Electron Cloud Measurements and Plans at Fermilab

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Contributors

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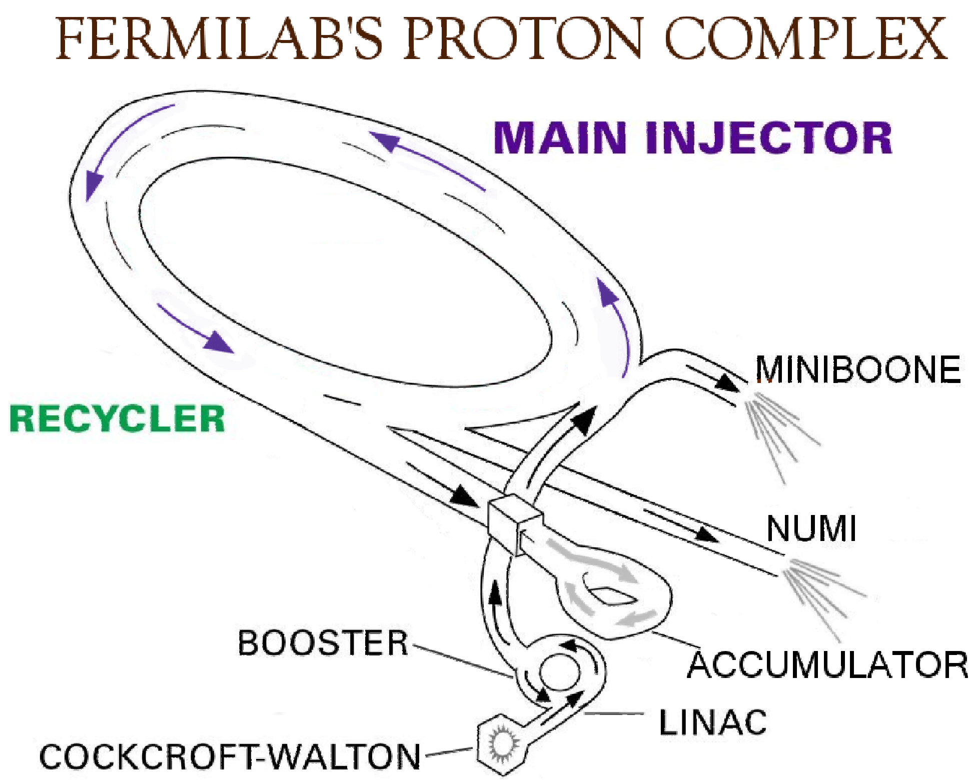
Driving Protons at the Main Injector

- Main Injector today produces 120 GeV proton beams for neutrinos and antiprotons
  - ➢ 400 kW average power
  - ➢ 4E13 protons per pulse
    - 10e10 Protons per bunch
- Near future upgrades (NOvA)
  - ➢ 700 kW, 4-5E13
- 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



Outline

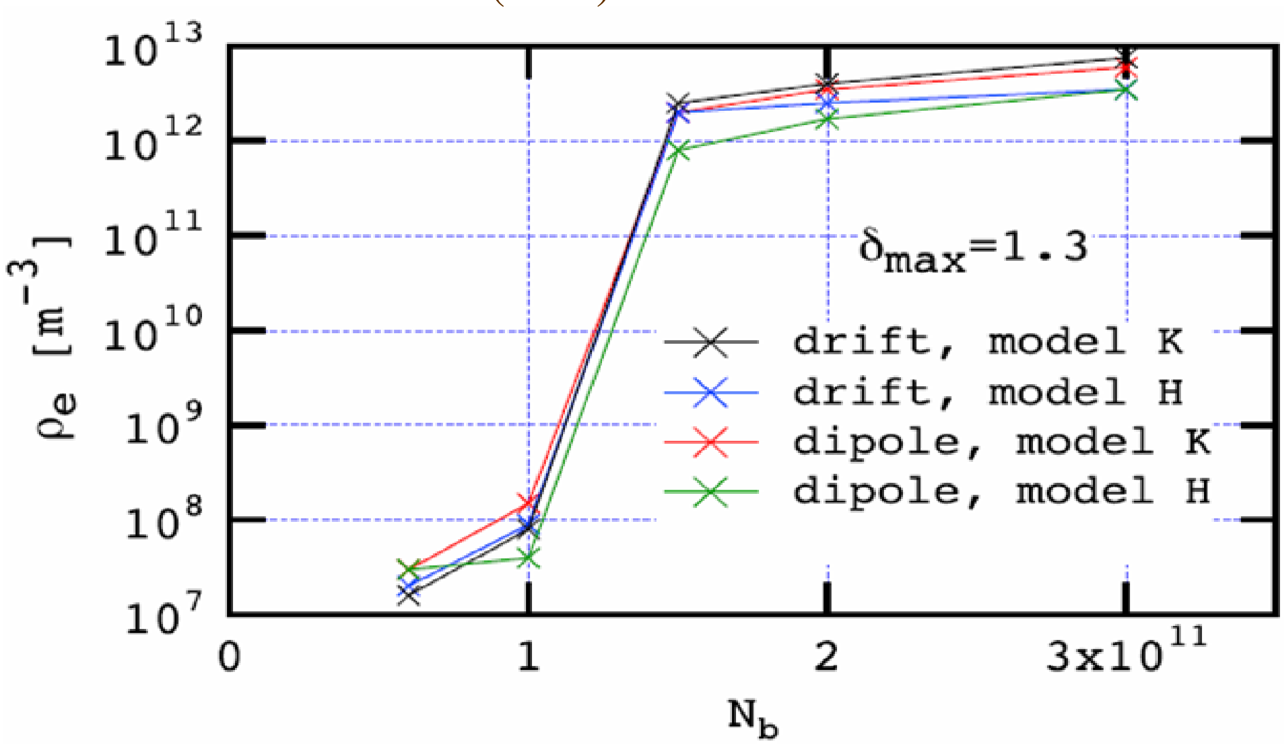
- Motivation
- Early Measurements made at the Main Injector
  - Observation of cloud buildup
- Mitigation Options in Main Injector
- Experiments with coatings in Main Injector
  - Mostly talks on Monday by C. Thangaraj and C.Y. Tan
- Considerations for Project X
- Plans for future study

- More in Monday talks (Lebrun, Thangaraj, Tan)

Early Simulation Input

- 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
- Led to a program of studies:
  - ➢ Try to find evidence of a cloud with present MI
  - ➢ Expand simulations
  - ➢ Look at secondary emission in the MI

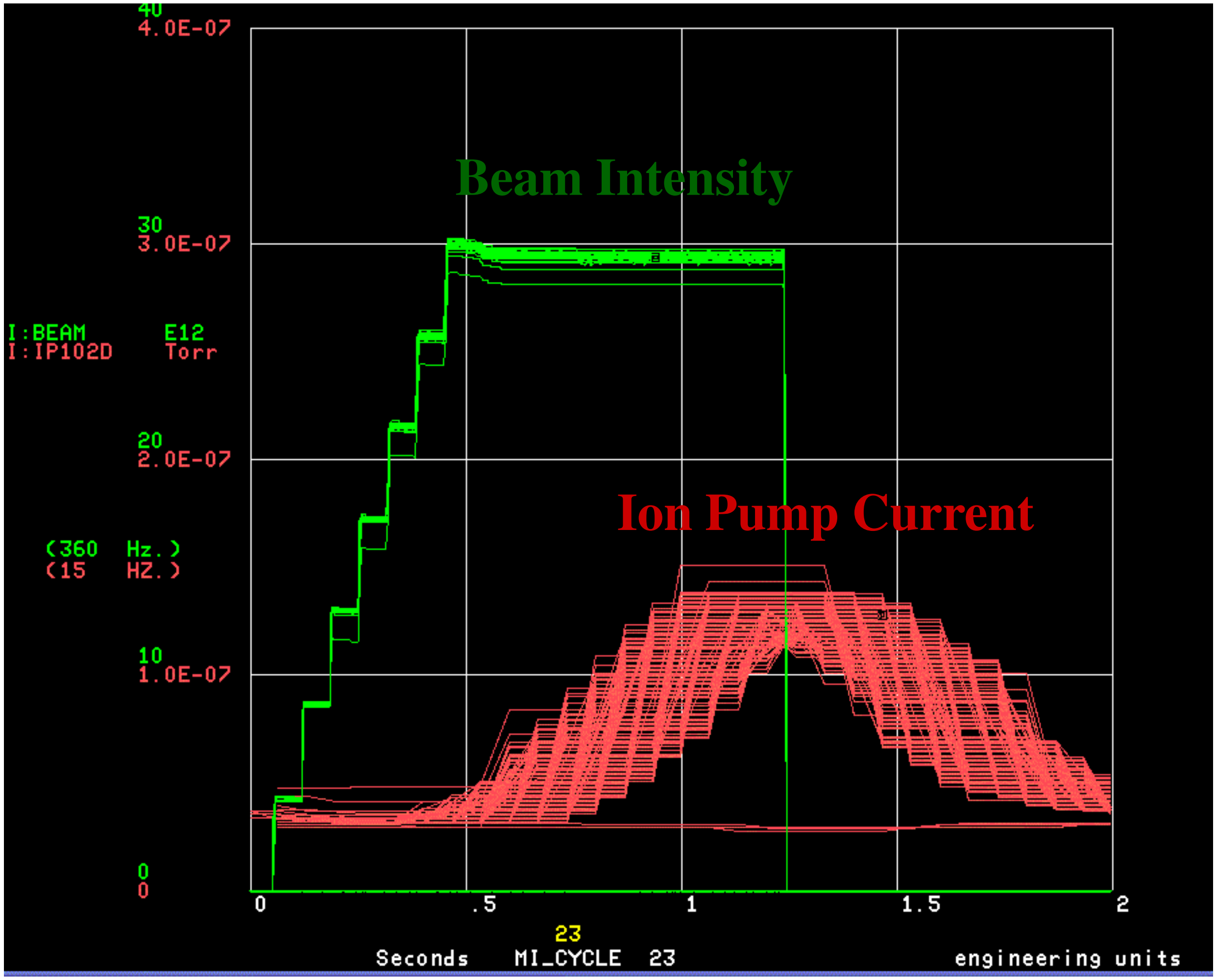
M. Furman (LBL) *FERMILAB-PUB-05-258-AD*



Critical Model for ECloud

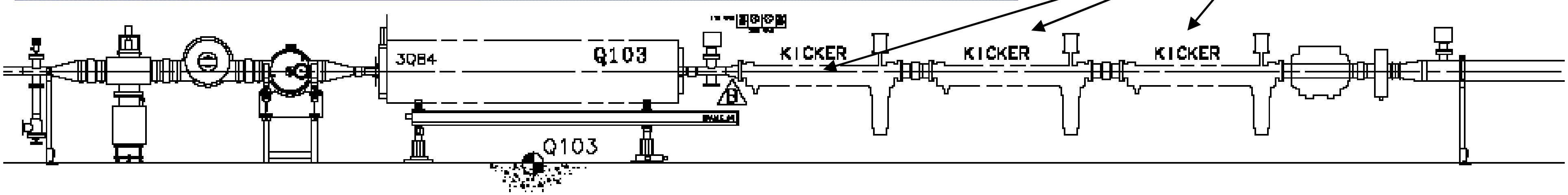
- Why such a threshold for the Main Injector?
- Consider equilibrium at marginal intensities
  - Criticality parameter: κ
    - Proportion of electrons that "survive" a bunch crossing
  - No straightforward equation for κ
    - Combination of energy gain, SEY curve, and slow loss between bunches
      - Comes from simulation
  - Below threshold, equilibrium density is primary production divided by $(1 - \kappa)$
- Primary production is the key difference
  - In CESR, can be ~ 1% / bunch
  - In MI it is order 1e-8 / bunch
- At $\kappa > 1$ there is exponential growth, and it must be suppressed by the space charge of the electrons
  - Automatically requires few % of beam
- Note: this is just a heuristic model for understanding the simulation results, don't take it too literally

Existing Pressure Rises in MI



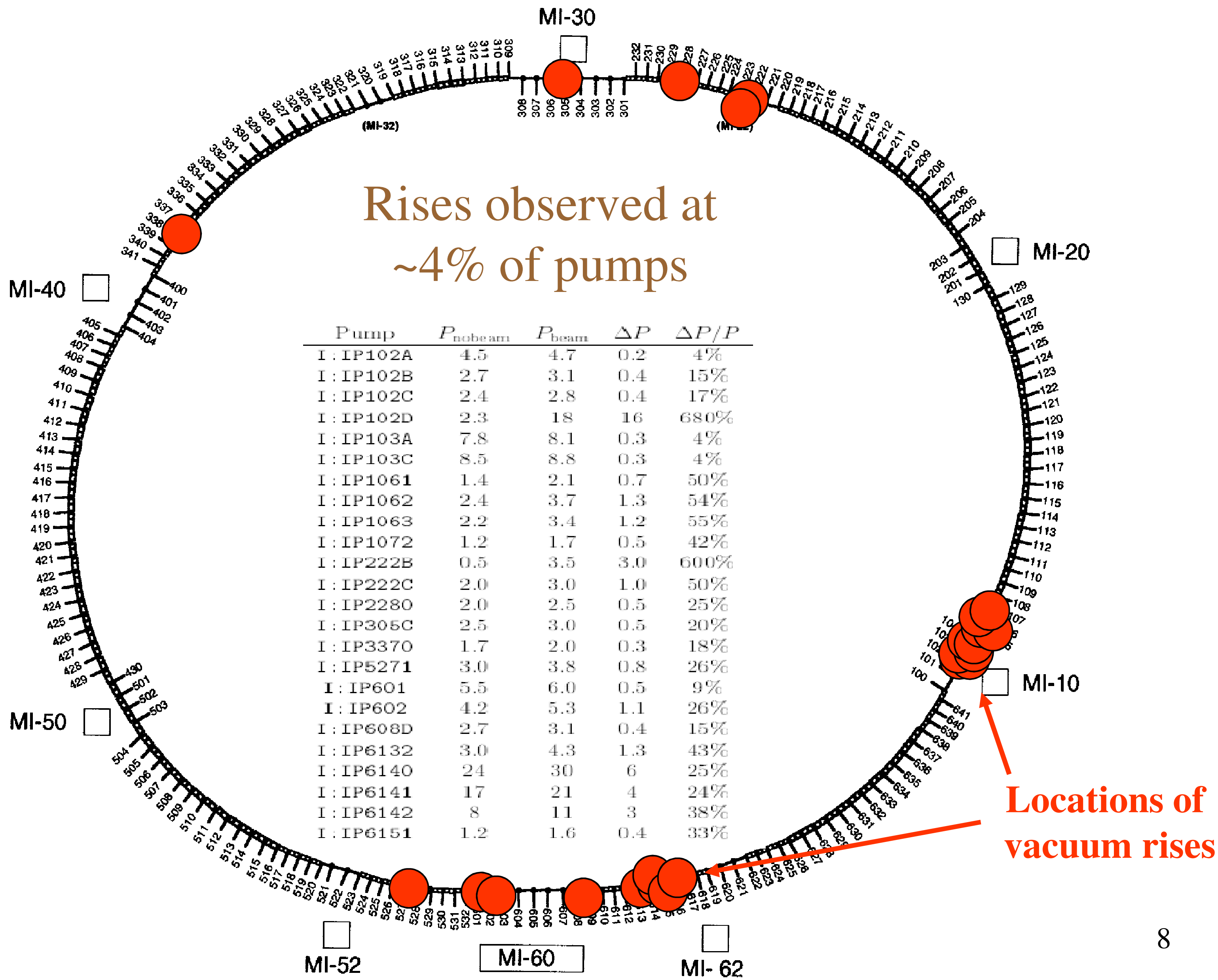
- See fast rise over the course of a cycle (1s)
- The control system induces delay
- Occurs only at location of uncoated ceramic

Ceramic beam pipes



Dynamic Rises Around the Ring

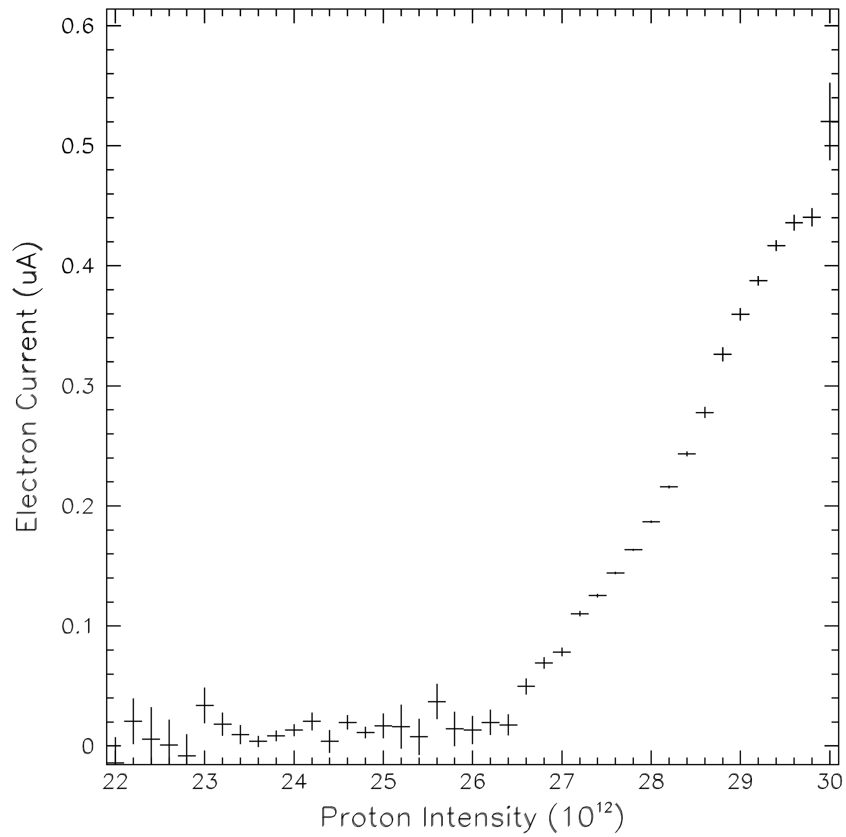
Rises observed at ~4% of pumps



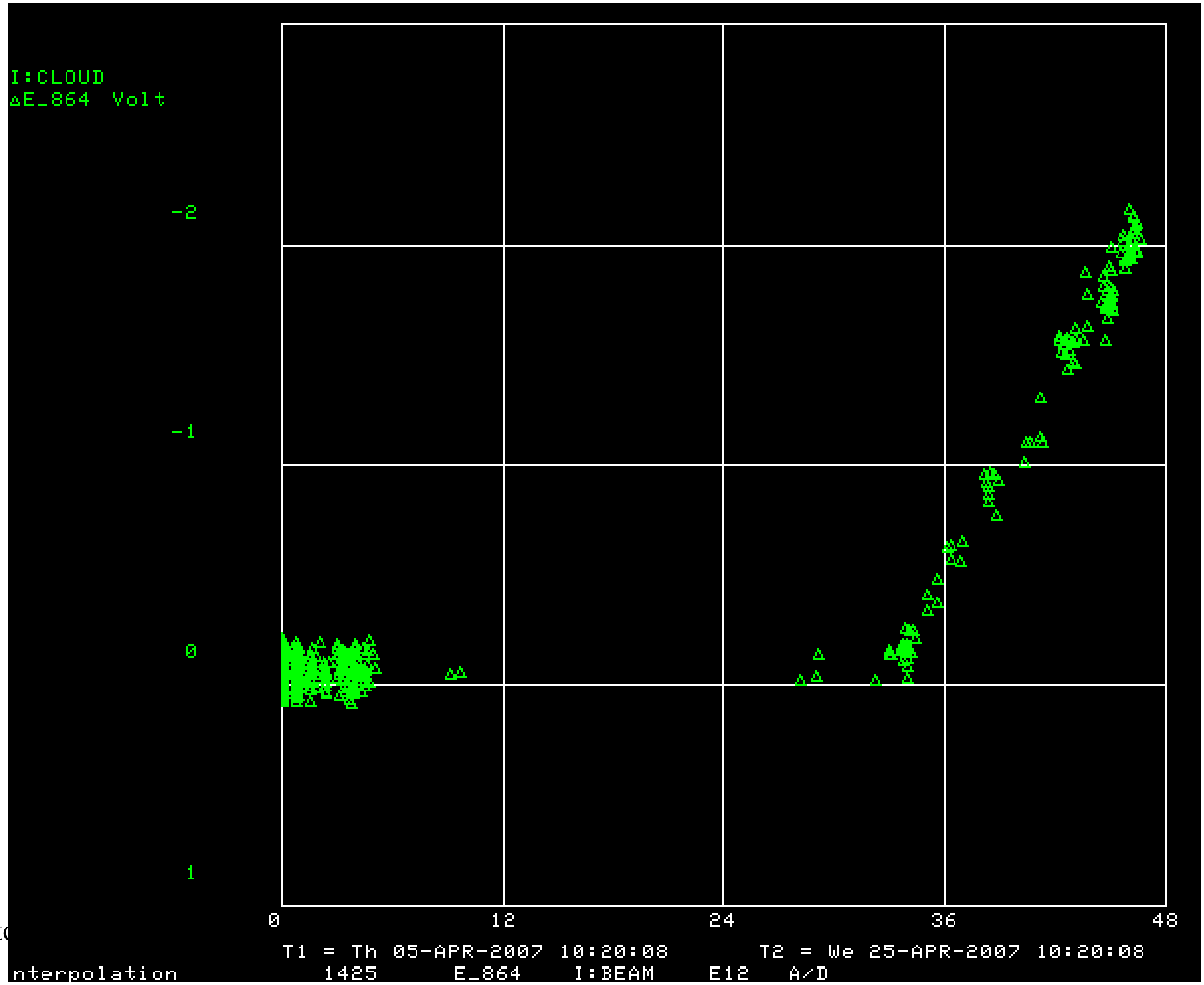
Pump	P_{nobeam}	P_{beam}	ΔP	$\Delta P/P$
I:IP102A	4.5	4.7	0.2	4%
I:IP102B	2.7	3.1	0.4	15%
I:IP102C	2.4	2.8	0.4	17%
I:IP102D	2.3	18	16	680%
I:IP103A	7.8	8.1	0.3	4%
I:IP103C	8.5	8.8	0.3	4%
I:IP1061	1.4	2.1	0.7	50%
I:IP1062	2.4	3.7	1.3	54%
I:IP1063	2.2	3.4	1.2	55%
I:IP1072	1.2	1.7	0.5	42%
I:IP222B	0.5	3.5	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 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 POSINST by Furman
  - Conditioned pipe gave ~ 1.3

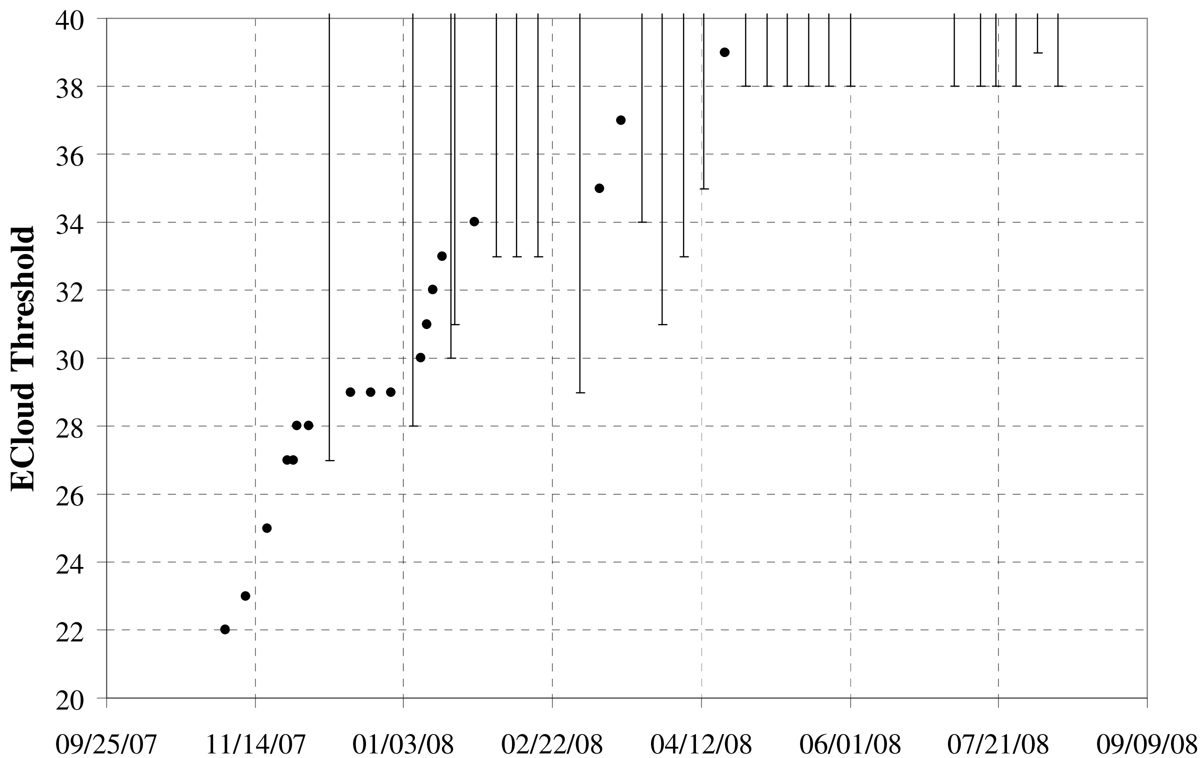


High-Intensity Operation



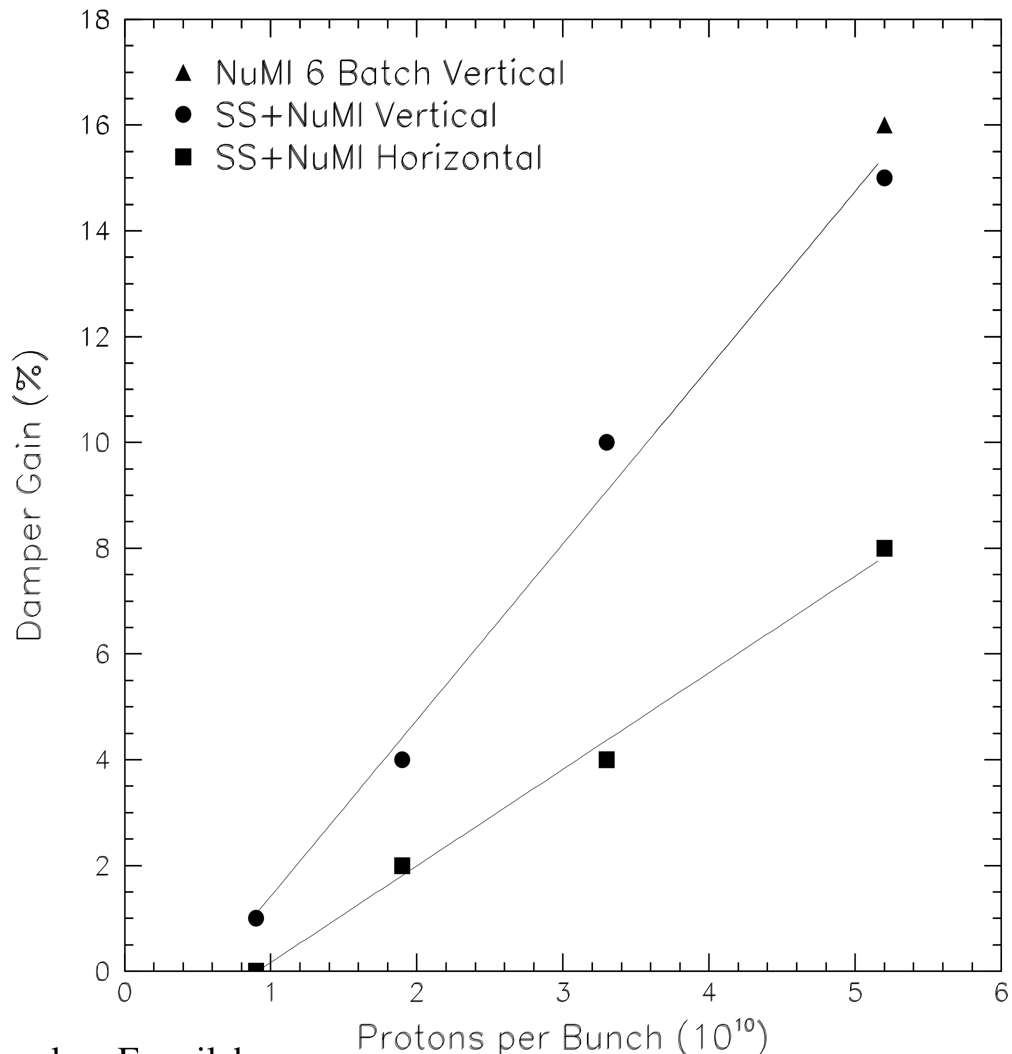
2007-2008 Run Summary

- Threshold started low and moved up to ~ 30e12 with beam studies
- When 11 batch 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



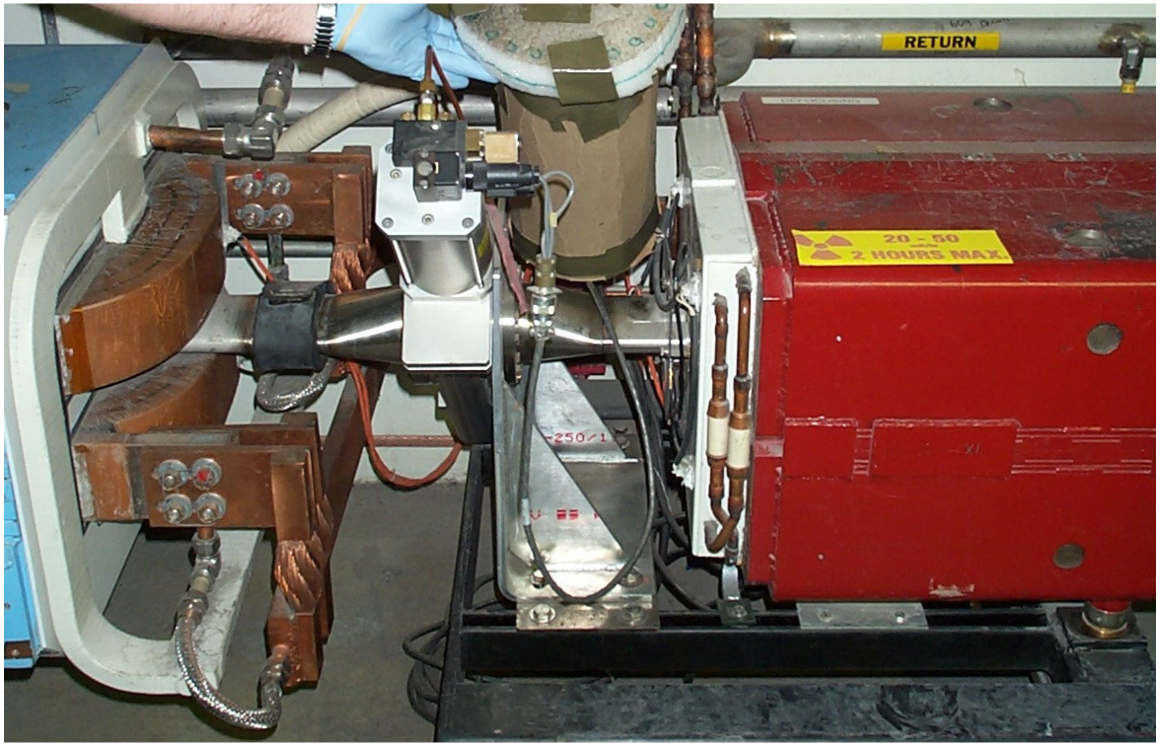
Instabilities in the MI

- High-intensity beam in the Main Injector is subject to a resistive-wall instability
- Damper system needed to prevent catastrophic beam loss, even at marginal intensities
  - Digital, bunch-by-bunch system
  - Masks any coupled-bunch instability due to ECloud
  - Also prevents tune measurement
- 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
- Present MI operation is incompatible with this study
  - Updated measurement at higher intensities would be nice



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
  - No way to add grooves or clearing electrodes
- Coating is most straightforward solution for Project X
  - Though certainly not easy or inexpensive
- A more exotic option would be to change our RF frequency, but we haven’t been able to get a solid answer on what is better, and what are the tradeoffs

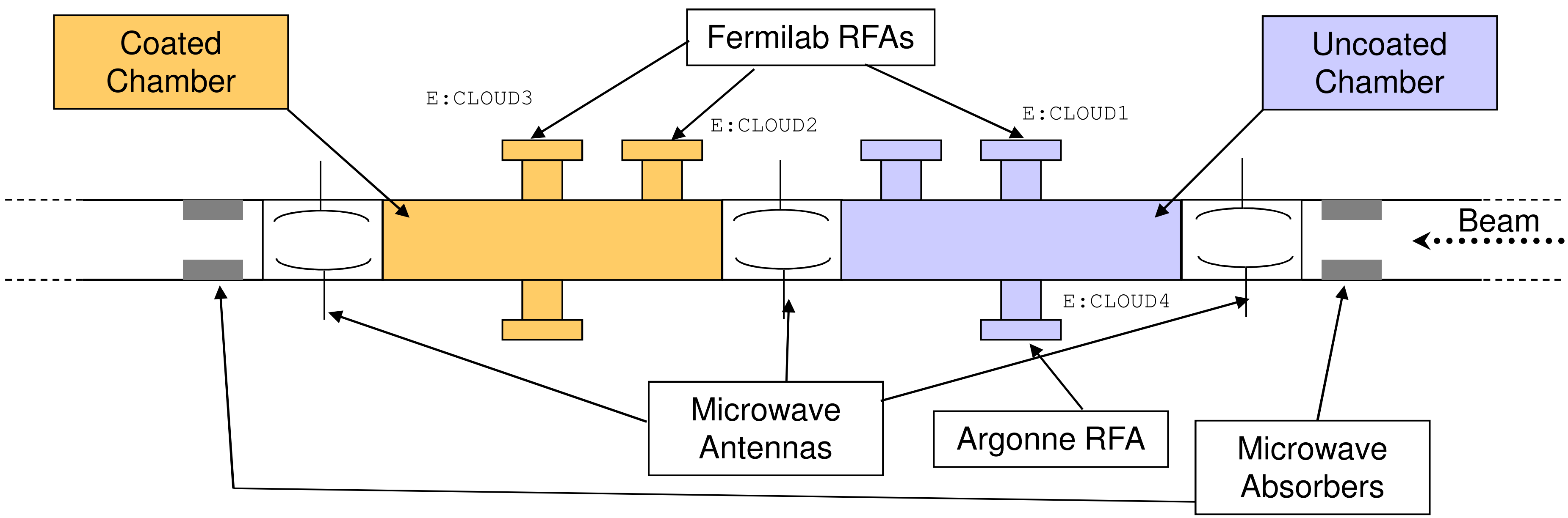


Electron Cloud Experimental Upgrade - 2009

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

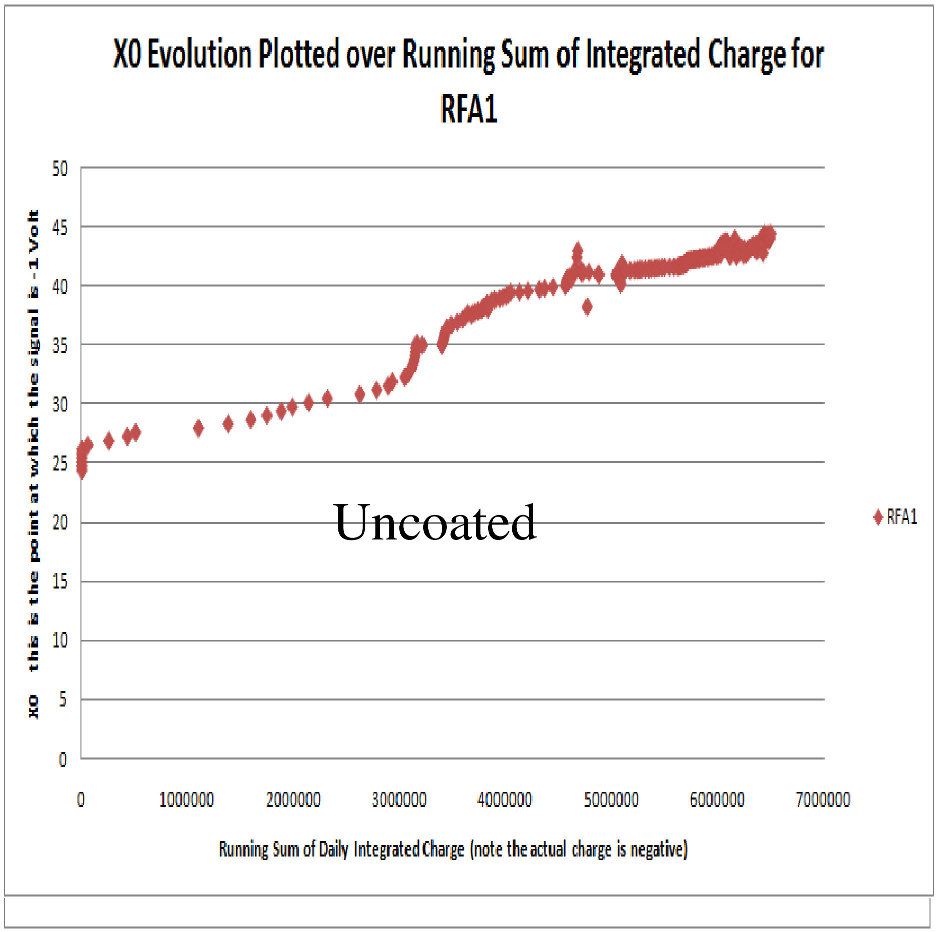
- TiN is a standard coating for ECloud mitigation
- Coating of test chambers performed at BNL
- Will need to adapt this procedure for *in situ* coating of 3000 m of Main Injector
- Also looking at adopting the SLAC procedure

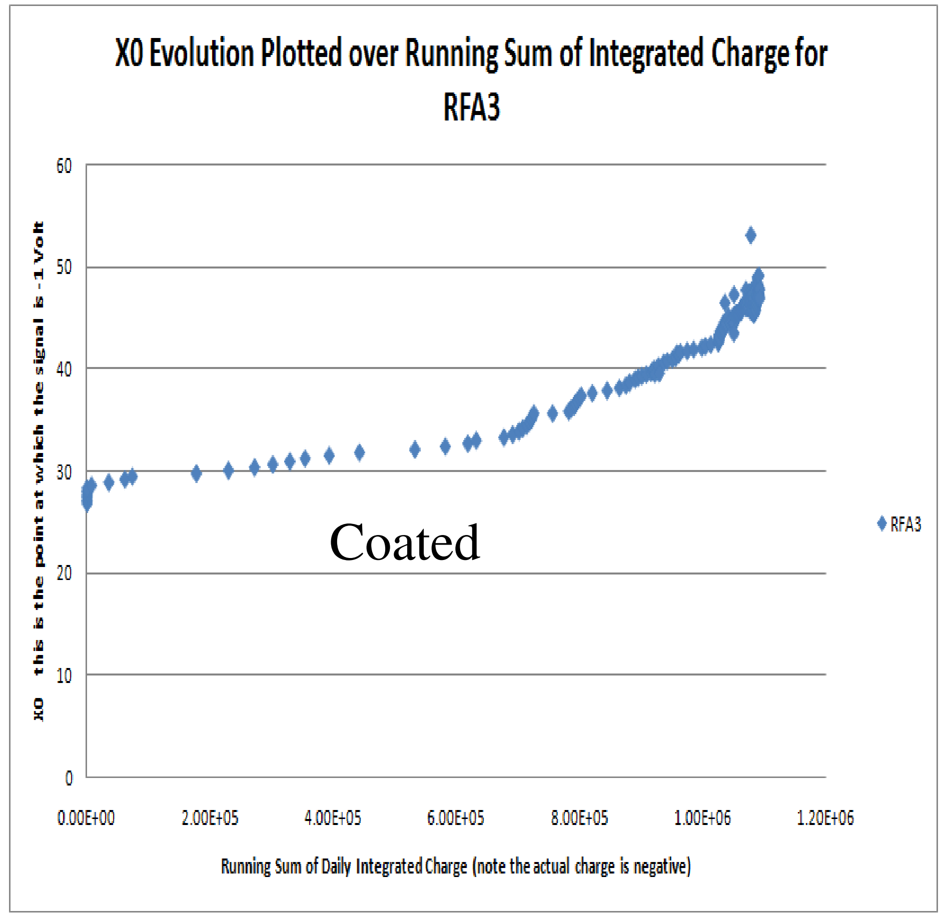
Electron Detectors

- 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

Evolution of Thresholds

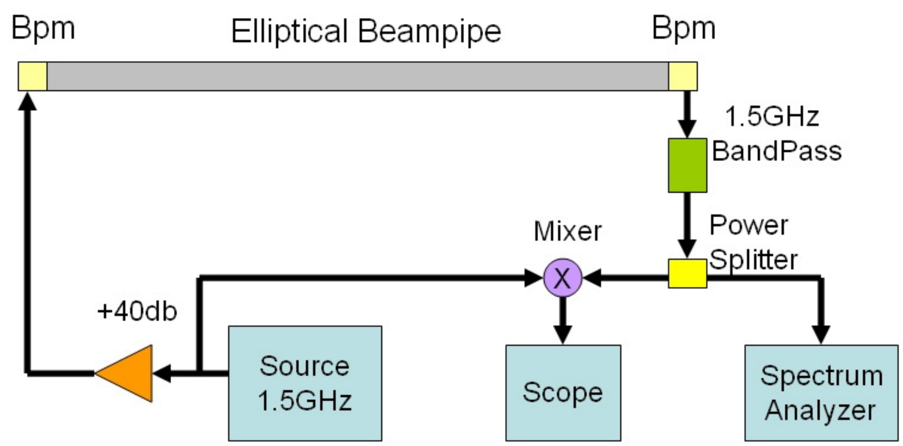
- Thresholds in RFA increase as evidence of conditioning
- More details in CY Tan's talk Monday

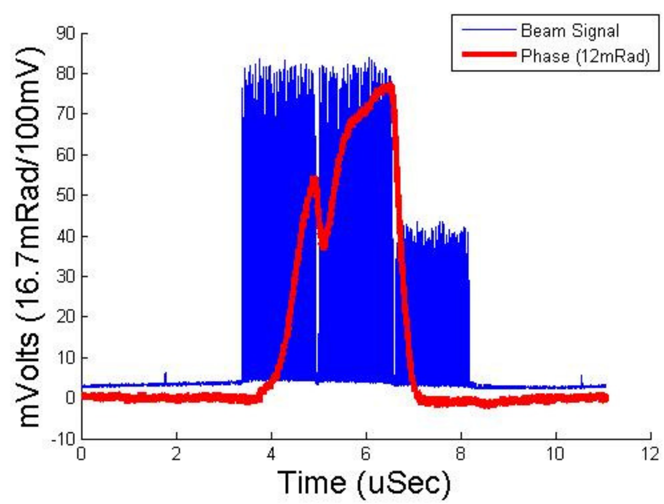




Microwave Measurements

- ECloud induced phase shift
- Sideband, zero-span, and direct phase measurements
  - Very good time-resolution with direct phase
- May allow measurement in dipole sections
  - No room for RFAs in Main Injector Dipoles
- Need better theoretical understanding of phase shift, particularly in magnets
  - Plasma modeling & ECR issues
- Need to understand the issues arising from reflections within the accelerator
  - Do not understand normalization
  - Uncertain where the measurement is occurring
- Much more on this in C Thangaraj's talk on Monday





Carbon Pipe

- CERN is very interested in amorphous carbon
  - ➢See it as superior to TiN in not requiring as much conditioning
- They built a chamber for us in short order and we installed it in MI this past summer
  - ➢Replacing our TiN test chamber
- Early results in CY Tan's talk Monday
- Conditioning history will be made like with TiN

Conditioning in MI

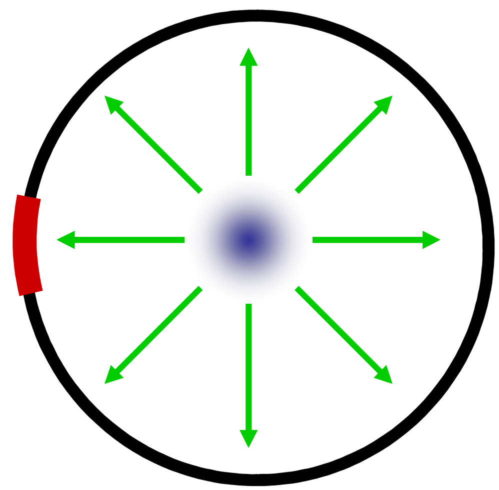
- Why does the material condition well in MI?
  - Especially, in comparison to other proton rings like PSR or SNS
- The major differences are the beam RF structure and the acceleration cycle
  - MI h=588 vs h=1 for SNS & PSR
  - MI has high-intensity beam for ~ 50,000 revolutions each second
    - SNS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

Project X Approach

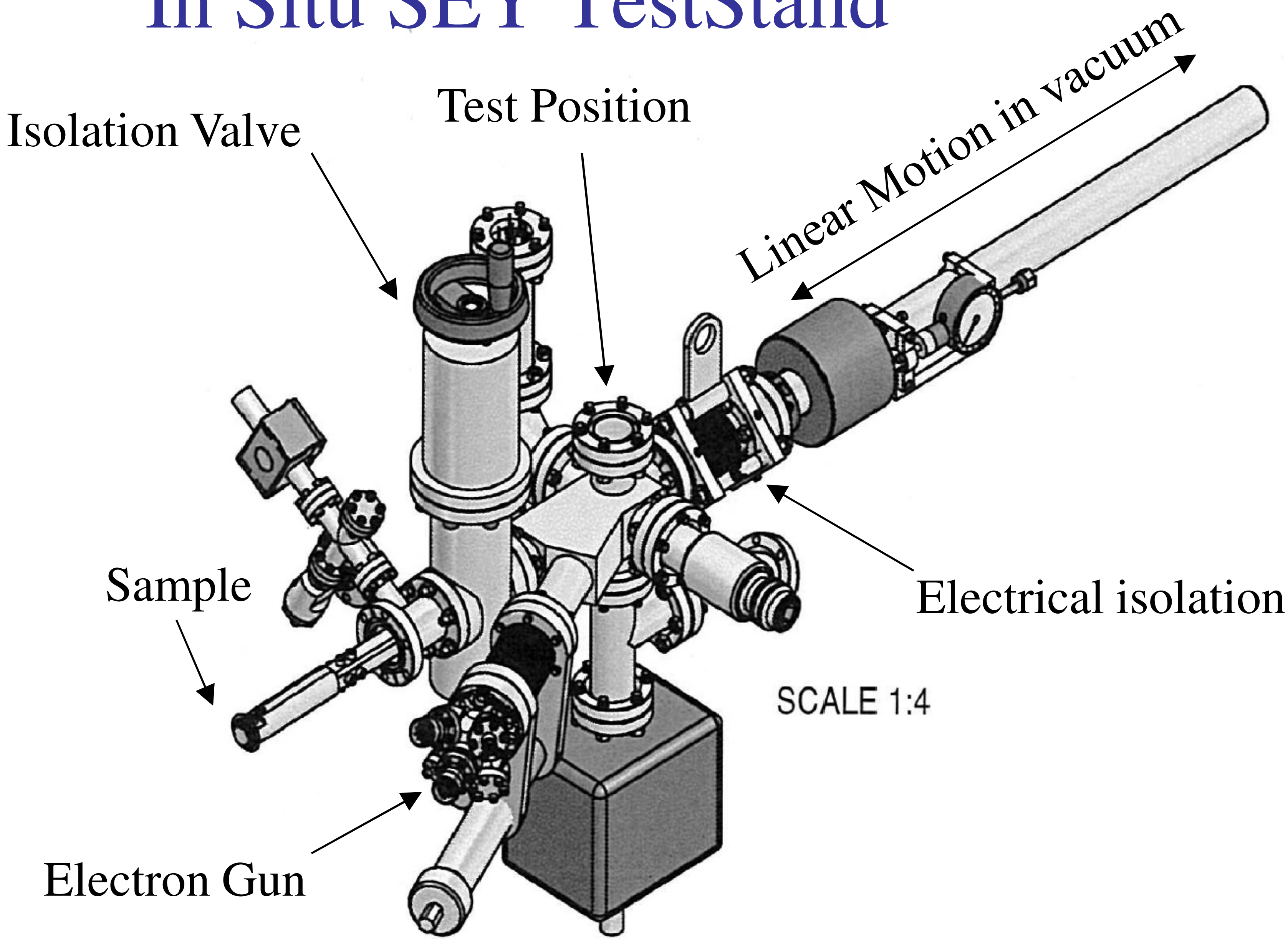
- We have a wide-ranging program of inquiry, but need to be focused on the questions for Project X
- Our default approach is to plan to coat all the MI magnets
  - Data in MI has shown that TiN is superior to stainless
  - Threshold moves as high as beam will condition the surface
  - Outside data shows that TiN can condition to SEY-max of < 1
  - Open to other coatings
- However, coating is expensive and time-consuming
- Lingering question is whether we can get away without coating
- Towards Project X:
  - Develop new instrumentation, particularly for the dipoles
  - Measure SEY conditioning in MI with Cornell station *and* eventually in a dipole
  - Program of simulation to be able to extrapolate the conditions of conditioning at higher intensity
  - Bench experiments with coatings and conditioning

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 416L
- 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
  - Differential scrubbing can be factored out



In Situ SEY TestStand



SEY in Dipole

- The SEY measurement station from Cornell will allow direct measurement of SEY conditioning in our straight sections
  - However, most of our ring is dipole
- Need to adapt a system for measurements in magnetic fields
  - MI magnets are not modifiable for this purpose
- Starting a conceptual design of a dogleg or chicane as an ECloud experimental station
  - C-magnets or other design that allows access to the beam pipe
  - Arbitrary magnetic field
  - SEY station for *in situ* and remote measurement
  - Also would allow instrumentation in a magnetic field

New Instrumentation

- Outstanding issue is being able to measure the ECloud in dipoles
  - No room for RFA type detectors in MI magnets
  - Microwave measurements have shown marginal success, but suffer from significant uncertainties
    - Reflections, normalization, fringe fields
- Optical detection approach (Paul Lebrun):
  - Look for UV light emitted from the secondary emission process on the beam pipe
  - We are planning a bench measurement of the UV spectrum from electron impacts
- Laser phase shift (Charles Thangaraj):
  - Measure direct phase shift of laser beam through clouds
  - More in Charles's Monday talk

Simulation

- Have had extensive input from several codes
- 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
- VORPAL (Tech-X & P. Lebrun)
  - Talk on Monday
- ORBIT (ORNL & L. Vorobiev)
  - Attempt to adapt ORBIT and its 3-D model to Main Injector
    - Would allow simultaneous consideration of ECloud, high-order tracking issues, and impedances
  - Problem is that ORBIT, and particularly its ECloud module, have a lot of hard-coded numbers or concepts for h=1 and long bunches
  - Development is proceeding part-time

Outlook

- Main Injector does not presently have any issues with Electron Cloud
- Cloud buildup has been observed at the Main Injector
  - 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
  - Ultimate conditioning is limited by beam intensity
- Further experiments needed for Project X
  - Direct SEY measurement
  - Extension of measurements to dipoles
  - Consistent understanding with simulation
  - For now, TiN coating looks like a viable solution

Electron Cloud Measurements and Plans

Bob Zwaska
Fermilab

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