Towards large dynamic range beam diagnostics and beam dynamics studies

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Motivation

- Linacs with average current 1-2 mA and energy 1-2.5 GeV are envisioned as drivers for next generation high average brightness Light Sources (up to 5 MW beam power) *vs. presently operational linac based X-ray sources 24 uA (FLASH) and 15 nA (LCLS)*
- JLab IR/UV Upgrade is a 9 mA ERL with average beam power of 1.2 MW – provides us with operational experience of high current linac and is a good testing ground for future development
- Halo - parts of the phase space with large amplitude and small intensity - is one of the limitations for high current linacs
- Linac beams have neither the time nor the mechanism to come to equilibrium *(unlike storage rings, which also run high current)*
- Besides Light Sources there is a number of linac application requiring high current operation with low or no beam halo

"The Grand Scheme"

I. Transverse beam profile measurements with LDR

- Wire scanner
- LDR imaging
- CW laser wire
- Coronagraph

II. Transverse phase space measurements <u>with LDR</u>

- Tomography – where linear optics work (135 MeV)
- Scanning slit - space charge dominated beam (9 MeV)

III. Longitudinal phase space <u>with LDR</u> (in injector at 9 MeV)

- Time resolving laser wire (Thomson scattering, CW)
- Transverse kicker cavity + spectrometer + LDR imaging

Drive Laser LDR measurements

to start modeling with LDR and real Initial conditions

- transverse
- longitudinal
- cathode Q.E. 2D

IV. High order optics to manipulate halo

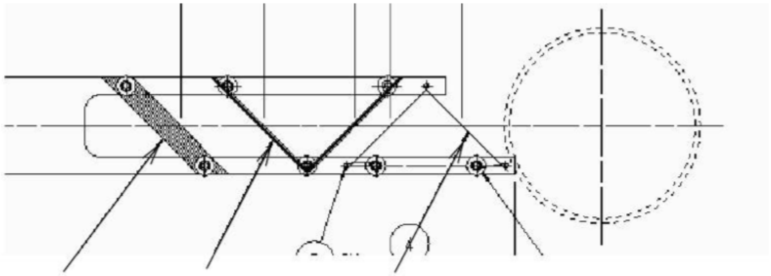
V. Beam dynamics modeling with LDR

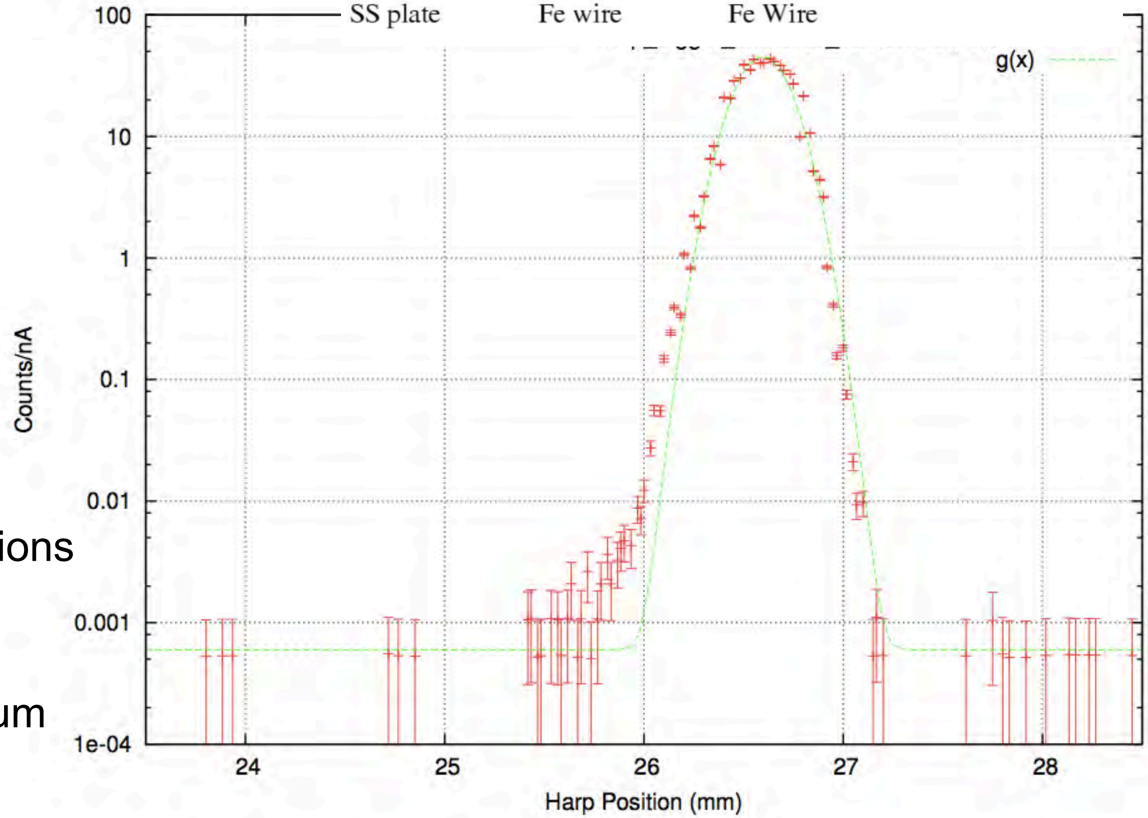
Jefferson Lab

Wire scanner measurements

A. Freyberger, CEBAF measurements, in DIPAC05 proceedings

- wire with diameter much smaller than the beam size interacts with beam as it is scanned across it
- there is a number of interaction mechanisms:
  - ✓ beam capture
  - ✓ secondary emission
  - ✓ scattering
  - ✓ conversion
- different ways to detect the signal
  - ✓ induced current
  - ✓ secondary particles (counting)
- only 1D projections of 2D distributions
- takes time ("patience limited")
- real LINAC beams – non-equilibrium





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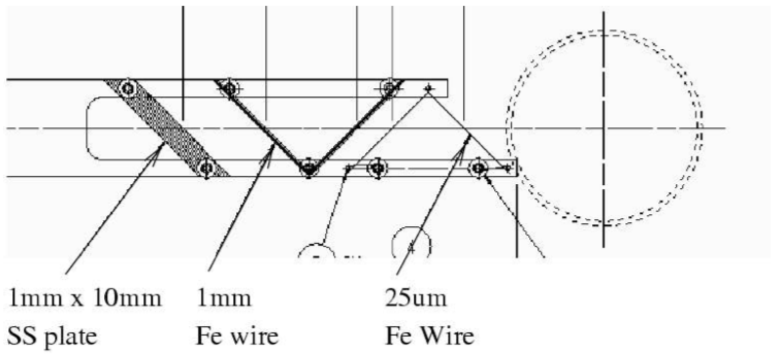
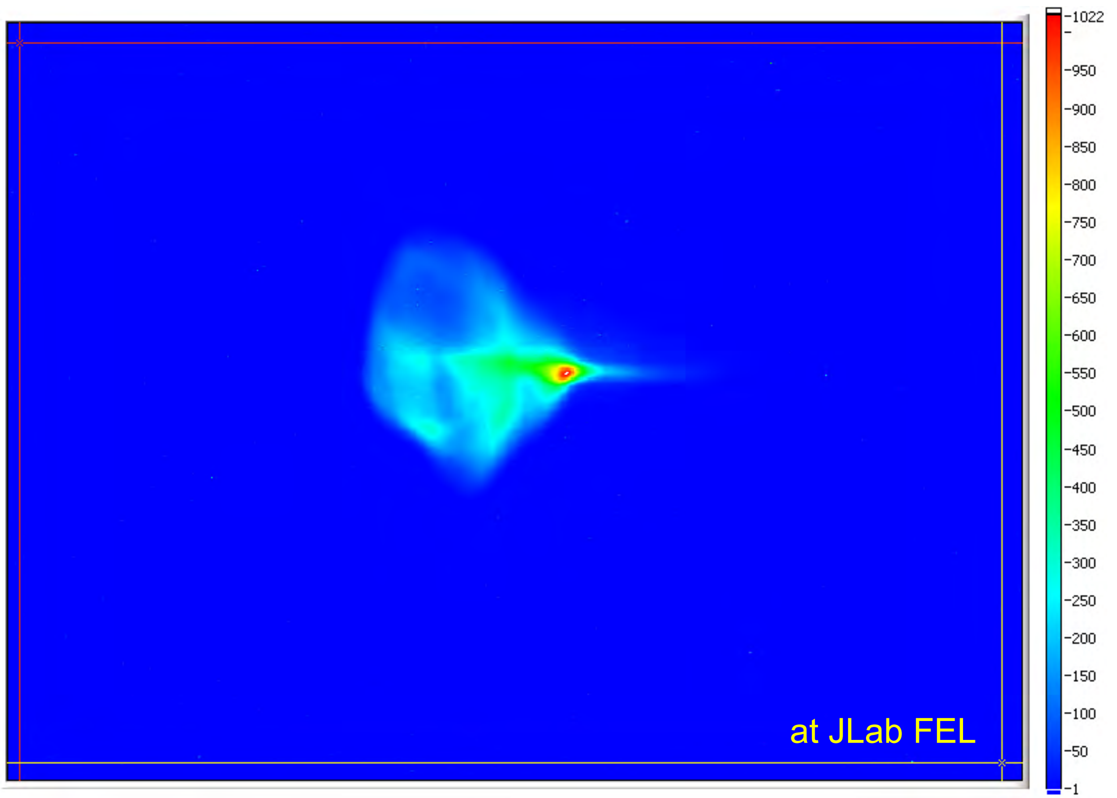
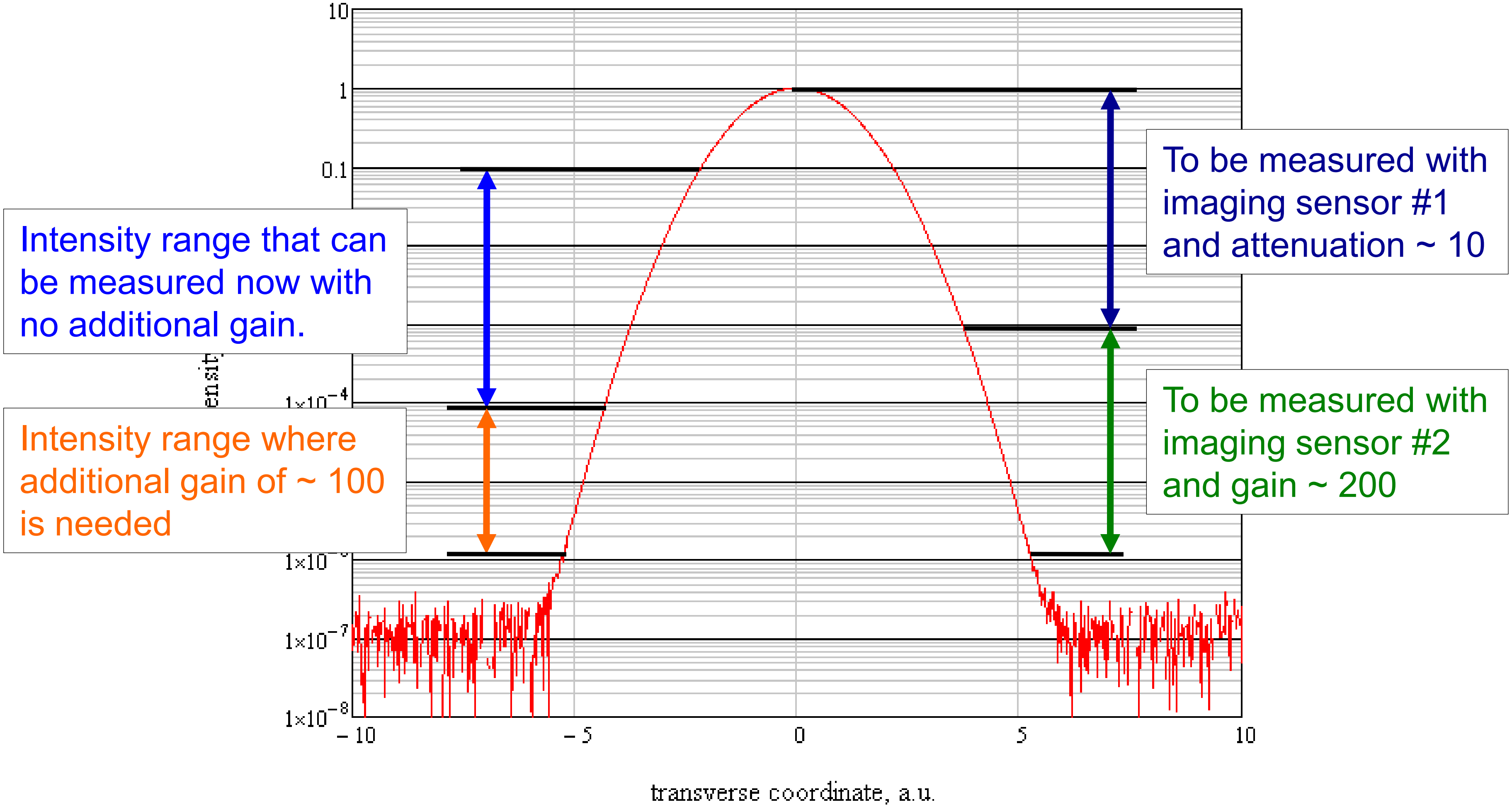




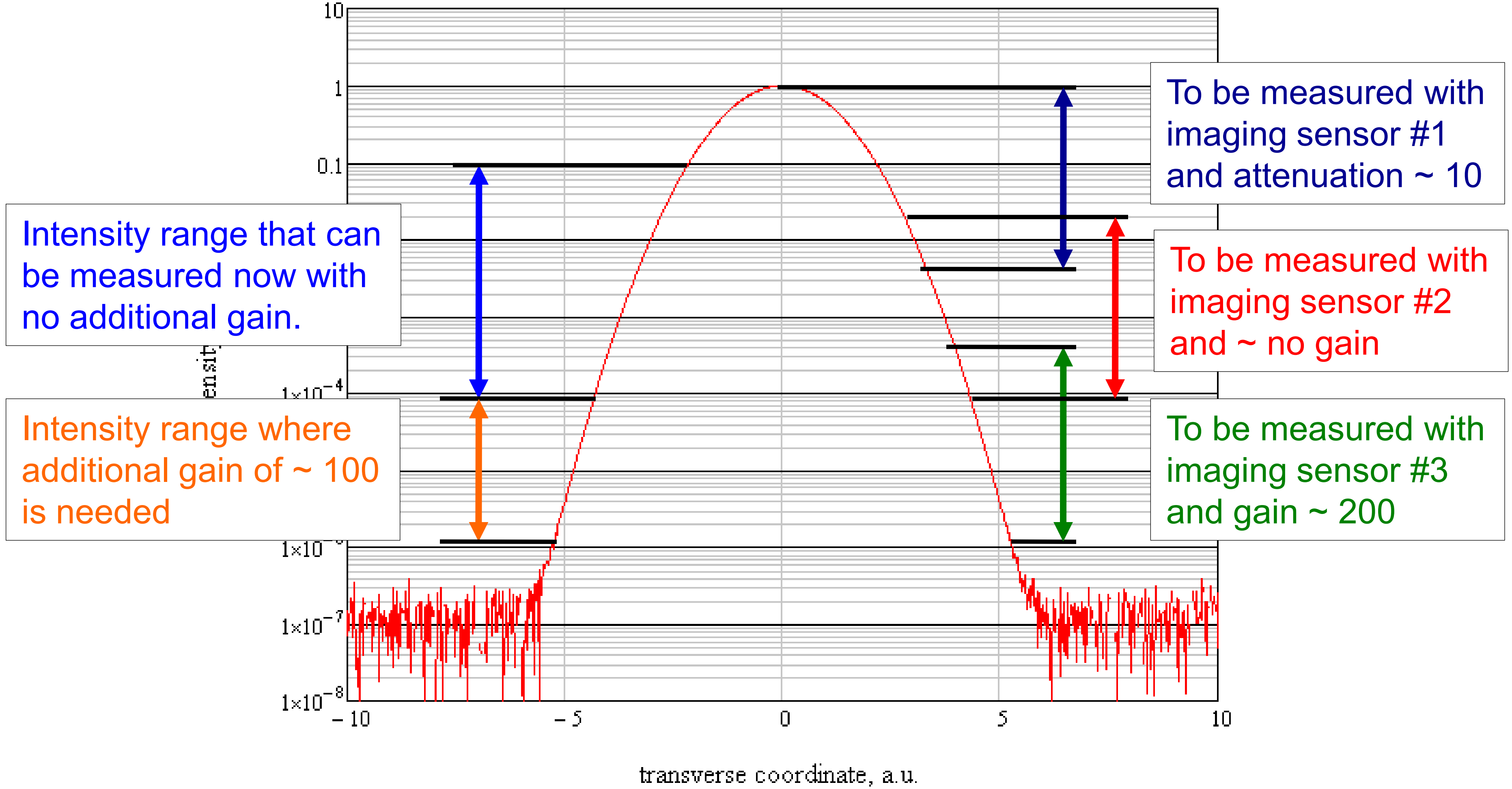
Large Dynamic Range imaging (1)

- To explain the idea we consider JLab FEL tune-up beam and the use of OTR.
- Beam – 250 μs macro pulses at 2 Hz, bunch rep. rate ~ 4.678 MHz, 135 pC bunch charge, ~ 158 nC integrated charge (limits the beam power to safe level)
- With typical beam size of few hundred μm OTR signal is attenuated by ~ 10 to keep CCD from saturation. For phosphor or YAG:Ce viewers attenuation of at least 100 is used. Insertable ND1 and ND2 filters are used.
- Quantitative OTR intensity measurements agrees well with calculations – well understood
- With OTR there is enough intensity to measure 4 upper decades. Lower two decades need gain of about 100 to be measured.
- The main principle is to use imaging with 2 or 3 sensors with different effective gain simultaneously and to combine data in one LDR image digitally
- The key elements:
  - image intensifiers (necessary gain and higher is available)
  - accurate alignment and linearity
  - the algorithm, data overlap from different sensors
  - understanding CCD well overflow - transverse extend

Large Dynamic Range imaging (2)



Large Dynamic Range imaging (3)



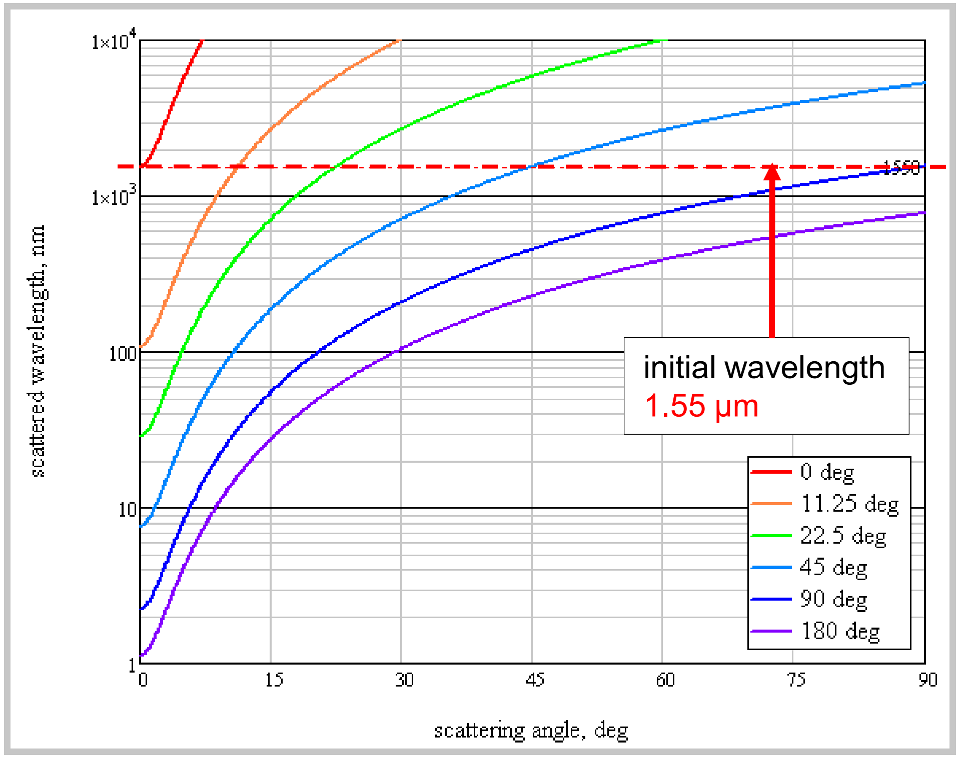
CW laser wire (1)

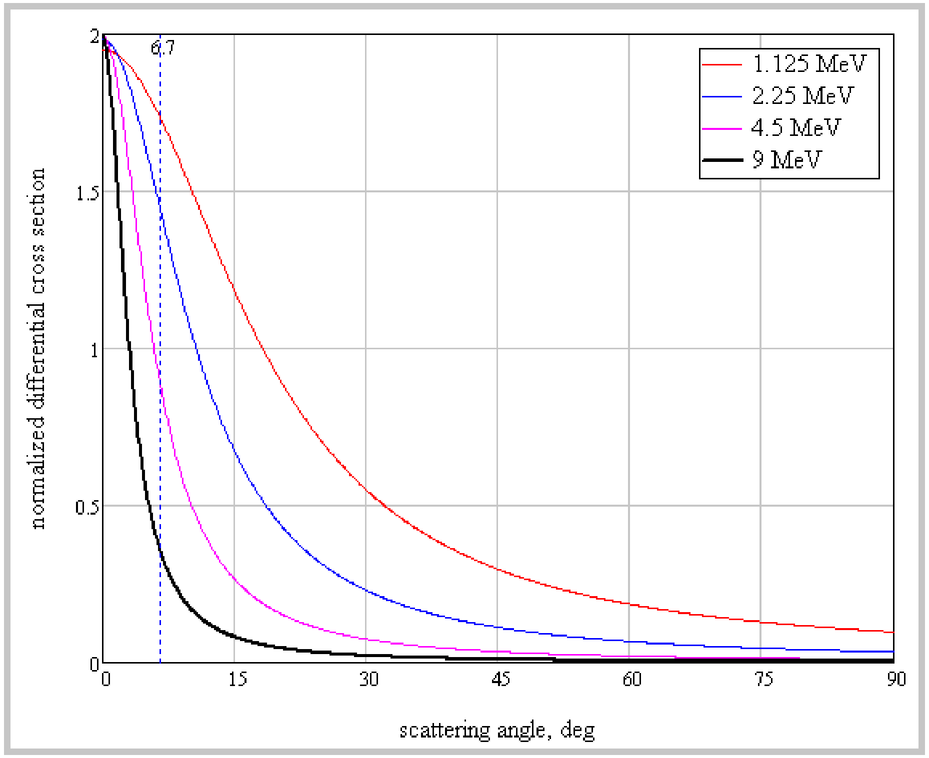
wavelength conversion assuming:
- beam energy 9 MeV
- laser wavelength 1.55 μm

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

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

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





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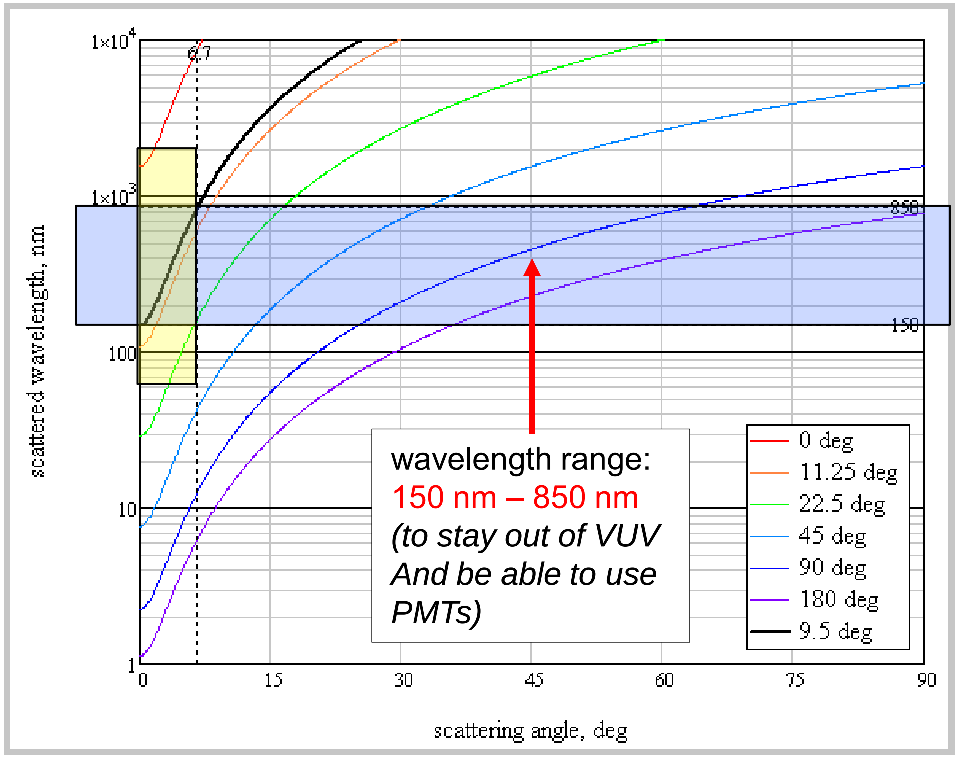

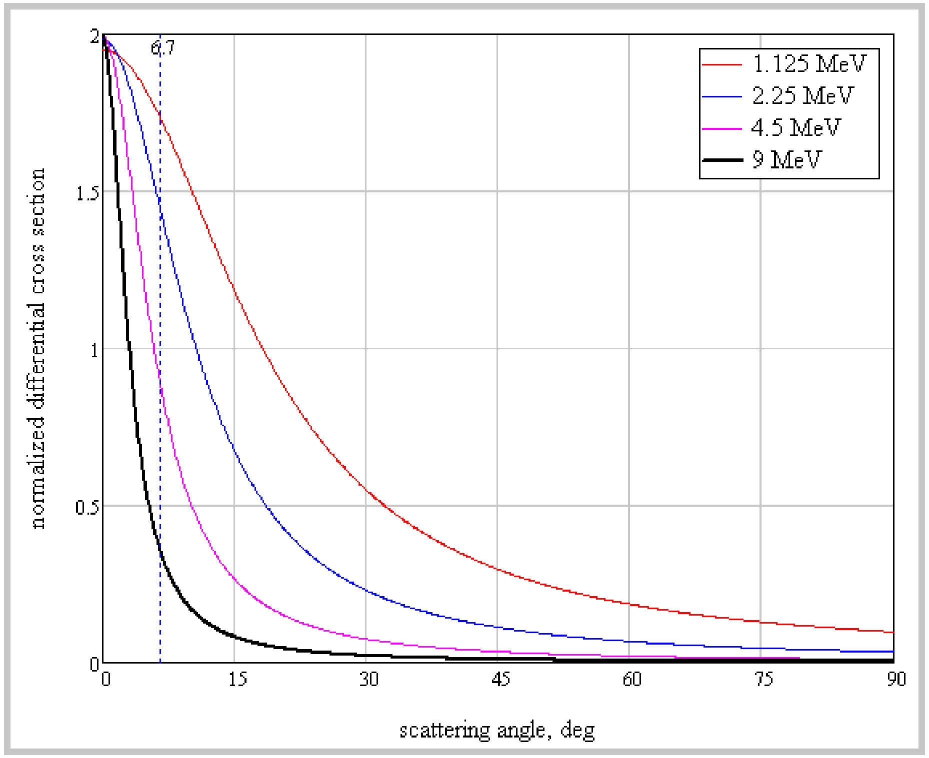

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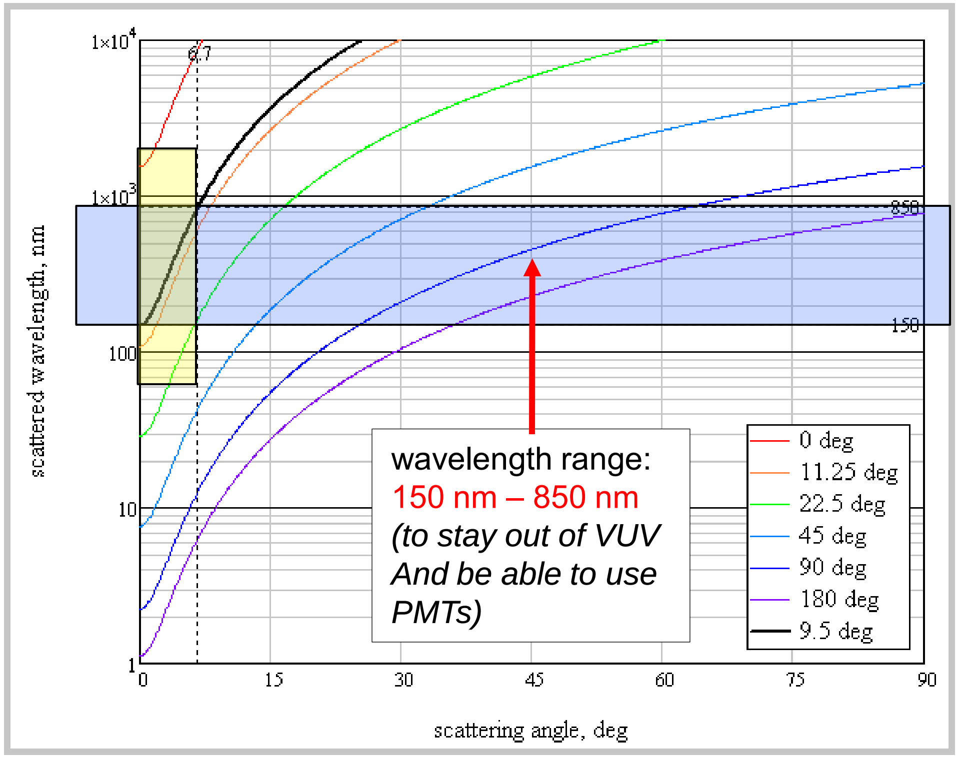


$$f_S = f_{beam} \cdot \left[\frac{N_{h\omega} N_e}{S} \frac{\tau_{lase}}{\tau_{beam}} \sigma_{Th} \right]$$ - photon rate

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

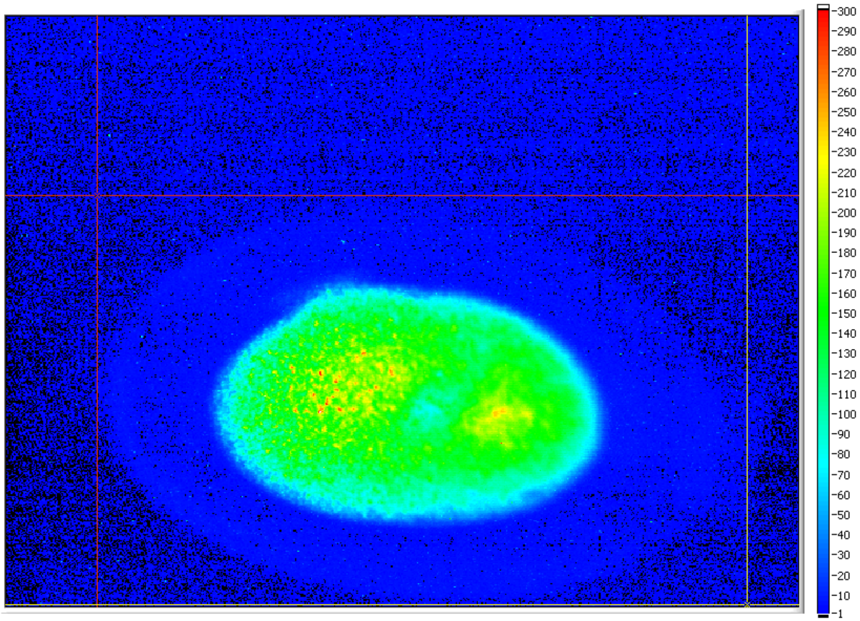
We get N_s=0.02, but f_s=174 kHz !

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

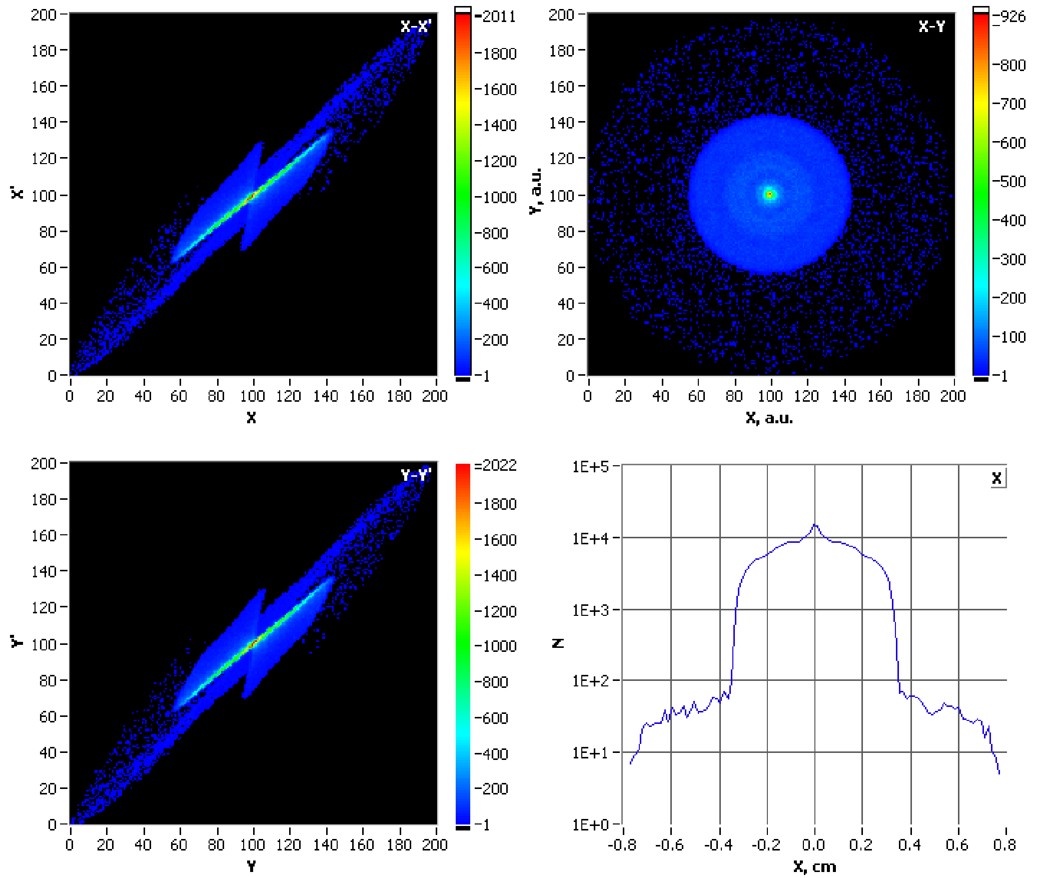
Plus lock-in amplifier improves SNR as:

$$\sqrt{f_0 \cdot \tau_{measure}} = \sqrt{9.356\ MHz \cdot 1s} = 3\times 10^3$$

Measurements vs. Modeling at the level ~10^3



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) non-linear beam dynamics can lead to formation of halo.

Conclusion / Outlook

- There are several part of the this program that cannot be mentioned here within 15 min talk (find me if you want to talk about them, suggestions and comment are welcome)
- The general approach of the program is the to:
  - develop and built diagnostics tools
  - study beam dynamics (phase space evolution)
  - implements beam optics for better manipulation of the halo
  - use the experimental data for modeling that is close to reality in sense of initial conditions (iterate between the experiments and the modeling)

JLab IR/UV ERL Light Source

E_{beam} 135 MeV
Bunch charge: 60 pC – UV FEL
135 pC – IR FEL
Rep. rate up to 74.85 MHz

25 μJ/pulse in 250–700 nm UV-VIS

120 μJ/pulse in 1-10 μm IR