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Noise in Intense Electron Bunches

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ABSTRACT

We report on our investigations into density fluctuations in electron bunches. Noise and density fluctuations in relativistic electron bunches, accelerated in a linac, are of critical importance to various Coherent Electron Cooling (CEC) concepts as well as to free-electron lasers (FELs). For CEC, the beam noise results in additional diffusion that counteracts cooling. In SASE FELs, a microwave instability starts from the initial noise in the beam and eventually leads to the beam microbunching yielding coherent radiation, and the initial noise in the FEL bandwidth plays a useful role. In seeded FELs, in contrast, such noise interferes with the seed signal, so that reducing noise at the initial seed wavelength would lower the seed laser power requirement. Our research goals are (1) to measure the electron beam density noise level in a 0.5 to 10 μm wavelength range, (2) to predict the beam noise level in order to compare with the measurements, and (3) to find mechanisms that affect the beam noise to control its level in a predictable manner. In this presentation we will describe our progress to date as well as our future experimental plans at Fermilab's FAST electron linac.

INTRODUCTION

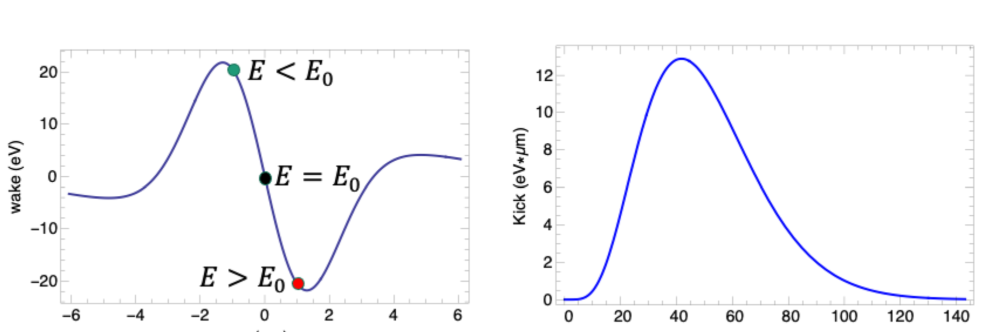
Noise and density fluctuations in relativistic electron bunches, accelerated in a linac, are of critical importance to various Coherent Electron Cooling (CEC) concepts as well as to free-electron lasers (FELs). For CEC, the beam noise results in additional diffusion in a cooled beam that counteracts cooling; and if this noise is not controlled at sufficiently low level, the noise heating effects can overcome cooling. There have been several proposals in the past to suppress the noise in the beam in the frequency range of interest in order to optimize the cooling effects. In SASE FELs a microwave instability starts from the initial noise in the beam and eventually leads to the beam microbunching yielding coherent radiation, and the initial noise in the FEL bandwidth plays a useful role. In seeded FELs, in contrast, such noise interferes with the seed signal, so that reducing noise at the initial seed wavelength would lower the seed laser power requirement.

Advanced cooling and FEL concepts not only require the knowledge of beam noise level but also call for its control. We are proposing to carry out a systematic theoretical and experimental study of electron beam noise at micrometer wavelengths at the Fermilab FAST facility. This wavelength-scale is of general interest in accelerator and beam physics as indicated by the community-driven research opportunities survey. The Fermilab FAST facility is well-suited for this research as it can provide electron bunches with charges 0 - 3 nC, 1-60 ps long rms and energies 50 - 300 MeV, making it perfectly relevant to future needs of electron-ion colliders as well as injectors for future FELs. Electron bunches are generated by Cs2Te photocathode and a UV laser. An L-band rf gun accelerates the beam to 5 MeV (typical). The facility also has a single-stage bunch compressor and a 100-m long FODO-based transport channel allowing for several experimental stations. For example, Table 1 compares the FAST beam parameters with that of an EIC CEC concept.

Table 1: FAST and proposed CEC beam parameters

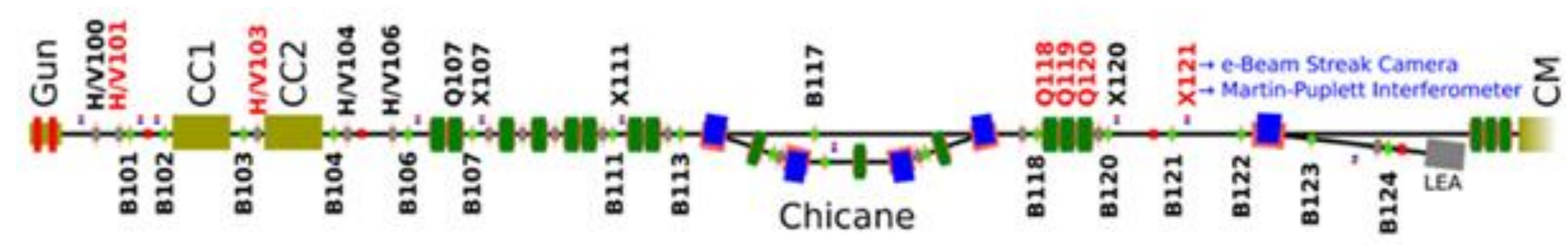
	FAST	**EIC (100 GeV)**	**EIC (275 GeV)**
Electron beam energy	50 – 300 MeV	50 MeV	137 MeV
Bunch charge	0 – 3 nC	1 nC	1 nC
Emittance (norm, rms)	~3 μm (at 1 nC)	2.8 μm	2.8 μm
Bunch length	0.3 – 20 mm	12 mm	8 mm
Drift section (amplifier)	80 m	100 m	100 m

CEC ENERGY KICK

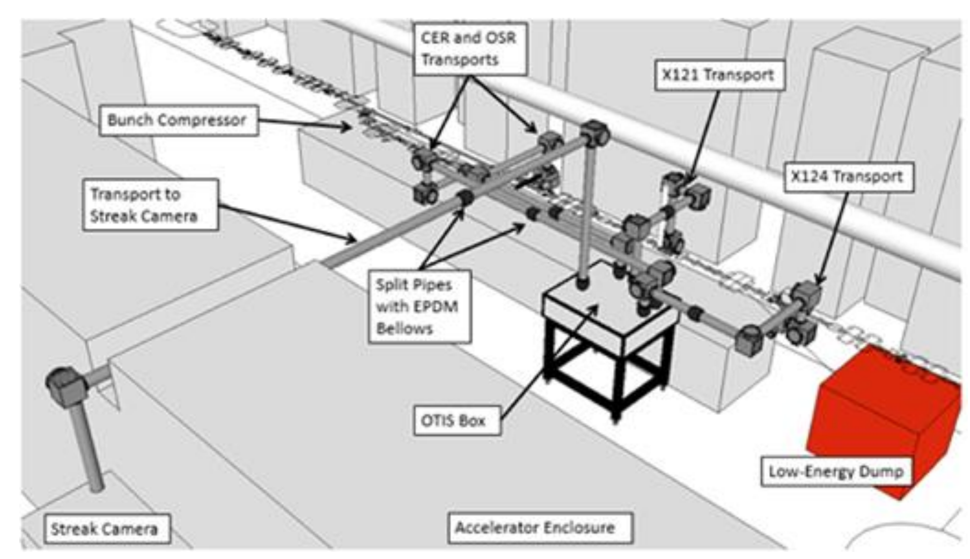


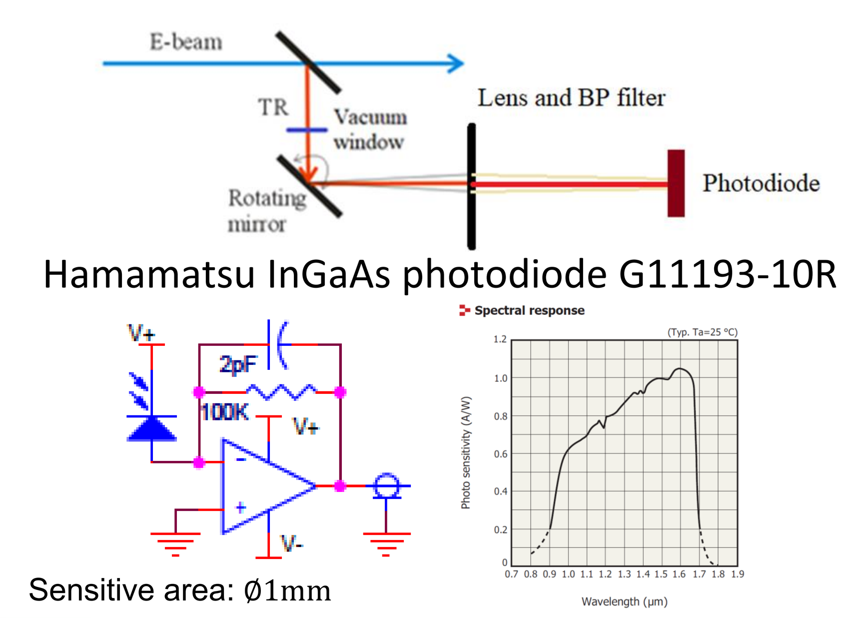
The energy kick, generated by one proton in the CEC kicker section. The longitudinal scale of the wake is ~ 3 μm, corresponding to the frequency bandwidth of interest of ~ 40 THz.

FAST FACILITY and APPARATUS



Diagnostics cross X121 (upstream of the SRF cyomodule) is presently equipped with an OTR screen, an Al-coated Si substrate, positioned at 45 degrees with respect to beam. Our Year-1 goal is to measure the single-bunch (45 MeV) OTR spectral energy density in the range of 0.9 – 2 μm.





RADIATION ENERGY on the DETECTOR

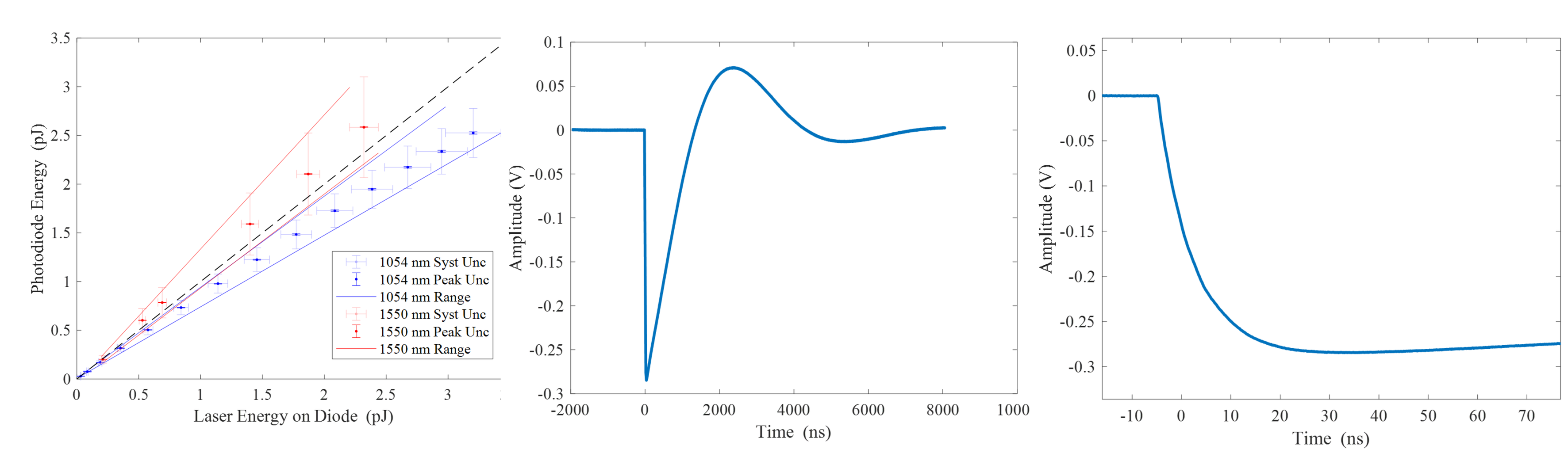
$$\frac{d^2W}{d\omega d\Omega} = \frac{Z_0 q^2}{4\pi^3}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2} \approx \frac{Z_0 q^2}{4\pi^3}\frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}$$

Assume $Q = 1$ nC and the collection angle 90°.

	0.5 – 1 μm	1 – 5 μm
Energy [nJ]	0.027	0.021

We are planning to measure the radiation pulse energy in a 100-nm band in the range 0.9 – 2 μm. We are expecting about 1 pJ per pulse.

DETECTOR CALIBRATION



Calibration of the photodiode / integrator was accomplished via two different laser systems: a 1054-nm Nd:YLF laser with a ~5-ps rms duration, and a 1550-nm Erbium fiber laser with a several-picosecond rms duration. The energy of the 1054 nm laser was measured with a Thorlabs S121C Si photodiode energy meter, and the energy of the 1550 nm laser was measured with a Thorlabs S145C integrating sphere InGaAs photodiode energy meter. The laser pulse energy was adjusted through a range from ~0.1 pJ up to ~3 pJ. Using the photodiode responsivity curve and the integrator calibration, one can plot measured energy using the photodiode / integrator vs. measured energy using the Thorlabs energy meters. The photodiode response curve is an average of 100 pulses.

The detector is now ready for commissioning in the FAST beam line.

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