Diagnostics and synchronization (emphasis on ERL)

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Outline

- introduction
- Transverse diagnostics
- Longitudinal diagnostics
- Synchronization issues

Some considerations

- **ERL**
  - High average current, CW operation,
  - Precise knowledge of longitudinal transfer functions
  - Non-interceptive monitors
  - Some diagnostics need to resolve both accelerated (“fresh”) and decelerated (“used”) beams

- **Pulsed mode “tune-up”**
  - Transverse parameters, emittance
  - Bunch length, energy spread
  - Beam halo

- **CW operation**
  - Diagnostics should be non-interceptive

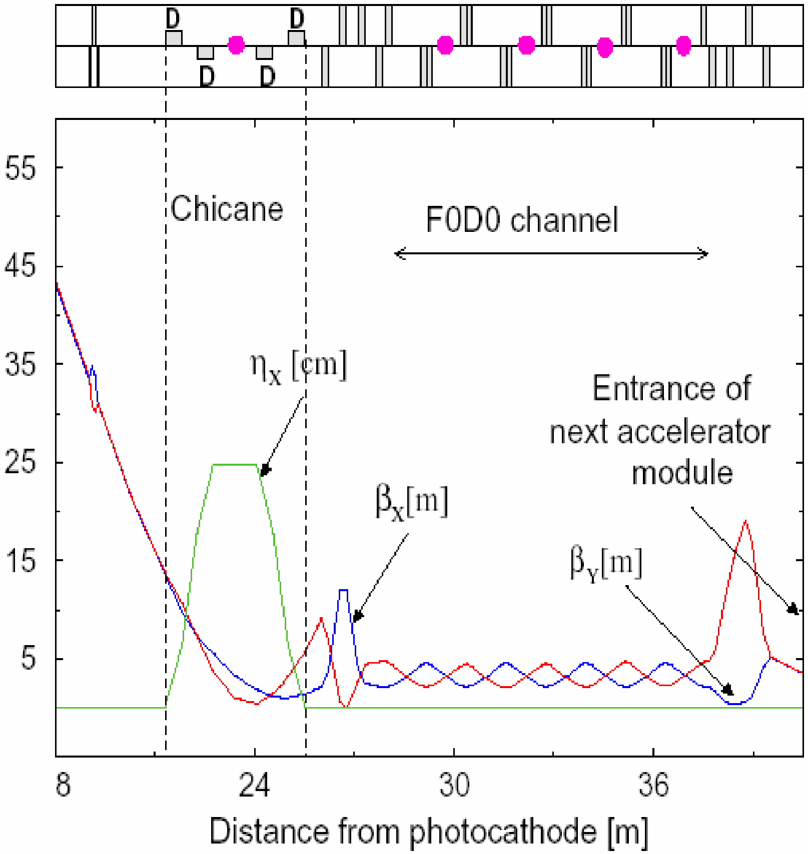
transverse phase space measurements

Device Type	Invasive	Single shot	measurement	resolution
OTR	Yes but high power OK	Yes	2D density	diffraction limited
SR	No but δp/p mainly	Yes	2D density, beam size (slits)	?
ODR	No	Yes	Beam size	few microns
Residual gas monitor	No	Yes	Beam profile	few microns
Wire (scanner, laser, Shintake)	Yes	No	Beam profile	few microns
90deg Compton scattering	No	Yes	2D density	few microns

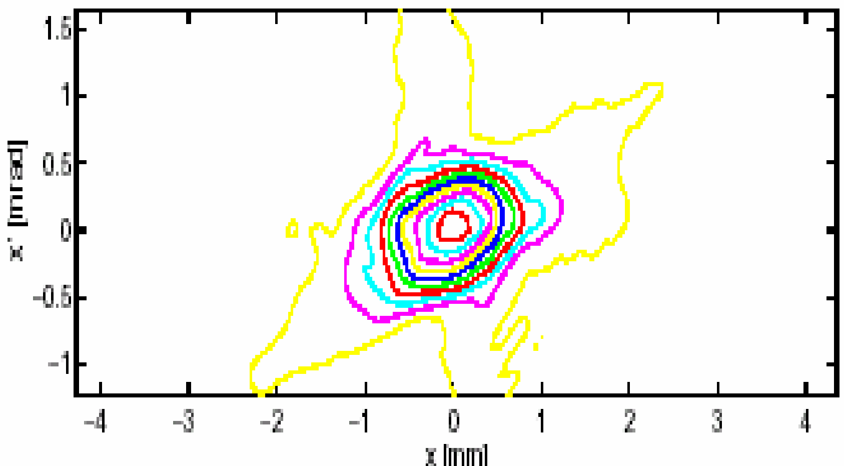
Transverse phase space measurements

- **Lattice measurement (BPM)**

- **Transverse phase space parameters:**
  - Slits technique
  - Envelope fitting technique:
    - Quad. scan/tomography
    - Multi-monitor



TTF-2 / XFEL design (2001)



M. Geitz *et al.* (EPAC1998)

Transverse beam position

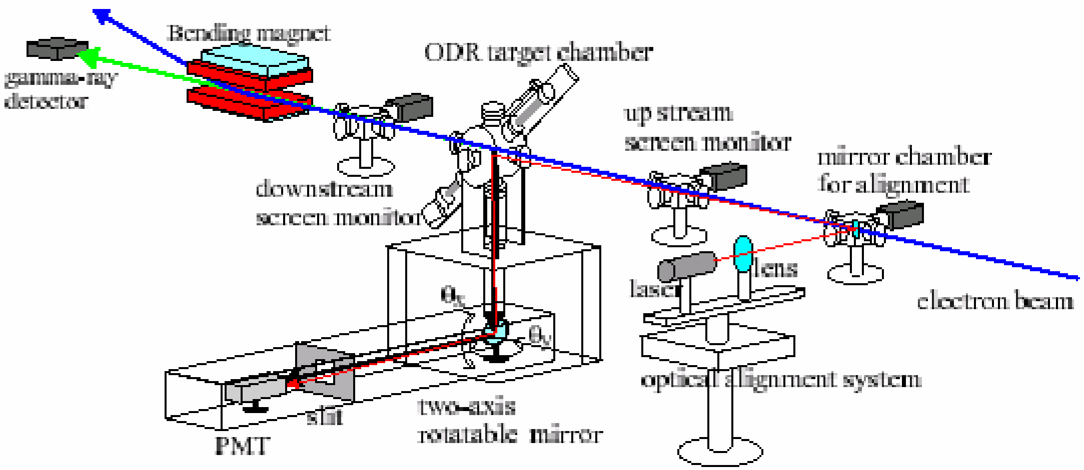
•In an energy recovering linac there can be locations with both fresh and used beam.

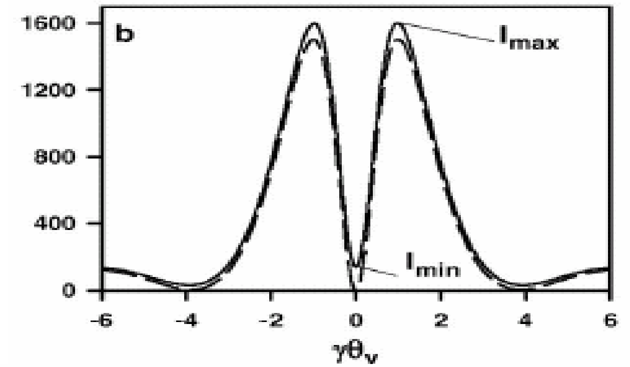
•Low repetition rate recirculating linacs with long recirculation path length (CEBAF), electronic needs to have a response time shorter than the once-around time

•For CW ERL, double frequency BPMs seem to be the easiest: measurements of fundamental and 2^{nd} harmonic can provide both position of the “fresh” and “used” beam

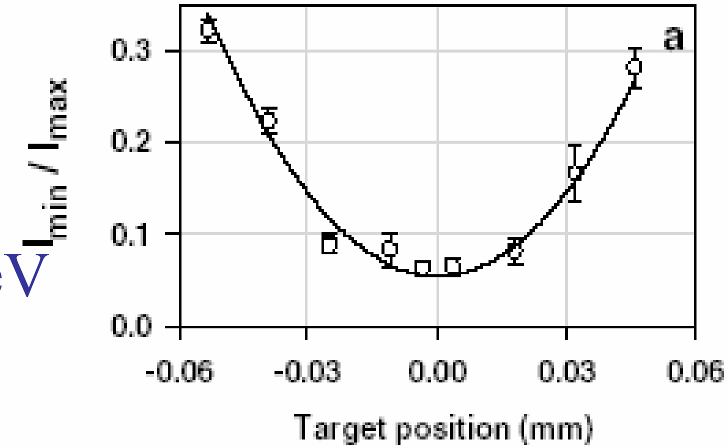
G. Krafft et J.-C. Denard (BIW2002)

Transverse beam size



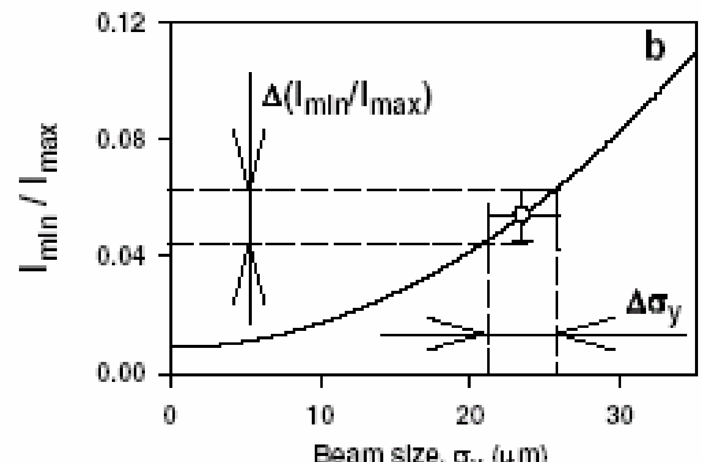


- Meas. at ATF/KEK extraction line 1.3 GeV



- Use optical diffraction radiation (intercept the beam with a hor. slit)

- Measure ratio of I_{min}/I_{max} intensity



- Assume the transverse profile is a Gaussian; retrieve σ_y

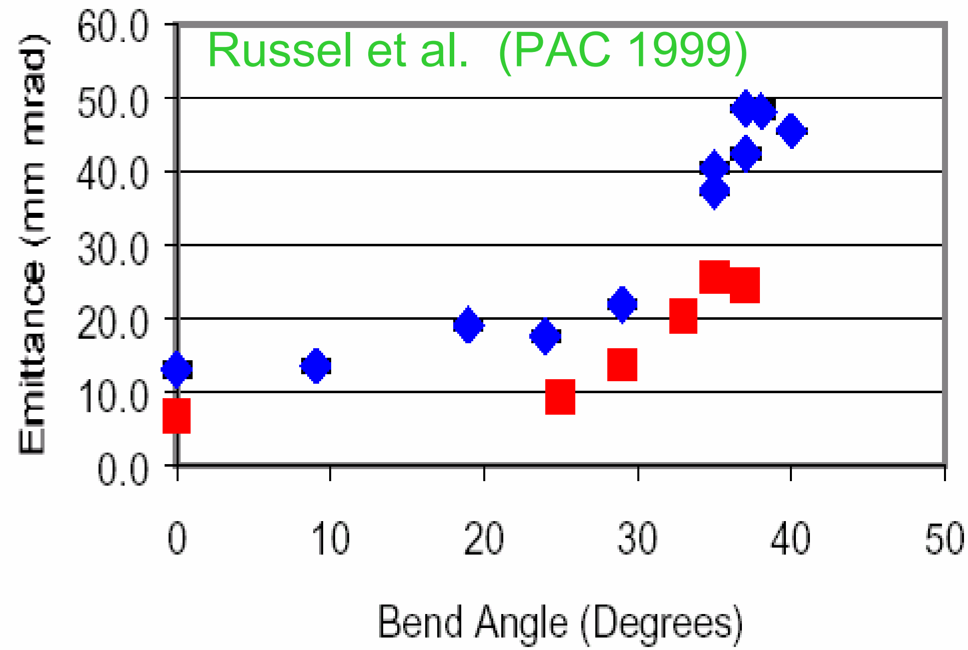
P. Karataev et al. PRL 93:244802 (2004)

Transverse beam 2nd order moments

•Old idea (1983) by R. Miller *et al.*: using beam position monitor to infer beam second order moments, implemented at Los Alamos

$$\langle x^2 \rangle - \langle y^2 \rangle + \langle x \rangle^2 - \langle y \rangle^2 \propto \frac{V_R + V_L - V_T - V_B}{V_R + V_L + V_T + V_B}$$

T,B,L,R: top, bottom, left right electrodes



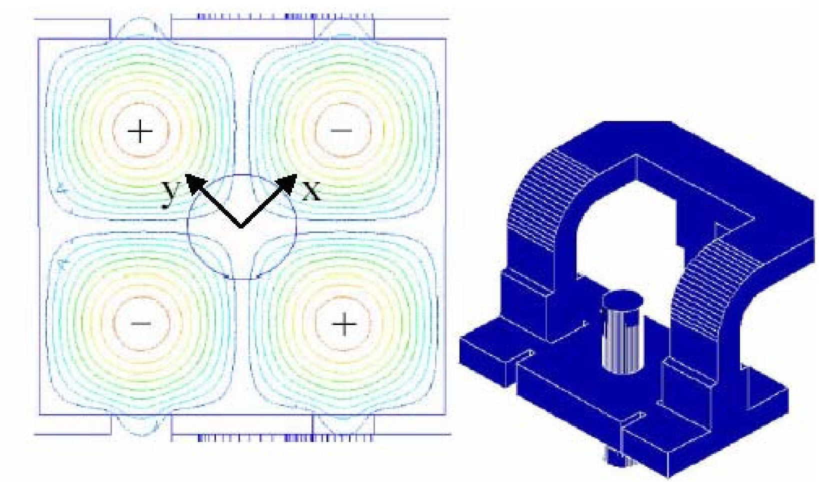


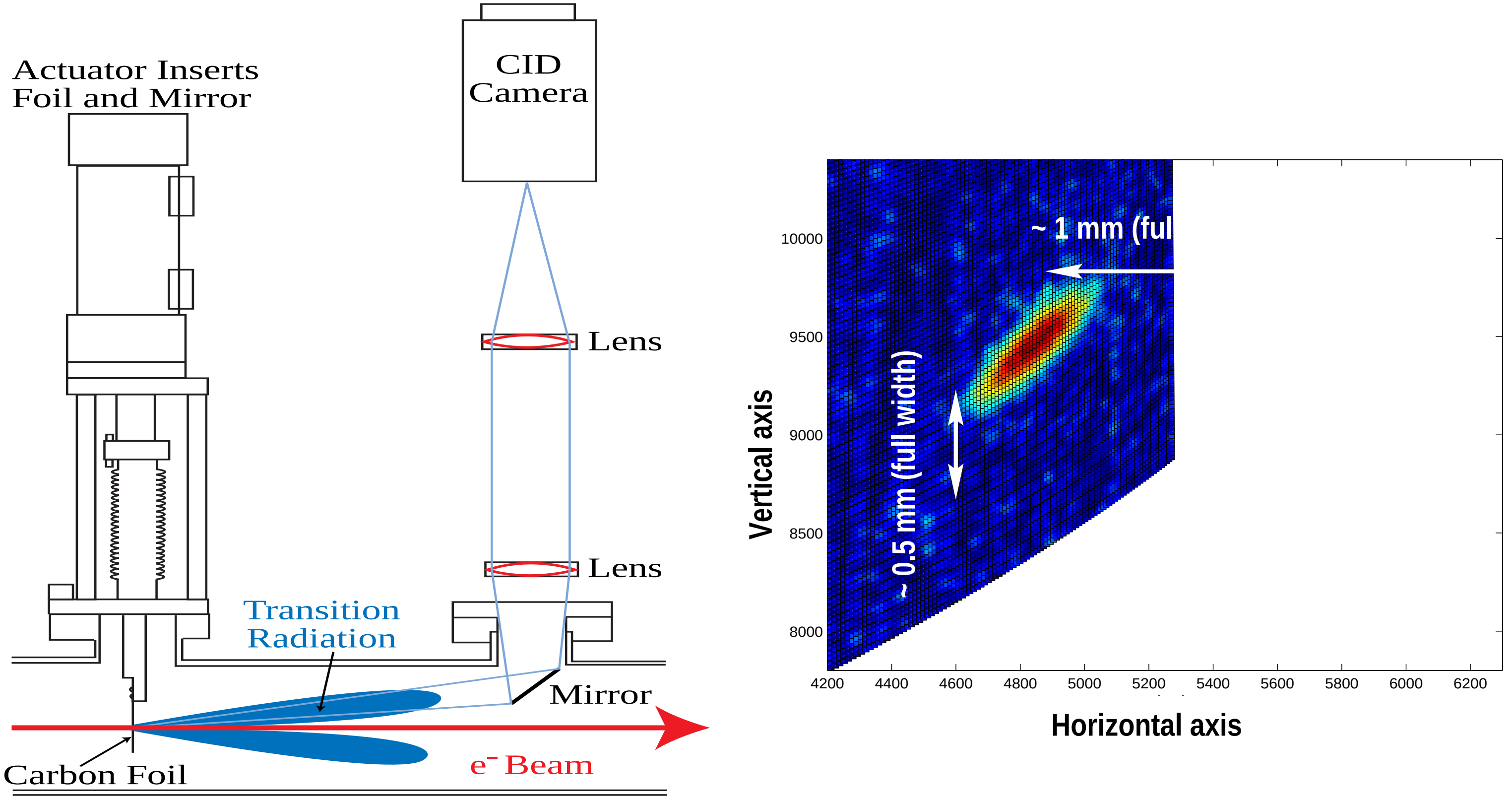
Figure 1: Quadrupole cavity a) 2-D geometry with field pattern and b) 3-D geometry with waveguide network.
a) b)

•Specially designed TM220 cavity (f=11.4 GHz) is being tested by SLAC/FarTech

C. Nantista *et al.* (LINAC2002)

Transverse beam density

•OTR can be non-interceptive: either by using very thin, low Z, radiators (CEBAF uses 0.25 μm C-foil) or grid wires (recent measurements at ATF Maryland/BNL, ATF Newsletter feb05)



(A) (B)

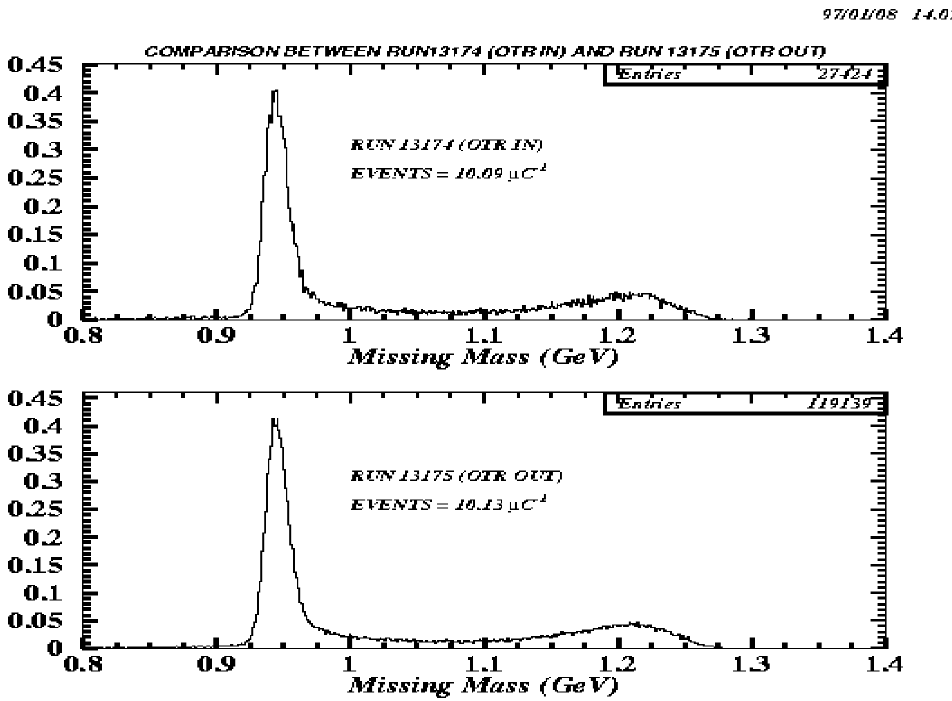
Measurement at CEBAF (1996)

Transverse beam density

•The C-foil-based OTR diagnostics was verified to be non-interceptive, could also measure CW beam with 200µA at CEBAF

•Used from 800 MeV

•Higher current should in principle be possible (depending on spot size)



Measurement at CEBAF/Hall C (1998)

•Special care, e.g. using of band pass filter because black body radiation

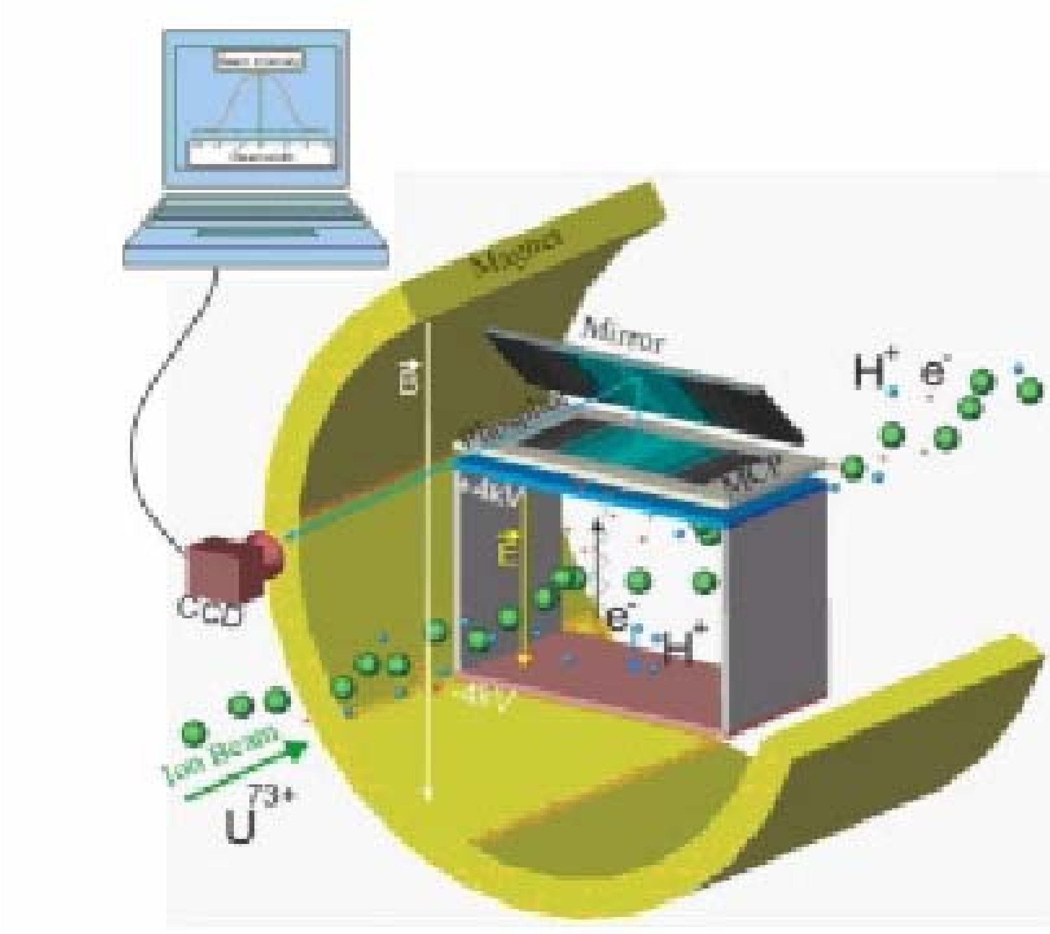
Residual gas monitors

•Non-invasive profile monitor

•Electrons ionize residual gas molecules in vacuum H_2, O_2, N_2,…

•Ions (or electrons) drifte toward an MCP by applying a DC voltage,

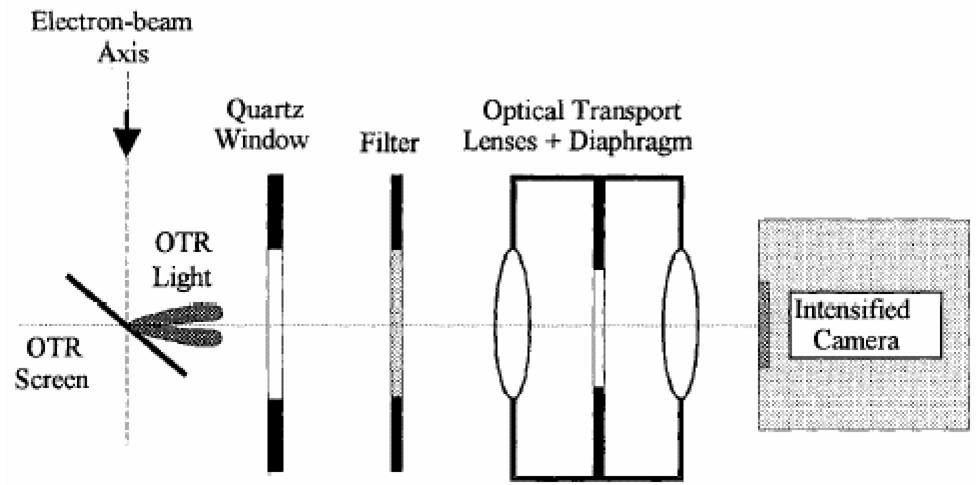
•signal is recorded by a video camera

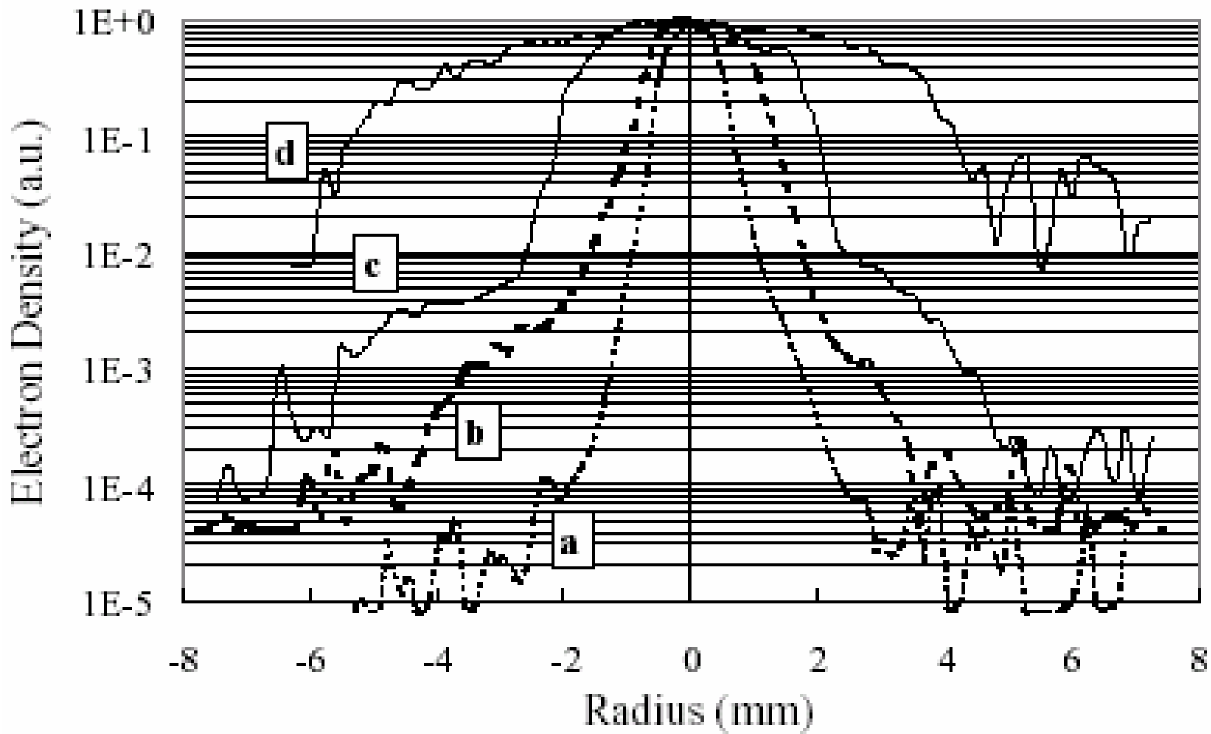


Babarin et al. EPAC 2004

Halo monitors

- A series of OTR radiator with bored hole with different diameter are mounted on an insertion device
- Non-bored radiator provides the core beam density
- Bored radiators intercept particle at larger radius
- Sensitivity depends on average current (number of bunch) used



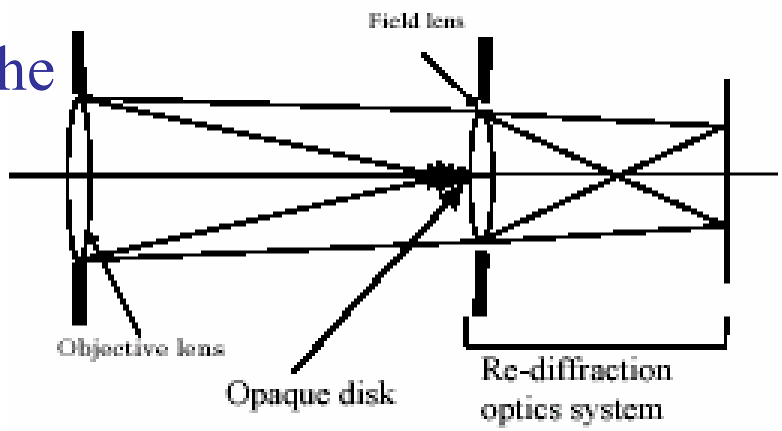


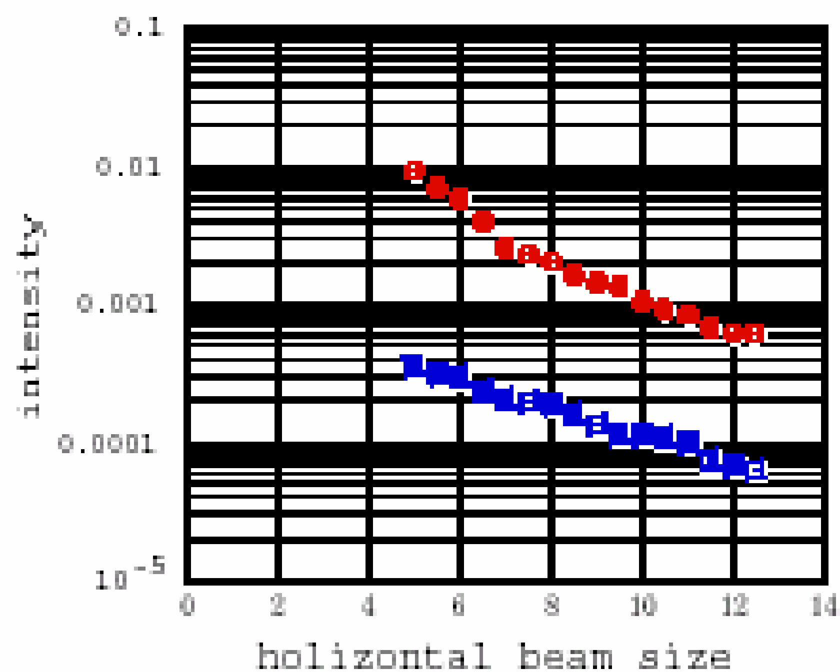
G. Haouat, et al. PAC1997

Halo monitors

•Use the coronograph technique: mask the central part of the radiated light

•Special attention on optics quality required, diffractive effects





T. Mitsuhashi, KEK (2004)

longitudinal phase space measurements

Device Type	Invasive	Single shot	Abs. or rel.	Timing	Min bunch length
Deflecting Cavity	Yes: 3 pulses or tomo.	No	Absolute	No	300 fs (JLab)
Zero-phasing	Yes: 3 pulses or tomo	No	Absolute	No	82 fs (JLab)
Streak camera	No, CSR Yes: 3 pulses	Yes	Absolute	No	200 fs
Coh. Rad. power	No, CSR Yes, CTR	Yes	Relative	No	few fs
Coherent radiation autocorrelation	No, CSR Yes, CTR	No	Absolute	No	50 fs (SSRL)
Fluctuation technique	No, CSR Yes, CTR	No	Absolute	No	?
Electro Optic Sampling	No	Yes	Absolute	Yes	20-50 fs (theo.)

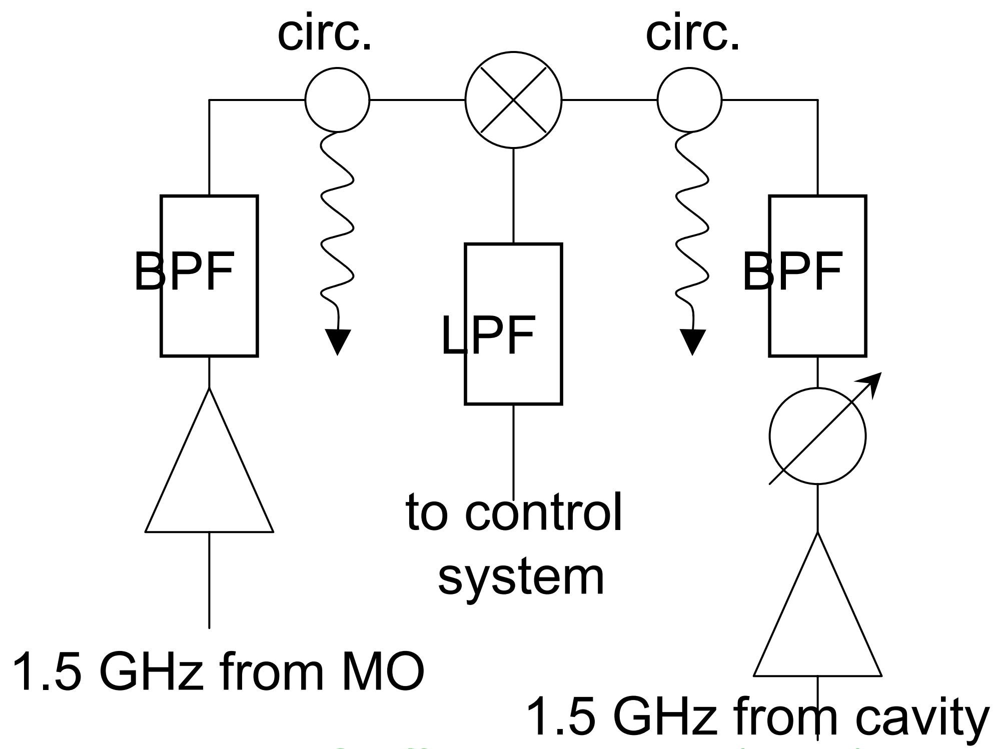
Adapted from P. Krejcik (SLAC)

Longitudinal lattice

- Measurement of time-of-flight provide a way to quantity the longitudinal transfer function of a lattice (by doing difference measurement corresponding to response to impress excitations) like, for instance, R_{56} and R_{55} but also nonlinear coefficients, e.g. T_{566}
- Signal can be picked-up by cavities (IRDEMO) or ring-type pickup (TTF-2)

- Resolution ~0.5 ps achieved

M. Wendt et al DESY (2003)



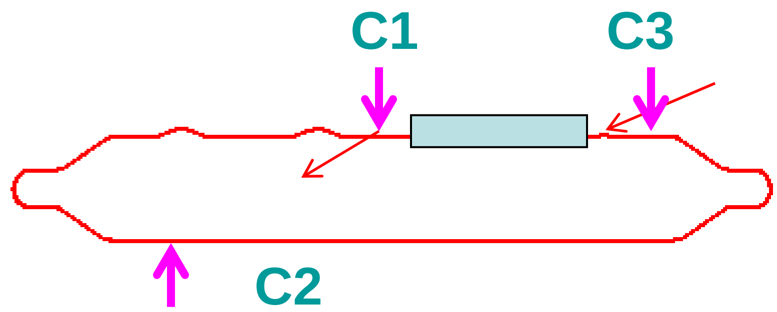
From Crofford et al JLab (1993)

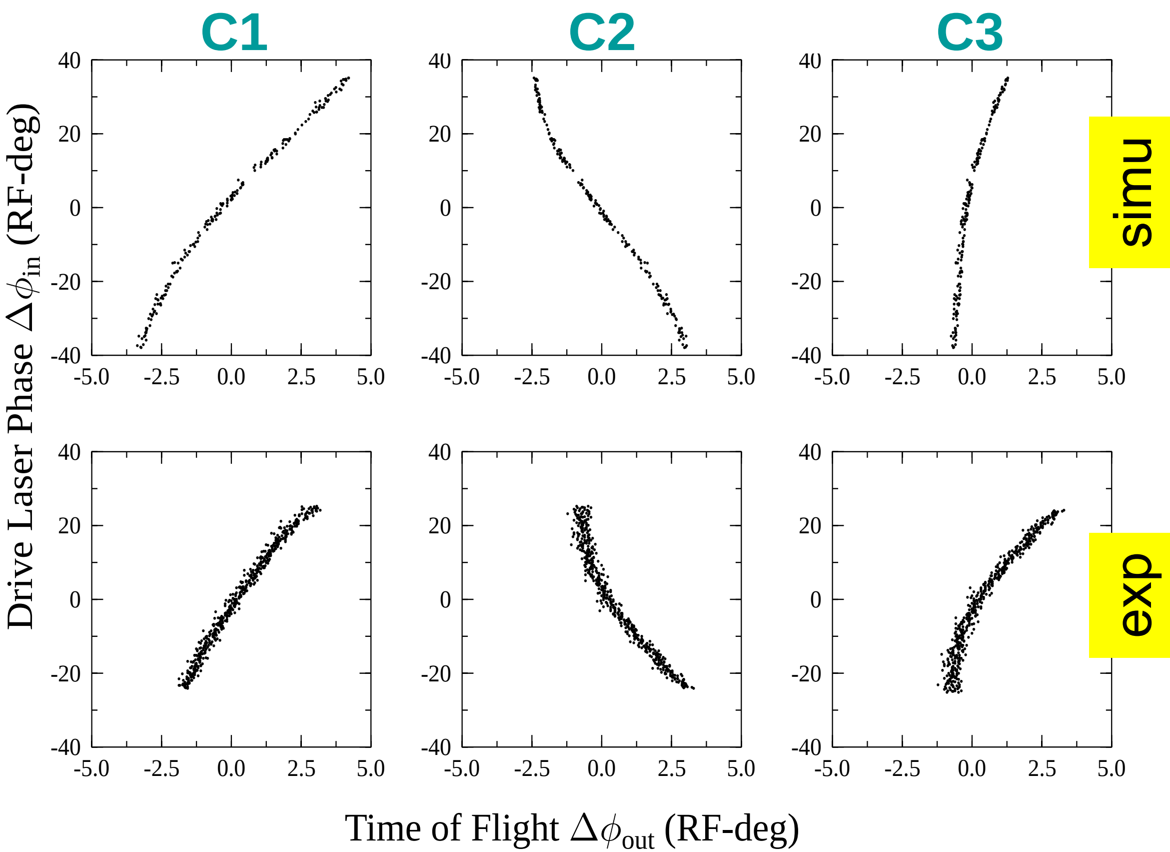
Longitudinal lattice

- •Difference measurement provides a way to check if the longitudinal lattice performed as devised from simulations

- •For day-to-day operation it also provide a method to recover nominal longitudinal lattice settings

- •One cavity located where the “fresh” and “used” beam are present provide a way to tune the path length

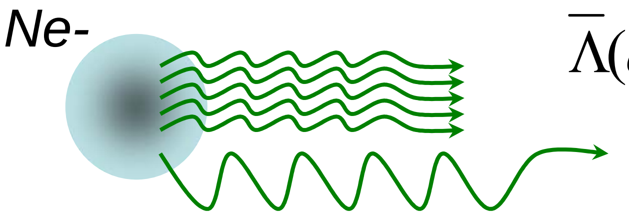




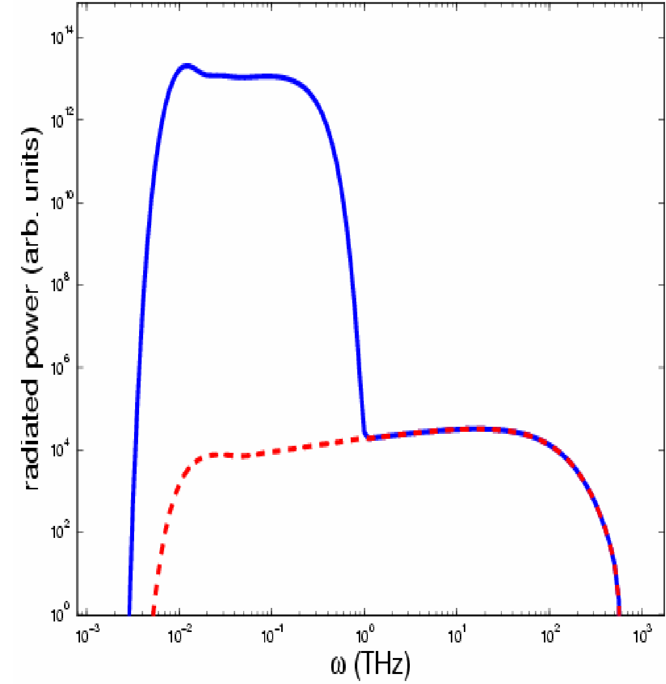
Measurement on IR-Demo (1998)

ω-domain

- Beam radiate e.m. field (e.g. via transition, synchrotron,… radiation)



$$\overline{\Lambda}(\omega) = \int \Lambda(z/c - t) e^{-i\omega t} dt$$



- 1st order correlation of Fourier transform

$$\left\langle I(\omega) I^*(\omega') \right\rangle \propto \left[N\overline{\Lambda}(\omega-\omega') + N(N-1)\overline{\Lambda}(\omega)\overline{\Lambda}^*(\omega') \right]$$

Incoherent radiation | Coherent radiation

- Time autocorrelation of coherent radiation provides:

$$\left\langle I(\omega) I^*(\omega) \right\rangle \propto \left[N(N-1) \left| \overline{\Lambda}(\omega) \right|^2 \right]$$

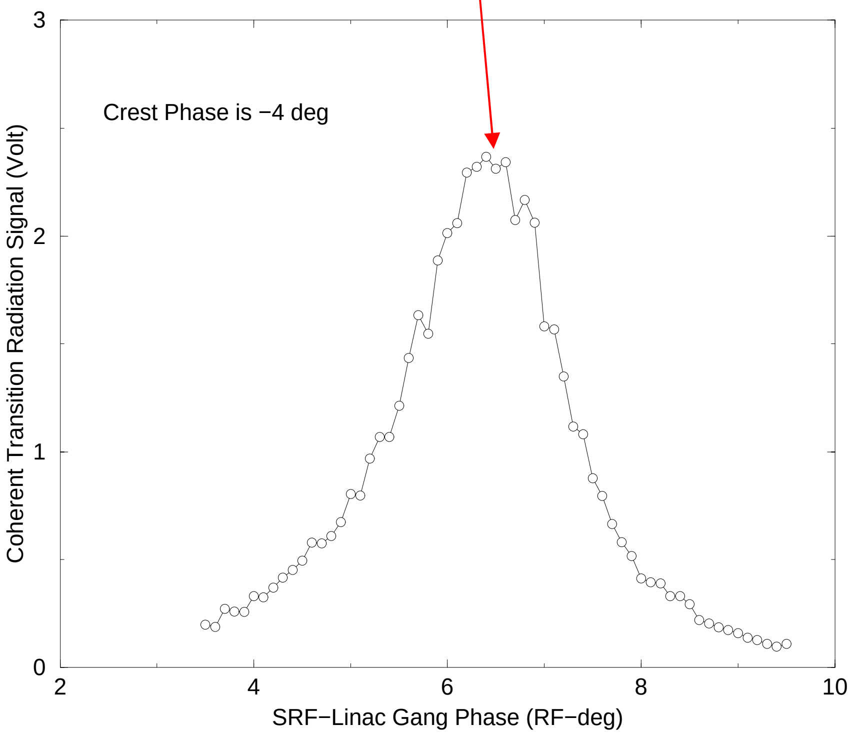
- Incoherent radiation: $\left\langle I(\omega) I^*(\omega') \right\rangle = e^2 N \overline{\Lambda}(\omega-\omega')$

ω-domain: coherent radiation

$$P(\omega) \propto N^2 \left| \overline{\Lambda}(\omega) \right|^2$$

- Detecting coherent radiation emitted by the bunch provide a bunch length monitor
- Calibration with other technique may provide a bunch length measurement
- This technique is usually used to phase an upstream linac located prior to a non-isochronous section (bunch compressor chicane)

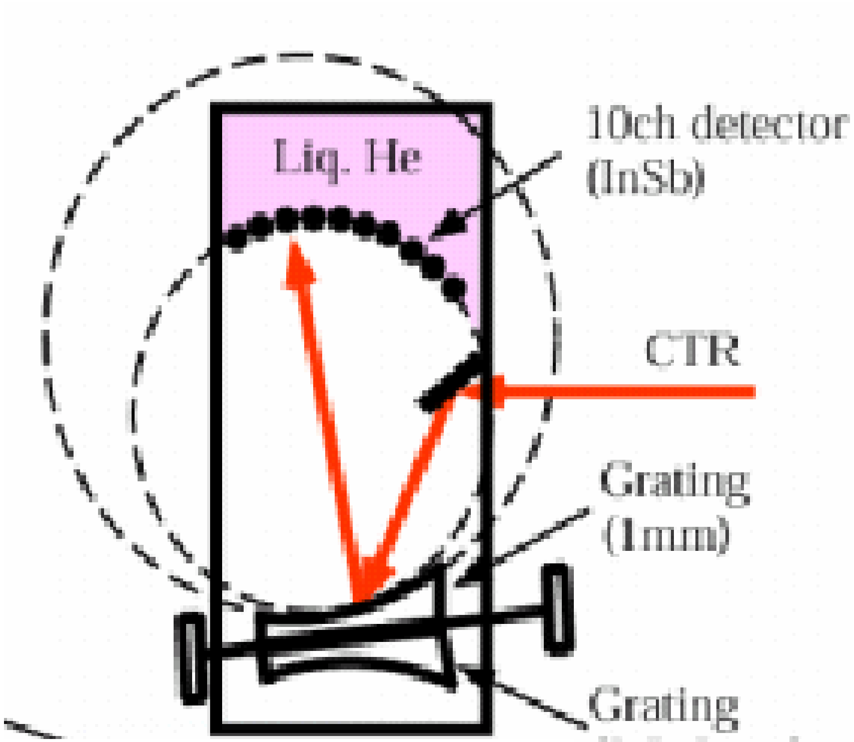
close to
best compression



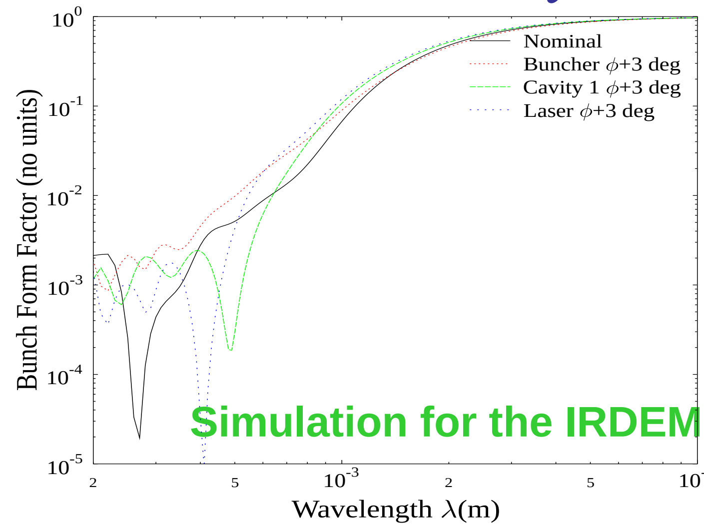
Detection of coherent transition radiation vs LINAC phase at JLAB IRDEMO (1997)

ω-domain: coherent radiation

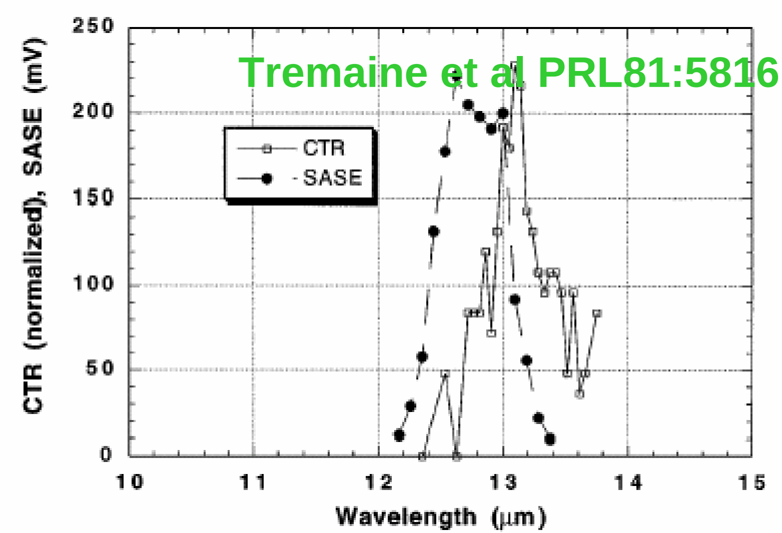
•Multi-frequency coherent radiation **monitor** can provide a way to monitor drift in the system and on-set of instability (μbunching), feedback on bunching



Tohoku Univ. (1997)



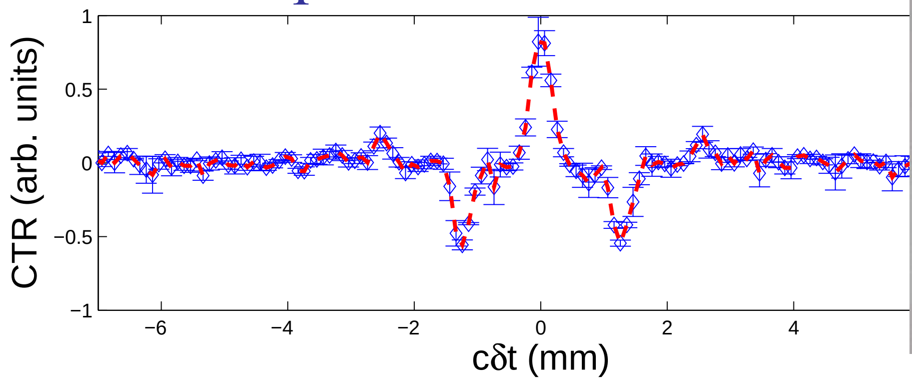
Simulation for the IRDEMO (1998)

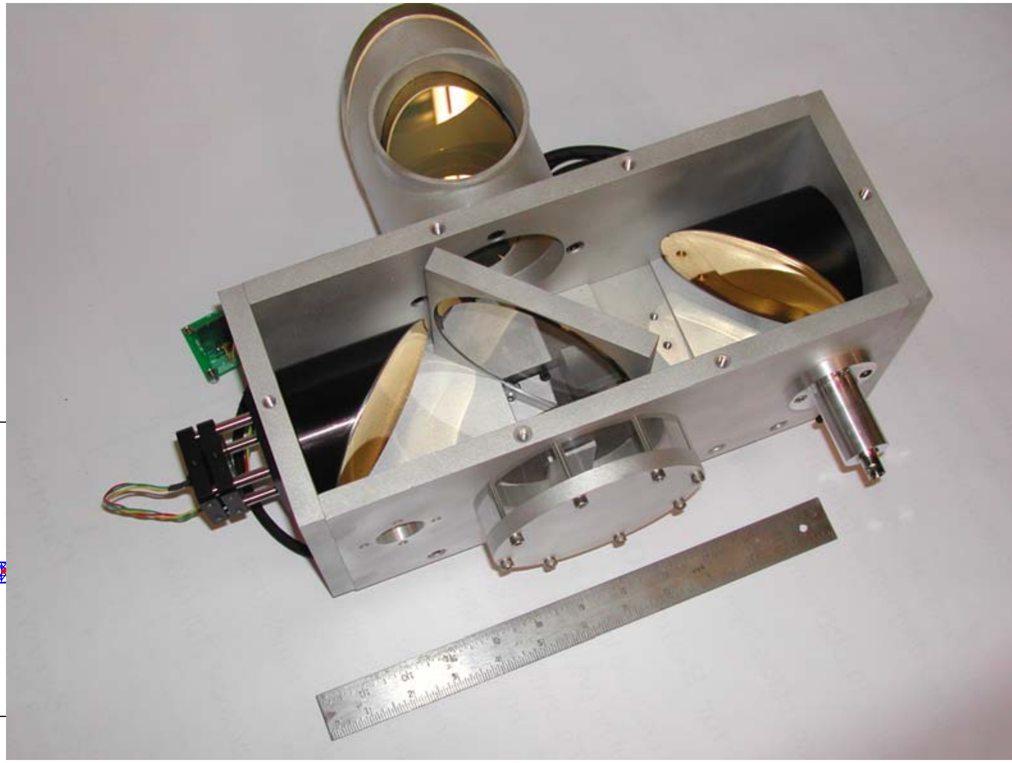


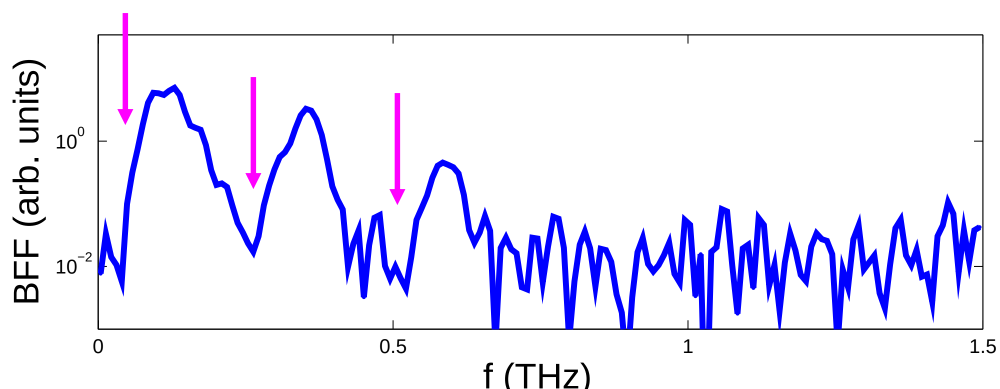
Tremaine et al PRL81:5816 (1998)

ω-domain: coherent radiation

- In the sub-mm regime Martin-Puplett autocorrelation
- Information on the bunch form factor theoretically can recover the time-profile





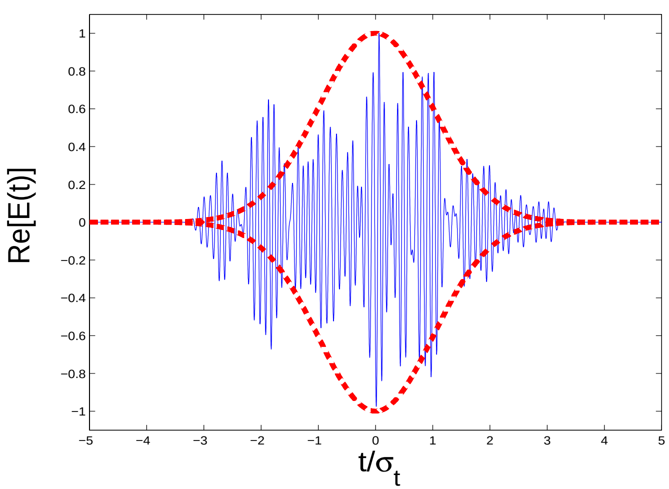


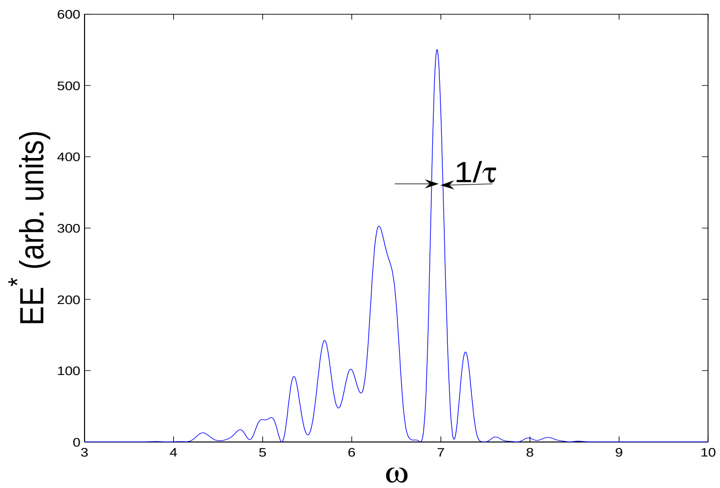
Measurement of CTR at FNPL
FNAL/U. Georgia/NIU (2004)

- Experimentally: frequency response of radiation beamline needs to be well known
- Low frequencies are not transmitted (e.g. due to diffraction)
- Technique easier to implement for short bunches

ω-domain: fluctuation technique

- Incoherent “chaotic” light still provides information on the bunch





- Second order spectrum autocorrelation

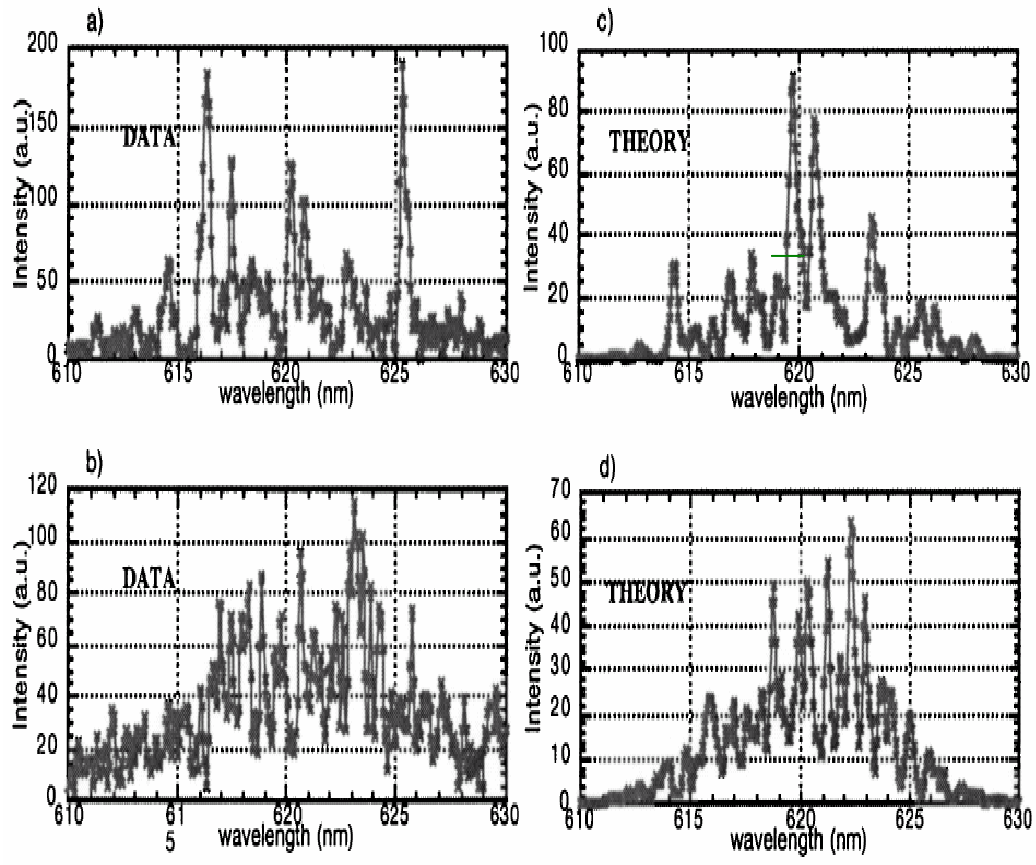
$$\left\langle \left|I(\omega)\right|^2 \left|I(\omega')\right|^2 \right\rangle = e^4 N^2 \left[1 + \left|\bar{\Lambda}(\omega - \omega')\right|^2 \right]$$

- Variance of the Fourier transform of the spectrum provides the convolution function of the charge distribution

Zolotorev/Stupakov PAC97, Krzwinsky et al TESLA-FEL97-03 (1997)

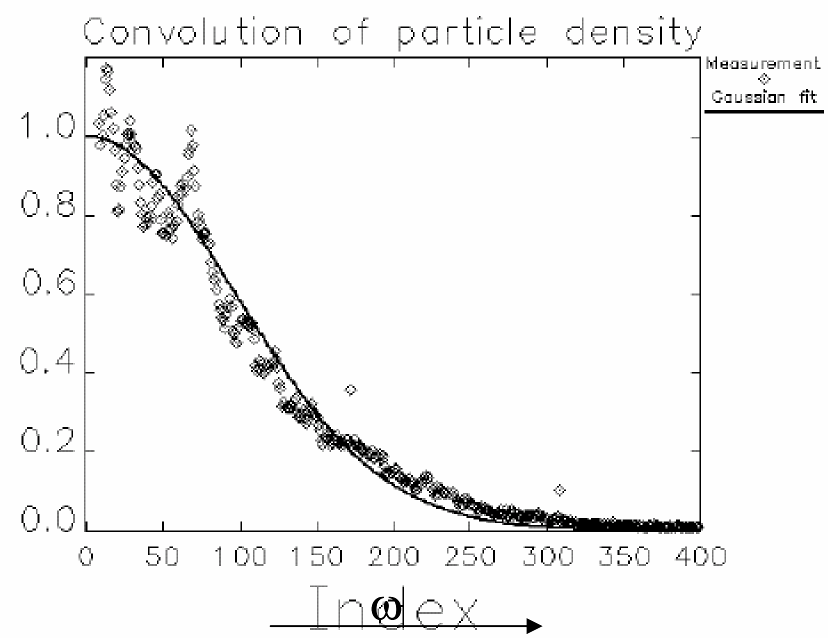
ω-domain: fluctuation technique

•Proof-of-principle measurement at ATF/BNL



P. Catravas et al. PRL 82:104801 (1999)

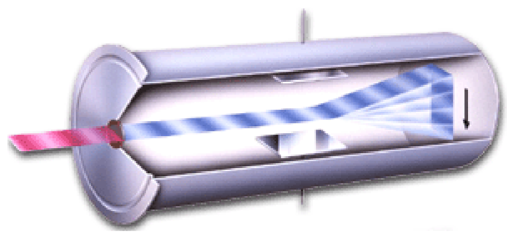
•Spectrum reconstruction and time-distribution retrieval at LEUTL/APS/ANL



V. Sajaev (EPAC 2004)

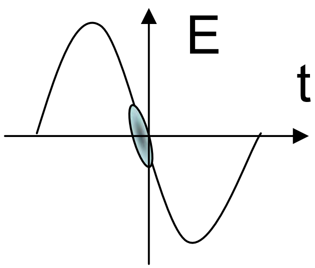
t-domain: streak "cameras"

- best streak cameras have 200 fs resolution (HAMAMATSU fesca-200)

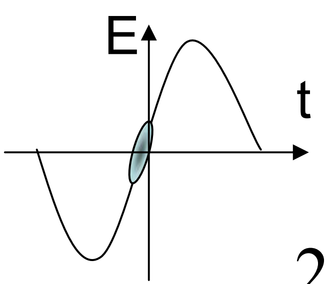


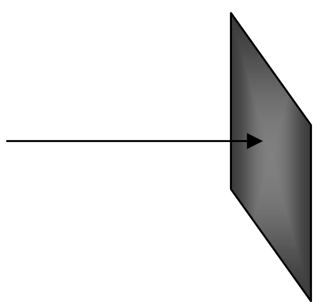
- e- converted to photon (e.g. TR, SR,…)
- streak camera: photons → e- → streak the e- beam → photons → imaging on a CCD

- Used of a rf accelerating cavity to directly streak the beam ("0-phasing")

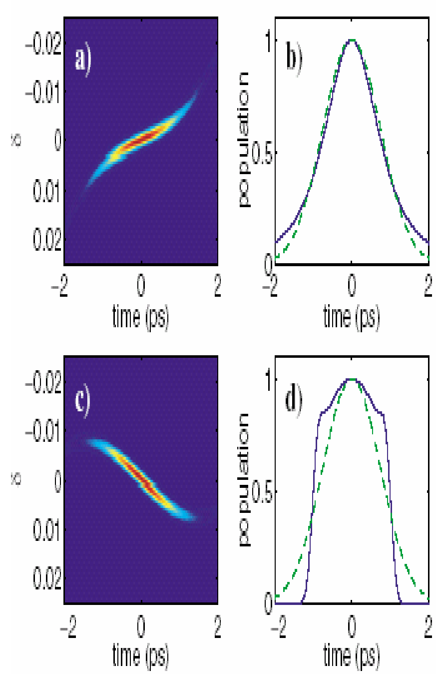


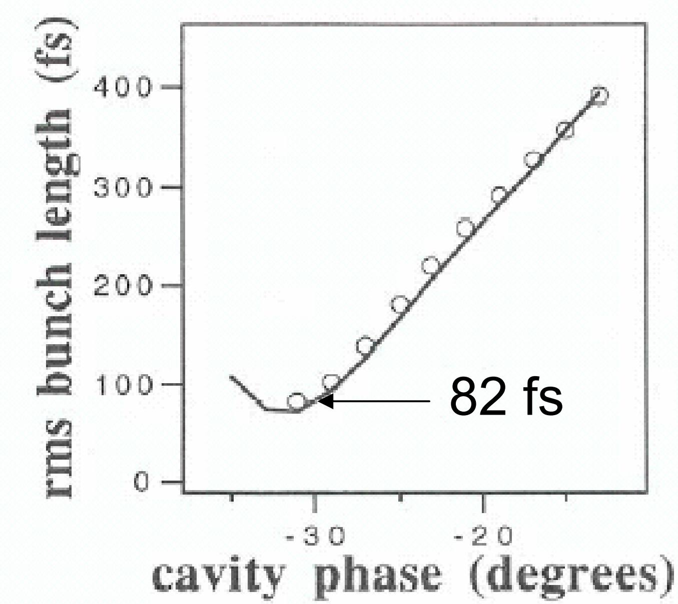
$$x(t) \approx \eta \frac{\Delta p}{p} \propto t$$





$$\Delta E(t) \approx \pm \frac{2\pi c V_{rf}}{\lambda_{rf}} t$$



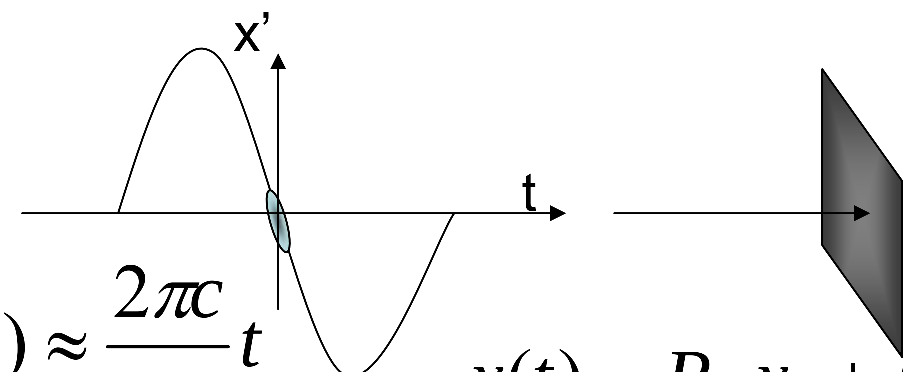


Wang et al. PRE57:2283 (1998)

t-domain: streak "cameras"

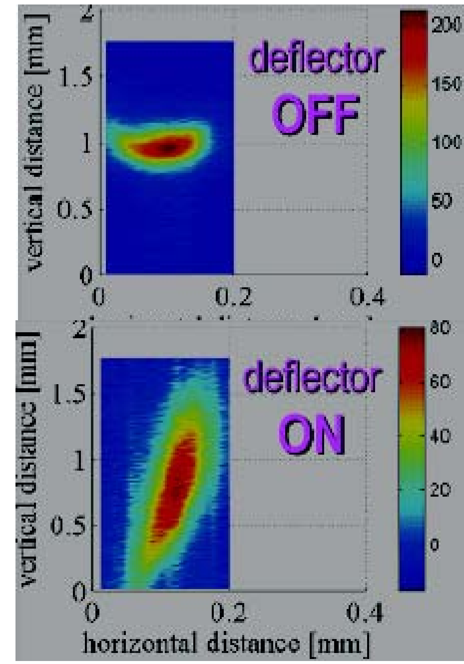
•Used of a rf deflecting cavity to directly streak the beam

- •rf-deflecting cavity TM110 streaks the beam
- •Observe streaked beam downstream



$$x'(t) \approx \frac{2\pi c}{\lambda_{rf}} t$$

$$x(t) = R_{11}x_0 + R_{12}x'_0(t)$$

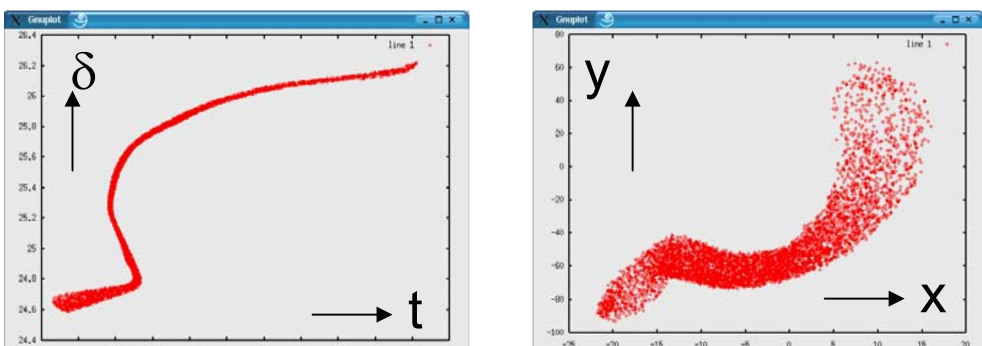


R. Akre et al. EPAC2002 (LOLA cavity)

•Can also quantify longitudinal phase space shape: hor. deflection + vertical spectrometer

$$x(t) = R_{11}x_0 + R_{12}x'_0(t)$$

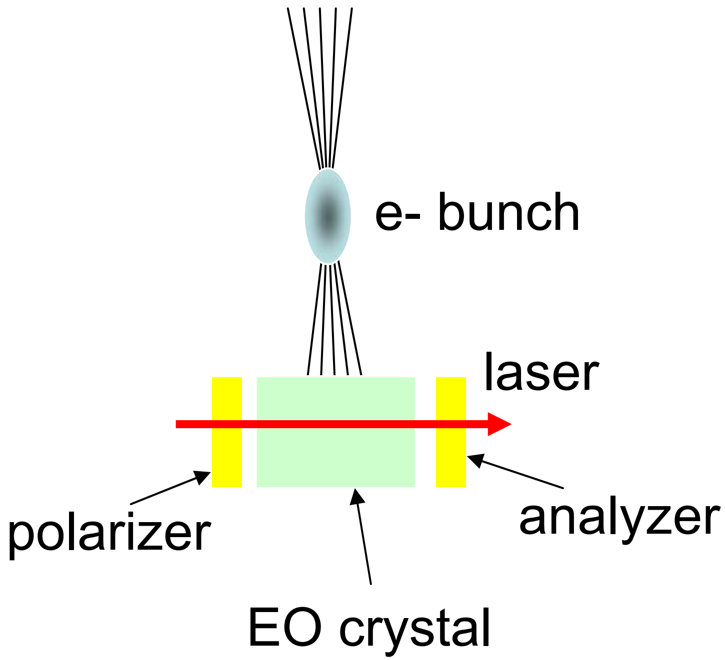
$$y(\delta) = R_{33}y_0 + R_{34}y'_0 + R_{16}\delta$$



Simulations using a 3.9 GHz dipole cavity

t-domain: electro-optics sampling

$$E_r(r,z,t) = \frac{eZ_0 c}{2\pi r}\delta(z - ct)$$



- Electro-optical effects:

$$P = \varepsilon_0 \left[\chi^{(1)} + \chi^{(2)} E + \chi^{(3)} E^2 + \ldots\right] E$$

linear EO (Pockel), SHG, PO, TWM

quad. EO (Kerr), SPM, FWM

- Frequency components extend to THz

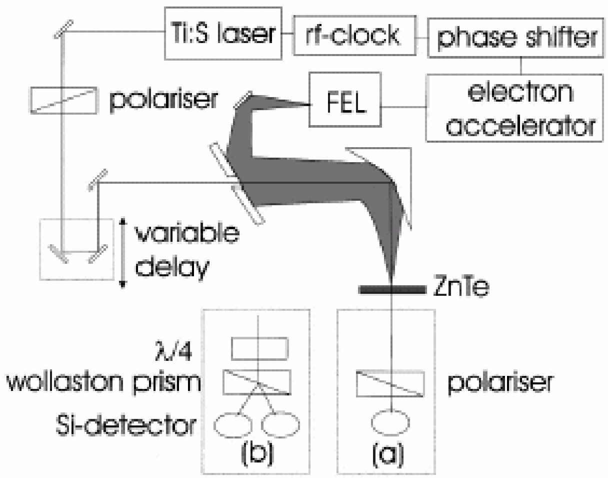
$$\overline{E}_r(\omega) \propto \overline{\Lambda}(\omega)$$

- Three main factors influence the resolution:
  - (probe) laser pulse length,
  - crystal thickness,
  - group velocity mismatch between optical and sampled fields.

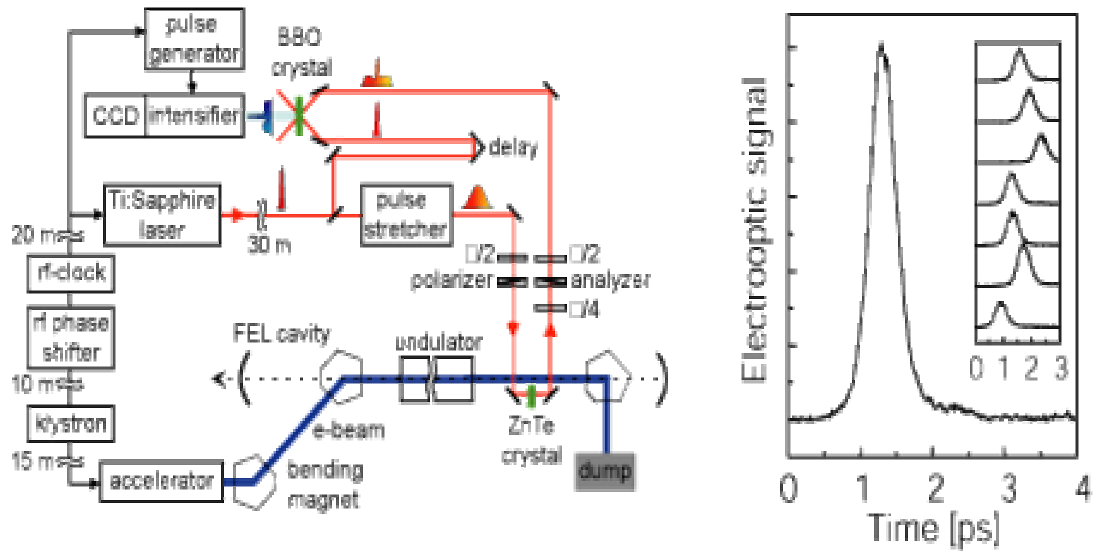
P. Channel et al, LANL AT-6:ATN-82-1 (1982)
Q. Wu, X. Zhang et al APL67 (1995)

t-domain: electro-optics sampling

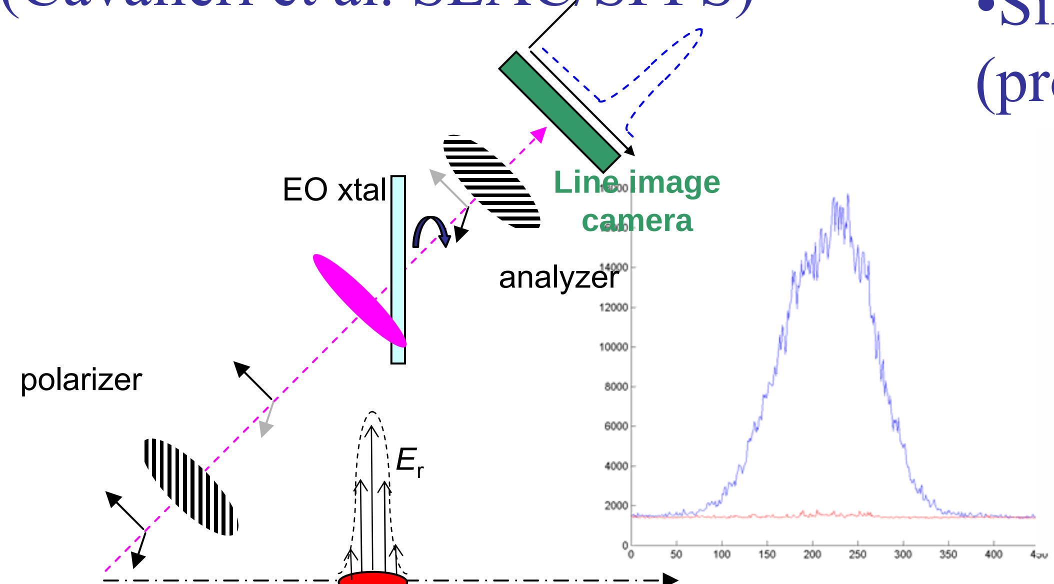
- 1st experiment (FELIX)



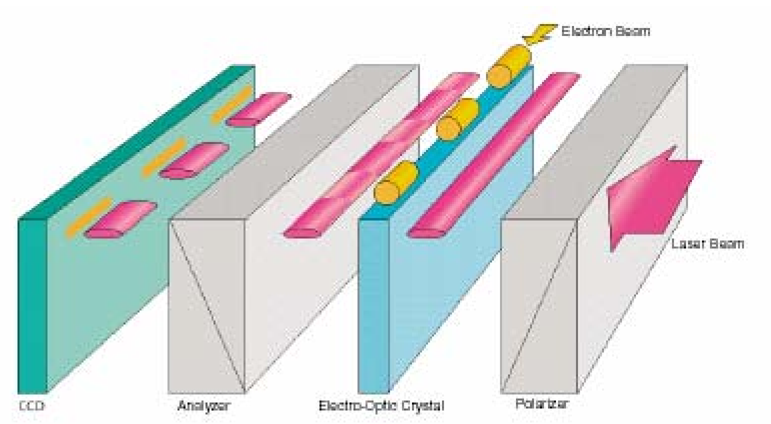
- Single-shot using t-ω chirp



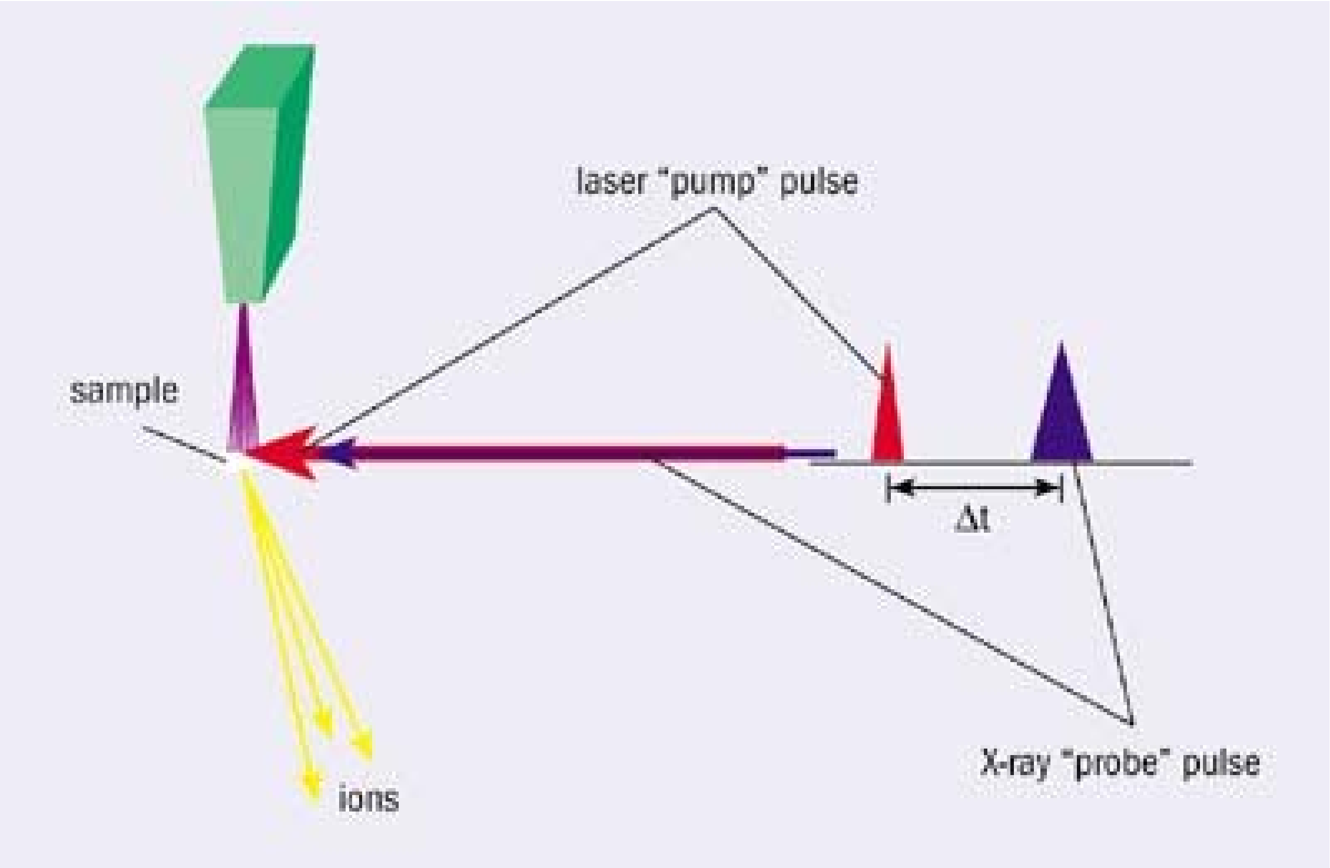
- Single-shot using t-x chirp (Cavalieri et al. SLAC/SPPS)



- Single-shot using ribbon laser (proposal BNL)



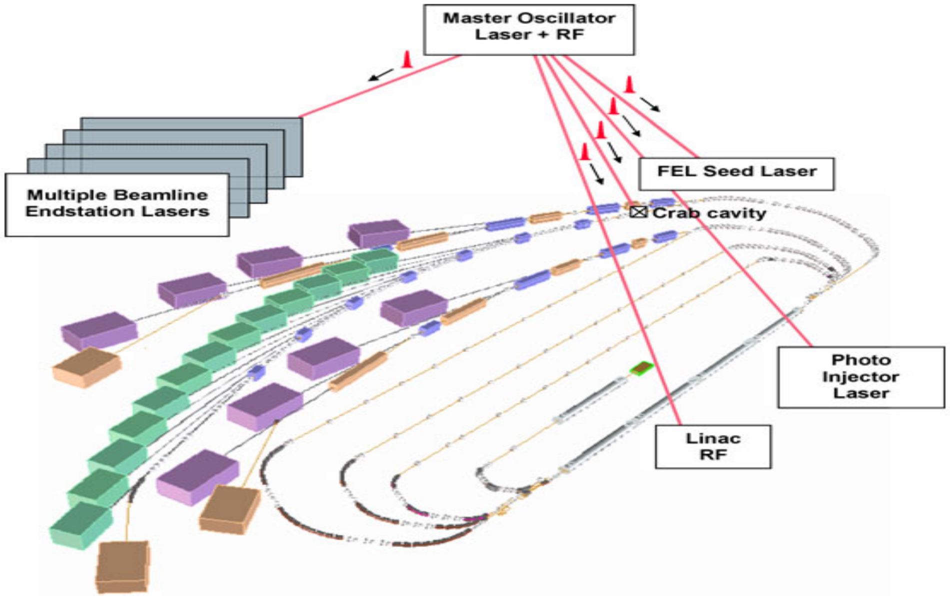
Synchronization aspects

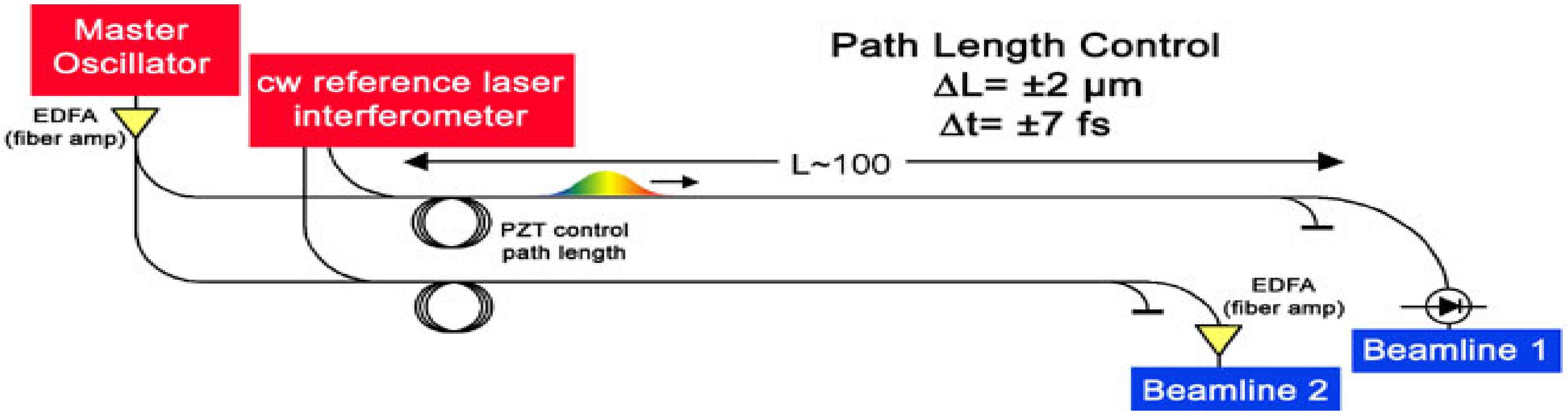


J. Corlett et al. CERN Courrier (2003)

synchronization aspects

- Example of LUX (LBNL)
- master oscillator designed around a laser oscillator stabilized by an rf oscillator
- Expect stabilization at 10-50 fs



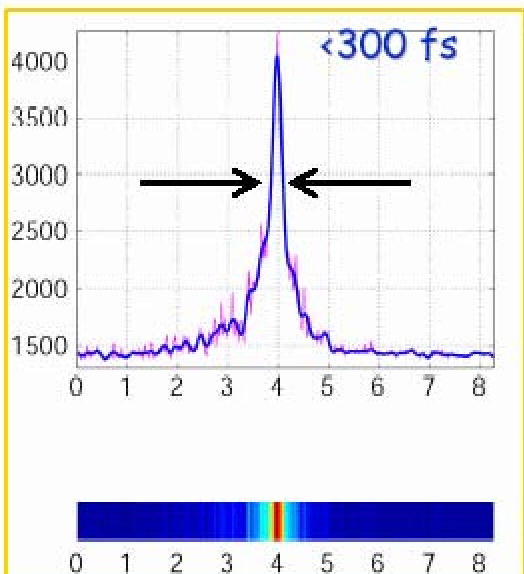


J. Corlett et al. PAC2003 (2003)

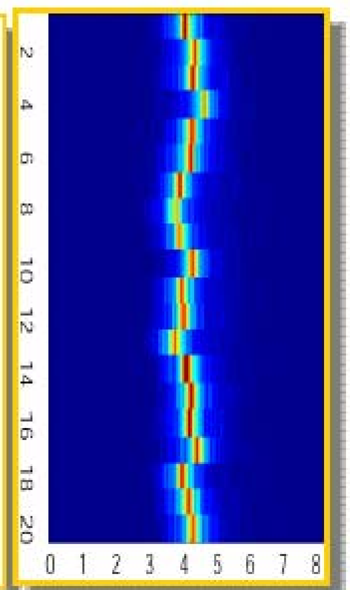
synchronization aspects

Femtosecond x-ray stopwatch

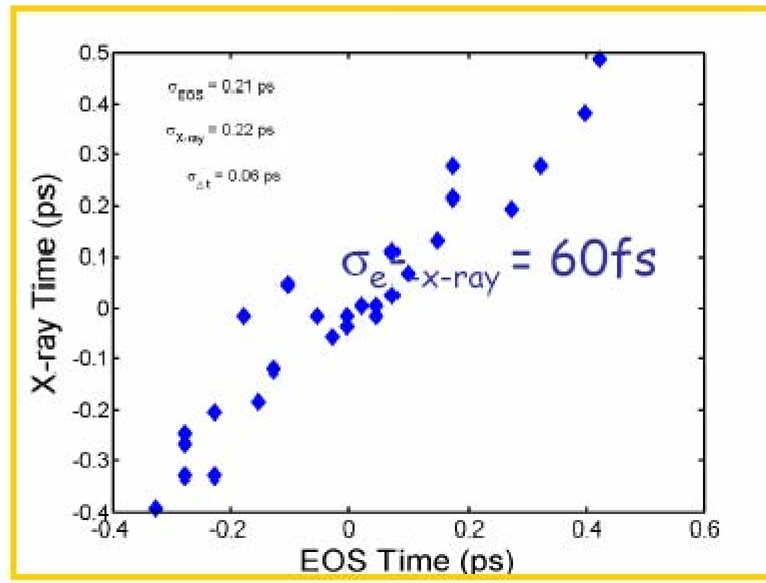
A. Cavalieri, D. Fritz, S. Lee, P. Bucksbaum, D. Reis and SPPS Collaboration



Single-Shot Electron Beam timing measurement



Timing Jitter (20 shots)



Strong Correlation between measured Electron Beam and X-ray beam timing

Summary

- I have tried to summarize possible beam diagnostics for ERL, especially non or quasi-non interceptive diagnostics

- I have not addressed "fancy" diagnostics: Compton scattering, Shintake interferometer, etc…

Acknowledgments

- I have freely borrowed material from many people cited in the previous slides…