Towards Large Dynamic Range Beam Diagnostics and Beam Dynamics Studies

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- 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)*
- 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 FEL 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
- Besides Light Sources there is a number of linac application requiring high current operation with low or no beam halo

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I. Transverse beam profile measurements with LDR
- Wire scanner
- LDR imaging
- CW laser wire
- Coronagraph

II. Transverse phase space measurements with LDR
- Tomography – where linear optics work (135 MeV)
- Scanning slit - space charge dominated beam (9 MeV)

III. Longitudinal phase space with LDR (in injector at 9 MeV)
- Time resolving laser wire (Thomson scattering, CW)
- Transverse kicker cavity + spectrometer + LDR imaging

Drive Laser LDR measurements

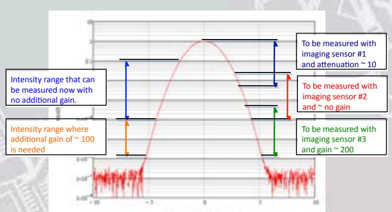
to start modeling with LDR and real Initial conditions
- transverse
- longitudinal
- cathode Q.E. 2D

IV. High order optics to manipulate halo

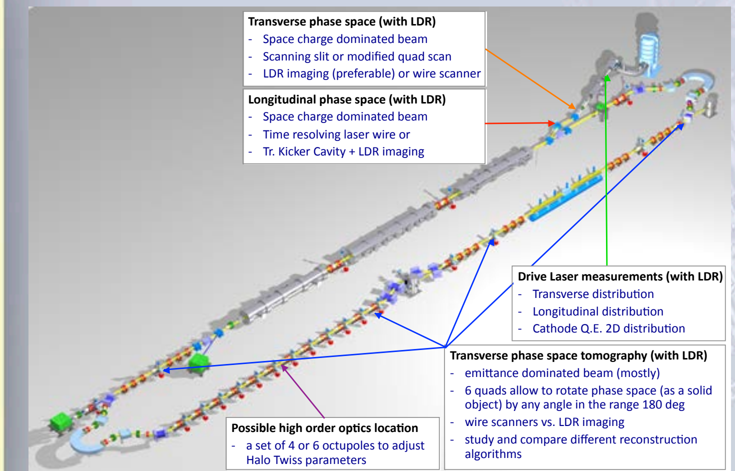
V. Beam dynamics modeling with LDR

Large Dynamic Range Imaging Approach

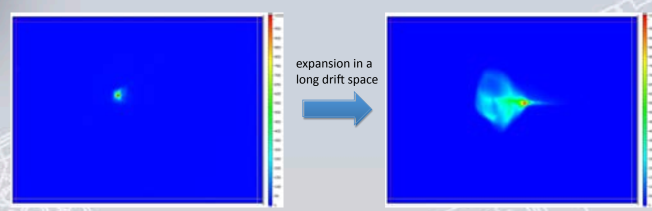
- consider JLab FEL tune-up beam and the use of OTR
- With OTR there is enough intensity to measure 4 upper decades. Lower two decades need gain of about 100 to be measured.
- The main principle is to use imaging with 2 or 3 sensors with different effective gain simultaneously and to combine data in 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 extent



JLab IR Upgrade FEL (9 mA; 135 MeV)



Making "Dave Douglas's hummingbird" distribution

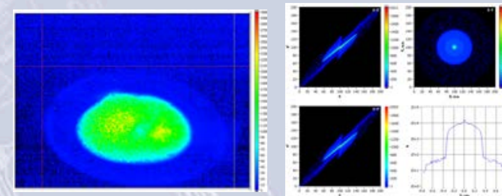


OTR radiators Si+Al

60 um thin Si

Linac viewers: Al foil ~ 10 um thin

Measurements vs. Simulations at 10^3 level



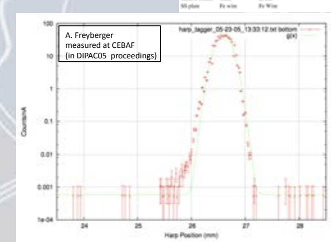
Measured in JLab FEL injector, local intensity difference of the core and halo is about 300 (500 would be measure as well) 10-bit frame grabber & a CCD with 57 dB dynamic range

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 a halo formatio.

Wire Scanner Large Dynamic Range Measurements

- 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



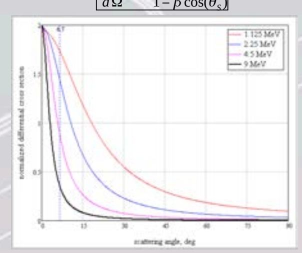
CW Laser Wire (time resolving for longitudinal phase space measurements)

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)

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



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

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