Time-Resolving “Laser Wire” for Large Dynamic Range Measurements at low beam energy - Design Considerations

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Why

- Setup/Tune-up and operation of high current systems (JLab FEL) approach so is:
  1. make detailed beam measurements and tuning with very low duty cycle beam
  2. monitor some of the beam parameters, not necessarily making detailed measurements with high power beam

- To monitor the transverse match is one the challenges in a linac. At high beam energy if bends are available and with SR monitors properly placed in the lattice (low dispersion locations) it can be done. However, at low beam energy in the injector (~10 MeV) SR is very far-IR.

- **Thus, it is not trivial to monitoring transverse beam size in an ERL injector**

- The same is true for longitudinal distribution measurementst of the beam with sub-ps resolution at the low beam energy.

- “Longitudinal halo” i.e. long temporal tails can be easily converted in to transverse halo due to strong, time dependent focusing by SRF linac.

- **One possible solution is to do wire scanner-like measurements, but replacing the physical wire, which would not survive high current beam, with a laser beam and use Thomson scattering**
“Tails” Longitudinal to Transverse

- Measured at JLab FEL, at DarkLight beam test target mockup
- Starting from nominal 135 pC setup
- Bunch charge increased by ~ 10 %
- Injector left unadjusted
- Observed a transverse tail rapidly changing with the bunch charge
- Found that the buncher cavity at injector has the strongest effect on the tail
- The beam dynamics in injector: transverse and longitudinal planes are coupled via space change
- Longitudinal tails from injector affect trans. match but also energy spread and energy tails
- Injector needs to be setup without significant long. tails
CW-LW: Thomson Scattering

Wavelength conversion assuming:
- beam energy 9 MeV
- laser wavelength 1030 μm

\[ \lambda_s = \lambda_0 \frac{1 - \beta \cos(\theta_s)}{1 - \beta \cos(\theta_{ini})} \]

Differential cross section (divergency on the beam energies \( \sim 1/\gamma \))

\[ \frac{d\sigma}{d\Omega} = r_e^2 \frac{1 - \beta^2}{1 - \beta \cos(\theta_s)} \]
CW-LW: Collection Efficiency

Wavelength conversion assuming:
• beam energy 9 MeV
• laser wavelength 1030 μm

\[ \lambda_S = \lambda_0 \frac{1 - \beta \cos(\theta_S)}{1 - \beta \cos(\theta_{ini})} \]

Collecting forward scattered photons in relatively large solid angle \( \theta = 0..5.6 \text{ deg} \), gives very large collection efficiency of \(~ 70 \%\).
Wavelength conversion assuming:
• beam energy 9 MeV
• laser wavelength 1030 μm

\[ \lambda_s = \lambda_0 \frac{1 - \beta \cos(\theta_S)}{1 - \beta \cos(\theta_{ini})} \]

Assuming:
• bunch charge 135 pC
• laser wavelength 1030 μm
• pulse energy ~10 μJ
• \( \tau_{laser} 500 \text{ fs} \)
• \( \tau_{beam} 2.5 \text{ ps} \)
• \( f_{beam} 1.169 \text{ MHz} \)
• \( r_{laser} 100 \text{ μm} \)

We get: \( N_s \approx 12 \), but \( f_s = 14.7 \text{ MHz} \) !!!

Also, one can take advantage of **CW time structure** of the beam and use lock-in amplifier techniques.

**Lock-in amplifier improves SNR as:**

\[ \sqrt{f_0 \tau_{measure}} = \sqrt{1.169 \text{ MHz}} \cdot 10^3 = 1 \cdot 10^3 \]
CW-LW: location, geometry

Booster: SRF 5cell x2
DC-350kV photo electron gun

Merger (3 sector dipoles)
Matching section (4 quads)

laser output port
laser input port
Scattering output port
e- beam output
e- beam input

CW-LW: interaction chamber

Scattering output port

laser output port

laser input port

e- beam output

e- beam input
Laser with parameters far beyond the *required* ones were demonstrated:

~10 J, 2.34 MHz, 25 W, 500 fs

Two technologies look particularly attractive:

1. large-mode-area fiber amplifiers
2. thin-disk lasers (oscillators)
Laser-Wire Potential

- Since it is a “wire scanner” → counting mode → **Large Dynamic Range (LDR)**
- Utilizing CW time structure of the beam and laser LDR measurements can be made without counting, by using lock-in detection techniques
- Laser pulses much shorter than beam can be used → **sub-ps time resolution can be achieved quite easily**
- Can be made in dispersive location → **energy resolved measurements**
- Combining all three above → **LDR measurements of longitudinal phase space**
- Can also be used in non-dispersive location to monitor transverse match
- Would works for essentially any high current, but does not rely on high current CW beam (only ~ 160 uA, as described here)