Progress of High Pressure RF Cavity Test

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On behalf of HPRF test group
APC, Fermilab

High pressure RF cavity test program

- Demonstrate potential of HPRF cavity for cooling & accelerating a muon beam
  - Study breakdown in a dense gas with a high RF gradient at a strong magnetic field
  - <u>Study influence of an intense beam on the cavity</u>
  - Investigate fast electronegative gases
  - <u>Study feasibility of gas filled dielectric loaded RF cavity</u>
  - Make an RF cavity for a real cooling channel

Goal of first beam test

- Does the cavity breakdown with an intense beam?
- What is the influence of beam on the cavity?
- How long does it take to recover RF field?
- Study plasma dynamics in a dense gas at a high RF gradient
- Search any clues to improve RF system

Collaboration

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+ AD external beam division
+ AD mechanical design
+ Machine shop
+ Rad/Hydrogen safety committees
+ Director/Division Heads
+ Operators & Technicians

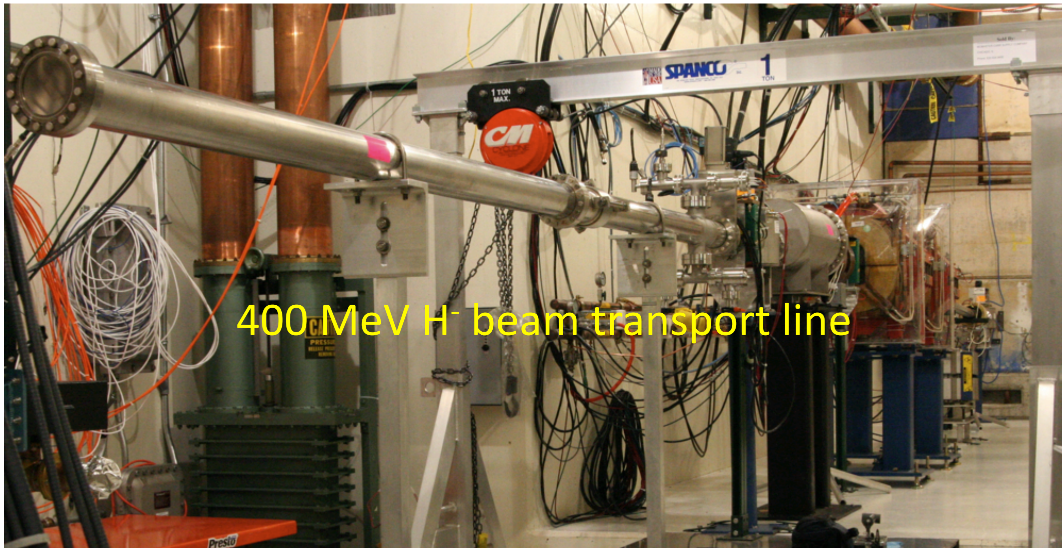
Supported for many years by the DOE HEP SBIR-STTR program

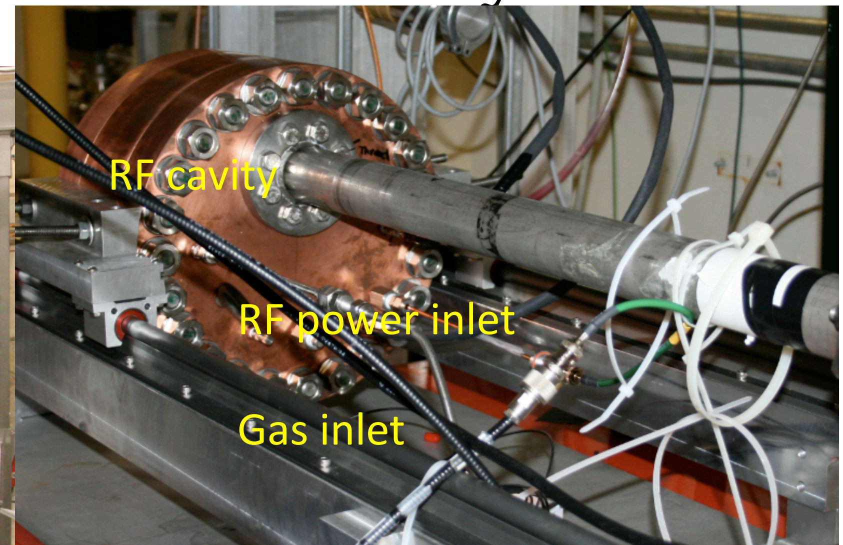
Muons, Inc.

APC

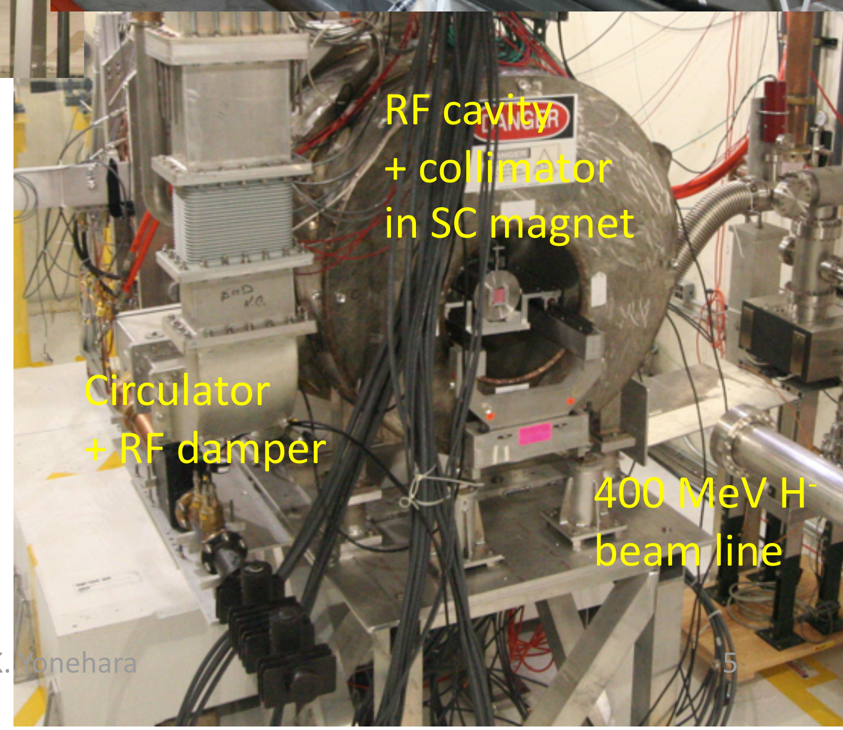
ILLINOIS INSTITUTE OF TECHNOLOGY

MTA beam line and HPRF cavity

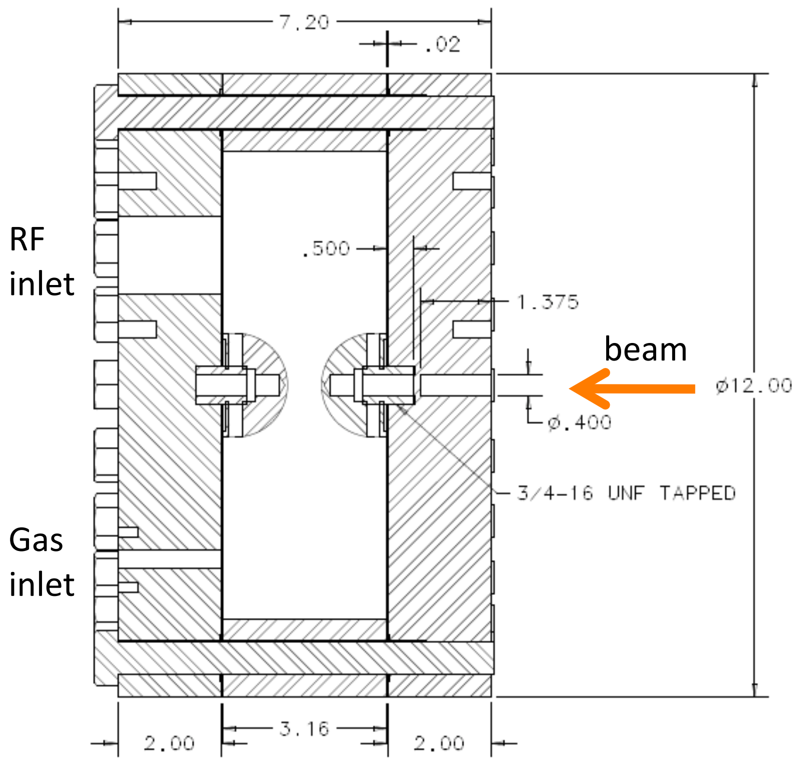


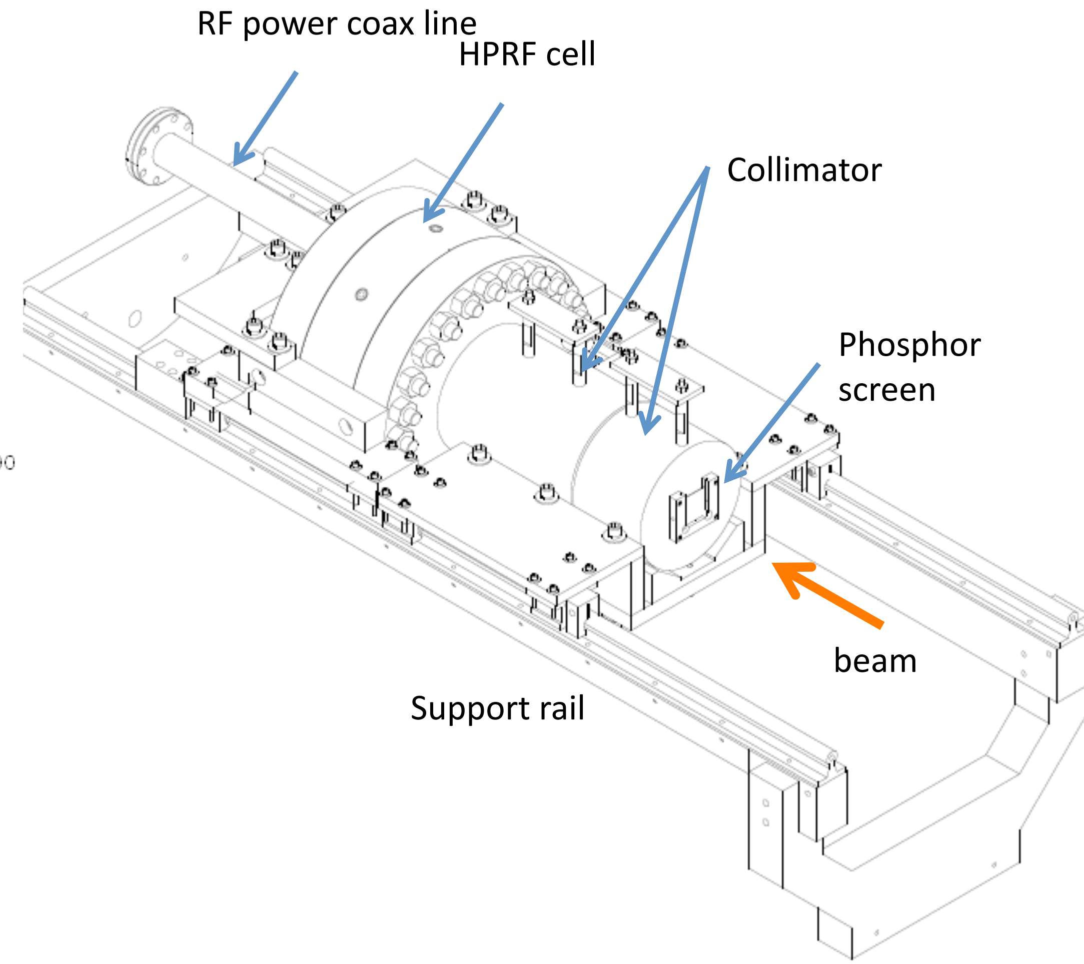


- 400 MeV H^- beam
- Beam pulse length 7.5 μs
- 5 ns bunch gap
- 10^9 H^-/bunch
- 20 % of transmission at the collimator system
- 2 10^8 protons/bunch passes through the cavity

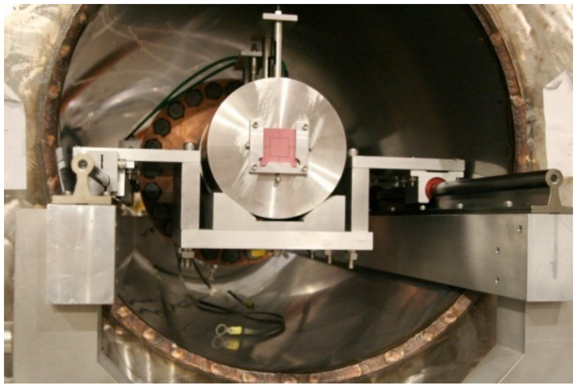


High pressure RF cavity & collimator

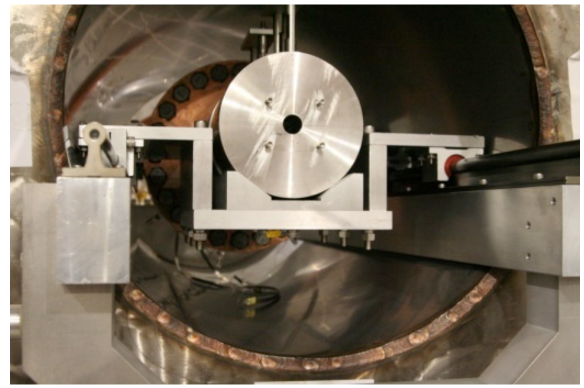




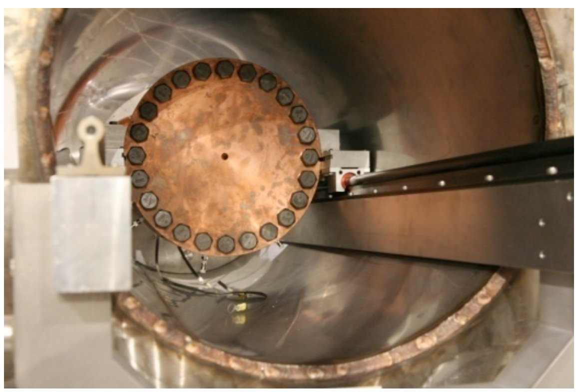
Assemble cavity, collimator, and toroid



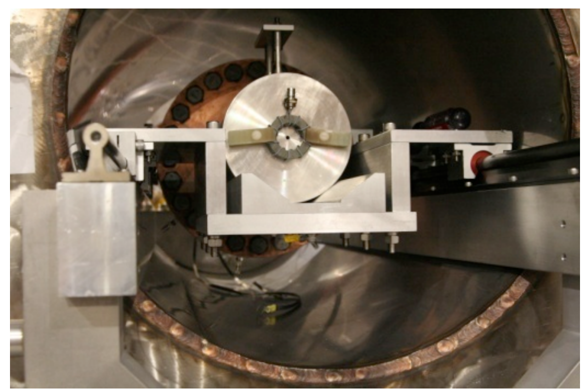
1^{st} Collimator & Chromox-6



1^{st} Collimator



HPRFCavity



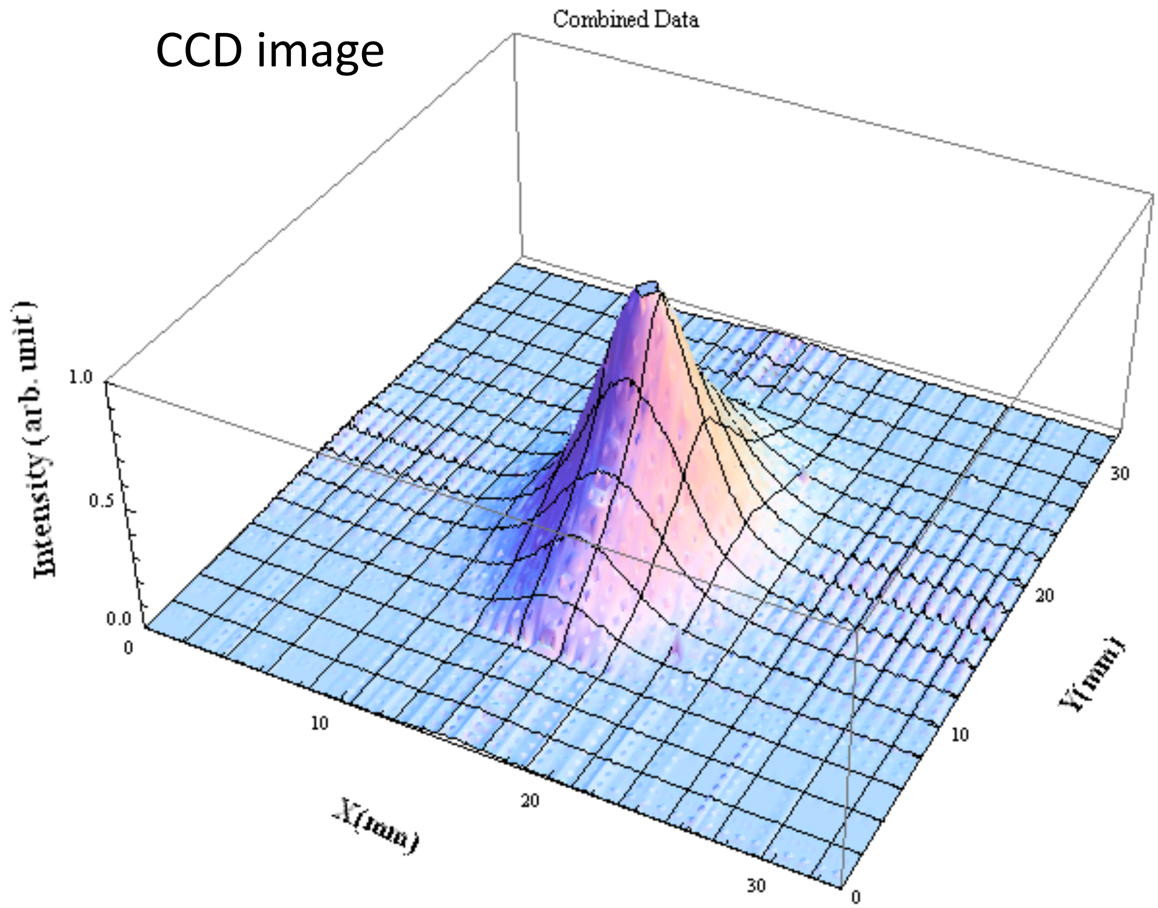
2^{nd} Collimator + Toroid

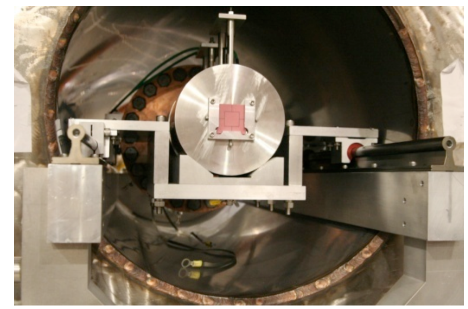
Beam profile monitor

Mukti

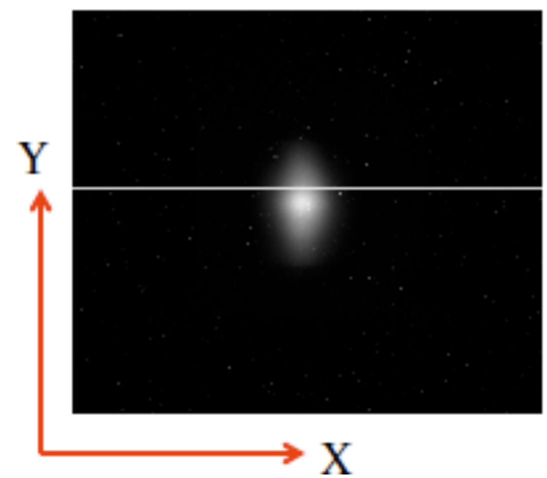
$\sigma_{horizontal,\,x}$ = 2.6 mm
$\sigma_{vertical,\,y}$ = 3.9 mm

CCD image



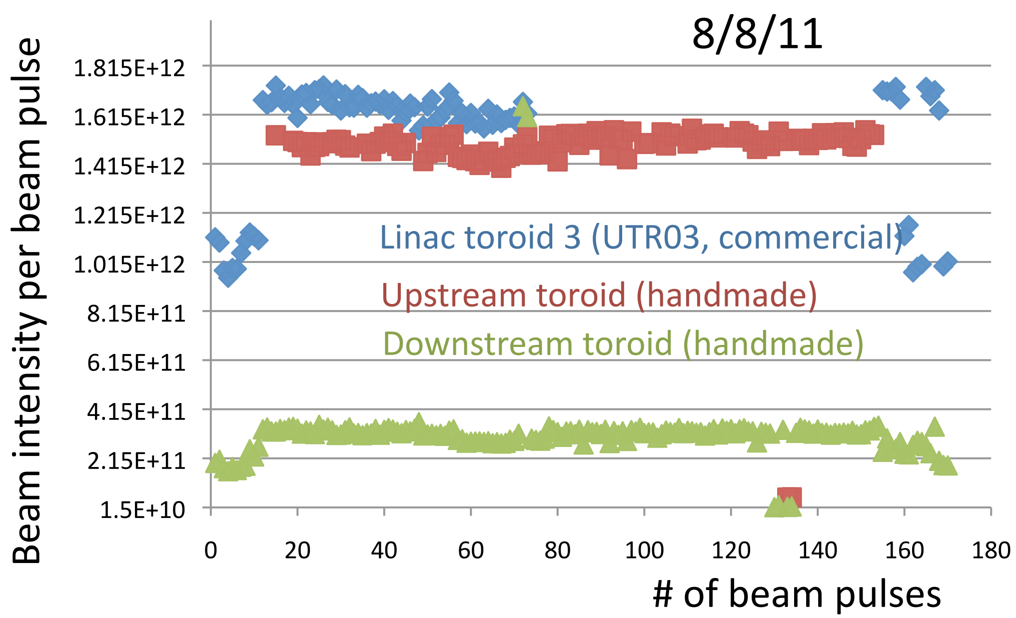


1st Collimator & Chromox-6

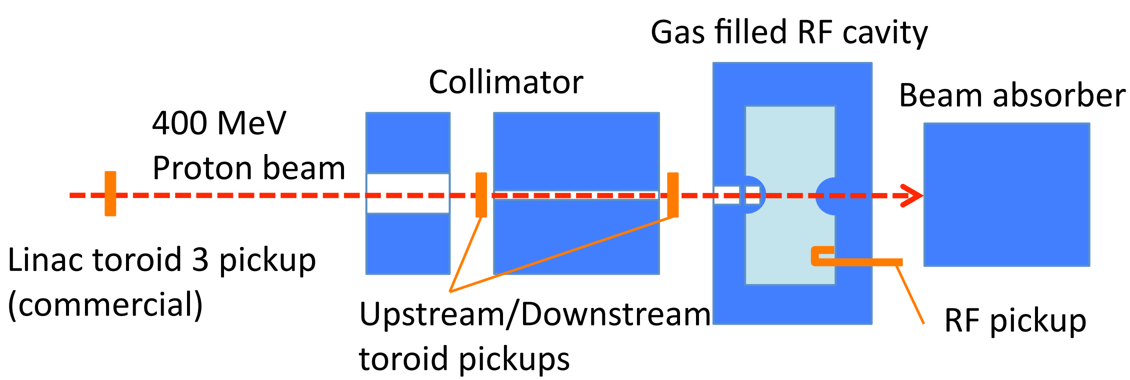


Observed beam intensity

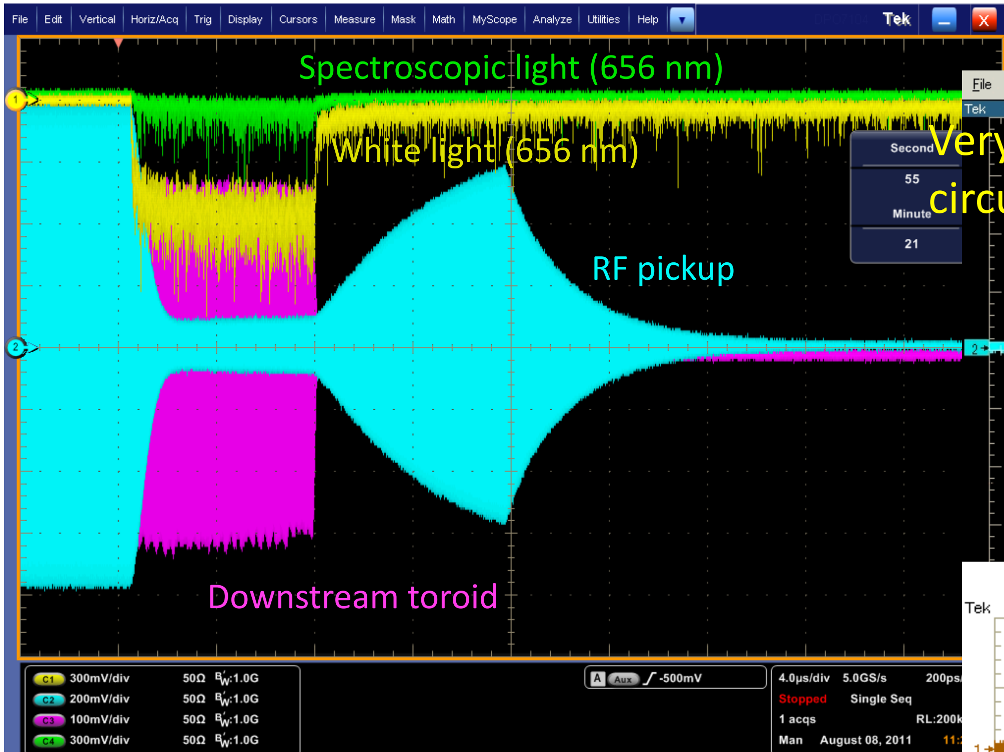
Ben Freemire

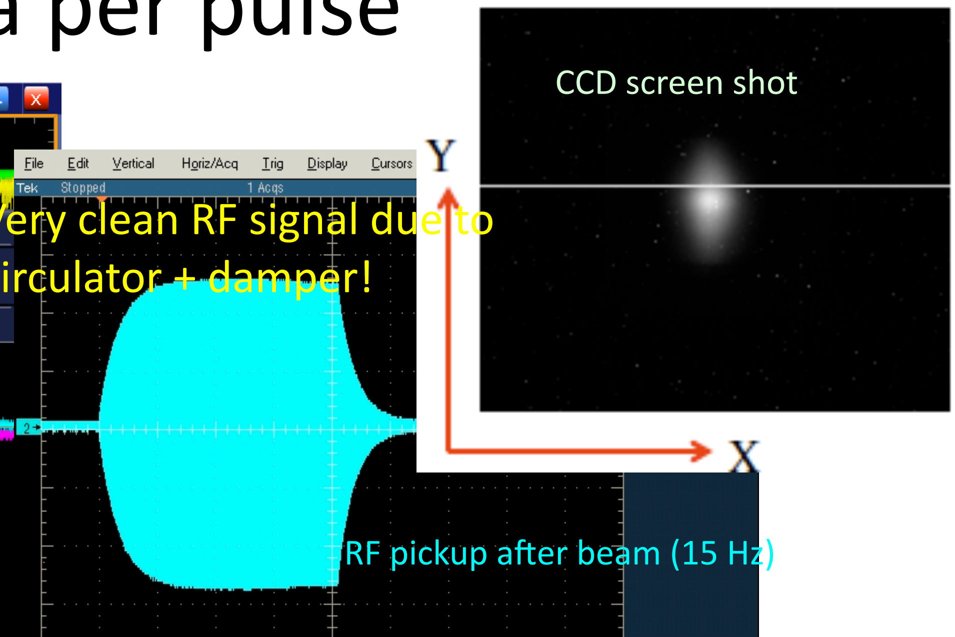


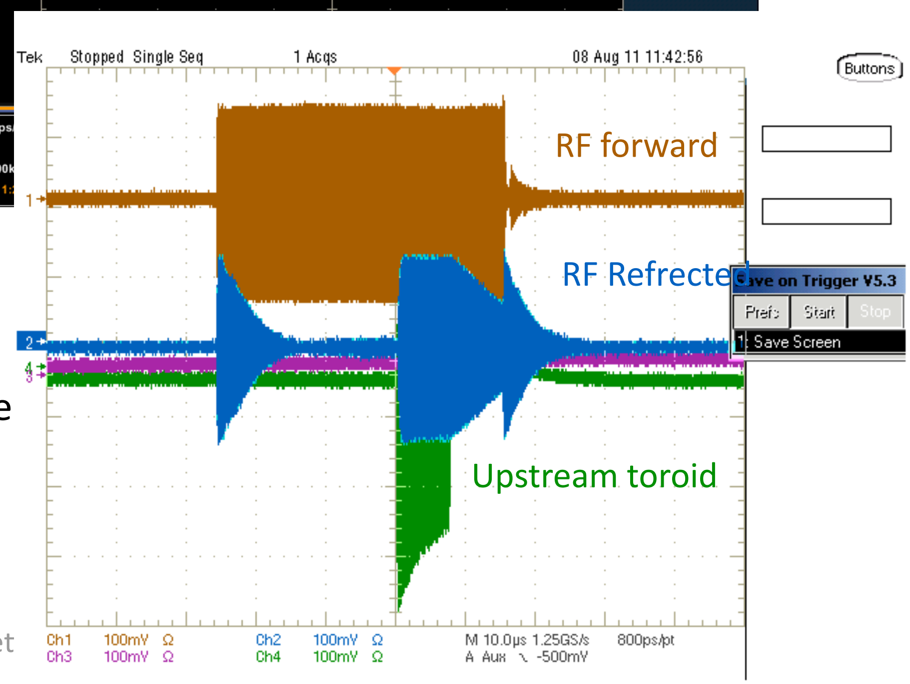
- Beam intensity is measured by a handmade toroid pickup coil
- Maximum transmission efficiency at the collimator (2mm$^{\phi}$) is 20 %.
- By tuning the upstream beam element, transmission efficiency goes down to 2 %.



Taken data per pulse







- Oscilloscopes are triggered by MTA beam signal
- CCD screen shot was taken by hand(!)
- We also monitored beam signal from a telescope counter

RF signals are cleaned by circulator + damper!

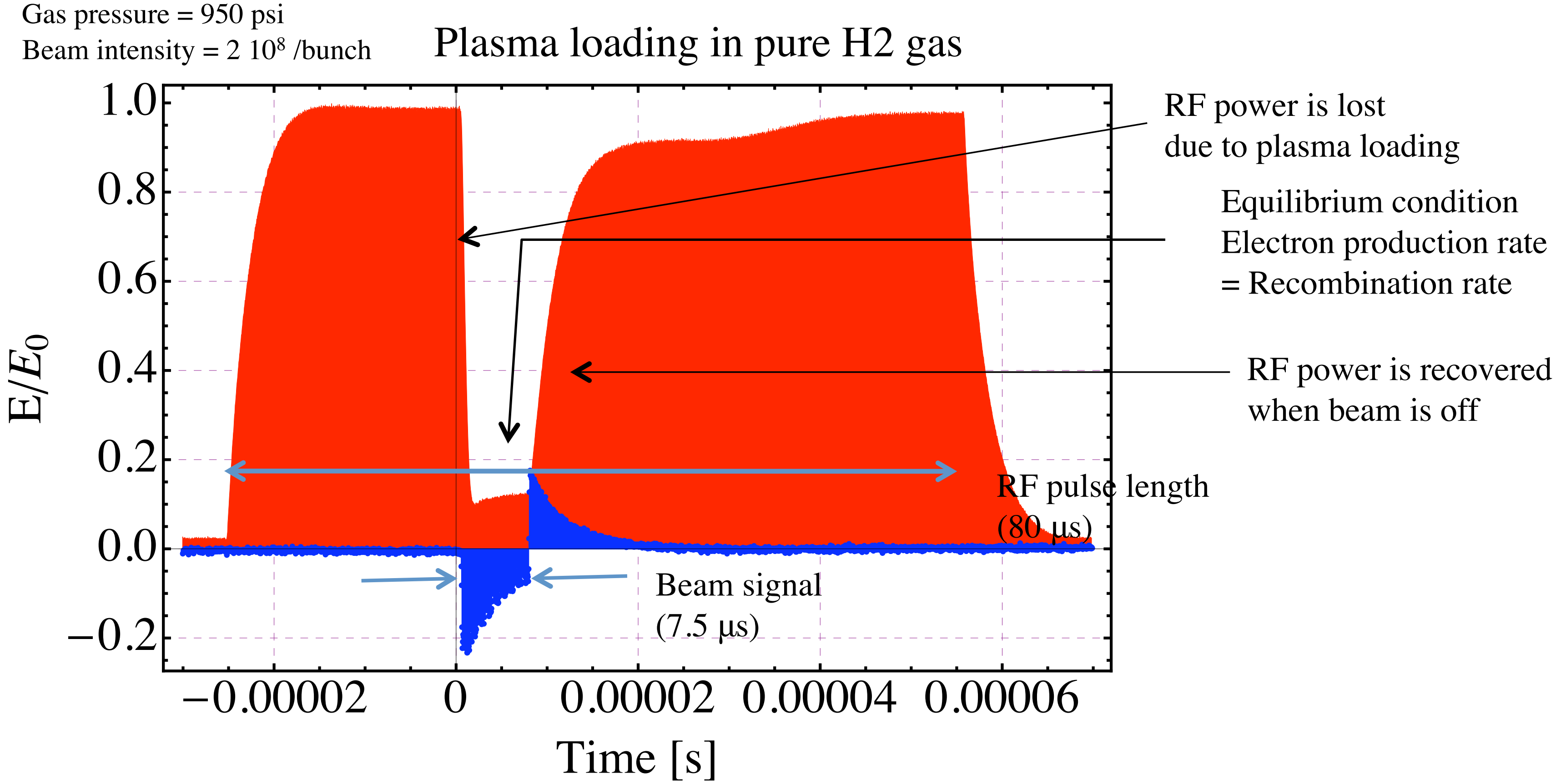
Run log

Date	Gas species	Pressure (psi)	Beam intensity[*1]
7/12	N2	500	High
7/14	H2	800	High
7/15	H2	950	High
7/19[*2]	H2	500	High
7/22	H2	500	High
7/25	H2	800	Low
7/27	H2	500, 800, 950	Medium
8/08	H2 H2+N2 H2+SF6	950 950[*3] 500, 800, 950[*3]	High

*1: "High" = 20 %, "Medium" = 7 %, "Low" = 2 % of transmission efficiency
*2: RF pickup probe was broken
*3: Concentration is 0.01 % at GH2 pressure 950 psi

Study interaction of intense beam with dense H2 in high gradient RF field

ν= 802 MHz
Gas pressure = 950 psi
Beam intensity = 2 10^8 /bunch

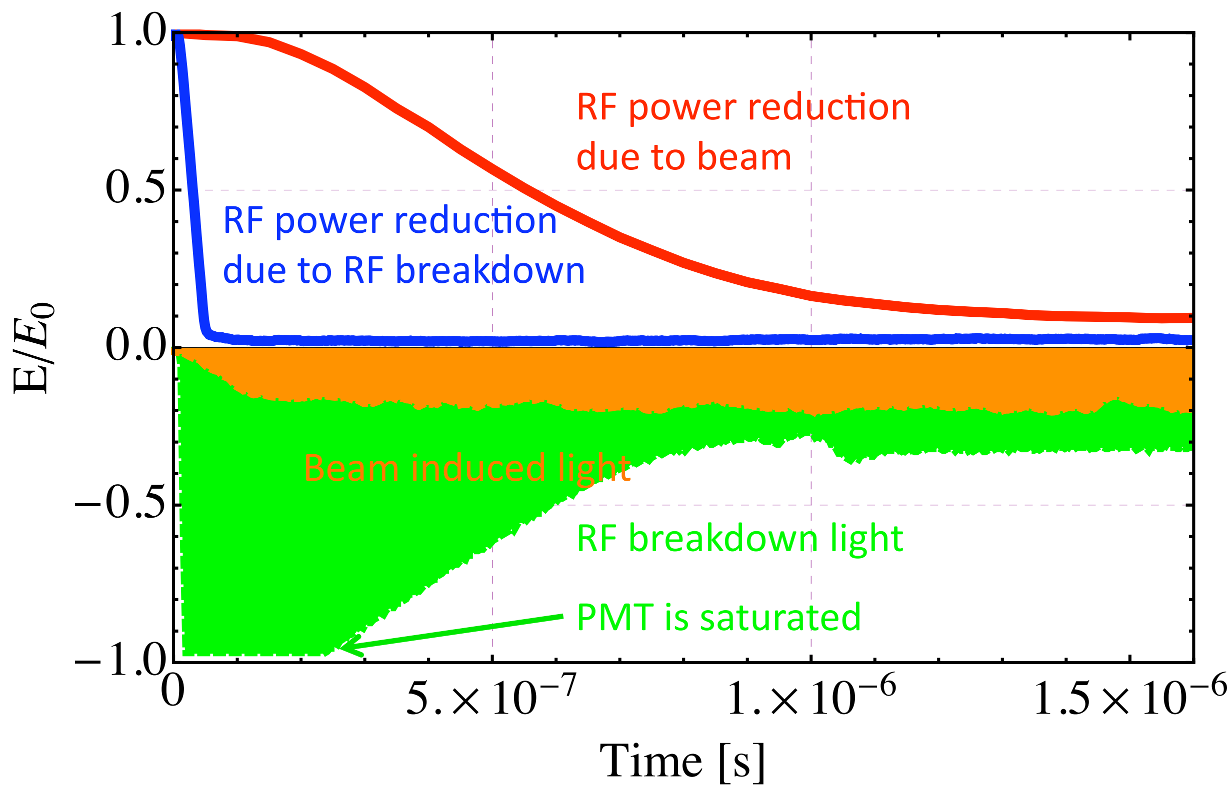


Ionization process

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

1,200 e^-/cm are generated by incident p @ K = 400 MeV

Compare with breakdown event



RF pickup and optical signals are quite different from these at the breakdown event

N_e in beam induced plasma = 10^{14} electrons/cm^3

N_e in breakdown plasma = 10^{19} electrons/cm^3

Model of RF power deposition per ionized electron

Alvin

Electron mobility in GH2

$$\mu(x) = 1.72 \times 10^{-2} \left(1 - 2.4 \times 10^{-2} x^{0.71}\right)^{-1.75} x^{-0.53}$$

$$x = E/p \quad \text{[V/cm/mmHg]}$$

$$v(x) = 5.93 \times 10^{7} \mu(x) x \quad \text{[cm/sec]}$$

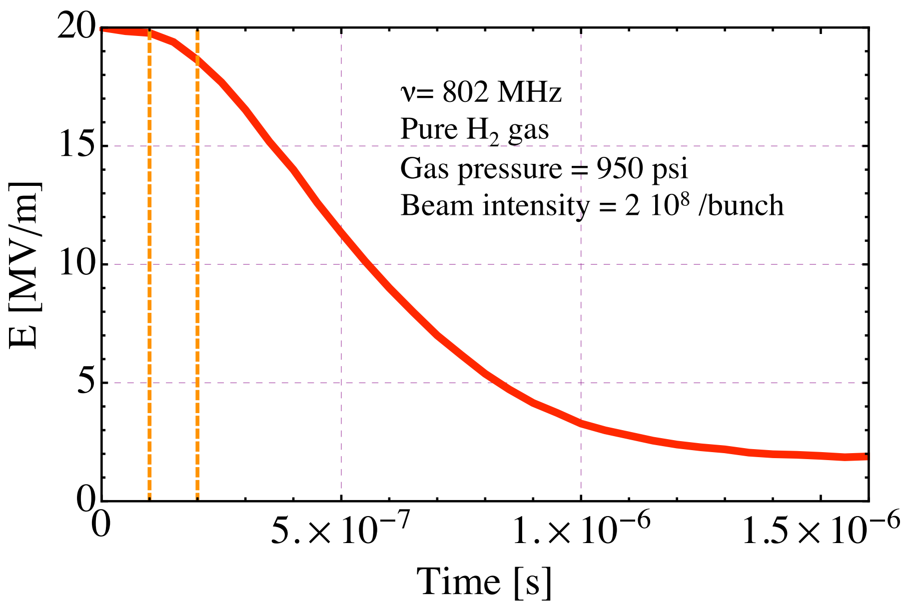
Power absorption of electron

$$dw = \int_0^{T_0} e E_0 Sin(\omega t) v(x,t) dt$$

For example, E_0 = 20 MV/m, GH2 pressure = 950 psi

$$dw = 4.9 \times 10^{-17} \quad \text{[Joules/electron/cycle/cm]}$$

Preliminary estimation of plasma loading effect in HPRF cavity for cooling channel



From RF amplitude reduction rate, RF power consumption by plasma can be estimated

$$\delta E = C V \delta V$$

$$= 4.2 \times 10^{-4}$$ Joules/RF cycle @ E = 20 MV/m

$$n_e = 6 \times 10^{12}$$ electrons@ t = 200 ns

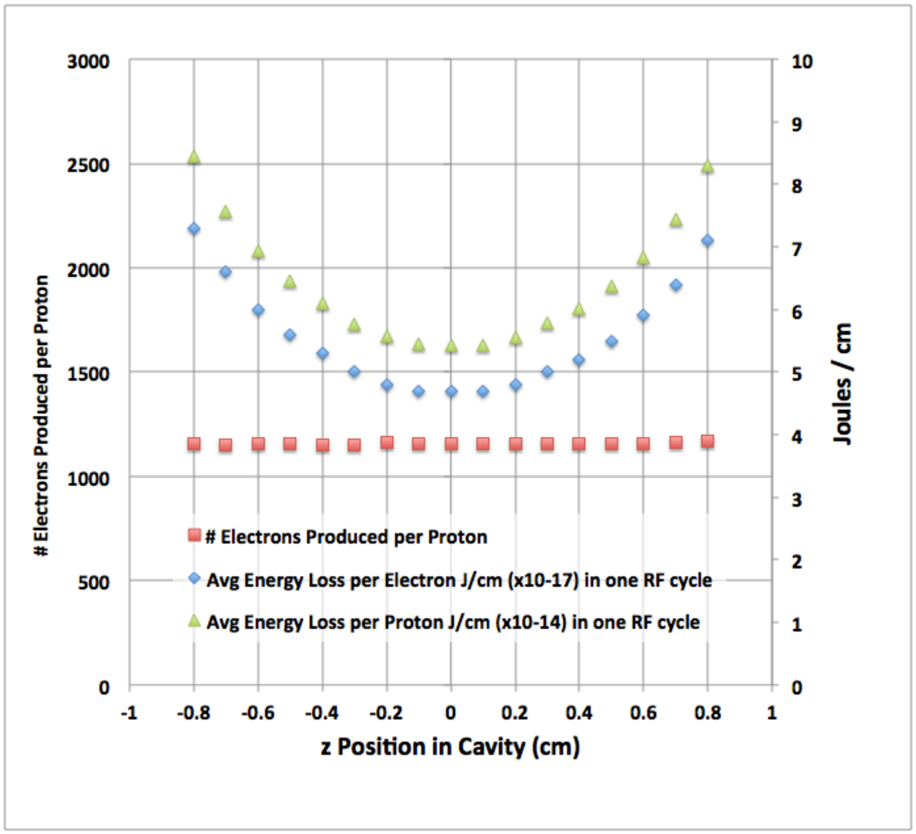
Hence, energy consumption by one electron is (including with initial beam intensity change)

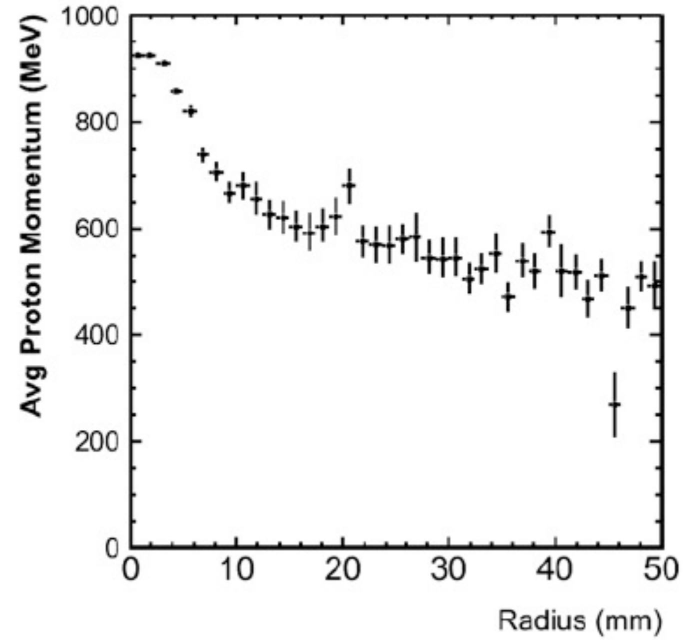
$$= 4.1 \times 10^{-17}$$ Joules/RF cycle/e/cm

Both experimental result and model are excellent agreement within 20 %

Estimate the number of ionized electron in the cavity from G4beamline simulation

Tom Schwarz

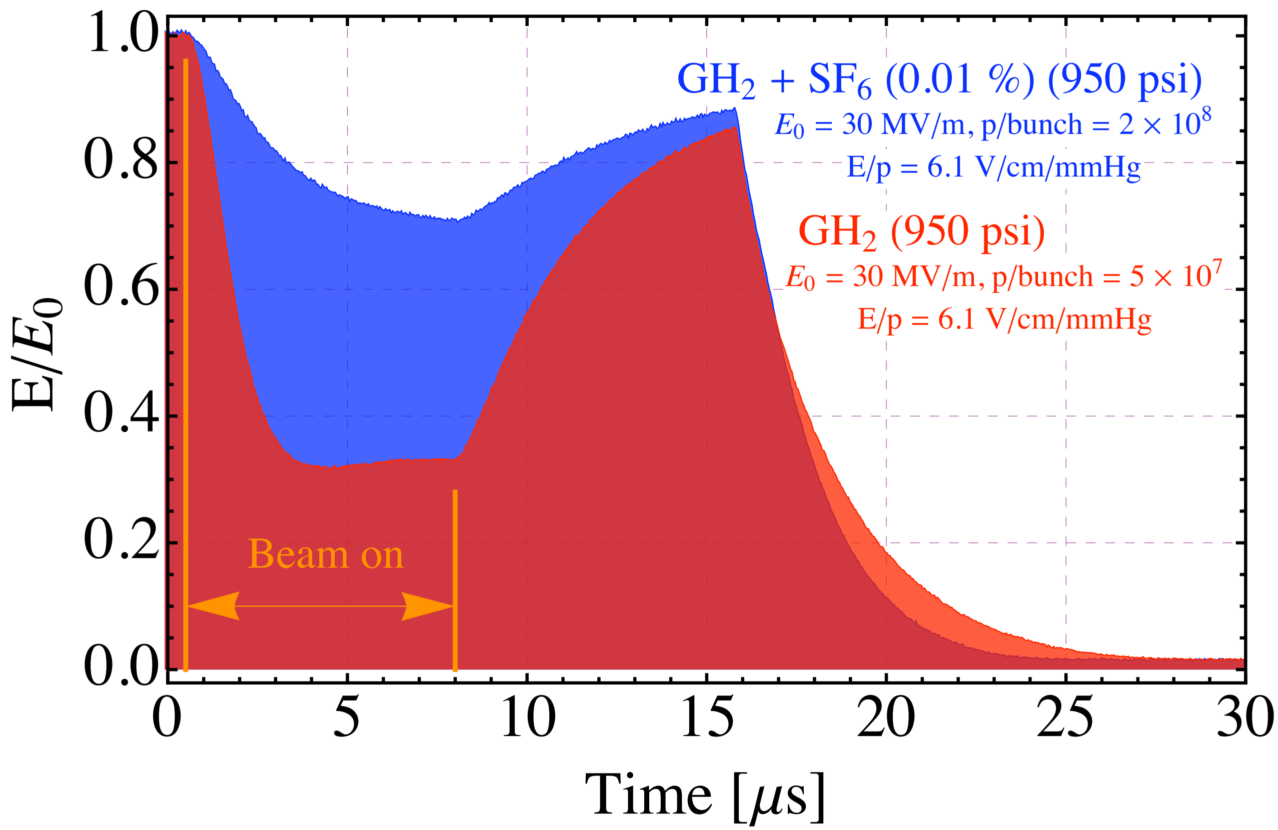




Proton momentum distribution as a function of radial position in the cavity is taken into account

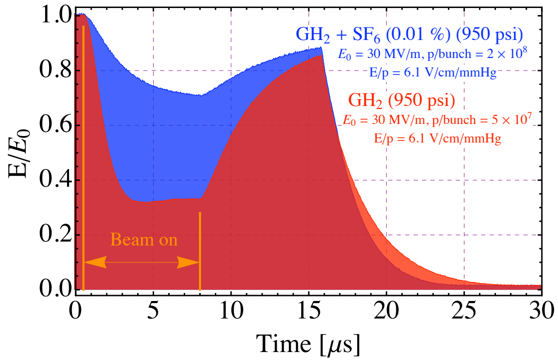
Estimated # of ionized electrons per proton ~ 1200 e/cm

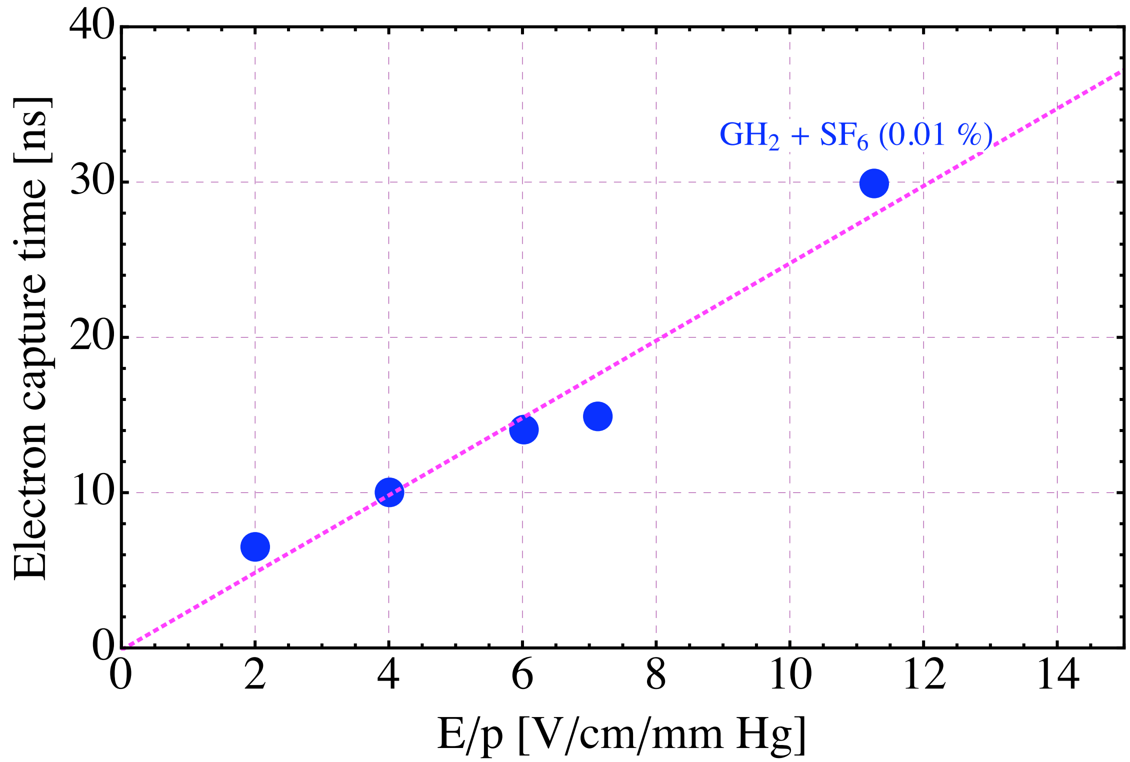
Study electronegative gas effect



SF6 removes residual electrons

Electron capture time in dopant

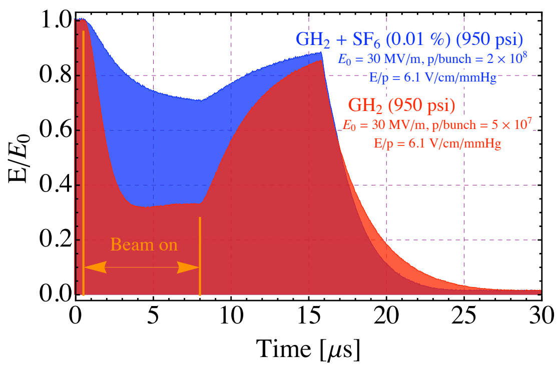


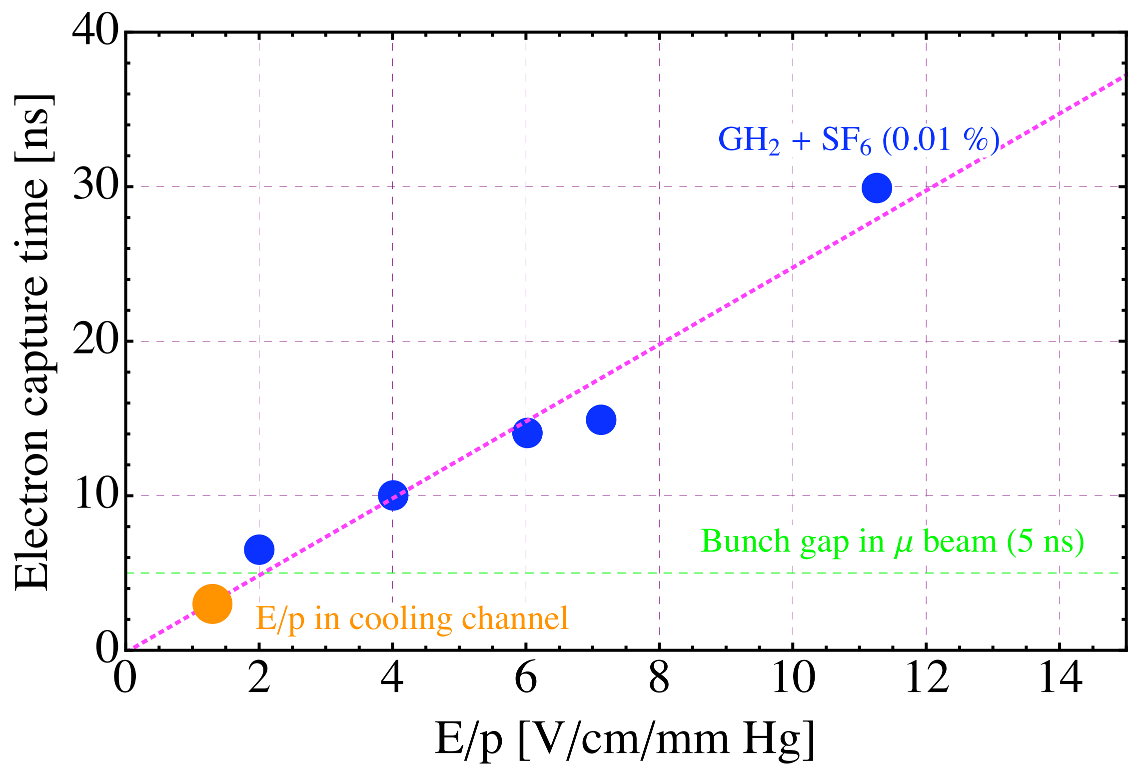


$$\text{Electron capture rate} = \frac{\text{\# of yield electrons by proton beam per second}}{\text{\# of electrons in the cavity at equilibrium RF signal}}$$

It is NOT a 1/e time constant

Compare with muon beam structure





- E/p in helical 6D cooling channel is 1.6 V/cm/mm Hg
- Electron capture time is fast enough to hold an E field in the cavity

Radiation length in GH2 with 0.01 % SF6

Based on PDG

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

In case of SF6

$$X_0 = 5.96$$ [g/cm²] @ 1 atm

Mixture gas

$$\frac{1}{X_0} = \sum_j \frac{\omega_j}{X_j}$$

ω_j: fraction by weight

$$X_0 = 34.9$$ [m] 200 atm GH2 with 0.01 % SF6

10 % shorter than that in a pure GH2

$$X_0 = 37.6$$ [m] 200 atm GH2

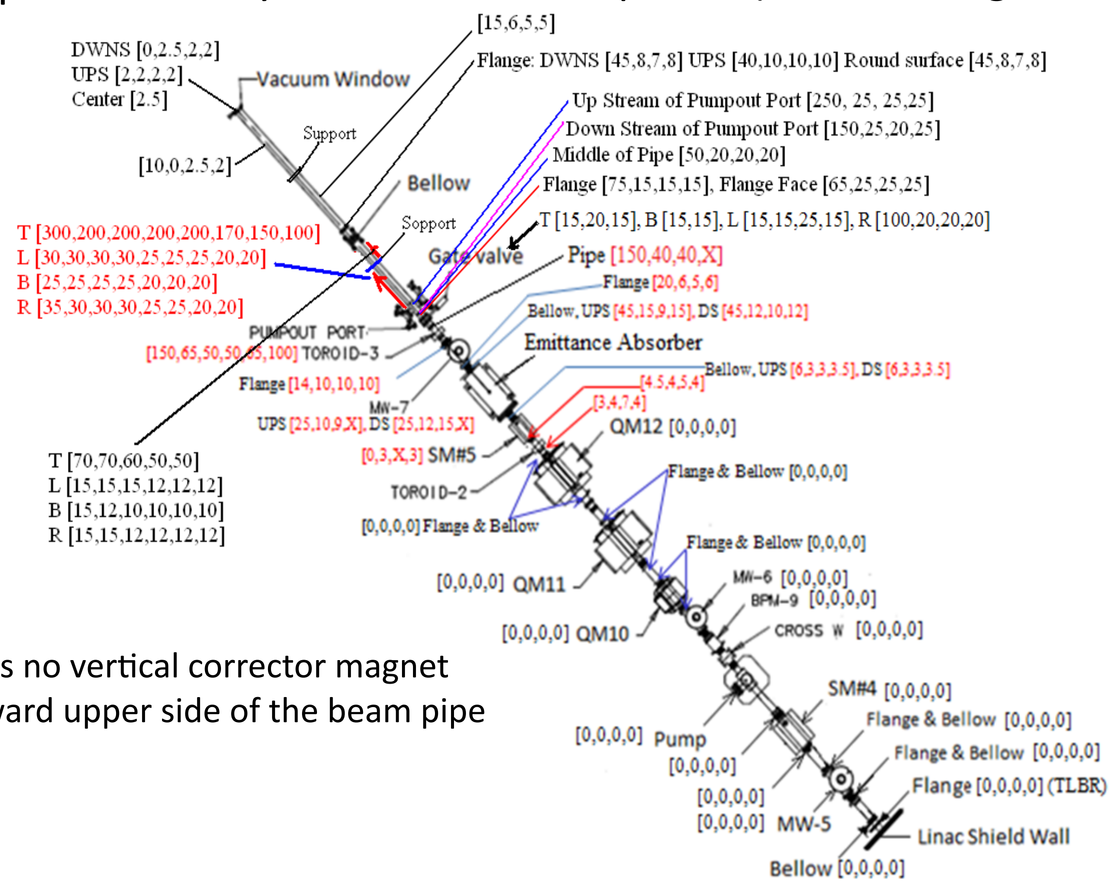
(Near) future plan

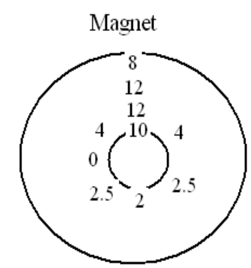
- Run HPRF cavity with denser gas condition
  - Presently, the maximum pressure is limited up to 1000 psi
  - Ramp up the maximum pressure up to 1600 psi
- Study more electronegative gas
  - F_2 and O_2 are a very attractive electronegative gas
  - Lowest Flammable Limit of O_2 in GH_2 is 7 %
  - It is possible to mix O_2 in GH_2 with a reliable gas monitor system
- Re-take HPRF cavity in a strong magnetic field
  - $E \times B$ force will induce a plasma instability that will break dense plasma condition in the cavity

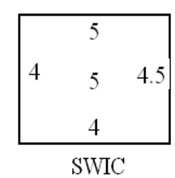
Survey residual radiation dose level

Mukti

Observed residual dose level at the MTA beam line (on contact)
One day after ~200 beam pulses (beam tuning test at 3/25/11)







Note: There was no vertical corrector magnet
Beam went toward upper side of the beam pipe

Conclusion

- First beam test has been done
- Energy deposition of single electron from RF power is 4.9 10^{-17} Joules/RF cycle/e/cm at E = 20 MV/m
- So far, we do not see any crucial problems (show stopper) of practicality of HPRF cavity for cooling channel
- Denser gas makes better RF recovery in pure GH2 condition (analysis is still underway)
- Electronegative gas works extremely well
- Need to investigate more electronegative gases
- Plan to have another beam test
  - B field effect
  - Real pillbox cavity