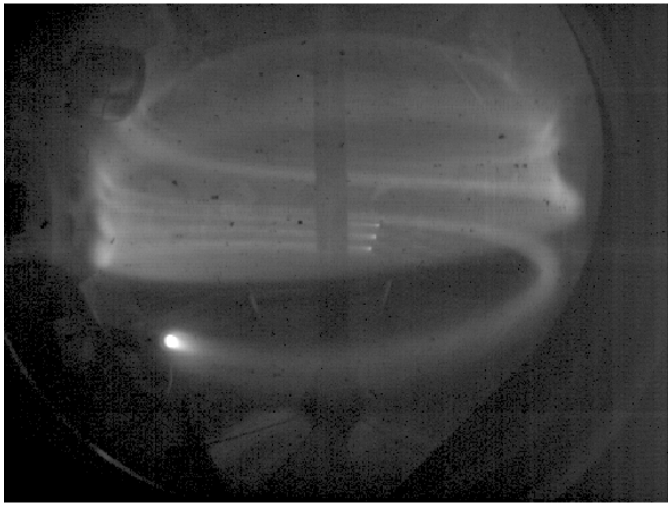
- Injector requirements include
  - V_{inj} > 1 kV
  - Large A_{inj}, J_{inj}
  - Δt_{pulse} ~ 10-100 ms
  - Minimal PMI

  …all adjacent to tokamak LCFS



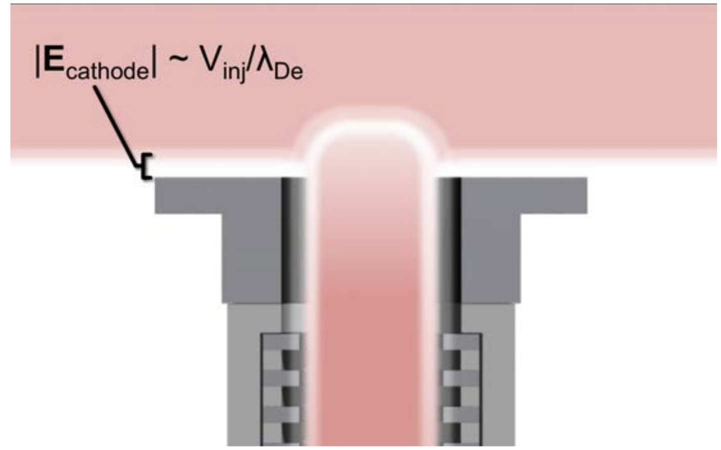


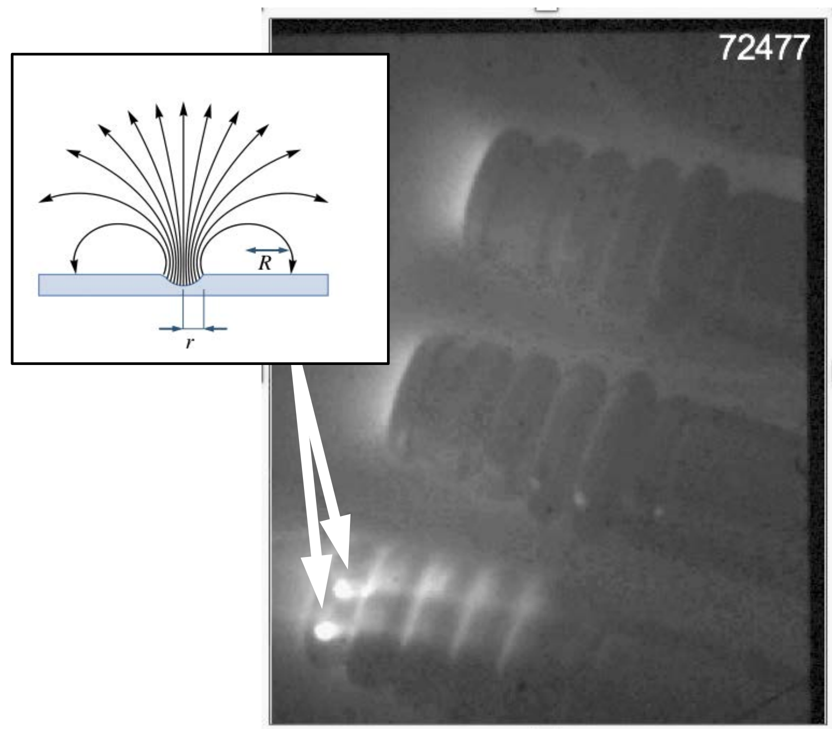
- Significant evolution of design to meet physics challenges
  - ~3x improvement in V_{inj}, Δt_{pulse}



Spots Move and Interact with Injector Structures

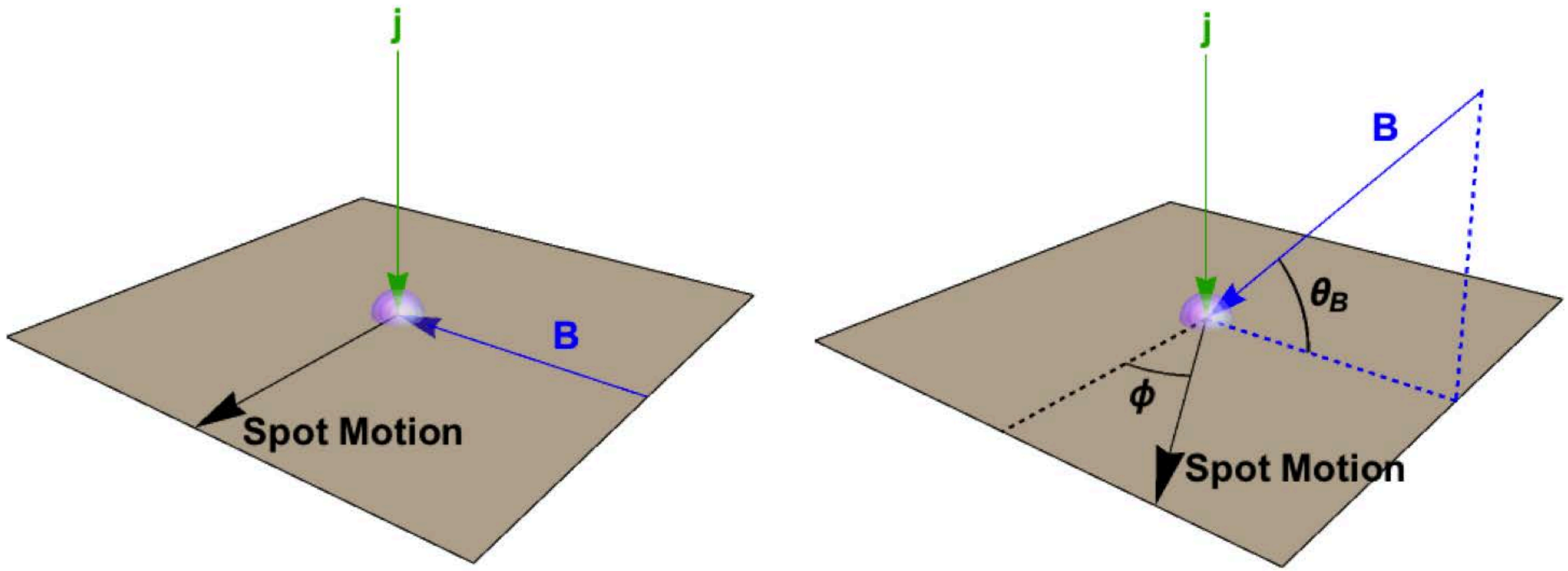
- Breakdown in the presence of plasma occurs ~10^5 V/cm
  - At $10^{18}/m^3$, 10eV plasma, this is ~1kV
- Cathode spots, when ignited, roam cathode surface
- Interaction with insulators cases outgassing, damage
- Motion in field can potentially be controlled





Cathode Spot Motion in a Field

- Spot motion occurs in –j x B direction, subject to angular displacement, ϕ



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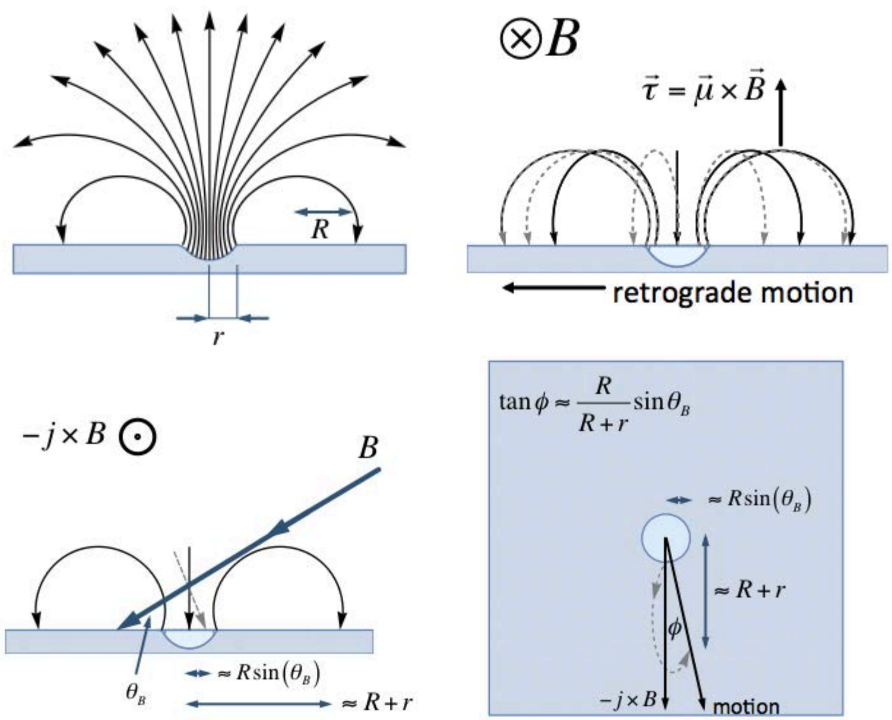
Barengoltz* Provides a Model for Motion in Arbitrary B Field

- Based on return currents seen in simulations
- New spots arise due to preferential bombardment by returning electrons
- ‘Small spots’ have r<<R, ‘Large spots’ have r=R



$$\phi \approx \arctan\left(\varrho \sin\left(\theta_B\right)\right)$$

$$\frac{1}{2} \le \varrho \le 1$$

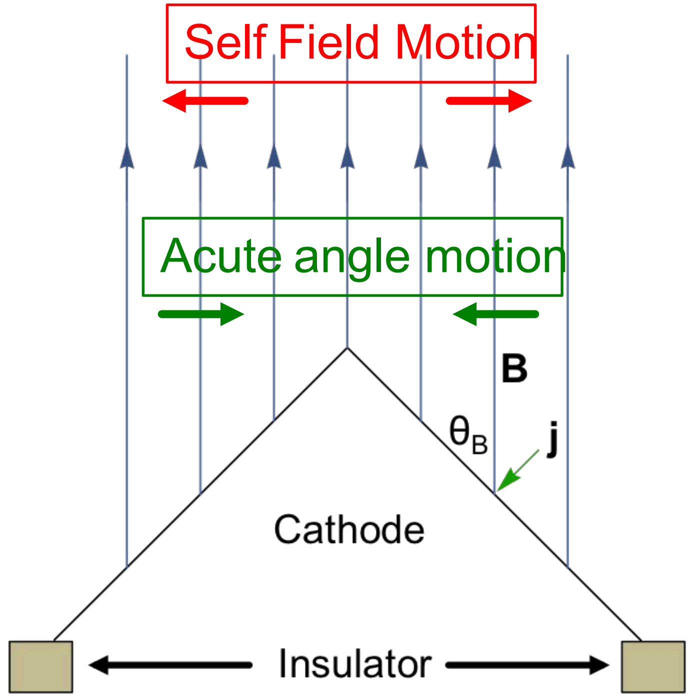
*Zh. Tekh. Fiz. **68**, 60–64 (June 1998)

Conical Frustum Design Implemented to Mitigate Cathode Spot Damage

- Conical shape used to induce inward motion of spots

- Self-magnetic field in Pegasus pushes spots outward radially

- Numerical approach necessary to balance these tendencies



- Heuristics are rendered as: $\vec{r}\,' = \varrho\left(\hat{b} - \hat{n}\left(\hat{n}\cdot\hat{b}\right)\right) + \hat{n}\times\hat{b}$

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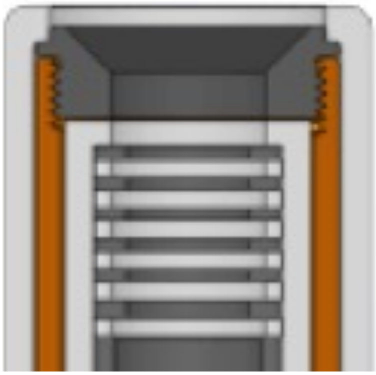
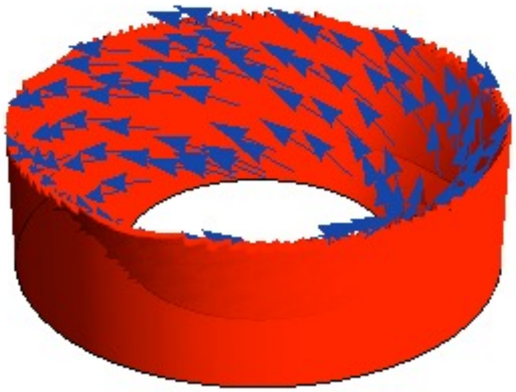
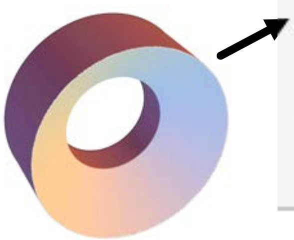
Motion ALWAYS Outward for Concave Shapes







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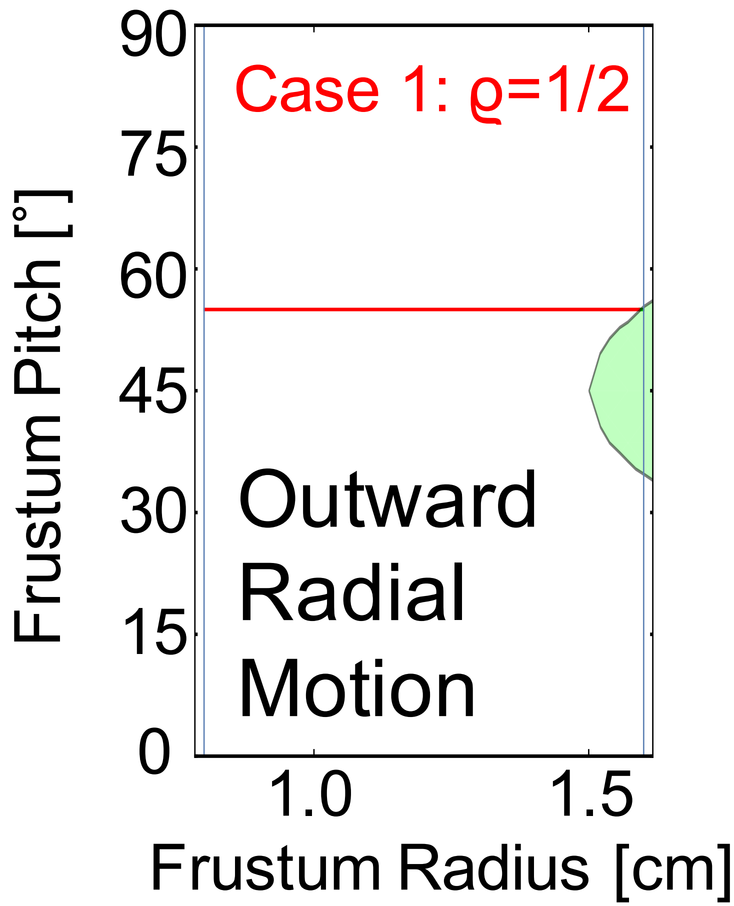
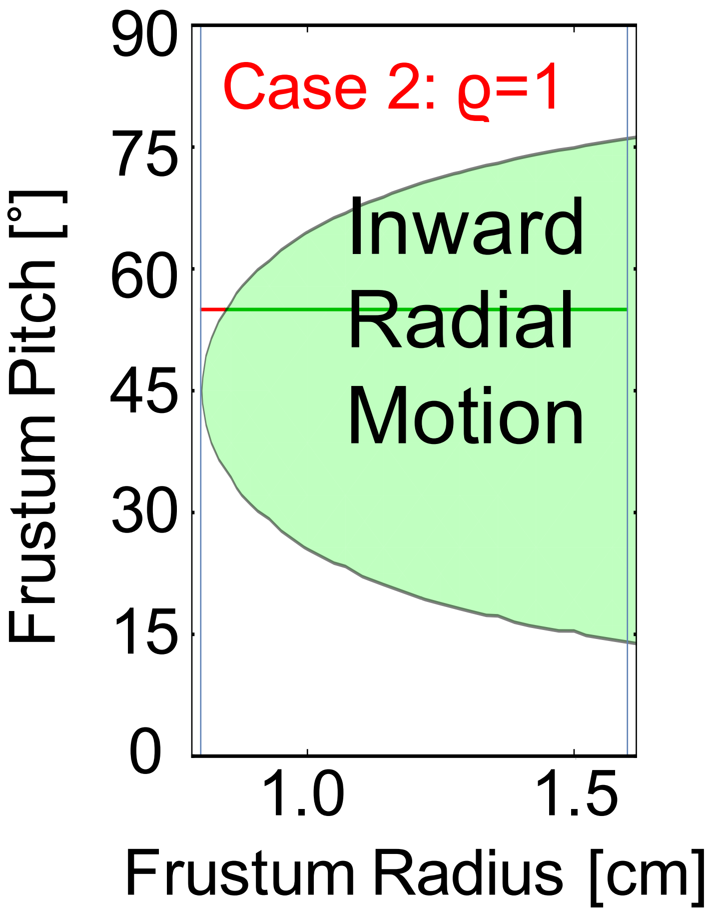
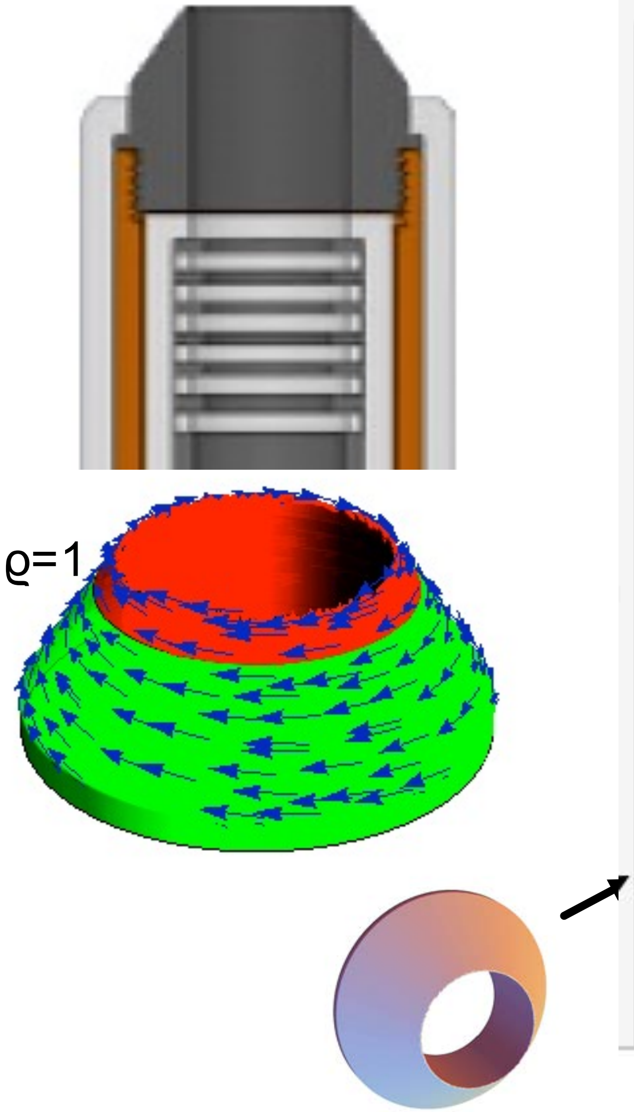
Convex Shape MIGHT Have Inward Motion

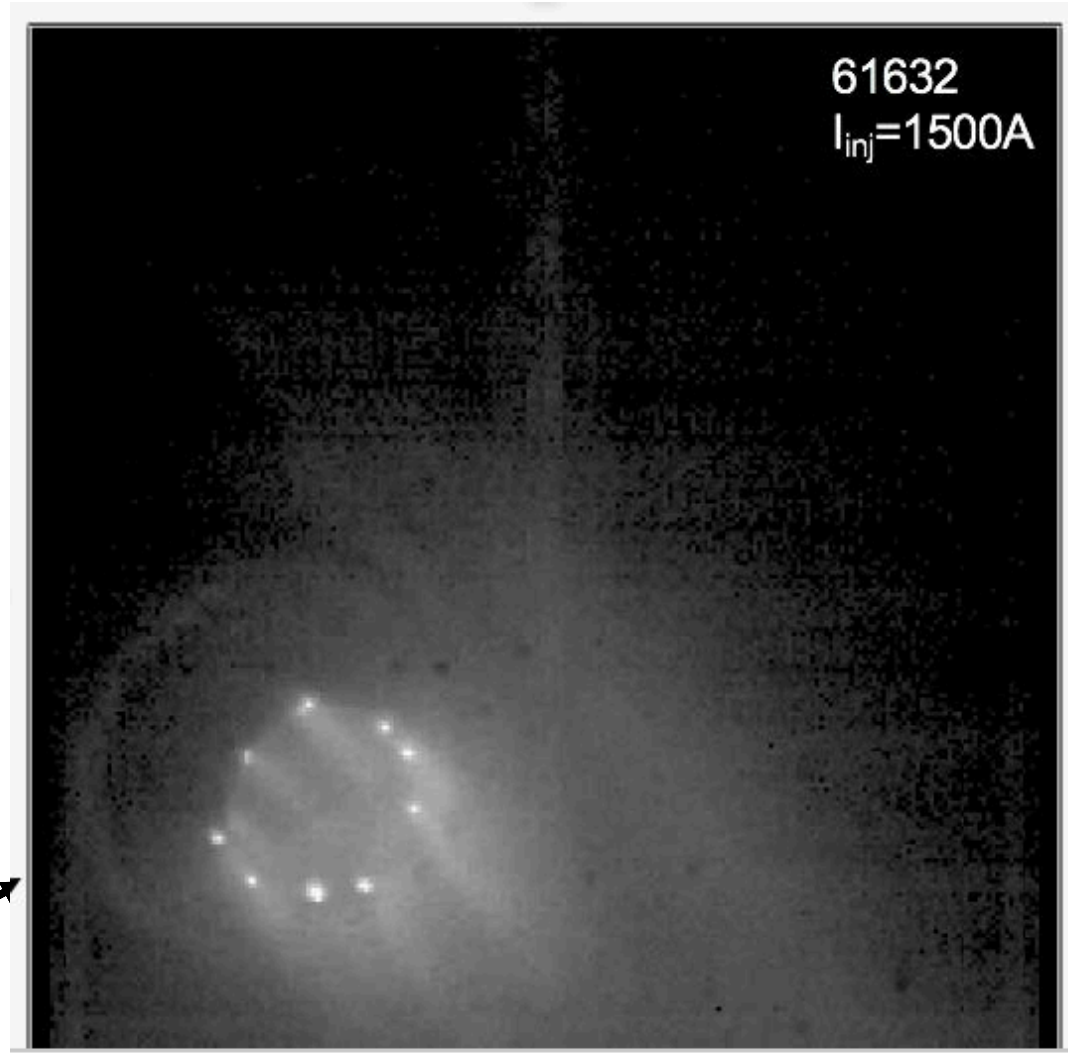
- The sign of $\vec{r}\,' = \varrho\left(\hat{b} - \hat{n}\left(\hat{n}\cdot\hat{b}\right)\right) + \hat{n}\times\hat{b}$ gives spot radial motion





Motion is Inward for Convex Cathodes in a Certain Interval





Summary

- Limits to max I_p in LHI depend on V_{INJ}, I_{INJ}, and are related by

$$I_{inj} = \min[n_{edge}, \beta n_{arc}] e \sqrt{\frac{2e}{m_e}} \sqrt{V_{inj}} A_{inj}$$

- Initial model to understand MHD was created and suggests an oscillating, coherent beam

- Injector design improvements are allowing access to higher power operations

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Reprints:

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