Electron Cloud Experiments at Fermilab: Formation and Mitigation

Bob Zwaska
Fermilab

March 28, 2011
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 $\sim 10^{11}$ protons

- Produce a few initial/primary electrons
  - Residual gas ionization
    - $O(\, e^- / m / \text{torr} / \text{proton})$
  - Lost protons
    - Can produce 100’s in beam pipe
    - Generally a small contribution

- Beam produces strong potential
  - Nonadiabatic appearance
  - Accelerates electrons

- Beam disappears
  - Electrons collide with wall
  - Produce more electrons through secondary emission

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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
(simple) Critical Model for ECloud

- Why such a threshold for the Main Injector?
- Consider equilibrium at marginal intensities
  - Criticality parameter: $\kappa$
    - Proportion of electrons that “survive” a bunch crossing
  - No straightforward equation for $\kappa$
    - Combination of energy gain, SEY curve, and slow loss between bunches
      - Comes from simulation
  - 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
    - $N_{eq} = f \times N_{beam}$ \{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

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

\[
N_{eq} = \frac{P}{1 - \kappa}
\]
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

Rises observed at ~4% of pumps

<table>
<thead>
<tr>
<th>Pump</th>
<th>$P_{initial}$</th>
<th>$P_{final}$</th>
<th>$\Delta P$</th>
<th>$\Delta P/P$</th>
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<td>4.5</td>
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<tr>
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<tr>
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<td>3</td>
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<td>1:IP6151</td>
<td>1.2</td>
<td>1.6</td>
<td>0.4</td>
<td>33%</td>
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</table>

Locations of vacuum rises
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 \( \sim 26 \times 10^{12} \) protons
  ➢ Threshold later moved higher

• Allowed fitting of simulation to data, giving an SEY
  ➢ Fit to simulation by Furman
  ➢ Conditioned pipe gave SEY \( \sim 1.3 \)
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 \textit{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

![Graph: X0 vs Absorbed Electrons per cm²](Image)
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

Isolation Valve
Test Position
Linear Motion in vacuum
Electrical isolation
Sample
Electron Gun

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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
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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