IPM EM Simulations

9th DITANET Topical Workshop on Non-Invasive Beam Size Measurement for High Brightness Proton and Heavy Ion Accelerators

15-18 April 2013

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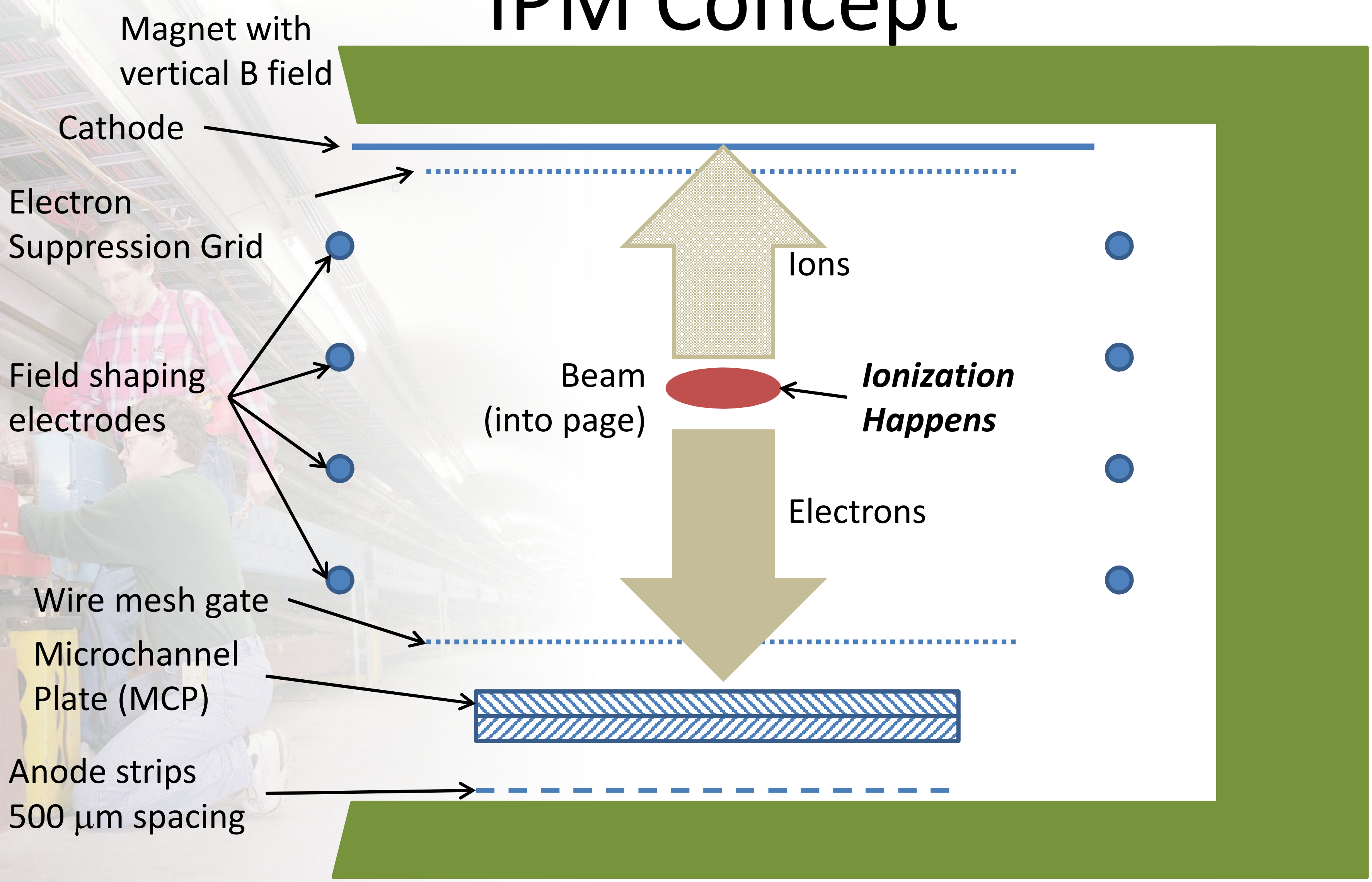
Fermilab

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

IPM Concept


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

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

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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

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

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

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

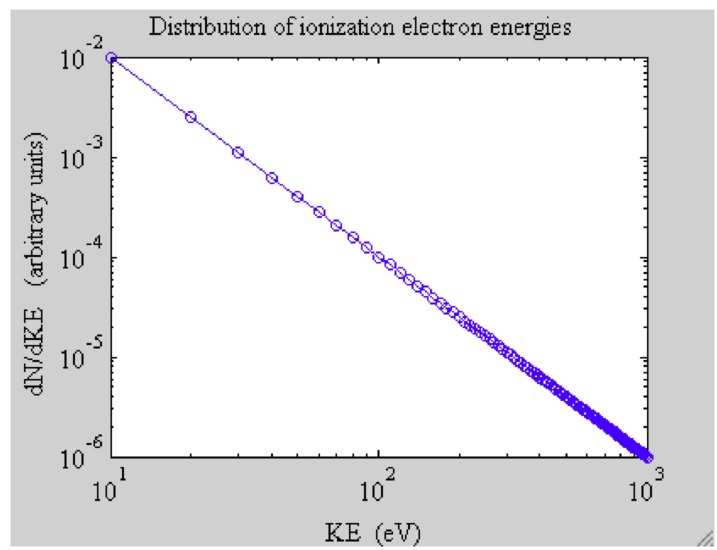
$$\mathbf{a} = \frac{1}{\tilde{\gamma}m}\left[\mathbf{I} - \tilde{\boldsymbol{\beta}}\tilde{\boldsymbol{\beta}}^T\right]\mathbf{F}$$

Matlab Simulation

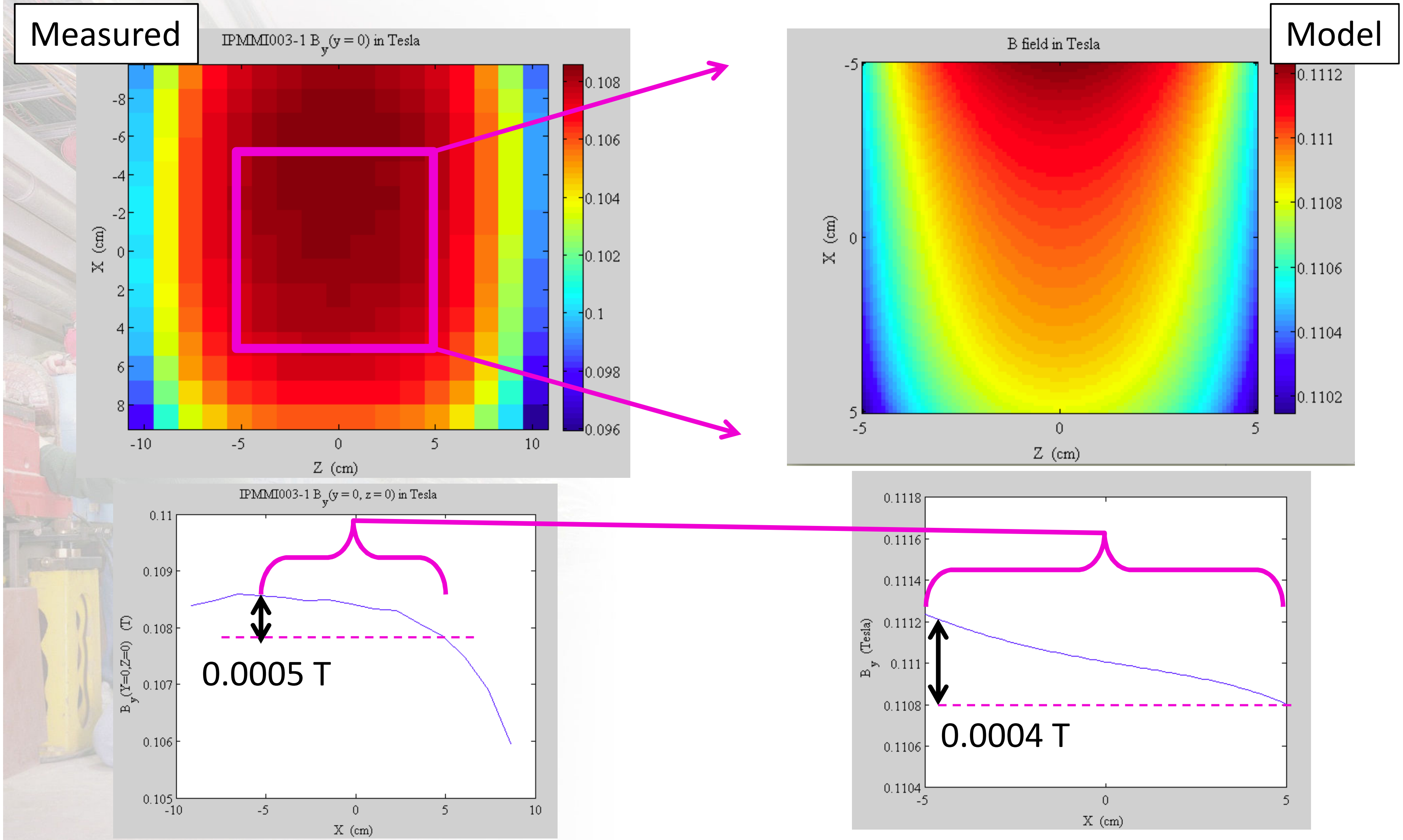
- Once the acceleration is determined, a discrete evaluation of the differential equation of motion is used to step the particles
- The magnetic and electric fields are handled separately
  - Magnetic contribution to the motion is only applied to the components perpendicular to the B field
  - Magnitude 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

Matlab Simulation

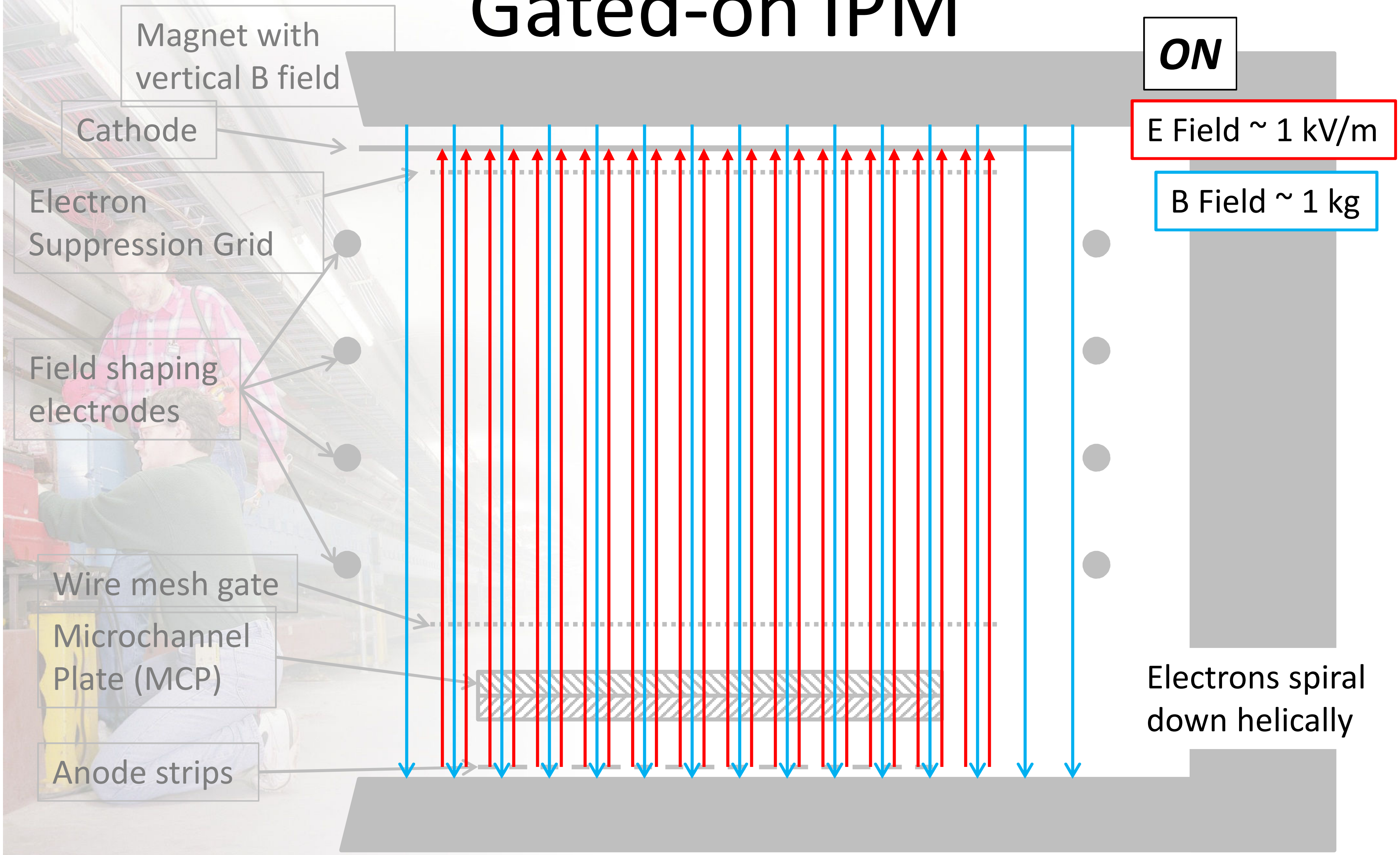
- The electric and magnetic fields of the bunch are calculated before hand for various bunch parameters
  - Shifted as a function of time to represent the moving beam
- Electric field of IPM from a Poisson calculation
- Magnetic field from 3-D magnet model
- Ionized particle distributions are random in emission angle with $1/E^2$ energy distribution



Magnetic Field in Simulation



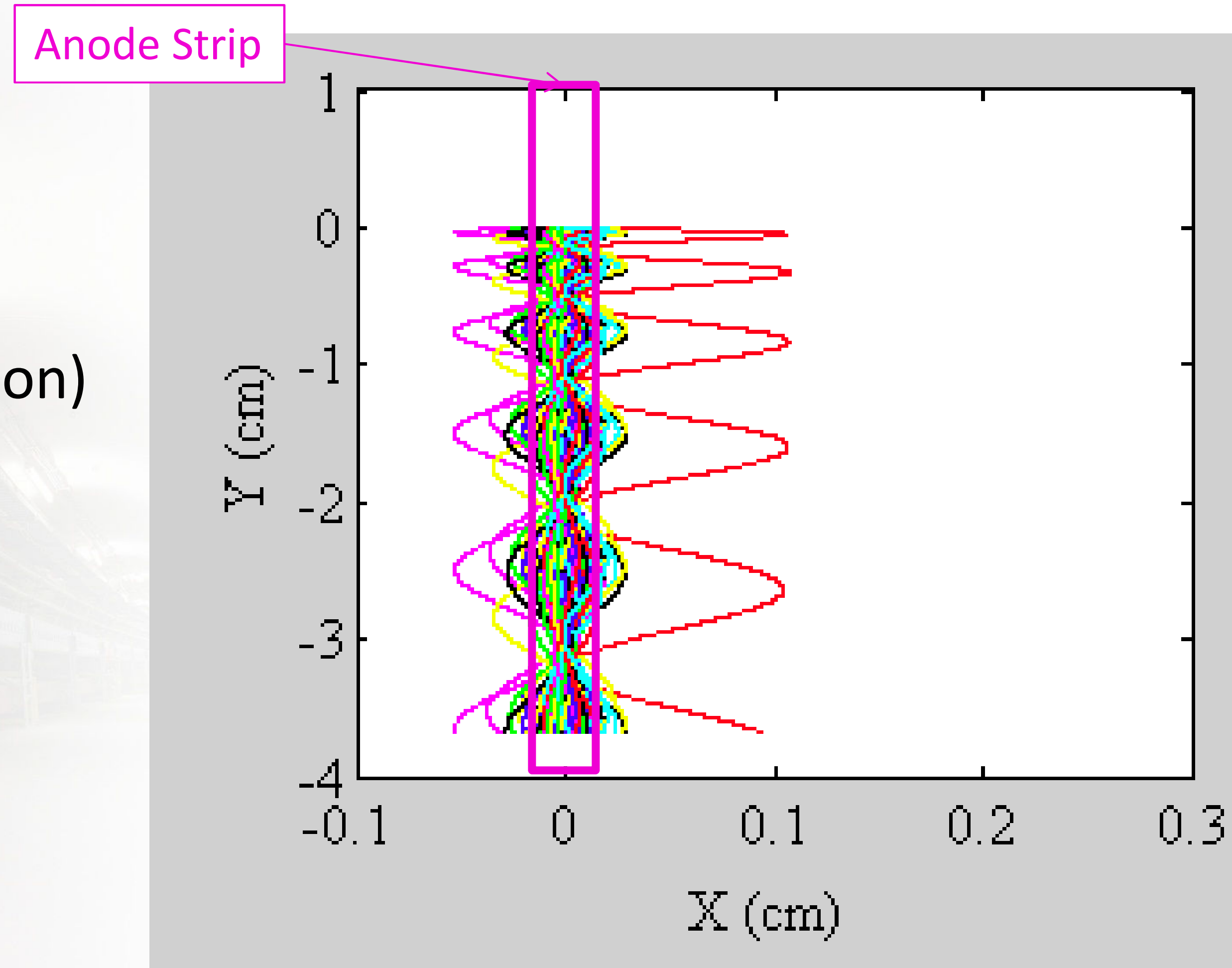
Gated-on IPM


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

Gated-on IPM

Particles originating from single point (resolution contribution)

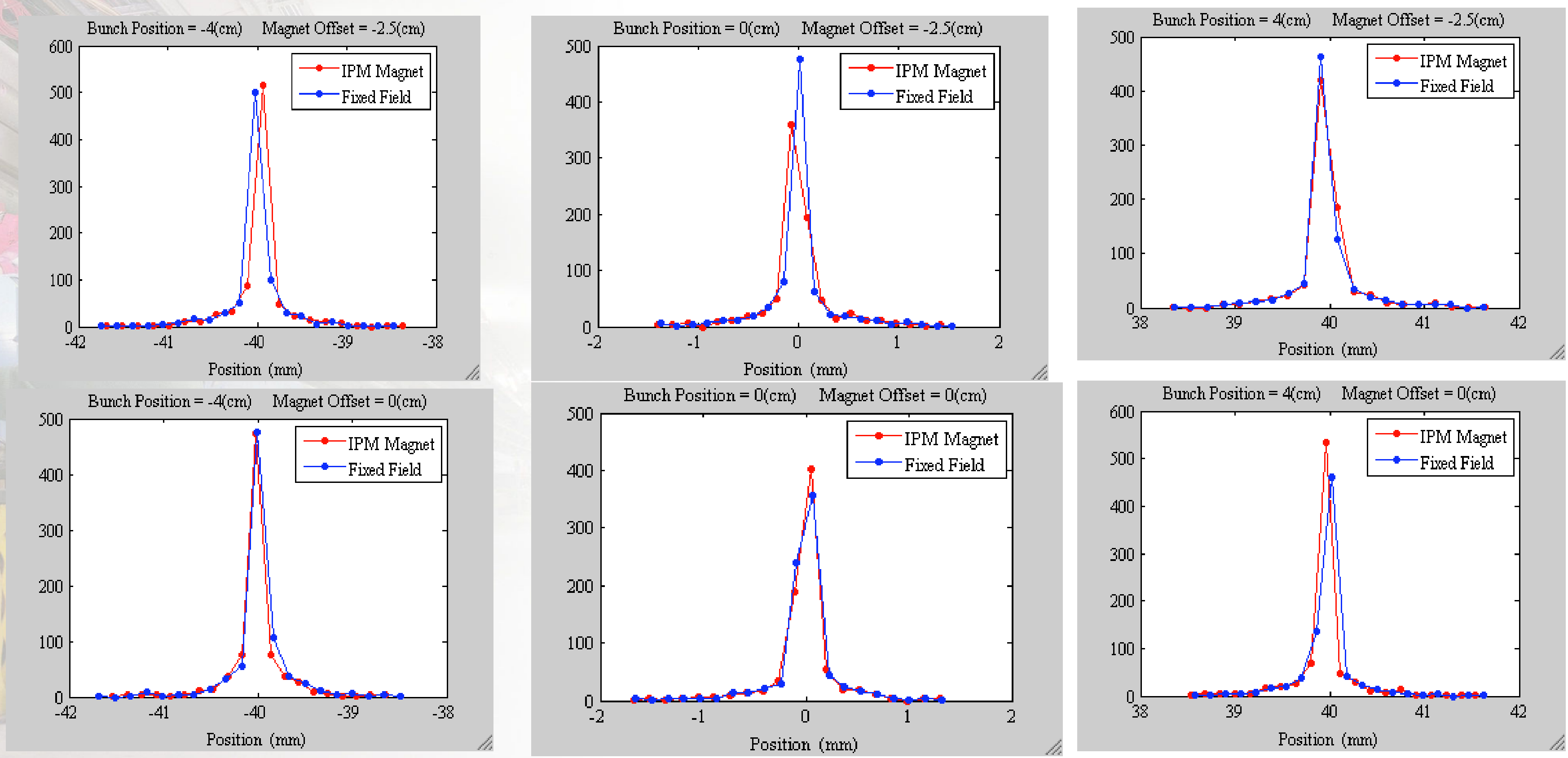
Elapsed time ~ 1.7 ns



Gated-on IPM

Particles originating from single point
(resolution contribution)

Bunch offset refers to x



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

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

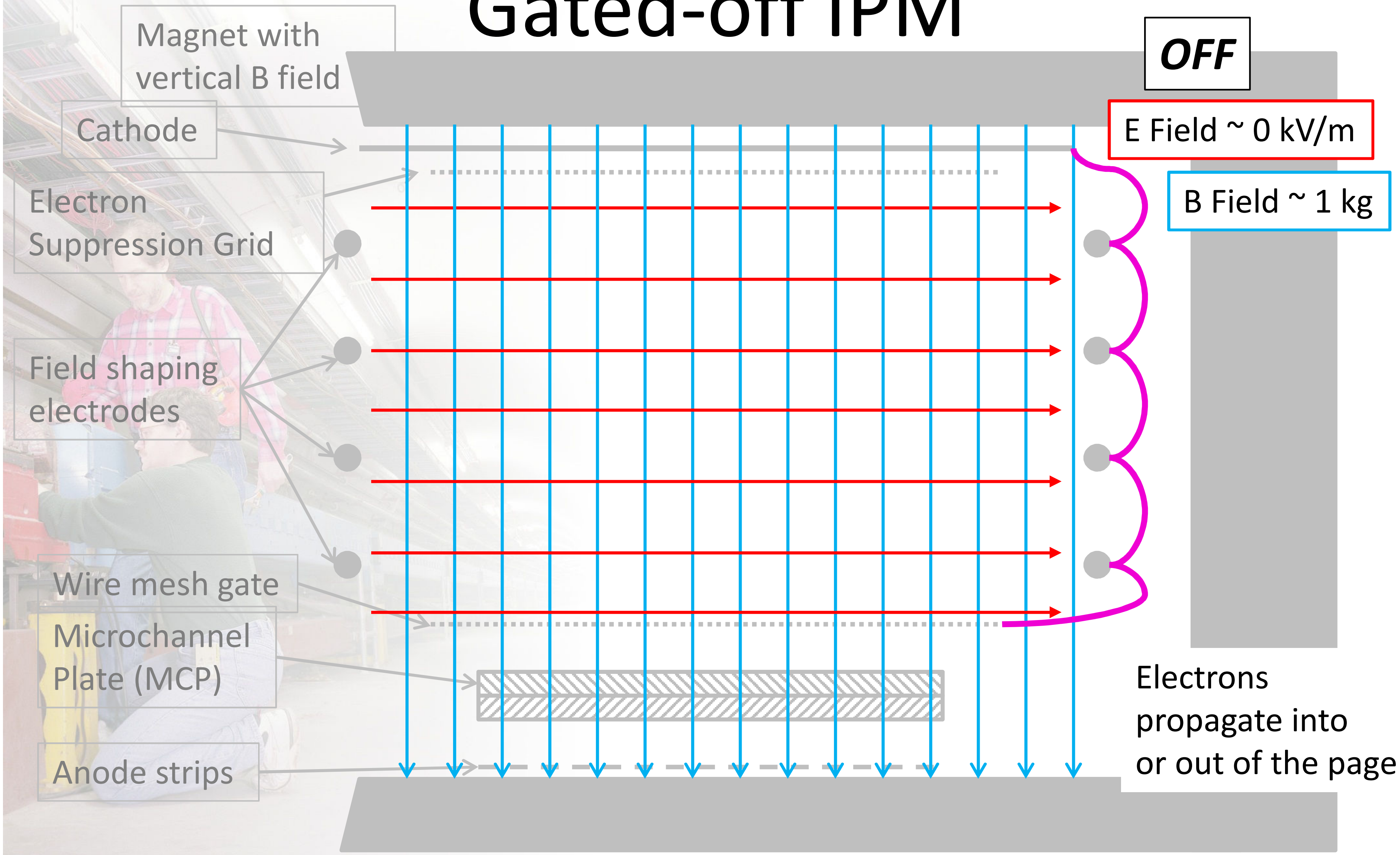
- Expressing this in terms of the proton bunch parameters and partial pressures in the beampipe one arrives at

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

- 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-off IPM



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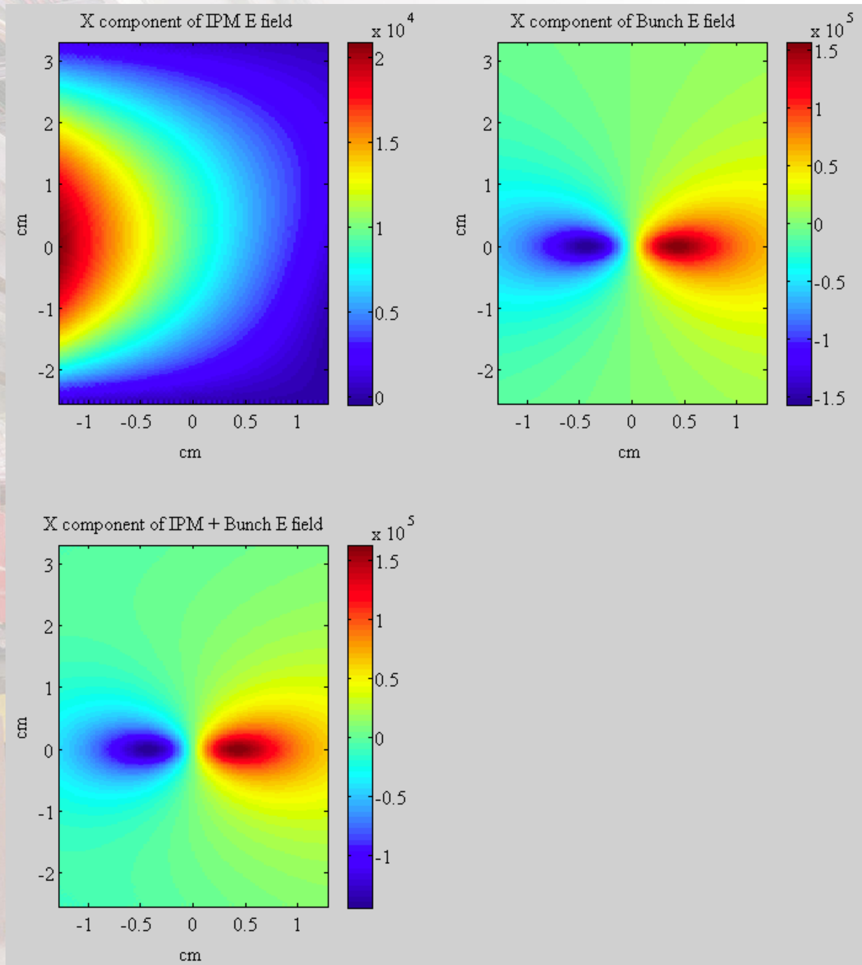
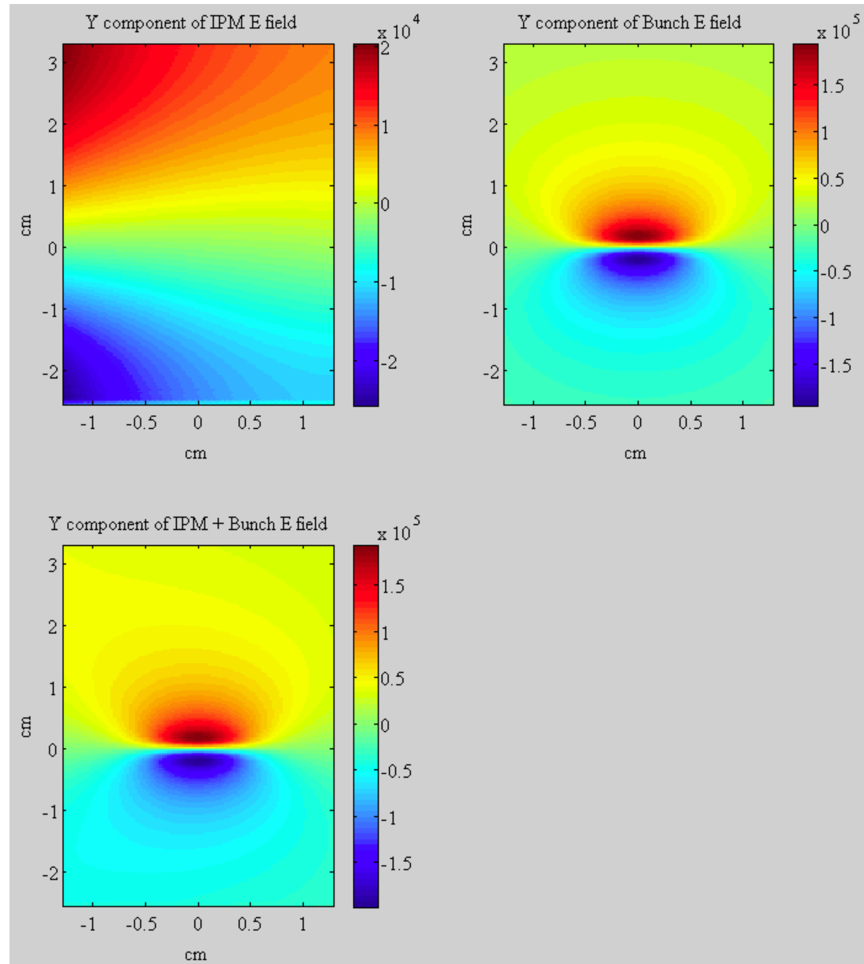
Gated-off Fields

X Component of E field

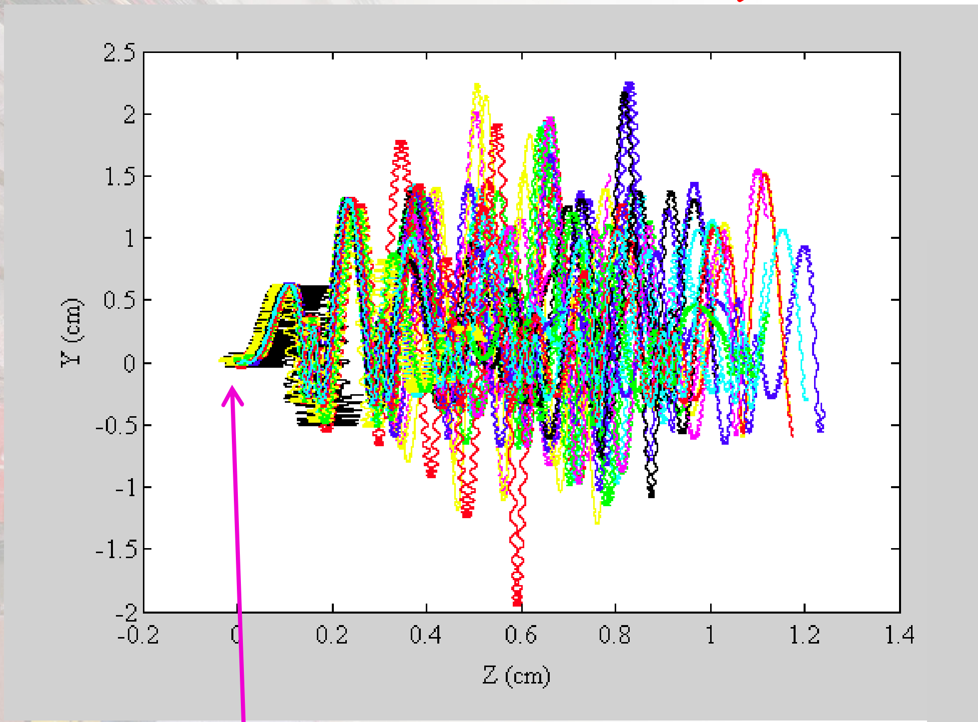
Y Component of E field





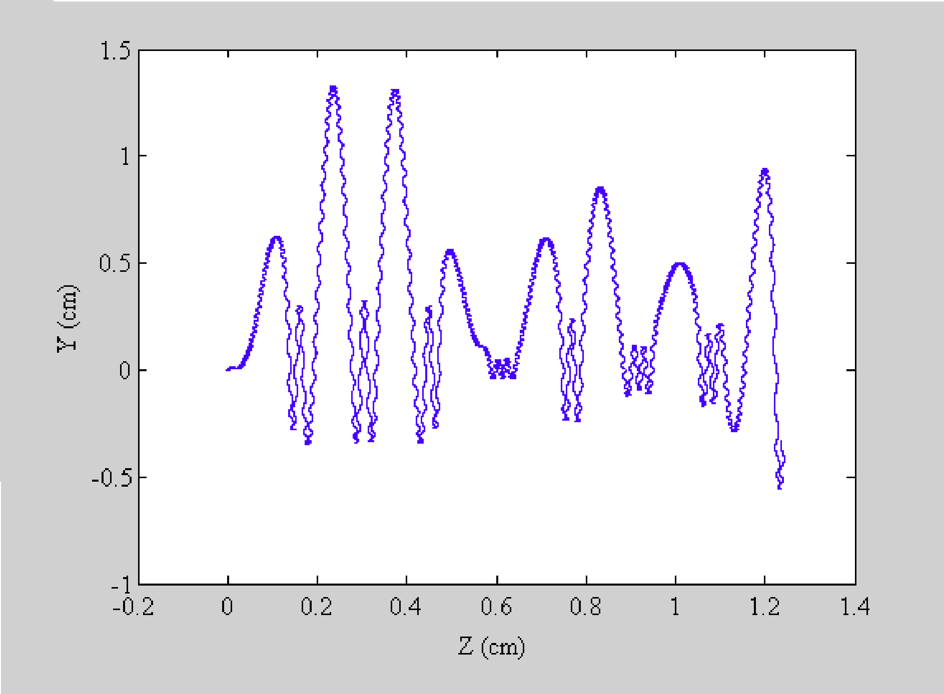
Gated-off Motion

Electron drift along beam direction



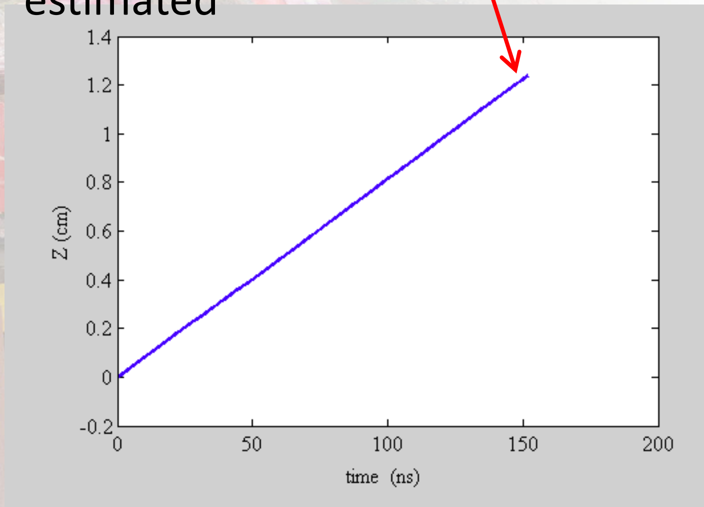
Particle origination point

Single particle

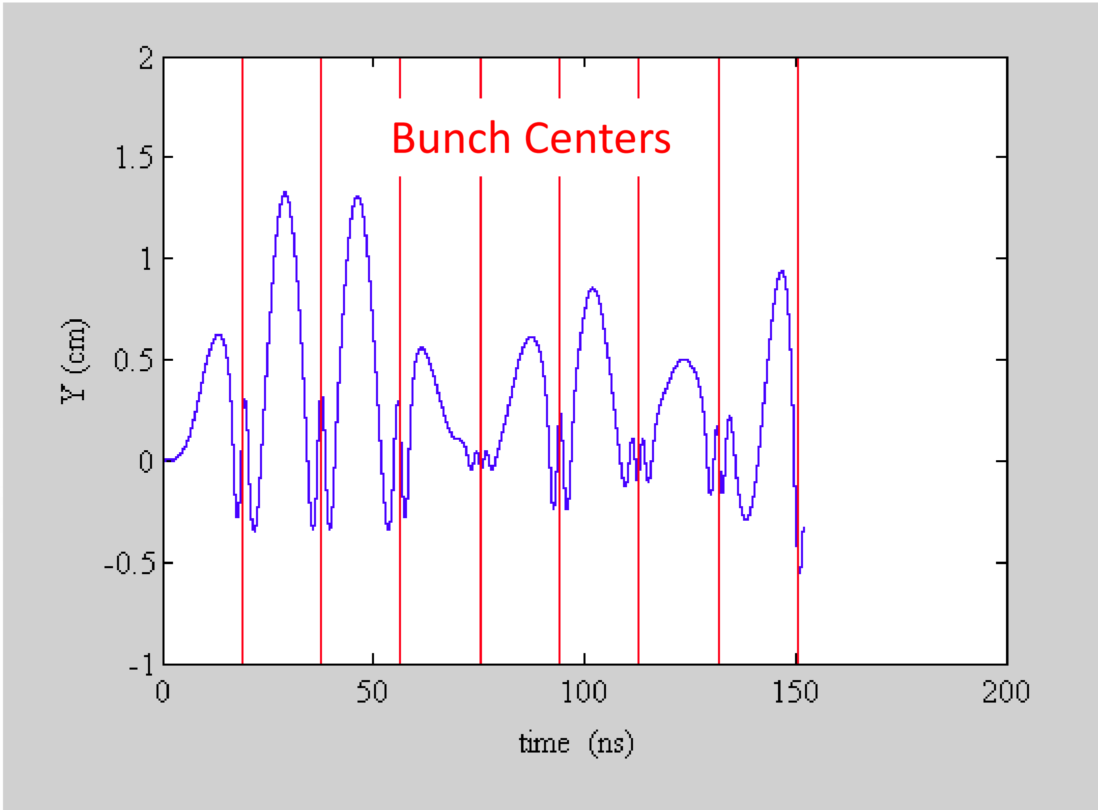


Gated-off Behavior

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



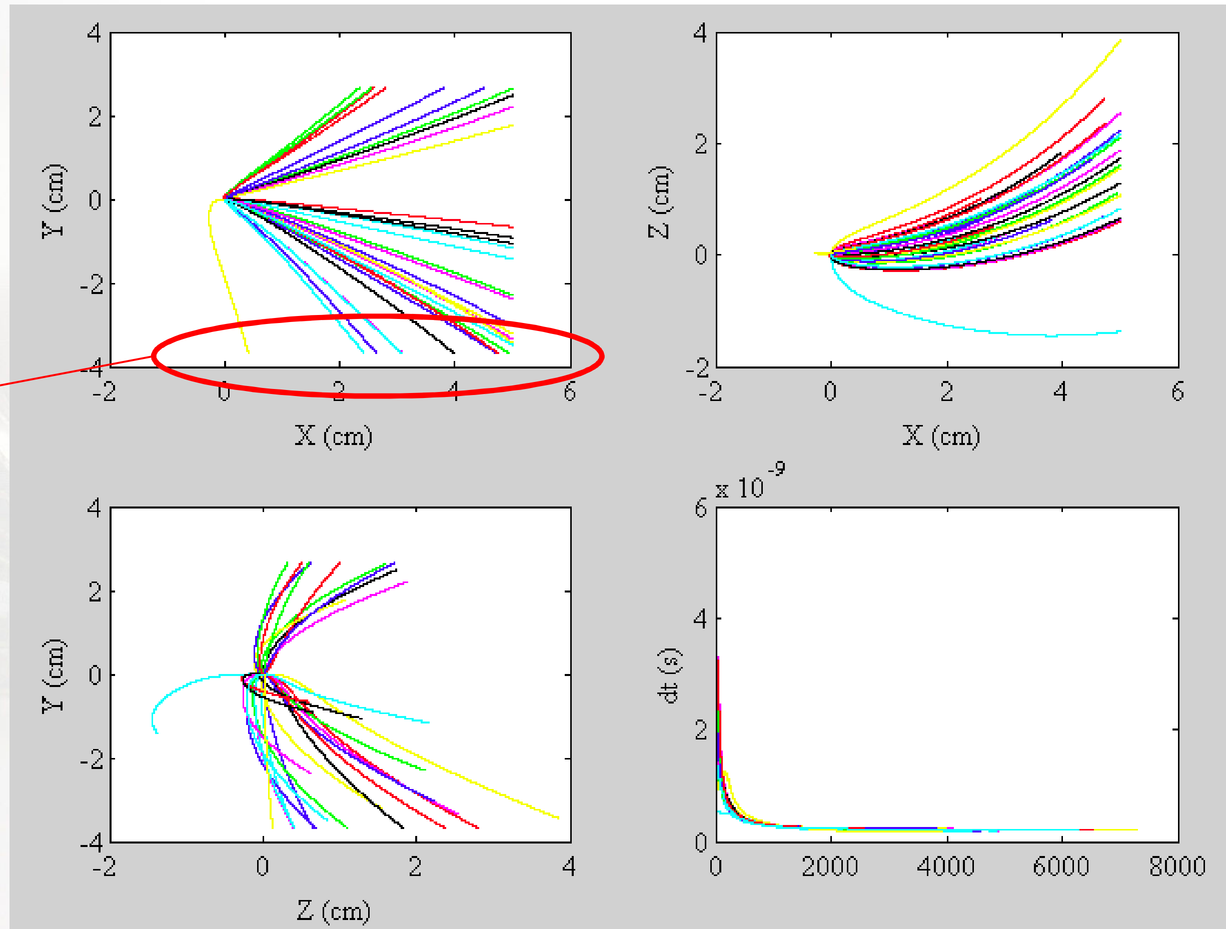
Y motion vs time



Gated-off Ion Paths

Elapsed time is ~1.5 μs

Ok, since ions do not go past the gating grid



Conclusions

- Where do the electrons go when they reach the edge of the E field region?
  - Need 3-D E field calculation

Extras

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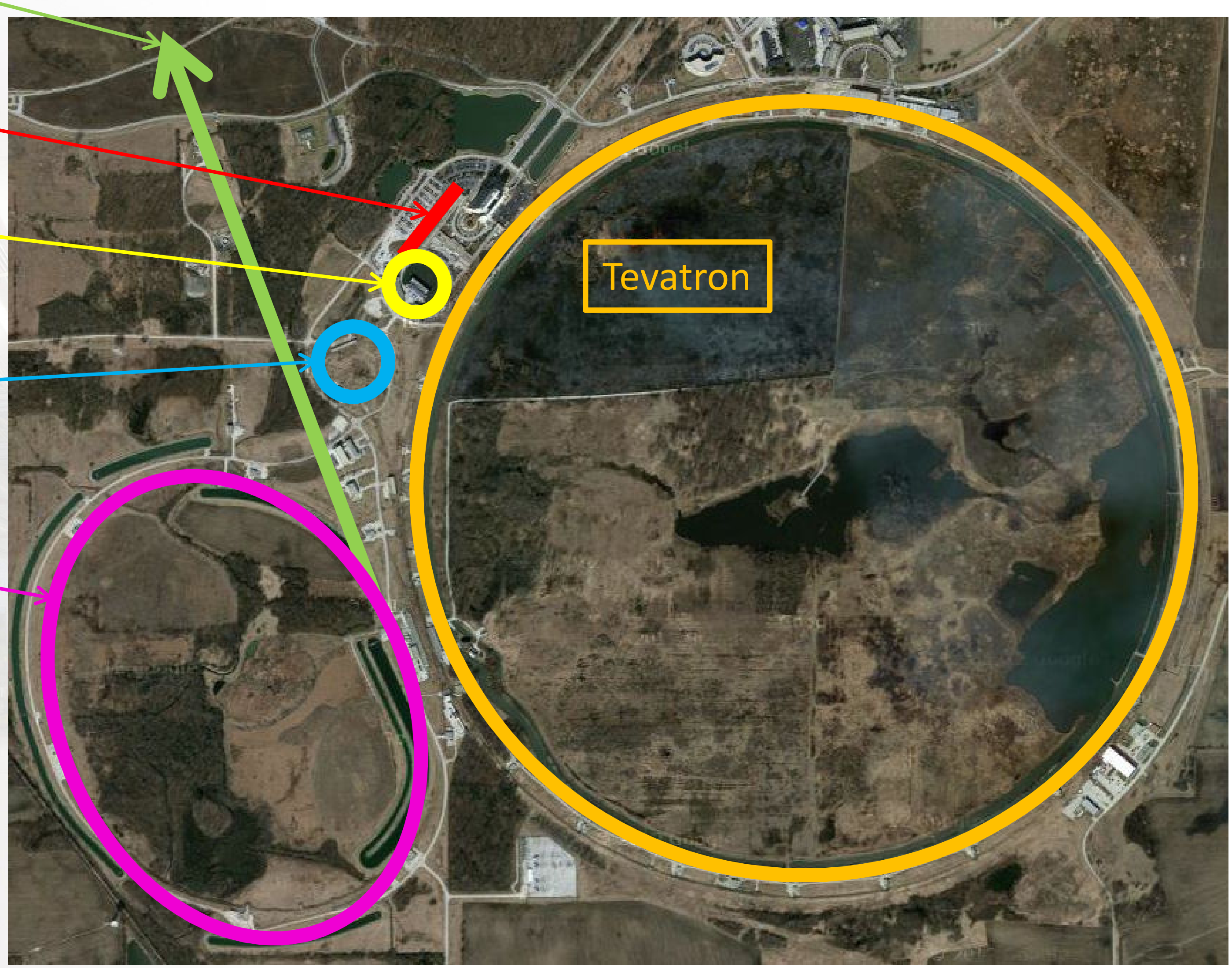
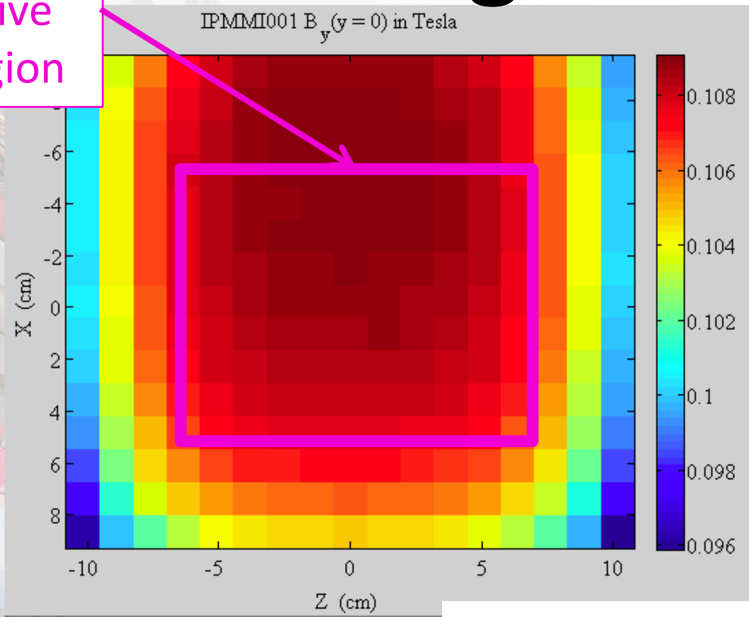
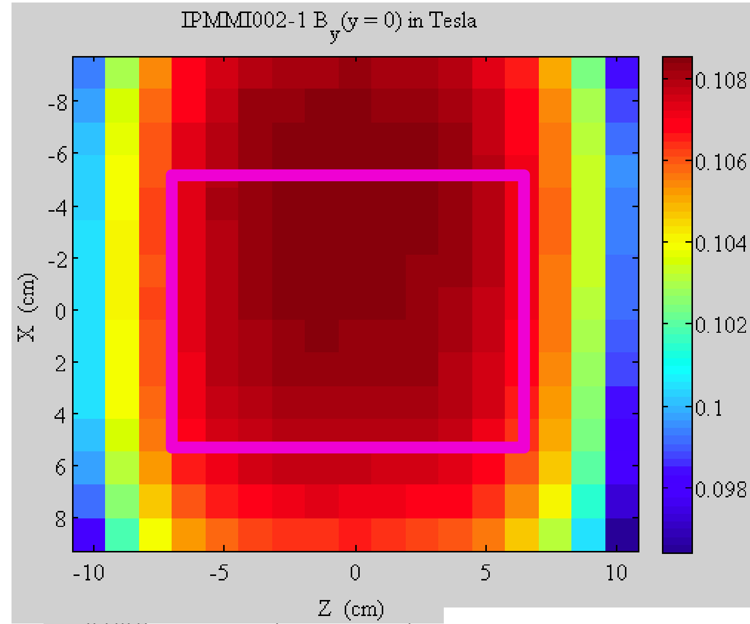


ν to Nova
Source and Linac
Booster Synchrotron
Antiproton Accumulator and Debuncher
Recycler and Main Injector
Tevatron

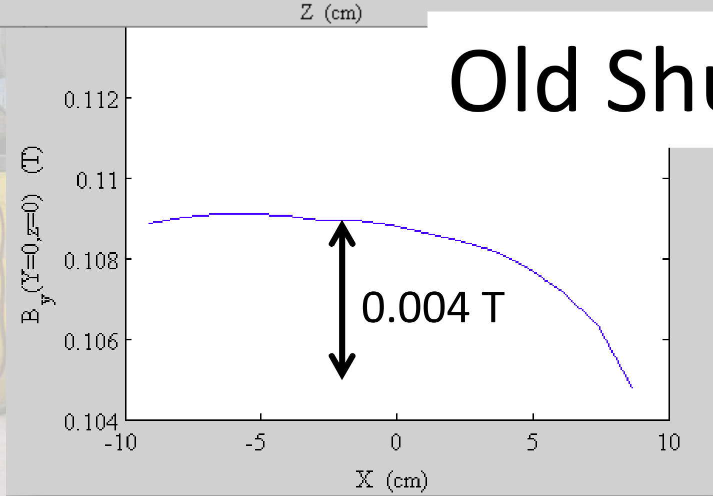
Magnet Measurements

IPM Active Region

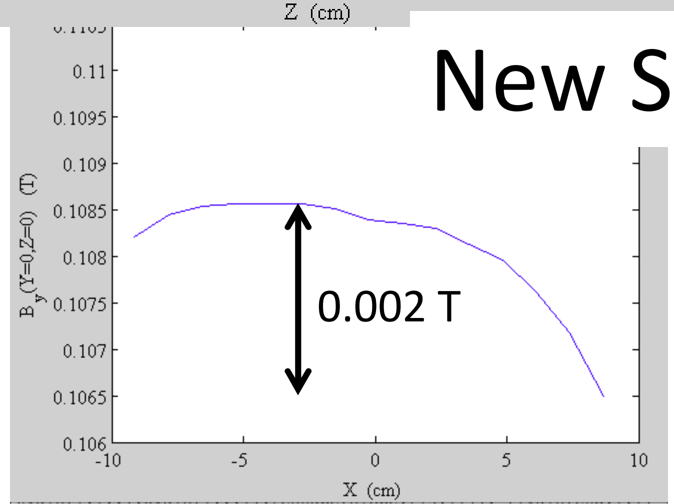




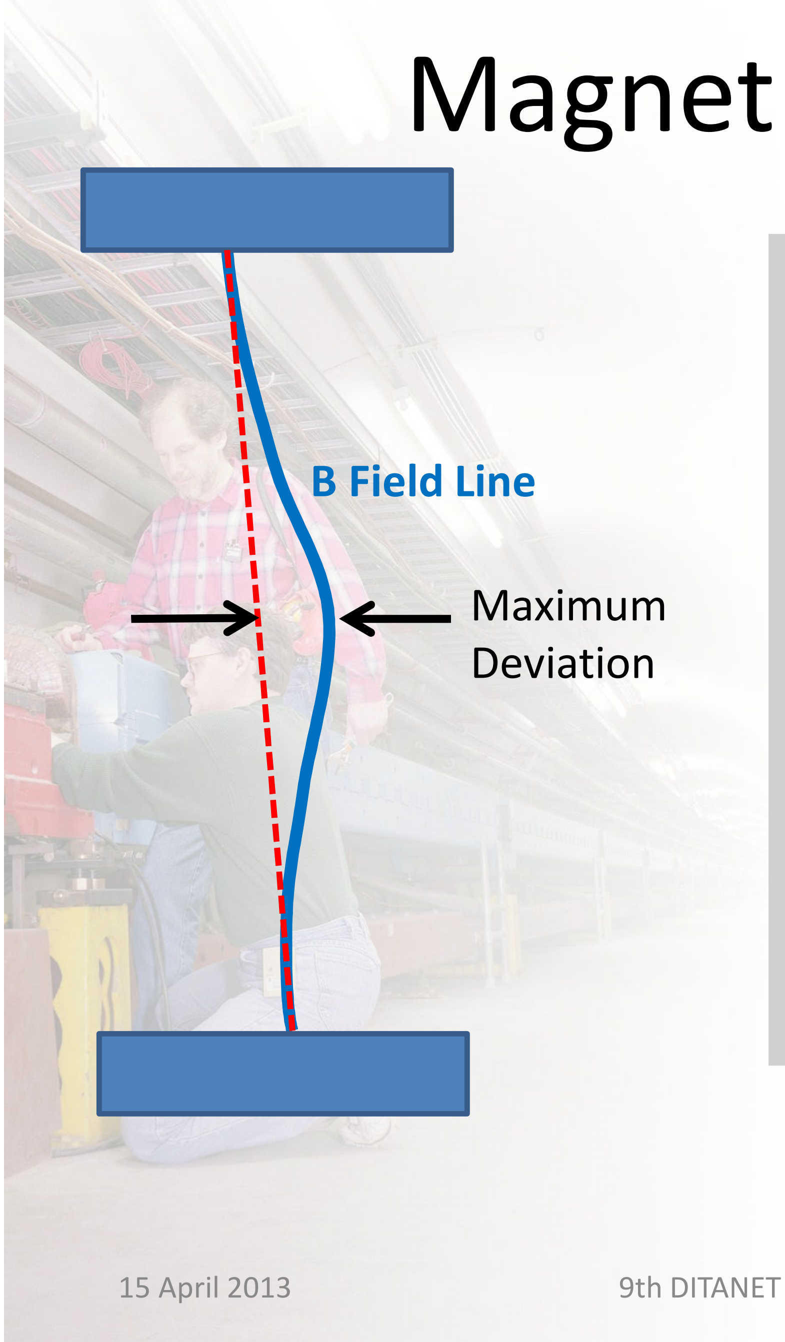
Old Shunt

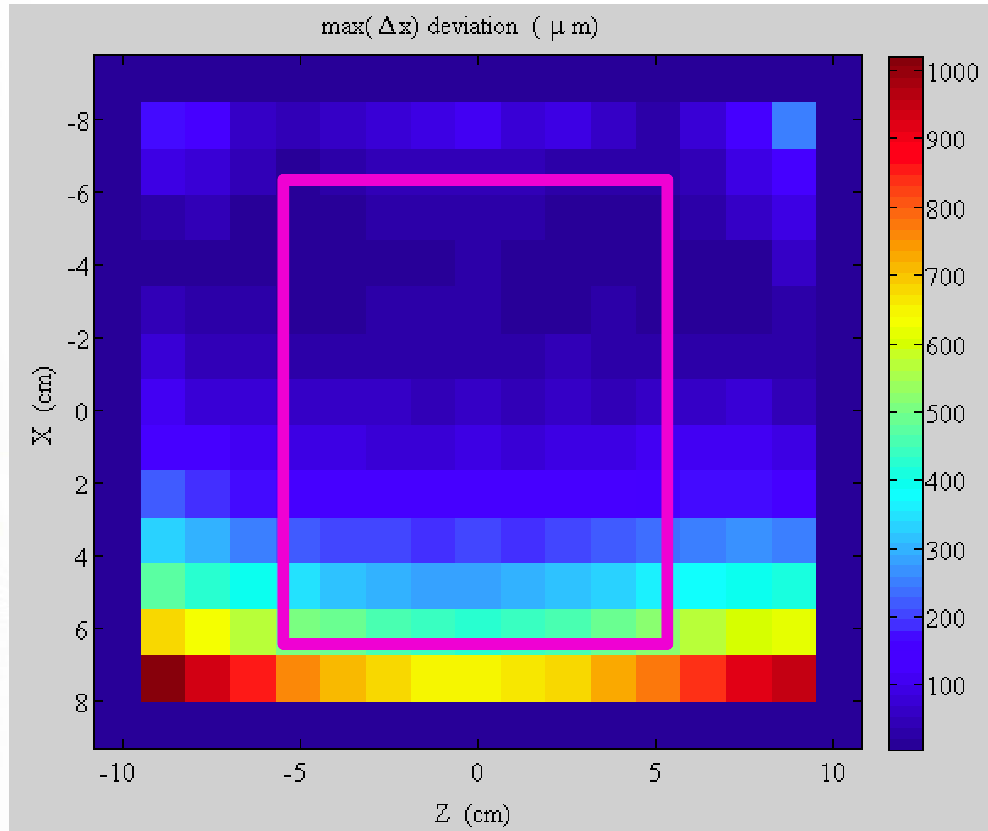


New Shunt

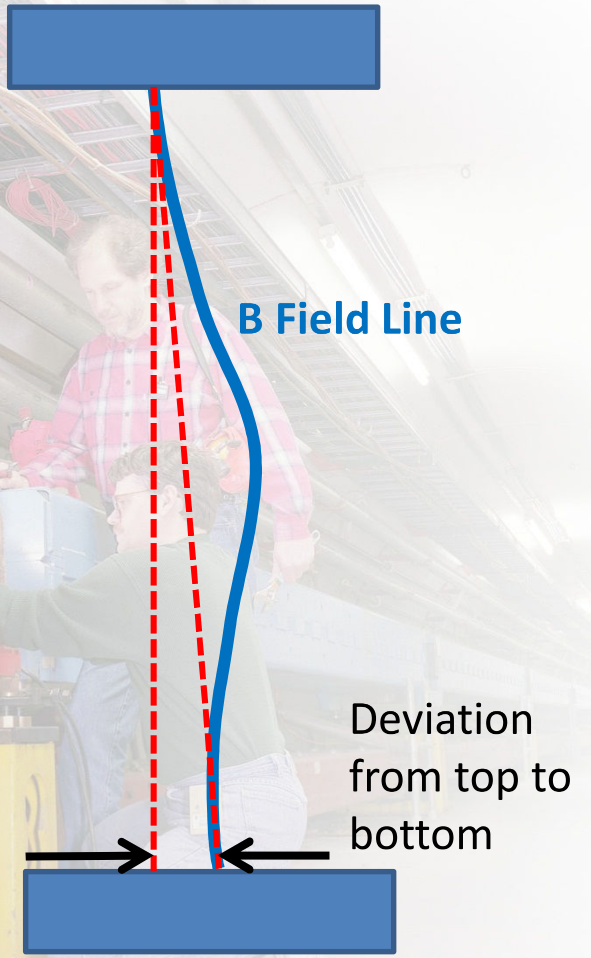


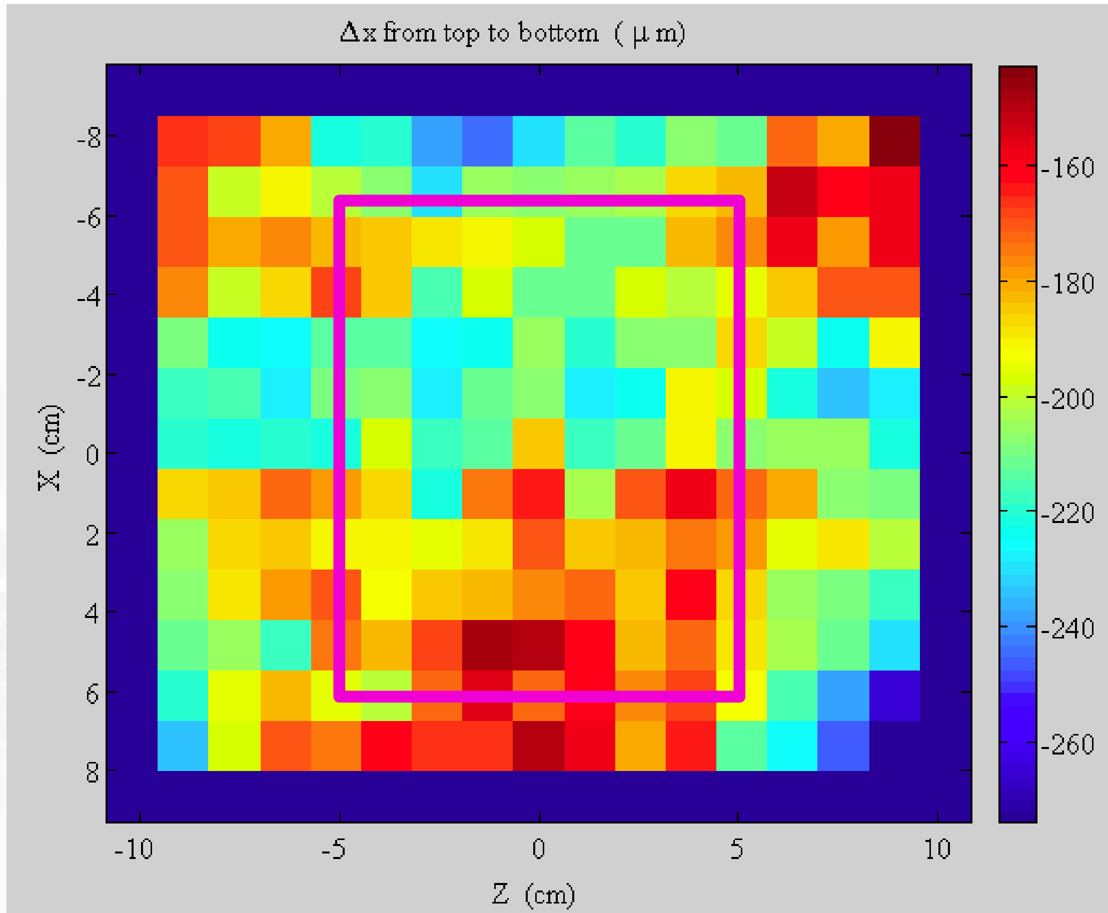
Magnet Measurements





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
  - $D \sim 0.001\ \mathrm{m}$