Electron Beam Diagnostics for High Current FEL Drivers

(*selected topics*)

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Motivation - High <I_b> machine specifics

- Very **large difference** in the average current of the tune up beam and the full power beam; for instance, JLab FEL 10 mA vs. 300 nA ➔ 3×10^4 difference
- So, somehow need to **make sure** the **full power** beam has **the same** properties
- due to the high <I_b> not every diagnostic or beam physics solution might be acceptable *(for instance, TCAV, high harmonic RF curvature linearization, high gradient guns until high current SRF guns are demonstrated)*
- since we are interested in the **FEL drivers** the important parameters are
  - high peak current (bunch length)
  - transverse emittance
  - transverse match of the beam to the wiggler and optical mode
  - energy spread (slice energy spread)
  - bunch charge
  - beam orbit
- While high current, most likely, **CW beam** makes some things harder it also **opens** up the **possibilities** that are not there otherwise *(Lock-in techniques)*

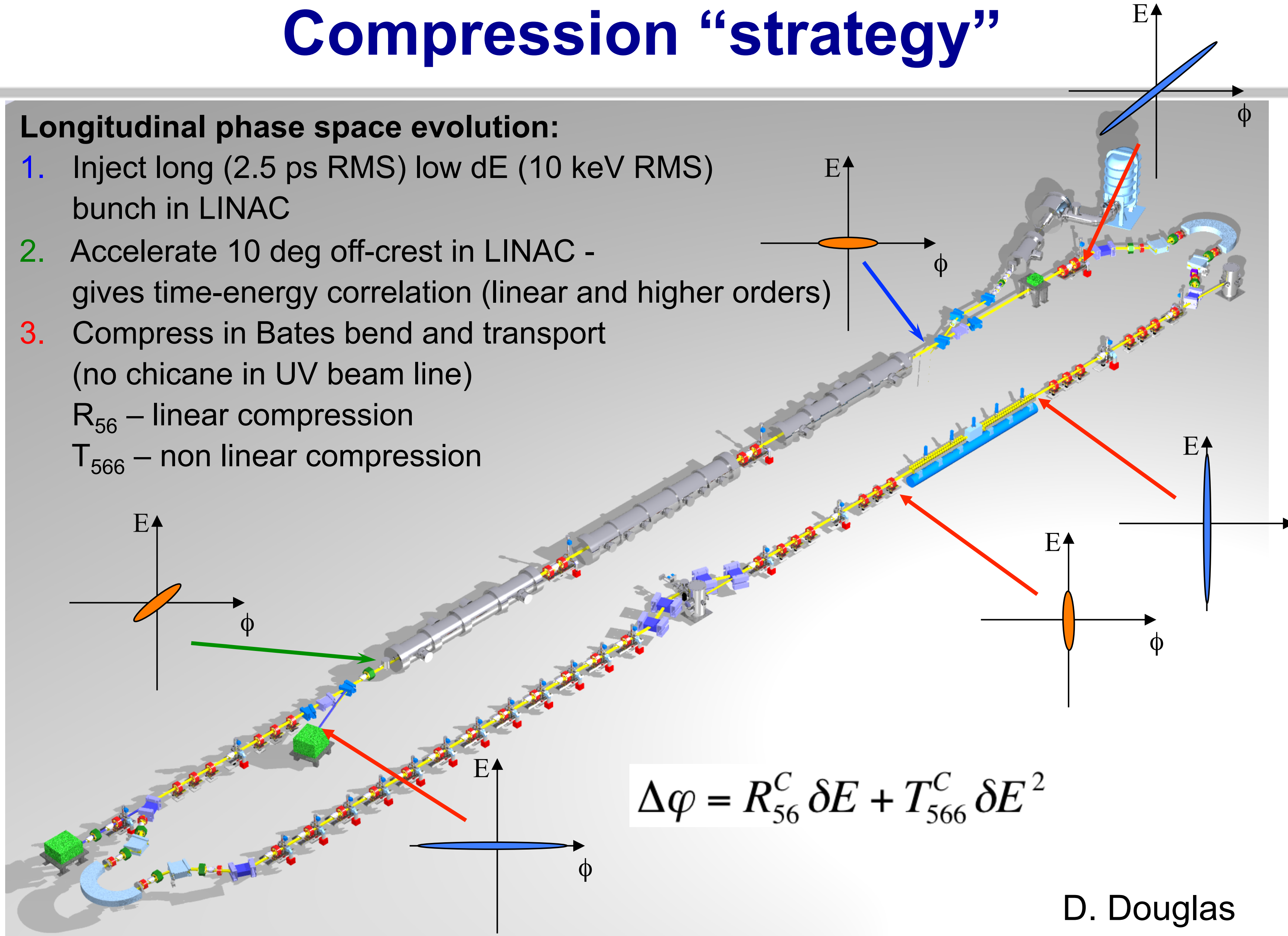
Outline

- **Bunch length related**
  - nonlinear compression and associated diagnostics
  - tune-up vs. CW bunch length measurements @ JLab FEL
- **Transverse beam (size) distribution related**
  - Optical Diffraction Radiation (ODR) for high energy
  - LINAC's non-equilibrium beams
  - Halo and Large Dynamic Range (outlook)
  - Low power CW laser wire for low energy
- **CW specific related**
  - the same laser wire (as an example)

Compression "strategy"

Longitudinal phase space evolution:

1. Inject long (2.5 ps RMS) low dE (10 keV RMS) bunch in LINAC
2. Accelerate 10 deg off-crest in LINAC - gives time-energy correlation (linear and higher orders)
3. Compress in Bates bend and transport (no chicane in UV beam line)
   R_{56} – linear compression
   T_{566} – non linear compression



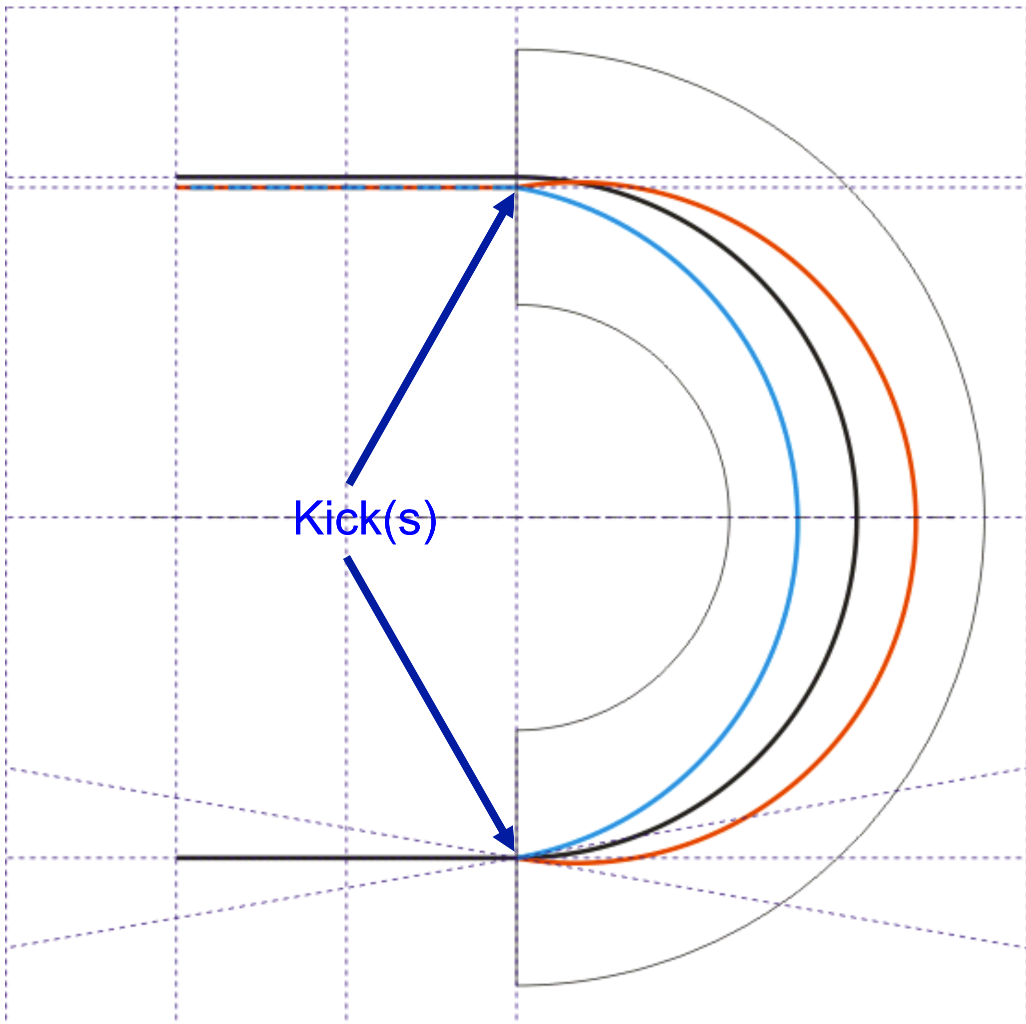
$$\Delta\varphi = R_{56}^{C}\,\delta E + T_{566}^{C}\,\delta E^{2}$$

D. Douglas

Bunch length evolution

- Beam is generated in a HV DC gun (325 kV now) – GaAs photocathode, Drive Laser with almost Gaussian distribution and ~ 13.5 ps RMS pulse length
- compressed down to ~ 5 ps by 1497 MHz buncher cavity before injection in to the booster where it is accelerated to 9 MeV
- During acceleration in the booster (5-cell SRF x2) gets compressed down to ~ 2.5 ps - not measured directly but inferred from δE downstream of the LINAC – in good agreement with PARMELA model
- Compressed in the first 180 deg band and transport line between the band and FEL wiggler; final bunch length 100 – 110 fs (UV); 130-150 fs (IR)
- LINAC RF curvature imprinted on the longitudinal phase space compensated for by sextupoles in the Bates bend (no harmonic RF) by introducing second order dependence of the path length on energy
- Compression ration from the cathode to the wiggler ~ 125 – 135

180° Bates bend (1)

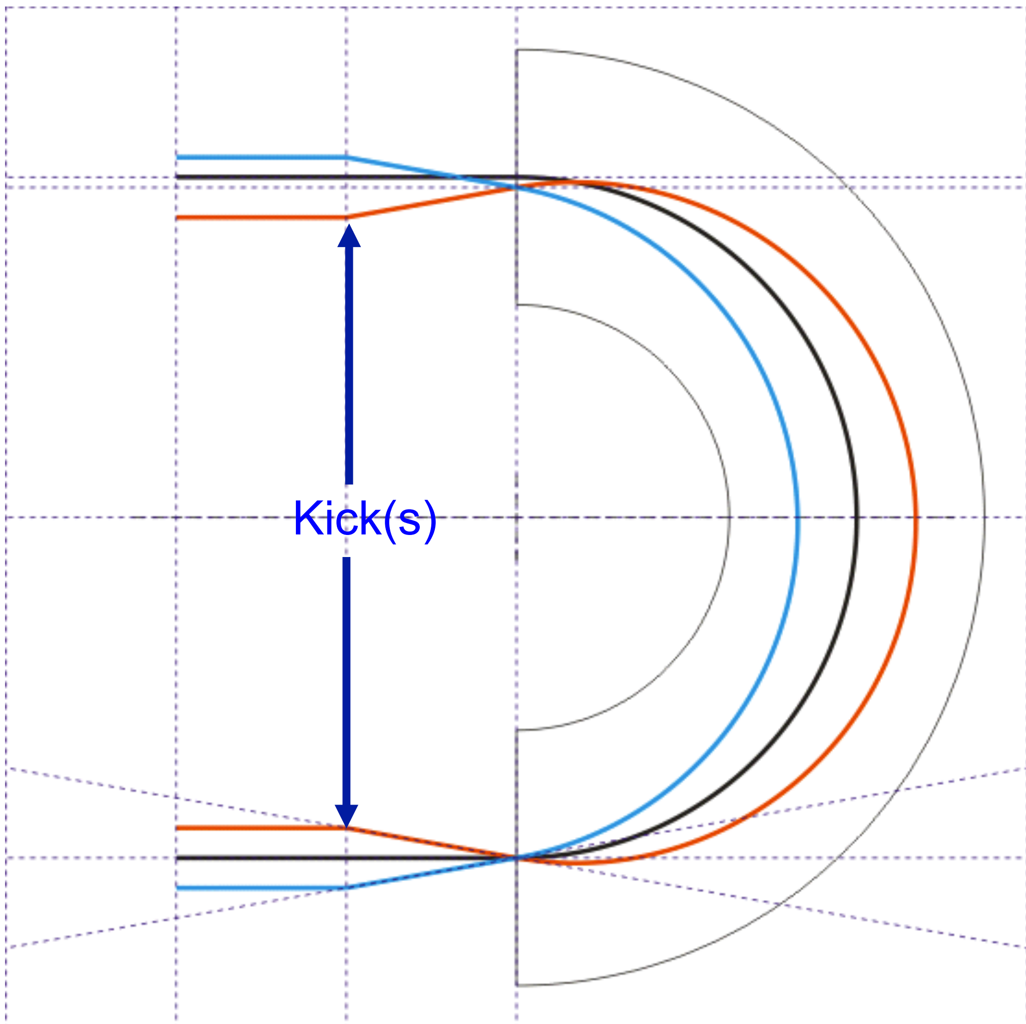


Path length change with kick;

$$\delta L = 2\rho\, \delta x'$$

Used to adjust the path length i.e. phase of the energy recovered beam

180° Bates bend (2)



Path length change with kick;

$$\delta L = 2\rho\,\delta x'$$

Kick by quadrupole;

$$\delta x'(x) = A \cdot x$$

Kick by sextupole;

$$\delta x'(x) = B \cdot x^2$$

Due to dispersion created by first two dipoles;

$$E \propto x$$

Connecting R_{56} & T_{566} to M_{55}

$$\varphi_W = \left(1 + R_{56}^C \cdot R_{65}^L\right)\varphi_0 + \left[R_{56}^C \cdot T_{655}^L + \left(R_{65}^L\right)^2 \cdot T_{566}^C\right]\varphi_0^2$$

taking second order transport matrix elements

directly measured

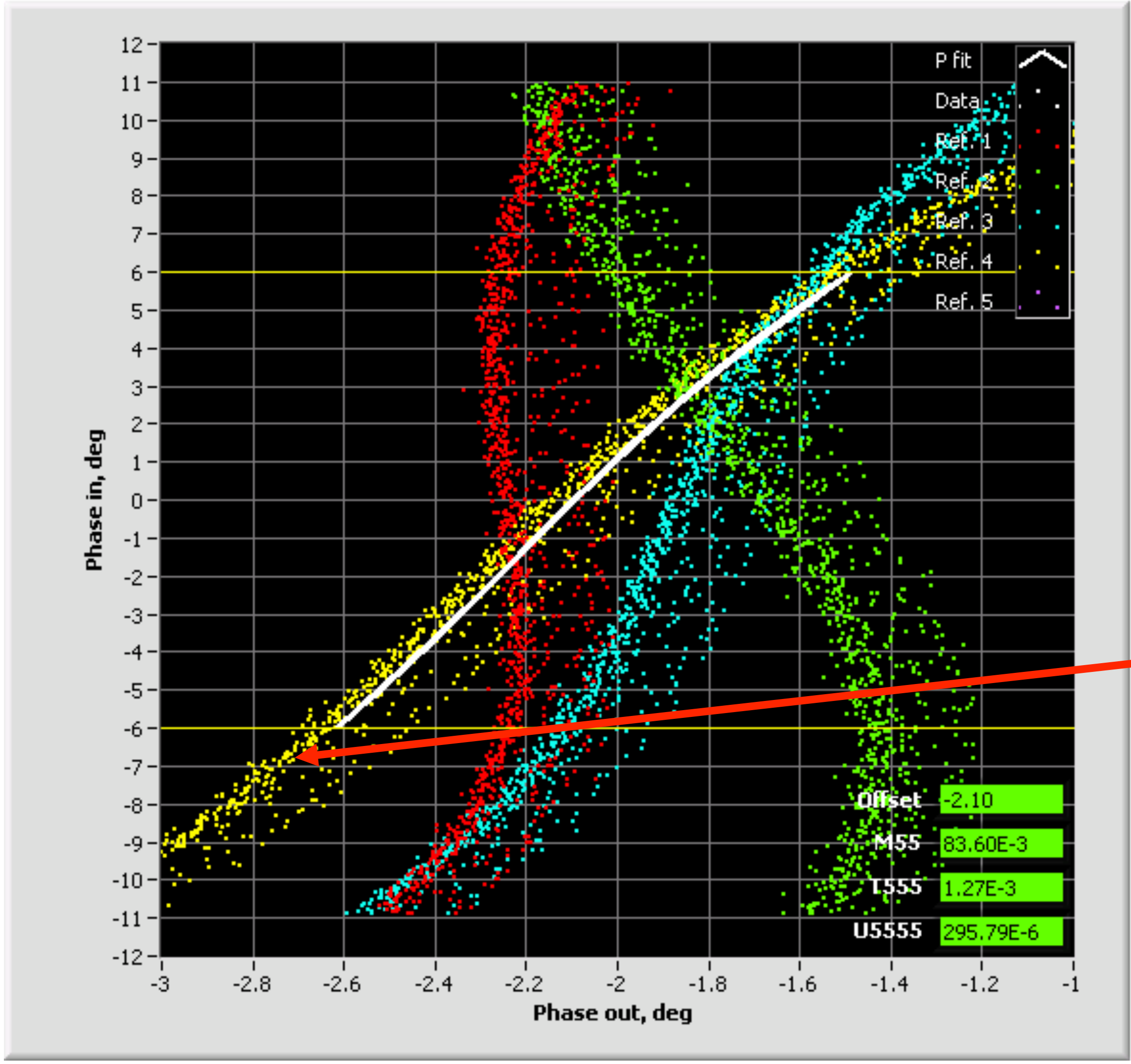
$$R_{55}^{inj \to w} = 1 + R_{56}^C \cdot R_{65}^L$$

$$T_{555}^{inj \to w} = R_{56}^C \cdot T_{655}^L + \left(R_{65}^L\right)^2 \cdot T_{566}^C$$

are adjusted in compressor

- R_{56} and T_{566} are validated via longitudinal transfer function measurements.
- Arrival phase is measured with a pillbox cavity + heterodyne receiver.
- Phase of the injector is modulated relative to the LINAC phase
- Essential ~ 15 % energy acceptance and ~ 30 % phase acceptance

M_{55} measurements vs. quads



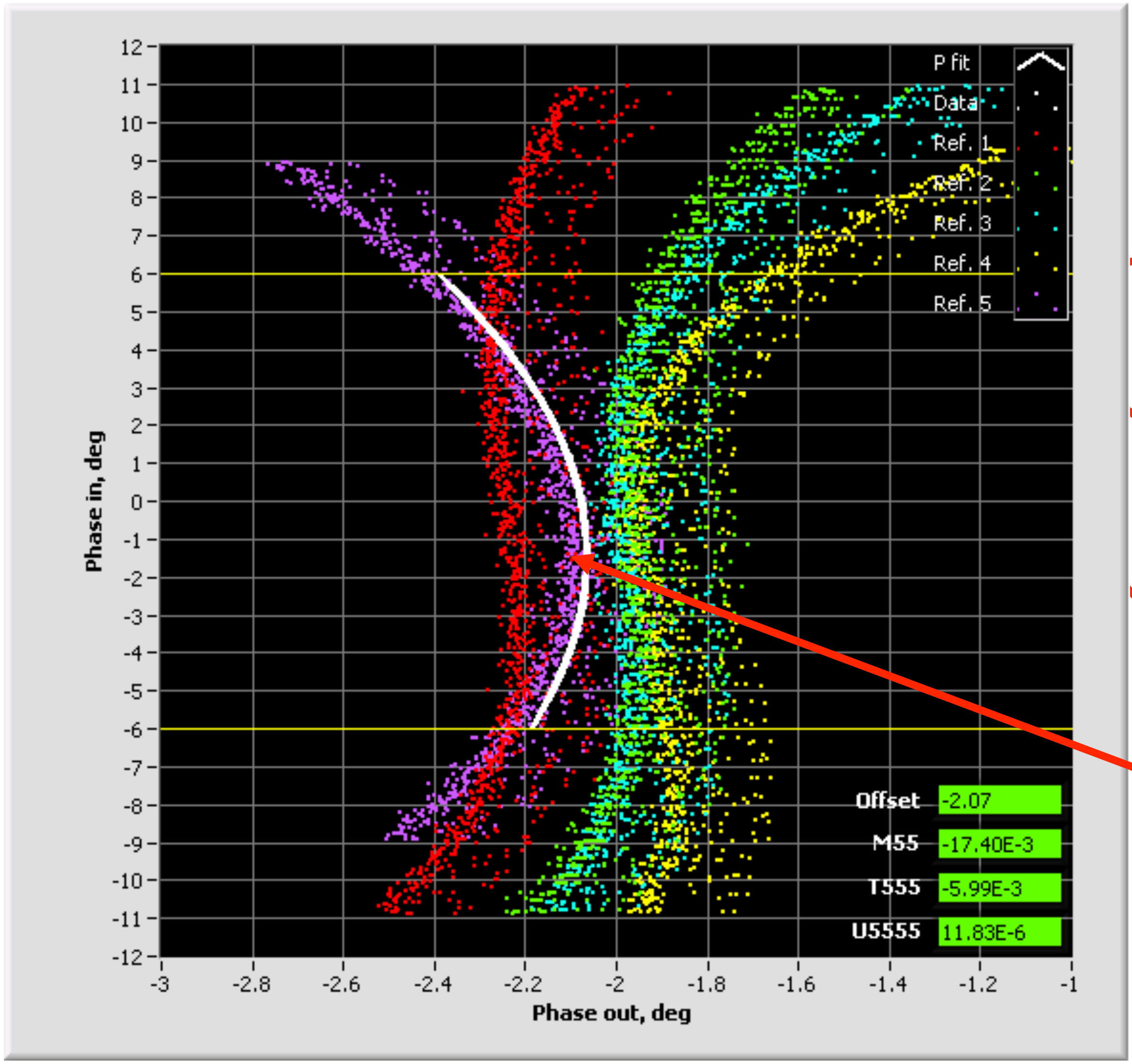
Trim quads – nominal set point of 700 G

Trim quads set point – nominal + 40 G (~ 5.7%)

Trim quads set point – nominal - 40 G (~ 5.7%)

Trim quads set point – nominal - 80 G (~ 11.4%)

M_{55} measurements vs. sextupoles



ARC1 sextupoles nominal set point 10730 G

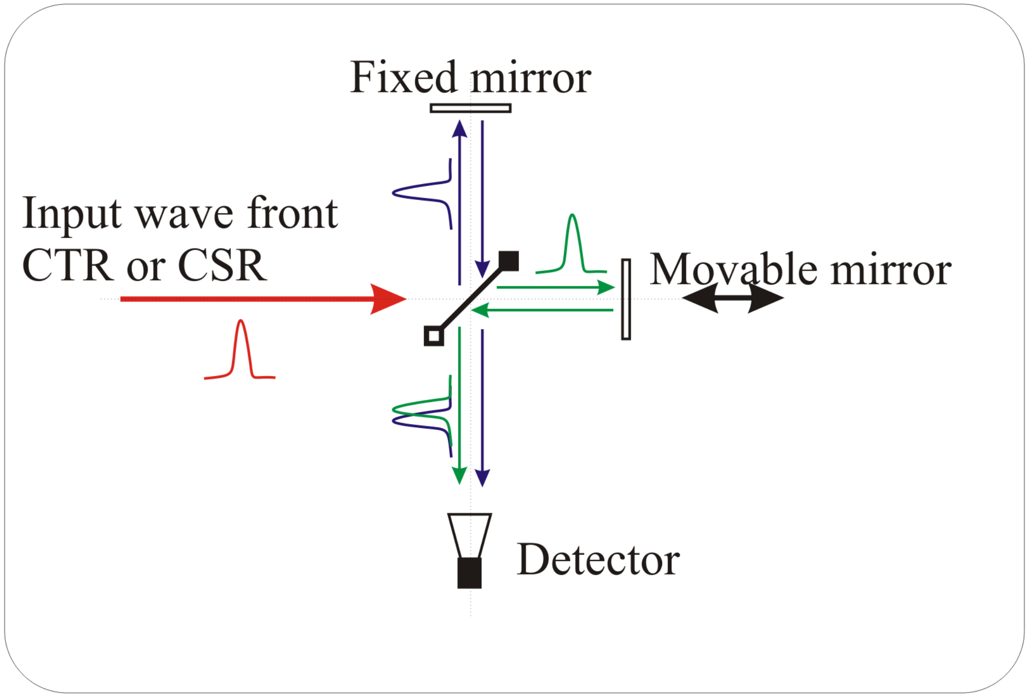
ARC1 sextupoles nominal set point +500 G (~ 4.7 %)

ARC1 sextupoles nominal set point +1000 G

ARC1 sextupoles nominal set point +2000 G

ARC1 sextupoles nominal set point -2000 G

Two interferometers: Martin-Puplett and FTIR



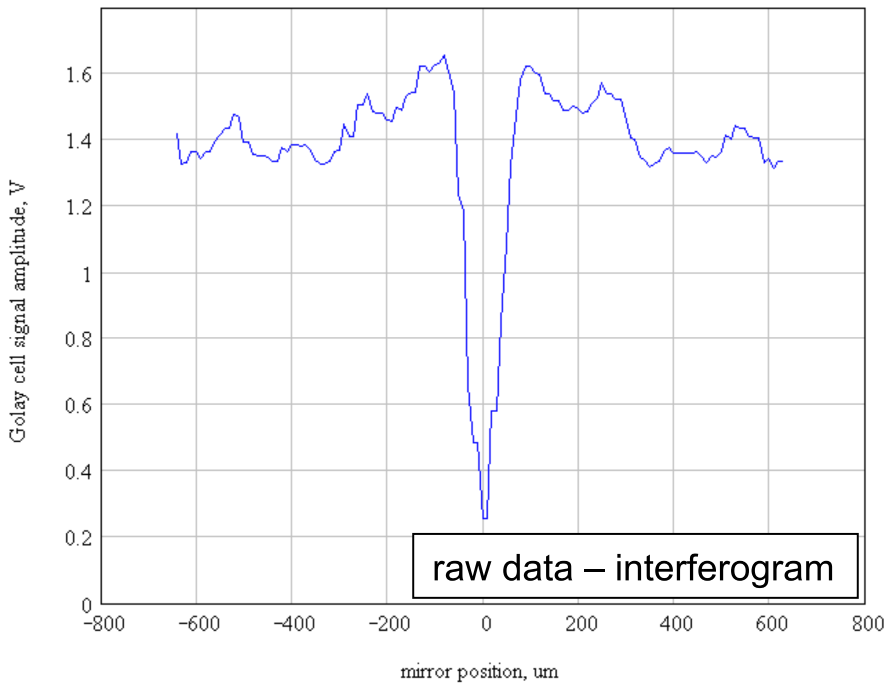
- used two different interferometers
- essentially both are a modification of the Michelson interferometer
- the difference is in implementation

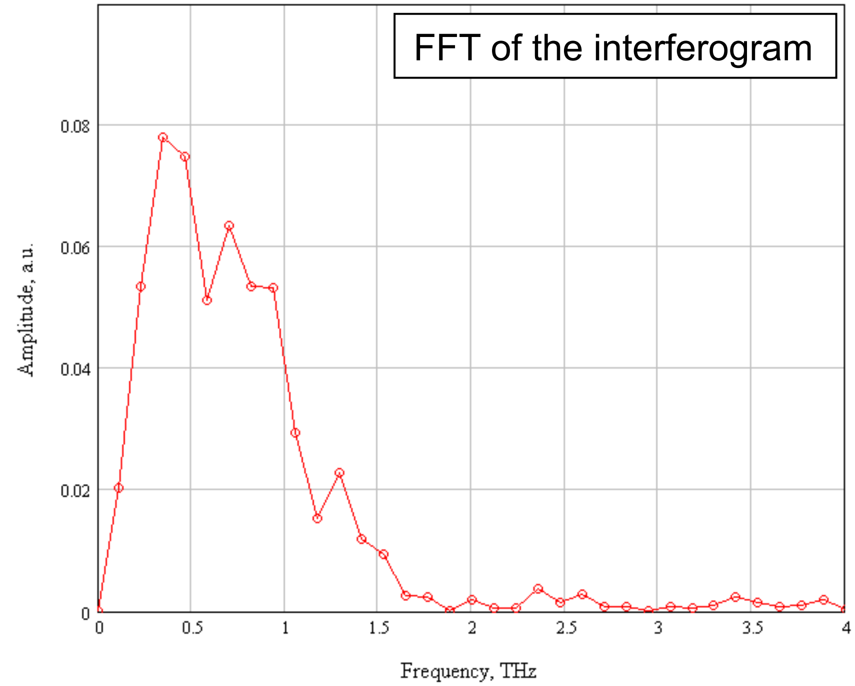
- beam splitter
- polarizer
- detector
- focusing element
- mirror position determination

Modified Marin-Puplett interferometer:
(step scan device - 2 min/scan)
beam splitter & polarizer (wire grids)
detector (Golay cell)
focusing (Plano-convex lens)
mirror position is set by
step motor
Used with CTR

Michelson interferometer:
(rapid scan device - 2 sec/scan)
beam splitter (silicon)
detector (pyroelectric)
focusing (parabolic mirrors)
mirror position is measured by
another built-in interferometer
Used with CSR

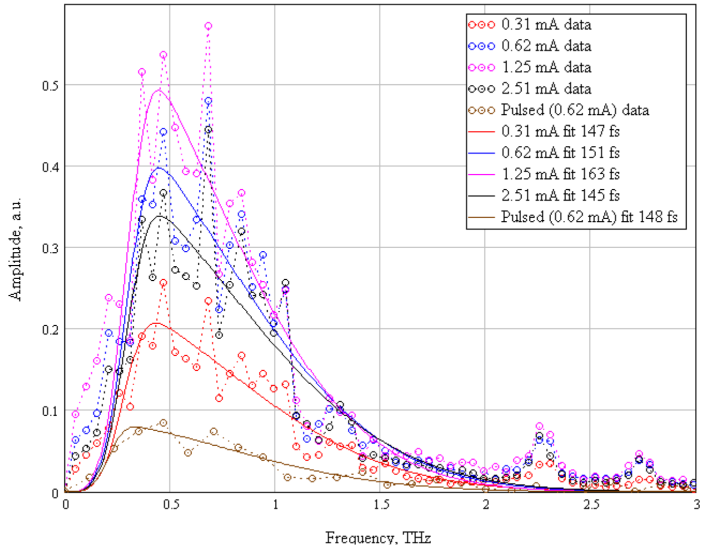
Interferogram – spectrum – bunch length

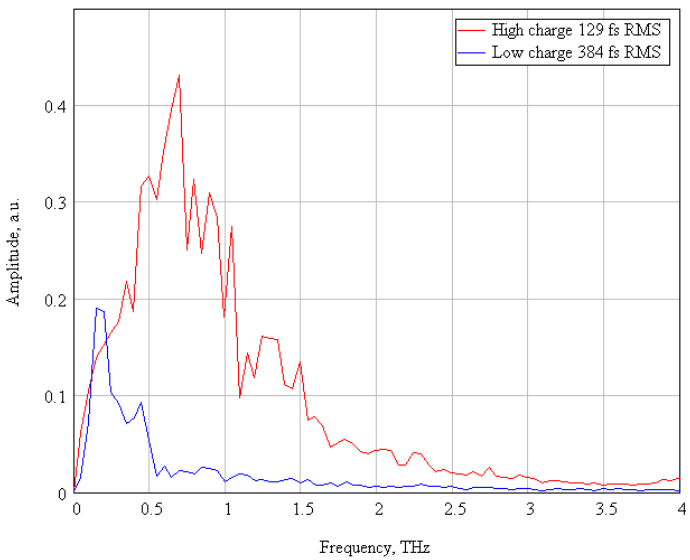


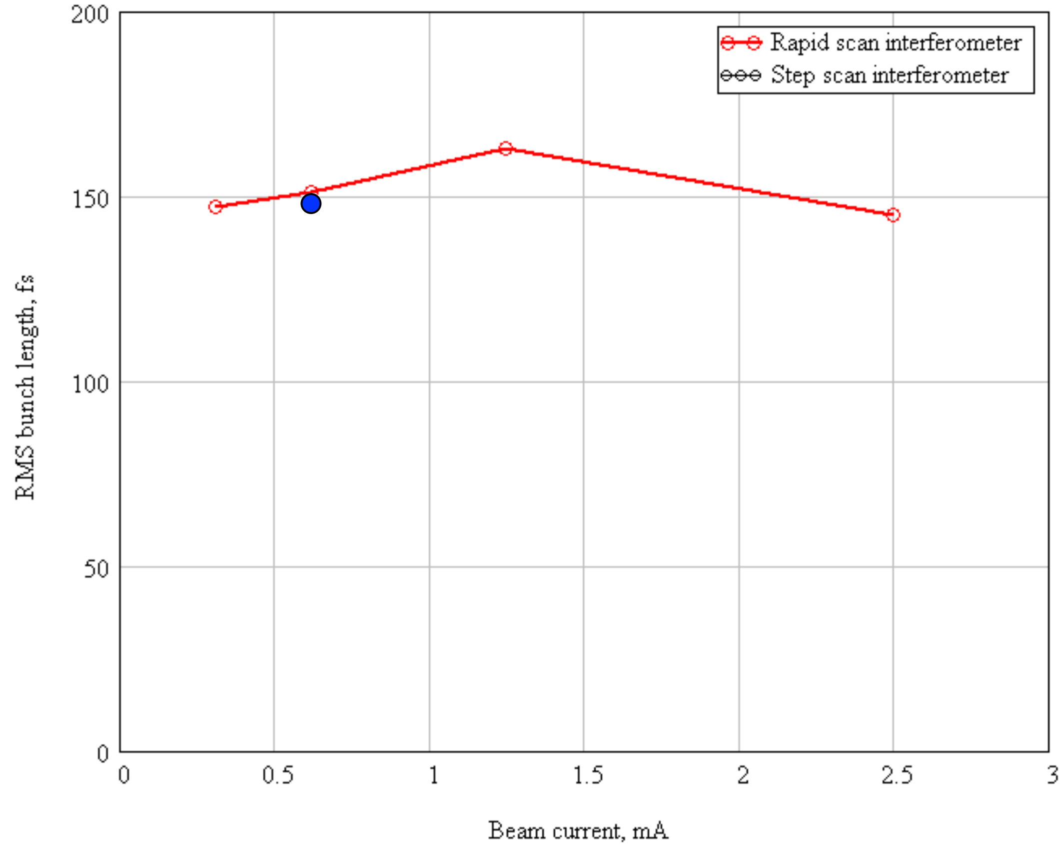


- bunch length estimation (its upper limit) is based on frequency domain fit
- measures autocorr
- data evaluation in frequency domain assuming Gaussian distribution
- Gaussian power spectrum × HPF fitted to measured spectrum
- blackbody spectral measurements used to estimate limit of the setup (~ 50 fs)

Tune-up vs. CW beam measurements







The bunch length vs. CW average beam current vs. tune-up beam measurements.

Optical Diffraction Radiation

The amplitude of a Fourier component of the transversal Coulomb field of an electron:

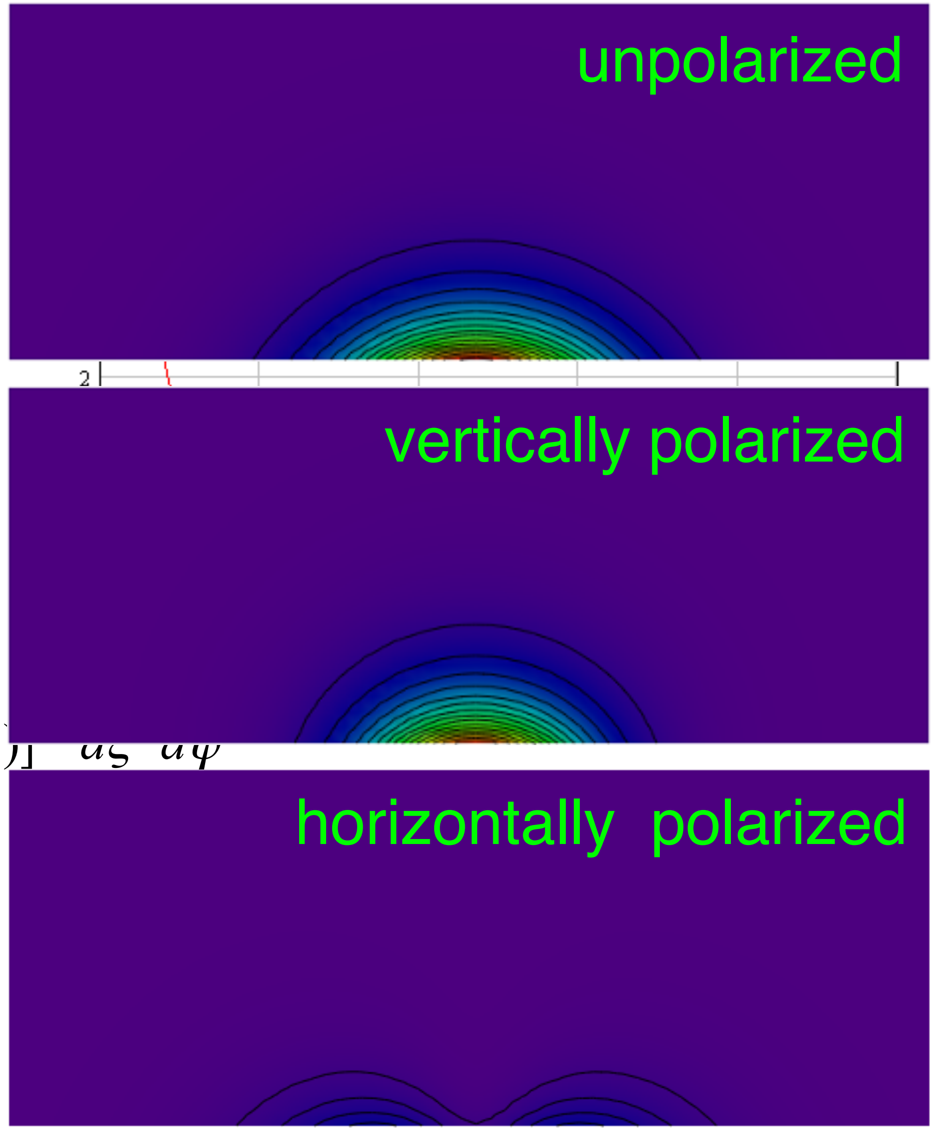
$$E_{r\omega} = \frac{q_0 \cdot \alpha}{\pi \cdot v} K_1(\alpha \cdot r) \qquad \alpha = \left(\frac{\lambda}{2\pi} \gamma \beta \right)^{-1}$$

$f_b(x, y)$ - transverse beam distribution

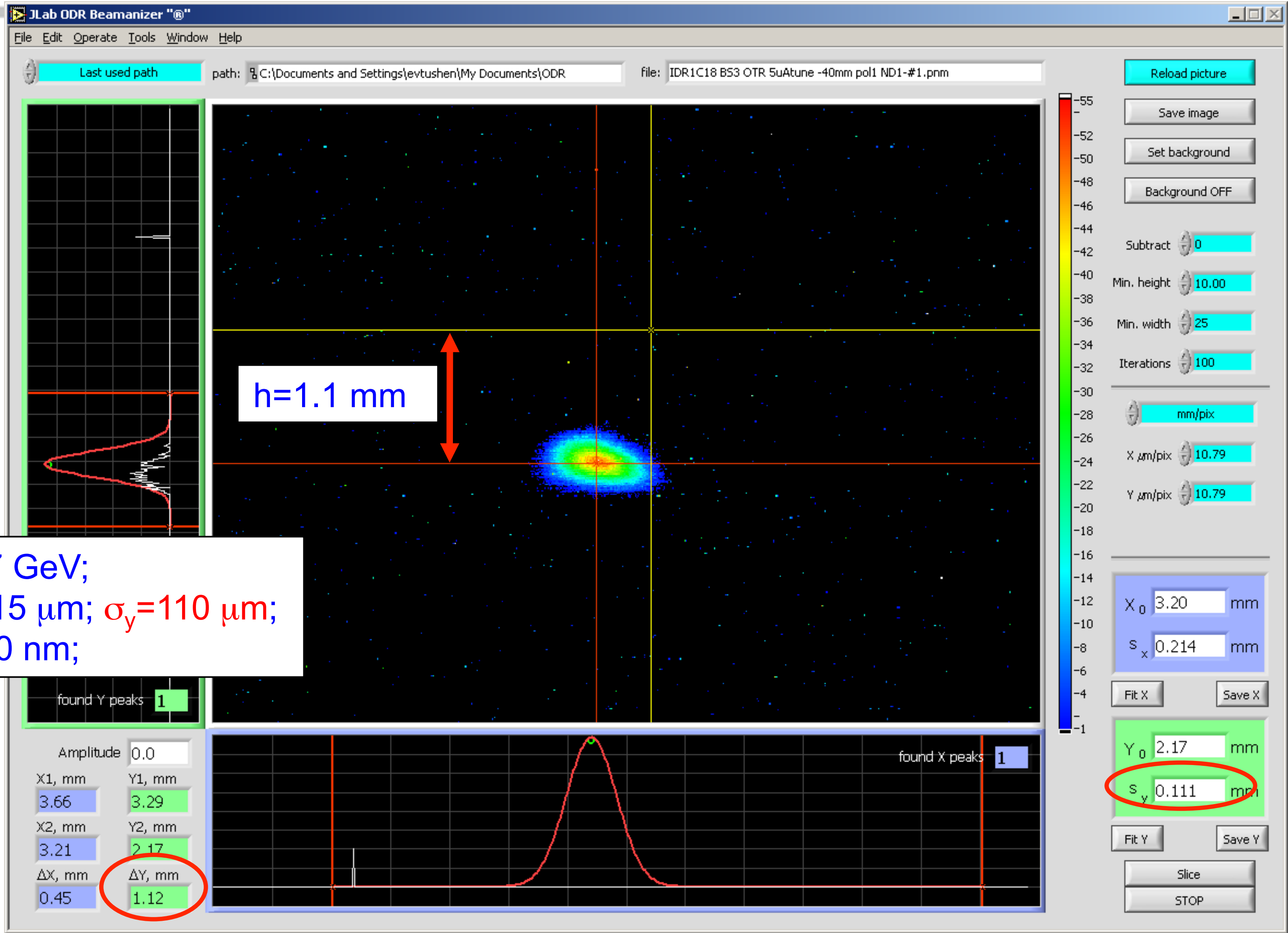
intensity of the ODR from the beam
Is 2D convolution of the f_b and $E_{r\omega}{}^2$

$$I_{beam} = \frac{1}{8\pi} \iint_{beam} f_b(\xi,\psi) \cdot [E_{r\omega}(\gamma, \lambda, x-\xi, y-\psi)] \, d\xi \, d\psi$$

Example assuming
4.597 GeV;
σ_x=215 μm; σ_y=110 μm;
λ=550 nm; h=1.1 mm

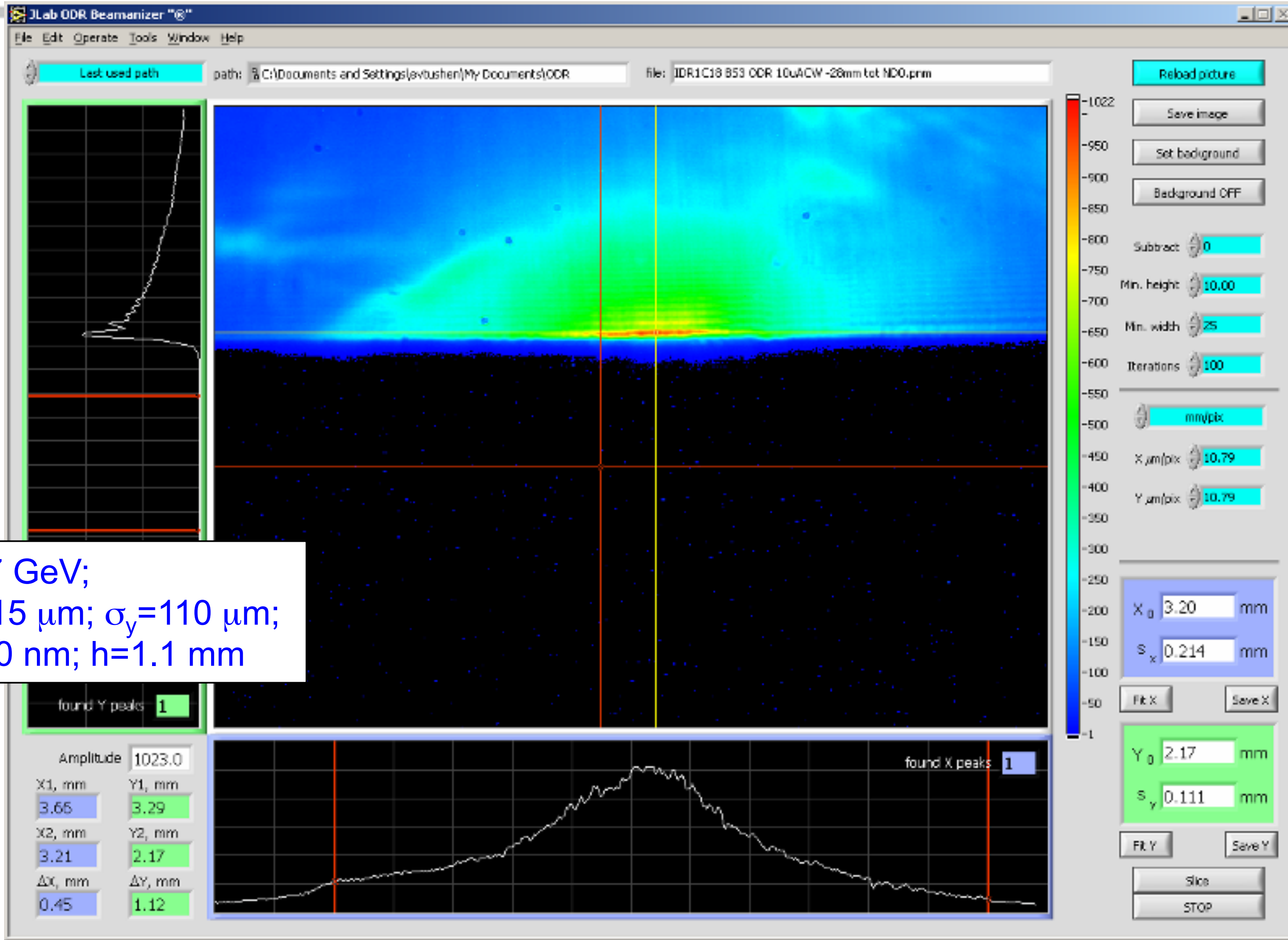


OTR - 5μA tune beam



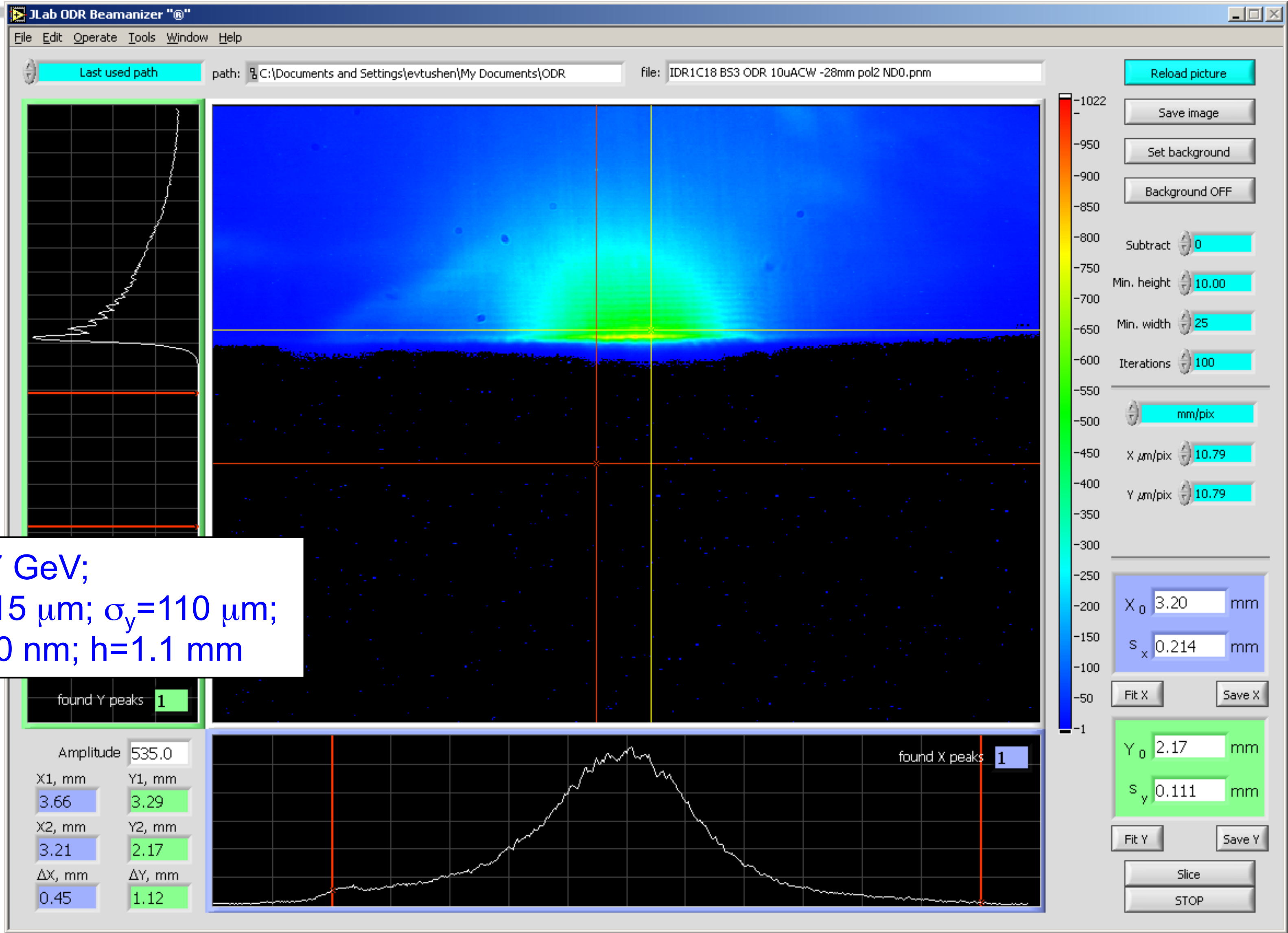
4.597 GeV;
σ_x=215 μm; σ_y=110 μm;
λ=550 nm;

10μA CW beam; ODR unpolarized



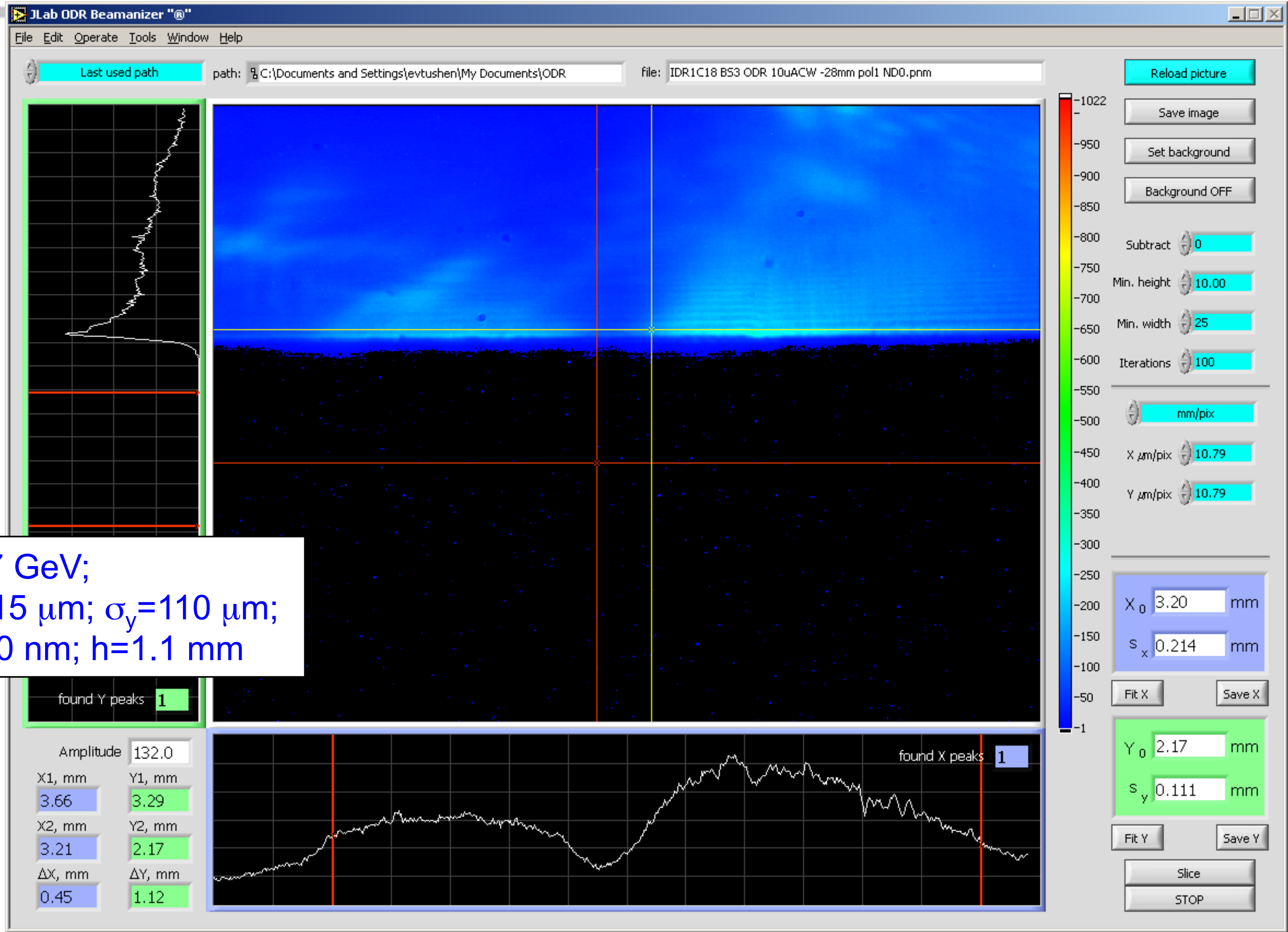
4.597 GeV;
σ_x=215 μm; σ_y=110 μm;
λ=550 nm; h=1.1 mm

10μA CW beam; ODR V. polarized



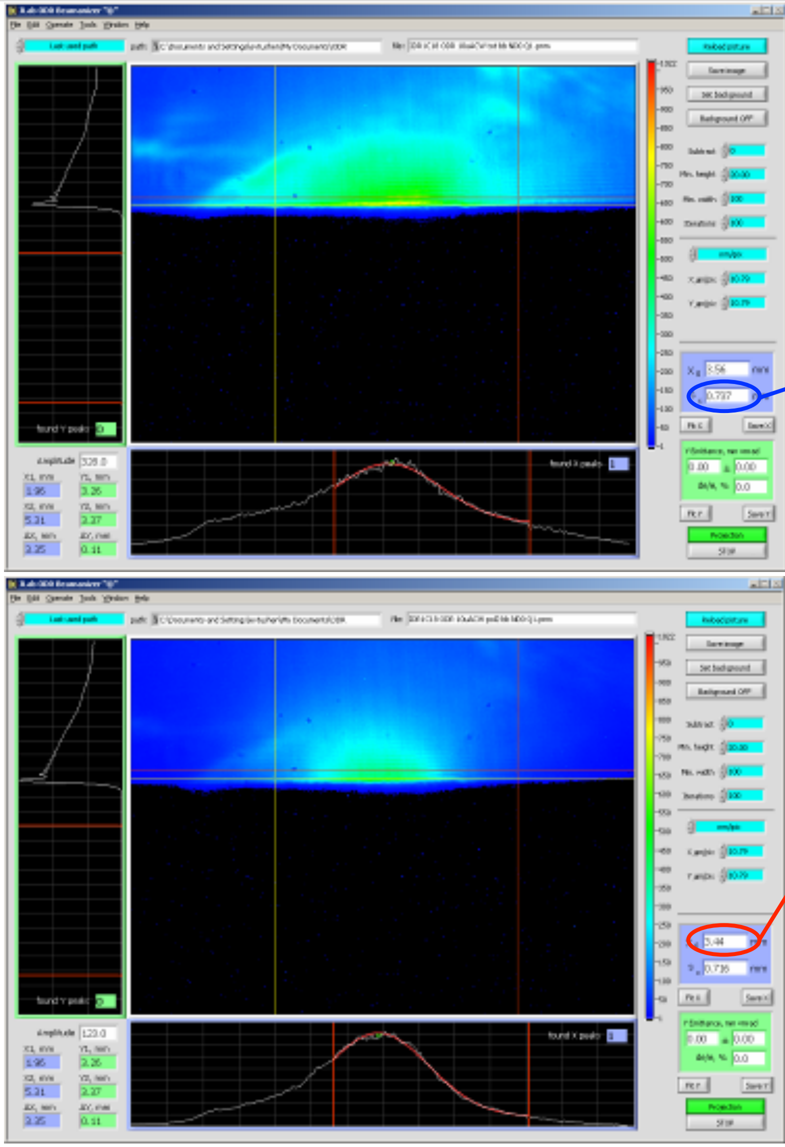
4.597 GeV;
σ_x=215 μm; σ_y=110 μm;
λ=550 nm; h=1.1 mm

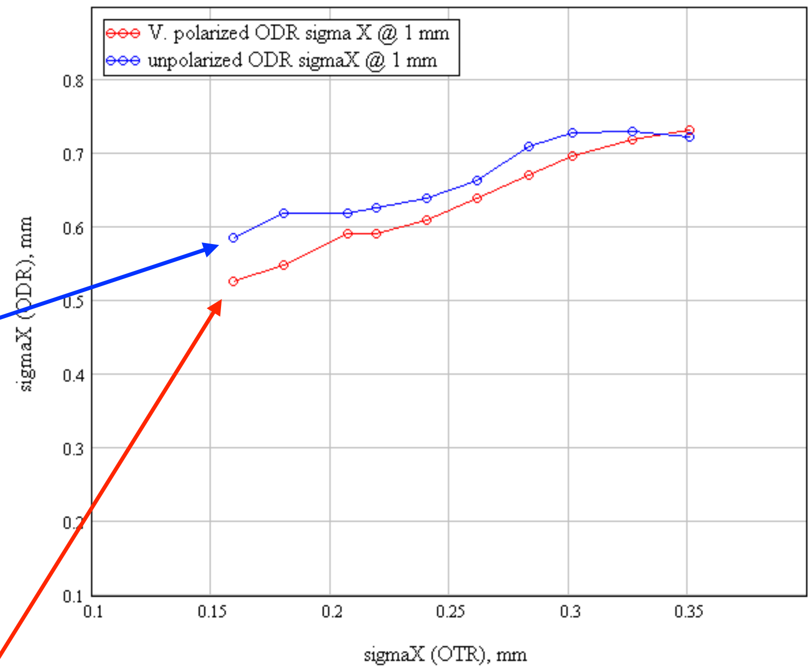
10μA CW beam; ODR H. polarized



4.597 GeV;
σ_x=215 μm; σ_y=110 μm;
λ=550 nm; h=1.1 mm

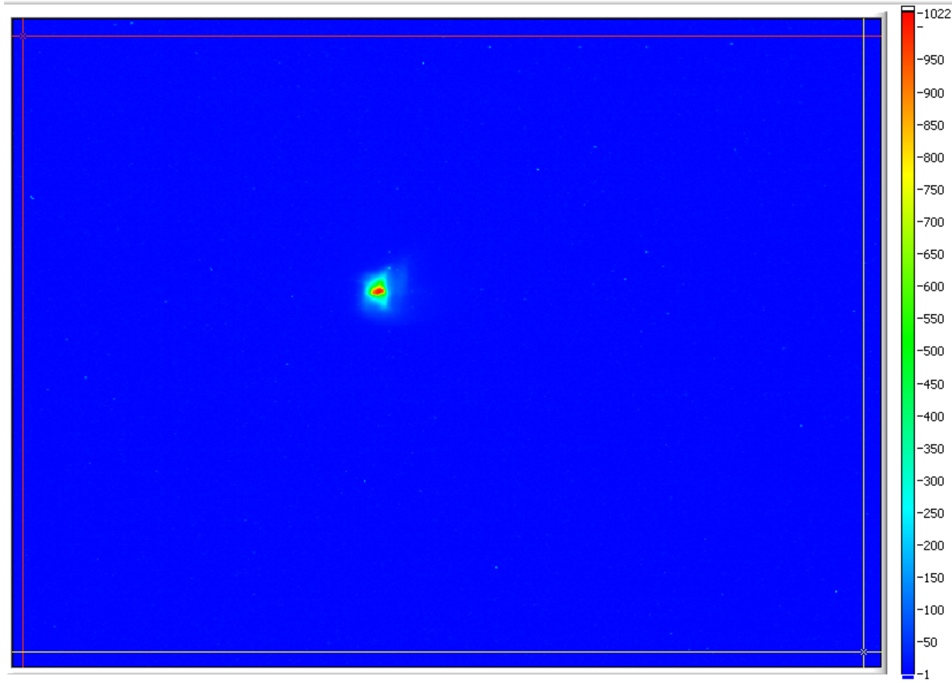
ODR distribution vs. beam size

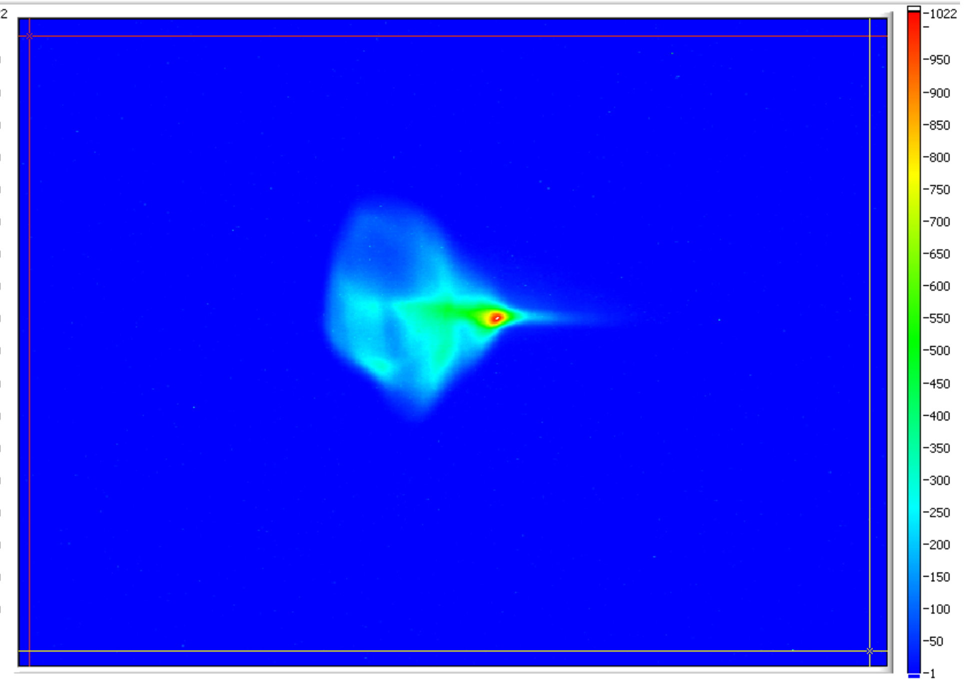




- ✧ ODR is in a development stage now
- ✧ Mitigation of the background is one of the problems
- ✧ Might need better modeling
- ✧ Demonstrated that can be used for relative beam size measurements
- ✧ Requires beam energy sufficiently high

LINAC beams are non-equilibrium

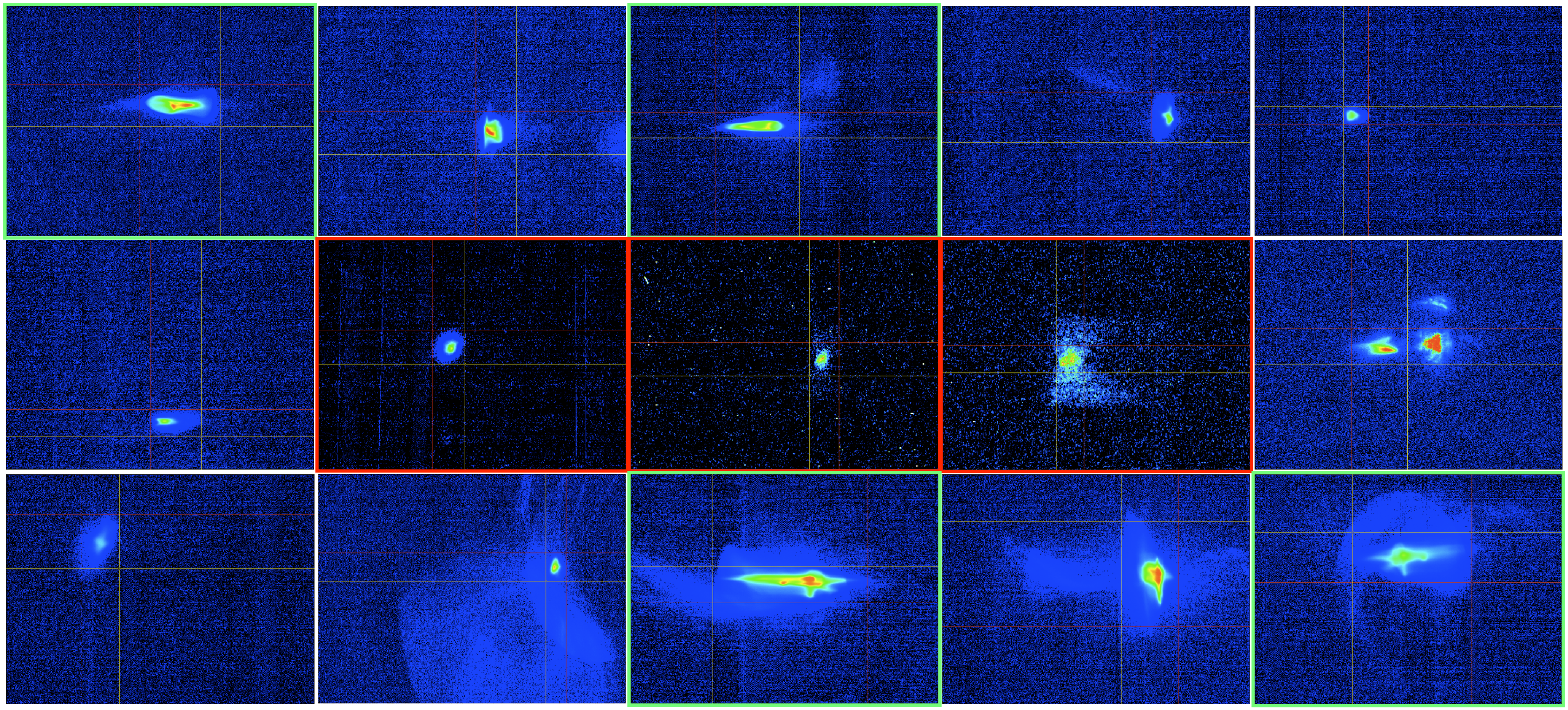




One of the JLab FEL transversal beam profiles a.k.a. "Dave Douglas's Hummingbird"

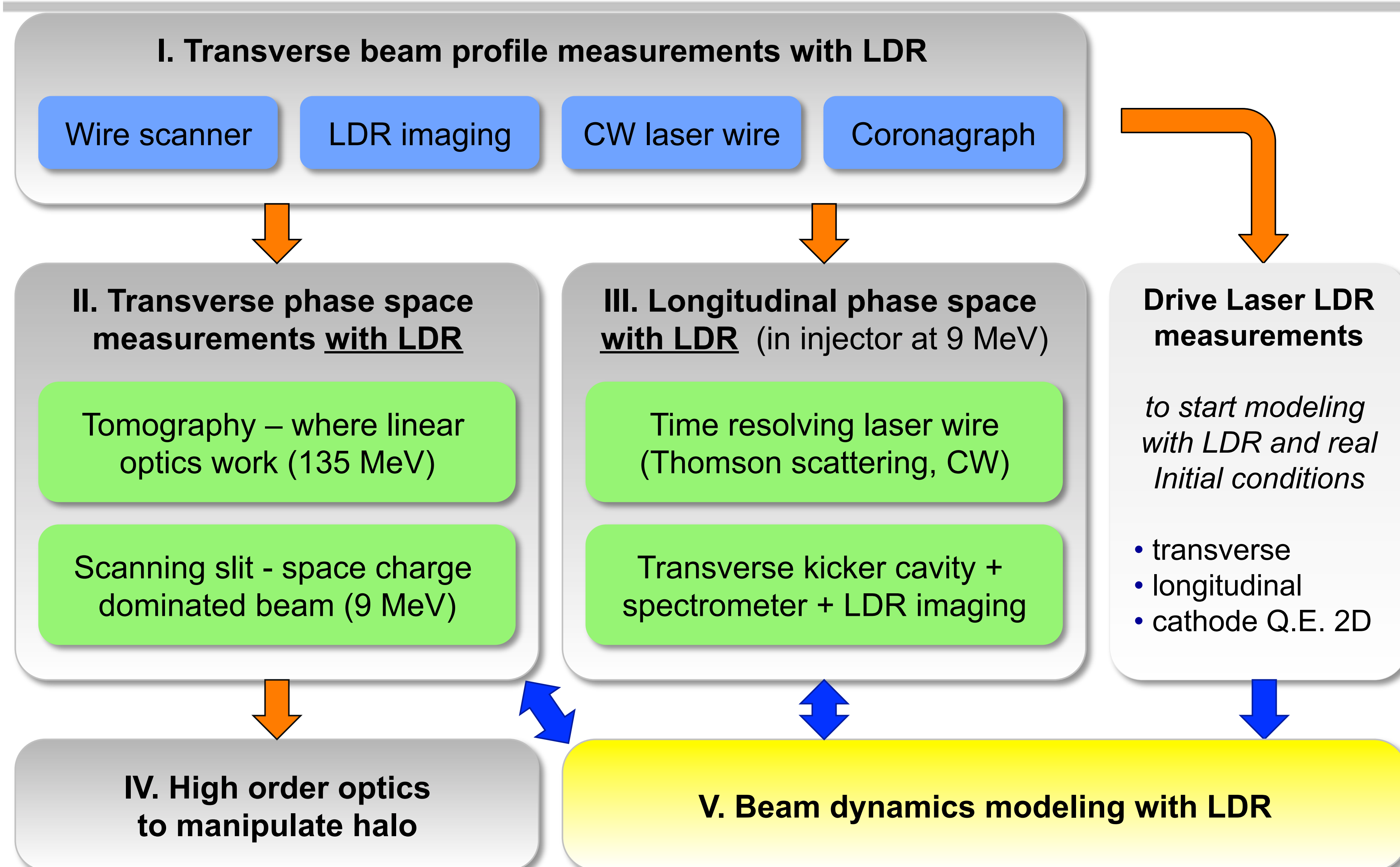
- Obtained in a "specially" setup measurements to show how much beam is non Gaussian
- Not how beam looks like during standard operation
- There is no Halo shown in this measurements in sense that all of it participates in FEL interaction
- The techniques we can borrow from rings assume Gaussian beam and therefore are concentrating on beam size (RMS) measurements

Transport / Transverse match

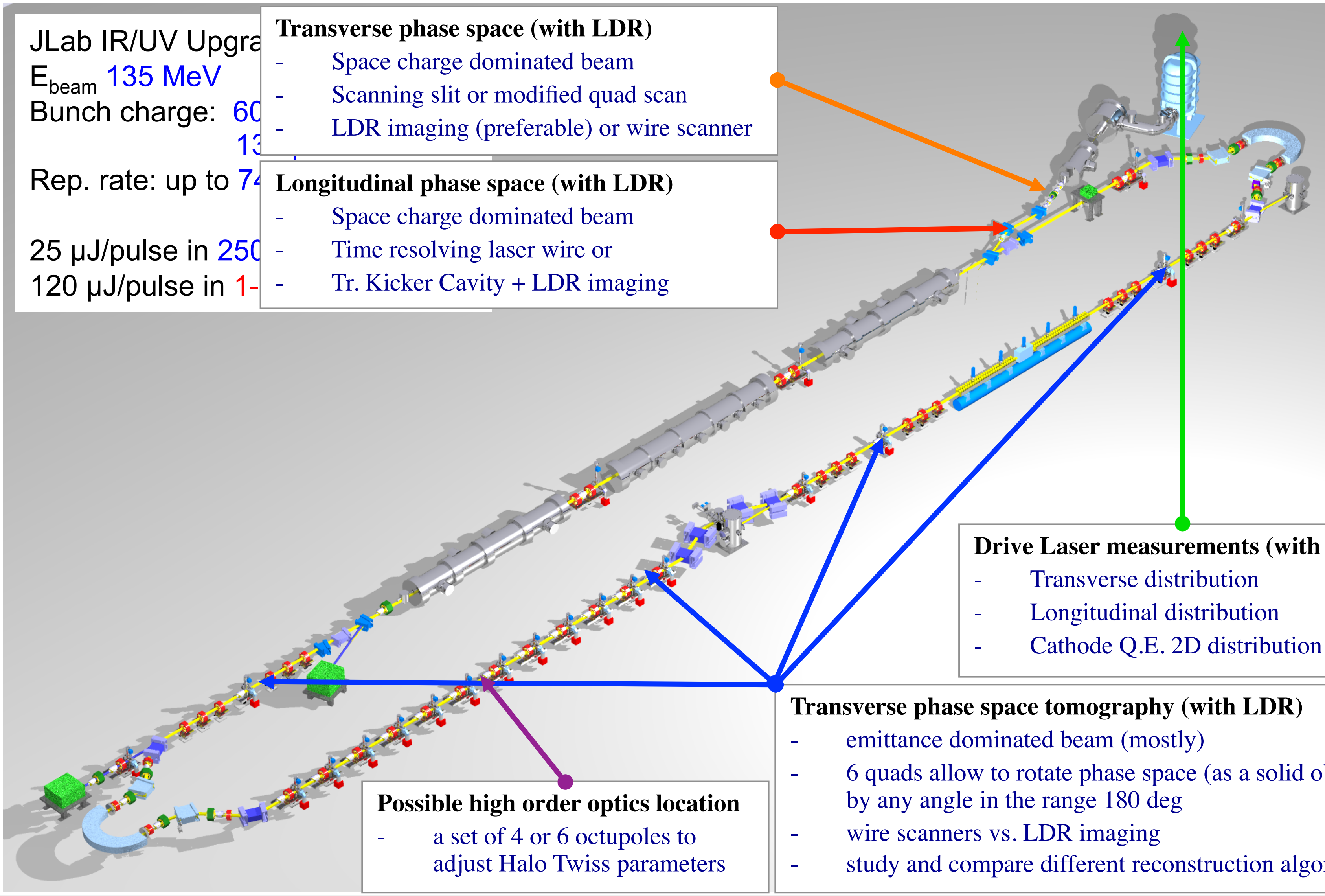


- ✧ set of transverse beam profiles measured through UV FEL beam line (~1/2 of the accelerator)
- ✧ combination of OTR and phosphor (P-46) coated viewer is used
- ✧ anything but Gaussian distributions *(live is hard)*
- ✧ with the machine optics model used to understand and adjust the transverse match
- ✧ iterative process between measurements and fitting/adjusting model and beam optics
- ✧ fully compressed beam (100 fs RMS) even at 135 MeV can be space charge dominated

“The Grand Scheme”



LDR beam dynamic studies (plan)



Transverse phase space (with LDR)

- Space charge dominated beam
- Scanning slit or modified quad scan
- LDR imaging (preferable) or wire scanner

Longitudinal phase space (with LDR)

- Space charge dominated beam
- Time resolving laser wire or
- Tr. Kicker Cavity + LDR imaging

Drive Laser measurements (with LDR)

- Transverse distribution
- Longitudinal distribution
- Cathode Q.E. 2D distribution

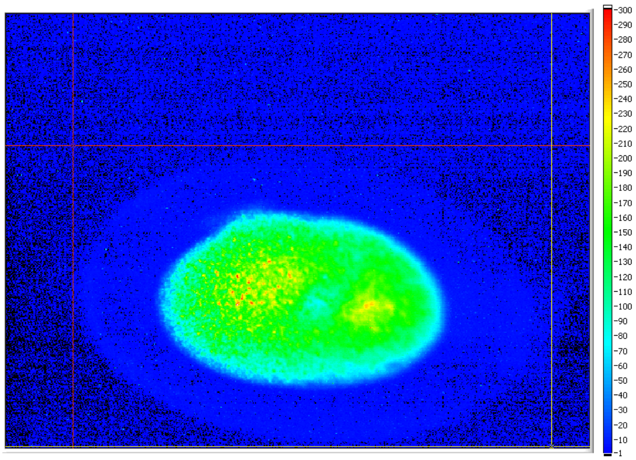
Possible high order optics location

- a set of 4 or 6 octupoles to adjust Halo Twiss parameters

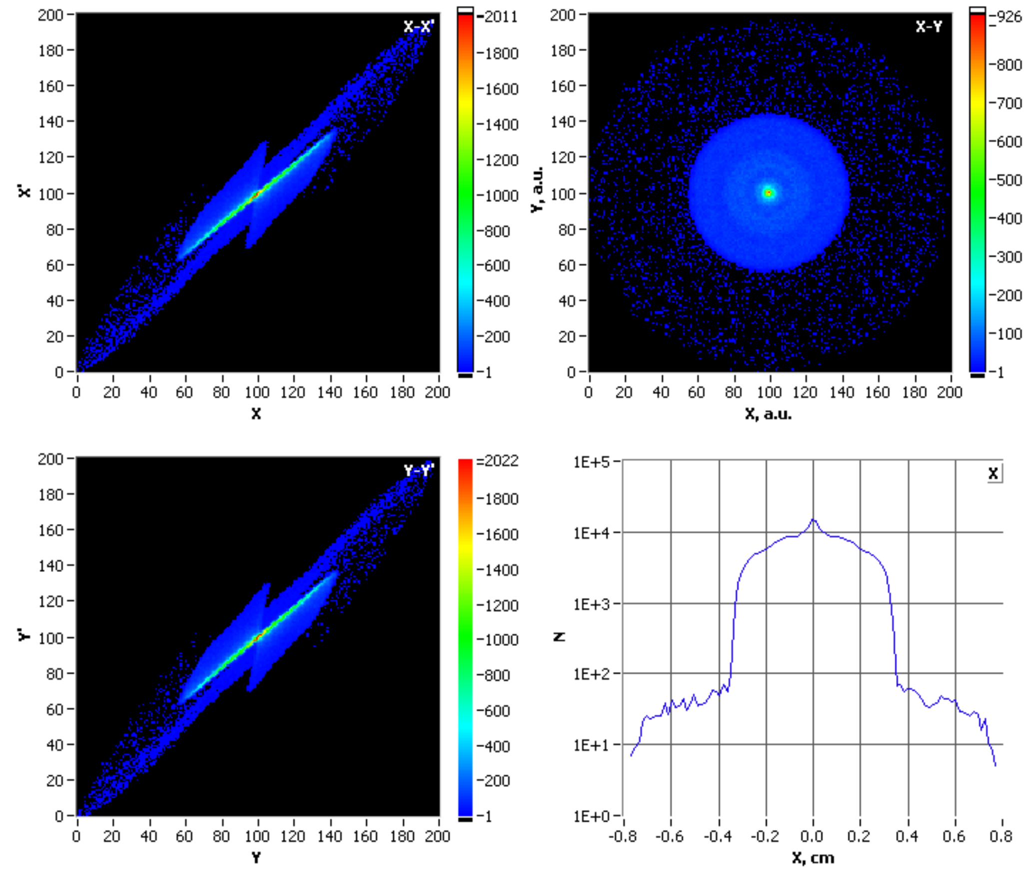
Transverse phase space tomography (with LDR)

- emittance dominated beam (mostly)
- 6 quads allow to rotate phase space (as a solid object) by any angle in the range 180 deg
- wire scanners vs. LDR imaging
- study and compare different reconstruction algorithms

Measurements vs. Modeling



Measured in JLab FEL injector, local intensity difference of the core and halo is about 300. (500 would measure as well)
10-bit frame grabber & a CCD with 57 dB dynamic range



PARMELA simulations of the same setup with 3E5 particles: X and Y phase spaces, beam profile and its projection show the halo around the core of about 3E-3.
Even in idealized system (simulation) beam dynamics can lead to formation of halo.

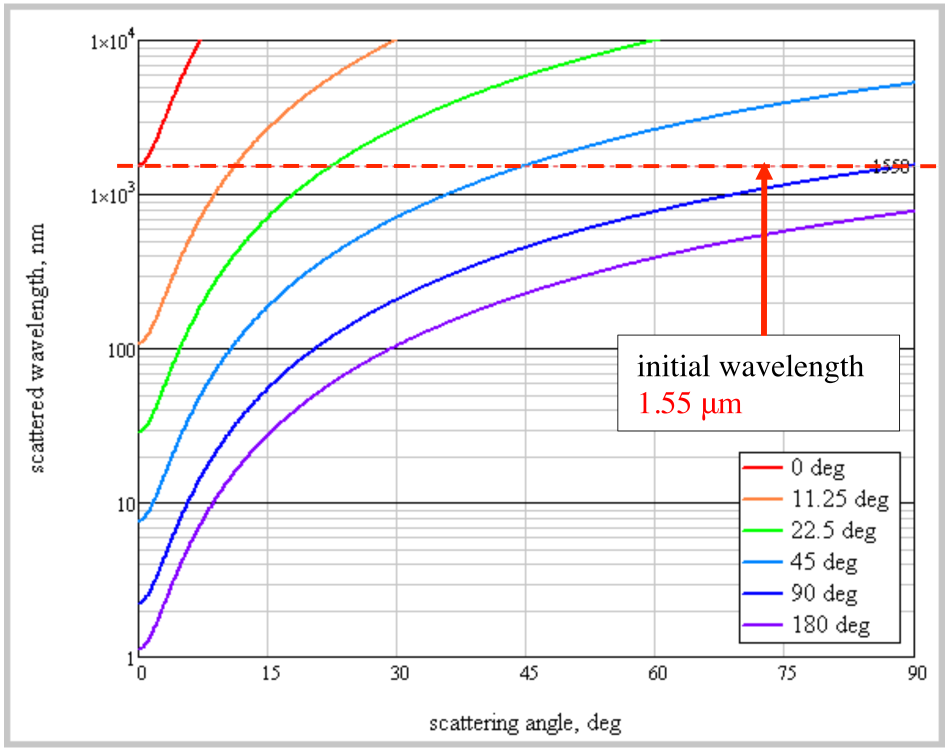
CW laser wire (1)

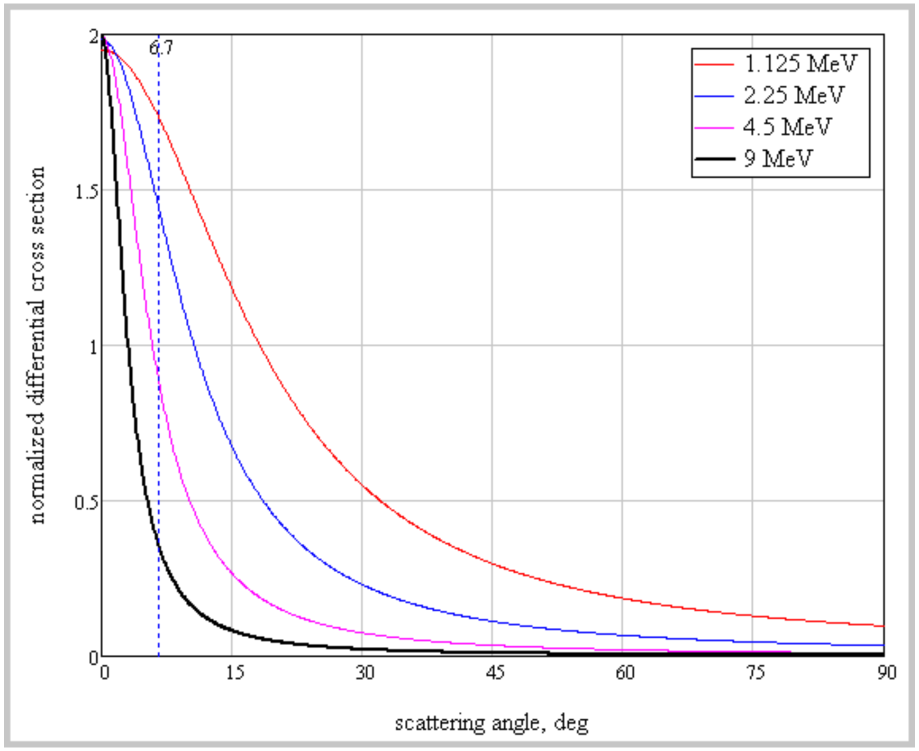
wavelength conversion assuming:
• beam energy 9 MeV
• laser wavelength 1.55 μm

$$\lambda_S = \lambda_S \frac{1-\beta\cos(\theta_S)}{1-\beta\cos(\theta_{ini})}$$

differential cross section
(angular extent dependence
on the beam energies)

$$\frac{d\sigma}{d\Omega} = r_e^2 \frac{1-\beta^2}{1-\beta\cos(\theta_S)}$$





CW laser wire (2)

wavelength conversion assuming:

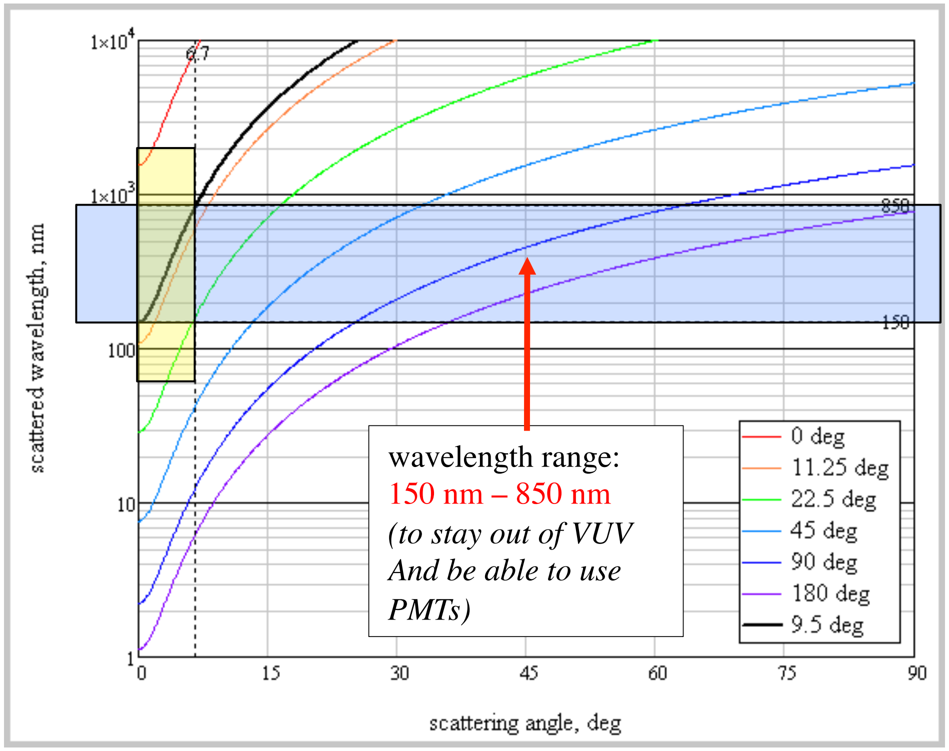
- beam energy 9 MeV
- laser wavelength 1.55 µm

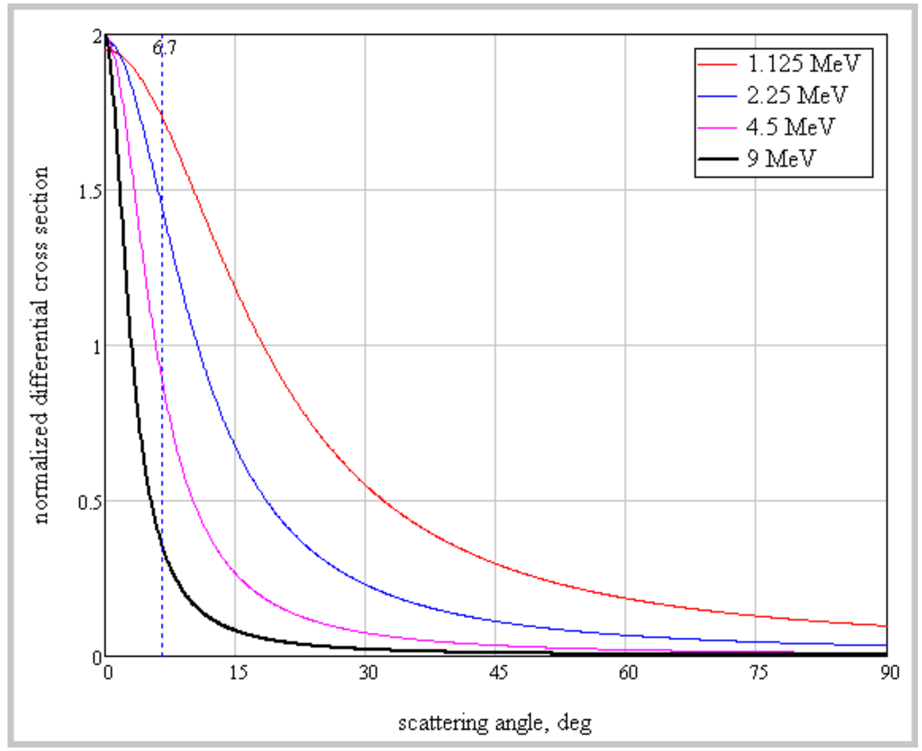
$$\lambda_S = \lambda_S \frac{1-\beta\cos(\theta_S)}{1-\beta\cos(\theta_{ini})}$$

differential cross section

(angular extend dependent on the beam energies)

$$\frac{d\sigma}{d\Omega} = r_e^2 \frac{1-\beta^2}{1-\beta\cos(\theta_S)}$$



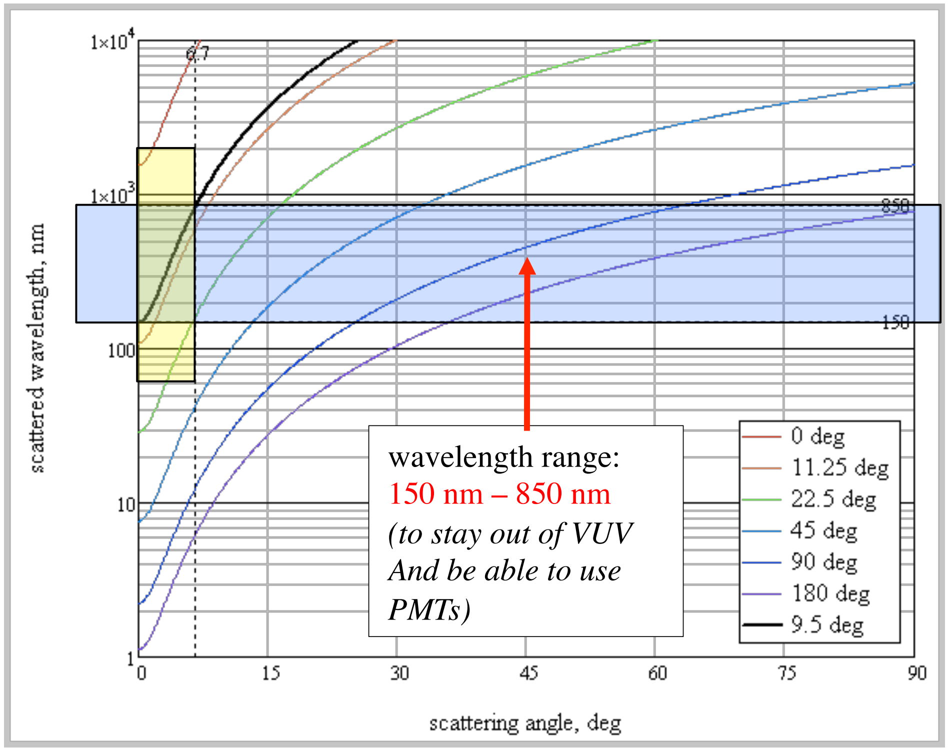


CW laser wire (3)

wavelength conversion assuming:

- beam energy 9 MeV
- laser wavelength 1.55 μm

$$\lambda_S = \lambda_S \frac{1-\beta\cos(\theta_S)}{1-\beta\cos(\theta_{ini})}$$



$$f_S = f_{beam}\cdot\left[\frac{N_{\hbar\omega}N_e}{S}\frac{\tau_{lase}}{\tau_{beam}}\sigma_{Th}\right]$$ - photon rate

Assuming:

- bunch charge 135 pC
- laser wavelength 1.55 μm
- pulse energy ~7 nJ
- τ_{laser} 500 fs
- τ_{beam} 2.5 ps
- f_{beam} 9.356 MHz
- r_{laser} 100 μm

We get N_s=0.02, but f_s=174 kHz !

There is factor of ~ 100 to be lost, but there is also factor of ~100 to be gained by pulse stacking.

Plus lock-in amplifier improves SNR as:

$$\sqrt{f_0\cdot\tau_{measure}} = \sqrt{9.356\ MHz\cdot 1s} = 3\times10^3$$

Thank you for your attention.