Time-Resolved Measurements

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Beam Diagnostics Using Synchrotron Radiation:
Theory and Practice
US Particle Accelerator School
University of California, Santa Cruz
San Francisco — 2010 January 18 to 22

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 scales require special and expensive cameras
- 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	Applications	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 (standard or fast-framing); 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 used multiplexed 4-channel frame grabbers (beam image, interferometer, alignment…).
  - Software recorded 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.

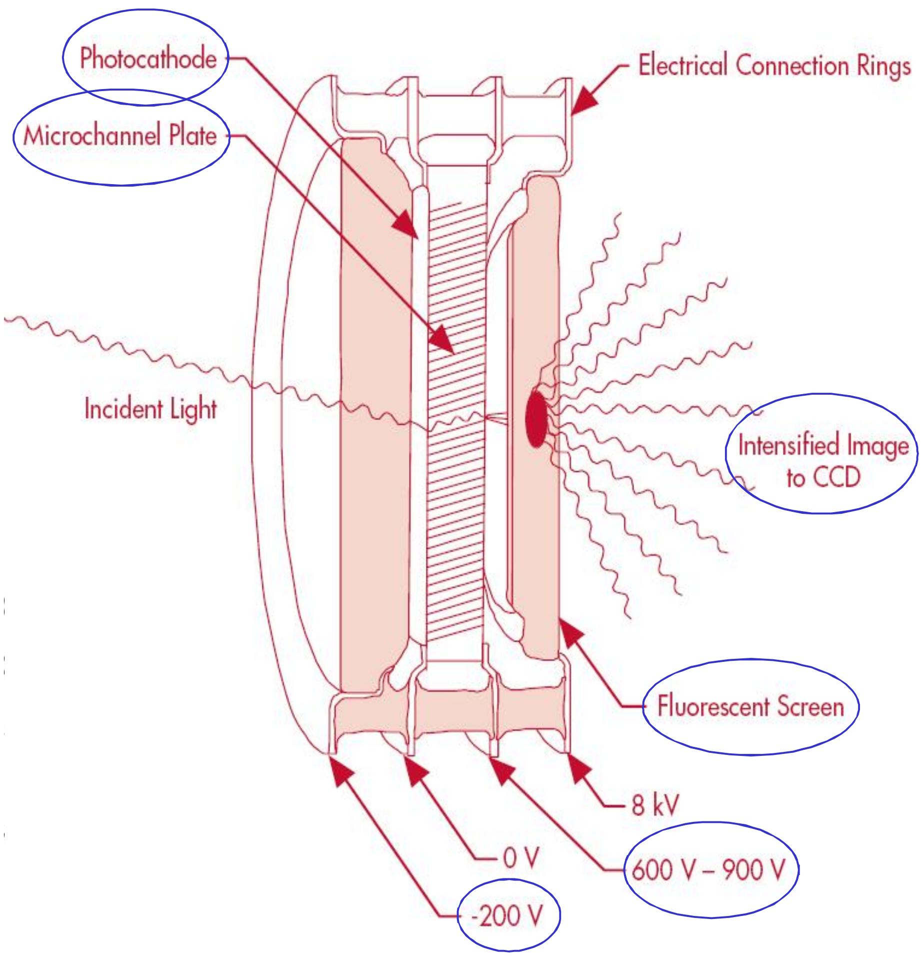
Movie Time

- Welcome to PEP-Flix, your movie source.

Video Cameras vs. Gated Cameras

- Give transverse (*x* and *y*) images of the beam.
- Video cameras have frame rates of 30 (or 25) Hz.
  - 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

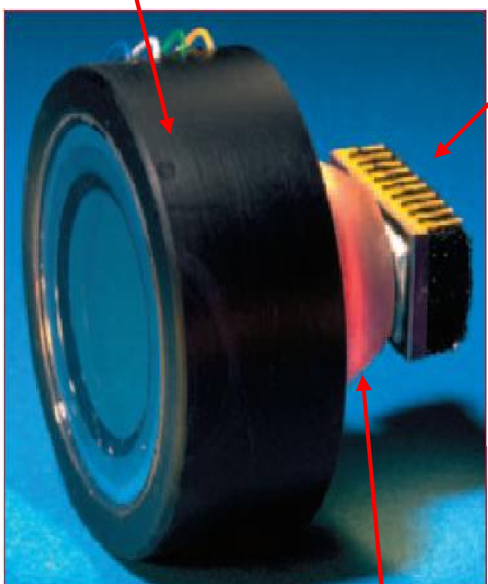


- Photocathode:
  - Converts light to electrons.
- Microchannel plate (MCP):
  - Intensifies the image.
- Fluorescent screen:
  - Converts the intensified image back to light.
- CCD camera (not shown):
  - Records the image.
- Photocathode bias voltage:
  - Can be gated at high speed.
- MCP bias:
  -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

Microchannel Plate

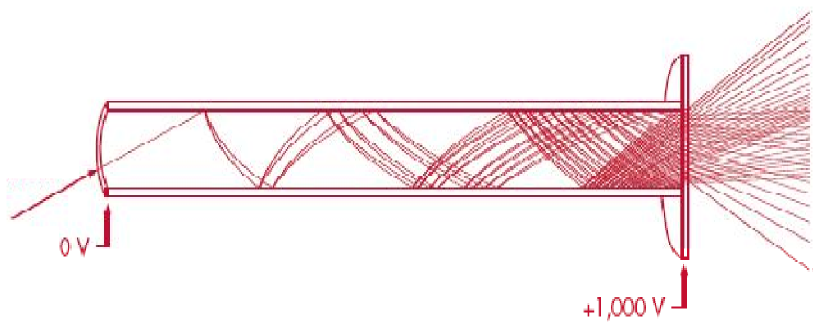
MCP

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.

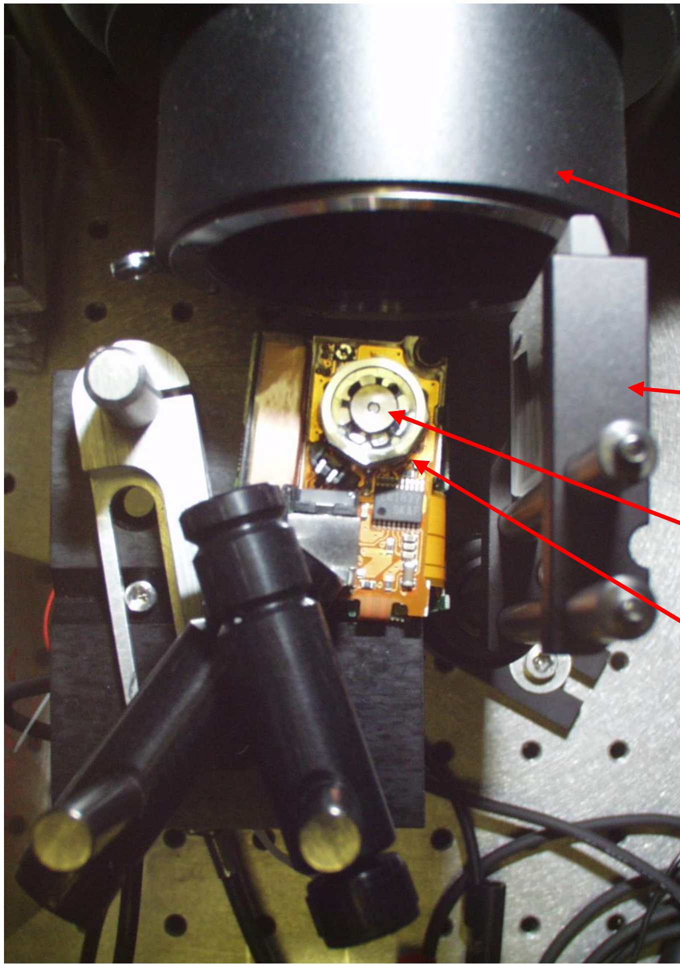
Sweep Images across Gated Camera

- 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 — 6.8º
  - 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.

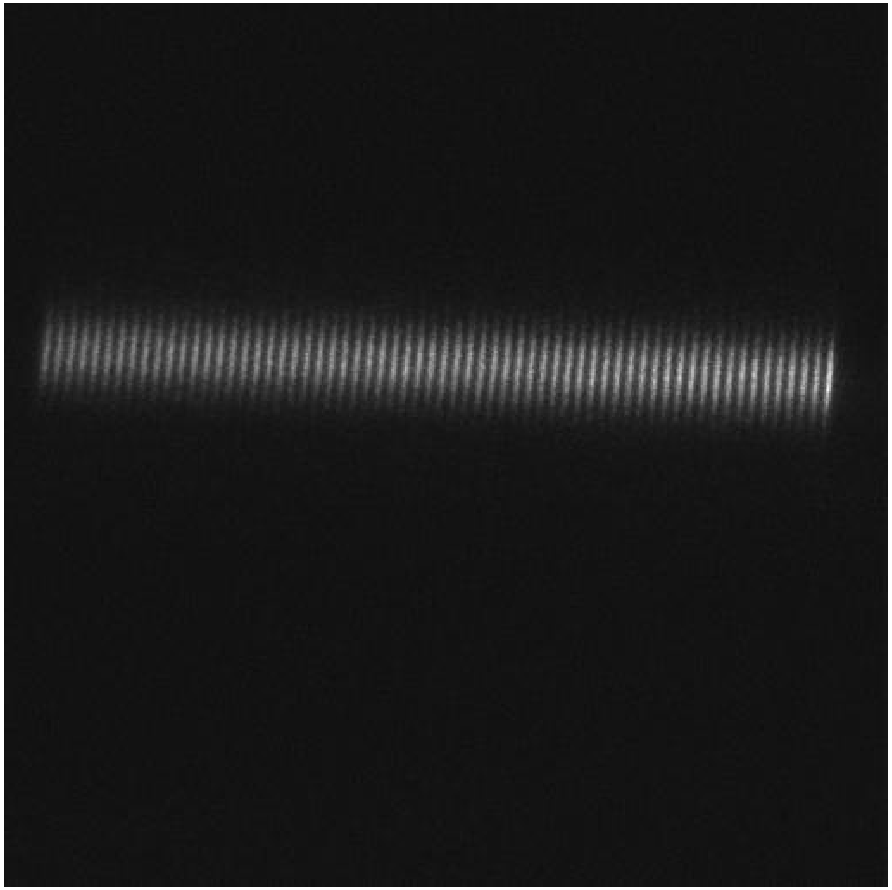
Aperture of gated camera

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:
  - Squash the beam's image horizontally, to let us resolve individual turns.
  - Maintain its vertical size, to let us observe any changes in that direction from turn to turn.
- Image rotation:
  - Transport periscopes turn the image by 90° on the way to the optical table.
  - 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 electrons.
  - Scanner issues a timing pulse on each turn of the polygon.
    - Used to trigger the camera.
    - Motor starts camera, rather than an accelerator 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

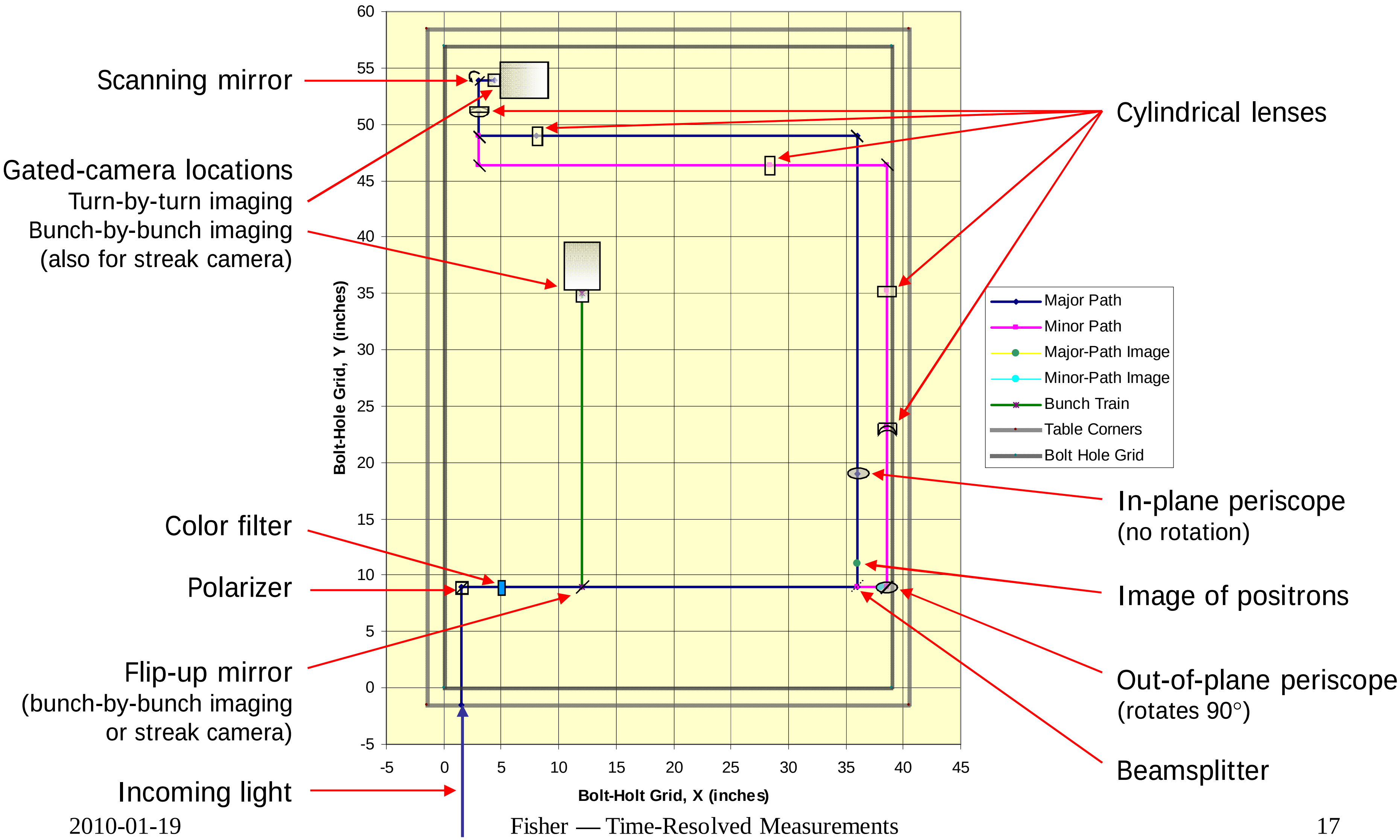
GSI Lumonics

- 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 accelerator 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.

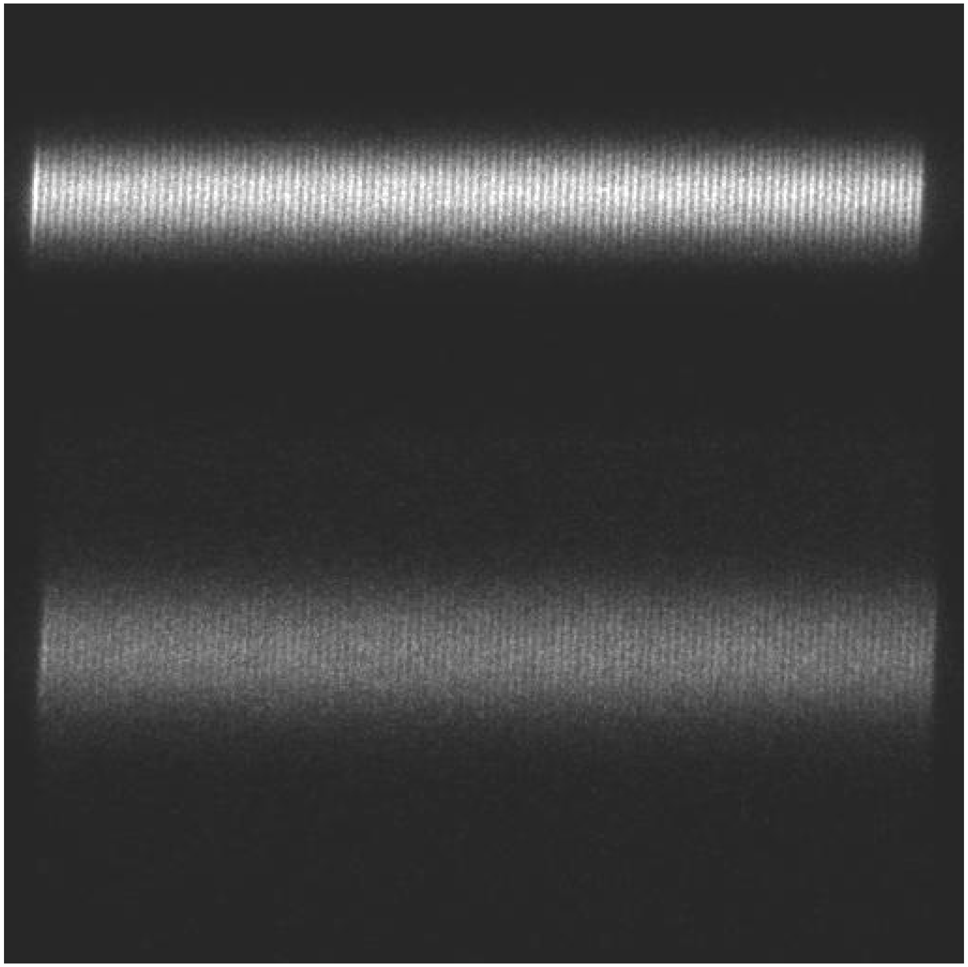
Measuring *x* and *y* Simultaneously

- 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

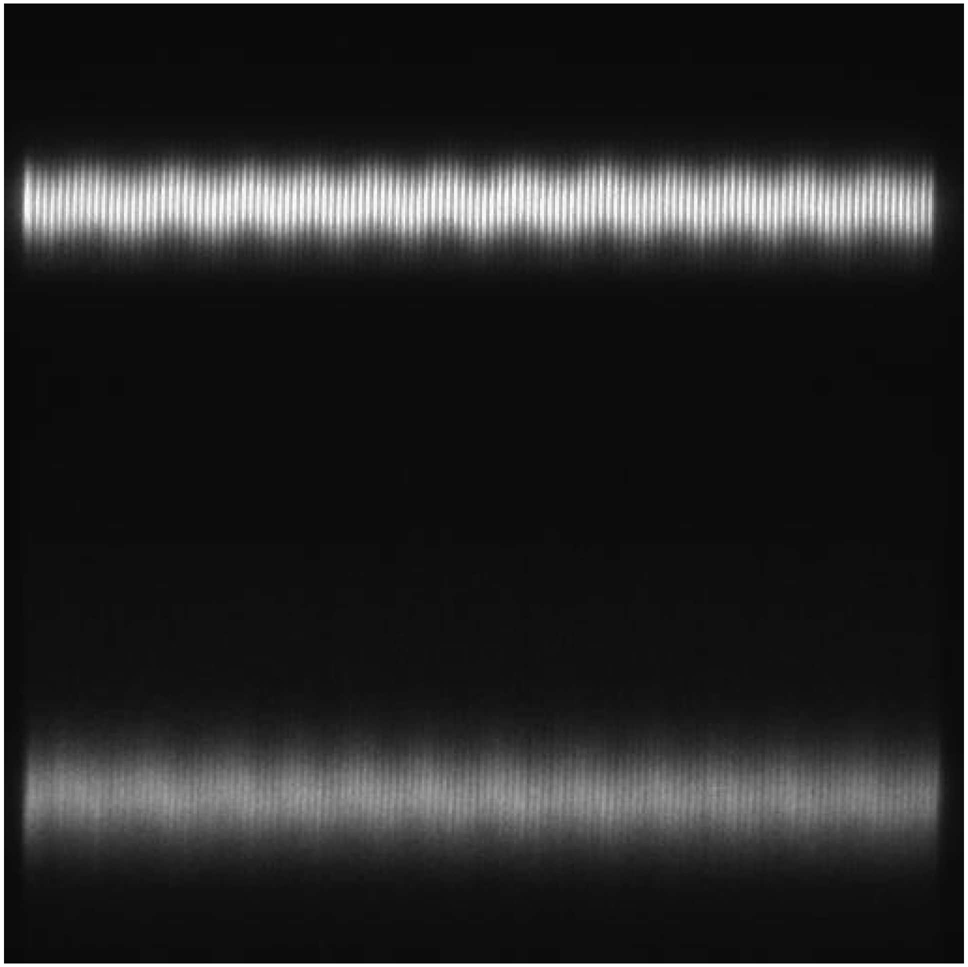


Instabilities and Beam Aborts

- 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.

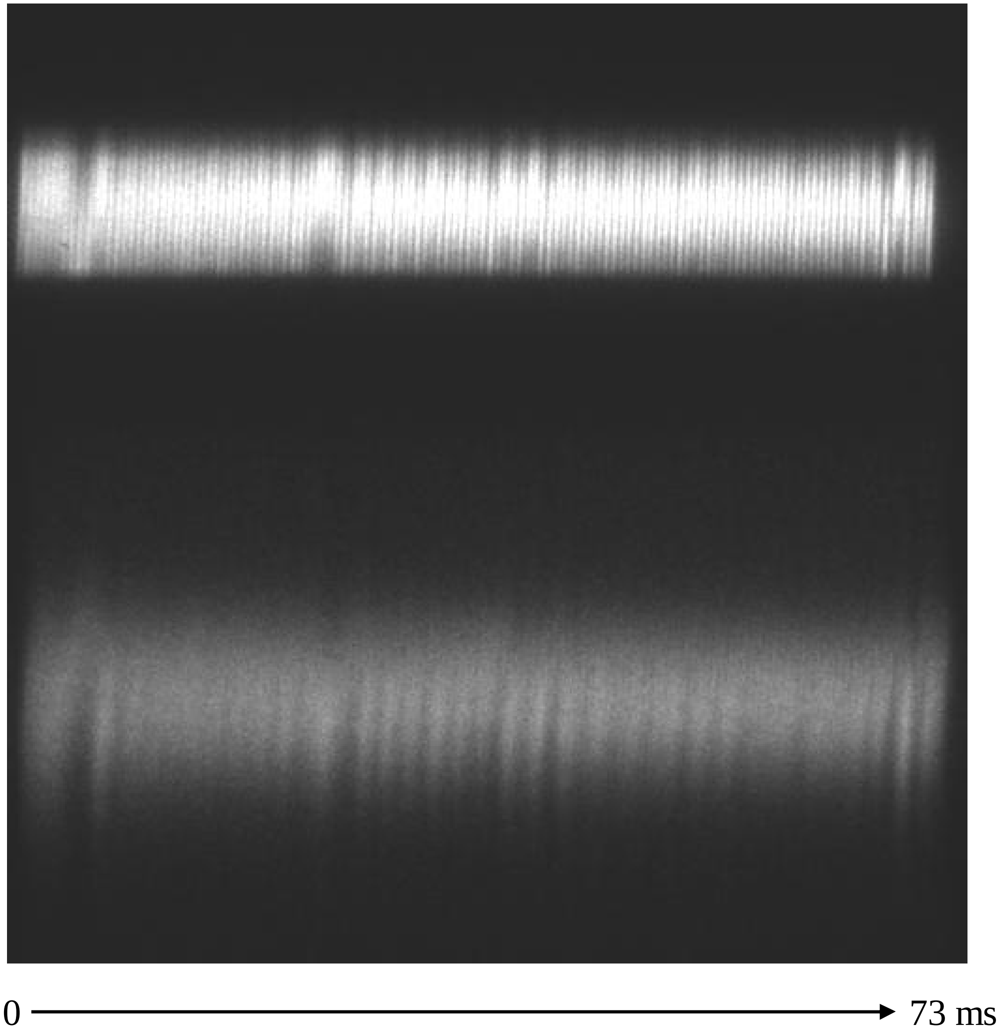


Major (x) axis of the beam

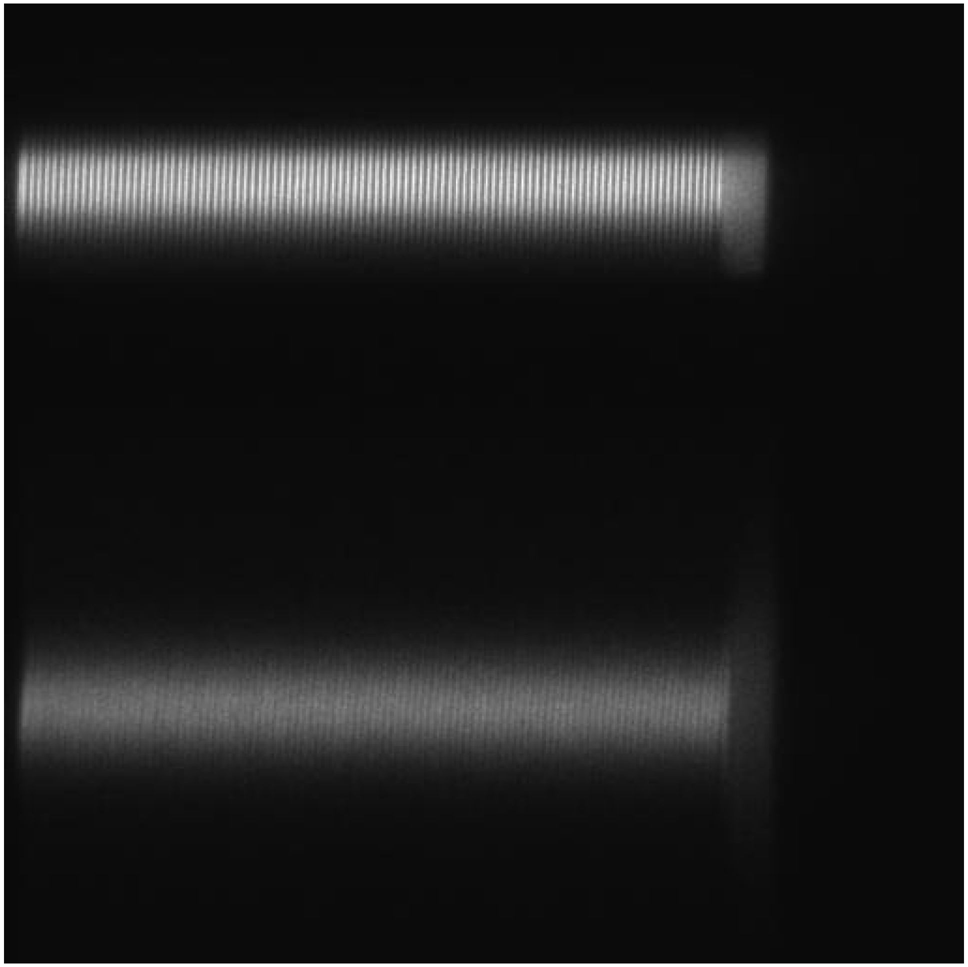
Minor (y) axis

0 → 73 ms

2005-12-07: LER Bursting Instability



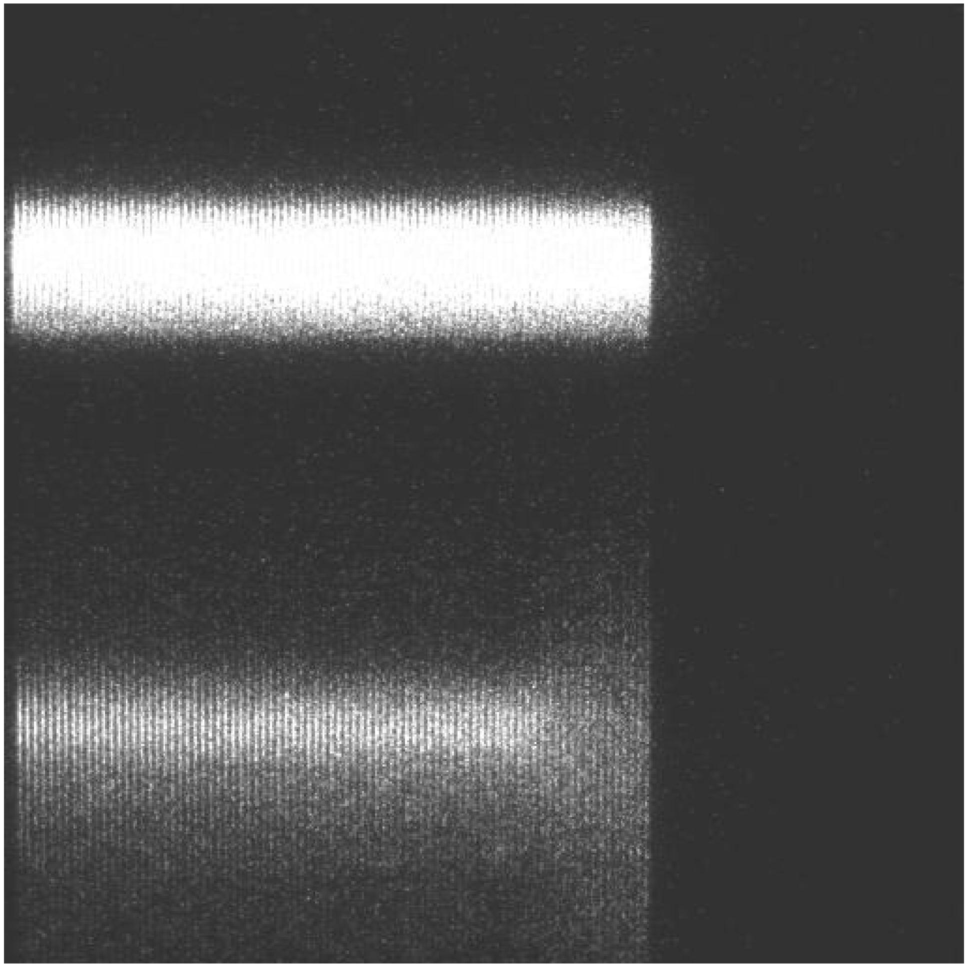
2005-12-07: Fast LER Blow-up in *x* and *y*



0 → 73 ms

- 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

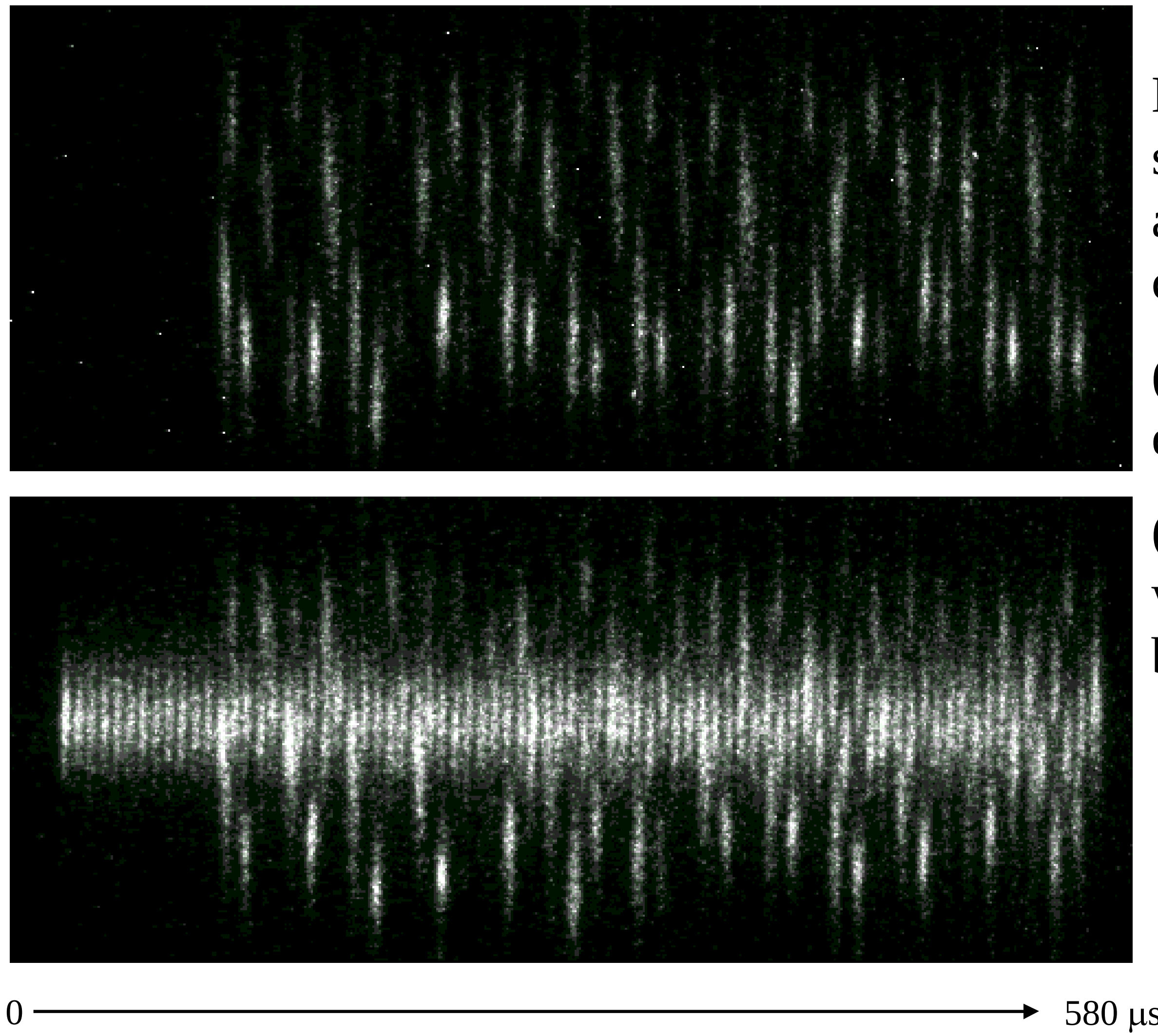


0 → 73 ms

Monitoring Injection

- Image the incoming bunch on every n^{th} turn as it damps.
  - For first injection into bucket 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

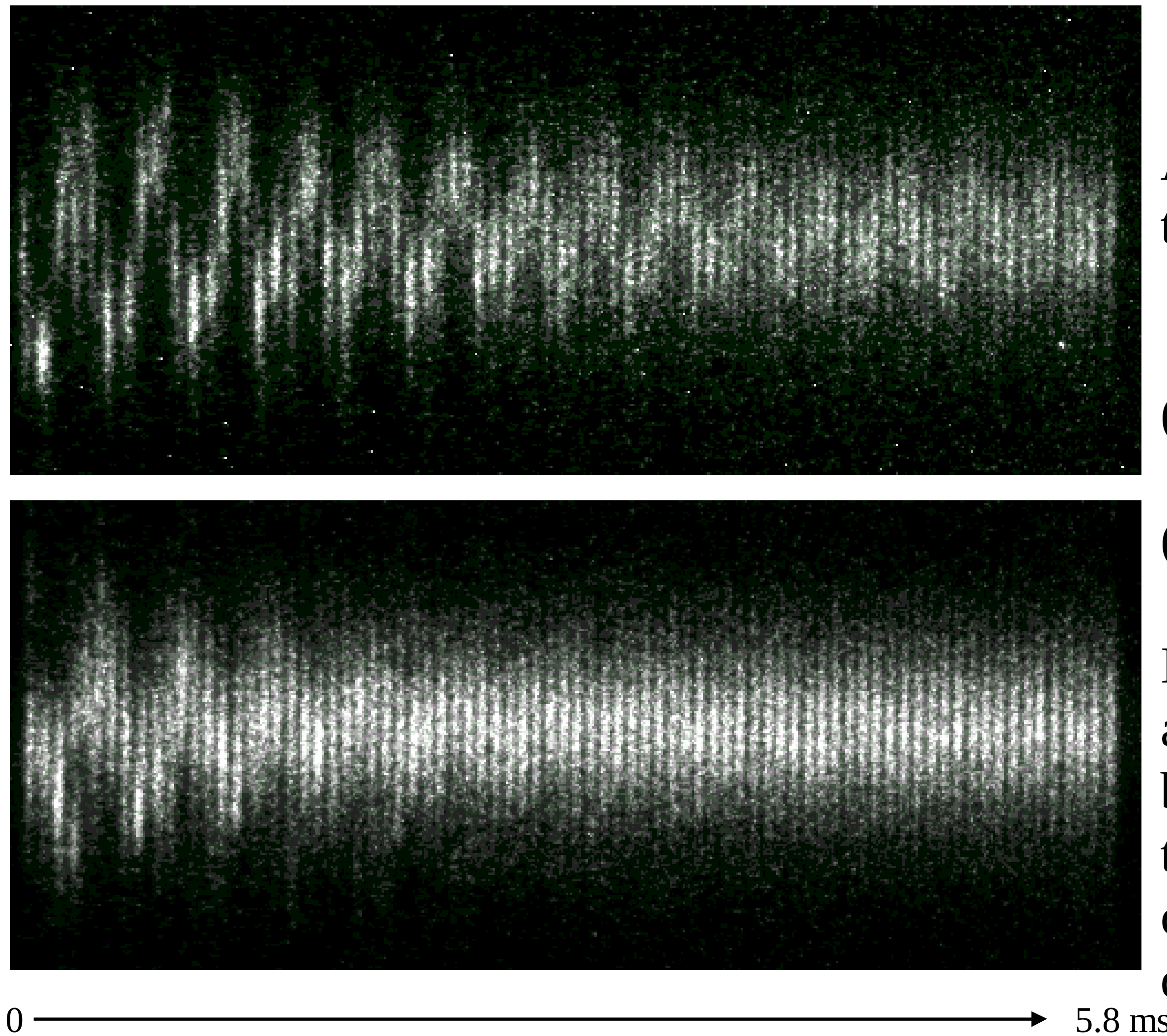


Minor-axis projection showing injected charge arriving on the 13th of 80 consecutive turns.

(a) Bucket is initially empty.

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

1st and 2nd Injections, 800 Turns



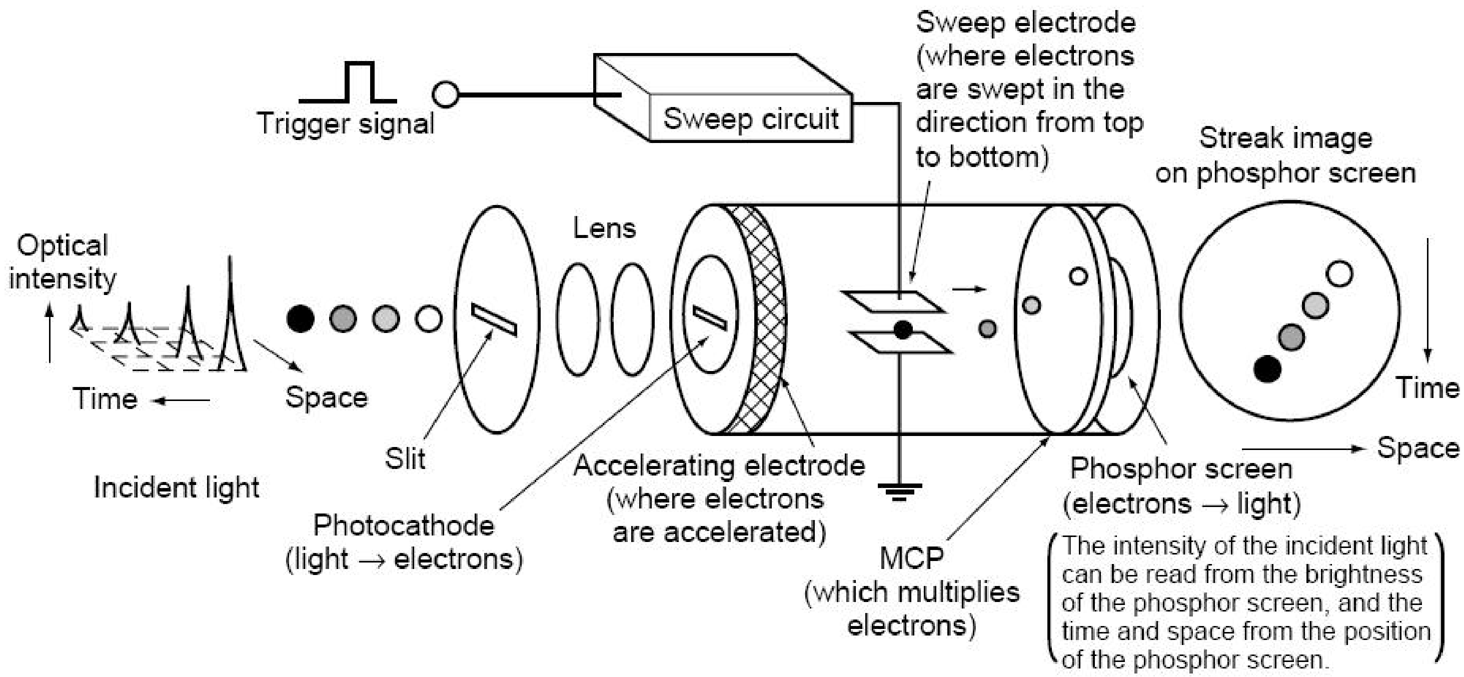
Again 80 images, but now taken on every 10th turn.

(a) Initially empty bucket.

(b) 2nd injection.

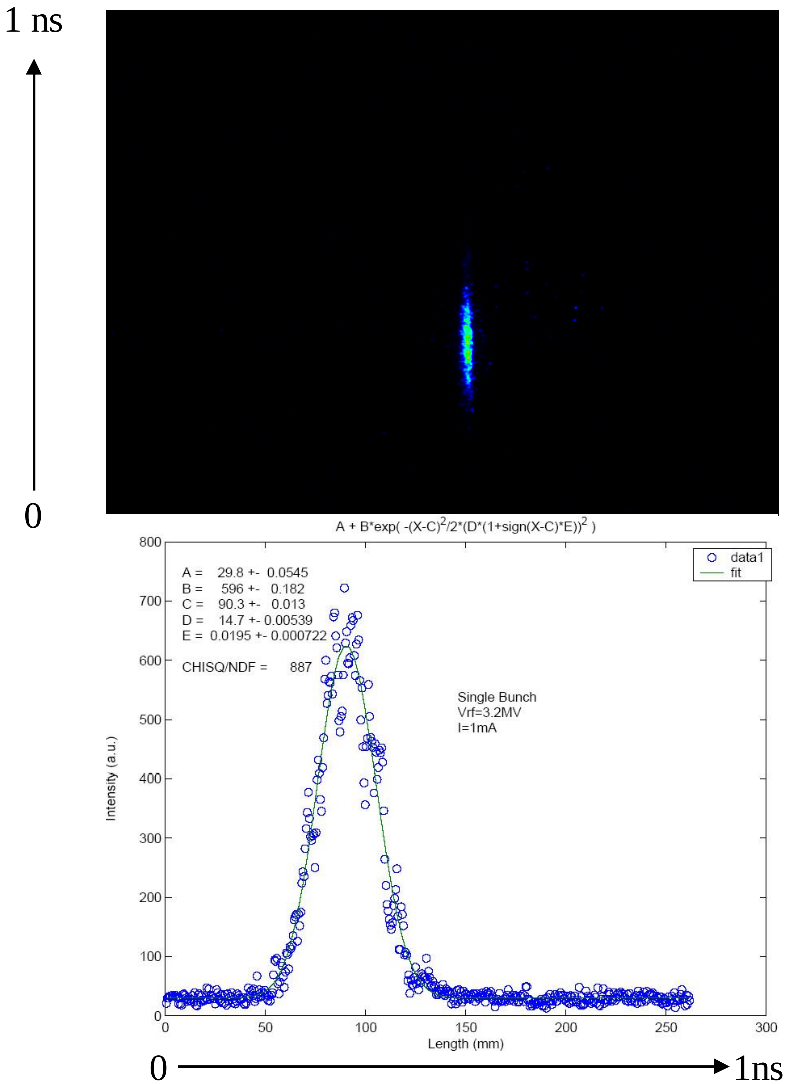
Injected charge oscillates about stored orbit and begins to damp, although time interval is an order of magnitude below the damping time.

Principle of the Streak Camera



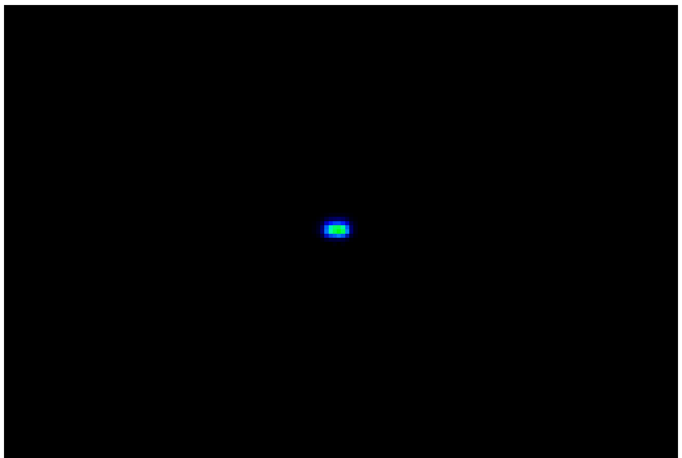
- Compare streak camera to gated camera:
  - Light→Photocathode→Electrons→MCP→Screen→CCD as before, but…
  - Remove: Vertical spatial information; replace with a tight focus and a thin slit.
  - Add: Accelerating electrode after the photocathode, followed by drift
  - Fast vertical sweep in drift space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

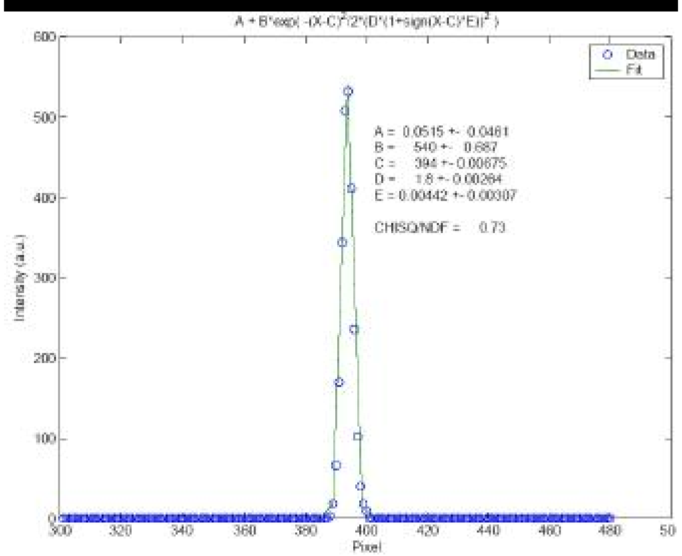
Single Bunch in LER, Triggered Sweep



- 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 Find Resolution





- A big spot when the sweep is off degrades time resolution.
  - Once sweep is on, source's height and time spread will mix.
- Adjust the 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 the 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 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.
      In Focus Mode, **always** attenuate the light heavily (~ 40 dB, also called an "optical density" or "neutral density" of 4) before opening the shutter.
  - The best time resolution is found with some noise visible in the image. Optimize by varying the attenuation and MCP gain to get the smallest size without too much noise.

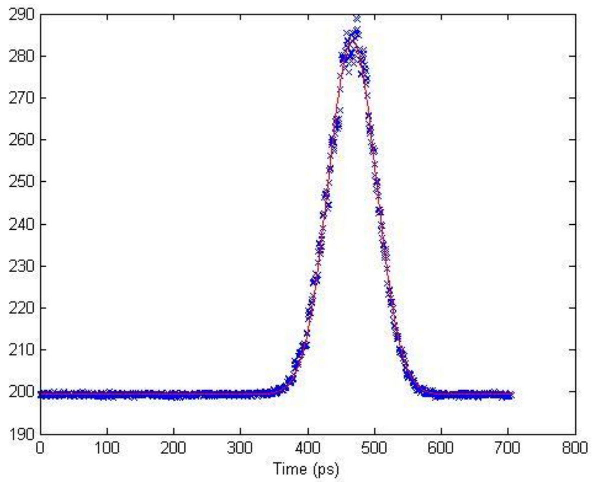
Jitter in the Sweep

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

Synchroscan Sweep

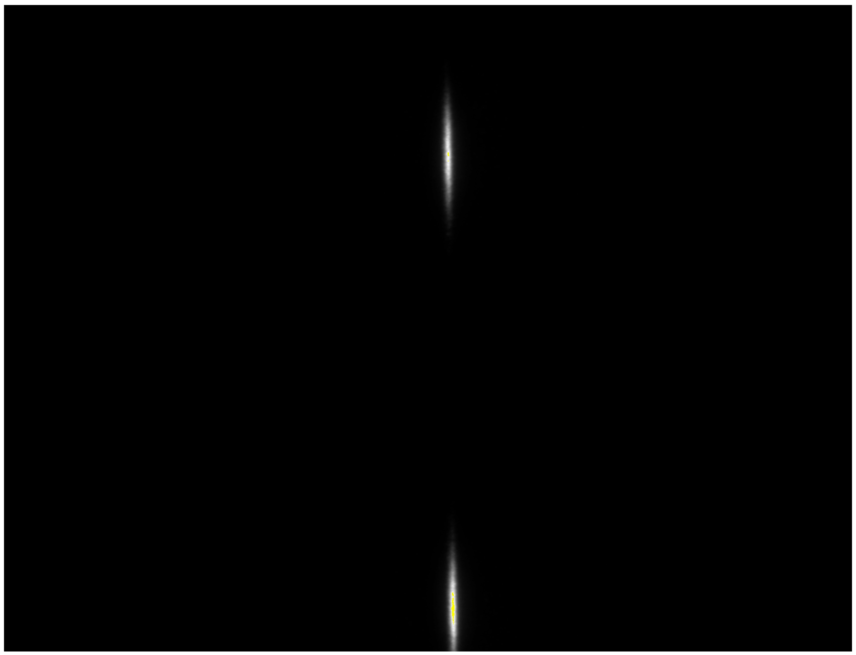
- For stable bunches stored in a ring, there is an alternative way to beat noise.
- Since the bunch is locked to the ring's RF frequency f_{RF}, a sine wave at $f_{sweep} = f_{RF}/n$ ($n \geq 1$) can sweep the beam without jitter.
  - Want only the linear part of the sine, near the zero crossing, on MCP.
    - Good for sweeps spanning short time scales: $\Delta t_{sweep} << 1/f_{sweep}$
  - 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 f_{sweep} for the resonator:
    - $f_{sweep} < 125$ MHz for our Hamamatsu C5680
    - Low compared to typical ring RF: $f_{RF} \approx 500$ MHz
  - PEP-II and SPEAR-3 use $f_{RF} = 476$ MHz
    - Our camera uses subharmonic $n = 4$: $f_{sweep} = 476/4 = 119$ MHz

Single Bunch in LER, Synchroscan



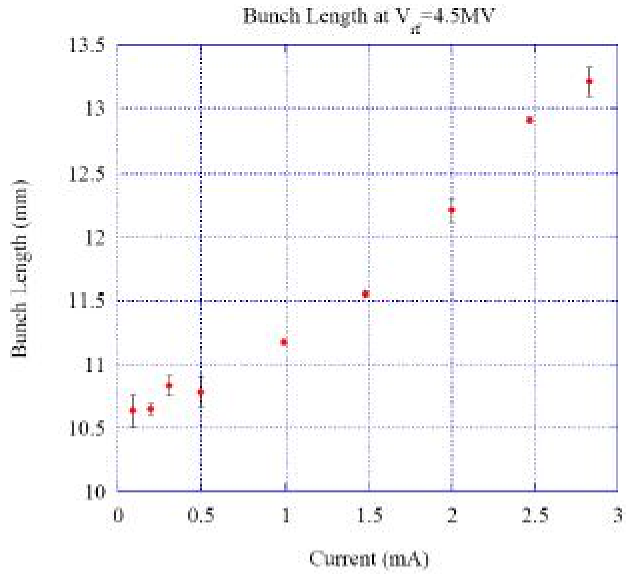
- Less noise in this image and profile than in single sweep.
- CCD accumulates signal over many sweeps (ms), and so the space charge is low.
  - Bright image without broadening or risk of damage.
- Direction of time axis in the image depends on the sine phase as the light arrives.
  - Sine sweeps up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

Mirror Images with Multiple Bunches



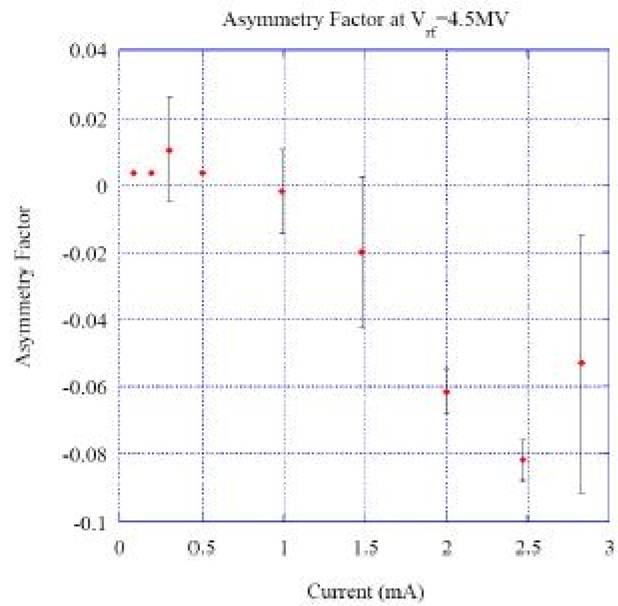
- If there is only one bunch per period of f_{sweep}, then all the images overlap.
- Since $f_{sweep} = f_{RF}/4$, we can have 4 bunches 90° apart in sweep phase.
  - We will see two if they arrive near the zero crossings.
    - For one, time axis goes up; for the other, down.
    - Add a small phase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

LER Synchroscan: Single Bunch, 4.5 MV



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

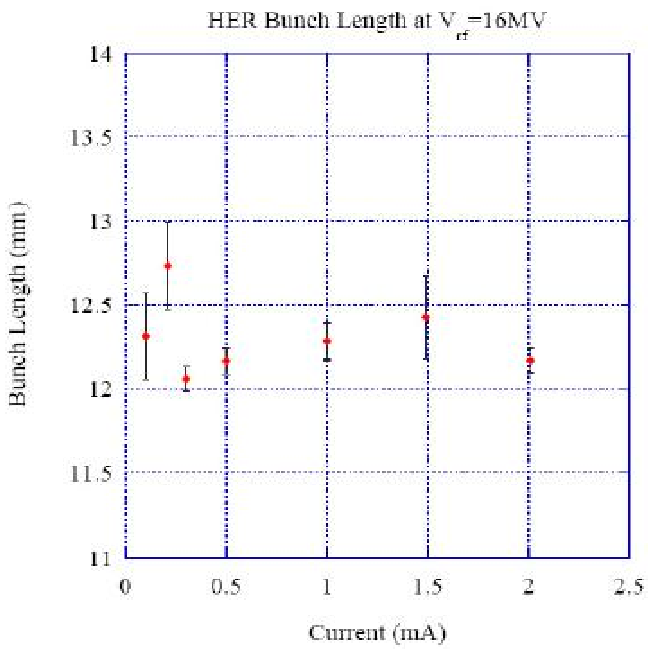
$$\sigma_z = \frac{\alpha c}{2\pi\nu_s}\left(\frac{\sigma_E}{E}\right) = 9.10\text{mm (zero current bunch length)}$$



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

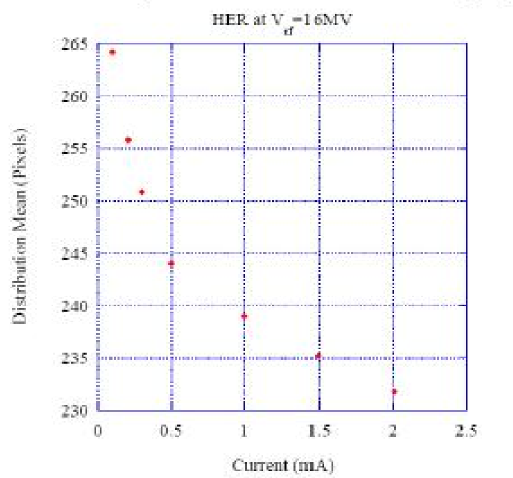
$$\frac{\sigma_E}{E} = 6.1\text{x}10^{-4} \qquad \alpha{=}2.41\text{x}10^{-3} \qquad \nu_s = 6.3867\text{kHz}$$

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

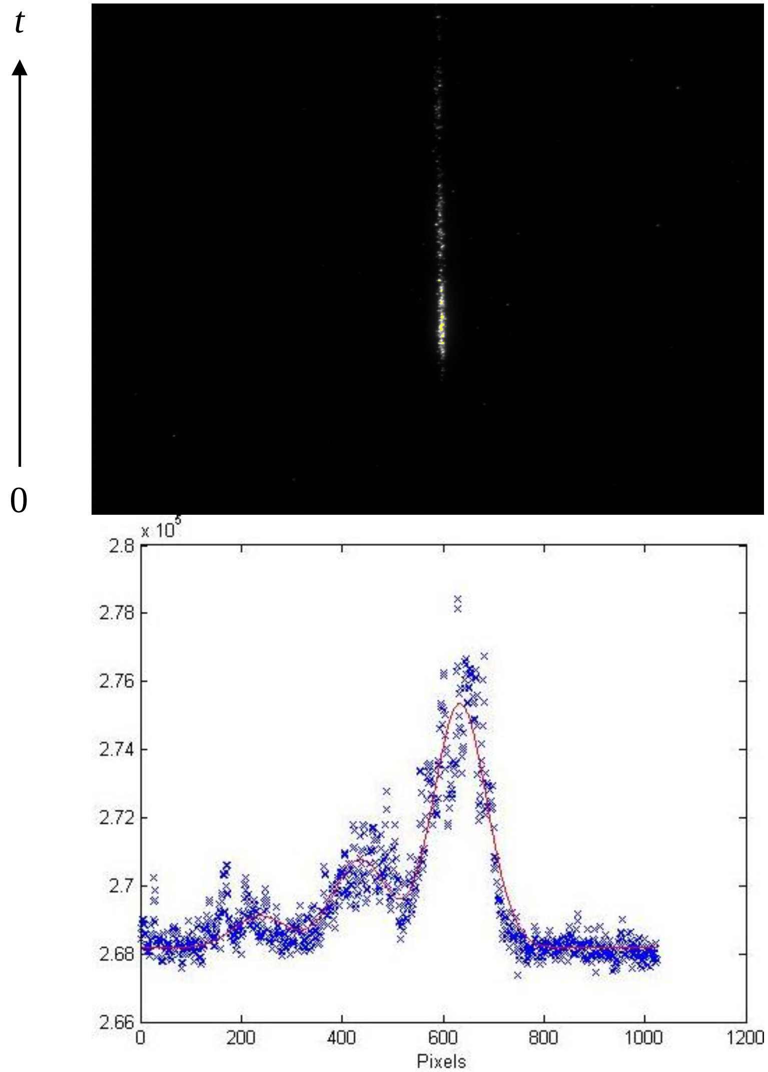
- No bunch length growth with current (except the 0.3mA data point is an aberration).

- ~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

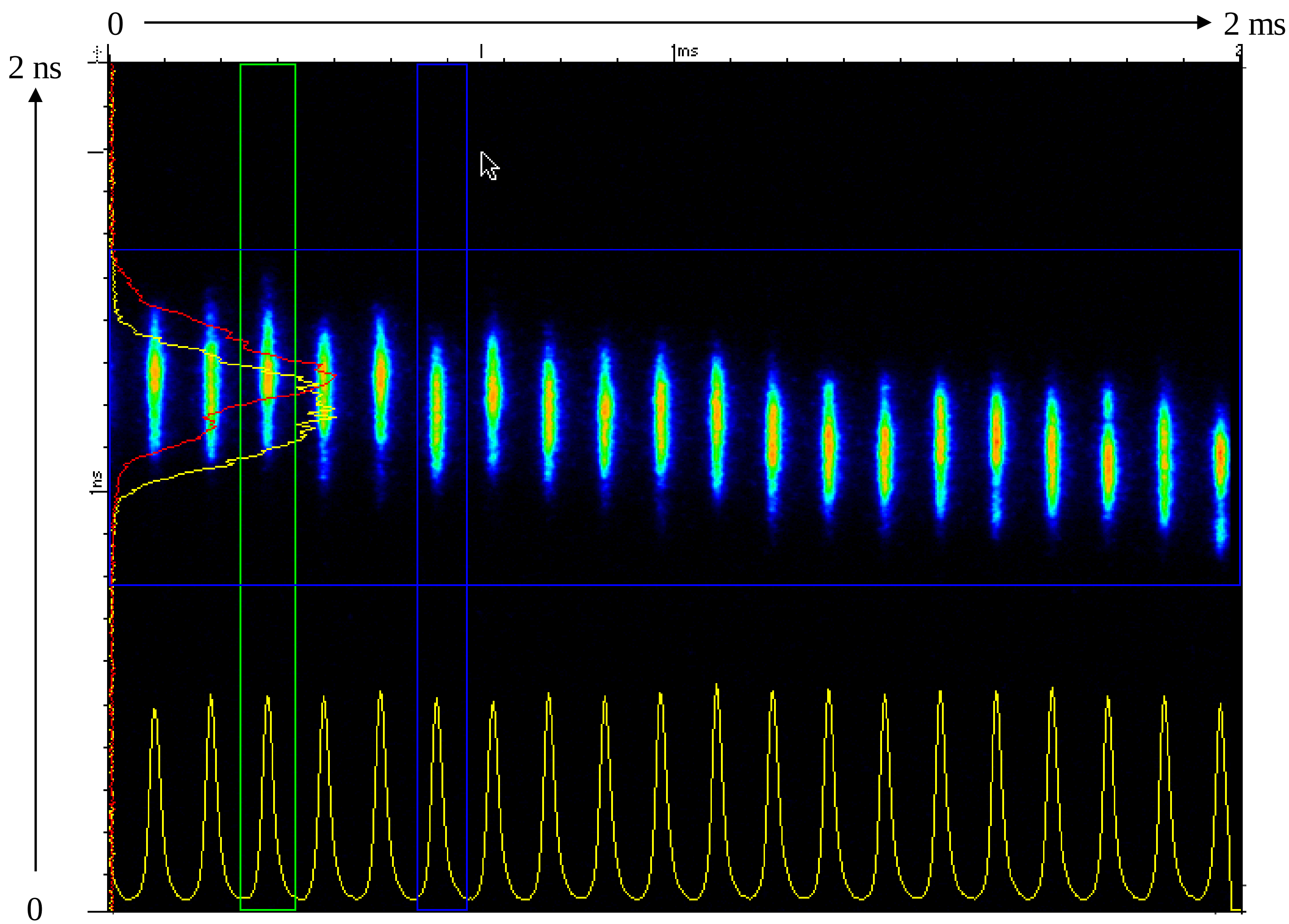


- Etalon: two parallel, partially reflective surfaces
  - We use a fused silica window, L=15.00 mm thick. Both sides have reflectivity $R=1-T\approx 0.5$.
- Insert etalon before streak camera.
  - Main peak is reduced by T^2
  - Internal reflection produces a series of echoes
    - Each smaller by factors 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

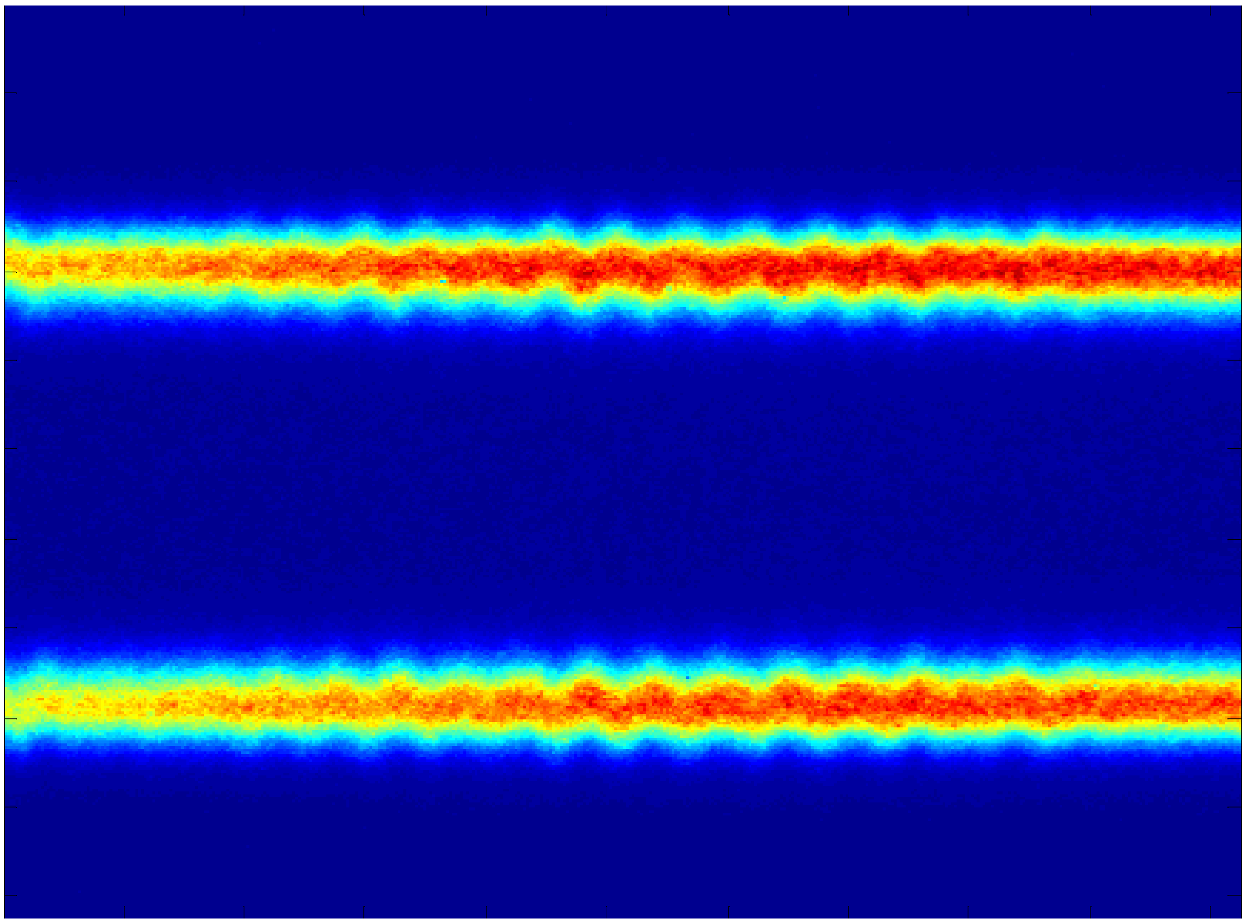
- Horizontal axis can have interesting spatial information.
  - Example: xt (or yt) coupling from a head-tail instability.
- But what if an instability changes along a bunch train or over several turns?
  - Add a second set of plates to sweep the beam horizontally.
  - This deflection is slow, spanning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

SPEAR-2, 1998: Quadrupole Oscillation



SPEAR-3, 2007: 10-ms Dual Sweep

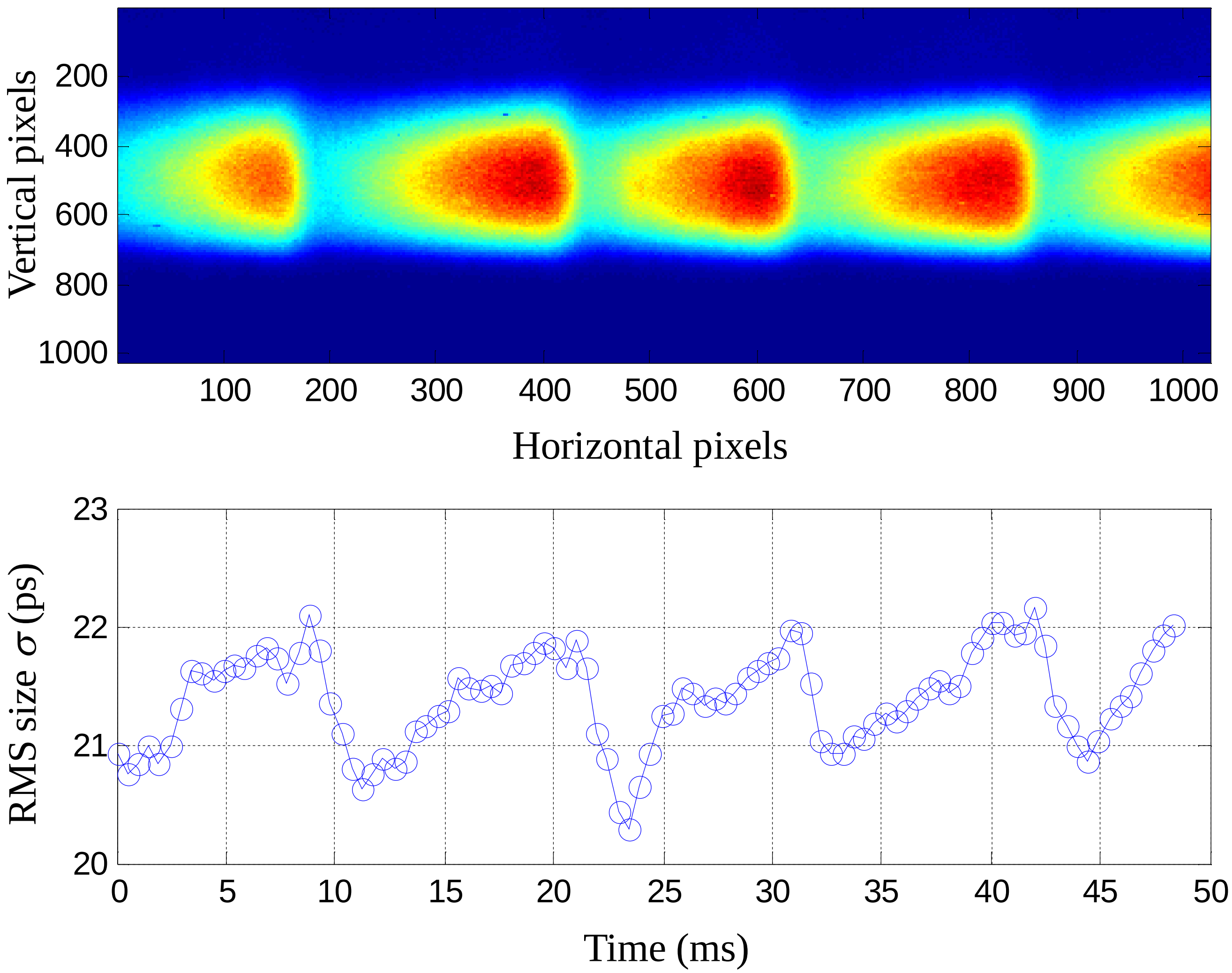
Instability during tests of a short-bunch (low-α) lattice



160 ps

10 ms

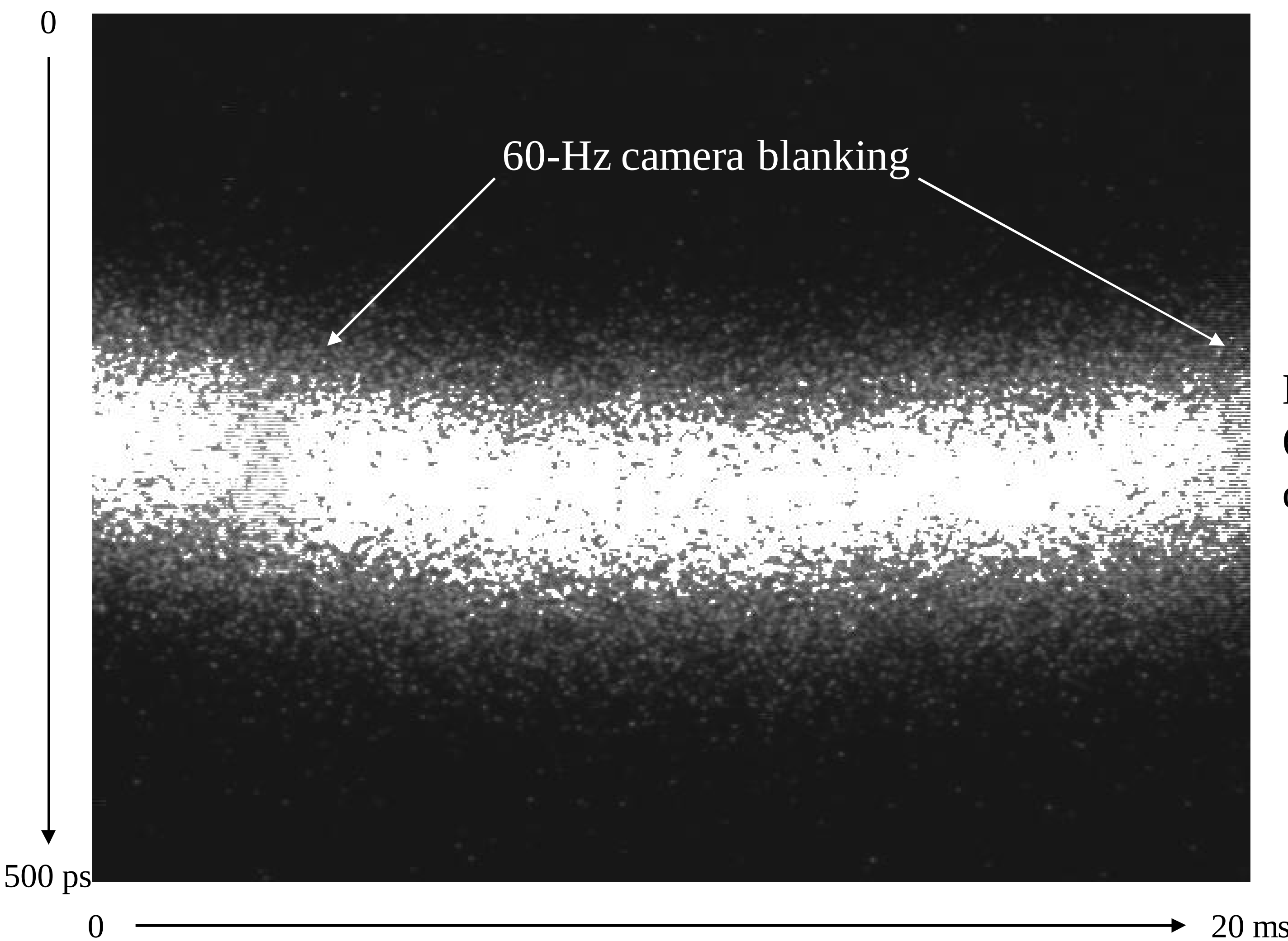
SPEAR-3, 2008: Bursting Instability



Longitudinal Motion During Aborts?

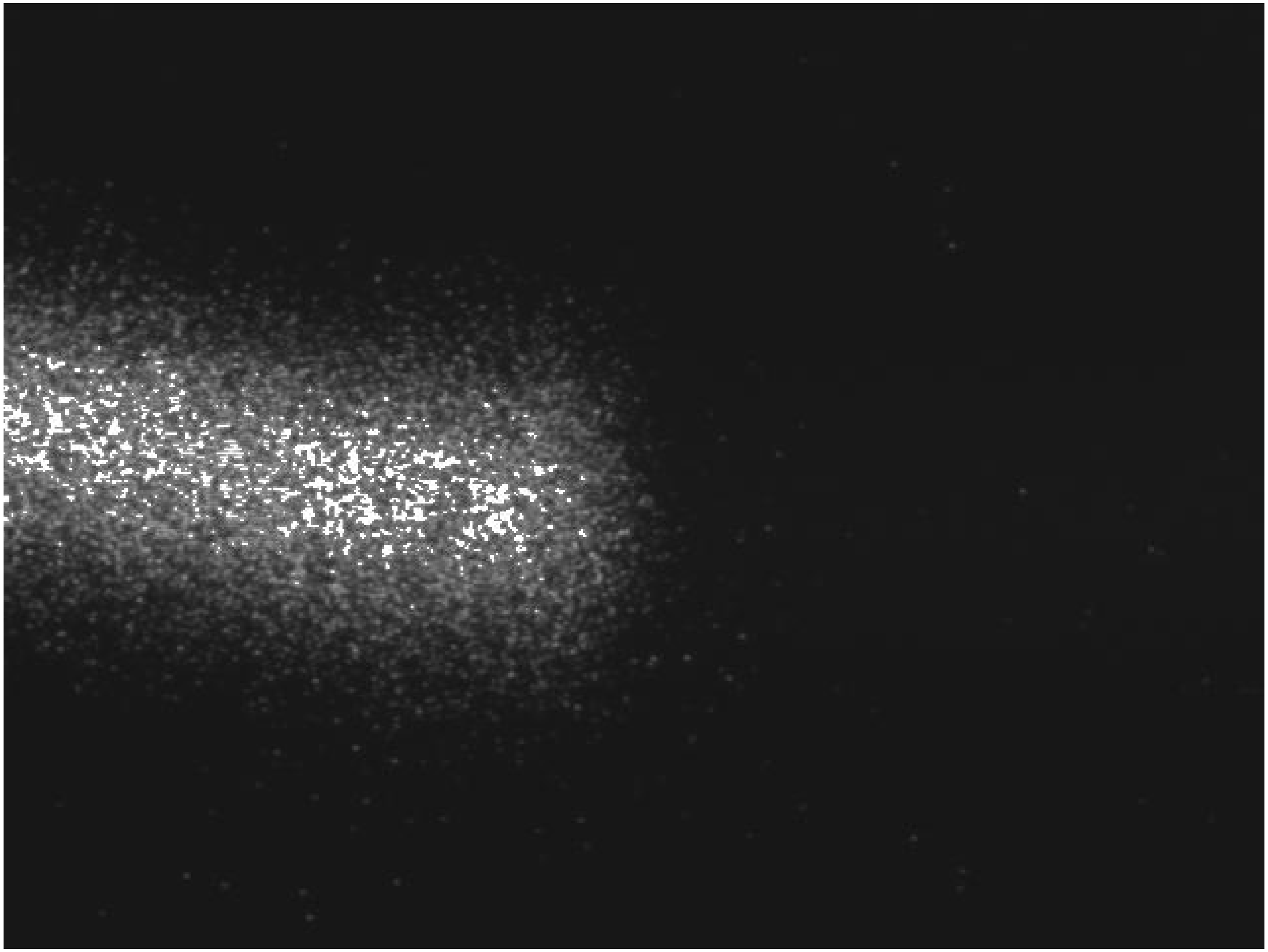
- LER abort spectra showed $2\nu_s$: Quadrupole motion?
- Dual-axis set-up:
  - Vertical:
    - 500-ps triggered time sweep
    - Image one bunch every 250 μs by retriggering the fast sweep
      - 80 images across the screen, with overlap, making a stripe
  - Horizontal:
    - 20-ms sweep.
    - Repeat every 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

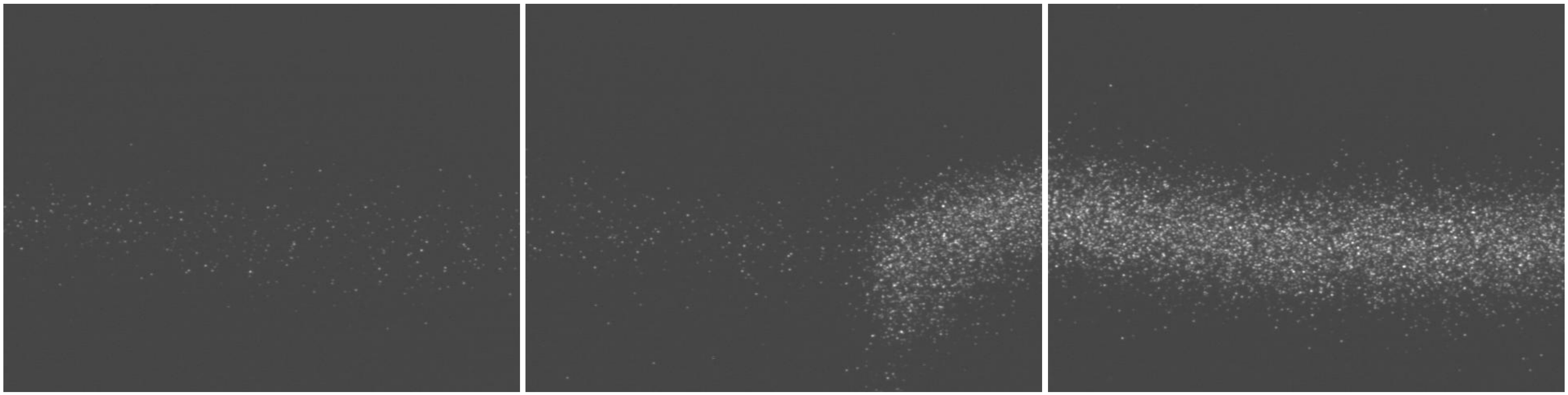


Bowed envelope: 60-Hz harmonic on the trigger?

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.

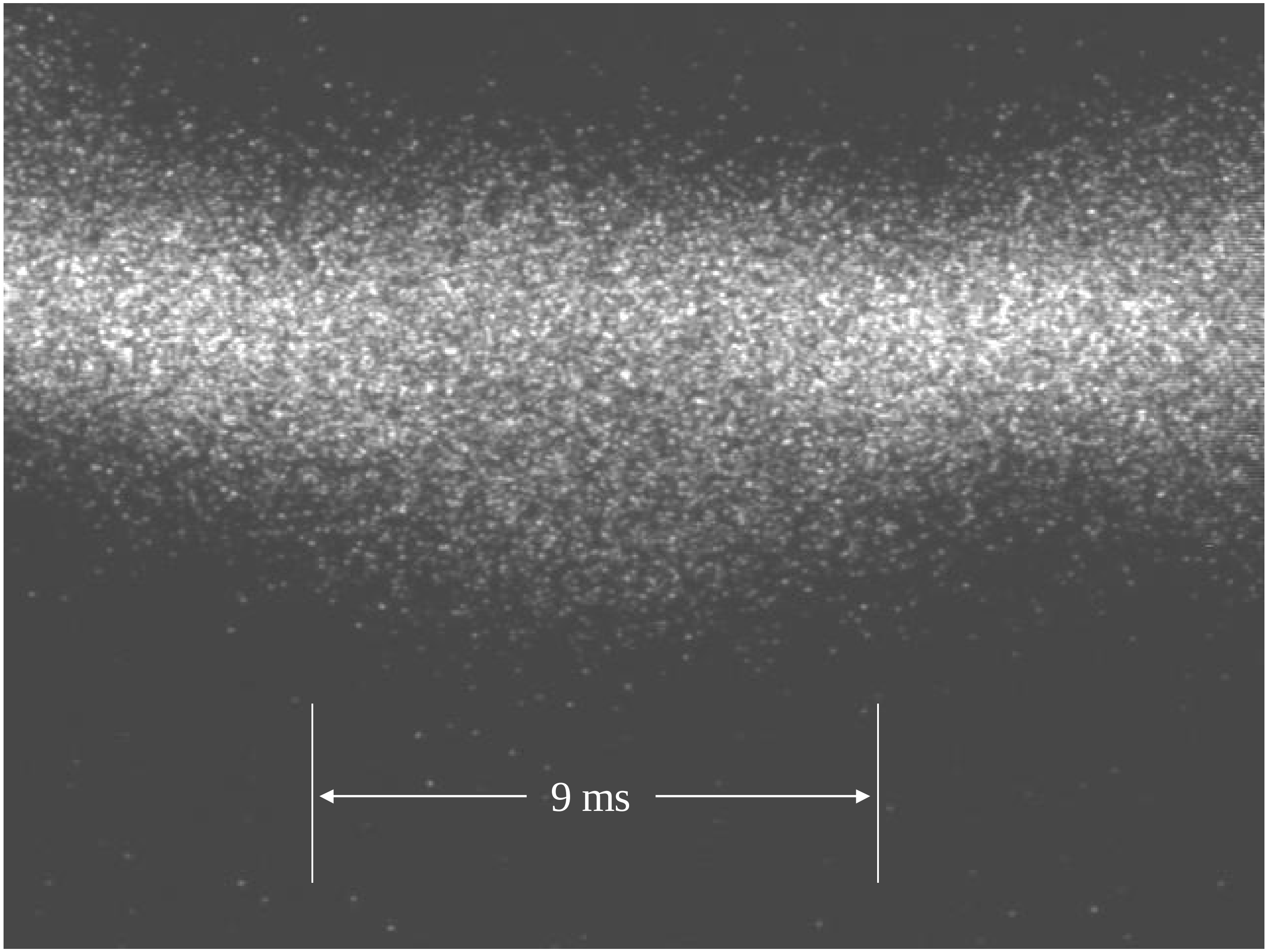
Image brightens.

Oscillation of injected
charge. 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 various bandwidths.
  - We used a blue bandpass filter centered at 450 nm, with width 30 nm FWHM.
  - By limiting the bandwidth, the effect of dispersion was not significant in measuring the 30-ps bunch.

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

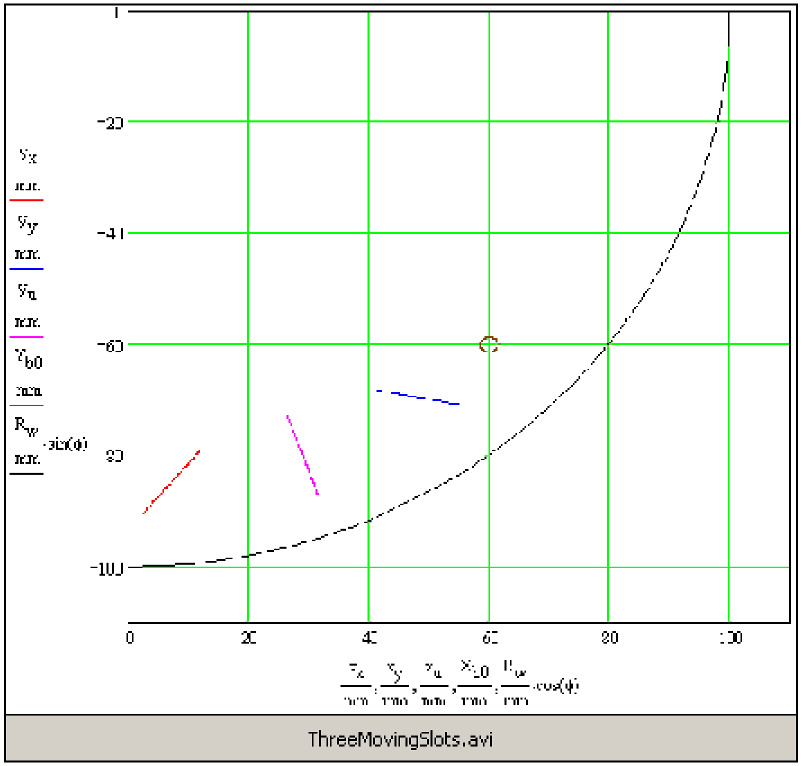
Turn by Turn: Fast-Framing Camera

- A burst of fast exposures is saved in the camera's memory, then uploaded over gigabit ethernet
- From 1,000 to 100,000 frames/s, depending on resolution
- Will make turn-by-turn measurements at the LHC (89 μs/turn)
  - No fast gate: the whole bunch train is imaged.

Frame Rates	Resolution 4:3	Standard 2 GB	Maximum 4 GB	Resolution 1:1	Standard 2 GB	Maximum 4 GB
1000 fps	1504 x 1128	1.26 s	2.52 s	1120 x 1120	1.71 s	3.42 s
2000 fps	1056 x 792	1.28 s	2.56 s	896 x 896	1.34 s	2.68 s
5000 fps	640 x 480	1.40 s	2.80 s	544 x 544	1.45 s	2.80 s
10'000 fps	416 x 320	1.61 s	3.22 s	352 x 352	1.73 s	3.46 s
20'000 fps	256 x 192	2.18 s	4.36 s	224 x 224	2.13 s	4.32 s
30'000 fps	192 x 152	2.44 s	4.88 s	160 x 160	2.78 s	5.56 s
50'000 fps	96 x 72	6.10 s	12.20 s	96 x 96	4.60 s	9.20 s
100'000 fps	32 x 24	23.97 s	47.94 s			

Bunch by Bunch: Rotating Mask

- A plan (never built) 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.
- Now being built for visible light from the LHC
  - Thin stainless steel rather than thicker Pt:Ir



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