Noise in Electron Bunches (NEB)

FAST/IOTA experimental proposal

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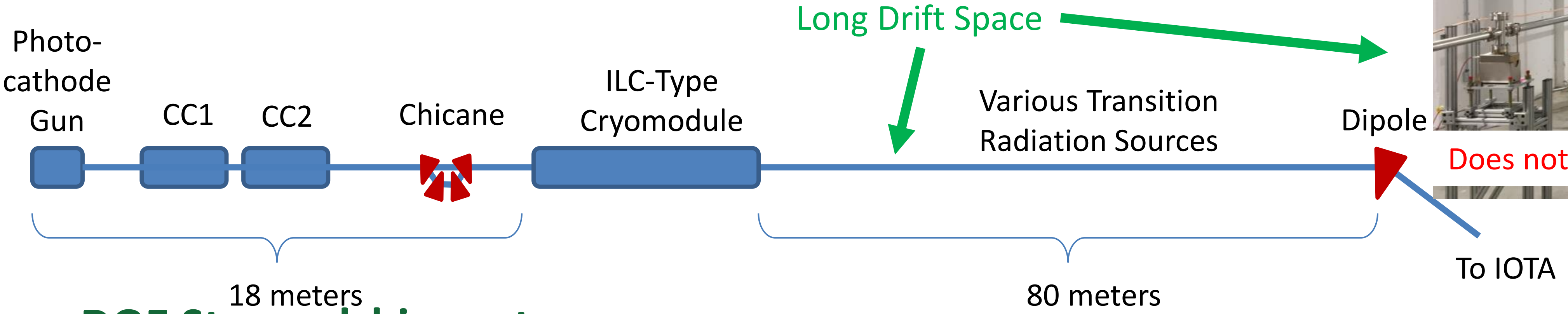
July 14, 2023

Project History (2021-2022)

- **A funded DOE ARDAP (Track-2) 3-year project (started in Oct 2021)**
- **A collaboration of UChicago, SLAC, Fermilab, RadiaBeam**
  - S. Nagaitsev (PI, UChicago), Y.-K. Kim (co-PI, UChicago), Z. Huang (co-PI, SLAC), R. Thurman-Keup (Key/Senior Team Member, Fermilab)
  - Experiments to be performed at FAST (Fermilab)



- **DOE Stewardship customers:**
  - NP (CEC concepts), BES (FELs)
- **NA-PAC’22 poster and paper: MOPA34.pdf**
- **SLAC-PUB-17684, "Beam noise with account of space charge effects"**

Project Status (2023)

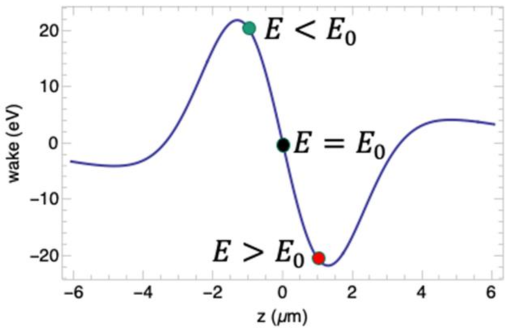
- **UChicago has relinquished funding back to the DOE: the remaining balance after 2 years. There is one more year of funding left in the original project.**
- **SLAC has received 2 years of funding (1 year left)**
- **Message from the DOE ARDAP:**
  - Some change in the participants is expected but be advised that we are expecting the work scope and overall cost to remain consistent with (1) finishing the current award by 8/31/2024, and (2) consistent with the timing and work scope of SLAC's subaward. A reach-back subaward to University of Chicago is a sensible step to preserve the collaboration, as is a modest amount of additional funding provided directly to FNAL to support FAST-IOTA operations for your work scope.
- **We are resubmitting our proposal from ODU (lead institution) with Fermilab, UChicago, SLAC as collaborating institutions.**
  - Fermilab PI change: Jinhao has agreed to serve as Fermilab PI on the proposal
  - Also supported by CBB

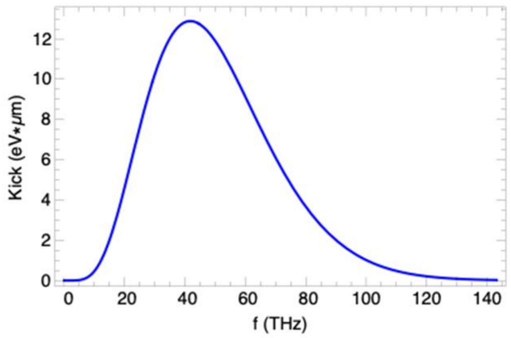
Motivation

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. 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.

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	9 mm	8 mm
Drift section (amplifier)	80 m	100 m	100 m

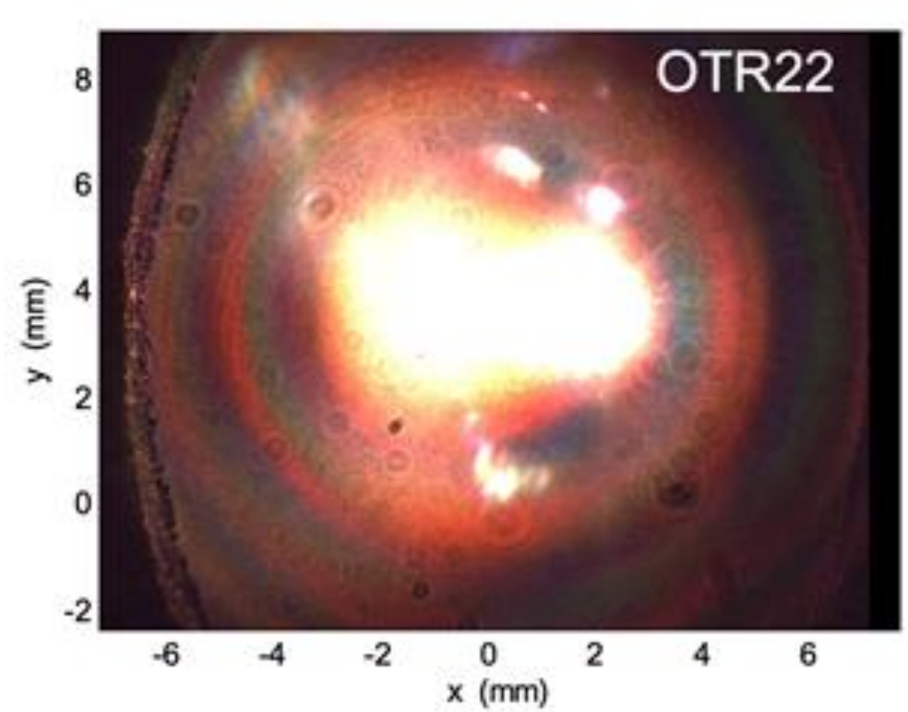




The energy kick, generated by one proton in the CEC kicker section. The longitudinal scale of the wake is ~ 3 μm, corresponding to the frequency bandwidth of interest of ~ 40 THz (~ 7 μm).

Noise in electron bunches

There is a lot of evidence for micro-structure in bunched electron beams. Bunches are much shorter and the slice energy spread is much smaller

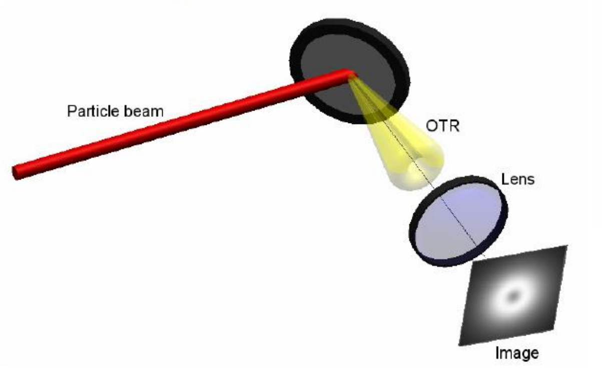


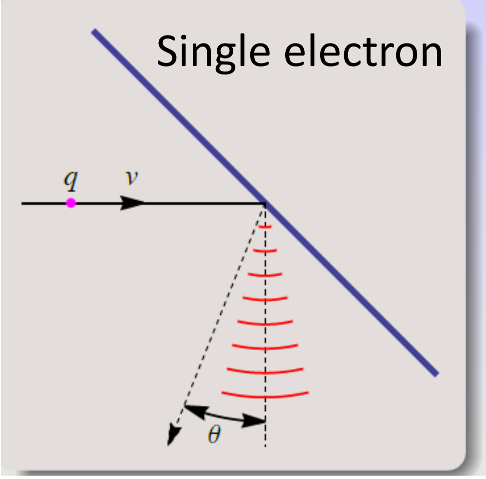
An example (from SLAC) of the OTR image of a beam with strong micro-bunching effect at optical wavelengths (< 1 um)

Transition radiation as a diagnostics tool for beam noise

Single foil OTR measuren

This method consists of observe the radiation emitted by charges in the transition of a single surface.



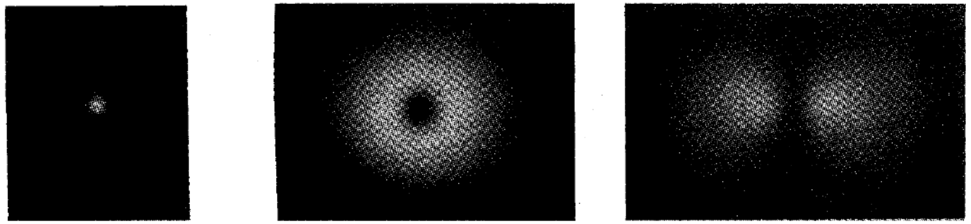


Energy radiated per unit frequency ω per unit solid angle, $\beta = v/c$

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

For randomly distributed electrons $W \times \delta\omega \sim N_e q^2 \delta\omega \sim N_e q^2 \frac{\delta\lambda}{\lambda^2}$

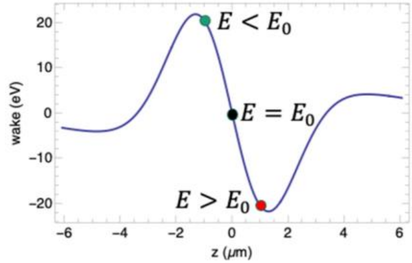
For random microbunches (10q) $W \times \delta\omega \sim \frac{N_e}{10}(10q)^2 \delta\omega \sim 10 N_e q^2 \frac{\delta\lambda}{\lambda^2}$



Near field observation | *Far field observation* | *Far field observation of the horizontal polarization*

We will measure the transition radiation energy per bunch to detect micro-bunching

Our wavelength of interest: 1-5 um



R. B. Fiorito and D. W. Rule - **Optical transition radiation beam emittance diagnostics**, AIP/BIW, vol 319, 21-37.

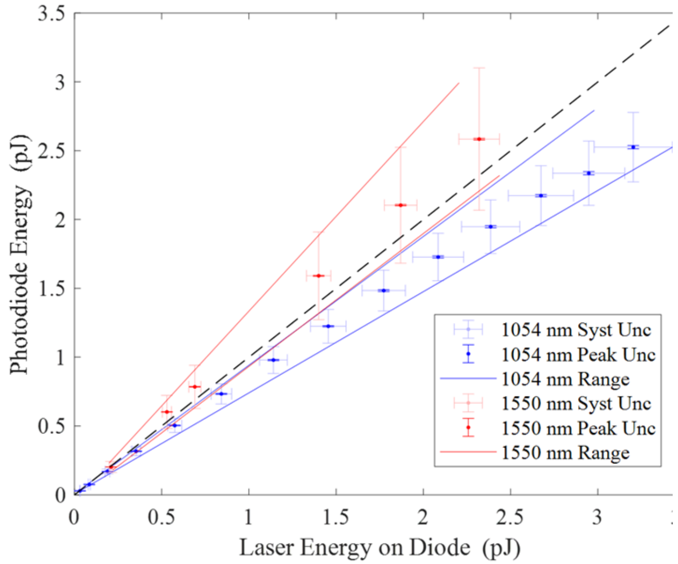
Transition Radiation Energy

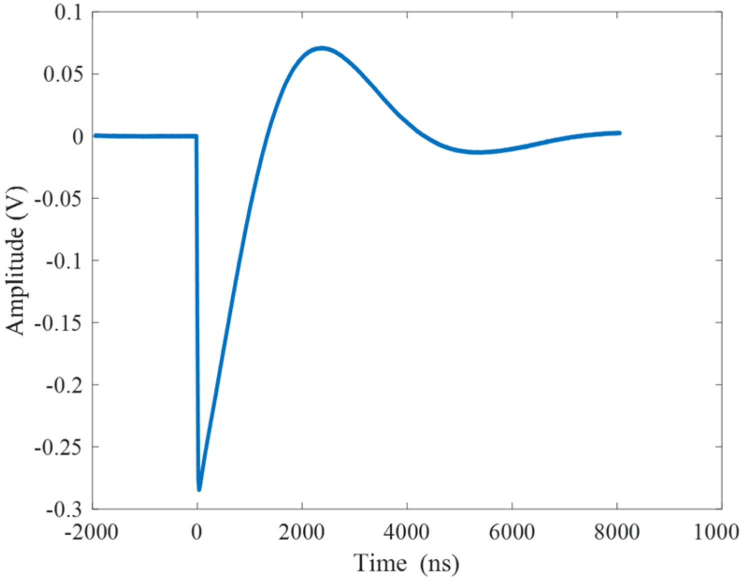
$$\frac{d^2W}{d\omega d\Omega} = \frac{Z_0 q^2}{4\pi^3} \frac{\beta^2 \sin^2\theta}{(1-\beta^2\cos^2\theta)^2} \approx \frac{Z_0 q^2}{4\pi^3} \frac{\theta^2}{(\gamma^{-2}+\theta^2)^2}$$

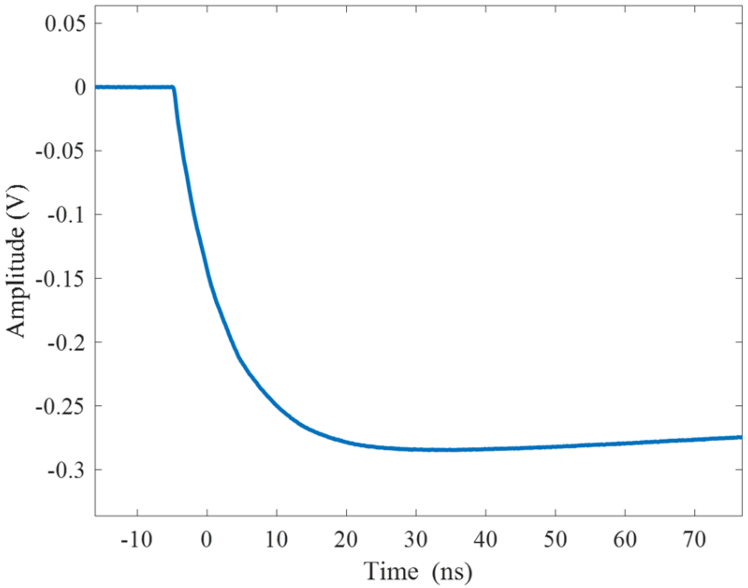
We are planning to measure the radiation pulse energy in a 100-nm band in the range 0.9 – 2.5 µm. We are expecting about 1 pJ per pulse (if there are no additional density fluctuations, above the shot noise level).

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

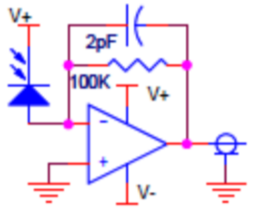
	0.5 – 1 µm	1 – 5 µm
Energy [nJ]	0.027	0.021

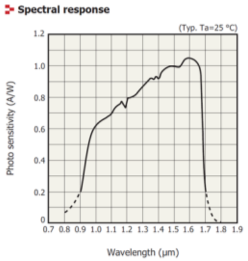






Hamamatsu InGaAs photodiode G11193-10R



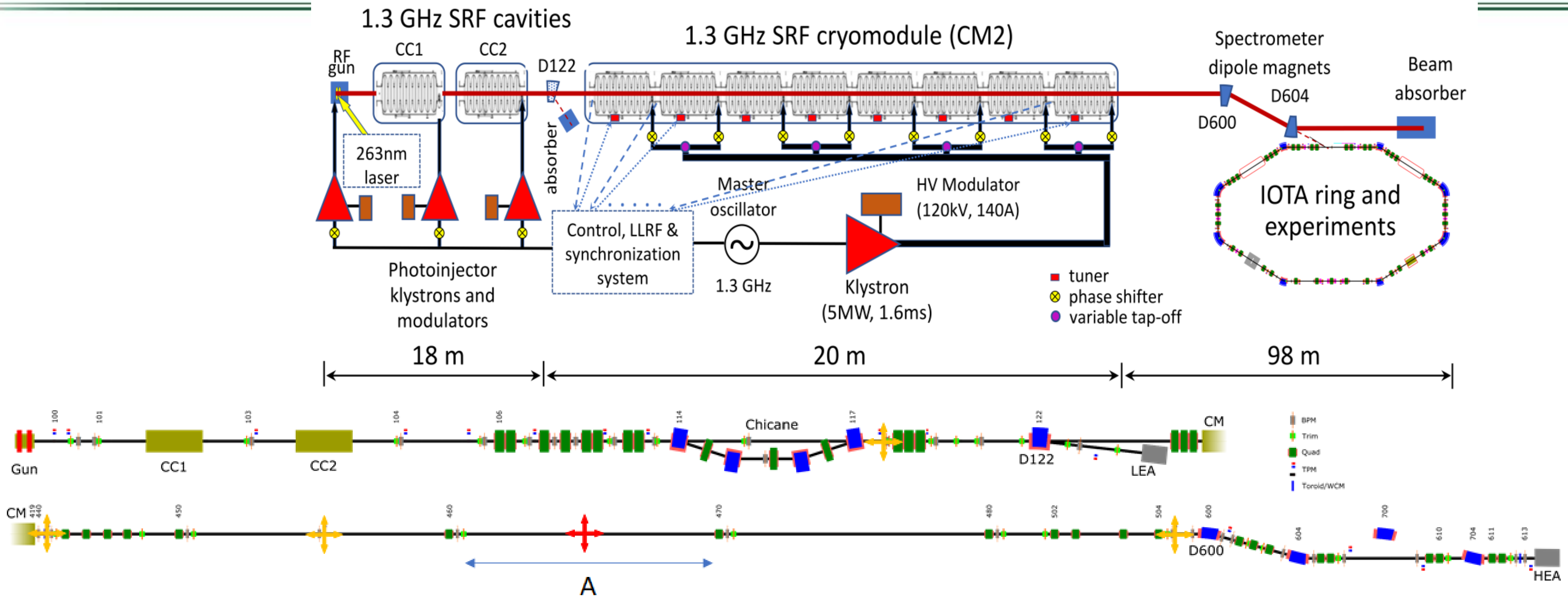


Sensitive area: Ø1mm

Detector (Hamamatsu diode) calibration with lasers

Photodiodes: ~ 1 pC/pJ

FAST beam line layout



A – 16m in 8 x 2m vacuum segments

B – 2.8m

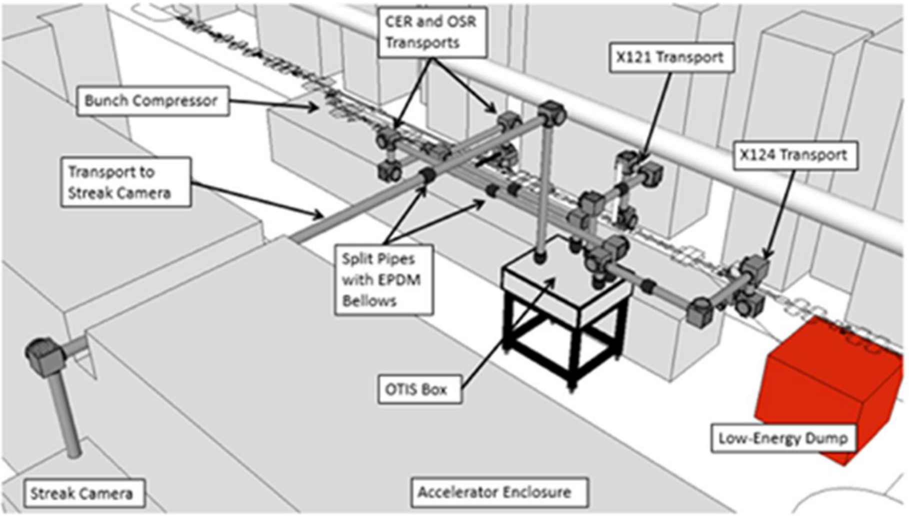
– Instrumentation Crosses with OTR screens

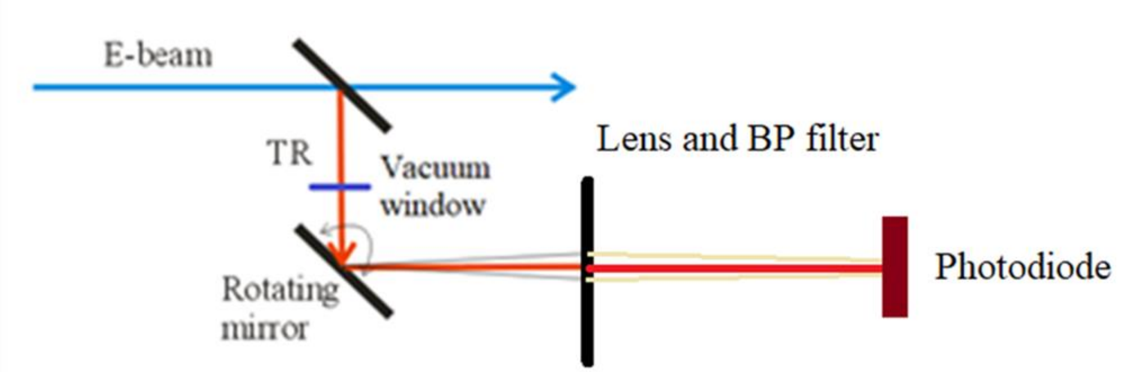
– New Instrumentation Cross for ~32m spacing after cryomodule

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

Experiment description

Present effort: 25-45 MeV electron bunches



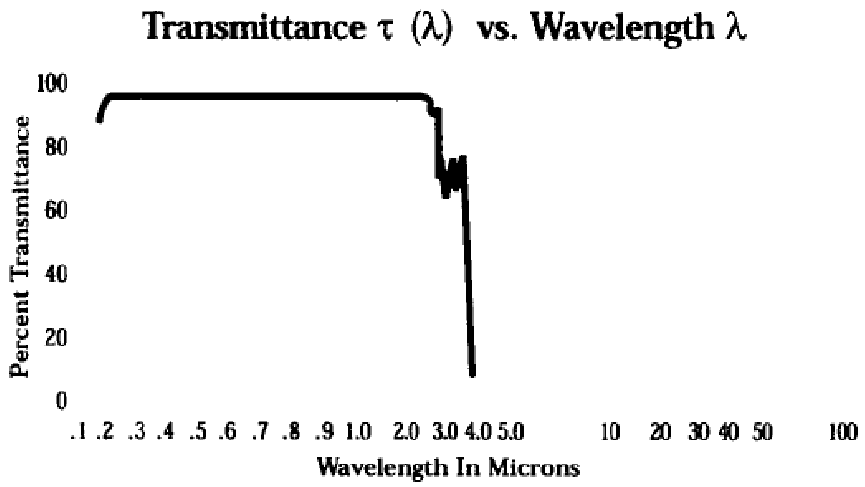


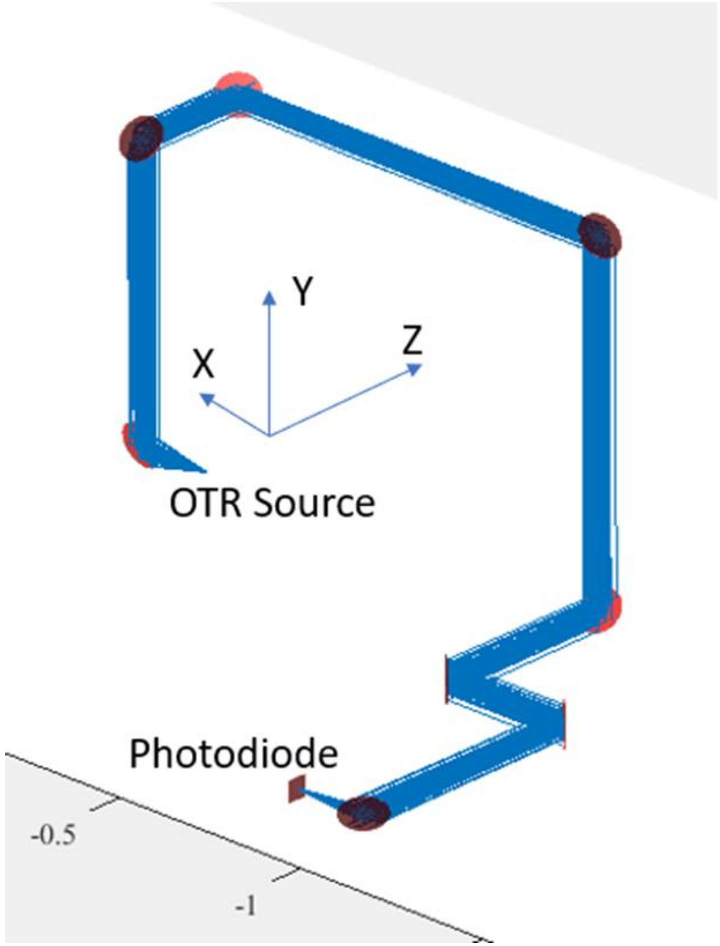
FAST: the diagnostics cross X121 (upstream of the SRF cyomodule) is presently equipped with an OTR screen, an Al-coated Si substrate, positioned at 45 degrees with respect to beam. Our Year-1 goal is to measure the single-bunch (45 MeV) OTR spectral energy density in the range of 0.9 – 2 µm.

Light transport from the OTR screen to photodiode

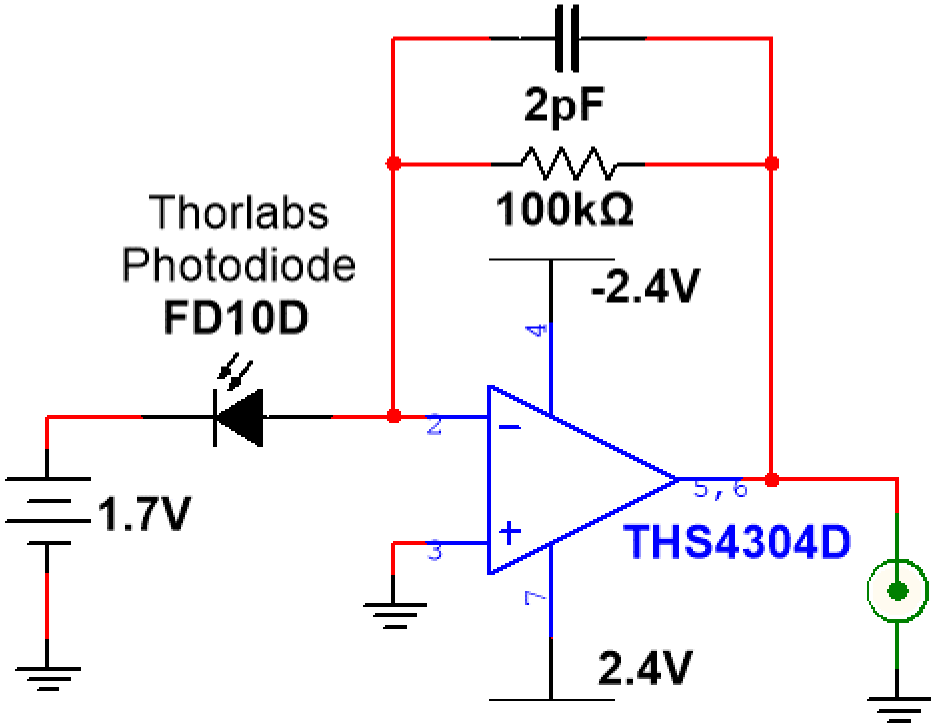
- **2 Al parabolic mirrors**
- **1 Al flat mirror**
- **5 Silver flat mirrors**

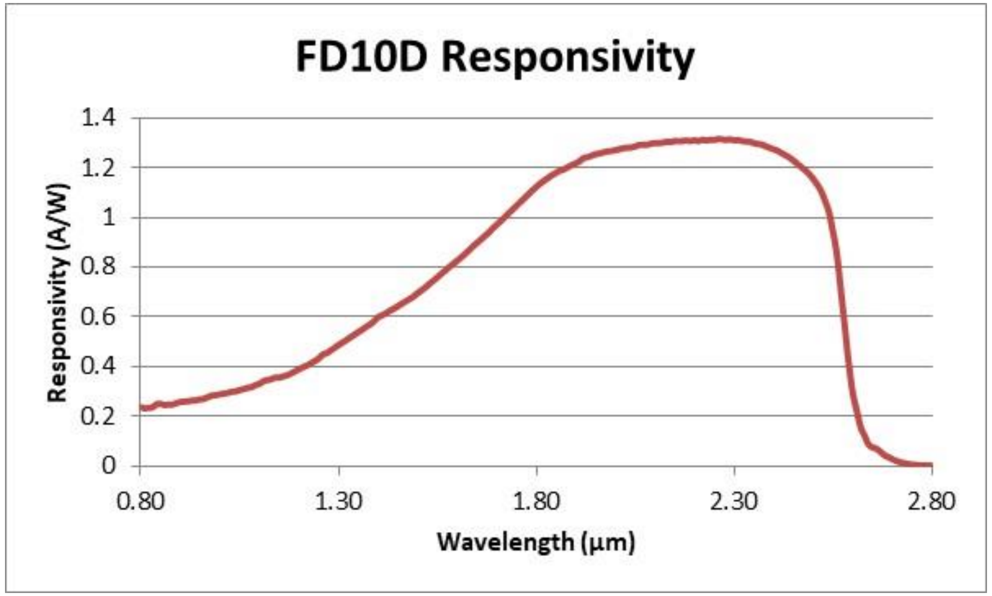
- **Vacuum viewport: SiO2 (fused silica) glass**
  - Limits our wavelength reach to 2.5 um





Present OTR detector (as installed at x121)





From Andrea's calibration data it looks like the effective capacitance is actually 3 pF

Nine filters on hand; Product type: rectangle 10mm x 10mm

770 nm: https://opticalfiltershop.com/shop/bandpass-filter/nir-bandpass-700nm-to-1100nm/nir-bandpass-filter-770nm-fwhm-100nm/

840nm: https://opticalfiltershop.com/shop/specialty-filters/lidar/nir-bandpass-filter-840nm-fwhm-100nm/

960 nm: https://opticalfiltershop.com/shop/bandpass-filter/nir-bandpass-700nm-to-1100nm/nir-bandpass-filter-960nm-fwhm-100nm/

1070 nm: https://opticalfiltershop.com/shop/specialty-filters/lidar/nir-bandpass-filter-1070nm-fwhm-125nm/

1180nm: https://opticalfiltershop.com/shop/bandpass-filter/swir-bandpass-filters-1-1um-to-3-0um/swir-bandpass-filter-1180nm-fwhm-120nm/

1361 nm: https://opticalfiltershop.com/shop/bandpass-filter/swir-bandpass-filters-1-1um-to-3-0um/swir-bandpass-filter-1361nm-fwhm-75nm/

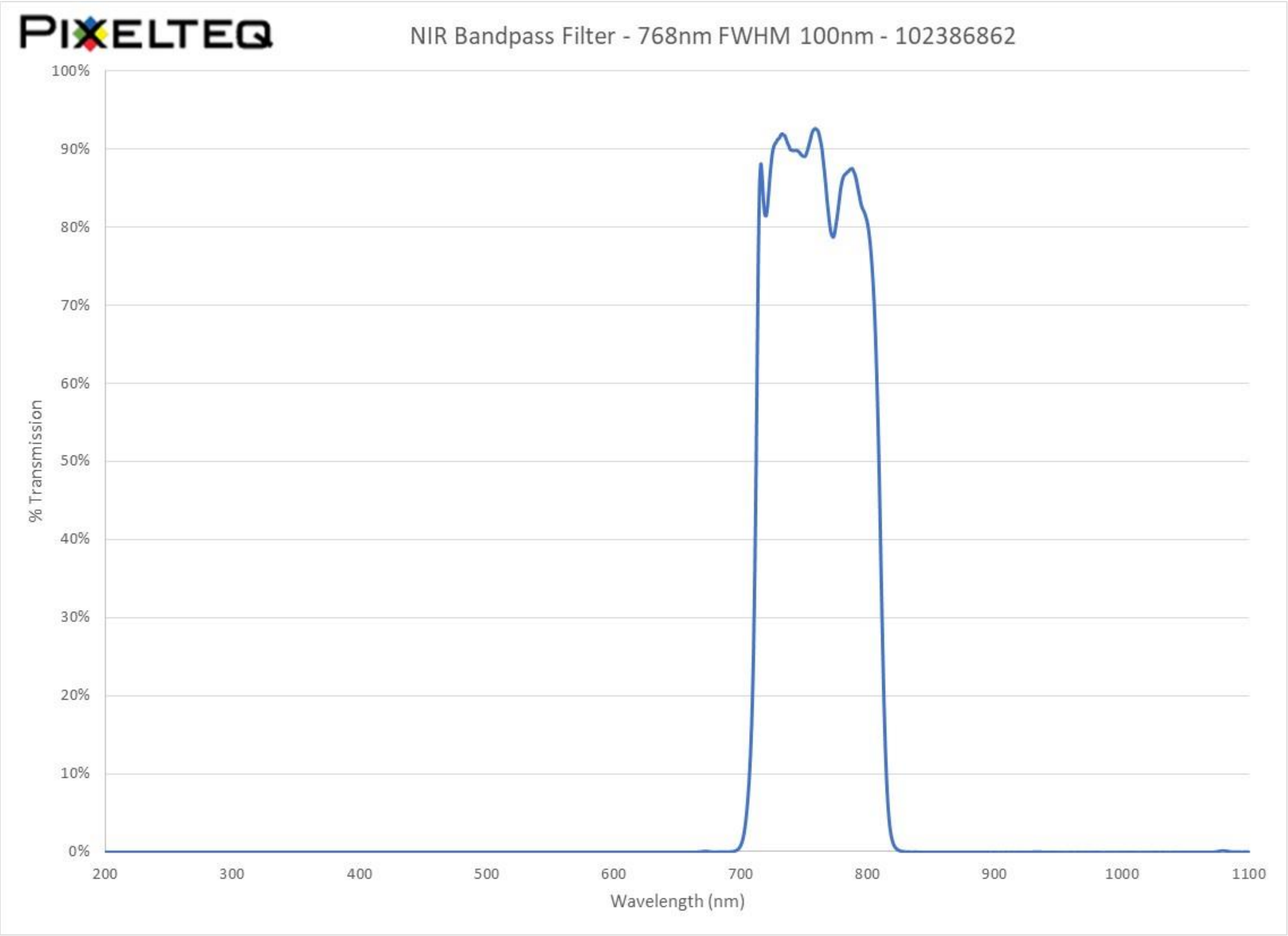
1424 nm: https://opticalfiltershop.com/shop/bandpass-filter/swir-bandpass-filters-1-1um-to-3-0um/swir-bandpass-filter-1424nm-fwhm-80nm/

1575 mn: https://opticalfiltershop.com/shop/specialty-filters/lidar/swir-bandpass-filter-1575nm-fwhm-75nm/

1700 nm: https://opticalfiltershop.com/shop/bandpass-filter/swir-bandpass-filters-1-1um-to-3-0um/swir-bandpass-filter-1700nm-fwhm-85nm/

Will procure more BP filters up to 2500 nm

At 770 nm



$q := 1.6 \cdot 10^{-19} \cdot C$ $\quad M := 0.511$ $\quad E := 25$

$Q := 1.2 \cdot 10^{-9} \cdot C$ $\quad N_b := \frac{Q}{q}$ $\quad N_b = 7.5 \times 10^{9}$

$Z := 377 \cdot ohm$

$\gamma := \frac{M + E}{M}$ $\quad \beta := \sqrt{1 - \frac{1}{\gamma^2}}$ $\quad c := 3 \cdot 10^{8} \cdot \frac{m}{s}$

$\lambda 1 := (0.77 - 0.050) \cdot 10^{-6} \cdot m$

$\lambda 2 := (0.77 + 0.050) \cdot 10^{-6} \cdot m$

$k_f := 0.9$ filter midpoint transmission

$d\omega := 2 \cdot \pi \cdot c \cdot \left(\frac{1}{\lambda 1} - \frac{1}{\lambda 2} \right)$

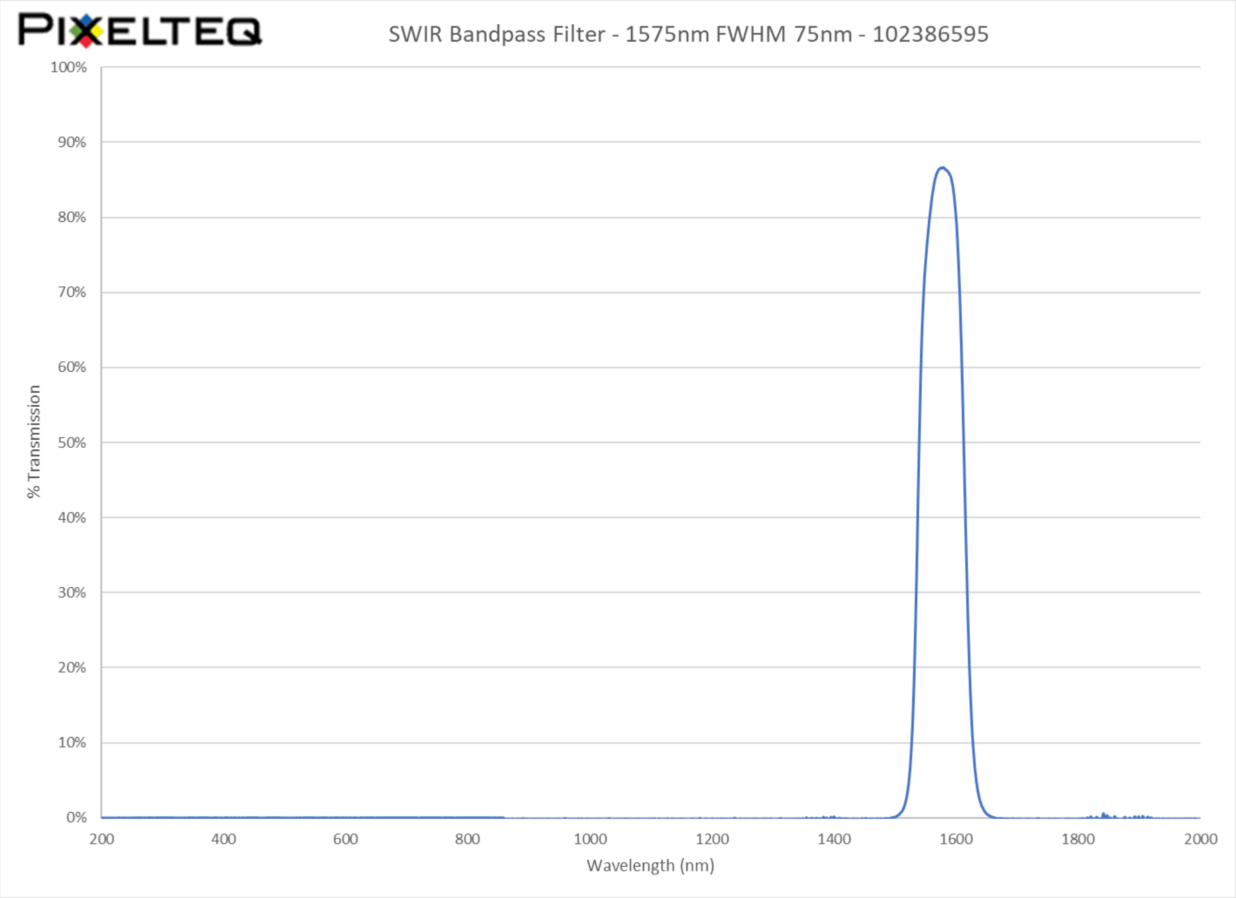
$$W := \frac{Z \cdot q^2 \cdot N_b \cdot d\omega}{4 \cdot \pi^2} \cdot \left[\left(\frac{1}{\beta} + \beta \right) \cdot \operatorname{atanh}(\beta) - 1 \right]$$

$W = 4.804 \times 10^{-12} J$ $\quad k_d := 0.23 \cdot \frac{C}{J}$

$C_d := 2 \cdot 10^{-12} \cdot F$ $\quad Q_d := W \cdot k_d \cdot k_f$

$\frac{Q_d}{C_d} = 0.497 V$

At 1575 nm



$q := 1.6 \cdot 10^{-19} \cdot C$ $M := 0.511$ $E := 25$

$Q := 1.2 \cdot 10^{-9} \cdot C$ $N_b := \frac{Q}{q}$ $N_b = 7.5 \times 10^{9}$

$Z := 377 \cdot ohm$

$\gamma := \frac{M + E}{M}$ $\beta := \sqrt{1 - \frac{1}{\gamma^2}}$ $c := 3 \cdot 10^{8} \cdot \frac{m}{s}$

$\lambda 1 := (1.575 - 0.037) \cdot 10^{-6} \cdot m$

$\lambda 2 := (1.575 + 0.037) \cdot 10^{-6} \cdot m$

$k_f := 0.87$ filter midpoint transmission

$d\omega := 2 \cdot \pi \cdot c \cdot \left(\frac{1}{\lambda 1} - \frac{1}{\lambda 2}\right)$

$W := \frac{Z \cdot q^2 \cdot N_b \cdot d\omega}{4 \cdot \pi^2} \cdot \left[\left(\frac{1}{\beta} + \beta\right) \cdot atanh(\beta) - 1\right]$

$W = 8.466 \times 10^{-13} J$ $k_d := 0.8 \cdot \frac{C}{J}$

$C_d := 2 \cdot 10^{-12} \cdot F$ $Q_d := W \cdot k_d \cdot k_f$

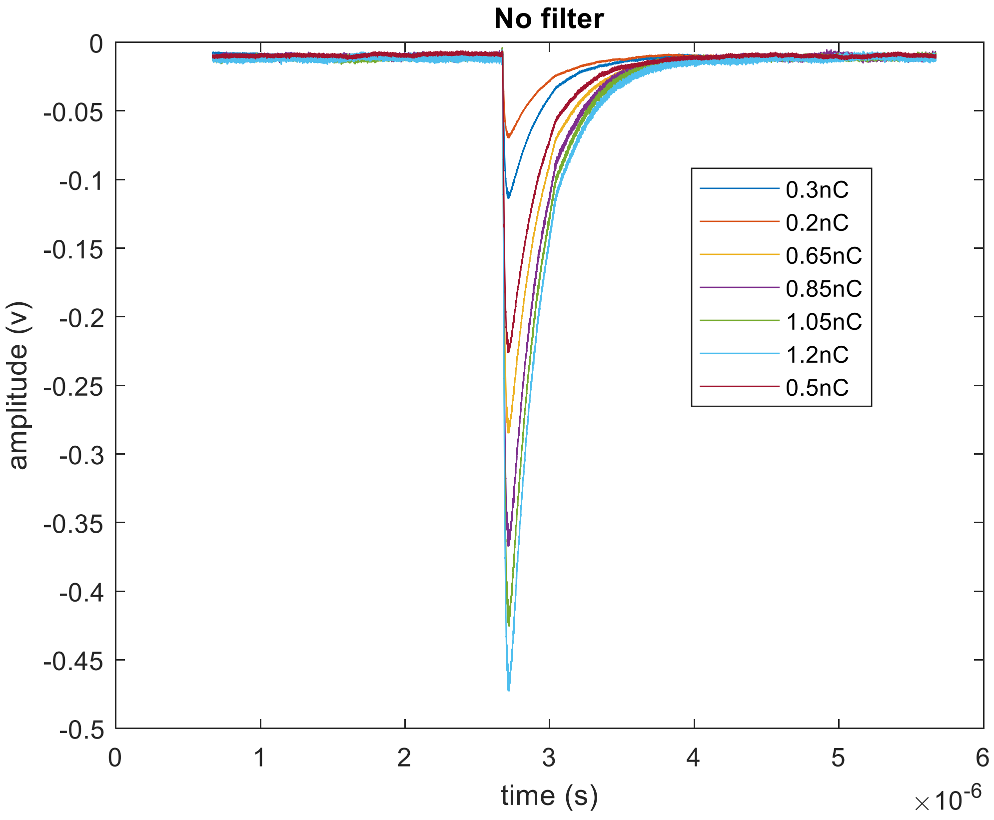
$\frac{Q_d}{C_d} = 0.295\,V$

Preliminary data taken on 04/25/2023
X121 with a 25-MeV beam (single bunches)

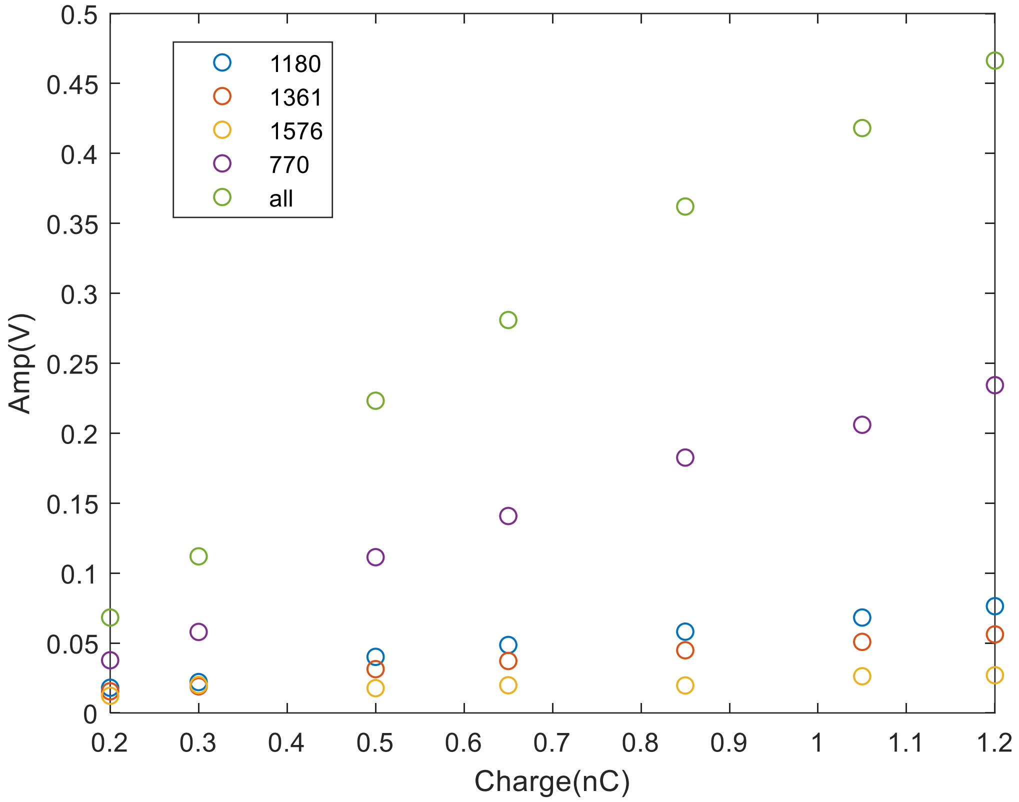
Jinhao Ruan, Randy Thurman-Keup, Andrea Saewert

Analysis by Sergei Nagaitsev

Preliminary data



Signal dependence with different filters



Our research plan

- **Measure amplifier signal amplitude as a function of bunch charge and bunch length for various band-pass filters**
  - Verify that all (or most of) OTR light is collected by our detector
- **Calibrate the amplifier at 2 wavelengths using ps-long laser pulses of known energy**
- **Calibrate the transmission coefficients of our optical channel using known lasers**
- **Develop a theoretical model of how TR energy behaves as a function of micro-bunching wavelength and density**
- **Simulate microbunching behavior from photo-cathode to the OTR screen**

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doi: https://doi.org/10.18429/JACoW-IPAC-23-WEPA041

SIMULATION OF SHOT NOISE EFFECTS IN THE EIC STRONG HADRON COOLING ACCELERATOR USING REAL NUMBER OF ELECTRONS*

J. Qiang†, LBNL, Berkeley, USA
E. Wang, BNL, Upton, USA

- **Finally, produce an estimate for the level of density fluctuations in beam (above random)**
- **Future direction: induce fluctuations in the beam and observe their evolution**

Beam request for Summer 2023

- **Measurement of the beam size dependence on the beam charge (two 4-hour shifts): we will generate beams with charge 0.2 – 2nC with ~0.1nC step and measure the beam length with the installed streak camera. The measurement series will be performed twice in order to increase accuracy and check for repeatability.**
- **Investigation of the OTR energy dependence on the beam charge (four 8-hours shifts)**
  - we will test 9 wavelengths with different bunch charges, including the slight energy variations using CC2 online. The exact parameters will depend on the beam size measurement results.

Prelim bunch length measurements