THE UNIVERSITY OF CHICAGO

Noise in Intense Electron Bunches

Sergei Nagaitsev

On behalf of: Zhirong Huang, Gennady Stupakov, Young-Kee Kim, Valeri Lebedev, Randy Thurman-Keup, RadiaBeam

Oct 29, 2021

Project description

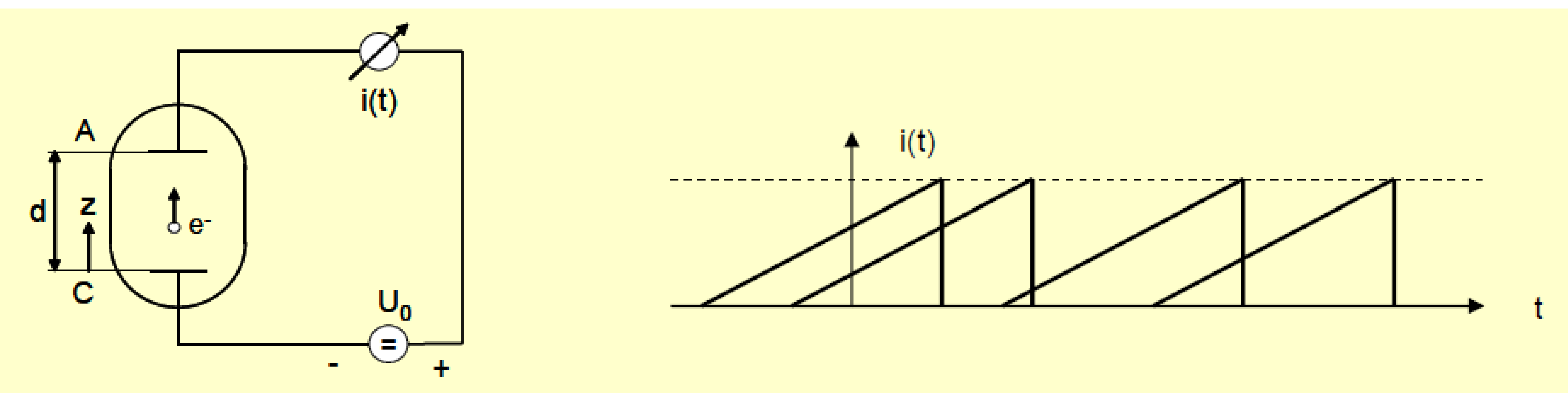
- This is a funded DOE Stewardship 3-year project (2021-23)
  - Funding for hardware and for research effort
  - No funding was provided (by DOE) for students or postdocs. We are discussing with CBB.
- A collaboration of UChicago (lead), SLAC, Fermilab, RadiaBeam
  - Experiments to be performed at FAST (Fermilab)
- DOE Stewardship customers:
  - NP (CEC concepts)
  - BES (FELs)

- There is a Fermilab LDRD application in progress.

What is beam noise?

- 1918: W. Schottky described spontaneous current fluctuations from DC electron beams; “Über spontane Stromschwankungen in verschiedenen Elektrizitätsleitern”, Ann. Phys. 57 (1918) 541-567

- See also: Shot Noise in Schottky's Vacuum Tube, C. Schönenberger, S. Oberholzer, E.V. Sukhorukov, H. Grabert, https://arxiv.org/abs/cond-mat/0112504



THE UNIVERSITY OF CHICAGO

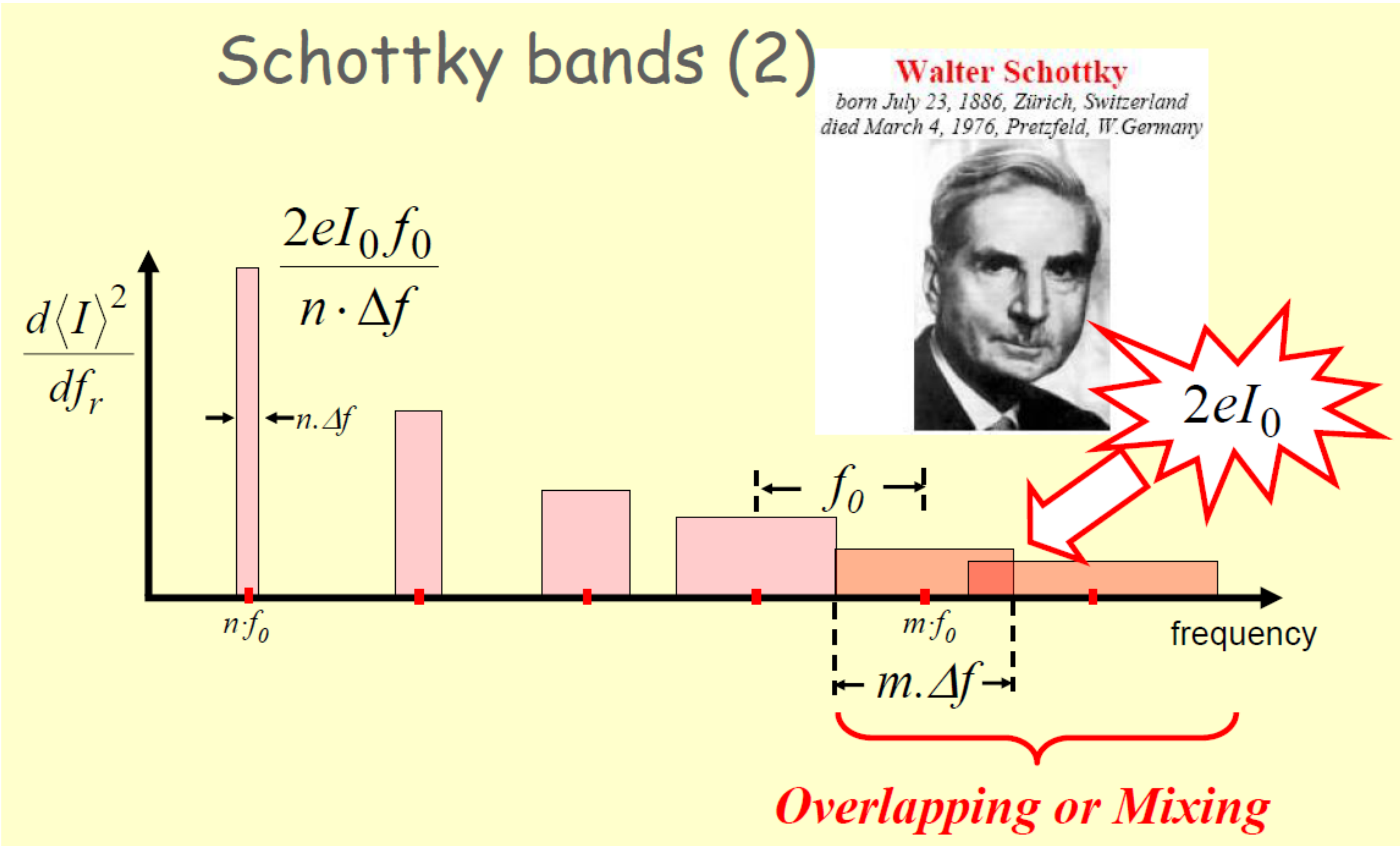
Schottky noise

- The result by Schottky, based on the assumption that the statistics of electrons passage is Poissonian, reads for the spectral noise density at the frequency *f*,

$$S(f) = 2e\left|I_0\right|$$

- The Schottky noise expression is purely due to random electron positions but there could be other contributions to current (density) fluctuations in intense beams:
  - Photocathodes: quantum effects, hot spots
  - Beam instabilities
  - CSR

Schottky spectrum diagnostics in rings



Is there more than shot noise in beams?

- Yes! There is a lot of evidence that beams can have coherent density clumps in a ~1 GHz freq. range
- Tevatron bunched beam cooling experiments, 1990-1995
- Observed strong coherent lines at each revolution frequency harmonic in Schottky power spectrum.
  - These strong coherent signals prevented bunched cooling;
  - Still unexplained

Bunched Beam Stochastic Cooling in the Fermilab Tevatron Collider

G. Jackson, E. Buchanan, J. Budlong, E. Harms, P. Hurh,
D. McGinnis, R. Pasquinelli, D. Peterson, D. Poll, P. Seifrid
Fermi National Accelerator Laboratory*
P.O. Box 500 MS 341
Batavia, IL 60510

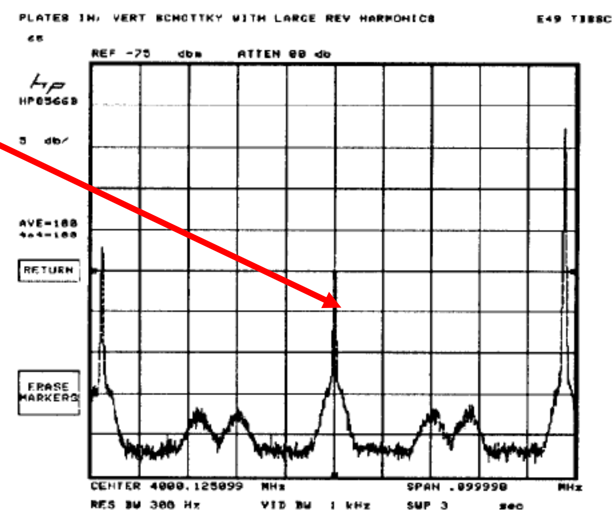
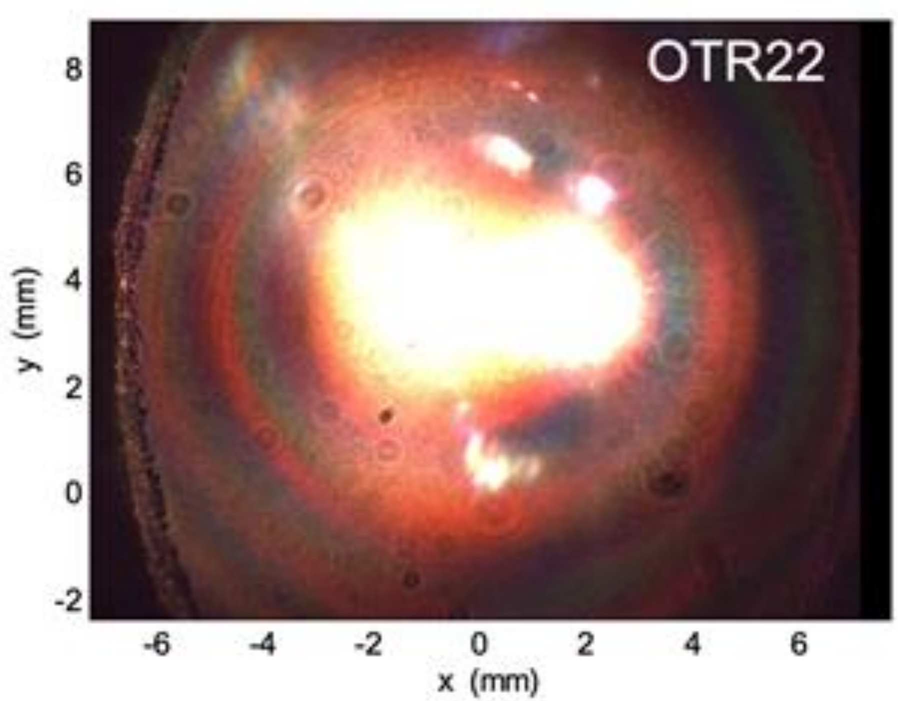


Figure 1: Measured beam spectrum from a vertical proton pickup. Note the large coherent lines at revolution harmonic frequencies at the left, center, and right. The betatron Schottky lines are clearly visible above the noise floor. The center frequency is 4 GHz and the scale is 10 kHz/div.

What about >THz frequency?

- There is a lot of evidence for micro-structure in bunched electron beams too!



An example of a OTR image of a beam with strong micro-bunching effect at optical wavelengths (< 1 um)

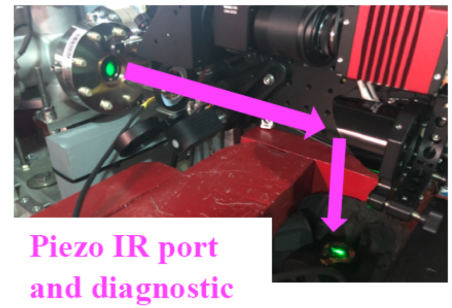
THE UNIVERSITY OF CHICAGO

CeC experiment at BNL (run 2020)

The e-beam noise level

At ~15 THz, 14 MeV beam

- Technique for beam noise measuring established in Run 19
  - The THz noise in the e-beam results far-IR radiation from dipole magnet, whose power is measured by the Gentec broad-band IR detector connected to a lock-in amplifier synchronized with pulsing electron beam.
  - IR radiation from the bending magnet is periodically blocked, (modulation-demodulation technique) to eliminate effect of X-rays from dumped beam on the IR detector
- The baseline power level (e.g. power from the Poisson shot noise) was measured using long low charge (~300 pC) beam propagating in relaxed low-beam transport lattice. Measurements were in good agreement with simulation.
- All measurements normalizes by average beam current
- The IR power generated by electron beam with 1.5 nC per bunch and the nominal compression was compared with the base line IR power level

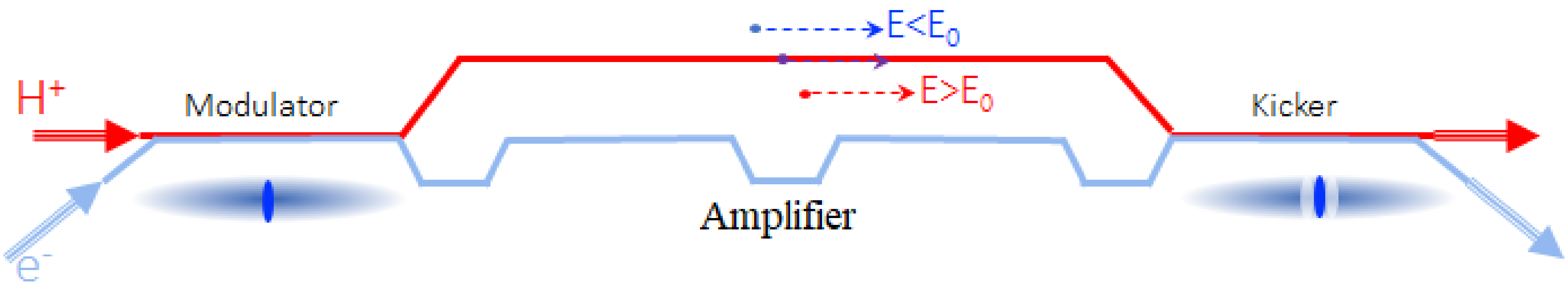


- **Summary of results**
- **Measured ratio of the noise power in the electron beam to the Poisson noise limit is more than 2 and less then 12**
- **Beam noise satisfy KPP**

Courtesy of Vladimir Litvinenko (SBU/BNL)

Understanding the noise

- Why is it important?
  – Example EIC CEC



- Y. S. Derbenev, “On possibilities of fast cooling of heavy particle beams,” *AIP Conference Proceedings*, vol. 253, no. 1, pp. 103–110, 1992, https://aip.scitation.org/doi/pdf/10.1063/1.42152
- V.N. Litvinenko and Y. S. Derbenev, “Coherent electron cooling,” Phys. Rev. Lett., vol. 102, https://link.aps.org/doi/10.1103/PhysRevLett.102.114801
- D. Ratner, “Microbunched electron cooling for high-energy hadron beams,” Phys. Rev. Lett., vol. 111, https://link.aps.org/doi/10.1103/PhysRevLett.111.084802

THE UNIVERSITY OF CHICAGO

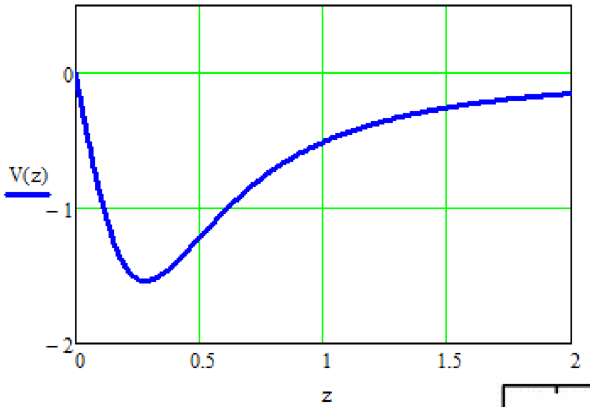
CEC system parameters (example)

Parameter	Symbol	Value	Unit
Proton energy	E_0	275	GeV
Lorentz factor	γ	290	
Ring circumference	C	3834	m
Revolution frequency	f_0	78.3	kHz
Protons per bunch	N_p	6.9	10^{10}
Prot. rms moment. spread	δ_p	6.8	10^{-4}
Prot. rms bunch length	σ_{pz}	6.0	cm
Electrons per bunch	N_e	6.3	10^9
El. rms bunch length	σ_{ez}	4.0	mm
El. rms beam size (vert)	σ_{ey}	0.6	mm
El. rms beam size (hor)	σ_{ex}	0.6	mm
Kicker section length	L_k	40	m

Wake field for a proton at the center of the electron beam.

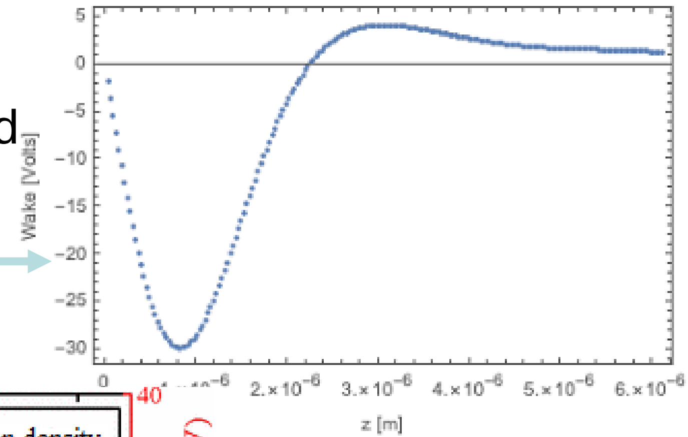
THE UNIVERSITY OF CHICAGO

Initial modulation after “Modulator”

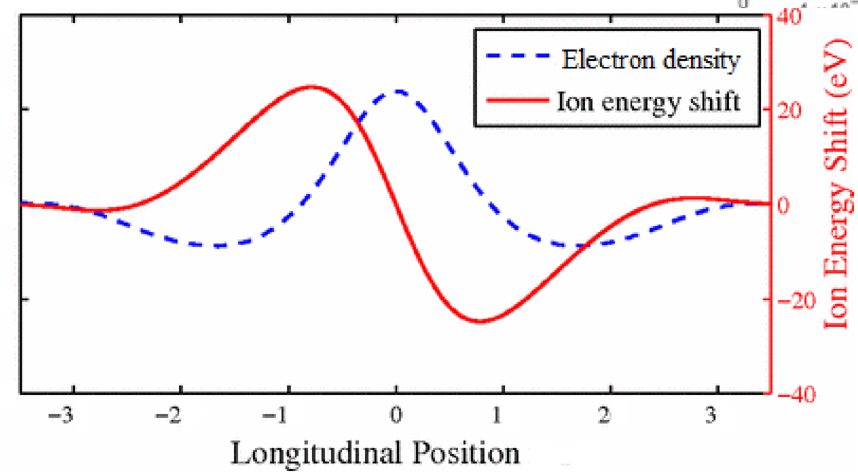


Amplification with some limited BW and some electron R56

Kick in the “Kicker” section



~300 THz band



Any electron density clumps at ~ 1um scale will be also amplified!

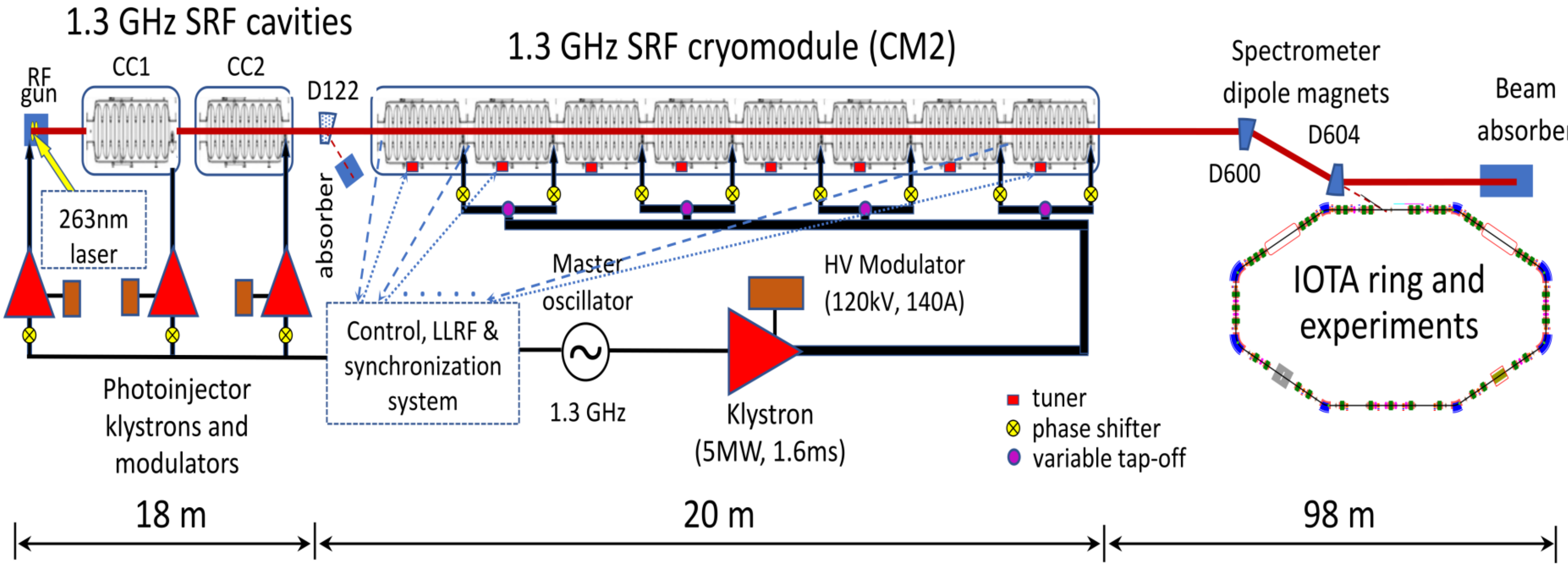
THE UNIVERSITY OF CHICAGO

Our project

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.

	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	14 mm	7 mm
Drift section (amplifier)	80 m	100 m	100 m

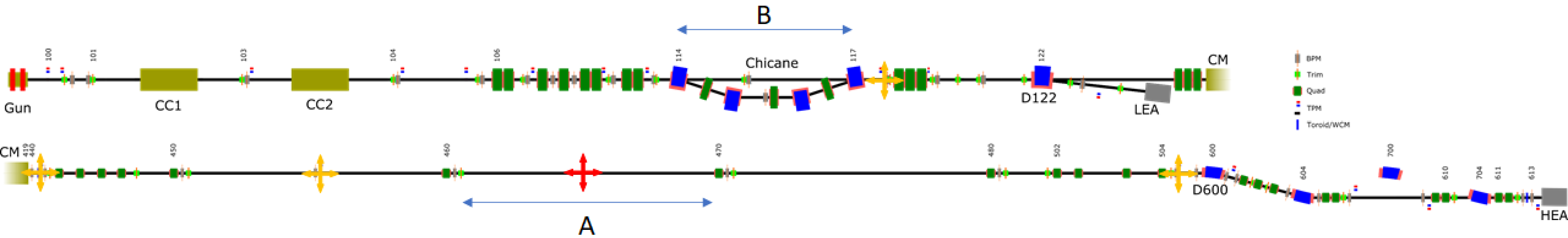
FAST facility



The proposed experimental apparatus will be installed in the 80-m long high-energy beam transport line, between the SRF cryomodule (CM2) and the dipole magnet D600

THE UNIVERSITY OF CHICAGO

Beam line



A – 16m in 8 x 2m vacuum segments

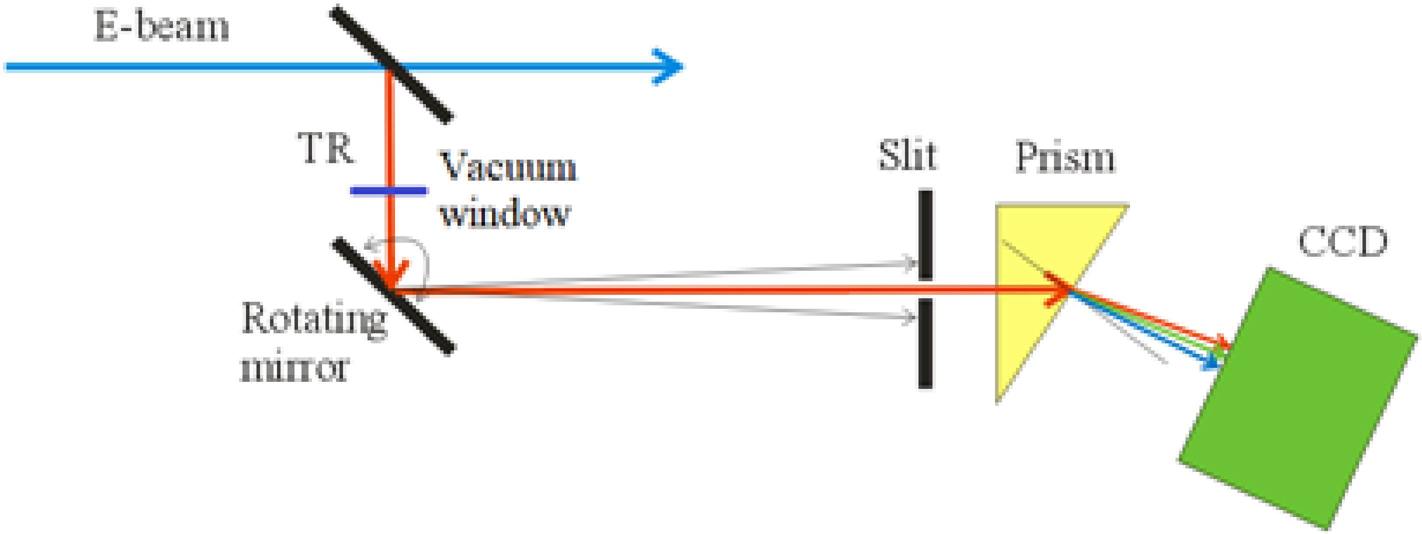
B – 2.8m

– Instrumentation Crosses

– New Instrumentation Cross for ~32m spacing after cryomodule

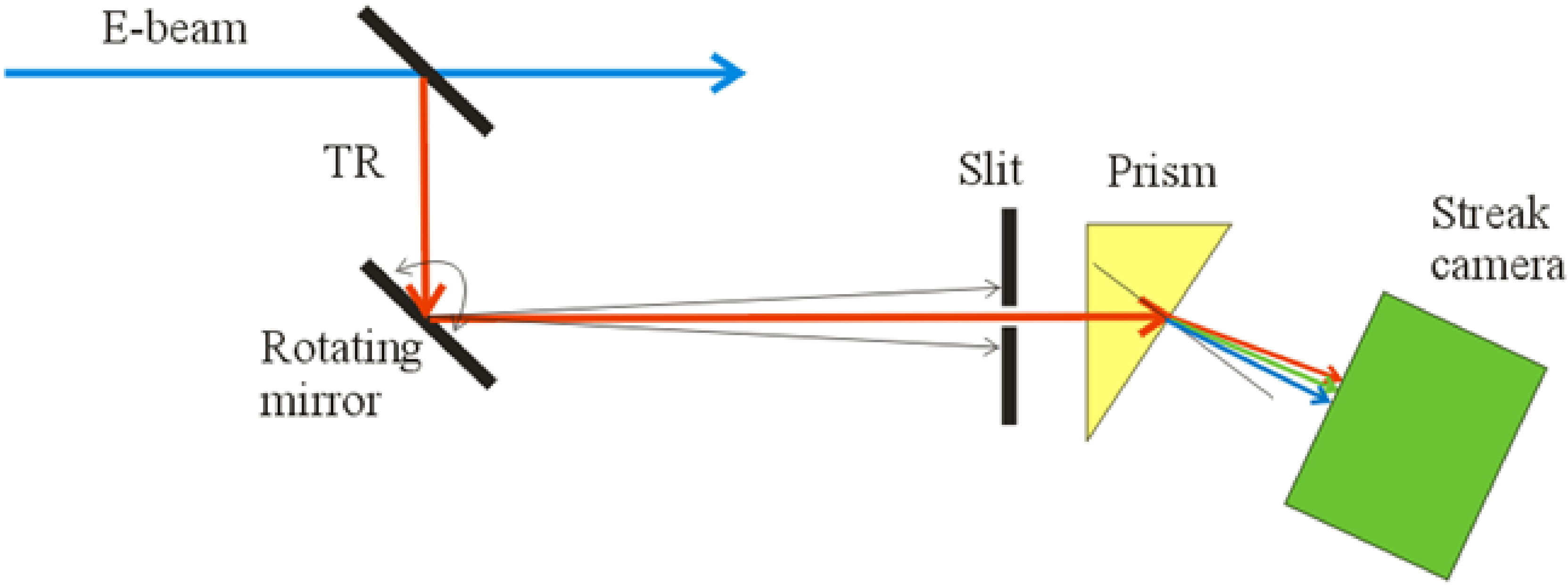
Planning for 3 experimental stations, ~30 m apart. Ballistic R56 = L/γ^2

TR-based spectrometer



The proposed schematic of the TR spectrometer. Note that Prism may be replaced with a grating.

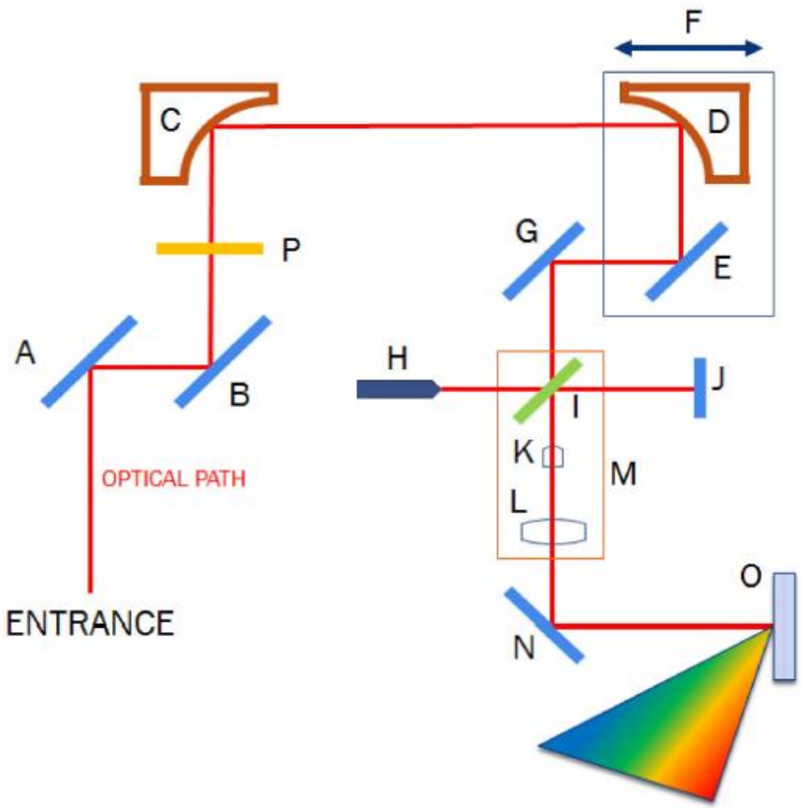
Enhanced TR-based spectrometer



The proposed schematic of the TR spectrometer enhanced by a streak camera to provide the temporal dependence along the bunch. Note that Prism may be replaced with a Grating

RadiaBeam's contribution

- RadiaBeam is lending at no cost a working prototype of their single-shot THz spectrometer to this project



Single-bunch THz-range spectrometer. Schematics of THz optical spectrometer: Entrance: THz radiation enters pseudo/uncollimated. A, B: motorized alignment mirrors; C, D: OAPs to refocus and recollimate beam; E, G, N: mirrors; F: translation stage for D, E to adjust collimation without affecting beam path; H: internal alignment laser; I: beam-splitter, allows alignment laser to propagate both upstream and downstream; J: mirror to reflect alignment laser back towards J; K: Powell lens to diverge point laser into a laser fan beam; L: lens to collimate laser fan beam to a line of ~2" length; M: removable kinematic base mount for I, K, L; O: diffraction grating (for THz viewing) OR mirror (for alignment); P: wire-grid polarizer.

RadiaBeam's spectrometer

THE UNIVERSITY OF CHICAGO

IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY, VOL. 11, NO. 3, MAY 2021

Optical Spectrometer With a Pulse-to-Pulse Resolution for Terahertz and mm-Wave Signals

Sergey V. Kutsaev, *Senior Member, IEEE*, Marcos Ruelas, Vladimir Goncharik, Hoson To, and Alex Murokh, *Member, IEEE*

TABLE I
GRATING PARAMETERS

Application	mm-wave accelerators	THz radiation sources
Central frequency	120 GHz	1.065 THz
Frequency range	1.6 GHz	500 GHz
Grating period	1.956 mm	282 µm
Incident Angle	25.5°	17.987°
Reflected angle for central frequency	57.8°	43.619°
Angular width	1.6°	65°
Blazing angle	41.7°	30.803°

Project activities

1. Install and commission three measuring stations in the high-energy transport line, ~40 m apart. Each station should be capable of single-shot (at 1 nC) measurements of transition radiation (TR) power spectrum in the range of 0.5 – 3 μm (stretch goal 10 μm) wavelength.
2. Measure TR spectra at 3 locations as a function of various bunch parameters: energy, bunch length, bunch charge, and if possible, emittance.
3. Develop a detailed theoretical model and corresponding computer simulations of how the density noise level in a beam is translated to TR spectral power.
4. Compare the measured and simulated TR power spectra in order to deduce the noise level in a bunch for various conditions.
5. Stretch objective: determine how to change the beam density noise level in a predictable manner, for example by changing the laser structure, the bunch compression procedure and the strength of quadrupole focusing. Test the measured and predicted TR spectra.

Summary

- We are starting an exciting project, funded by the DOE Stewardship Office and relevant to both NP and BES.
  - Also, discussing a collaboration with CBB
- We would like to request beam time at FAST and will submit a formal proposal soon.
- We see many potential connections to photocathodes since density structure can originate from hot spots, lasers.