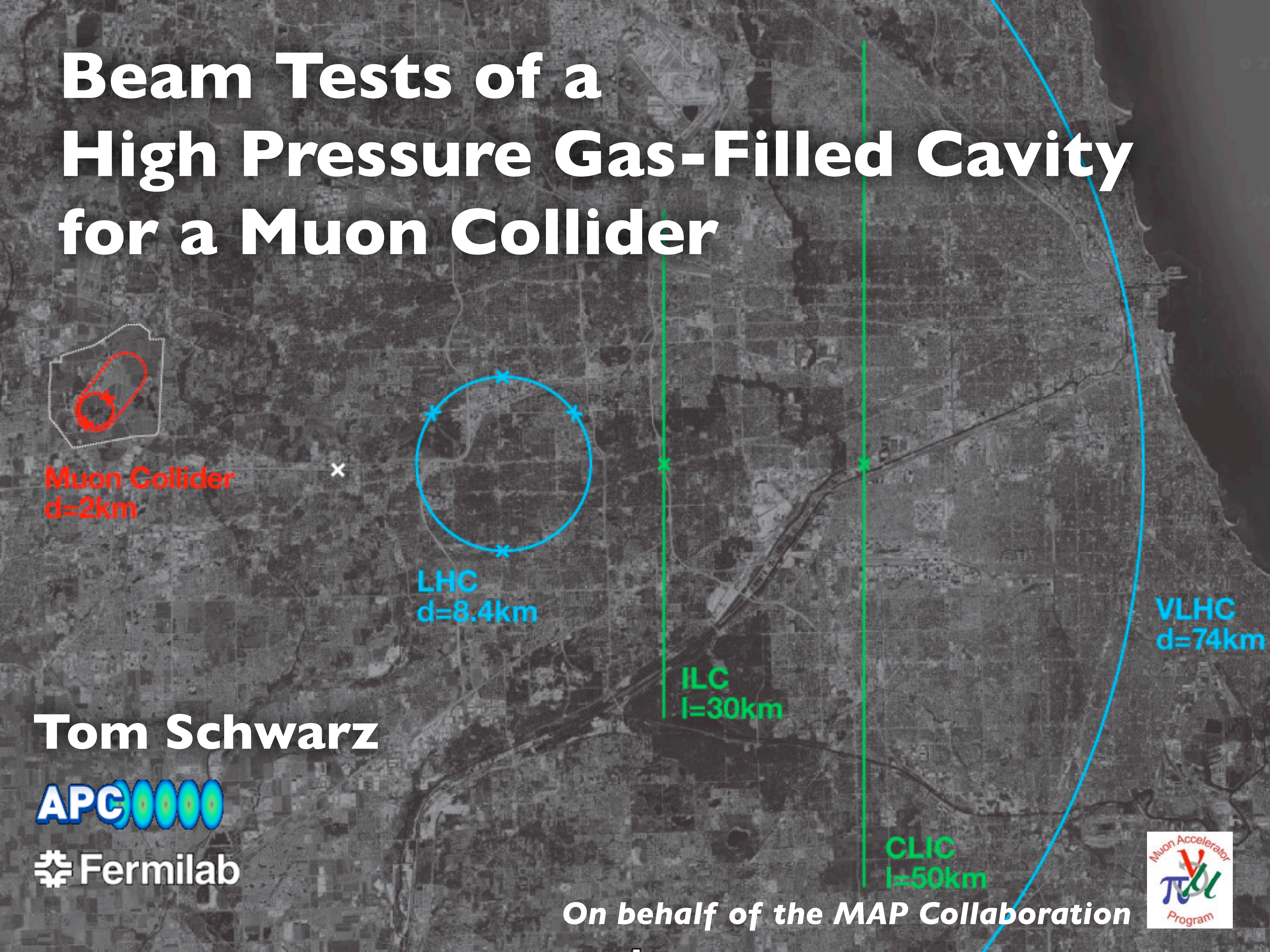
Beam Tests of a High Pressure Gas-Filled Cavity for a Muon Collider



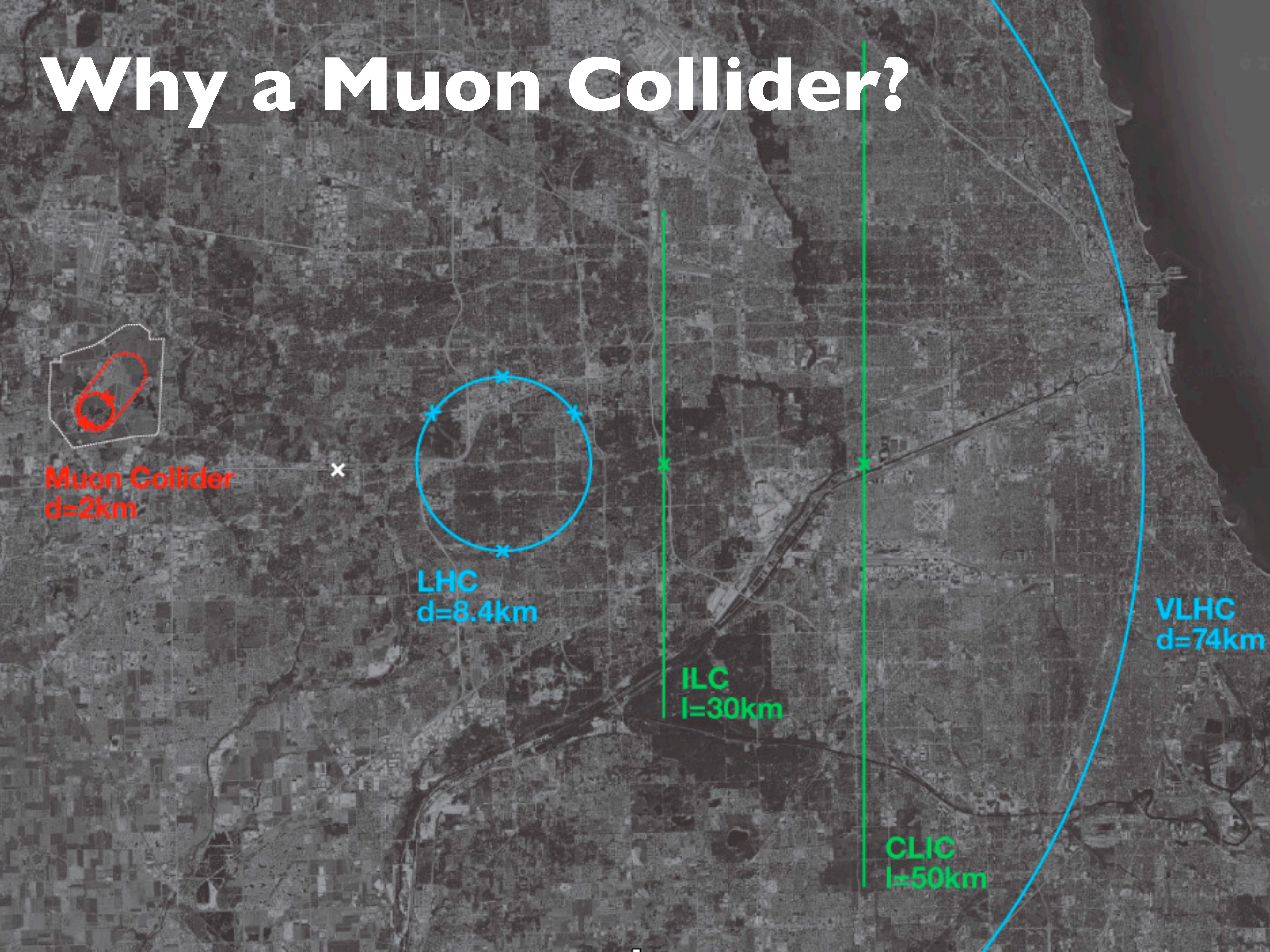
Tom Schwarz

APC

Fermilab

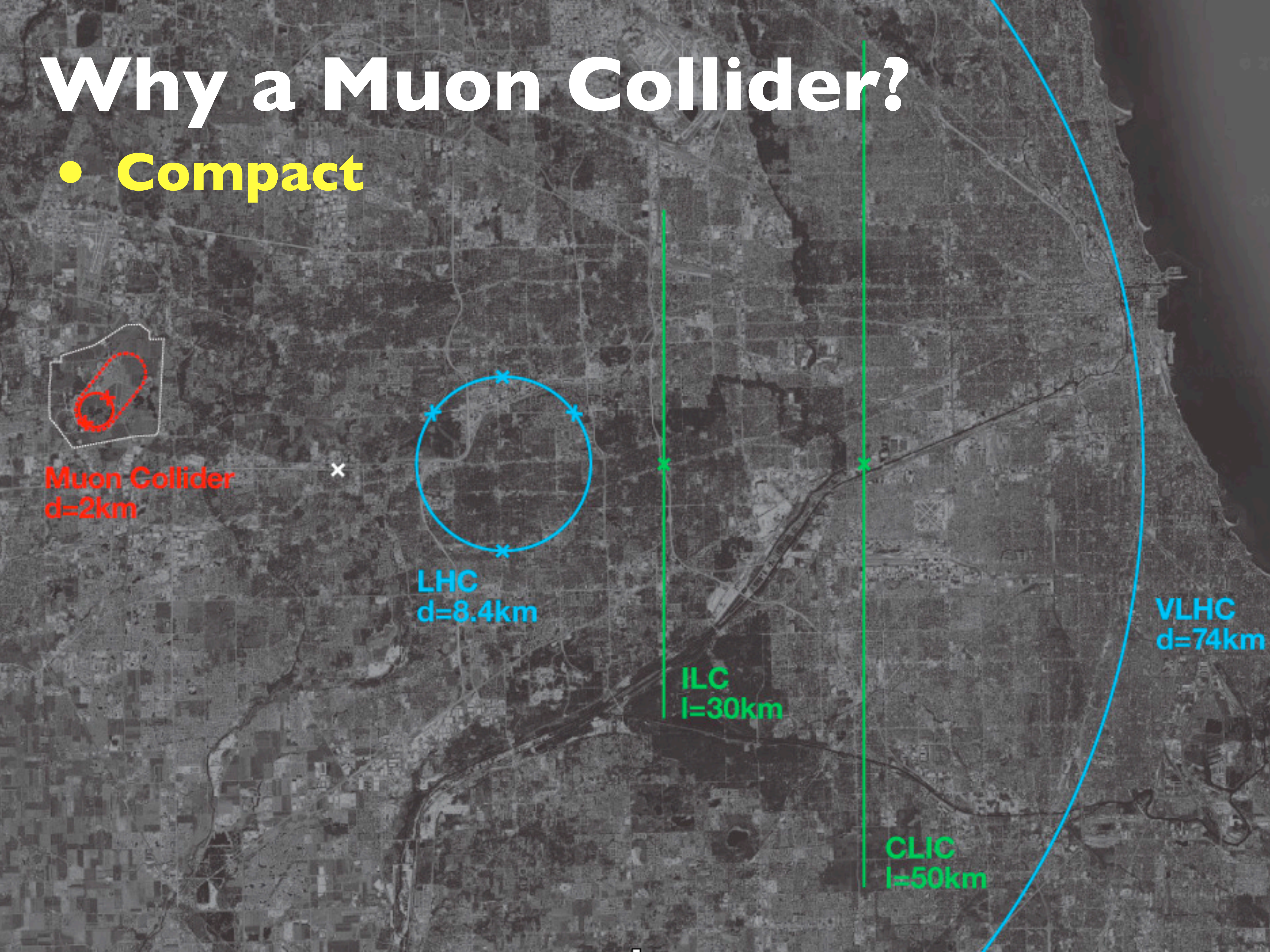
On behalf of the MAP Collaboration

Why a Muon Collider?



Why a Muon Collider?

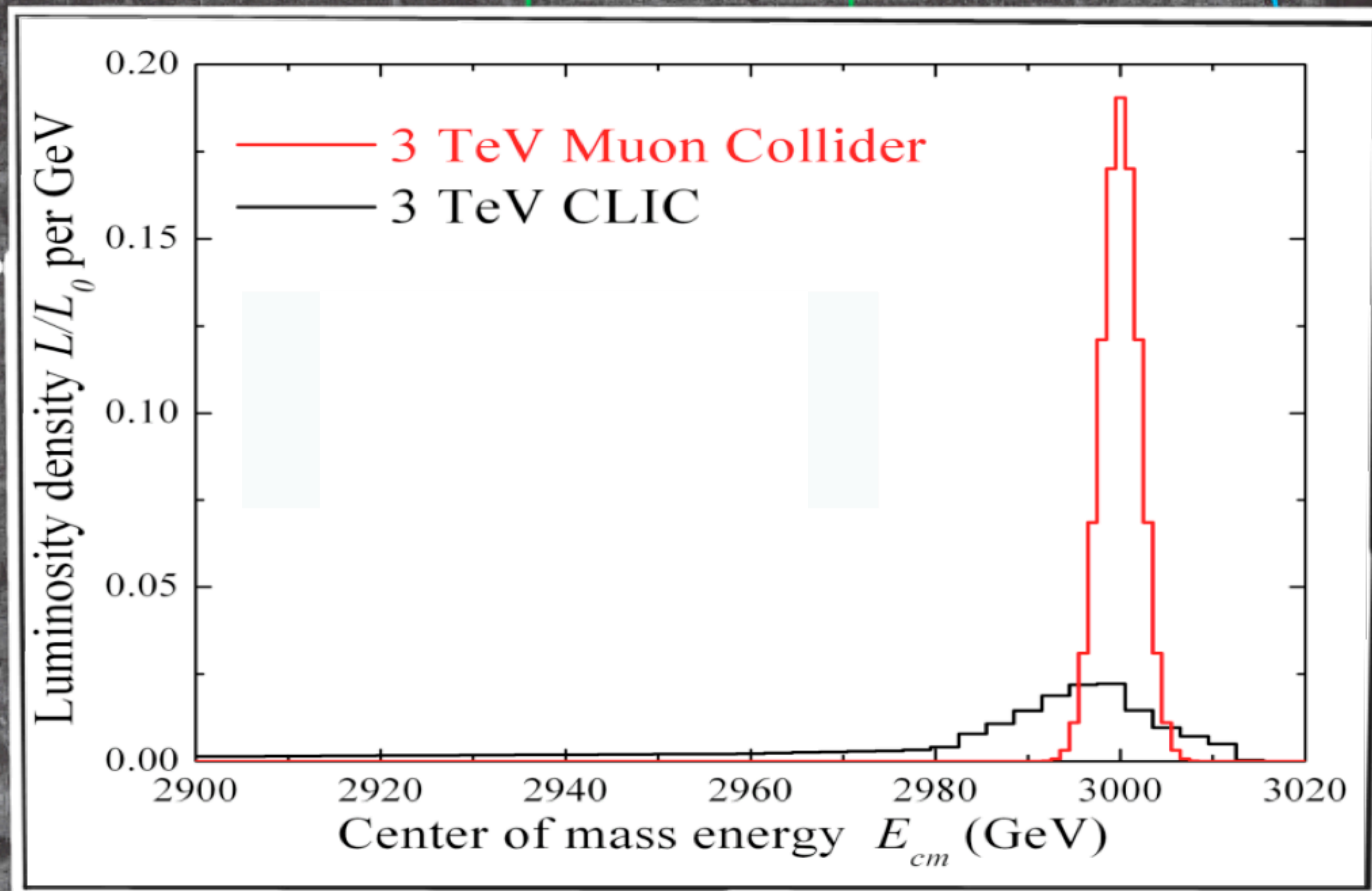
- Compact



Why a Muon Collider?

- **Compact**
- **Narrow Energy Spread**

Muon Collider
d=2km



HC
74km

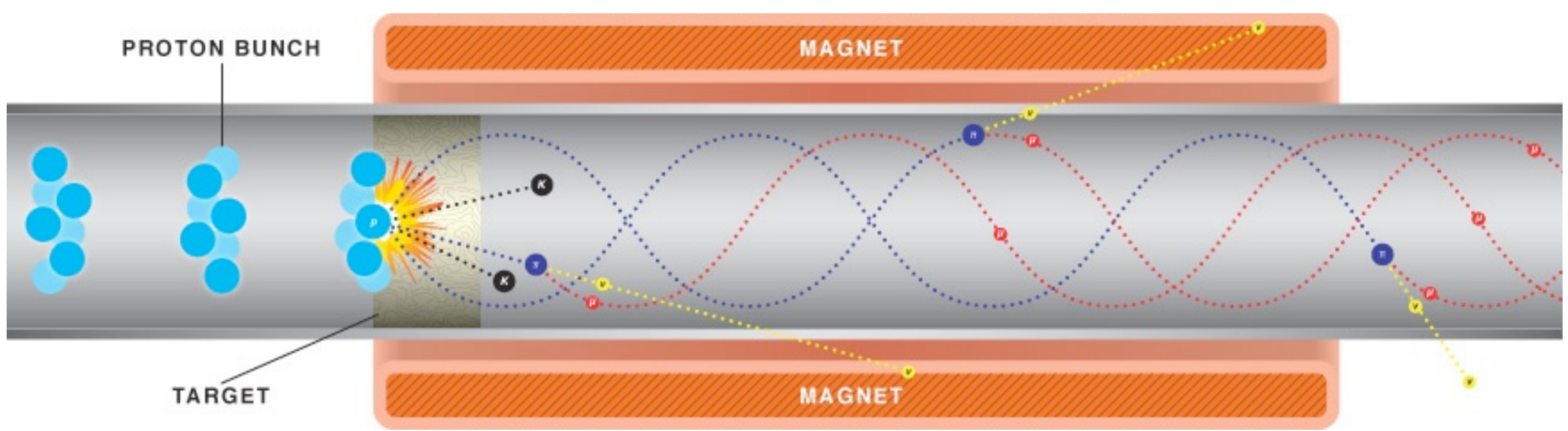
l=50km

Muon Collider Challenges

- **Muons are produced via decay of other particles**
  - requires a large proton source (MW)

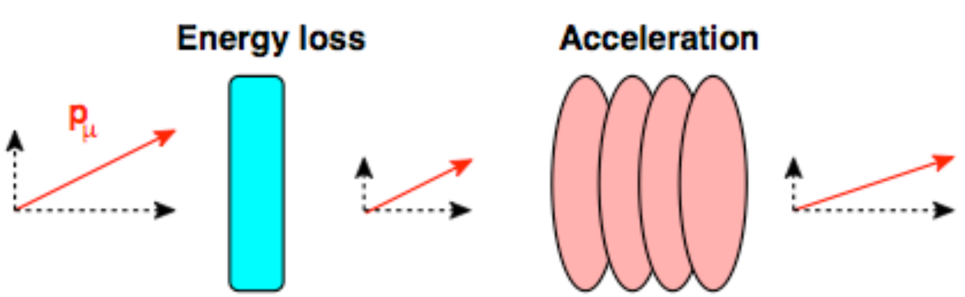
- **Muons emerge from production with a large 6D phase**
  - 6D Cooling

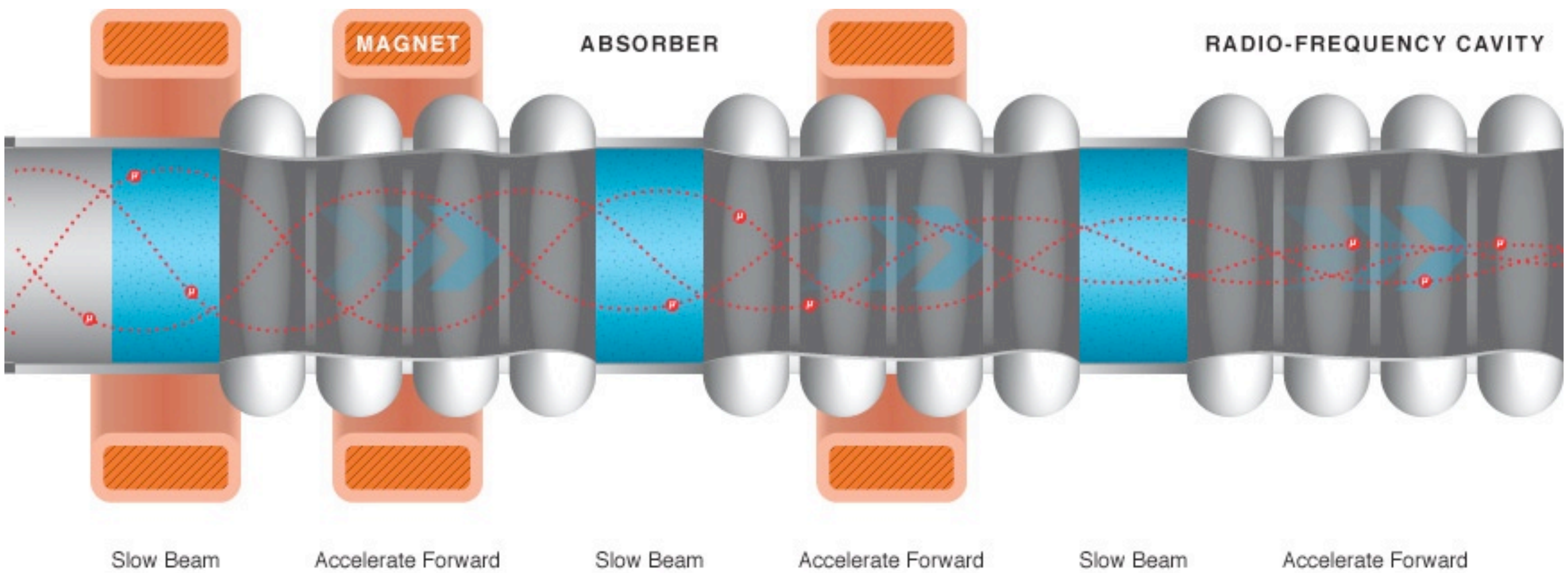
- **Muons decay quickly - need rapid cooling and ramping**



Muon Ionization Cooling

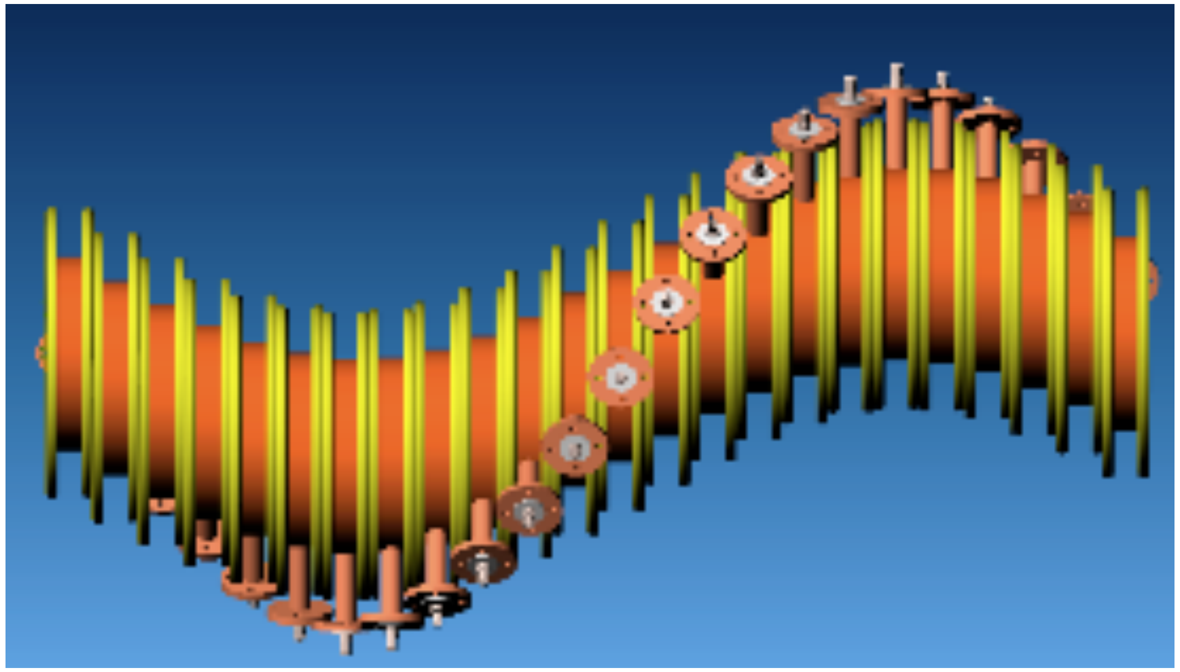
- **Beam squeezed by solenoids while losing momentum**
  ➜ Only restored longitudinally

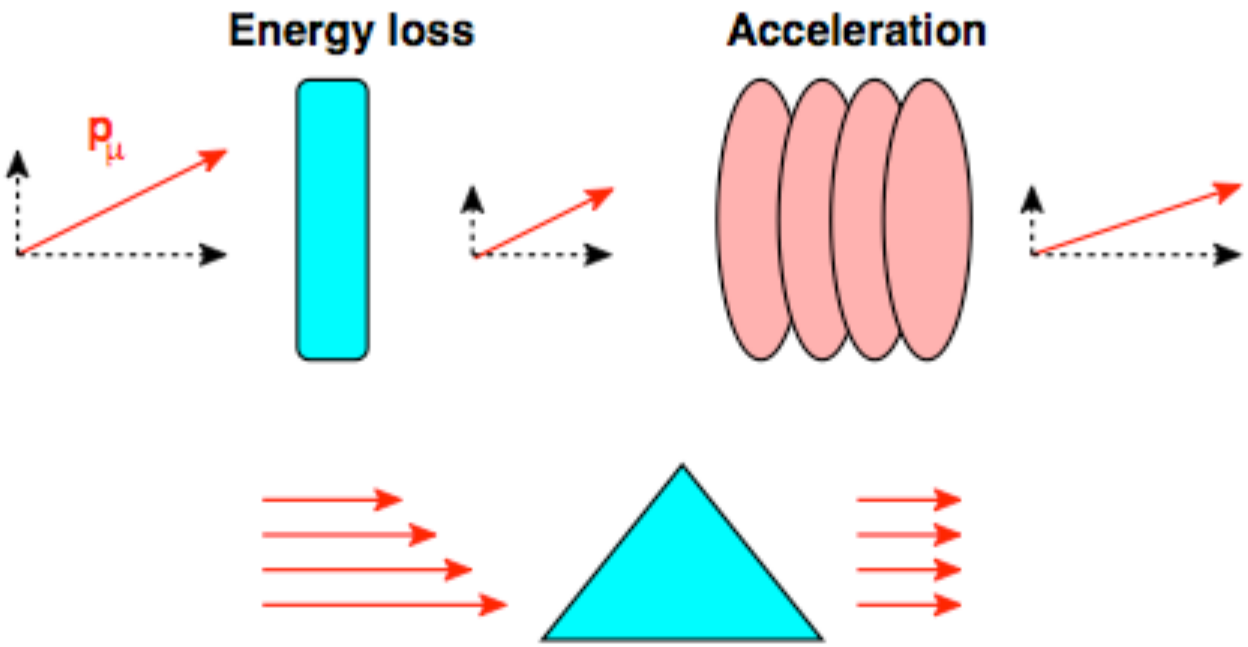




6D Cooling

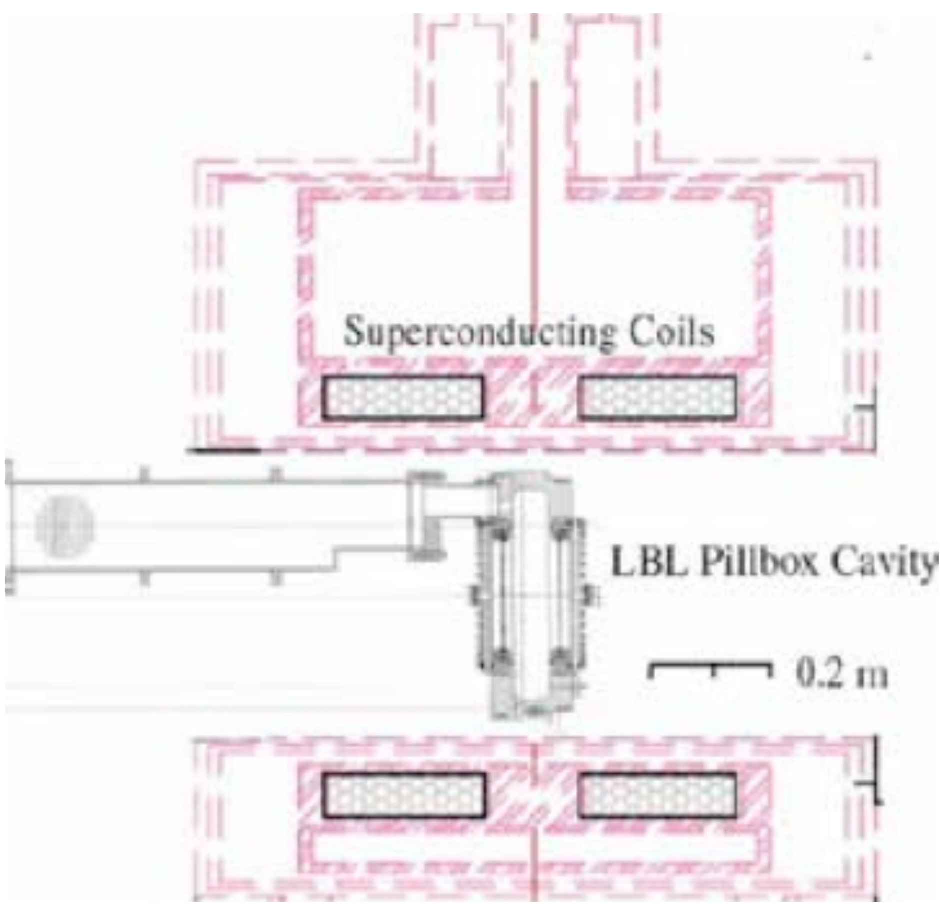
- **Cool longitudinally as well**
- **Helical cooling channel ➔ muons with higher momentum experience more material**

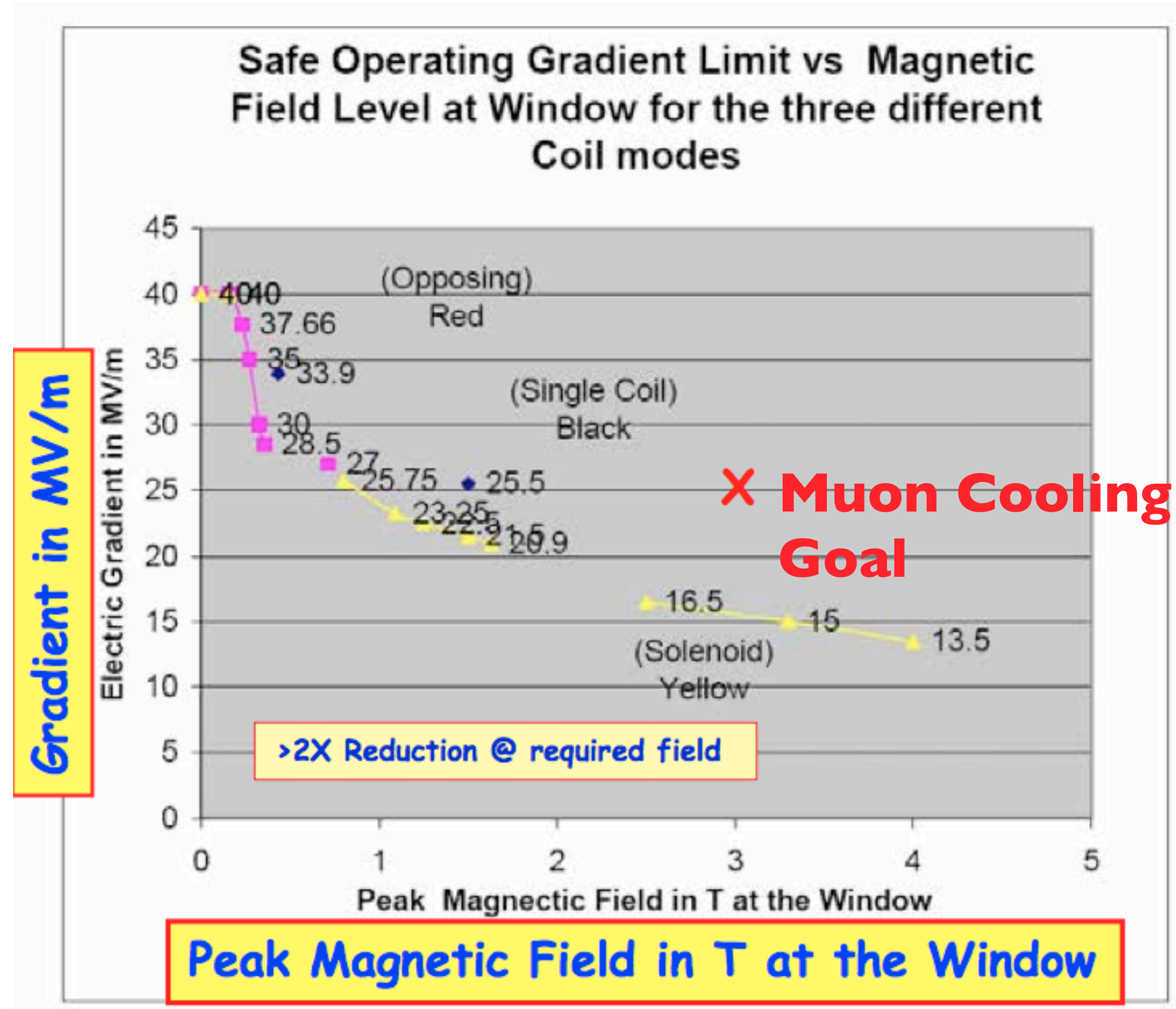




Cooling Channel for a Muon Collider

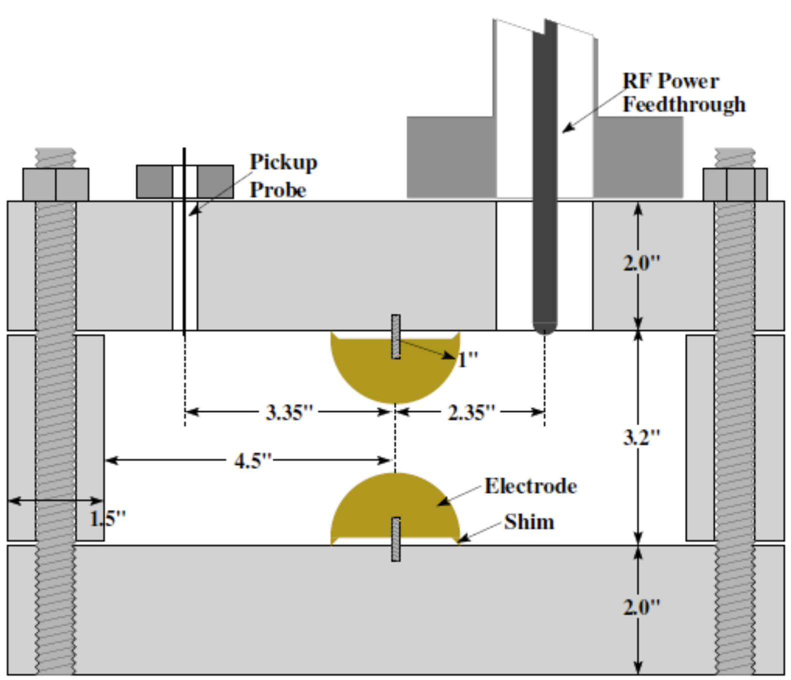
- **Maximum stable gradient degrades with increased magnetic field**

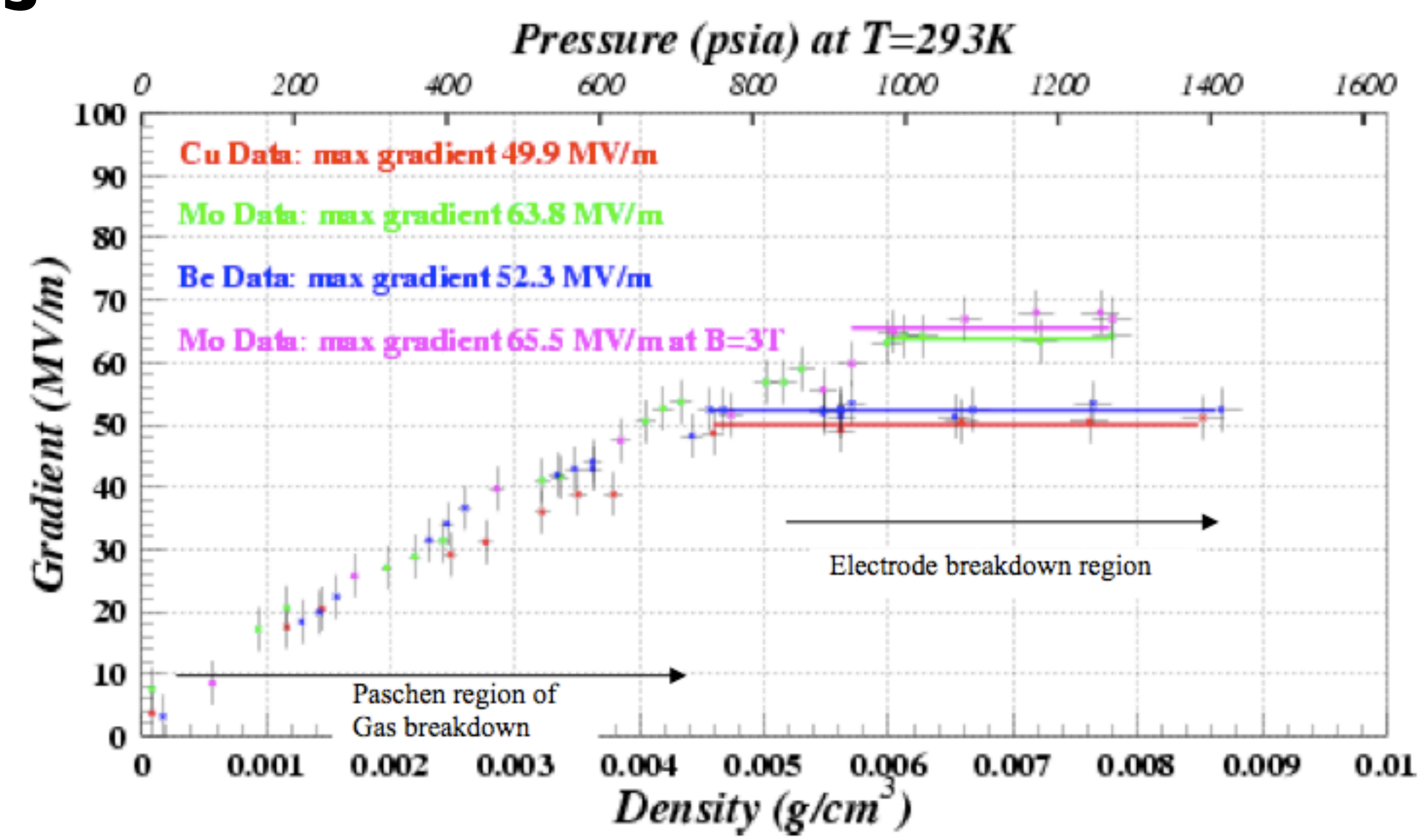




High Pressure Gas-Filled Cavity

- **Utilize high pressure gas to mitigate breakdown from field emission**
- **Use a high pressure test cell to study breakdown properties of materials**





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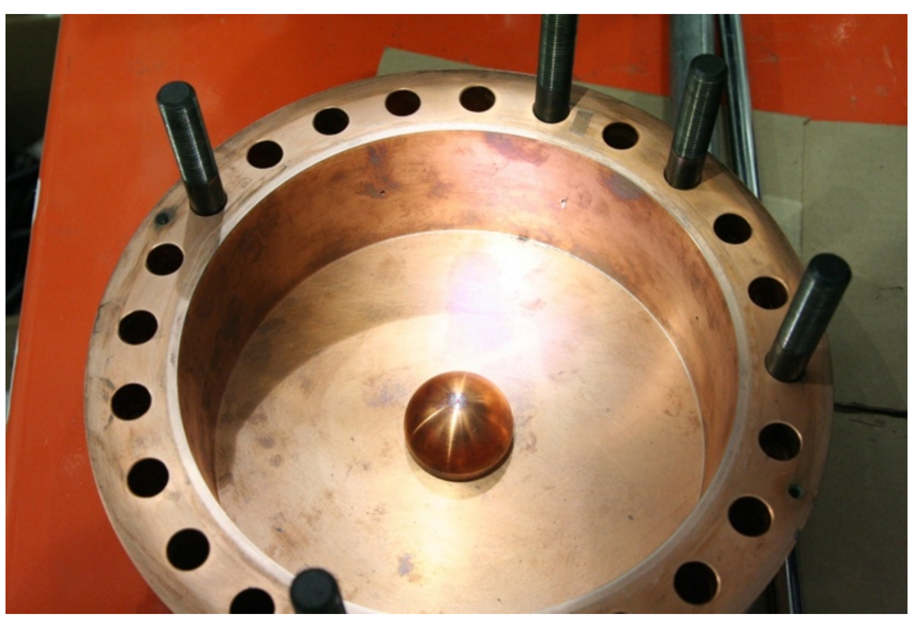

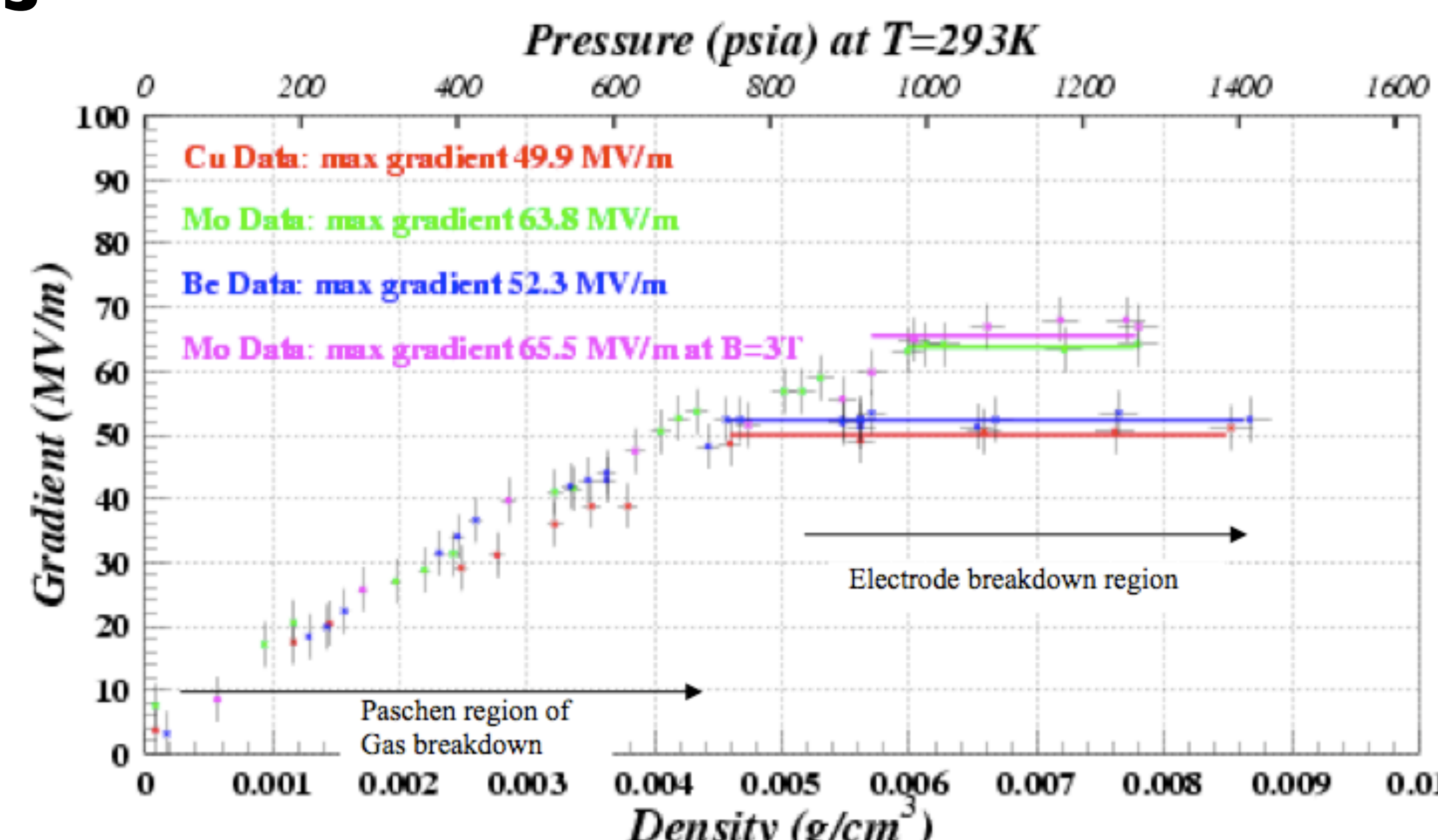

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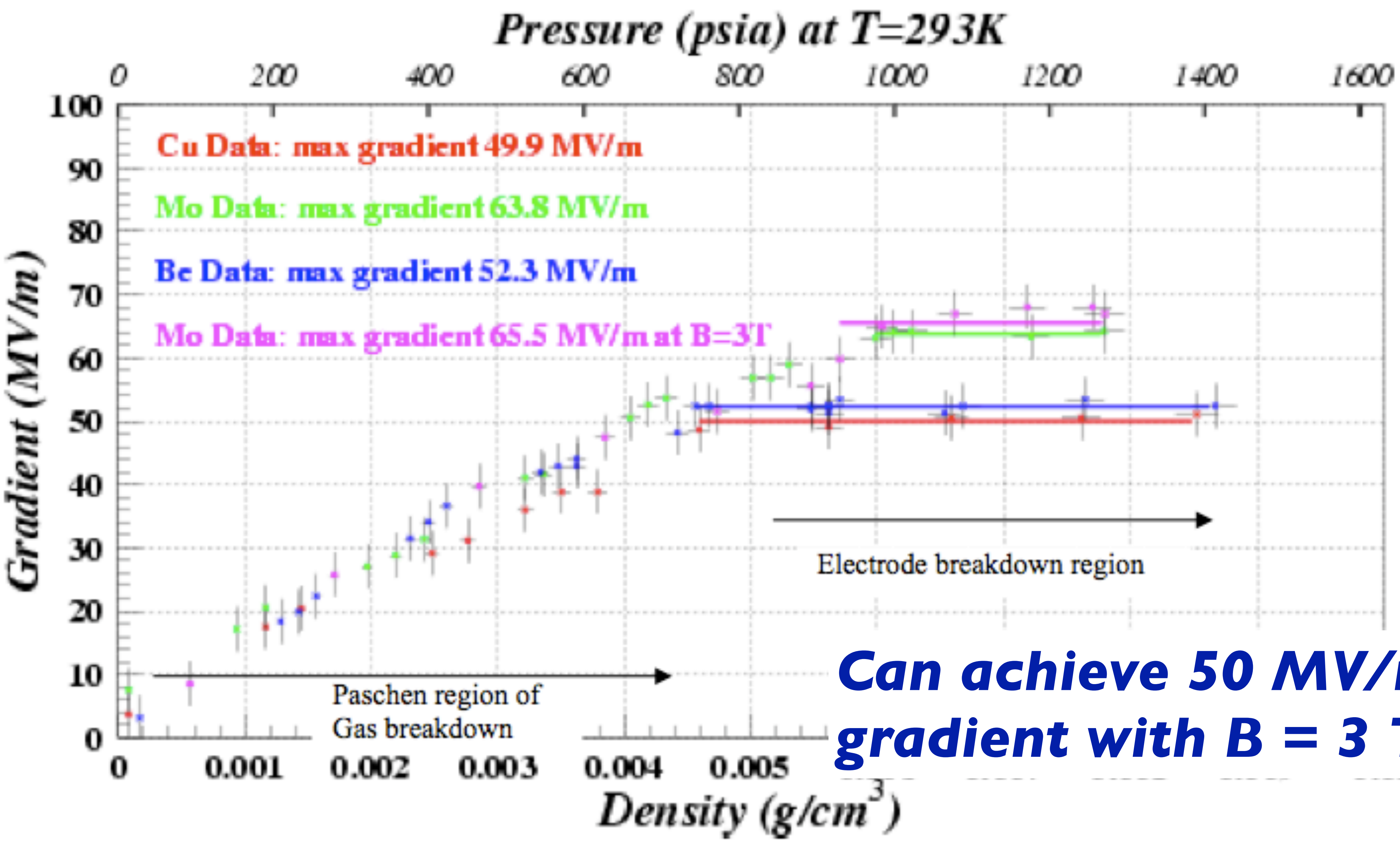
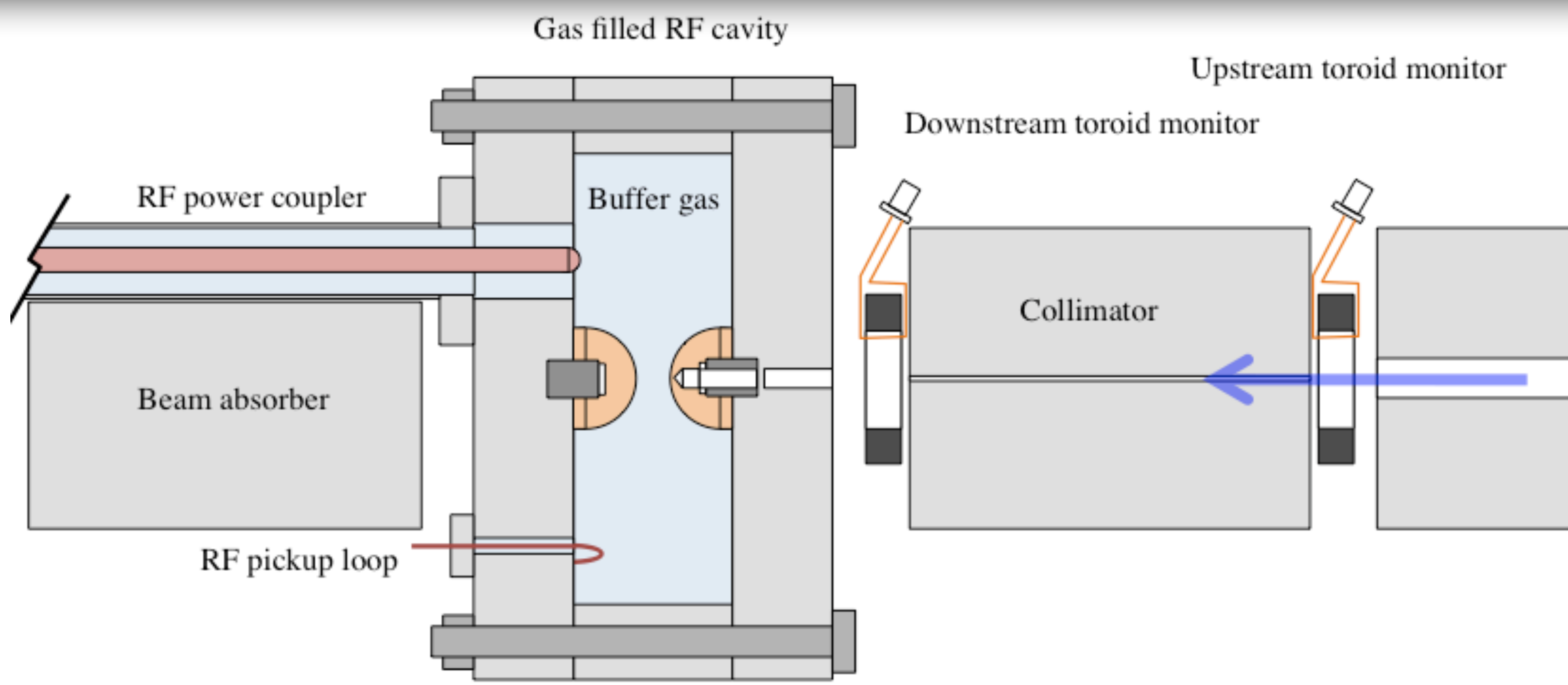


Can achieve 50 MV/m gradient with B = 3 Tesla

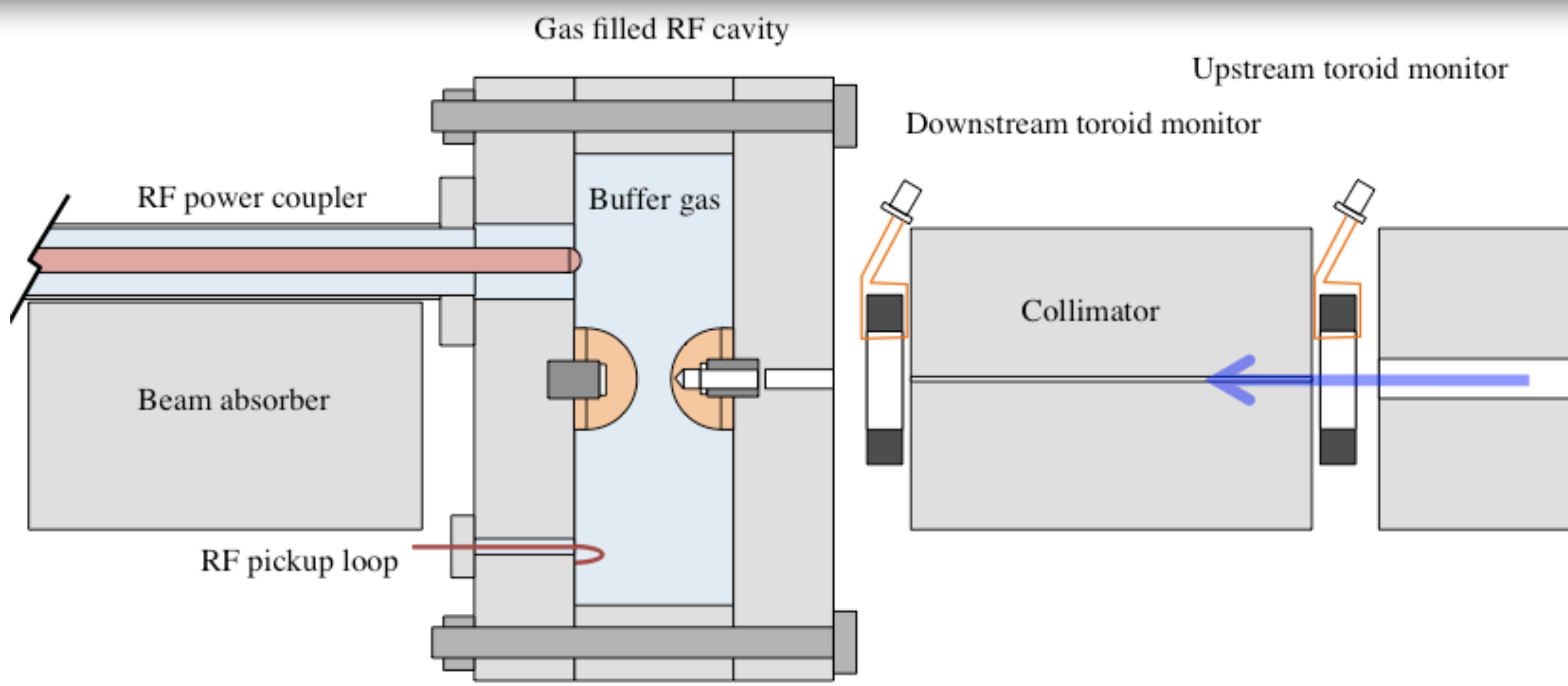
MTA Beamline and Apparatus



400 MeV H⁻ beam

- **Primary 1.5×10^{12} H^-/beam pulse**
- **10 μs beam pulse length**
- **~ 20% Acceptance through collimators**
- **$H^- \rightarrow H^+$ at vacuum window and cavity wall**

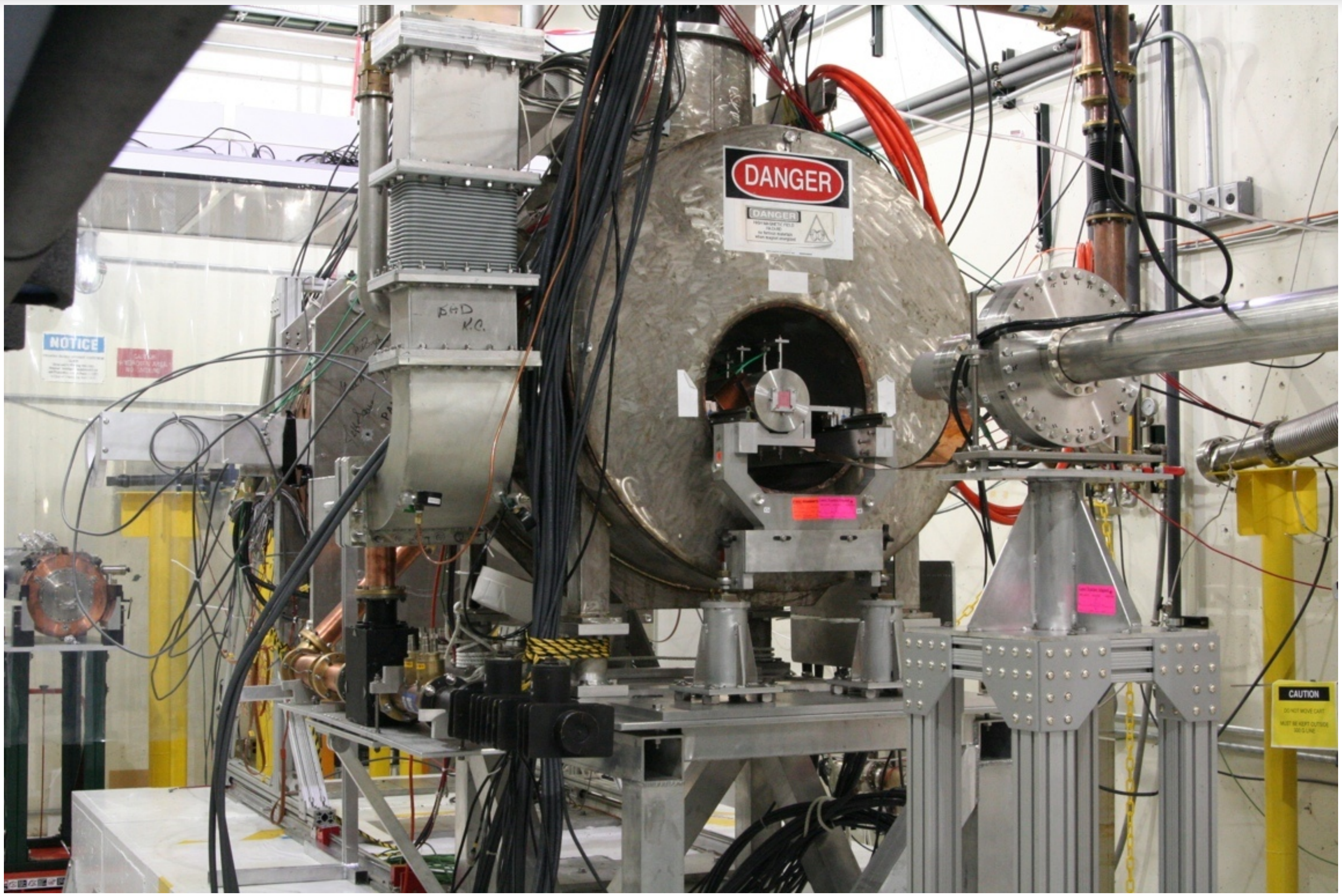
MTA Beamline and Apparatus



Instrumentation

- **RF Power 201 MHz (5 MW) and 805 MHz (12 MW)**
- **4 Tesla Solenoid (250W LHe Cryo-plant)**
- **Instrumentation: Passive measuring of beam position, toroids counters, optical signals, spectrometer, in-cavity probes (developing acoustic sensory)**

MTA Beamline and Apparatus



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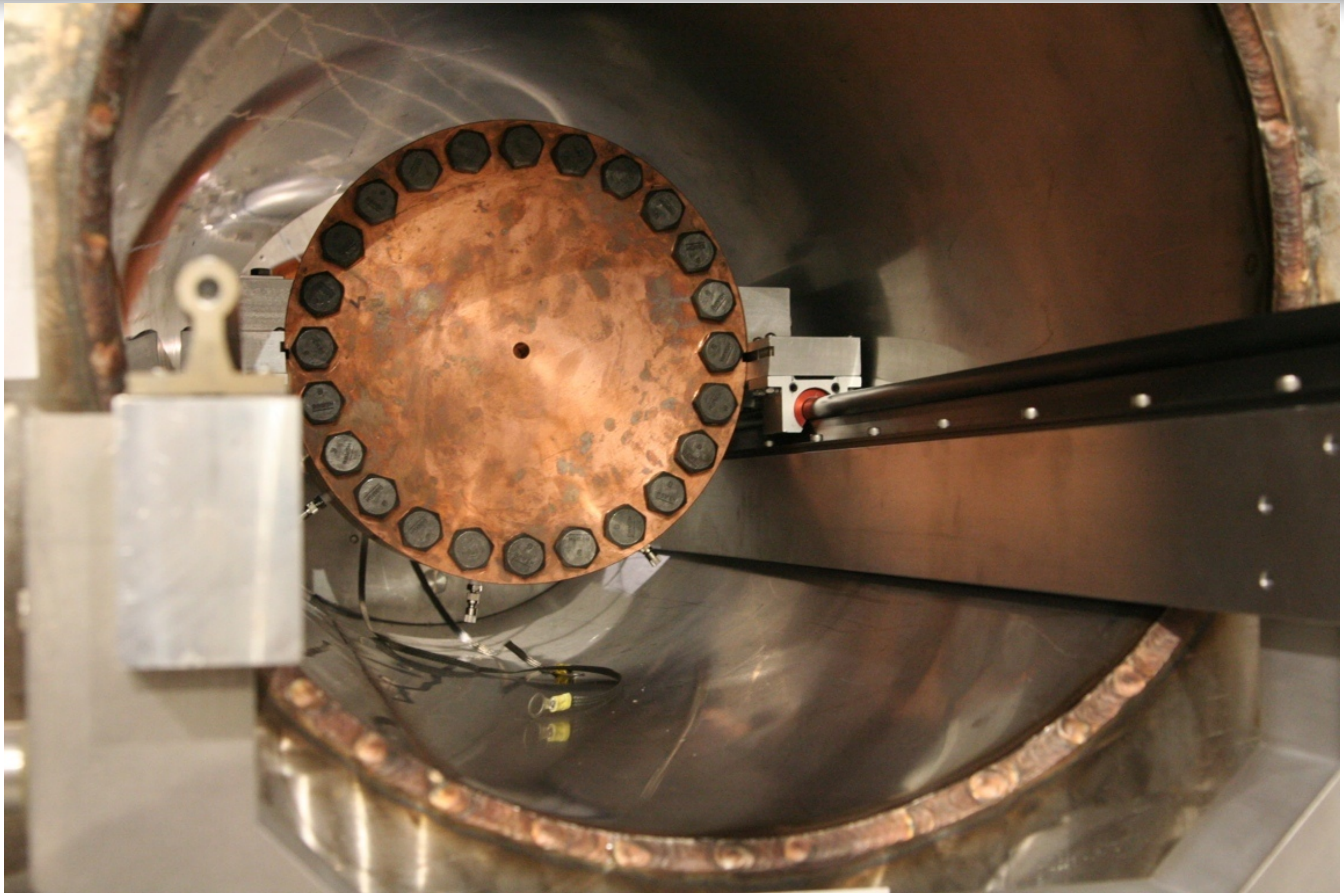
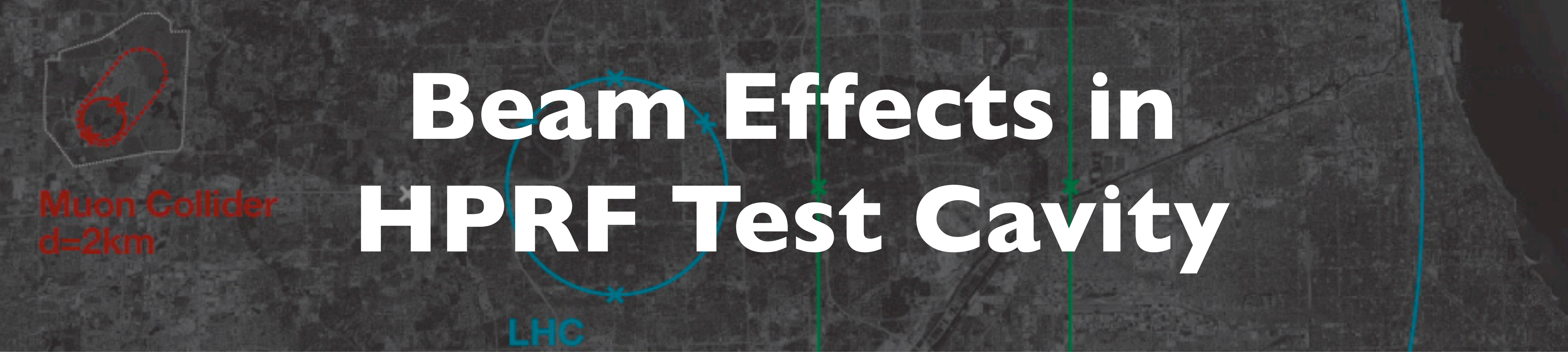
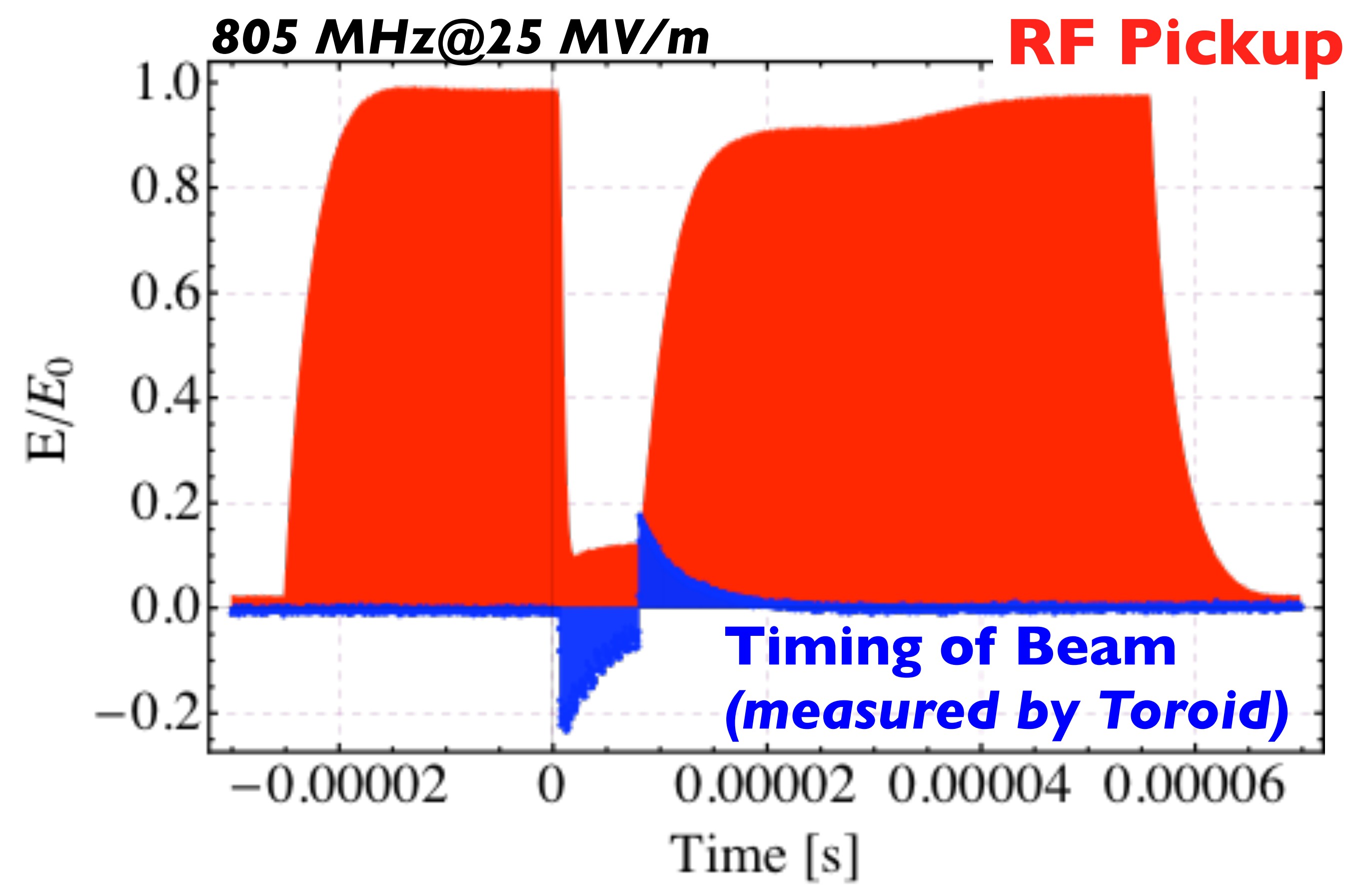




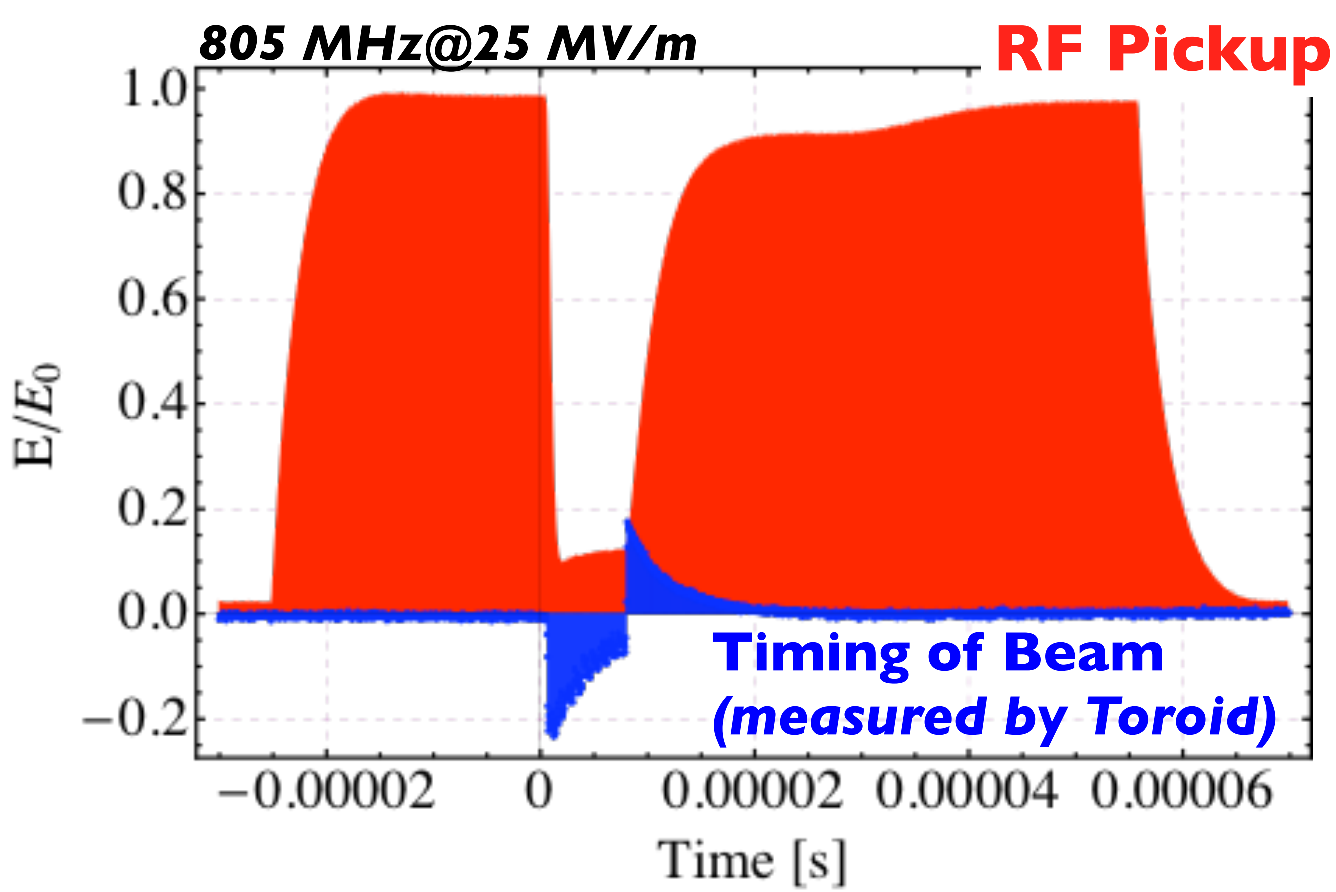
Beam Effects in HPRF Test Cavity

- Studying beam effects in test cavity with 40 μs of RF (800 MHz) at various gradients (5-30 MV/m) and no B-Field
- Test cavity filled with high pressure gaseous H^2 (up to 100 atm)
- 10 μs of beam fired mid-way through 40 μs of RF
- Toroid outside cavity measures timing & # protons
- RF pickup probe in cavity measures effect on E-field



Beam Effects in HPRF Test Cavity

- **As beam enters cavity, gaseous hydrogen is ionized and electrons are released - about 2000 per proton**
- **Electrons begin to absorb the energy stored the cavity**
- **Equilibrium reached when the energy absorbed by the electrons is balanced by the klystron pumping energy into the cavity**



Predicted Energy Loss

Energy loss per electron is related to the electric field in the cavity and the electrons drift velocity

$$\mathrm{E_{loss}} = \mathrm{q} \cdot \mathrm{E_{Field}} \cdot \mathrm{v_{drift}} \cdot \frac{1}{\mathrm{f_0}}$$ *per RF cycle*

Total energy loss observed in the cavity is of course dependent on the total # electrons

 # electrons produced in a gas predicted by the Bethe-Bloche Formula

$$\mathrm{N_{e-}} = \left\langle \frac{\mathrm{dE}}{\mathrm{dx}} \right\rangle \cdot \frac{\rho_{\mathrm{gas}}}{35\ \mathrm{eV}}$$ *per cm beam travels in gas*

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Predicted Energy Loss

Energy loss per electron is related ... **he cavity and the electrons drift velo**...

electron mobility

$$\mathrm{v_{drift}} = \mu \cdot \mathrm{E_{field}}$$

$$\mathrm{E_{loss}} = \mathrm{q} \cdot \mathrm{E_{Field}} \cdot \mathrm{v_{drift}} \cdot \frac{1}{\mathrm{f_0}}$$

per RF cycle

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@ 25 MV/m

$$\mathrm{E_{loss}} = \mathrm{q} \cdot \mathrm{E_{Field}} \cdot \mathrm{v_{drift}} \cdot \frac{1}{\mathrm{f_0}}$$

$E_{loss} \approx 4 \times 10^{-17}$ J / cycle

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Energy loss per electr... the cavity and the electro...

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 # electrons produced i... oche Formula

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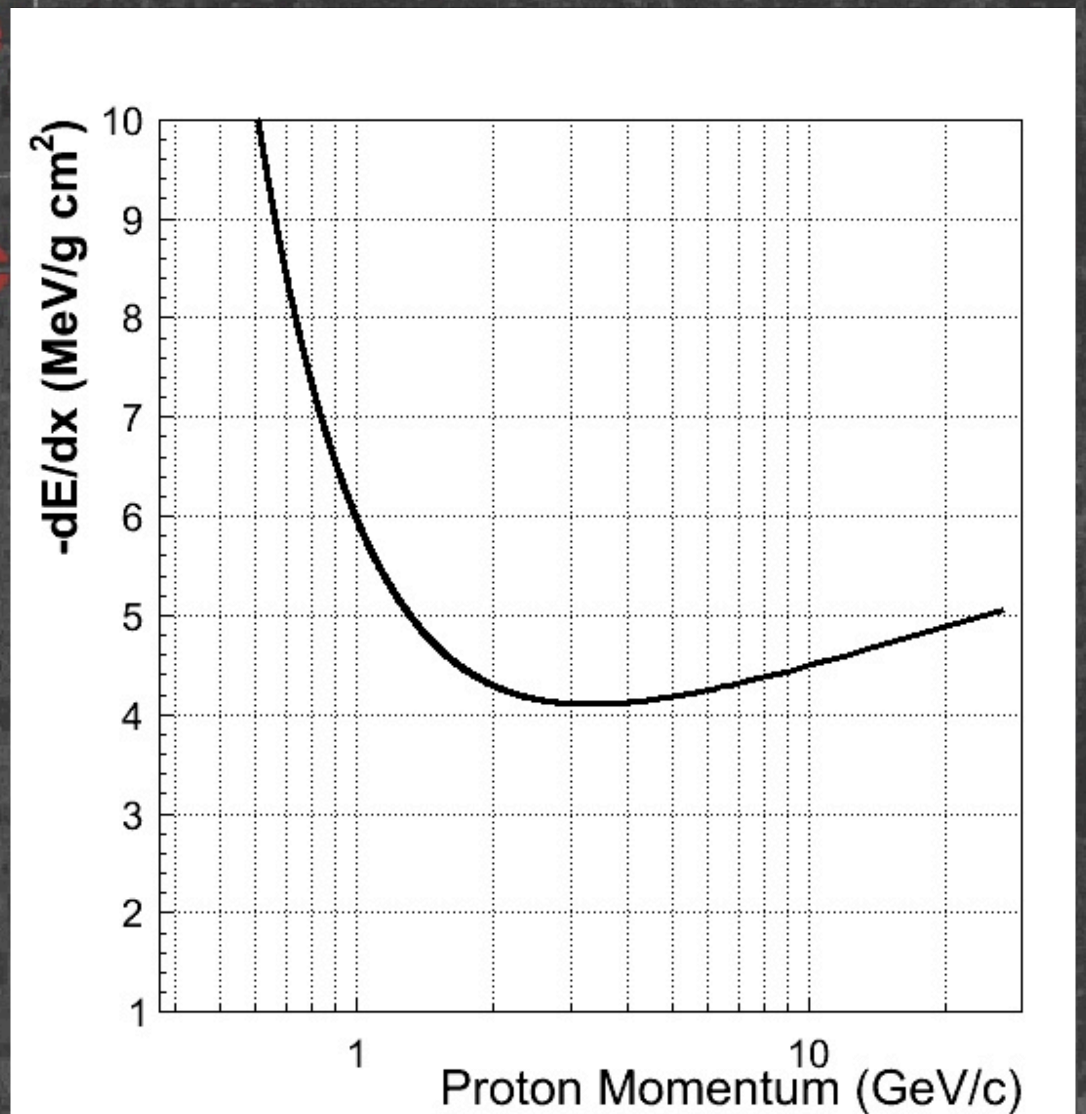

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$$\mathrm{N_{e-}} = \left\langle \frac{\mathrm{dE}}{\mathrm{dx}} \right\rangle \cdot \frac{\rho_{\mathrm{gas}}}{35\ \mathrm{eV}}$$

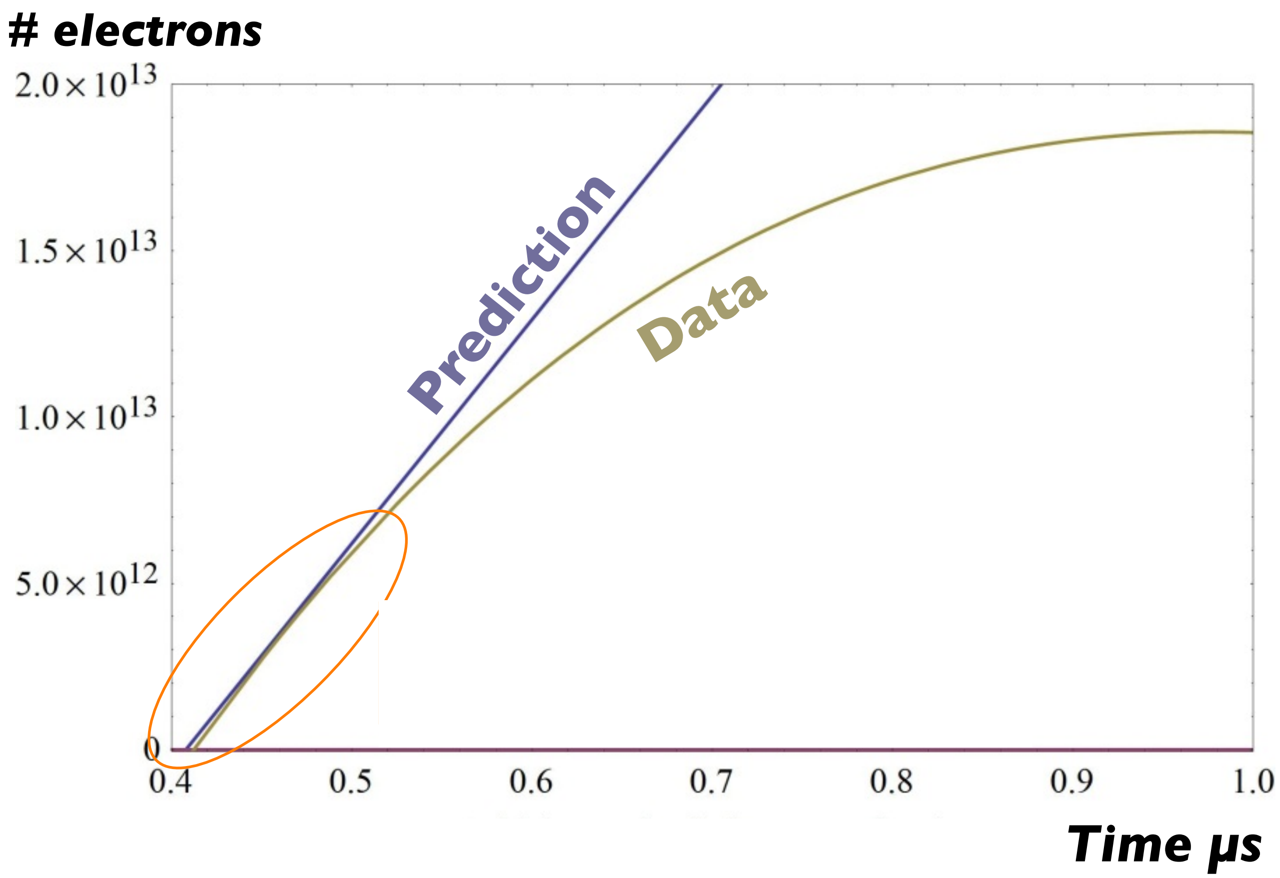
$N_{e-} \approx 2000$ / proton

H^2 @ 100 atm

$$-\left\langle \frac{dE}{dx} \right\rangle = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Prediction vs Experiment

- **Electrons absorb energy as predicted in first 100 ns**
- **Afterwards, electron recombine with free ions in the gas (H^{3+}, H^{5+}...)**
- **Recombination rate can be empirically determined by fitting a model to the data**

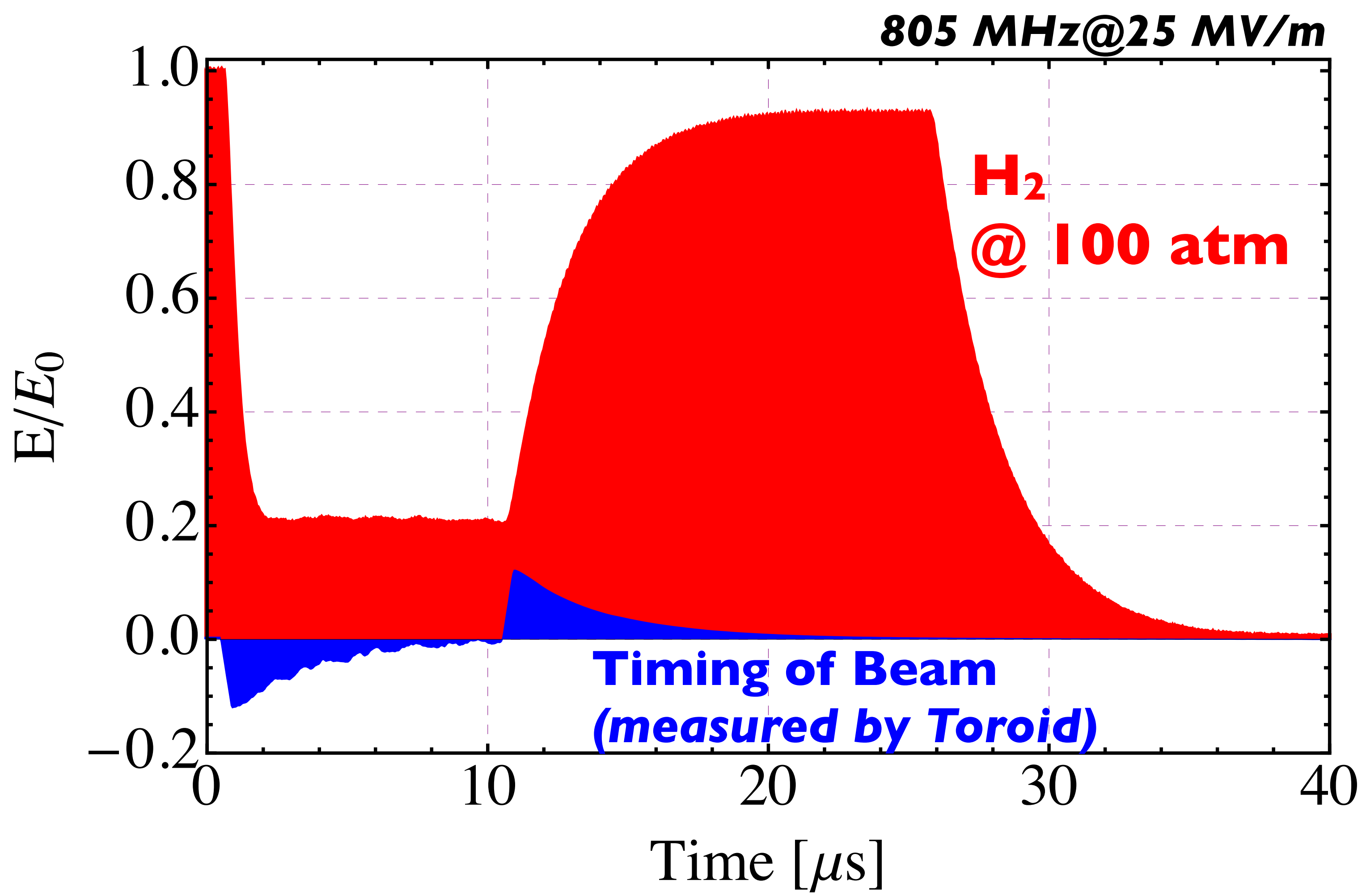


$$\frac{dn_e}{dt} = \frac{dn_{e,beam}}{dt} - \beta n_e n_{ions}$$

$$\beta \approx 1.2\times10^{-8}\ cm^3/s$$

Beam Loading

- **How does this translate into beam loading in a possible muon collider? ➜ What is the relative gradient each bunch in the train will experience?**
- **Cooling Channel**
  - ***$3.5 x 10^{12}$ μ's per bunch***
  - ***12 bunches***
  - ***60 ns bunch train***



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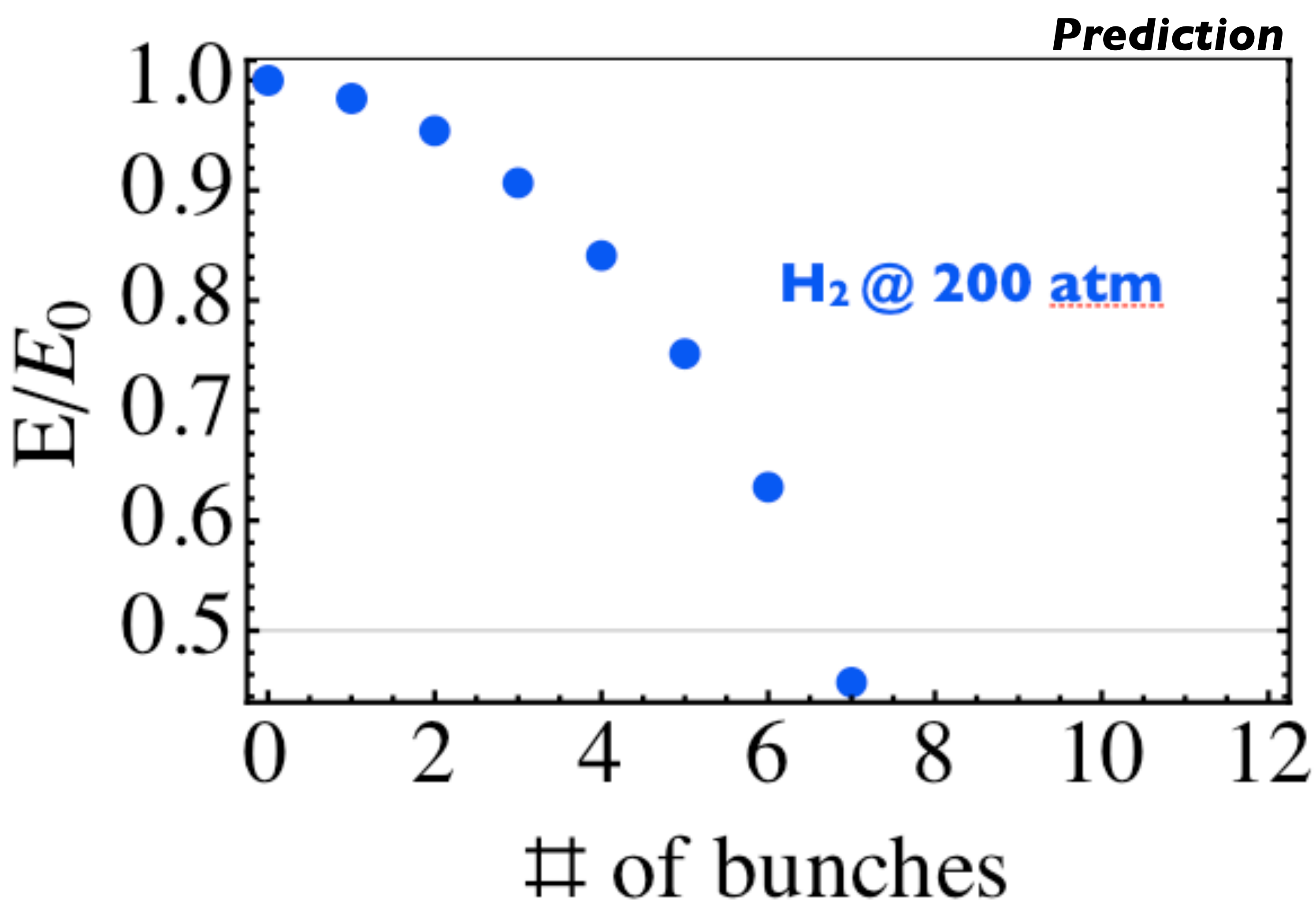
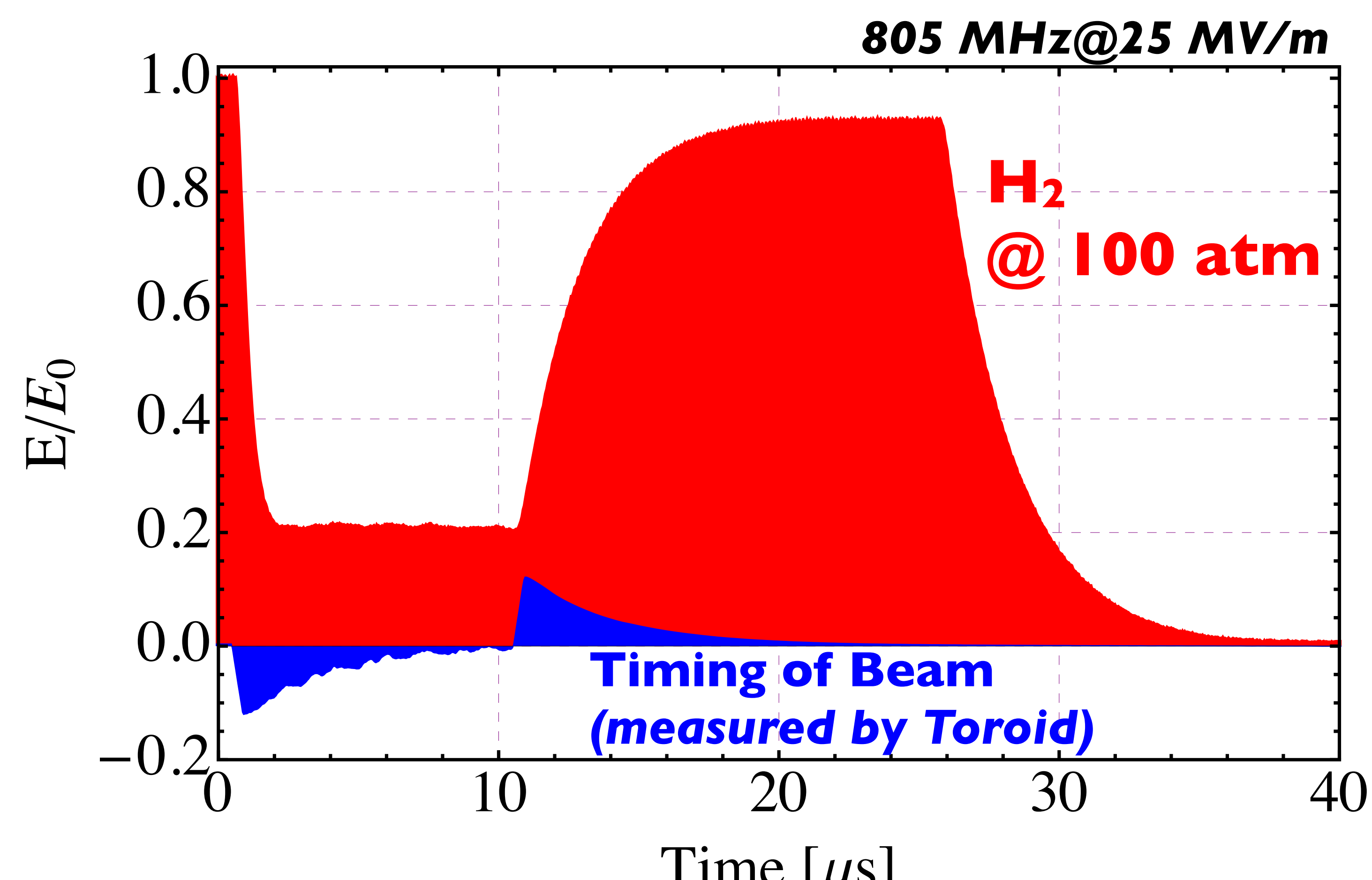


Using Electronegative Gases

- **Absorbing electrons is the key ➜ recombination rate of H^2 is too slow**
- **Dope gaseous H^2 with an electronegative gas (0.01% of SF_6) to absorb free electrons**



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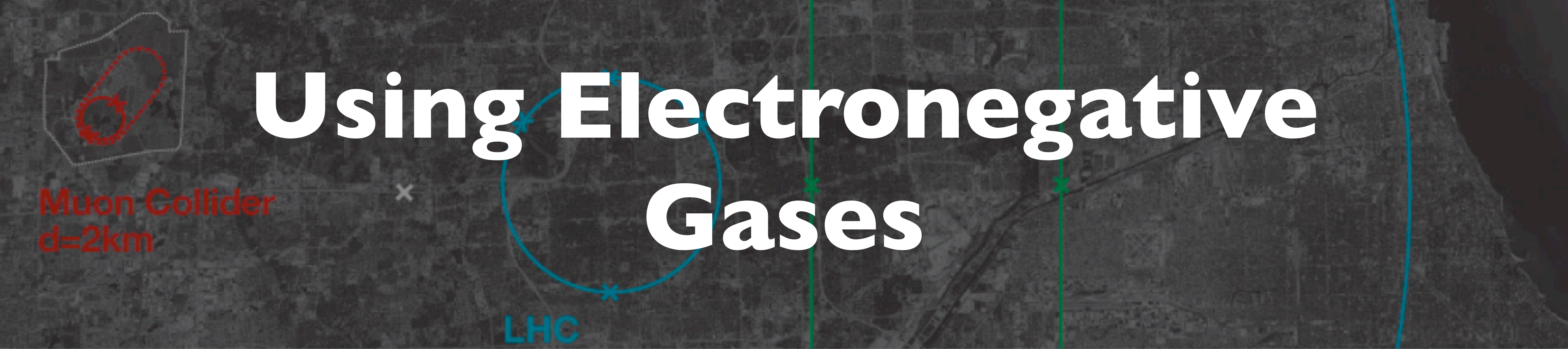
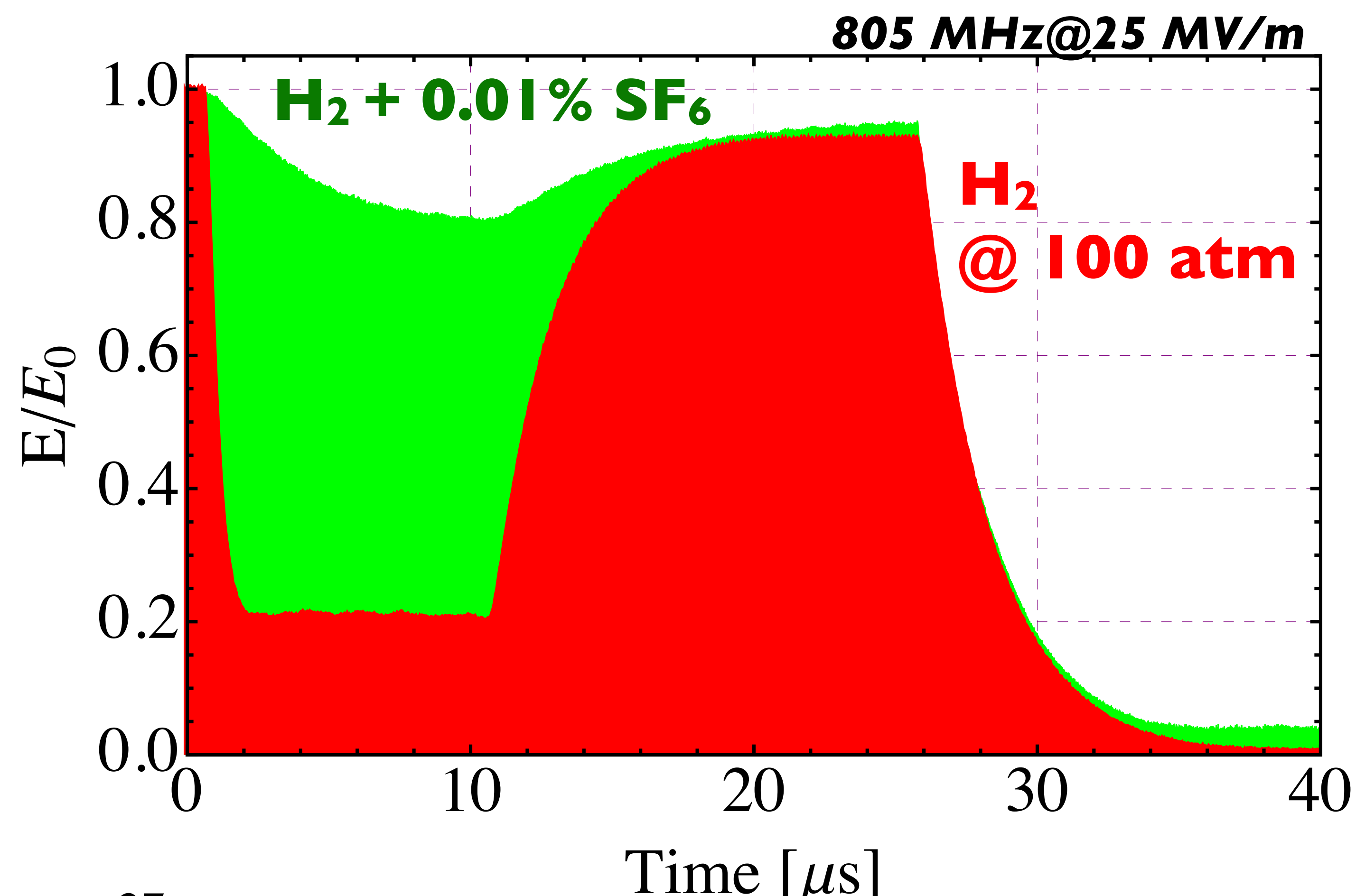


- **Absorbing electrons is the key ➜ recombination rate of H² is too slow**
- **Dope gaseous H² with an electronegative gas (0.01% of SF_6) to absorb free electrons**
- **Small amount of SF_6 drastically improves performance**

$$\frac{dn_e}{dt} = \frac{dn_{e,beam}}{dt} - \beta n_e n_i - \alpha n_e$$

Capture Time
SF_6 < nano second



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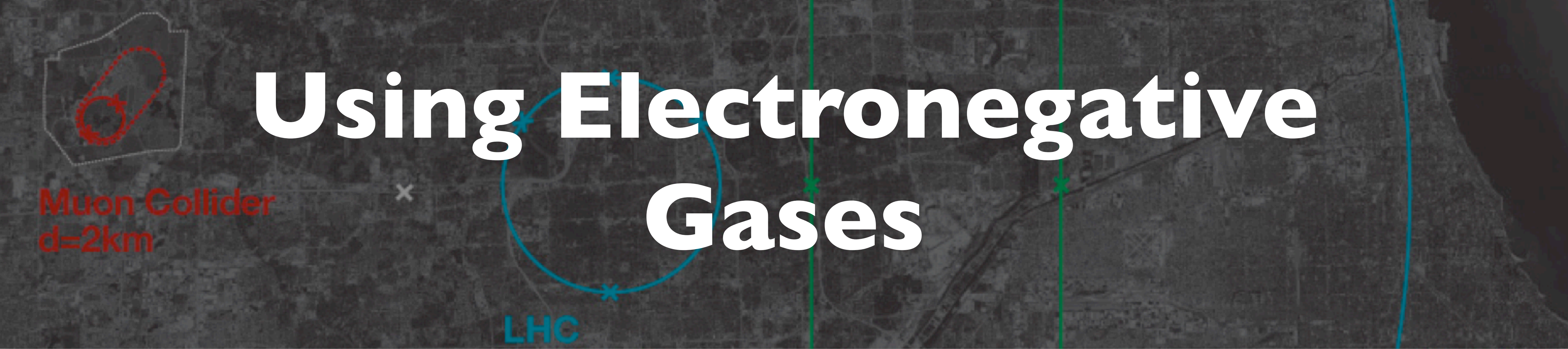
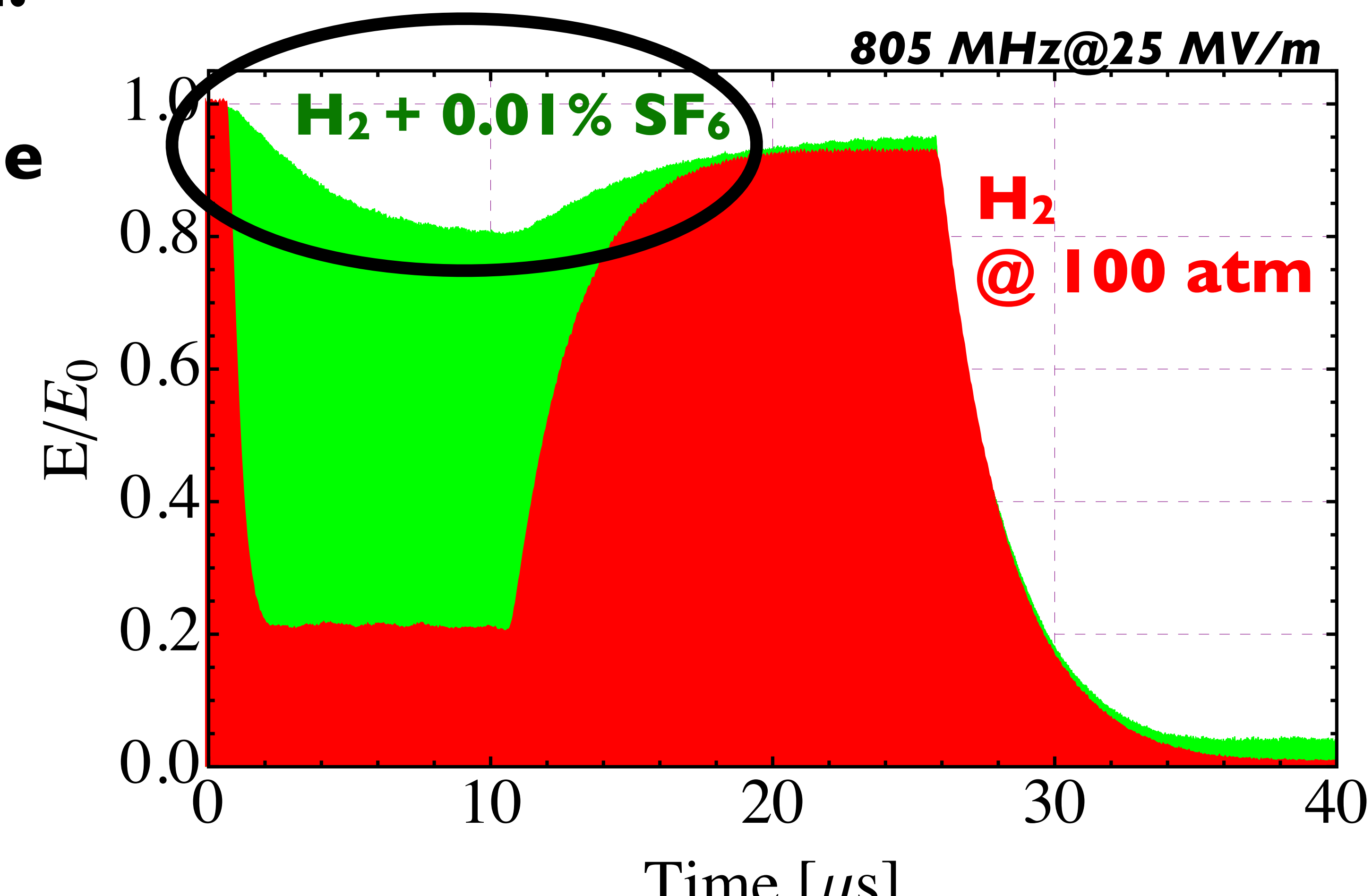
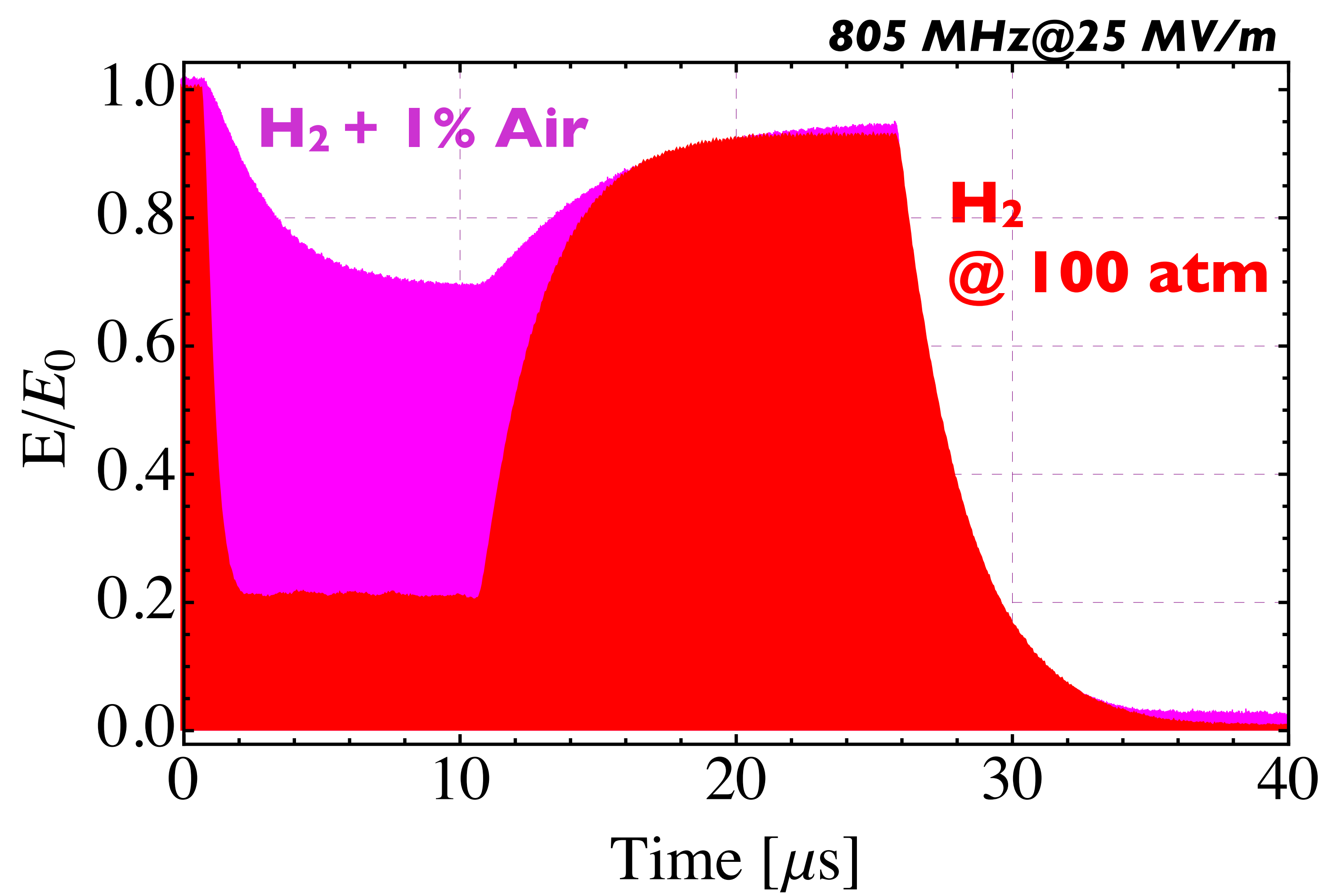


- **Attachment cross-section for SF_6 is such that most electrons in the cavity should be removed within a few RF cycles**
- **Why the loss in energy still?**
- **SF_6^- absorb little energy due to mass**
- **However, H^{3+}, H^{5+}, etc. will still remove energy**
- **Still investigating**



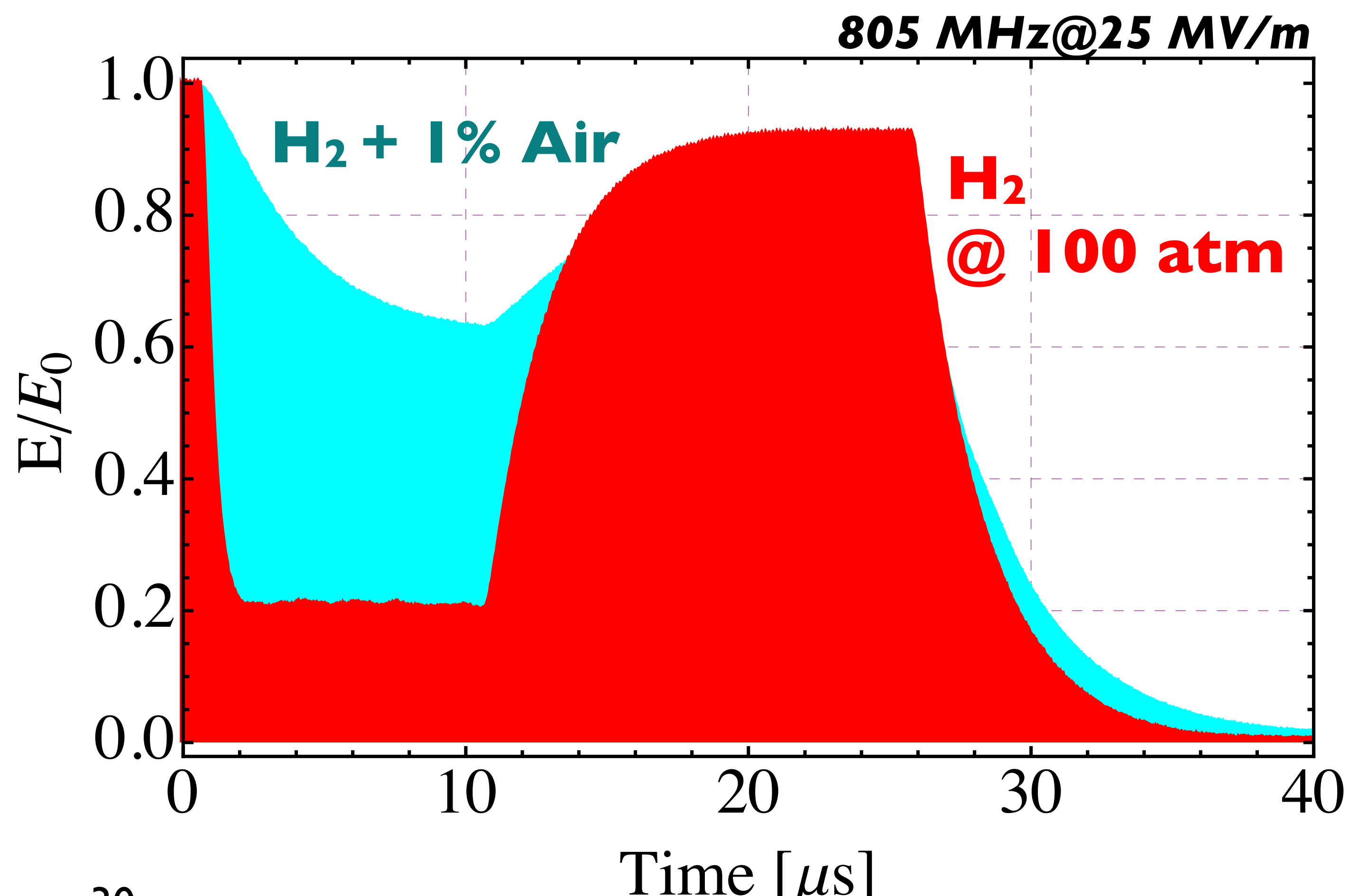
Oxygen

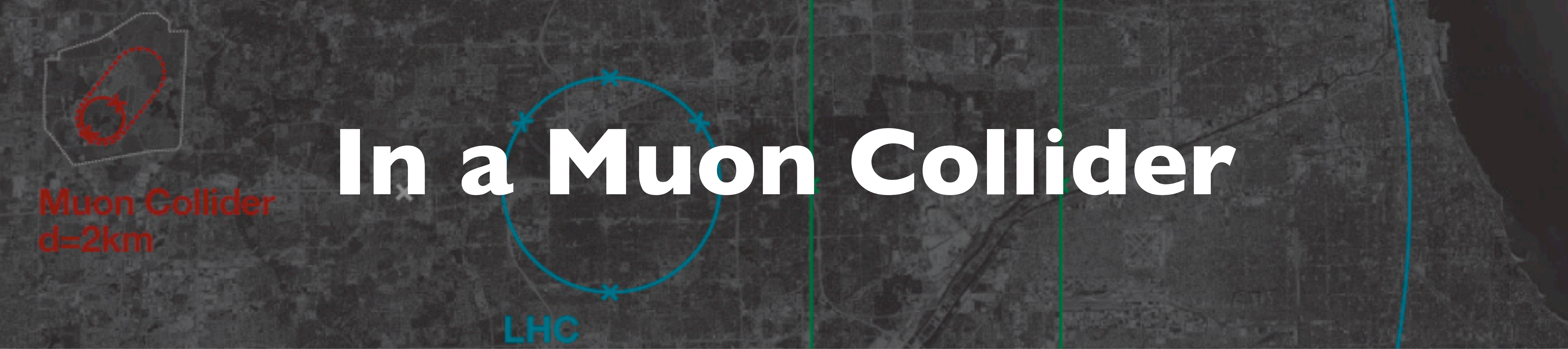
- Unfortunately, SF_6 freezes at liquid N_2 temperatures and is corrosive → O^2 is also a great electronegative gas
- Add 1% of Air (0.2% O_2)
- Similar Performance to SF_6
- Very safe → much lower concentration than lowest explosive level of O_2 in H_2



Magnetic Field Test

- **Putting it all together**
- **Gradient set to 25 MV/m, B-Field at 3 Tesla, using 100 atm H^2 and 1% Air - in a high intensity proton beam**
- **No effective difference in performance!**
- **Successful demonstration of beam in a 25 MV/m HPRF cavity in a 3 Tesla B-Field**





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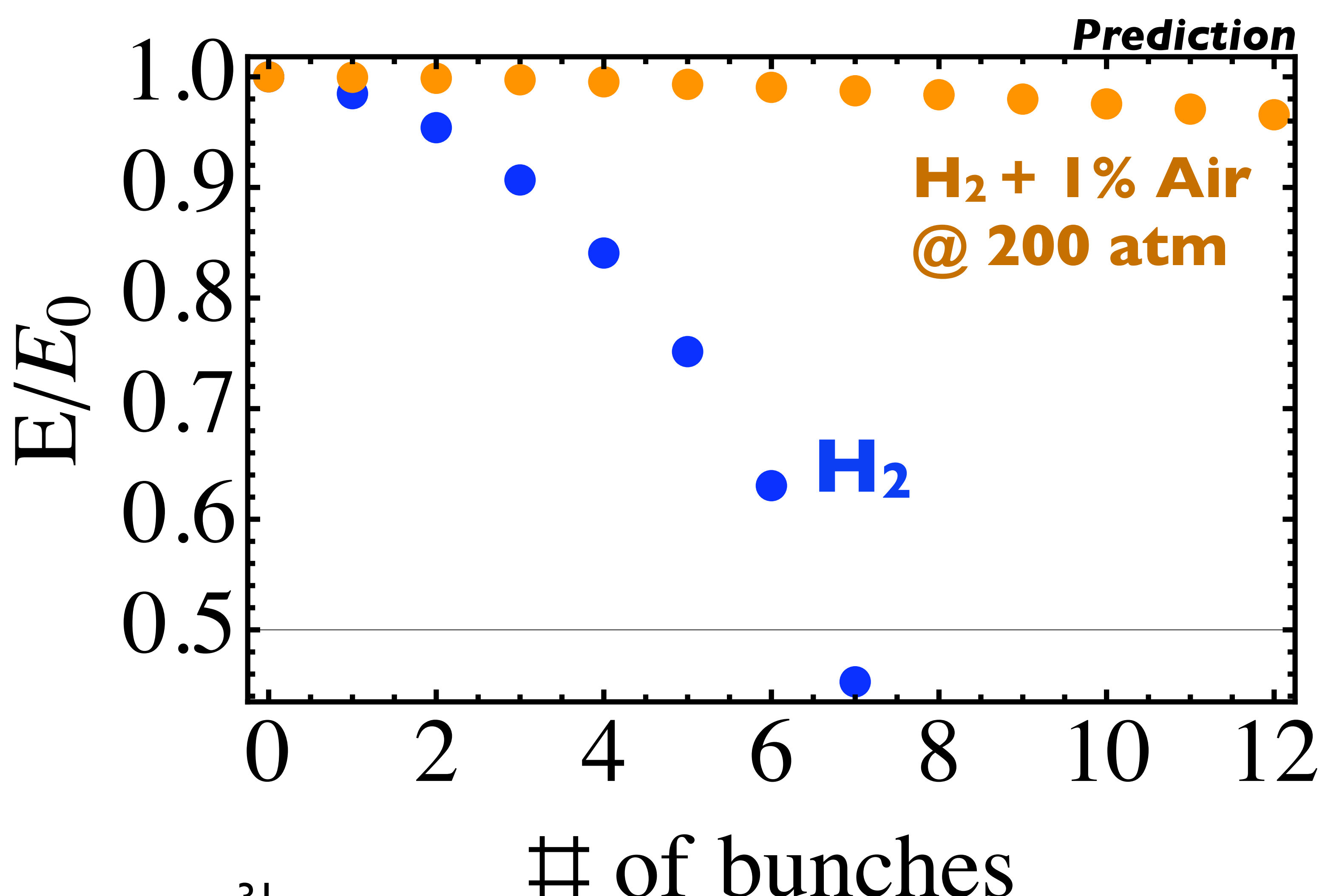
Last Bunch
< 5% Reduction



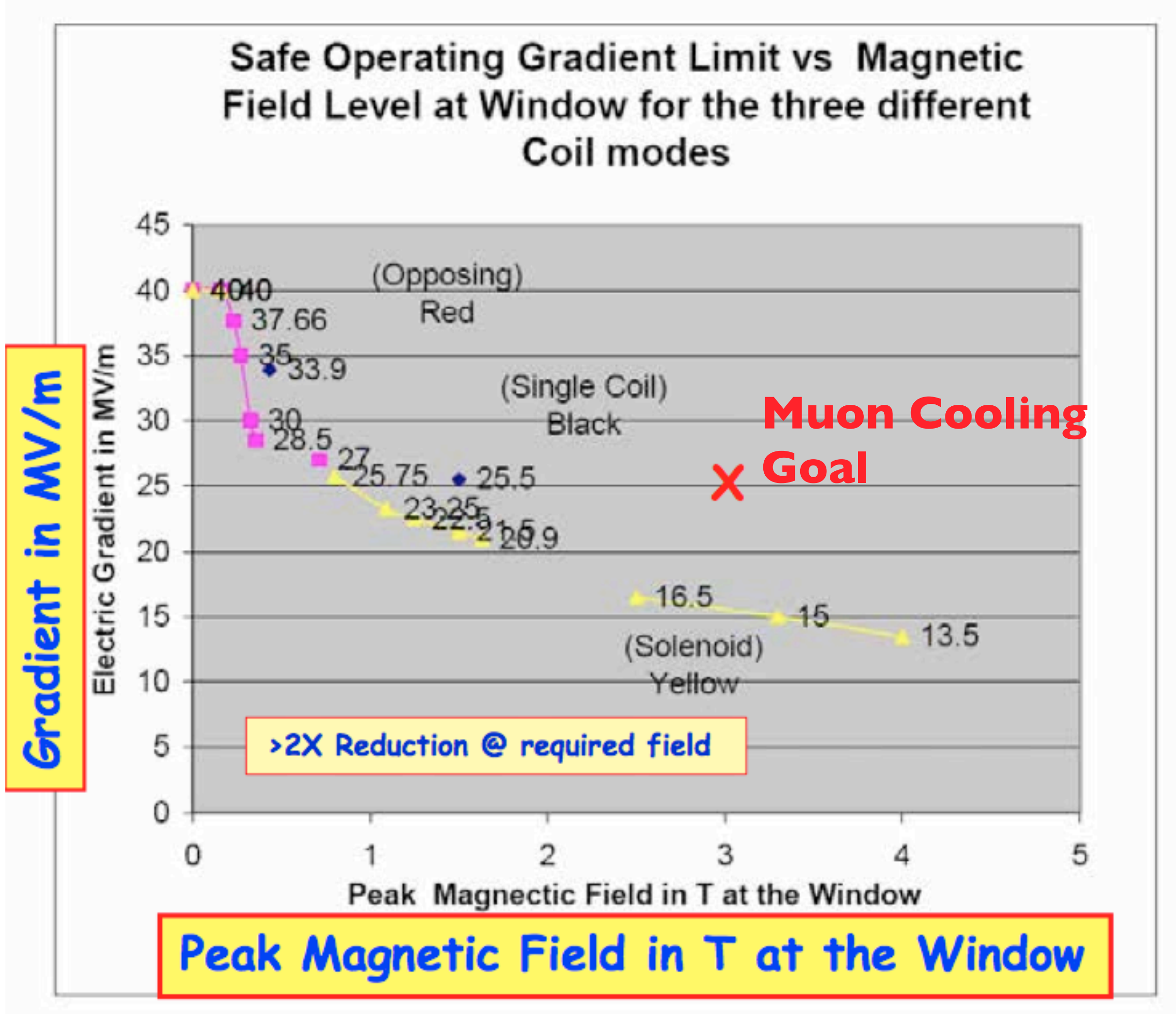
Summary

- **Successfully demonstrated HPRF cavities can achieve a high gradient within a strong magnetic field**

  >50 MV/m and B ~ 3 Tesla

- **Difficult to maintain stable gradients bunch-to-bunch due to gas-beam interactions**

- **Successfully demonstrated the use of electronegative gas dopants as a technique to mitigate these beam effects**



Thanks!!

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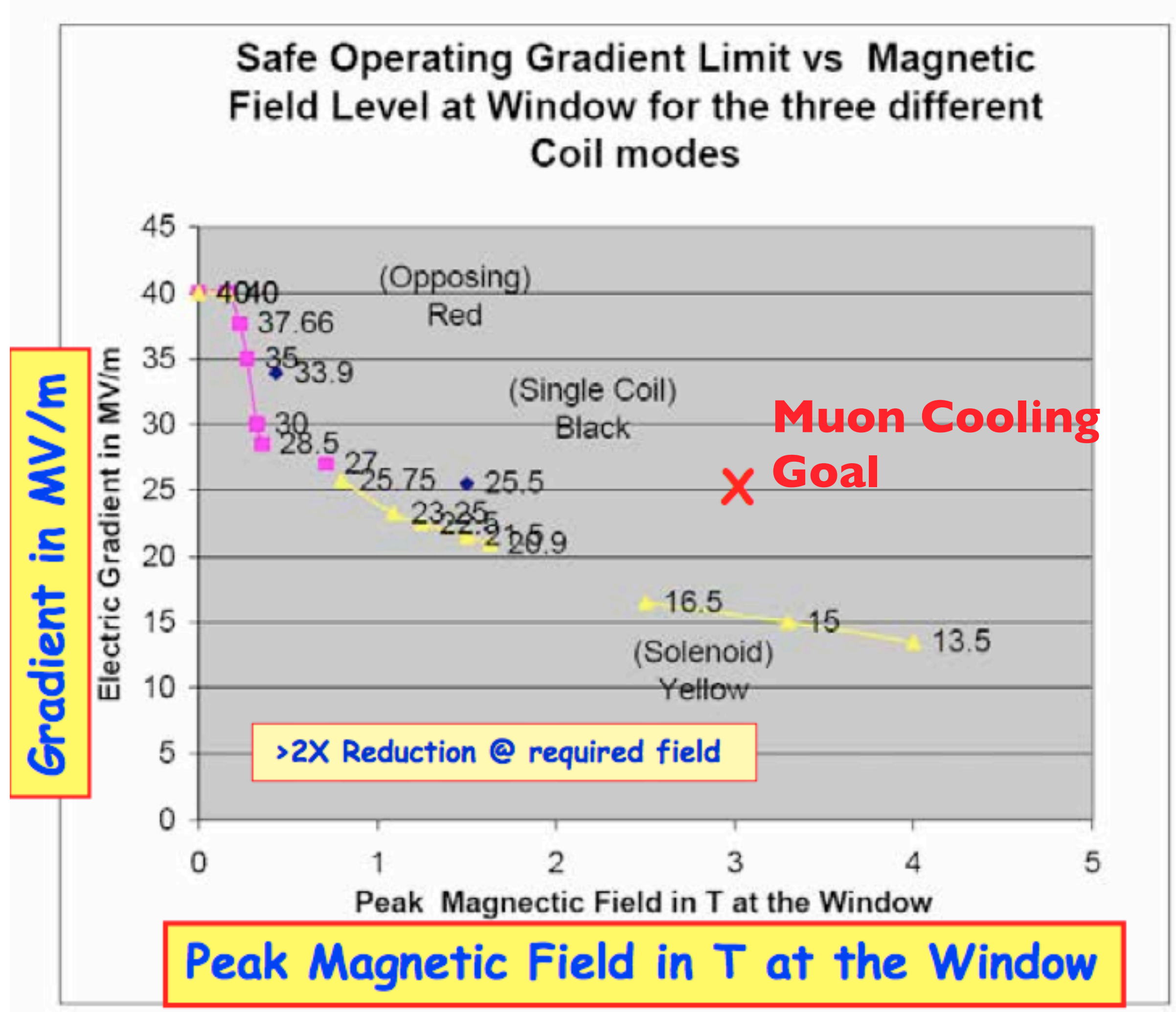
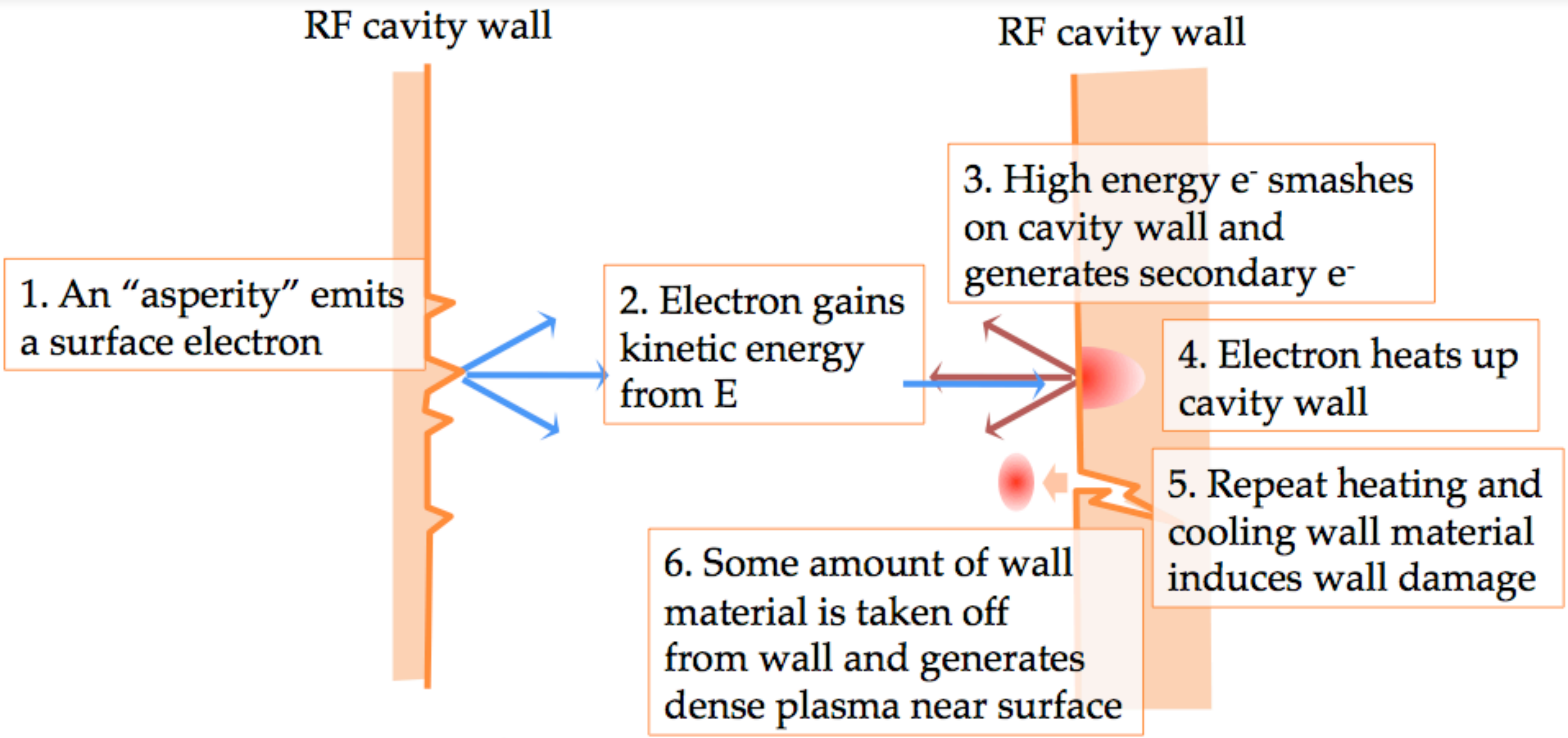


High Pressure Gas-Filled Cavity



B-Field focuses this electron 'beam' which enhances the breakdown process

MTA Beamline and Apparatus