

# **Selective Injection and Trapping of Hydrogen from vacuum discharge**

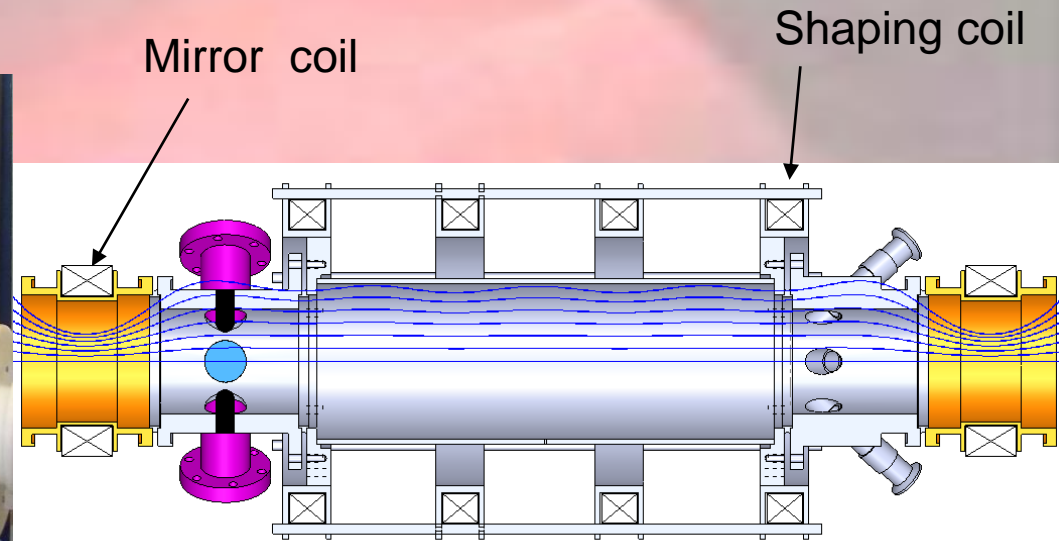
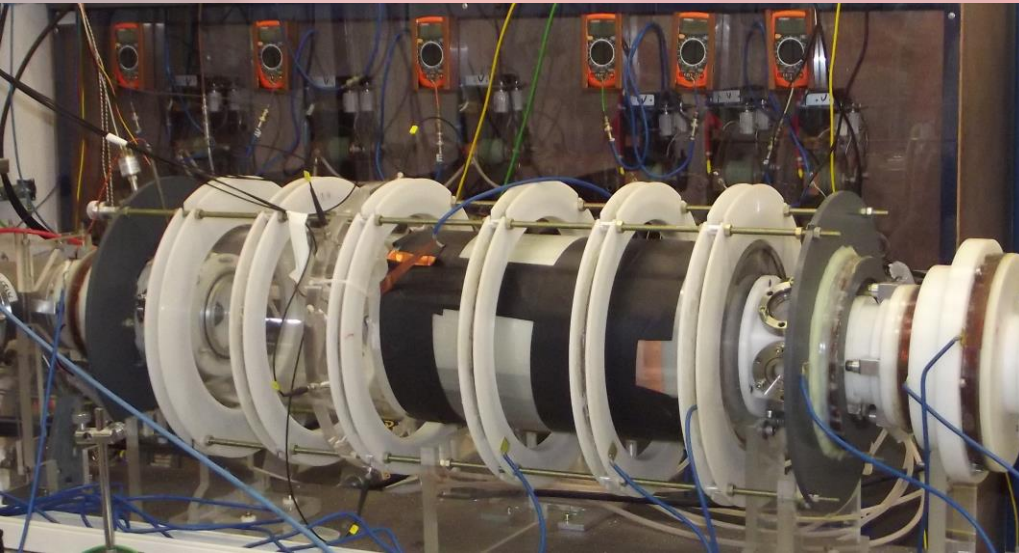
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# Plasma mirror machine at RPL



Maximal magnetic field – 2T  
Mirror ratio – 3-20  
Vacuum vessel diameter – 120 mm  
Trap length – ~1 m  
Base pressure –  $5 \cdot 10^{-6}$  torr

**Main research goal:**  
Stabilization of the flute instability by active feedback and RF field.

Be'ery I, Seemann O, Fruchtman A, Fisher A, Ron A, (2014) "Multi-mode stabilization of flute instability in mirror machine by active feedback", Plasma Phys. Control. Fusion **56**, 075002.

# Hydrogen fueling in magnetic confinement machines

Most hydrogen fuel injection sources for magnetic confinement machines rely on gas puff, pellet injection and neutral beams.

- Slow injection ( $>$ hundreds of  $\mu$ s).
- Technically complex.
- Vacuum issues.
- Inject neutral hydrogen.

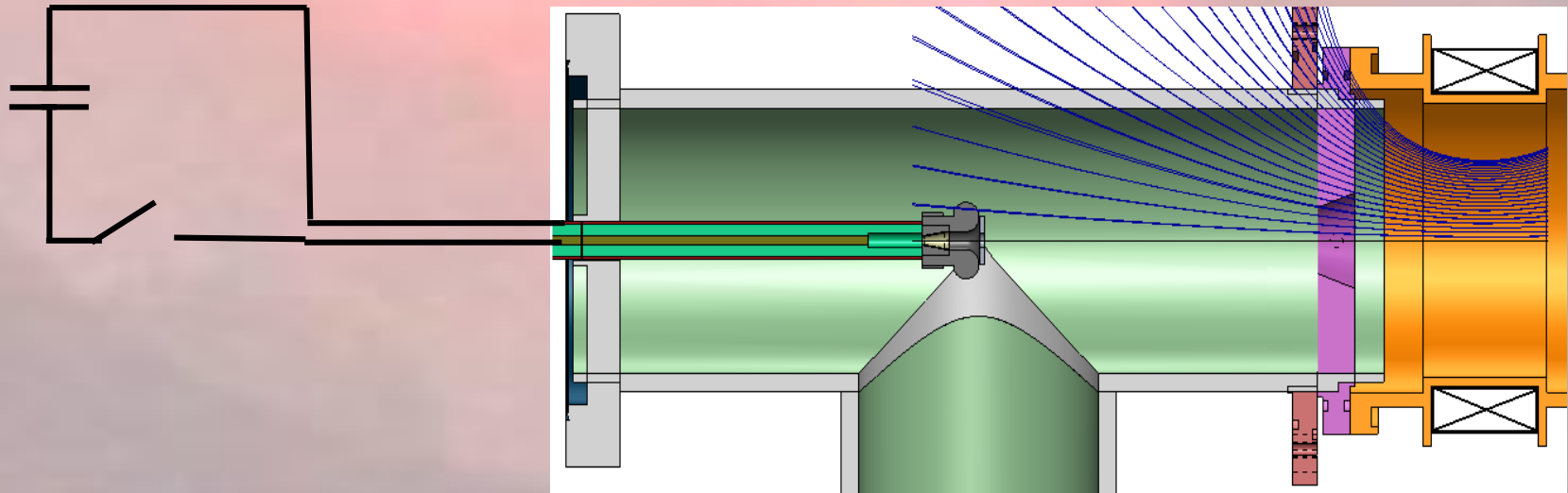


**Vacuum arcs can be put into beneficial use!**

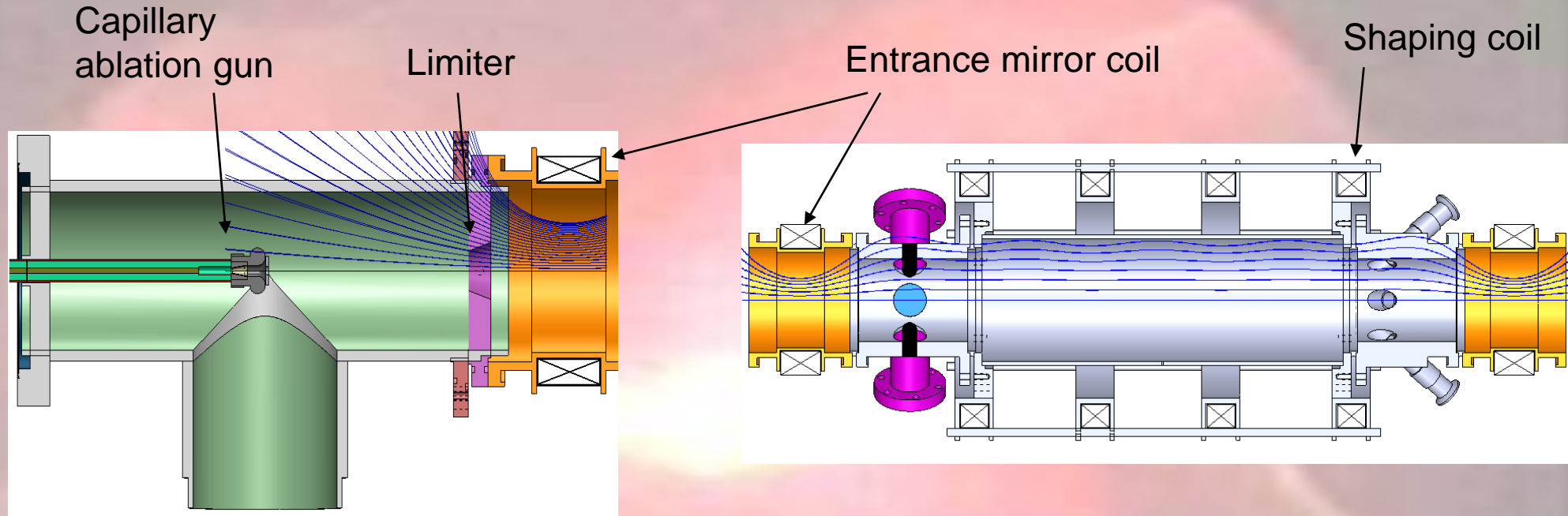
# Vacuum Arcing Plasma Source (VAPS)

How it works:

1. Initial HV pulse sparks surface discharge.
2. Additional current ablates  $\text{CH}_2$  and ionizes hydrogen and carbon.
3. Unmagnetized plasma spreads from the nozzle.
4. Magnetized species moves along field lines.

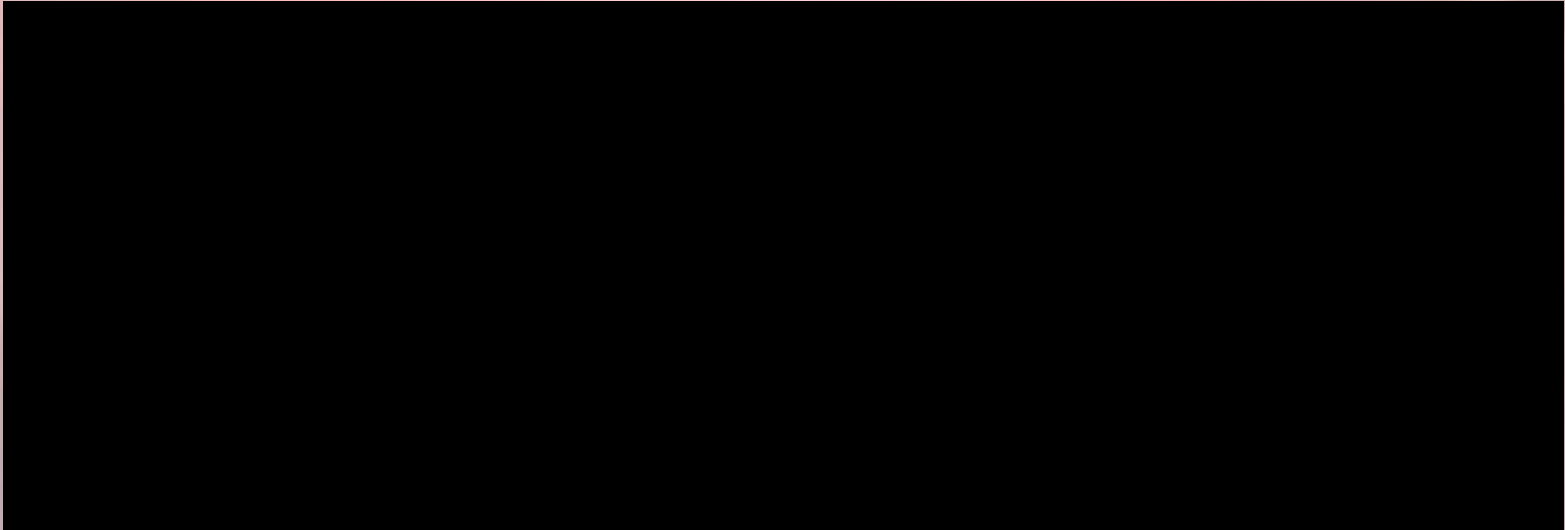
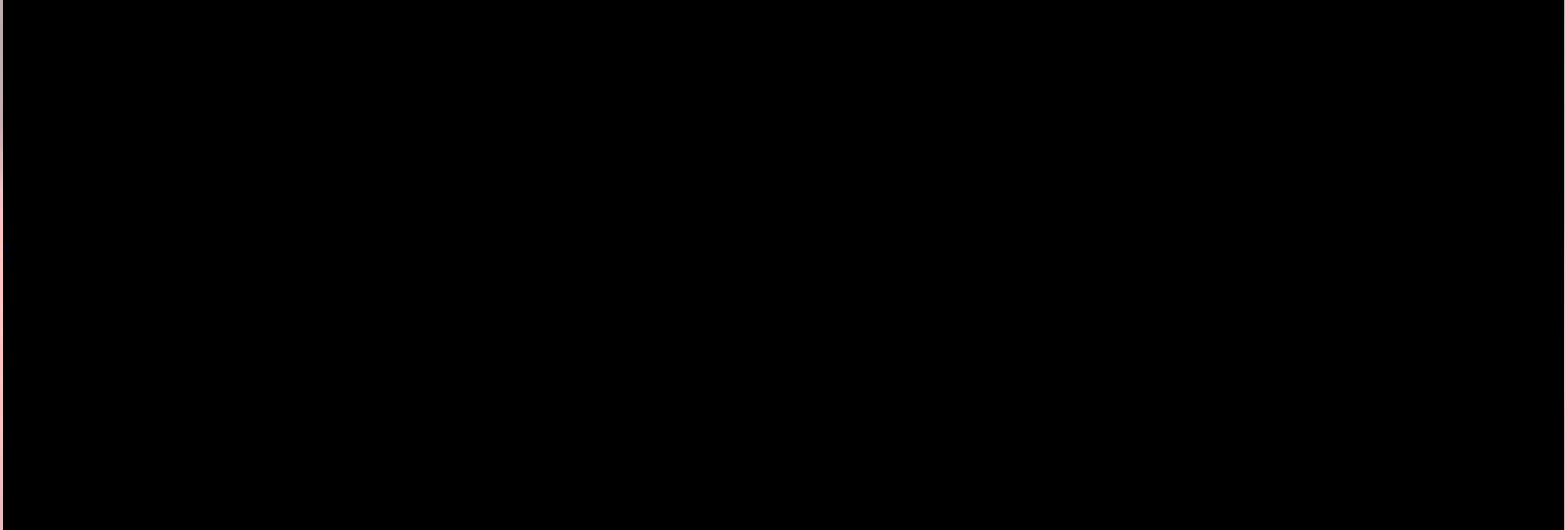


# VAPS injection into mirror

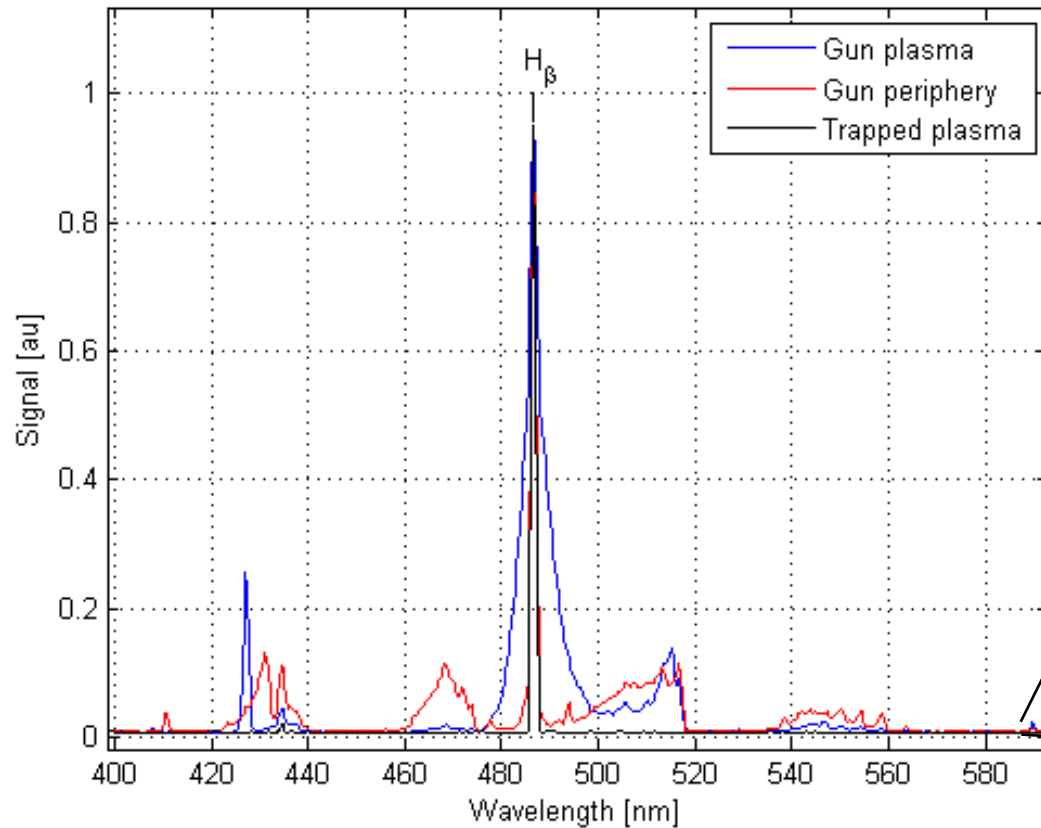


Hydrogen plasma is produced by the VAPS. The pulse length is up to 1 ms

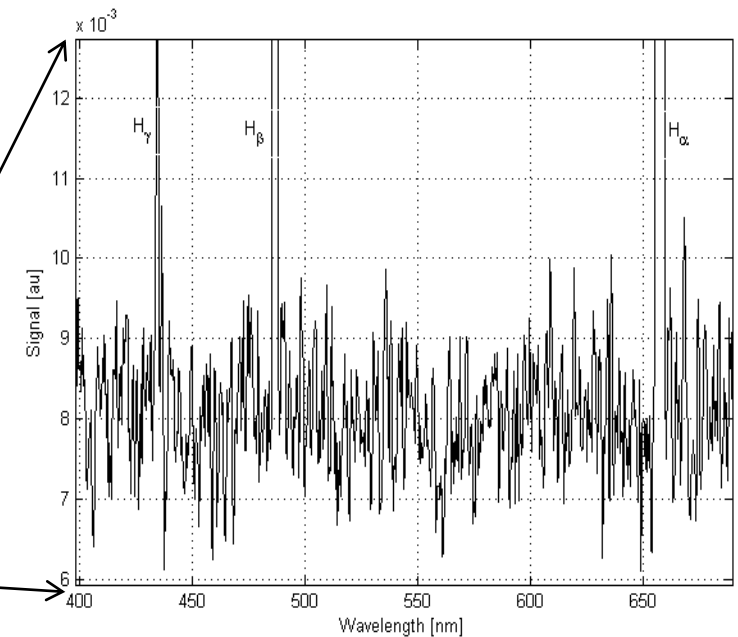
Some of the resulting plasma is injected through a limiter into one of the mirrors



# Gun plasma vs. trapped plasma:

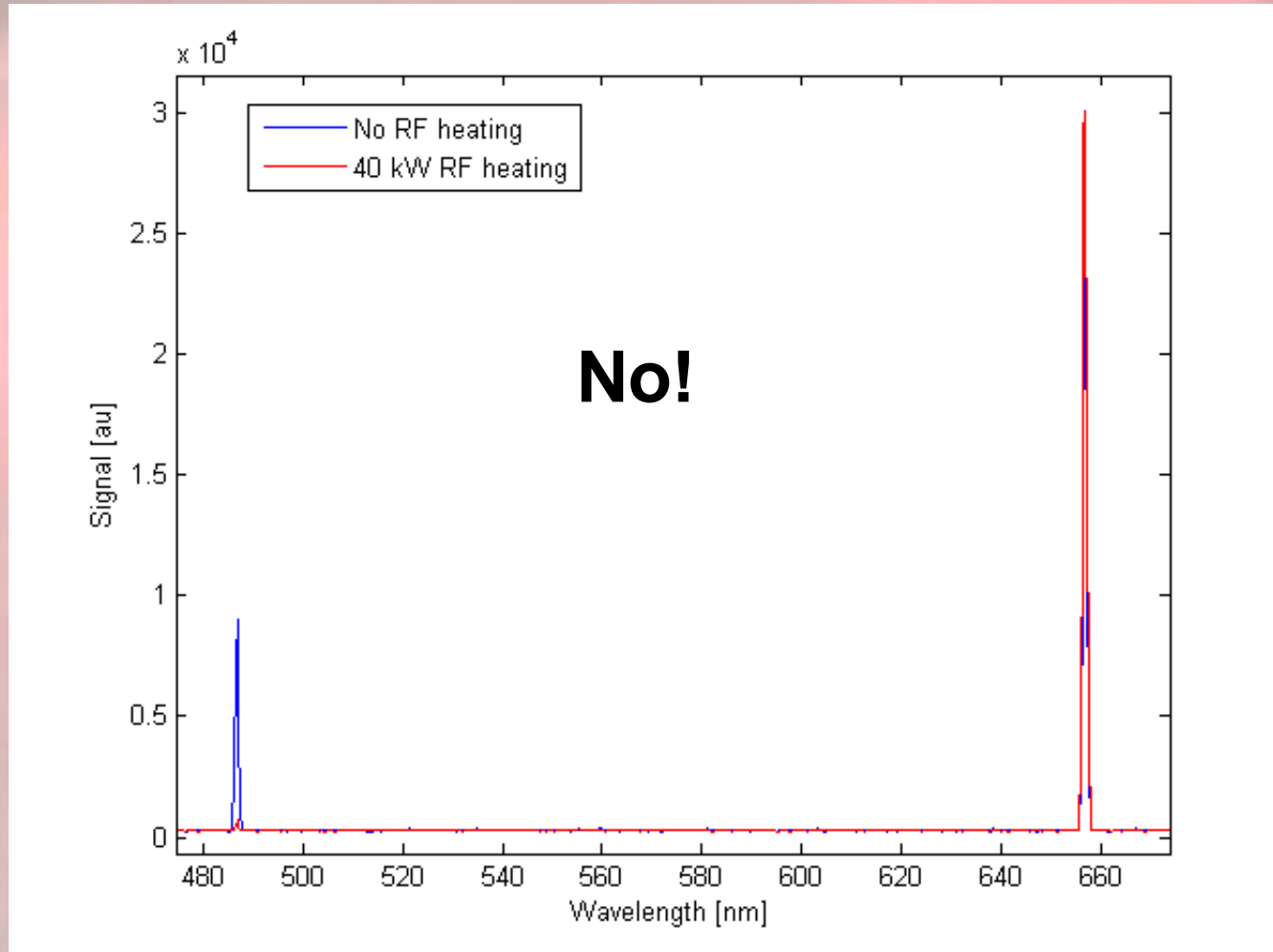


Trapped plasma spectrum, showing only H $\alpha$  and H $\beta$



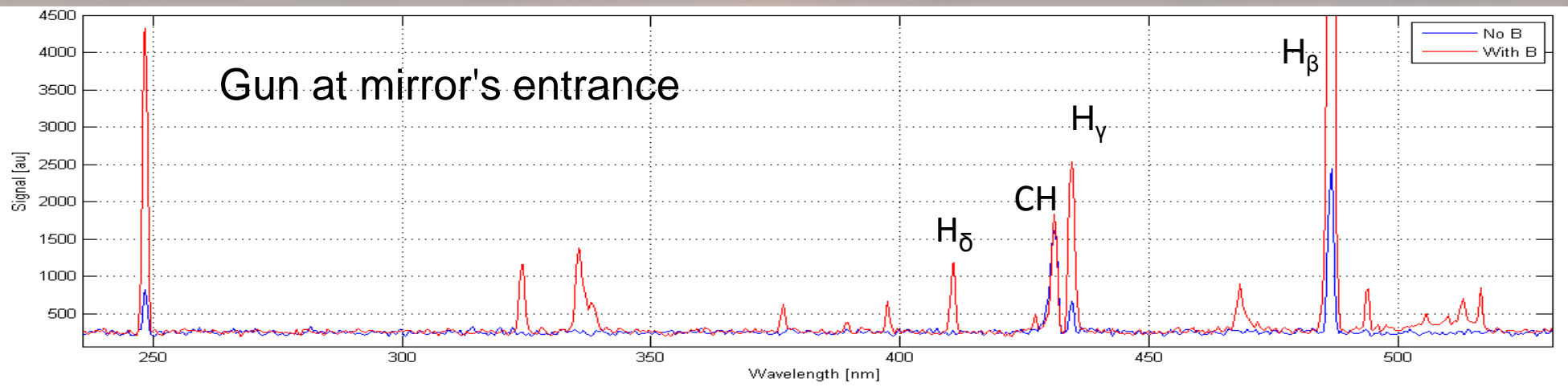
Impurity level in the trap is lower by at least a factor of 100 relative to the plasma emerging from the gun.

# Will RF heating reveal a hidden carbon population?

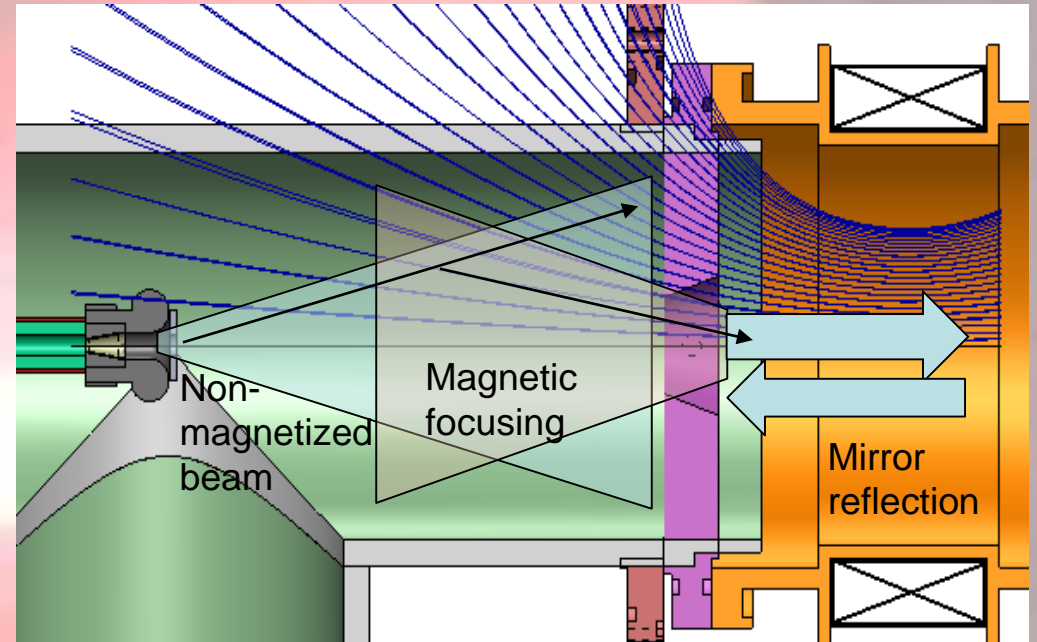
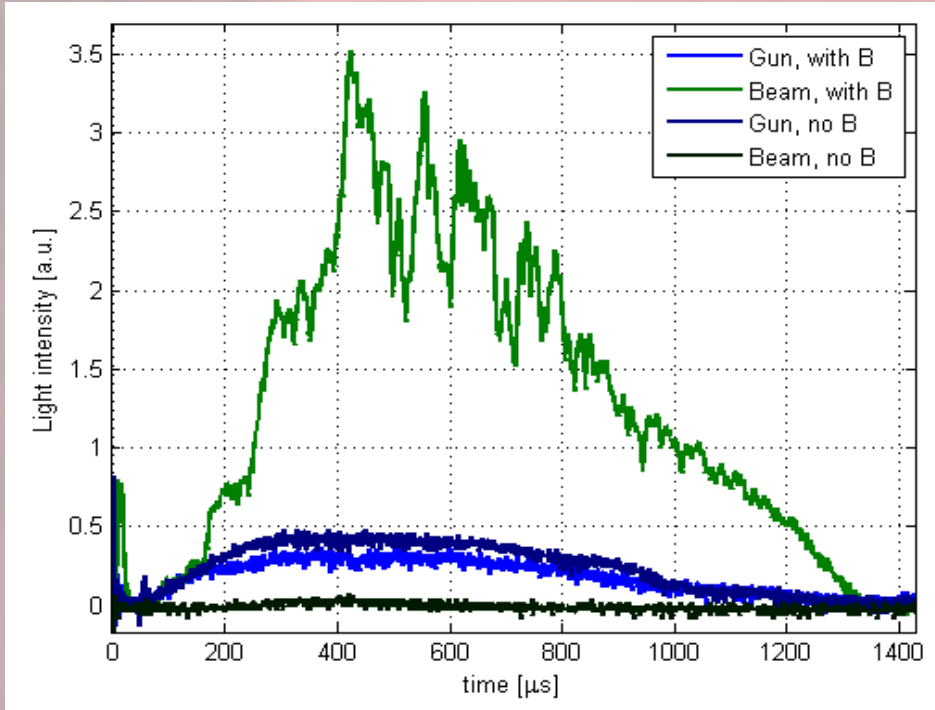


**How can a mixed plasma source generate pure hydrogen in the trap?**





# Magnetic field has a major role in channeling the plasma into the trap:



The ratio of particles entering the trap depends on:

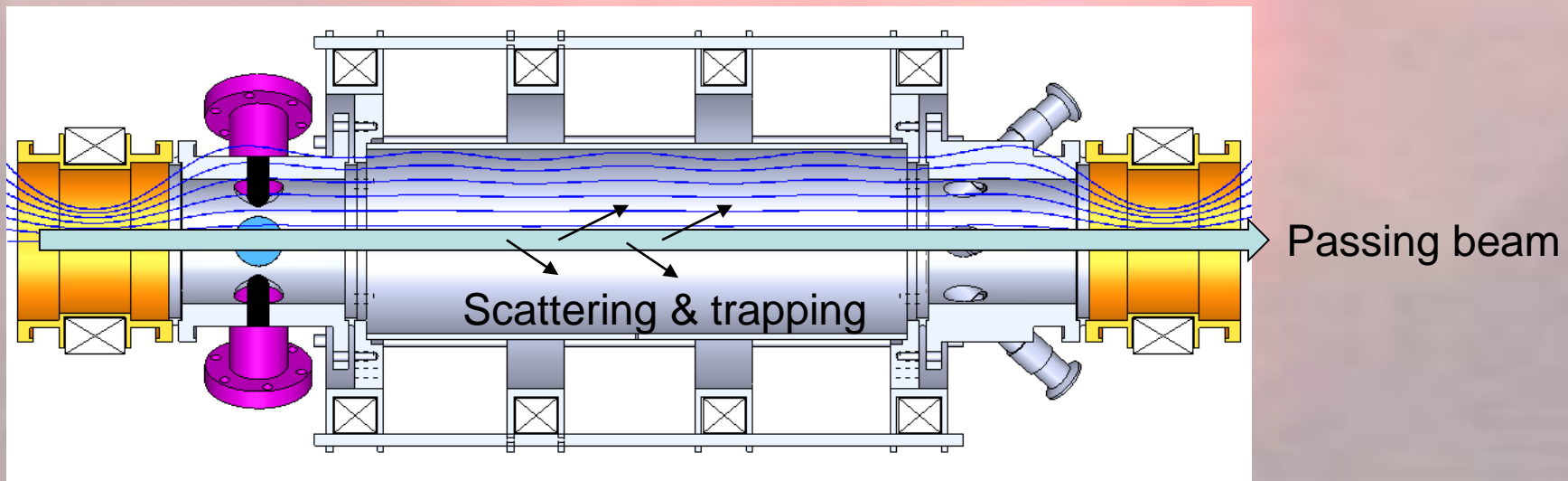
- Magnetic field and magnetic geometry
- Gun to mirror distance and collimator aperture
- $q/m$ , temperature and density of the charged particles

# Selective trapping

Ions entering the trap from the entrance mirror occupy the loss cone, and will escape through the opposite mirror unless scattered out of the loss cone.

Carbon ions are more scarce to start with, so most of the scattering is done by Hydrogen ions. The C-H scattering frequency is smaller by  $m_C / m_H$  than the H-H scattering frequency. On the other hand, the carbon ions are slower by  $\sqrt{m_C / m_H}$ , so the scattering probability in a single pass between the mirrors is smaller by  $\sqrt{m_C / m_H}$ .

This accounts for a factor of  $\sim 4$  in the selectivity.



# Centrifugal separation

In the presence of electric field, the particles experience electric as well as magnetic field. The condition for particles to pass the mirror is<sup>1</sup>:

$$W_{\parallel} < W_{\perp} (R_m - 1) + mE_r^2 / 2B_z^2 (1 - R_r^{-1})$$

When the centrifugal term is dominant, the mass selectivity depends on the centrifugal loss-cone volume, which is proportional to  $m^2$

The centrifugal mass filter has been suggested for nuclear waste separation<sup>2</sup>, but the effect has never been experimentally investigated.

1. Fetterman, Abraham J., and Nathaniel J. Fisch. "The magnetic centrifugal mass filter." *Physics of Plasmas* (2011): 094503.
2. Gueroult, R., and N. J. Fisch. "Plasma mass filtering for separation of actinides from lanthanides." *Plasma Sources Science and Technology* 23.3 (2014): 035002.

## Plasma rotation:



... but the rotation is too slow to induce effective centrifugal separation.

# Mobility separation

Near the gun the plasma is not magnetized. As the plasma moves closer to the mirror, the particles get magnetized in a successive order: electrons → hydrogen → carbon.

Electron magnetized	Hydrogen magnetized	Carbon magnetized	Ion separation?
no	no	no	no
yes	no	no	yes?
yes	yes	no	yes
yes	yes	yes	up to Larmor radius

## Three fluids equations system

$$m_i n_i \left( \frac{\partial \bar{u}_i}{\partial t} + (\bar{u}_i \cdot \nabla) \bar{u}_i \right) = n_i q_i (\bar{E} + \bar{u}_i \times \bar{B}) - \nabla \bar{P} - \sum_{j \neq i} R_{ij} (\bar{u}_i - \bar{u}_j) \quad i = e, H, C$$

$$\frac{\partial \bar{n}_i}{\partial t} + \nabla \cdot (\bar{u}_i \bar{n}_i) = 0$$

$$P = nk_B T$$

$$\sum_i n_i q_i = \sum_i n_i q_i \bar{u}_i = 0 \quad (\text{quasi-neutrality})$$

For light, magnetized species we assume:

Pressure balance by diamagnetic current -  $n_e q_e u_{\perp} \times B - \nabla P_{\perp} \cong 0$

Small (drift) acceleration -  $m_i n_i \left( \frac{du_{\perp}}{dt} \right) \cong 0$

The EOM then becomes:  $\sum_j \frac{\bar{u}_i - \bar{u}_j}{\mu_{ij}} = \bar{E}$

## Analytic model of ion separation

EOM for magnetized electron and hydrogen and unmagnetized carbon:

$$m_C n_C \frac{du_C}{dt} = n_C e E - \frac{\partial P}{\partial x} = 0$$

$$u_H = \mu_H E$$

$$f_H u_H + f_C u_C = \mu_e E, \quad f_H + f_C = 1 \quad (\text{quasi-neutrality})$$

The last two equations yields E:

$$E = - \frac{f_C u_C}{\mu_e + f_H \mu_H}$$

And the resulting velocities are:

$$u_C = \frac{\mu_e + f_H \mu_H}{f_C} \frac{1}{en_C} \frac{\partial P}{\partial x}$$

$$u_H = -\mu_H \frac{1}{en_C} \frac{\partial P}{\partial x}$$



Heavy ions move outward, while light ions move inward.

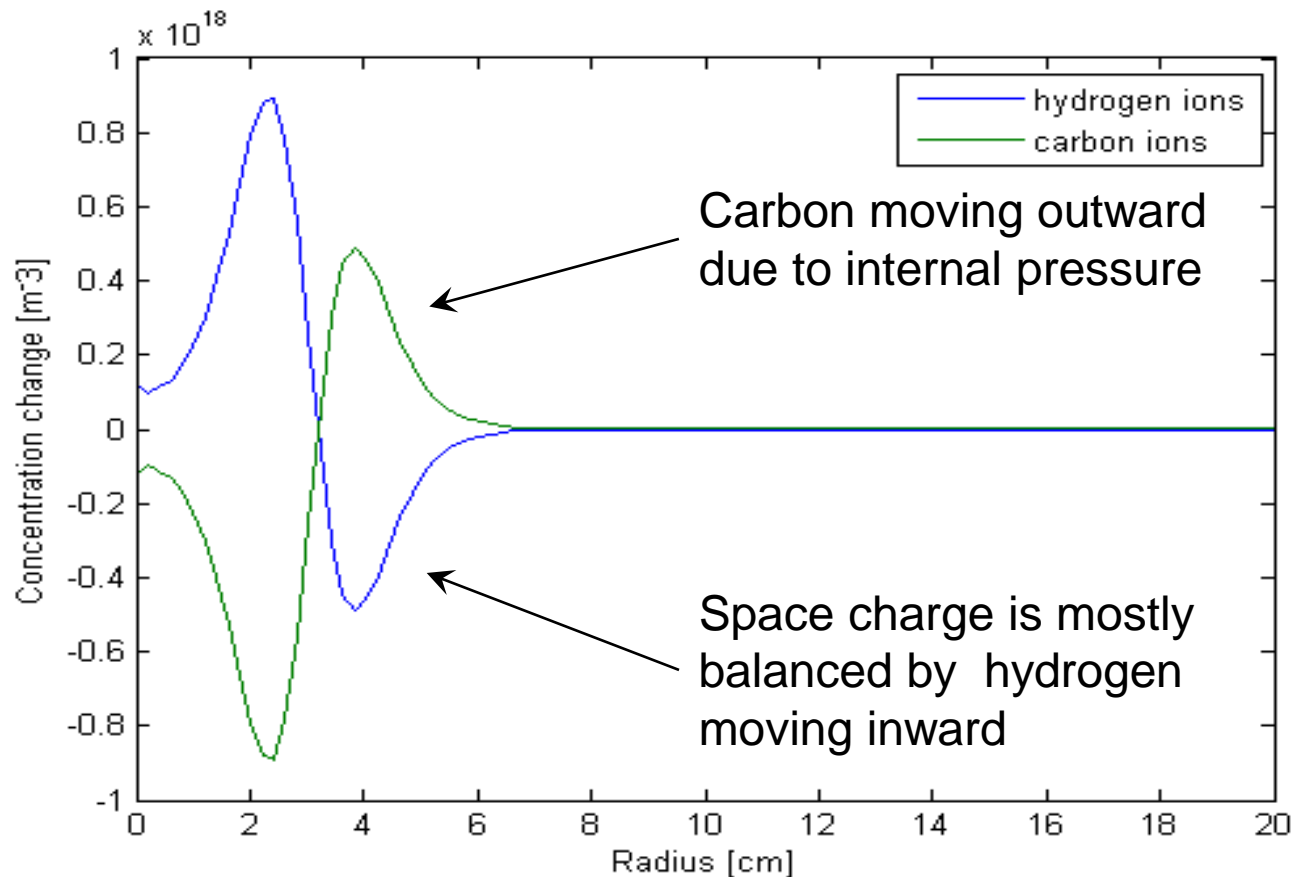


## One-dimensional simulation of the model:

Model: One dimensional cylindrical plasma distribution in x-y plane. Uniform perpendicular magnetic field,  $B_z$ . Carbon unaffected by the magnetic field, while hydrogen and carbon are magnetized.

Initial conditions:

$$n_C(t=0) = n_0(1 + \tanh(r_1 - r_2 r)), \quad n_H(t=0) = 2n_C(t=0), \quad n_e = n_C + n_H$$
$$u_C(t=0) = u_H(t=0) = u_e(t=0) = 0$$



# Conclusions:

- Vacuum arcs can be put into beneficial use:
  - Very simple, fast and clean hydrogen plasma source.
- Several possible mechanism for ion separation:
  - Selective trapping can explain ion separation ratio of up to 4.
  - Centrifugal separation is non-relevant due to slow rotation.
  - Simplified 3-fluid model demonstrates ion separation in partly magnetized plasma. A more extensive calculation is under way to verify these results.
- Multi-species plasma can do funny things under electric and magnetic fields.

# Relevant example?

Gradients in oscillating electric field in RF cavity generates pondermotive force:

$$F = -\frac{e^2}{4m\omega^2} \nabla E^2$$

Electrons move too fast  $\Rightarrow$  not affected directly.

Copper ions move  $\sim 1$  mm to the lower E regions.

Lighter impurities move faster by  $m^2 \Rightarrow$  ion separation.