Time Projection Chambers for the Muon-Collider Cooling Experiment

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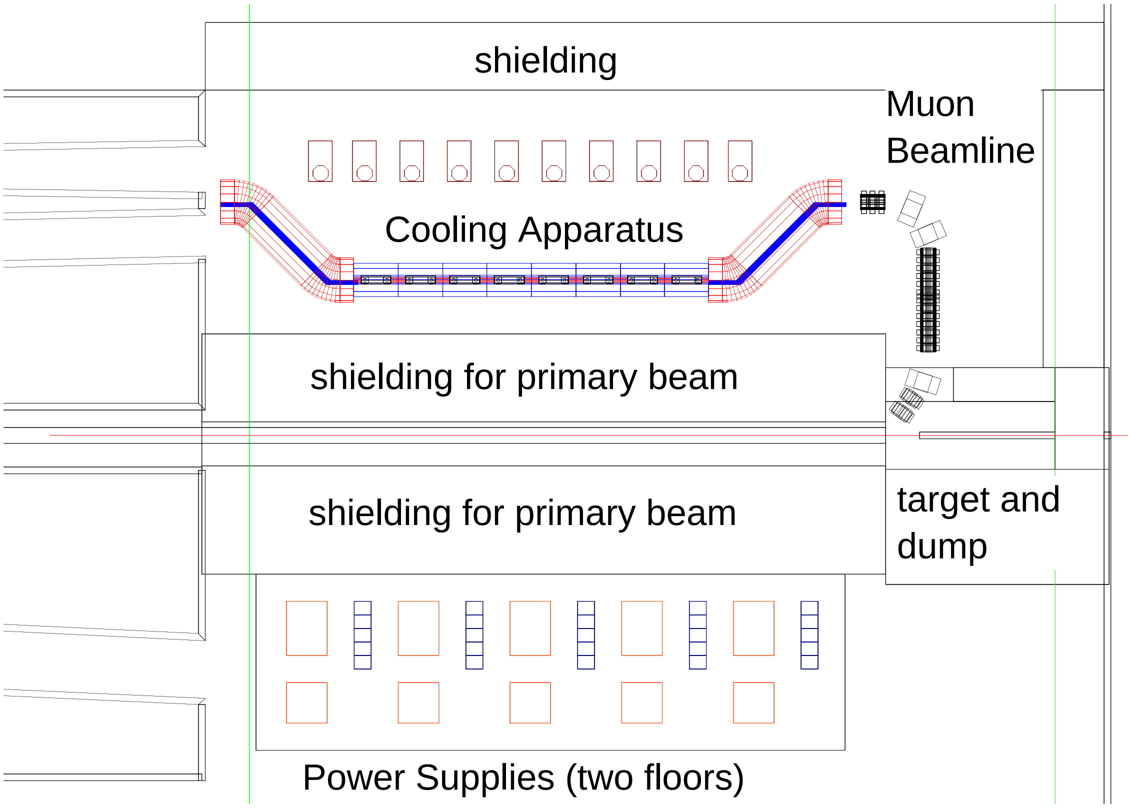
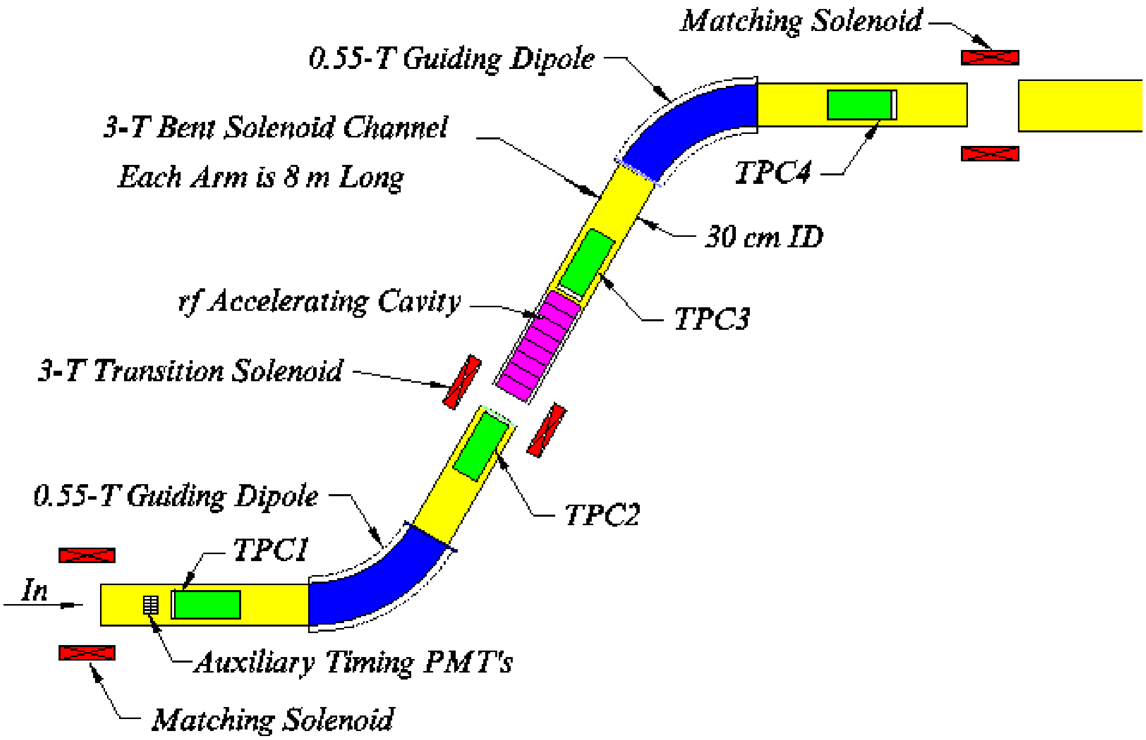
`http://www.hep.princeton.edu/~mcdonald/mumu`

Goal: Measure the emittance of the muon beam to 3% accuracy before and after the muon cooling apparatus.

Possible site: Meson Lab at Fermilab:



Measure 6-D emittance before and after cooling:



Overview

Measure muons individually, and form a virtual bunch in software:

$\Rightarrow$ Must know timing to $\approx$ 10 psec to select muons properly phased to the 800-MHz RF of the cooling apparatus.

$\Rightarrow$ Use RF accelerating cavity to correlate time with momentum.

$\Rightarrow$ Must measure momentum 4 times.

[$\Rightarrow$ Must also have coarse timing ($\lesssim$ 300 psec) to remove phase ambiguity.]

Large transverse emittance, $\epsilon_{N,x} = 1500\pi$ mm-mrad:

$\Rightarrow$ Confine the muon beam in a 3-Tesla solenoid channel.

$\Rightarrow$ All muon detection in the 3-T field.

$\Rightarrow$ Use bent solenoids (toroidal sectors with guiding dipoles) for momentum dispersion.

Muon momentum = 165 MeV/c:

$\Rightarrow$ Larmor period of 1.15 m sets scale for detector arrangement.

$\Rightarrow$ Resolution limited by multiple scattering.

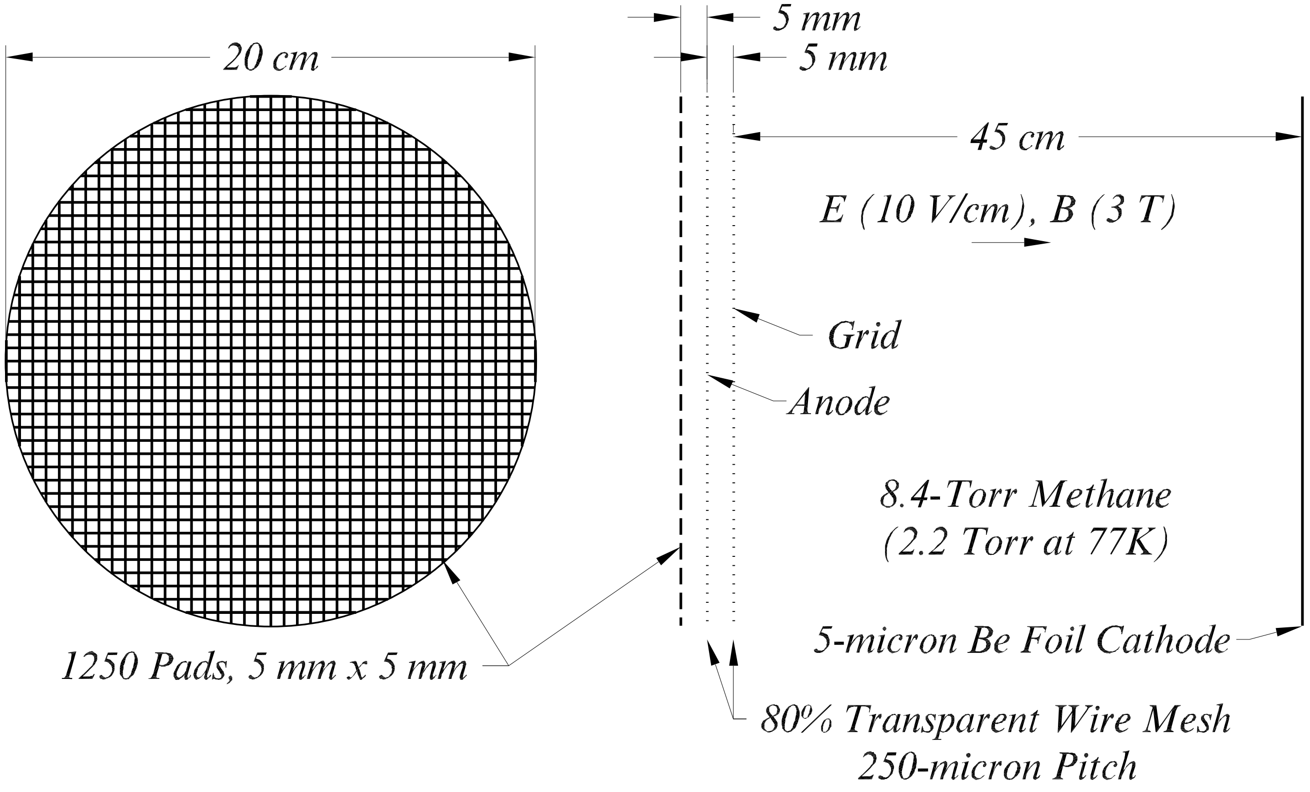
$\Rightarrow$ Perform tracking in a low-pressure gas.

3-T magnetic field $\Rightarrow$ simplest if detector $\mathbf{E} \parallel \mathbf{B}$.

$\Rightarrow$ **Time Projection Chambers** (TPC's)

Higher momentum muons $\Rightarrow$ higher B and/or larger radius magnets.

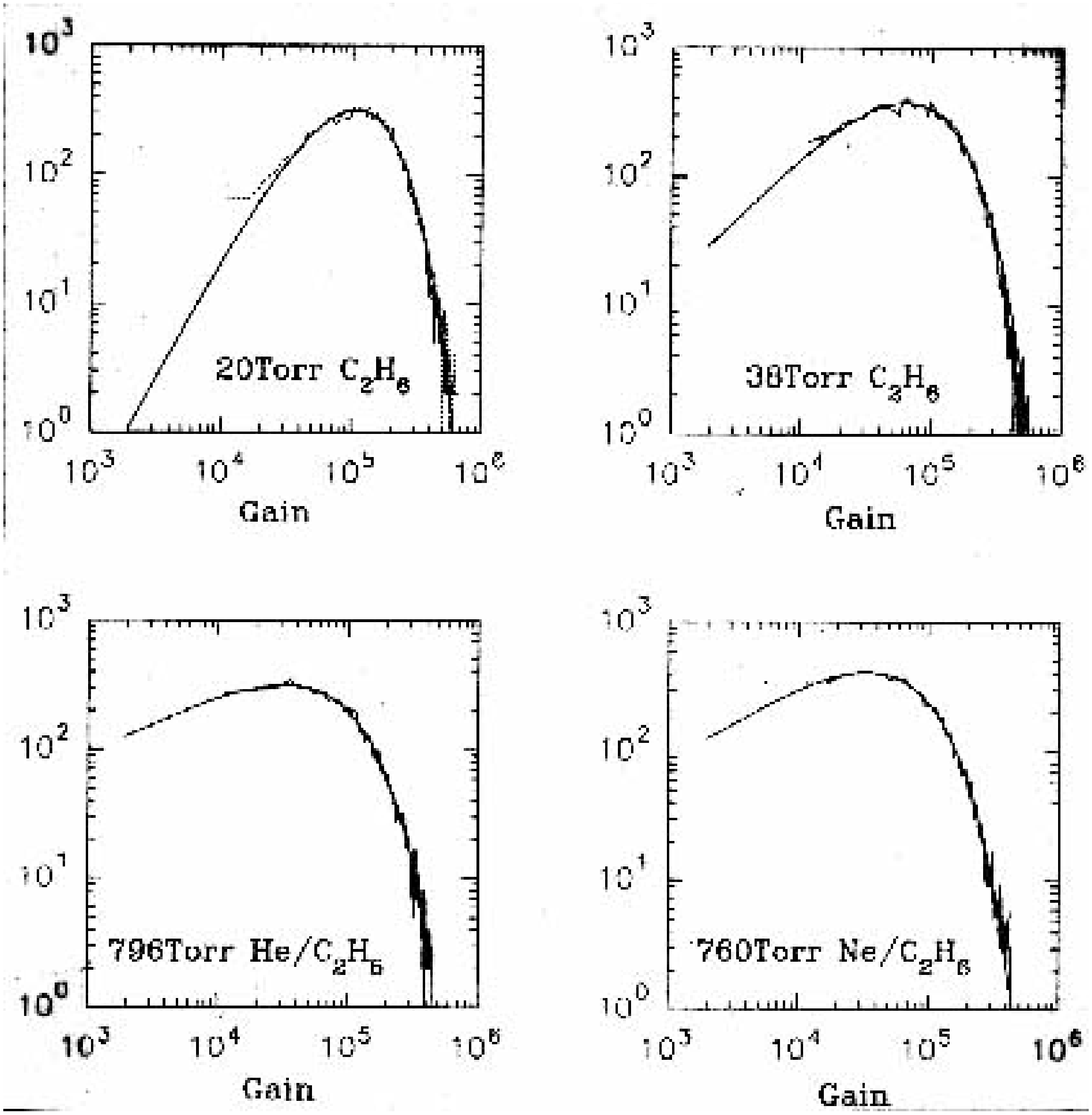
Time Projection Chamber



- Two TPC's in same pressure vessel for each of 4 momentum spectrometers.
- Low gas pressure ⇒ low operating voltage.
- 1250 cathode pads, 50-MHz timing sampling.
- Analog pipeline via 512-deep switched-capacitor arrays.
- No trigger: capture entire 10 μsec window.
- Could process ≈ 10 tracks ⇒≈ 1 MHz rate capability.

Gas Gain at Low Pressure

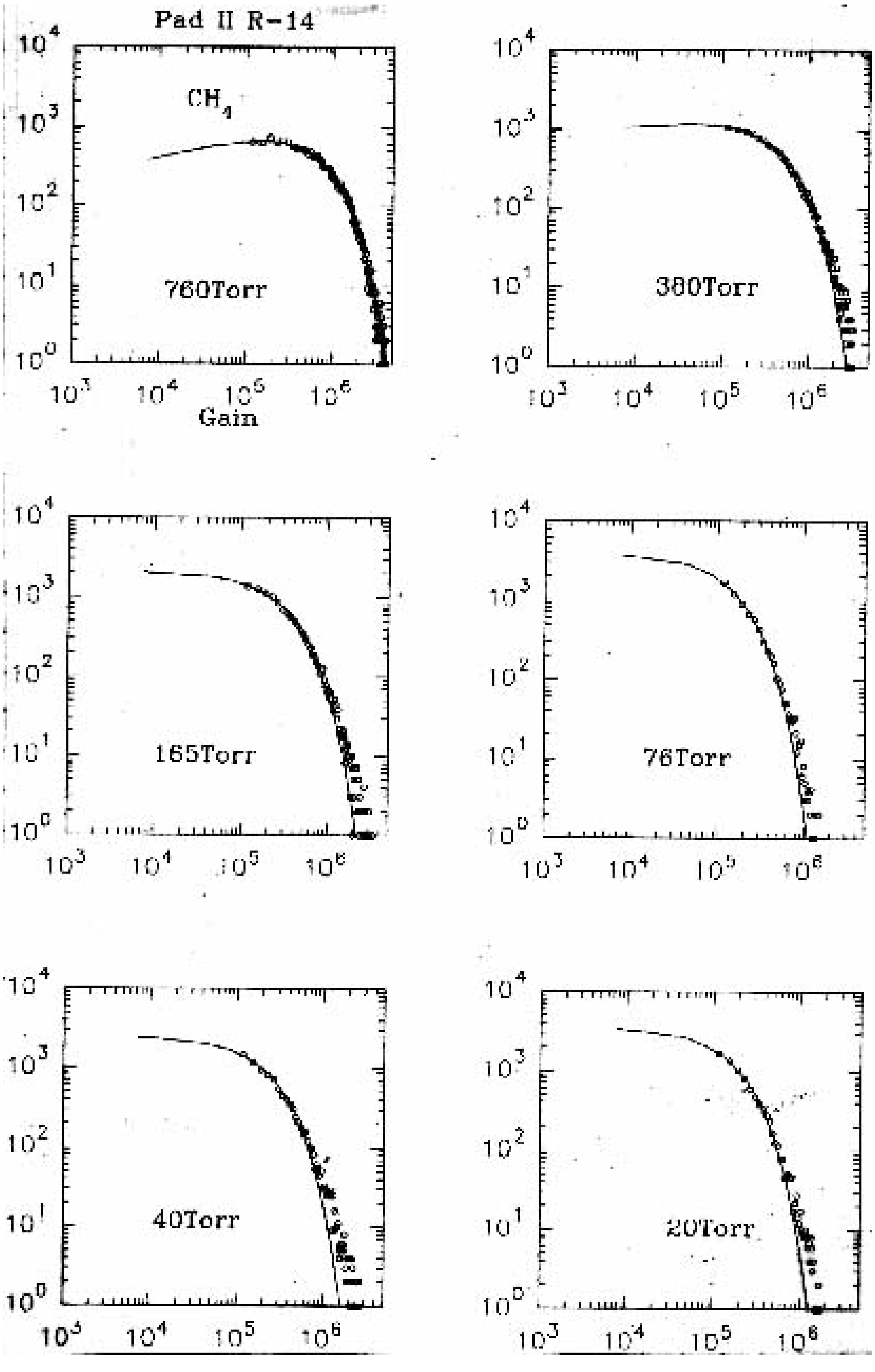
C_2H_6 (or isobutane) reasonably stable at 20 Torr:



Can gain additional stability by adding helium as a buffer.

[C. Lu *et al.*, NIM **A334**, 328 (1993).]

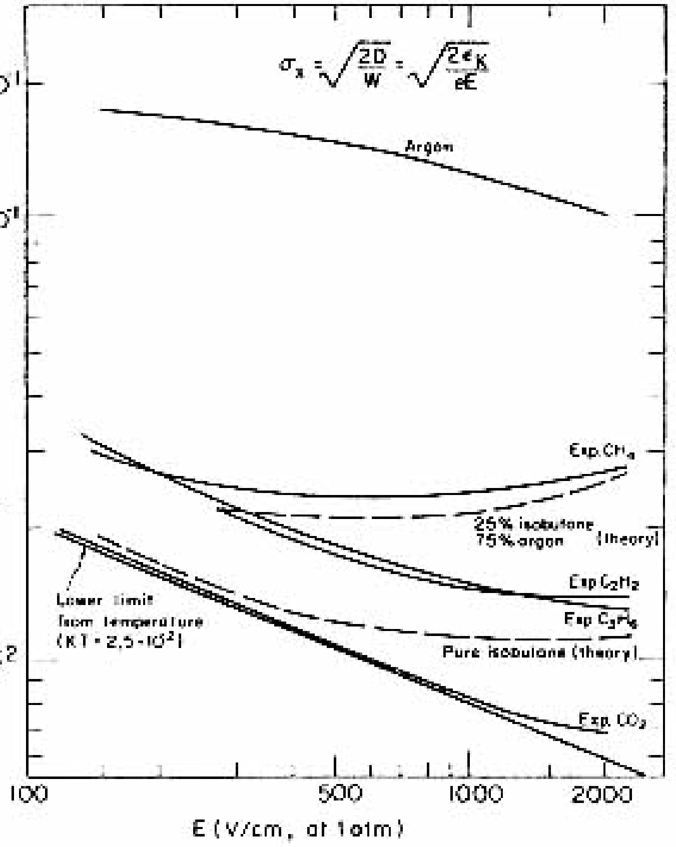
Gain of 10^5 possible, but difficult for CH_4 at 20 Torr:



Diffusion

Mean free path longer at low pressure ⇒ larger diffusion!

$$\text{Spatial smearing;} \qquad \sigma = \sqrt{2Dt} = \sqrt{\frac{2Dz}{v_d}}.$$



But in a magnetic field, transverse diffusion ≪ longitudinal.

Our measurement of $P_\perp$ in unaffected by longitudinal diffusion.

$$P = \frac{P_\perp}{\tan\theta} \approx \frac{P_\perp}{\theta} \qquad \Rightarrow \frac{\delta P}{P} = \sqrt{\left(\frac{\sigma_{P_\perp}}{P_\perp}\right)^2 + \left(\frac{\sigma_\theta}{\theta}\right)^2}.$$

Longitudinal Diffusion When $\mathbf{E} \parallel \mathbf{B}$

$$D_\parallel \approx \frac{v_d kT}{eE} \quad \text{(Einstein)} \qquad \Rightarrow \qquad D(E,T) = \frac{T}{T_0}\frac{E_0}{E} D(E_0, T_0).$$

$D_\parallel = 10^5\ \mathrm{cm^2 s^{-1}}$ at the saturation velocity $v_d = 10^7$ cm/s in methane at 100°K and 0.01 atmosphere.

$$\Rightarrow \qquad \sigma_z = \sqrt{\frac{2D_\parallel x}{v_d}} \equiv A\sqrt{z}, \qquad \text{where} \qquad A = 0.135\ \mathrm{cm}^{\frac{1}{2}}.$$

Fit for track angle θ via $u = z/\theta$ where $\hat{\mathbf{u}} \perp \hat{\mathbf{z}}$ and U is measured on the surface of the helix.

$$\chi^2 = \sum_i^N \frac{(z_i - u_i/\theta)^2}{\sigma_{z_i}^2} = \sum_i^N \frac{(z_i - u_i/\theta)^2}{A^2 z_i},$$

$$\Rightarrow \qquad \frac{1}{\sigma_\theta^2} = \frac{\partial \chi^2}{\partial \theta^2}, \qquad \text{and hence} \qquad \sigma_\theta = A\theta\sqrt{\frac{\theta}{Nz}}.$$

$\sigma_{\theta,\text{diffusion}} \approx 0.00006$ for $N = 15$, $z = 45$ cm, and $\theta_{\text{rms}} = 0.05$.

$\Rightarrow$ Longitudinal diffusion not a problem.

Transverse Diffusion When $\mathbf{E} \parallel \mathbf{B}$

Field $\mathbf{B}$ ⇒ transverse mean free path $\lesssim$ Larmor radius.

$$\Rightarrow \qquad D_\perp \approx \frac{r_B}{l} D_\parallel = \frac{kT}{m\omega_B}.$$

$$\text{noting} \qquad \frac{r_B}{l} = \frac{v_d/\omega_B}{v_d\tau} = \frac{1}{\omega_B\tau} \approx \frac{1}{3000}, \qquad \text{and} \qquad v_d \approx \frac{eE}{m}\tau.$$

$\Rightarrow D_\perp \approx 33\ \mathrm{cm}^2\mathrm{s}^{-1}$,

using $\omega_B = 1.8 \times 10^{11}$ Hz $\times\, B$ [Tesla], and $B = 3$ T.

$$\Rightarrow \qquad \sigma_{\perp,\text{diffusion}}(45\ \text{cm}) \approx \sqrt{\frac{2 \cdot 33 \cdot 45}{10^7}}\ \text{cm} = 170\ \mu\text{m}.$$

⇒ Transverse diffusion not a problem.

Delta Rays

When an atom is struck by a high-energy particle, ≈ 100 eV is deposited, with a long tail (δ-rays) to higher energies.

$\Rightarrow$ 'Cluster' of 1-2 secondary ionizations + primary ionization.

Does this compromise the spatial resolution of the detector?

- No problem transverse to magnetic field lines:

$$r[\mathrm{m}] = \frac{p[\mathrm{MeV}/c]}{300B[\mathrm{T}]} = \frac{\sqrt{\mathrm{KE}[\mathrm{MeV}]}}{300B[\mathrm{T}]},$$

  $\Rightarrow r = 10\ \mu$m for KE $= 100$ eV, $B = 3$ T; 100 μm for 10 KeV.

- What is longitudinal range of 100-eV electrons?

  Mean free path of few-eV electrons is 600 μm in CH_4 at 7.6 Torr.

  keV electrons: $\mathrm{Range}[\mu\mathrm{m}] \approx 0.025\frac{A}{\rho Z^{0.85}}(\mathrm{KE}[\mathrm{MeV}])^{1.69} \approx 160\ \mu\mathrm{m}$ for KE $= 100$ eV.

  [C. Feldman, Phys. Rev. **117**, 455 (1960).]

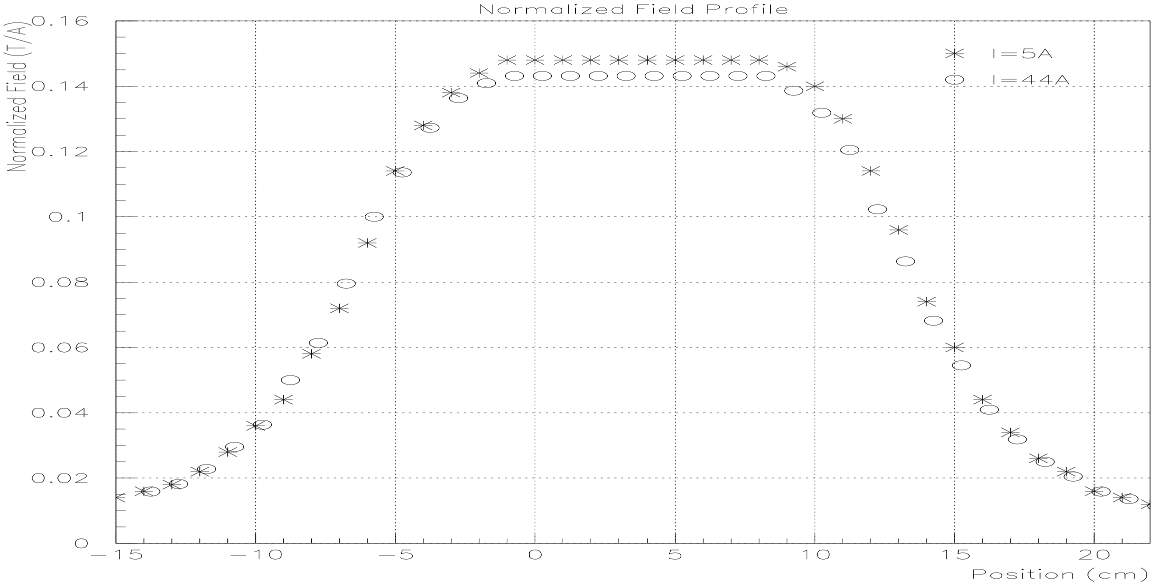
Detector R&D at Princeton

We are now building a small 16-channel low-pressure TPC, which can fit inside an old 6-T magnet that we recently recomissioned.

To study:

1. Accuracy of time and space interpolation via charge sharing on readout pads.
2. Measurement of gas gain, drift velocity and diffusion at low temperature and pressure for methane and other candidate gases.
3. Verification of detector performance over long drift paths in a strong magnetic field.
4. Viability of placement of readout electronics next to pad plane (inside the magnetic field).
5. Dynamic range the STAR SCA at 50 MHz (somewhat higher than nominal).

6-T, 3.5-cm-Diameter, Warm-Bore Magnet



Prototype TPC