Beam Diagnostics and Instrumentation

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Jefferson Lab

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- My Route to a career in Accelerator Physics
- Beam parameters and customers
- Making the electrons talk
- Some recent instrumentation
  - Synchrotron Light Interferometer
  - Beam Charge Calorimeter for Current Calibrations

CV

Ph.D. High Energy Physics Carnegie-Mellon University. Thesis Topic: Charm Production in 800GeV/c Proton-emulsion interactions.

Post-Doc CLEO experiment. Charm and Beauty Decays, V_{cb},V_{cd}....

Staff Scientist Hall-B JLAB. electron scattering with a Large Acceptance Spectrometer. Main responsibility: Beam line instrumentation. As well as some software.

Staff Scientist Accelerator Division JLAB: Beam diagnostics and instrumentation.

Beam Parameters

$x, x', y, y', \tau, \delta$ six-dimensions that define the beam. τ is the time or phase of the beam arrival andδ is the energy difference from the expected energy.

x, x', y, y' are the transverse dimensions, controlled by corrector and quadrupole magnets. Monitored by beam position monitors.

τ,δ are the longitudinal dimensions, controlled by modifying the pathlength of the machine [changing the length of a “dog-leg”] and by keep the accelerating cavities at the correct phase and energy so the beam energy is consistent with the magnet strengths.

Beam polarization is also important at JLAB. The electron beam is polarized at the levels greater then 85%. The electron helicity are flipped at a 30Hz rate for experimentalist as they often wish to measure the cross section differences.

Customers

Accelerator Operations/Physics

- Typically require measurements at the 10% level [or 2 sigma level].
- Positions at the 0.1mm level. Keep it in the beam pipe!!!
- Transverse measurements dominant.
- Longitudinal measurements difficult, important at the front-end of the machine.

Experimentalist (particle/nuclear physicists)

- Always need more resolution and bandwidth then before.
- Absolute currents for cross section measurements.
- Beam Helicity correlated measurements for parity experiments. Position differences at the nano-meter level.
- Beam halo at the ppm level.

Making the electrons talk-interactions in material

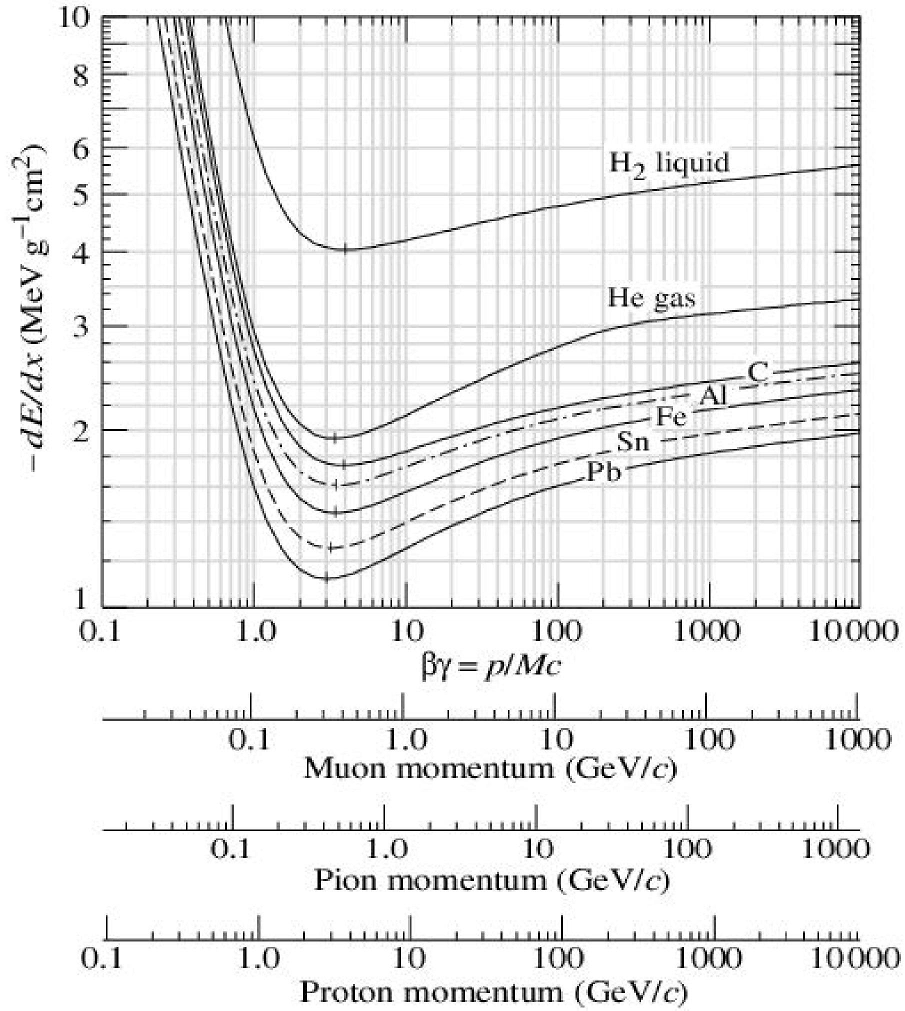
- Multiple Scattering
- Energy Loss/Deposition
- Secondary Electron Emission
- Scintillation/Fluorescence
- Gas Ionization
- Beam Absorption

JLAB Diagnostics the utilize Beam-Material interactions:

✔ Viewers: Fluorescent screens
✔ Wire Scanners: Secondary emission or multiple scattering
✔ Faraday cup: Absorption
✔ Ion Chambers: ionization
✔ Beam Loss Monitors: Multiple scattering

Bethe-Bloch Equation:

Describes the energy loss for particles more massive then electrons as they traverse material: $-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{max}}{I^2} - \beta^2 - \frac{\delta}{2}\right]$



Radiation Length:

Mean distance over which the electron will loose 1/e of its energy. And it is 7/9 of the mean free path for photons to travel before pair converting.

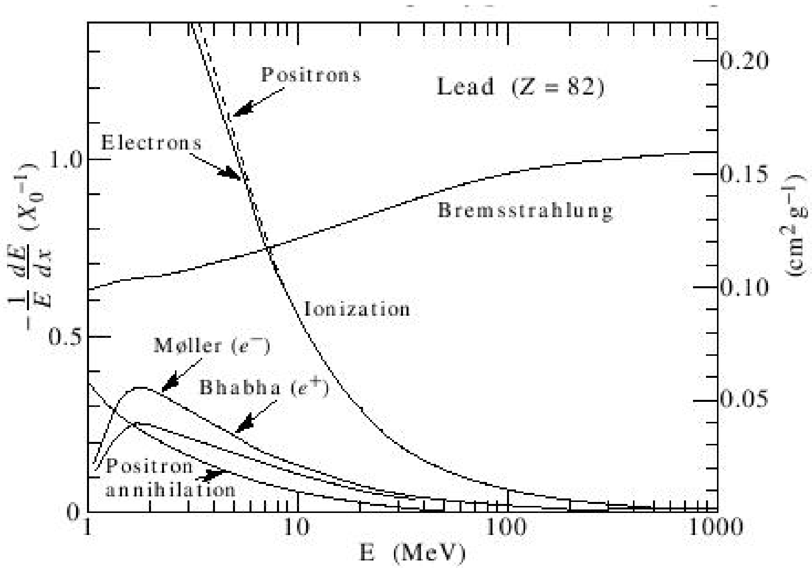


Figure 27.9: Fractional energy loss per radiation length in lead as a function of electron or positron energy. Electron (positron) scattering is considered as ionization when the energy loss per collision is below 0.255 MeV, and as Møller (Bhabha) scattering when it is above. Adapted from Fig. 3.2 from Messel and Crawford, *Electron-Photon Shower Distribution Function Tables for Lead, Copper, and Air Absorbers*, Pergamon Press, 1970. Messel and Crawford use $X_0(\mathrm{Pb}) = 5.82\ \mathrm{g/cm^2}$, but we have modified the figures to reflect the value given in the Table of Atomic and Nuclear Properties of Materials ($X_0(\mathrm{Pb}) = 6.37\ \mathrm{g/cm^2}$).

Electrons Talk-EM field of moving electron

- Antenna Pickups: Beam Position Monitors
- Resonant Cavities: Beam position and current monitors

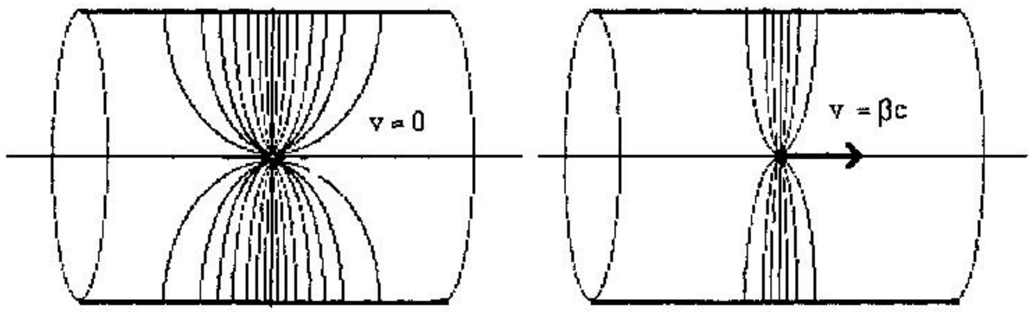


Fig. 12.1. The longitudinal field distribution of a static and moving charge ($\beta = 0.9$) in a grounded conducting cylinder. The longitudinal distribution contracts to a flat disk for highly relativistic particles. For slow particles, the field lines extend about $\pm b/\sqrt{2}$ longitudinally both in front of and behind the particle.

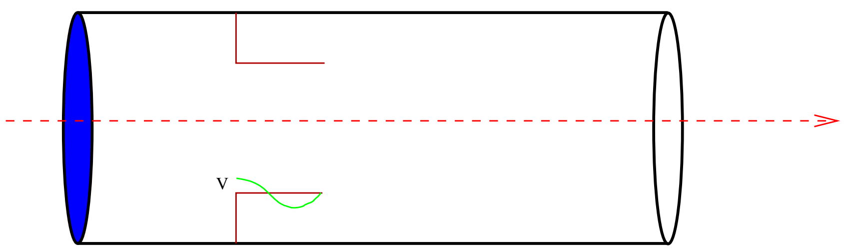
Beam Position Monitor with Antenna Pickups

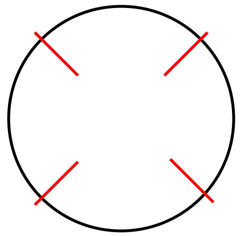
Electric field is picked up by an antenna sticking into the beam pipe.

$\frac{2n-1}{4}\lambda$ antenna length.

Response: $V(\omega,x,y) = s(x,y)Z(\omega)I_{beam}(\omega)$ where $Z(\omega_0)$is typically 50$\Omega$and s(x,y) is the sensitivity function which is either analytically derived or numerically calculated.

Near the center of the BPM, the position is found to be to a good approximation: $X = \frac{V_a - V_b}{V_a + V_b}$, the difference over the sum with the current dependence conveniently canceling.





Resonant Cavities [Beam Current and Position]

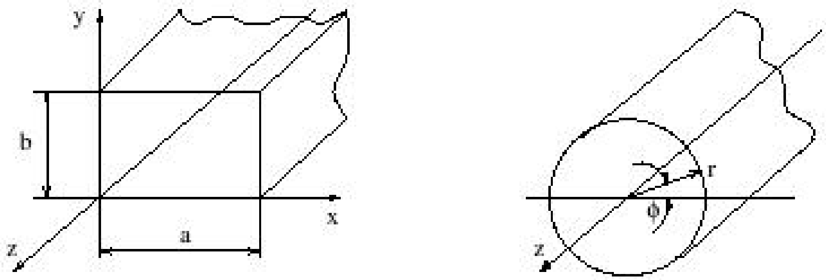


FIGURE 1. Coordinate systems for rectangular and for circular waveguides.

Rectangular Waveguides

Following the coordinate system in Figure 1, the field generating functions of the TM modes and the cut-off wave numbers of rectangular waveguides are given [5] by

$$\psi_{nm} = \cos\left(\frac{n\pi x}{a}\right) \cdot \sin\left(\frac{m\pi y}{b}\right) \qquad k_{c,nm} = \left(\frac{n\pi}{a}\right)^2 + \left(\frac{m\pi}{b}\right)^2. \tag{3}$$

Circular waveguides

Using Figure 1, the field generating functions of the TM modes and the cut-off wave numbers of circular waveguides are given [5] by

$$\psi_{mn} = J_m\left(k_{c,mn}\right) \cdot \cos\left(m\phi\right) \qquad k_{c,mn} = \frac{a_{mn}}{r} \tag{4}$$

where a_{mn} is the n-th zero of the Bessel function J_m.

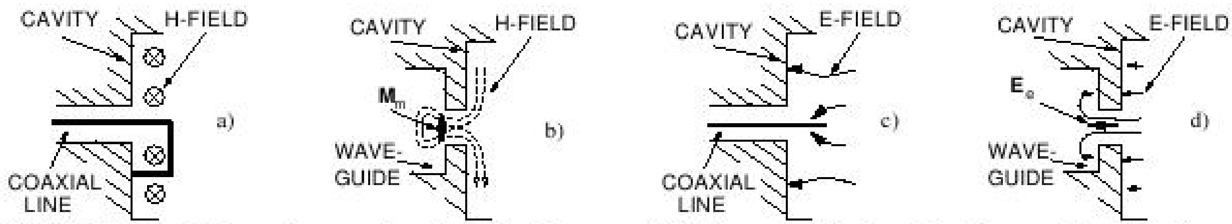


FIGURE 2. Magnetic coupling by a) a loop and b) through a hole; electric coupling by c) an antenna and d) through a hole.

For monopole modes the response is proportional to the beam current. For dipole modes the response is proportional to the product of position and current.

Dipole mode as zero response at center of cavity. Not a good feature for precise beam positioning on axis...

Phase of the dipole mode determines the sign of the beam position.

Electrons Talk-EM field interactions with fields/material

Transition Radiation

- When a charged particle transitions from the vacuum through a conductor, light is emitted.
- The effect is due to the collapse of the image charge in the conductor when the beam particle enters the conductor.
- Some of this light is in the optical portion of the spectrum [OTR]. This makes it convenient as simple CCD cameras can be used to image the light.
- At JLAB, OTRs are used to measure the beam size. To minimize the amount of beam scattering caused by the metal, 200nm carbon foils are used. This makes the measurement almost non-invasive.

Synchrotron Light

- When a charge particle is accelerated it will radiate.
- The portion of this radiation in the optical can be imaged with CCD cameras.
- The usual location for synchrotron light monitor is in dipole magnet bends.

Synchrotron Light Interferometry

Energy Spread Requirements

1. Why Interferometry?
   (a) Expected beam size and diffraction limit
2. Instrumentation
3. Performance and Results
4. Conclusions

Experimental Requirements

- In order to resolve fine mass splitting [at the 100keV level] 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 $\sigma_\beta = \sqrt{\varepsilon\beta}$ 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].

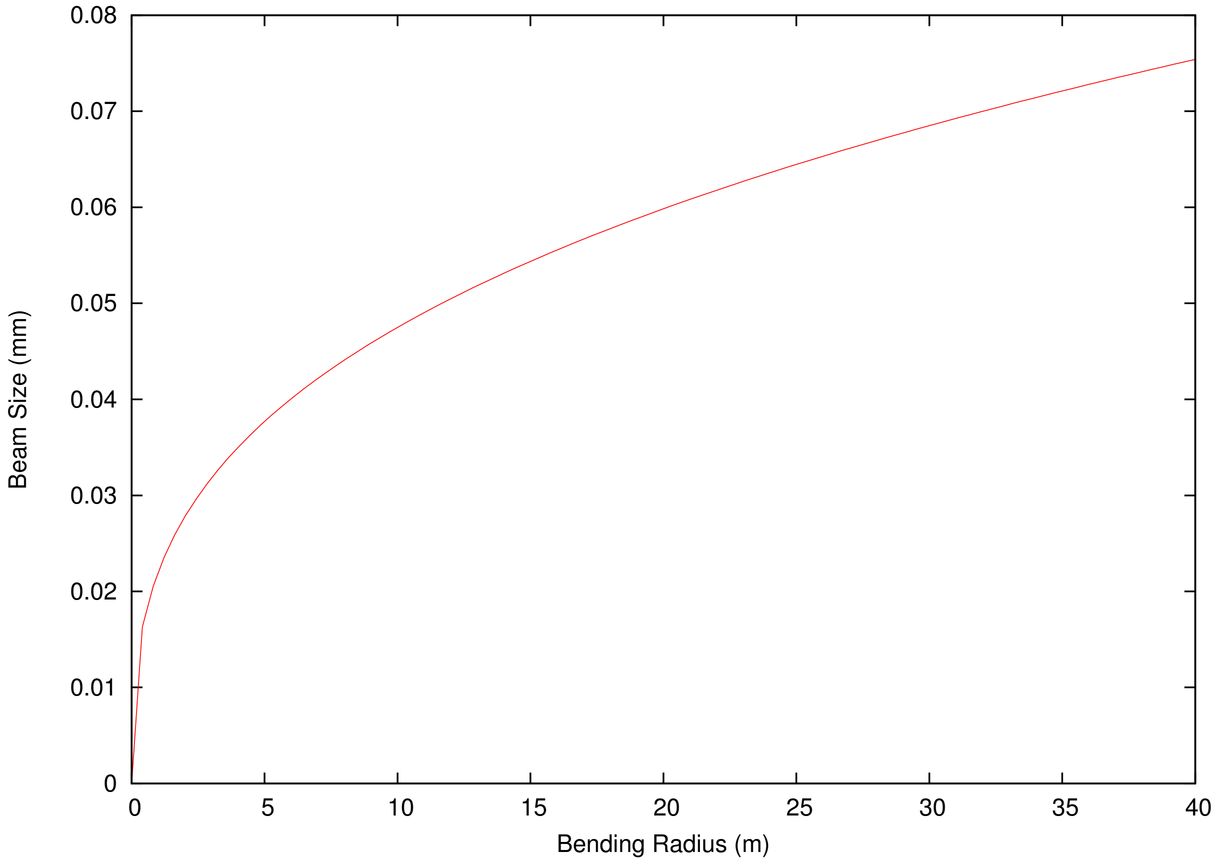
$$\psi_{rms} = 0.45 \left(\frac{\lambda}{\rho}\right)^{\frac{1}{3}}$$

- 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:

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

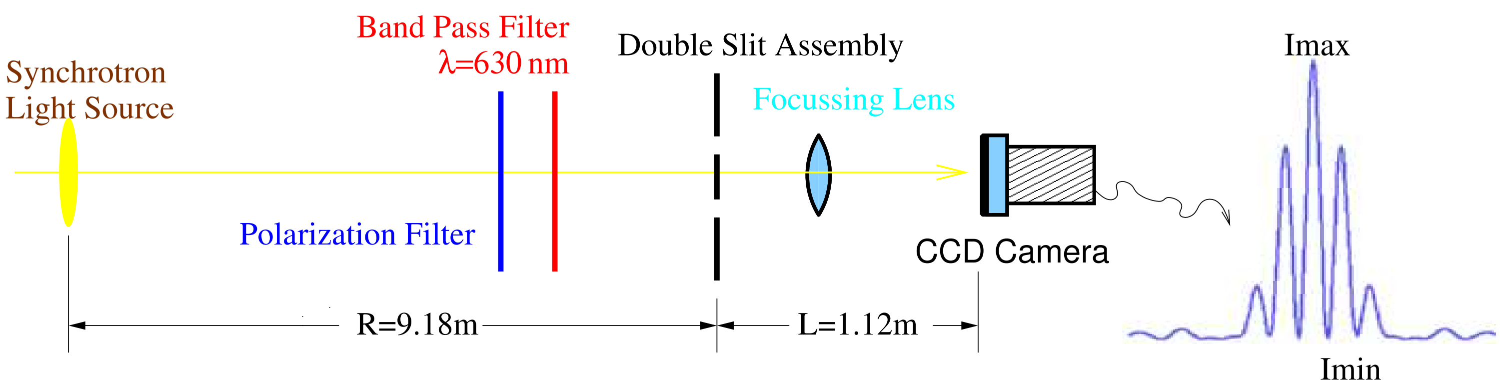
Diffractive limit vs Bending Radius

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



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.

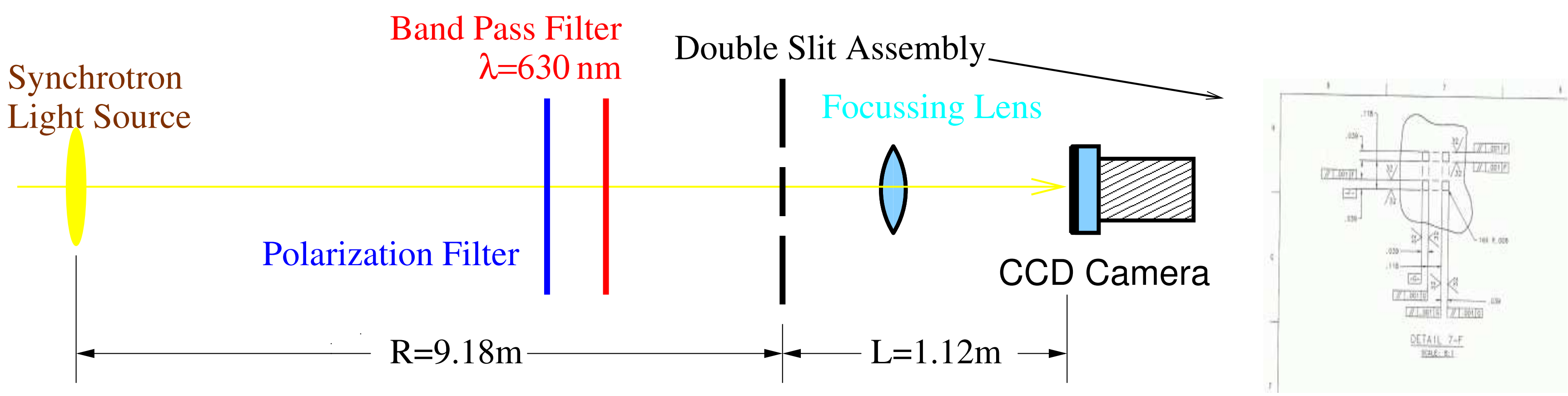


- ✔ Beam size is a function of the visibility on the interference pattern:

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

- ✔ 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].
- ✔ $\mathcal{V}$ is a ratio, most systematics involved in digitization cancel

SLI continued:



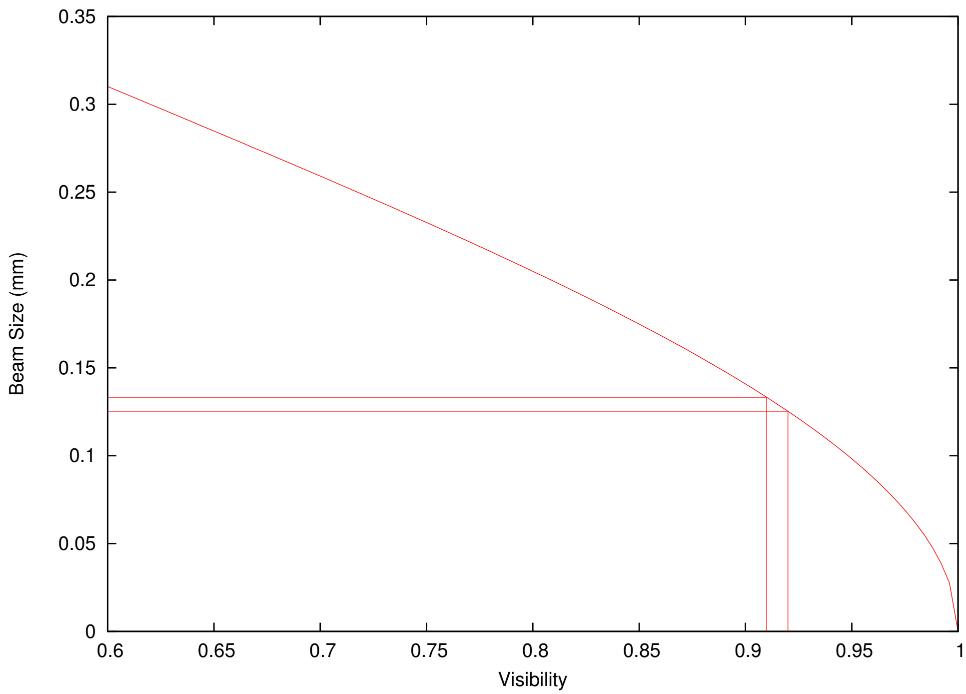
- ✔ distance between slit centers is d=3mm.
- ✔ For **Gaussian** beam profile:

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

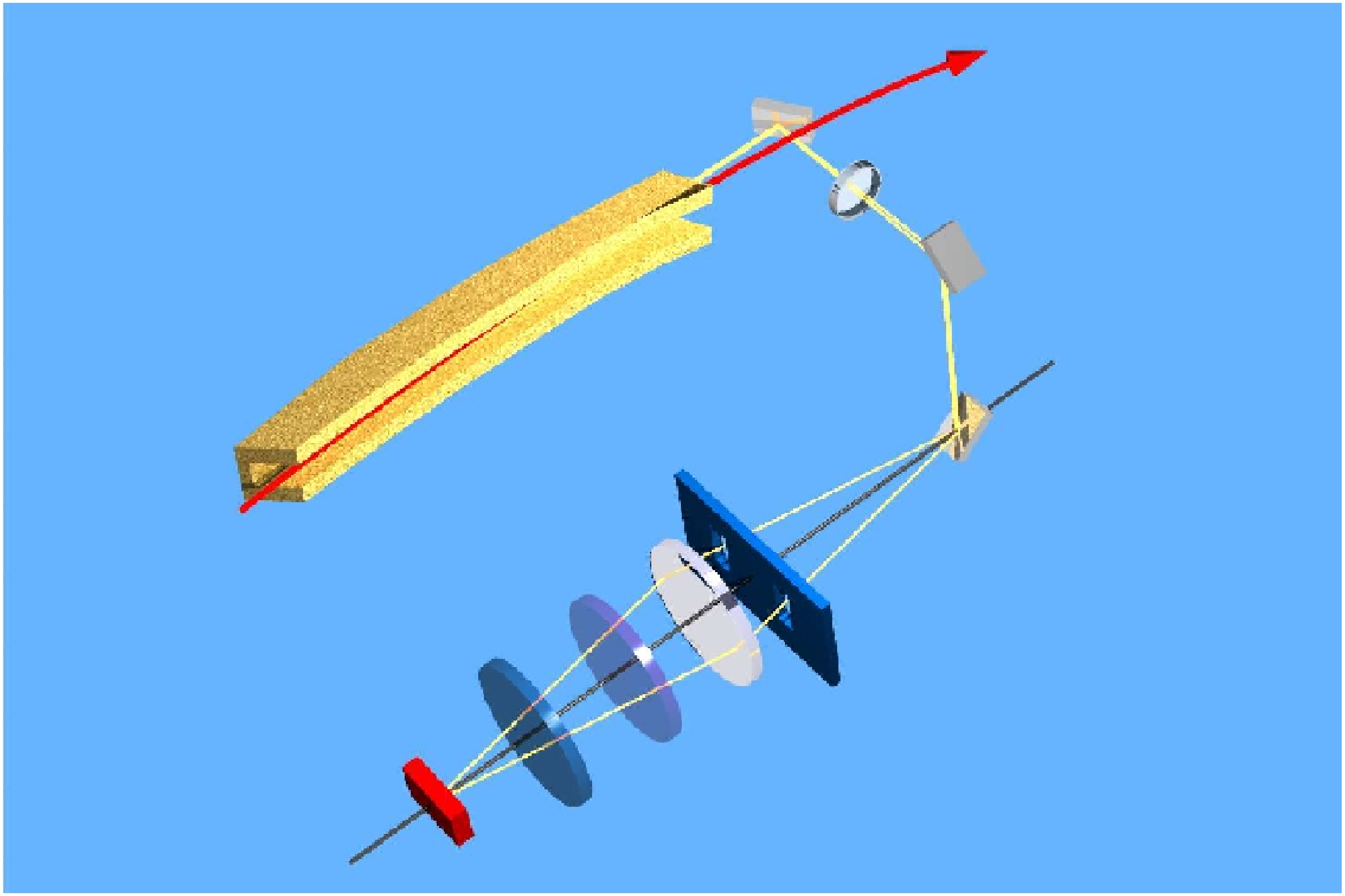
- ✔ Cooled astronomical CCD camera, needed for the very low light yield.
  - ✔ automatic background subtraction
  - ✔ variable integration time [no need for neutral density filters].

Resolution

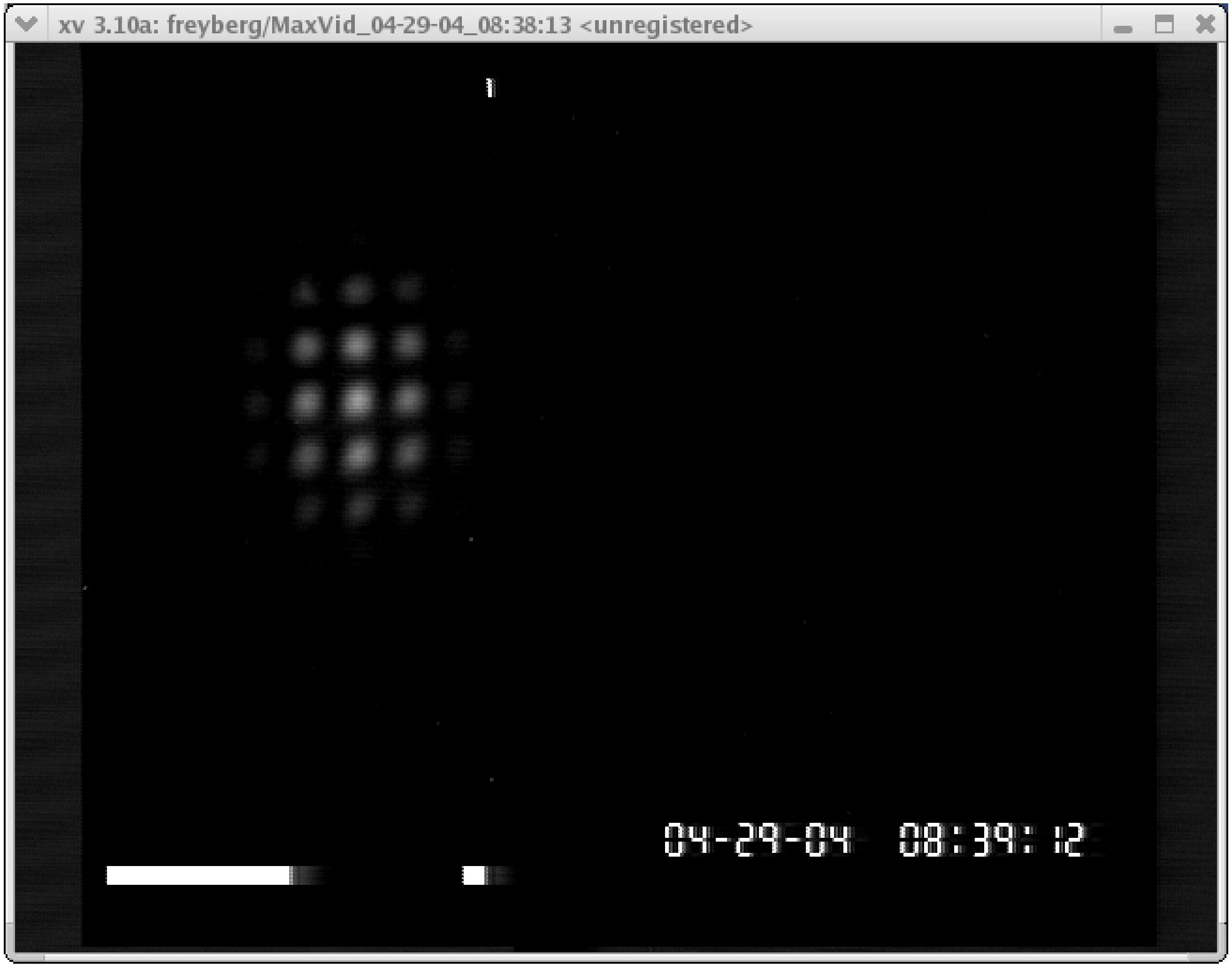
- Beam width resolution is determined by how well the $\mathcal{V}$ is measured.
- On-line fits to the interferogram are performed; I_{min} and I_{max} are determined from the results of the fit.
- Frame grabber has 8bits [maximum value 255]
- 1% precision on $\mathcal{V}$ gives an error of 10μm for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



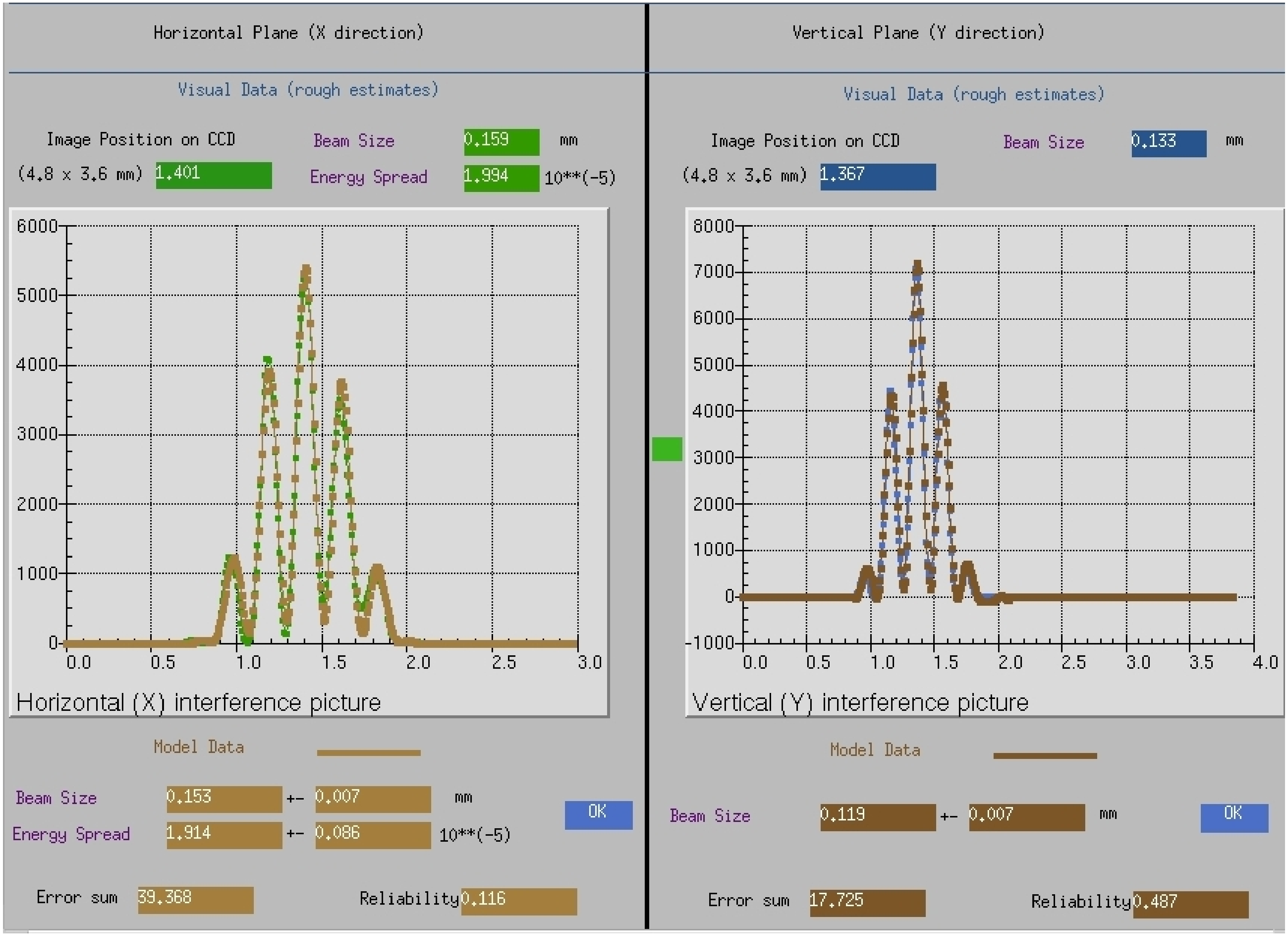
SLI 3D view



SLI Image


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

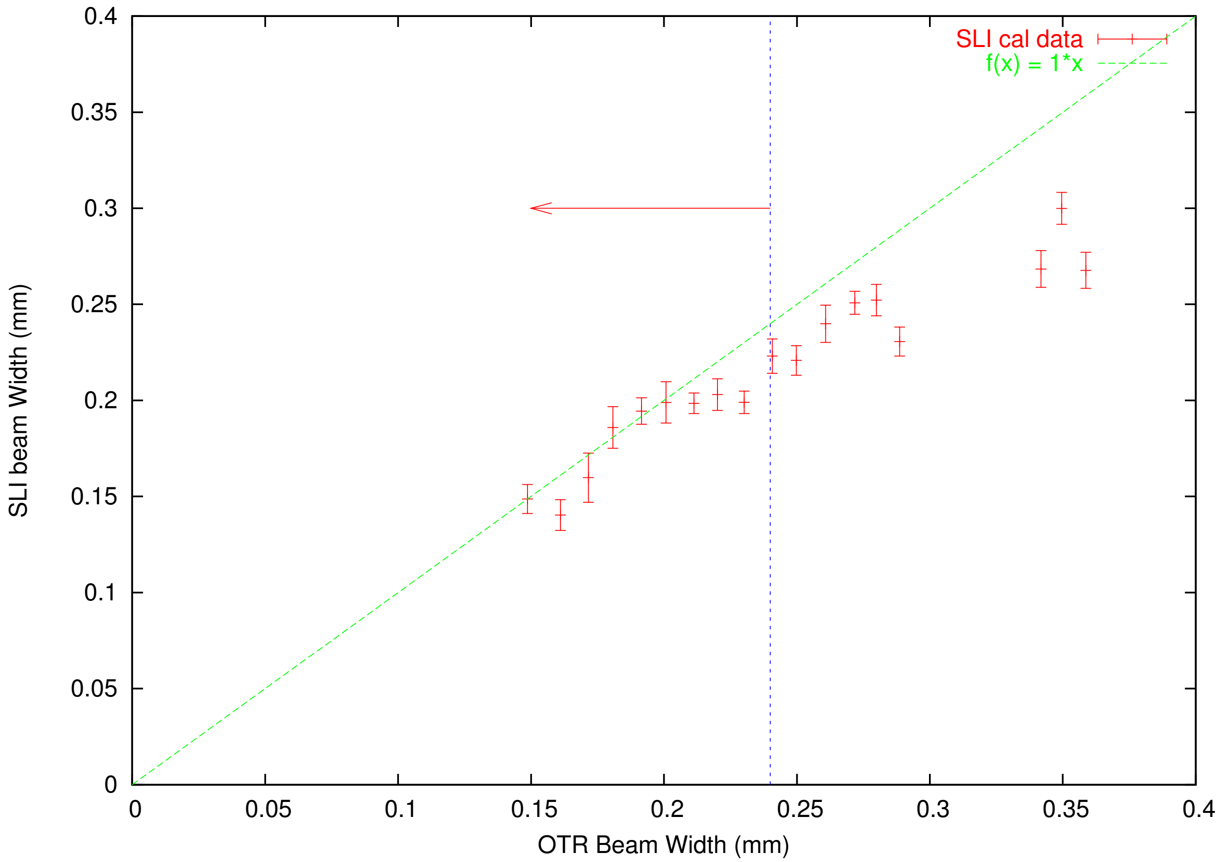
SLI screen



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

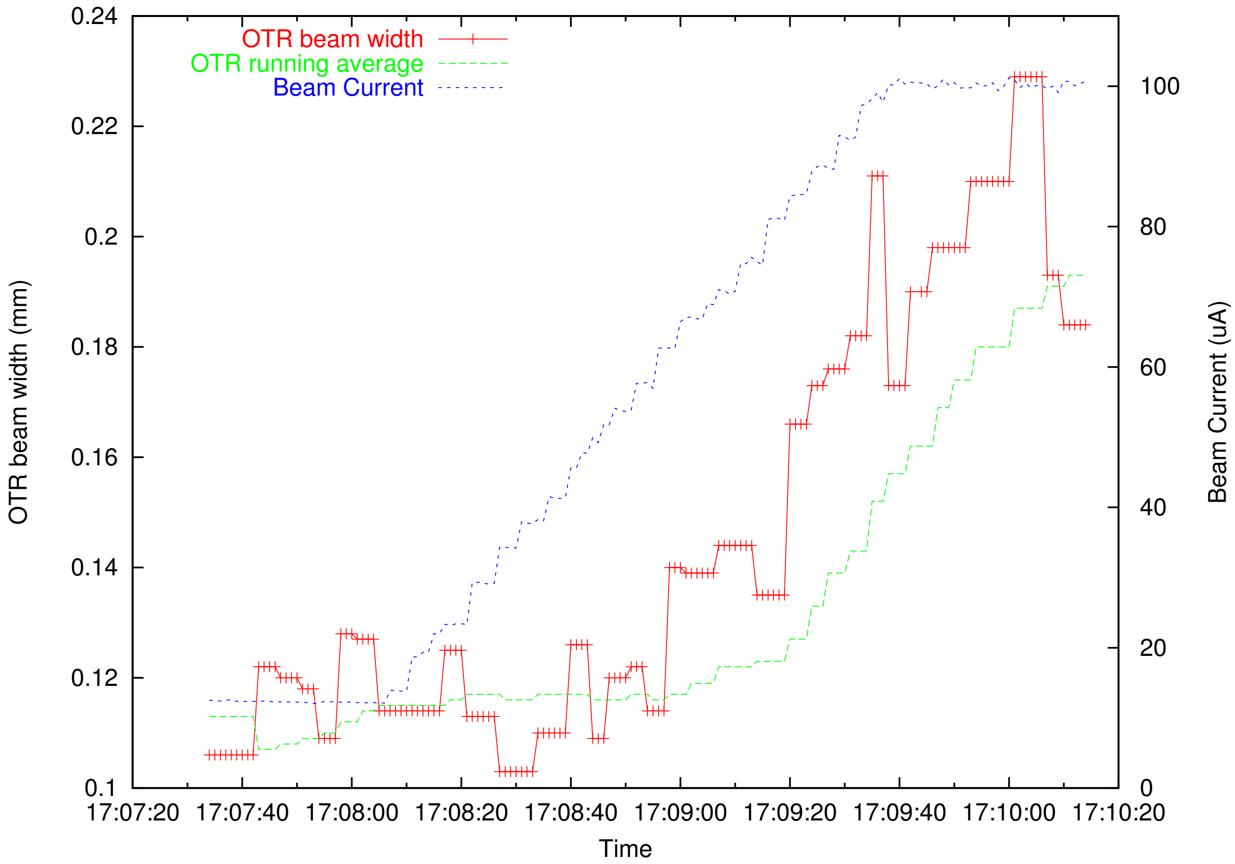
SLI Beam Width Comparison with OTR Beam Width

- ✔ 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.



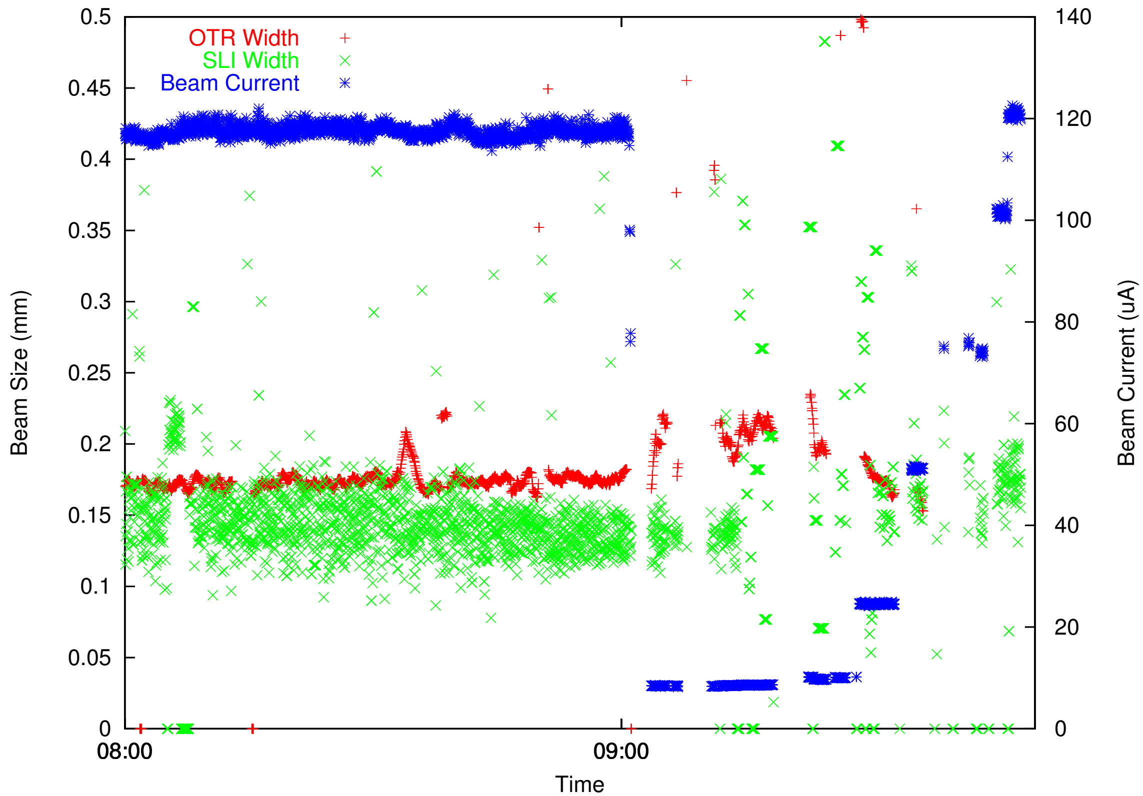
Energy Spread vs Beam Current

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].

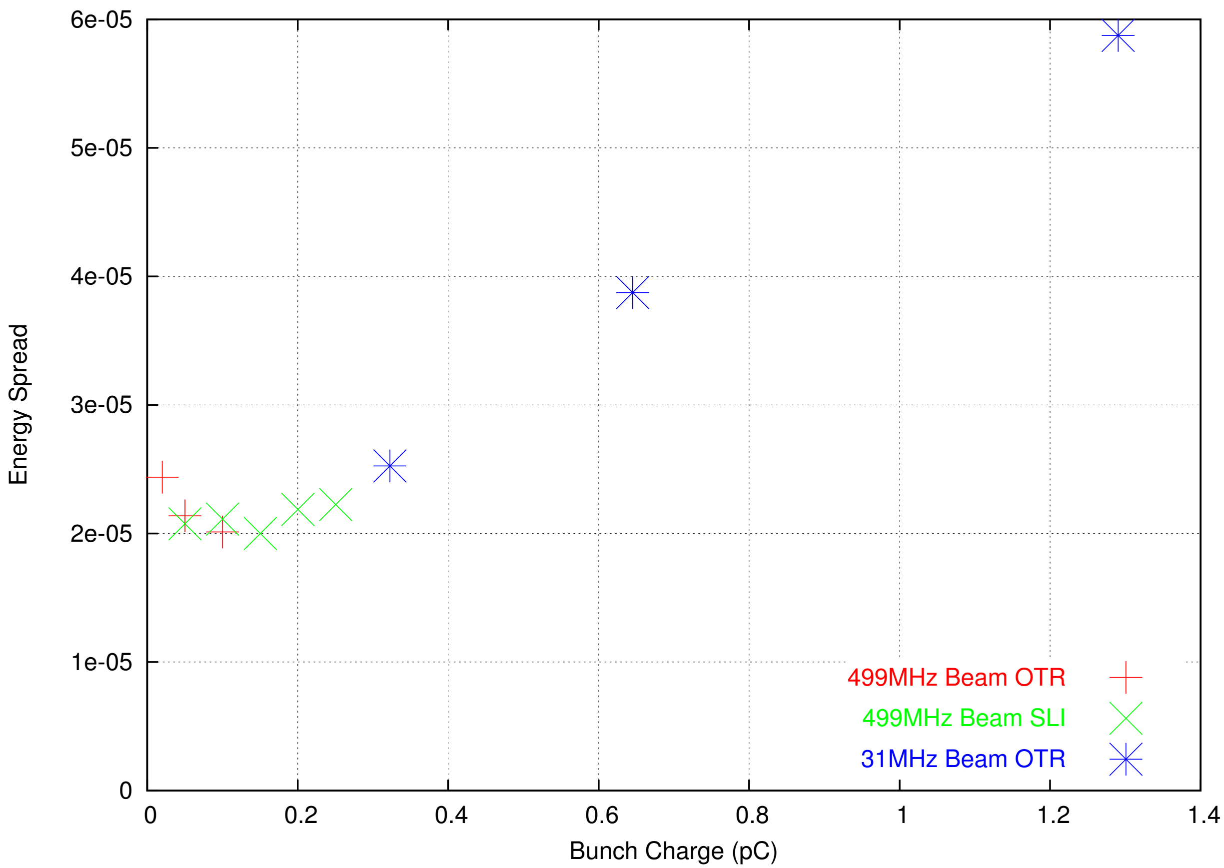


Energy Spread vs Beam Current (After RF has been fixed)

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

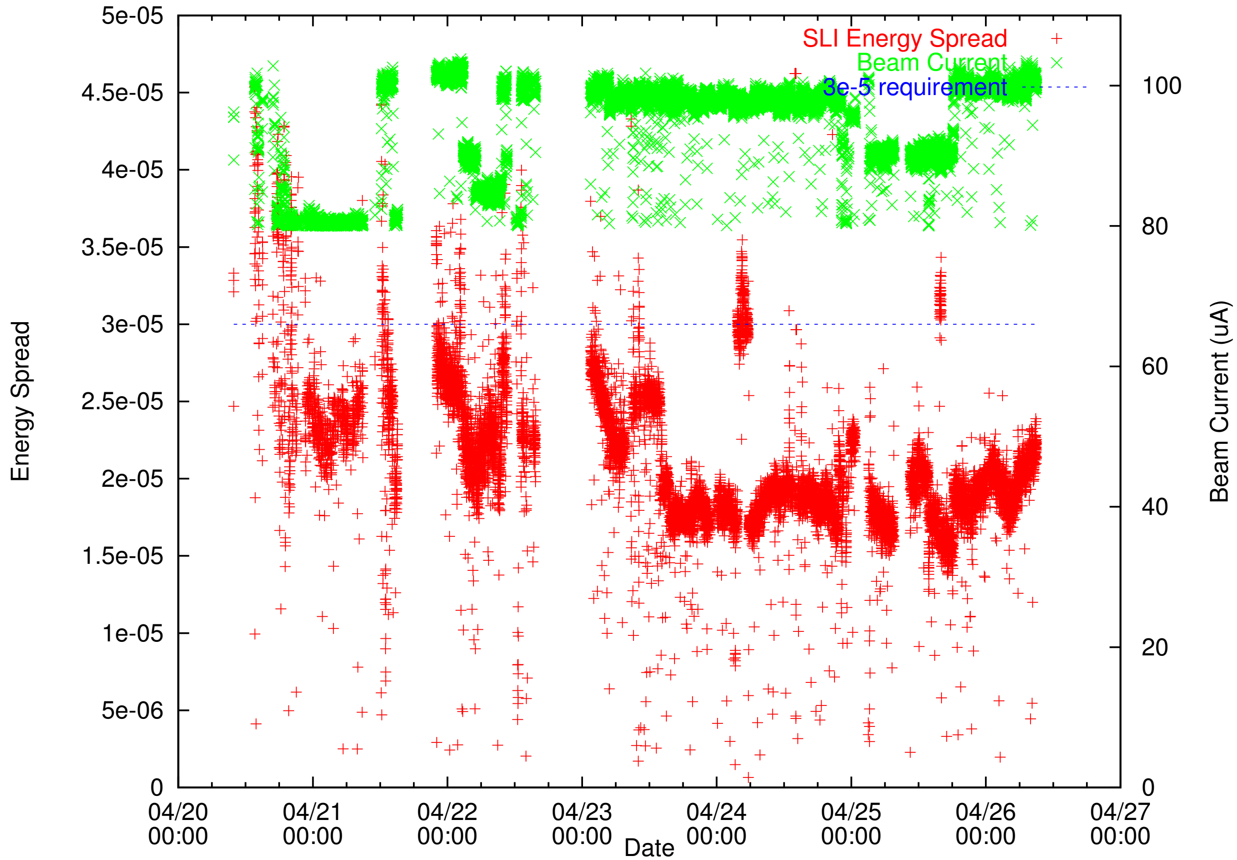


Energy Spread as a function of Bunch Charge



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.

Charge Calorimeter for Precise Beam Current Calibrations

Define the Problem

- ✔ Present the Solution
- ✔ Present the Status

The Problem

- Several Hall-A experiments require absolute beam current measurements with beam currents below 5μA.
- The beam current cavities (BCM) are presently cross calibrated against the Parametric Current Transformer (PCT). This is typically done with currents above 10μ A, with reliable accurate operation at currents above 50μ A.
  - ✘ The PCT electronics has a large offset drift which makes low current operation problematic.
  - ✘ Extrapolation from the high currents where the offset drifts are not a big effect down to low currents is not an acceptable solution.
- 1% of 1μA is 10nA

The Solution (part one)

Faraday Cup Dump all the charge into a conductor, bled the charge into low impedance current to voltage amplifier.

✔ Easy to calibrate electronics

✘ Requires a large ($1m^3$) of Pb (or equivalent) to contain the electromagnetic shower (Hall B Faraday Cup).

✘ Beam power at about 5kW suggests that cooling will be required for lengthy operation. Making total electrical isolation difficult.

SQUID Superconducting loop, senses magnetic field of the beam

✘ Challenging R&D project, 1% accuracy not achieved yet.

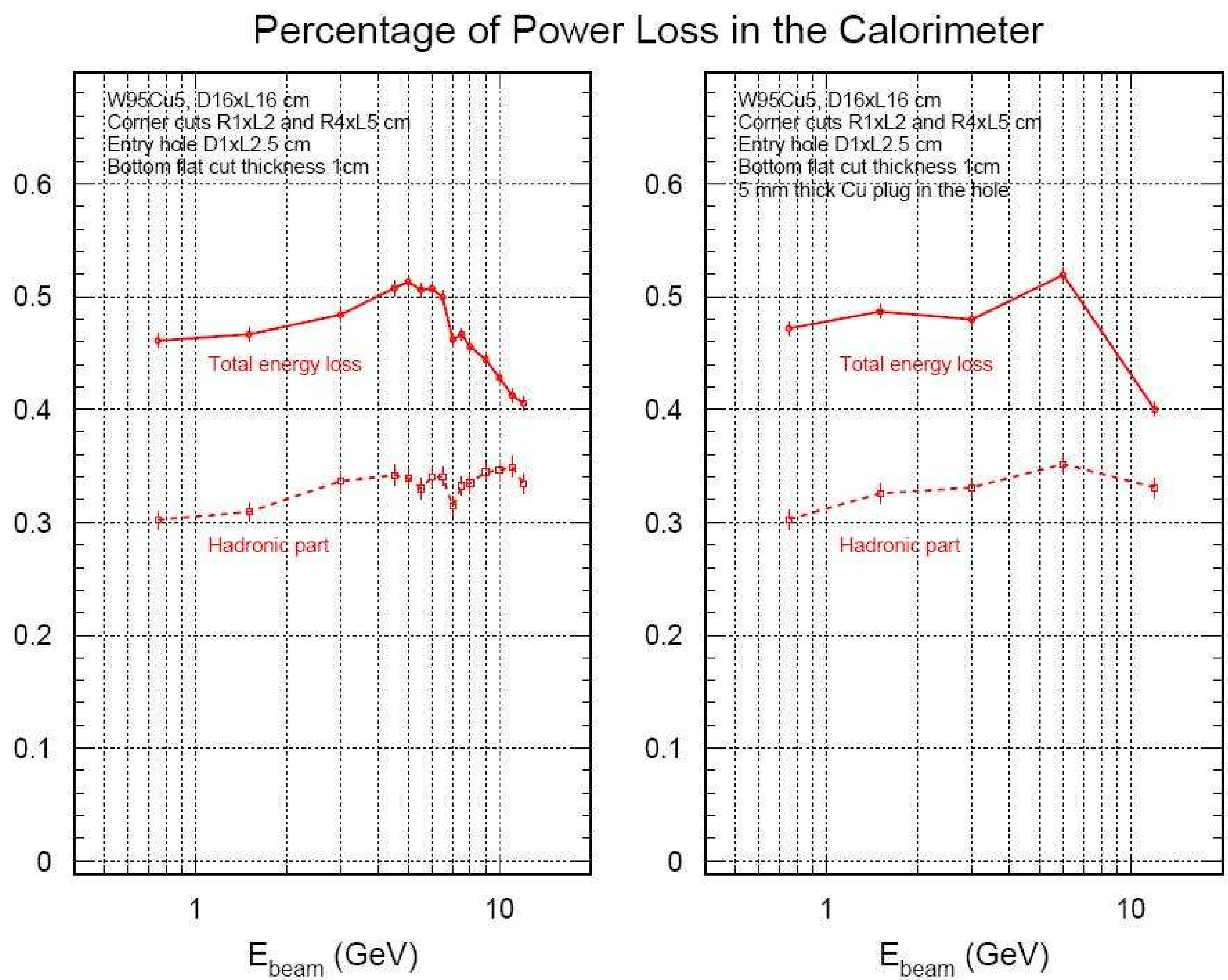
✘ Certainly sounds like a fun device though.....

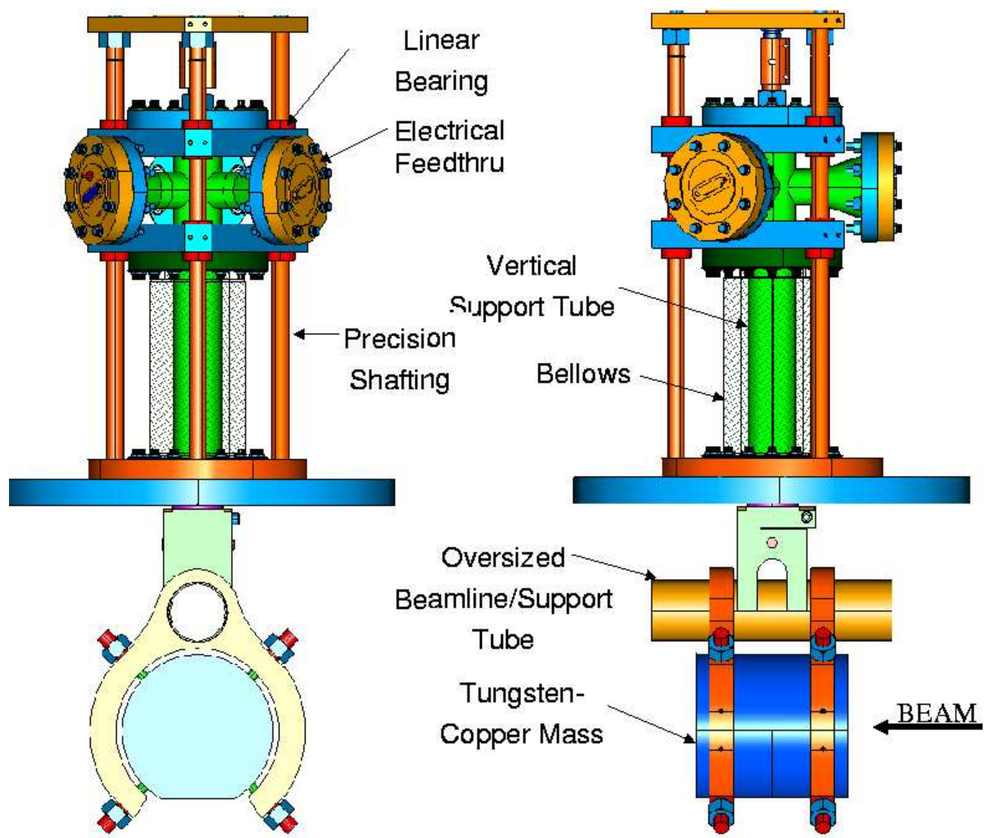
The Solution (part two)

Calorimeter Dump the energy in a dense block, and measure the temperature rise.

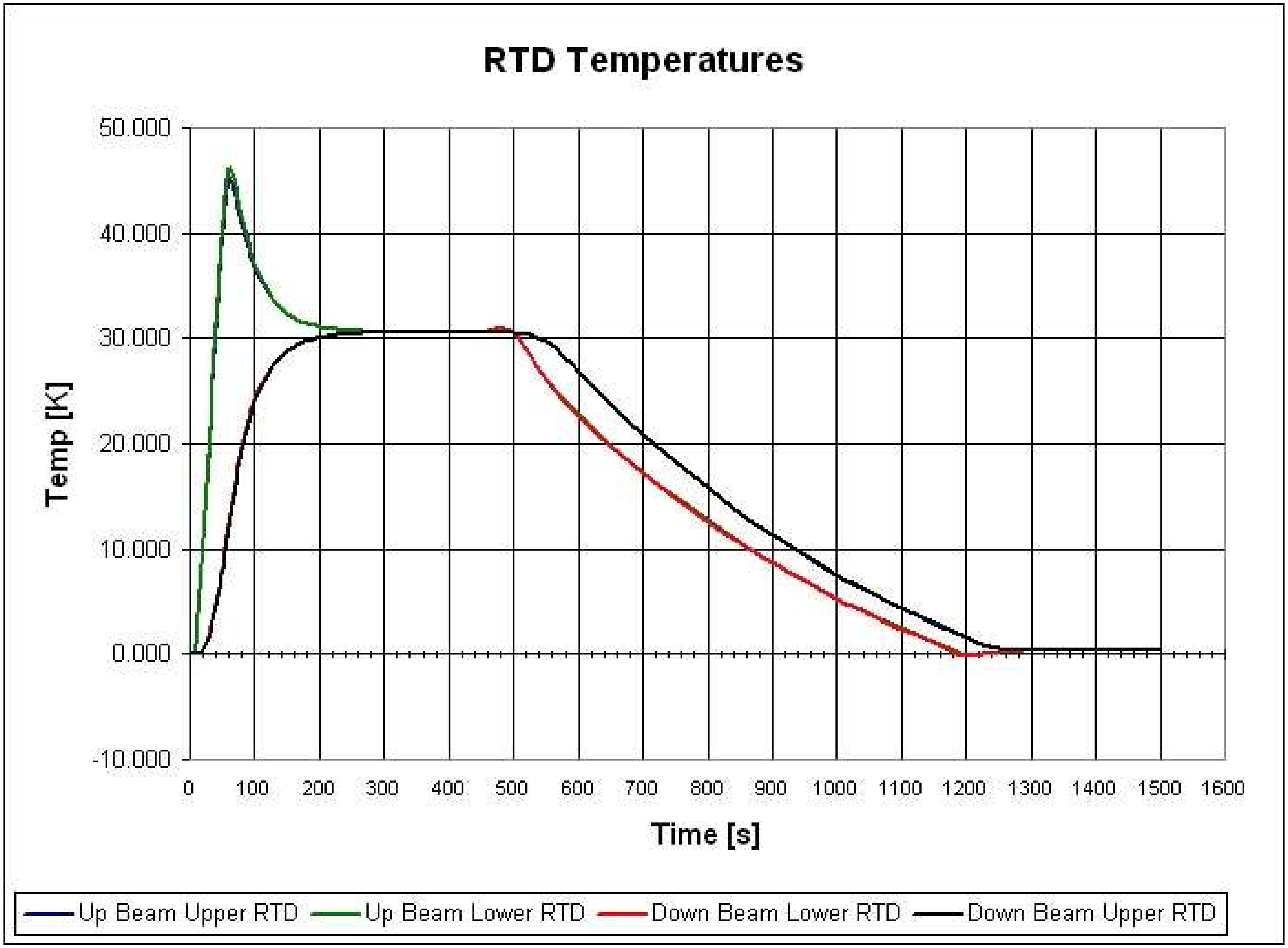
- ✔ Size must be large enough to contain the energy, this is typically smaller then an F-Cup has energy losses are not quantized as they are for F-Cup.
- ✔ Easy to thermally isolate
- ✔ Old well understood technique, SLAC 1970s, the Sinclair Factor......
- ✔ Need to model energy loss. Present estimate is $0.5 \pm 0.2\%$
- ✔ use a material with large thermal conductivity so that the “slug” reaches equilibrium quickly after the beam exposure. Silver has fantastic thermal conductivity, but simulations show that Tungsten has better energy containment.
- ✔ Final design is a 10cm diameter cylinder, 10cm long of mostly Tungsten.
- ✔ Small 1cm bore entrance hole in front surface.

Energy Loss due to Escaping Particles





Linear
Bearing
Electrical
Feedthru
Precision
Shafting
Vertical
Support Tube
Bellows
Oversized
Beamline/Support
Tube
Tungsten-
Copper Mass
BEAM


RTD Temperatures
Temp [K]
50.000
40.000
30.000
20.000
10.000
0.000
-10.000
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
Time [s]
Up Beam Upper RTD
Up Beam Lower RTD
Down Beam Lower RTD
Down Beam Upper RTD

Charge Calorimeter

The charge, Q, is related to the temperature rise via:

$$Q = \Delta T \bullet C_{heat} \bullet m \bullet e / E_{beam},$$

where ΔT, is the temperature rise, C_{heat} is the specific heat of the slug, e, is the electron charge and E_{beam} is the energy of the beam. The specific heat times the mass of the slug, $C_{heat} \bullet m$, is determined by adding a known amount of energy to the slug via a resistive heater.

$$C_{heat} \bullet m = P_{\Omega} \bullet \Delta t / \Delta T_{\Omega},$$

where ΔT_{Ω} is the measured temperature change due to the resistive heater, P_{Ω}, is the power ($V_{\Omega} \bullet I_{\Omega}$) of the heater and Δt is the amount of time the heater is on. Replacing $C_{heat} \bullet m$ in the equation for Q, yields:

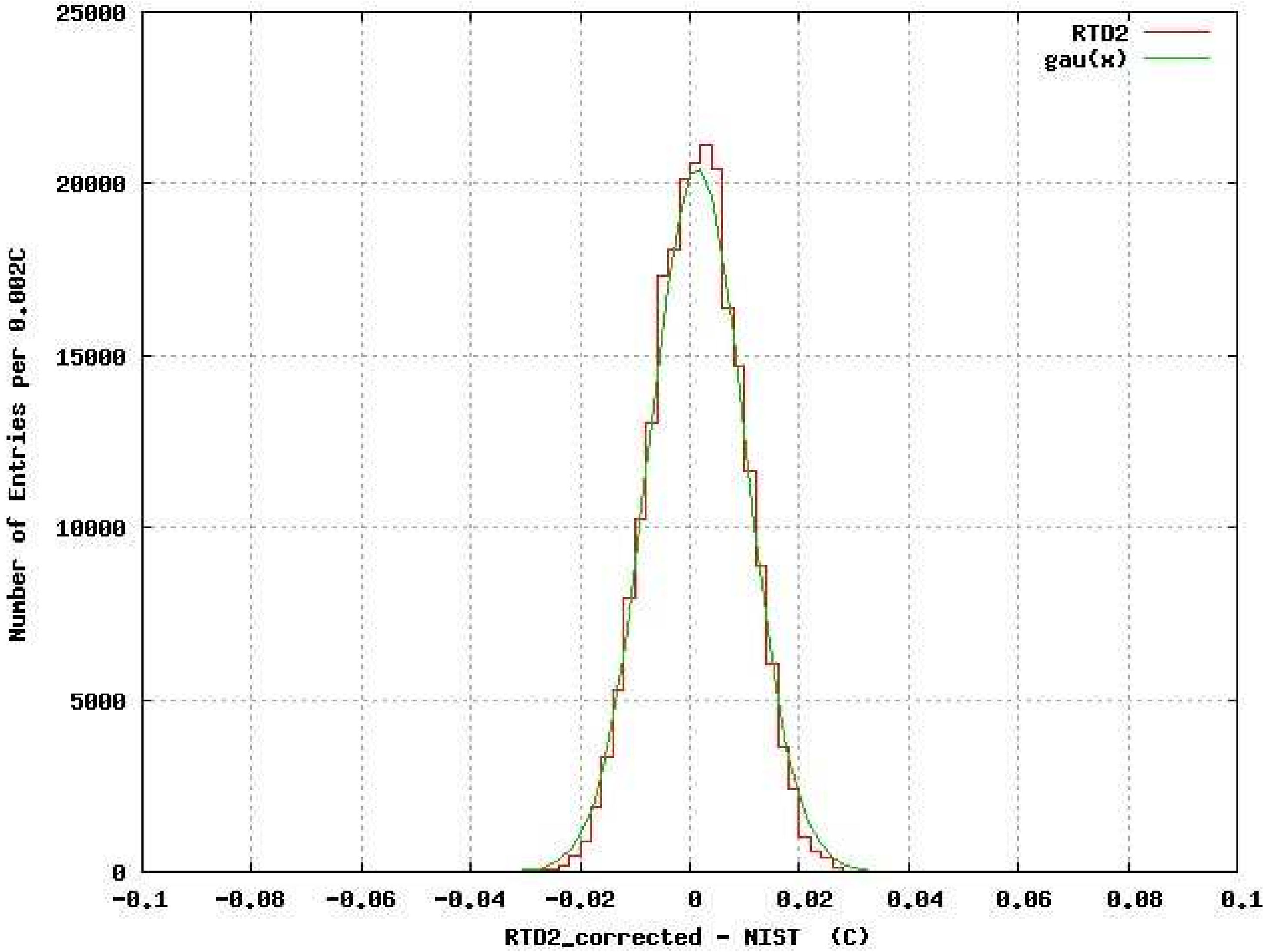
$$Q = \Delta T \bullet e \bullet P_{\Omega} \bullet \Delta t / (E_{beam} \bullet \Delta T_{\Omega}),$$

note Q depends on the ratio of the two measured temperature changes.

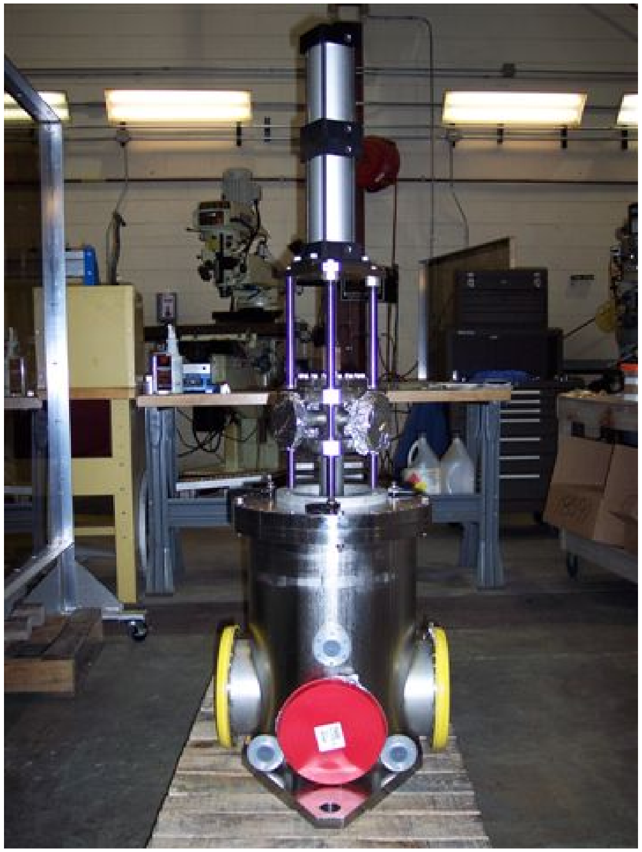
Instrumentation

The goal is to make a precision 0.5% device. Simulations have shown that losses due to escaping energetic particles will be at this level, so the instrumentation error should be significantly below 0.5%. The Table below shows the projected error allocation:

Quantity	Precision	Accuracy	Relative Error
ΔT	0.025$^\circ C$		0.1%
I_Ω		13.5mA	0.07%
V_Ω		6mV	0.006%
Total			<0.12%


RTD2
gau(x)
25000
20000
15000
10000
5000
0
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
Number of Entries per 0.002C
RTD2_corrected - NIST (C)

Vacuum Vessel



The Status

- ✔ Vacuum Vessel Complete
  - ✔ working out handling issues, need lifting fixture in ARC Lab
- ✔ RTD calibration complete
- ✔ Actuator Controls

Work List:

1. Test Assembly
2. Trial Heat Capacity Determination [Jan 2006]
   (a) I and V precision measurement [Jan 2006]
   (b) heater power supply controls [Jan 2006]
3. Chiller controls [???]
4. Chassis fabrication [Feb/Mar 2006]
5. Girder Modification [May 2006]
6. Cable runs [May 2006]
7. Installation [May 2006]
8. Final Operation Procedure [July 2006]

Summary

- Beam Diagnostics involves many aspects of Physics. This is what makes it fun.
- Experimental requirements often require new beam diagnostics.
- Accelerator operability/availability improvements also require improved diagnostics or better analysis tools.
- Skill set:
  - Strong physics background
  - Electronics and instrumentation
  - RF engineering [time domain vs frequency domain....]
  - software skills [from device drivers to sophisticated analysis software]
  - Communications [need to communicate with software, mechanical, electrical engineers, experimental and accelerator physicists.]