Energy Recovery Linacs Diagnostics Necessities

Working group 2

Where are we and what needs work…

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Outline for talk

- Guiding concepts for addressing diagnostic needs
- Overview of different machine design parameters
  - Details of required measurements and locations
- Injector requirements (<10 MeV)
- Linac requirements (> 100 MeV)
- Lessons learned
- JLab ERL diagnostics
  - Invasive & non-invasive diagnostics
- Open Discussion

Guiding Concepts

- Emittance preservation is crucial
  - Keep injector compact as possible
    - Trade off; Diagnostics require space – which increases emittance
  - Limit beam line shunt impedance
    - Shield ion pump drops and diagnostics
    - Use cookie cutters & dampers to minimize wake fields
- Must monitor injector for drifts, linac drifts can be seen with SLMs, BPMs, & BCMs
  - Pulse picker suggested at last years ERL workshop – more later…
- 2 or more instruments to measure the same beam parameters
  - Allows for *confidence* check
- Where possible diagnostic devices should be multi-function
- Developers must work with operators, electrical and mechanical engineers
  - Magnet stands were designed to shield BPM electronics
- Teams should be formed now with both users and diagnostic developers
  - JLab FEL can be used as a test bed for development

Future Light Sources Vary Greatly

Tallahassee FEL – Accelerator Specifications

Parameter	Value	Units
Energy	8 to 60	MeV
Average Current	1	mA
Peak Current	45	A
Micropulse Width	0.5 to 20	ps
Macropulse format	CW, macropulse capability	
Emittance	20	mm mrad
Energy Spread	0.3	%
Fundamental Frequency	1300	MHz
Beam Pulse Rate	11.8 MHz	MHz

THE CORNELL PROTOTYPE

Table 1: The Cornell ERL Prototype and light source

Parameter		Prototype	Light source
Energy	(GeV)	0.1	5
Current	(mA)	100	100
Inj. energy	(MeV)	5–15	5–15
Rep. Rate	(GHz)	1.3	1.3
Acc. gradient	(MV/m)	20	20
Q of cavities	(10^{10})	1	1
external Q	(10^{7})	2.6	2.6
Charge/Bunch	(pC)	77	77
nominal σ_E	(10^{-3})	0.2	0.2
nominal σ_τ	(ps)	2	2
nominal ϵ_N	(μm)	2	2
short pulse σ_τ	(ps)	< 0.1	< 0.1
microbeam ϵ_N	(μm)	0.2	0.2
Main Linac Cavities		5	≈ 250
Cooling@2K	(kW)	0.2	≈ 17

Machine parameters set by design/model

(courtesy S. Benson, JLab FEL)

Measurement	Method	Diagnostic	Resolution/Accuracy
Charge	Measure Beam current (macropulse & CW) & divide by repetition rate.	Faraday cup, Cavity monitor, Transformer	0.1% / 1.0%
Energy	Spectrometer	Dispersion section (~0.5m) + BPM and/or beam position in viewer	0.02% / 0.25%
Energy spread*	Measure beam size at dispersed location.	Dispersion section + viewer + framegrabber	0.03% limited by transverse spot size
Bunch length*	Measure Cerenkov light pulse	Cerenkov viewer + Streak camera	1.0 ps nominal
Transverse emittance	Phase space sampling	Multislit + viewer. Cross-check with wire scanner	0.1 mm-mrad-rms / ?
Beam spot size	Direct measurement with framegrabber	Viewer + framegrabber	Set by framegrabber resolution (tens of microns)

* With these two measurements we can map out the longitudinal phase space

Injector Diagnostics

- Emittance growth from space charge drives injector design to be short as possible
  - This limits the number and type of diagnostics
  - Energy is too low for either OTR/DTR or synchrotron light
  - Multislit emittance monitor
  - BPMs and phosphor coated flags OK
  - Watch out for Ghost Pulses!
- Want to shorten the beamline as much as possible so there is not much room for diagnostics, but…
  - Need enough diagnostics to set up the beam per the model (PARMELA) using beam-based measurements
  - Would like a diagnostic for each adjustable parameter (knob)
  - Want to study limiting phenomena like halo and beam stability
- Use pulse picking; during normal operation kick out a few 10nsec of beam @ 0.01 to 10 Hz to dedicated low energy destructive diagnostic line so injector drifts can readily be identified
  - In Linac synchrotron light comes *free*

Linac Transverse Diagnostics

- At energies > 100 MeV there are copious amounts of synchrotron light
  - Insertable ND filters required; we have OD1 and/or OD2 on each
  - This can be imaged directly for energy and energy spread
  - Instabilities can be observed on diode arrays
- OTR with frame grabber
  - Use for Commissioning and beam studies in pulsed mode
- Laser Wire profile monitors
- Beam position and loss monitors
- Multi-pass BPMs are required
  - Problem is that energy is also recovered in BPM resulting signal is the difference of the accelerated and decelerated beams
  - Joe Frisch et al (SLAC) working with TTF to develop algorithms for HOM BPMs, we are joining collaboration

Linac Longitudinal Diagnostics

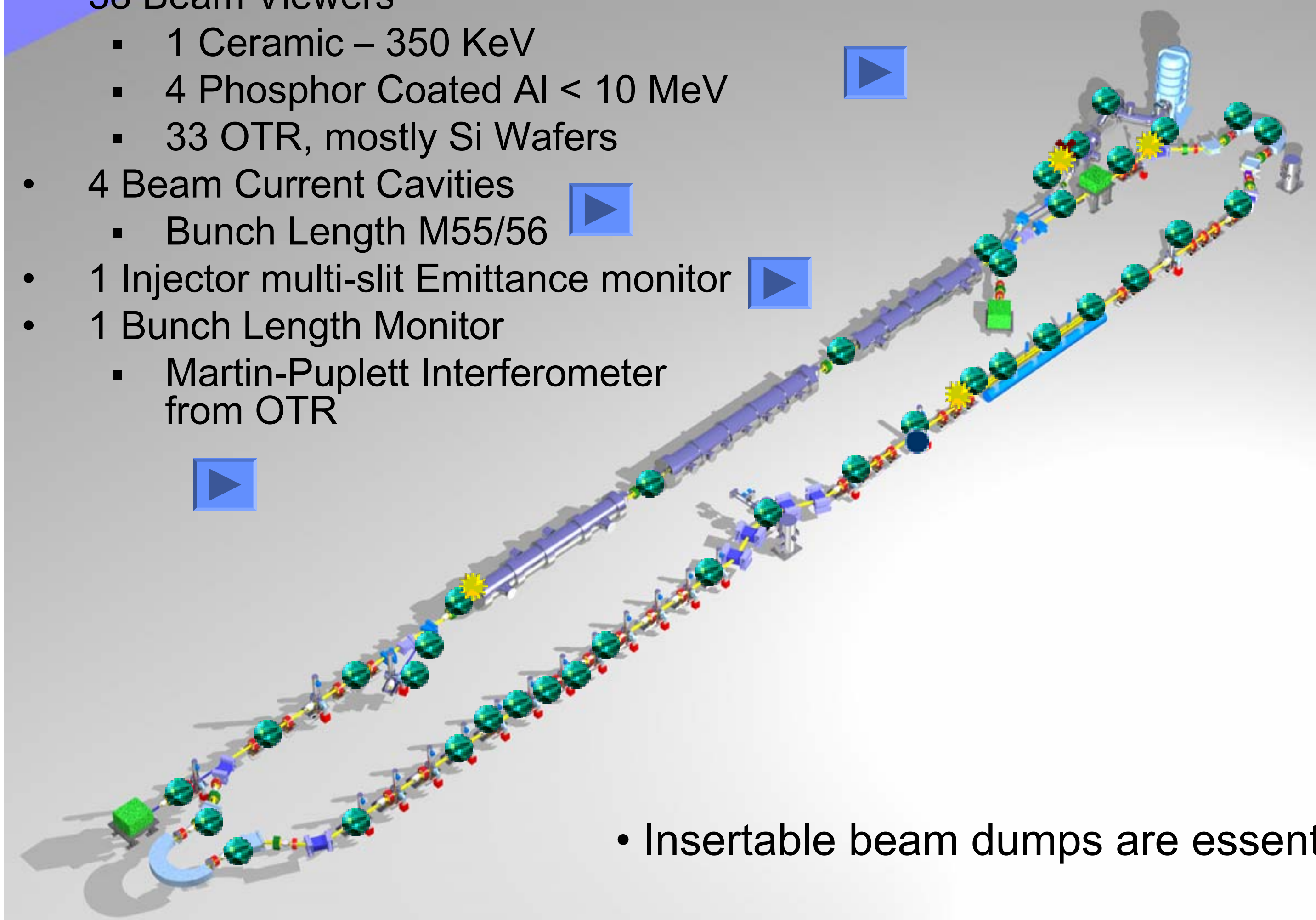
- Where bunch is short coherent THz can be monitored with FTIR spectrometer
- Synchrotron light with streak camera (temporal resolution limit~500 fsec)
- Transverse kicker cavity
- Electro-optical sampling techniques

Lessons Learned; We did a lot of things right but…

- We need multipass BPMs for the linac
  - Where there are two beams one needs more than just viewers w/holes
  - We are working on two different schemes for use in pulsed beam
- OTR viewers work great – even better when properly aligned!
  - Design in ports to allow alignment HeNe to pass through machine
  - Si wafers 50mm diameter, 250 micron thick ($10) are current favorite material – polished surface helps alignment
  - OTR is very weak at energies below 10 MeV (our tune-up beam is 1000 micropulses of 135 pC or 135 nC over 250 microsec @ 2Hz)
- DESY style phosphor screens are the best for injector & dump – THANKS!
- Streak cameras work well with proper care and feeding
  - We image SL ~ 5 meters upstairs; both optical transport AND timing must be correct
- We are working with U of Md to examine OTRI (Optical Transition Radiation Interferometry) as an emittance diagnostic

JLab FEL Diagnostics - Invasive

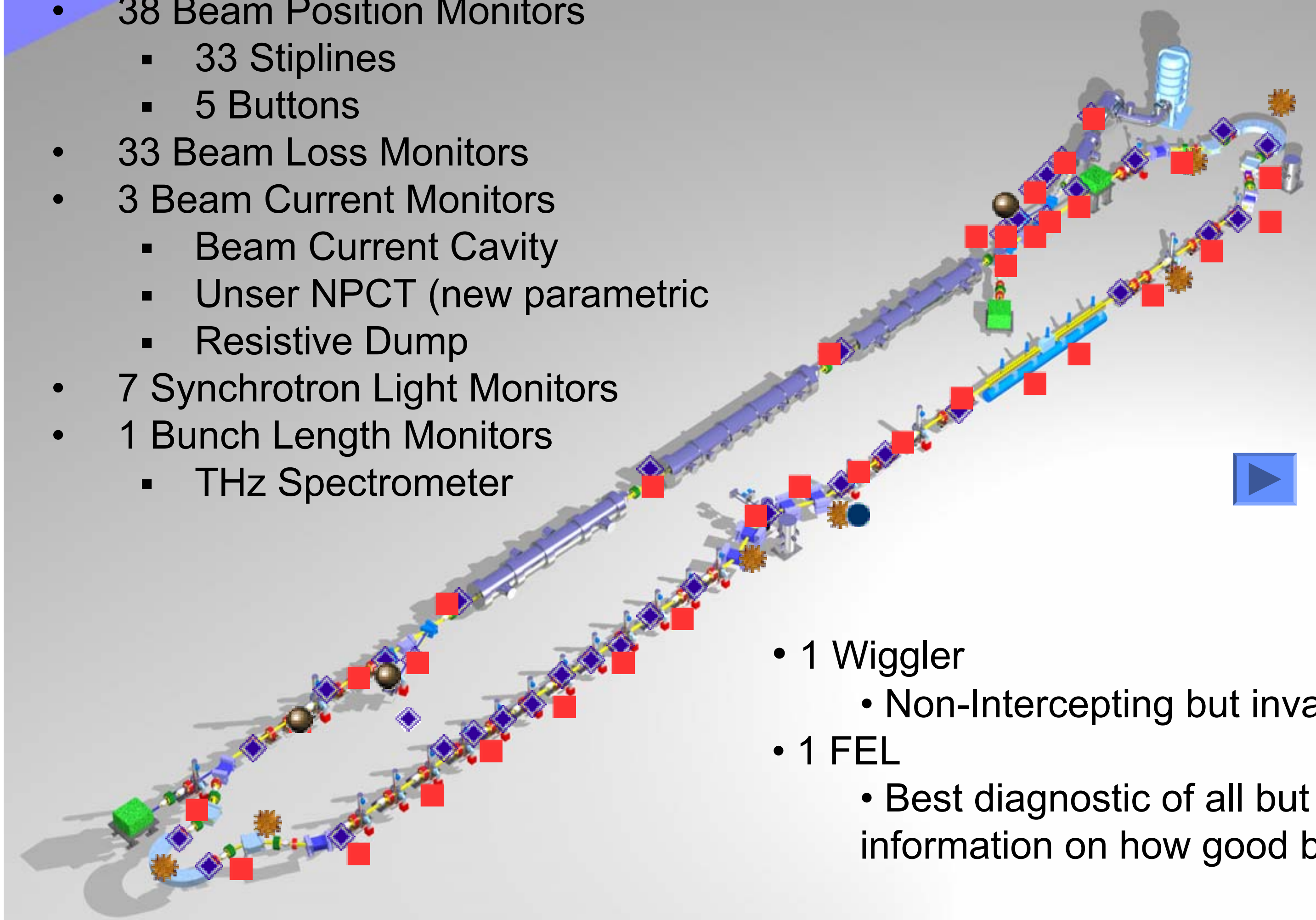
- 38 Beam Viewers
  - 1 Ceramic – 350 KeV
  - 4 Phosphor Coated Al < 10 MeV
  - 33 OTR, mostly Si Wafers
- 4 Beam Current Cavities
  - Bunch Length M55/56
- 1 Injector multi-slit Emittance monitor
- 1 Bunch Length Monitor
  - Martin-Puplett Interferometer from OTR



- Insertable beam dumps are essential

JLab FEL Diagnostics; Non-Invasive

- 38 Beam Position Monitors
  - 33 Stiplines
  - 5 Buttons
- 33 Beam Loss Monitors
- 3 Beam Current Monitors
  - Beam Current Cavity
  - Unser NPCT (new parametric
  - Resistive Dump
- 7 Synchrotron Light Monitors
- 1 Bunch Length Monitors
  - THz Spectrometer



- 1 Wiggler
  - Non-Intercepting but invasive
- 1 FEL
  - Best diagnostic of all but only gives information on how good beam is

CSR Enhancement

- Low energy is on left high energy on right. SLM located in second arc dipole, gradient in linac is changing ~ 3MeV This changes position in the first arc sextupoles where their quad component changes bunching. Bean is CW, 4 MHz, 135pC/bunch average current is ~600micoamp

- Back up slides

Requirements and Status of ILC Diagnostics
(Courtesy/stolen from **Jung Yun Huang** ILC workshop Dec. 2004)

Most critical measurements for Linear Collider

- **nanometer beam position measurement near IP (σ_z ~ 1000 - 5 nm)**
  - **-best cavity BPM (cBPM) ~ 25 nm**
  - **-best stripline BPMs (sBPM) ~ 1 µm**
- **nanometer beam size measurement at IP**
  - **- best laser wire scan ~100 nm**
  - **- best metal wire scan ~ 5 µm**
  - **- laser interference slit scan ~ 50 nm (Shintake)**
    resolution limited by wavelength
- **fs bunch length measurement**
  - **- electro-optic/ CSR, CTR/ rf deflector ~30 fs**
- **Various techniques for PAL XFEL will be also applicable for ILC**

Ghost Pulses

- Drive laser is capable of providing the full repetition rate for the ERL.
  - For 100 mA beam assume 10^9 pulses/second with 100 pC/pulse
- Most diagnostics cannot handle more than 10 μA and we prefer to limit the current to <1 μA (keeps vacuums stable and preserves cameras)
- This means we must limit the pulses/sec. to $<10^4$. Factor of 10^5 reduction.
- Mechanical shutter can cut the duty cycle down by a factor of ~1000.
- Can get another factor of 10^4-10^5 reduction from electro-optic cells.
- When running pulsed you need to keep current down to what you can accelerate without energy recovery (in IR Upgrade 600 μA)
- Ghost pulses are what still gets through the EO cells.
- Note that ghost pulses have a different match from the main pulses.

Beam Viewers

- Variety of flag materials & coatings
  - Cromox ceramic in the 350KeV region – subject to blooming
  - “DESY” style phosphor coated Al in the 10 MeV regions – both the injection line & ER dump – extremely linear!
    - 2 insertable neutral density filters (OD1 & OD2) available for attenuation 10 to 1000
  - Thin Al flags elsewhere, 1 to 10 microns thick
  - Forward and backward OTR used
  - Two locations Silicon wafers for mirror finish
- Cohu series 1100 CCD cameras used, 0.05 Lux sensitivity
  - Bare board cameras mounted in home built enclosure, $100 CCD elements are replaced 3 months to 2 years when radiation damaged
- Red LEDs are used for illumination, **band pass filters used to limit OTR flux** (562nm;10 & 80 nm width) without attenuating the fiducial visualization.
  - The problem is that the OTR is too bright & ghost pulses contaminate spot size measurements
- Linux based Frame grabber, Scion model LG3-64

CRT PHOSPHOR - TYPE QMPK58/F-C1

YTTRIUM ALUMINIUM GALLIUM OXIDE : CERIUM
$Y_3(Al,Ga)_5O_{12}$: Ce
TEPAC-WW TYPE : P46(Ga)

<u>PHYSICAL PROPERTIES</u>

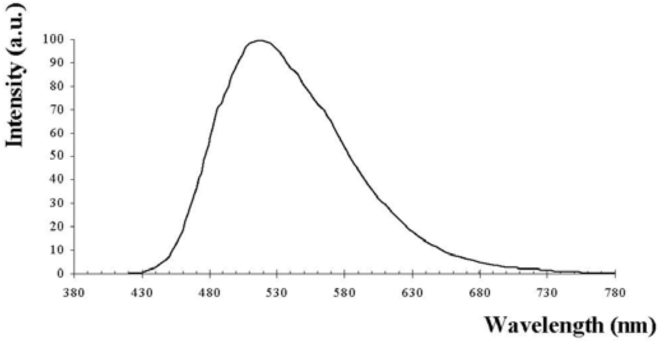
Material Density, g/ml : 5.2
Particle size distribution - by Coulter Counter (100 µm Aperture)
Ultrasonic Dispersion. Sizes at listed Volume %

vol %	5	25	50	75	95
µm	1.8	2.7	3.5	4.5	6.7

Quartile Deviation: 0.25

<u>OPTICAL PROPERTIES</u>

Emission colour : Yellow-Green   Wavelength at peak, nm : 515
CIE Colour Co-ordinates : x=0.306, y=0.521
Decay Classification : Very Short



CRT PHOSPHOR - TYPE GL29/F-C1

ZINC SULPHIDE : COPPER
ZnS : Cu
TEPAC-WW TYPE : P31-GH

PHYSICAL PROPERTIES

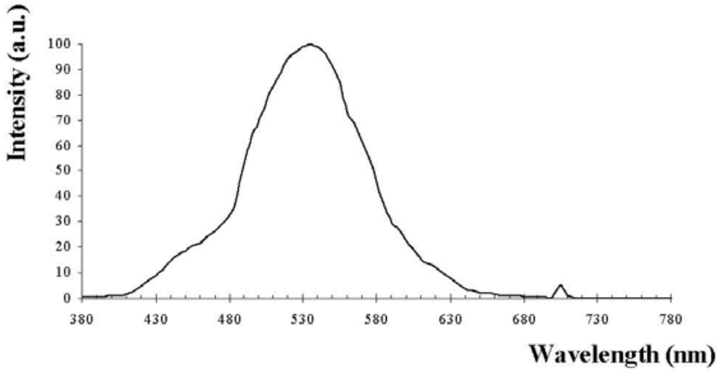
Material Density, g/ml : 4.1
Particle size distribution - by Coulter Counter (100 μm Aperture)
Ultrasonic Dispersion. Sizes at listed Volume %

vol %	5	25	50	75	95
μm	1.8	2.7	4.0	5.4	9.0

Quartile Deviation: 0.33

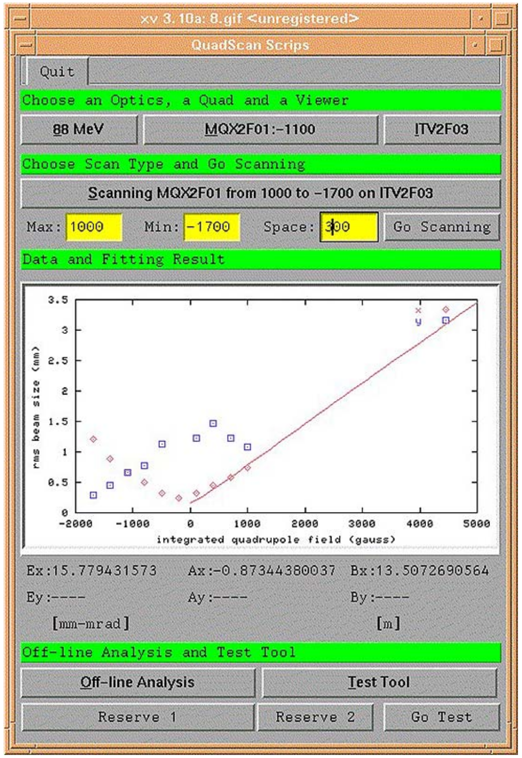
OPTICAL PROPERTIES

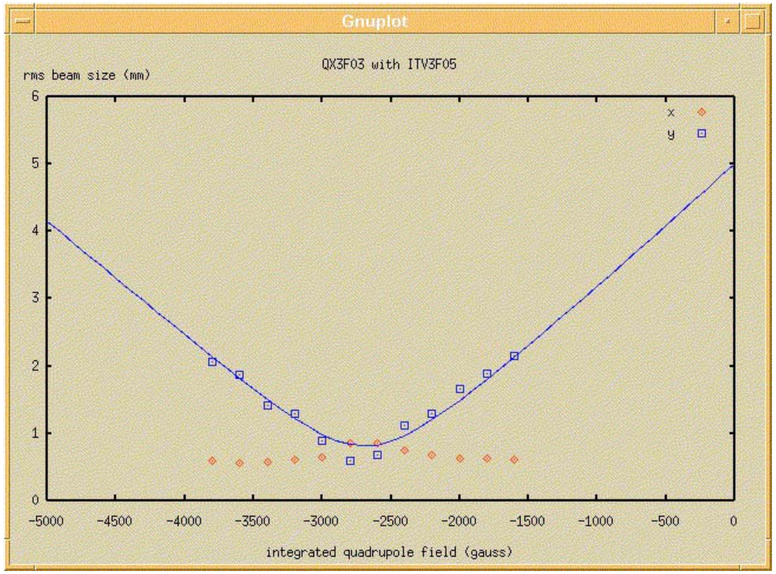
Emission colour : Green   Wavelength at peak, nm : 530
CIE Colour Co-ordinates : x=0.287, y=0.521
Decay Classification : Medium Short



Emittance Measurements

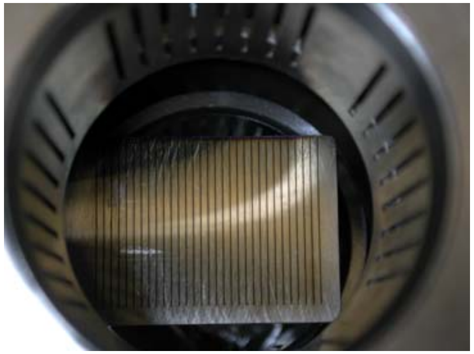
- New slit system has been designed with independent horizontal and vertical slits for ease of alignment
  - Slit width is 127 microns, cut by wire EDM
  - This system will be recommissioned over the next weeks
- An automated quad scan technique being developed by Noboyuki Nishimori (below)





Quad strength vs. spot size plot

Old Multislit w/o horizontal slits

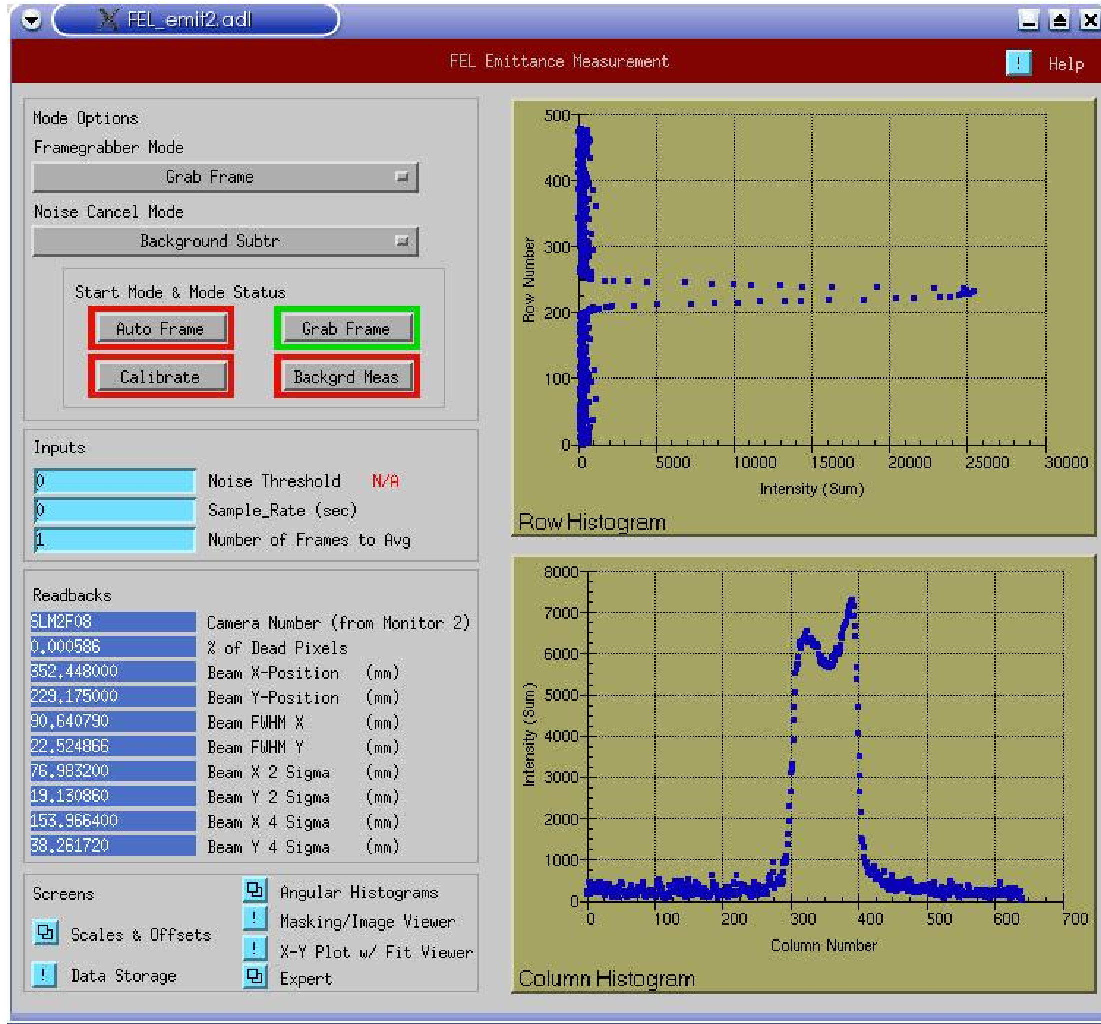


New slits, wire EDM cut

Beam Profile Measurements with WesCam Frame Grabber

MEDM Controls Screen

SLM2F08



Uses

- Injector phasing
- Beam spot sizes for Emittance Measurements
- Recirculator setup based on beam size and position
- Determining the energy distribution of the bunch
- Determining the energy spread

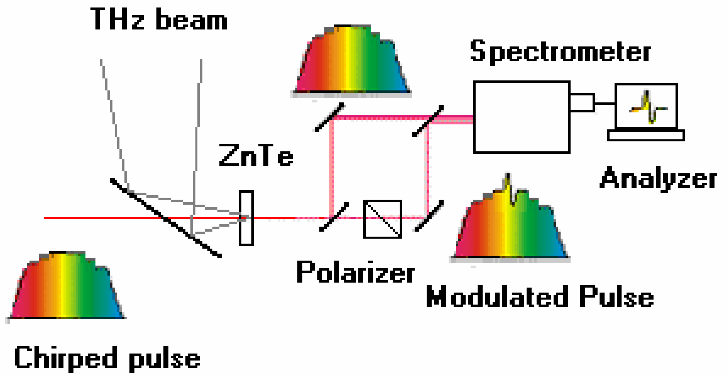
<u>Next step, automate Linac phasing using beam positioning</u>

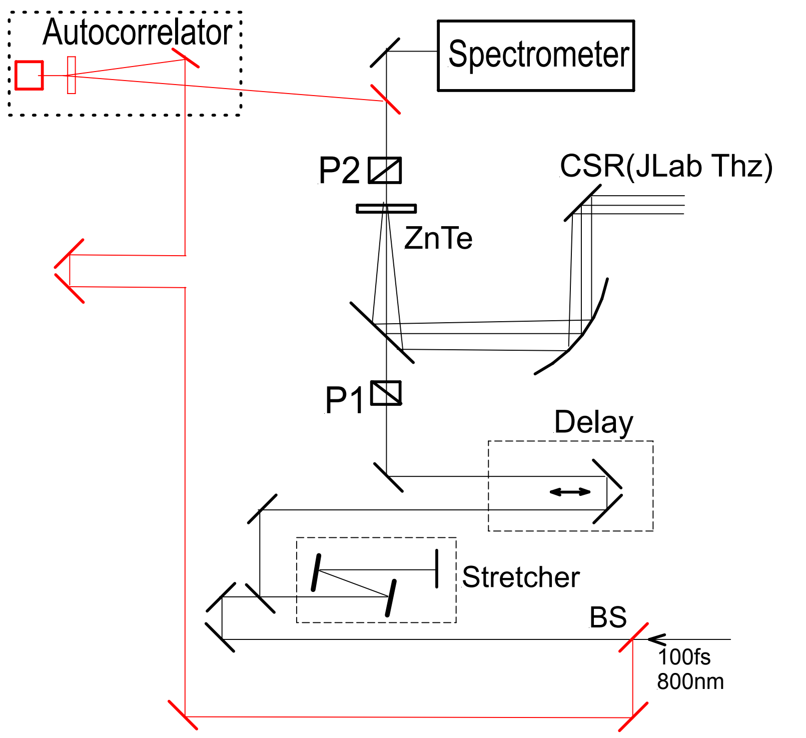
Bunch Length Measurement by EO Sampling
(courtesy S. Zhang, JLab FEL)

- We have set up an EO sampling system to measure the shorter (<500fs) bunch length which is beyond the steak camera capability.

- Thz-pump chirped-pulse-probe scheme

Concept: A chirped-pulse probe detection system is used to map the modulation on the linearly dispersed spectrum of the probe induced in EO crystal by the THz electric field. In stead of doing the time delay scanning, the temporal profile of the THz pulse can be obtained from the probe spectrum which has been modulated (by X-C Zhang etc.).



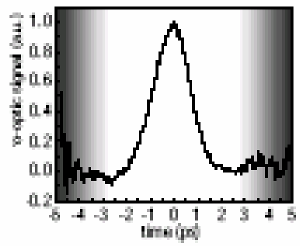


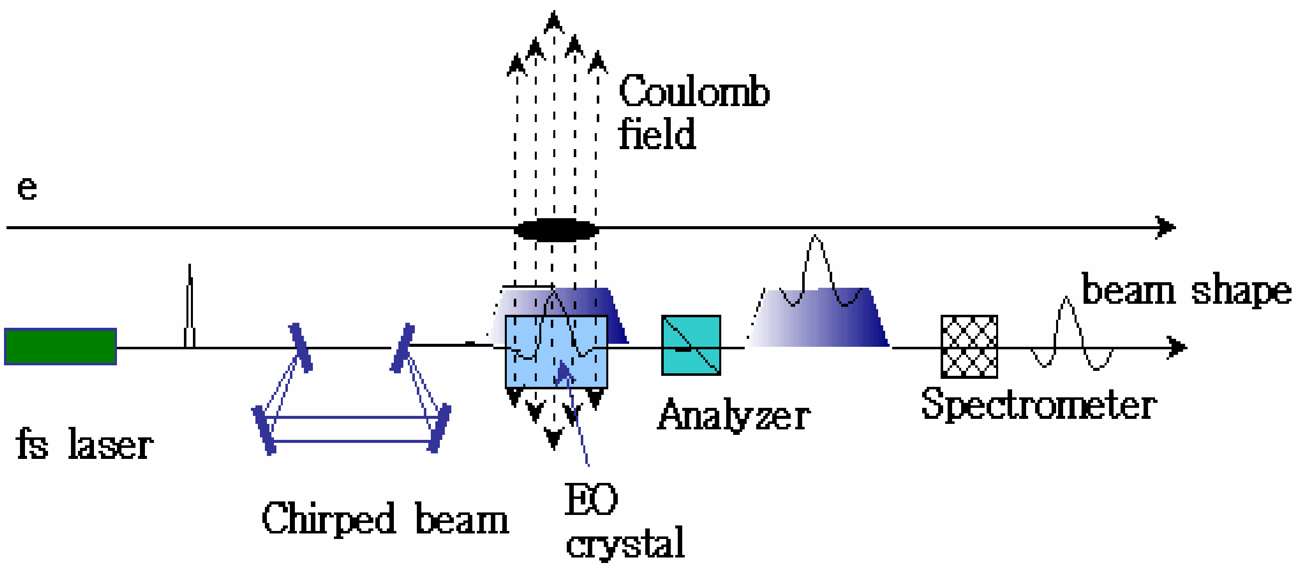
Beam Bunch Length Measurement by EO Sampling

Electro-optic method I
(Courtesy/stolen from **Jung Yun Huang** ILC workshop Dec. 2004)

- **Example application in accelerator**: single shot with chirped beam

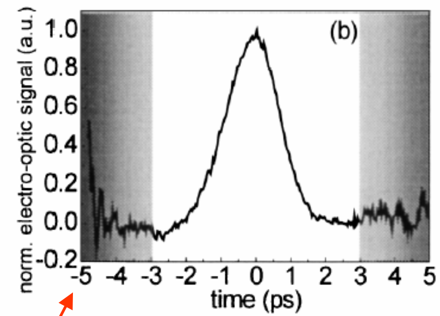
FELIX in Netherland

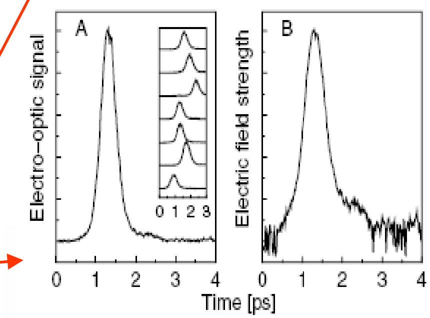


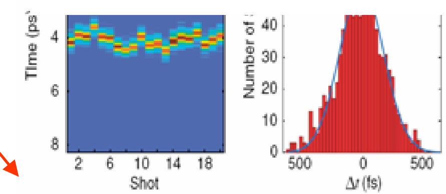


EO history and its application in beam measurement
(Courtesy *Yuelin Li ANL, ICFA 2005*

- **Observation of optical rectification, 1962**
- Bass et al., PRL 9, 446 (1962)
- **Demonstration of picosecond optical sampling, 1982**
- Valadmanis et al, APL 41, 212, (1982)
- **Demonstration of single-shot EO techniques, 2000-**
- Chirped laser pulse, Jiang and Zhang, APL 72, 1945 (1998)
- THz/Probe correlation, Shan et al, OL 25, 426 (2000)
- Double correlation, Jamison et al, OL 28, 1710 (2003)
- FROG EO: proposed by Bolton (2002)
- **Application in beam measurement, 1998-**
  - FNAL and BNL: 100 ps- ns temporal resolution
  - FELIX: Yan et al., PRL 85, 3404 (2000);
  - FELIX: Wilke et al., PRL 88, 124801 (2002), 2 ps
  - FELIX: Berden et al., PRL 93, 114802 (2004), 300 fs
  - SLAC/SPPS: Cavalieri et al., PRL 94, 114801 (2005), 300 fs







LBPM

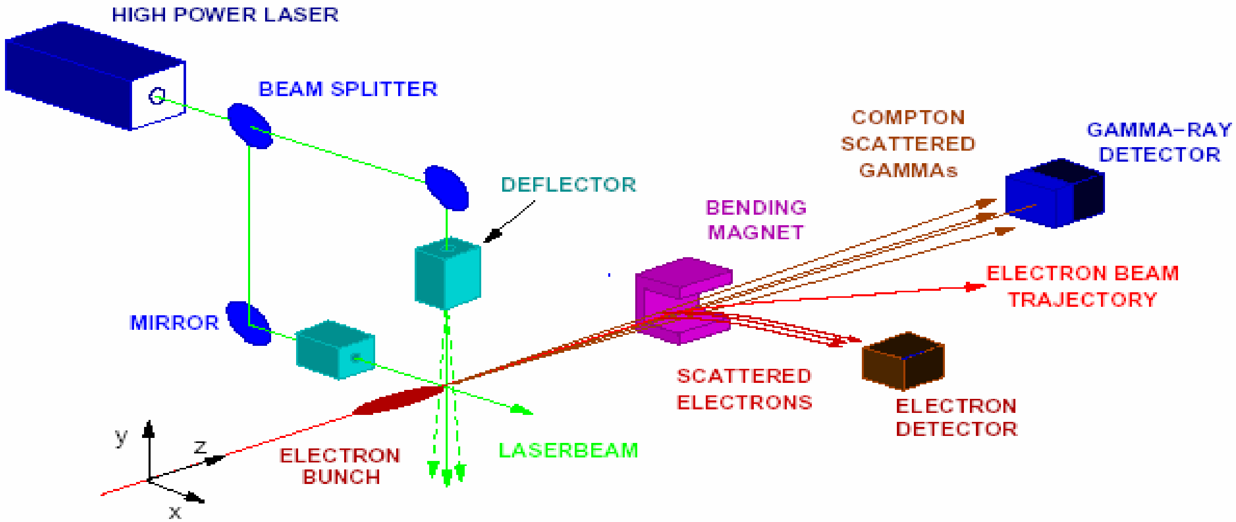
(Slide courtesy T. Kamps)

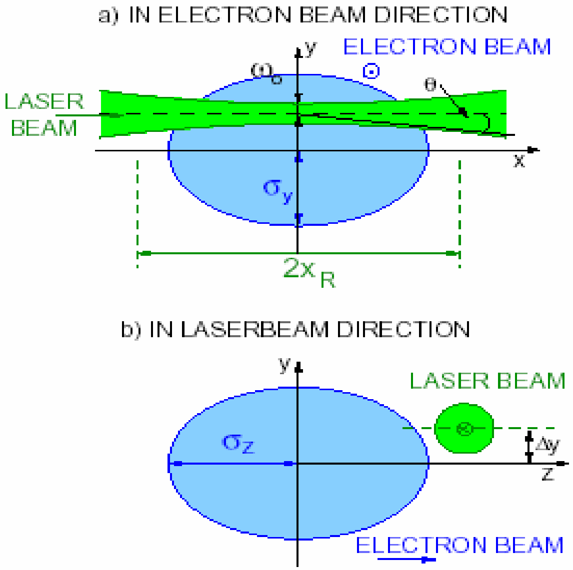
- Oxford
- RHUL
- DESY
- UCL
- CERN

Laser-wire; laser, mechanics and optics

Fast Scanning systems and electronics for the laser-wire. Optical design and data analysis.

Simulation of laser-wire systems in the beam diagnostics section.

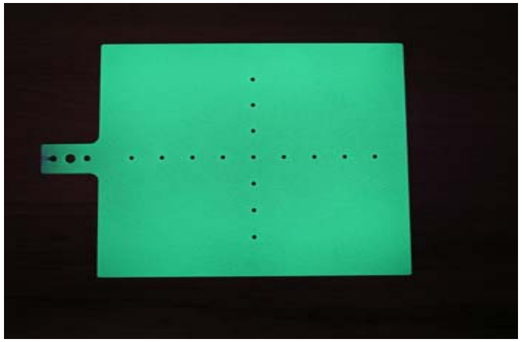




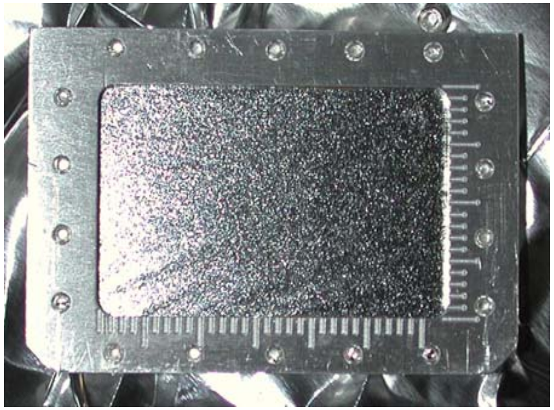
PETRA, ATF → Global Collaboration

Possible use of GAN systems for remote operation

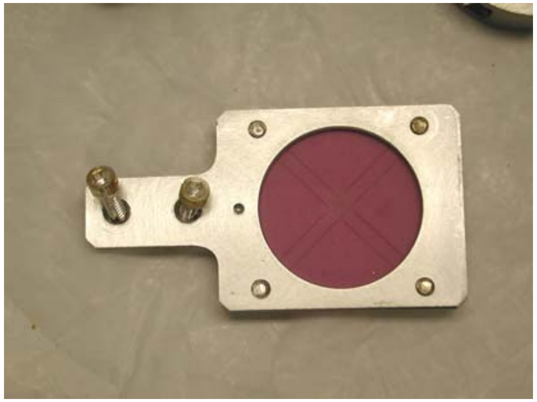
Examples of Viewer Flags



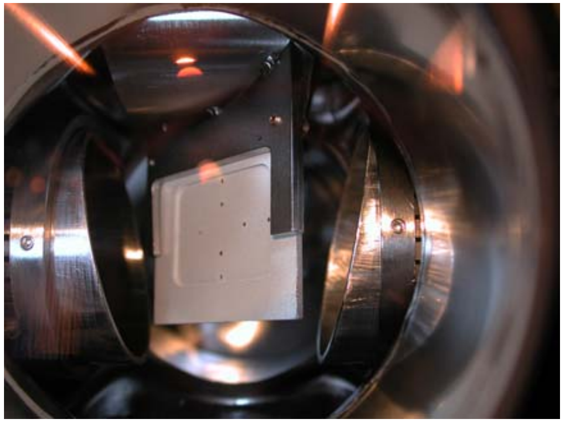
‘DESY’ coating under black light



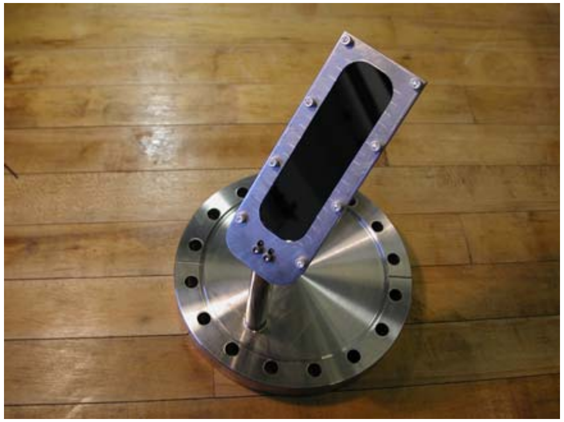
1.5 micron Al foil
1 mm reference marks



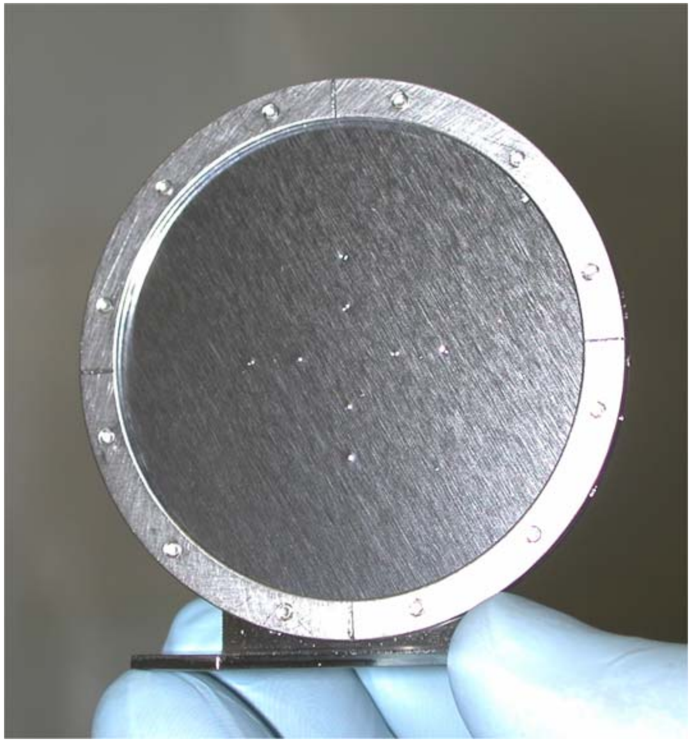
Cromox ceramic
1” dia. Used @ 350keV



‘DESY’ Phosphor coating

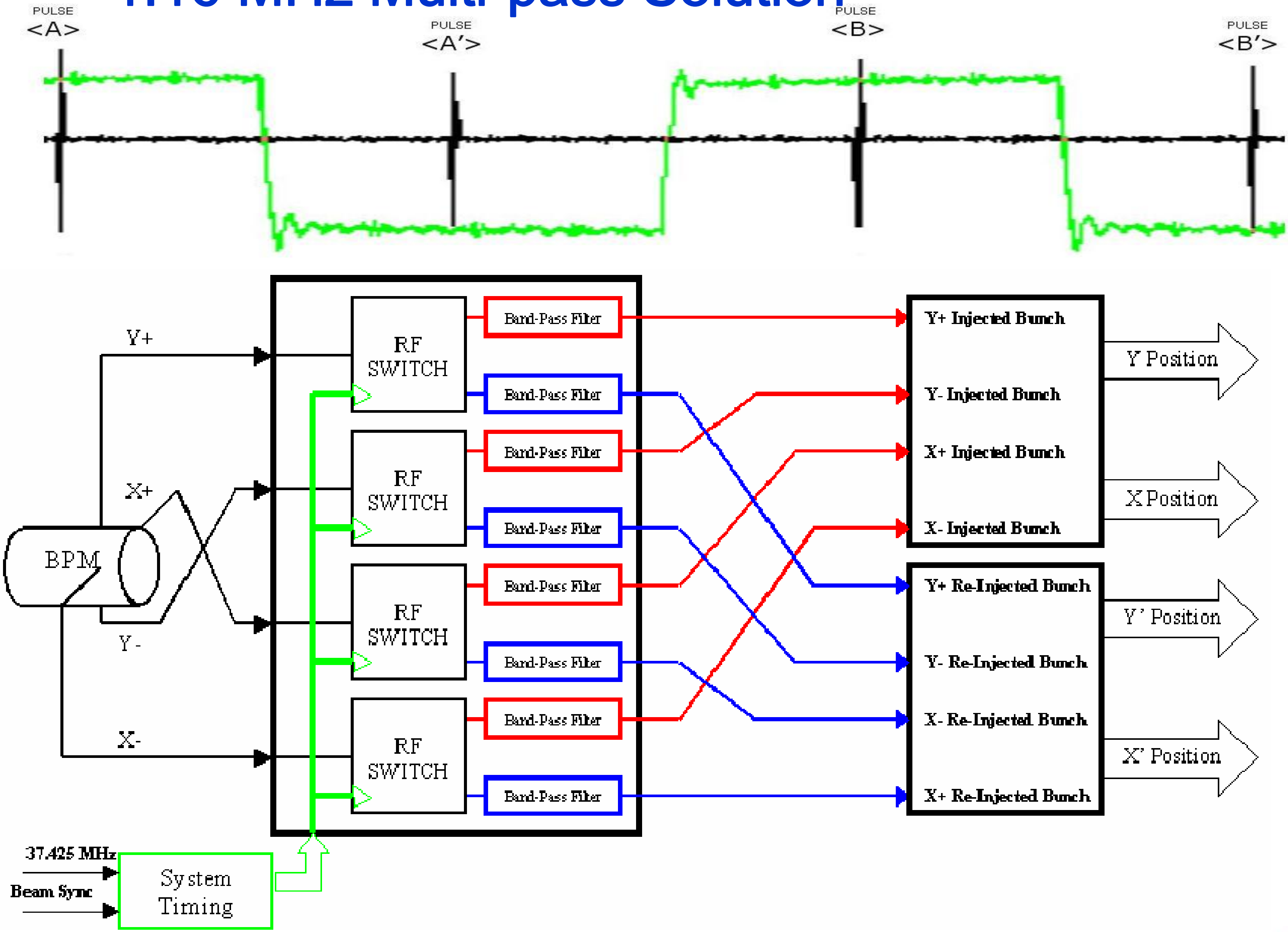


Si wafer fixed for spectrometer



5 micron Al 2” dia. $\pm$ 5, 10mm reference

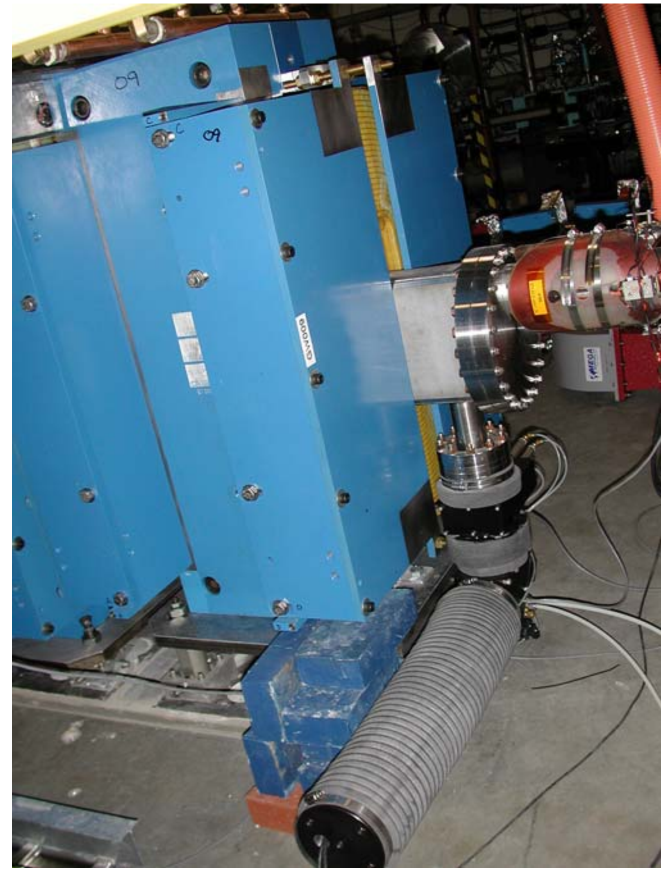
1.16 MHz Multi-pass Solution



Synchrotron Light Monitors

- SLM ports are installed even in unlikely locations
- Large dipoles were built with telescopes to bring out light
- THz chicane has a mirror in vacuum to *peek* into magnet
- All locations have insertable neutral density (ND) filters to attenuate signal, SLM bright even at 88MeV pulsed beam
    - OD1 (10x) and OD2 (100x) filters extend dynamic range of cameras 3 orders of magnitude

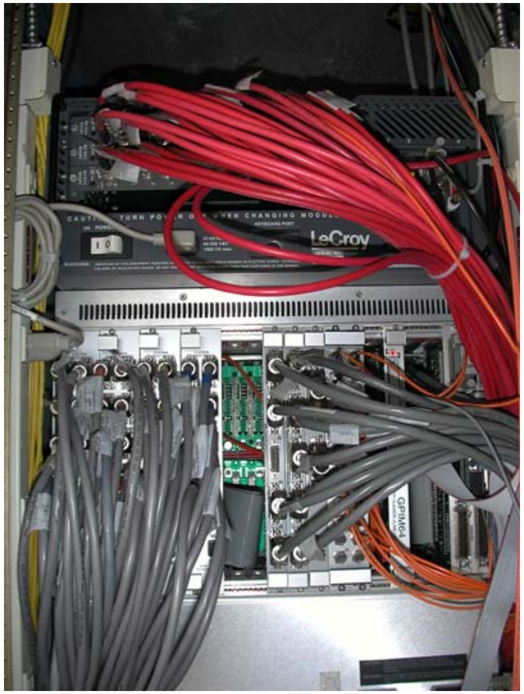
SLM port 5F02 with CCD camera and attenuators



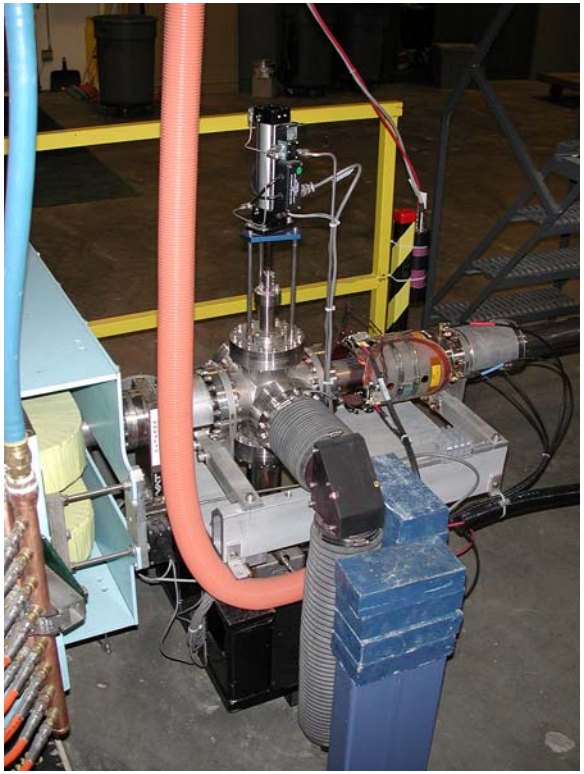
THz debuncher SLM port

Beam Loss Monitors

- Crucial to setting up machine and
- 931B PMTs used with programmable HVPS
- All 48 analog signal available through the AMS
- Trip levels are set to 1 micro amp CW loss



48 channels shown, 4 x 12 channel VME BLM boards shown with AMS and FSD connections on front and tube and high voltage on rear, also shown are the connections to the MPS system

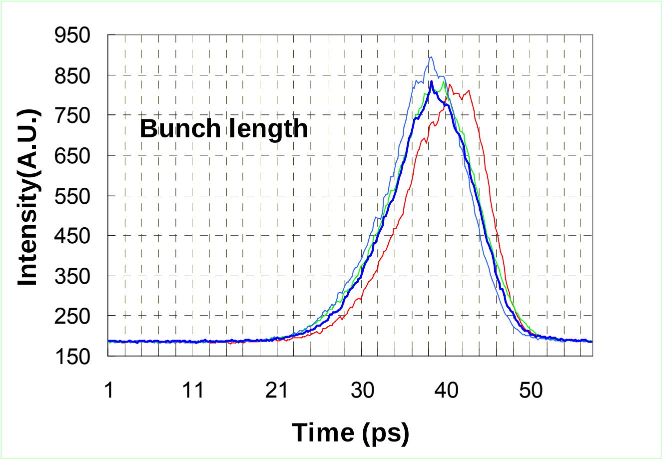


Left is a typical beam viewer with BLM mounted in background, note air core correctors mounted on top of BPMs

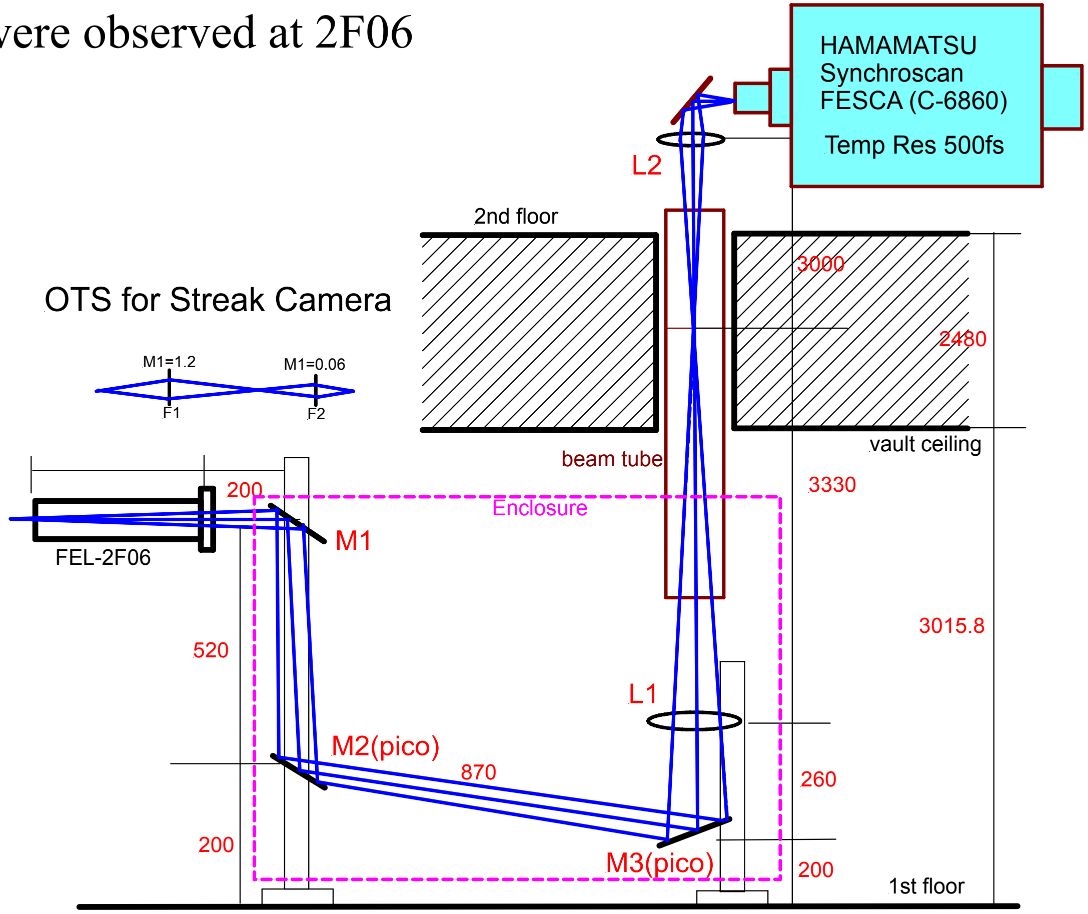
Bunch Length Measurement by Streak Camera

(Shukui Zhang)

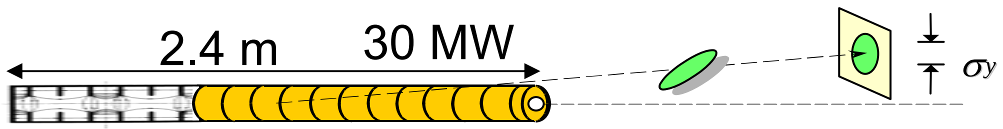
- We have established a bunch characterization system with a femtosecond Streak Camera
- Bunch length and timing jitter were observed at 2F06 region before ARC1 magnet
- More OTS will be available for further beam characterization (Tomography…)

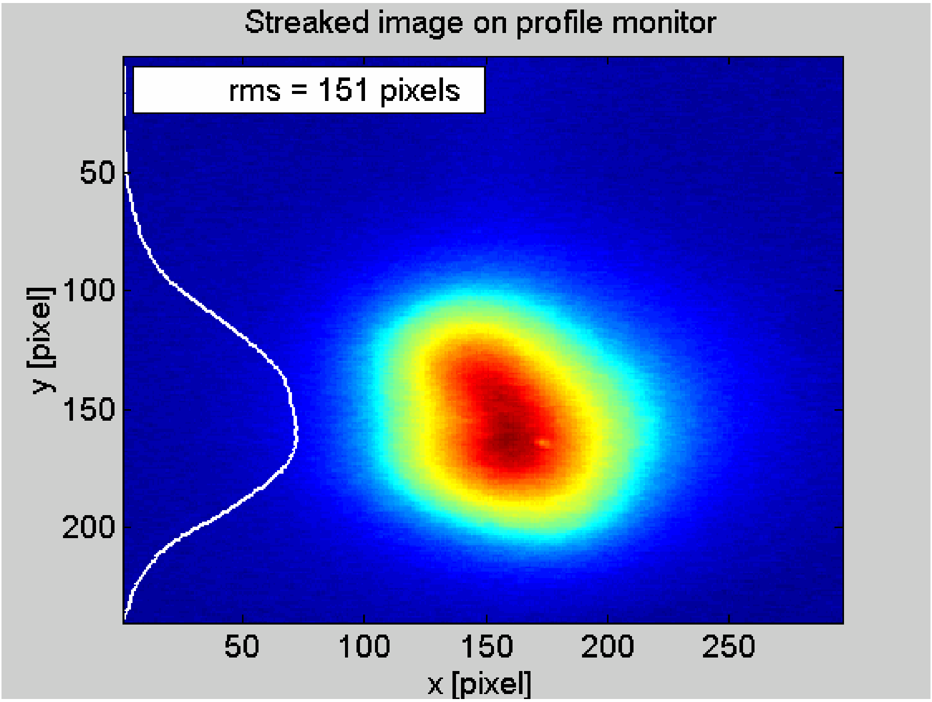


Bunch length measurements for e-beam energy 88Mev/CW 9MHz



Bunch Length Measurements with the RF Transverse Deflecting Cavity (P. Krejcik)



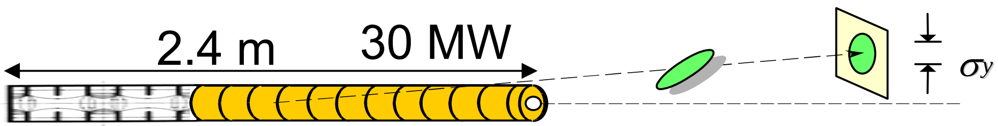


LoLa*

An S-band DLW structure with a TM_{11} transverse deflecting mode at 2856 MHz

*Loew, Larsen 1964

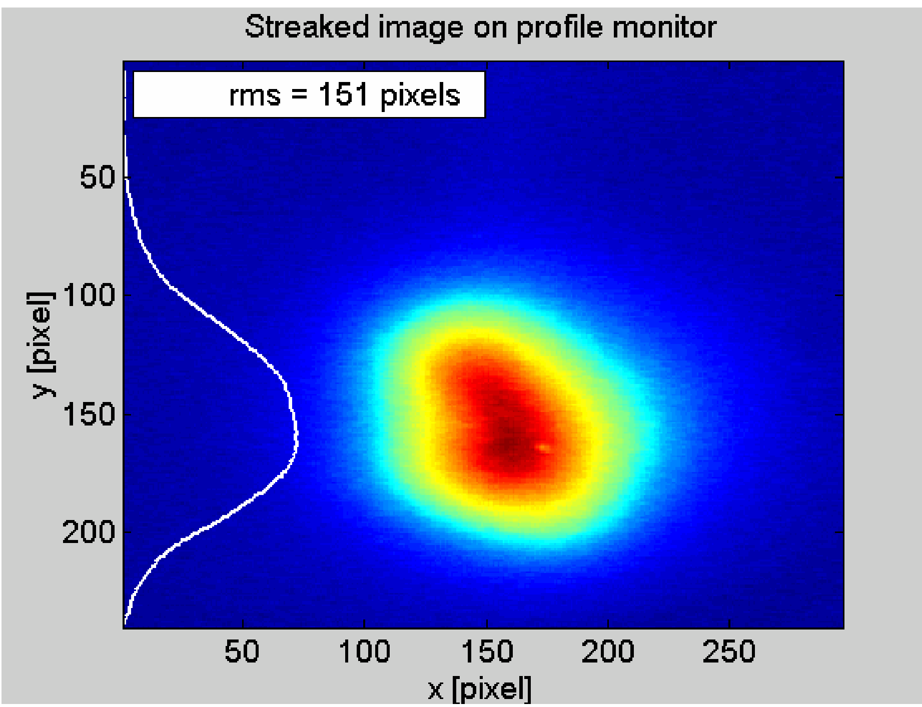
Bunch Length Measurements with the RF Transverse Deflecting Cavity (P. Krejcik)

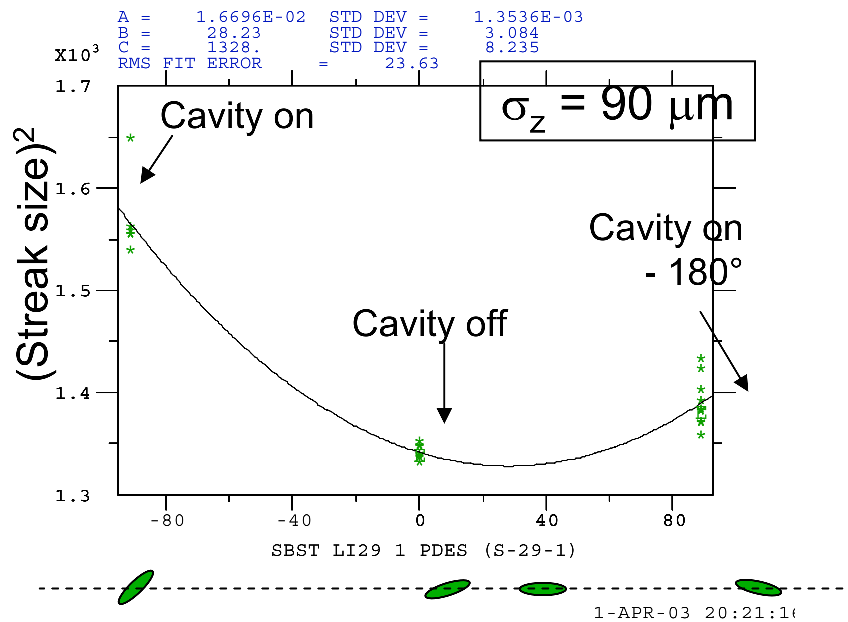


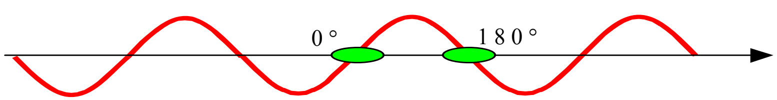
Bunch length reconstruction

Measure streak at 3 different phases

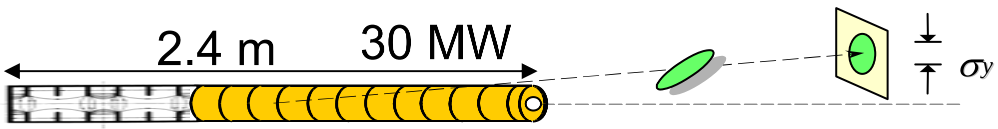
$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$







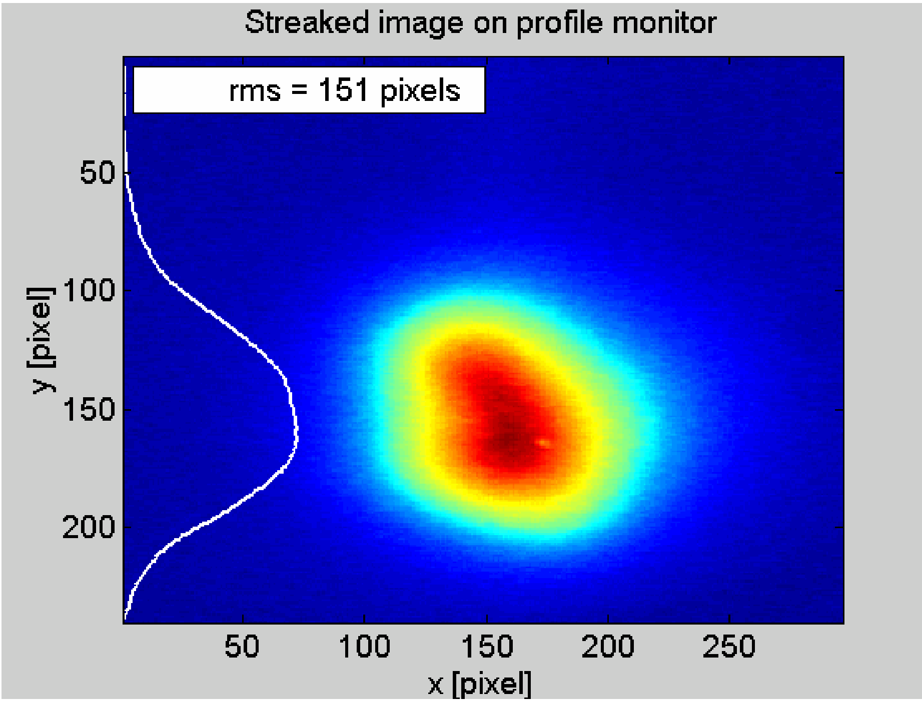
Bunch Length Measurements with the RF Transverse Deflecting Cavity (P. Krejcik)

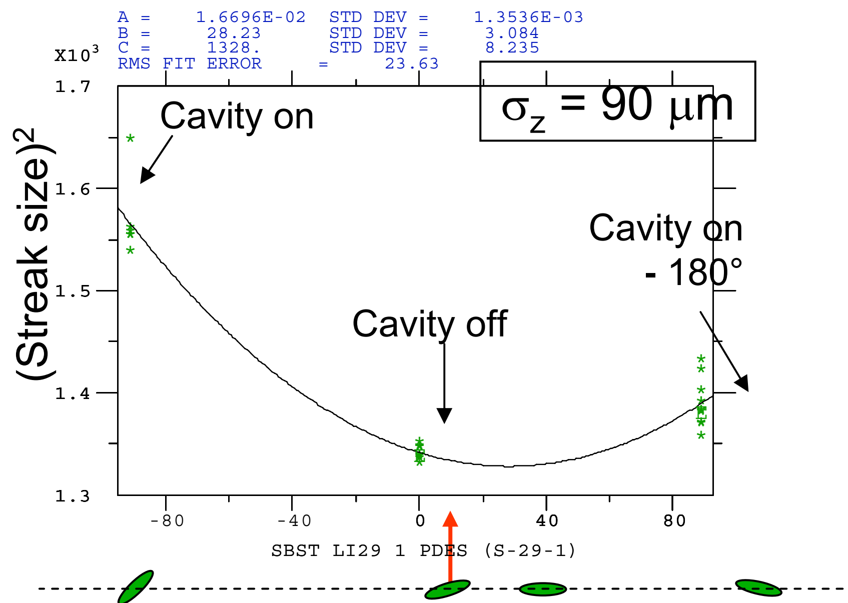


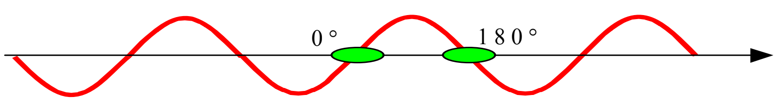
Bunch length reconstruction

Measure streak at 3 different phases

$$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$$

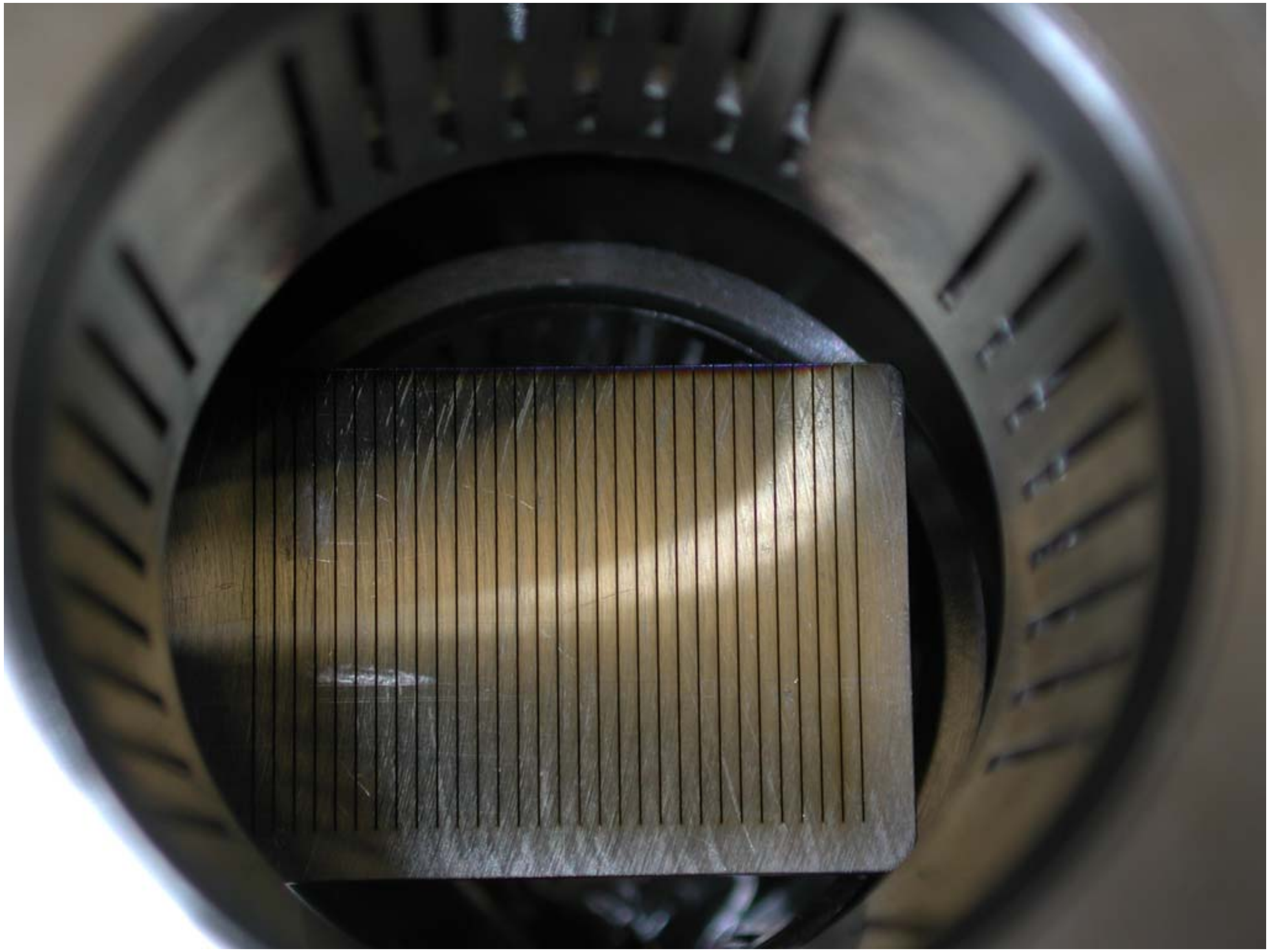






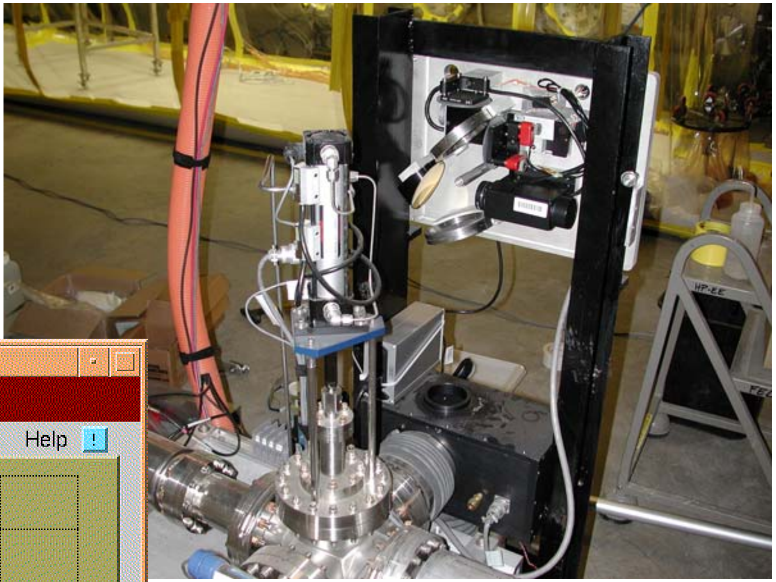
Asymmetric parabola indicates incoming tilt to beam

New multislit

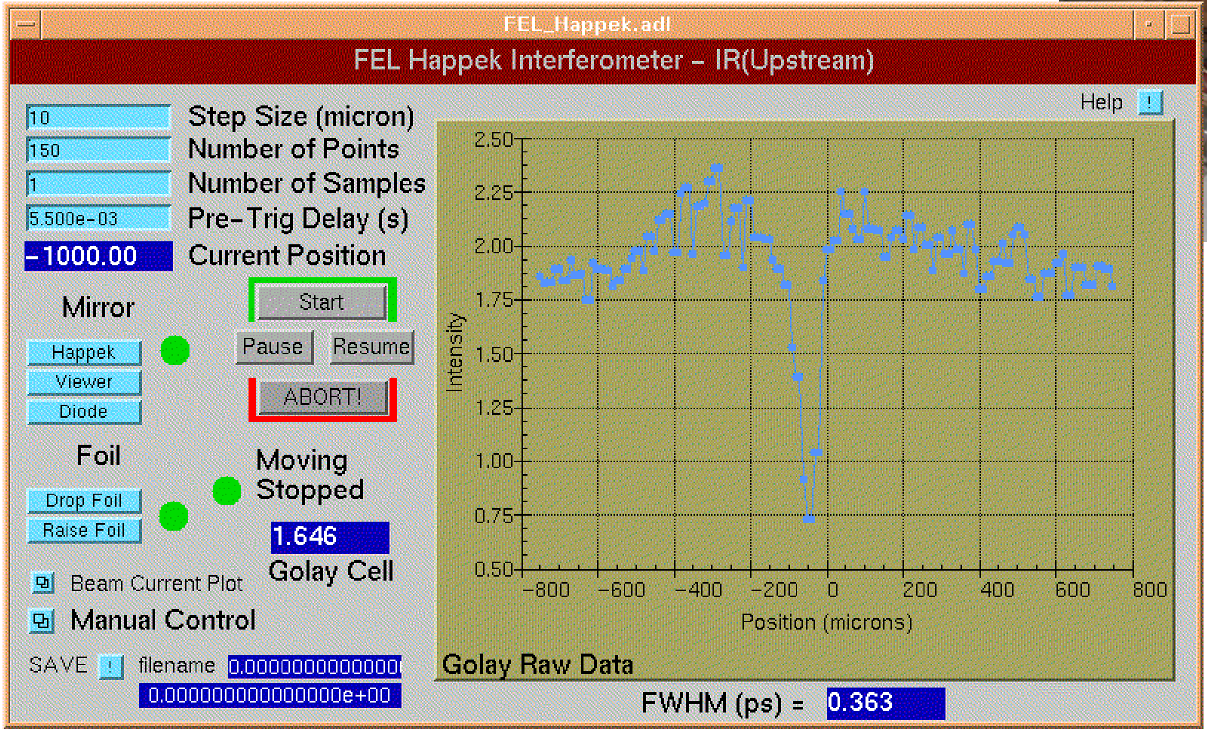


‘Happek’ Bunch Length Monitor Installation

- Happek used to set injector phase, then bunch is optimized using FEL
- OTR signal from beam viewer
- Movable mirror to direct signal to interferometer or CCD camera
- Broad band lens (Shiny Bald Guy) used to collimate the THz signal to Golay cell detector in Martin-Puplett interferometer



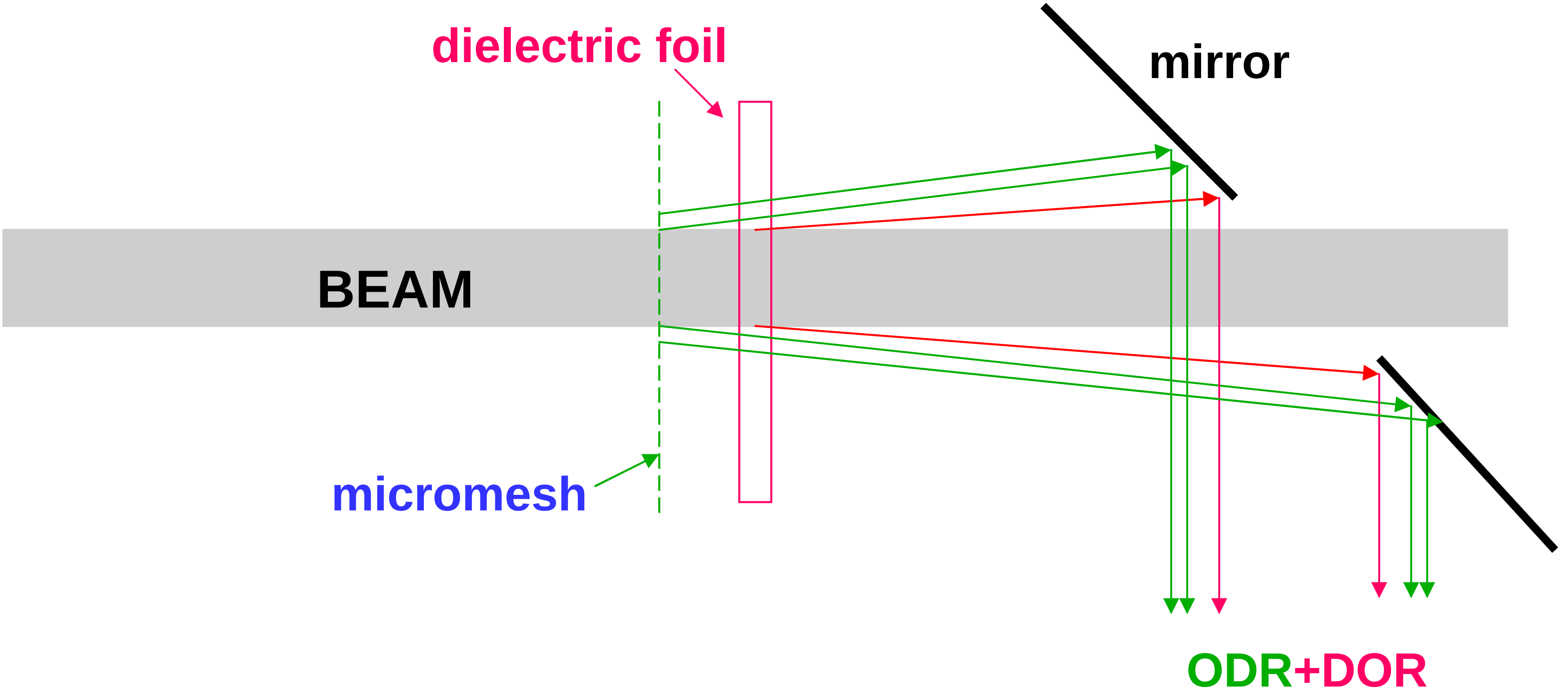
Interferometer shown with cover removed



Low Energy (Injector) Diagnostics using ODR and OR from Dielectric Foil

PROBLEM: for low energy beams the inter-foil spacing L required is too small to directly observe backward reflected OTR or ODR from a mesh - metal foil **e.g. L (8 MeV, 650 nm) ~ $\gamma^2\lambda$ ~ 1 mm**

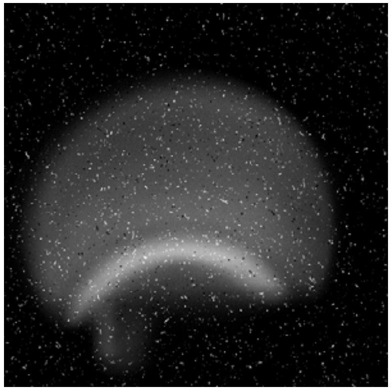
SOLUTION: observe interference between forward directed ODR from mesh and forward dielectric optical radiation (DOR).



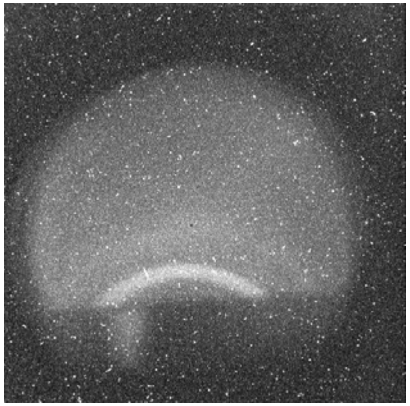
Preliminary Results: ODR-ODFR Interferences from the 8 Mev ANL AWA

(Kapton foil (t = 13 μm), mesh-dielectric spacing = 1.36 mm)

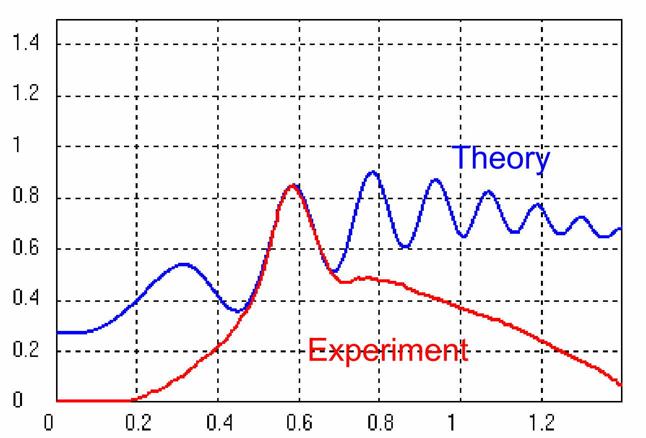
666 nm x 80 nm



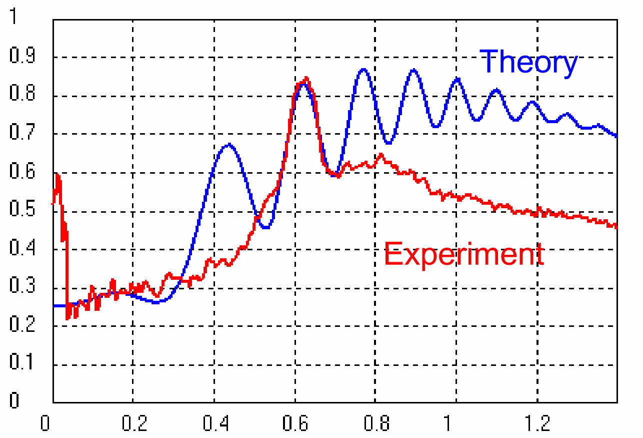
Filter 505 x 10 nm



Fit: λ = 660 nm, **σ = 2 mrad**



Fit: λ =505 nm, **σ = 1.8 mrad**



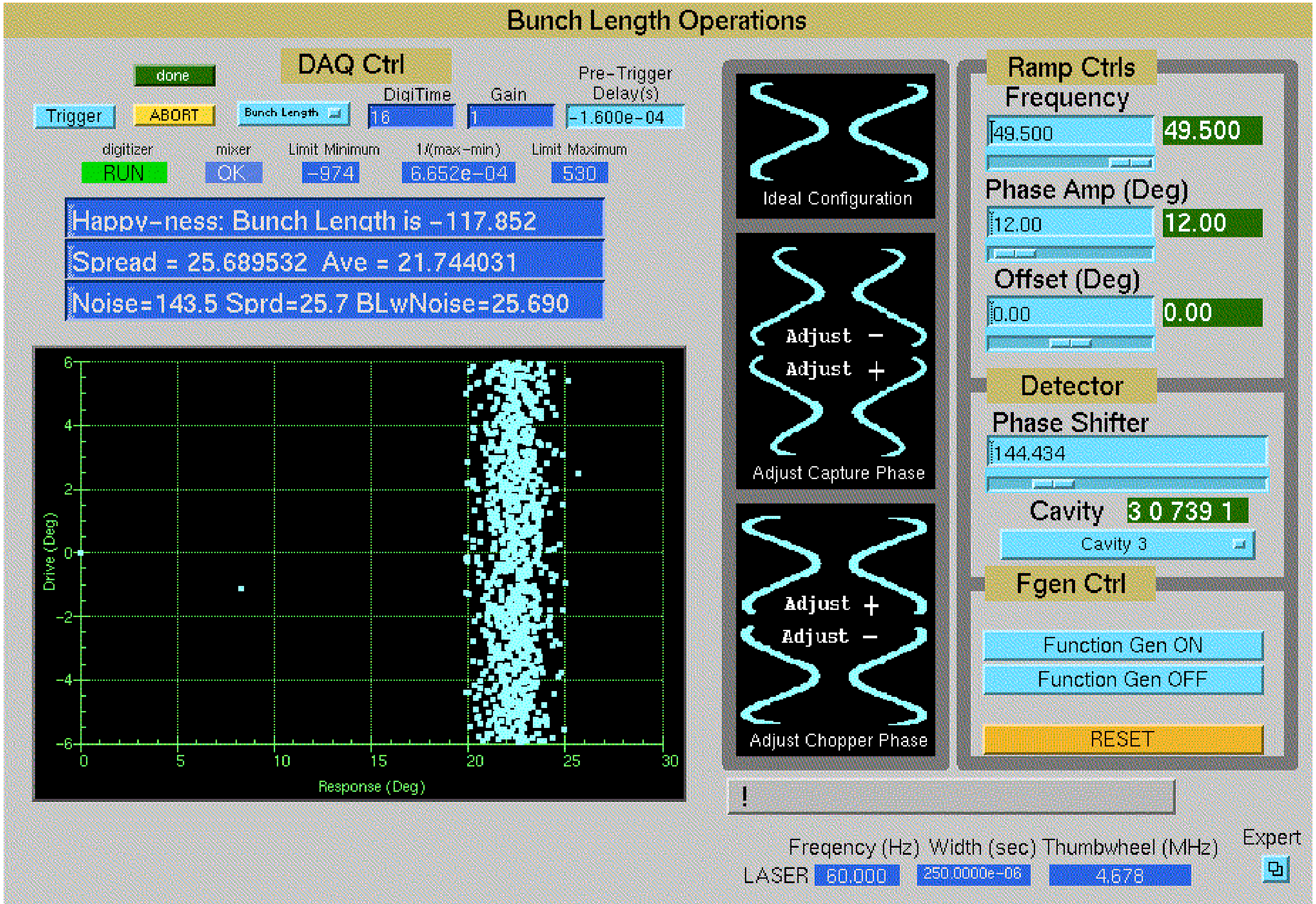
FOV (theory): 0.3/γ (reflector) to 1.7/γ

Actual FOV: 0.5/γ (reflector) to 0.7/γ (beam offset)

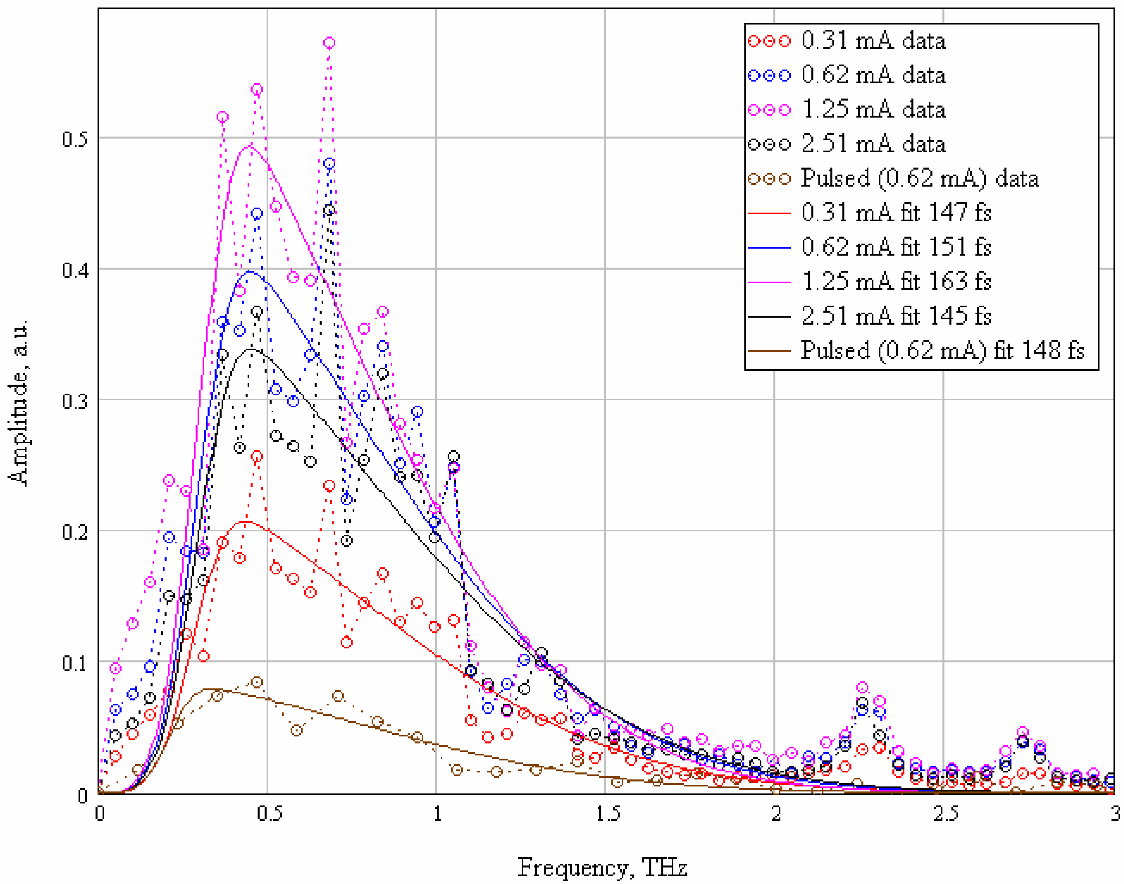
Beam transport and beam optics

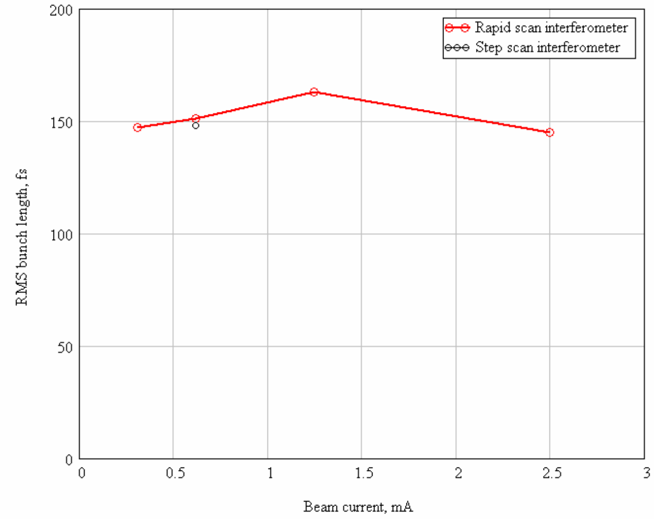
Device	Diagnostic	Resolution/Accuracy
Steering coils/correctors	BPMs and viewers	0.1 mm/1 mm in position
Quadrupole pair	BPMs, viewers and multislit	TBD
Cavity phases	Spectrometer + BPM	0.5 deg / 1 deg
Cavity gradients	Spectrometer + BPM	0.01% / 0.5%
Focusing solenoid	Viewer & multislit	Set by limitations of using model based study

The M55 cavity system can map out phase response of any of the elements in the injector



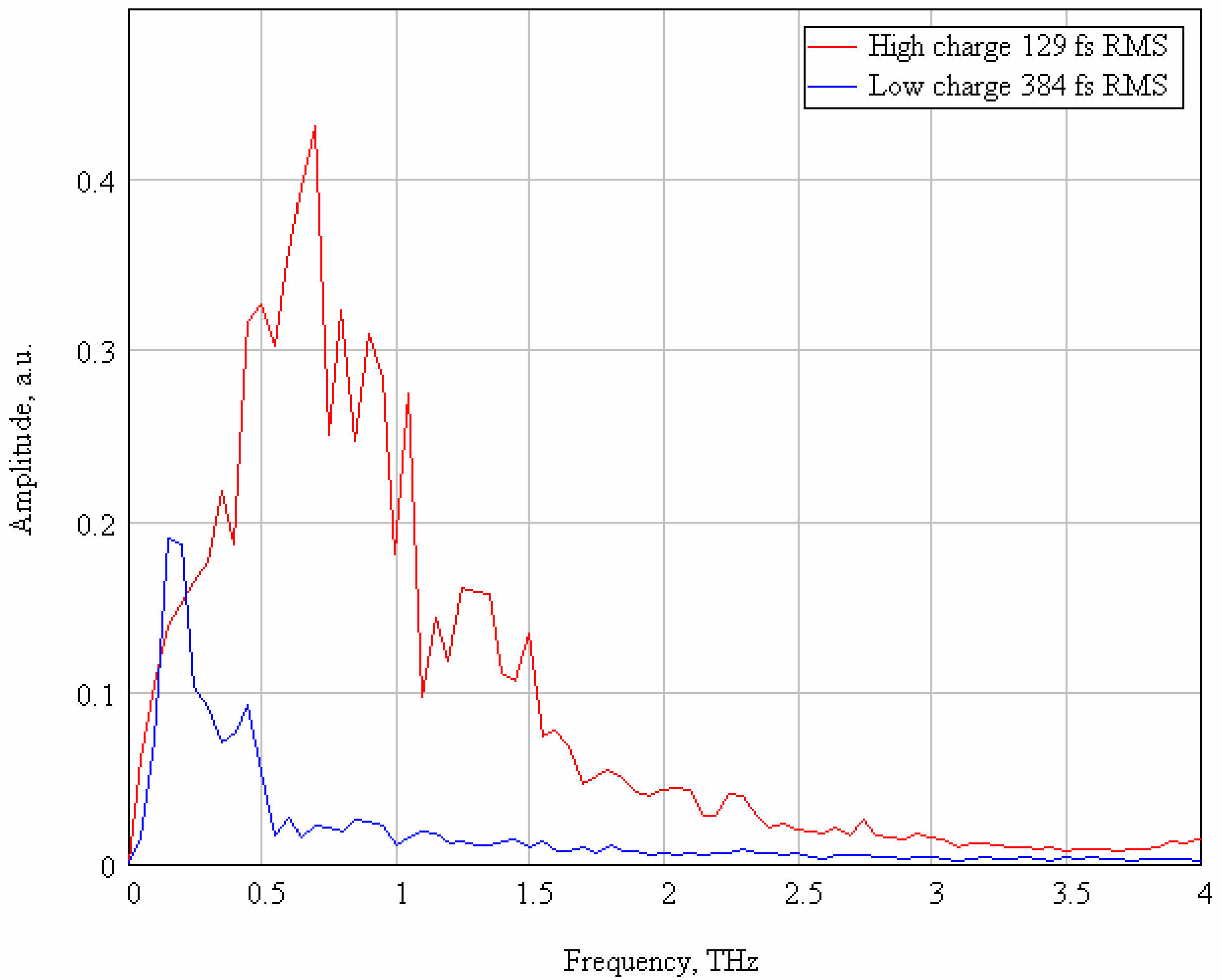
Pulsed beam measurements vs. CW beam (Courtesy Pavel Evtushenko)





The bunch length does not change with beam current.

Very short and very long bunches (Courtesy Pavel Evtushenko)



The bunch compression is optimized for the nominal (135 pC) bunch. It is also strongly bunch charge dependent.