Time-Resolved Measurements

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Beam Diagnostics Using Synchrotron Radiation:
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Considerations

- Time scales
  - Picoseconds to seconds
- Transverse versus longitudinal
  - The electron bunch is, of course, three dimensional.
  - So far we've looked at imaging the beam's transverse (*xy*) projection, with typical scales of 0.1 to 1 mm RMS.
  - It's longer in *z* (1 cm), but it flashes by in 30 ps (c = 0.3 mm/ps)
    - Short time scale requiring a special and expensive camera
- Bunches or full train
  - Measure individual bunches, or a composite of all bunches in the ring?
- Techniques
  - Choose the right tool for the purpose.

Time Resolution Can Mean…

Time Scale	Purposes	Some Techniques
ps	Bunch length	Streak camera (synchroscan); fast photodiode
ns	Size or phase variations along a bunch train	Streak camera (dual-axis mode); photodiode; gated camera
μs	Turn-by-turn changes in a bunch or train; injection and damping.	Gated camera plus rotating mirror; streak camera
ms	Instabilities and beam aborts	Video (still images and movies); gated camera with mirror
s	Correlations and drift in beam size, for full train or individual bunches	Video camera, gated camera, moving mask

Beam-Abort Movies: Instant Replays

- Using the computer of the synchrotron-light monitor:
  - The SLMs of PEP-II use multiplexed 4-channel frame grabbers (beam image, interferometer, alignment…).
  - Software records a 1.5-s (45-frame) movie every time it switches to the beam-image camera.
    - Disadvantage: Not always recording this channel during the abort.
  - Previous movie is overwritten, except after an abort.
    - Then the movie is saved to disk.
- Using a digital video recorder in Main Control:
  - 4-input DVR with 24-hour capacity.
    - Records light and x-ray images.
    - Advantage: Always available after the abort.
    - Disadvantage: Some resolution loss from cable-TV system and from compression of 4 signals onto one recorded video track.

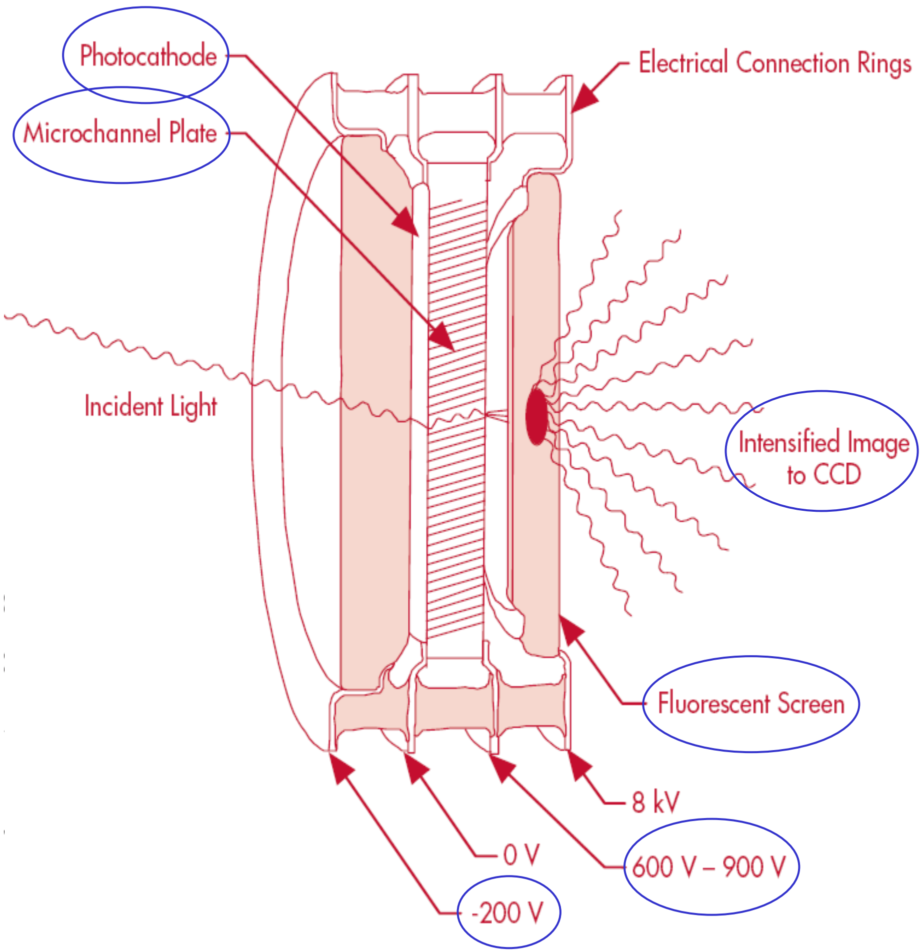
Movie Time

- Welcome to PEP-Flix, your movie source.

Video Cameras vs. Gated Cameras

- Video cameras have frame rates of 30 (or 25) Hz.
  - Give transverse (*x* and *y*) images of the beam.
  - Some have electronic shutters down to 0.1 ms.
- Cameras are available with a much faster gate, one that can open and close in 2 ns.
  - Comparable to bucket spacing: Can capture single-bunch images in a full ring.
  - Can be gated repeatedly on successive turns.
  - Image intensifier gives sufficient brightness.
- How does this camera work?
- What can we do with one?

Front End of the Gated Camera

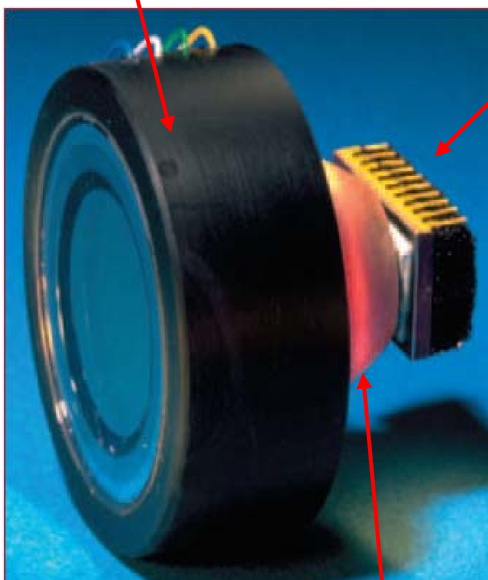


- Photocathode:
  - Converts light to electrons.
- Microchannel plate (MCP):
  - Intensifies the image.
- Fluorescent screen:
  - Converts the intensified image back to light.
- CCD camera (not shown):
  - Records the image.
- Photocathode bias voltage:
  - Can be gated at high speed.
- MCP bias:
  - A secondary, slower gate for background reduction.

Microchannel Plate

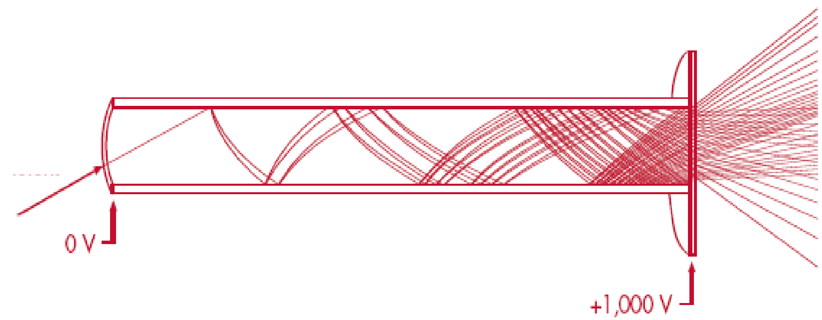
MCP

CCD



Fiber coupling from fluorescent screen to CCD

One channel amplifying an incoming photoelectron by secondary emission on the inside wall of the channel.



Walter will present the details of operating our camera and its software in the next lecture.

Turn-by-Turn Transverse Imaging

- A snapshot of one bunch on a single turn is interesting, but what if we want to:
  - Image the transverse profile of a single bunch:
    - Over many turns
    - In a full ring
  - See changes over 100 or 1000 turns during:
    - Steady running
    - Injection, as charge is added to the bunch
      - Investigate injection backgrounds
    - Instability, perhaps leading to a beam abort
- Just take consecutive images with the gated camera?
  - Image readout is much too slow: a few Hz.

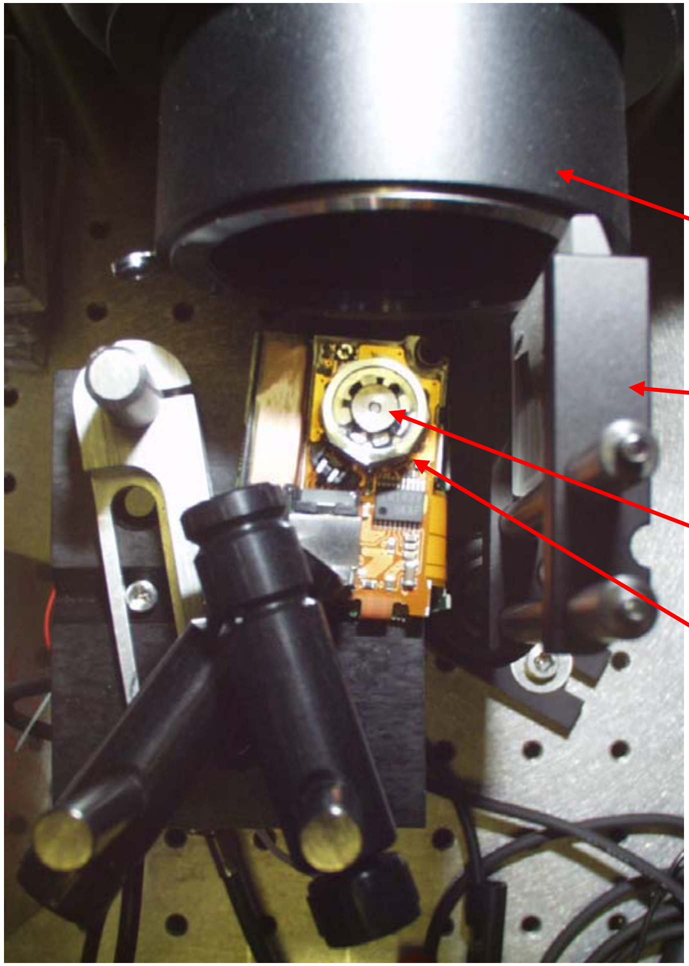
Sweep Images across Gated Camera

- Project the transverse image onto one axis at a time.
  - Reshape the beam ellipse with cylindrical lenses.
    - Different horizontal and vertical magnifications.
    - Lenses turn the ellipse into a thin vertical stripe.
  - Split the light into two paths, rotate one, form two images.
    - One shows a projection along the beam's x axis, another along y.
    - Image these projections onto gated camera at different heights.
- Retrigger the gated camera on one bunch over many consecutive turns (or every n^{th} turn).
- Rapidly rotating mirror sweeps images across camera.
  - One camera readout then captures many turns.

A Rotating Mirror? For Microseconds?

- Can a mirror really turn fast enough to be useful? Consider this example:
  - Width of photocathode — 12 mm
  - Distance from mirror to cathode — 50 mm
  - Change in mirror angle to span cathode — 6.8^{o}
  - One ring turn in PEP-II — 7.34 μs
  - Revolution rate to sweep across the cathode in 100 turns — 26 Hz
- This is a realistic rate for a small mirror. In fact, these are very common items…

A Dissected Bar-Code Scanner



Quick proof-of-principle test in 2004, using the PEP-II low-energy ring and an ordinary supermarket scanner.

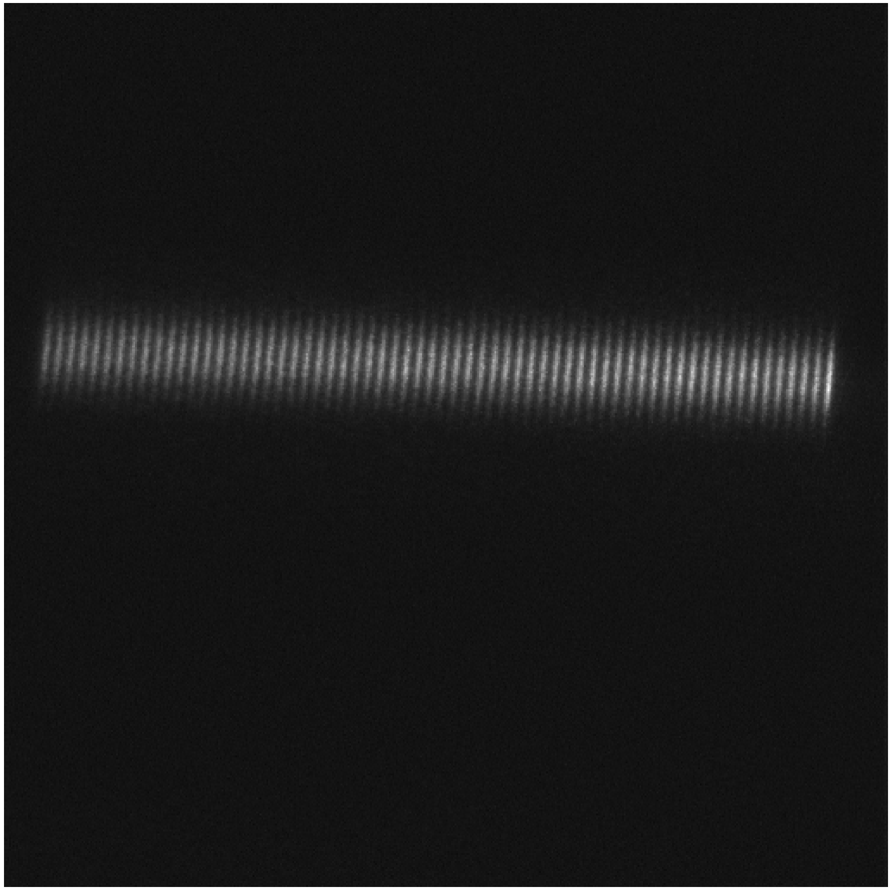
Aperture of gated camera

Cylindrical lens for
horizontal demagnification

DC motor with servo

Rotating octagonal mirror,
3 mm high, 13 mm across

2004 July 30: 64 Turns



0 ——→ 460 μs

- Cylindrical-lens imaging:
  - Squashed the beam's image horizontally, to let us resolve individual turns.
  - Maintained its vertical size, to let us observe any changes in that direction from turn to turn.
- Image rotation in the tunnel:
  - Transport periscopes turn the image by 90º
  - This layout displays changes in the *x* size of the positron beam.

What Needed Improving?

- Cannot be triggered to take data after injection.
  - Motor is free running, not synchronized with PEP.
  - Scanner issues a timing pulse on each turn of the polygon.
    - Used to trigger the camera.
    - Motor starts camera, rather than a PEP-II timing signal.
- The polygon is too small—3 mm high—while the camera's photocathode is a 12.4-mm square.
  - Needs demagnification vertically, which then requires even more demagnification horizontally.
- Only measures one axis of the beam.
- Dissected scanner can't be mounted rigidly.

Scanning Galvanometer

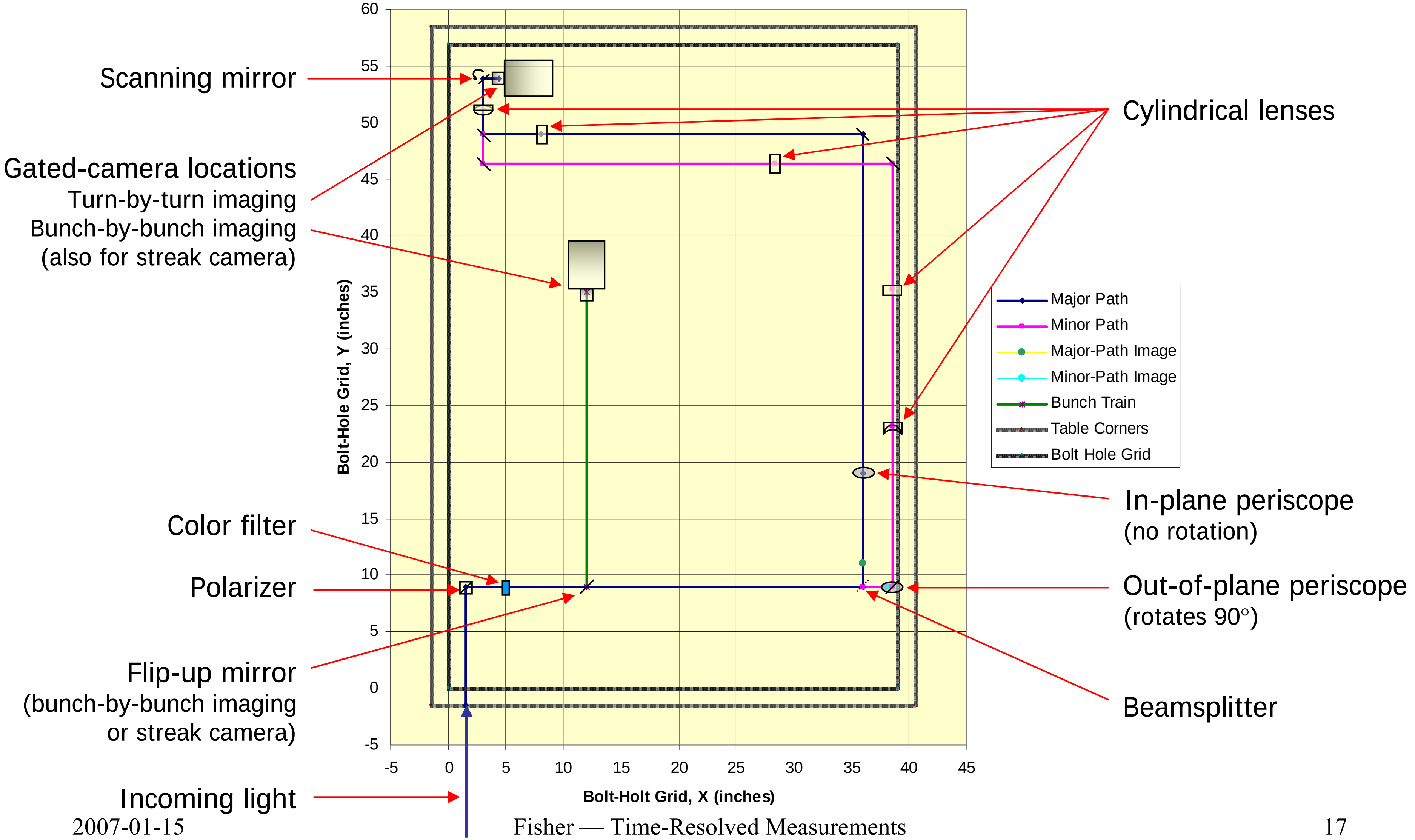
GSI Lumonics

- Mirror on a servo motor
  - Used for laser scanners, often in pairs for raster scans.
  - Built for stable mounting.
- Driven by a ramp waveform
  - Triggered by PEP timing.
- A large but thin mirror:
  - 14.2 mm high × 8.7 mm wide
  - Mounts on VM500 motor (smallest one in photo).
  - Still fast enough for our sweep.

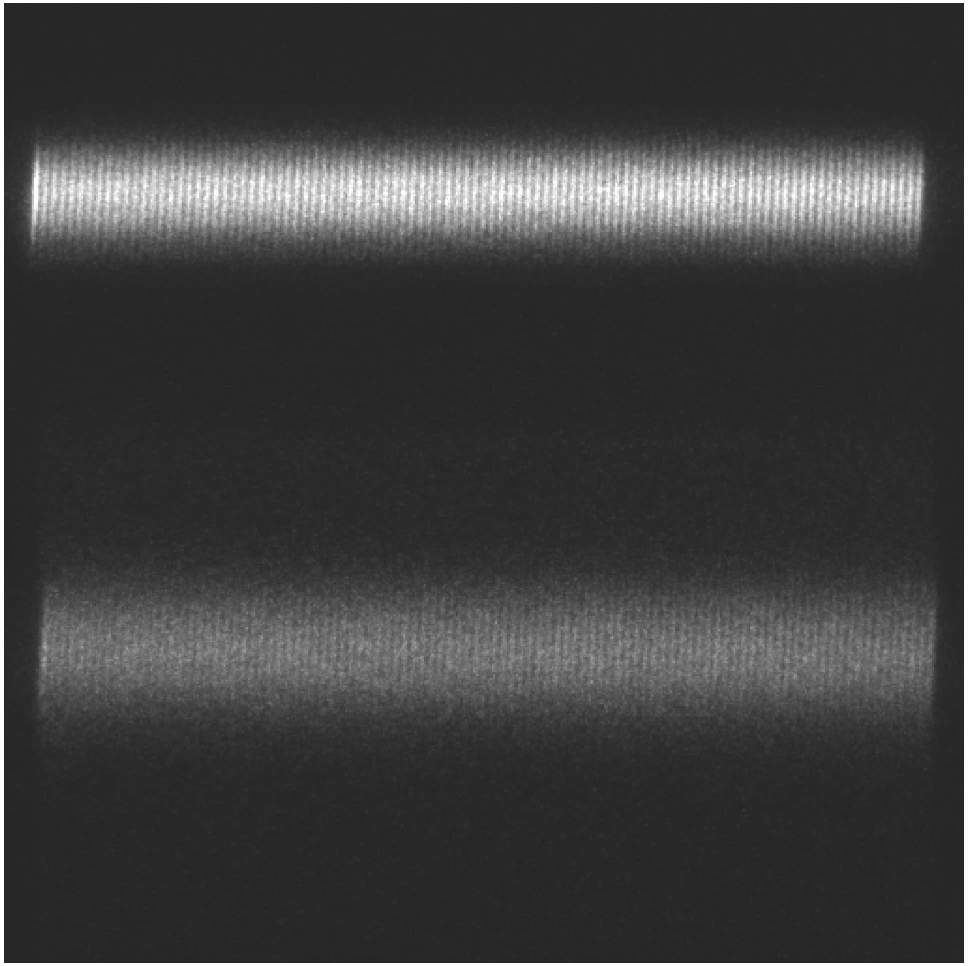
Measuring *x* and *y* Simultaneously

- Split the light, then rotate one beam by 90°.
- Image one path onto the top half of the camera, the other onto the bottom half.
  - Two sets of stripes swept out across the camera.
  - Different magnifications needed for each path.
  - Major-axis projection of beam ellipse viewed on top half of video image, minor axis on bottom.
  - Paths must be equal within 2 ns to catch the same bunch in the camera's gate.
- New optics installed in 2005.

Optical Table Layout for LER Hutch



2005 Oct 8: Stable Beams, 100 Turns



Major (x) axis of the beam

Minor (y) axis

0 → 730 μs

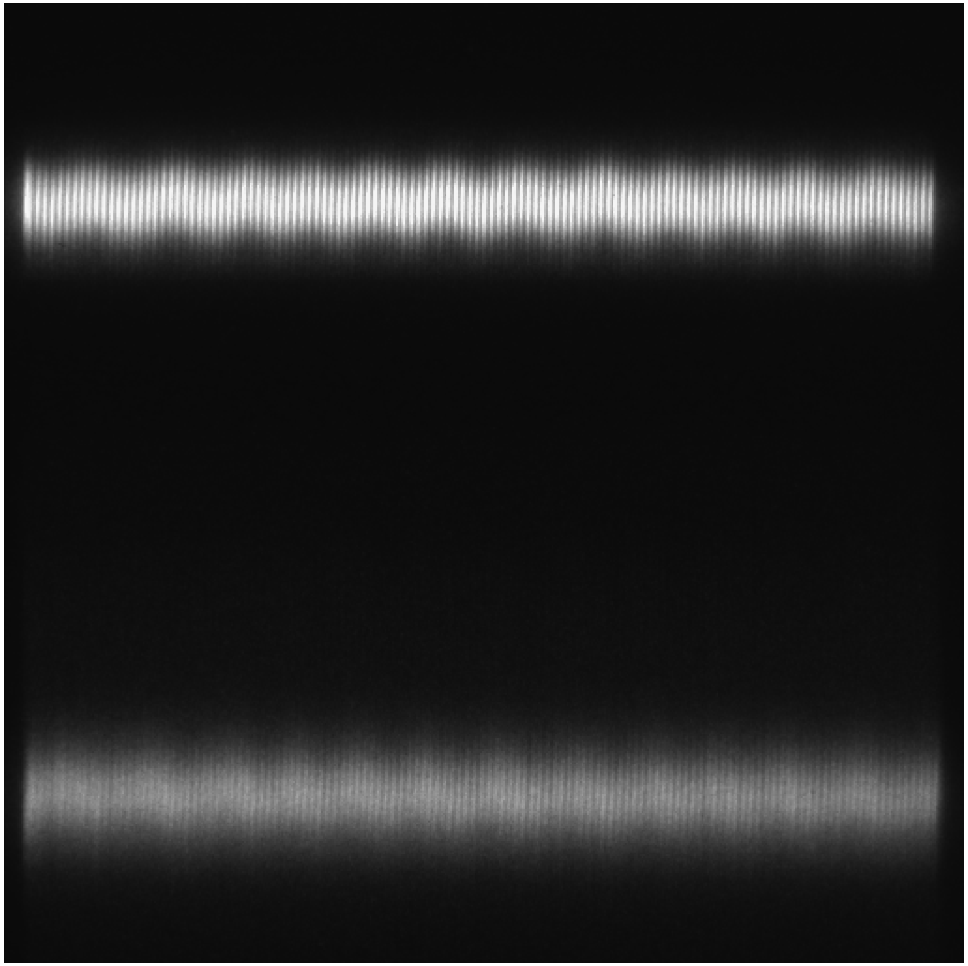
Measuring Beam Aborts

- Triggering to view milliseconds before an abort:
  - Image one bunch every n^{th} turn over a longer time.
    - Image every 80^{th} turn (587 μs) 125 times = 10,000 turns (73 ms).
  - Repeat as fast as possible.
    - 2 Hz due to camera's readout and transfer to computer.
    - Chance of capturing any one abort is then 73/500 = 15%.
  - Disable camera's trigger on an abort.
    - Trigger the "fast" DG535 (1 of 2 needed) on the ring-turn clock.
    - Abort logic signal controls the Trigger Inhibit of the "slow" DG535.
    - You'll see how this works in this afternoon's lab.

2005-12-13: LER Transverse Instability

LER oscillating following a HER abort.

Taken while monitoring beam aborts with a 73-ms time scale.

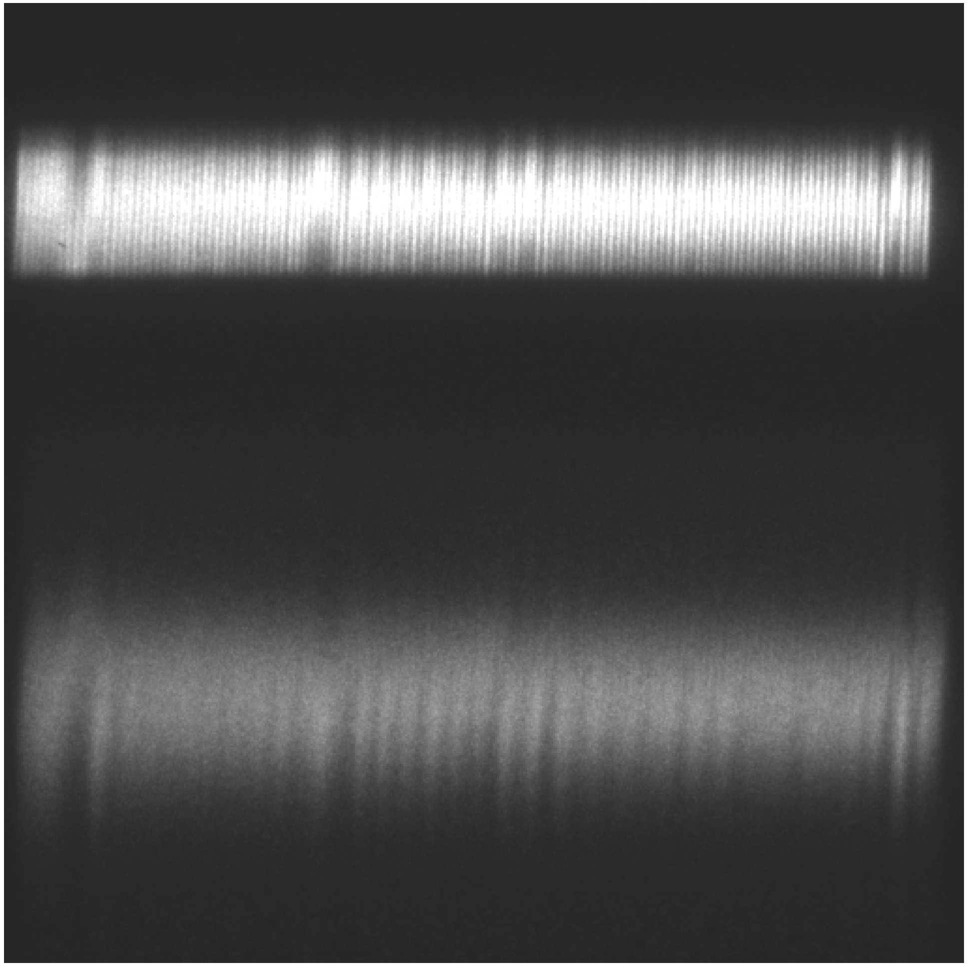


Major (x) axis of the beam

Minor (y) axis

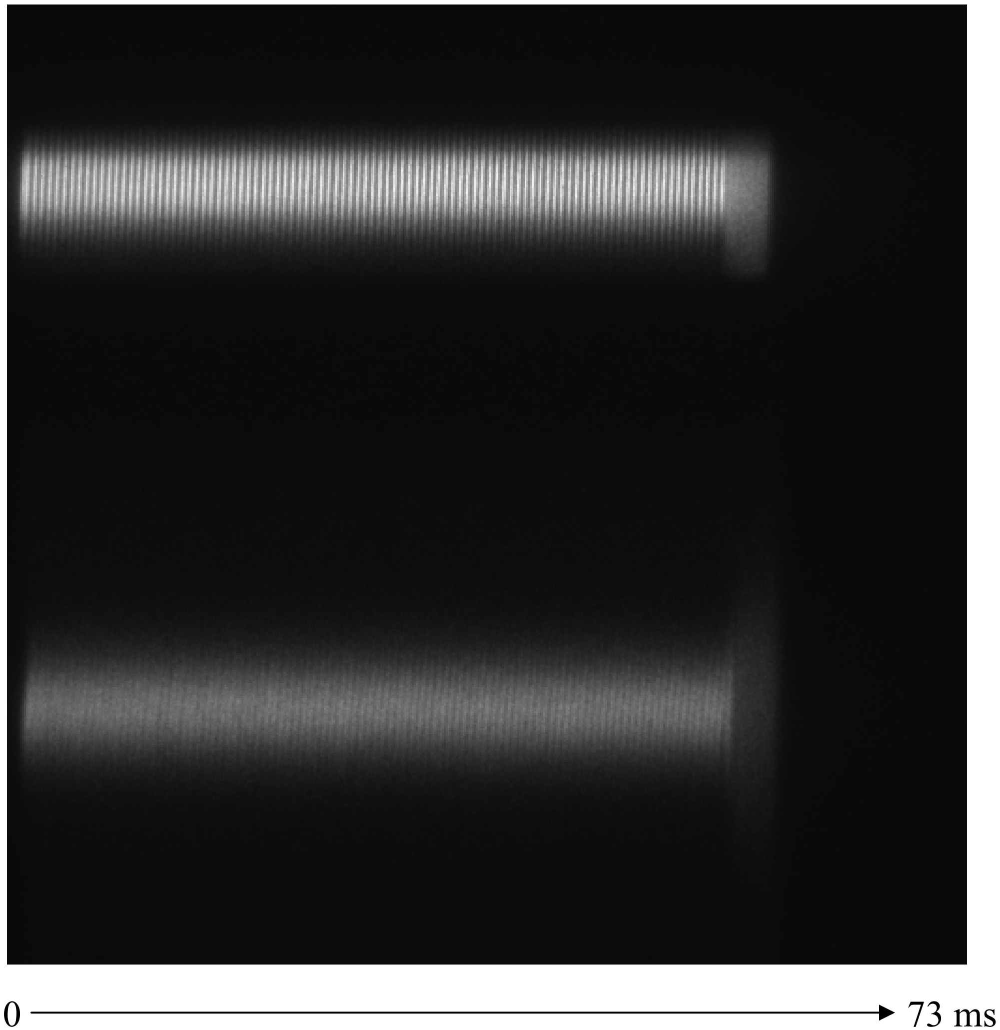
0 → 73 ms

2005-12-07: LER Bursting Instability



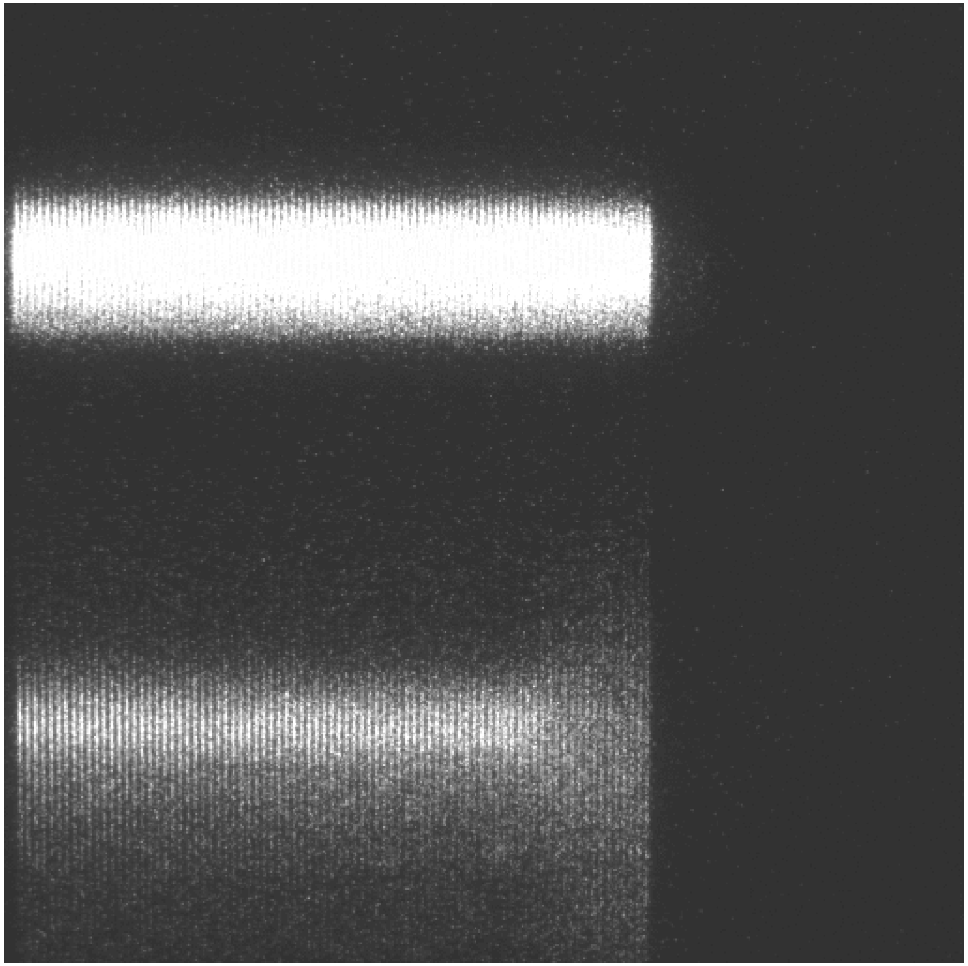
0 → 73 ms

2005-12-07: Fast LER Blow-up in *x* and *y*



- Blows up in both planes within 5ms.
- Correlate with beam-abort data from BPMs & transverse feedback:
  - LER centroid motion in BPMs for ~1 ms.
    - Seen here in last image before blow-up.
  - Current drops for ~3 ms while beam blows up.
  - Abort triggered by LER current loss (dI_L/dt).

2006-07-03: HER *y* blow up in 14 ms

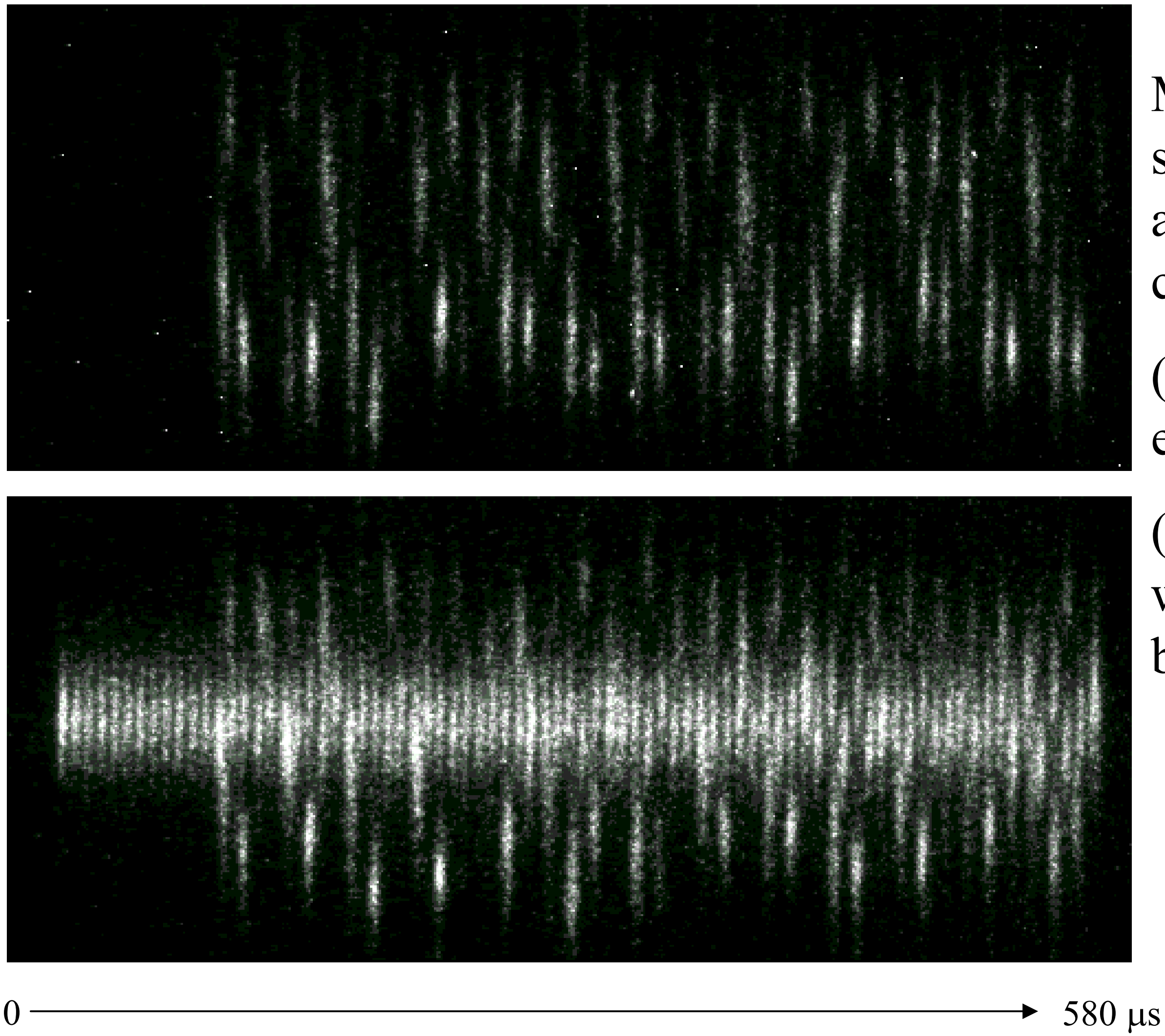


0 → 73 ms

Monitoring Injection

- Image incoming bunch on every n^{th} turn as it damps.
  - For first injection and for adding charge to a stored bunch.
- Use an injection trigger, not the ring-turn clock.
- Run the camera in "movie mode."
  - Acquires an image sequence at maximum speed
    - Images held in RAM for viewing afterward.
- Search for the delay from the injection trigger to the arrival of light from the bunch at the camera.
  - Inject 5 pulses at 1 Hz into a single bunch.
  - For T_0 = ring turn, set gate width = $T_0/5$ and scan gate delay in steps of $T_0/5$. Only one of these 5 images will show light.
  - Reduce gate width by factor of 5 and repeat.

1st and 2nd Injections into a LER Bucket

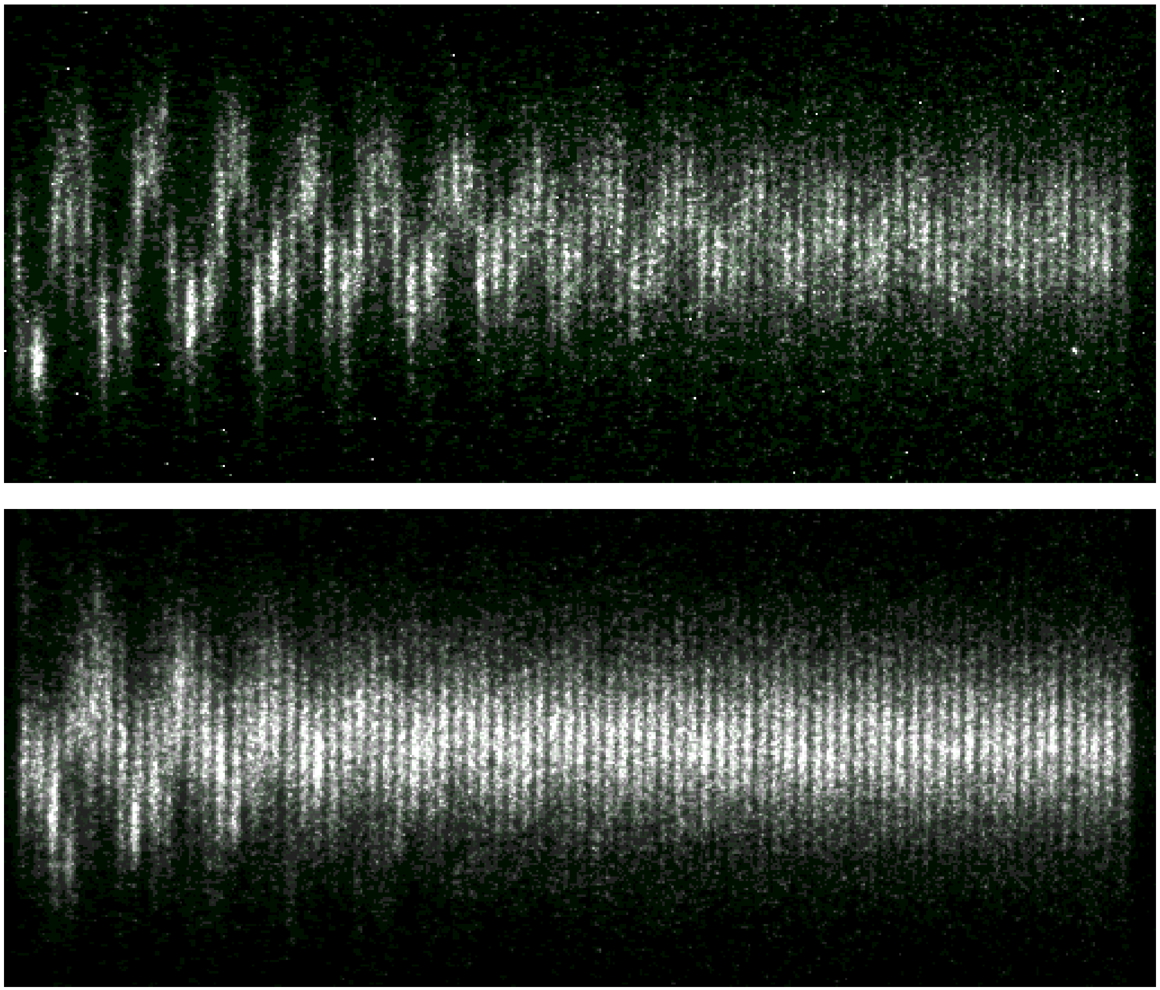


Minor-axis projection showing injected charge arriving on the 13th of 80 consecutive turns.

(a) Bucket is initially empty.

(b) 2nd injection merges with previously stored bunch.

1st and 2nd Injections, 800 Turns



0 → 5.8 ms

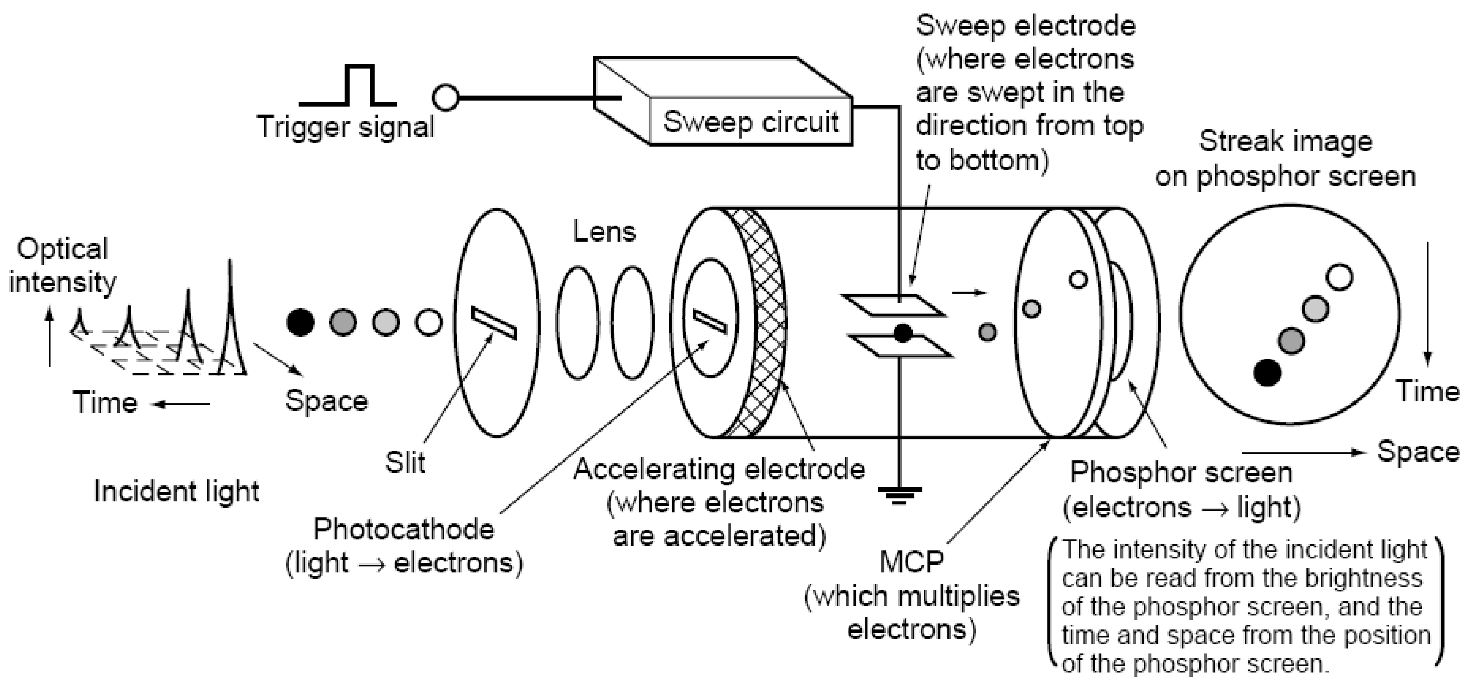
Again 80 images, but now taken on every 10th turn.

(a) Initially empty bucket.

(b) 2nd injection.

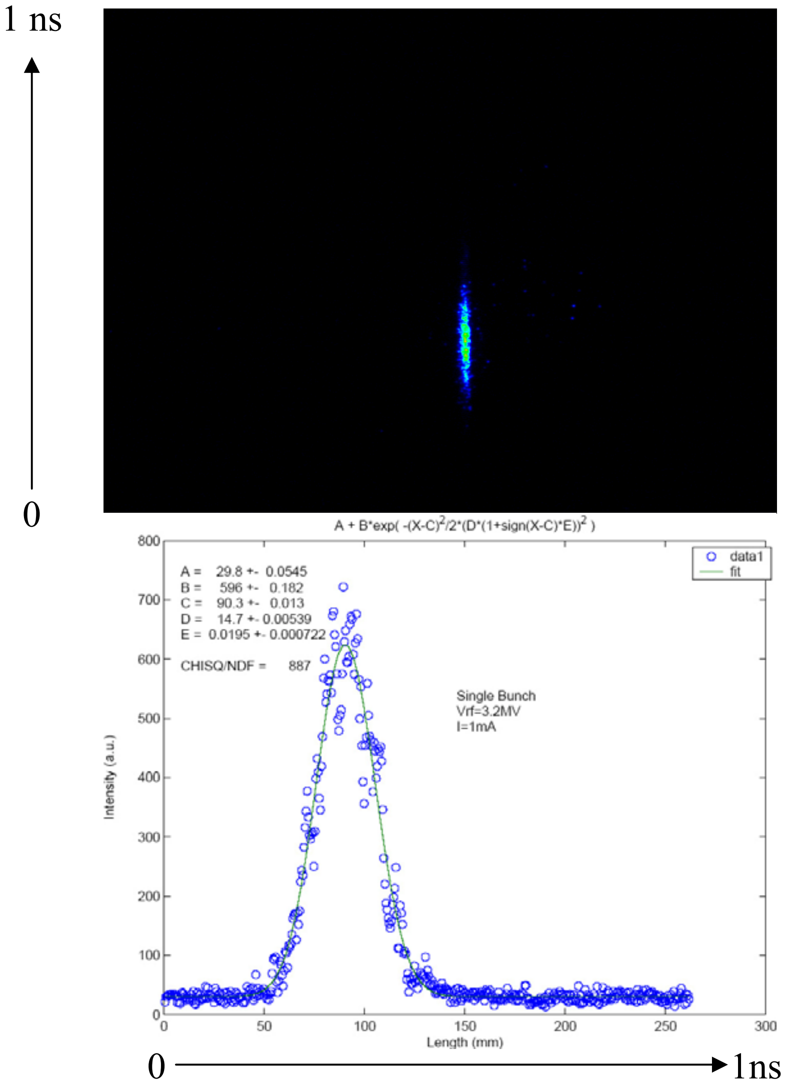
Injected charge oscillates about stored orbit and begins to damp, although time interval is an order of magnitude below the damping time.

Principle of the Streak Camera



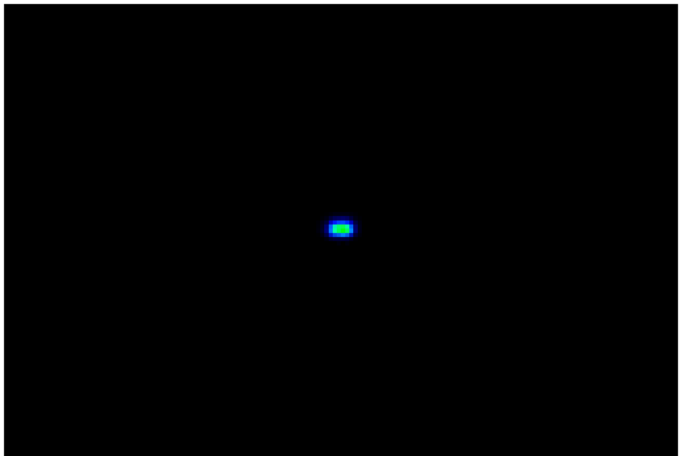
- Compare streak camera to gated camera:
  - Light→Photocathode→Electrons→MCP→Screen→CCD as before, but…
  - Remove: Vertical spatial information, with a tight focus and a thin slit.
  - Add: Accelerating electrode after the photocathode
Fast vertical sweep in drift space before the MCP
  - Vertical coordinate now displays the arrival time of the photons.

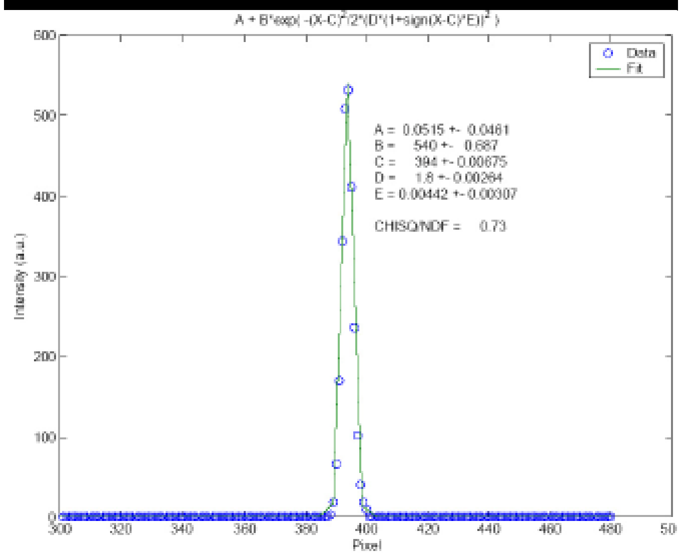
Single Bunch in LER, Triggered Sweep



- Single bunch in the LER (low-energy ring) of PEP-II
- Projection along the vertical axis gives the profile in time.
  - Beam fits an asymmetric Gaussian (faster rise than fall)
  - Studied variation with ring current and RF voltage.

Focus Mode: Streak Off to Measure Resolution





- A big spot with the sweep off degrades time resolution.
  - Once sweep is on, source’s height and time spread will mix.
- Check setup in Focus Mode.
  - Use a narrow entrance slit.
    - Typically 10 to 30 μm
  - With sweep off, focus all optics, both external and within the camera, to get the smallest spot on the CCD.
  - Measure RMS spot size in pixels.
- Correct streak data for resolution.
  - Convert pixels to time scale of streak.
  - Subtract resolution in quadrature from beam’s measured RMS length.

$$\sigma = \sqrt{\sigma_{\text{meas}}^2 - \sigma_{\text{res}}^2}$$

Noise on the Image

- How much light?
  - Too little gives shot noise and more error in the fit, as shown in the previous single-bunch streak image.
  - Too much:
    - Space charge between the photocathode and the MCP spreads out the electron pulse, broadening the measured temporal profile
    - Damage to the photocathode, MCP, and phosphor screen.
    - **Warning!** The screen is easily damaged in Focus Mode, since without the sweep, the light is concentrated in a small spot. Always attenuate the light heavily (~ 40 dB, also called an optical density of 4) before opening the shutter in Focus Mode.
  - The best time resolution is found with visible noise in the image. Optimize by varying the attenuation and MCP gain.

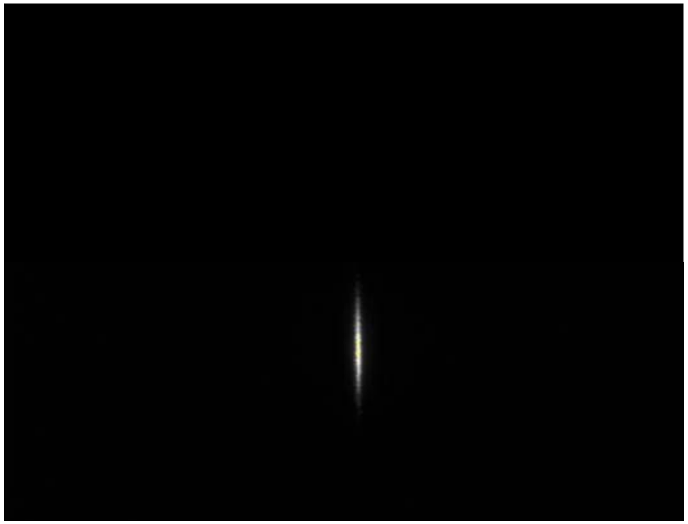
Jitter in the Sweep

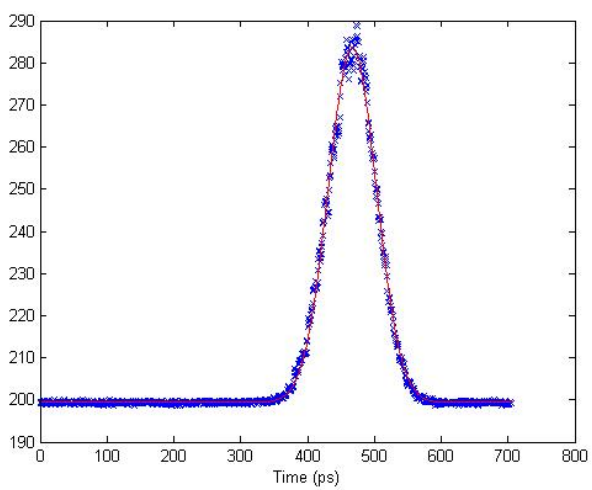
- One cure for noise is to add images from several measurements.
  - But if the sweep time is not fixed relative to the beam, the sum will be broader than any one fit.
  - Jitter in sweep (~ 20 ps) can be close to bunch length.
  - Jitter in trigger can be worse: DG535 has 50 ps.
  - And any synchrotron oscillation will add to this spread.
- First find the mean of the time profile of each image, and then overlap them at their means.

Synchroscan Sweep

- For stable bunches stored in a ring, there is an alternative way to beat noise.
- Since the bunch is locked to the ring's RF, an RF sine wave can sweep the beam without jitter.
  - Want only the linear part of the sine, near the zero crossing.
    - Good for sweeps spanning short time scales: $\Delta t_{\text{sweep}} \ll 1/f_{\text{sweep}}$
  - Deflection plates incorporated in a high-Q resonator tuned to f_{sweep} to get enough field to sweep the full MCP in Δt_{sweep}
  - Upper limit to drive frequency for the resonator
    - $f_{\text{sweep}} < 125$ MHz for our Hamamatsu C5680
    - Low compared to typical ring RF: $f_{\text{RF}} \approx 500$ MHz
    - PEP-II and SPEAR-3 use $f_{\text{RF}} = 476$ MHz, and so our camera uses a subharmonic: $f_{\text{sweep}} = 476/4 = 119$ MHz

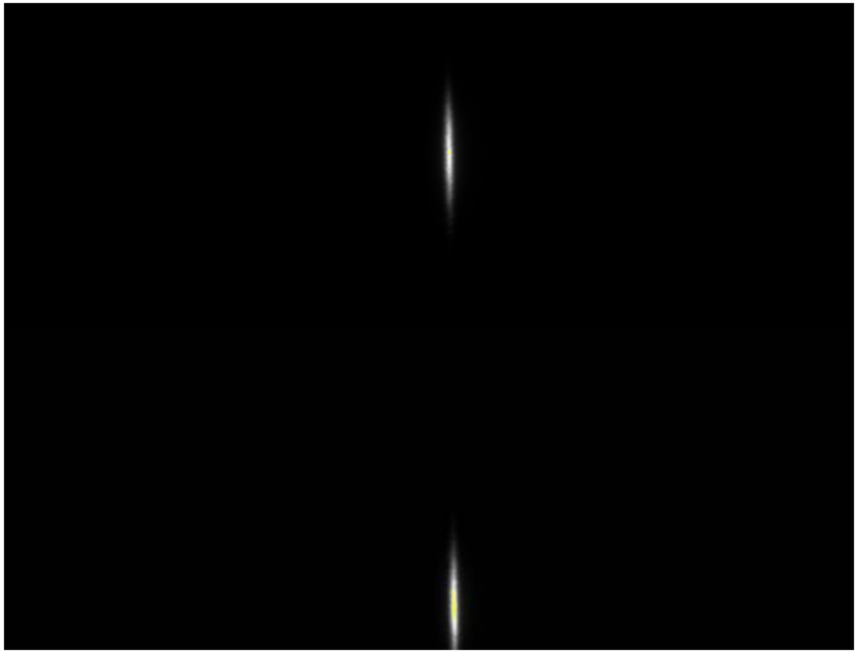
Single Bunch in LER, Synchroscan





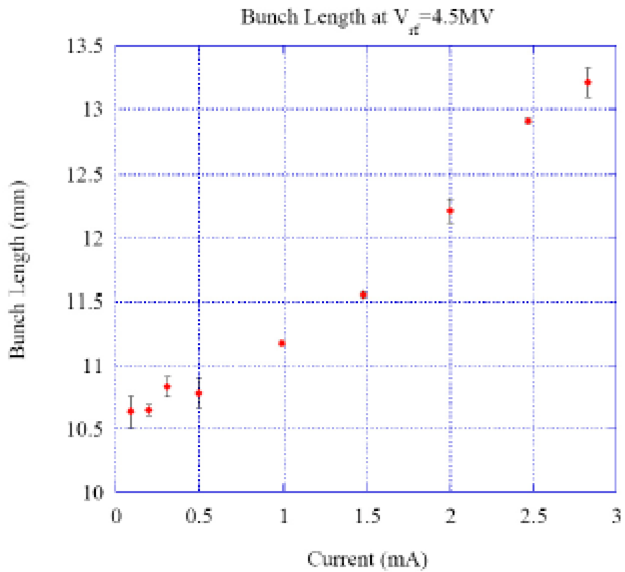
- Less noise in this image and profile than in single sweep.
- CCD accumulates signal over many sweeps (ms), and so the space charge is low.
  - Bright image without broadening or risk of damage.
- Direction of time in the image depends on the sine phase as the light arrives.
  - Sine sweeps up and down.
  - Camera remains on, capturing signal in both directions.

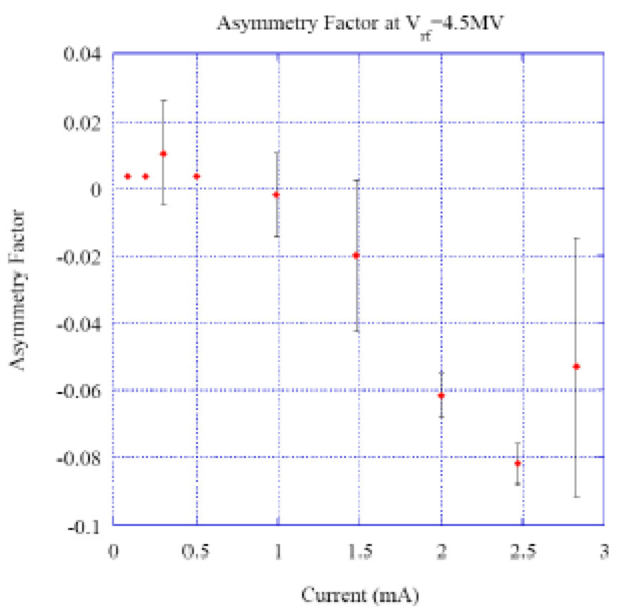
Mirror Images with Multiple Bunches



- If there is only one bunch per period of f_{sweep}, then all the images overlap.
- Since $f_{sweep} = f_{RF}/4$, we can have 4 bunches 90º apart in sweep phase.
  - We will see two if they arrive near the zero crossings.
    - For one, time axis goes up; for the other, down.
    - A small phase offset from 0º and 180º separates them on the screen.
  - The other two will then be near the extrema of the sine and will be off screen.

LER Synchroscan: Single Bunch, 4.5 MV





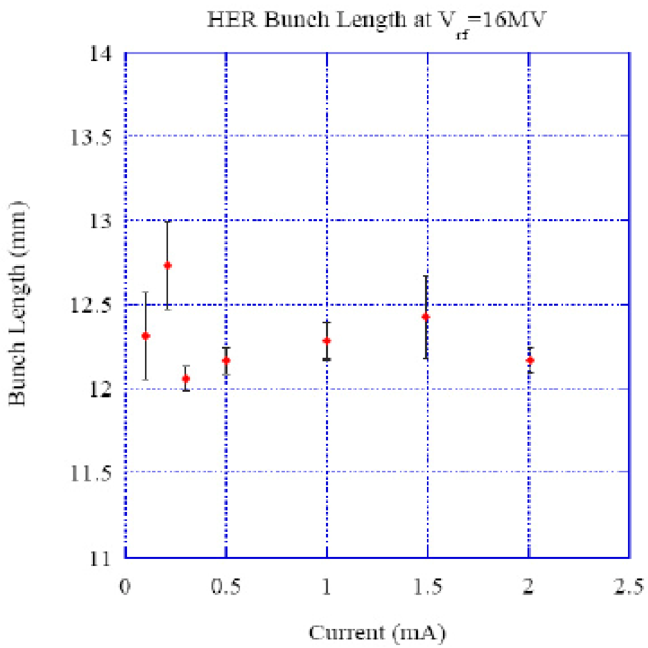
$\alpha = 1.23\text{x}10^{-3}$, ν_s=4.192kHz, and $\frac{\sigma_E}{E} = 6.5\text{x}10^{-4}$

$$\sigma_z = \frac{\alpha c}{2\pi\nu_s}\left(\frac{\sigma_E}{E}\right) = 9.10\text{mm}$$ (zero current bunch length)

Bunch length growth ~0.8mm/mA!

Asymmetry of bunch distribution increases with current-tail gets longer!

HER Synchroscan: Single Bunch, 16 MV



All RF Stations on
RF station 4-1: 1400kV
RF station 8-1: 2150kV
RF station 8-3: 2550kV
RF station 8-5: 2550kV
RF station 12-1: 2100kV
RF station 12-3: 2600kV
RF station 12-5: 1450kV
RF station 12-6: 1200kV

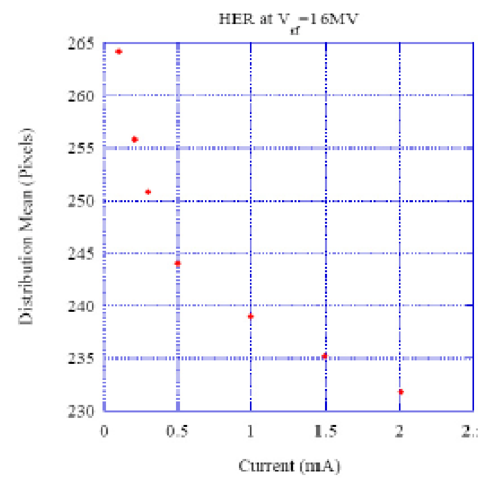
$$\frac{\sigma_E}{E} = 6.1\text{x}10^{-4} \qquad \alpha{=}2.41\text{x}10^{-3} \qquad \nu_s = 6.3867\text{kHz}$$

$$\sigma_z = \frac{\alpha c}{2\pi\nu_s}\left(\frac{\sigma_E}{E}\right) = 10.98\text{mm} \ \ \text{(zero current bunch length)}$$

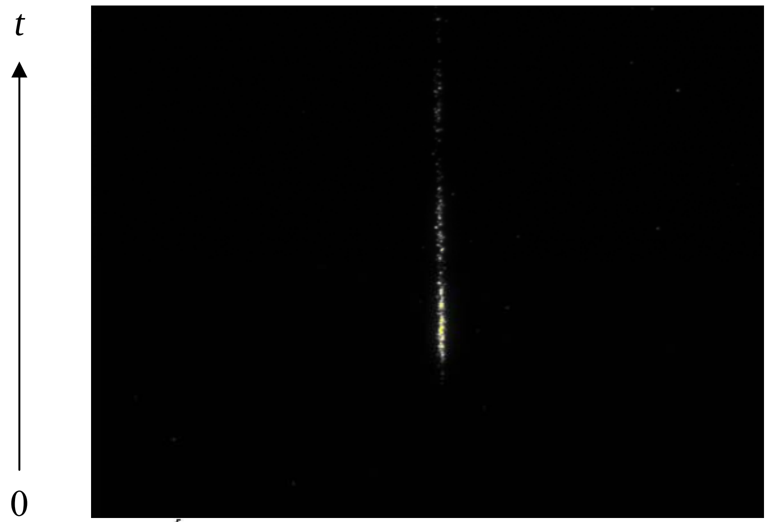
- No bunch length growth with current (except the 0.3mA data point is an aberration).

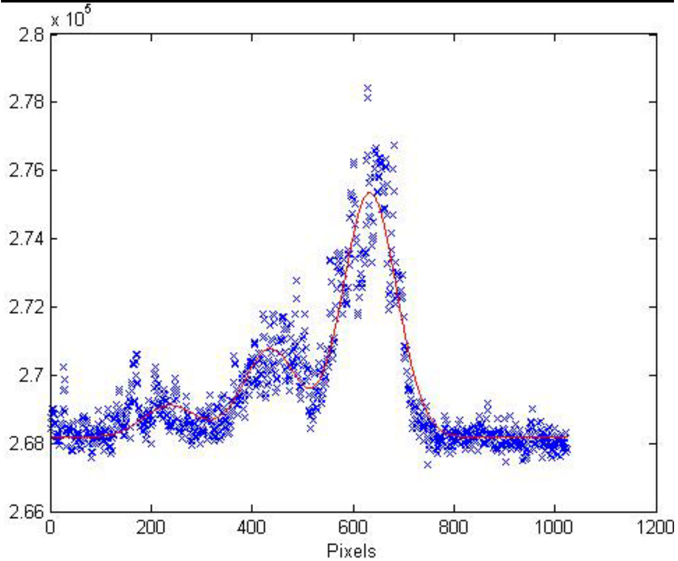
•~12% difference between measured and expected bunch length.

•Bunch distribution was near the center of the sweep (pixels 232-264).



Calibration with Etalon at 0.8 mA, LER



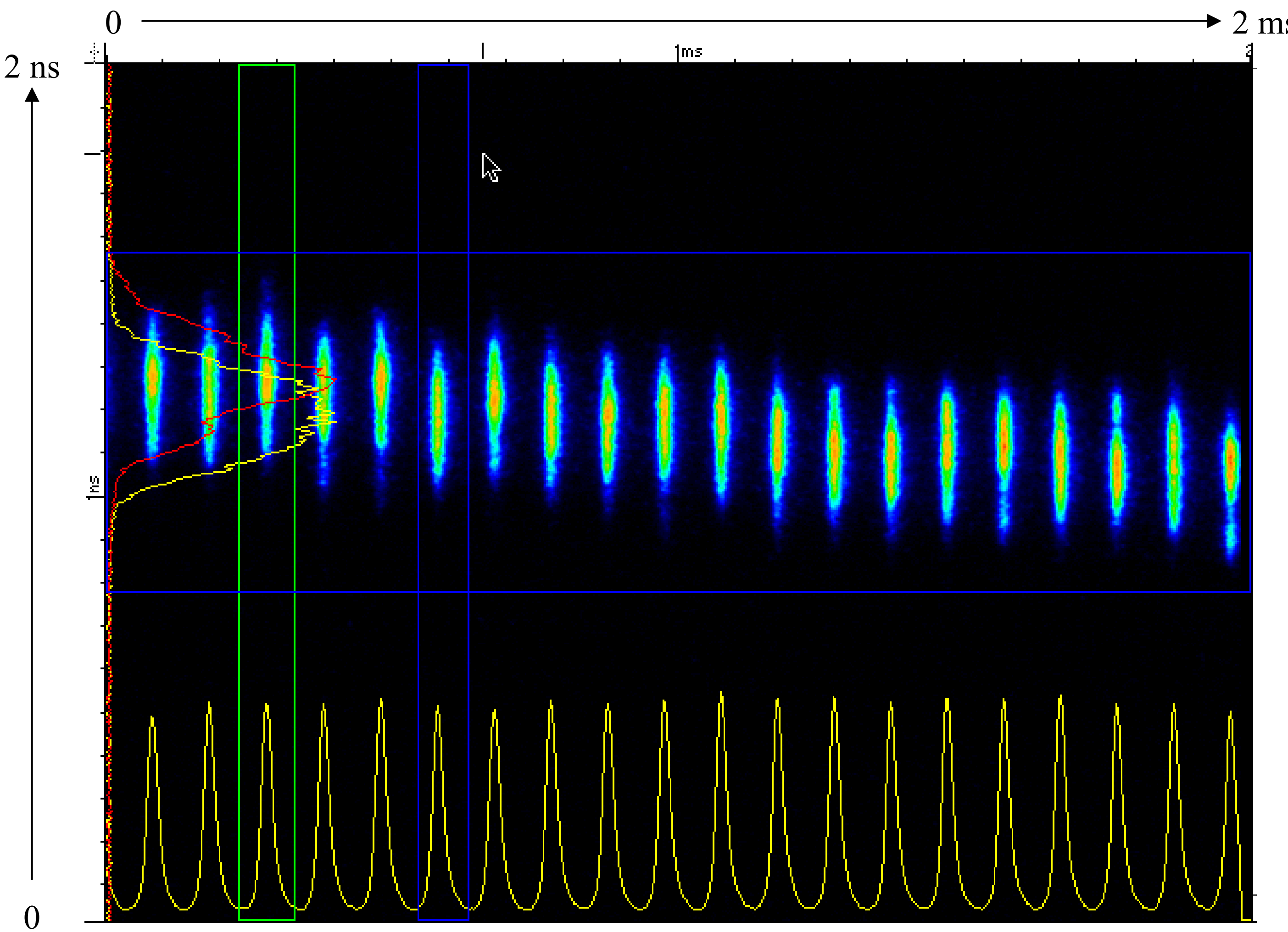


- Etalon: two parallel, partially reflective surfaces
  - We use a fused silica window, L=15.00 mm thick. Both sides have reflectivity $R=1-T \approx 0.5$.
- Insert near streak camera.
  - Main peak is reduced by T^2 .
  - Internal reflection produces a series of echoes
    - Each smaller by factors of R^2
    - Each delayed by nL/c
    - n is the index of refraction (~1.5) at the wavelength used
  - Fit to series of delayed Gaussians to calibrate ps/pixel

Add a Second Time Axis

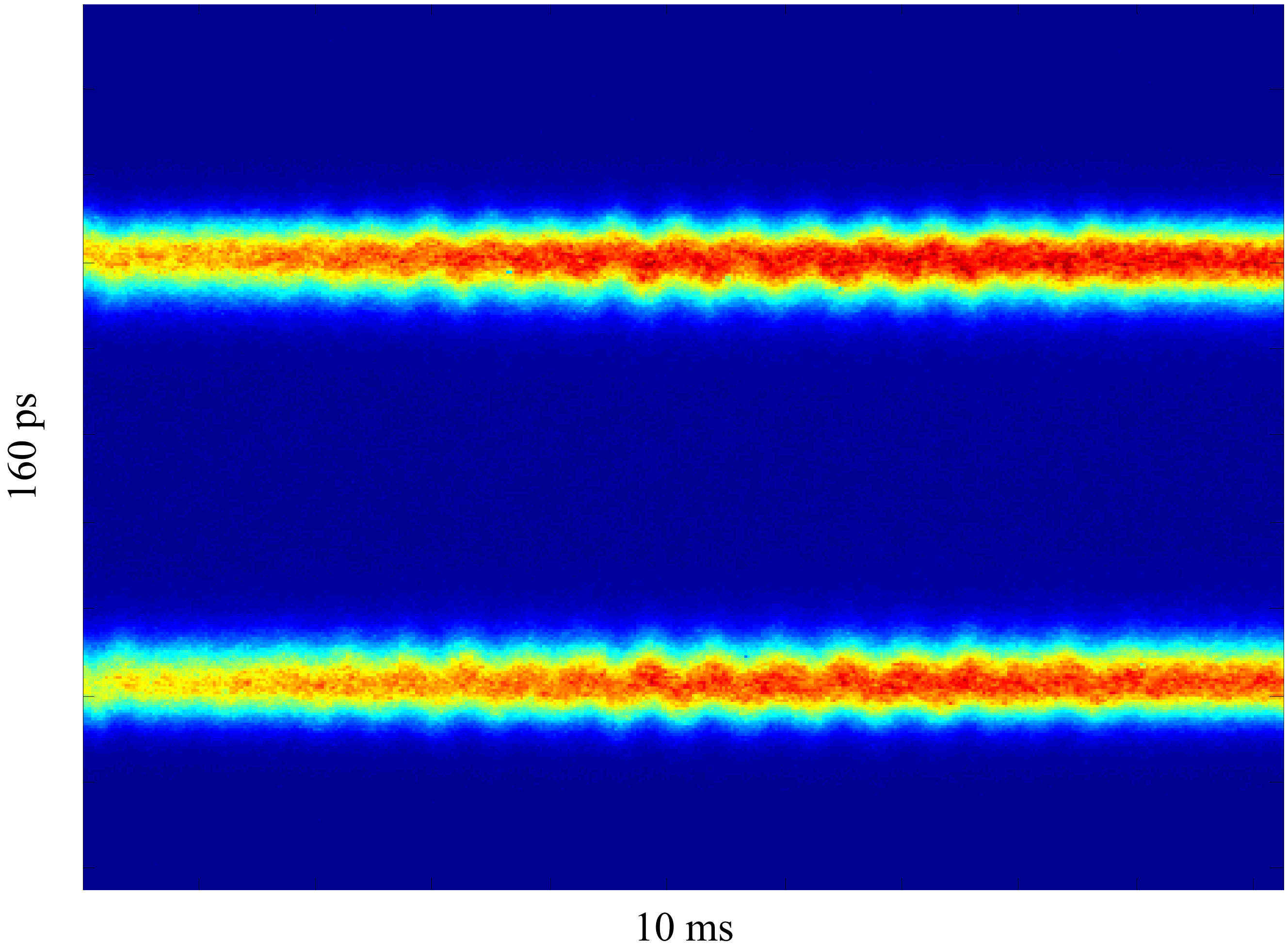
- Horizontal axis has interesting spatial information.
  - Reveals *xt* (or *yt*) coupling: head-tail instability.
- But what if the instability changes along a bunch train or over several turns?
  - Add a second set of plates to sweep the beam horizontally.
  - This deflection is slow, spanning ns, μs, or even ms.
  - Makes a stripe of consecutive bunches.
    - Like the rotating mirror, but on a faster time scale, and displaying longitudinal rather than transverse behavior.

SPEAR-II, 1998: Quadrupole Oscillation



SPEAR-III, 2007: 10-ms Dual Sweep

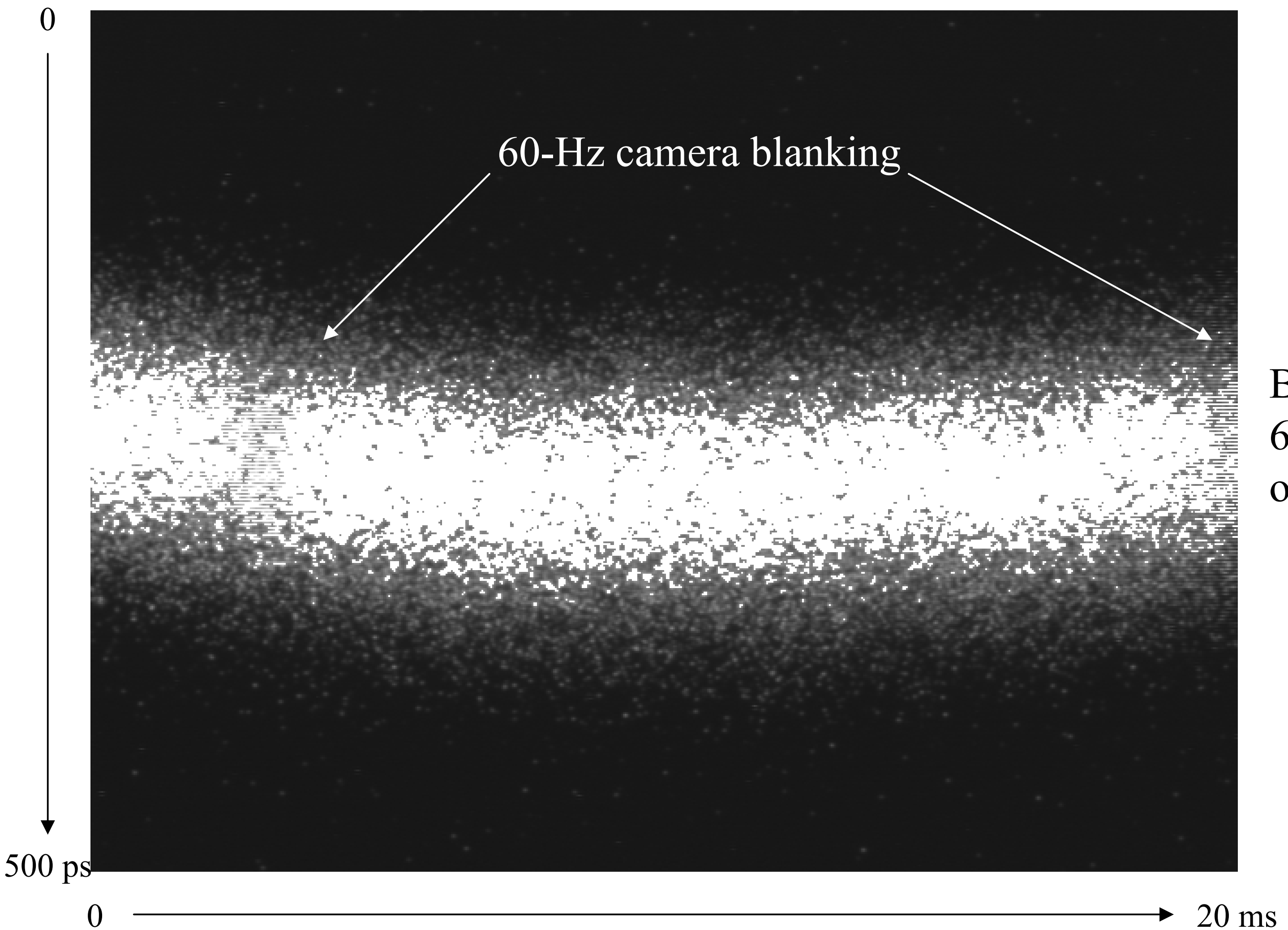
Instability during tests of a short-bunch (low-α) lattice



Longitudinal Motion During Aborts?

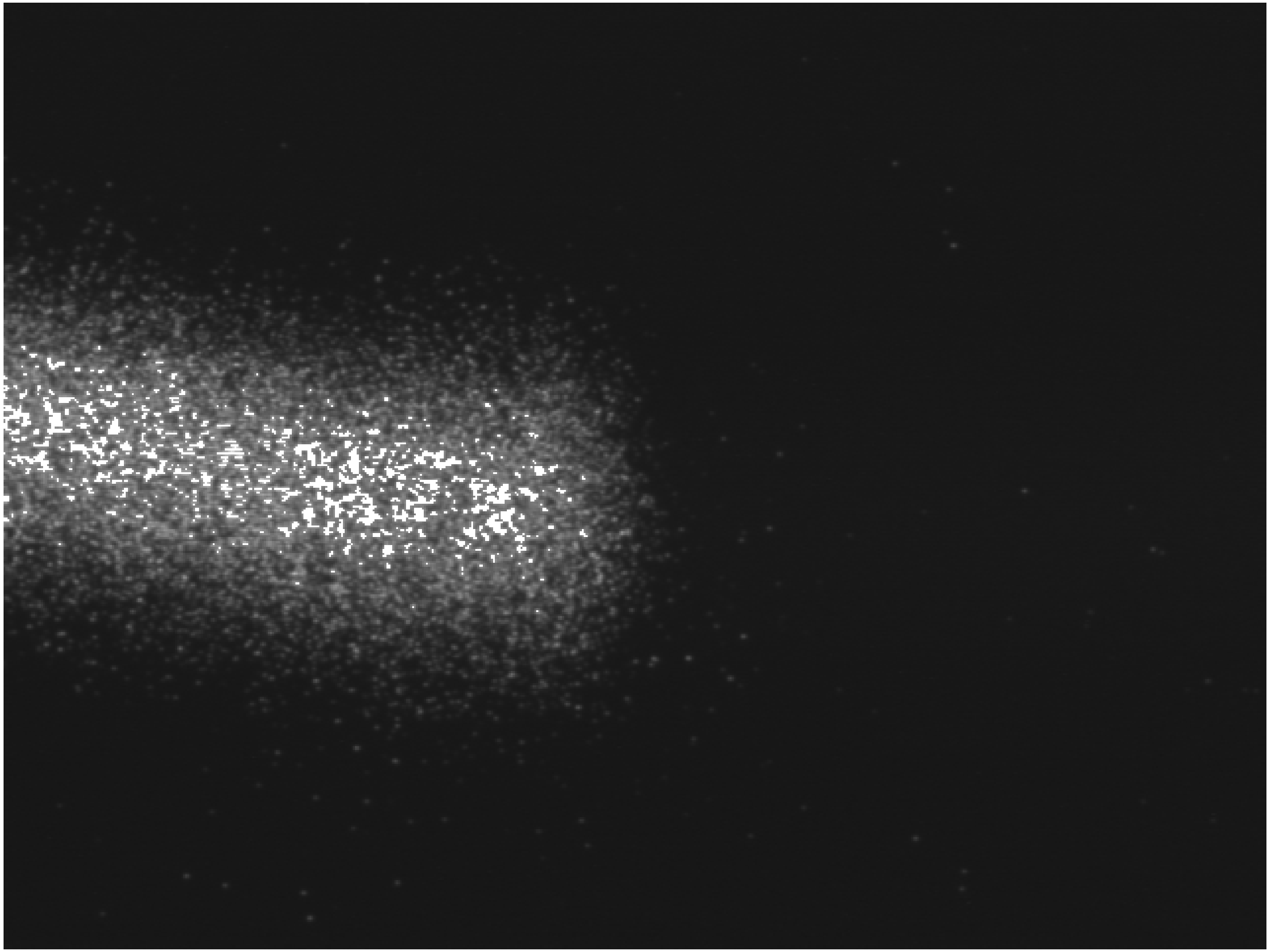
- LER abort spectra showed $2\nu_s$: Quadrupole motion?
- Dual-axis set-up:
  - Vertical:
    - 500-ps triggered time sweep
    - Image one bunch every 250 μs, retriggering the fast sweep
      - 80 images across the screen, with overlap, making a stripe
  - Horizontal:
    - 20-ms sweep.
    - Images separated by 133 ms (eight 60-Hz periods)
      - Borrowed LBNL's camera, with an analog CCD at 60 Hz
      - Retrigger rate limited by image readout
      - 15% chance of capturing any one abort

Dual-Axis Streak of Stable Beam

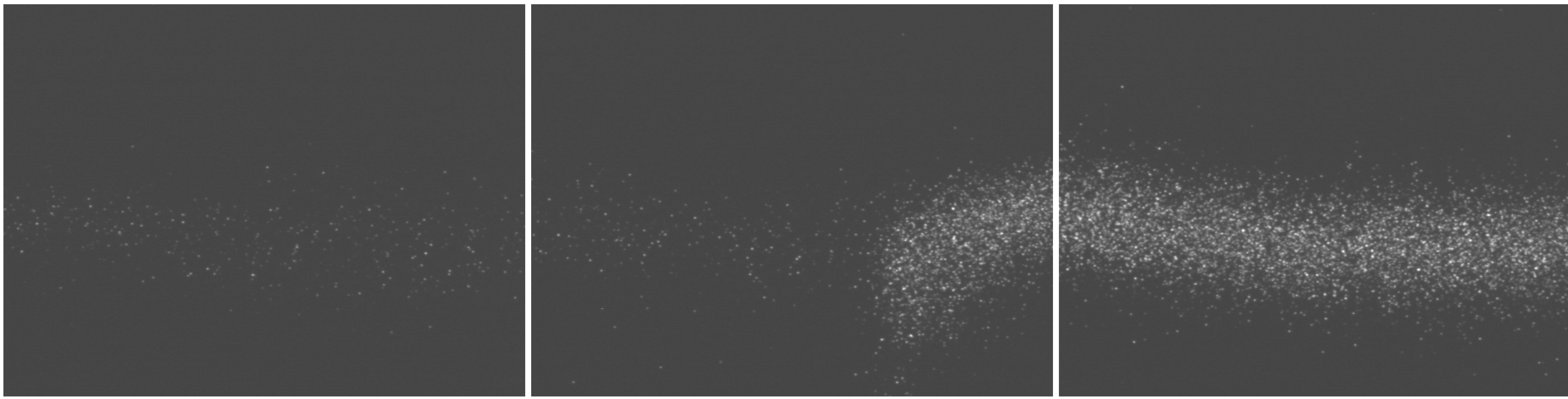


Bowed envelope: 60-Hz harmonic on the trigger?

Radiation Abort: No Longitudinal Motion



Adding Charge to a Bucket during a Fill



After first injection.

Dim image:
≈ 0.1 mA in bunch.

Second injection enters, a bit late in phase.

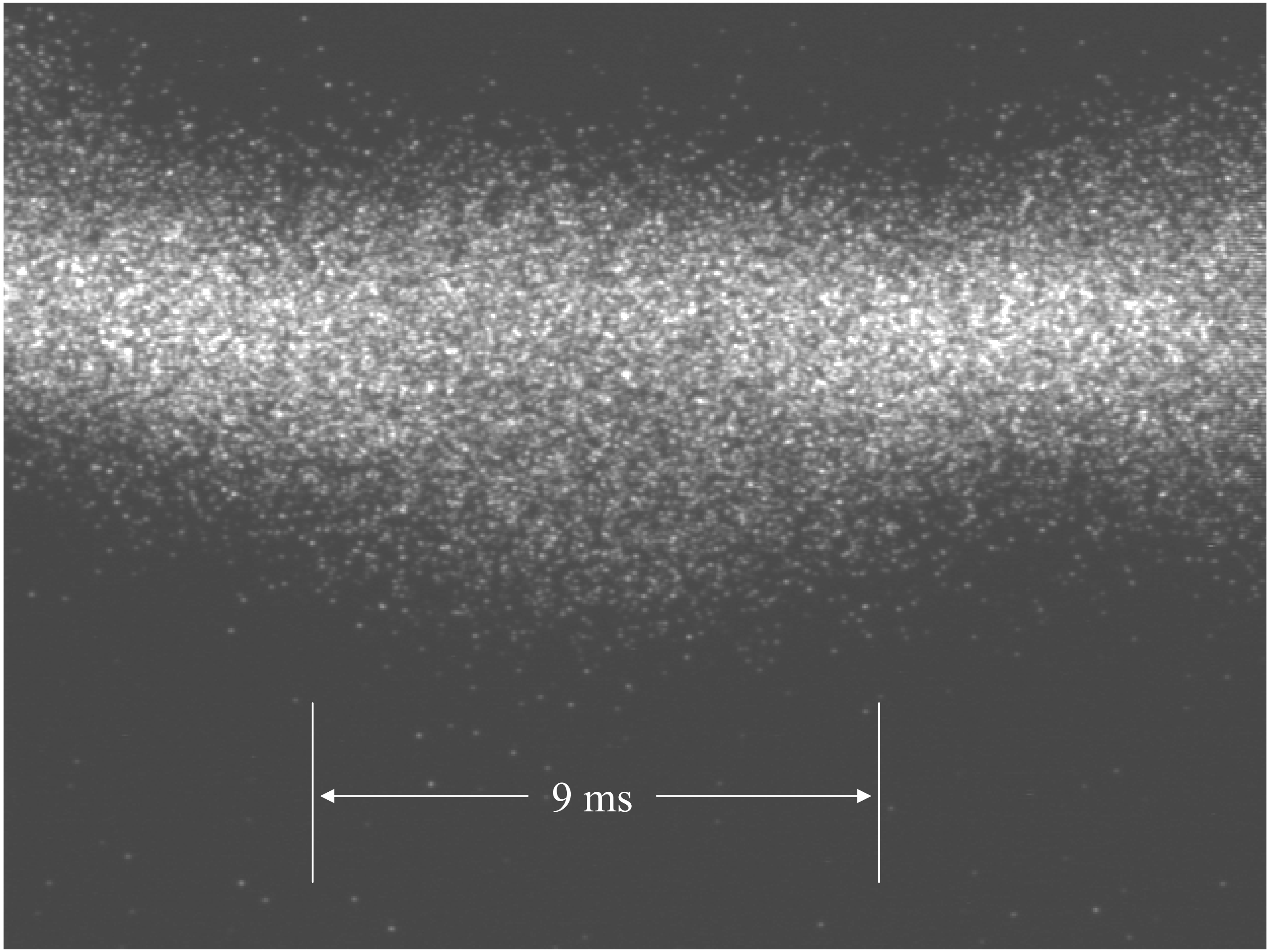
Image brightens.

Injected charge oscillates, starts to damp.

Next image, 133 ms later.

Oscillation has damped.

Longitudinal Growth and Recovery



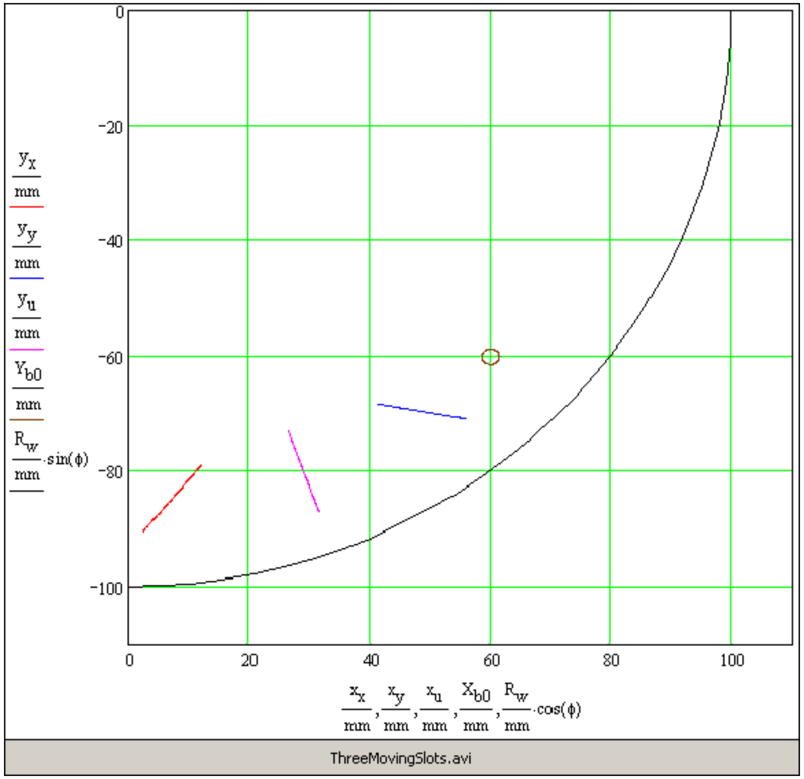
Dispersion

- Refractive index varies with color: Spread in arrival time
- For the LER's optical path:
  - Fused silica: 3 windows + 4 lenses + 1 beamsplitter = 70.8 mm
  - All mirrors are front-surface aluminum: no dispersion.
- The table shows the effect of the index change over the band of the blue bandpass filter.
  - Centered at 450 nm, with a width of 30 nm FWHM.
  - Not important for a 30-ps bunch, but only because we limited the band.

Wavelength Range		n at	n at	Δn	$L\,\Delta n$	$L\,\Delta n/c$
Lower	Upper	Lower	Upper		(mm)	(ps)
445	455	1.46595	1.46519	0.00076	0.054	0.179
430	470	1.46719	1.46415	0.00304	0.216	0.719
400	500	1.47012	1.46233	0.00779	0.552	1.840

Bunch-by-Bunch Transverse Profiles

- A plan for bunch data from LER x-ray pinhole camera
- Modeled on a wire scanner
- A rotating x-ray mask based on modified optical chopper wheel
- 100-µm-thick Pt:Ir
- 3 moving slots on the image plane.
  - Form projections on *x*, *y*, and *u* (45°) axes as slots move.
- Followed by a 1-ns scintillator and PMT.



Slots scanning across a 5σ beam ellipse
(Click to play movie.)