Improving spheromak helicity injection by eliminating the constraint imposed by Paschen breakdown physics

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Classic theory of spheromaks

Taylor's original conjecture

- Magnetic turbulence or instability dissipates magnetic energy, but not helicity

- Conjecture: System decays to lowest magnetic energy consistent with original helicity inventory

Relaxed state

- Any process which dissipates energy while conserving helicity will cause the system to relax to state described by

$$\nabla \times \vec{B} = \lambda \vec{B}$$

Spheromak is a solution to this equation

Spheromak has nested toroidal flux surfaces, like tokamak

Offers potential for self-organized magnetic confinement

Relation of Relaxed state to MHD Equation of motion

$$\rho \frac{d\vec{U}}{dt} = \vec{J} \times \vec{B} - \nabla P$$

Equilibrium

$$\rho \frac{d\vec{U}}{dt} = \vec{J} \times \vec{B} - \nabla P$$

Ignore hydrodynamic pressure

$$\rho \frac{d\vec{U}}{dt} = \vec{J} \times \vec{B} - \nabla P$$

Force-free equilibria

Magnetic force $\vec{J} \times \vec{B} = 0$

So $\vec{J}$ is parallel to $\vec{B}$

Force-free equilibrium

Therefore $\vec{J} = \lambda \vec{B}$

Which gives

$$\nabla \times \vec{B} = \lambda(\vec{x})\vec{B}$$

for force-free equilibrium

Summary of relaxation theory

- No dynamics: system evolves through sequence of relaxed states

- Dynamics assumed to be either non-existent, or irrelevant mystery

- No pressure gradients: zero beta assumption

Summary of recent Caltech results on spheromak formation

- Dynamics is important
- Finite beta is important
- System does not evolve through sequence of relaxed states
- Helicity has to be injected into system
- Injection of helicity involves injection of magnetic flux and hence injection of plasma

Have to keep/consider all terms in equation of motion,
more complicated than relaxation model

$$\rho \frac{d\vec{U}}{dt} = \vec{J} \times \vec{B} - \nabla P$$

Find steady-state has <u>axial flow</u>

$$\nabla \cdot (\rho \mathbf{U}\mathbf{U}) = \mathbf{J} \times \mathbf{B} - \nabla P$$

Find steady-state has axial flow

$$\nabla \cdot (\rho \mathbf{U}\mathbf{U}) = \mathbf{J} \times \mathbf{B} - \nabla P$$

Solve radial force balance for $P(r,z)$ →

$$0 = (\mathbf{J} \times \mathbf{B})_r - \frac{\partial P}{\partial r}$$

Find steady-state has axial flow

$$\nabla \cdot (\rho \mathbf{U}\mathbf{U}) = \mathbf{J} \times \mathbf{B} - \nabla P$$

Solve radial force balance for $P(r,z)$ →

$$0 = (\mathbf{J} \times \mathbf{B})_r - \frac{\partial P}{\partial r}$$

$$\frac{\partial}{\partial z}(\rho U_z^2) = (\mathbf{J} \times \mathbf{B})_z - \frac{\partial P}{\partial z}$$

Substitute for $P(r,z)$ from radial force balance

Practical Issues

- Plasma needs to be formed,
  i.e., need breakdown

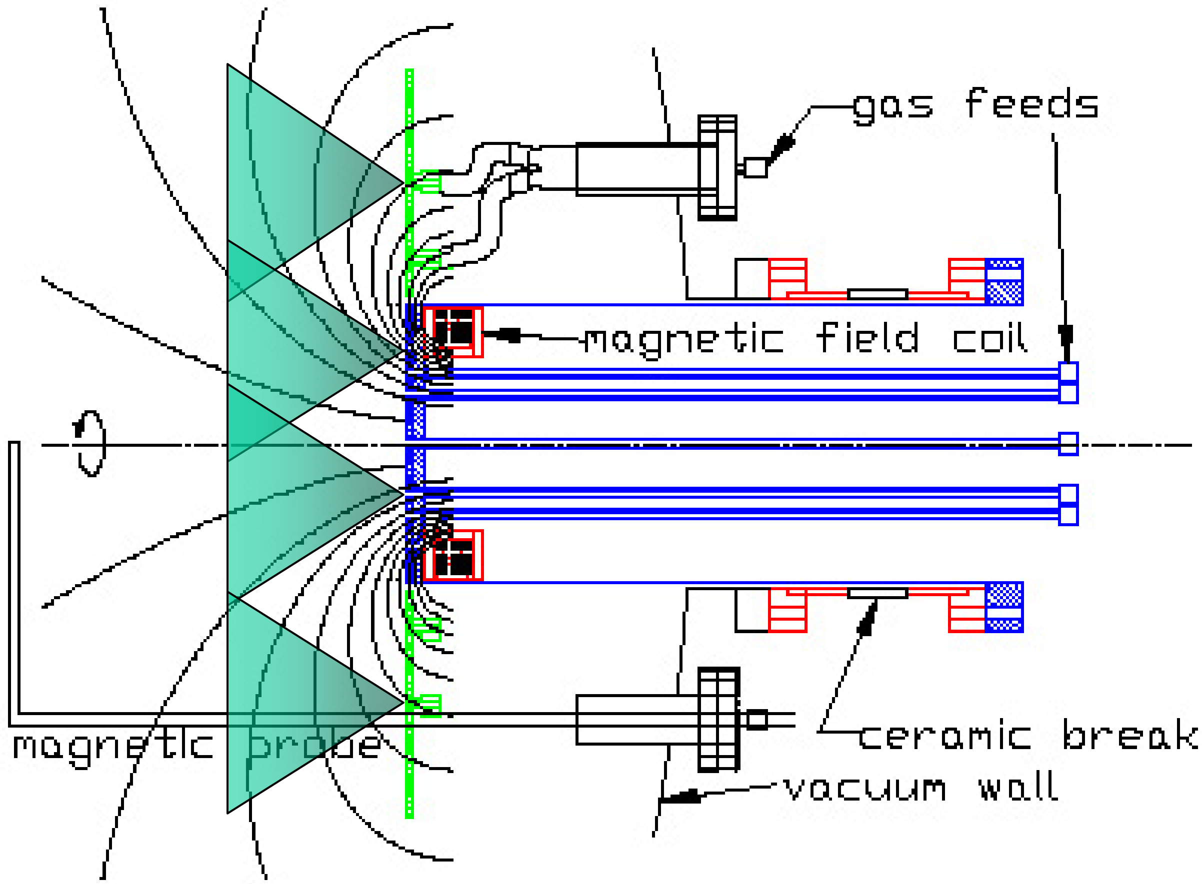
- Helicity has to be injected

- Contemporary spheromaks achieve breakdown according to Paschen criterion

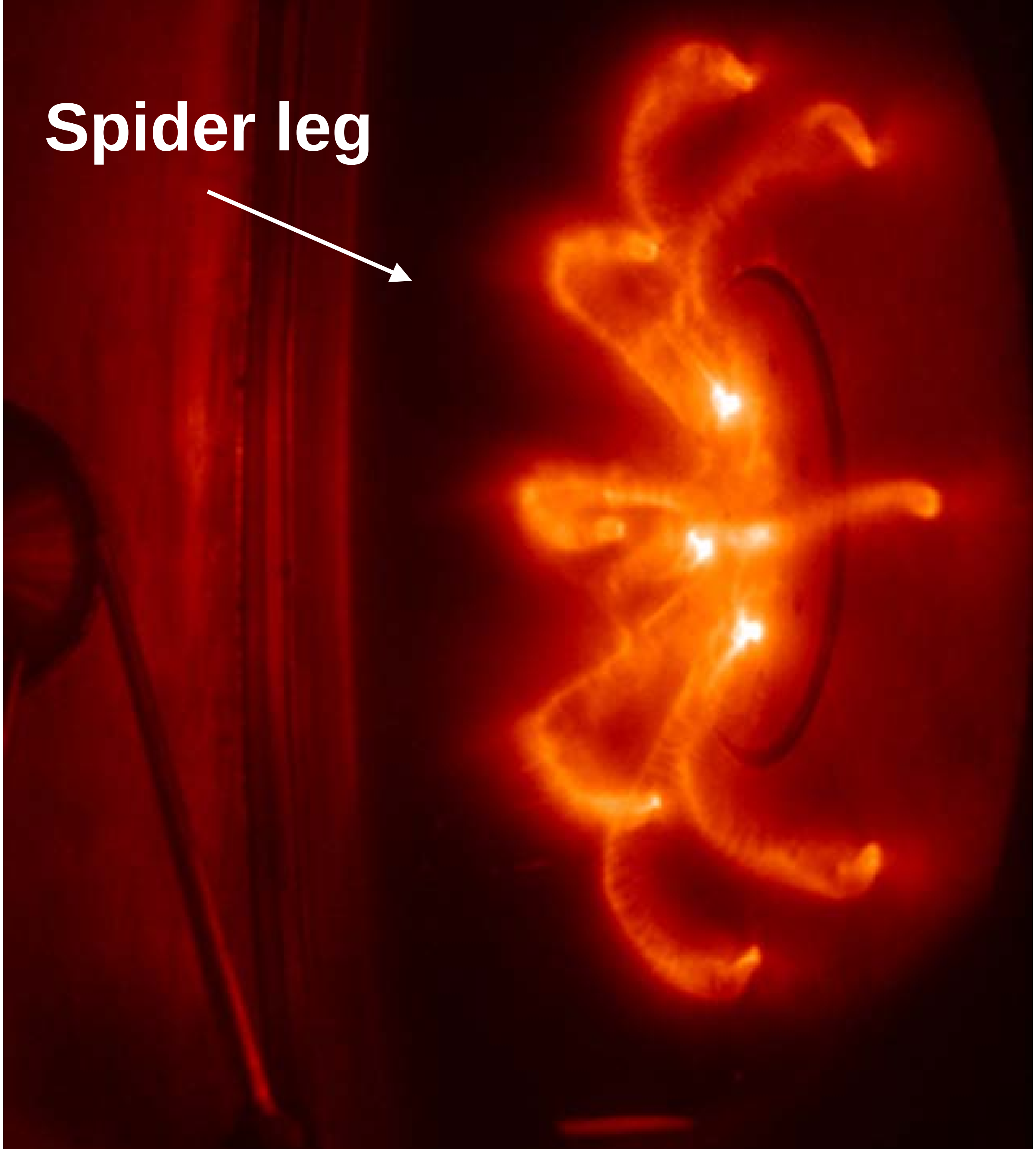
Paschen Criterion

- An avalanching process involving atomic physics
- Paschen "sweet spot" involves critical *Pd* product where *P* is pressure, *d* is inter-electrode distance
- Standard logic: Since having whole chamber at required *P* would result in excessive plasma density, use fast gas valves to have transient, localized required *P*

Puff in neutral gas



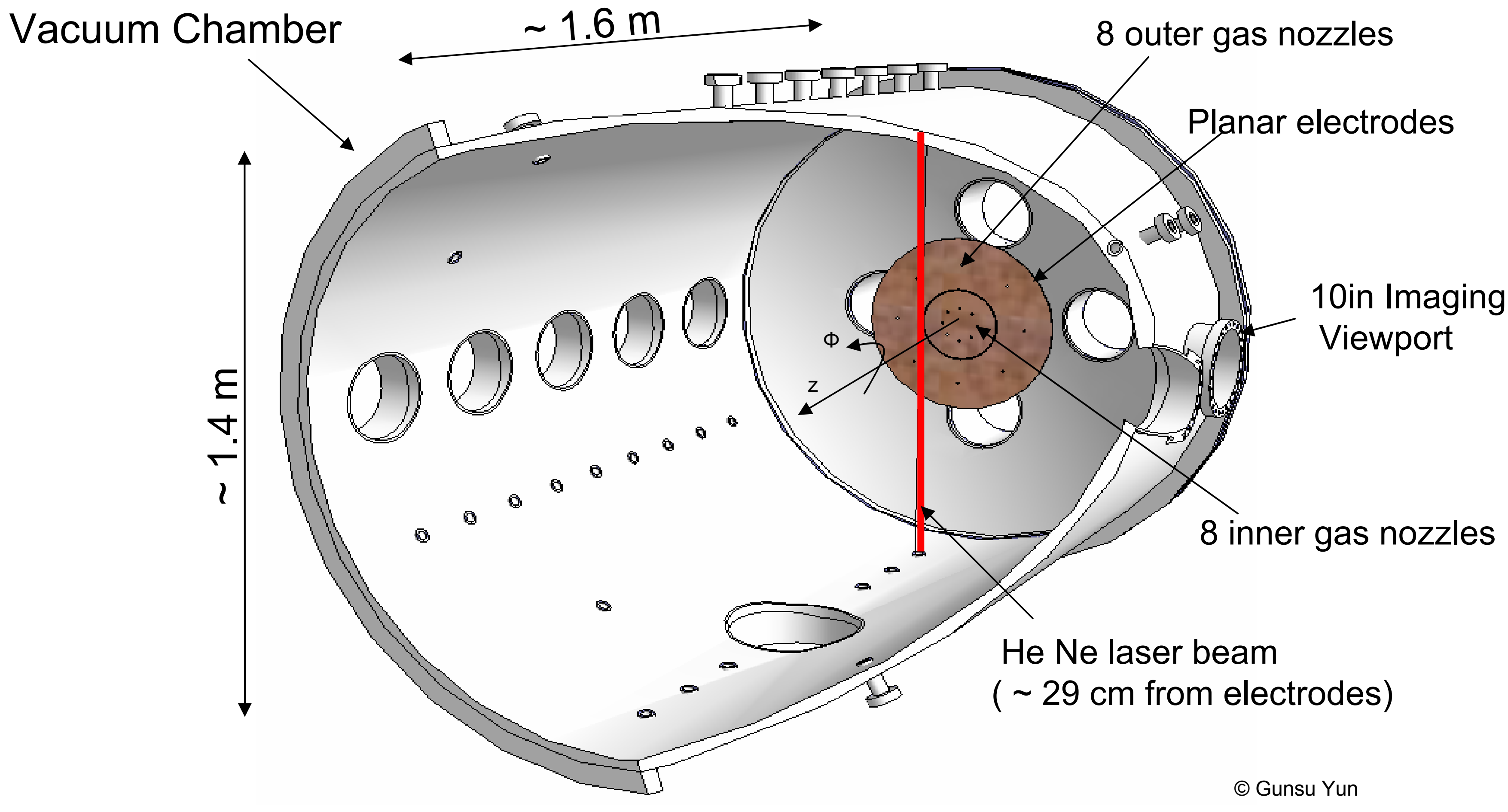
breakdown
is along field
lines



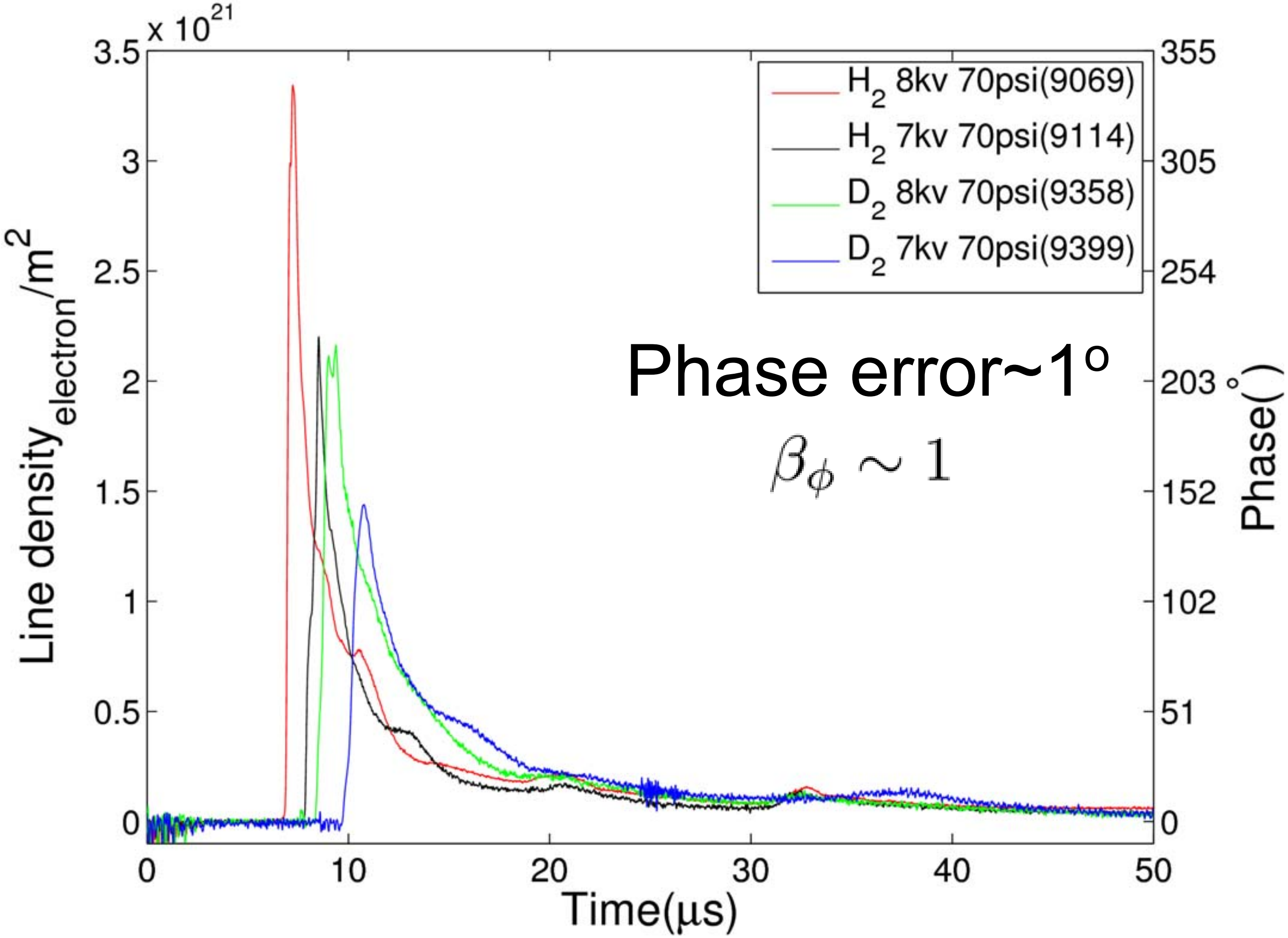
Key result

- Plasma density is NOT just the density of the gas puff, i.e., plasma does not result from just ionization of the gas puff
- Instead, a strong MHD-driven pumping process ingests dense plasma from gas nozzles to form a dense jet
- Jet density is orders of magnitude higher than gas puff density

Measurement of jet density/velocity with HeNe inteferometer (Kumar thesis 2009)



Time-of-flight and density information from interferometer



Prediction of jet flow velocity

- Axial flow velocity at jet tip

$$U_z = \frac{1}{2\pi a}\sqrt{\frac{\mu_0}{\rho}}\, I$$

I = jet electric current

a = jet radius at source electrode

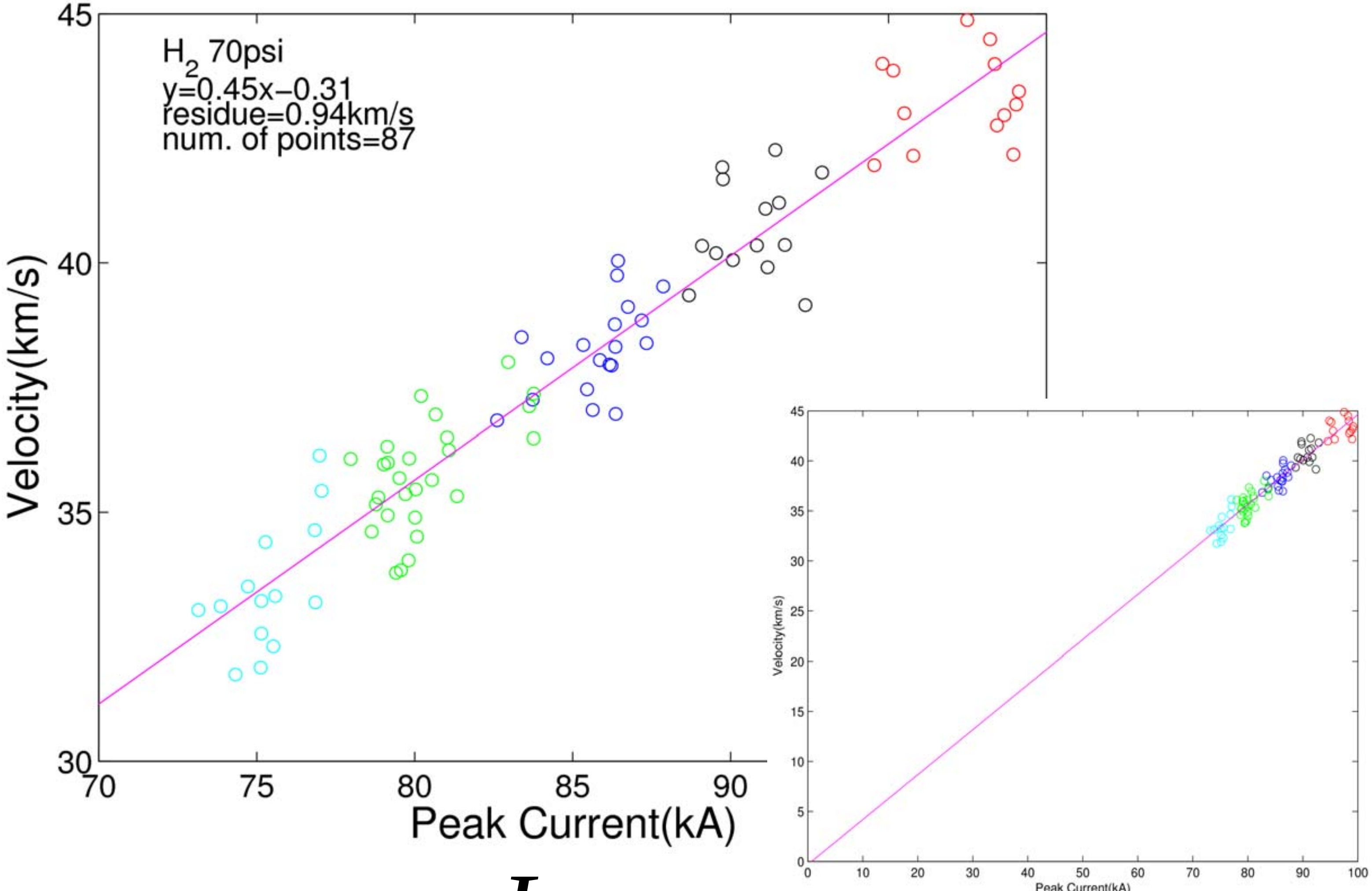
ρ = mass density at jet tip

- Verified using jet time-of-flight measurement

(D. Kumar, PhD thesis, 2009)

Verification of $U_z = \frac{1}{2\pi a}\sqrt{\frac{\mu_0}{\rho}}\, I$

U_z



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So…

- Plasma is not just “there”
- Instead is pumped in at pseduo-Alfvenic velocity

- Need to do this to inject helicity

- Toroidal flux associated with new helicity is frozen into inward flowing plasma jet

- Paschen breakdown makes jet too dense

Improvement Scheme

- Instead of having neutral <u>gas</u> at nozzle and breakdown in chamber, have <u>plasma</u> at nozzle
- Thus, ionize low density gas in nozzle
- Planning to try this at Caltech

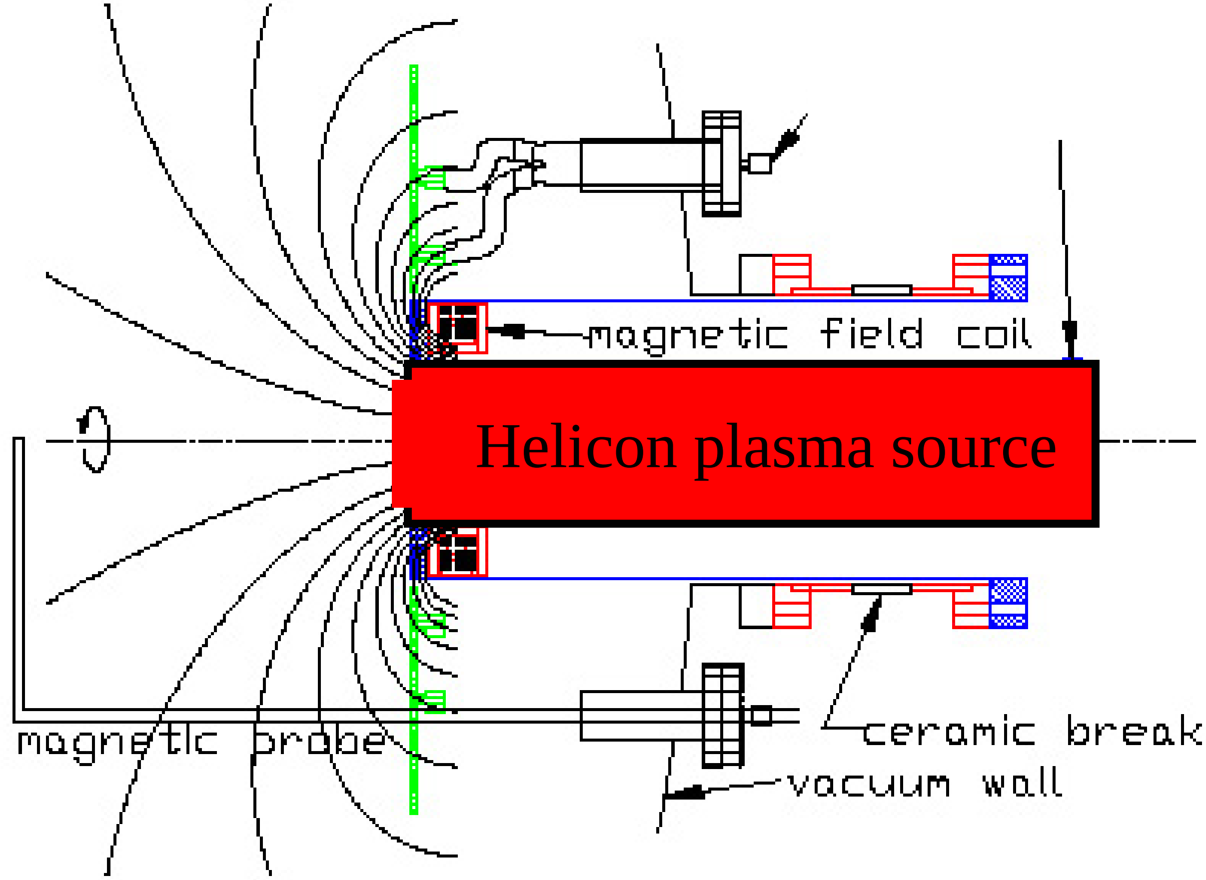
Possible pre-ionization schemes and advantages/disadvantages

- Electrodes in nozzle
  - Advantage: simple
  - Disadvantage: not much control, Paschen again
- Helicon source
  - Advantage: provides desired lower density, controllable, mature technology
  - Disadvantage: more complicated
- ECRH
  - Advantages/Disadvantages similar to helicon

Possible set-up:
pulsed helicon plasma instead of gas valves

Bias field

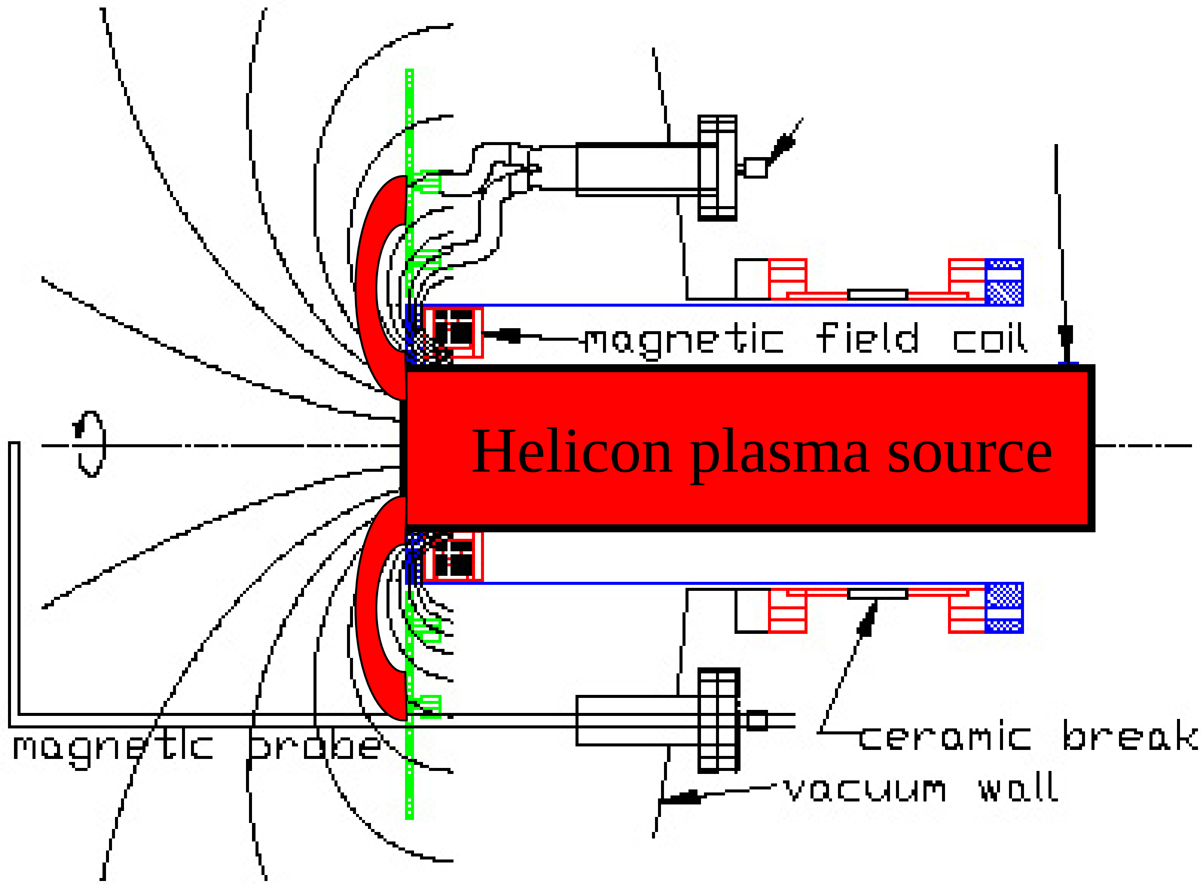
high vacuum



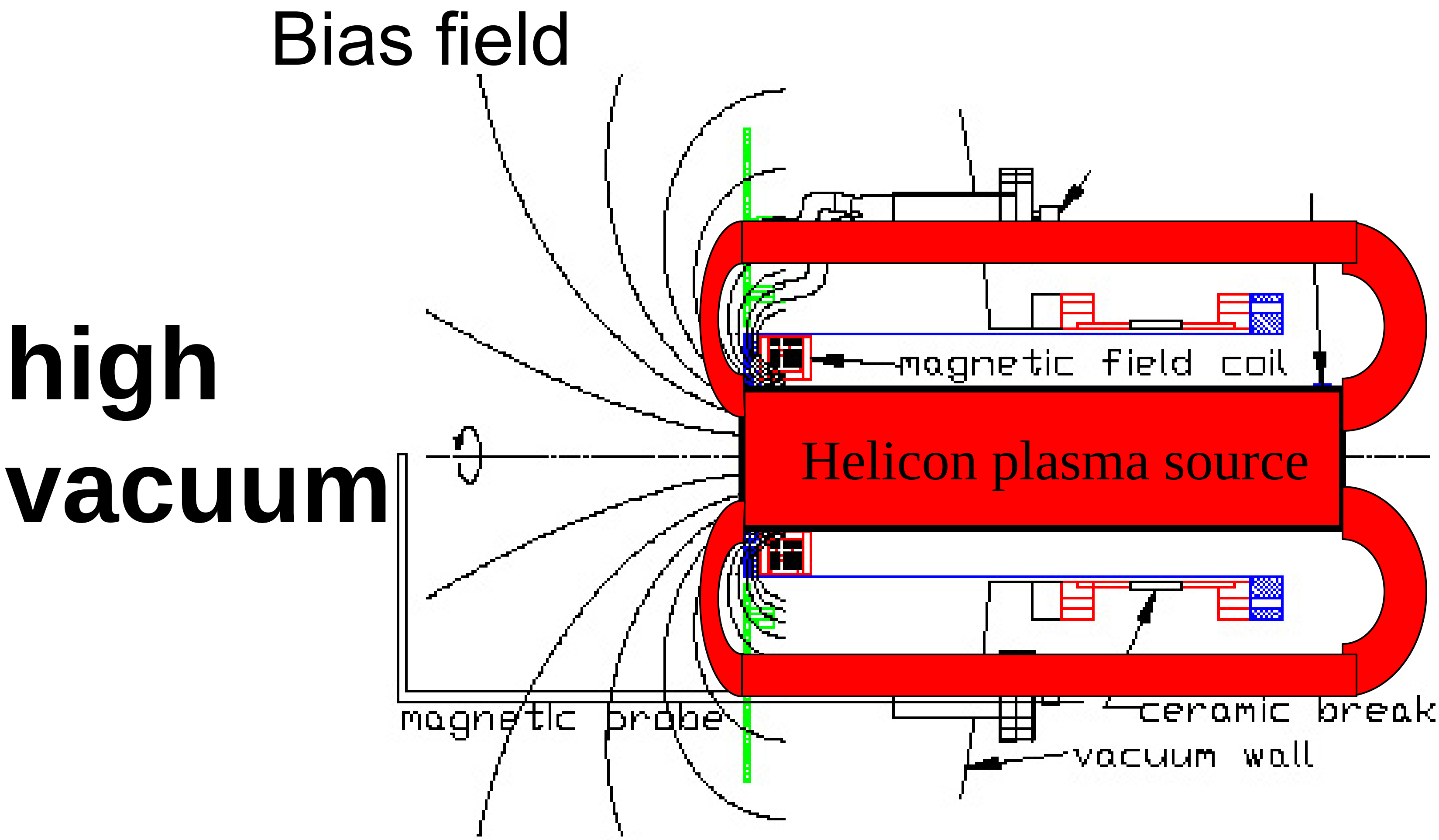
High voltage across gun electrodes pumps out helicon plasma to form spider legs

Bias field

high vacuum

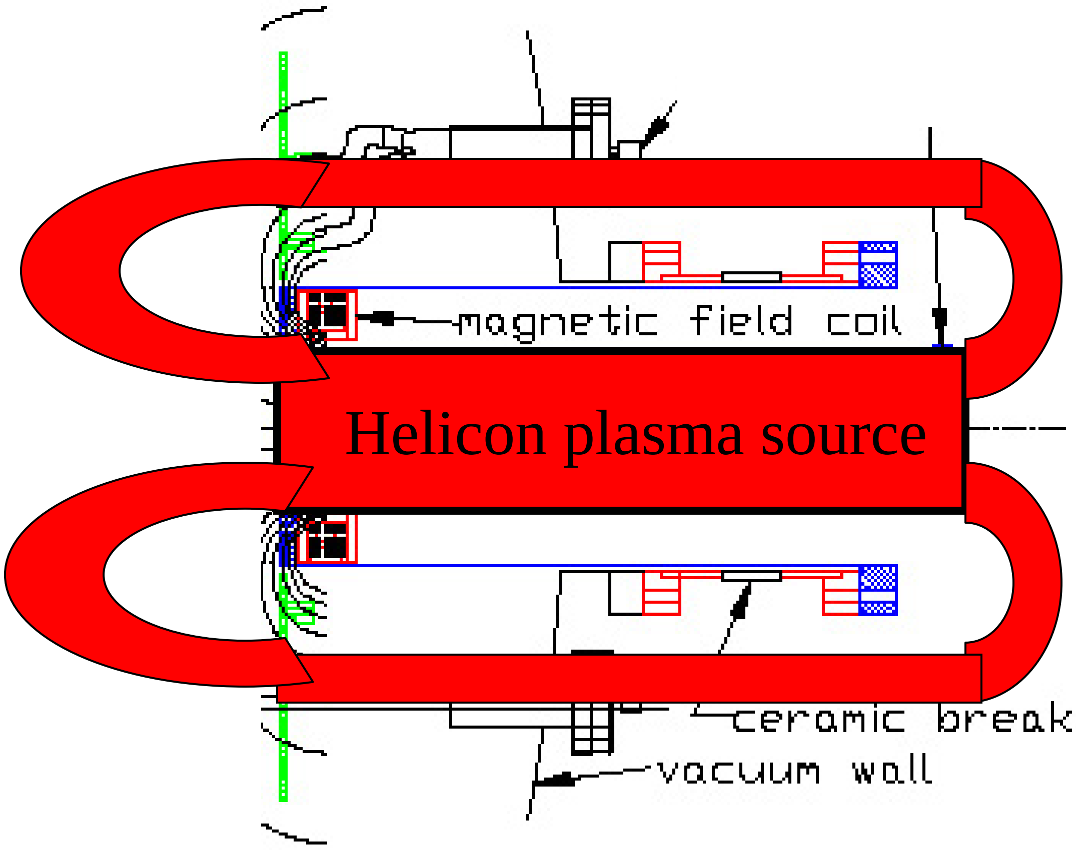


Or possibly


Bias field
high vacuum
magnetic field coil
Helicon plasma source
magnetic probe
ceramic break
vacuum wall

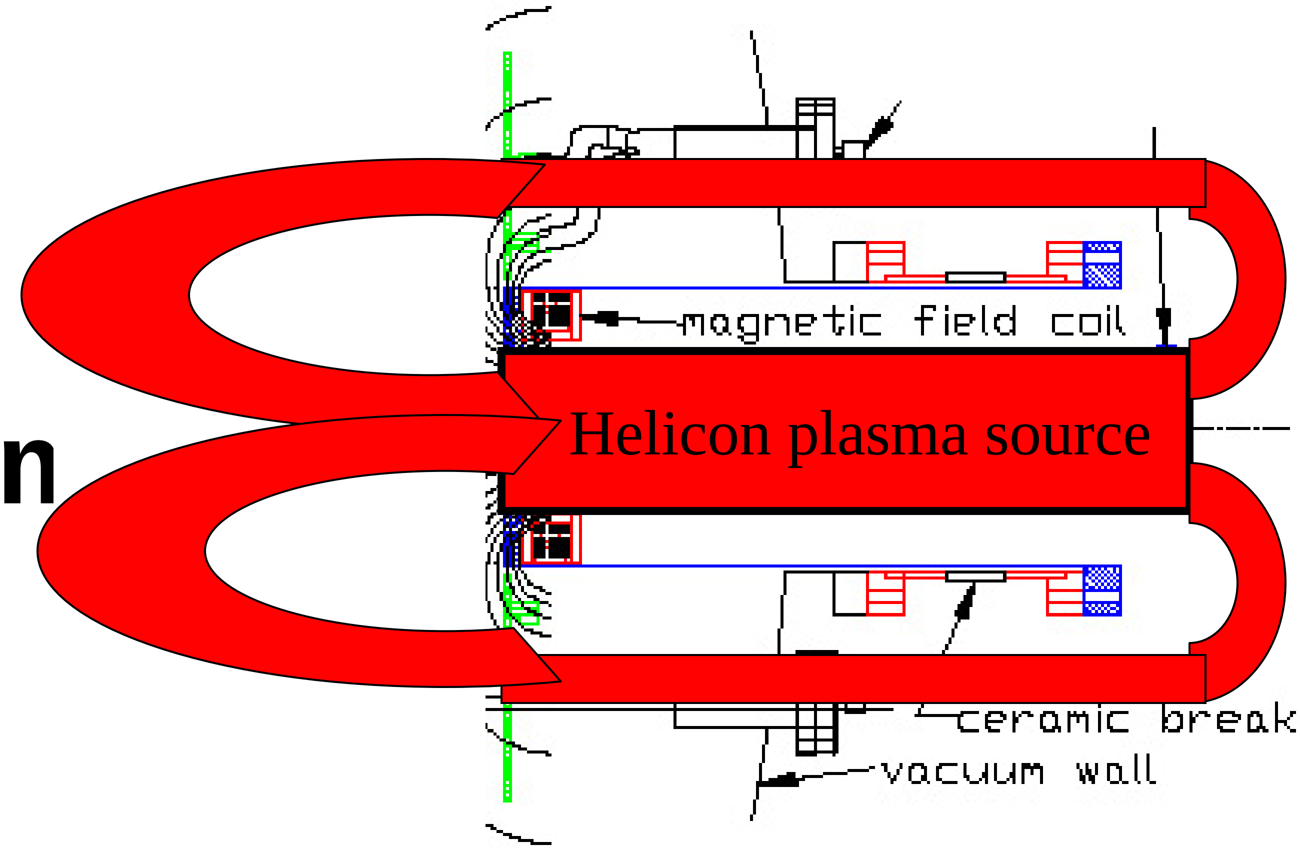
Spider legs expand

high vacuun



Form low density jet bringing in helicity

high vacuun



Helicon/ECRH source

- Pulsed solenoid magnetic field
- Pulsed rf (high power)
- Gas puff to feed helicon/ECRH source

- Obtain controlled lower density

- Breakdown decoupled from helicity injection

Virtues of lower density

- Faster jet
- Hotter particles
- Cleaner (less electrode ablation)

- Opens door to hotter spheromaks

Hotter = Better

Plan

- Examine several pre-ionization approaches
  - Find what works best
  - Avoid empiricism, understand fundamentals

- Goal: inject helicity while minimizing injection of cold particles