Progress of High Pressure Hydrogen Gas Filled RF Cavity Test

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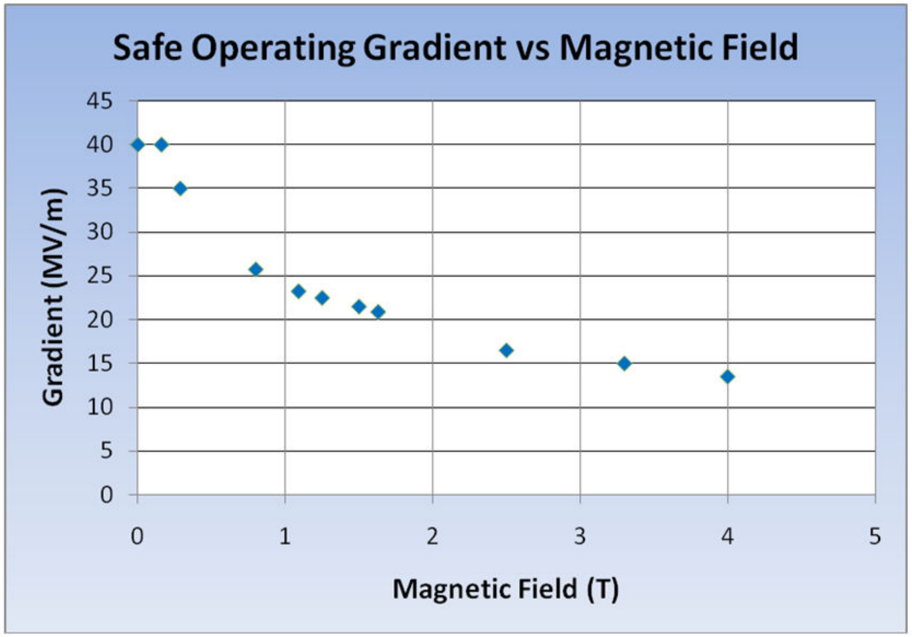
Advantage of using high pressure hydrogen gas

Challenge in MAP RF program



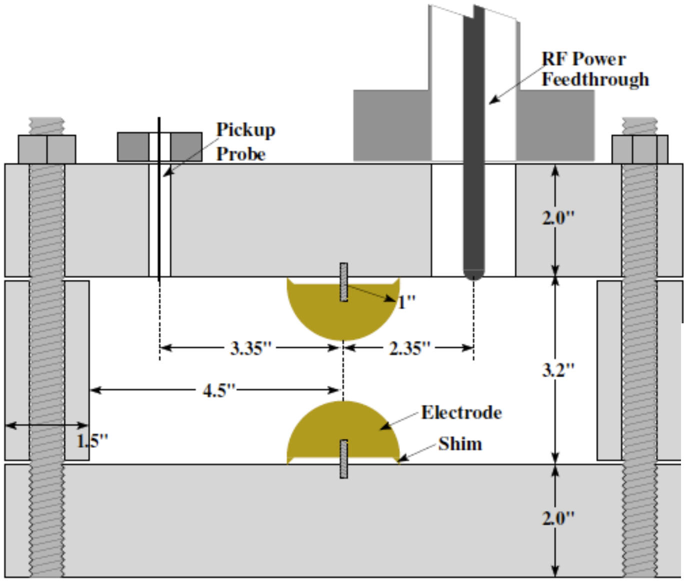
We have a problem to operate RF cavities under strong magnetic fields in ionization cooling channels

Field emission electron plays an important role to induce RF breakdown although the breakdown mechanism is not fully understood yet

By filling RF cavity with dense hydrogen gas, field emission electron has a short mean free path in the cavity and breakdown probability is greatly reduced

R.P. Johnson and D.M. Kaplan, MuCoolNote0195

Historic result in high pressure RF cavity



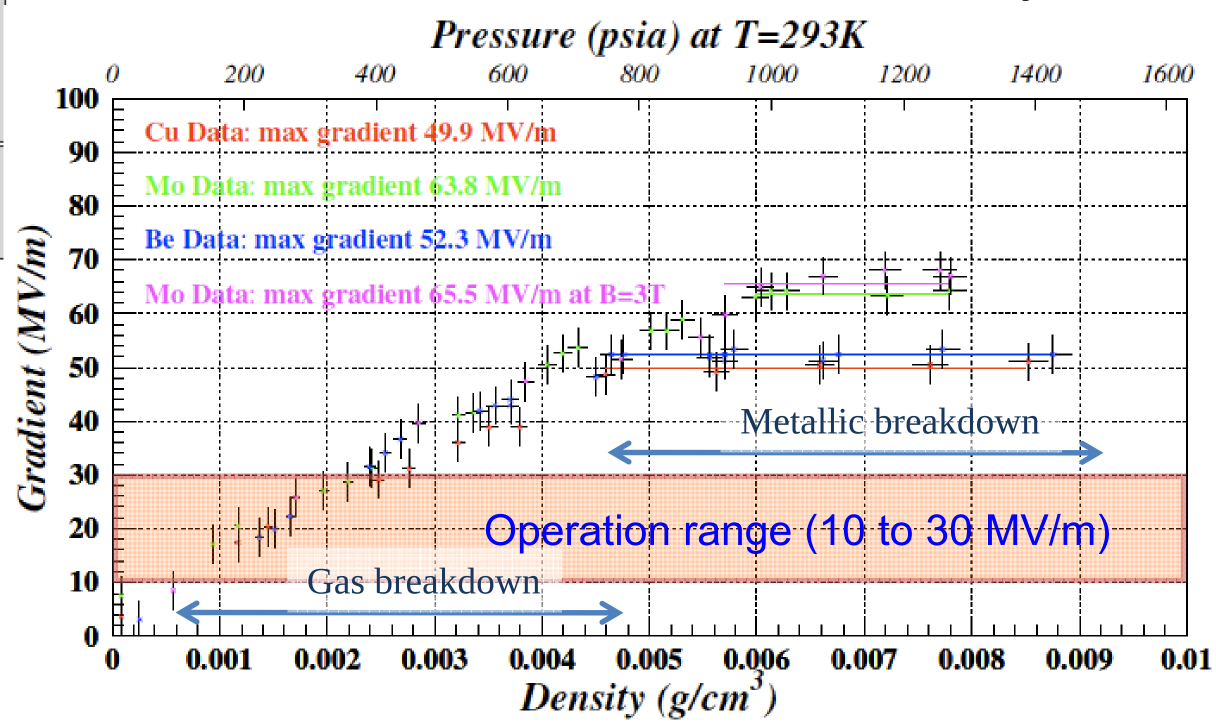
Schematic view of HPRF cavity

Gas breakdown:
- Linear dependence
- Governed by electron mean free path

Metallic breakdown:
- Plateau
- Depend on electrode material
- No detail study have been made yet

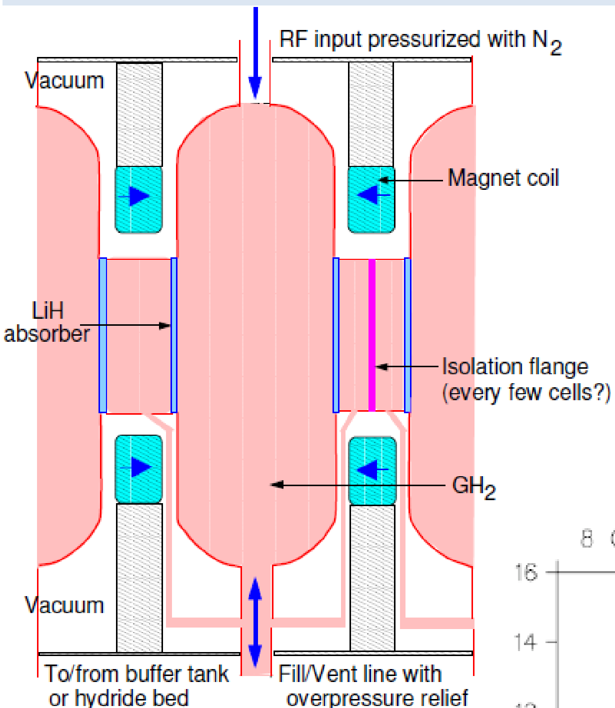
High Pressure RF (HPRF) cavity has been successfully operated in strong magnetic fields

Maximum electric field in HPRF cavity



P. Hanlet et al., Proceedings of EPAC'06, TUPCH147

Apply HPRF cavity in front end channel

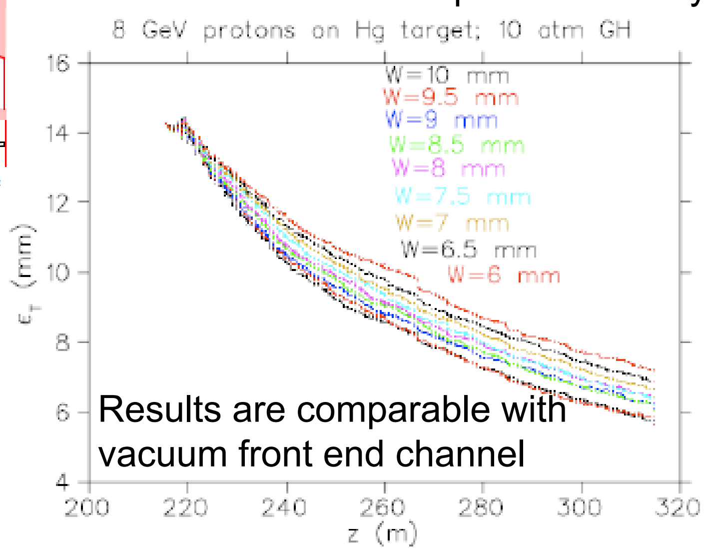


Schematic drawing of HPRF cavity in frontend pre-cooler channel

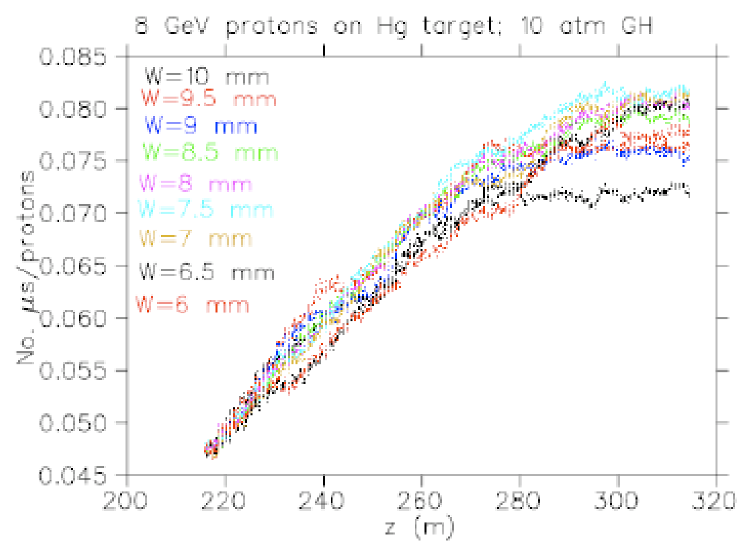
- Dense hydrogen gas can be used as an ideal buffer to suppress breakdown and also be used as an ionization cooling absorber
- GH2 cools down RF windows

Simulation of muon emittance in hybrid front end channel

Hybrid: LiH (various widths (6~10 mm) in simulation)
+ 10 atm GH_2
Be pressure safety window is included

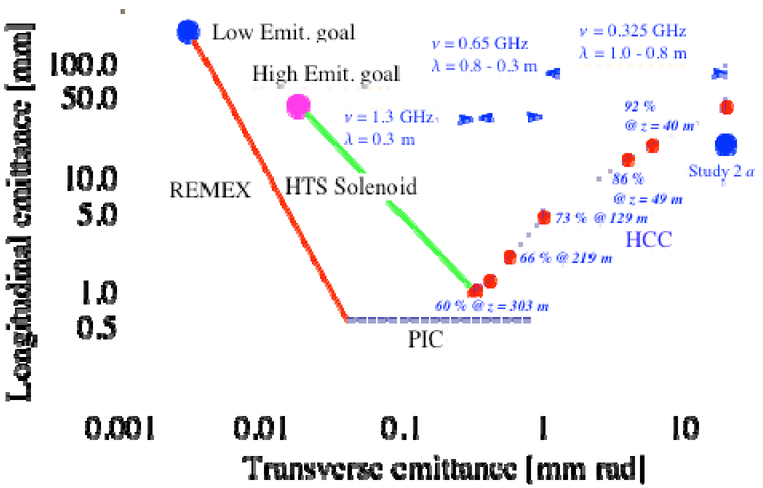


Results are comparable with vacuum front end channel



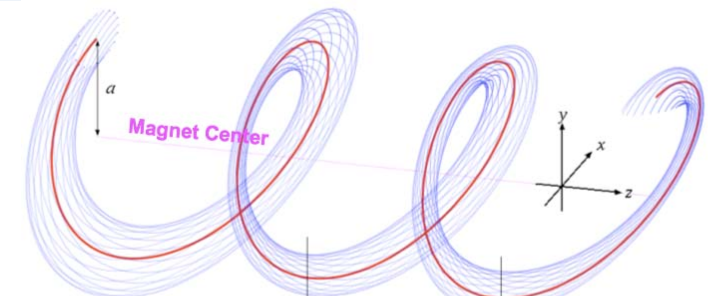
J.C. Gallardo & M.S. Zisman et al., Proceedings of IPAC’10, WEPE074

Apply to Helical 6D Cooling Channel

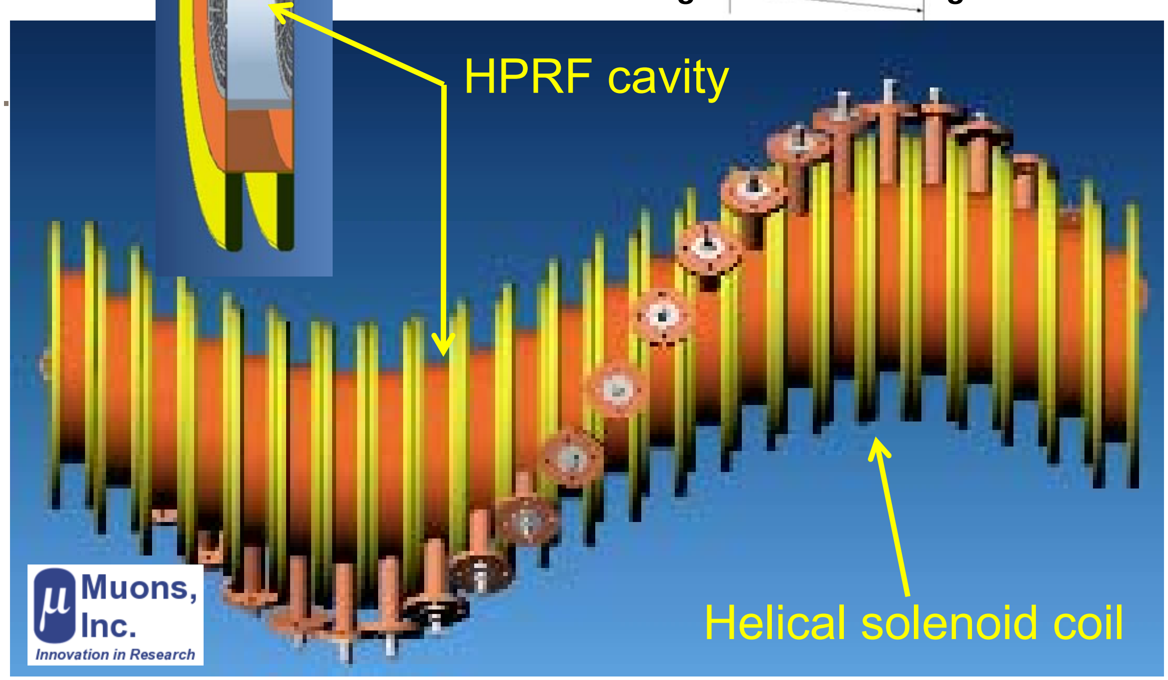


Simulation of muon emittance evolution in helical cooling channel

- Apply HPRF cavity (p = 200 atm) in helical 6D cooling channel
- 6D cooling factor > 10^5 in 300 m
- Transmission efficiency 60 %



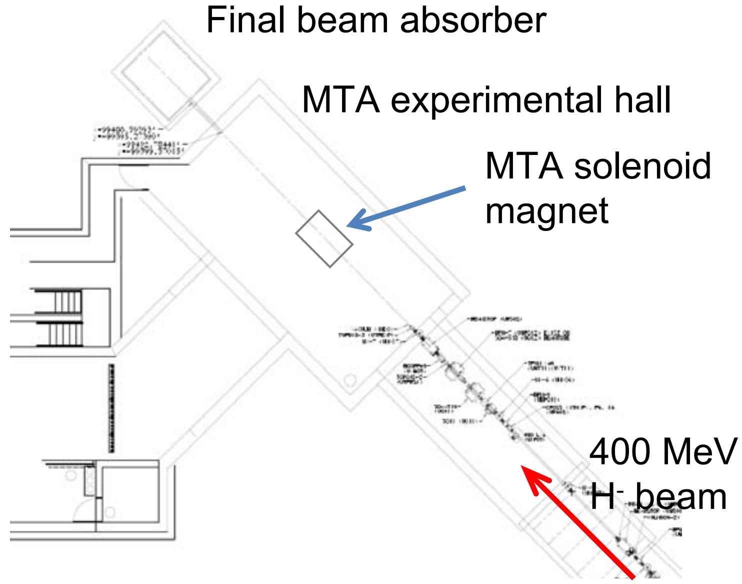
Particle tracking in helical cooling channel



CAD drawing of helical cooling channel

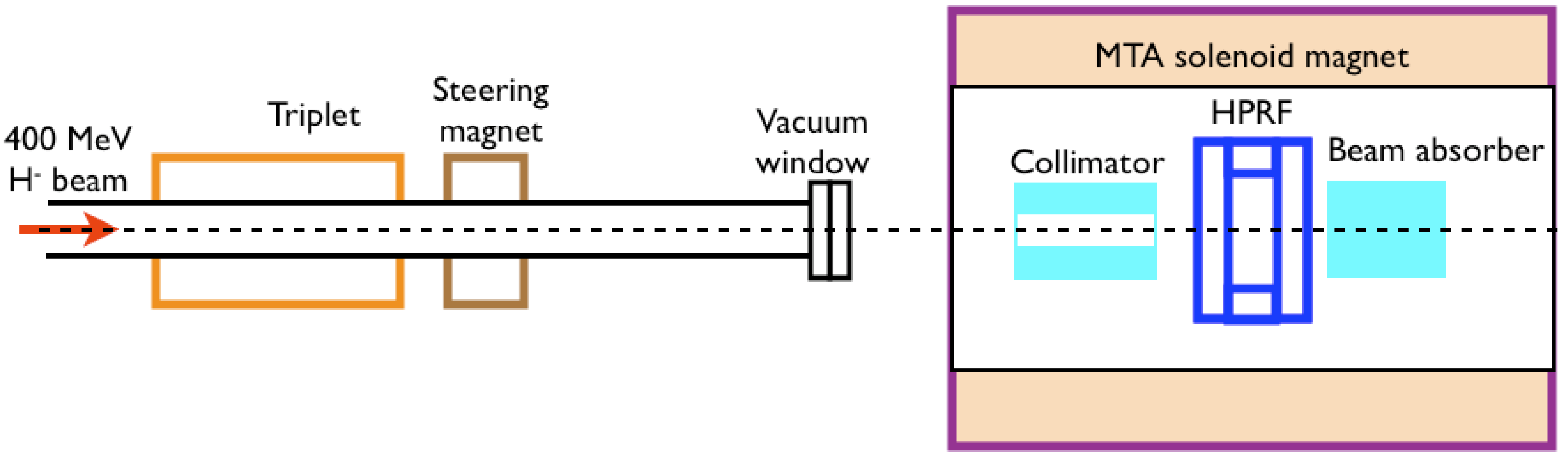
K. Yonehara et al., Proceedings of IPAC'10, MOPD076

HPRF beam test: MTA Beam line



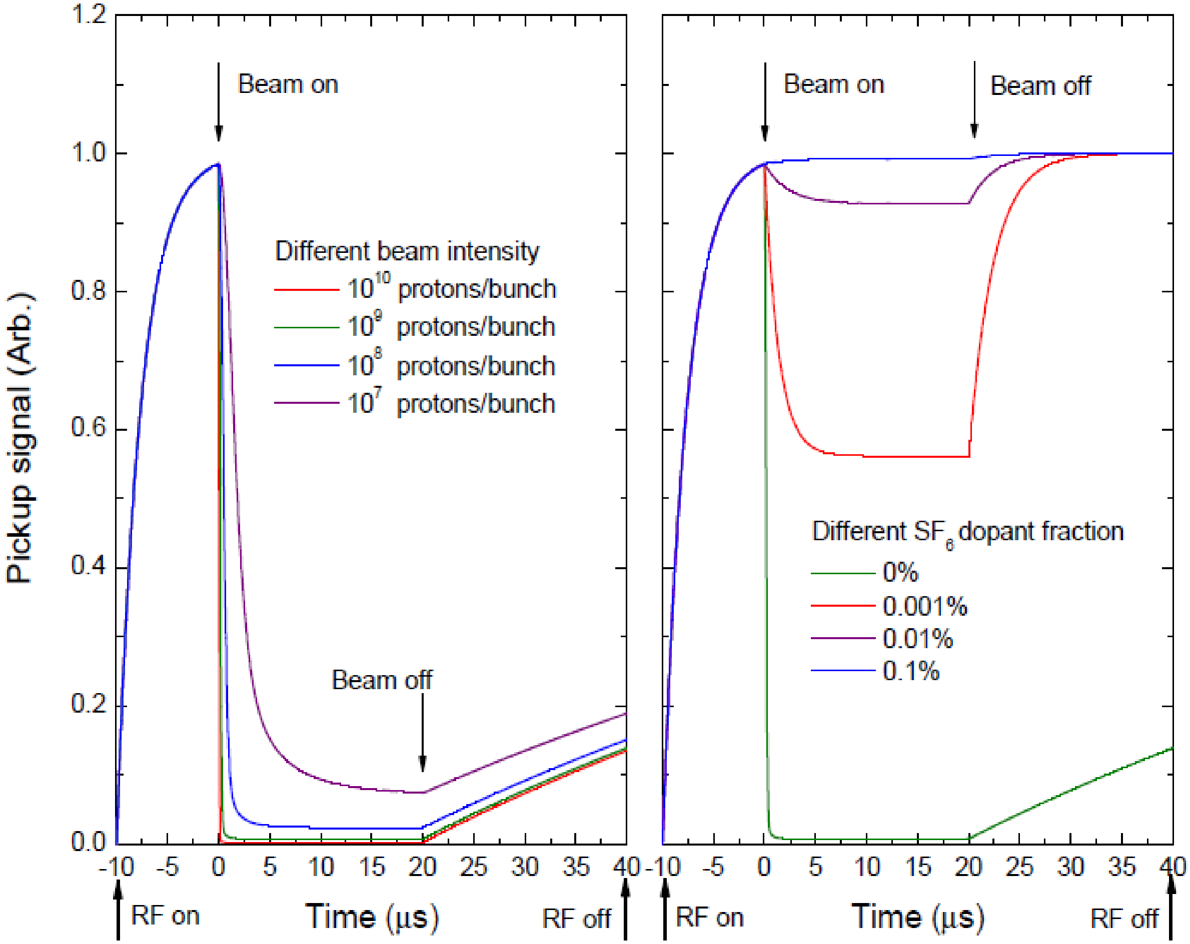
Beam profile

- Deliver 400 MeV protons in the MTA exp. hall
- 10^{12} to 10^{13} protons/pulse
- Tune beam intensity by collimator and triplet (reduce factor 1/10)



Possible problem: Beam loading effect in HPRF cavity

Simulated RF pickup signal in HPRF cavity with high intensity proton beam passing though the cavity



M. Chung et al., Proceedings of IPAC'10, WEPE067

Beam loading effect:

- Beam-induced ionized-electrons are produced and shaken by RF field and consume large amount of RF power
- Such a loading effect was estimated as a function of beam intensity
- Recombination rate, 10^{-8} cm^3/s are chosen for this simulation

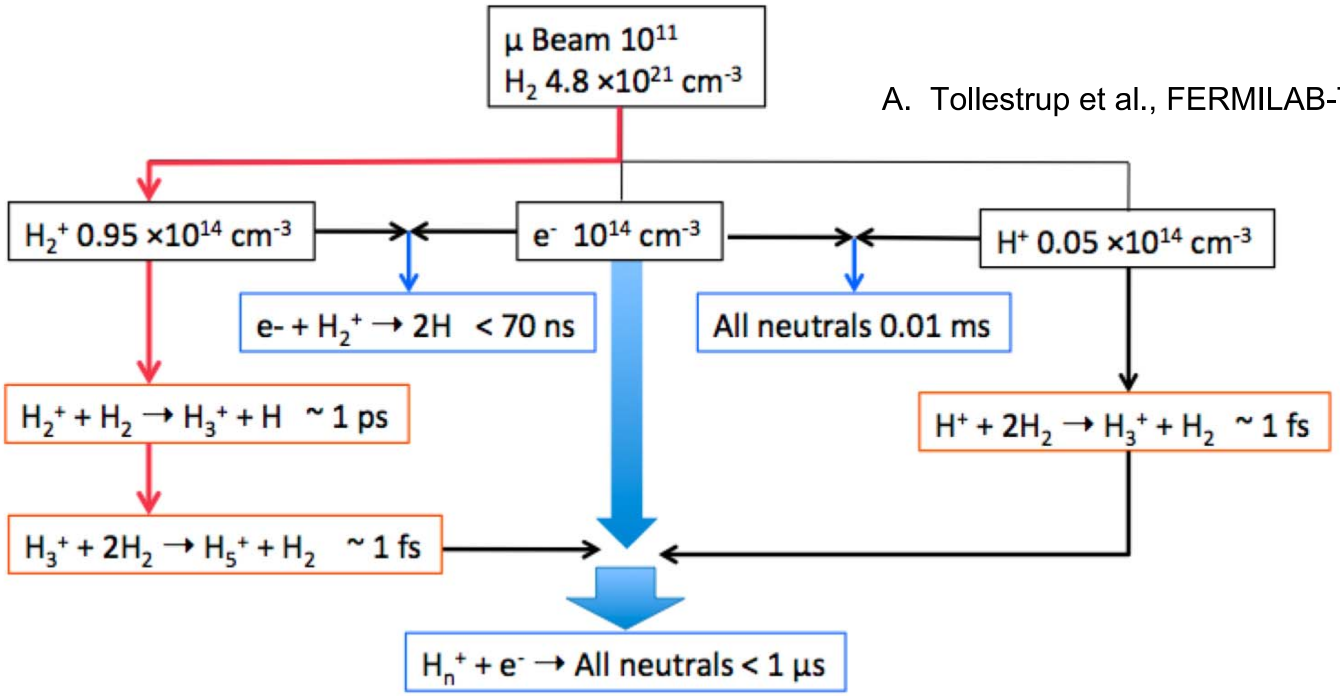
Scientific goals:

RF field must be recovered in few nano seconds

- Measure RF Q reduction to test beam loading model
- Study recombination process in pure hydrogen gas
- Study attachment process with electronegative dopant gas
- Study how long does heavy ions become remain in the cavity

Recombination in pure GH2: Polyatomic hydrogen

A. Tollestrup et al., FERMILAB-TM-2430-APC

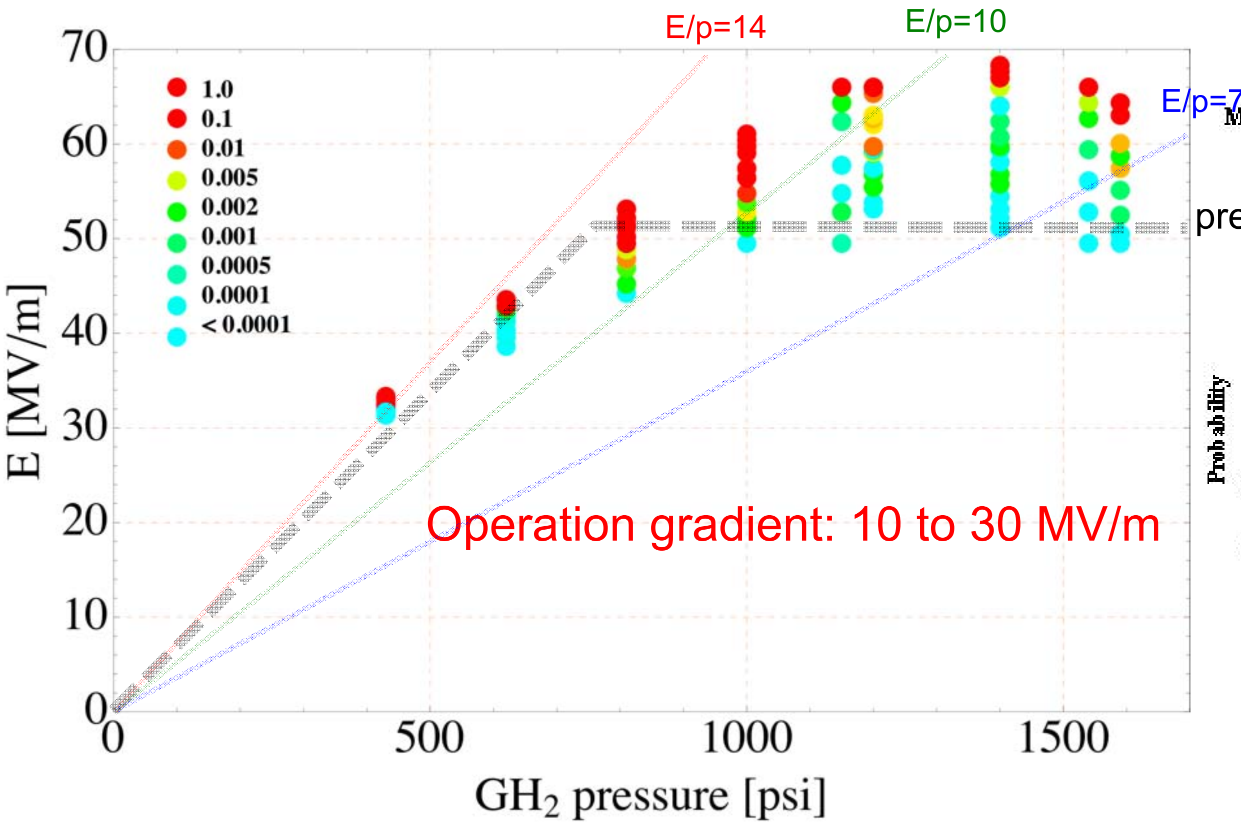


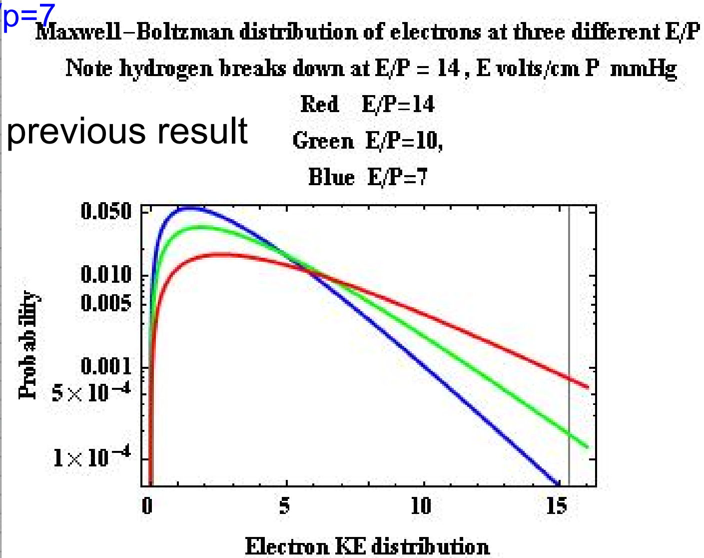
Hydrogen ion chemistry

Polyatomic hydrogen cluster:

- H_n^+ are formed from H_2^+ and H^+ in very short time
- Recombination of H_n^+ is < 1 μs that has been observed in dilute condition
- No measurement has been done in dense hydrogen environment
- Careful RF Q reduction measurement with beam (as shown in previous slide) will indicate recombination rate with polyatomic hydrogen cluster

Study breakdown in HPRF cavity: Breakdown probability



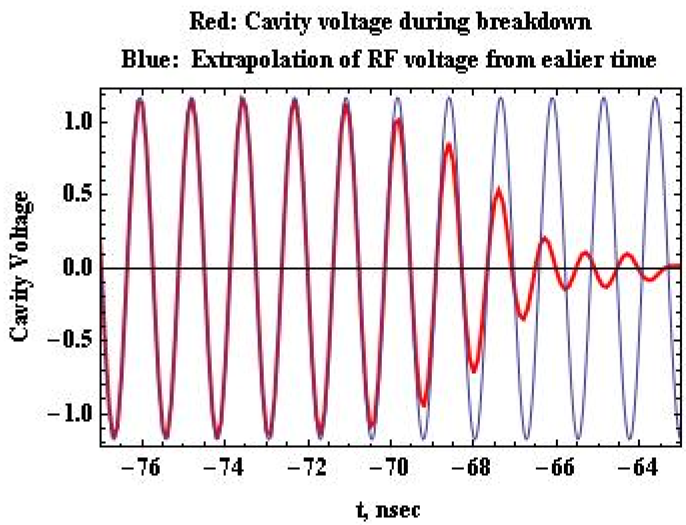


Breakdown probability around boundary

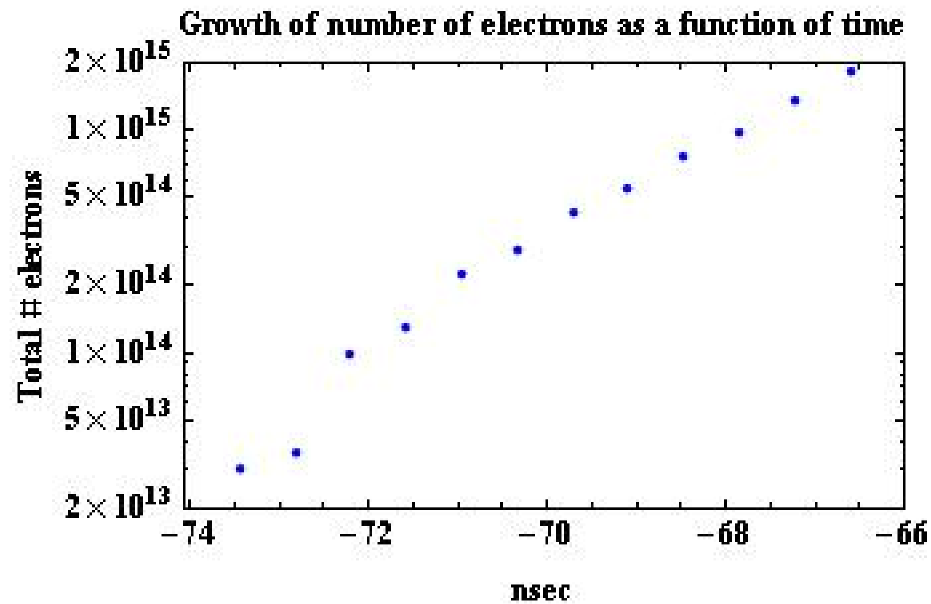
The data was systematically taken with copper electrodes

K. Yonehara et al., Proceedings of IPAC'10, WEPE069.

Study hydrogen plasma dynamics: Analyze RF pickup signal

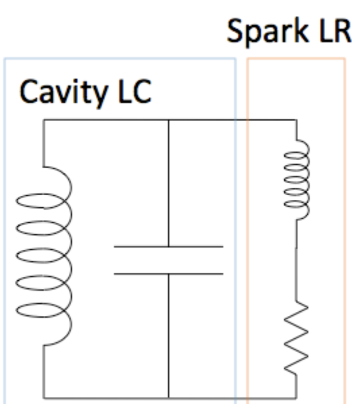


RF pickup signal in breakdown process



Electron density from RF pickup signal analysis

- Current can be estimated from L, R and drift velocity of electrons in hydrogen plasma

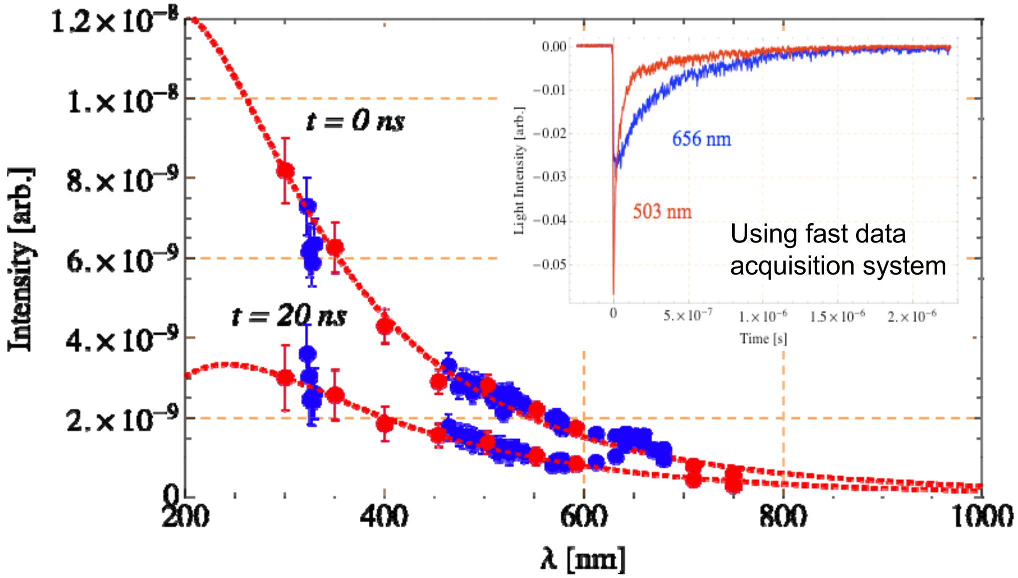


Equivalent resonance circuit

- Resonance circuit of normal RF cavity consists of L and C
- Breakdown makes streamer
- It produces additional L and R
- Resonance frequency is shifted by them

A. Tollestrup et al., FERMILAB-TM-2430-APC,
K. Yonehara et al., Proceedings of IPAC’10, WEPE069

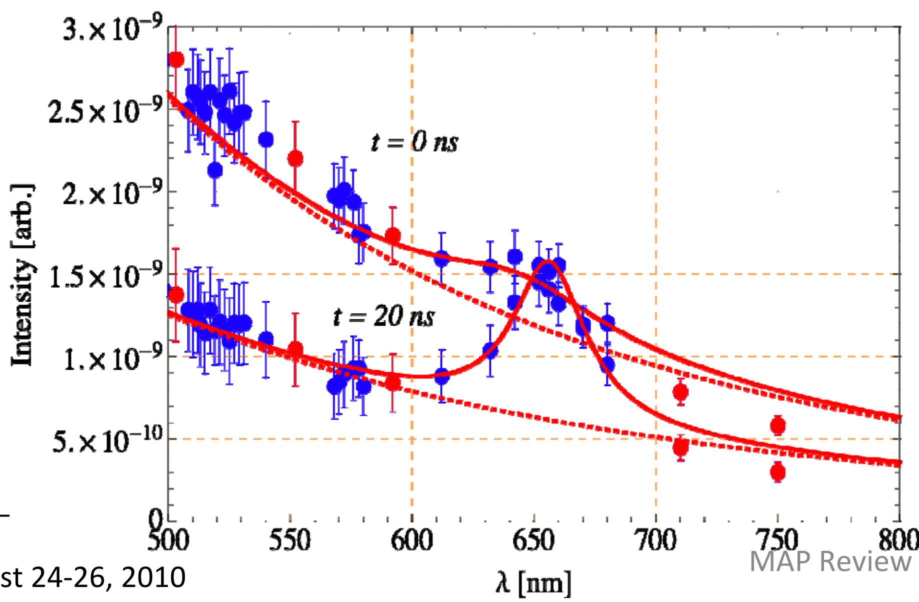
Study hydrogen plasma dynamics: Spectroscopy of breakdown light



Spectroscopy in the high pressure RF cavity

Thermal radiation:

- Broken line is a least square fitting of thermal radiation formula by taking into account red points which is on neither any hydrogen nor copper resonance lines
- "0 ns" is a peak light intensity
- Plasma temperature is raised up to 18,000 K in 5 ns and down to 10,000 K in 50 ns



Spectroscopy at Balmer line

Spontaneous emission:

- Solid line is a least square fitting of Lorentz function by taking into account all points
- Timing delay due to lifetime of de-excitation
- Broadened Balmer line is observed
- Stark effect well-explains resonance broadening
- Plasma density 10^{18}~10^{19} electrons/cm^3

K. Yonehara et al., Proceedings of IPAC'10, WEPE069

Critical issues for down selection

RF field must be recovered in few nano seconds

1.DC to 800 MHz, Hydrogen breaks down at E/P = 14. It indicates we can use DC data as a framework to explain results.

Need higher frequency measurements to test frequency dependence

2.Electrons move with a velocity, $v = \mu E_{rf}$. Current $J = nev$.

Power dissipation due to electrons in phase with RF and dissipate energy through inelastic collisions = $j \times E_{rf} = (ne\mu E_{rf})E_{rf}$

Measurements with beam verify mobility numbers and verify our loss calculation

3.Electrons recombine with positive ions and removed. If this is very fast they don't load cavity, if slow cause trouble

Beam measurement will give the recombination rate

4.Solution: use electronegative gas(es) to capture electrons and form negative ions

Beam measurement will verify attachment rate

5.A+e →A^- heavy negative ions. How long do these hang around and do they cause the breakdown voltage of the cavity to be lowered

Beam measurement will give necessary answers

Feasibility, including a hydrogen safety analysis, also must be assessed

Conclusion

- High pressure RF cavity is a potential element for muon ionization cooling channel
  - Successful HPRF cavity tests in strong magnetic fields have been done
  - Physics rich subject: Not only accelerator physics but also plasma & atomic physics topics are involved in R&D
- Beam test is scheduled to demonstrate HPRF cavity in high radiation condition
  - First 400 MeV proton beam test will be finished at the end of 2010
  - Study recovery time of RF field
  - R&D will be finished in FY11
- Start building prototype high pressure RF cavity for real cooling channel in FY12 if this technology is selected