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NATIONAL ACCELERATOR LABORATORY

# LHC Synchrotron-Light Monitors: Status and Possible Upgrades

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# CERN Collaborators

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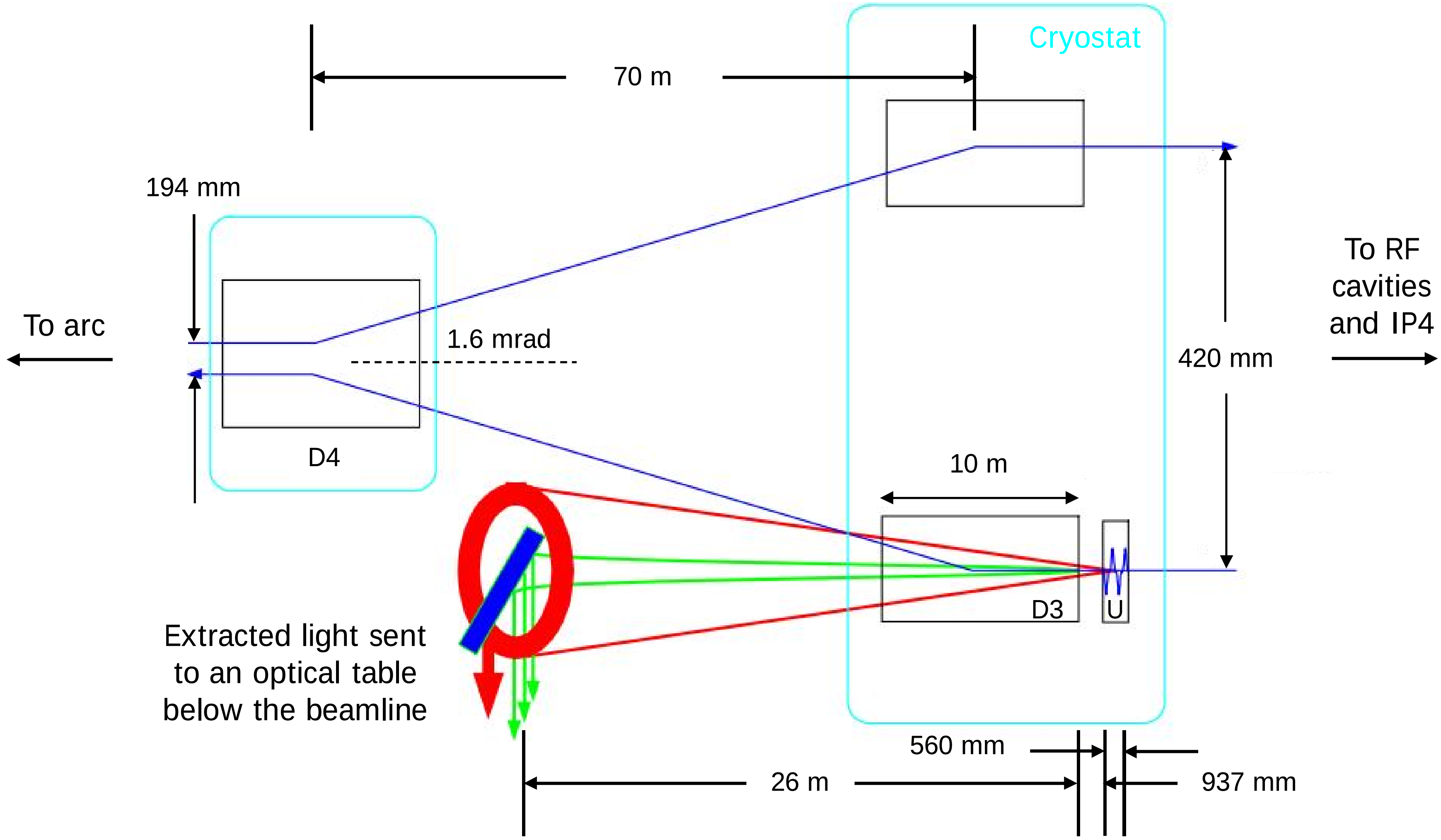
I want to thank Federico and Adam for sending data taken since my last visit in January.

# Synchrotron-Light Monitors

- Four applications:
  - BSRT: Imaging telescope, for transverse beam profiles
  - BSRA: Abort-gap monitor
    - Verifying that the gap is empty
    - Monitoring RF cleaning of the gap
  - LDM: Longitudinal-density monitor
  - Halo monitor (possbile upgrade)
- Two particle types:
  - Protons
  - Lead ions
- Three light sources:
  - Undulator radiation at injection (0.45 to 1.2 TeV)
  - Dipole edge radiation at intermediate energy (1.2 to 3 TeV)
  - Central dipole radiation at collision energy (3 to 7 TeV)

    Consequently, the spectrum and focus change during ramp

# Layout: Emission and Extraction

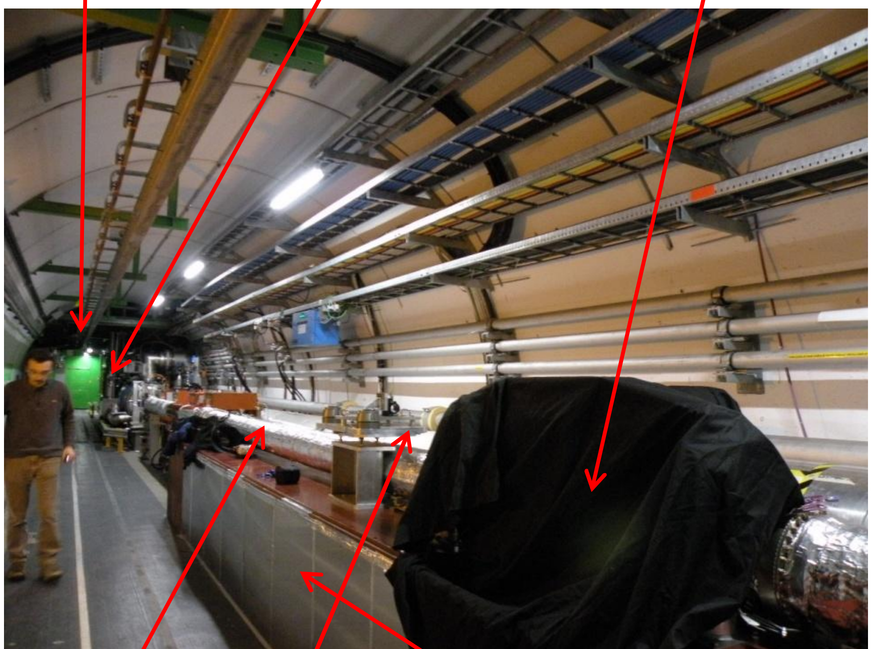


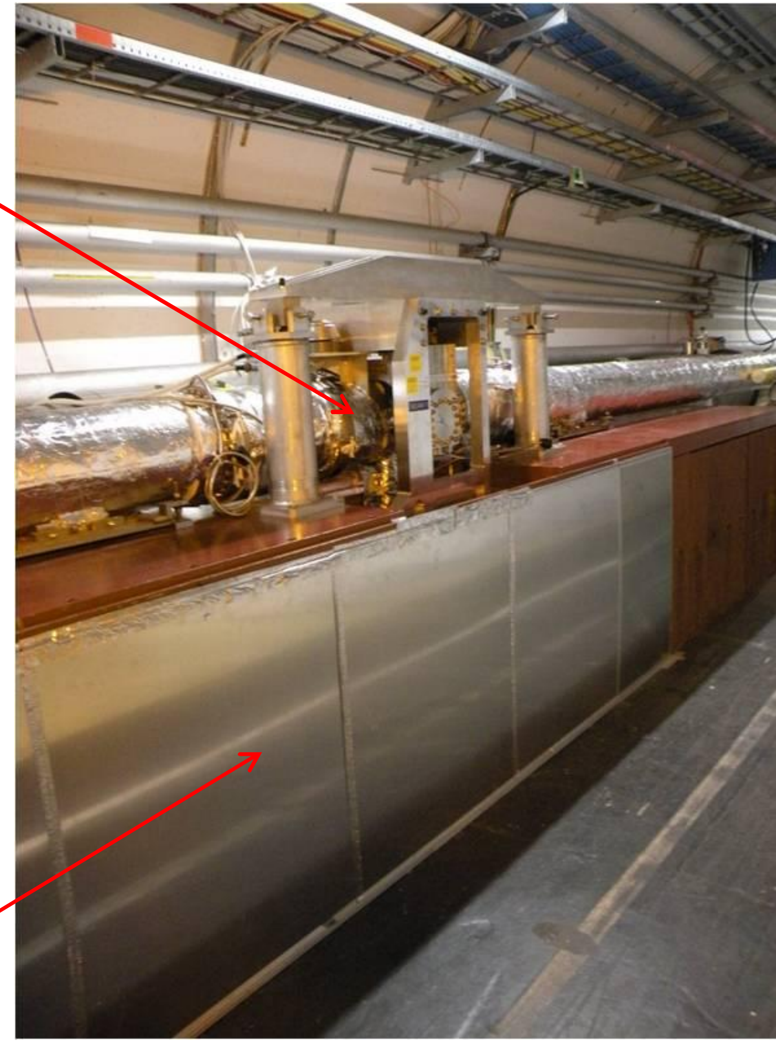
# BSRT for Beam 1

Door to
RF cavities
(IP4)

Undulator
and dipole

B1 Extraction mirror
(covered while hunting
for a light leak)



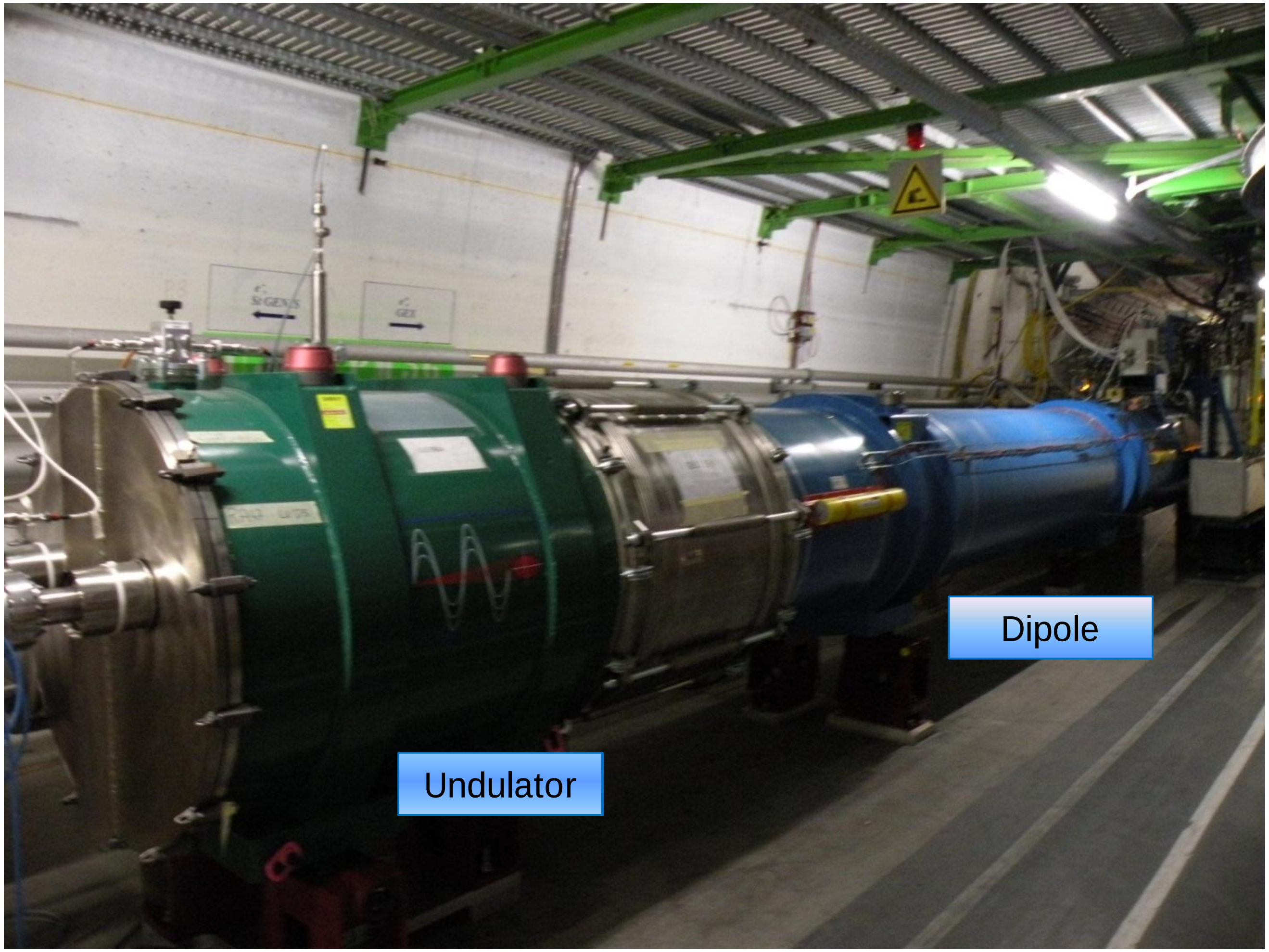


Beam 1

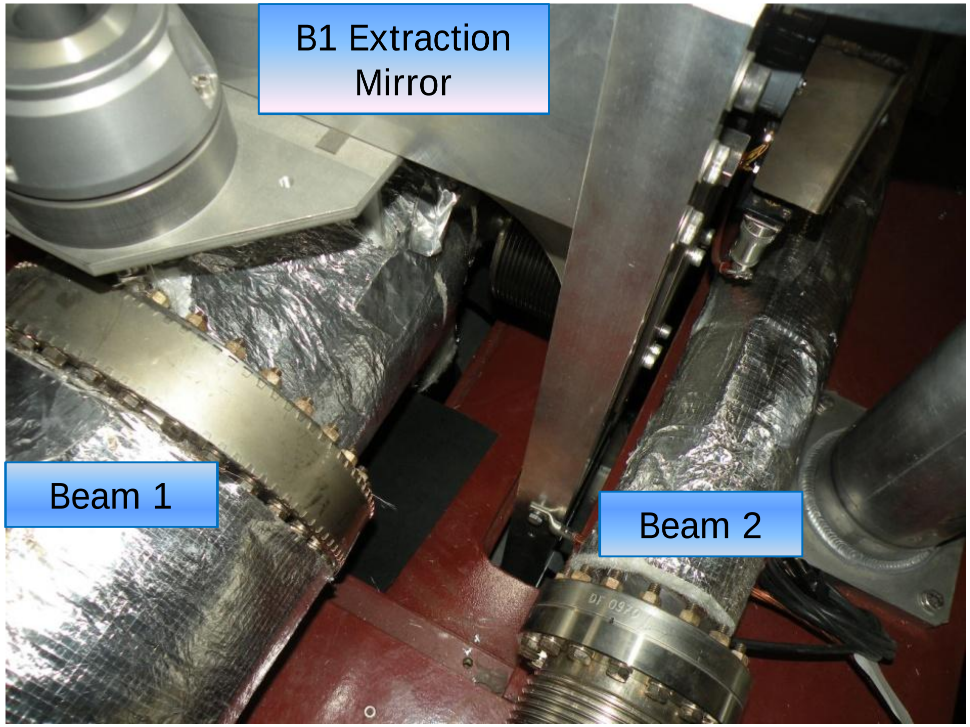
Beam 2

Optical Table

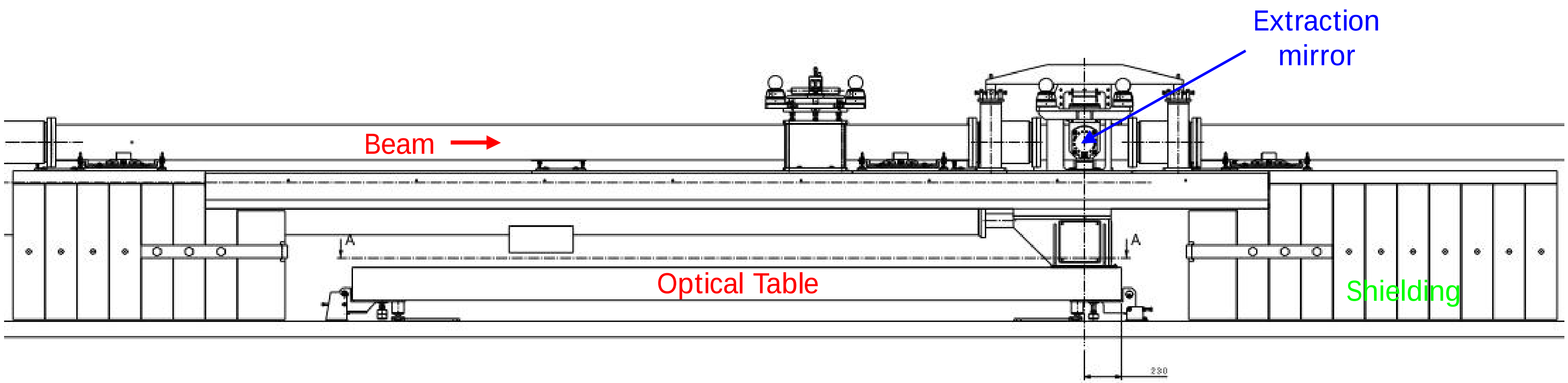
# Undulator and Dipole

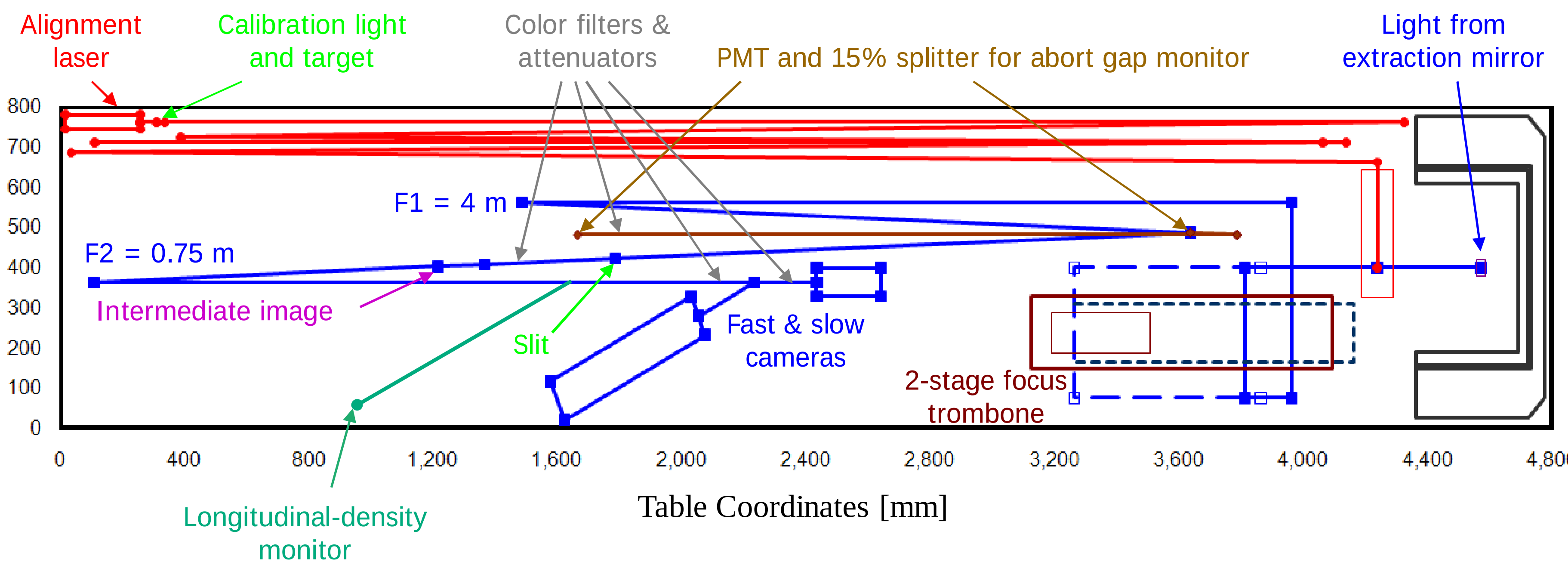


# Extraction Mirror




# Optical Table



# Progress Since CM15

LARP

- November-December 2010: First run with lead ions
  - Synchrotron light images from **lead**
- November: Duplicate optical table set up in lab
  - Detailed study of imaging
- January 2011: Shutdown work in the tunnel
  - New “slow” camera with a 25-ns gate, intensifier for “fast” camera
  - Camera translation stage added for precise focus
  - Thorough check and adjustment of component positions and alignment
  - Longitudinal density monitors
- March-May: Measurements with beam
  - Bunch-by-bunch beam size
  - Longitudinal structure
- Summer: Testing upgrade ideas at SLAC (SPEAR3 ring)
  - Halo monitor and rotating mask

# First Images of Lead Ions at Injection

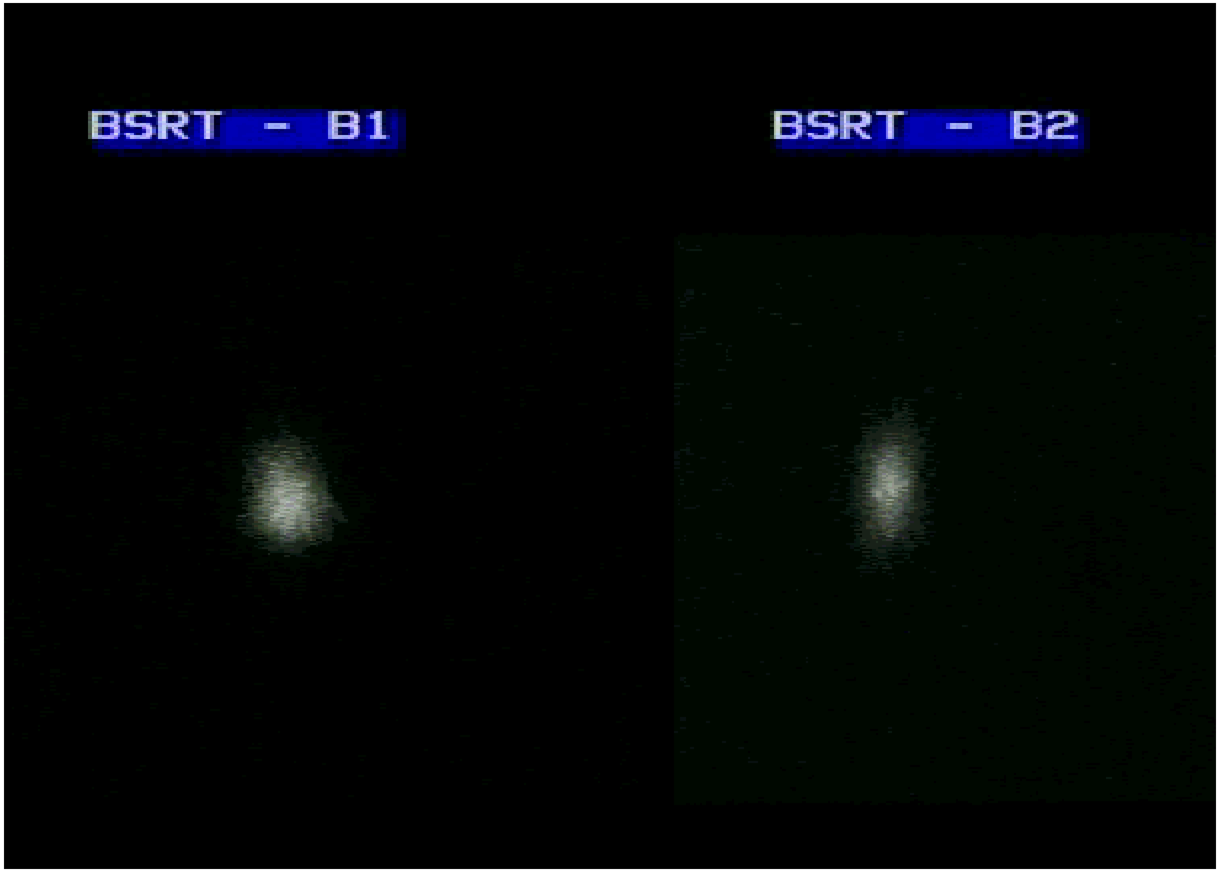
- 2010 Nov 10: Light from 17 bunches, integrated over 20 ms
- Images are faint, since most emission is infrared at this energy
  - Original prediction:  1-s integration needed for a clear image of a single bunch
    - Equivalent to 20-ms integration of 50 bunches
    - 1-s integration directly on the CCD would require only an additional logic pulse

Streaming video at 50 Hz (20 ms)

Numerical accumulation over a few seconds

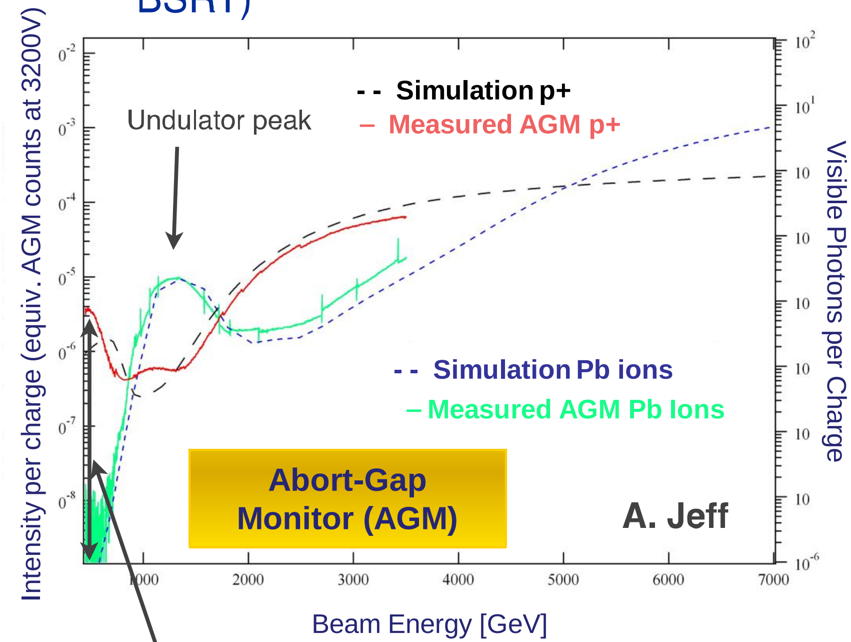
# First Images of Lead Ions during Ramp

- 2010 Nov 5: Light from one bunch during ramp
- Images taken at 2.3 TeV (equivalent proton energy)
    - More light: Emission shifts into the visible at higher energy

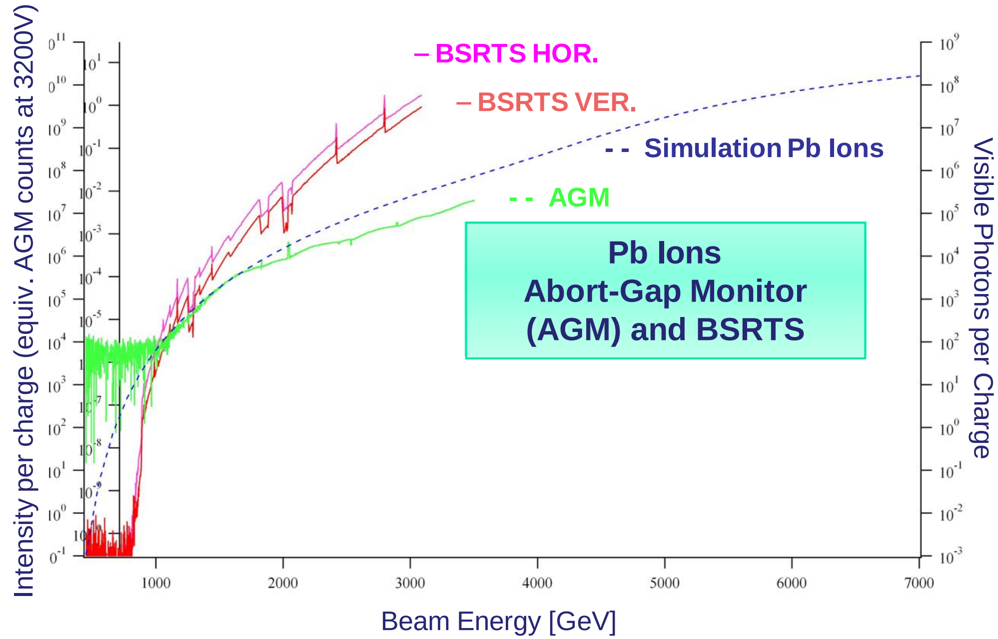


# Simulated vs Measured Light Intensity

Photons per charge as simulated and measured by **Abort Gap monitor** (that shares light with BSRT)




Photons per charge as simulated and measured by **BSRT** during a ramp with IONS without Undulators

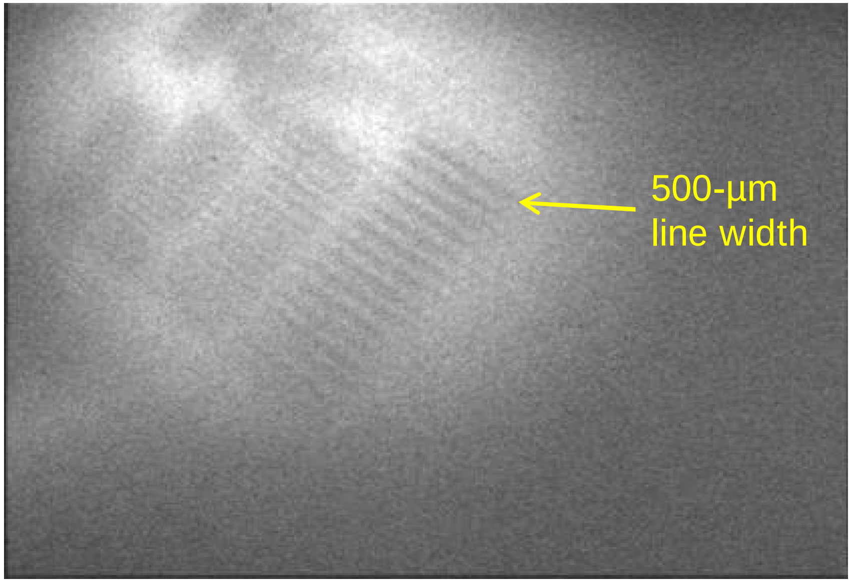


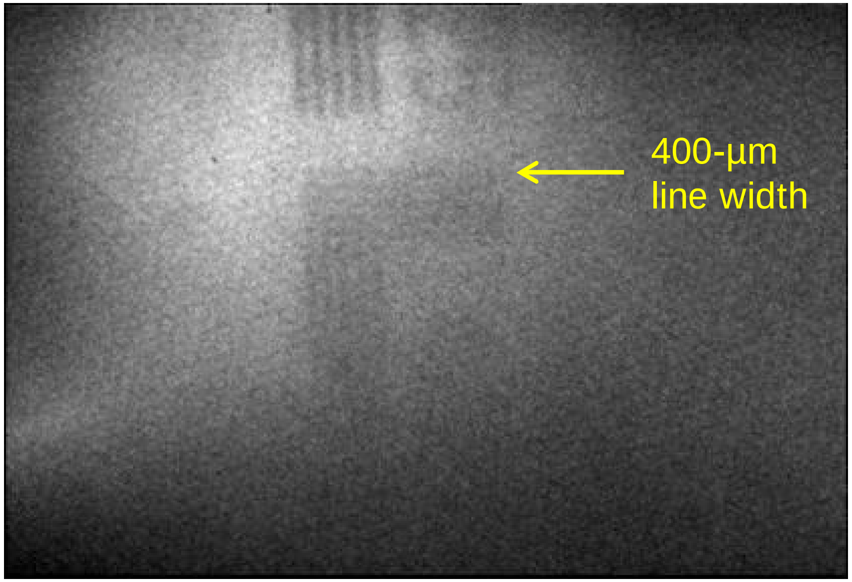

At least a factor of $10^4$ between protons and ions at injection energy.

Nevertheless, it was possible to image the ions at injection.

# Nov 2010: Duplicate Optical Table

- New table in the lab with a copy of the tunnel optics
- Resolution is adequate, but limited by camera and digitizer:
  - Fixed **hexagonal pattern** from intensifier or fiber coupling
    - **Increased magnification** can reduce blurring effect
  - Digitizer grabs **every 2nd line**
    - Made for transfer line, not ring
    - Significant for high energy, where beams are small
    - Blurs the hexagonal pattern
- Also, to steer entering light onto table axis, add another motorized mirror



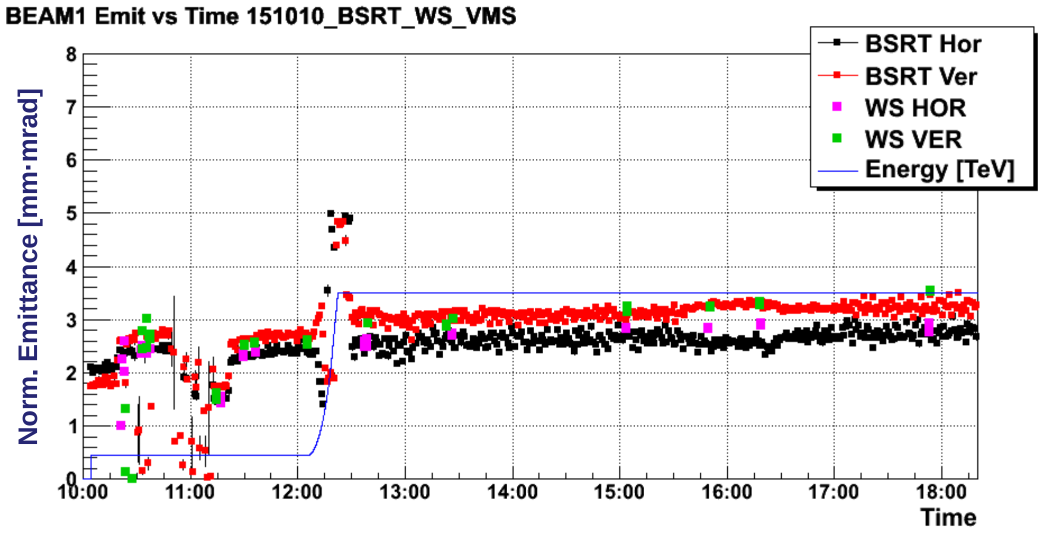
# Jan 2011: Optics Work during Shutdown

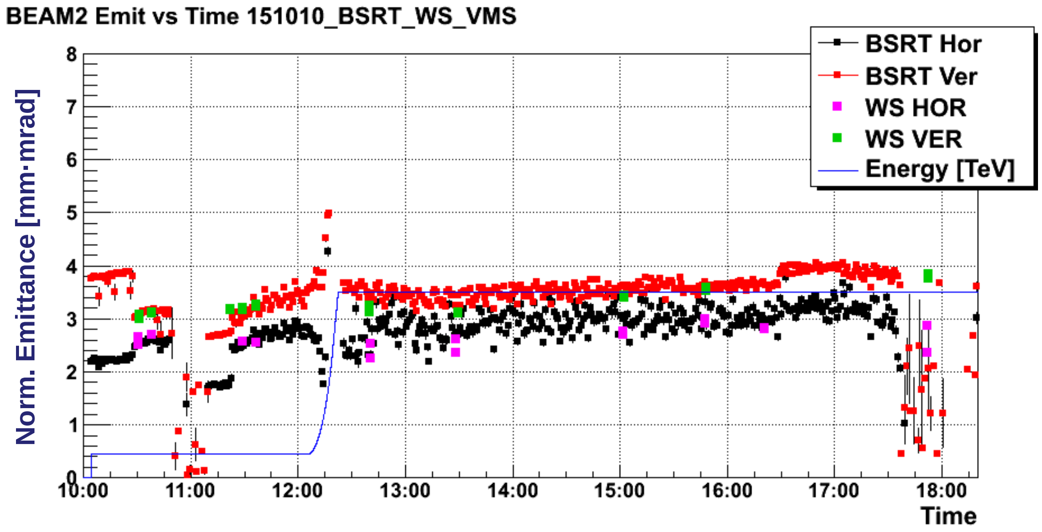
# Slow and Fast Cameras

- Slow camera (BSRTS):
  - Intensified camera from Proxitronic
  - Newer version with video-rate (50 Hz) and gated modes
  - Minimum gate of 25 ns at a maximum rate of 200 Hz
  - Can gate a single bunch on every 55$^{th}$ turn: bunch-by-bunch emittance
  - Status: In routine use
- Fast camera (BSRTF):
  - Fast framing camera from Redlake
  - Maximum image rate of 100 kHz (for reduced region of the imager)
  - Added a custom Photek fiber-coupled image intensifier with a 3-ns gate
  - Intended for turn-by-turn measurements of individual bunches
  - Status: Testing gain of fiber-coupling and intensifier

# Calibration vs Wire Scanners

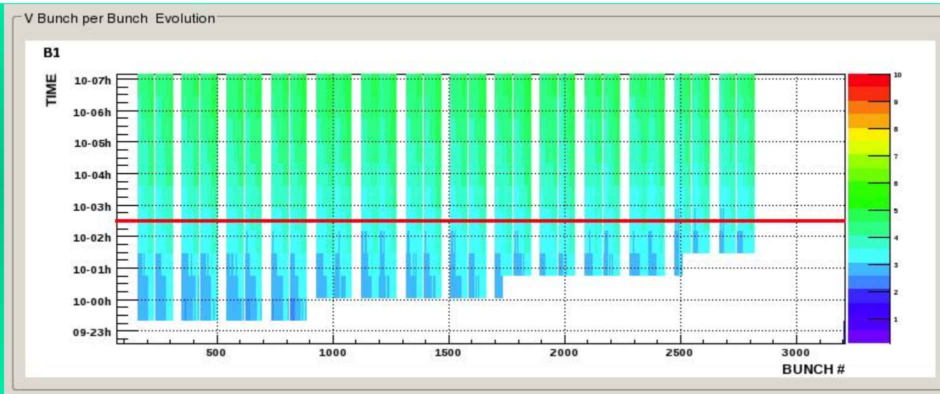
- Wire Scanners (WS)
  - Reference for LHC transverse profile measurements
  - Can be used with just over $10^{13}$ protons without causing wire damage or a quench
- BSRTS calibration vs WS
  - Measured for each beam and plane, as a function of energy
  - Corrections applied in quadrature to BSRT beam-size data
- Corrections of 400–500 µm
  - Possible sources: camera, digitizer, slit adjustment, diffraction



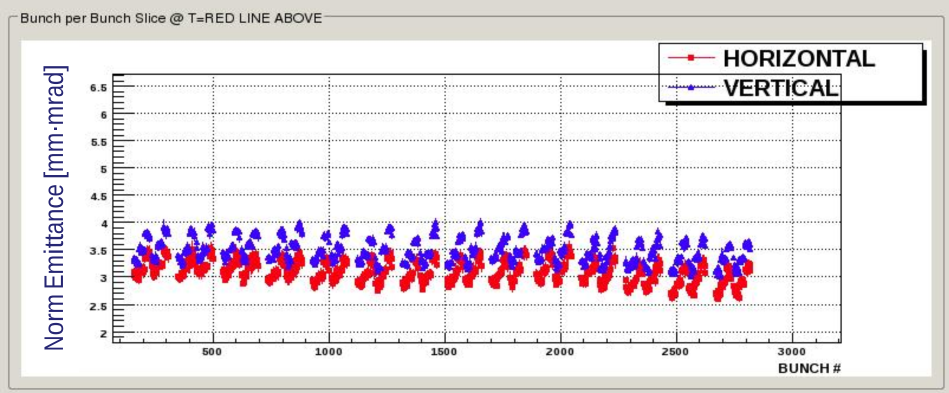
# Monitoring LHC Emittance with BSRT

Transverse vertical emittance versus bunch number and time



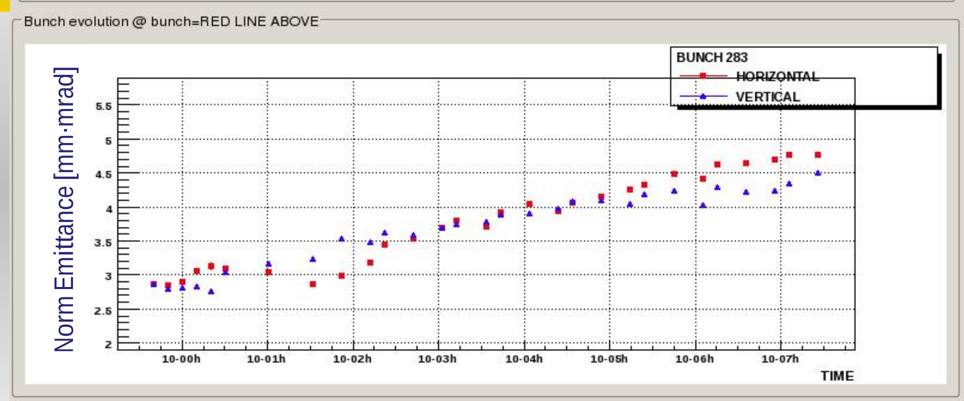

Bunch-by-bunch emittance at a fixed time

Structure comes from injectors. Sawtooth pattern here repeats with PS period.

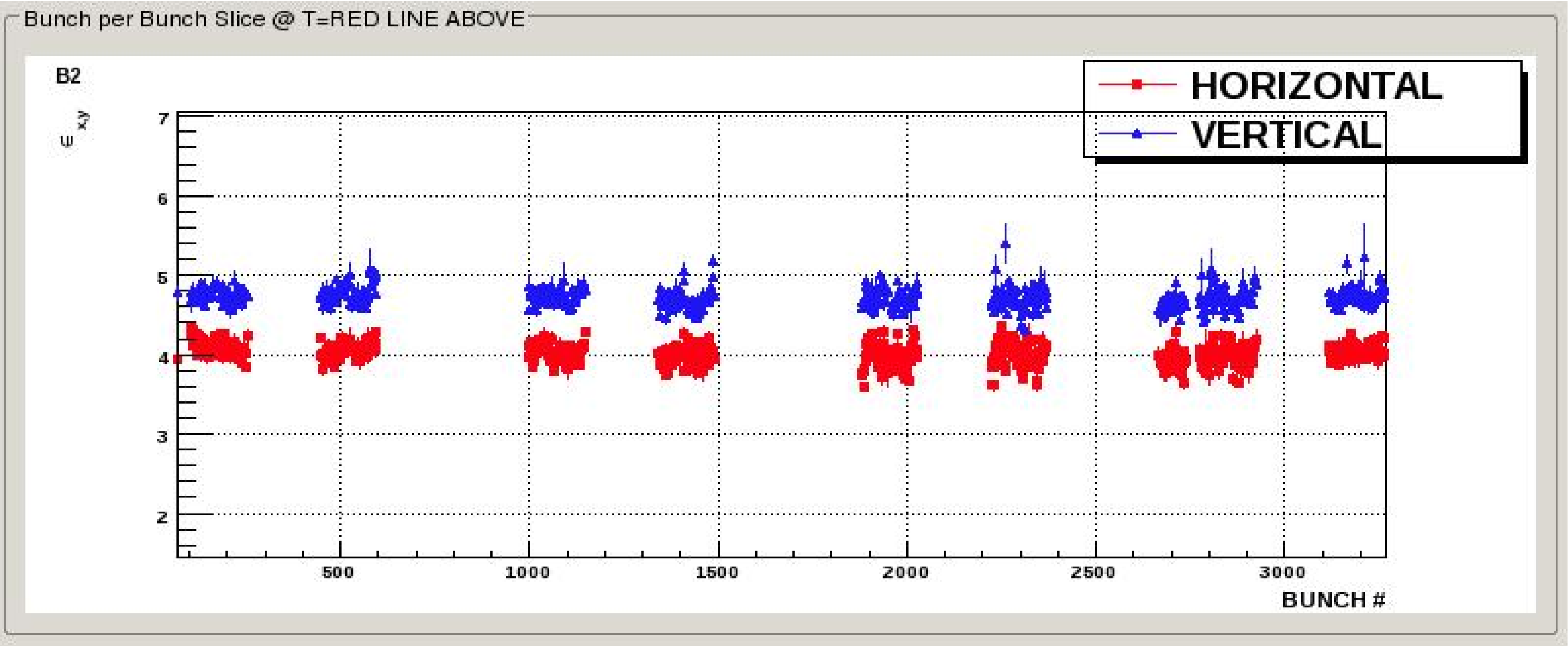



Single-bunch emittance vs time

Emittance reduction between two measurements on the same bunch gives estimate of statistical error.



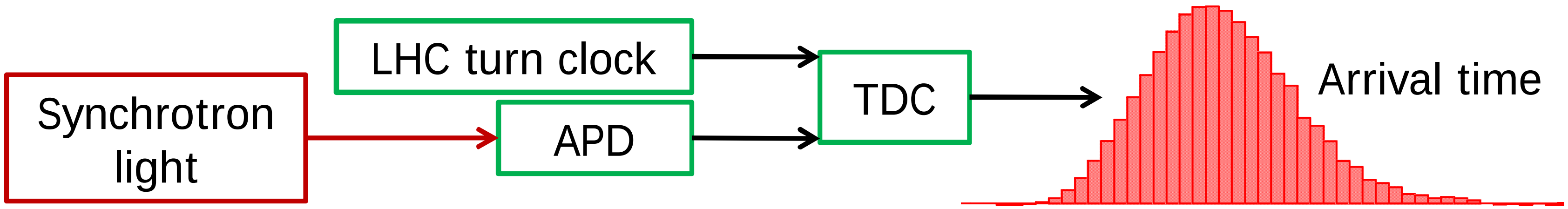
# Improving Emittance using BSRT Data




After tuning injectors to make emittance along bunch trains more uniform

# Longitudinal-Density Monitor

- Monitor built by Adam Jeff
  - Photon counting using an avalanche photodiode (APD)
  - 1% of the BSRT's synchrotron light
  - Histogram of time from turn clock to APD pulse, with 50-ps bins
  - Now installed on both beams



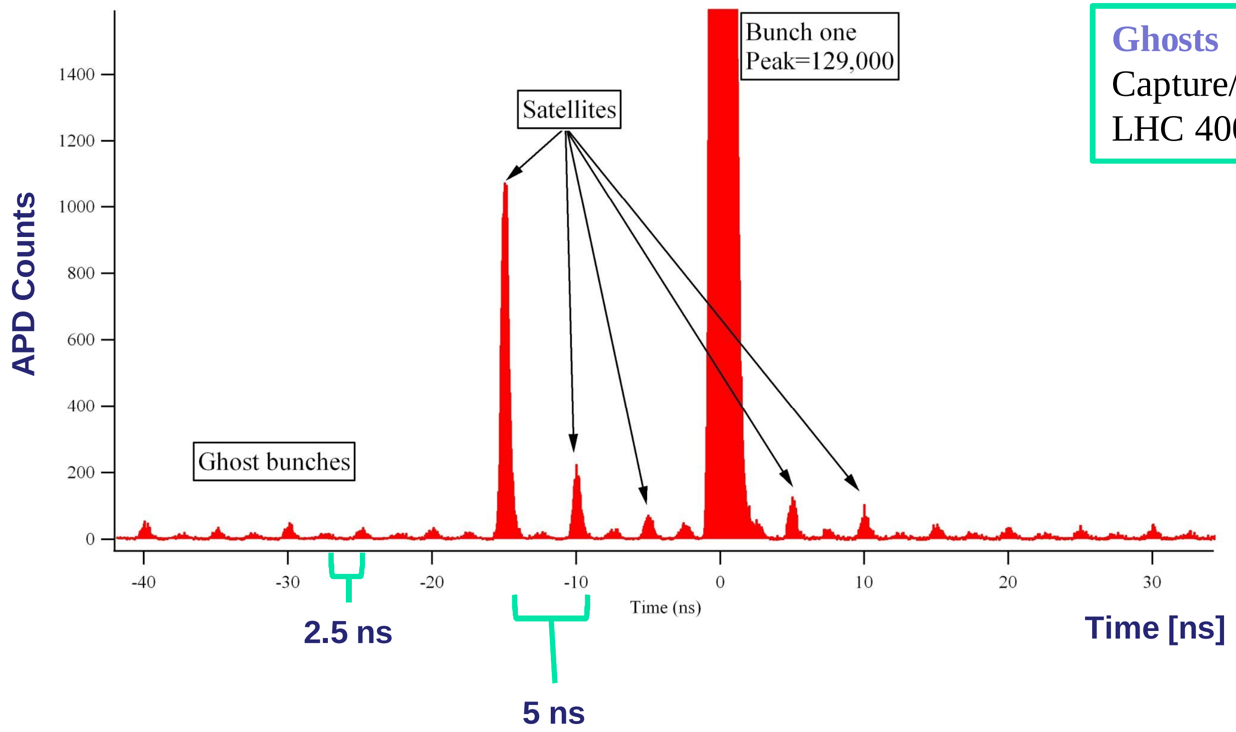

- Modes:
  - Fast mode: 1-ms accumulation, for bunch length, shape, and density
    - Requires corrections for photon pile-up, APD deadtime and afterpulsing
  - Slow mode: 10-s accumulation, for tails and ghost bunches down to $5\times10^5$ protons ($4\times10^{-6}$ of a nominal full bunch)
    - Only 1 photon every 200 turns

# LDM Measurement

Ions with 10-min integration

**Satellites**
Capture/splitting errors in the injectors
SPS 200 MHz → 5 ns

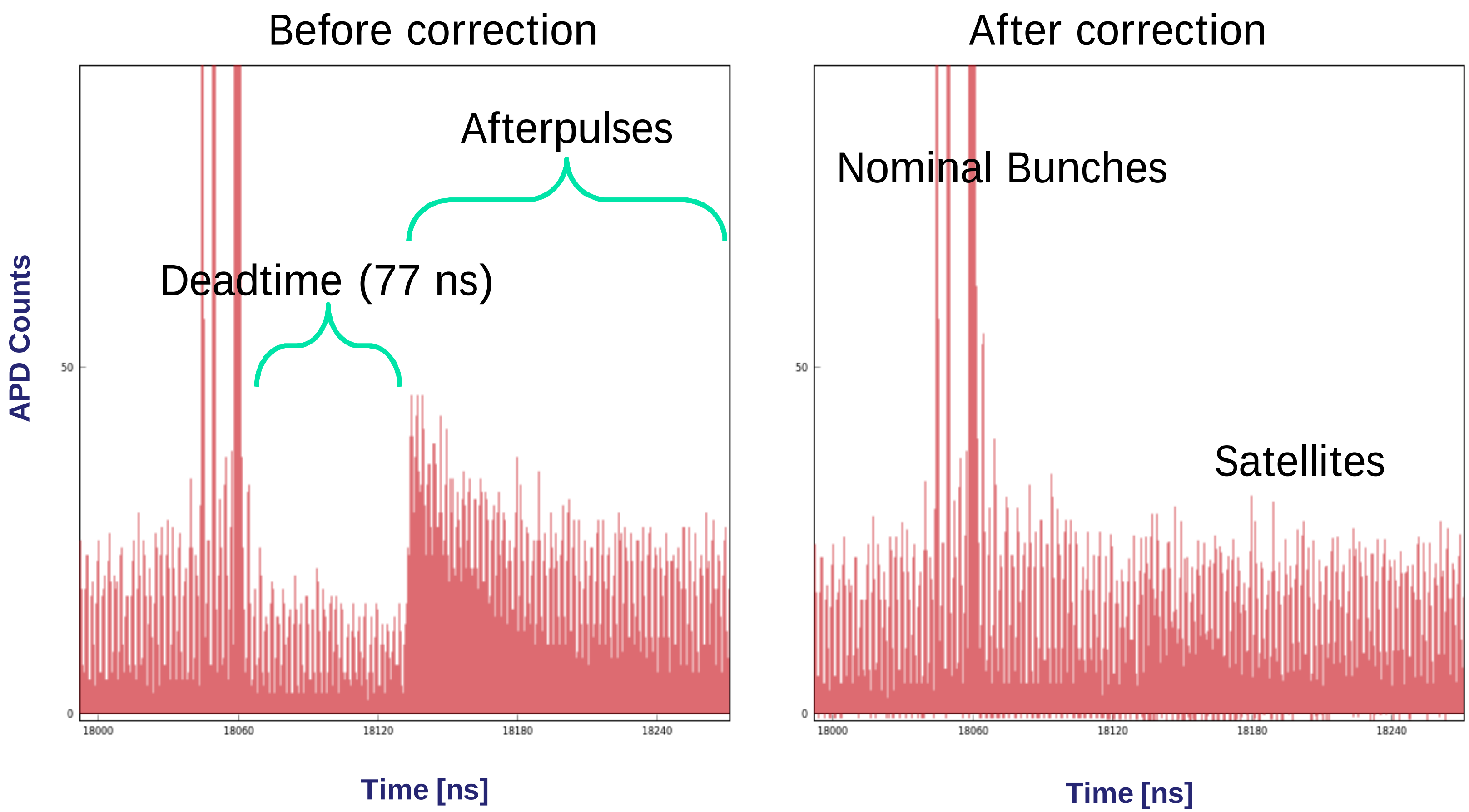
**Ghosts**
Capture/splitting errors in the LHC
LHC 400 MHz → 2.5 ns




**LDM** is the only LHC system able to see all structures from RF, with enough **dynamic range** and **time resolution** for monitoring satellites and ghosts

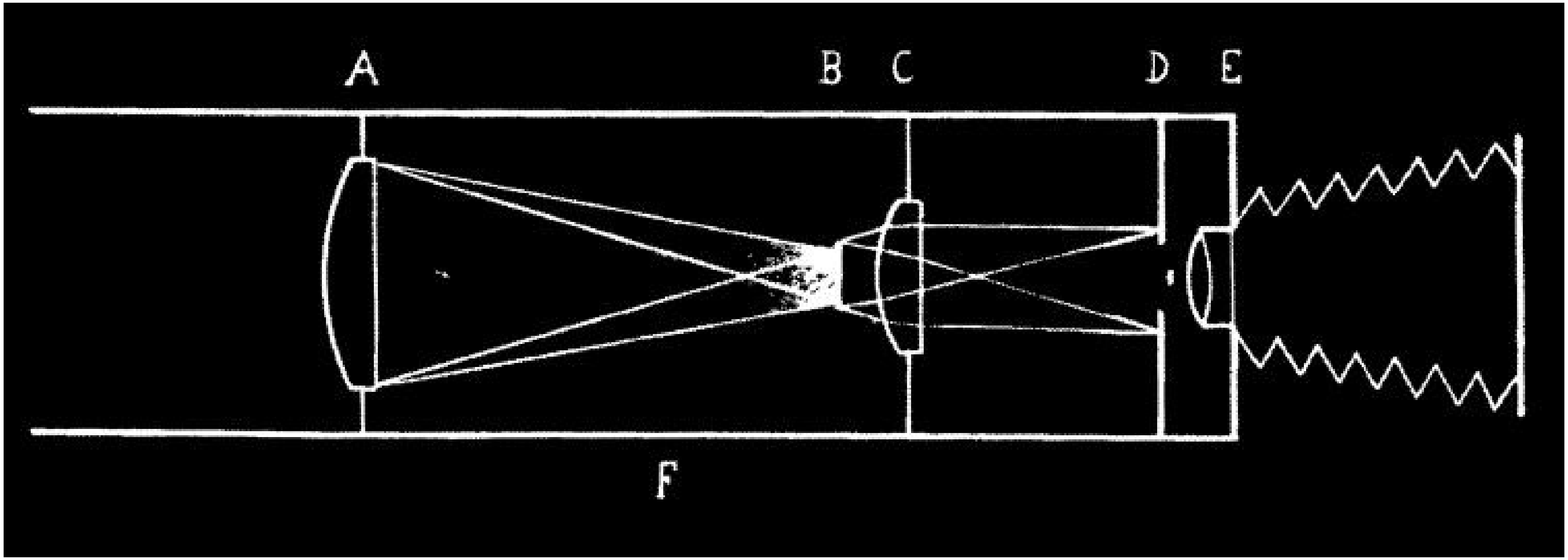
# Deadtime and Afterpulse Correction

- Measurement with beam



# The Solar Corona and Beam Halo

- Lyot invented a coronagraph in the 1930s to image the corona
  - Huge dynamic range: Sun is $10^6$ times brighter than its corona
  - Block light from solar disc with a circular mask *B* on image plane
  - Diffraction from edge of first lens (*A*, limiting aperture) exceeds corona
    - Circumferential stop *D* around of image of lens *A* formed by lens *C*
- Can we apply this to measuring the halo of a particle beam?

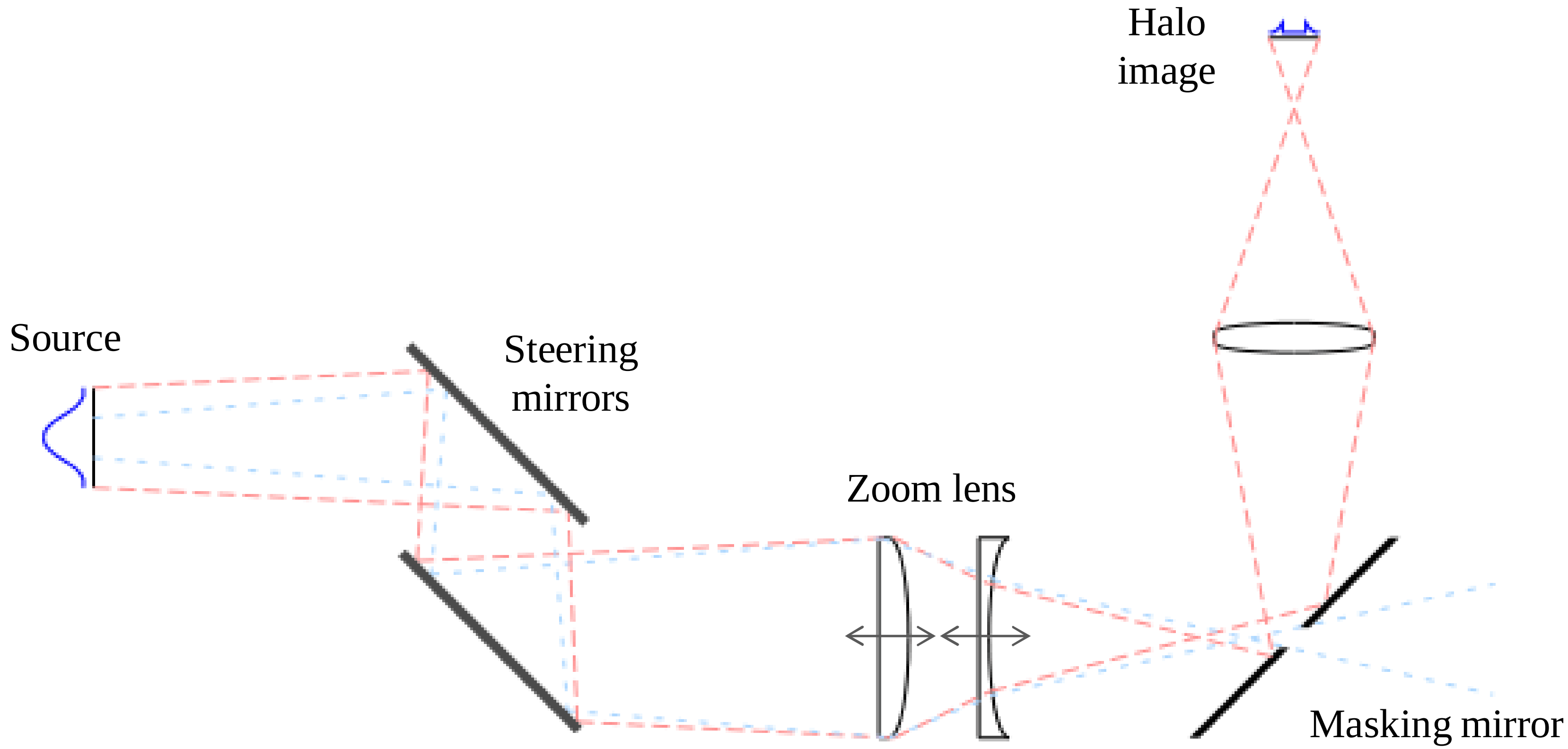



Bernard Lyot, Monthly Notices of the Royal Astronomical Society, **99** (1939) 580

# Beam-Halo Monitor

- Halo monitoring was part of the original specification for the synchrotron-light monitor.
  - LARP's involvement in both light monitors and collimation makes this a natural extension to the SLM project.
- But the coronagraph needs some changes:
  - The Sun has a constant diameter and a sharp edge.
  - The beam has a varying diameter and a profile that is roughly Gaussian
- An adjustable mask is needed. Two approaches…

# Fixed Mask with Adjustable Optics




- But the SLM images a bandwidth from near IR to near UV
  - Reflective zoom is difficult compared to a zoom lens
  - Bandwidth is a problem for refractive optics
    - Limited by need for radiation-hard materials
    - But a blue filter is used for higher currents: Fused silica lenses could work

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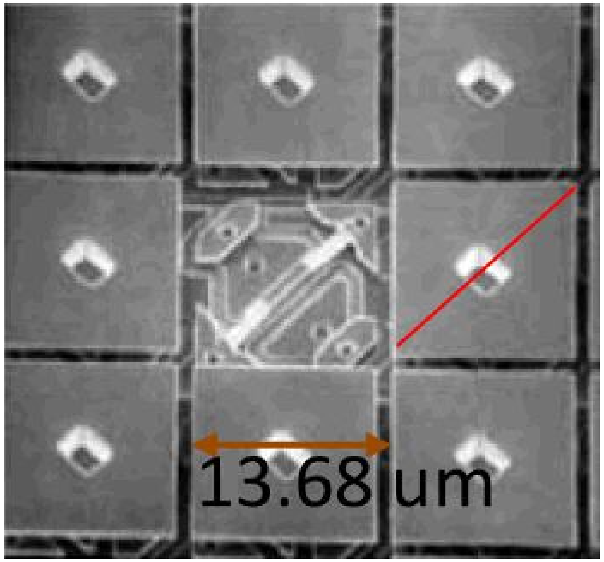
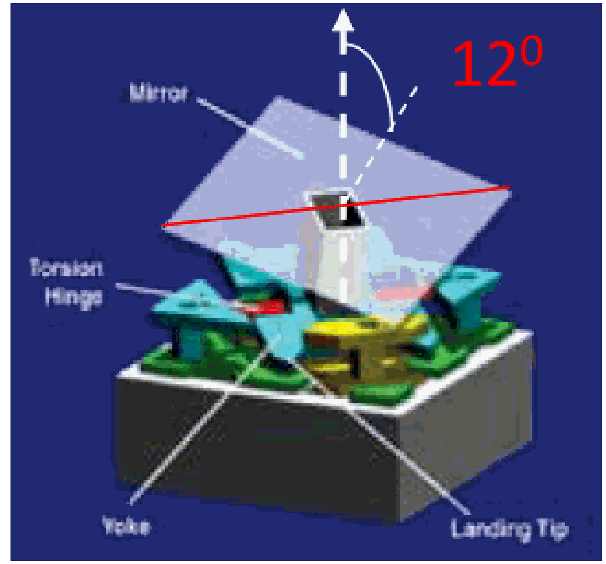
# Digital Micro-Mirror Array (DMA)

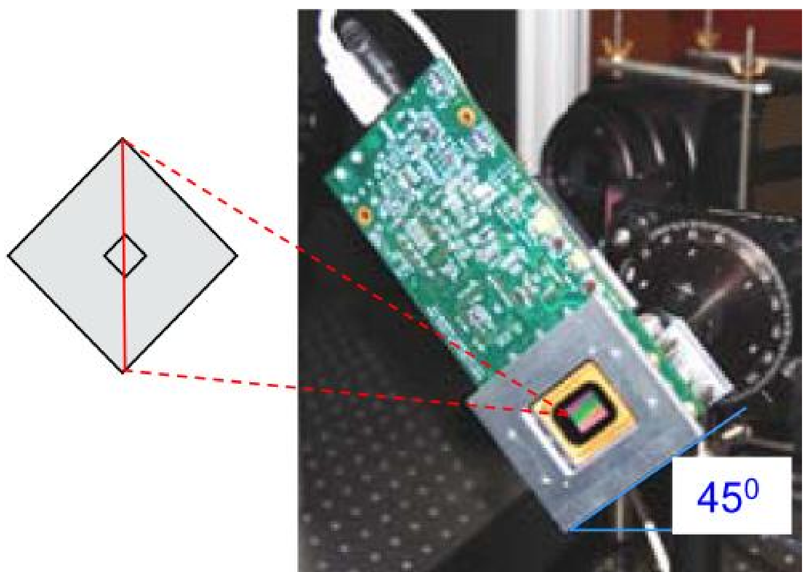
1024 × 768 grid of 13.68-μm square pixels




Pixel tilt toggles about diagonal by ±12°

Mirror array mounted on a control board, which is tilted by 45° so that the reflections are horizontal.



# Digital Micro-Mirror Array vs Fixed Mask

- Advantages of DMA:
  - Flexible masking due to individually addressable pixels
    - Adapts well to flat beams in electron rings
    - But the LHC beams are nearly circular
- Disadvantages of DMA:
  - The pixels are somewhat large for the LHC
    - F1 is far from source: Intermediate image is demagnified by 7
    - RMS size: 14 pixels at 450 GeV, but only 3.4 pixels at 7 TeV
  - Reflected wavefront is tilted
    - DMA has features of a mirror and a grating
    - Corrected by tilting camera face by 24°
      - Known as Scheimflug compensation
- Testing a DMA this summer on the SPEAR3 ring at SLAC

# Rotating Mask

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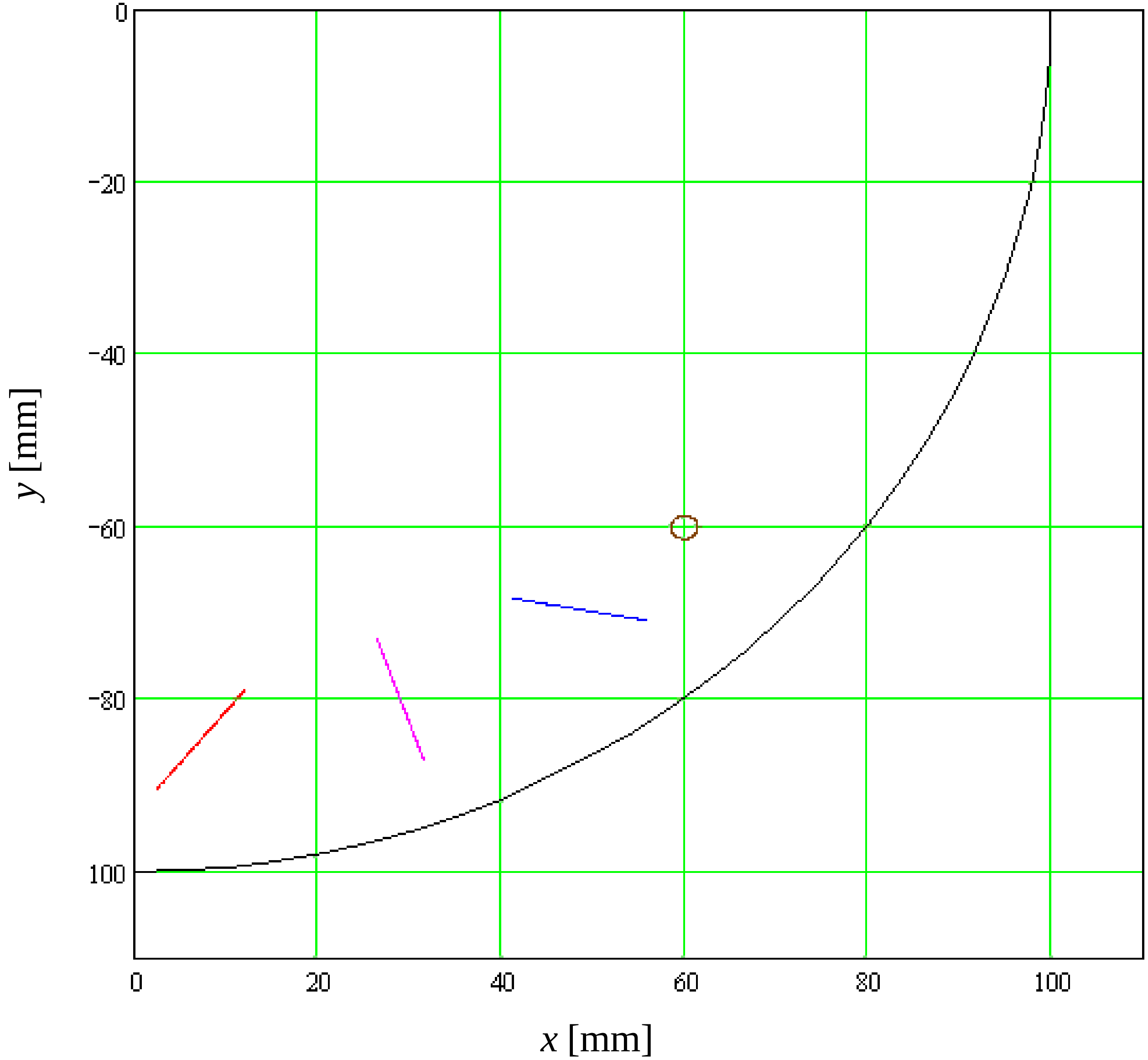
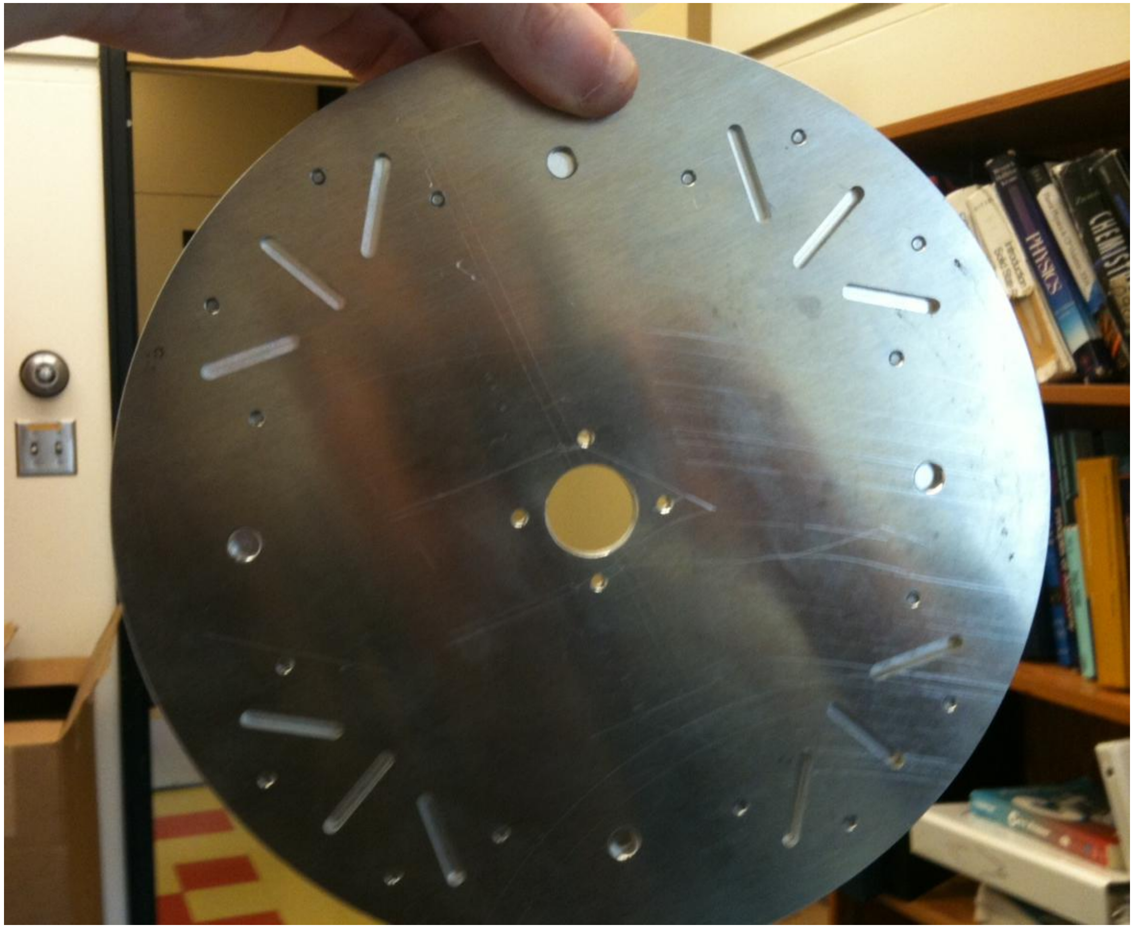
- Bunch-by-bunch scans have limitations:
  - 2 sec/bunch for good statistics: Scanning 2808 bunches takes 1.6 hours
  - The expensive gated cameras may eventually be damaged by radiation, once the rings are full
- Instead, an optical analog of a wire scanner that:
  - Scans a thin slit across the synchrotron-light image of the proton beam
  - Detects transmitted light with a photomultiplier
  - Sorts the PMT pulses by bunch number and by slit position
  - Gets **profiles of every bunch at 1 Hz**
  - 3 slits at different angles on a rotating disc
    - Horizontal, vertical and 45° profiles
    - Beam size on major and minor axes, plus tilt of beam ellipse

# Movie: Mask Rotating across Beam



# Photograph of Mask



- 4 sets of slots: Rotation at 0.25 Hz for 1-Hz data
- Ready for testing this summer on the SPEAR3 ring at SLAC

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# Summary

- Lead-ion beams were imaged with synchrotron light for the first time in November.
- A table with a copy of the optics in the tunnel was set up in November for detailed studies of imaging.
- Some improvements and additions to the optics were installed during the shutdown.
- Bunch-by-bunch emittance measurements have been helpful in machine tuning.
- The longitudinal-density monitors have been commissioned.
- Tests of two possible upgrades, a halo monitor and a rotating-mask profiler, will begin this summer on SLAC's SPEAR-3 ring.