High Pressure Gas Filled RF Cavity Status and Plans

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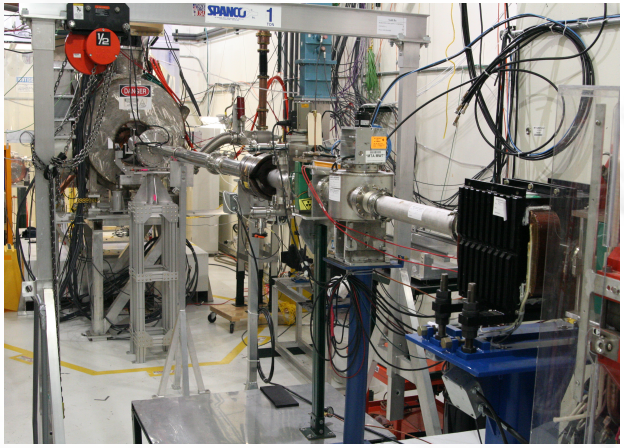
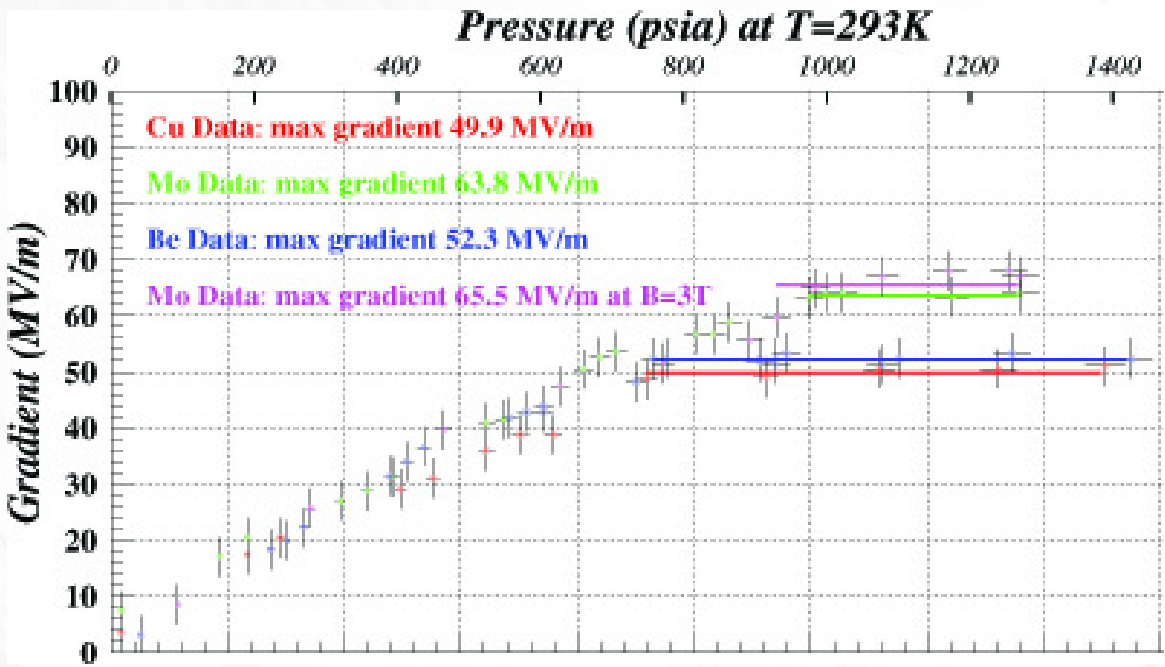


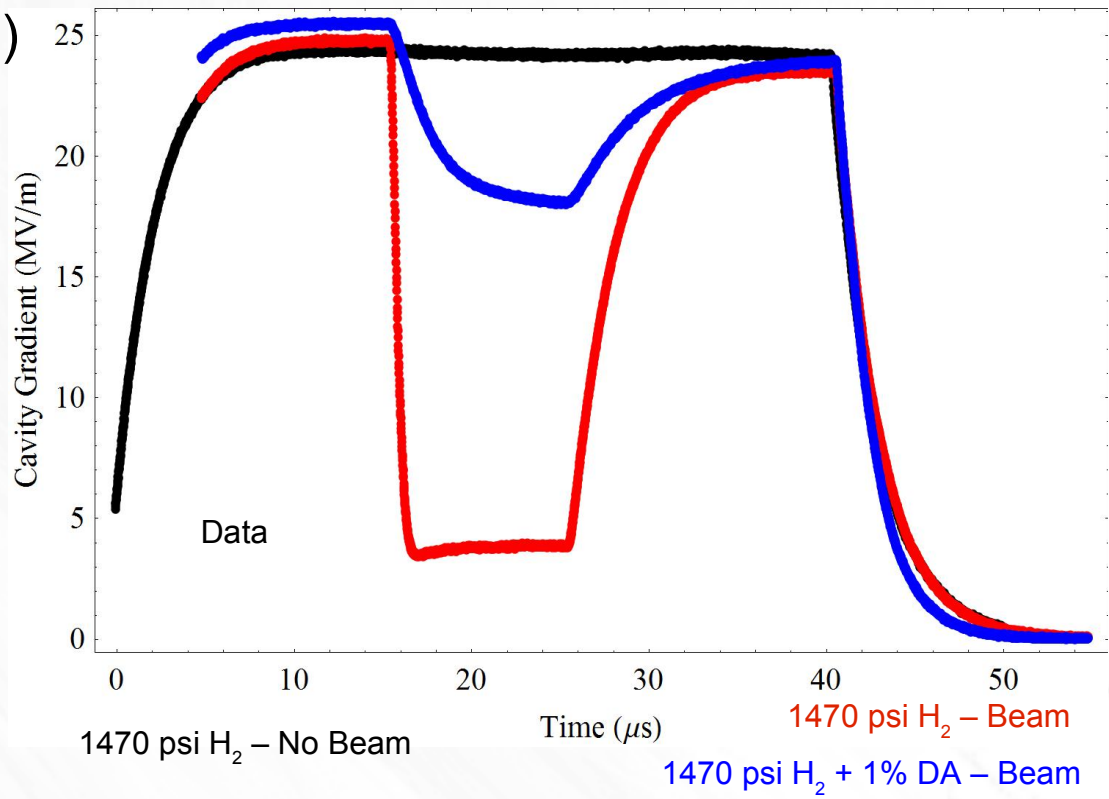
A Brief History

- To cool muons sufficiently, RF cavities must be placed in magnetic fields
- Traditional vacuum RF cavities break down at low gradients in strong magnetic fields
- Rolland Johnson suggested filling an RF cavity with a high pressure gas to both mitigate breakdown and serve as a medium for cooling
- HPRF cavity was successfully shown to operate in strong magnetic fields without beam (Hanlet et al, EPAC '06, Yonehara et al, PAC '09)
- What happens when you put a beam through the cavity?



Physics Inside the Cavity

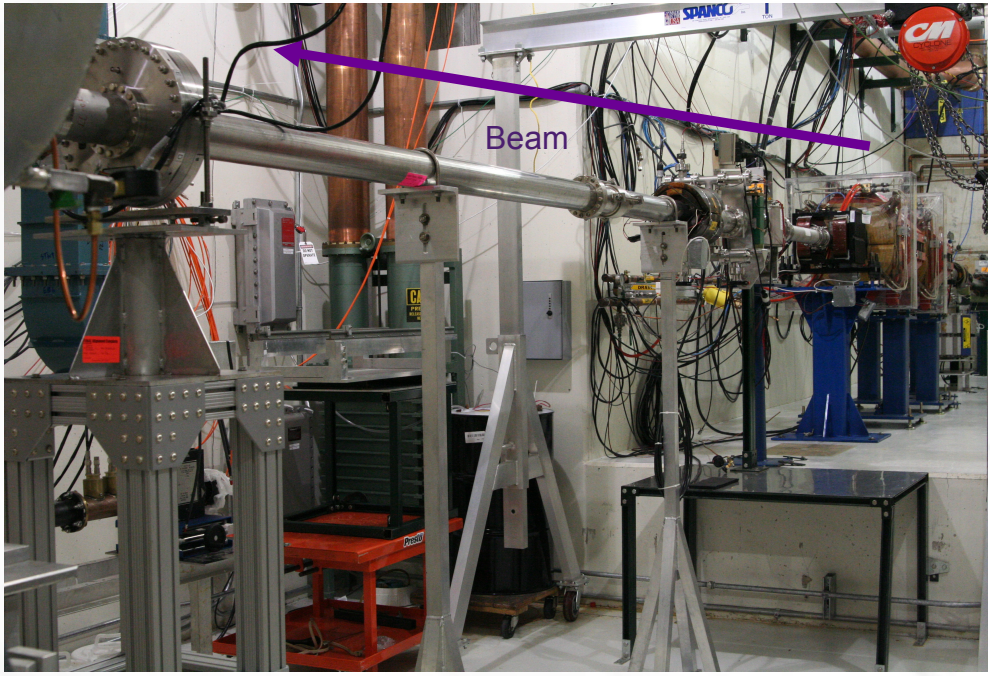
- Beam ionizes the gas (mostly H_2) in the cavity
- Plasma forms and is shaken by RF field, absorbing power
- Plasma "swarm" comes into statistical equilibrium with RF field
- Addition of a small amount of electronegative gas (SF_6, O_2) removes the electrons through three body processes



- Ions (H_3^+, H_5^+... and SF_6^- or O_2^-) remain and absorb a small amount of RF Power (HPRF cavity has 159 mJ stored energy at 25 MV/m)

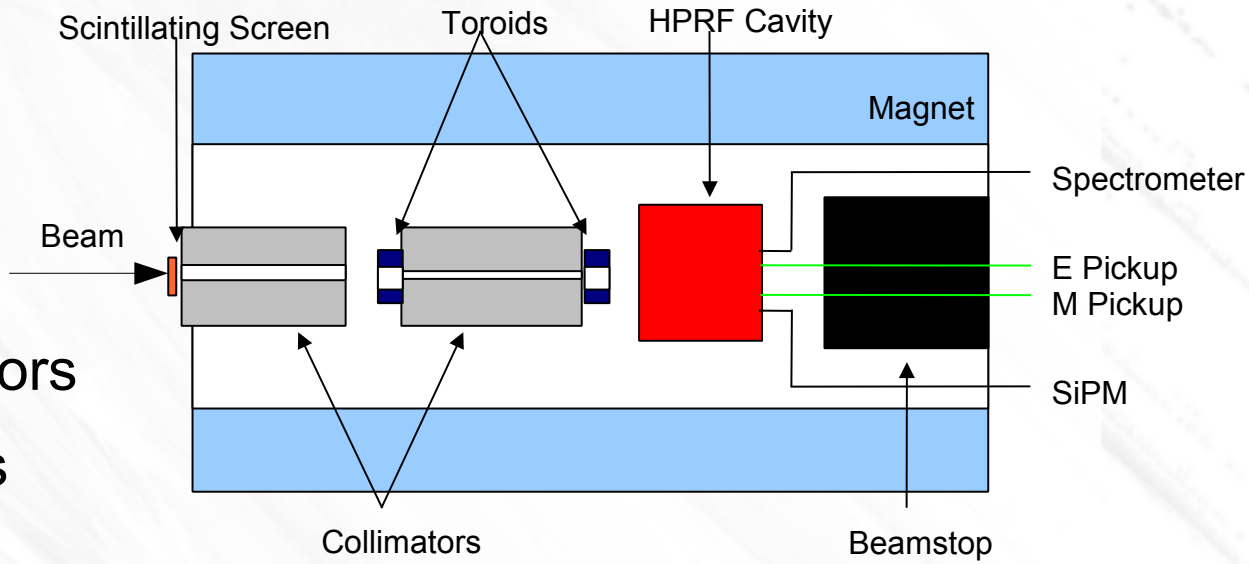
MuCool Test Area - Beamline

- Experimental hall located at the end of the Fermilab linac
- Utilizes 400 MeV H^- beam (electrons stripped in Ti window)
- $2x10^8$ p/bunch maximum
- Collimator system allows for intensity selection
- 1500 – 1900 bunches/pulse
- 1 pulse/minute

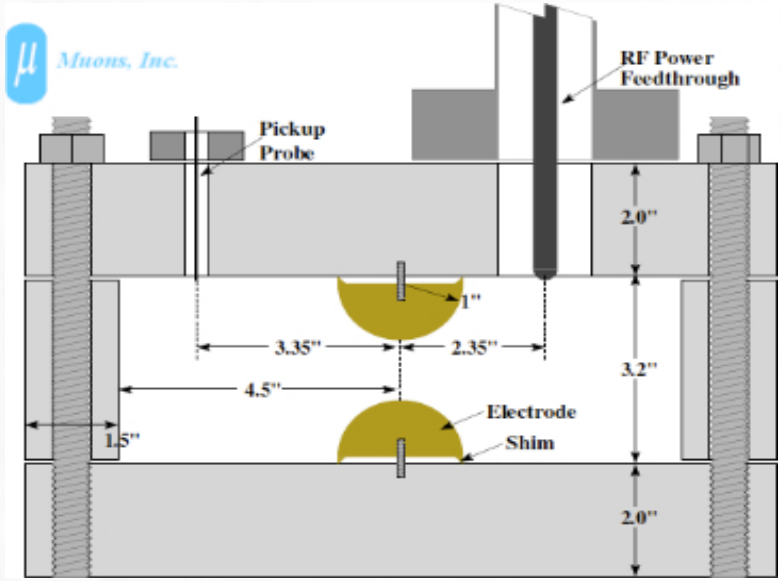


MTA – Instrumentation

- RF signal monitors
  - E & B pickups
  - Directional couplers
- Light signal monitors
  - PMTs / SiPMs
  - Spectrometer
- Safety monitors
  - Radiation sensors
  - Flammable gas sensors
- Beam diagnostics
  - Multiwires, BPMs
  - Intensity monitors
  - CCD camera – Scintillating screen



MTA – Cavity Setup



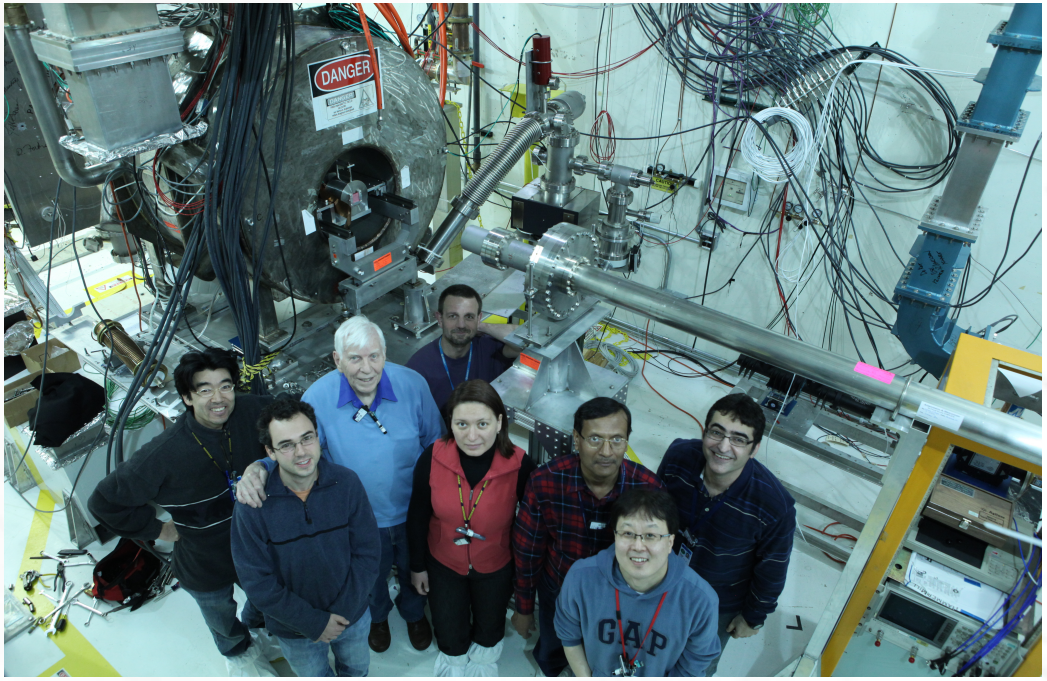
- 800 – 810 MHz
- 40 μs RF pulse length
- 15 Hz rep. rate
- 5 – 50 MV/m
- H_2, D_2, He, N_2, Dry Air (DA) base gases
- N_2, DA, SF_6 dopants (varying concentrations)
- 300, 500, 800, 1100, 1300, 1470, 1520 psi

Beam Test I

- July – August 2011
- Small variable range (Limited to 950 psi (safety), Limited to 30 MV/m (low power circulator), H_2, N_2, SF_6 gases)

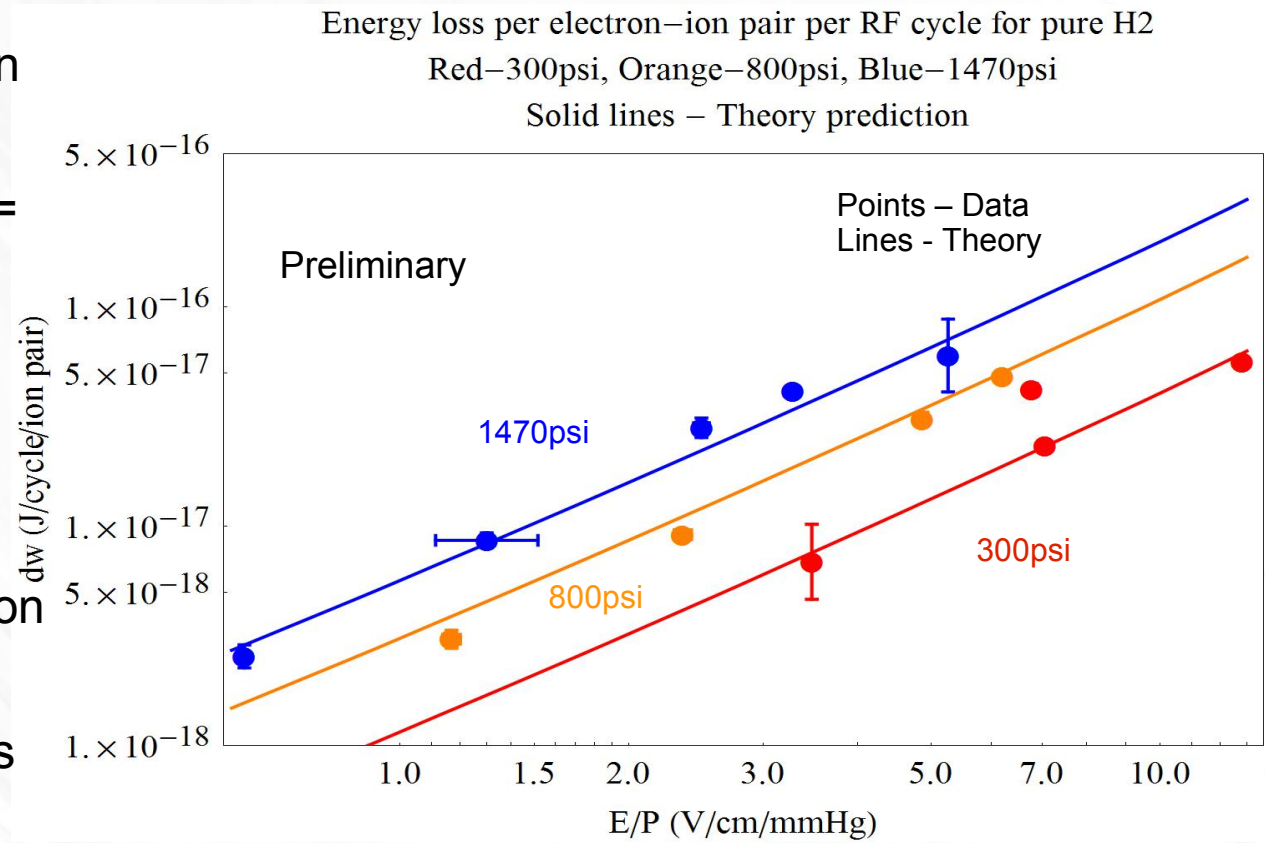
Beam Test II

- April – May 2012
- Expanded range of E and P
- Additional gases
- Improved instrumentation
- Magnetic field



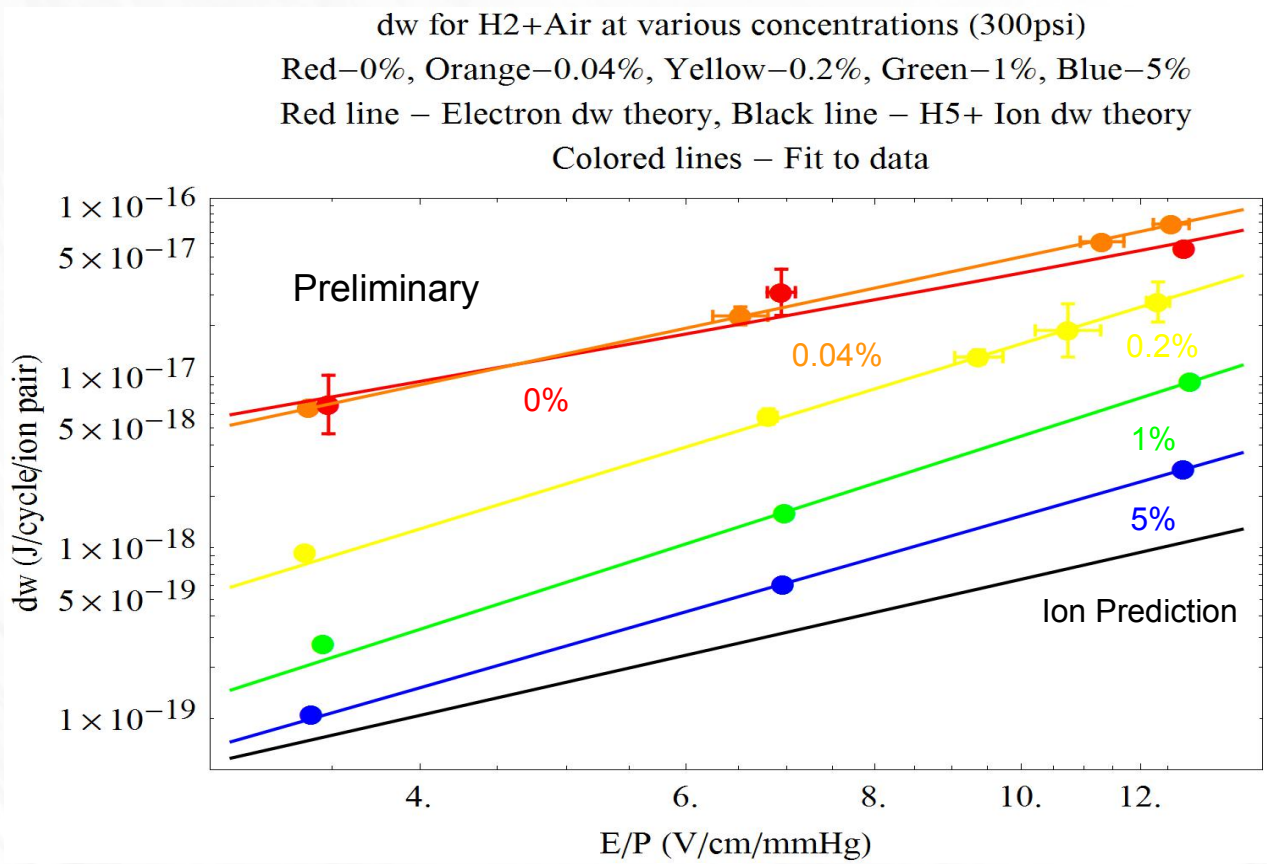
Energy Loss in Pure Hydrogen

- Colors correspond to constant pressure, so increasing horizontal axis corresponds to increasing electric field
- Larger E field = larger electron KE
- For a constant E/P, higher P = higher E, so again larger electron KE
- Energy loss due to ionized electrons, with small contribution from H^+ clusters
- Does not include recombination in theory prediction
- Model for electron energy loss matches data



Energy Loss in Dry Air Doped H_2 – I

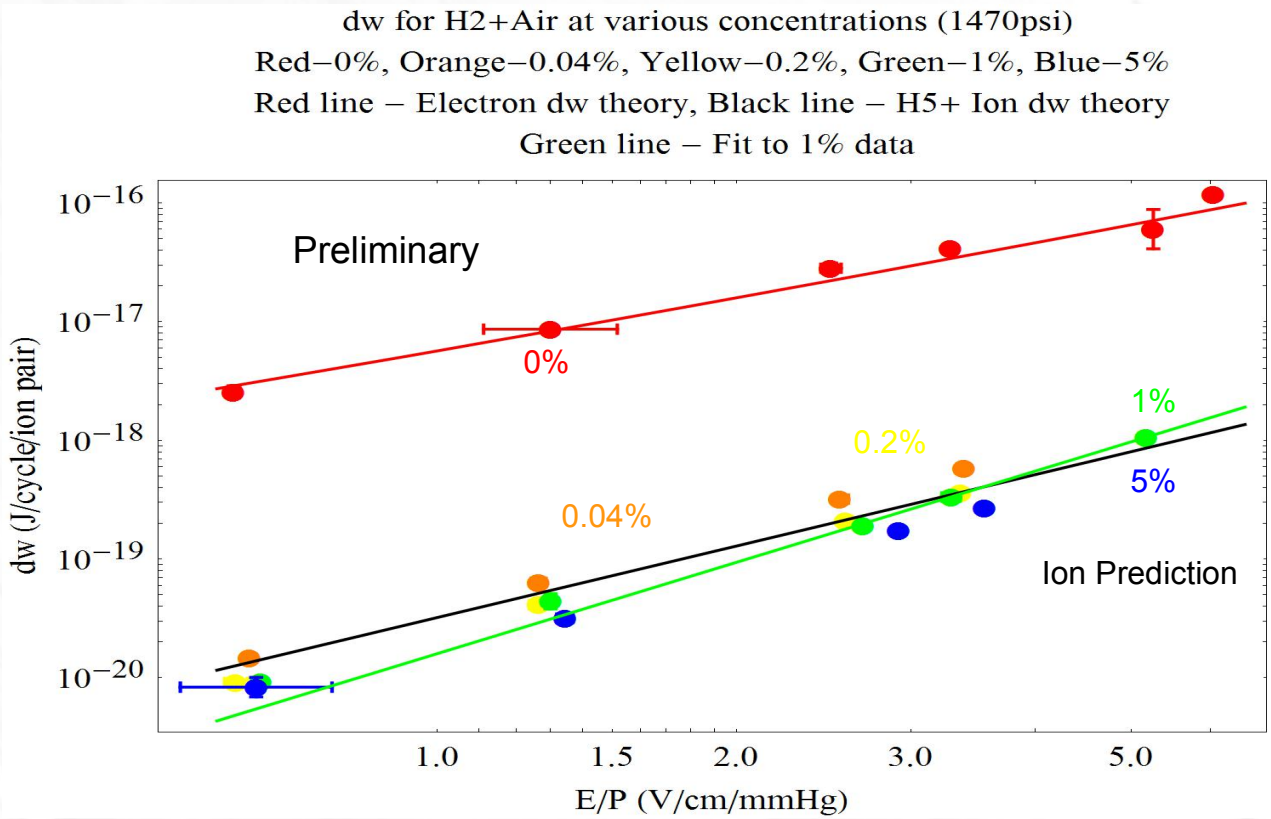
- Clear concentration dependence at 300 psi
- Red line – energy loss for electrons only (one extreme)
- Black line – energy loss for H_5^+ only (the other extreme)
- Energy loss coming from a combination of electrons and ions



Energy Loss in Dry Air Doped H_2 – II

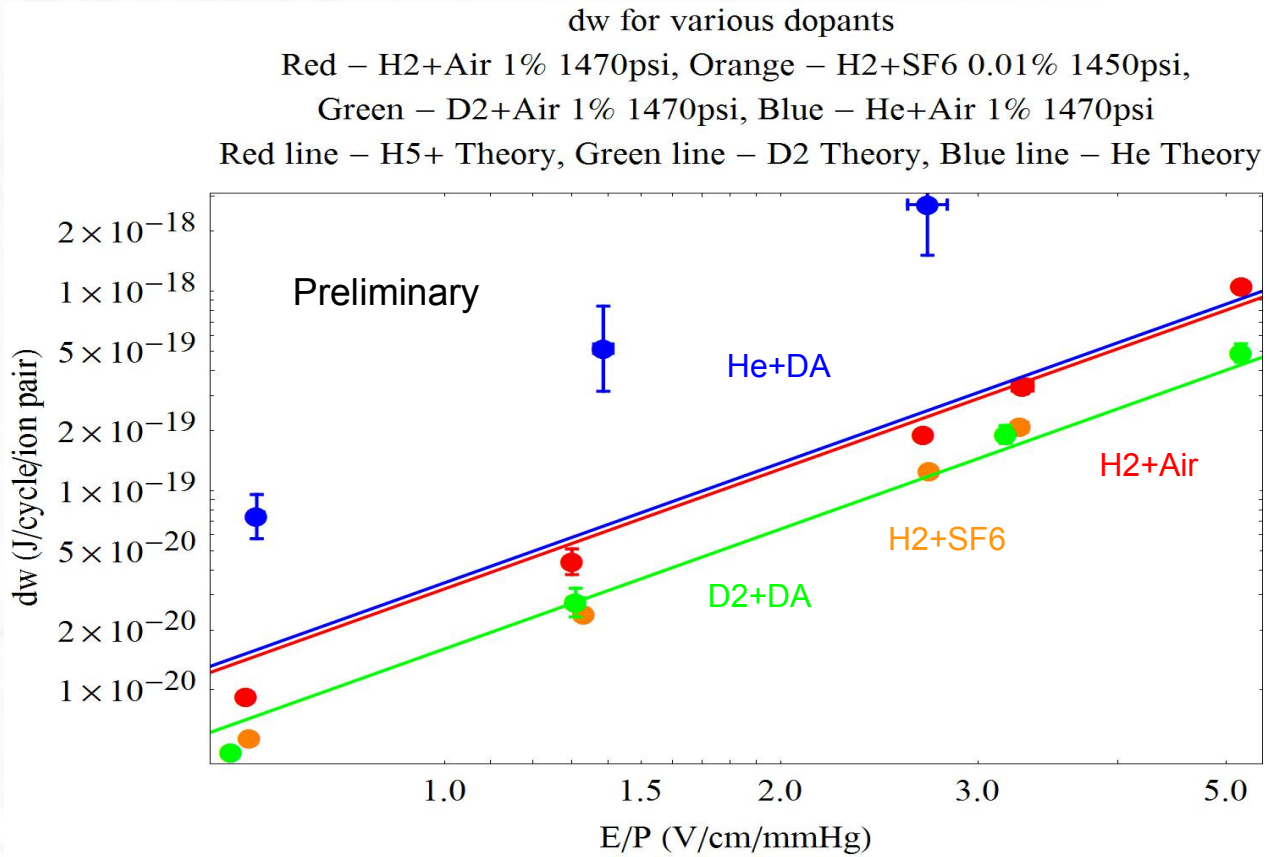
- Electron attachment relies on three body reactions
  $e + H_2 + O_2 \rightarrow H_2 + O_2^-$ and $e + O_2 + O_2 \rightarrow O_2 + O_2^-$

- At 1470 psi, concentration dependence is significantly lower
- Three body reaction dominates ($\propto P^2$), i.e. most electrons have been absorbed by O_2
- Energy loss comes mainly from ions



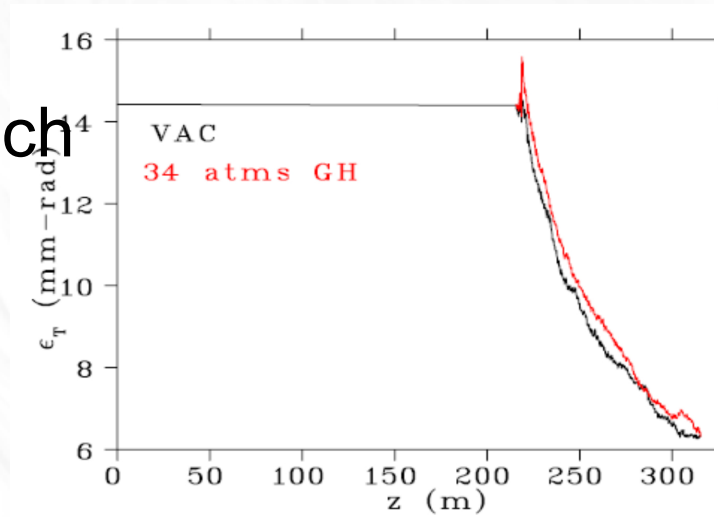
Ion Energy Loss

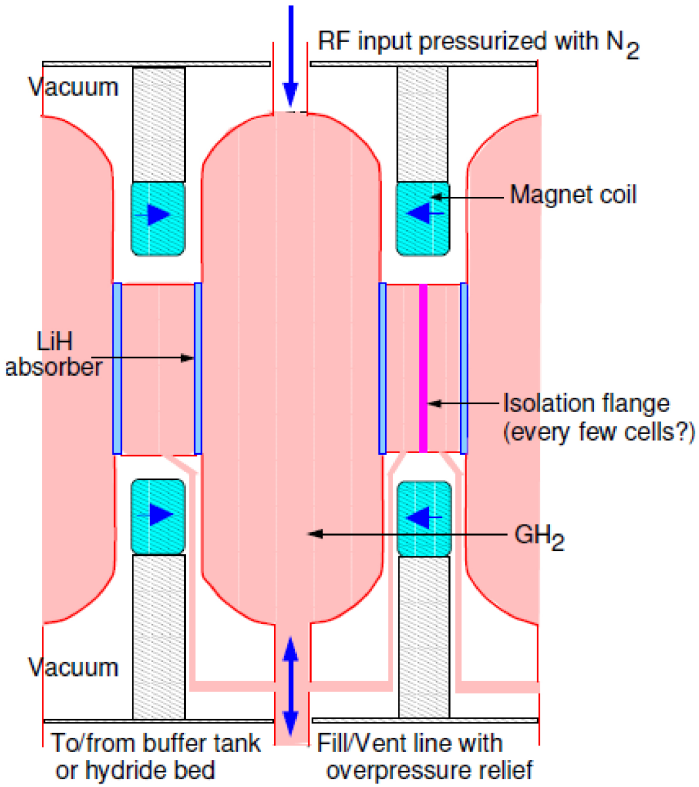
- To reduce the energy loss per ion, use a more massive ion, i.e. D_2
- D_2 + DA comparable to H_2 + SF_6
- D_2 + DA better than H_2 + DA
- He + DA shows worse energy loss than the model for just He^+ ions, indicating remaining electrons in the cavity



Neutrino Factory Parameters

- Does the HPRF work for a Neutrino Factory?
- Based on Zisman, Gallardo, IPAC '10
- 201 MHz
- 15 MV/m
- 4.2×10^{11} μ/bunch
- 24 bunches
- 34 atm





HPRF in a NF Cooling Channel

- Number of electron-ion pairs produced = 1.56×10^{14} ion pair/bunch/cm (3.26×10^{11} ion pair/bunch/cm in the MTA)
- E/P (15 MV/m)/(34 atm) = 5.80 V/cm/mmHg
- dw for H_5^+ ion model = 2.53×10^{-18} J/ion pair/cycle
- Energy loss = 0.95 J (out of 275 J stored energy, for 1 m)
- Insignificant energy loss in the HPRF for a NF!

HPRF in a Muon Collider

- Number of electron-ion pairs produced in 180 atm H_2 by 1.75×10^{12} μ/bunch = 3.44×10^{15} ion pair/bunch/cm (3.26×10^{11} ion pair/bunch/cm in the MTA)
- E/P (16 MV/m)/(180 atm) = 1.17 V/cm/mmHg
- dw for H_5^+ ion model = 1.36×10^{-19} J/ion pair/cycle
- Energy loss = 2.24 J (out of 19.5 J stored energy, assuming 1 m)
- Non-insignificant energy loss, but probably still feasible

Conclusions

- Energy loss in pure and doped Hydrogen is well understood
- HPRF cavity should operate in a Neutrino Factory
- HPRF cavity will probably work for a Muon Collider
- Further R&D is required to confirm feasibility

Future Plans

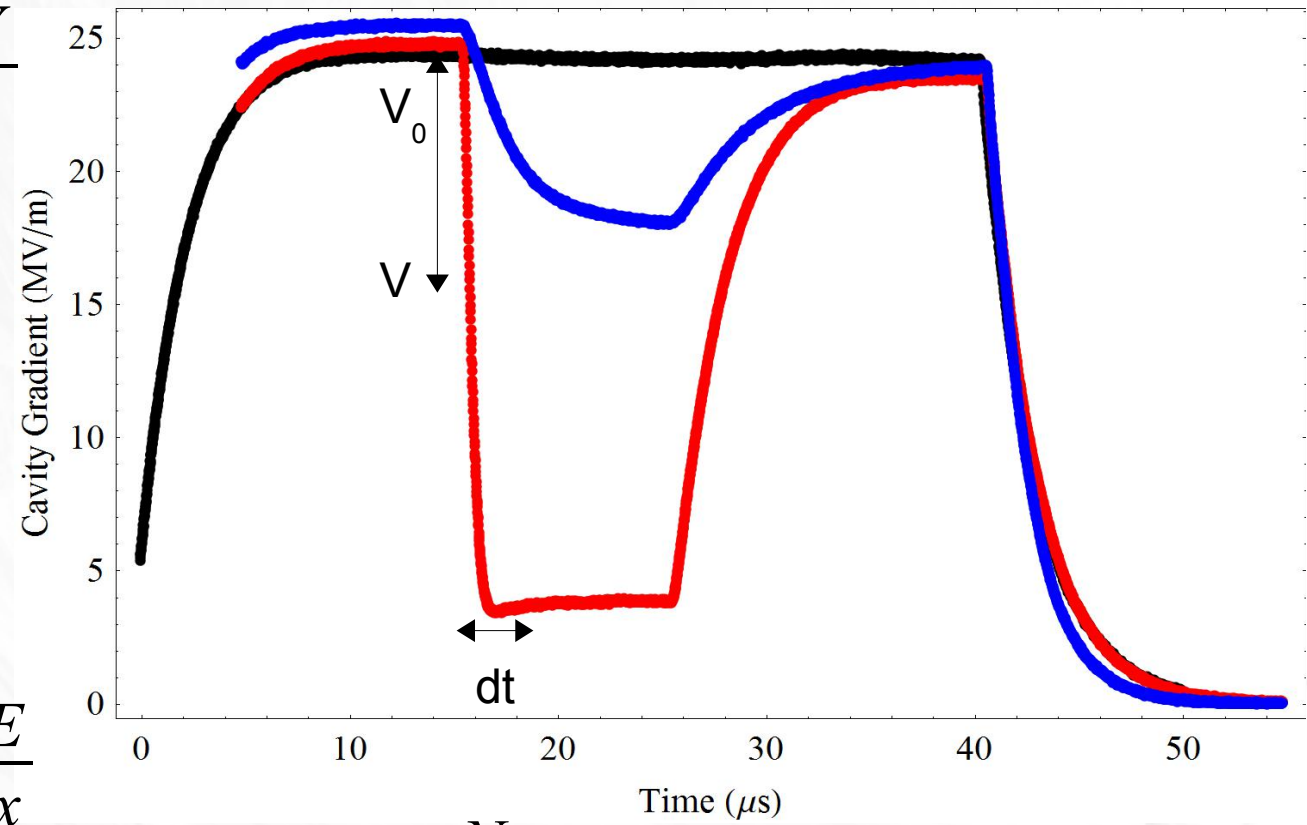
- Phase lock RF to beam
- Run cavity at cryogenic temperatures
- Dielectric loaded cavity (6-D cooling)
- Collective effects simulation
- Build a realistic cavity for cooling channel

Backup Slides

How dw is Measured

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

$$dw=\frac{P}{n_e}\frac{1}{f}$$



$$n_e=\rho_{H_2}\cdot\frac{\frac{dE}{dx}}{energy\ loss\ per\ ion\ pair\ produced}\cdot N_p$$

Energy Loss Calculation

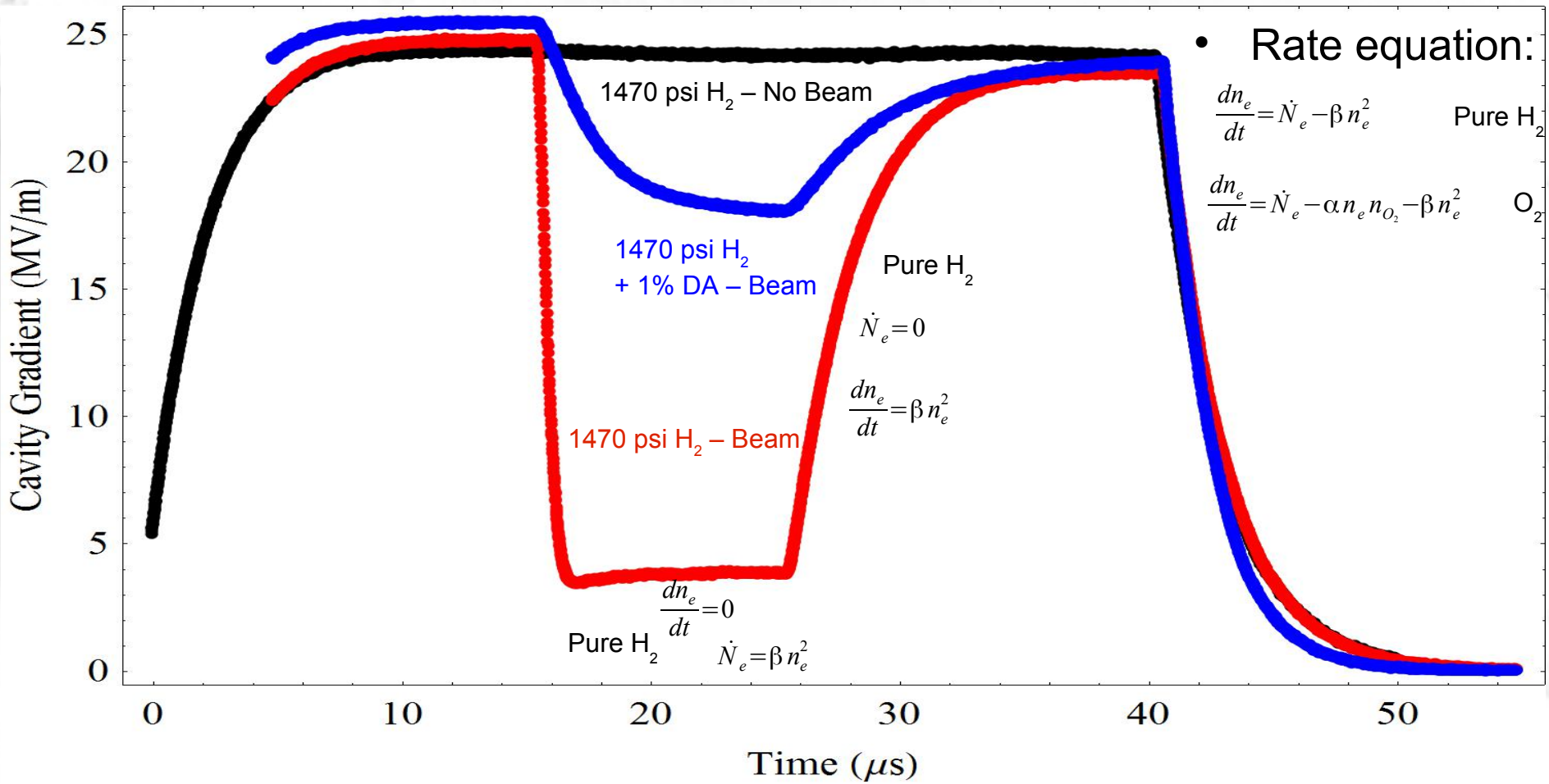
For muons in Hydrogen:

$$10.9\frac{ion\ pair}{atm\ cm}\cdot 34\text{atm}\cdot 4.2\times 10^{11}\frac{\mu}{bunch}=1.56\times 10^{14}\frac{ion\ pair}{bunch\ cm}$$

$$1.56\times 10^{14}\frac{ion\ pair}{bunch\ cm}\cdot 2.53\times 10^{-18}\frac{J}{ion\ pair\ cycle}=3.95\times 10^{-4}\frac{J}{bunch\ cm\ cycle}$$

$$3.95\times 10^{-4}\frac{J}{bunch\ cm\ cycle}\cdot 1\,cycle\cdot 24\,bunches\cdot 100\,cm=0.95\,J$$

Recombination / Attachment



- Rate equation:

$$\frac{dn_e}{dt} = \dot{N}_e - \beta n_e^2 \quad \text{Pure } H_2$$

$$\frac{dn_e}{dt} = \dot{N}_e - \alpha n_e n_{O_2} - \beta n_e^2 \quad O_2 \text{ doped } H_2$$