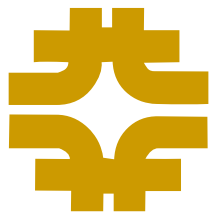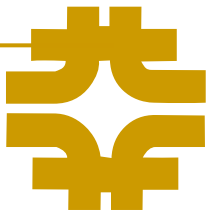# Monitoring Beam Intensity in the Tevatron Abort Gap Using Synchrotron Radiation

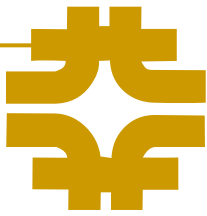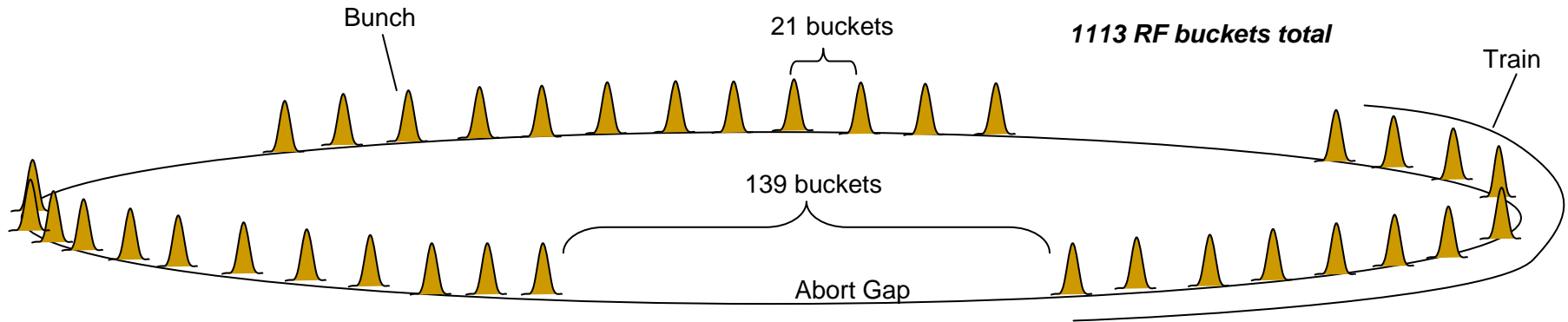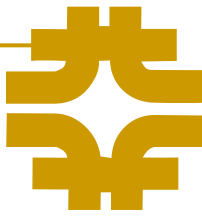Randy Thurman-Keup

FNAL / AD / Instrumentation

Outline

- Motivation for Monitoring the Abort Gap Beam Intensity

- Synchrotron Radiation

- Synchrotron Radiation Devices in the Tevatron

- Some Results

- Other Odds and Ends

Contributors

- **Tom Meyer** – AGI DAQ
- **Eugene Lorman** – Synclite
- **Sten Hansen**, **Heide Schneider** – Gating circuit
- **Carl Lundberg**, **Dale Miller** – Technical expertise
- **Sasha Valishev** – Synch. Rad., Acc. Phys., etc…
- **Alan Hahn**, **Harry Cheung**, **Pat Hurh** – Synclite
- **Jim Fast**, **Ken Schultz**, **Mark Ruschman**, **Carl Lindenmeyer**, **Ron Miksa** – Mech. Mods
- **Morris Binkley** – Big giant pulser
- **Stefano de Santis**, **John Byrd** – LBNL Gated PMT
- **Stephen Pordes** – Driving force

Introduction

Labels on figure: Bunch, 21 buckets, *1113 RF buckets total*, Train, 139 buckets, Abort Gap
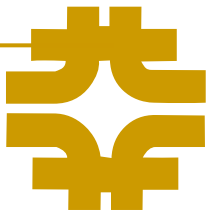
- ## The Tevatron operates with 36 bunches in 3 groups called trains
- ## Between each train there is an abort gap that is 139 RF buckets long
  - RF bucket is 18.8 ns → Abort gap is 2.6 μs
- ## In this talk, abort gap beam intensity measurements are usually normalized to beam around the ring

Motivation
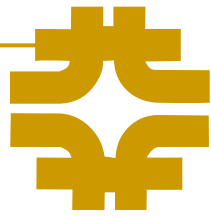
- During an abort
    - Abort kicker magnet ramps up during abort gap
    - Beam in the abort gap is directed towards magnets, CDF, etc...
        - Quenches (in the past, 10×10^9 caused quenches)
            - Recent experience......~40×10^9 did not quench (better collimation)
        - CDF silicon detector damage
            - DØ not impacted as much, protected by CDF collimator
- Previous monitors relied on counters external to the beampipe that were timed with abort gap
    - Measured stuff leaving the abort gap, not stuff still in it
- Use synchrotron radiation to directly measure abort gap beam
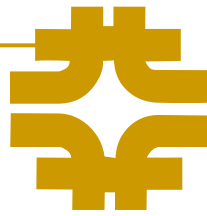   - Want to be sensitive to a DC beam that is 1 part in 10^4 of the total beam

Synchrotron Radiation History

- **100 yrs ago, calculations of radiation from circular paths**
  - *Larmour, Liénard, Schott, Schwinger(later), etc...*
- **1947, Observed at 70 MeV e^- synchrotron at GE**
  - 1944, Could have been betatron radiation if not for the shielding around the tube
- **1977, R. Coïsson calculates radiation from non-uniform magnetic fields such as magnet edges**
  - Significant radiation beyond the cutoff frequency which makes it possible to see at high-energy proton machines
- **1979, First observation of proton synchrotron radiation at CERN**
- **Early 90s, A. Hahn and P. Hurh produce prototype synchrotron radiation detector for Tevatron**
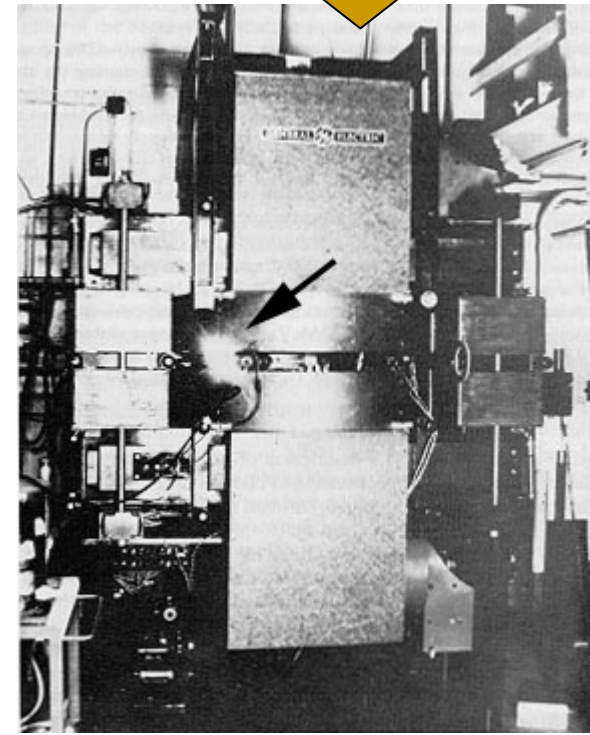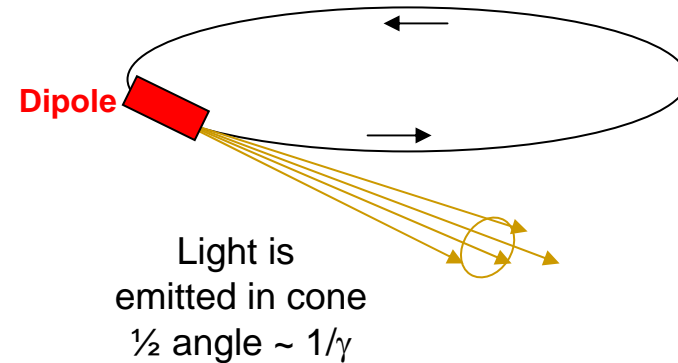
Synchrotron Radiation

$$\mathbf{E}(\mathbf{x}, t) = \frac{e}{c} \left[\frac{\mathbf{n} \times \{(\mathbf{n} - \boldsymbol{\beta}) \times \dot{\boldsymbol{\beta}}\}}{(1 - \boldsymbol{\beta} \cdot \mathbf{n})^3 R} \right]_{\text{ret}}$$

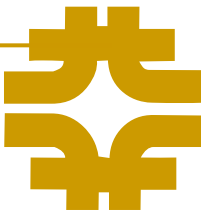$$\mathbf{B}(\mathbf{x}, t) = \left[\mathbf{n} \times \mathbf{E} \right]_{\text{ret}}$$

$$\dot{\beta} \sim B_{\text{magnet}}$$

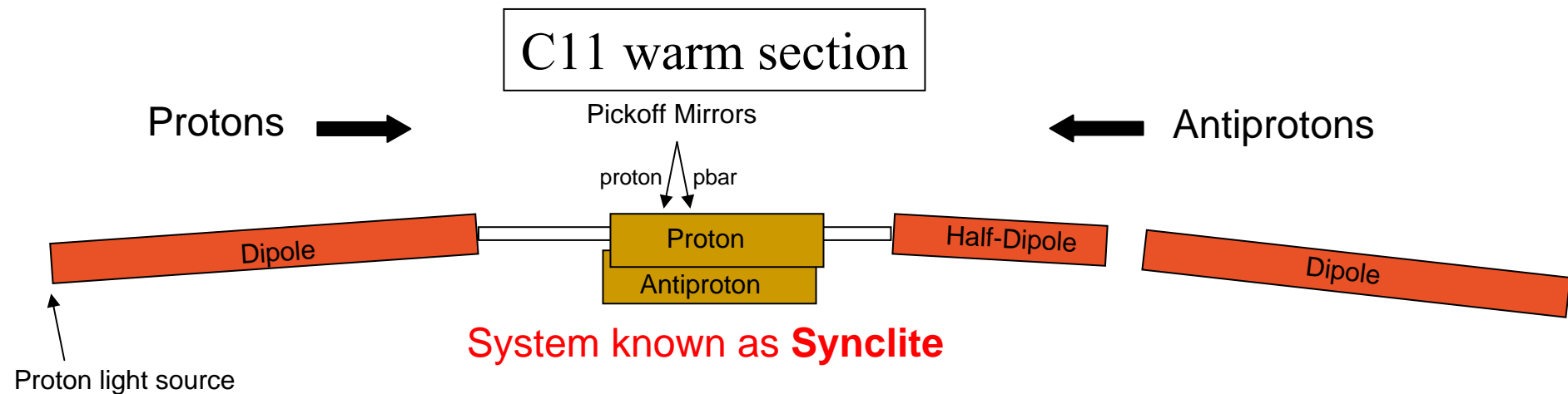$$\frac{d^2 I}{d\Omega d\omega} \propto \left| \int \left[R\mathbf{E} \right]_{\text{ret}} e^{i\omega t} dt \right|^2$$

Dipole

Light is emitted in cone ½ angle ~ $1/\gamma$

- Radiated intensity $\propto \gamma^4$
- Radiated intensity has a peak near the "critical frequency" and drops exponentially beyond
  - Critical frequency $\propto \gamma^3$
- Usually too infrared in proton machines
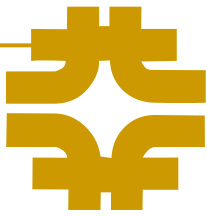- Magnet edge enhances higher frequencies

Synchrotron Radiation @ FNAL

- ## TeV Dipole
  - ### Critical wavelength ~ 2700 nm
- ## TeV Dipole Edge
  - ### Critical wavelength ~ 220 nm

C11 warm section

Protons ➡   Pickoff Mirrors   ⬅ Antiprotons

proton   pbar

Dipole   Proton   Half-Dipole   Dipole

Antiproton

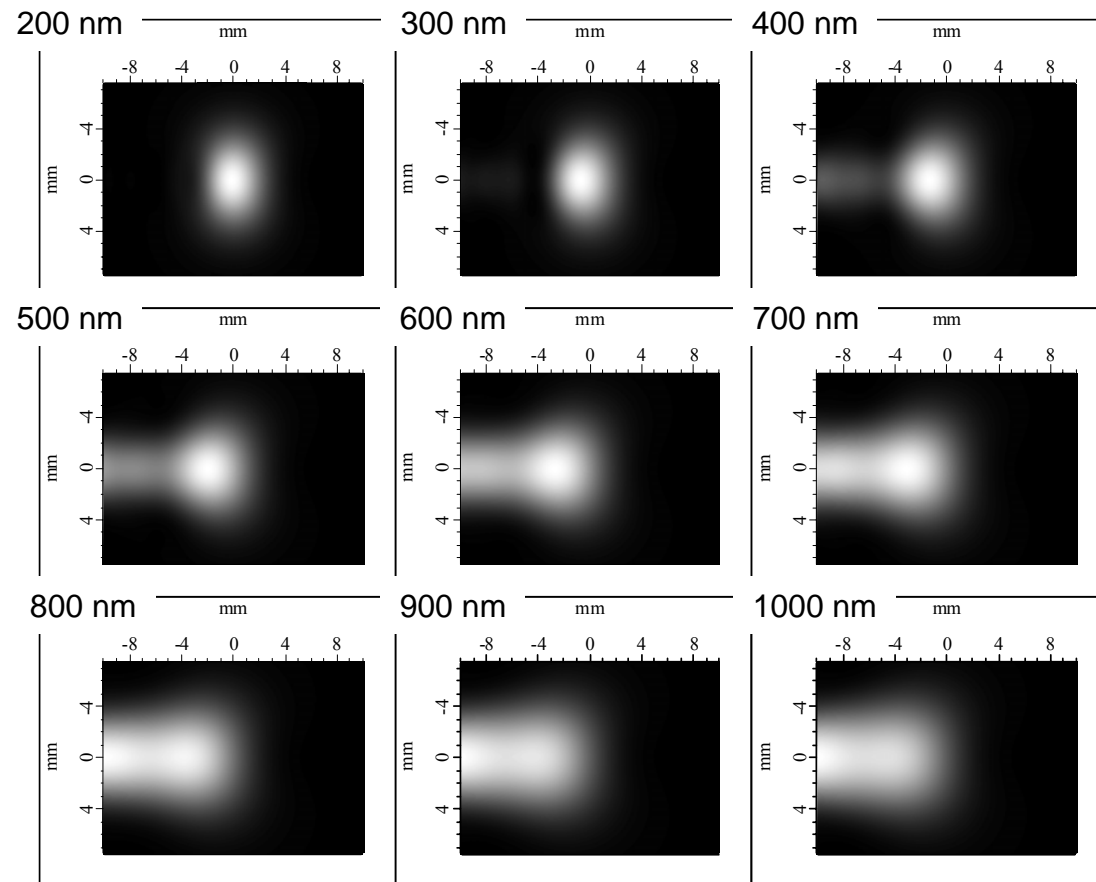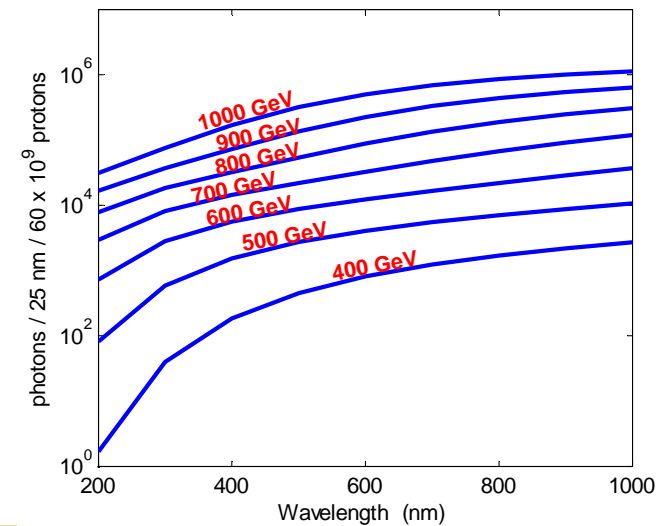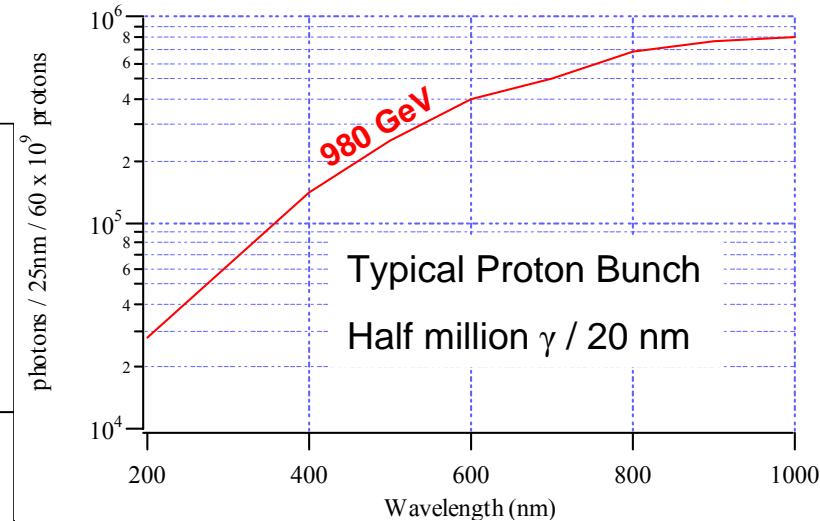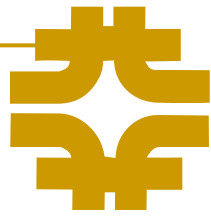System known as **Synclite**

Proton light source

Synchrotron Radiation @ FNAL

Illumination at the pickoff mirror

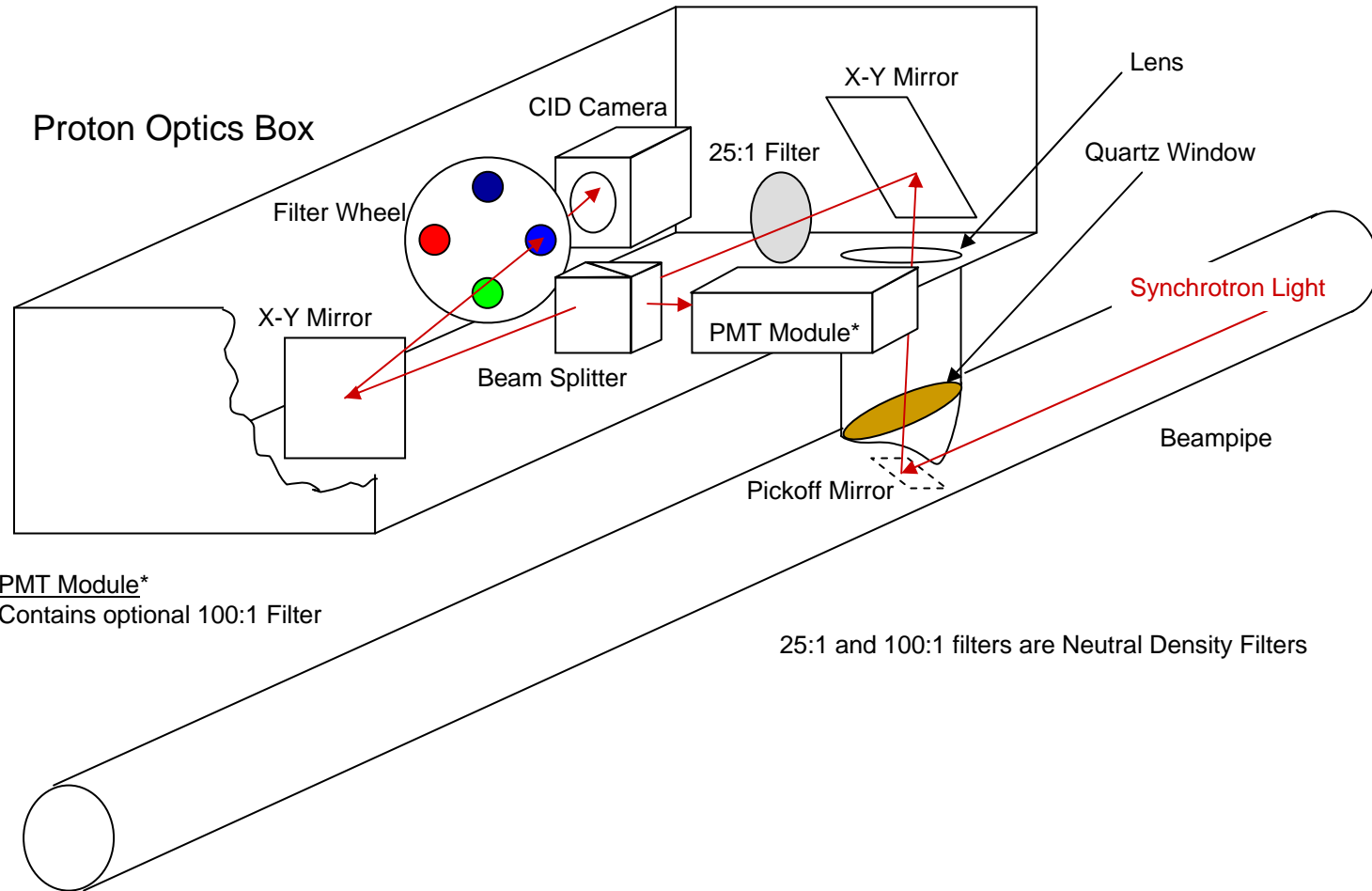**This data generated by Synchrotron Radiation Workshop (SRW) calculation**

Typical Proton Bunch

Half million γ / 20 nm

Expected # of photons

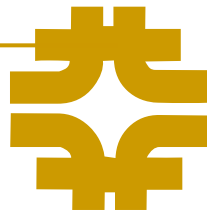- Wanted to measure DC beam of 1 part in 10^4
  - Total beam is 10^{13} → want to measure 10^9 →1.2×10^8 / abort gap
- Synchrotron radiation calculation
  - # of 400 nm photons / 25nm / 6×10^{10} protons ~ 2×10^5
- Optical losses ~ 35% efficiency *(50% from beam splitter)*
- # of photons / 10^9 DC beam / 25 nm / rf bucket ~ 1

- Wavelength acceptance ~ 200nm
- Gating duration ~ 30 buckets
- PMT Quantum Efficiency ~ 15%
- Typical # of photoelectrons ~ 40

Abort Gap Intensity Monitor
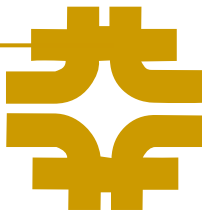
- Made use of existing synchrotron light system
  - Measures beam profile, including abort gap, using lens and camera
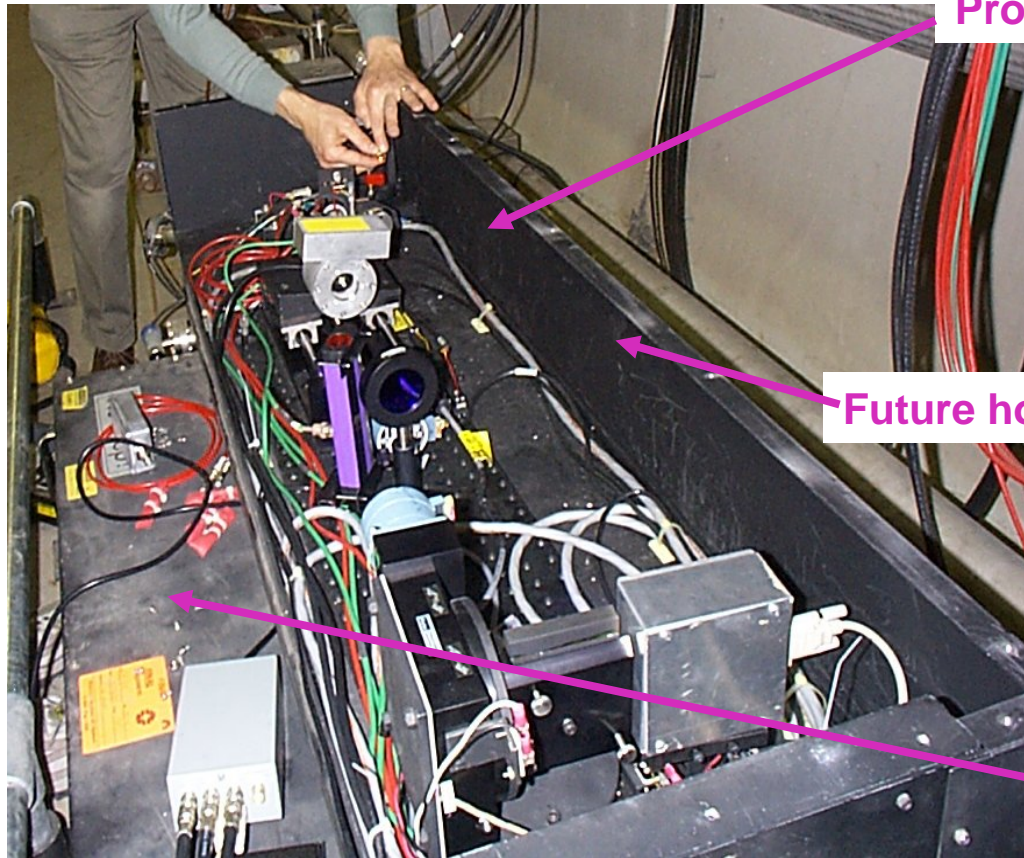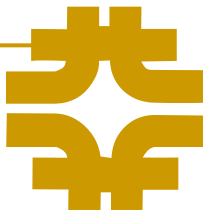- Added beam splitter and gated photomultiplier tube

Synclite Device

Proton Optics Box

CID Camera

X-Y Mirror

Lens

25:1 Filter

Quartz Window

Filter Wheel

Synchrotron Light

X-Y Mirror

PMT Module*

Beam Splitter

Beampipe

Pickoff Mirror

PMT Module*
Contains optional 100:1 Filter

25:1 and 100:1 filters are Neutral Density Filters

Synclite Device

Proton Synclite Box

Picture taken before PMT installation

Future home of PMT
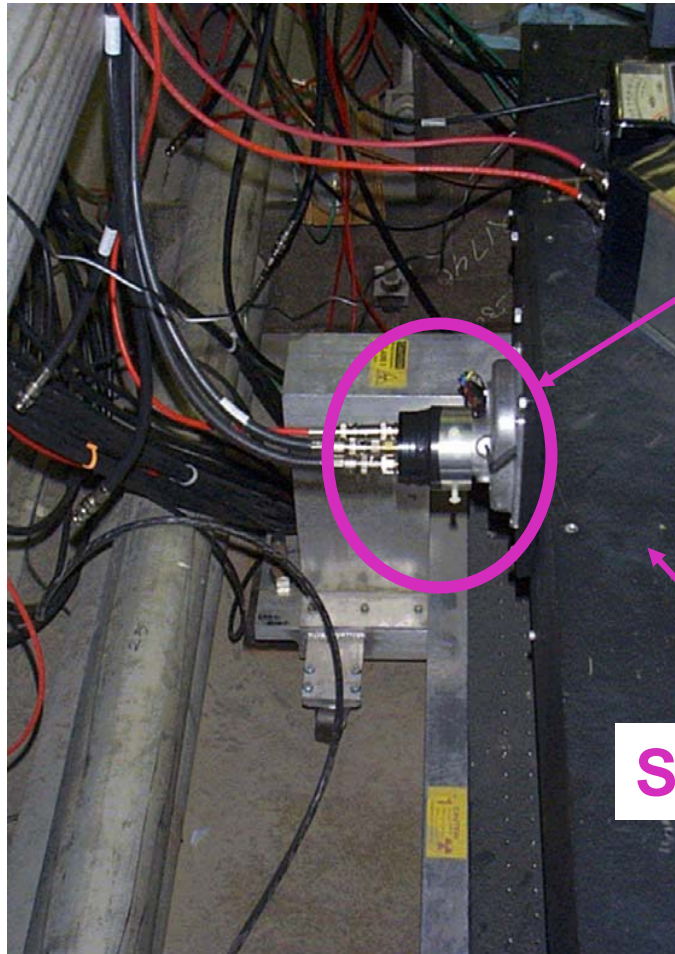
Antiproton Synclite Box

Synclite Device

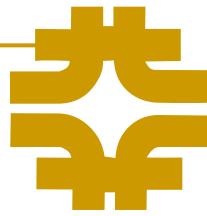**Synchrotron light spot**

Beam splitter

~ 9 in
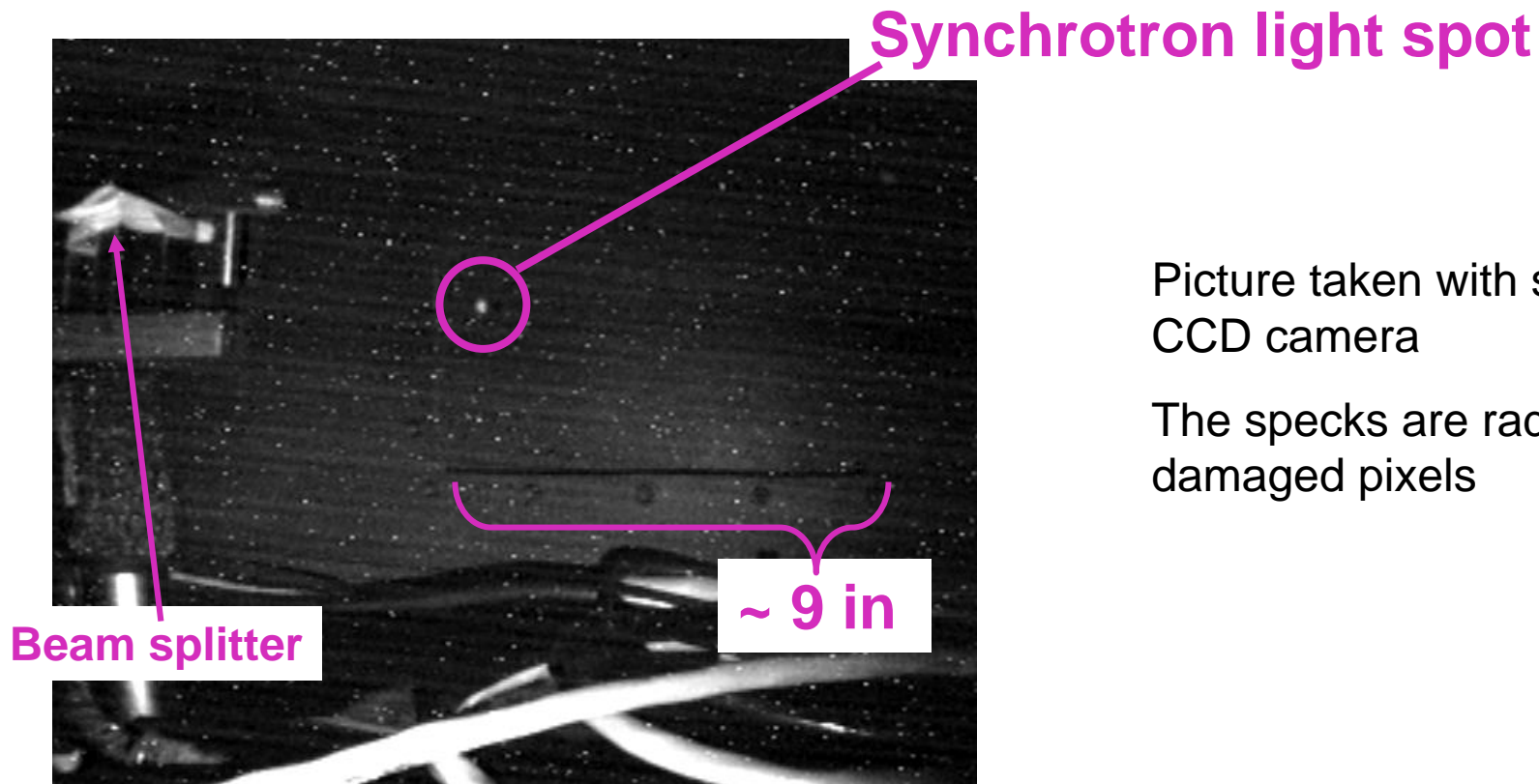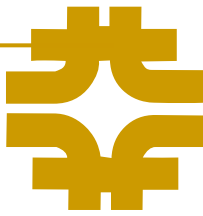
Picture taken with small CCD camera
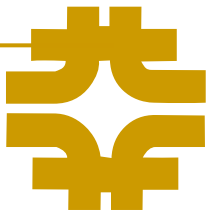
The specks are radiation-damaged pixels

Abort Gap Intensity Monitor

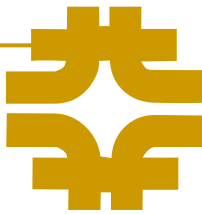**Abort Gap PMT**
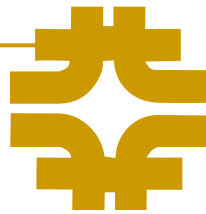
Synchrotron light box
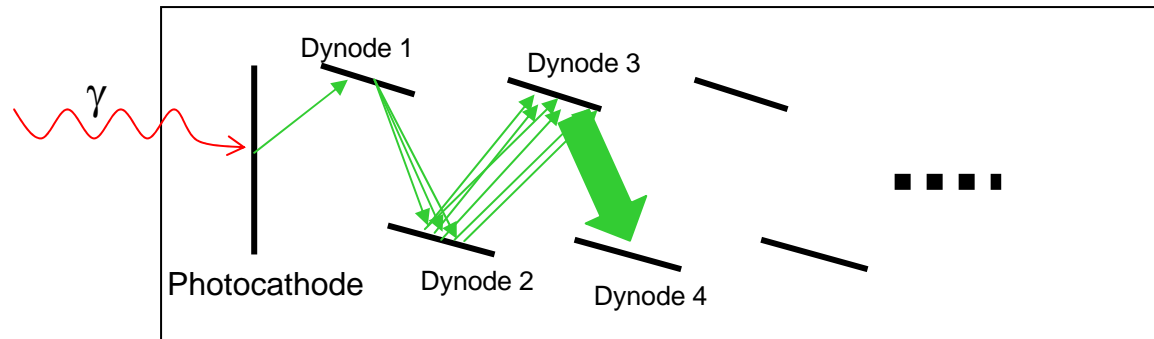
Abort Gap Intensity Monitor

- Made use of existing synchrotron light system
    - Measures beam profile, including abort gap, using lens and camera
- Added beam splitter and gated photomultiplier tube
- Photomultiplier had to be gateable and insensitive to light present just before the gate (bunch intensity is several thousand times brighter than DC beam)
    - Rules out just gating the output of the PMT

Abort Gap Intensity Monitor

- Made use of existing synchrotron light system
    - Measures beam profile, including abort gap, using lens and camera
- Added beam splitter and gated photomultiplier tube
- Photomultiplier had to be gateable and insensitive to light present just before the gate (bunch intensity is several thousand times brighter than DC beam)
    - Rules out just gating the output of the PMT
    - Custom gating circuit for generic photomultiplier
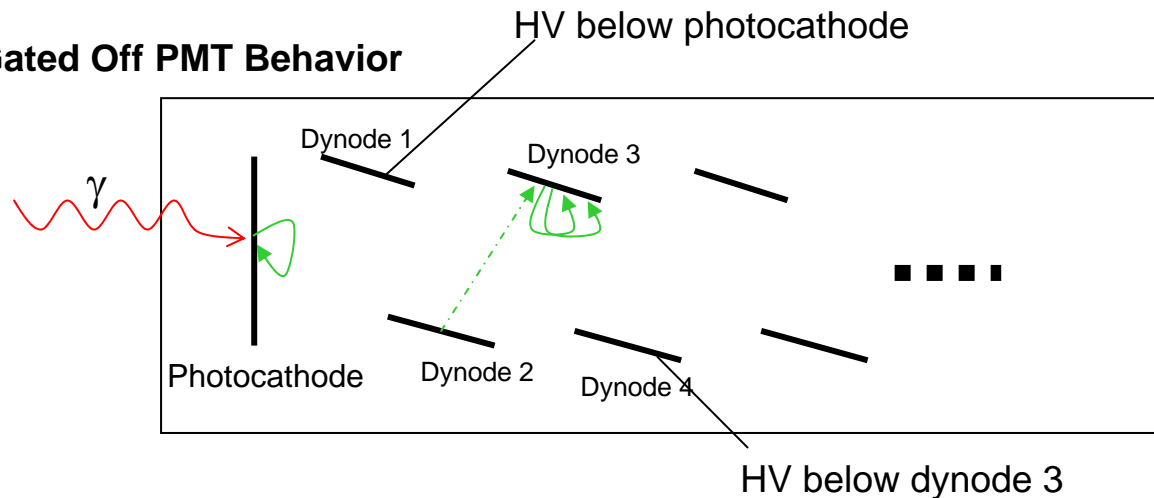   - Pulse two dynodes

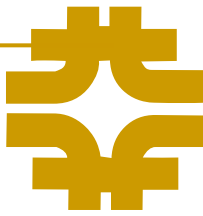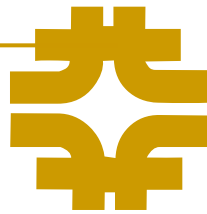# Abort Gap Intensity Monitor

Nominal PMT Behavior (Gated On)

Two dynodes are capacitively coupled to pulsed voltage source.

When pulsed, the dynodes are pushed to their nominal voltage level.

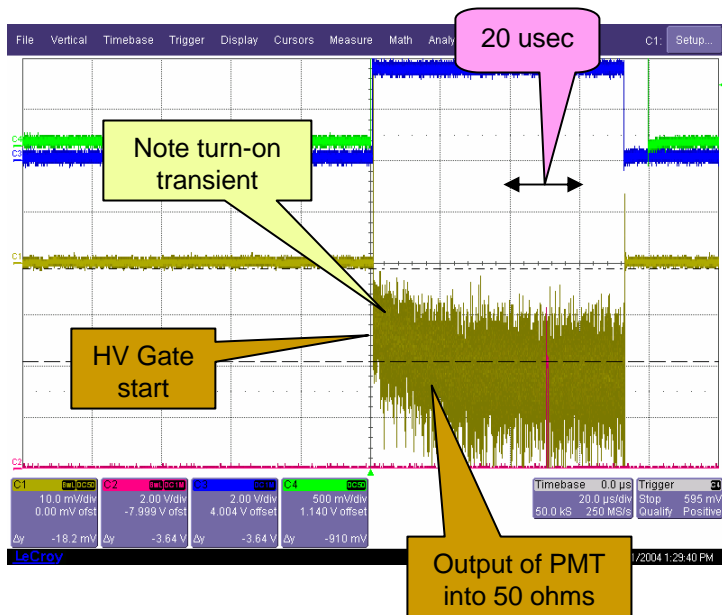**Gated Off PMT Behavior**

Abort Gap Intensity Monitor

- Made use of existing synchrotron light system
  - Measures beam profile, including abort gap, using lens and camera
- Added beam splitter and gated photomultiplier tube
- Photomultiplier had to be gateable and insensitive to light present just before the gate (bunch intensity is several thousand times brighter than DC beam)
  - Rules out just gating the output of the PMT
  - ## Custom gating circuit for generic photomultiplier
    - Pulse two dynodes
    - ~200 ns settling time after gate application
    - Relatively inexpensive
    - Not all PMT's work correctly
      - End window tube had 10 μs transient after application of gate
      - Side window tube worked better, installed for several months
    - Some sensitivity to pre-gate light
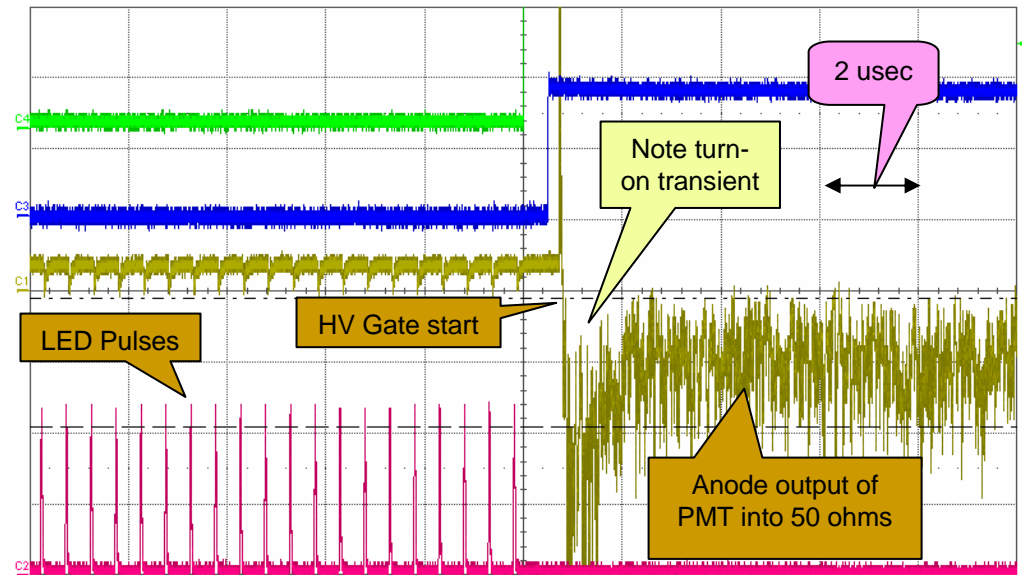
Abort Gap Intensity Monitor

Test stand used a pulsed blue LED to simulate the beam bunches and a constant low level green LED to simulate the DC beam
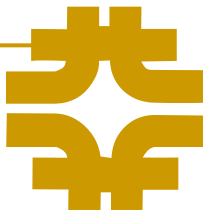
End-window tube gating transient

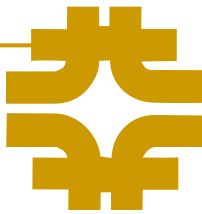Pre-gate light sensitivity

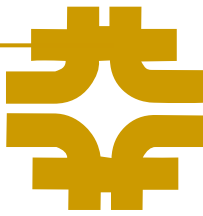# Abort Gap Intensity Monitor

- Made use of existing synchrotron light system
    - Measures beam profile, including abort gap, using lens and camera
- Added beam splitter and gated photomultiplier tube
- Photomultiplier had to be gateable and insensitive to light present just before the gate (bunch intensity is several thousand times brighter than DC beam)
    - Rules out just gating the output of the PMT
    - Custom gating circuit for generic photomultiplier
    - Hamamatsu gated regular PMT (inexpensive, $5K)
        - PMT module → complex circuitry would be in tunnel
        - Exhibited same sensitivity to light as FNAL gating circuit

Abort Gap Intensity Monitor

- Made use of existing synchrotron light system
  - Measures beam profile, including abort gap, using lens and camera
- Added beam splitter and gated photomultiplier tube
- Photomultiplier had to be gateable and insensitive to light present just before the gate (bunch intensity is several thousand times brighter than DC beam)
  - Rules out just gating the output of the PMT
  - Custom gating circuit for generic photomultiplier
  - Hamamatsu gated regular PMT (inexpensive, $5K)
  - Hamamatsu gated MCP style PMT on loan from LBNL
    - Expensive! (~$20K /tube)
    - 2-stage Micro Channel Plate PMT – Gain of <= 10^6
    - 5ns minimum gating time w/no noticeable settling time
    - No sensitivity to pre-gate light
    - Very large extinction ratio

DAQ Systems

Synclite DAQ System

For abort gap:

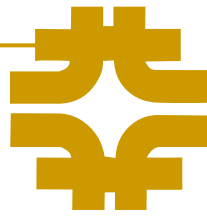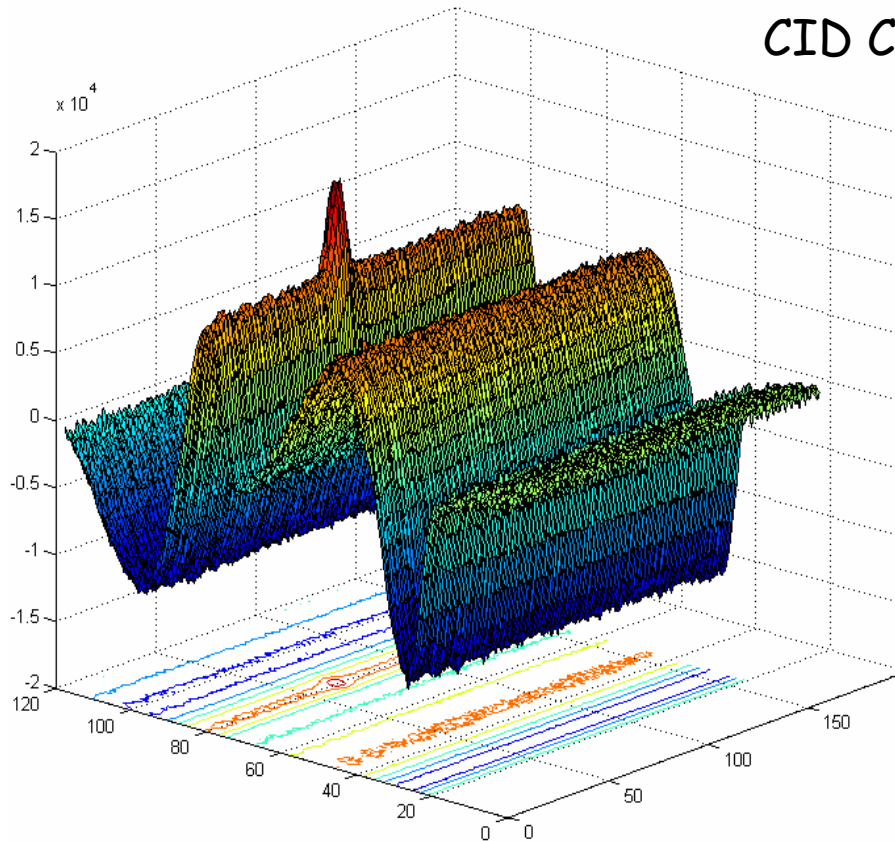Average 200 camera frames of data, each containing ~75 turns

RS-170 Video

CID Camera in tunnel

Framegrabber

Rackmount PC in service building

Accelerator Network
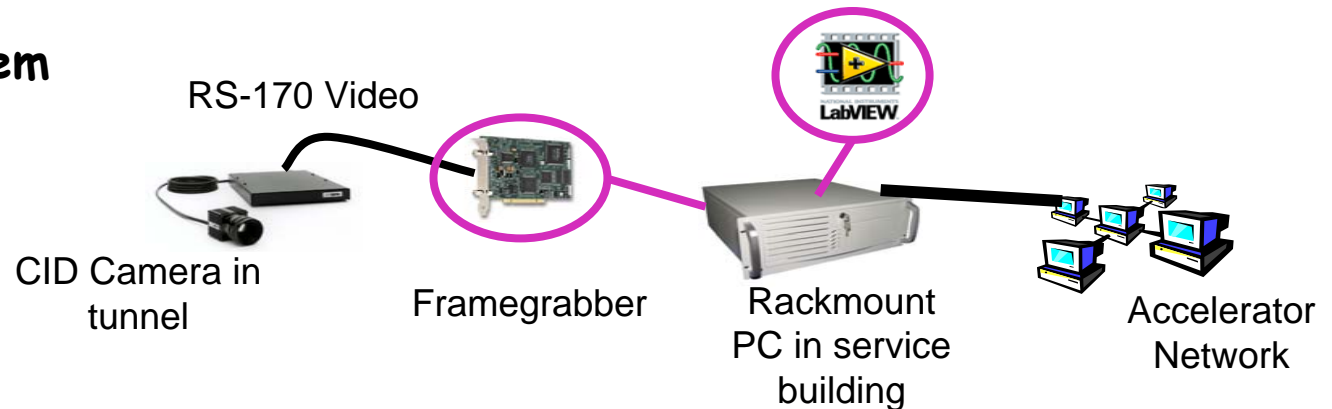
Abort Gap DAQ System

Average 1000 turns of data in each of the 3 abort gaps.

Gated PMT in tunnel

Linear Amplifier in service building

Fast Integrator

Digitizer

MVME Processor

VME Crate

Accelerator Network
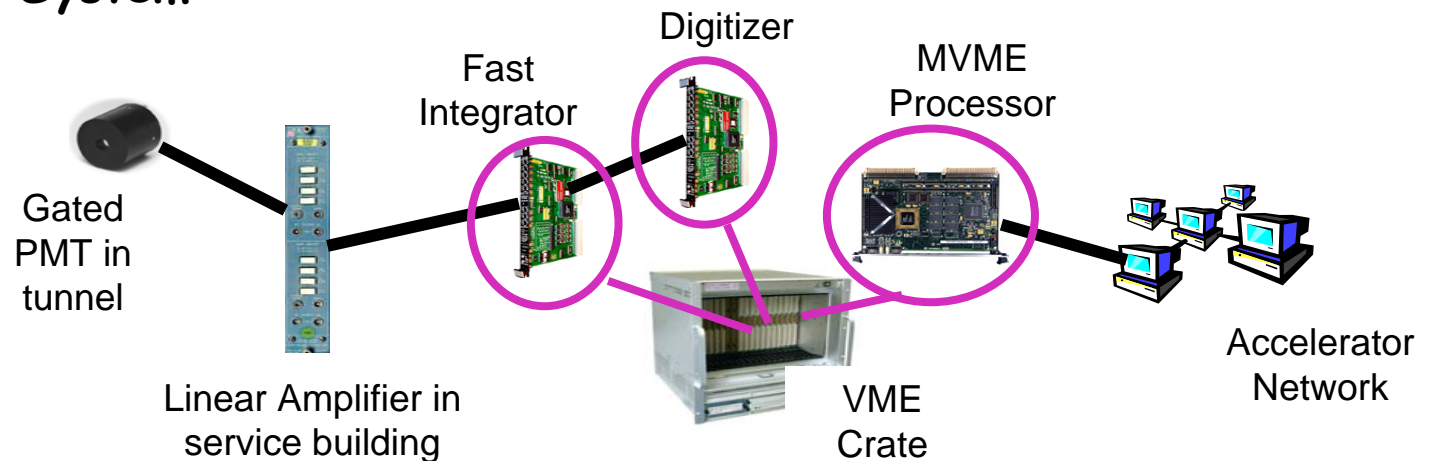
Abort Gap Intensity (Synclite)

CID Camera Image

Peak is ~7 x 10^9

Raw
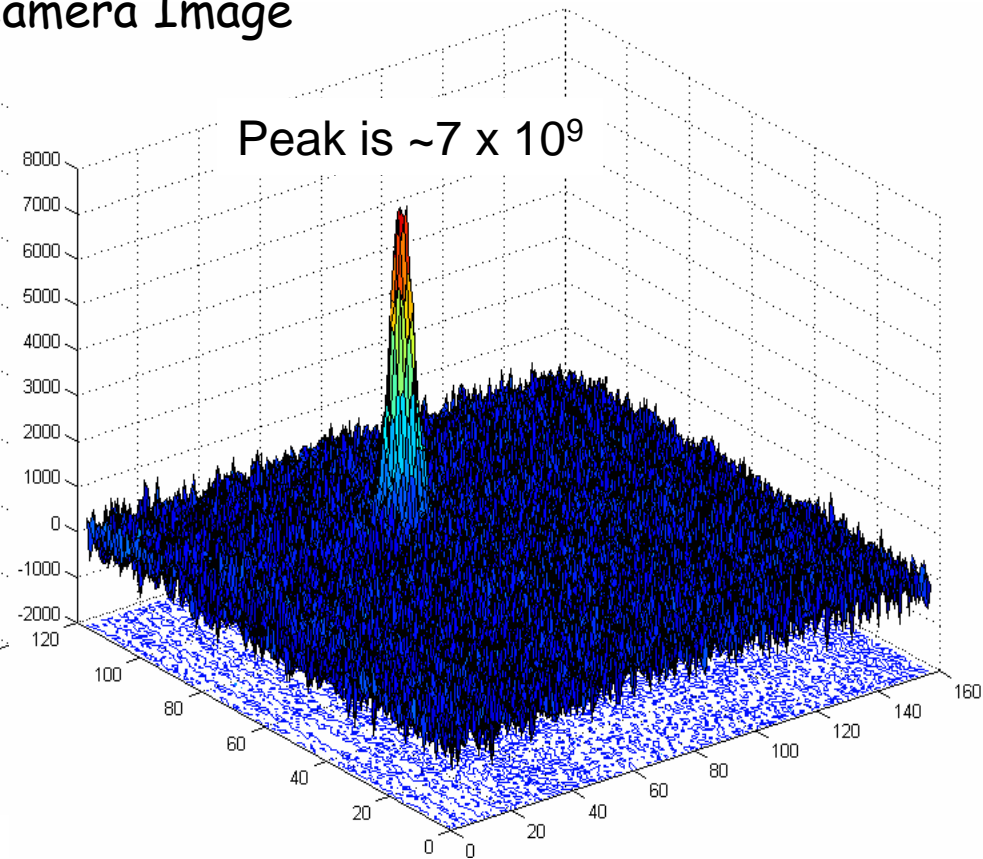
Background Subtracted
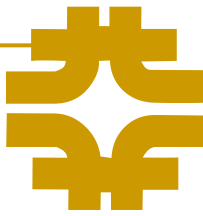
Abort Gap Intensity Monitor
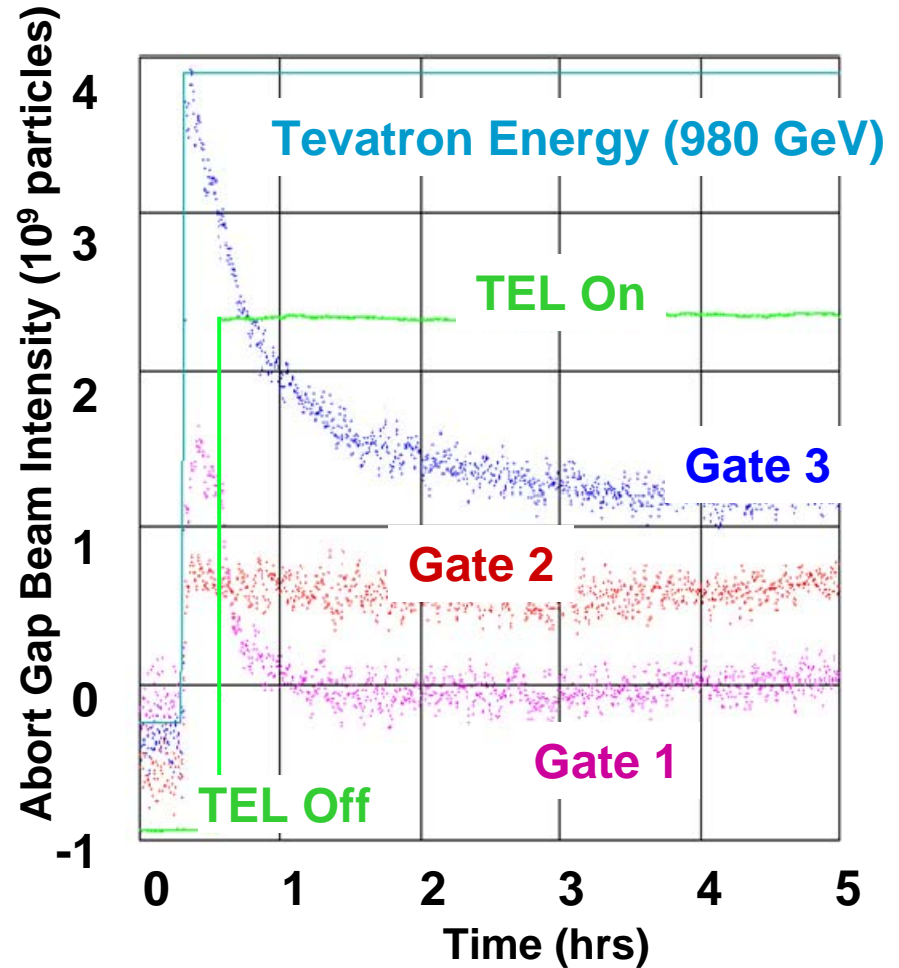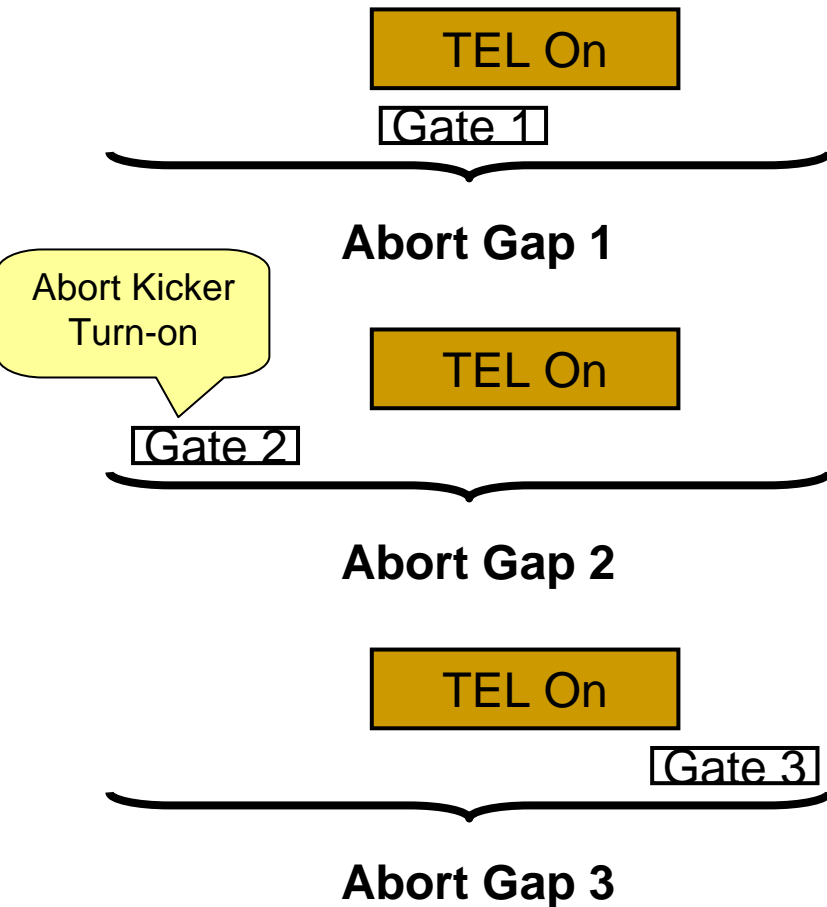
Calibration
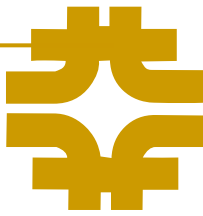
Two options:

Calibrate by gating on a bunch (with attenuators in place) and comparing to FBI intensity
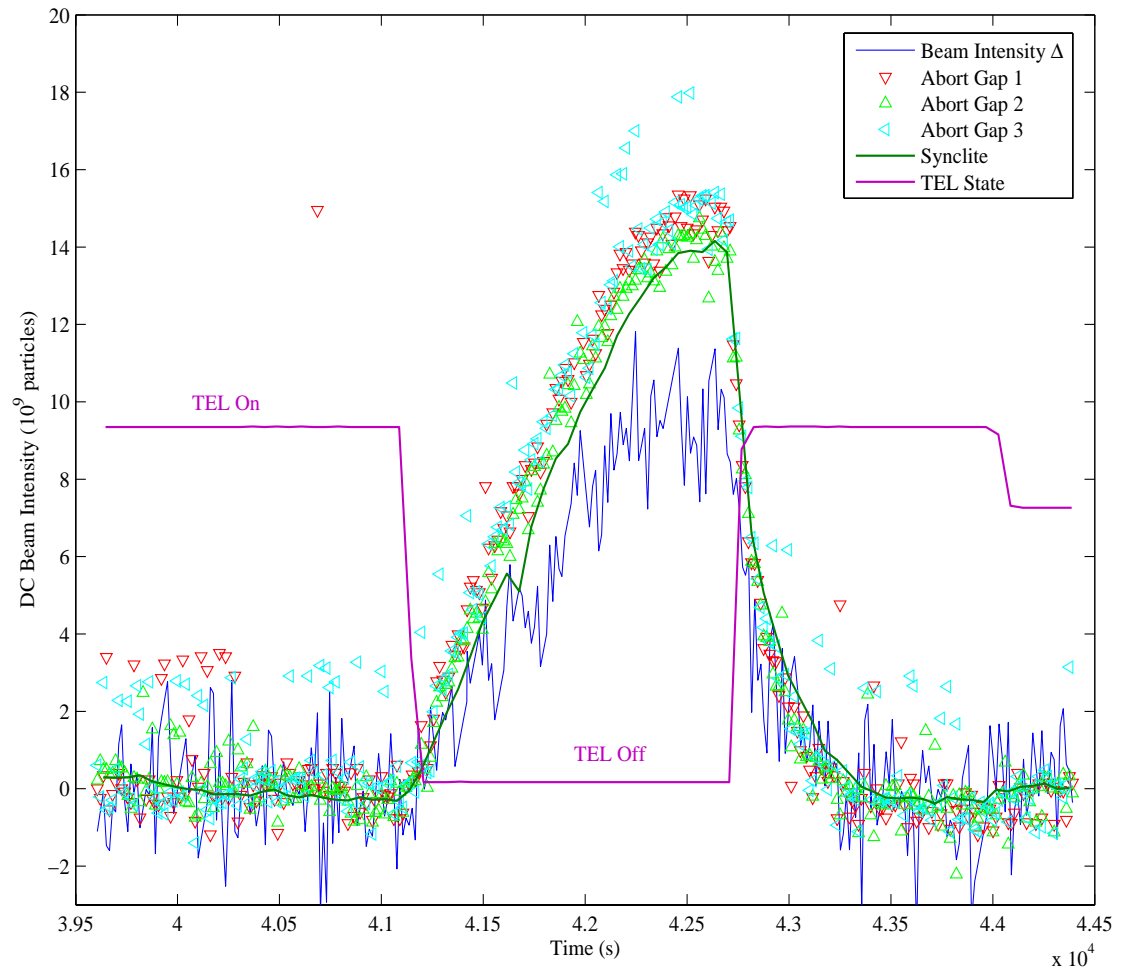
Calibrate by turning the TEL off and then back on and comparing to the DCCT measurement of the accumulated beam intensity
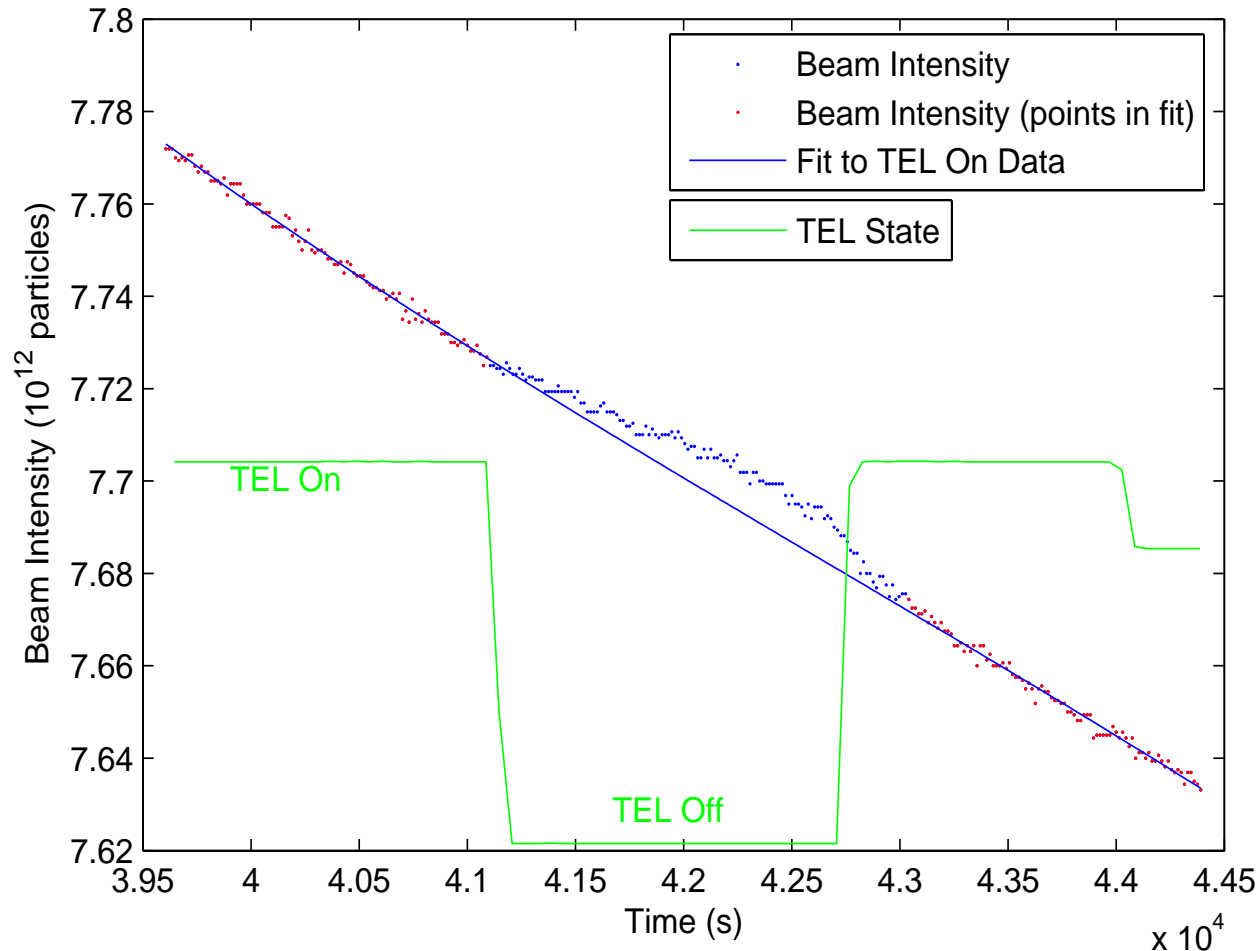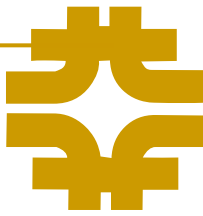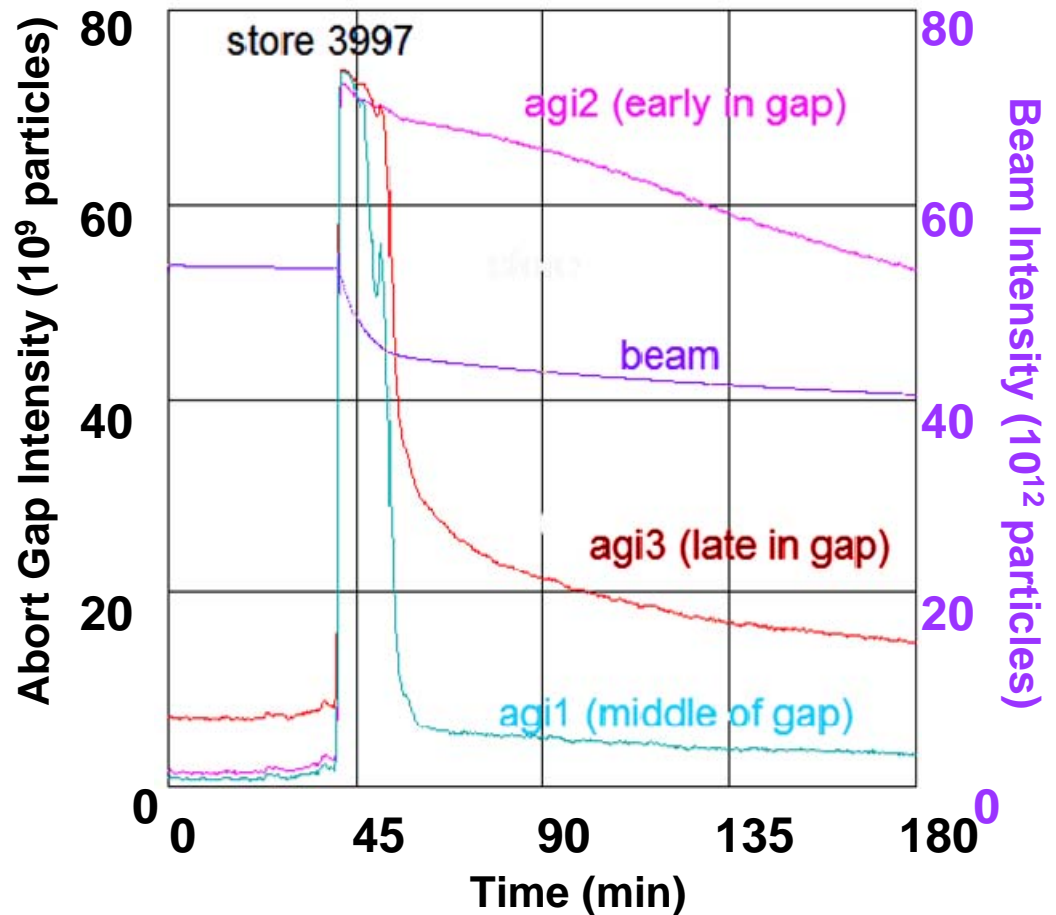
Calibration

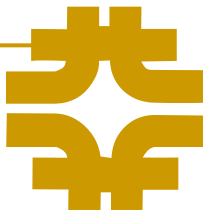Periodically check this using TEL trips. Seems to vary by 40-50%

Abort Gap Intensity Monitor

Abort gap beam intensity
after longitudinal damper
went berserk and started
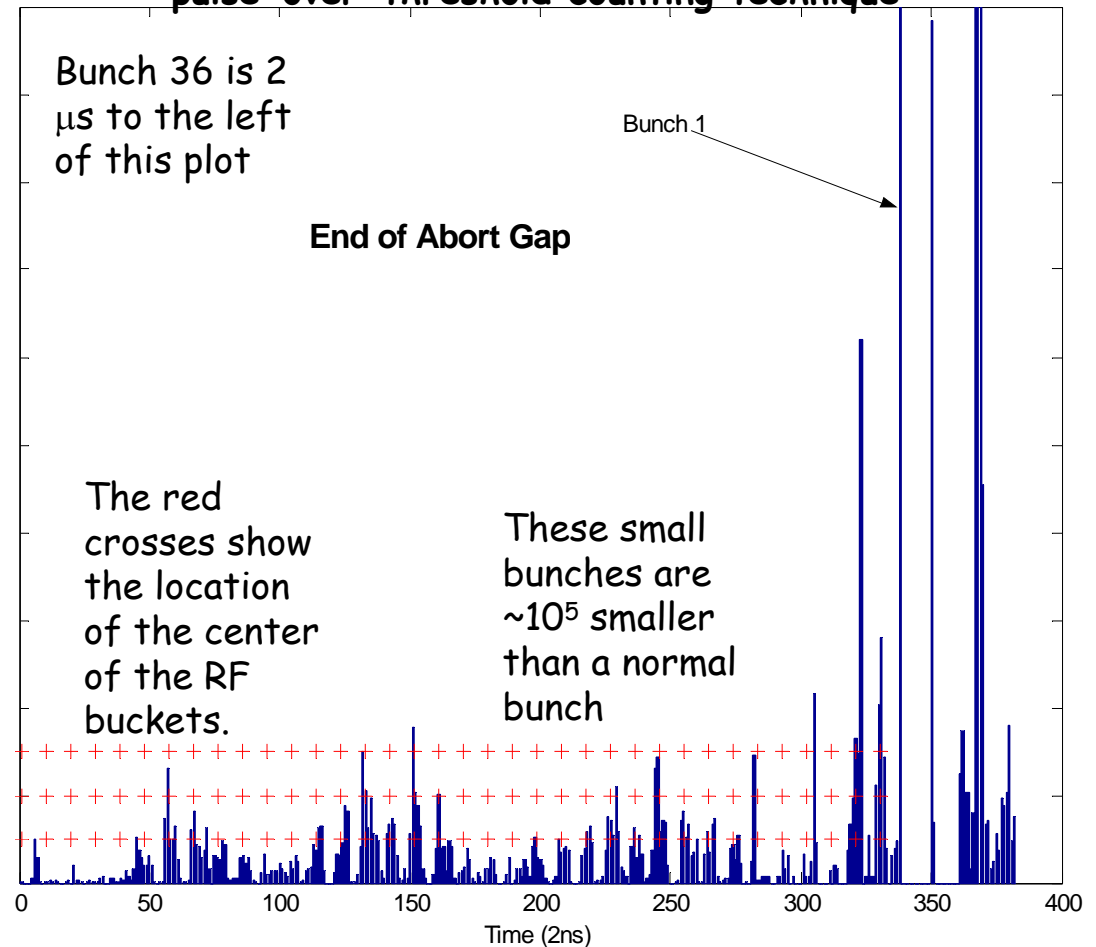shaking beam everywhere
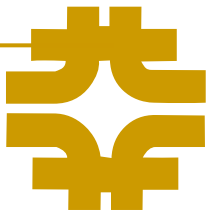(AGI saturates at ~70E9)

Microbunches

Longitudinal profile in the end of an abort gap

Captured beam should be bunched in the center of RF buckets

**These data were collected using a PMT pulse-over-threshold counting technique**

Bunch 36 is 2 μs to the left of this plot

Bunch 1

End of Abort Gap

The red crosses show the location of the center of the RF buckets.

These small bunches are ~10^5 smaller than a normal bunch
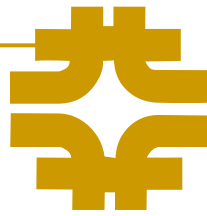
Time (2ns)

DC Beam Elsewhere

- Take 1 6-bucket sample between each bunch and ~10 in each abort gap

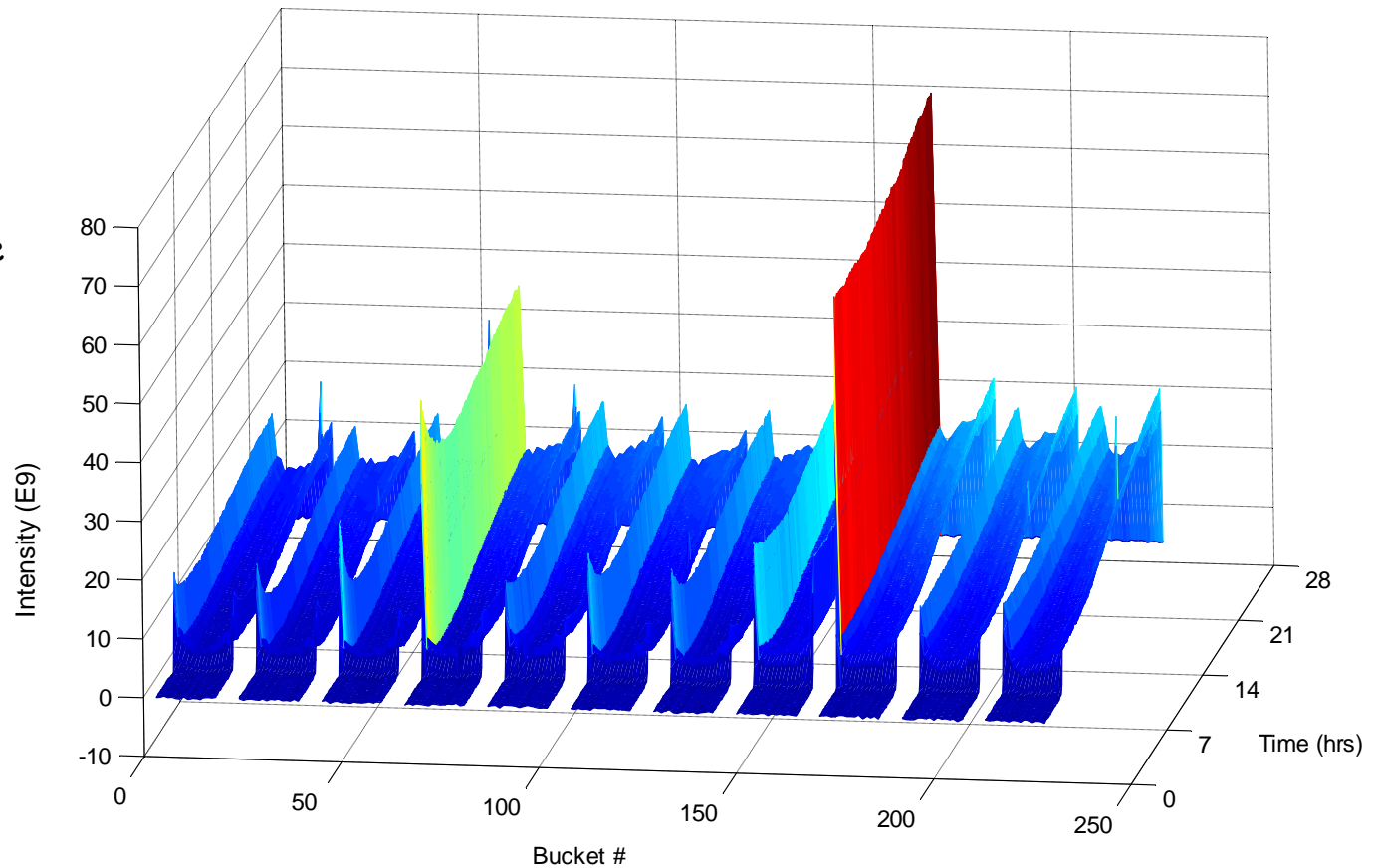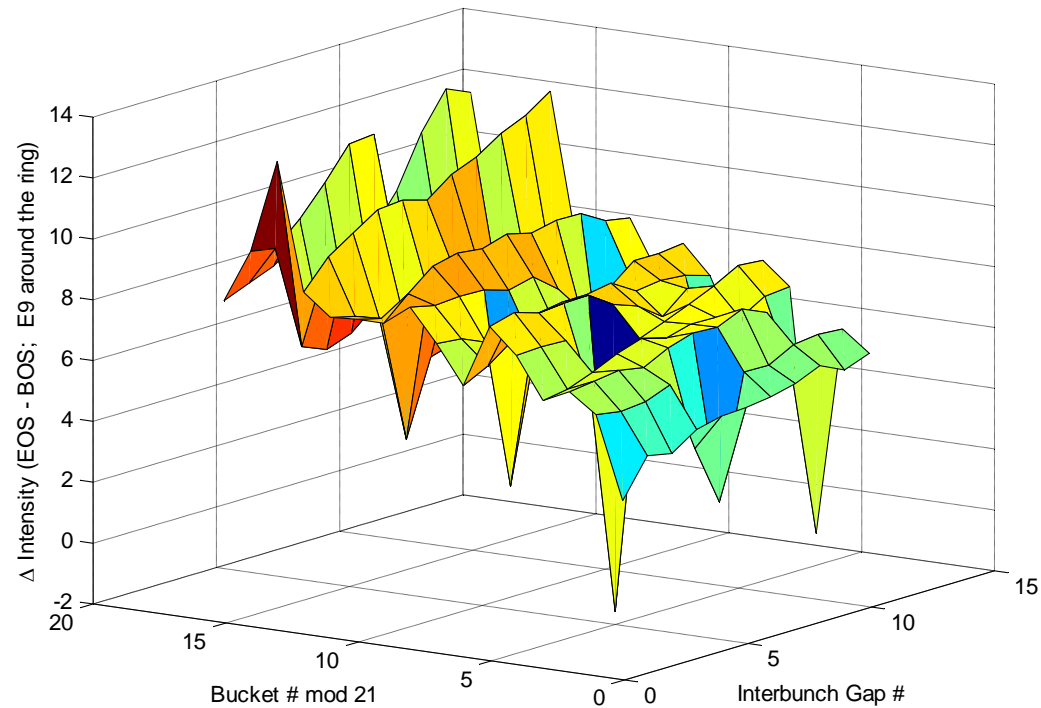- ~30 hour store duration (sample # = time)
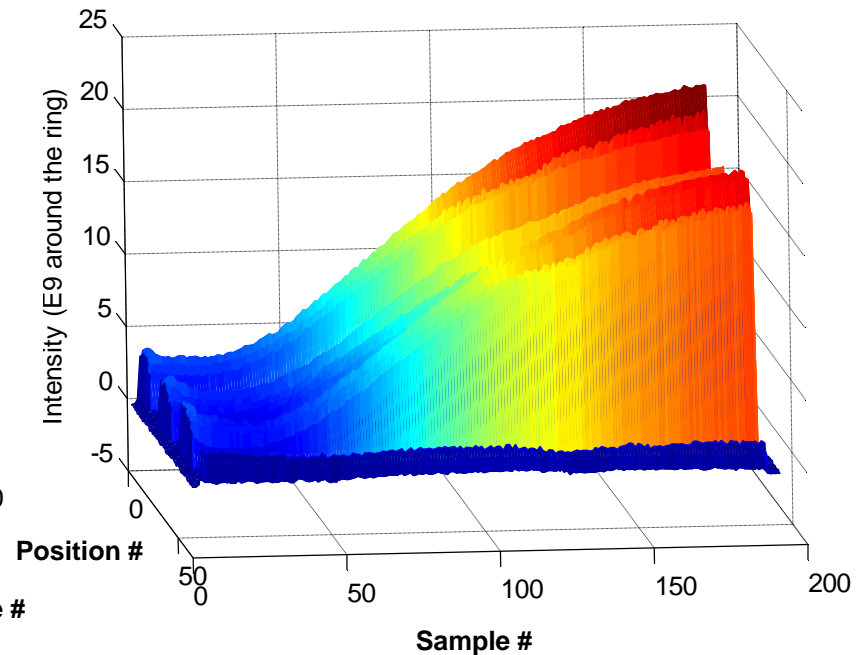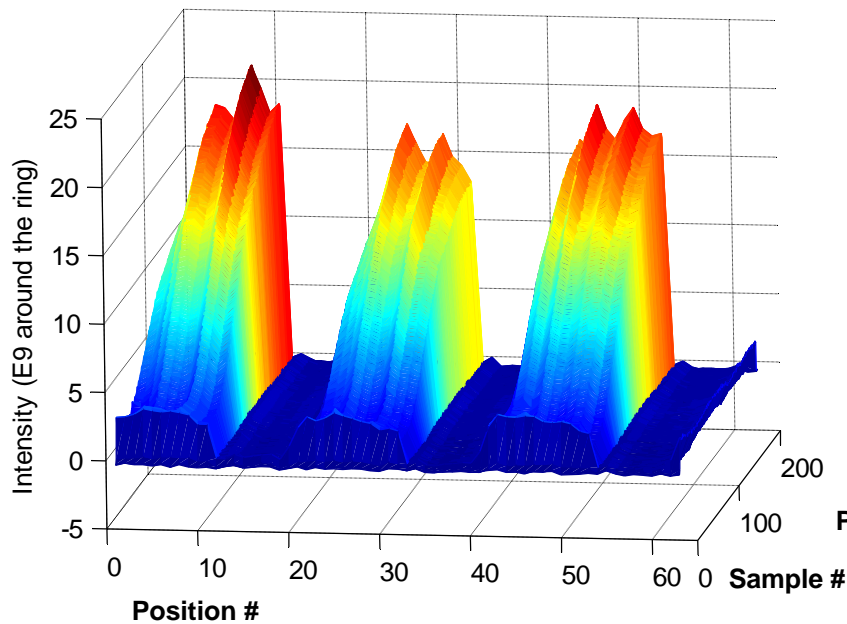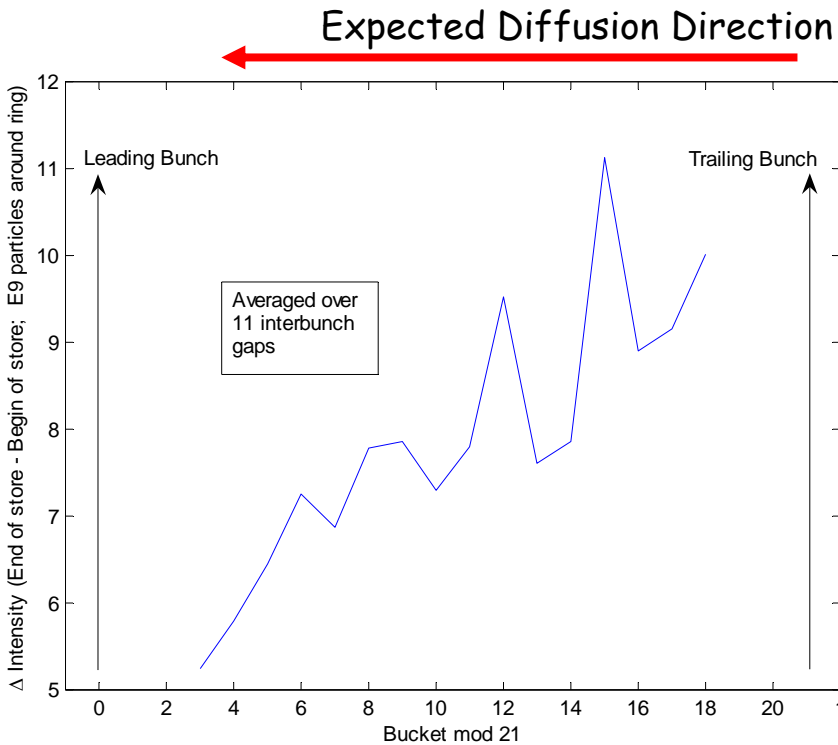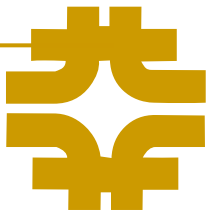
DC Beam Elsewhere

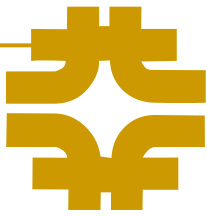Measure every bucket in 1 train except the 5 centered on each bunch

Compare change from beginning to end of store as a function of bucket

DC Beam Diffusion

Issues

- ## No automatic pedestal subtraction
  - Pedestal varies by ± 1 E9 over time
  - Pedestal very sensitive to beam synchronous EM noise
    - Will be helped by new PMT (see Future)
- ## No automatic gain measurement
  - Checked periodically (TEL trips)
  - Correlation between TEL and bunch calibrations
- ## Cross-talk from Synclite
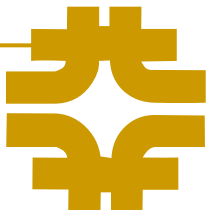 - Need synchronization for any automatic solutions
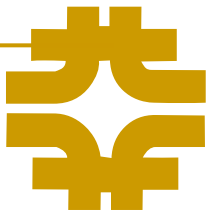   - OAC?

Pedestal behavior
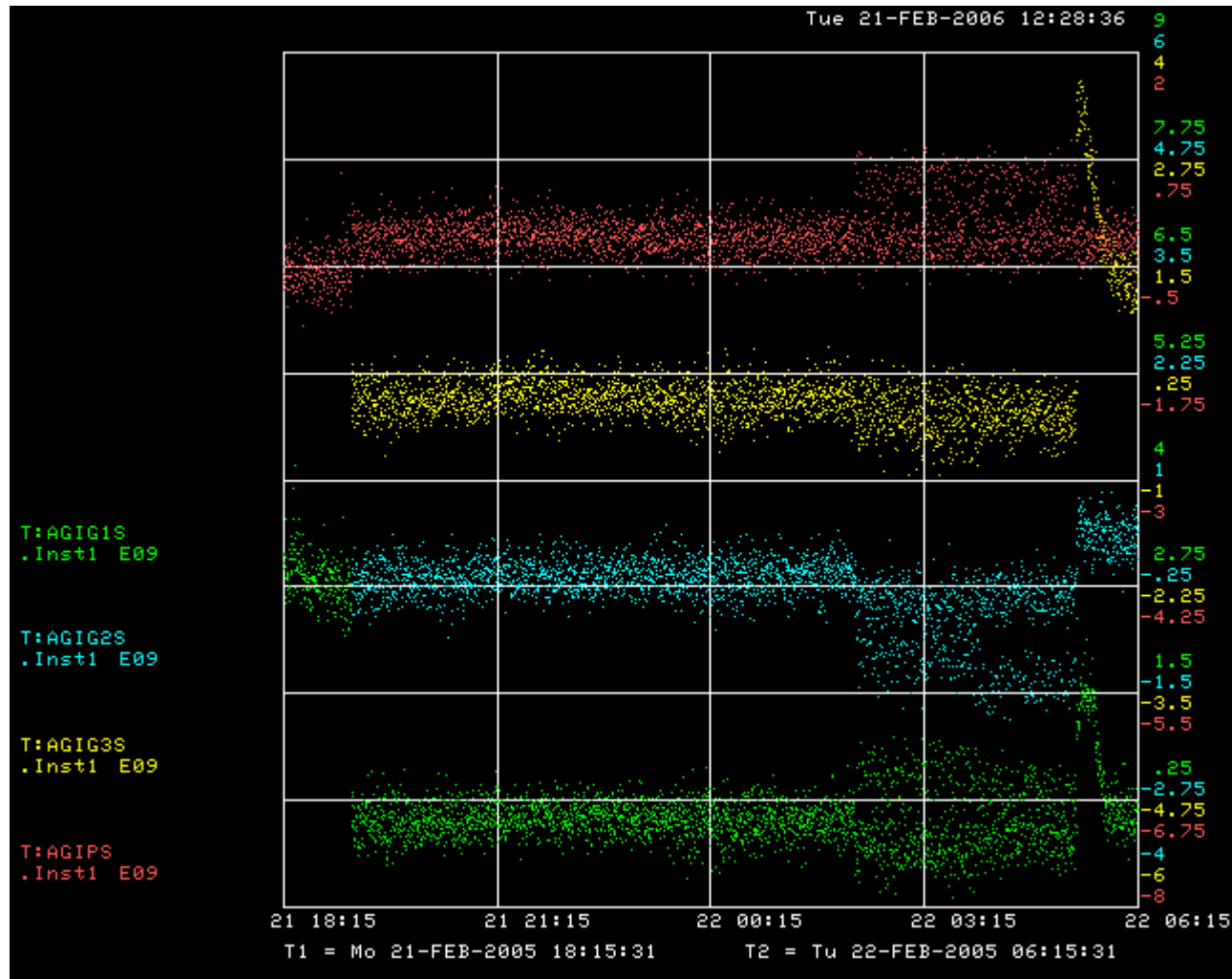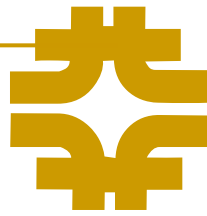
Pedestal behavior
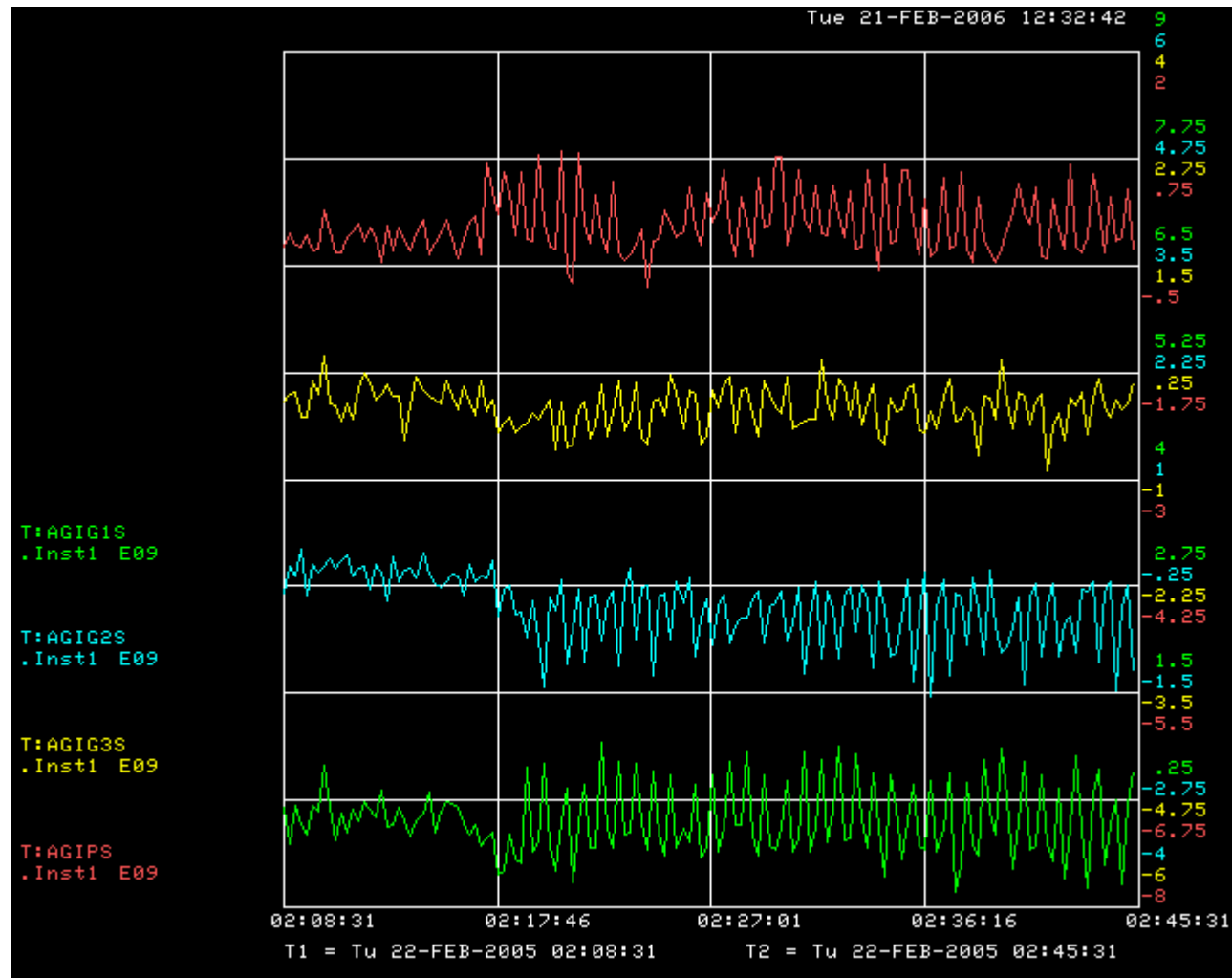
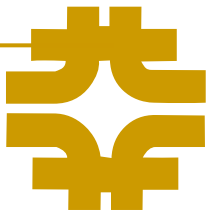# Summary

- ## Abort Gap Monitoring PMT has been in use for nearly 2 years

- ## Integral part of TeV operations

  - ### Checked by the sequencer before normal beam aborts

  - ### Watched by CDF and MCR

    - #### i.e. I get paged when it hiccups

Future

- ## 2006 Shutdown
  - ### Replace LBNL PMT with newly purchased PMT
    - Hamamatsu R5916U-50 ++
      - 3 stage MCP vs. 2 stage (better S/N; N being EM pickup)
      - 10% duty cycle vs. 1% duty cycle for gating
  - ### Install second one in antiproton box
    - Typical proton bunch intensity is 250-300 E9
    - Pbar bunch intensities now approaching 100 E9
      - Efforts to see pbar abort gap beam in Synclite have not seen anything large (maybe possibly hints of < 1E9 at beginning of store, but complicated by pickoff mirror movement)
  - ### Possibly attempt to automate gain and pedestal measurements
    - OAC?

Stuff

- ## R. Coïsson,
    - Opt. Commun. 22, (1977) 135
      On Synchrotron Radiation in Non-Uniform Magnetic Fields
    - Phys. Rev. A20 (1979) 2
      Angular-Spectral Distribution and Polarization of Synchrotron Radiation from a "Short" Magnet
- ## R. Bossart, *et. al.*,
    - Nucl. Instr. and Meth. 184 (1981) 349
      Observation of Visible Synchrotron Radiation Emitted by a High-Energy Proton Beam at the Edge of a Magnetic Field