Non-Invasive Energy Spread Monitoring for the *JLAB* Experimental Program via Synchrotron Light Interferometers*

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Experimental Requirements

- In order to resolve fine mass splitting in hyper-nuclear states, the experimental requirement on the energy spread is:
$$\frac{\sigma_E}{E_{beam}} < 3 \times 10^{-5}$$
- Maximum dispersion [D] in the transport line: 4m $<$D $<$ 8m
- The transverse beam size, σ_{beam}, measured in a dispersive location has two sources:
$$\sigma_{beam} = \sqrt{\sigma_\beta^2 + \sigma_\delta^2},$$
where $\sigma_\beta = \sqrt{\epsilon\beta}$ is the beam's betatron size and σ_δ is the size due to dispersion.
- The energy spread is:
$$\frac{\sigma_E}{E_{beam}} = \frac{\sigma_\delta}{D}$$
- ignoring the betatron contribution (which is safe to do when $\frac{\sigma_\beta}{\sigma_\delta} << 1$) the upper limit on the energy spread is:
$$\frac{\sigma_E}{E_{beam}} < \frac{\sigma_{beam}}{D}$$
- Transverse beam size due to energy spread is:
$$D \cdot \frac{\sigma_E}{E_{beam}} = \sigma_{beam}$$

Presentation of the Problem

- While the energy spread specification is set at, $3 \cdot 10^{-5}$, the expected energy is spread will be lower, perhaps as low as $2.0 \cdot 10^{-5}$.
- Need to measure transverse beam sizes of order $4m(2 \cdot 10^{-5}) = 80\mu m$ in a location with 4m of dispersion.
- Experimenters want this information continuously to make sure that the energy spread is within specifications during data taking.
- Non-invasive or nearly non-invasive technique is required.
  1. Optical Transition Radiation [OTR] Viewer with very thin Carbon foil [200nm]
  2. Direct imaging of synchrotron light
  3. Synchrotron Light Interferometry

Other parameters:

- CW beam current: $10\mu A < I < 100\mu A$
- Beam Energy: $3GeV < E < 5GeV$

OTR viewer and direct imaging of Synchrotron Light Spot

- The 200nm Carbon foil does introduce some beam scattering which is undesirable to the experimenter.
- Synchrotron light is confined within a cone, $\theta_c < 1/\gamma = 10^{-4} radians$ [E=5GeV], for the critical frequency. This cone acts as an aperture and causes diffraction.
- Optical light is far from the critical frequency [E = 5GeV], properties of the optical portion of the synchrotron light spectrum are independent of γ, and depend only on the bending radius and wavelength[Hofmann].

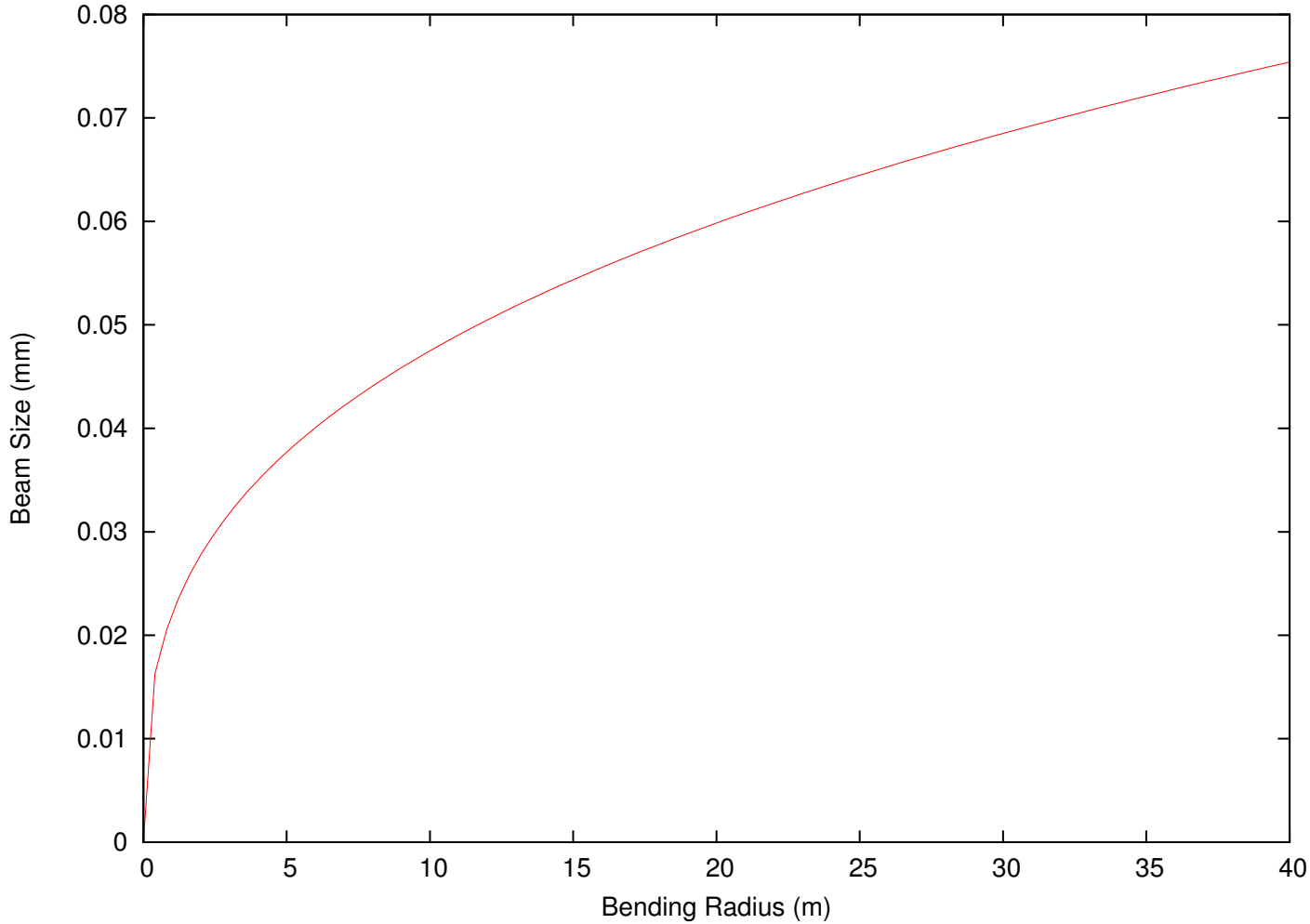
$$\psi_{rms} = 0.45 \left(\frac{\lambda}{\rho}\right)^{\frac{1}{3}}$$

- Bending radius at maximum dispersion: $\rho = 40$m
- Wavelength of synchrotron light matched to ccd camera sensitivity: 630nm
- This results in a cone with angular range of 10^{-3}radians and a diffractive limit of:

$$\sigma_{diffractive} = 0.3(\lambda^2 \rho)^{\frac{1}{3}} = 75\mu m$$

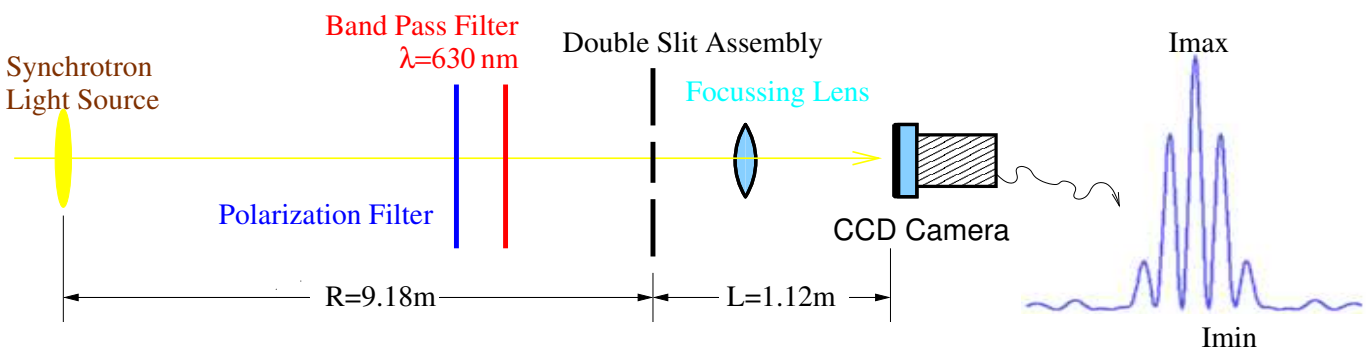
Diffractive limit vs Bending Radius

$$\sigma_{diffractive} = 0.3(\lambda^2\rho)^{\frac{1}{3}} = 75\mu m$$



Synchrotron Light Interferometer [SLI]

- ✔ Pioneered by T. Mitsuhashi at KEK, 2004 Faraday Cup Award winner.
- ✔ Double Slit Interferometry (similar to Michelson stellar interferometer) to achieve resolution beyond the diffractive limit.
- ✔ Completely non-invasive, no restrictions on beam power.

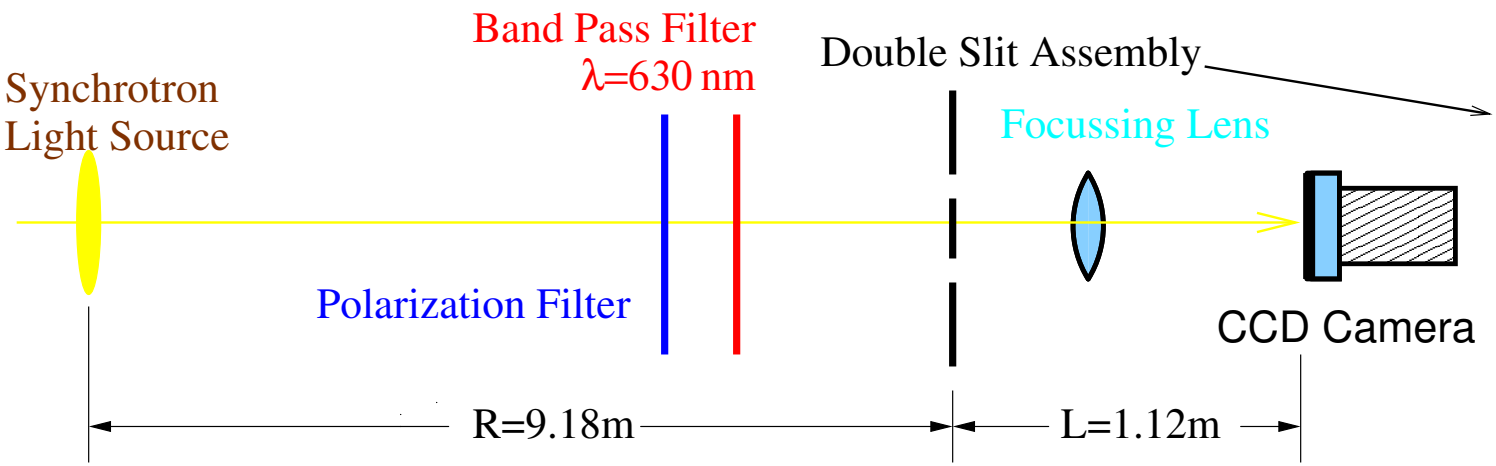


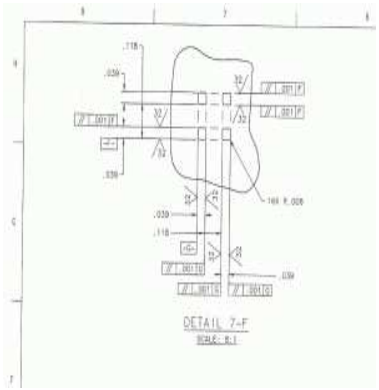
- ✔ Beam size is a function of the visibility on the interference pattern:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}.$$

- ✔ Note: I_{min} and I_{max} depend on the intensity [ADC], pixel size is not important [need small enough pixel to determine the minimum and maximum of the interference pattern].
- ✔ V is a ratio, most systematics involved in digitization cancel

SLI continued:





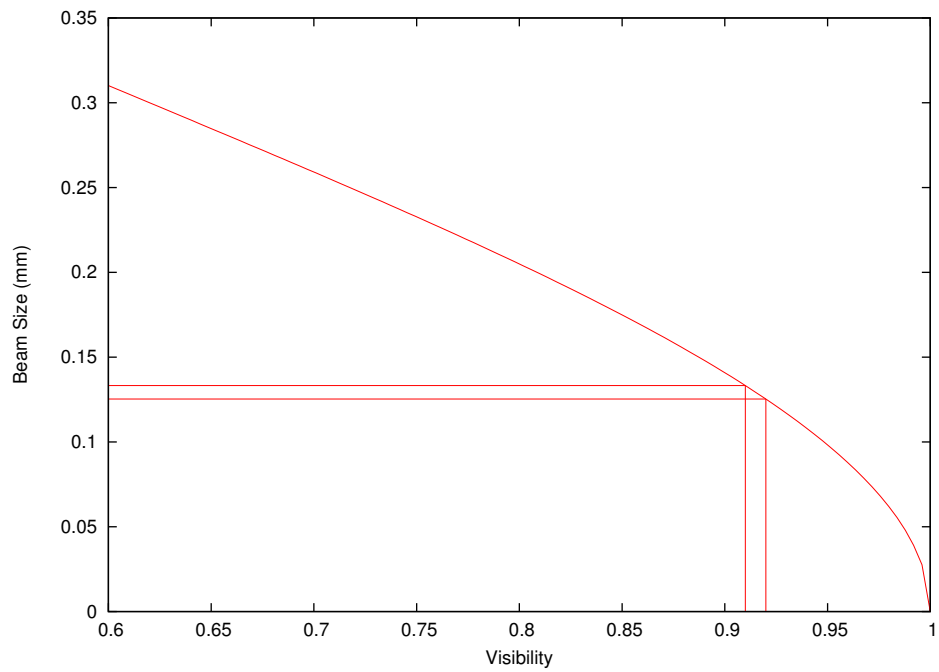
- ✔ distance between slit centers is d=3mm.
- ✔ For **Gaussian** beam profile:

$$\sigma_{beam} = \frac{\lambda_0 R}{\pi d}\sqrt{0.5\ln(1/\bigvee)}$$

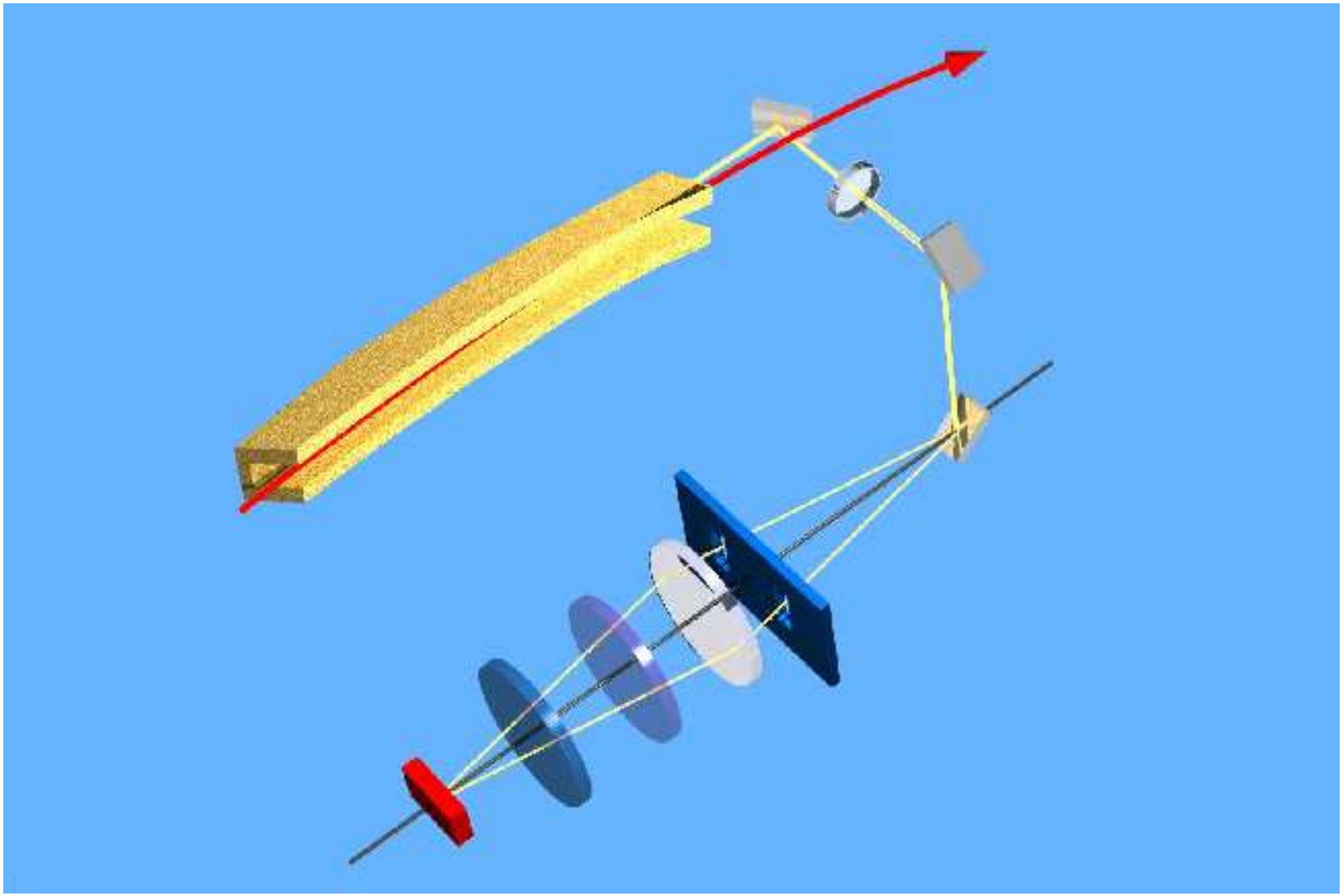
- ✔ Cooled astronomical CCD camera, needed for the very low light yield.
  - ✔ automatic background subtraction
  - ✔ variable integration time [no need for neutral density filters].

Resolution

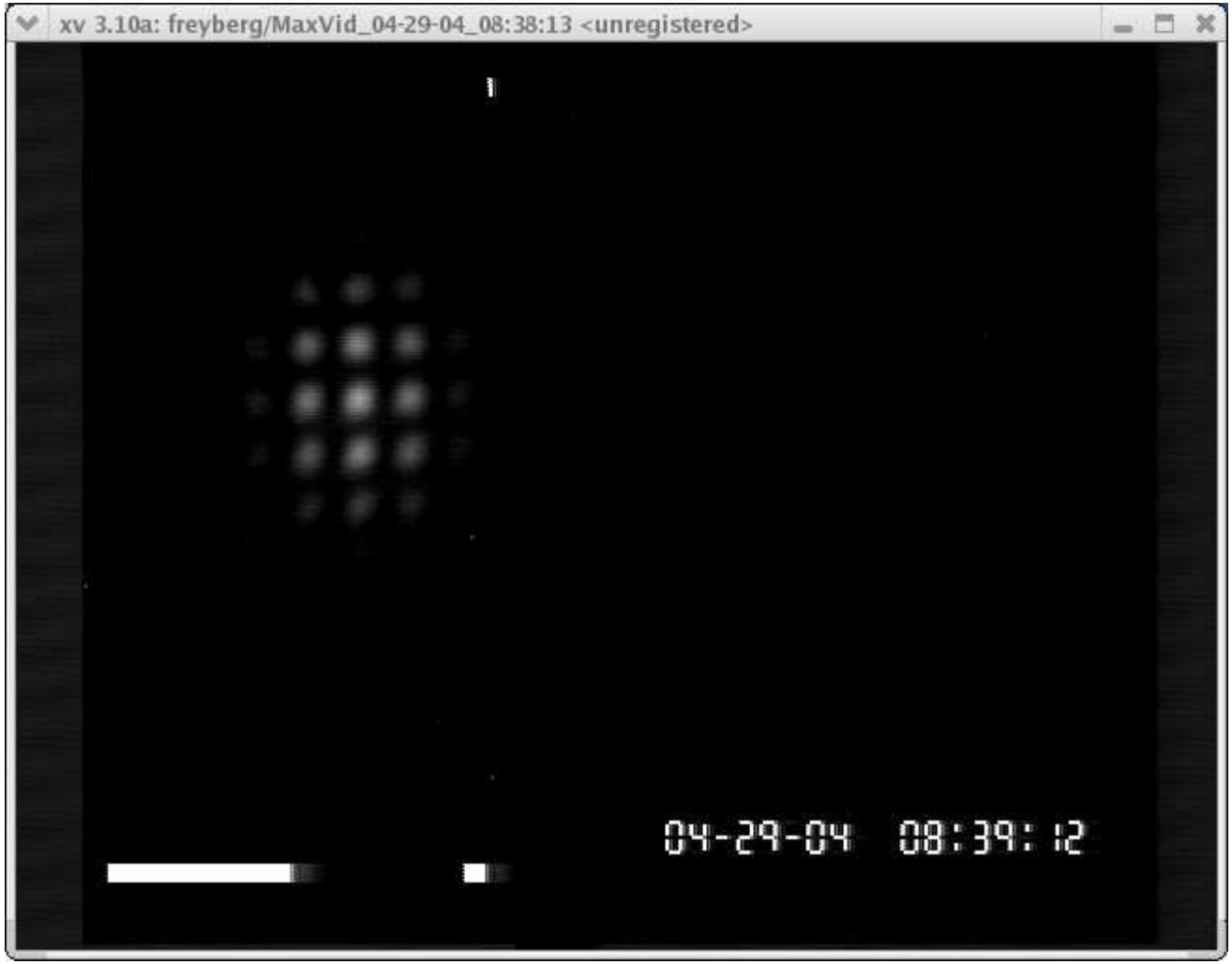
- Beam width resolution is determined by how well the $\bigvee$ is measured.
- On-line fits to the interferogram are performed; I_{min} and I_{max} are determined from the results of the fit.
- Frame grabber has 8bits [maximum value 255]
- 1% precision on $\bigvee$ gives an error of 10μm for 120μm beam widths. The resolution gets worse as the $\bigvee \rightarrow 1$.



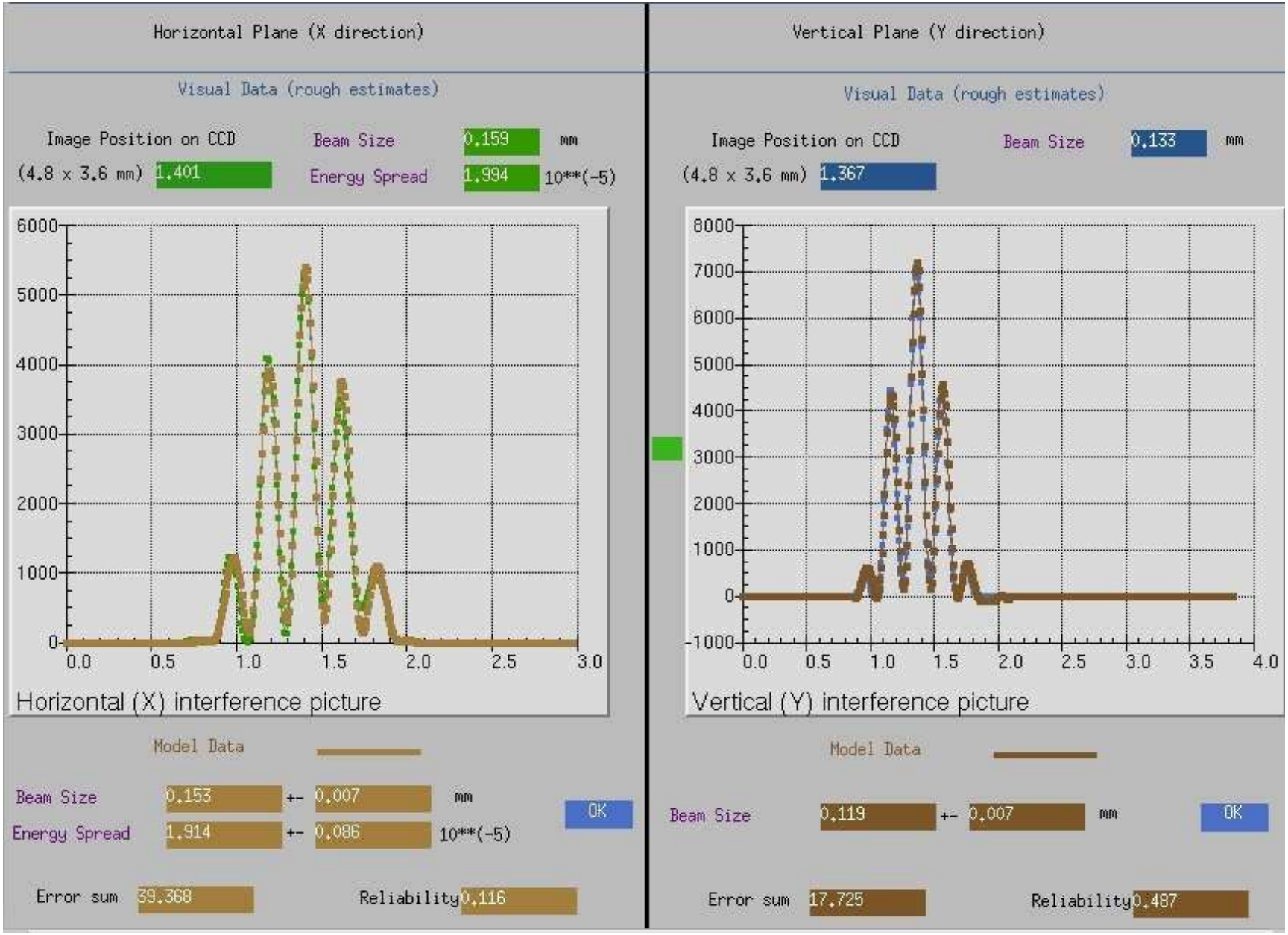
SLI 3D view



SLI Image

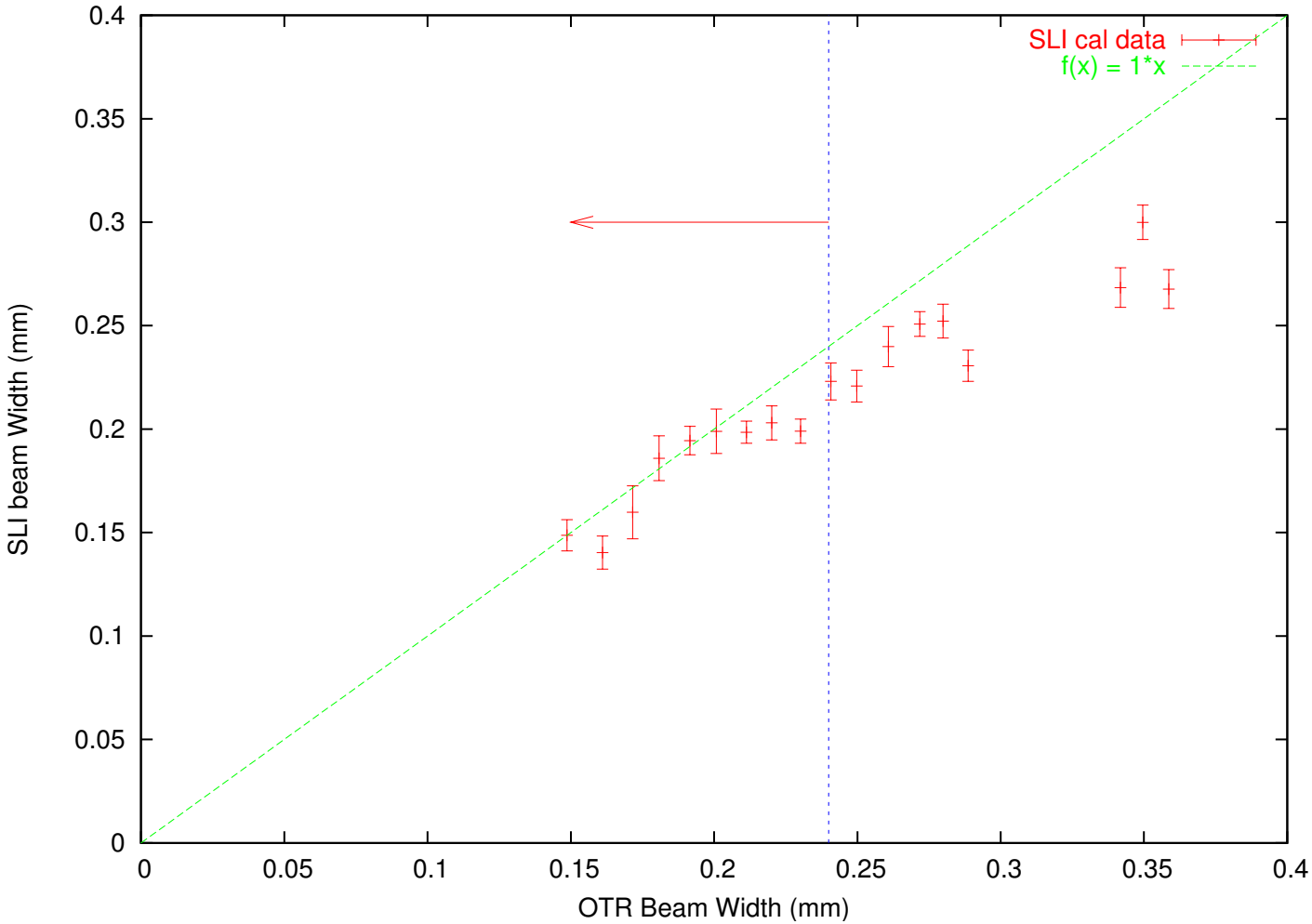

xv 3.10a: freyberg/MaxVid_04-29-04_08:38:13 <unregistered>
04-29-04 08:39:12

SLI screen


Horizontal Plane (X direction)
Visual Data (rough estimates)
Image Position on CCD
(4.8 x 3.6 mm) 1.401
Beam Size 0.159 mm
Energy Spread 1.994 10**(-5)
Horizontal (X) interference picture
Model Data
Beam Size 0.153 +- 0.007 mm
Energy Spread 1.914 +- 0.086 10**(-5)
OK
Error sum 39.368
Reliability 0.116
Vertical Plane (Y direction)
Visual Data (rough estimates)
Image Position on CCD
(4.8 x 3.6 mm) 1.367
Beam Size 0.133 mm
Vertical (Y) interference picture
Model Data
Beam Size 0.119 +- 0.007 mm
OK
Error sum 17.725
Reliability 0.487

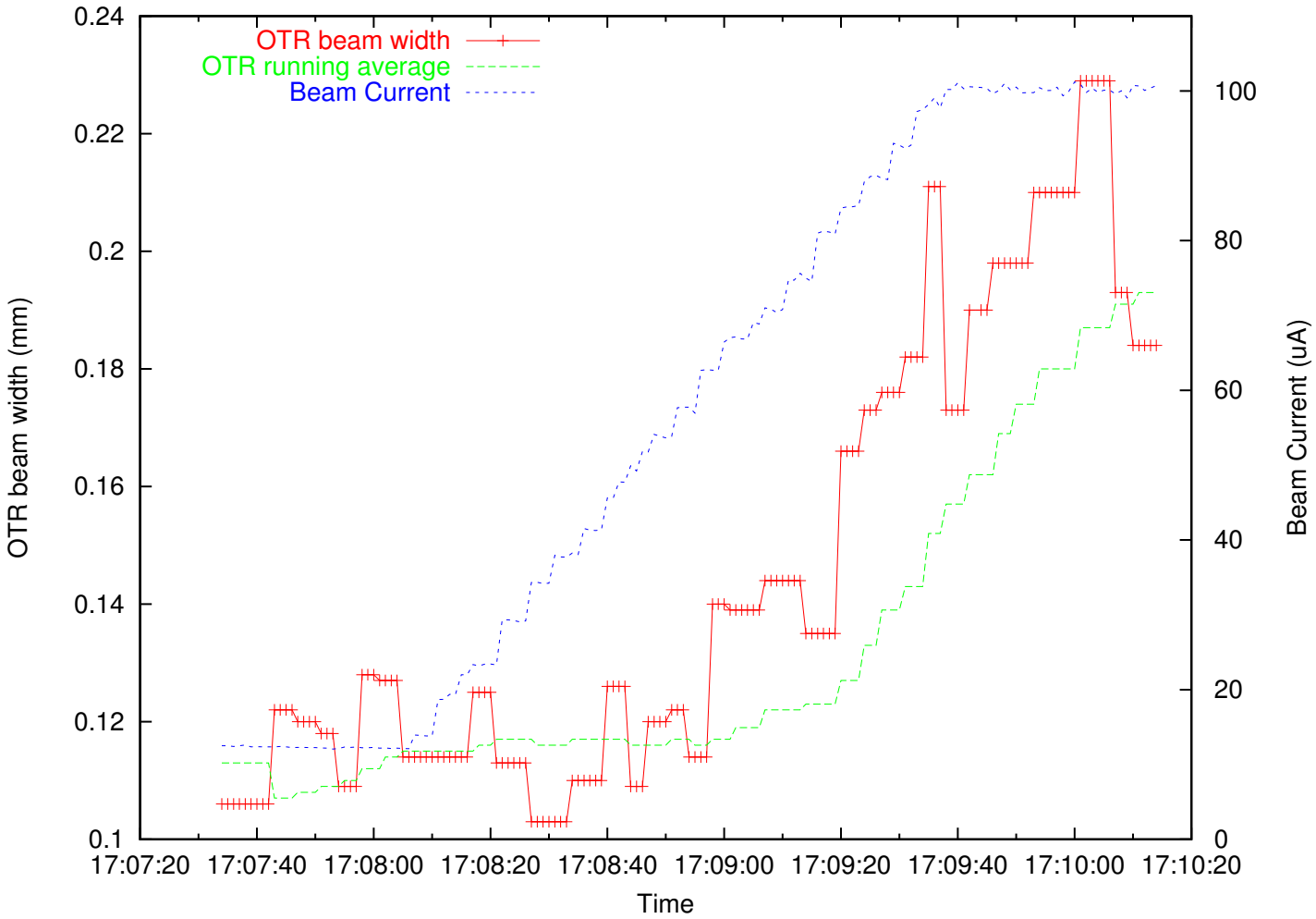
SLI Beam Width Comparison with OTR Beam Width

- ✔ The SLI beam width is compared to the width as measured by the OTR.
- ✔ No corrections to the SLI beam width extraction need to be performed.



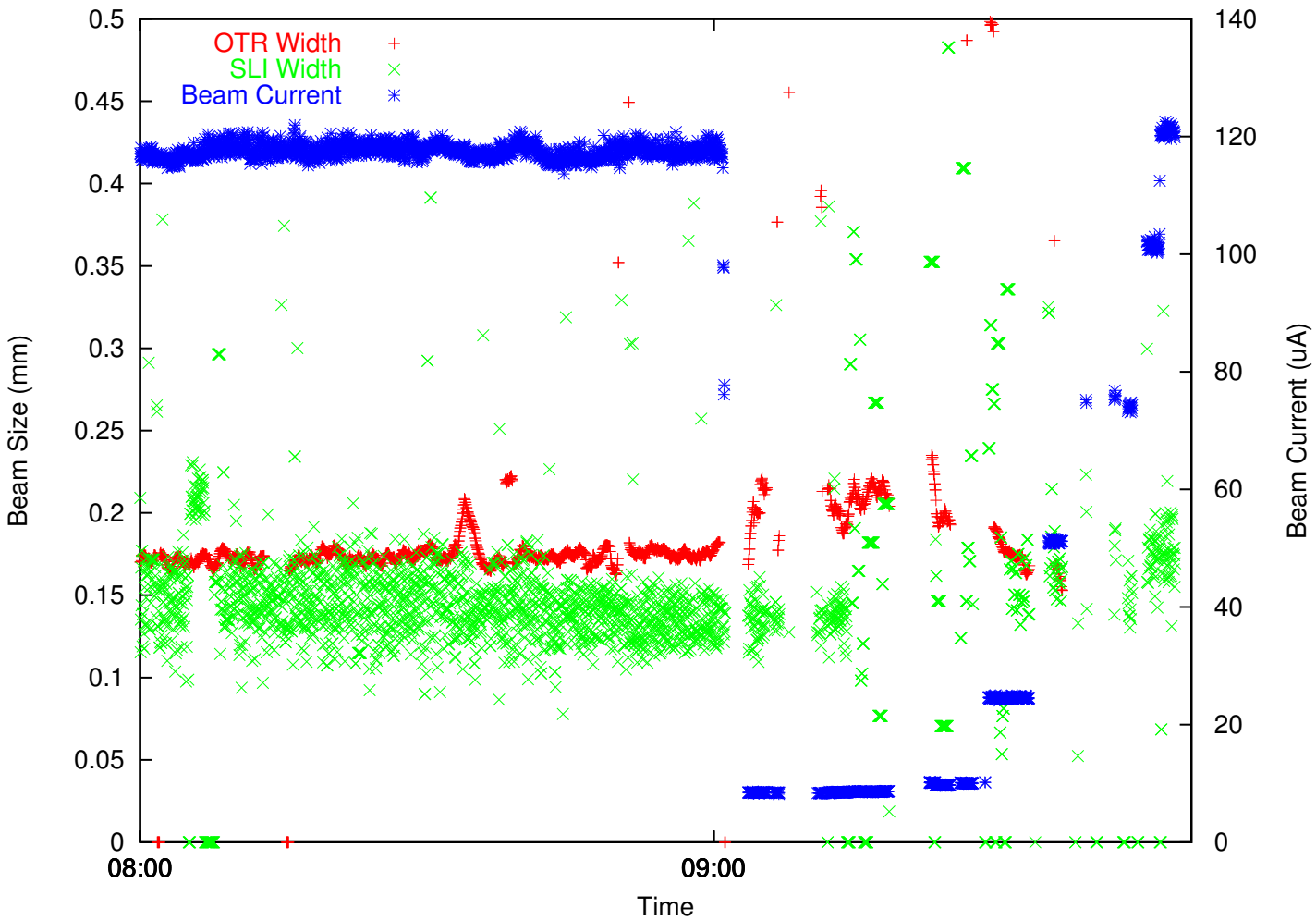
Energy Spread vs Beam Current

Initially some RF cavities were not regulating well and would add energy spread at large beam currents. These measurements were made with the OTR [SLI was in the process of being commissioned].



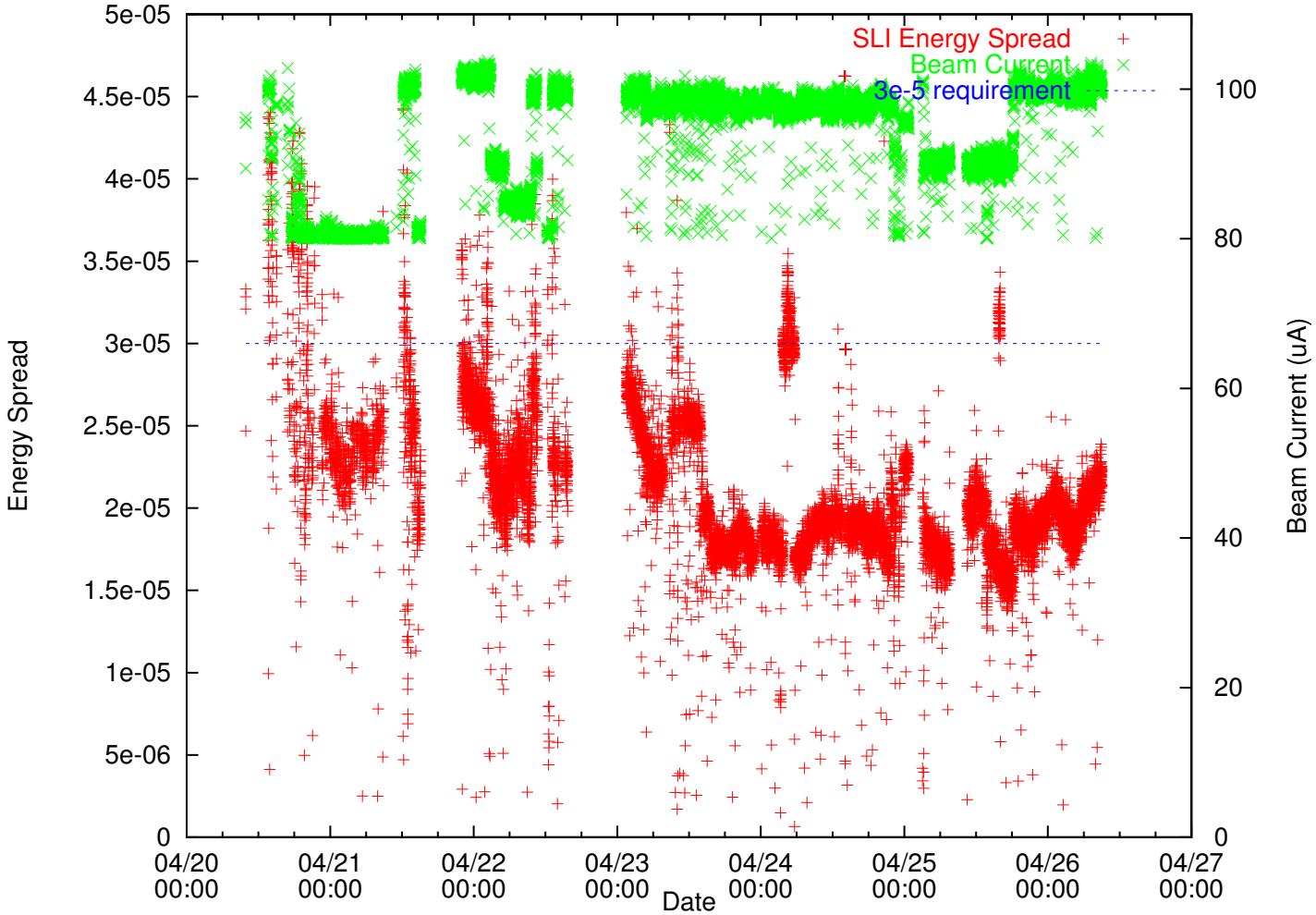
Energy Spread vs Beam Current (After RF has been fixed)

Beam width versus beam current after of few days of fine tuning the RF system. No beam loading effects observed.



Energy Spread Stability

The improvements/changes are all related to changes to the phasing of the machine or detuning bad RF cavities.



Conclusions

- ✔ Real-time continuous non-invasive Energy Spread Monitor of high power CW electron beam at all beam currents.
- ✔ Beam size as measured by Synchrotron Light Interferometry has different systematics than other techniques [OTR, wire scanners].
- ✔ Minimum spot size determined by how well the visibility can be measured.

Visibility Precision	Minimum Spot size
1%	40μm
0.5%	30μm
0.1%	15μm

- ✔ Use fitting to achieve best possible determination of the visibility.

ISSUES:

- ✘ In vacuum mirror damaged due to beam strikes. Plan to replace with all metal mirrors.
- ✘ Alignment of the grid much more difficult then alignment of slits. Probably simpler to use a beam splitter and two cameras.