Electron Cloud Experiments at Fermilab: Formation and Mitigation

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Fermilab

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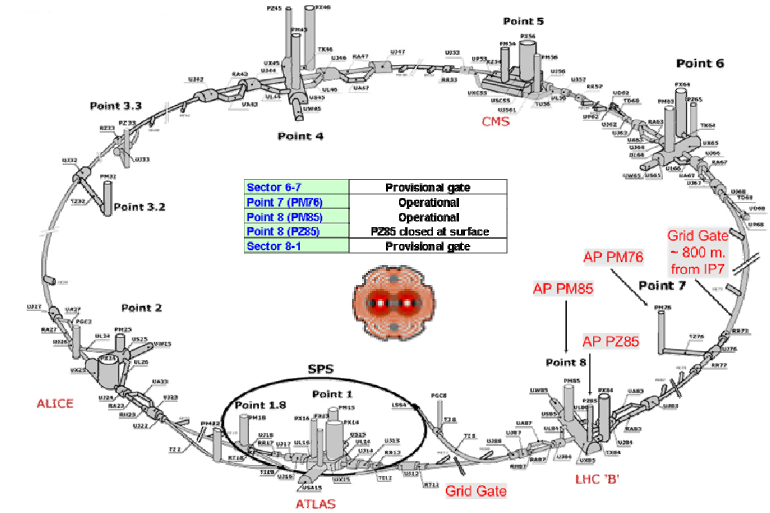
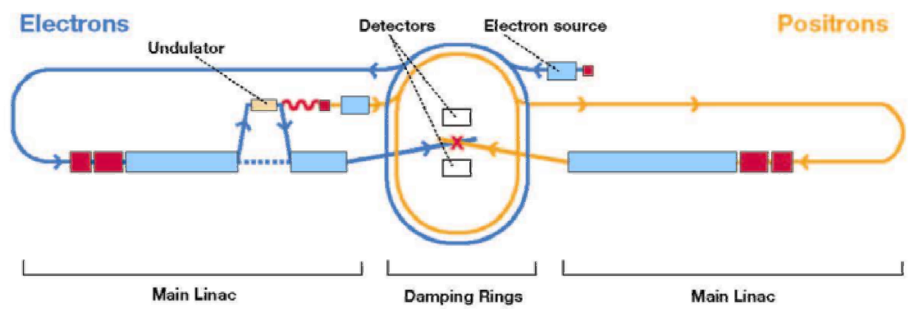
Particle Accelerator Conference

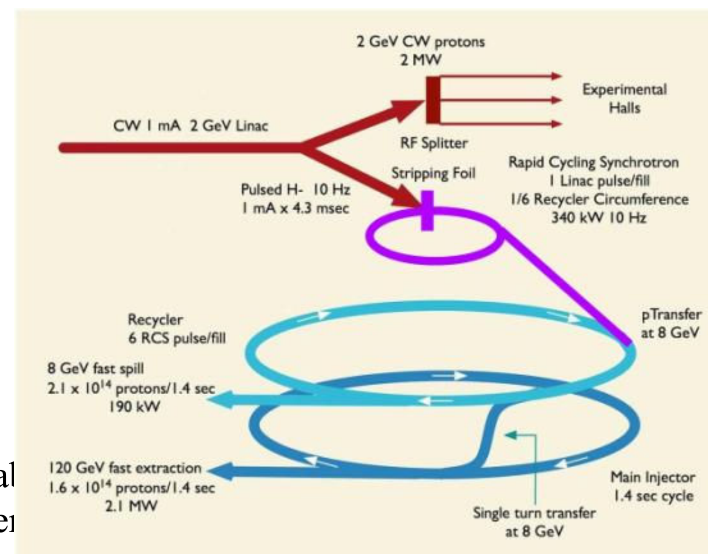
Introduction

- New accelerators / brighter beams
  - ➢ LHC/ILC/PrX
- Collective effects scale strongly
  - ➢ Space Charge, Impedance
  - ➢ **Electron Cloud**
- ECloud is a somewhat recent instability
  - ➢ Doesn't form at all for low-intensities
  - ➢ No obvious signature in conventional beam instrumentation

Generally, with any intense positive beam, a cloud of electrons can form within the vacuum vessel – degrading the performance of the machine

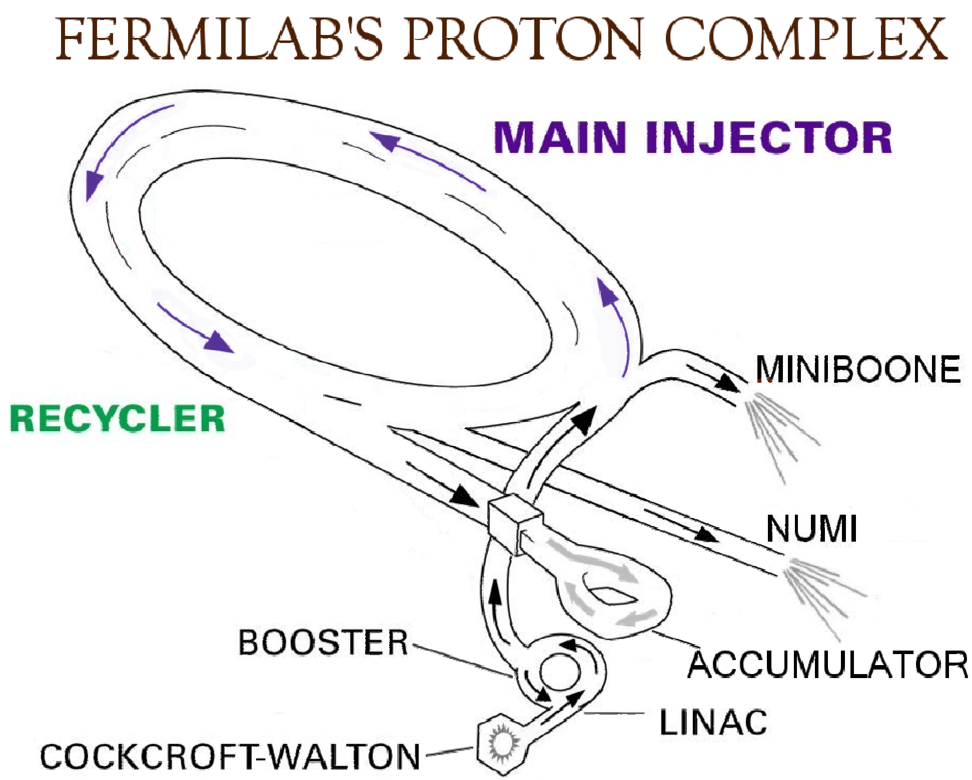






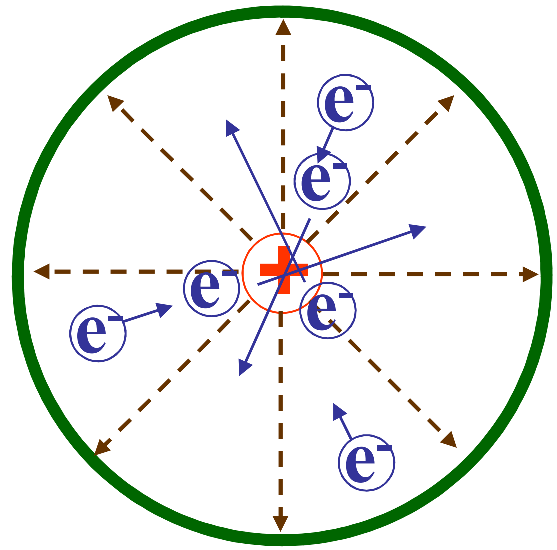
Driving Protons at the Main Injector

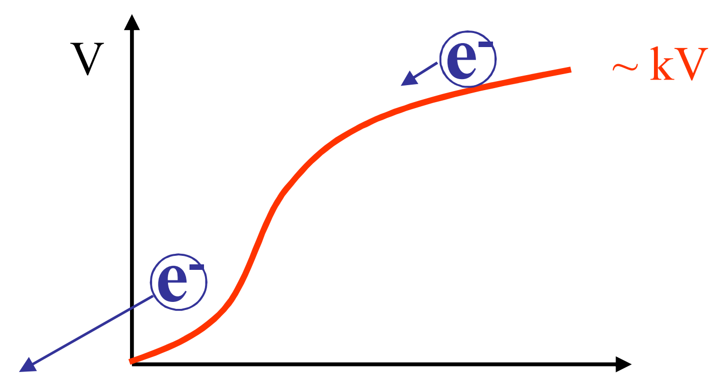
- Main Injector today produces 120 GeV proton beams for neutrinos and antiprotons
  - ➢ 400 kW average power synchrotron
  - ➢ 4-5E13 protons per pulse
    - 10e10 Protons per bunch
- Near future upgrades (NOvA)
  - ➢ 700 kW, 4-5E13 protons per pulse
- Upgrades in planning –Project X
  - ➢ 2+ MW at 60-120 GeV in Main Injector
  - ➢ 15+ E13 protons per pulse
    - 30e10 Protons per bunch
- Electron cloud on the top of our minds as a problem for tripling the beam intensity



Electron Cloud Model at Fermilab

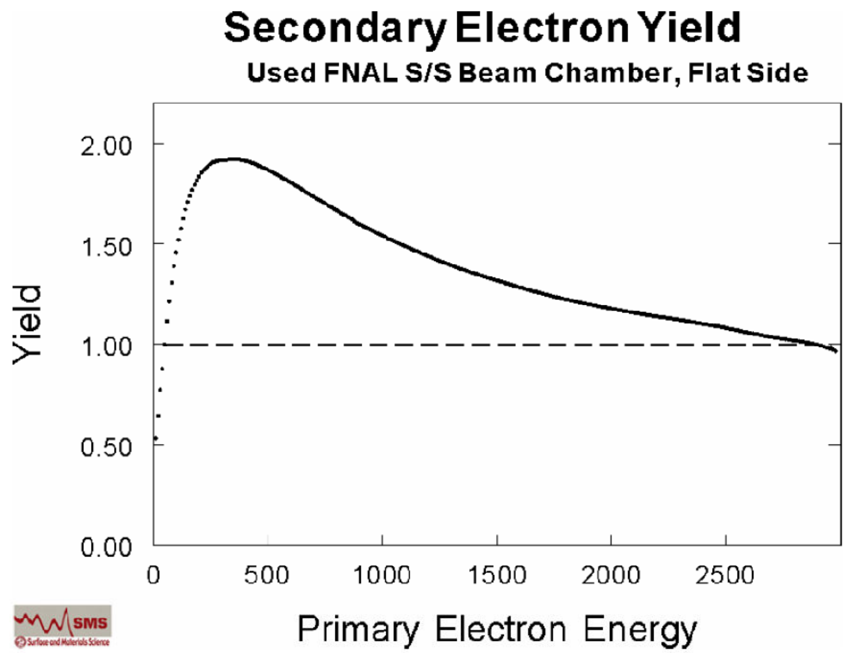
- Considering the Main Injector beam
  - 1-8 ns long bunches every 19 ns
  - 1-5 mm transverse sigma
  - Bunch intensities of ~10^{11} protons
- Produce a few initial/primary electrons
  - Residual gas ionization
    - O(e^- / m / torr / proton)
  - Lost protons
    - Can produce 100's in beam pipe
    - Generally a small constribution
- Beam produces strong potential
  - Nonadiabatic appearance
  - Accelerates electrons
- Beam disappears
  - Electrons collide with wall
  - Produce more electrons through secondary emission





Secondary Emission

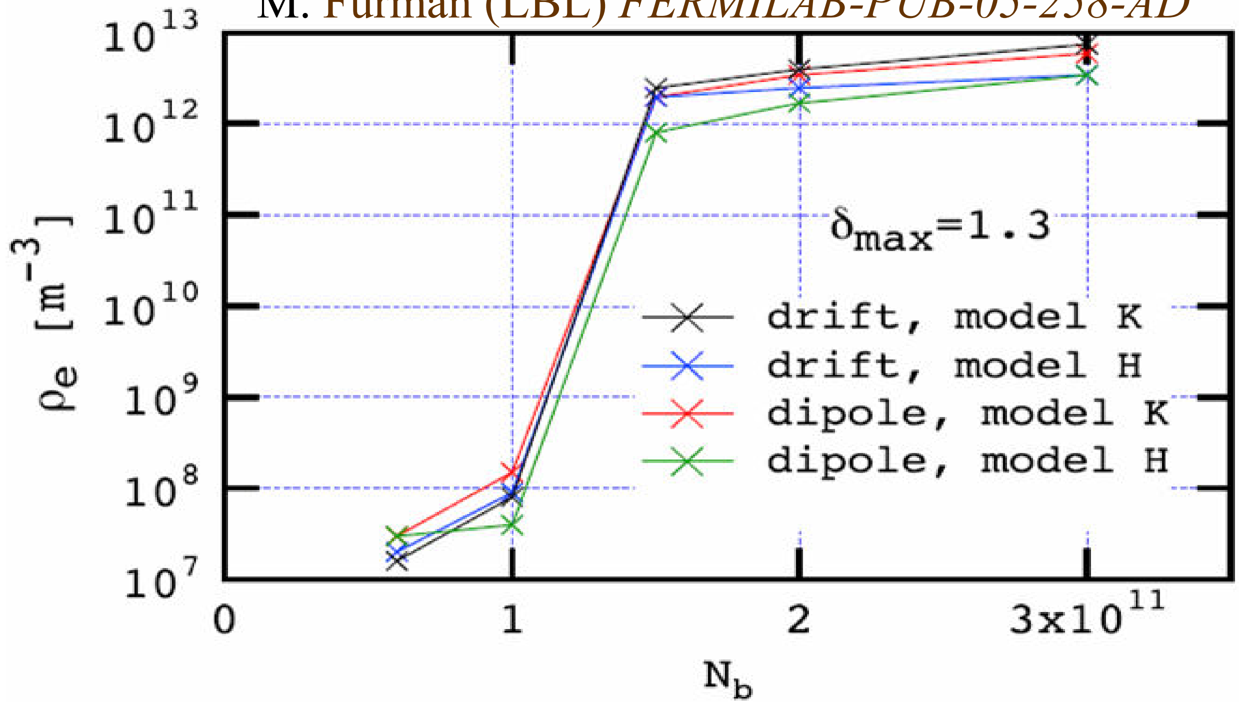
- Electrons produced upon collision with wall
  - ➢ Conversion of energy to multiplicity
- On average, 2 electrons produced per incident 400 eV electron on unconditioned MI pipe
  - ➢ Over time, this number decreases
- Secondary electron yield (SEY) depends on the energy of the incident electron
- Different materials and geometries can have different SEYs
- Produced electrons have much lower energies, typically 1-10 eV



Simulation of Entire Process

- Simulations suggested that MI might be near a threshold for electron cloud formation
  - ➢ 4-5 orders or magnitude increase of cloud density with a doubling of bunch intensity
  - ➢ Used existing code: POSINST
    - Had been applied to several other electron cloud situations
- We operate now just on the lower side of the threshold
  - ➢ We could move above it through these upgrades and be hit without warning

M. Furman (LBL) *FERMILAB-PUB-05-258-AD*



(simple) Critical Model for ECloud

- Why such a threshold for the Main Injector?
- Consider equilibrium at marginal intensities
  - Criticality parameter: κ
    - Proportion of electrons that "survive" a bunch crossing

$$N_{b+1} = \kappa \times N_b + P$$

  - No straightforward equation for κ
    - Combination of energy gain, SEY curve, and slow loss between bunches
      - Comes from simulation

$$N_{eq} = \frac{P}{1-\kappa}$$

  - Below threshold, ($\kappa < 1$) equilibrium density is reached
- At $\kappa > 1$ there is exponential growth, and it is limited only by the space charge of the electrons screening the proton beam potential
  - Requires at least a few %, quickly approaches line density of the same order as the beam

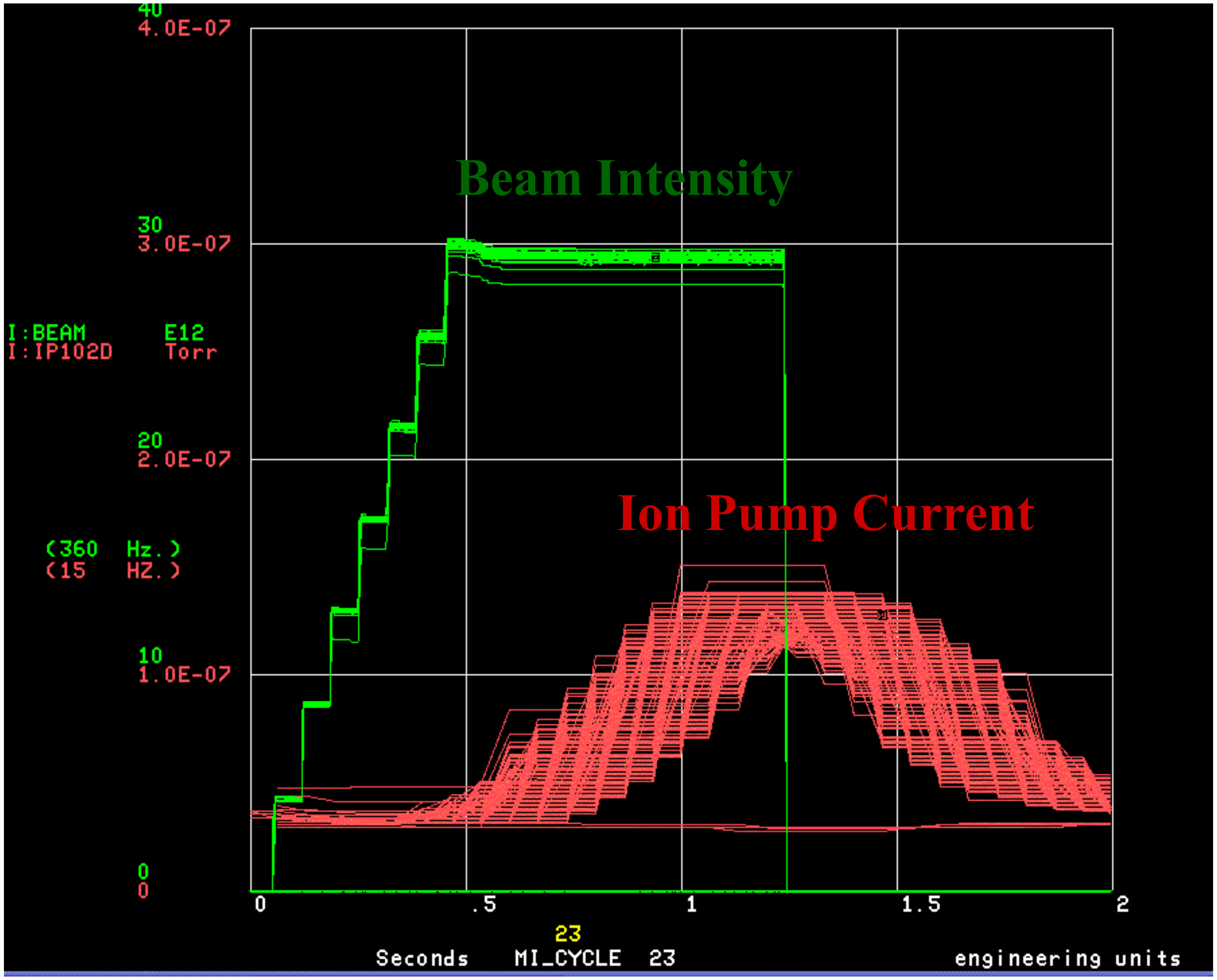
$$N_{eq} = f * N_{beam} \qquad \{0.1 < f < 1\}$$

  - f comes from simulation. Typically around 70%
- Primary production is the key difference
  - In electron/positron machines, can be ~ 1% / bunch
    - Electron density is large even if $\kappa < 1$, so transition is weak
  - In MI it is order 1e-8 / bunch, so the transition at $\kappa=1$ is very strong

Project X Approach

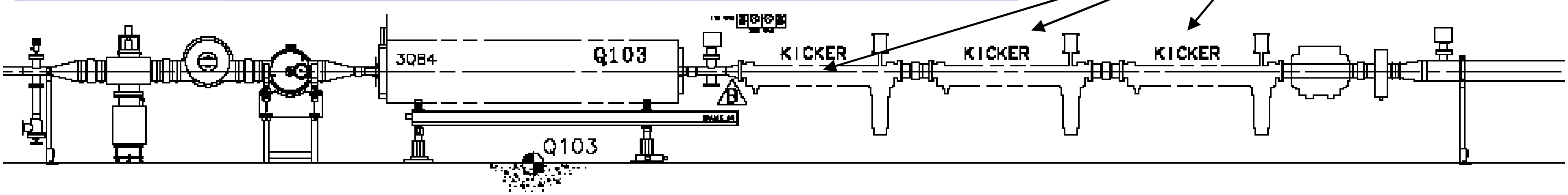
- Program of experiments and simulation addressing the questions for Project X
  - Tripling the MI Intensity
- Measurements with the existing beam have shown evidence for the beginning of a threshold
- Our default approach is to plan to coat all the MI magnets
  - Coatings can reduce the secondary electron yield
- However, coating is expensive and time-consuming
- Lingering question is whether we can get away without coating
  - Or coating a single ring, or only part
- Towards Project X:
  - Develop new instrumentation, particularly for the dipoles
  - Measure SEY conditioning in MI and at Cornell
  - Program of simulation to be able to extrapolate the conditions of conditioning at higher intensity
  - Bench experiments with coatings and conditioning

First Evidence: Pressure Rises in MI

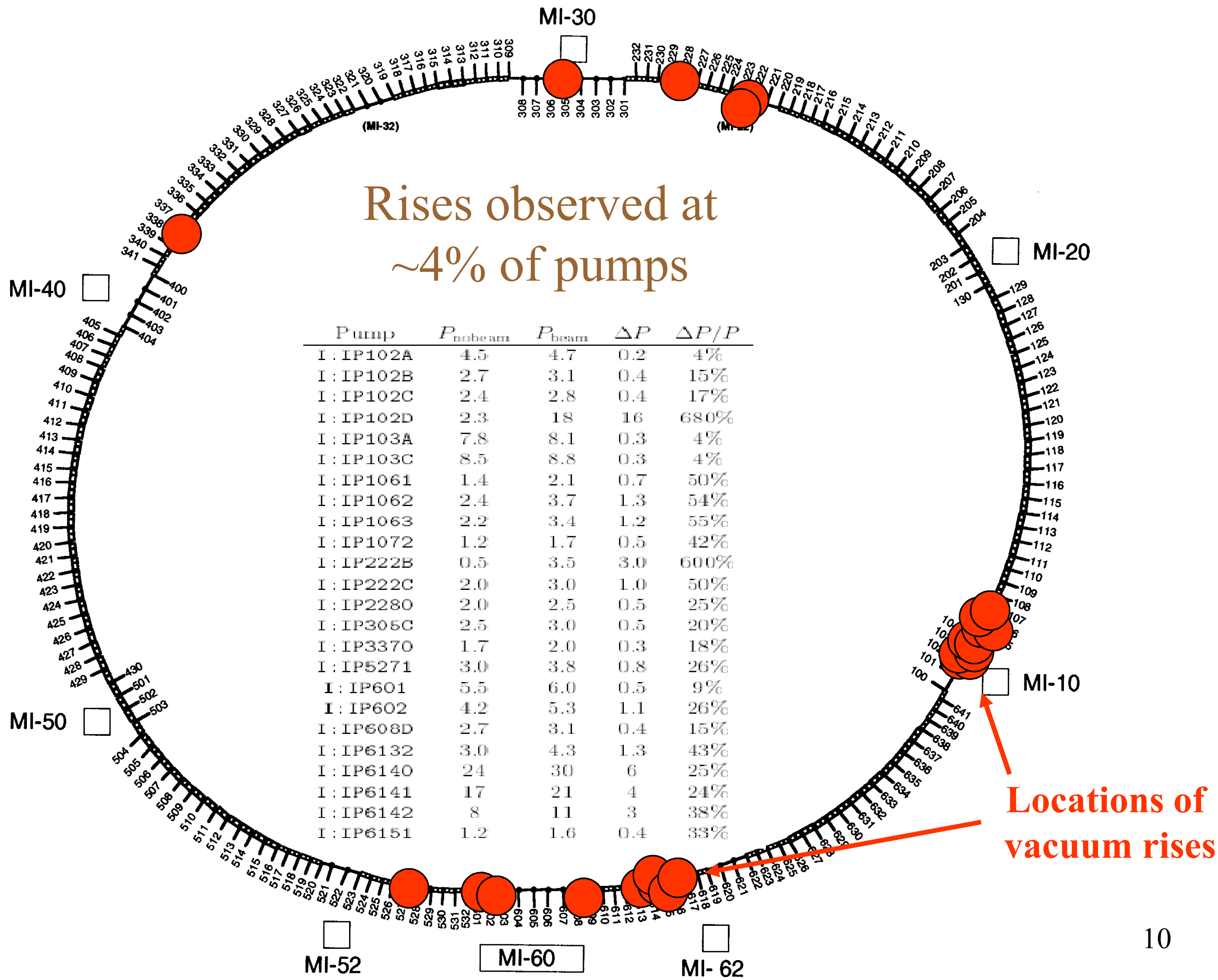


- See fast rise over the course of a cycle (1s)
- The control system induces delay
- Occurs only at location of uncoated ceramic

Ceramic beam pipes



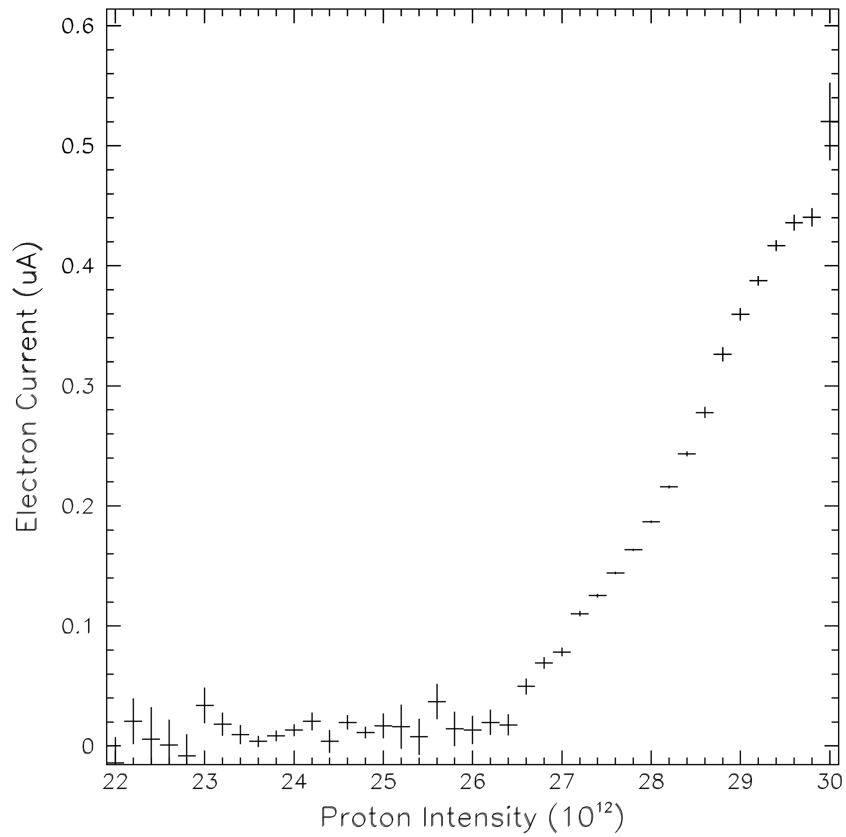
Dynamic Rises Around the Ring



Pump	P_{nobeam}	P_{beam}	ΔP	$\Delta P/P$
I:IP102A	4.5	4.7	0.2	4%
I:IP102B	2.7	3.1	0.4	15%
I:IP102C	2.4	2.8	0.4	17%
I:IP102D	2.3	18	16	680%
I:IP103A	7.8	8.1	0.3	4%
I:IP103C	8.5	8.8	0.3	4%
I:IP1061	1.4	2.1	0.7	50%
I:IP1062	2.4	3.7	1.3	54%
I:IP1063	2.2	3.4	1.2	55%
I:IP1072	1.2	1.7	0.5	42%
I:IP222B	0.5	3.5	3.0	600%
I:IP222C	2.0	3.0	1.0	50%
I:IP2280	2.0	2.5	0.5	25%
I:IP305C	2.5	3.0	0.5	20%
I:IP3370	1.7	2.0	0.3	18%
I:IP5271	3.0	3.8	0.8	26%
I:IP601	5.5	6.0	0.5	9%
I:IP602	4.2	5.3	1.1	26%
I:IP608D	2.7	3.1	0.4	15%
I:IP6132	3.0	4.3	1.3	43%
I:IP6140	24	30	6	25%
I:IP6141	17	21	4	24%
I:IP6142	8	11	3	38%
I:IP6151	1.2	1.6	0.4	33%

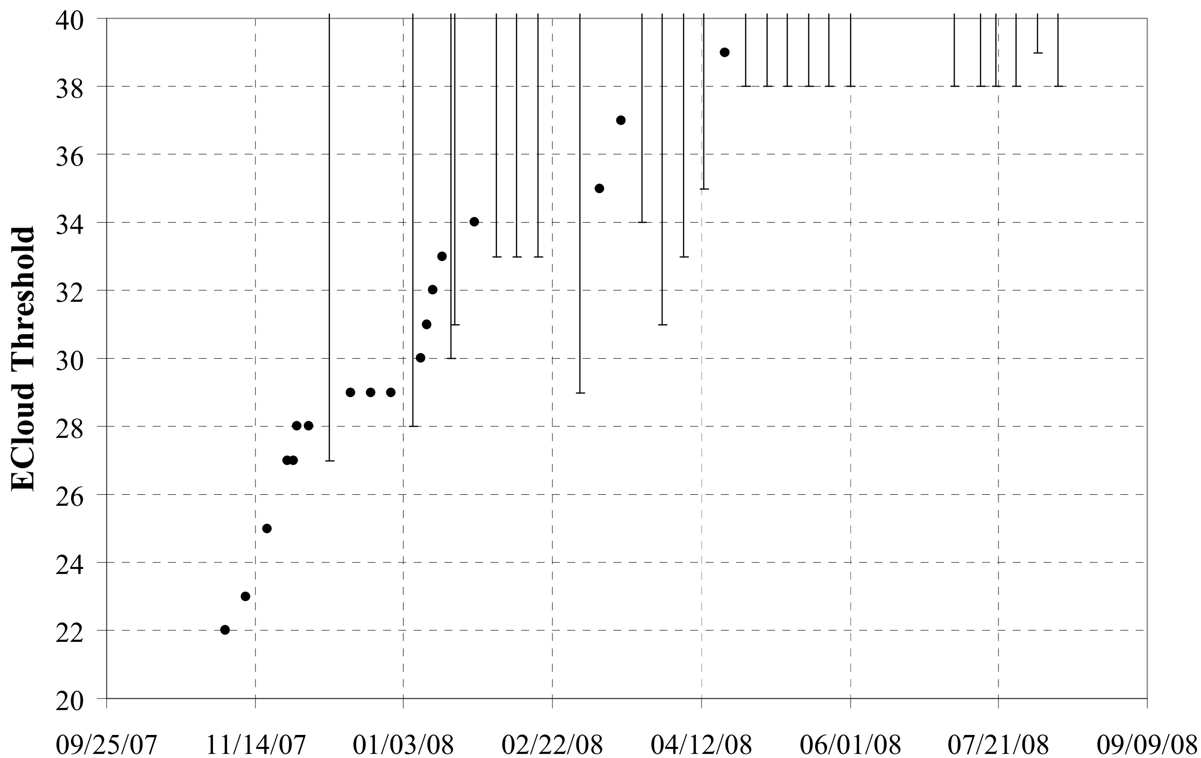
Early Data - Threshold

- Installed a single electron detector
  - Argonne RFA in straight section
- Large number of cycles sampled at maximum electron current
- Clear turn-on at higher intensities
  - Threshold at ~ 26e12 protons
  - Threshold later moved higher
- Allowed fitting of simulation to data, giving an SEY
  - Fit to simulation by Furman
  - Conditioned pipe gave SEY ~ 1.3



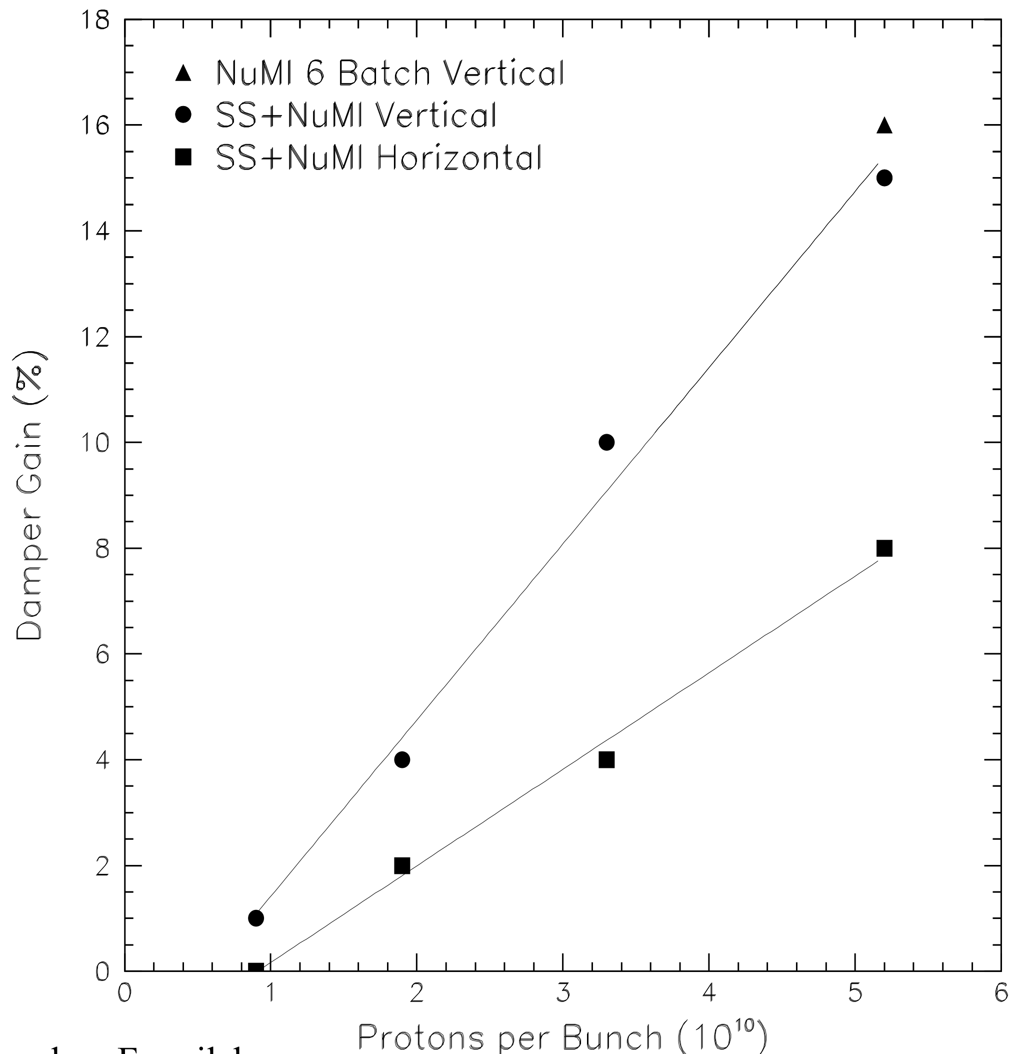
2007-2008 Run Summary

- Threshold started low and moved up to ~ 30e12 with beam studies
- When 11 batch (high-intensity) became operational, threshold increased quickly
  - Generally threshold moves with the beam intensity
- At the end of the run, the threshold was beyond maximum MI intensity
  - ~ 42e12



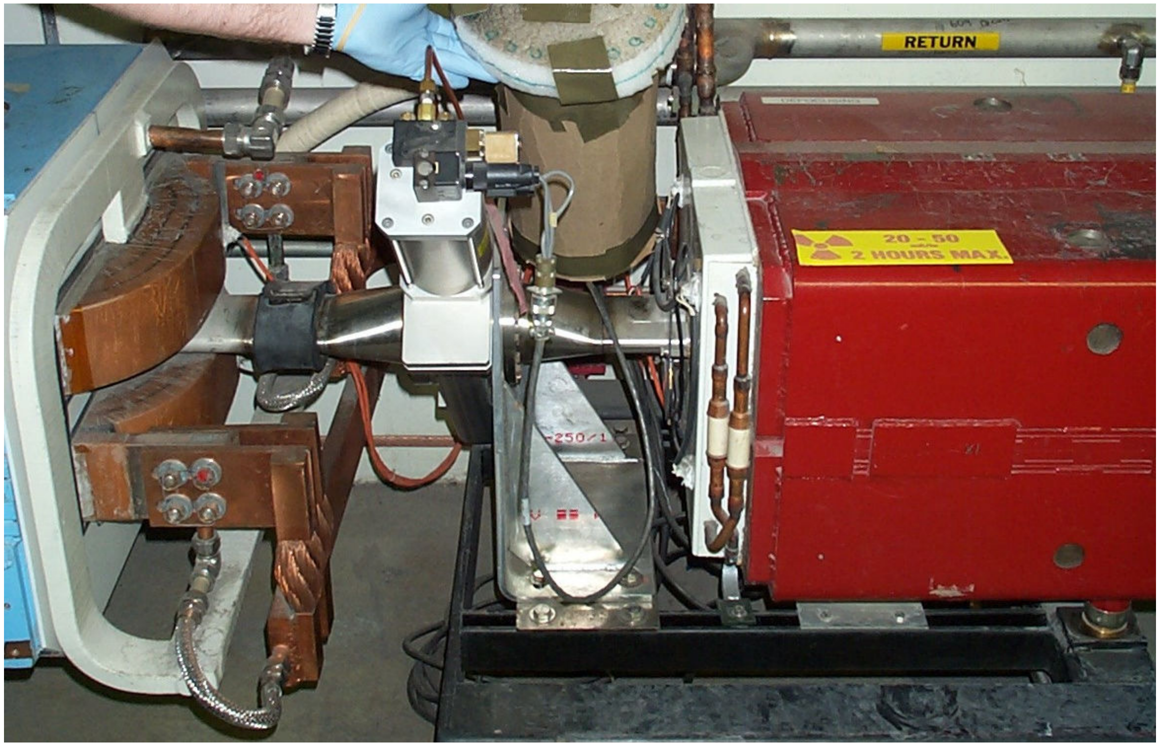
Instabilities in the MI

- High-intensity beam in the Main Injector is subject to a resistive-wall instability
  - ➢ Any search for electron cloud instability must be disentangled from this
- Damper system needed to prevent catastrophic beam loss, even at marginal intensities
  - ➢ Digital, bunch-by-bunch system
- Studied instability threshold variation with intensity
  - ➢ Generally, the scaling is linear in damper gain, which is what is expected for RWI
  - ➢ ECloud would be a nonlinear rise at high-intensity



Mitigation Options for MI

- Main Injector is 60% dipole, 25% quadrupole
  - < 5% bare straights, so solenoids are ineffective
- Beam pipe is captured in magnets and aperture is tight
  - Electrodes are not an option
- Coating is most straightforward solution for Project X
  - Though certainly not easy or inexpensive
  - Would try to do this in the tunnel, but would require at least moving the magnets and breaking vacuum in many places

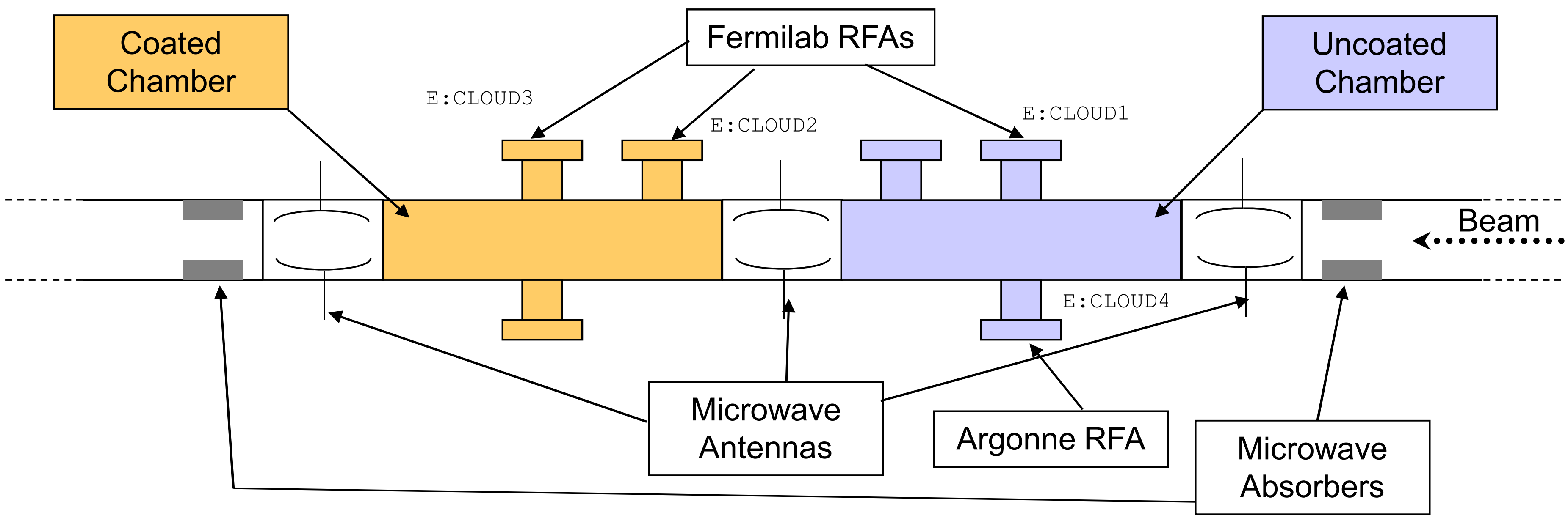


Electron Cloud Experimental Station - 2009

Major upgrade installed summer 2009

- 2 New experimental Chambers
  - Identical 1 m SS sections, except that one is coated with TiN
- 4 RFAs (3 Fermilab & 1 Argonne)
- 3 microwave antennas and 2 absorbers
  - Measure ECloud density by phase delay of microwaves

- Primary Goal: validate coatings as potential solutions for Project X
- Secondary Goals:
  - Remeasure threshold and conditioning
  - Further investigate energy-dependence
  - Measure energy spectrum of electrons
  - Test new instrumentation
  - Directly compare RFA and Microwave
  - Measure spatial extinction of ECloud



TiN Coating

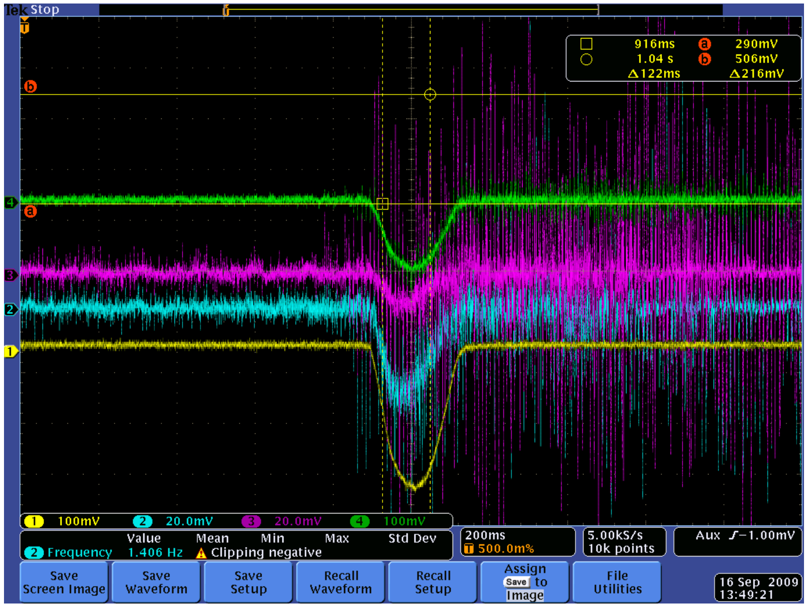
- TiN is a standard coating for ECloud mitigation
- Coating of test chambers performed at BNL
- Will need to adapt this procedure for *in situ* coating of 3000 m of Main Injector
- Also looking at adopting the SLAC procedure

Electron Detectors

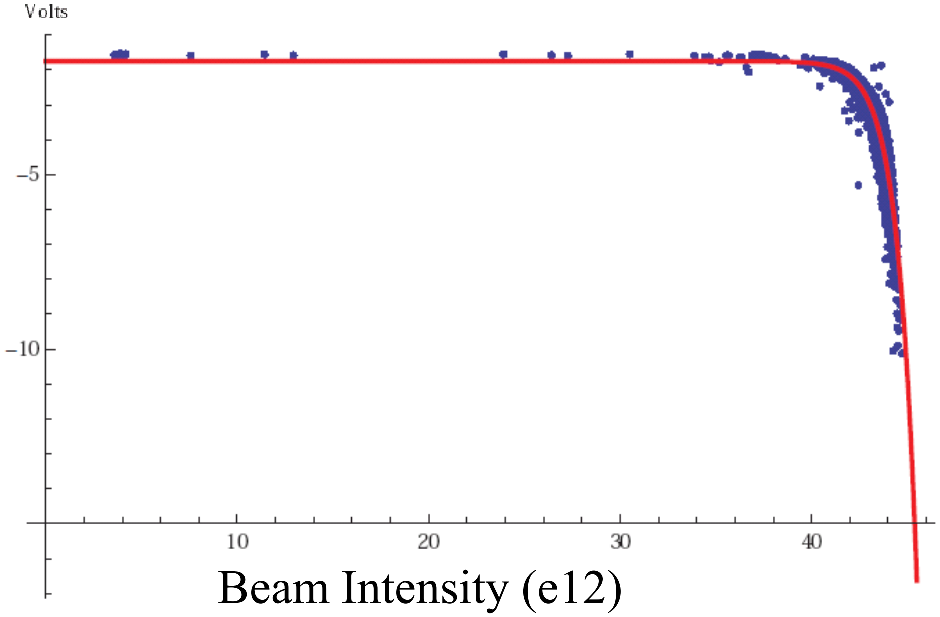
- Retarding field analyzers
  - Based on Argonne design
- Maximize signal with enlarged area and by removing ground grid
  - Ground is provided by the beam pipe
- Shaping of electrodes optimizes energy filter performance
  - Also, more hermetic
- Amplifier/filter in tunnel
  - Better-quality cables to surface

Threshold Measurement

- Data collected on every Main Injector cycle
- Electron cloud time structure shows a peak flux near the minimum bunch length
- TiN showed immediately superior results to stainless steel

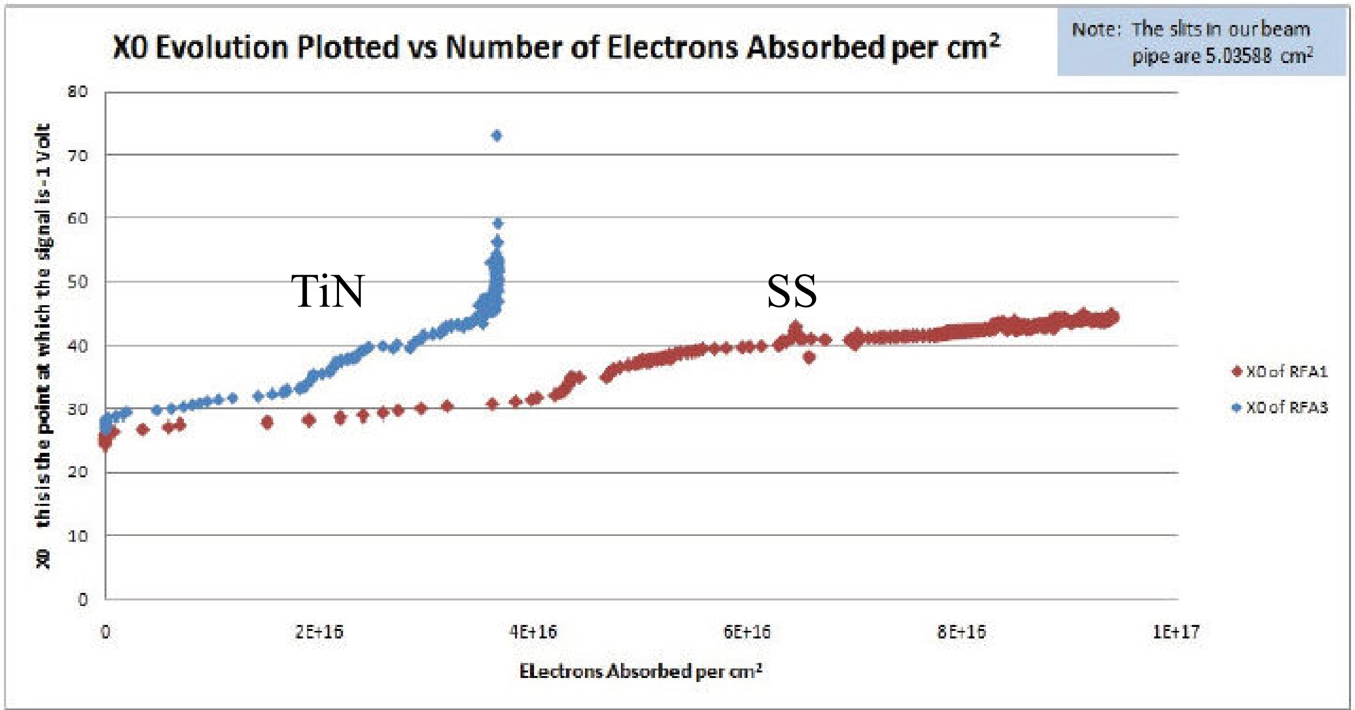


- Record the maximum current for every cycle
- Plot vs beam intensity
  - ➢ Very strong threshold behavior
- Fit to extract a threshold factor
  - ➢ Only use data from a short period of time



Evolution of Thresholds

- Thresholds increase over time
  - ➢ Best measure is the total absorbed electron dose
    - Integration under the data curve from the RFAs
- Increase of threshold is evidence of conditioning
  - ➢ Surface chemistry is changing to our advantage
  - ➢ Limited by the available intensity in the Main Injector
    - ECloud eventually disappeared for TiN
    - Continued at a low level for stainless

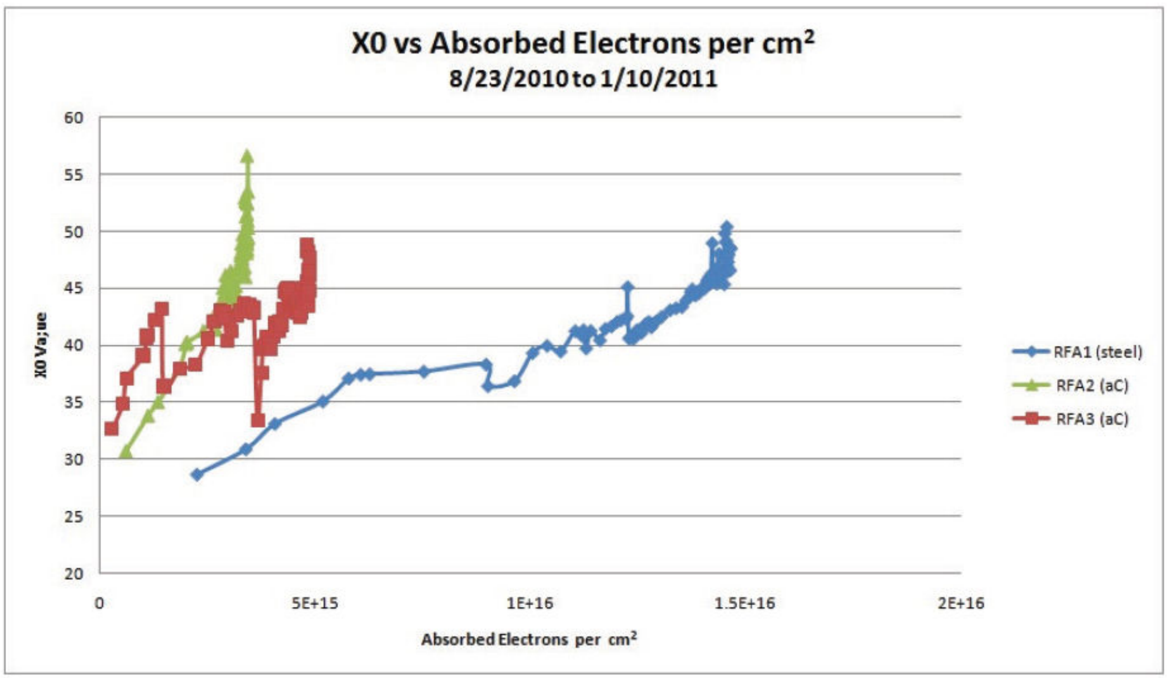


Conditioning in MI

- Why does the material condition well in MI?
  - Especially, in comparison to other proton rings like PSR or SNS
- The major differences are the beam RF structure and the acceleration cycle
  - MI h=588 vs h=1 for SNS & PSR
  - MI has high-intensity beam for ~ 50,000 revolutions each second
    - SNS & PSR have only a few hundred or thousand turns
- In total, the same maximum cloud densities in the machines will produce about 50,000 times more electron flux at the beam pipe of the Main Injector than the others
  - The dose is too low at other machines to condition in a similar way

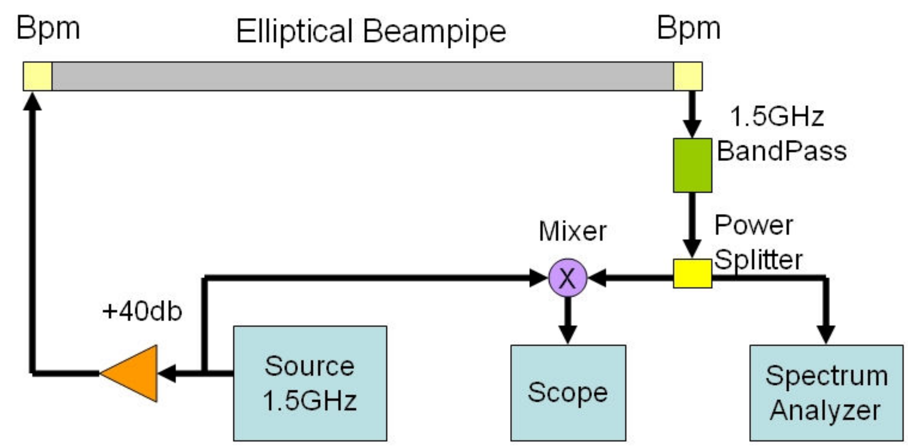
Carbon Pipe

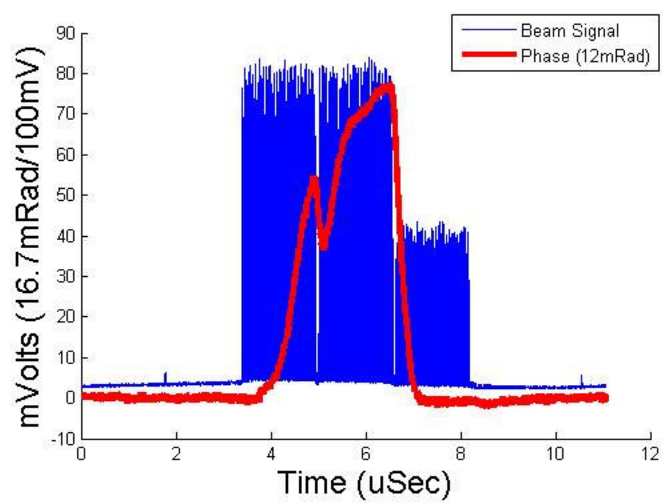
- CERN is very interested in amorphous carbon
  - See it as superior to TiN in perhaps not requiring as much conditioning
- They built a chamber for us in short order and we installed it in the MI in 2010
  - Replacing our TiN test chamber
  - Conditioning history made like with TiN
- Initial results were similar to TiN (required conditioning)
- Tests were interrupted by a vacuum leak
  - Small leak at the edge of carbon pipe
  - Seems to have poisoned a portion of the surface
    - Detector close to leak saw behavior that was worse than SS until very late in conditioning
    - Detector further away showed behavior more similar to TiN



Microwave Measurements

- ECloud induced phase shift
  - Carrier is injected with BPMs at just above the cutoff for the elliptical beam pipe
  - Beam modulates the ECloud
  - ECloud cause PM of carrier
  - PM accumulates over the distance
- Sideband, zero-span, and direct phase measurements
  - Sidebands come from modulation, give intensity (convolved with harmonic information)
  - Zero-span gives a cycle-wide measurement of intensity
  - Very good time-resolution with direct phase
    - Issue is getting enough transmission
- May allow measurement in dipole sections
  - No room for RFAs in Main Injector Dipoles



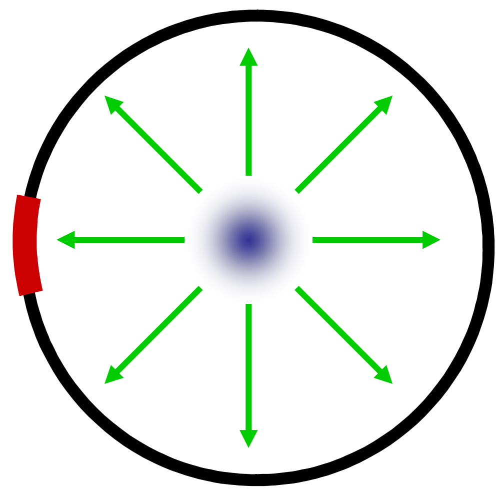


Problems with Microwave Measurements to Date

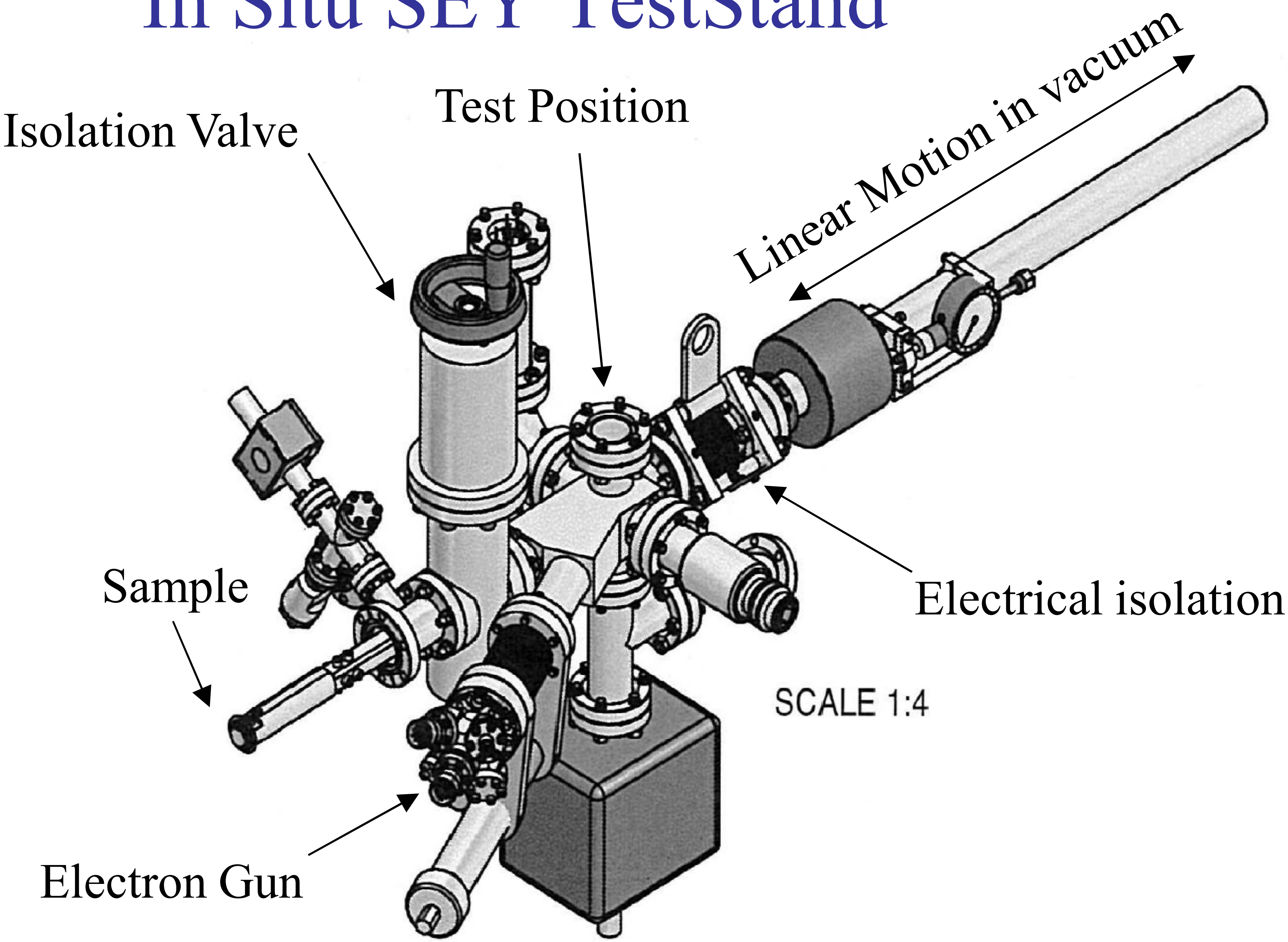
- The microwave technique is initially attractive, but suffers two significant flaws:
  1. **Non-Locality:** the measurement will most often not be representative of the targeted area, but a much larger expanse of beam pipe
  2. **Normalization:** a direct extraction of the electron density has been elusive
- Chief problem is reflection
  - Propagating a wave slightly above cutoff is asking for reflections
    - Numerous reflections inside and outside of the target region create many, longer paths from the transmitter to the receiver
- Observed this with the placement of ferrite absorbers around the measurement region
  - Transmission of carrier dropped x20, and ECloud modulation was not extractable
- Plan a new installation:
  - Create a cavity with obstructions in the beam pipe, only slightly narrowing the aperture
    - Prevents carrier from escaping the measurement region, providing locality
    - Allows use of a carrier further above the beampipe cutoff
  - Use reflections within the cavity to enhance the signal in a controlled way
    - Allow normalization
  - Design of new station is in progress

Direct SEY Measurement

- SEY measurement station from Cornell
  - Adapted from SLAC
  - Allows in situ measurement of SEY on samples
- Place sample “buttons” of materials as portion of beampipe circumference
  - Beampipe made of standard materials – for us: Stainless 316L
- Directly measure the SEY of the sample
  - SLAC did this by removing the button and testing in a surface physics lab
  - At Cornell, it has been modified for *in situ* measurement
- Will allow comparison between conditioning in electron/positron ring and our proton ring
- Other considerations:
  - Change pieces without breaking accelerator vacuum
  - Monitor electron flux for scrubbing history
  - Differential scrubbing can be factored out
- Stations have been built and we are preparing for installation



In Situ SEY TestStand



Summary

- Electron cloud build up has been observed at the Fermilab Main Injector
  - However, this cloud density has not negatively affected the beam
  - Threshold behavior is qualitatively in agreement with simulation predictions
- Program is wide-ranging, but primary goal is to plan for Project X
- Experiments have shown that MI pipe and coatings condition with beam exposure
  - Coatings condition more quickly and effectively than bare beam pipe
    - Both TiN and amorphous carbon appear similar, though carbon may be more susceptible to contamination
  - Ultimate conditioning has been limited by beam intensity
  - Coating is a viable option for the Main Injector
    - Lingering questions are whether it is necessary, and what procedure is best
- Further experiments needed for Project X
  - Direct SEY measurement
  - Consistent understanding with simulation
  - Measurements with dipole magnets, where possible

Electron Cloud Experiments at Fermilab: Formation and Mitigation

Bob Zwaska

Fermilab

March 28, 2011

Particle Accelerator Conference

Simulation

- Have had extensive input from several codes, two make most of the impact:
  - VORPAL (Tech-X & P. Lebrun f/ Fermilab)
  - POSINST (M. Furman, LBL)
- Some future needs:
  - Simultaneous (or nearly so) simulation of cloud build-up and instabilities
  - Guidance for SEY experiments
    - Electron flux and spectrum
  - Updates of expectations with conditioning
  - Understanding of instrumentation
- Codes have focused on simulating the ECloud buildup
  - Our approach has been to prevent crossing the transition to high density
  - An extension for simulation would be to approach the question of directly simulating the beam instability with the electron cloud
    - Computationally challenging, but may give us leeway with our mitigations