Results from the High Pressure Gas Filled RF Cavity Beam Test

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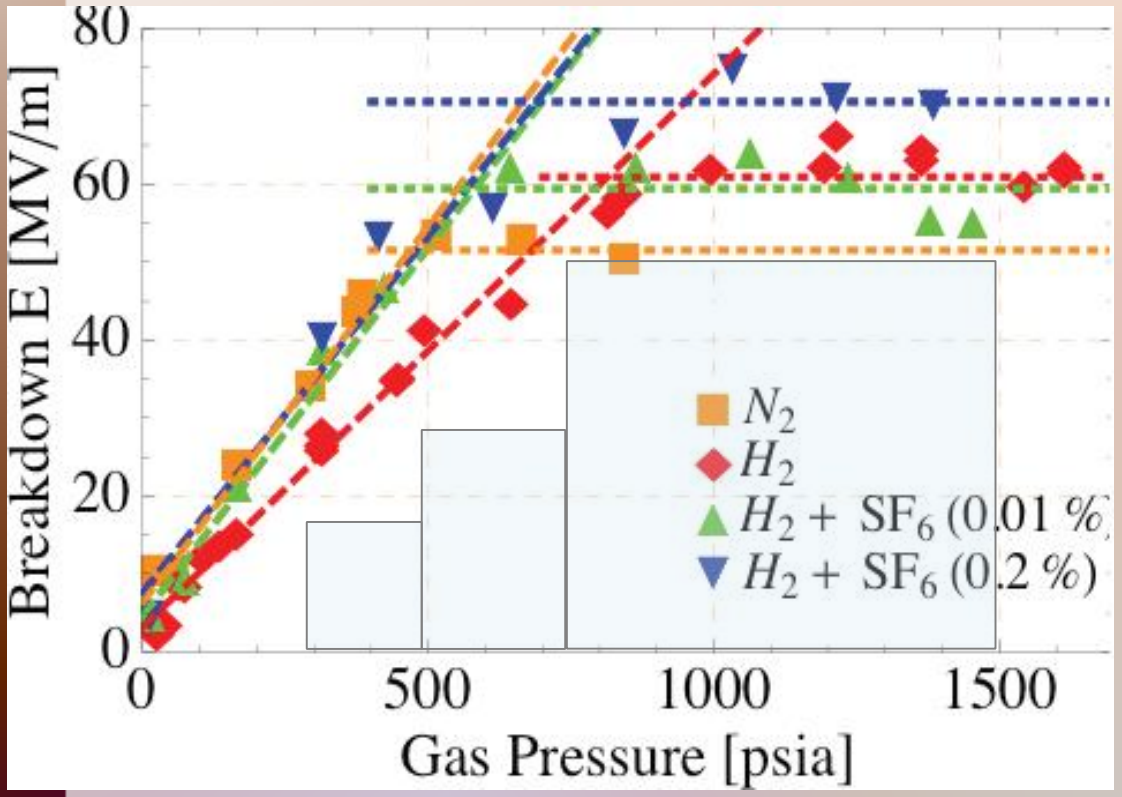
Background & Purpose

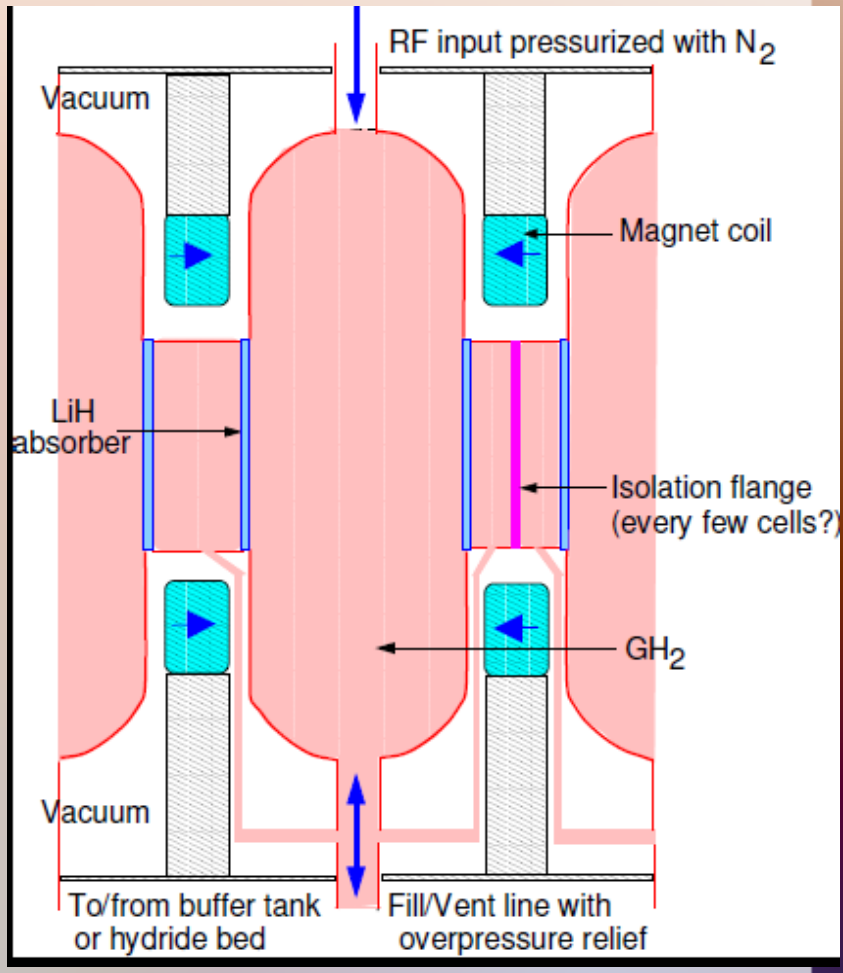


- Filling an RF cavity with a high pressure gas solves the problem of breakdown in an external magnetic field
- Breakdown studies have been conducted with various gas species and electrode materials over a range of pressures
- We are not interested in finding the breakdown limit, but need a sufficiently high pressure to prevent it

- The purpose of the beam tests is to study beam induced plasma loading effects in our test cell
- The goal is to extract numbers for energy loss, recombination rates, etc, for use in predicting accelerator scale plasma loading

Hybrid Cooling Channel

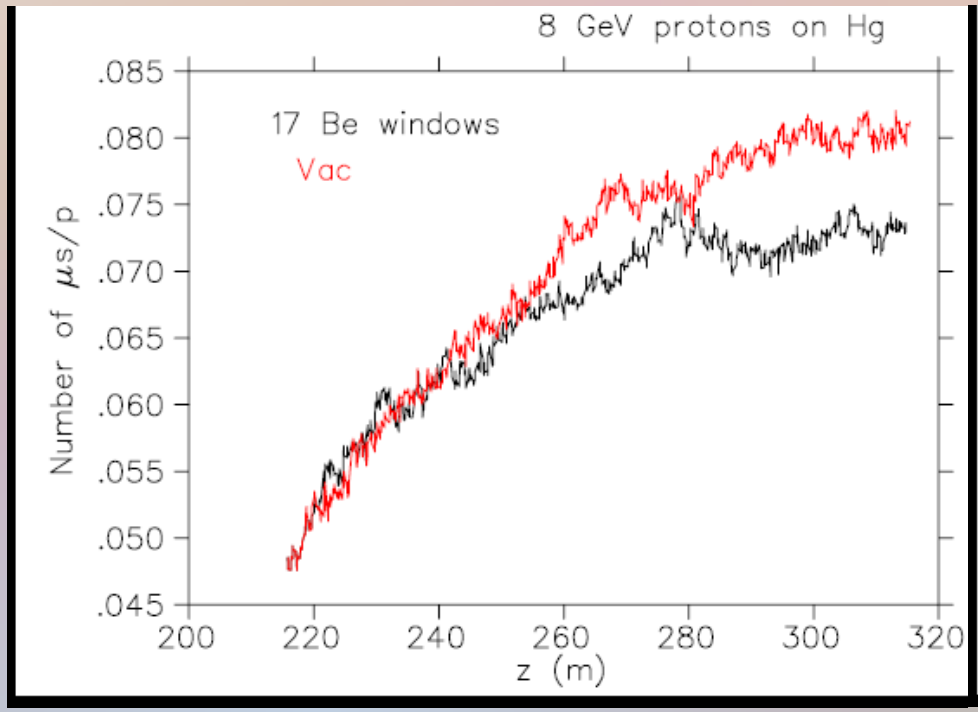
- How does this apply to ionization cooling?
- A hybrid cooling channel with similar parameters to the NF Study 2a channel has been simulated
- The idea was to present a realistic alternative to a vacuum cavity cooling channel
- The electric field was 15 MV/m so a low gas pressure (500 psi) is required to prevent breakdown
- H_2 was used as the breakdown suppressant
- The channel was simulated at room temperature
- LiH absorbers with Be pressure windows were used

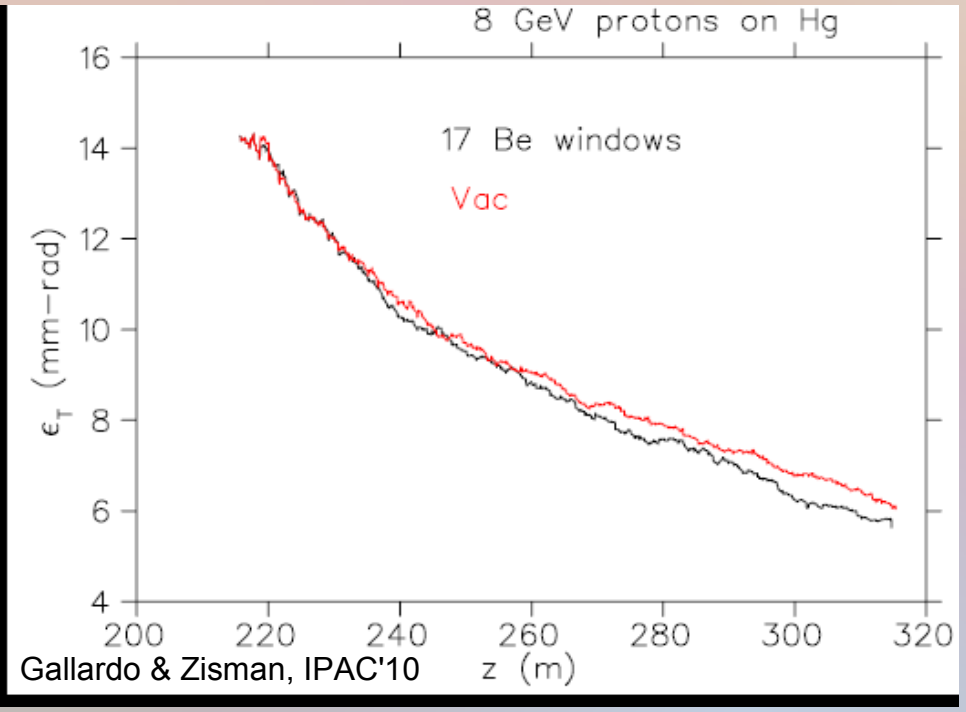


Gallardo & Zisman, IPAC'10

HPRF vs Vacuum Performance Comparison

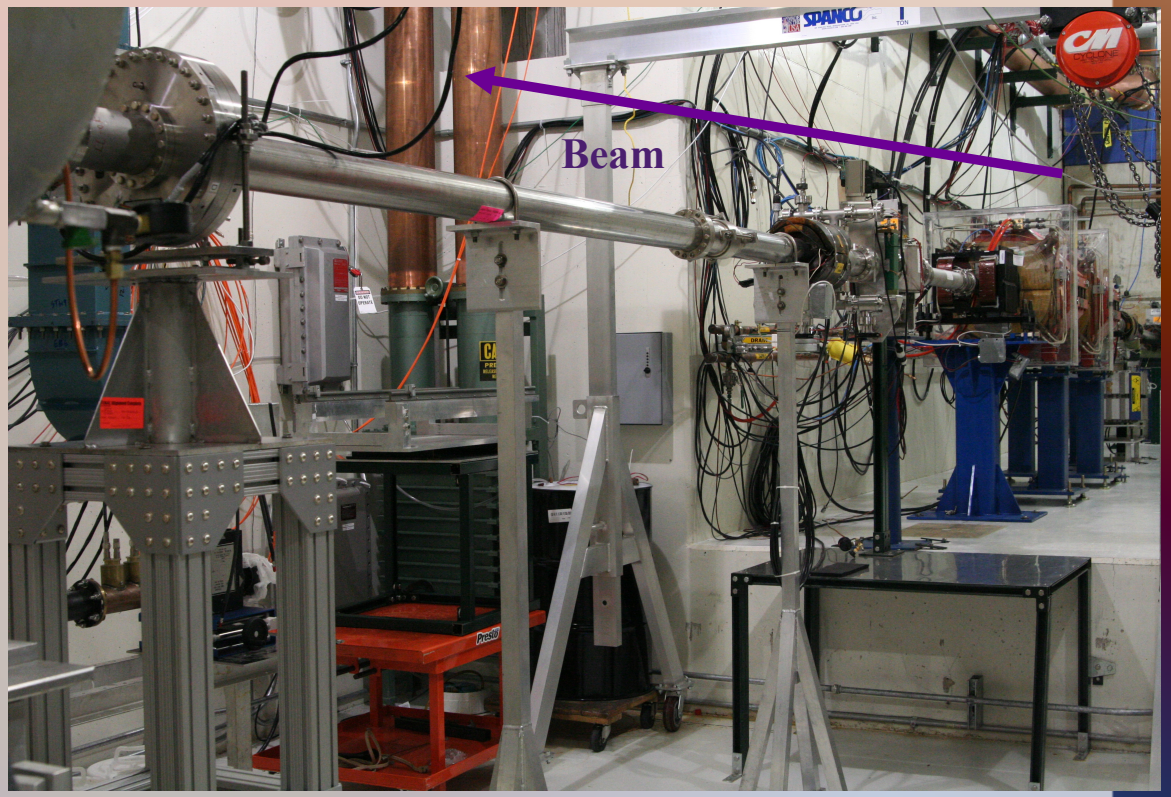
- Performance of HPRF through a 100 m long cooling channel using real NF parameters is comparable to vacuum cavities and within the design tolerances
- Transverse emittance reduction is slightly better, transmission is slightly worse
- So this cooling channel could be built today and operate successfully, except for the question: How does plasma loading affect the cavity's performance?





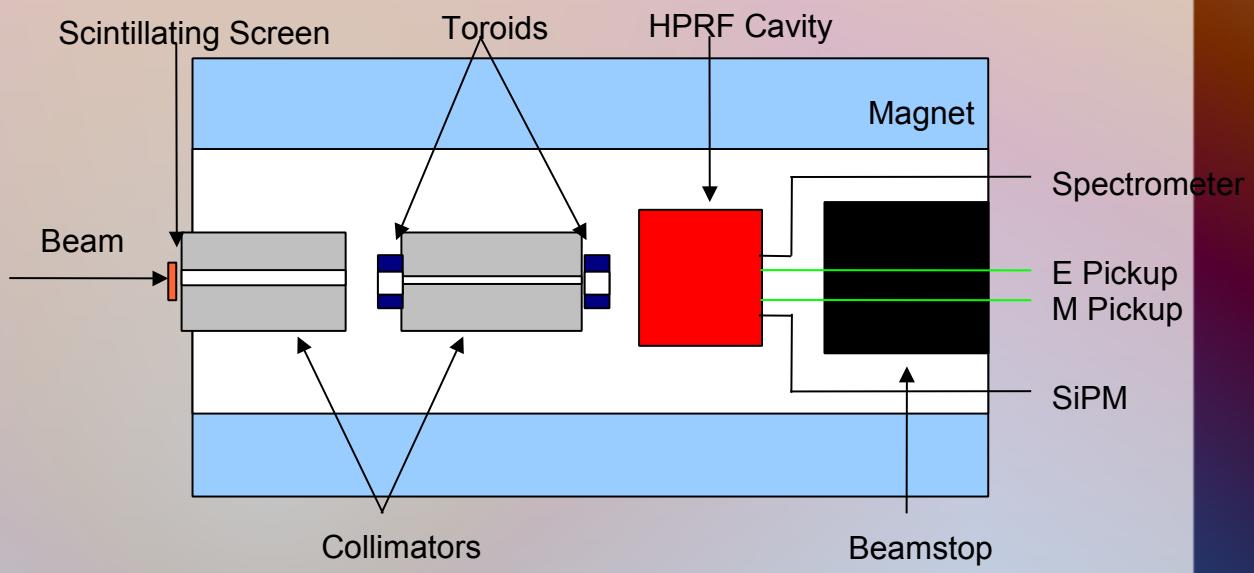
MuCool Test Area - Beamline

- 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



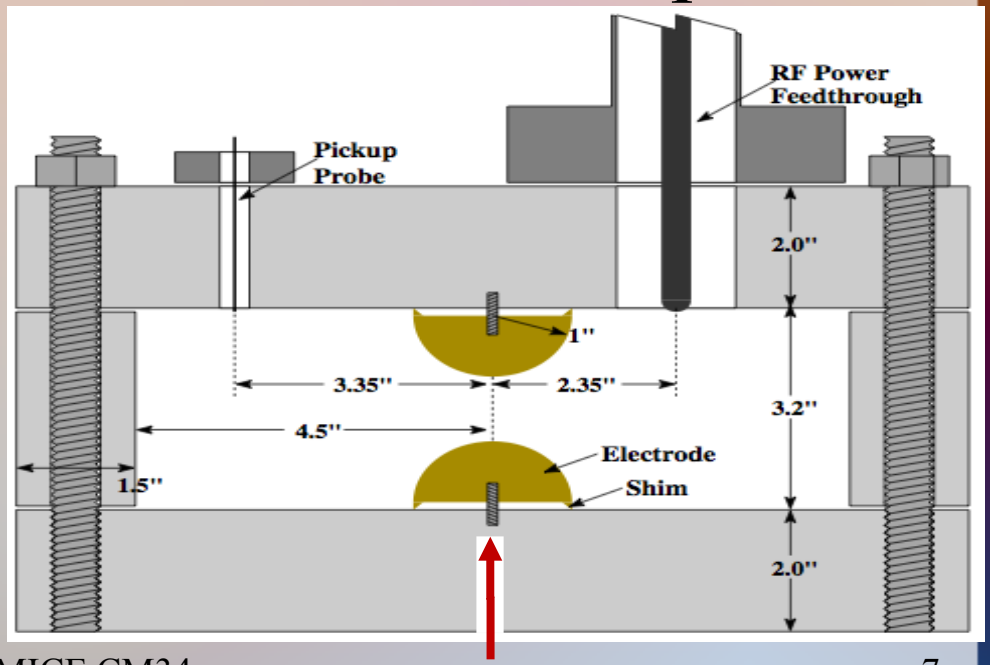
MTA – Instrumentation

- 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

- H_2, D_2, He, N_2, Dry Air (DA) base gases
- N_2, DA, SF_6 dopants (varying concentrations)
- 300, 500, 800, 950, 1100, 1300, 1470, 1520 psi
- 800 – 810 MHz
- 40 μs RF pulse length
- 5 – 50 MV/m



Plasma Physics Processes in HPRF

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

Electron-ion pair production

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

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

RF energy dissipation (From plasma loading)

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

- Resistive dissipation by plasma motion in parent gas driven by RF electric field
- Drift velocity of the electron and ion ($\bar{v}$) are known from past experiments
- Model predicts electron *dw* >> ion *dw*

No model dependence

Linear Theory

Recombination / Attachment

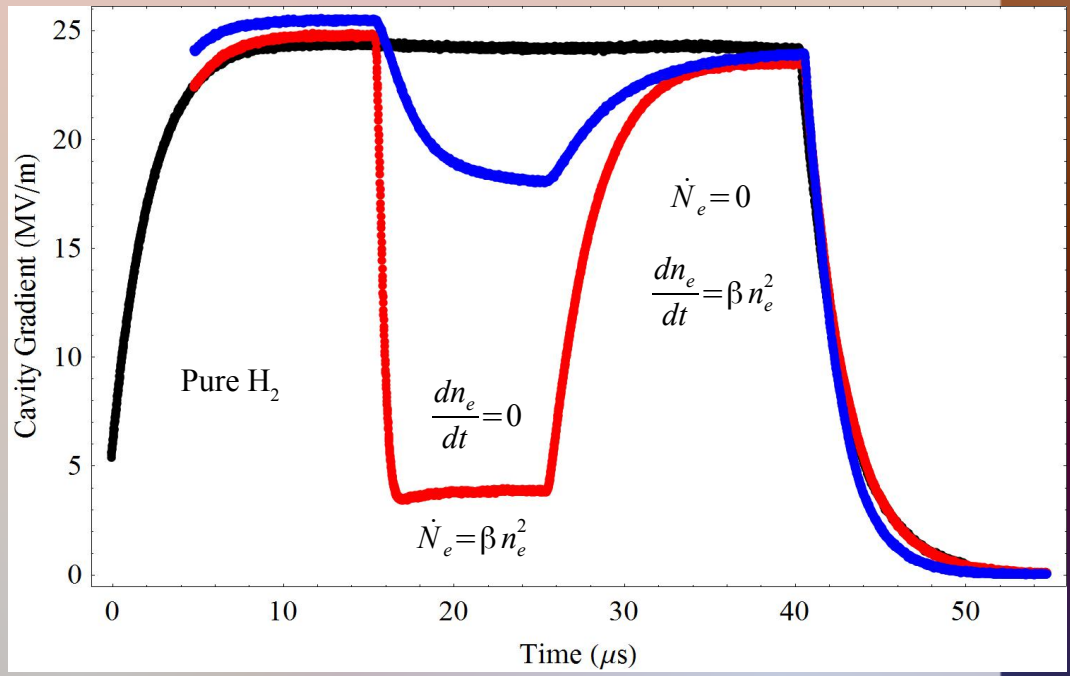
- Why does the beam not kill the cavity?
- In pure H_2, recombination of electrons with clusters of H^+ eventually reaches an equilibrium with production of electron – ion pairs; energy going in equals energy taken out
- For the dopant case, attachment of electrons with the electronegative gas also occurs (and is much faster than recombination)
- H_2 processes have been well studied & provide a good basis for prediction

- Rate equations:

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

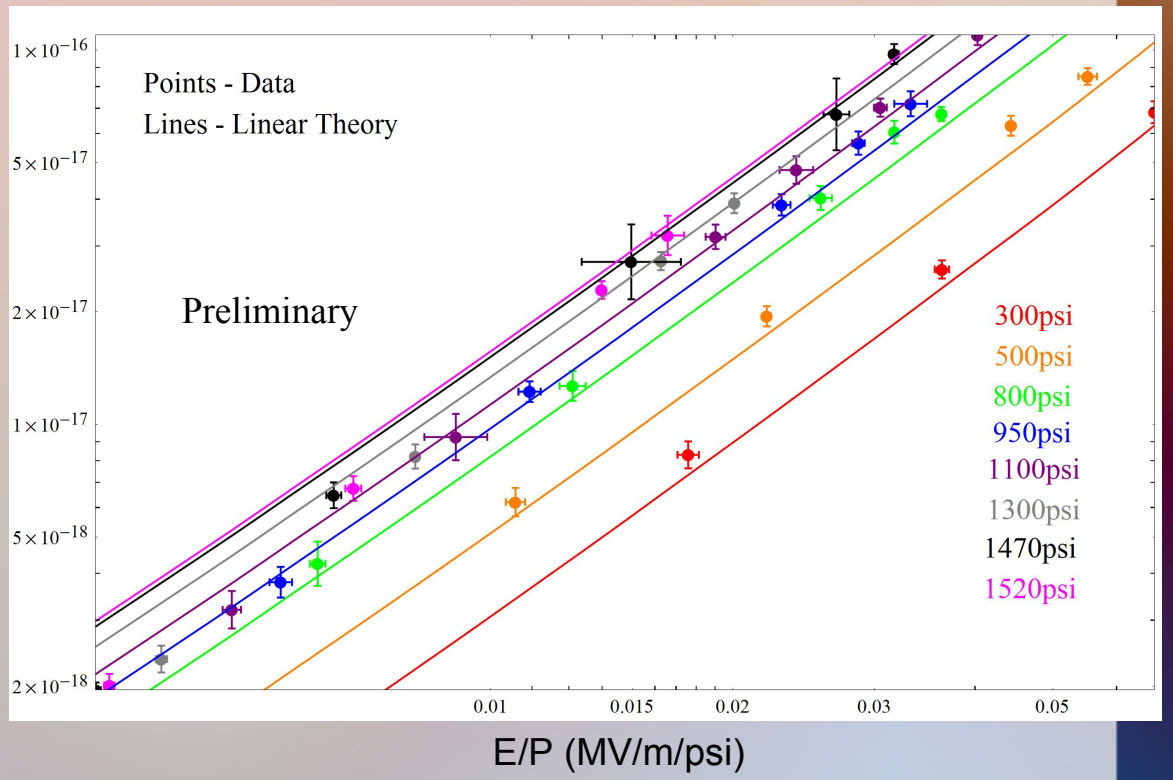
O_2 doped H_2 $$\frac{dn_e}{dt} = \dot{N}_e - \sum \alpha n_e n_{I_1} n_{I_2} - \beta n_e n_H$$

1470 psi H_2 – No Beam 1470 psi H_2 – Beam 1470 psi H_2 + 1% DA – Beam



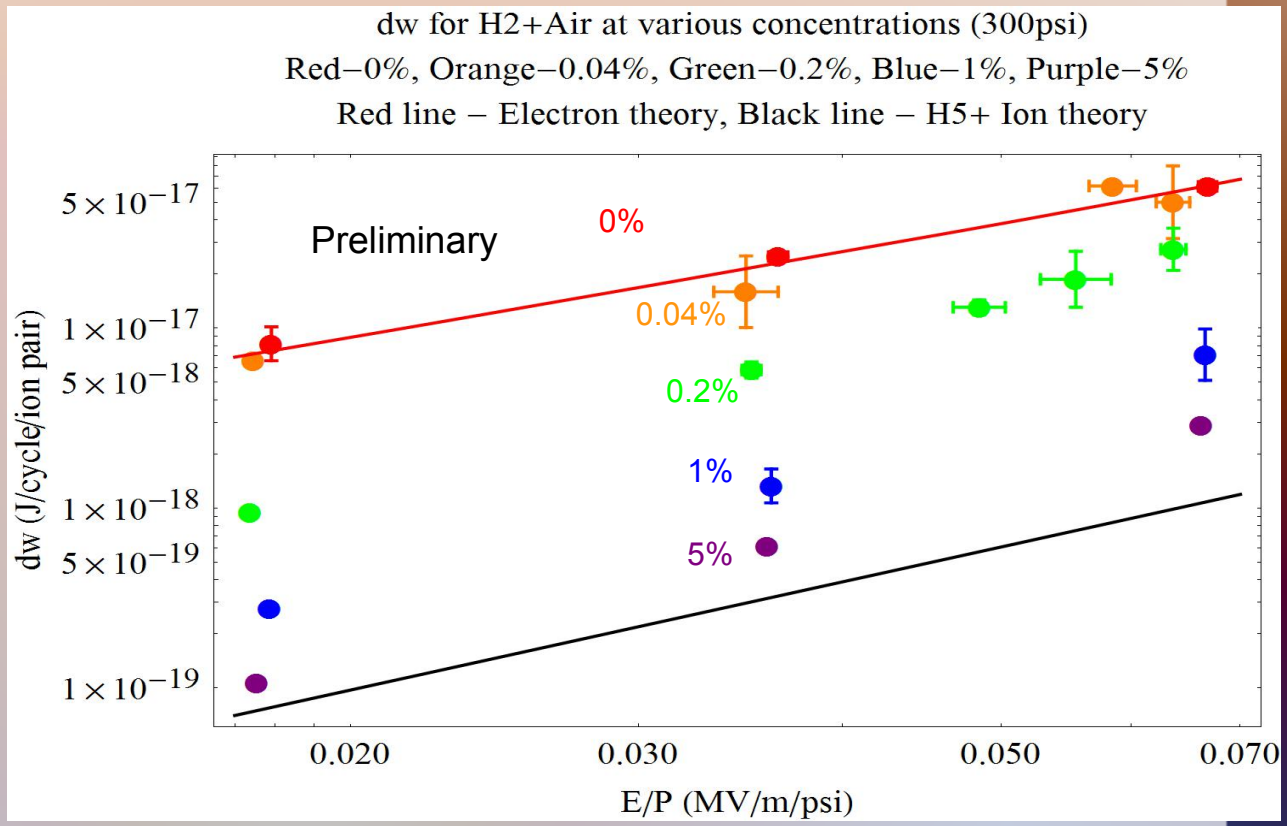
Energy Loss in Pure Hydrogen

- Colors correspond to constant pressure, so increasing horizontal axis corresponds to increasing electric field for a given pressure
- For a constant E/P, higher P = higher E, so larger electron KE
- Energy loss due to ionized electrons, with small contribution from H^+ clusters
- Theory prediction does not include recombination
- Simulations by D. Rose agree with model



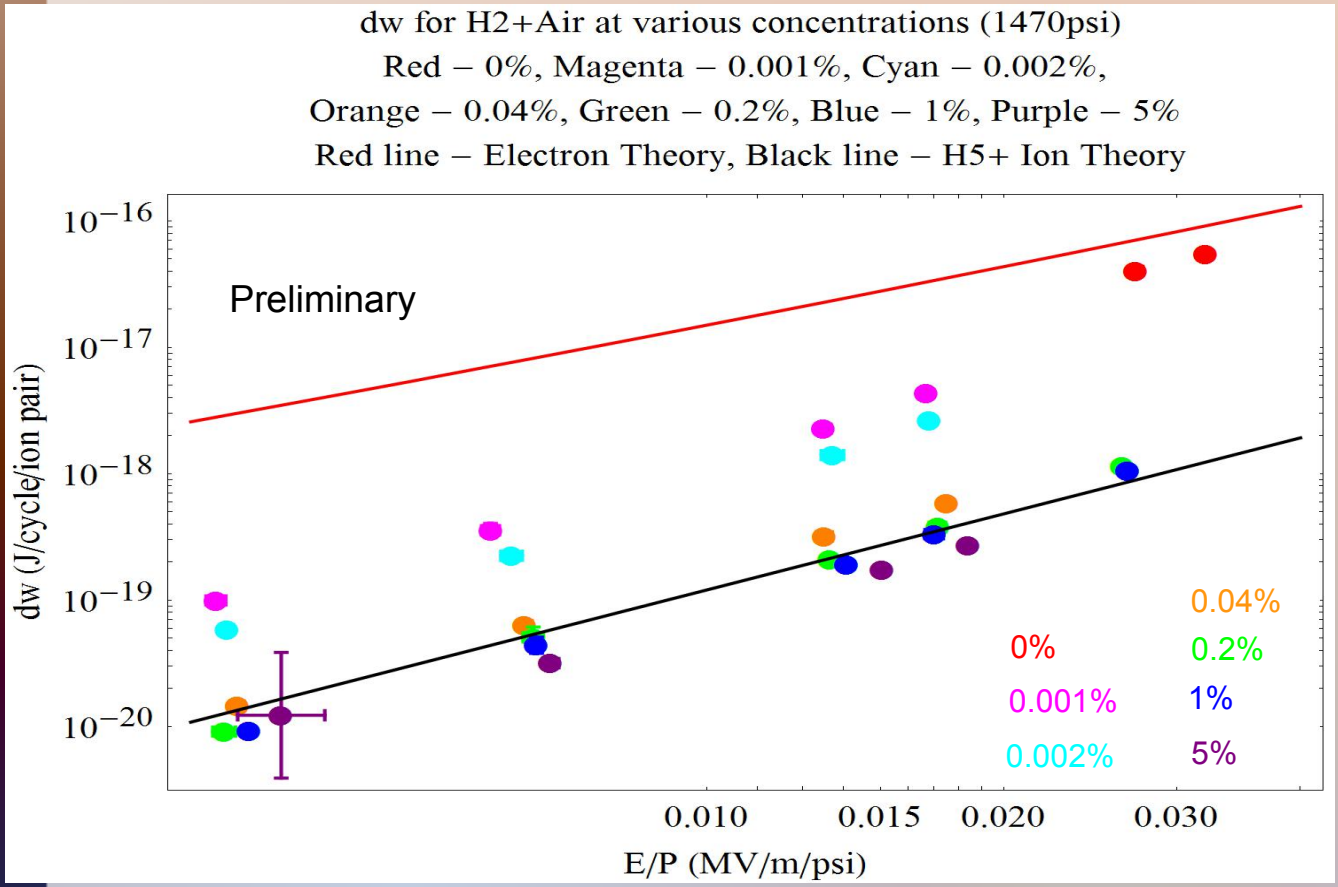
Energy Loss in Dry Air Doped H_2 – I

- Dope H_2 with varying concentrations of Dry Air (interested in O_2)
- 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

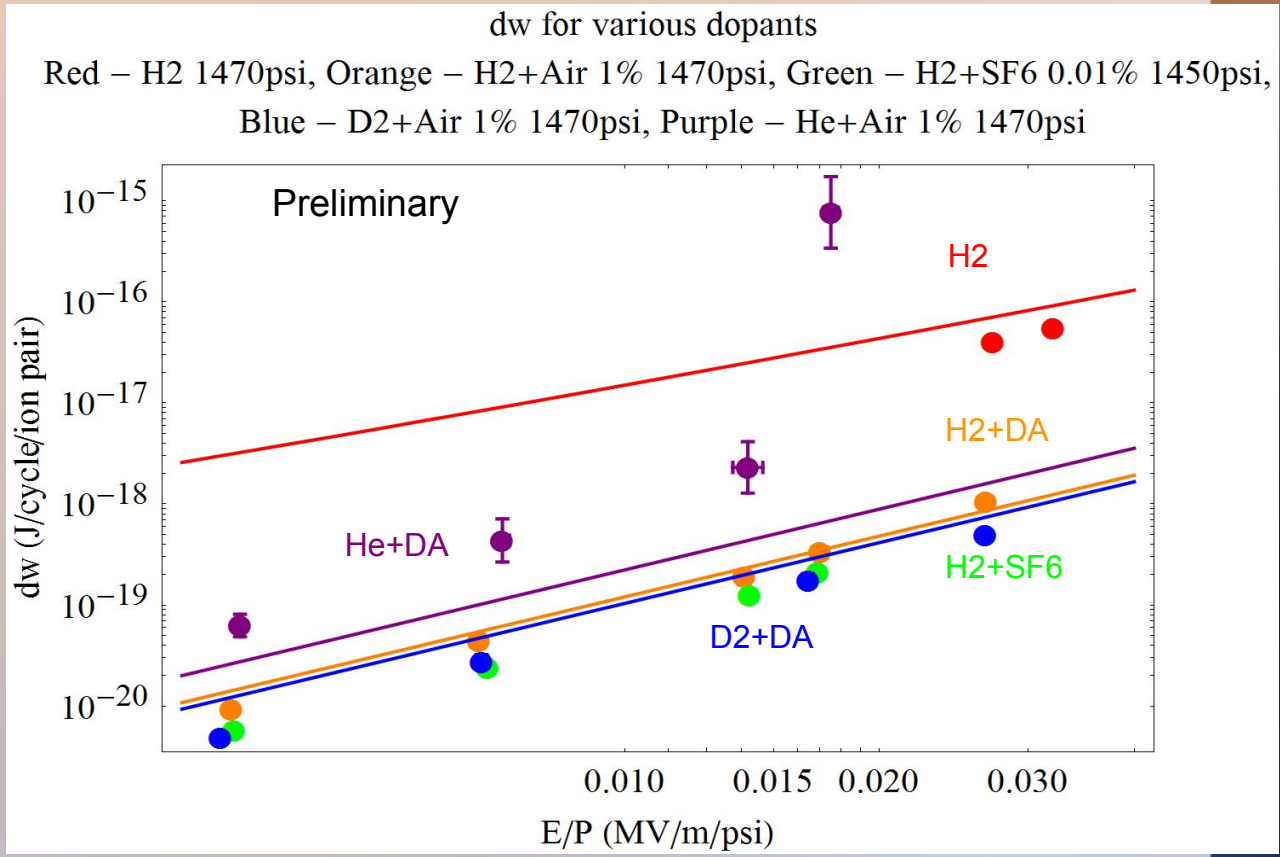
- Electron attachment relies on three body reactions $e + H_2 + O_2 \rightarrow H_2 + O_2^-$ and $e + O_2 + O_2 \rightarrow O_2 + O_2^-$



- At 1470 psi, three body reactions dominate and virtually all electrons are removed from the cavity
- The concentration of O_2 must be very small to begin seeing any residual electrons
- Reminder: DA is 20% O_2 – very little O_2 is needed to remove electrons

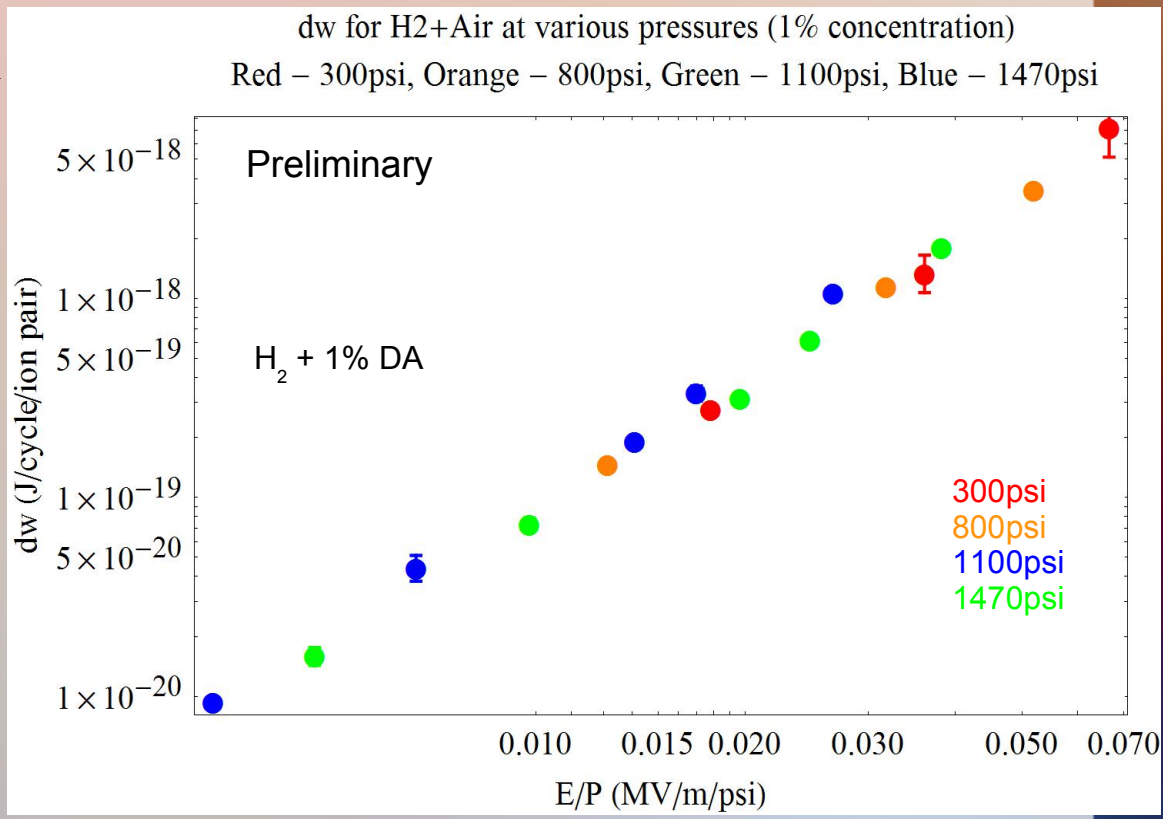
Ion Energy Loss

- Ions with more mass should have a smaller mobility and therefore produce less energy loss
- D_2 + DA is produces less energy loss than H_2 + DA
- D_2 + DA comparable to H_2 + SF_6
- He + DA shows worse energy loss than the model for just He^+ ions, indicating remaining electrons in the cavity
- Ions are the primary source of energy loss when all electrons have been removed



Extrapolation

- Is it valid to predict the energy loss in a cavity with a more dense gas and a more intense beam, operating at a different frequency?
- The HPRF cavity is an 805 MHz test cell, not a true pillbox, and has a small stored energy
- We believe the physics processes are the same in a 201 MHz cavity and can be applied to greater gas densities and beam intensities
- There is very little energy loss dependence on pressure for a given concentration
- The measured energy loss is normalized to a single electron-ion pair produced; independent of beam intensity
- Extrapolation to higher intensities and pressures seems valid



HPRF in a Muon Collider

- Number of electron-ion pairs produced in 2650 psi H_2 by 1.75×10^{12} μ/bunch = 3.43×10^{15} ion pair/bunch/cm (3.26×10^{11} ion pair/bunch/cm in the MTA)
- E/P (16 MV/m)/(2650 psi) = 0.006 MV/m/psi
- Assuming all electrons have been removed from the cavity:
- Measured dw = 4.0×10^{-20} J/ion pair/cycle
- Energy loss = 3.62 J/m (out of 19.5 J/m stored energy in an 805 MHz cavity)
- This is a worst case scenario, assuming no ion neutralization and a constant energy loss

HPRF in a Neutrino Factory

- Number of electron-ion pairs produced in 500 psi H_2 by 2.1×10^{11} μ/bunch = 7.78×10^{13} ion pair/bunch/cm (3.26×10^{11} ion pair/bunch/cm in the MTA)
- E/P (15 MV/m)/(500 psi) = 0.03 MV/m/psi
- Assuming all electrons have been removed from the cavity:
- Measured dw = 3.65×10^{-19} J/ion pair/cycle
- Energy loss = 0.78 J/m (out of 313 J/m stored energy in a 201 MHz cavity)
- Insignificant energy loss in the HPRF for a NF!

Conclusions

- A great deal of progress has been made in understanding what happens when a beam of particles traverses the cavity
- Pressure and dopant concentration dependencies have been measured
- Measurements of recombination and attachment rates have been made
- It is very difficult to obtain experimental values for actual cooling channel beam intensities
- We are obtaining good results to be used as input into real accelerator parameter simulations
- It appears that an HPRF cavity cooling channel would work for both a Neutrino Factory and Muon Collider

Backup Slides

Energy Loss Calculation

For NF muons in DA doped H_2:

$$2.1\times10^{11}\frac{\mu}{bunch}\cdot10.9\frac{ion\ pair}{atm\,cm}\cdot\ 34\ atm=7.78\times10^{13}\frac{ion\ pair}{bunch\,cm}$$

$$7.78\times10^{13}\frac{ion\ pair}{bunch\,cm}\cdot3.65\times10^{-19}\frac{J}{ion\ pair\,cycle}\cdot100\frac{cm}{m}=2.84\times10^{-3}\frac{J}{bunch\,m\,cycle}$$

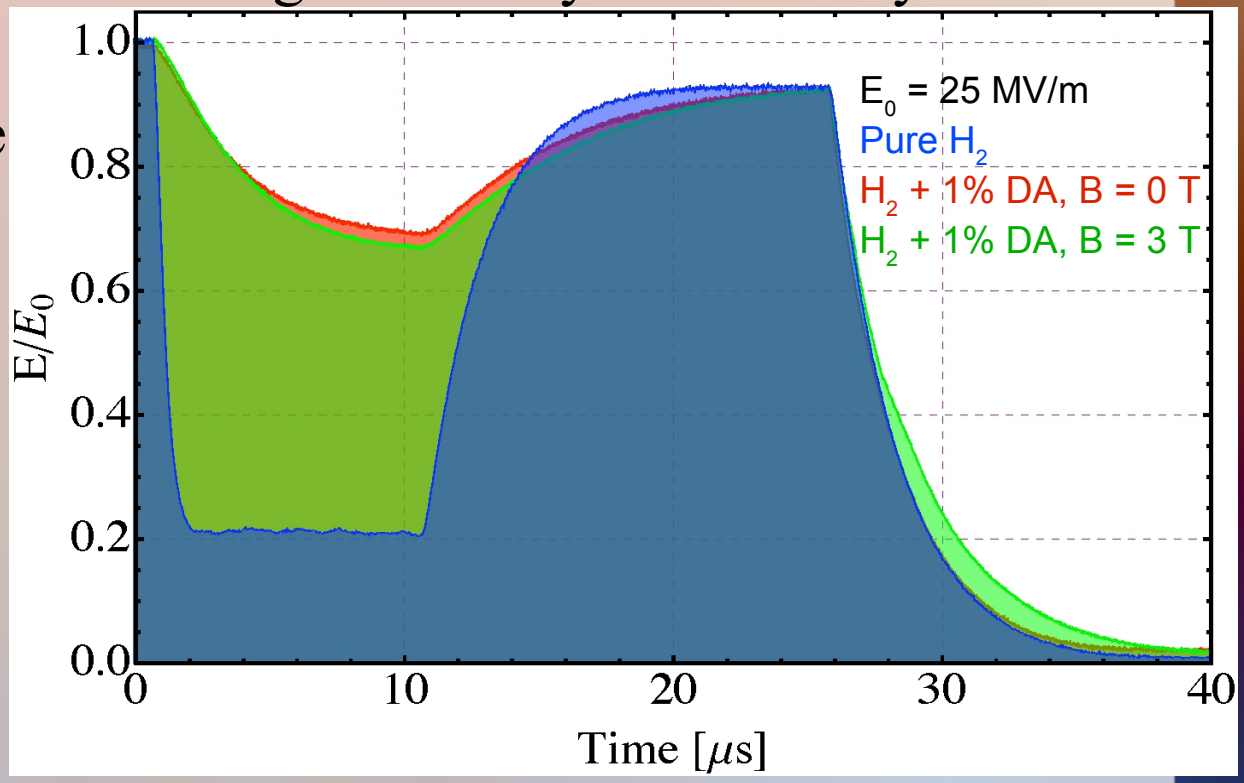
$$2.84\times10^{-3}\frac{J}{bunch\,m\,cycle}\cdot\frac{201\ MHz}{201\ MHz}\cdot0.5\times23\left(23+1\right)bunch\ \ cyle=0.78\frac{J}{m}$$

For MC muons in DA doped H_2:

$$1.75\times10^{12}\frac{\mu}{bunch}\cdot10.9\frac{ion\ pair}{atm\,cm}\cdot\ 180\ atm=3.43\times10^{15}\frac{ion\ pair}{bunch\,cm}$$

$$3.43\times10^{15}\frac{ion\ pair}{bunch\,cm}\cdot4.0\times10^{-20}\frac{J}{ion\ pair\,cycle}\cdot100\frac{cm}{m}=1.37\times10^{-2}\frac{J}{bunch\,m\,cycle}$$

$$1.37\times10^{-2}\frac{J}{bunch\,m\,cycle}\cdot\frac{805\ MHz}{201\ MHz}\cdot0.5\times11\left(11+1\right)bunch\ \ cycle=3.62\frac{J}{m}$$

Magnetic Field + Beam

- Magnetic field makes beam current measurement by toroids impossible
- There is a correlation between the light intensity in the cavity and the beam current
- A rough estimation of the beam current can be made from the light signal
- Preliminarily there is little qualitative difference between beam with and without magnetic field data