International MUON Collider Collaboration

Hydrogen gas filled RF cavities

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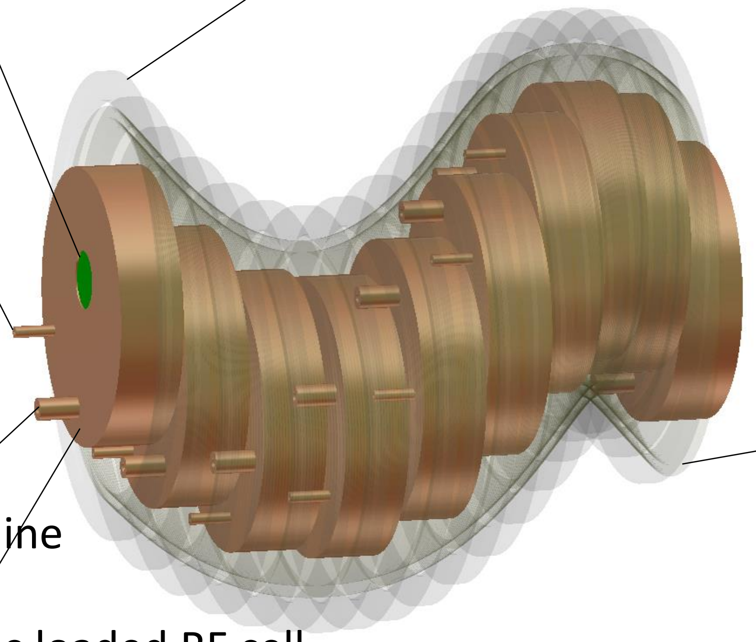
Fermilab

Outline

- Concept of Hydrogen gas filled RF cavities
- Study gas breakdown
- Study beam-gas-plasma interactions
- Summary

Concept



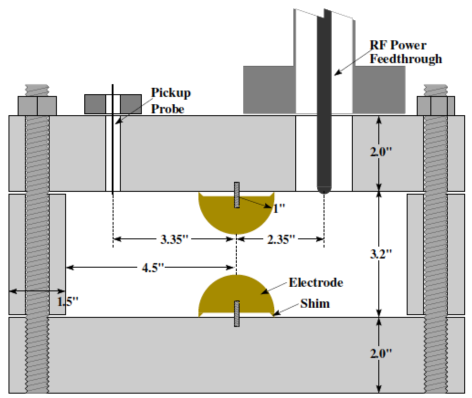
RF length
10 cm for 325 MHz
5 cm for 650 MHz

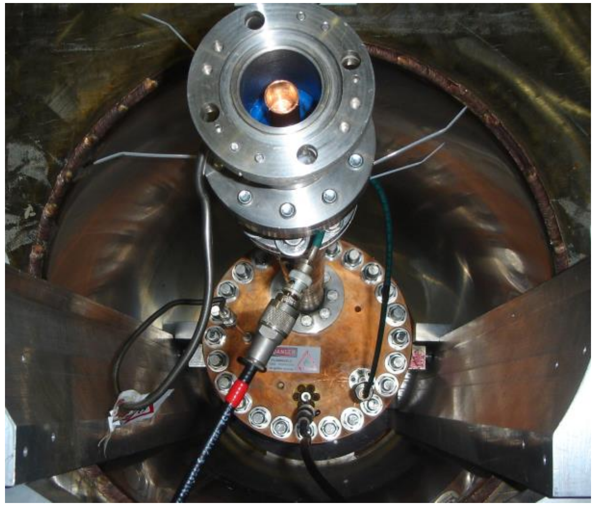
- Hydrogen gas resists a dark current flow in a high gradient RF field
- Hydrogen gas is the best ionization cooling material
- Hydrogen gas generates a plasma focusing
- Hydrogen gas works as a coolant of a beam window

Suppress RF breakdowns

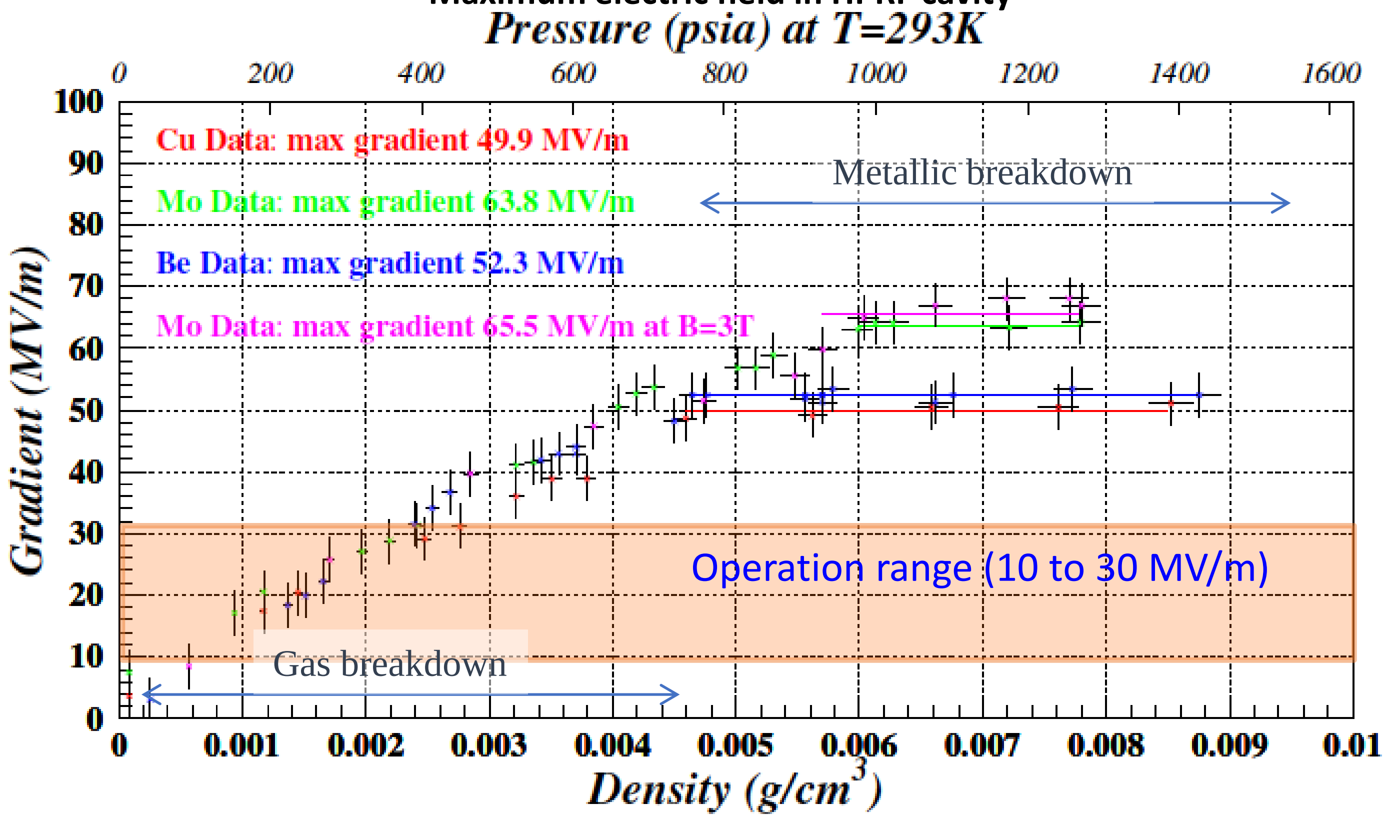
- Observed "gas breakdown" and "metallic breakdown" in gas filled RF test cell
- Slope in gas breakdown depends on gas species (H2, He, N2, + dopant)
- Flat level in metallic breakdown depends on electrode material
- No magnetic field effect in gas filled RF test cell

Schematic view of HPRF test cell

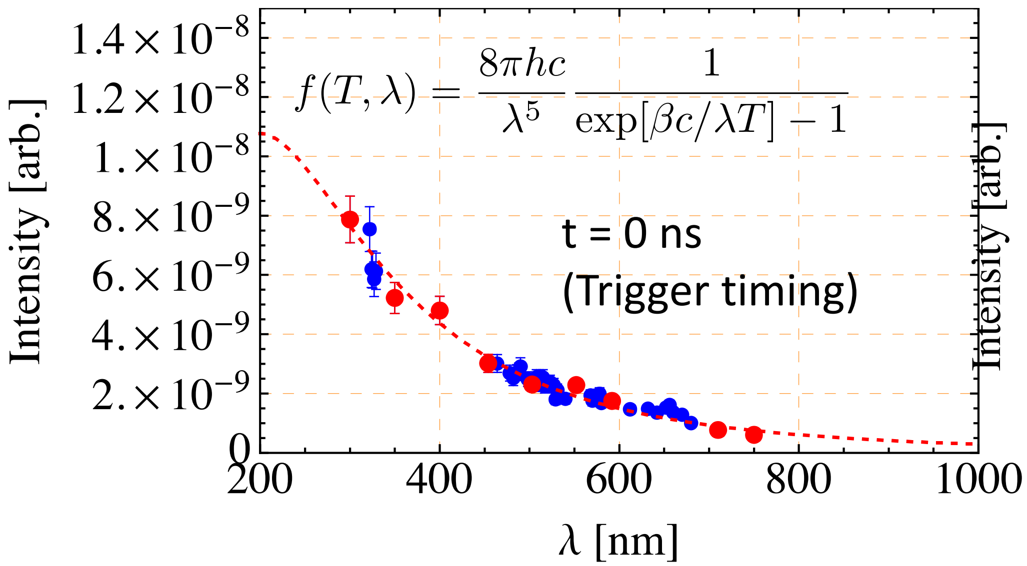


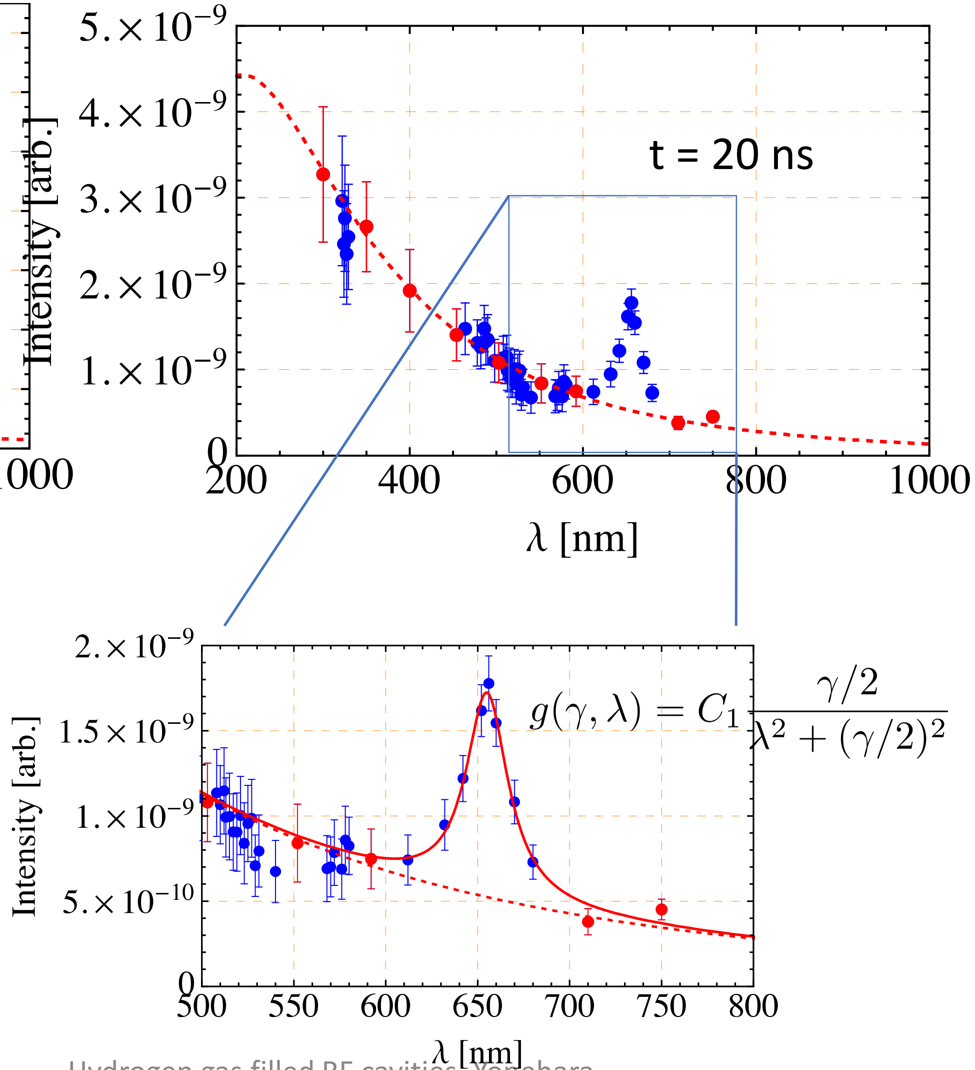


Maximum electric field in HPRF cavity



Study gas breakdown mechanism

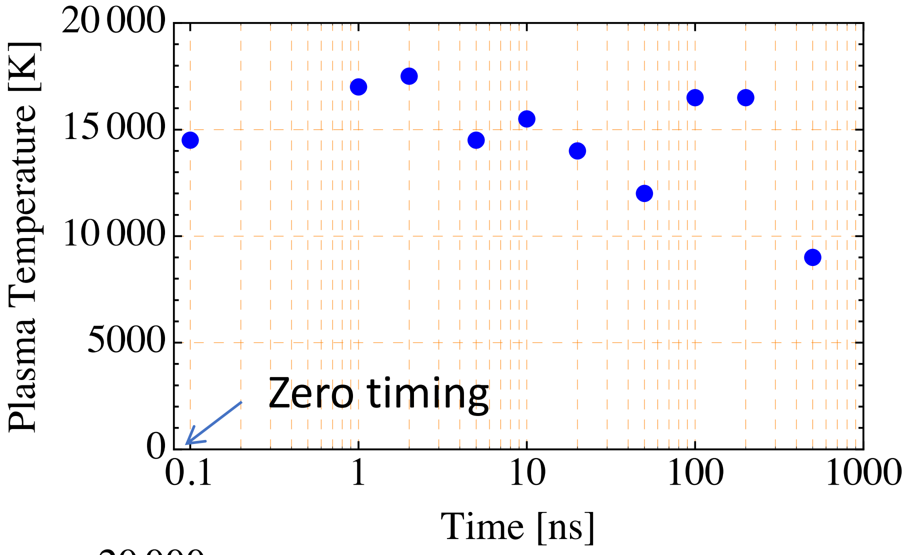


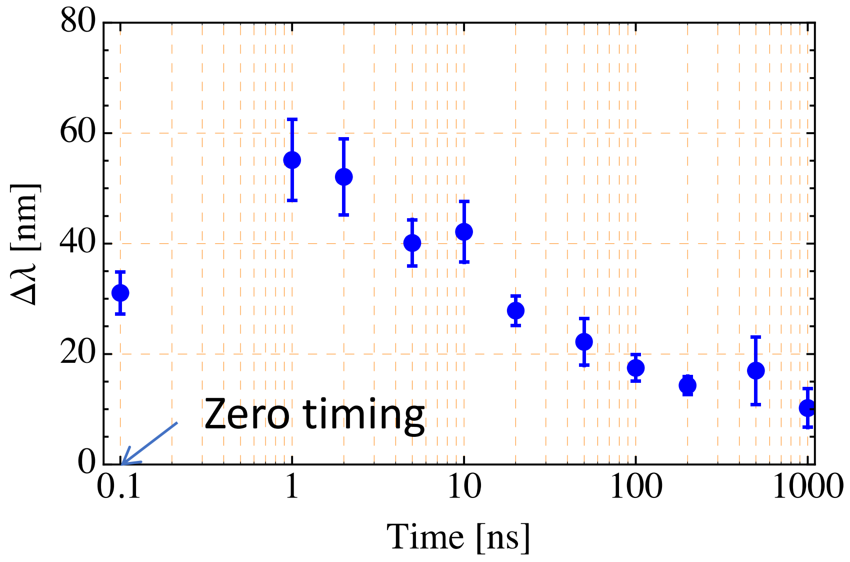


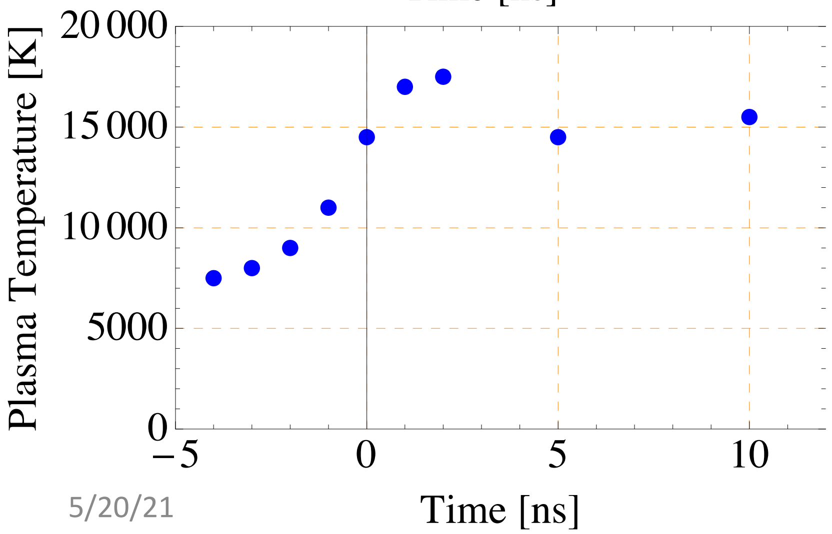
Monochrometer

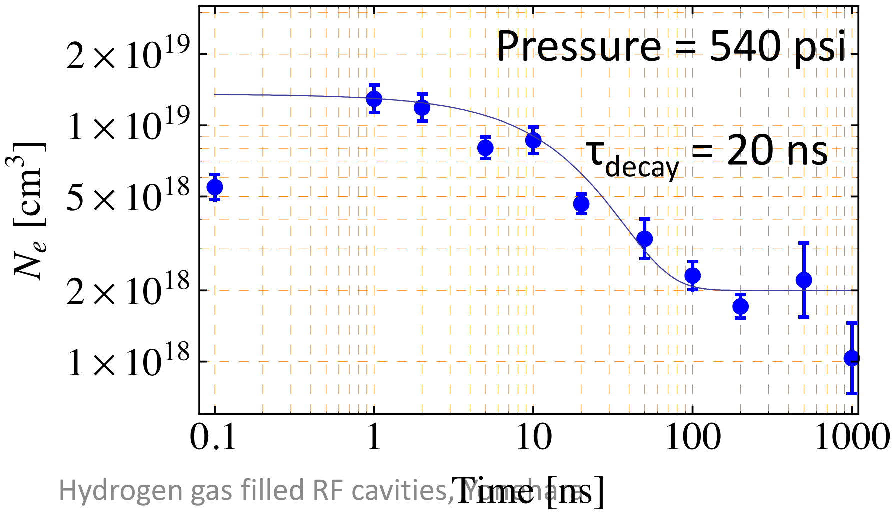
- A continuous curve corresponds to a blackbody radiation emitted by H_2
- Sharp spectrum corresponds to the atomic hydrogen
- Broaden of resonant line is due to the Stark effect by a local plasma electric field (probe for a plasma density)

Plasma density of gas breakdown

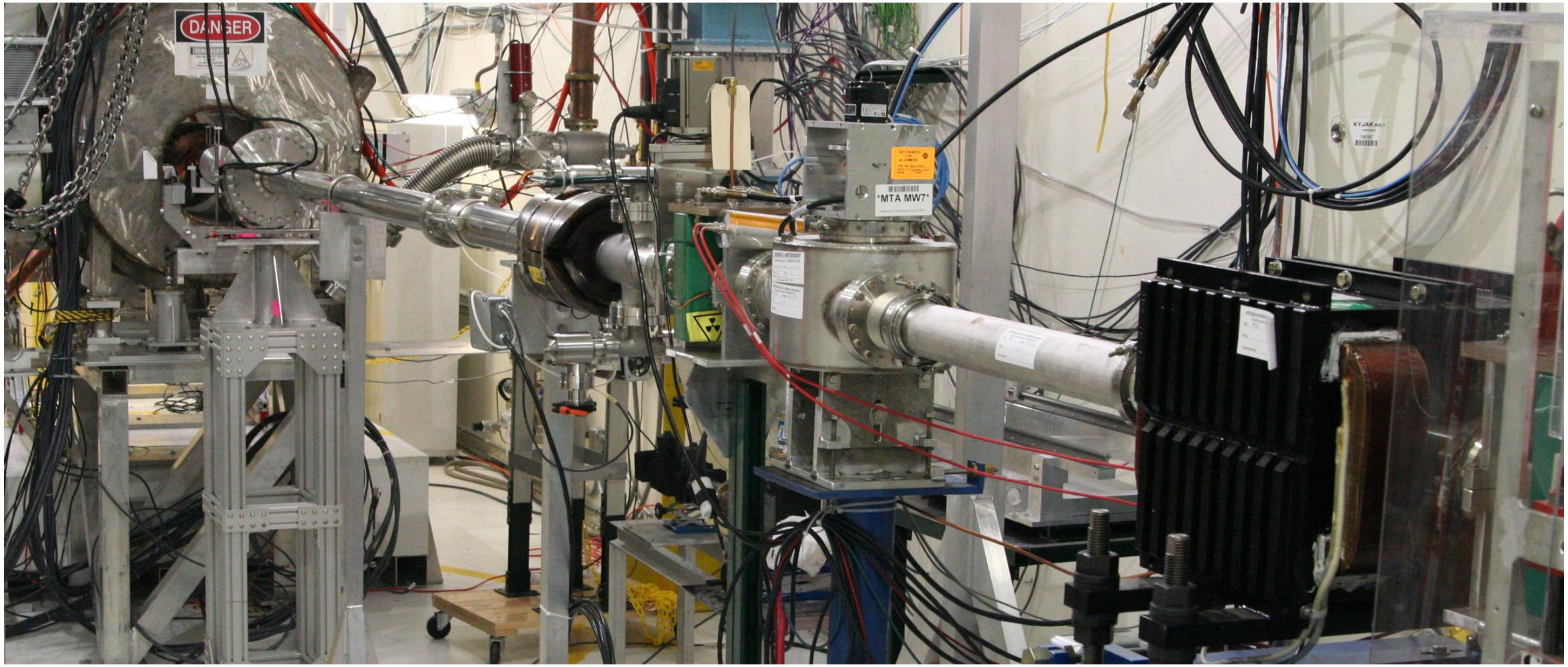






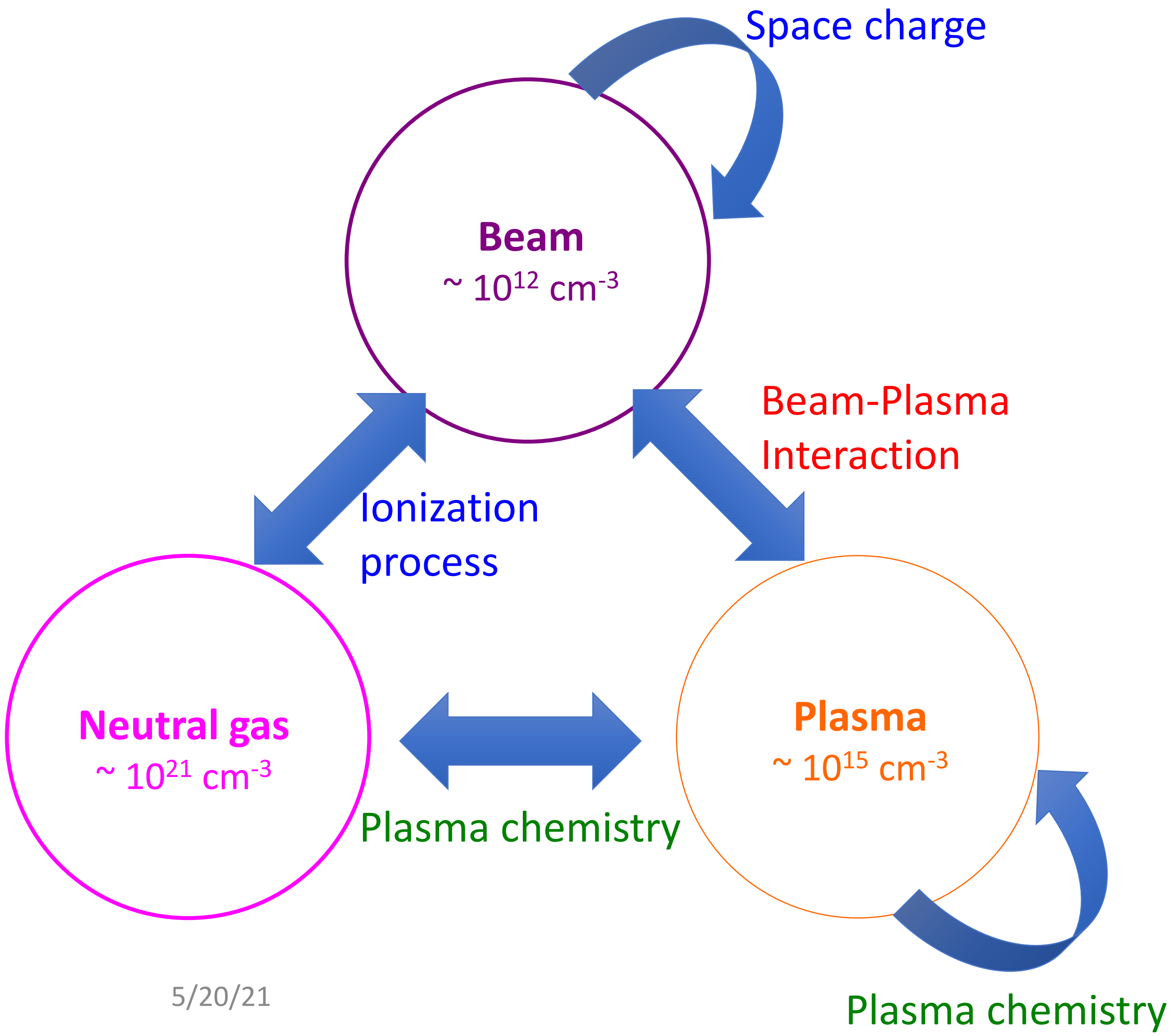


- Breakdown electron density can be > 10^{19} cc
- Plasma temperature reaches 20,000 K



Beam Program

Beam-gas-plasma interactions



- Ionization process
  - How many electron-ion pairs create per single incident charged particle?
- Plasma chemistry
  - Density effect?
  - Plasma temperature effect?
- Beam-plasma interaction
  - Collective motion in extreme plasma affects beam dynamics

Estimate density of electron-ion pair

Ionization process
(Produce beam-induced plasma)

$$p + H_2 \rightarrow p + H_2^+ + e^-$$

$$\Updownarrow$$

$$\mu^{+/-} + H_2 \rightarrow \mu^{+/-} + H_2^+ + e^-$$

- Same plasma production process with different incident charged particles

Number of electron-ion pairs

$$\dot{N}_e = \frac{\left\langle dE/dx \right\rangle_{p=p_0}}{W_i} \rho_{H_2} \cdot I_{incident}$$

- Known ionization energy loss
- Known ion pair production energy (W_i)
- Easy to estimate total number of electron-ion pairs

RF energy dissipation
(Generate plasma loading)

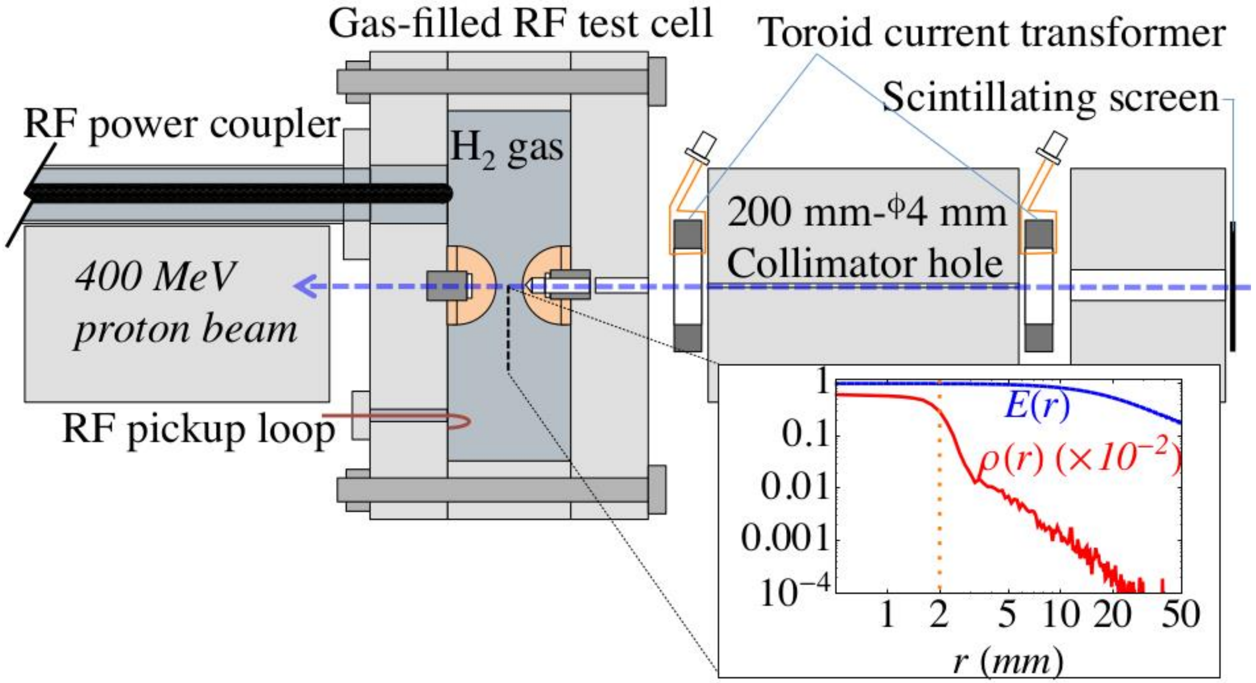
$$dw = \int_T q\bar{v}E(t)\,dt$$

- RF energy dissipation is modeled as a resistive motion of plasma in a matter by an RF field
- Drift velocity of electron & ion ($\bar{v}$) are known from other experiments
- Model predicts
  Electron dw >> Ion dw

No model dependence

Linear Theory

Observed plasma loading

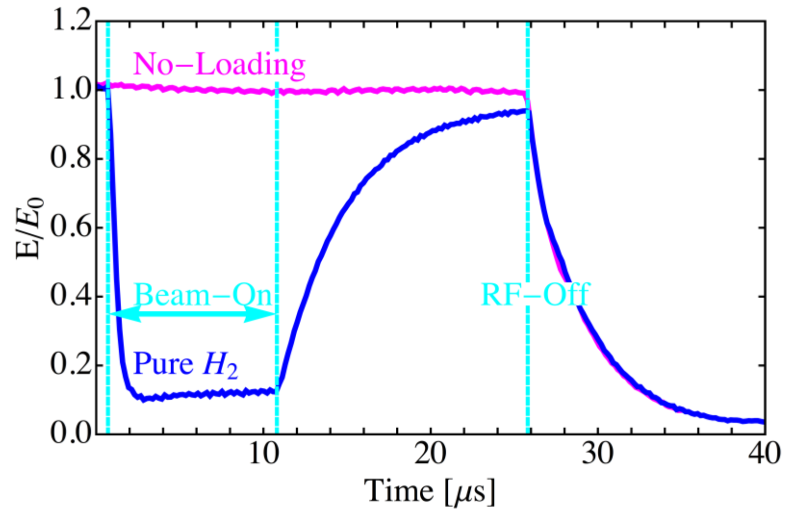


- Observed RF envelops

Magenta: No beam

Blue: With beam during $0 < t < 10$ μsec

Cyan: Beam-On & OFF and RF-OFF

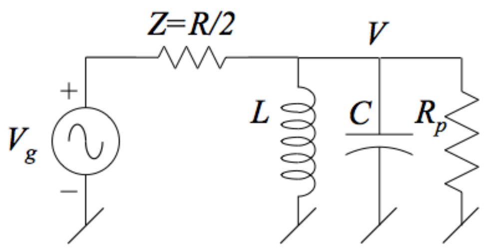


Main physics variables:

- H_2 gas pressure 20 to 100 atm at 300 K
- RF frequency 800 - 810 MHz
- RF amplitude 5 to 50 MV/m
- Beam current 10^{17}-10^{20} protons/s
- 3-Tesla solenoid field on/off

Study plasma chemistry

$$P = \frac{V(V_0 - V)}{R} - CV\frac{dV}{dt}$$



- RF power consumption by ionized plasma can be given from RF amplitude

  V_0: Maximum RF amplitude (flattop)

  R: Shunt impedance

  R_p: Plasma resistance

  C: Capacitance

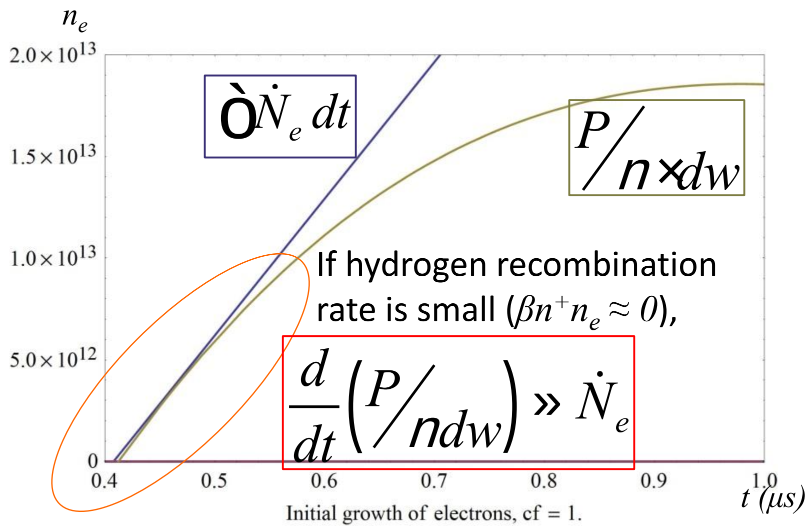
A. Tollestrup et al., "Handbook for gas filled rf cavity aficionados'"

$$\frac{dn_e}{dt} = \dot{N}_e - \beta n^+ n_e - \frac{n_e}{\tau}$$

β: Recombination rate

τ^{-1}: Electron capture rate

(τ^{-1} is negligible in pure H_2)



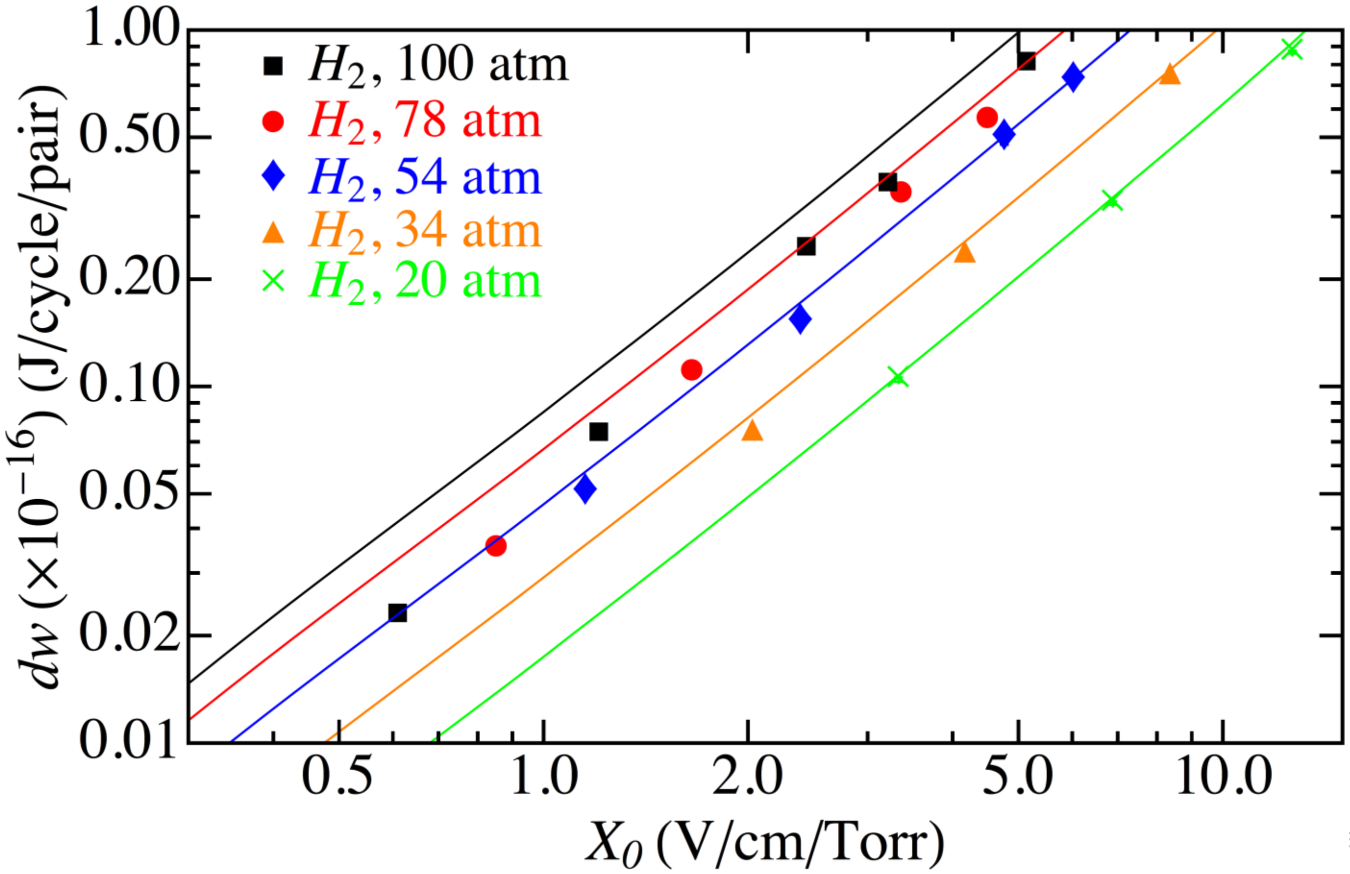
Initial growth of electrons, cf = 1.

- # of ion pairs can be estimated from RF power consumption P/dw
  - A blue line in left plot shows the integrated N_e and a yellow one is the estimated # of ion pairs
  - Deviation of P/vdw curve in initial state should match to the total amount of ion pair production N_e
- dw is estimated from this correlation

Gas density effect

dw : Observed energy consumption per single electron-ion pair from RF cavity per one RF cycle

Solid line: Prediction from simple model

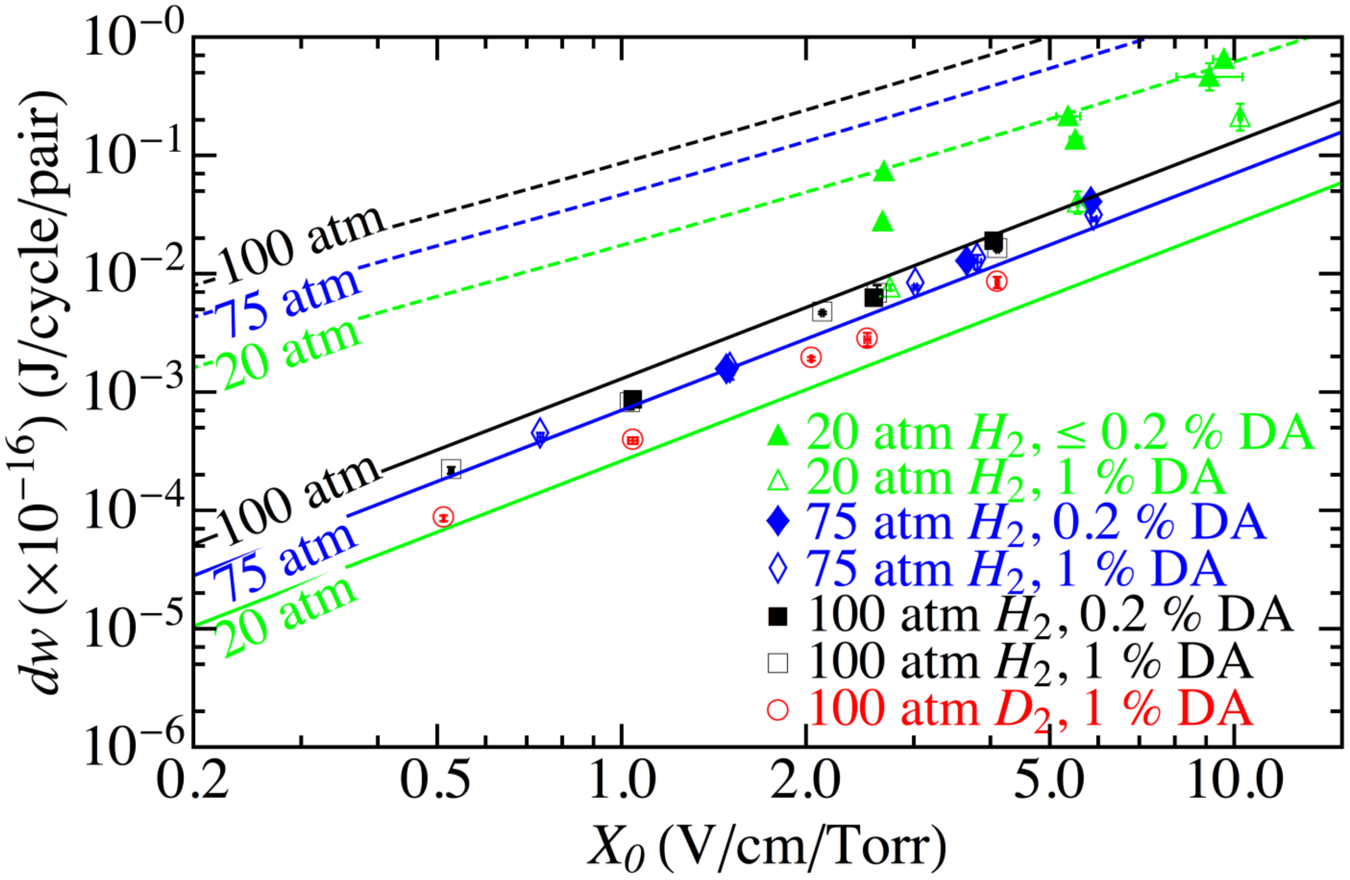


- Theoretical estimation agrees with measurement at low gas pressure
- Measurement deviates bigger in higher gas pressure
- Such a density effect could be explained by quantum theory

Control plasma by dopant

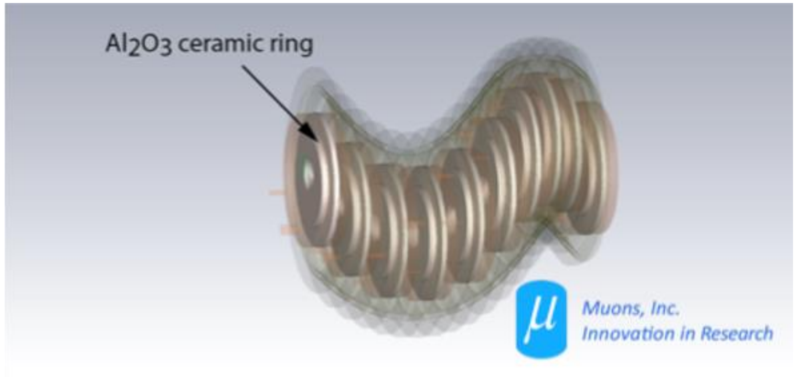
dw : Observed energy consumption per single electron-ion pair
from RF cavity per one RF cycle

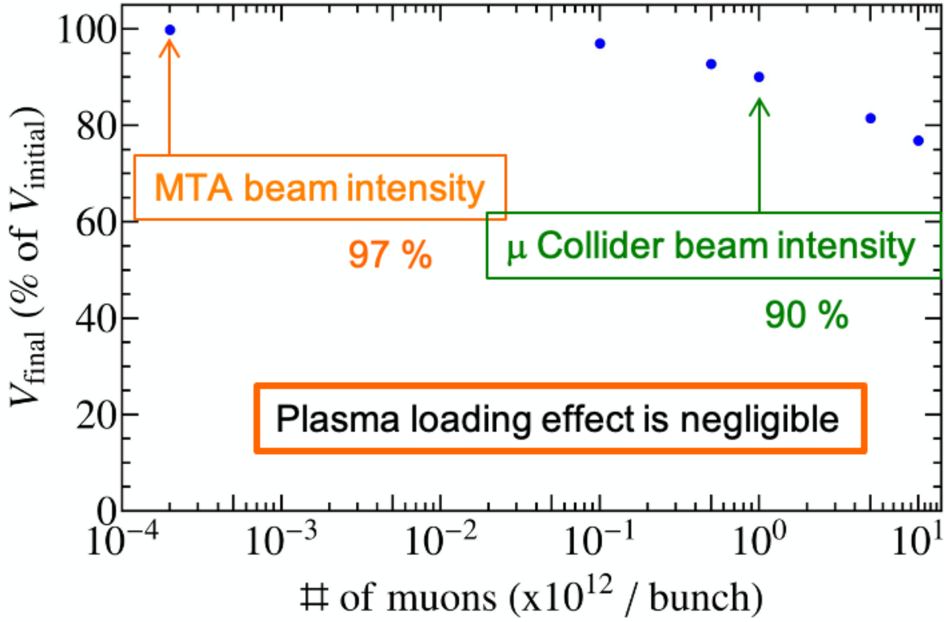
Dashed & Solid lines: Prediction from electron-ion pair & only heavy ions



- DA is dry air
- O2 is a good electron catcher
- A small amount of O2 is sufficient to catch free electron
- D2 is even lower plasma loading than H2 since D2 drift velocity is slower than H2

Estimate plasma loading in cooling channel

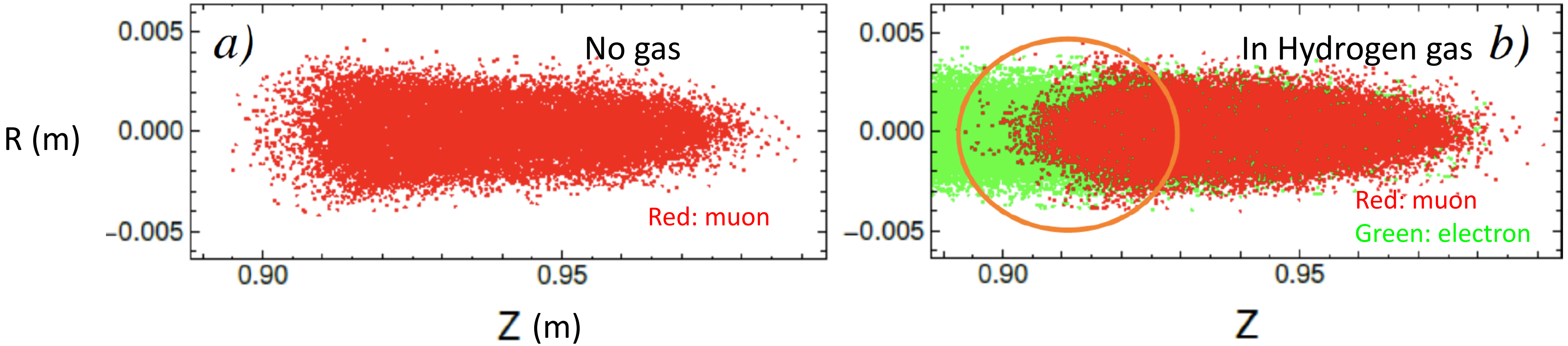




- Estimate plasma loading for Helical FOFO, HCC, rectilinear channel
- Plasma loading effect will be smaller in cold RF cavities

Plasma focusing (Simulation study)

- Strong radial beam focusing will appear in a dense Hydrogen gas-filled RF cavity
  - Space charge is neutralized by dielectric polarization of gas plasma, as a result, beam induces a toroidal self-focusing field



- Can this effect be adopted for cooling channel design?
- Easy to induce a resonance in a channel of azimuthally symmetric lenses
  - Focal parameter of each lens must be less than 1/4th of the distance between adjacent lenses
- Will strong radial plasma focusing allow one to tame the beam smear and take advantage of parametric resonance ionization cooling?

Summary

- Hydrogen gas filled RF is a promising device for ionization cooling channels
- Safety is the biggest concern (GH2 volume in HCC 3,534 litters vs LH2 volume in 2-m-bubble chamber 1,150 litters)
- Propose beam test to study the plasma focusing