Fermilab

IPM Simulations at Fermilab

3-4 March 2016

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Nova Era Main Injector / Recycler

- Recycler accumulates protons from Booster synchrotron
  - 8 GeV
  - ~5 x 10^{13} protons
- Main Injector receives beam from Recycler
  - 8 GeV incoming
  - Up to 120 GeV outgoing
    - Nova neutrino experiment
  - 588 53-MHz rf buckets
    - each bucket ~18 ns
    - 1 x 10^{11} protons per bucket
    - Bunch length typically ~1-3 ns
  - Few millimeters transverse sigma

MATLAB Simulation

- Simulation tracks particles through arbitrary E and B fields
- Uses interpolation to obtain the fields at any point from previously calculated field distributions
- Propagates using a relativistic formula

$$\mathbf{F}(\mathbf{r},t)=\frac{d\mathbf{p}}{dt}=m\frac{d\tilde{\gamma}\mathbf{v}}{dt}$$
$$=m\left(\mathbf{v}\frac{d\tilde{\gamma}}{dt}+\tilde{\gamma}\mathbf{a}\right)$$
$$\mathbf{F}(\mathbf{r},t)=m\tilde{\gamma}\left(\mathbf{a}+\tilde{\gamma}^2\tilde{\boldsymbol{\beta}}\left(\tilde{\boldsymbol{\beta}}\cdot\mathbf{a}\right)\right)$$

Invert →

$$\mathbf{a}=\frac{1}{\tilde{\gamma}m\left(1+\tilde{\gamma}^2\tilde{\beta}^2\right)}\left[\mathbf{I}+\tilde{\gamma}^2\left(\tilde{\beta}^2\mathbf{I}-\tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right)\right]\mathbf{F}$$
$$=\frac{1}{\tilde{\gamma}m}\left[\mathbf{I}-\frac{\tilde{\gamma}^2}{\left(1+\tilde{\gamma}^2\tilde{\beta}^2\right)}\tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right]\mathbf{F}$$
$$\mathbf{a}=\frac{1}{\tilde{\gamma}m}\left[\mathbf{I}-\tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right]\mathbf{F}$$

Matlab Simulation

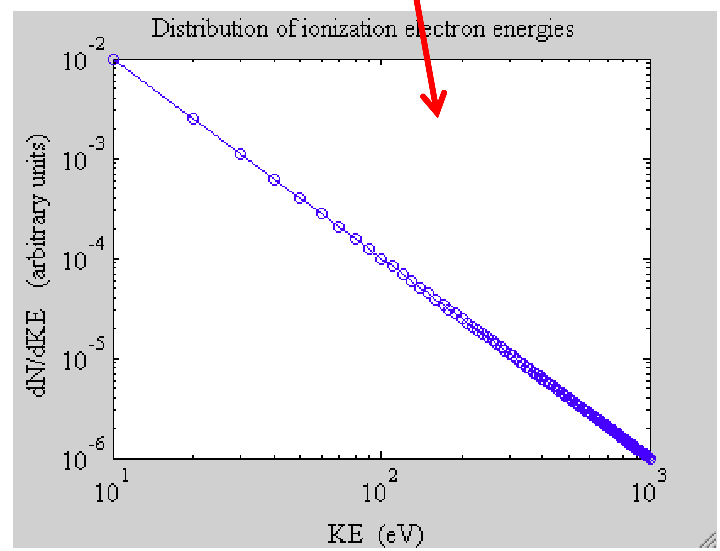
- Once the acceleration is determined, a discrete evaluation of the differential equation of motion is used to step the particles
  - $\mathbf{v}_{i+1} = \mathbf{v}_i + \mathbf{a}_i \Delta t$
  - $\mathbf{r}_{i+1} = \mathbf{r}_i + \mathbf{v}_i \Delta t + \frac{1}{2} \mathbf{a}_{i+\frac{1}{2}} \Delta t^2$
- The magnetic and electric fields are handled separately
  - Magnetic contribution to the motion is only applied to the components perpendicular to the B field
  - Magnitude of the velocity perpendicular to the B field is forced to be preserved, since the B field does no work
    - This in particular helps with the tight spirals along the field lines

Source Fields

- The electric and magnetic fields of the bunch are calculated before hand for various bunch parameters
  - Evaluated with proper time delay to represent the moving beam
- Electric field of Fermilab IPM determined from a 2-D Poisson calculation
  - Would like to create a more detailed 3-D electric field distribution using CST
  - Try to explain discoloration on beam chamber out from ends of IPM active region
- Magnetic field of Fermilab IPM from 3-D magnet model

Ionization Particle Distributions

- Ionized particle distributions are random in emission angle with $1/E^2$ energy distribution
  - Don't think random emission is correct
- Not sure how to deal with low KE regime
  - Dominated by quantum effects?
  - Does it matter?



Gated-on Expected Signal

- From figure 7 of Sauli [#], the number of primary ion pairs produced in one centimeter of a gas species *i* at one atmosphere of pressure by one minimum ionizing particle can be roughly parameterized as

$$n_i \approx \frac{3}{2} Z_i$$

- Expressing this in terms of the proton bunch parameters and partial pressures in the beampipe one arrives at

$$n_j(t) \approx \frac{QL\delta}{500e\sigma_T\sigma_t 2\pi}\left[e^{-\frac{(j\Delta)^2}{2\sigma_T^2}}\right]\left[e^{-\frac{t^2}{2\sigma_t^2}}\right]\sum_i Z_i P_i$$

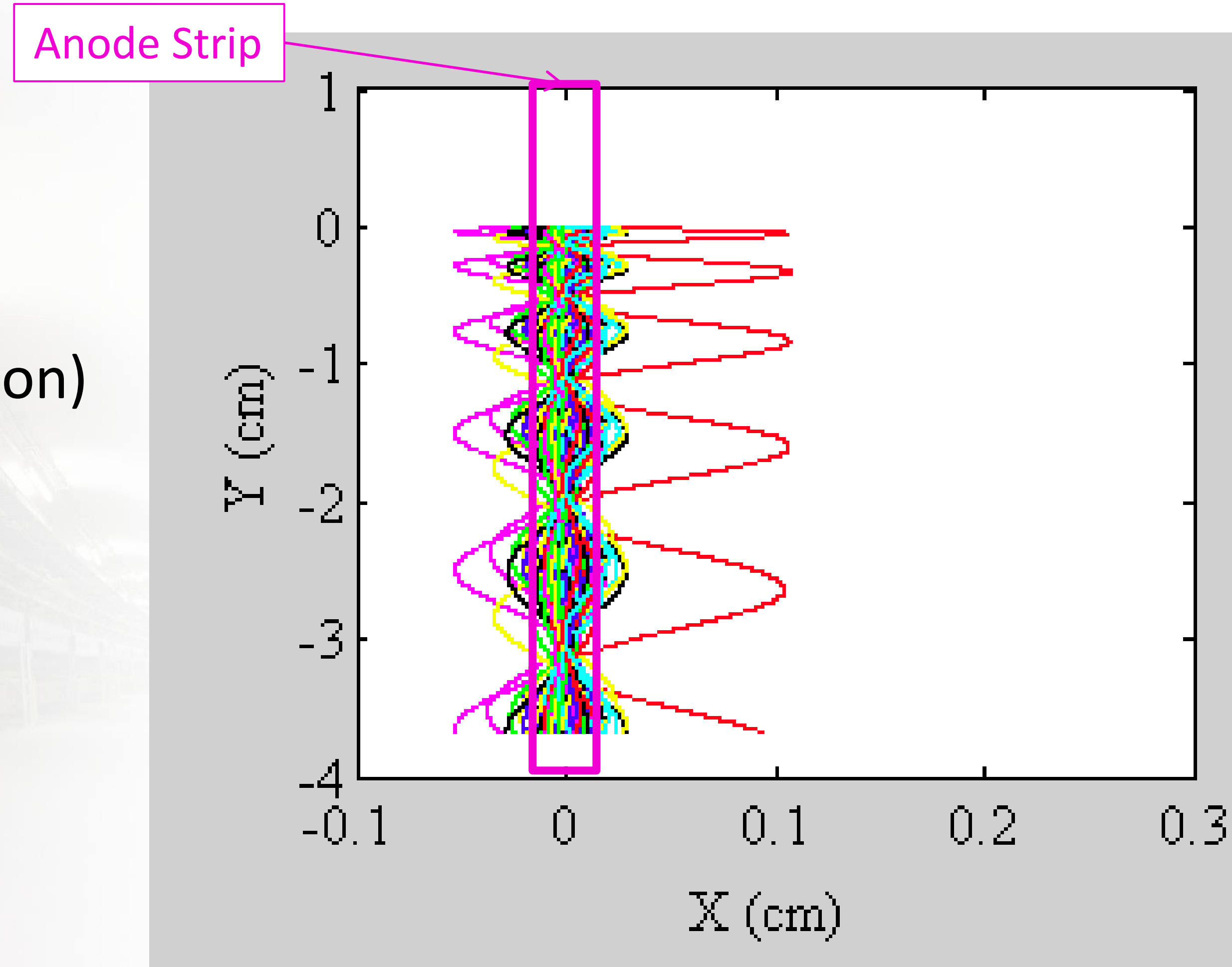
- At the peak of a Main Injector bunch, the number of ionization electrons is ~10 per anode strip (no MCP gain)

[#] *F. Sauli, "Principles of Operation of Multiwire Proportional and Drift Chambers", CERN 77-09, 3/5/77.*

Gated-on IPM

Particles originating from single point (resolution contribution)

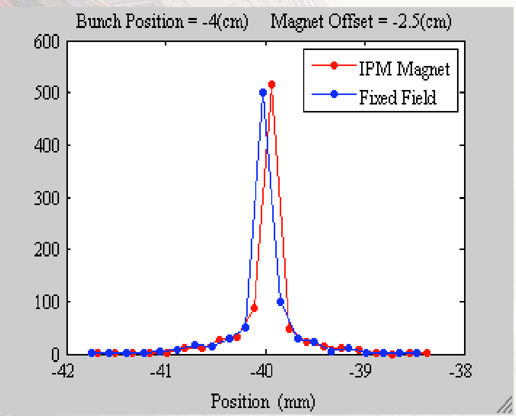
Elapsed time ~ 1.7 ns

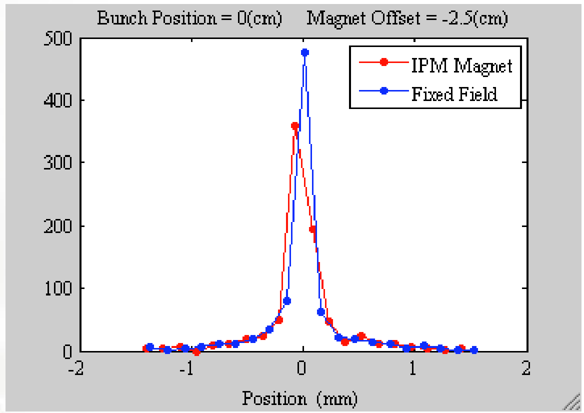


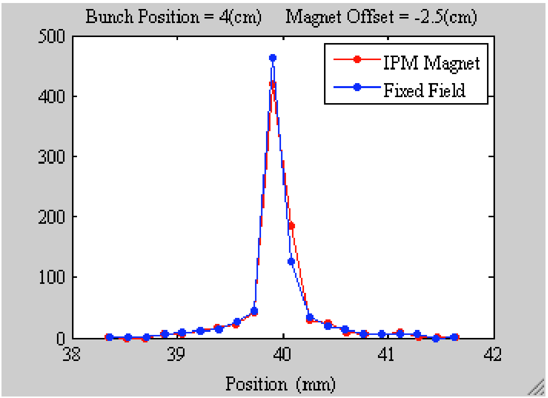
Gated-on IPM

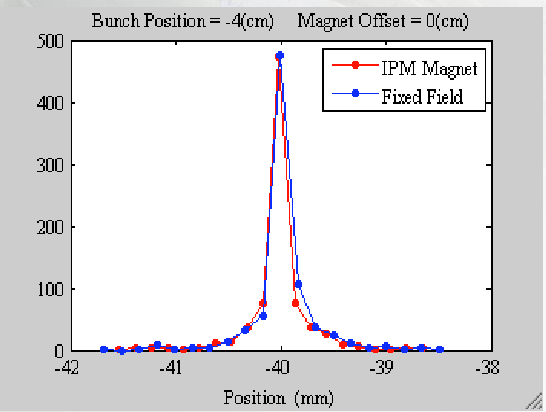
Particles originating from single point
(resolution contribution)

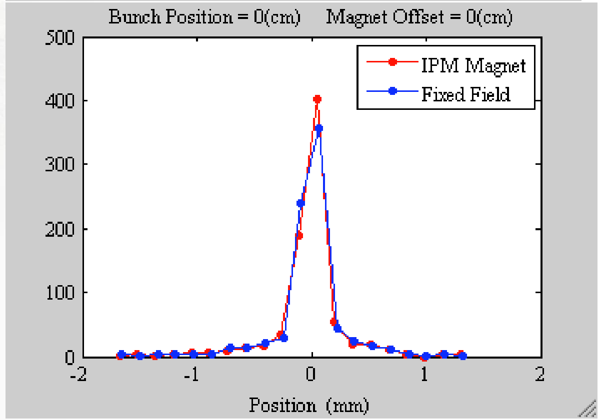
Bunch offset refers to x

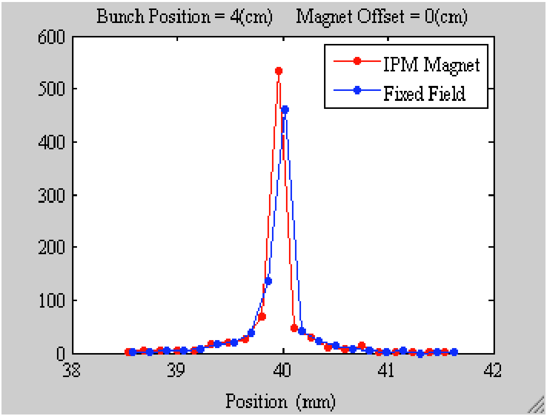












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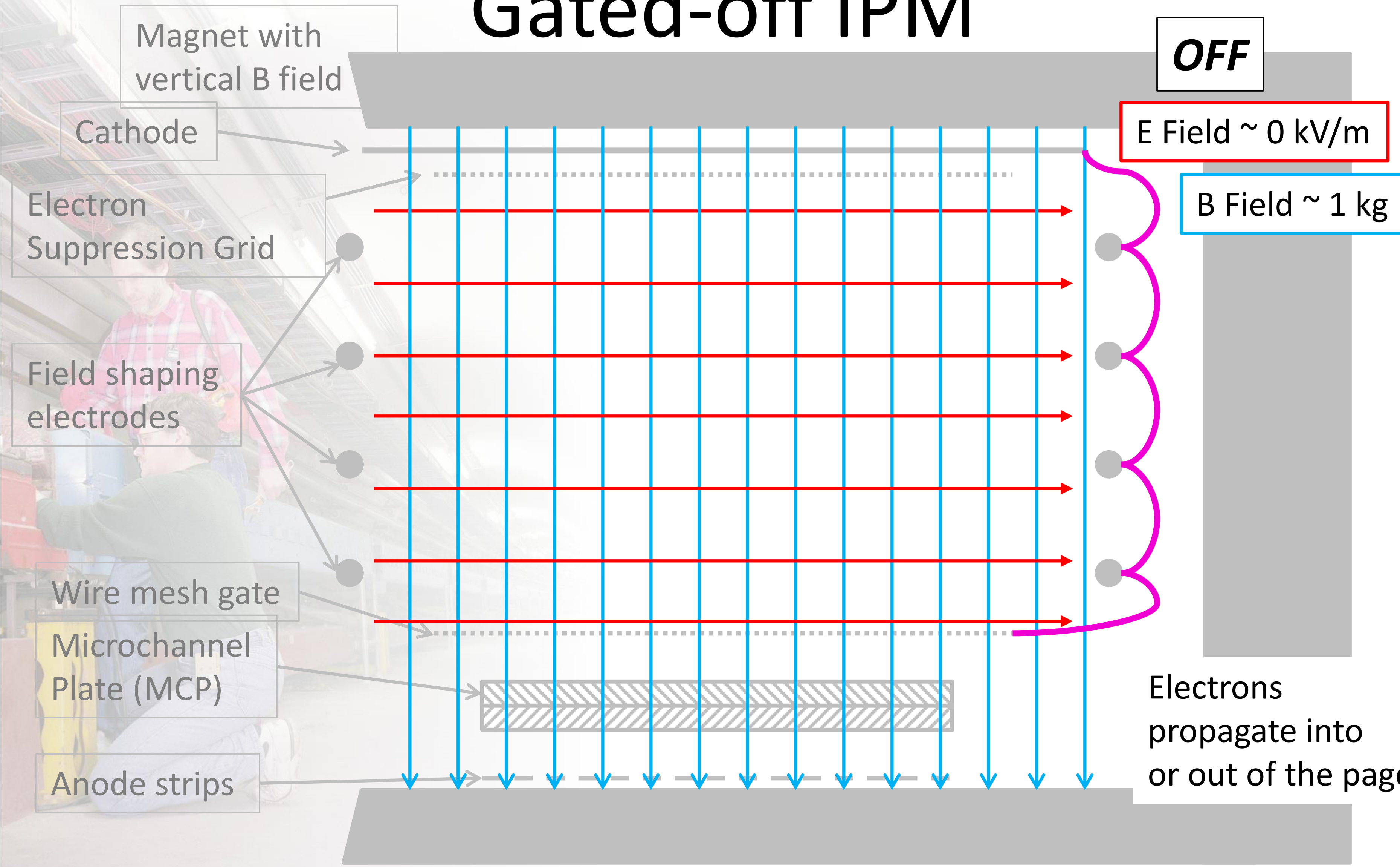
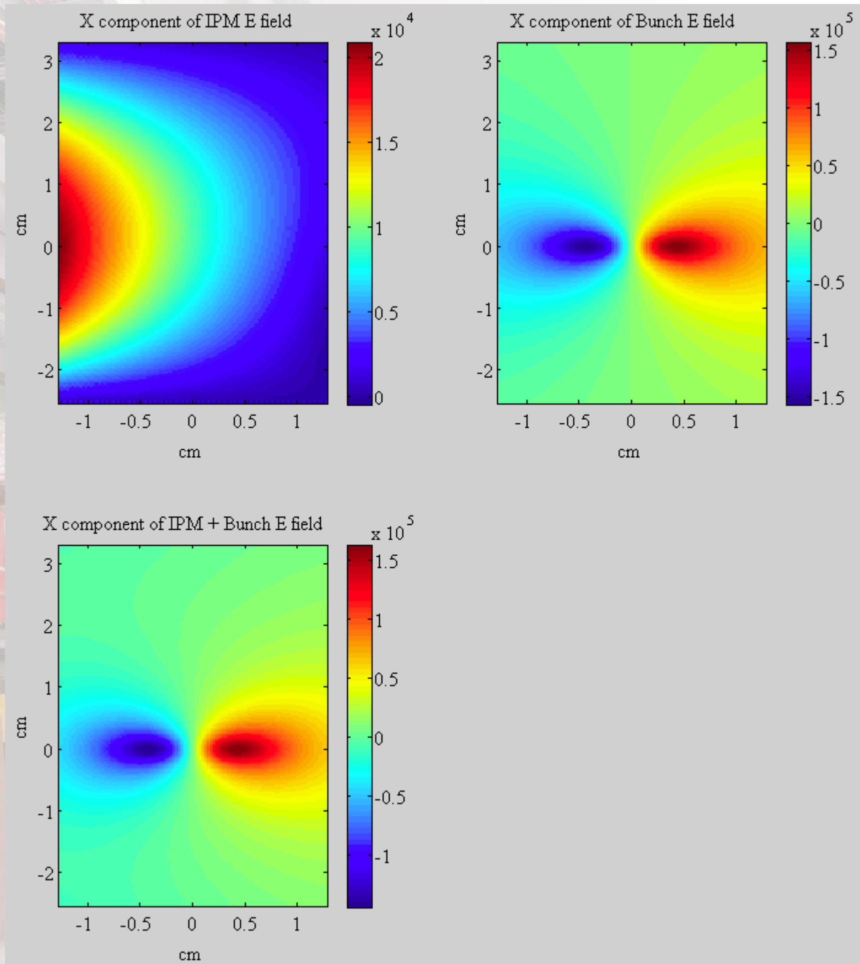
Gated-off IPM



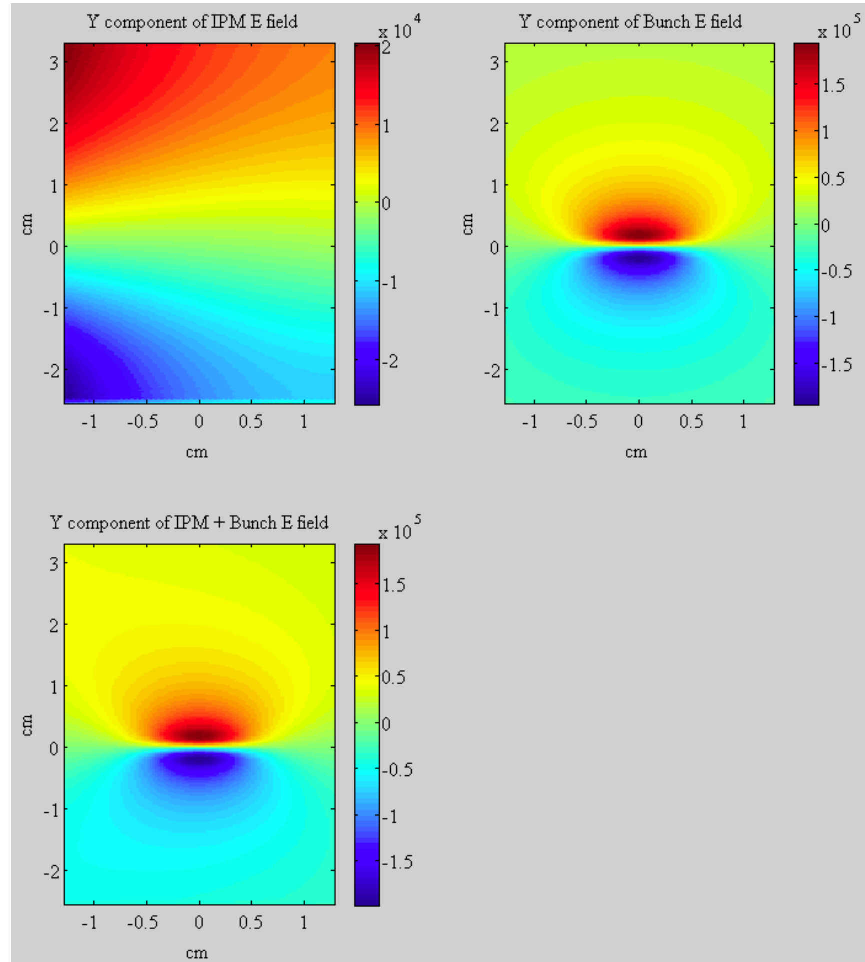
Electrons propagate into or out of the page

Gated-off Fields

X Component of E field

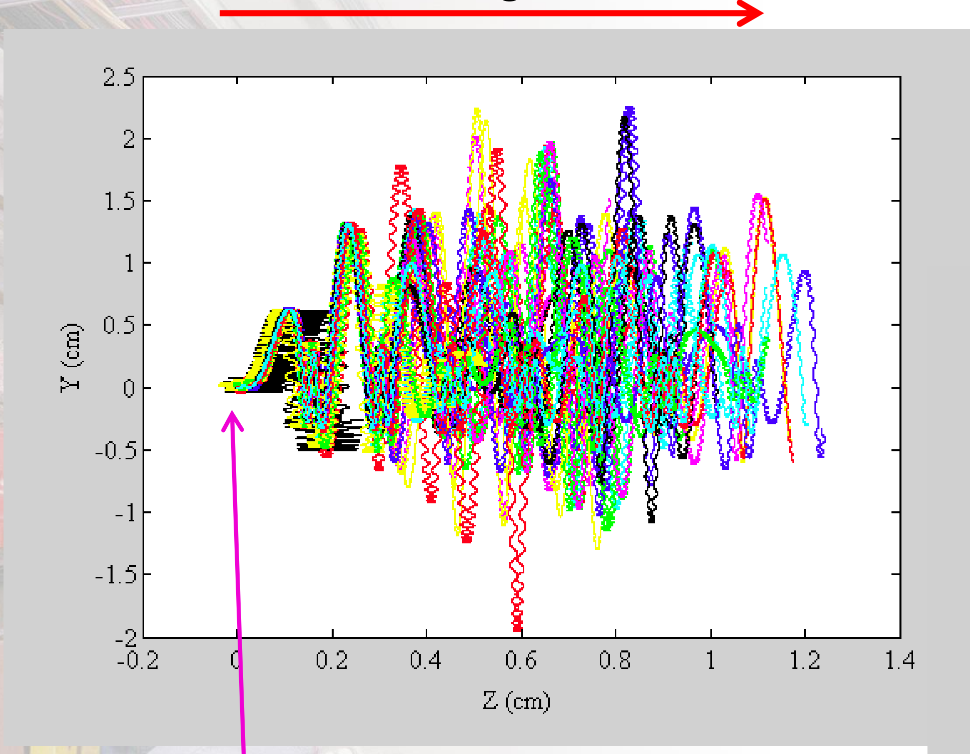


Y Component of E field



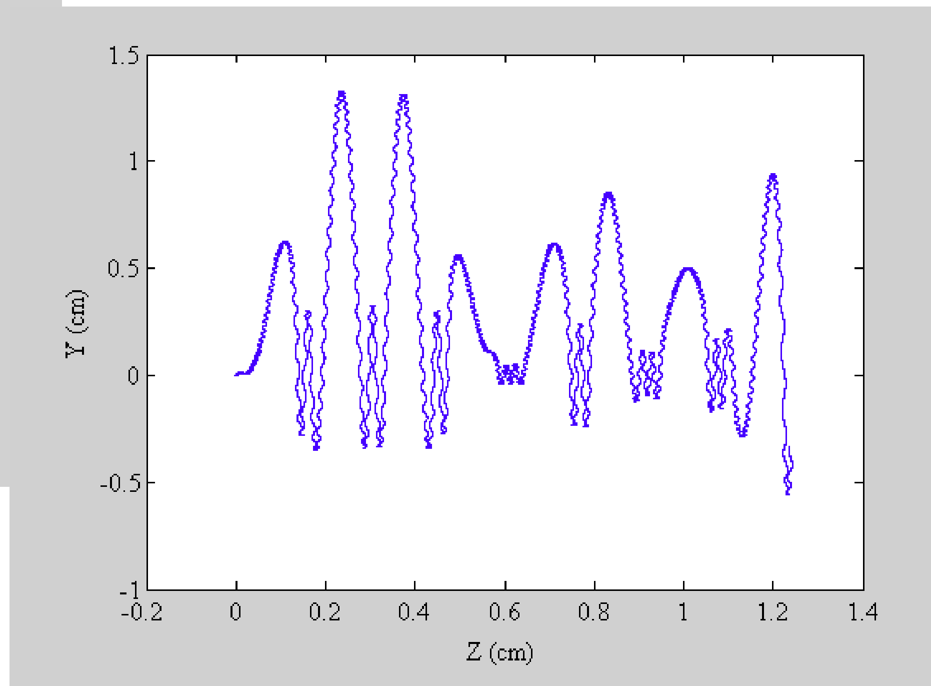
Gated-off Motion

Electron drift along beam direction



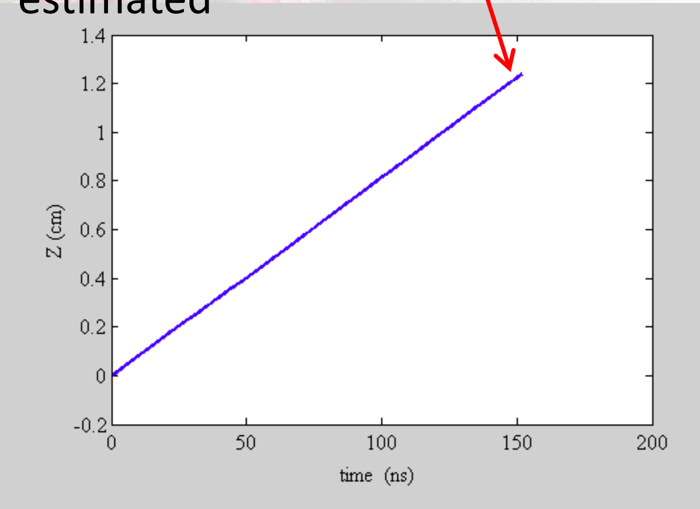
Particle origination point

Single particle

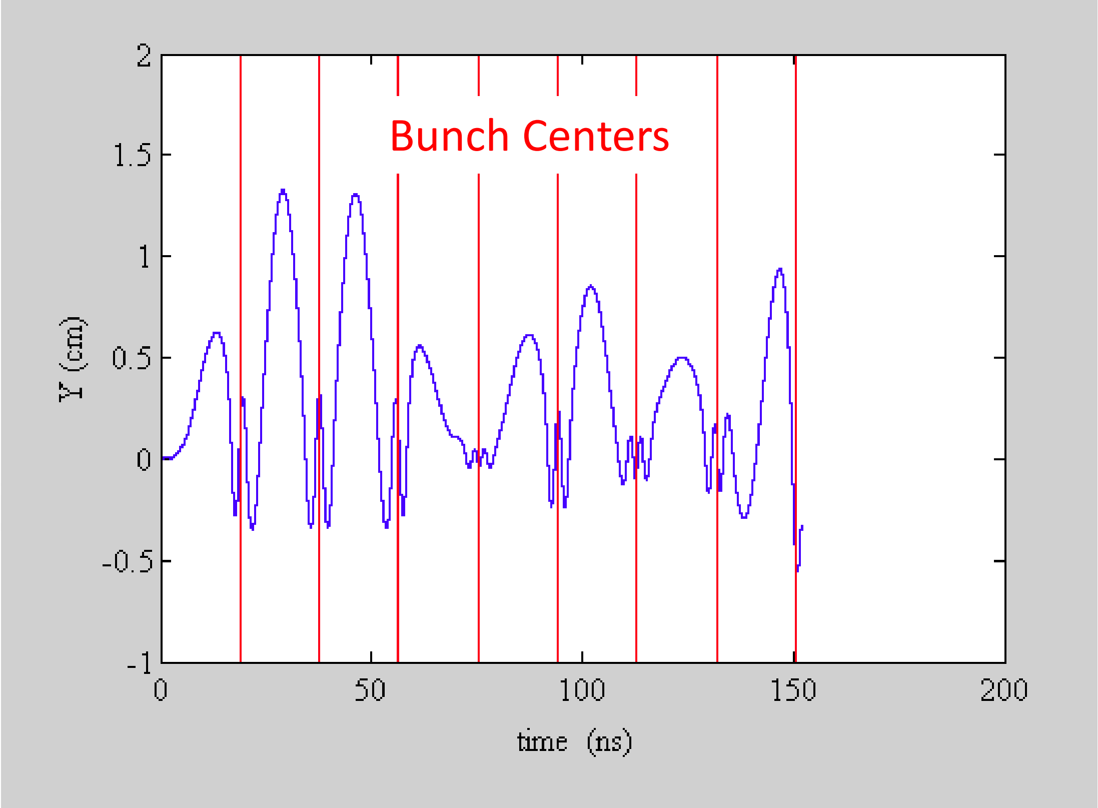


Gated-off Behavior

Drift Velocity
1.2 cm / 150 ns = 8 cm/μs
Compared to
10 cm/μs analytically estimated



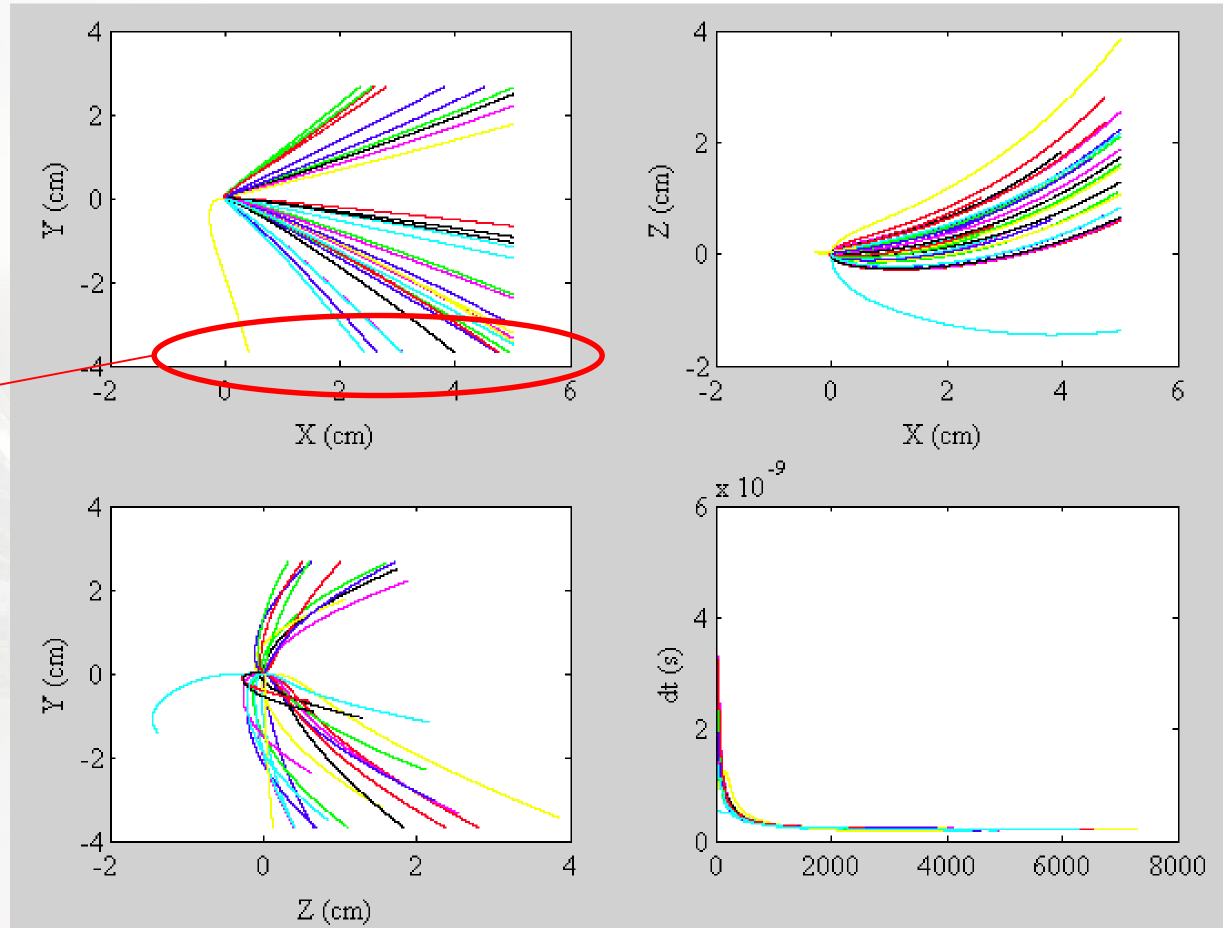
Y motion vs time



Gated-off Ion Paths

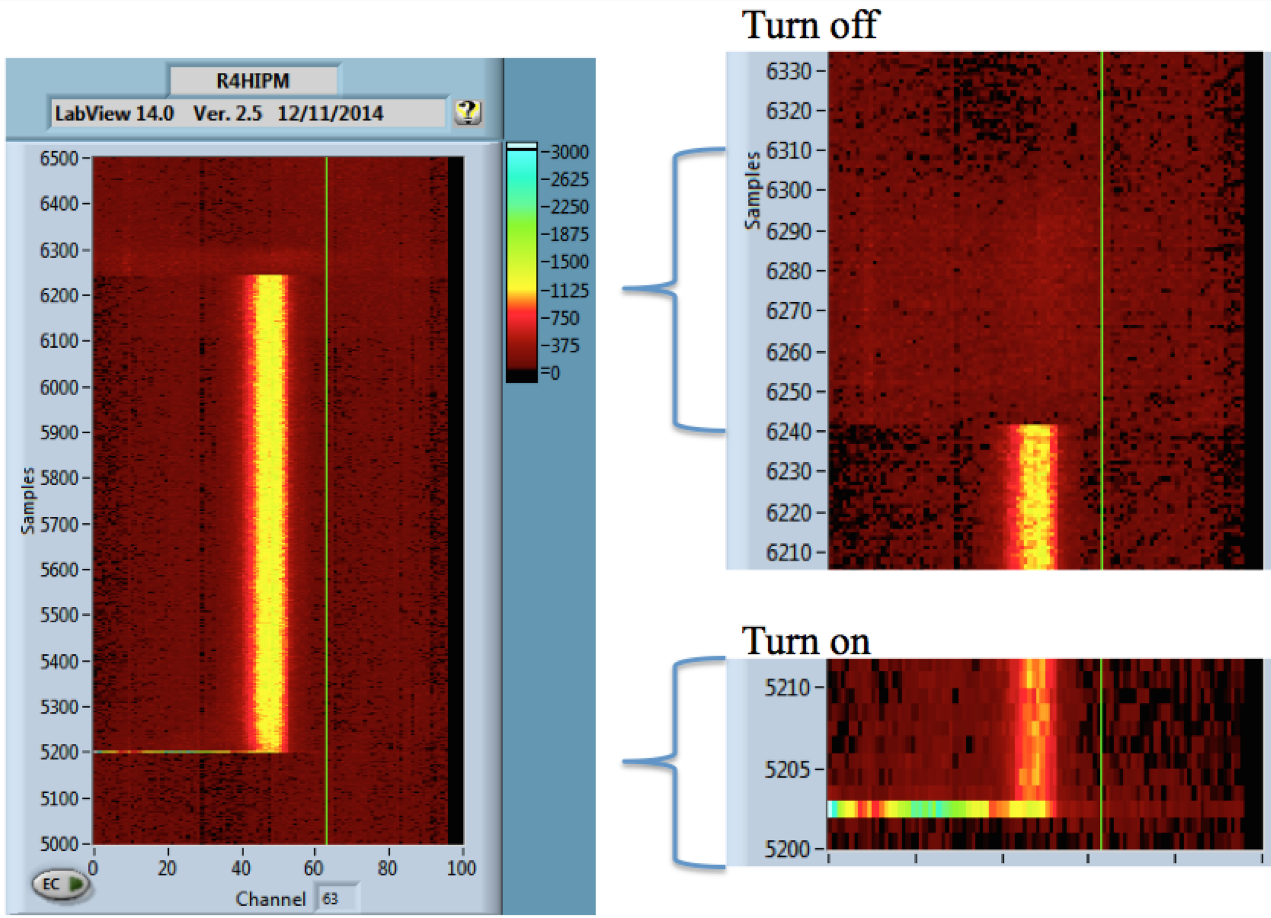
Elapsed time is ~1.5 μs

Ok, since ions do not go past the gating grid



Gated Grid Test

Control Grid Upstairs Test R4H



Conclusions

- Use of Matlab simulation with fields generated from other sources allowed an evaluation of the gating grid behavior for the new IPMs at Fermilab
- Matlab historically not the best choice for tracking since it is/was an interpreted language
  - Works well if problem can be formulated in matrix form
- Details of initial momenta of ionization products very crude
  - Decided that details were probably only relevant for low momentum transfers
  - Low momentum transfers quickly overcome by clearing and magnetic fields

Extras

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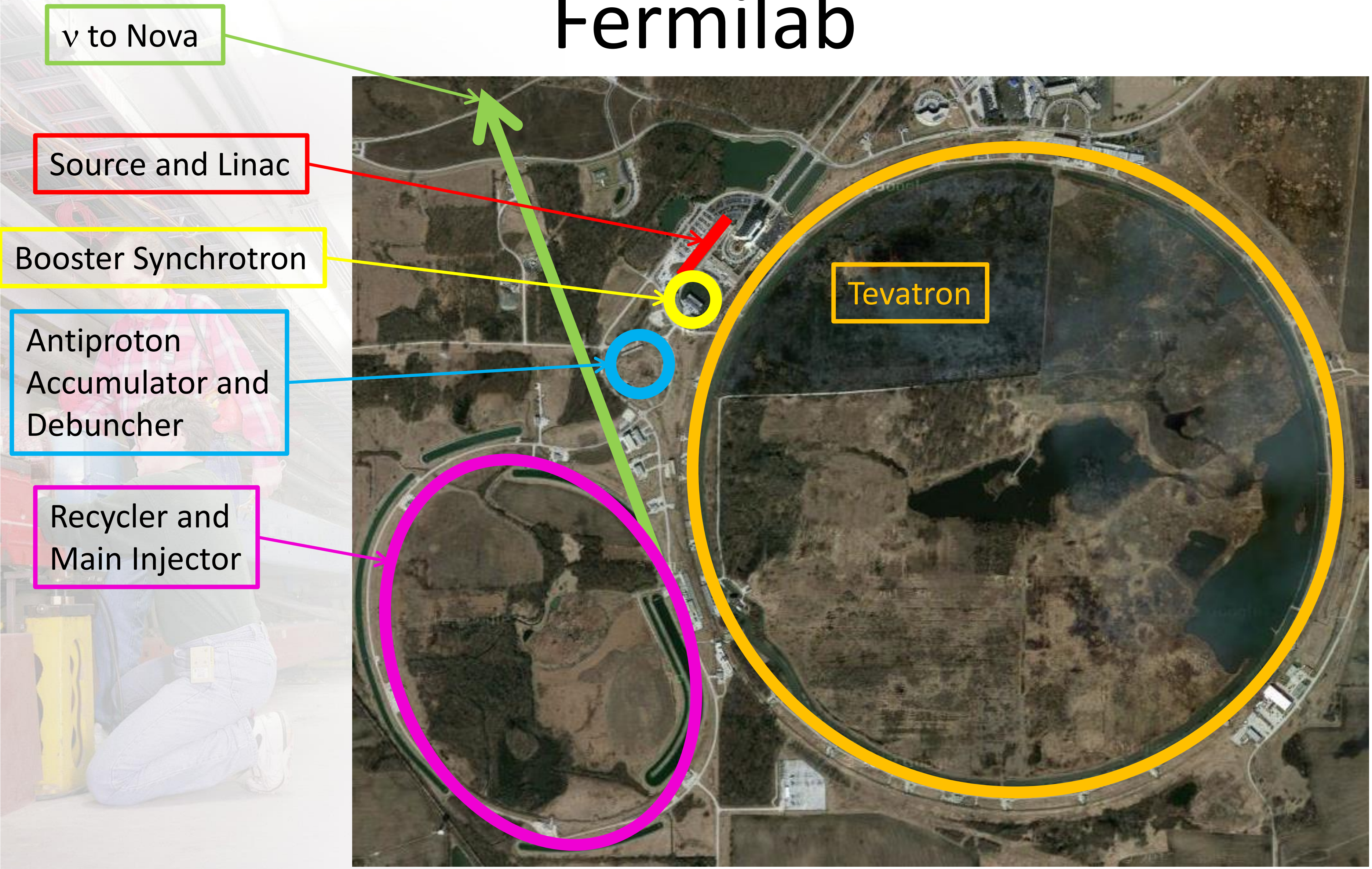
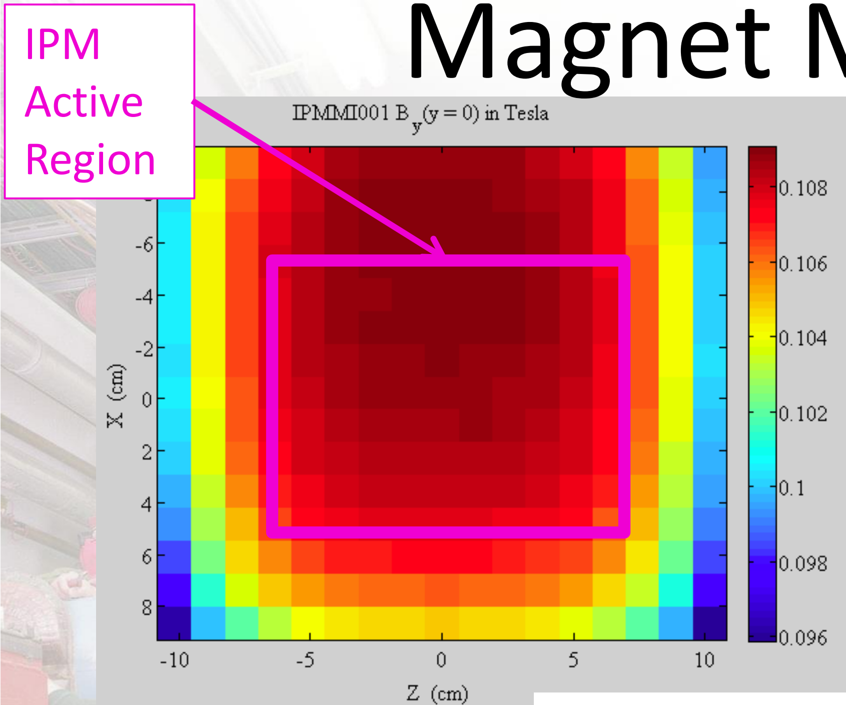
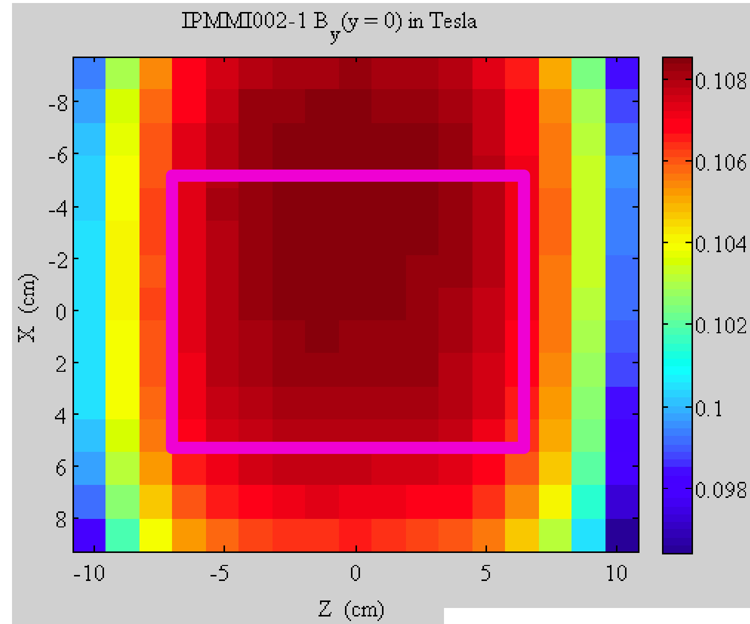
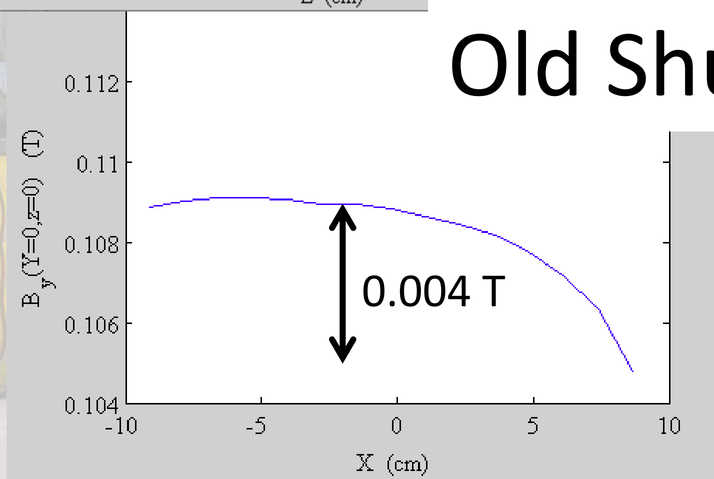

ν to Nova
Source and Linac
Booster Synchrotron
Antiproton Accumulator and Debuncher
Recycler and Main Injector
Tevatron

Magnet Measurements

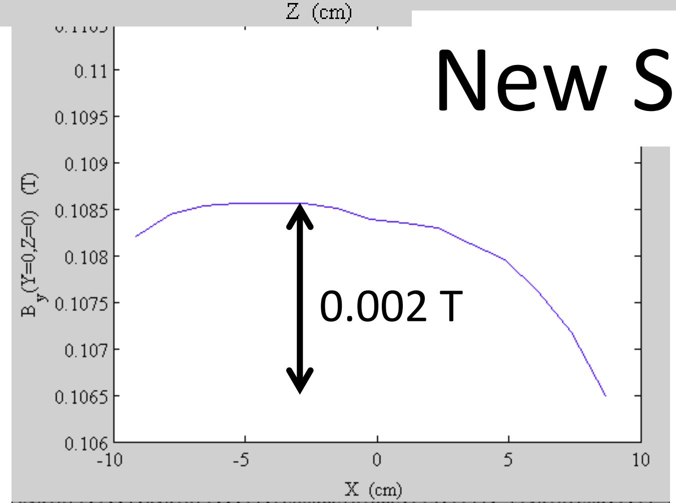




Old Shunt



New Shunt



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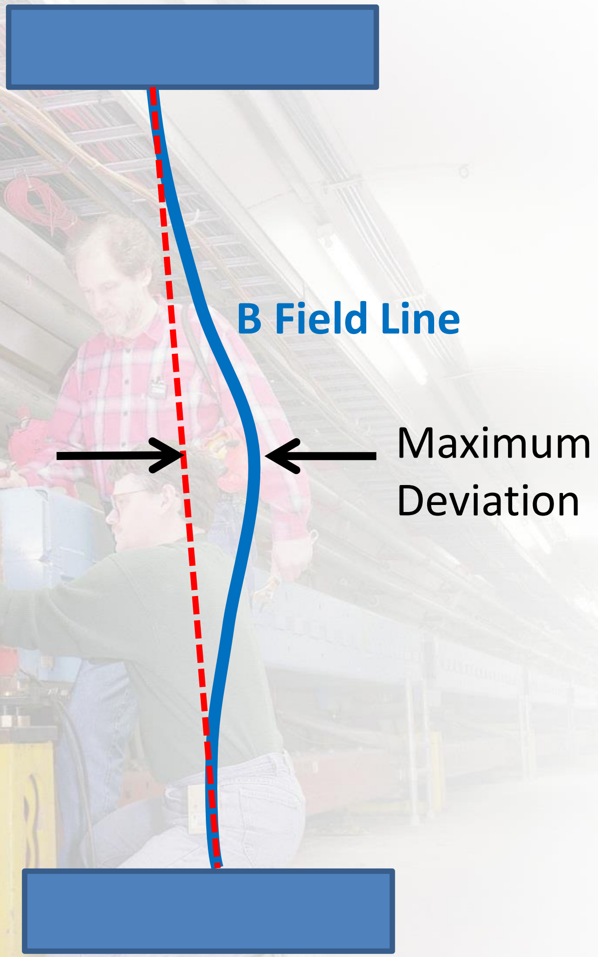
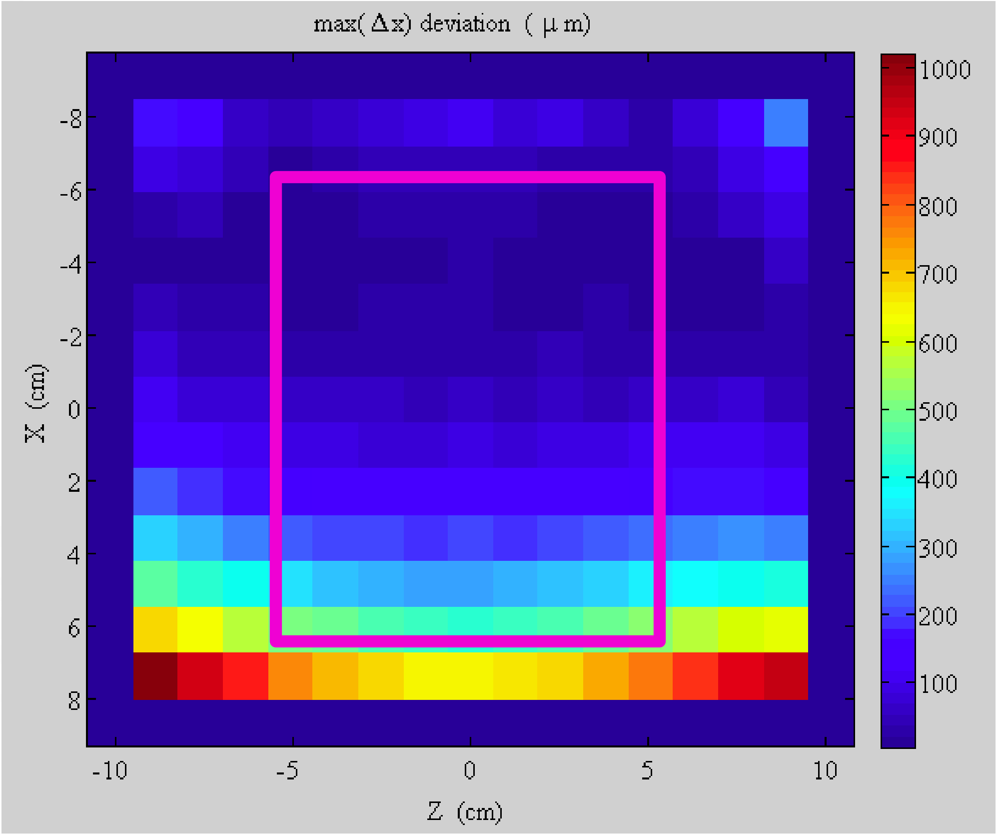
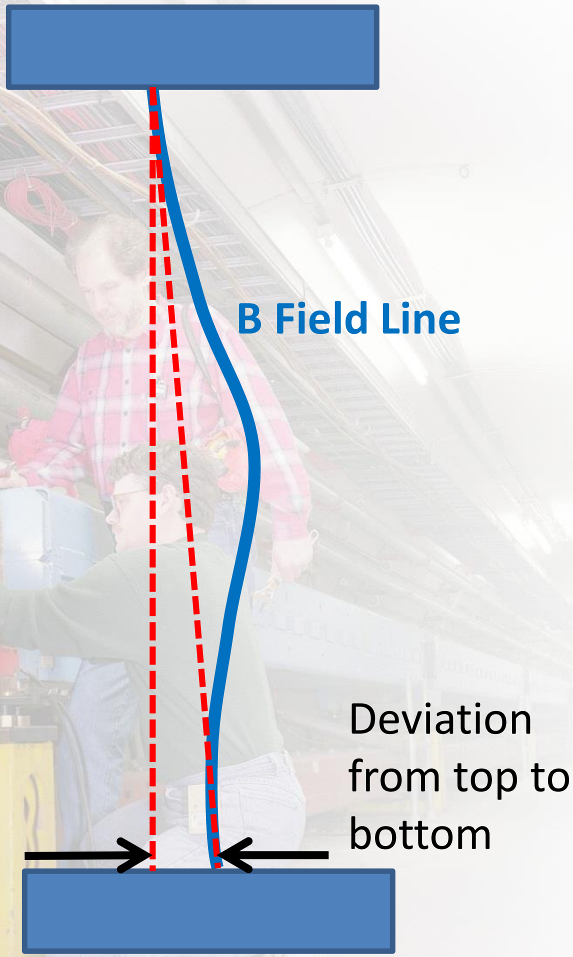
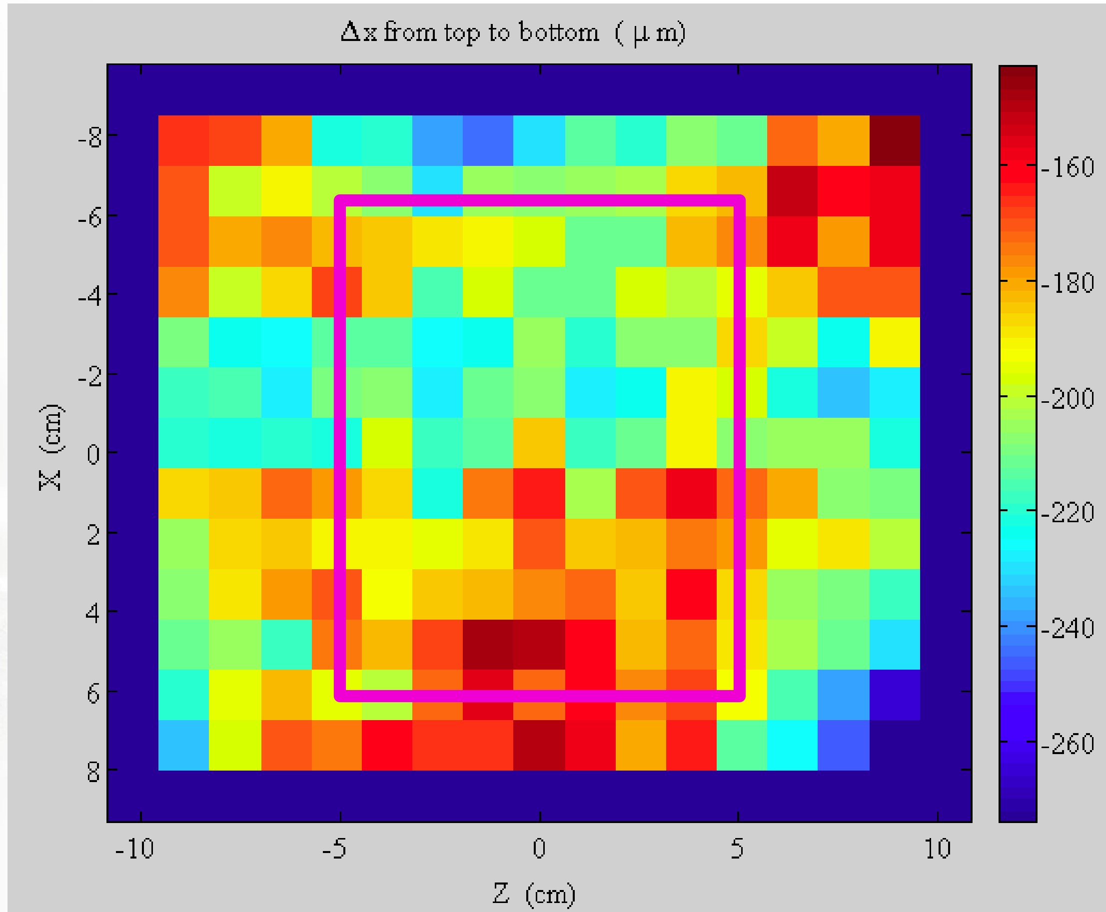
Magnet Measurements





Magnet Measurements





Average value of 200 μm could be hall probe rotation; corresponds to ~0.1 degrees

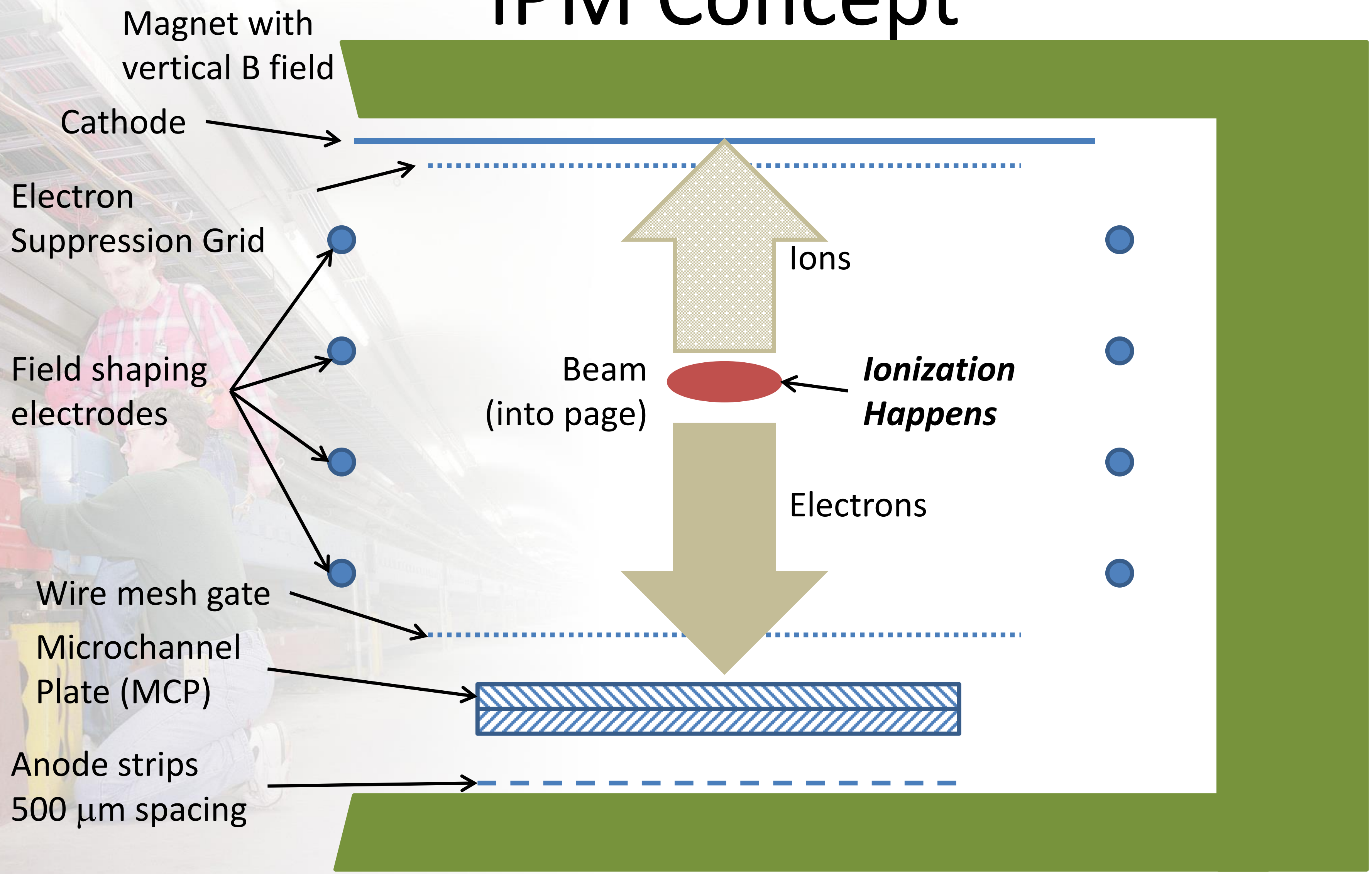
MI Orbit Perturbation

- Measured magnet integrated field is $\sim 0.001\ \mathrm{T{-}m}$
- Maximum displacement around the ring for the measured field integral is

$$D = \frac{\int B_y \, dl}{\rho_m} \frac{\beta}{2 \sin \pi\nu}$$

- For the Main Injector $\rho_m \sim 27\ \mathrm{T{-}m}$ and the maximum β is 50 and the tune, ν, is 0.43
  - $D \sim 0.001\ \mathrm{m}$

IPM Concept


Magnet with
vertical B field
Cathode
Electron
Suppression Grid
Field shaping
electrodes
Wire mesh gate
Microchannel
Plate (MCP)
Anode strips
500 μm spacing
Ions
Beam
(into page)
Ionization
Happens
Electrons

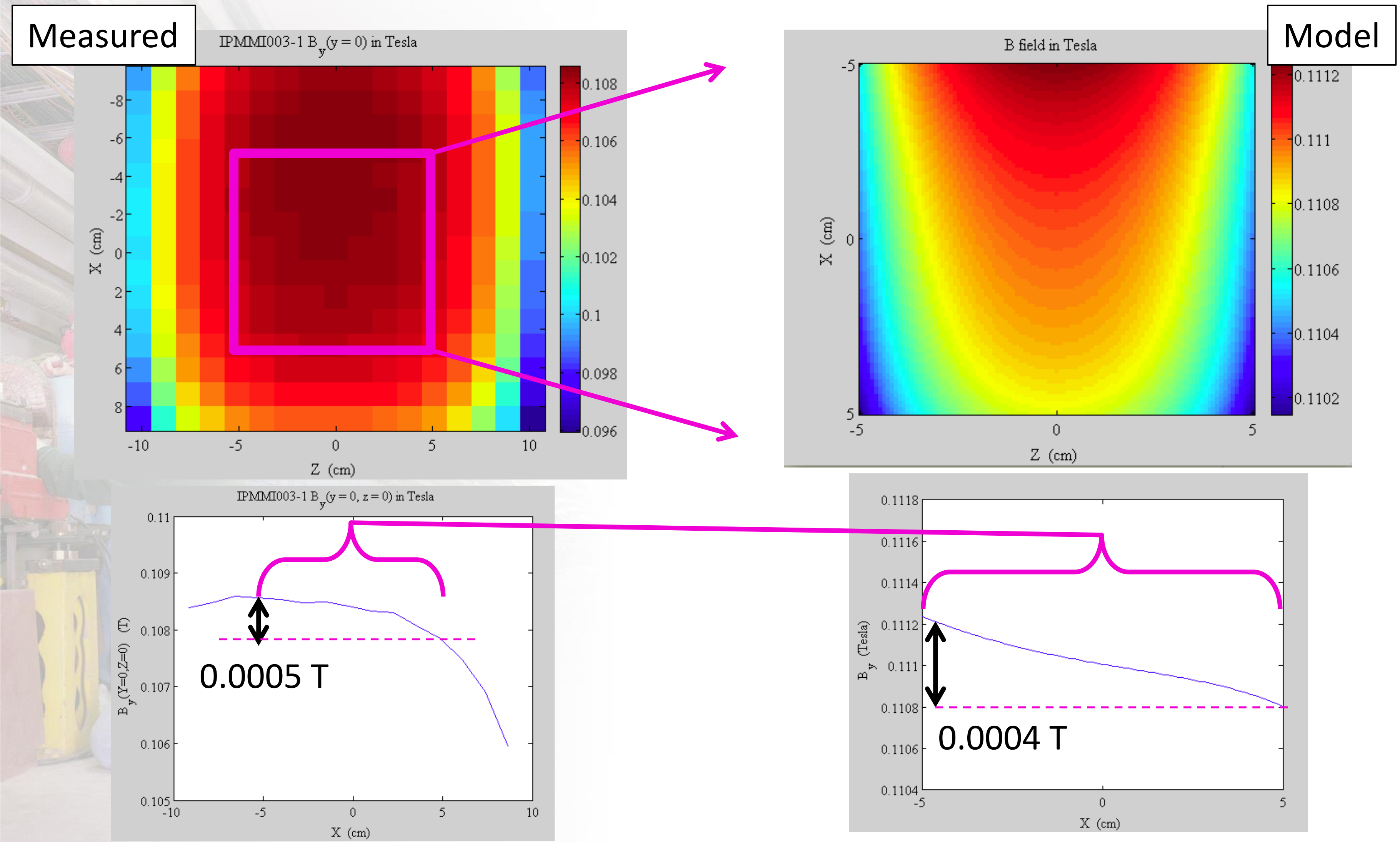
Gated IPM Concept

- Problem with MCP is short lifetime
  - Plate is using up lifetime whenever beam is in the machine and the IPM voltage is on
  - Voltage takes a while to raise and lower
- Would like to be able to gate the charge to preserve the MCP
  - Stop the electrons and ions from reaching the MCP
  - Allow the electrons and ions an escape path from the IPM active region
    - i.e. no Penning traps

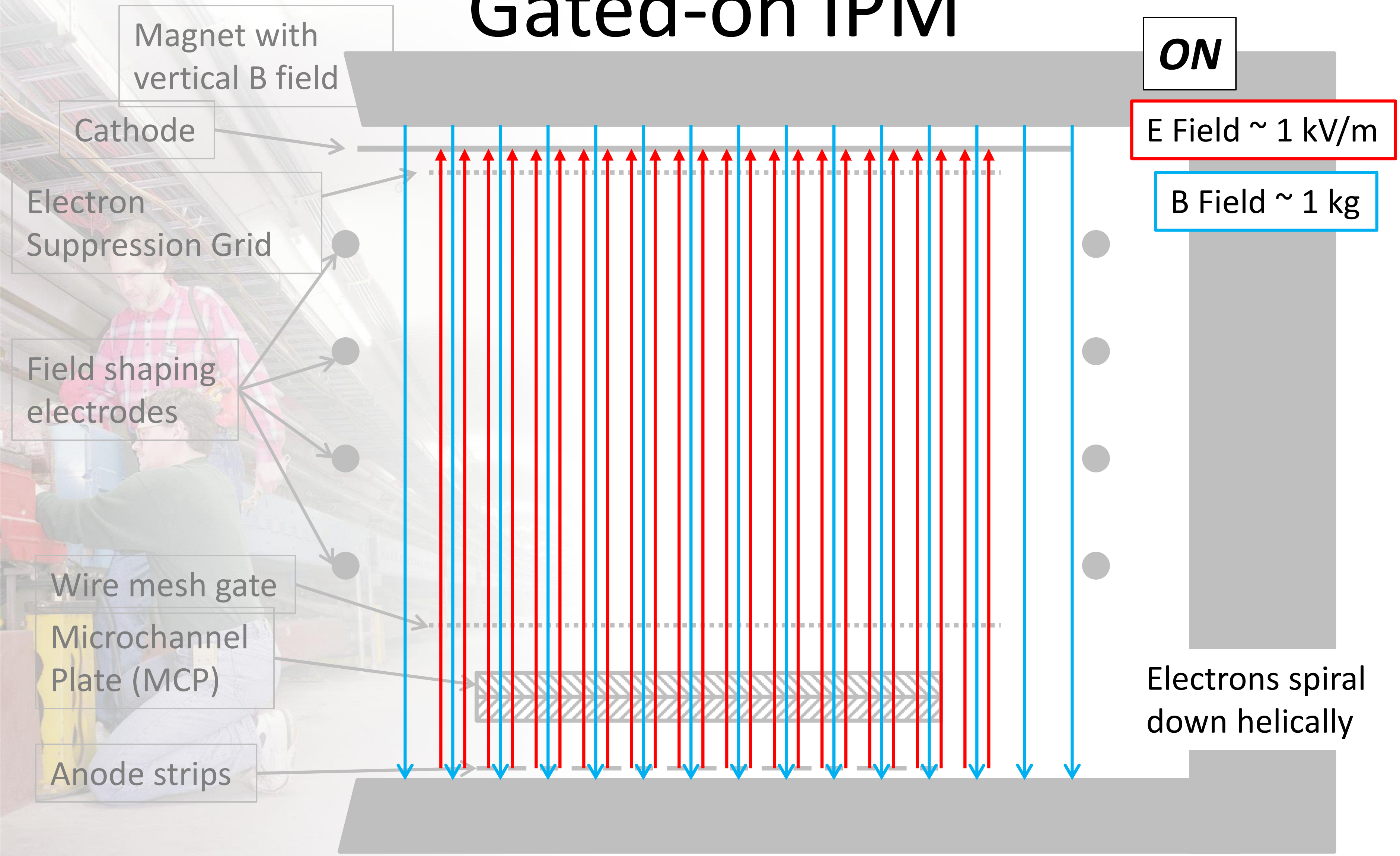
Gated IPM Concept

- The force on a charged particle is
  $\vec{F} = q\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) = m\frac{d\vec{v}}{dt}$
- Assume that $\vec{E} = E_0\hat{x}$ and $\vec{B} = B_0\hat{y}$
- Solve the differential equations and one gets the usual solution of circular motion in the $\hat{x} - \hat{z}$ plane, constant motion along $\hat{y}$ and a drift along $\vec{E} \times \vec{B}$ which in this case is $\hat{z}$, i.e. along the beam
- Putting in the values for the electric and magnetic fields gives us a drift velocity of ~10 cm/μs along the proton beam direction
  - The electrons will have drifted beyond the MCP in ~1-2 μs

Magnetic Field in Simulation



Gated-on IPM


Magnet with vertical B field
Cathode
Electron Suppression Grid
Field shaping electrodes
Wire mesh gate
Microchannel Plate (MCP)
Anode strips
ON
E Field ~ 1 kV/m
B Field ~ 1 kg
Electrons spiral down helically