LARP

NATIONAL ACCELERATOR LABORATORY

LHC Synchrotron-Light Monitors: Status and Possible Upgrades

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SLAC

LARP CM15

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2010 November 2

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Synchrotron-Light Monitors

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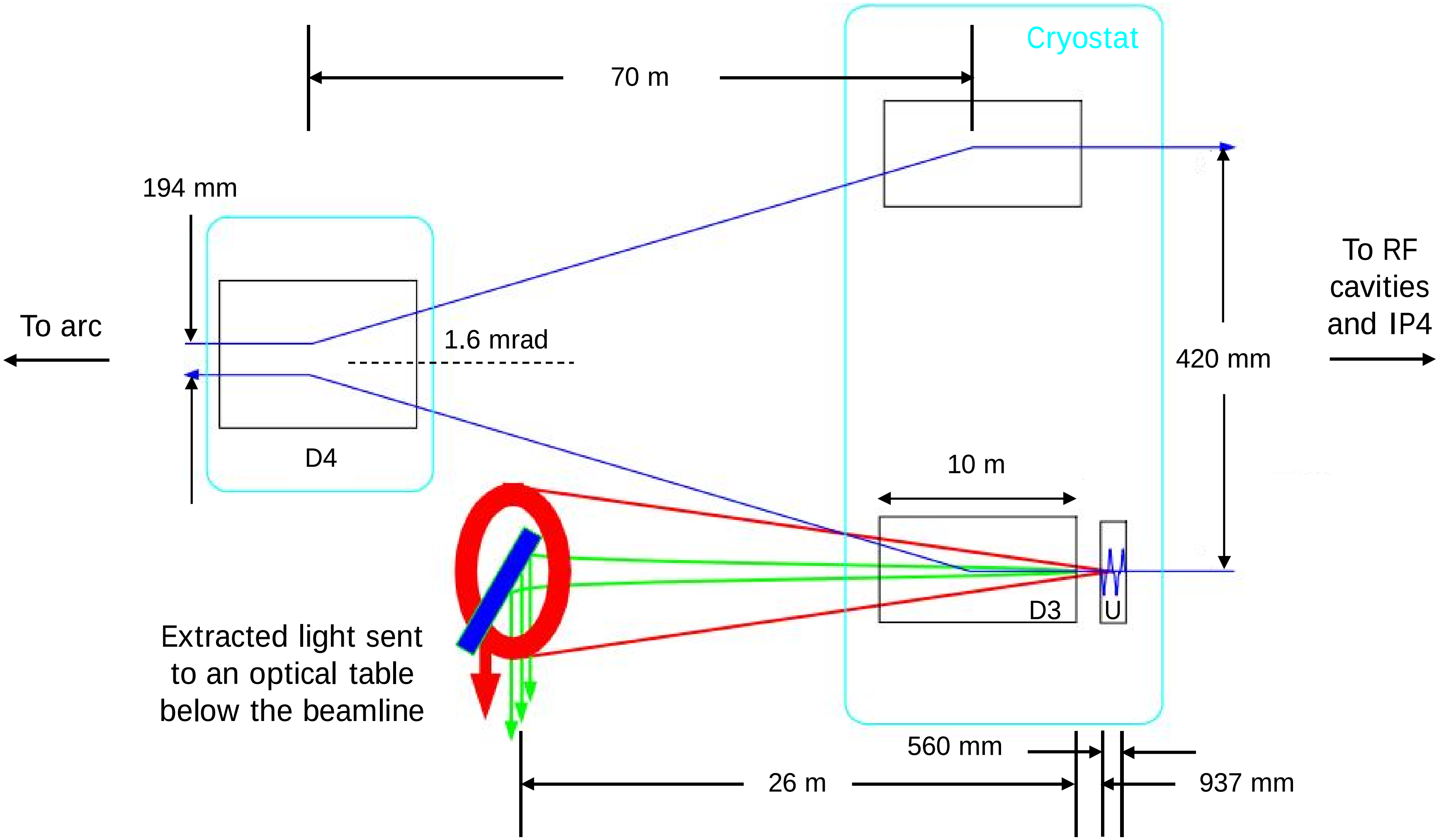
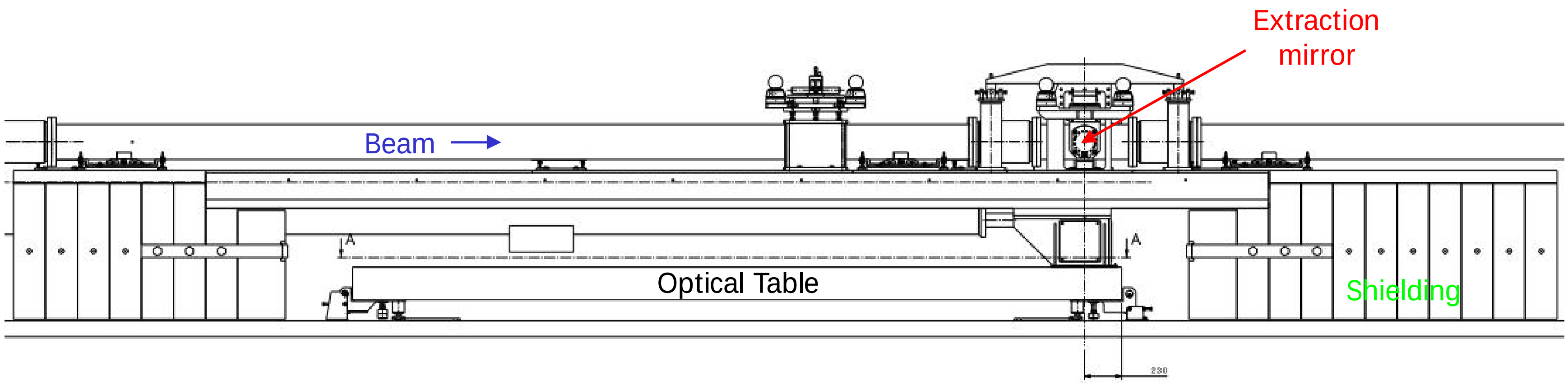
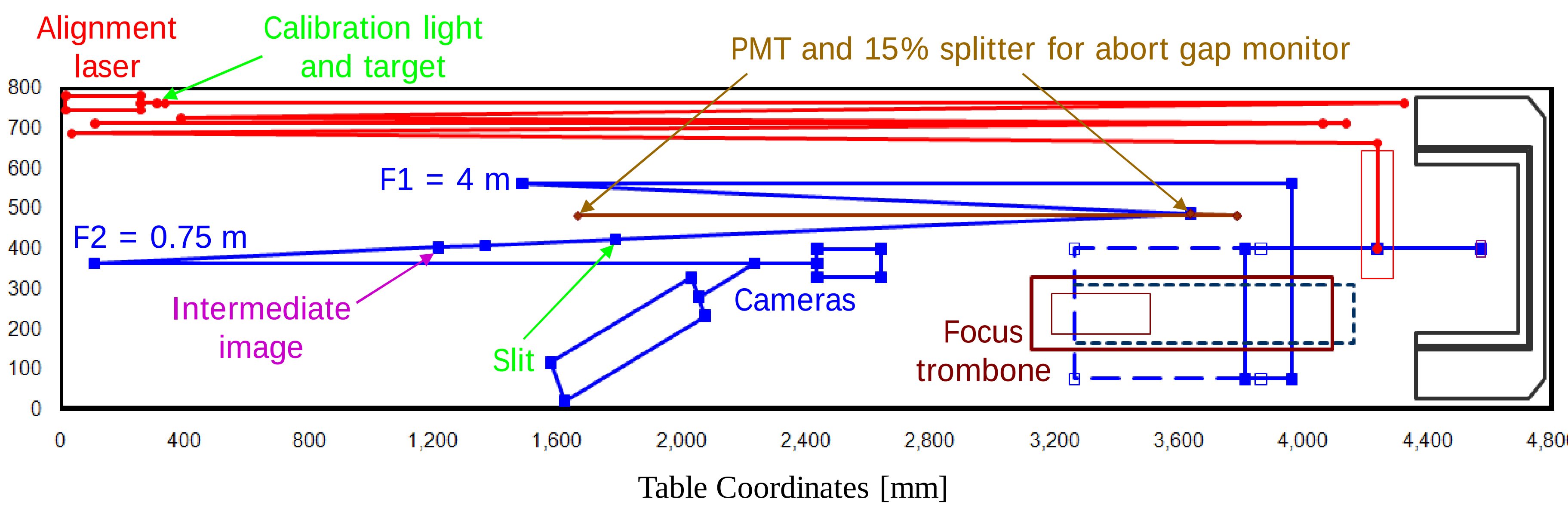
- Five applications:
  - BSRT: Imaging telescope, for transverse beam profiles
  - BSRA: Abort-gap monitor, to verify that the gap is empty
    - When the kicker fires, particles in the gap get a partial kick and might cause a quench.
  - Abort-gap cleaning
  - Longitudinal density monitor (in development)
  - Halo monitor (future upgrade)
- Two particle types:
  - Protons
  - Lead ions: First ion run starts in one week
- 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



Optical Table

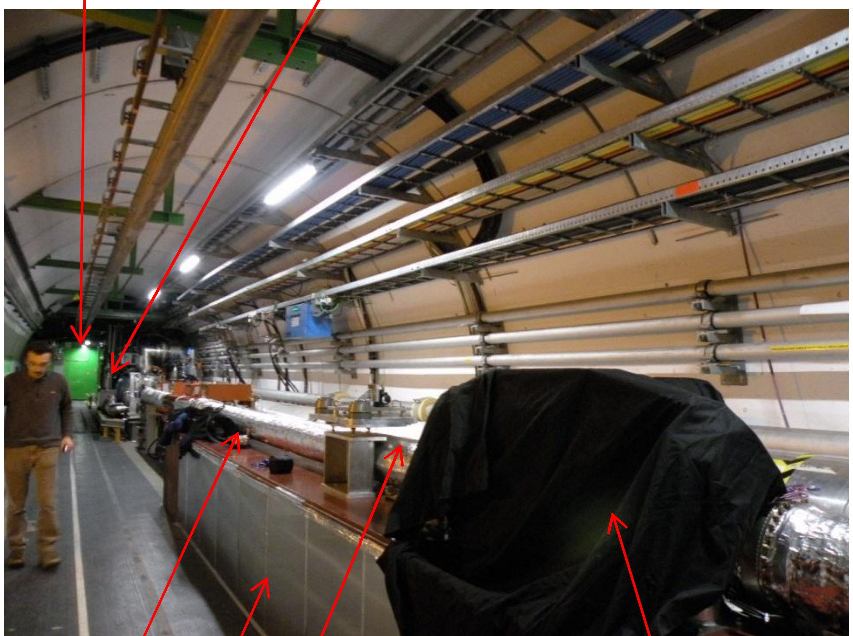




BSRT for Beam 1

Door to
RF cavities

Undulator
and dipole



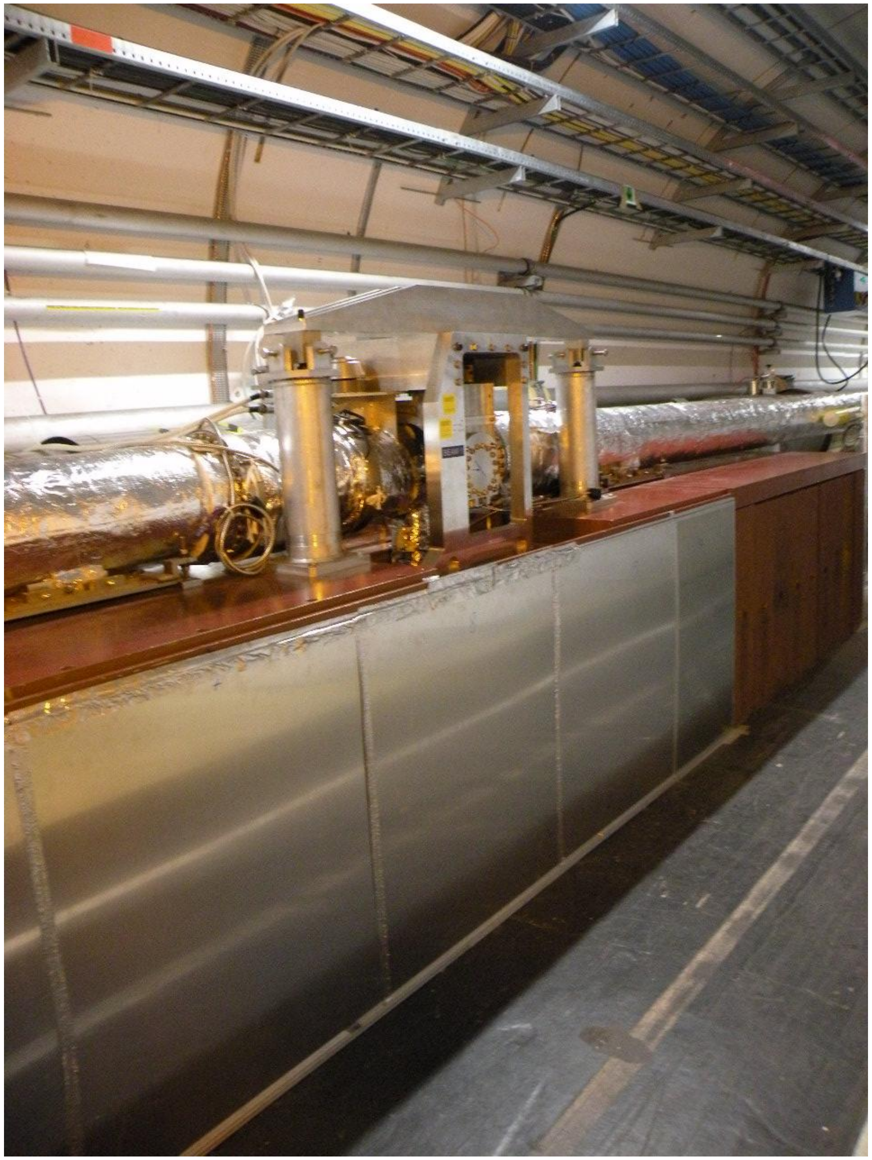
Beam 1

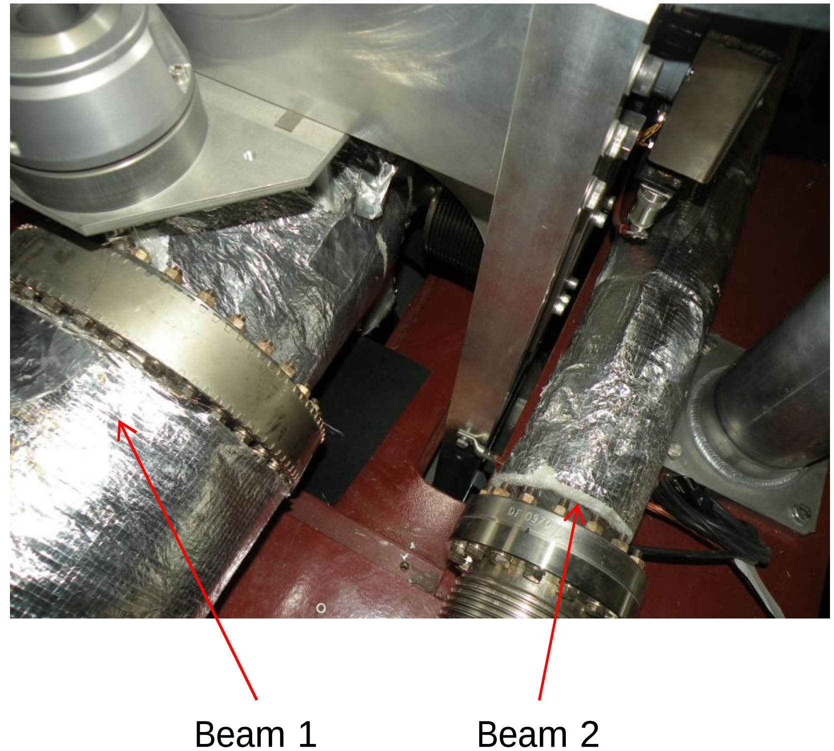
Beam 2

B1 Extraction mirror
(covered to hunt for a light leak)

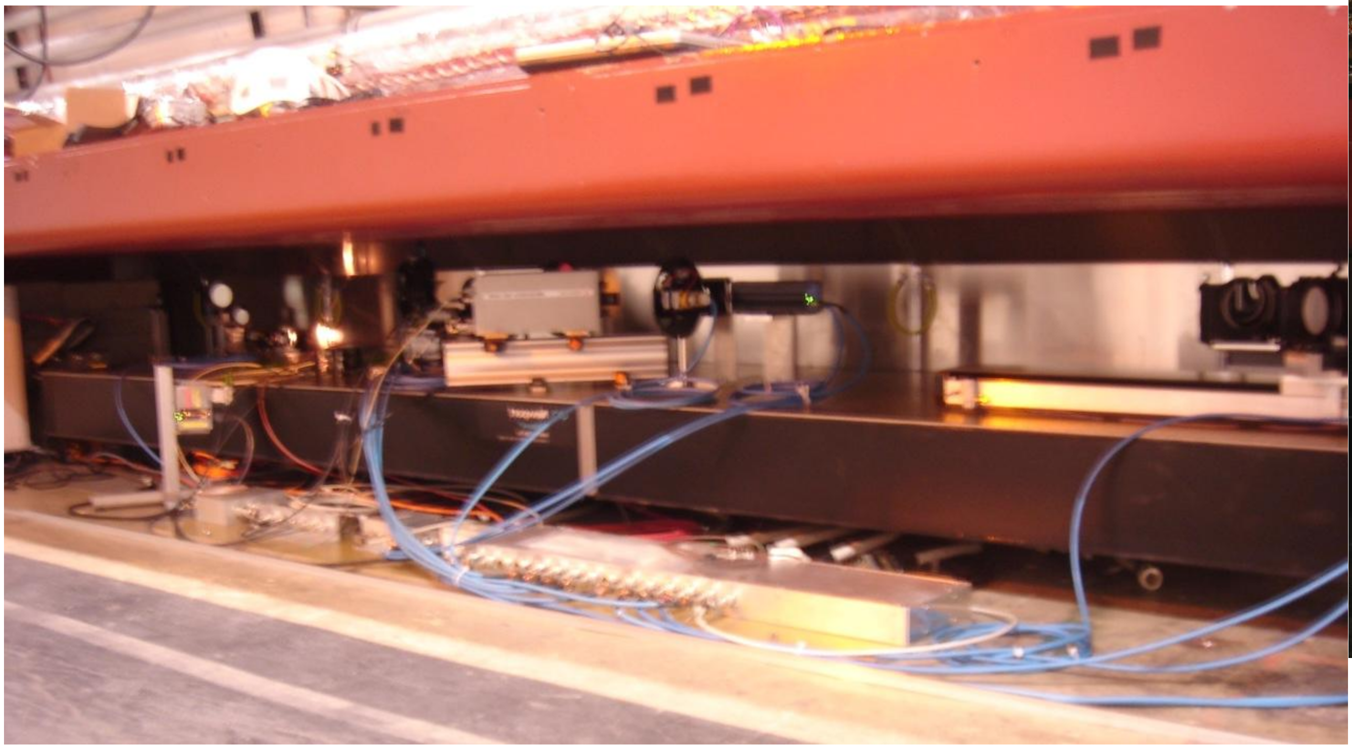
Optical Table

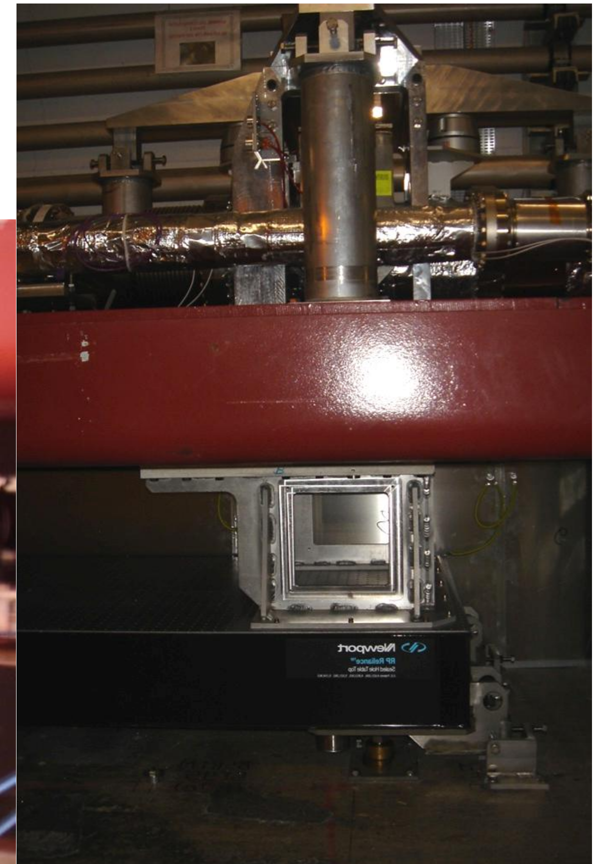
Table Enclosure under Extraction Mirror



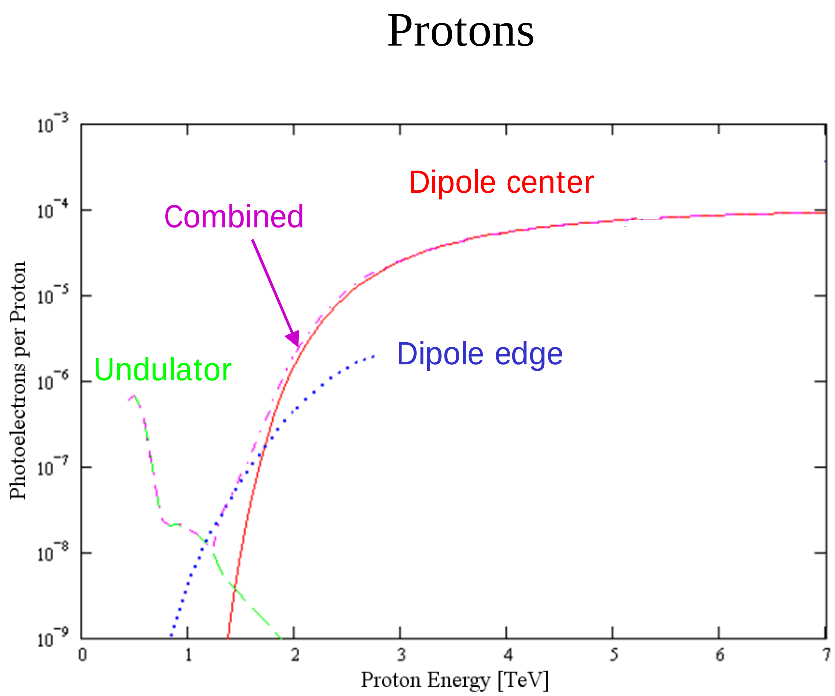


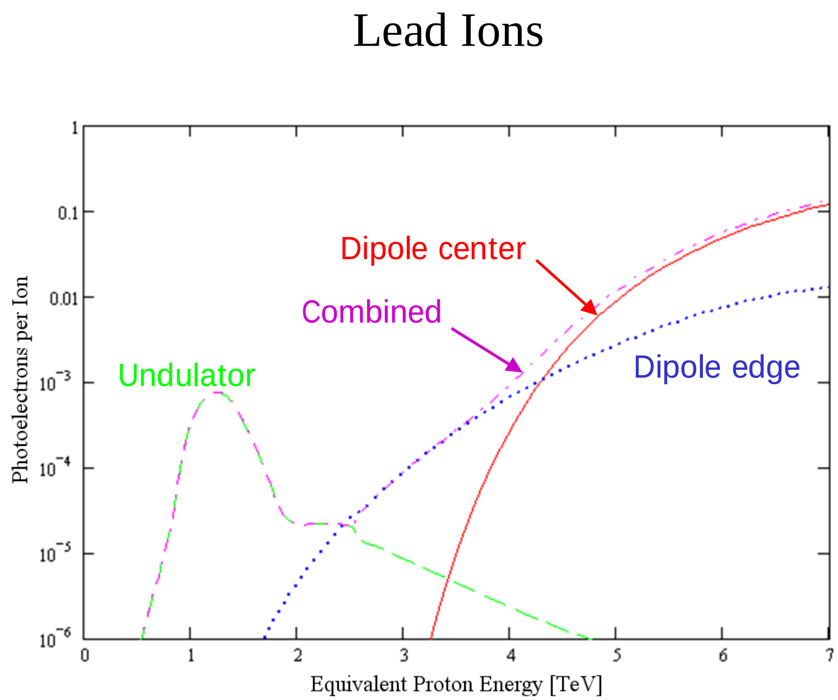
Optical Table





Photoelectrons per Particle at Camera





- In the crossover region between undulator and dipole radiation:
  - Weak signal
  - Two comparable sources: poor focus over a narrow energy range
- Focus changes with energy: from undulator, to dipole edge, to dipole center
- Dipole edge radiation is distinct from central radiation only for $\omega >> \omega_c$

LHC Beams at Injection (450 GeV)

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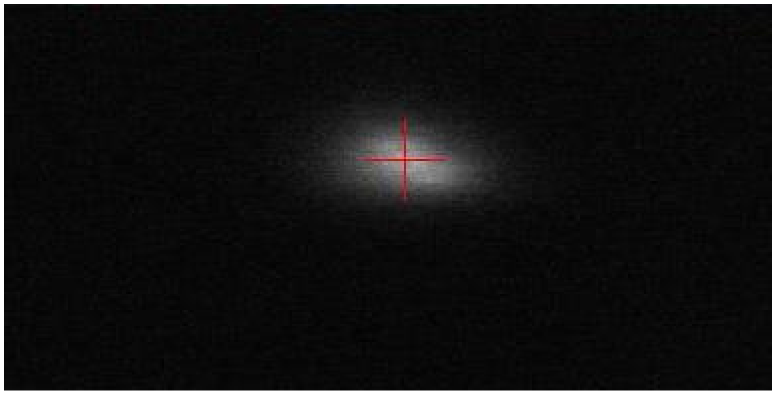
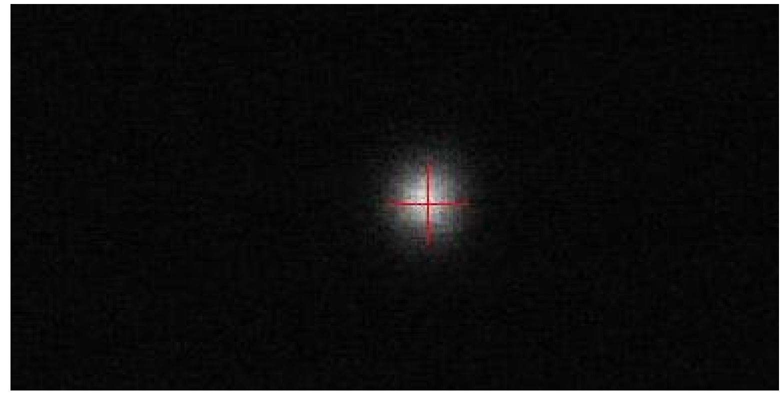
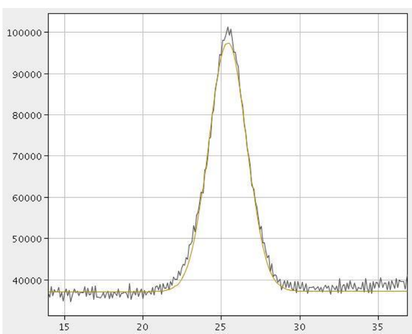
Beam 1



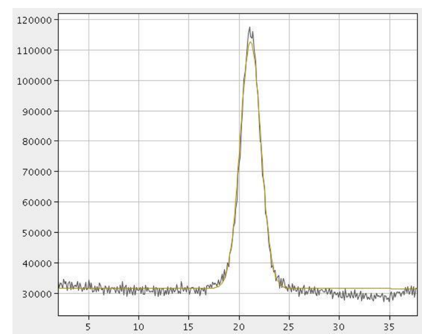
Beam 2

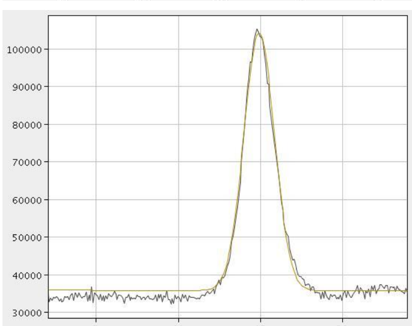




Horizontal

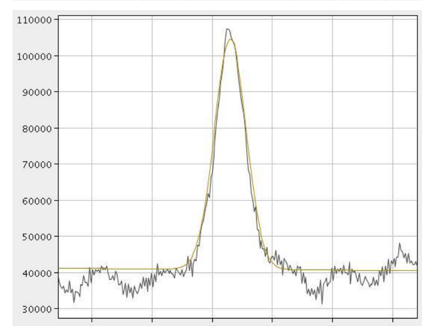
1.3 mm 1.2 mm





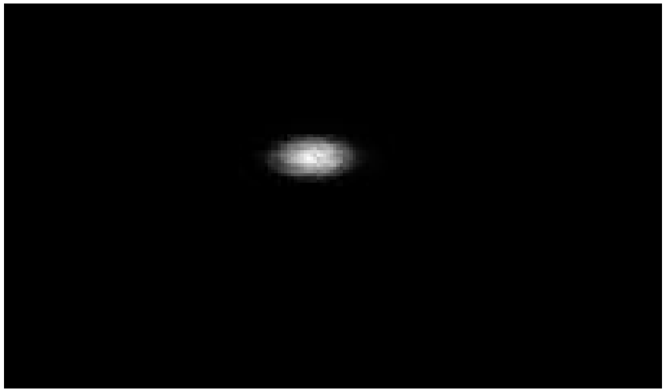
Vertical

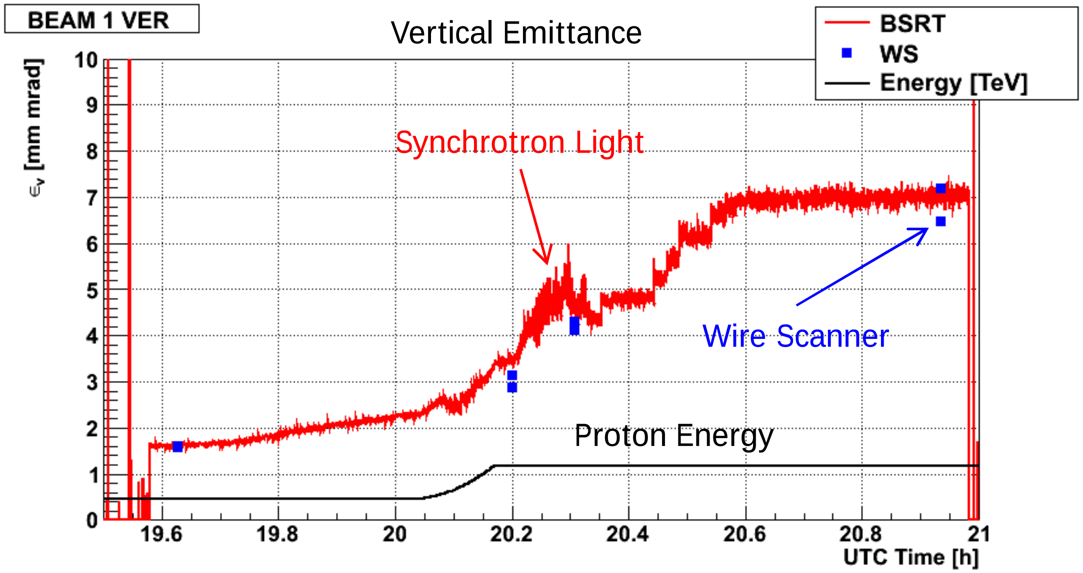
0.9 mm 1.7 mm



Light from undulator.
No filters. Open slit.

Beam 1 at 1.18 TeV

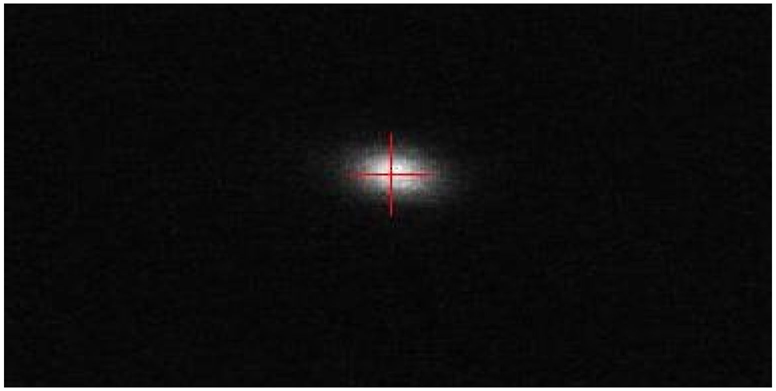




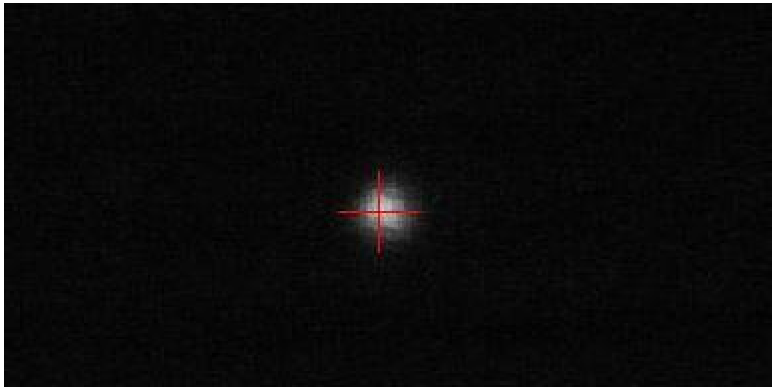
- 1.18 TeV has the weakest emission in the camera’s band.
  - Undulator’s peak has moved from red to the ultraviolet
  - Dipole’s critical energy is still in the infrared
- Nevertheless, there is enough light for an adequate image.
  - Some blurring from two comparable sources at different distances
- Vertical emittance growth before and after ramp
  - Comparing synchrotron light to wire scanner

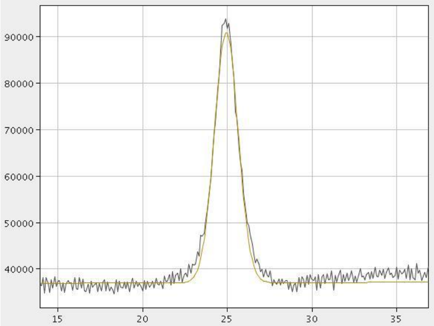
LHC Beams at 3.5 TeV

Beam 1



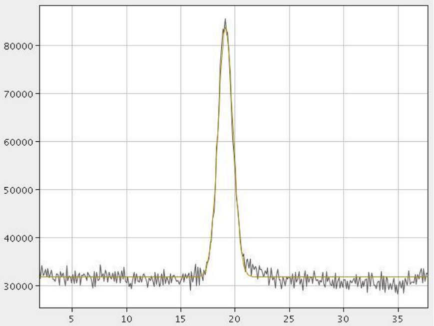
Beam 2

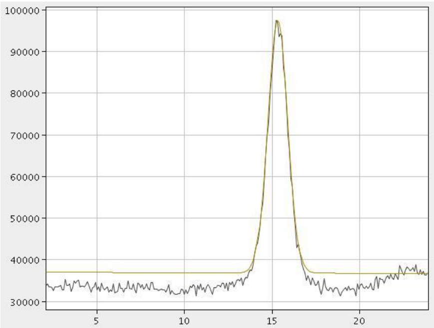




Horizontal

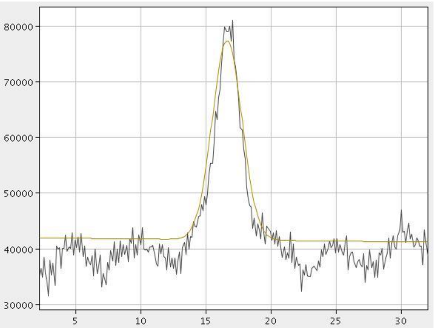
0.68 mm 0.70 mm





Vertical

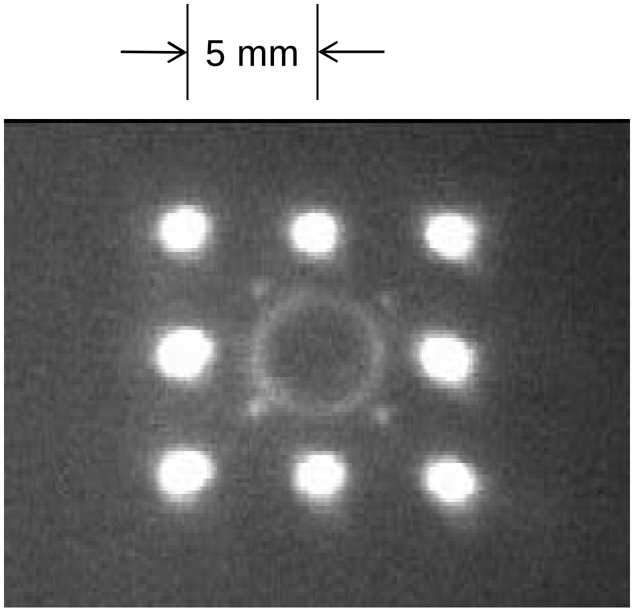
0.56 mm 1.05 mm



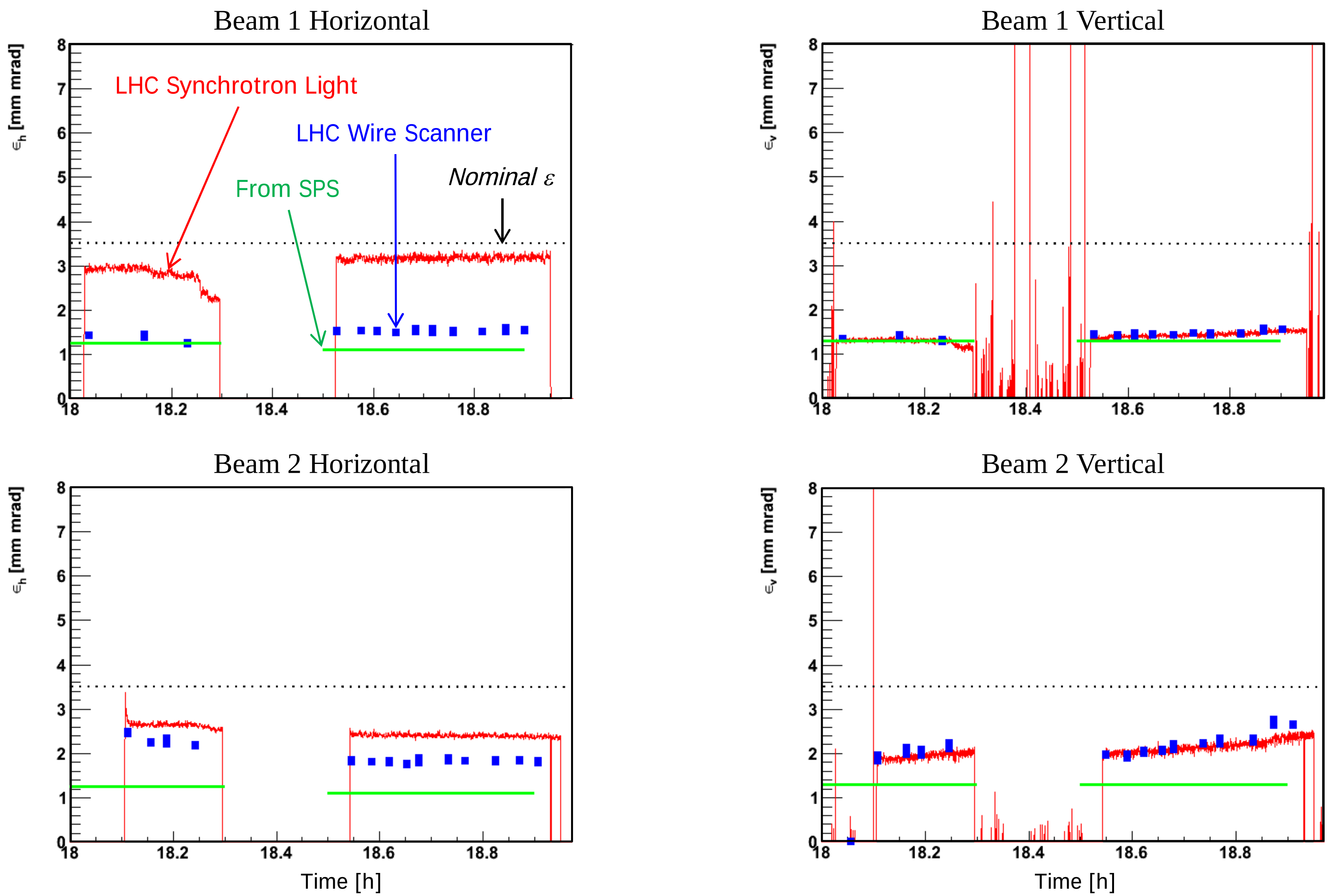
Light from D3 dipole.
Blue filter. Narrow slit.

Calibration Techniques

- Target
  - Incoherently illuminated target (and alignment laser) on the optical table
  - Folded calibration path on table matches optical path of entering light
- Wire scanners
  - Compare with size from synchrotron light, after adjusting for different $\beta_{x,y}$
- Beam bump
  - Compare bump of image centroid with shift seen by BPMs



Emittance Comparisons at 450 GeV

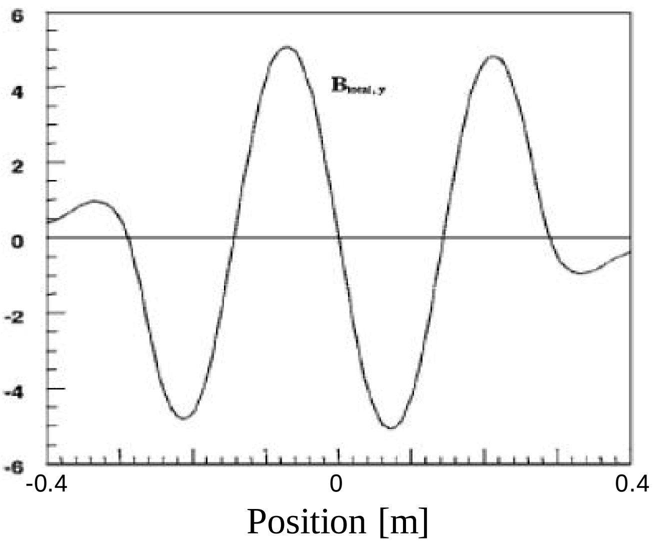


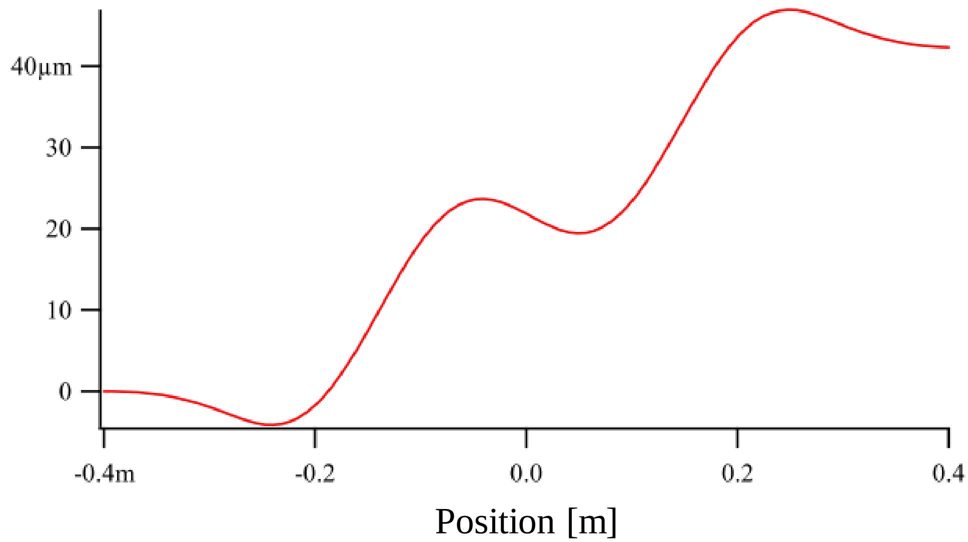
Disagreement with Wire Scanners

- The horizontal size—but not the vertical—measured with synchrotron light is larger than the size from the wire scanners.
  - Beam 1: Factor of 2 in x emittance ($\sqrt{2}$ in beam size)
  - Beam 2: Factor of 1.3 in x emittance
- β beat isn't large enough to explain this.
- But image of calibration target doesn't appear distorted in x.
- Various explanations have been considered...

x Oscillation in the Undulator

B_y [T] along Undulator Axis





- The proton beam oscillates in *x*, spreading out the source
- The end poles of the undulator are full-strength, causing the beam to shift to one side
- But the motion is too small, less than 60 µm, to explain the large *x* measurements
- And a discrepancy is seen with dipole light too.

Off-Normal Incidence in *x*?

- The rays in the LHC design are incident at 1° to the normal in the horizontal plane.
- Zemax (optics code) shows:
  - Increasing aberration with angle
  - Image stretched more in x than in y
  - But not enough to explain the factor of 1.4 in size, even using 1.5° to the normal

Zemax: Off-Normal Incidence in *x*

Rays Imaged from a Point Source

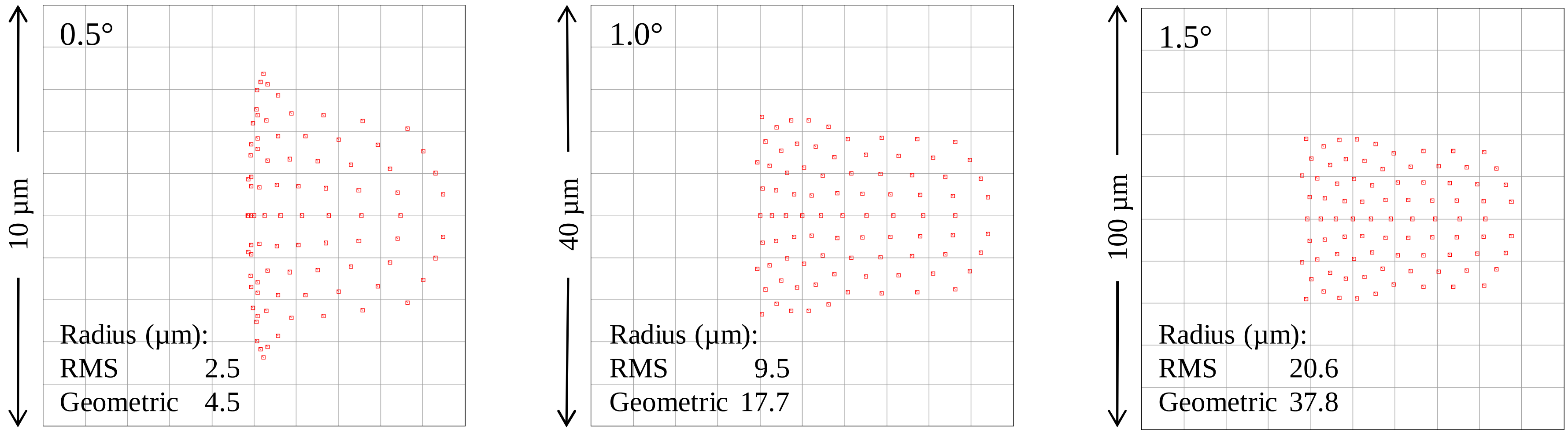
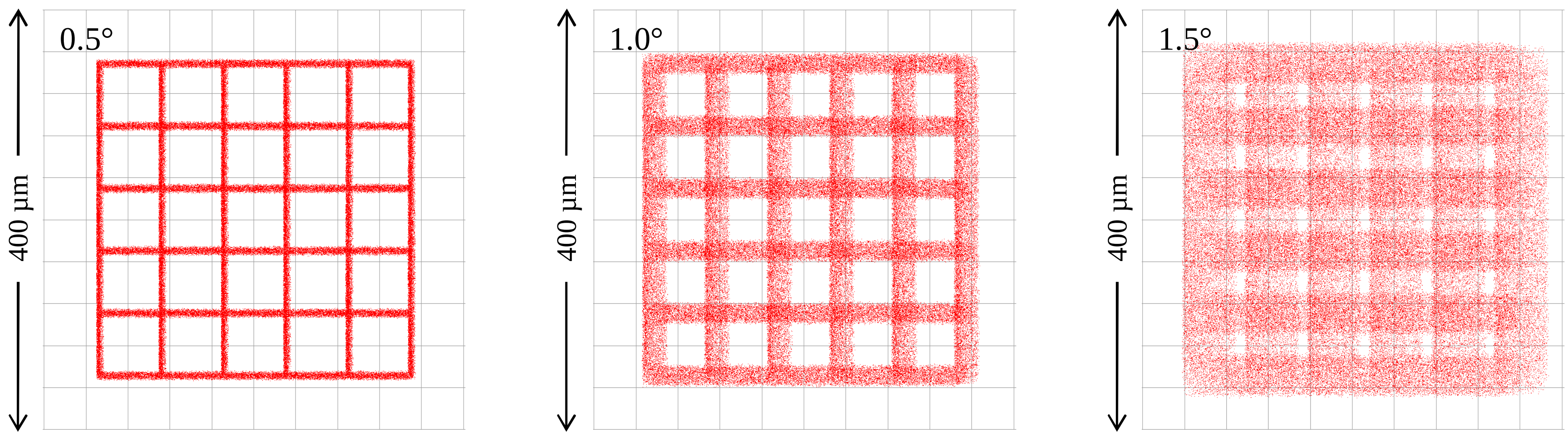


Image of a 1-mm-Wide Grid (magnification = 0.3)

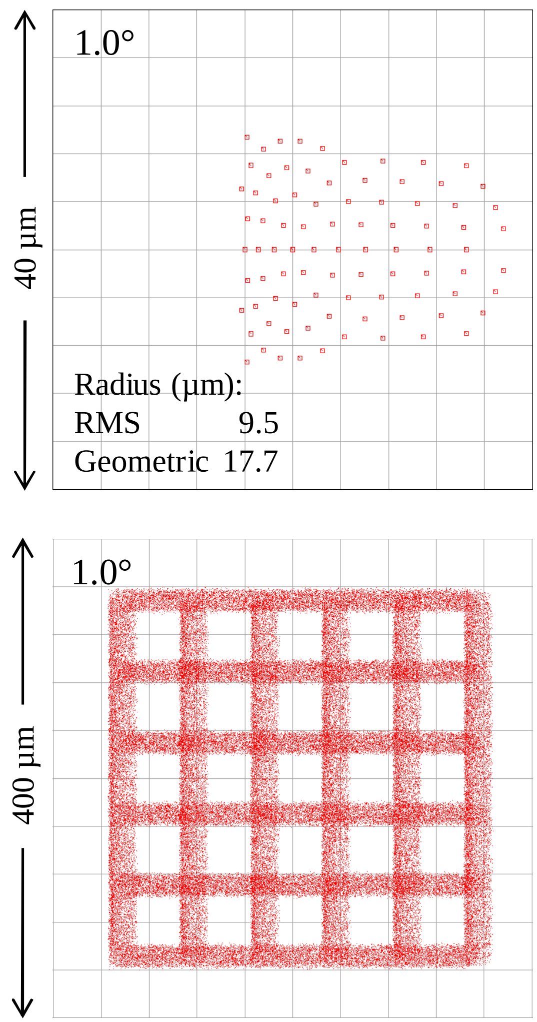


Off-Center Extraction Mirror?

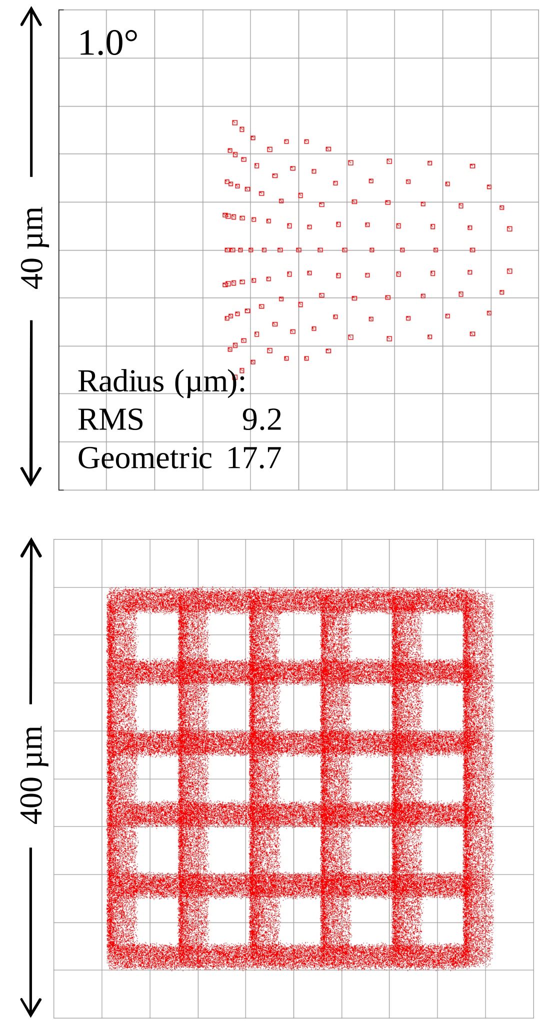
- Extraction mirror is off-center in *x*
  - Shifted to one side to keep edge away from proton beam
  - Mirror is 40 mm wide
  - Central ray from undulator hits mirror 7 mm off center
  - Does clipping on one side introduce asymmetry?
- Clipping near focusing optic should have little effect on image
  - Similar to closing the iris in a camera lens, which doesn’t change the image.
  - Zemax confirms that the effect is small.

Zemax: Off-Center Extraction Mirror

Nominal extraction mirror:
40 mm wide, 7 mm off center in *x*



Larger mirror:
60 mm wide, on center



Problem with First Focusing Mirror?

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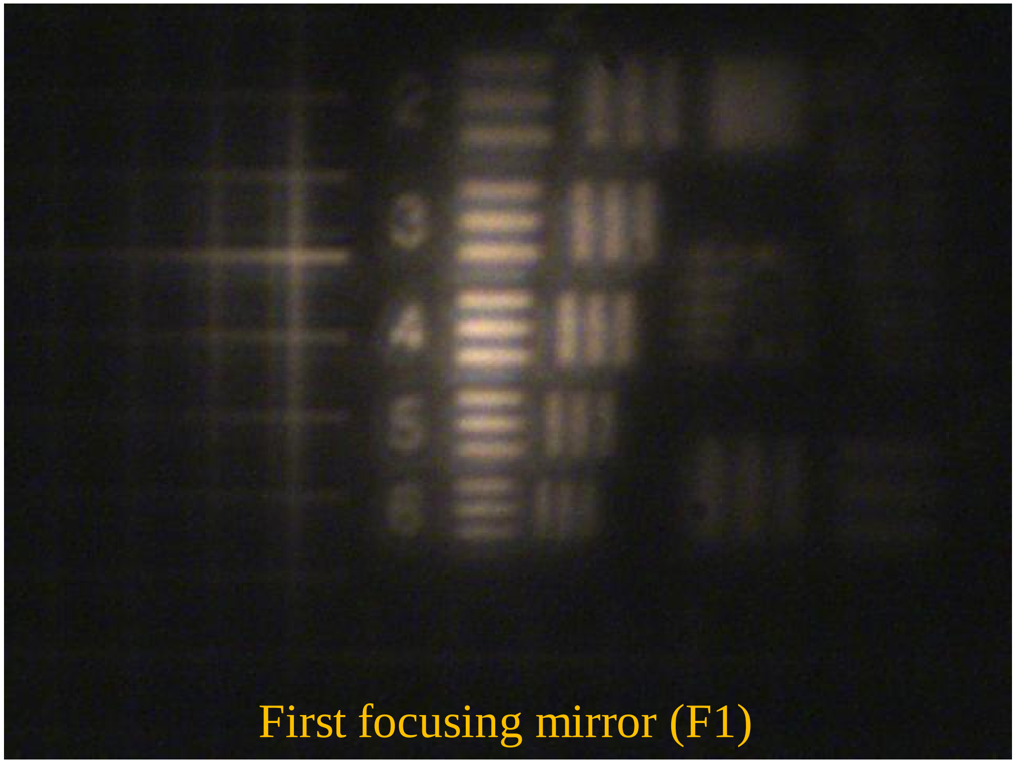
- In June 2009, I bench-tested the optical system
  - On a temporary table, since the new, large optical tables hadn't arrived
  - Found that first focusing mirrors (F1) for both beams were deformed
- Mirrors hastily replaced that summer, but without time for testing before installation in the tunnel
  - During setup in the tunnel, the focal lengths of the two new F1 mirrors were found to be out of spec (~5%) and not equal.
  - F1 had to be repositioned to maintain image location
    - Increased the angle of incidence, but remained < 1.25°
- But an F1 error should also distort the calibration image
  - Perhaps main target holes are too big, while small ones are hard to see
  - Considering a new target with slots in *x* and *y* comparable to beam size
- Discrepancy remains despite replacing mirrors in May 2010

Test Table

- My test setup in the lab had to be disassembled
  - Only enough parts for the two setups in the tunnel (for Beams 1 and 2)
  - More parts, and another table, ordered last spring
  - Table arrived in July 2010
- I visited CERN in early October to test the optical system on the new table, but it was still sitting on the loading dock.
- Crane was needed to lift table up to lab, one story above ground, and install it through the windows
  - Riggers on vacation in August
  - Delays in September
  - Table just installed in the lab last week
- So I did other tests while there…

Mirror Tests in October

- I tested both mirrors at magnification of 1 using a temporary setup
  - 1° to normal incidence horizontally, but no sign of distortion
  - Focal lengths now correct within ~1%
  - F1 (f = 4 m, D = 75 mm) sensitive to diffraction
    - Diffraction lines visible ≈100 µm away from the lines of a 500-µm grid
    - With these optics, diffraction maximum expected around $3f\lambda/D \approx 80$ µm



First focusing mirror (F1)

Observations with Beam

- Beam spot moves on B1 and B2 cameras when scanning the focus trombone
- Misalignments mean mirrors aren't filled: Increases diffractive blurring compared to design
  - May be different in *x* and *y*
  - Off-axis incidence in *x* makes it more sensitive to blurring
- An additional motorized mirror is needed at table entrance to align incoming light with table path
  - Need 2 degrees of freedom in both *x* and *y*
  - First mirror on the table has motors, but the extraction mirror in the beamline has no steering

Next Steps

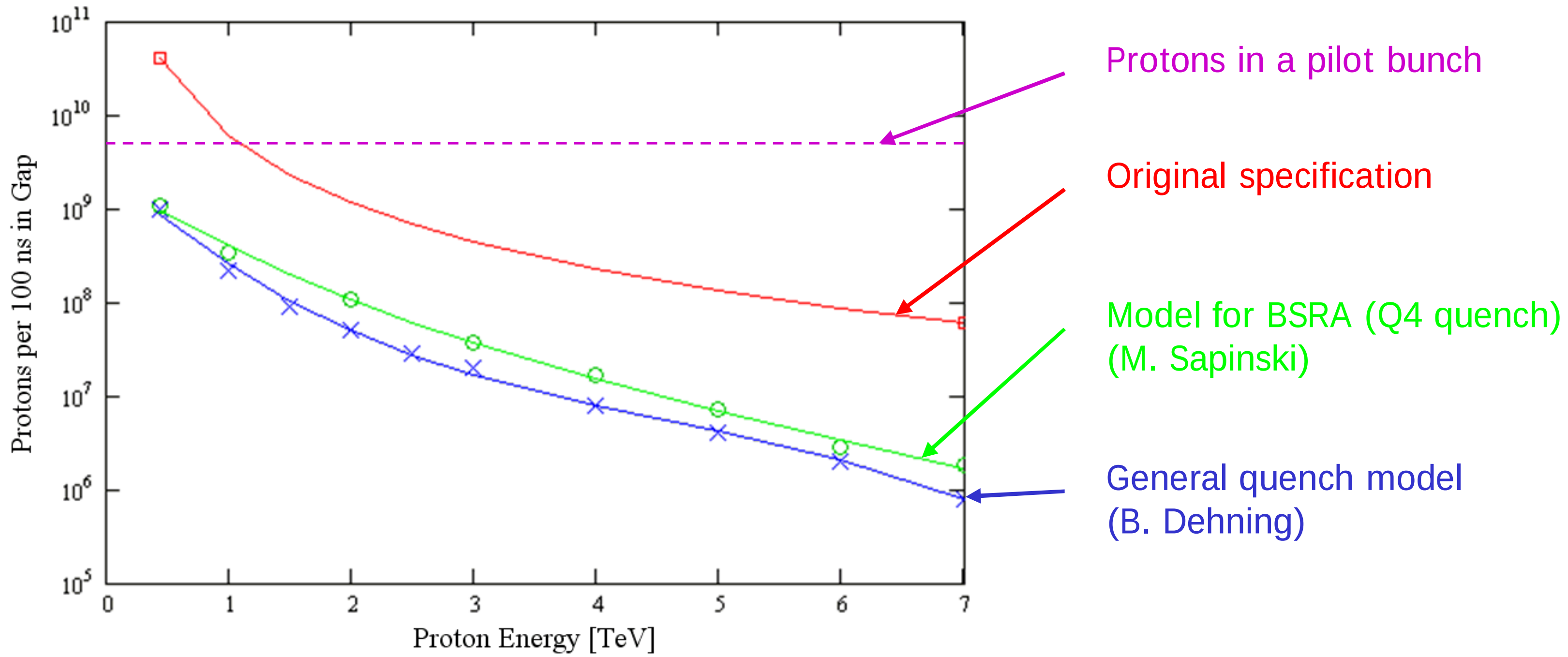
LARP

- I will go to CERN next week for 10 days, to:
  - Set up and test optical system on the lab table
  - Find optimal positions for optics
  - Develop an alignment procedure for optics in the tunnel
  - Observe first light from lead ions
- Return during the January shutdown
  - Align tunnel systems
  - Add additional steering for entering light
- Also, new cameras with fast gate on image intensifier for bunch-by-bunch measurements
  - Recently arrived and (I think) now in the tunnel

BSRA: Abort-Gap Monitor

- Gated photomultiplier receives ~15% of collected light
  - PMT is gated off except during the 3-μs abort gap:
    - High gain needed during gap
    - Avoid saturation when full buckets pass by
  - Beamsplitter is before all slits or filters, to get maximum light
- Gap signal is digitized in 30 100-ns bins
  - Summed over 100 ms and 1 s
- Requirement: Every 100 ms, detect whether any bin has a population over 10% of the quench threshold
  - Longer integration, 1 s, is needed where PMT signal is weak (protons near 1.2 TeV, ions at injection)
  - Worst case signal-to-noise is 10 for 1-s integration with a population of 10% of quench threshold

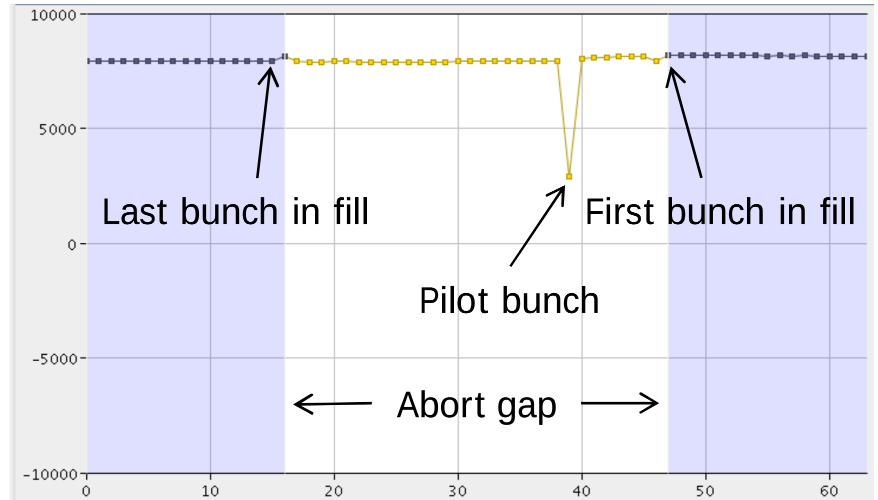
Protons/100ns at the Quench Threshold

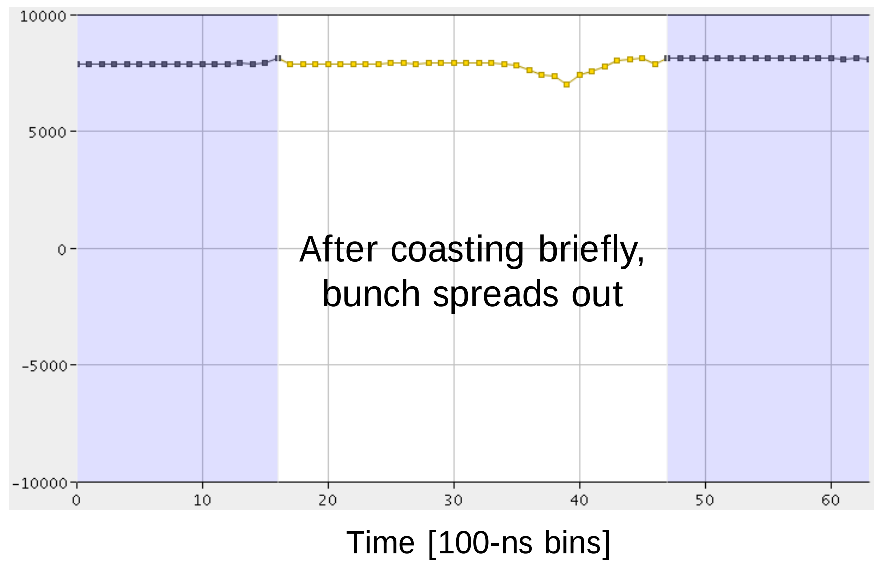


- Original thresholds, specified only for 0.45 and 7 TeV, were too generous
  - Must detect levels well below a pilot bunch
- BLM group provided improved models: using Sapinski's calculation
- Ion threshold is scaled from proton threshold:
  - Ion fragments on beam screen
  - Deposits same energy as *Z* protons at same point in ramp

Calibration of BSRA

- Inject a "pilot" bunch
- Charge measured by bunch-charge and DC-current electronics
- Attenuate light by a factor of ≈ bunch charge / quench threshold
- Move BSRA gate to include the pilot bunch
- Find PMT counts per proton (adjusted for attenuation) as a function of PMT voltage and beam energy
- Turn RF off (coast) for 5 minutes to observe a small, nearly uniform fill of the gap
  - Useful to test gap cleaning…





2009 Dec 16: Test of Abort-Gap Cleaning

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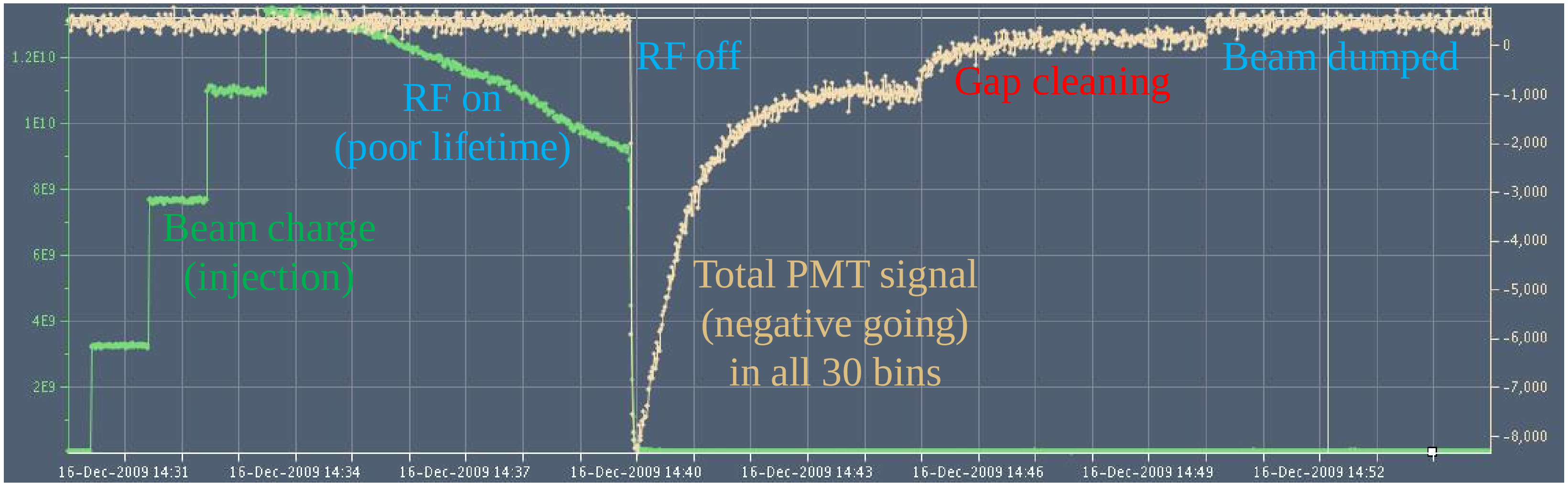
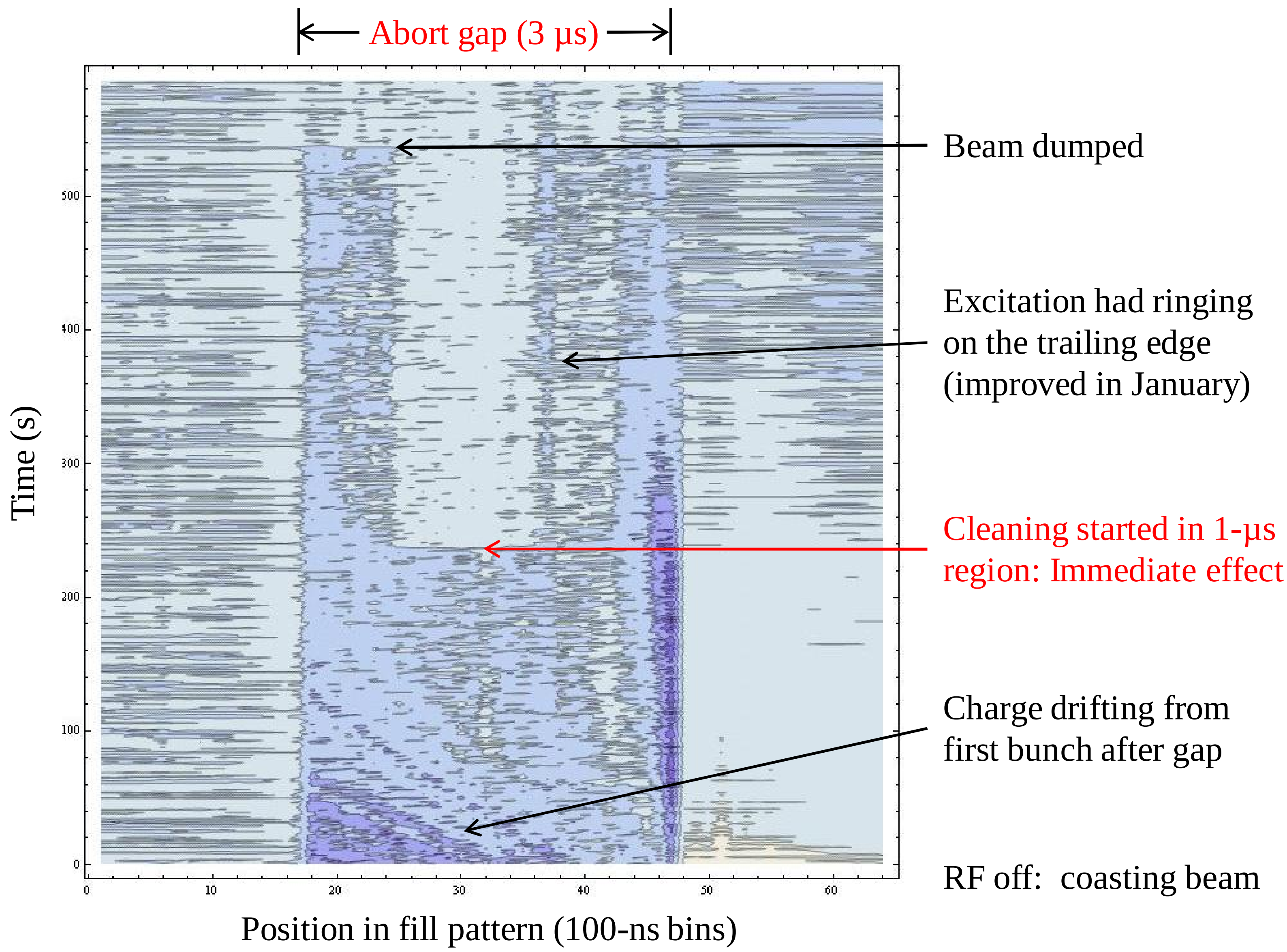
- Injected 4 bunches into Beam 2
  - Poor lifetime, but not important for this experiment
- Turned off RF, and coasted for 5 minutes
- Abort-gap monitor detected charge drifting into the abort gap
- Excited 1 μs of the 3-μs gap at a transverse tune for 5 minutes
  - How well did this work? Look inside the gap...



0 25 minutes

Charge in Abort Gap



2010 Sep 30: Test with Improved RF Pulse

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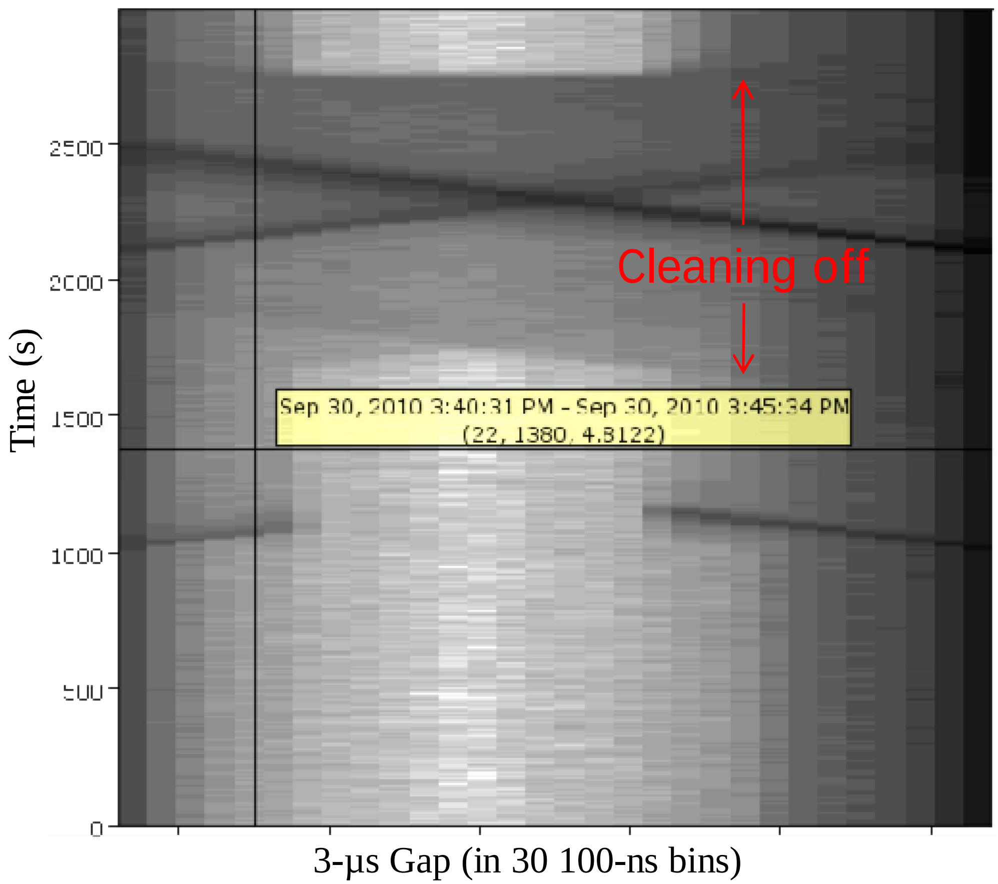
- Injected 2 bunches (1 and 1201), 3 μs apart; no ramp
  - Another test at 3.5 TeV took place on 2010 Oct 22
- Cleaning pulse applied between the bunches at the *x* or *y* tune
- RF voltage reduced in steps; debunched protons drift into gap



Cleaning resumed.

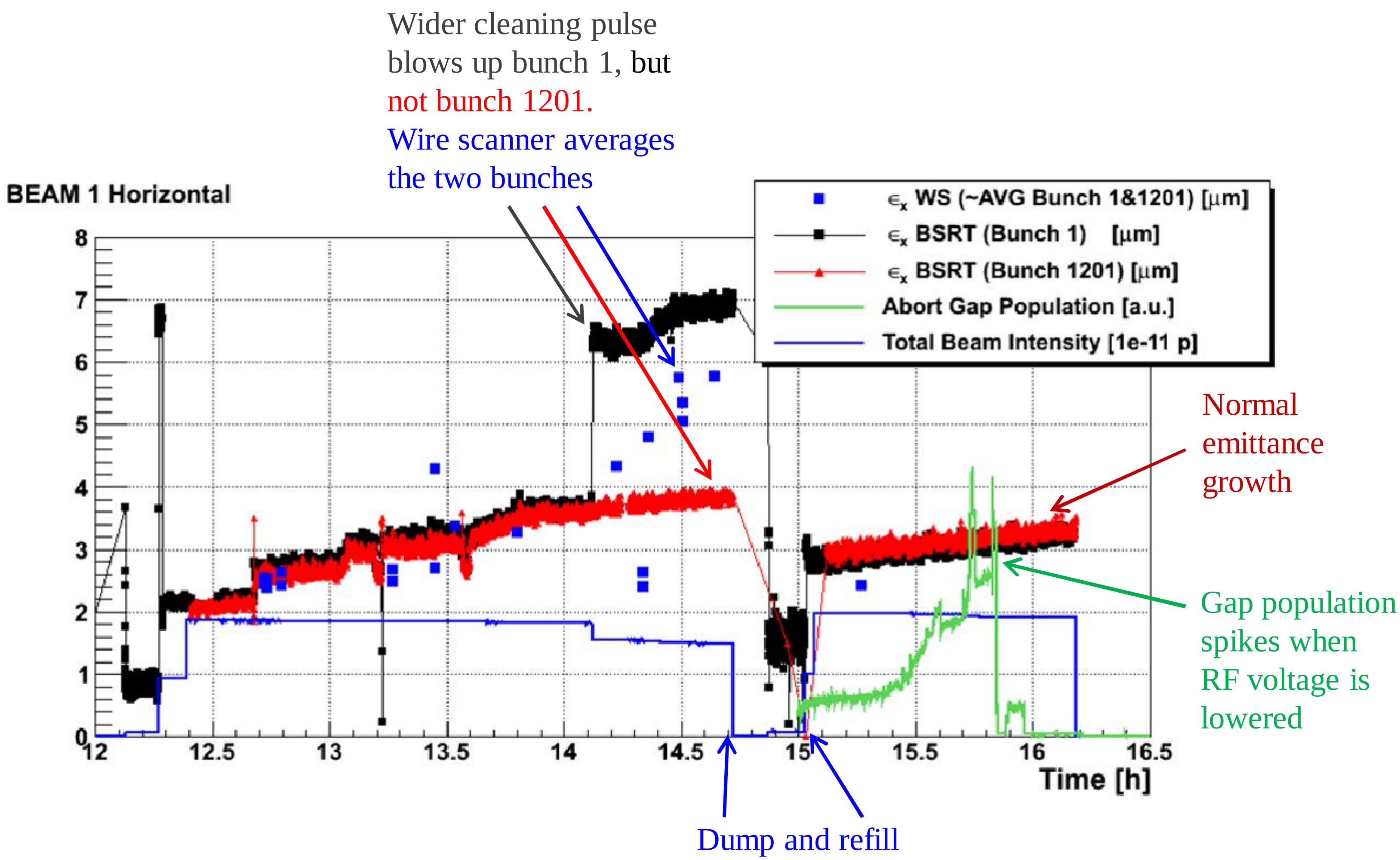
Voltage lowered by another step.

Cleaning turned off.
Protons repopulate cleaning region.

RF voltage lowered.
Low/high momentum protons drift into gap from bunches on left/right.
Encounter cleaning region.

Darker = More protons

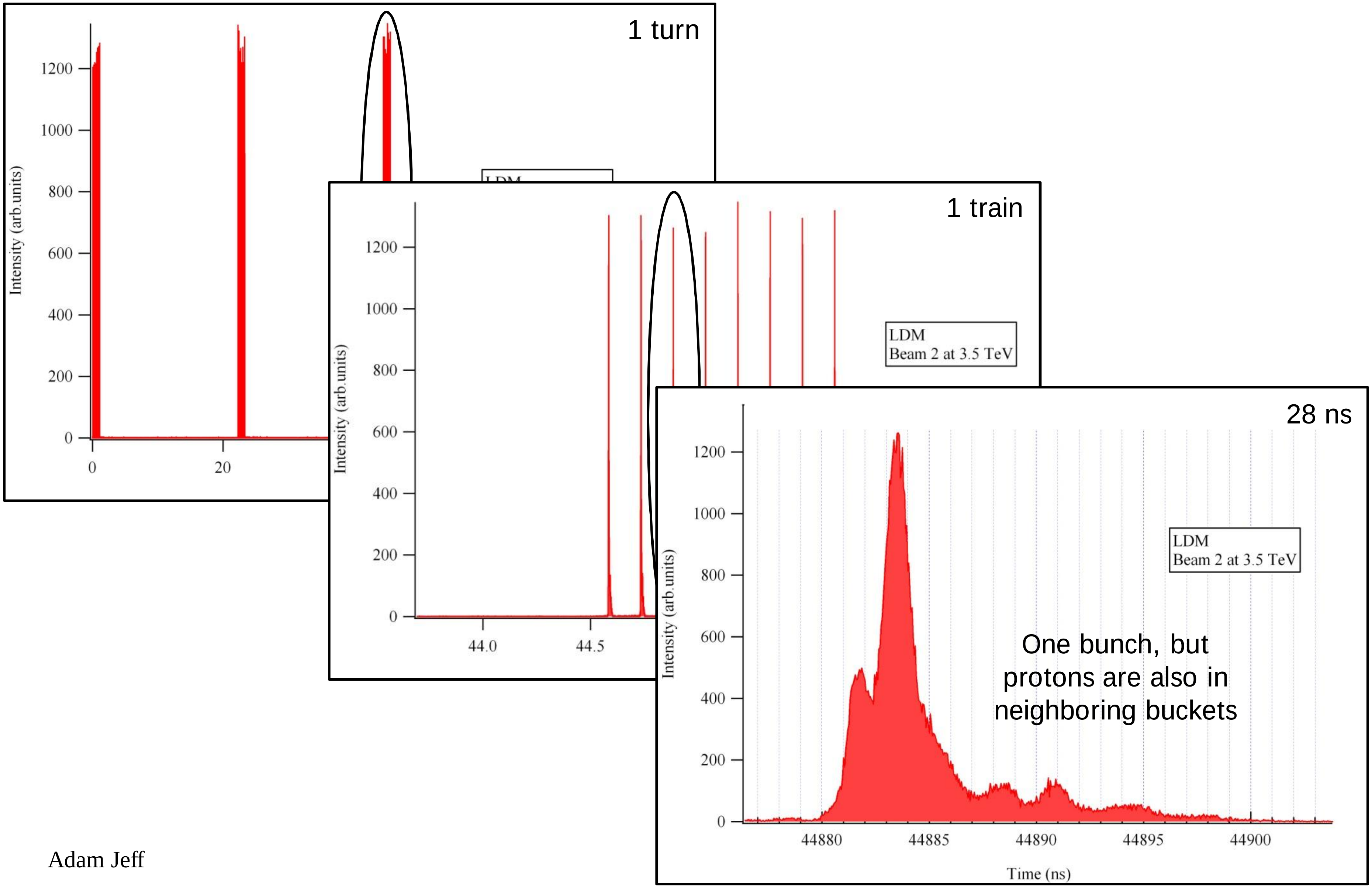
Emittance Growth during Cleaning



Longitudinal-Density Monitor

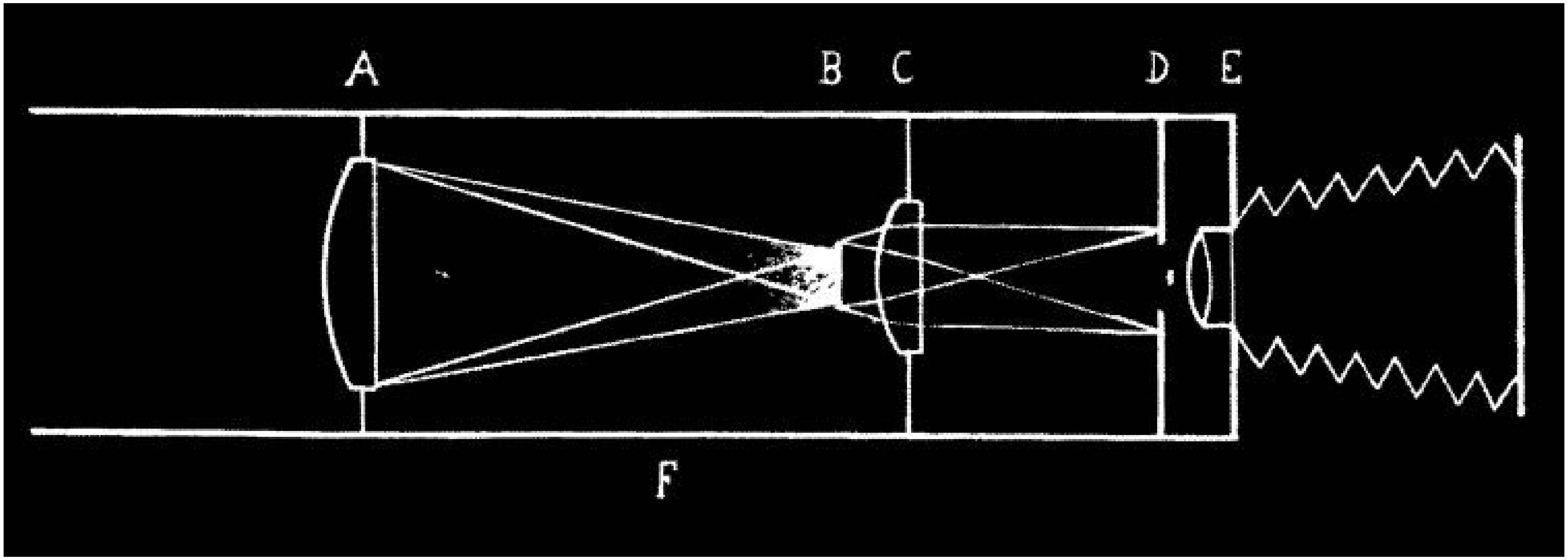
- Monitor is being developed by Adam Jeff
  - Photon counting using an avalanche photodiode (APD)
  - Fiber collects 1% of the BSRT's synchrotron light
    - Sufficient signal: 10^3 photons/bunch at 1 TeV, and 3×10^6 for $E \geq 3.5$ TeV
    - Requires corrections for deadtime and pile-up
  - Measure time from ring-turn clock to photodiode pulse
  - Accumulate counts in 50-ps bins
  - One unit has been installed on Beam 2 for testing
- Modes:
  - Fast mode: 1-ms accumulation, for bunch length, shape, and density
    - Requires corrections for APD deadtime and for photon pile-up
  - Slow mode: 10-s accumulation, for tails and ghost bunches down to 5×10^5 protons (4×10^{-6} of a nominal full bunch)
    - Only 1 photon every 200 turns
  - May require 2 APDs: APD for slow mode gated off during full bunches

Testing the Longitudinal-Density Monitor



Observing the Solar Corona

- 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

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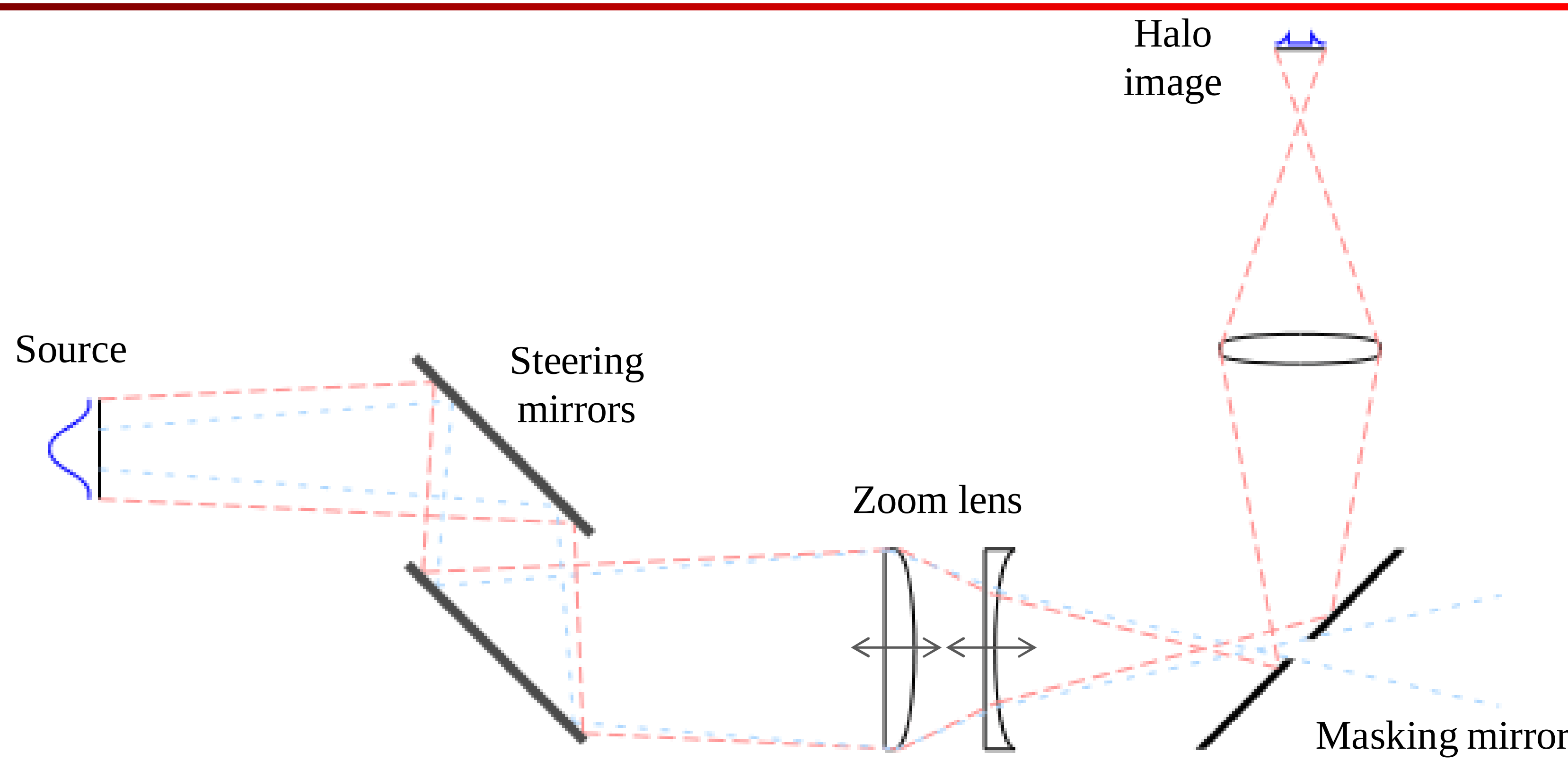
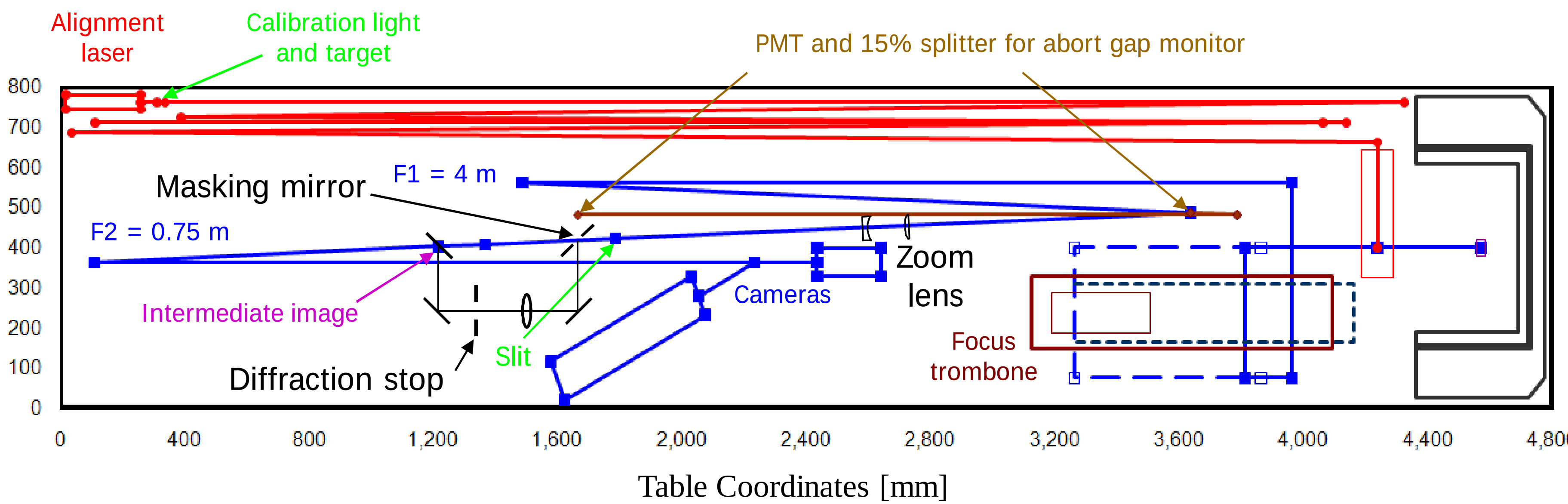
- Halo monitoring is part of the original specification for the synchrotron-light monitor
  - LARP's involvement in both light monitors and collimation makes this a natural extension to the SLM project
- But the coronagraph needs some changes:
  - The Sun has a constant diameter and a sharp edge
  -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

Fixed Mask with Adjustable Optics



- SLM images a broad bandwidth: 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

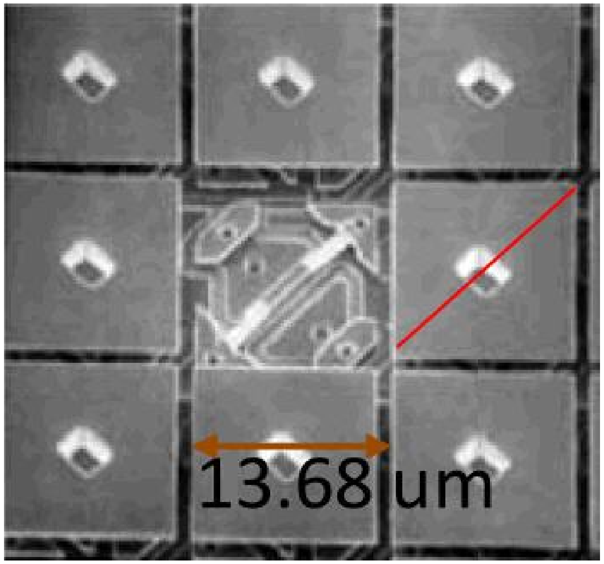
Halo Monitor with Masking Mirror

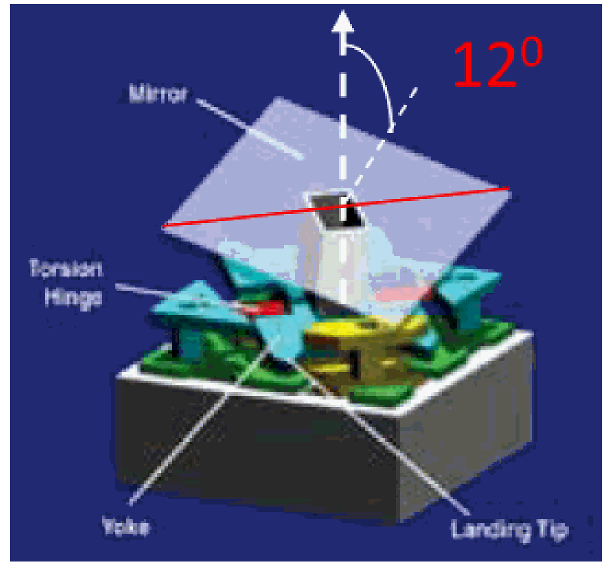


During halo measurements:
Insert zoom lens, masking mirror, and return mirror.

Digital Micro-Mirror Array

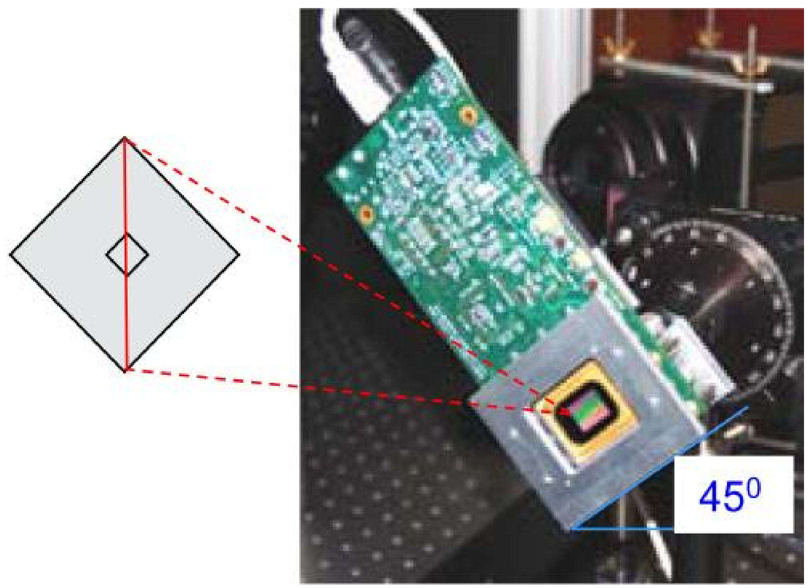
1024 × 768 grid of 13.68-µm square pixels





Pixel tilt toggles about diagonal by ±12°

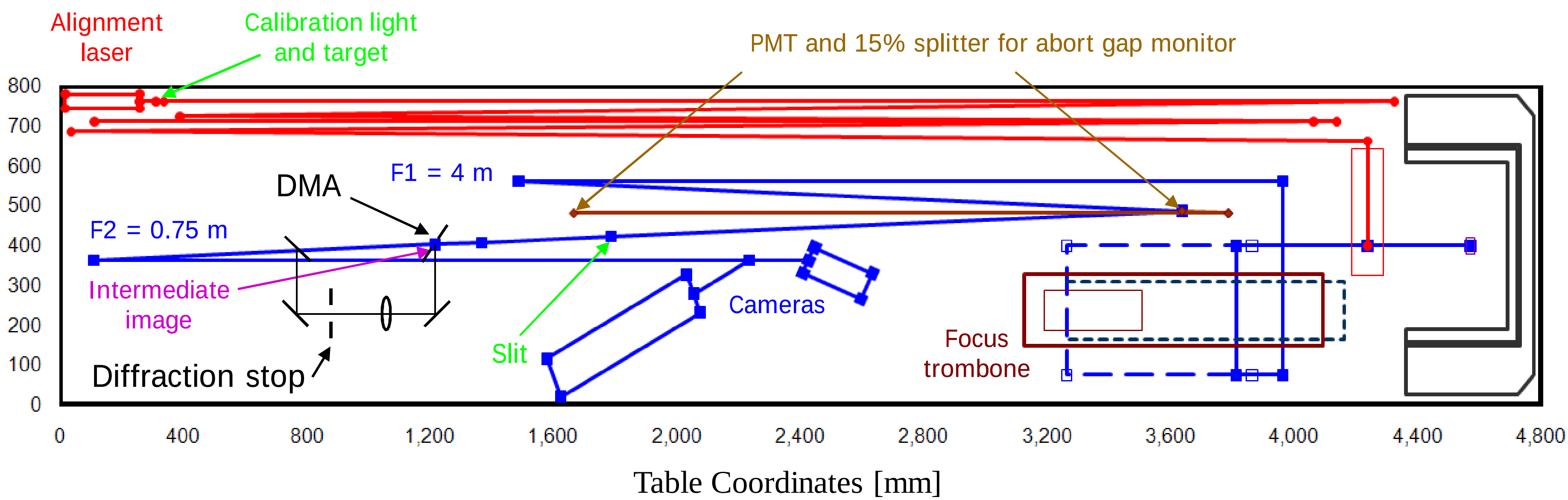
Mirror array mounted on a control board, which is tilted by 45° so that the reflections are horizontal.



Digital Micro-Mirror Array

- Advantages:
  - Flexible masking due to individually addressable pixels
    - Adapts well to flat beams in electron rings
    - But the LHC beams are nearly circular
- Disadvantages:
  - 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
    - Camera face must tilt by 24° to compensate for tilt
      - Known as Scheimflug compensation

Halo Monitor with Digital Mirror Array



During halo measurements:
Insert DMA and return mirror; rotate camera.

Summary

- Synchrotron light is in routine use for observing the beam size and for monitoring the abort gap.
- Work to improve the horizontal resolution, using duplicate optics in the lab, will commence next week.
- Two tests of abort-gap cleaning have been successful, with the abort-gap monitor showing changes in the gap population.
- A longitudinal-density monitor is being developed.
- Tom Markiewicz and I have begun discussing a LARP project to add a halo monitor. First tests could measure the halo on SLAC's SPEAR-3 ring, where access to the light is easy.