Noise in Intense Electron Bunches at FAST

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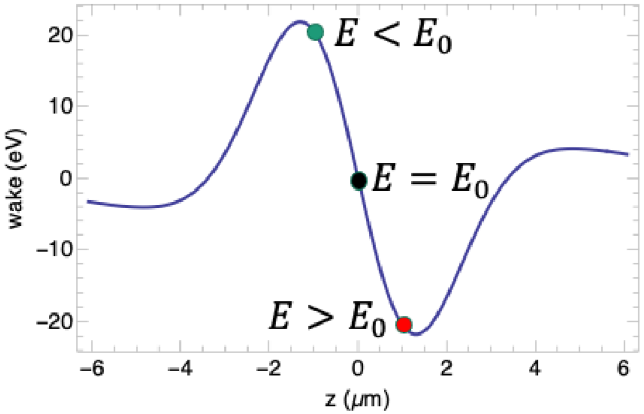
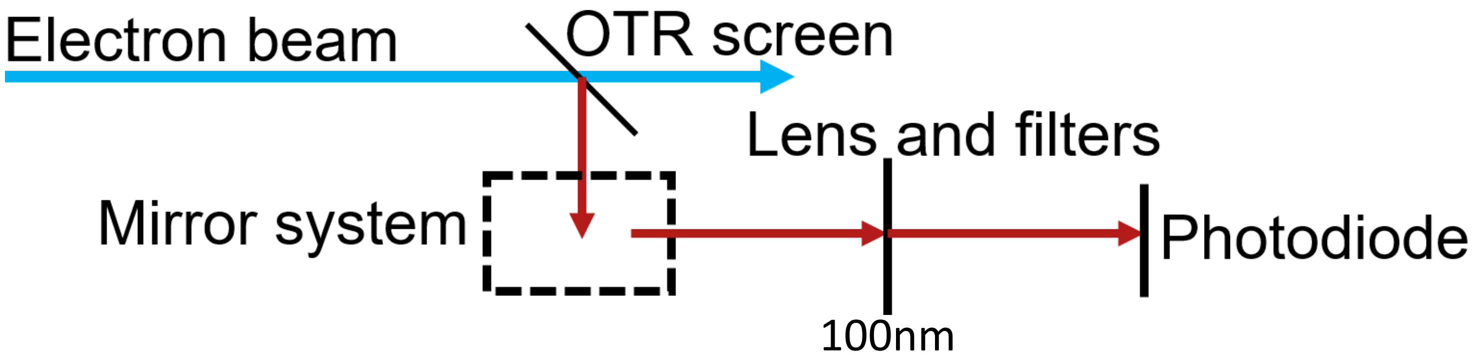
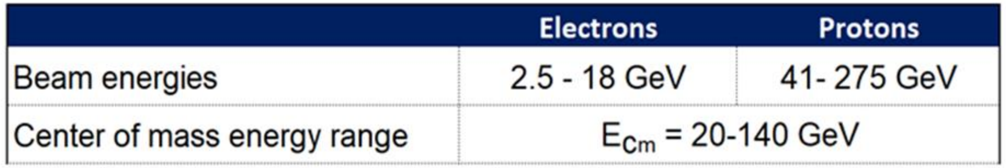


$0 - 6\ \mu m$

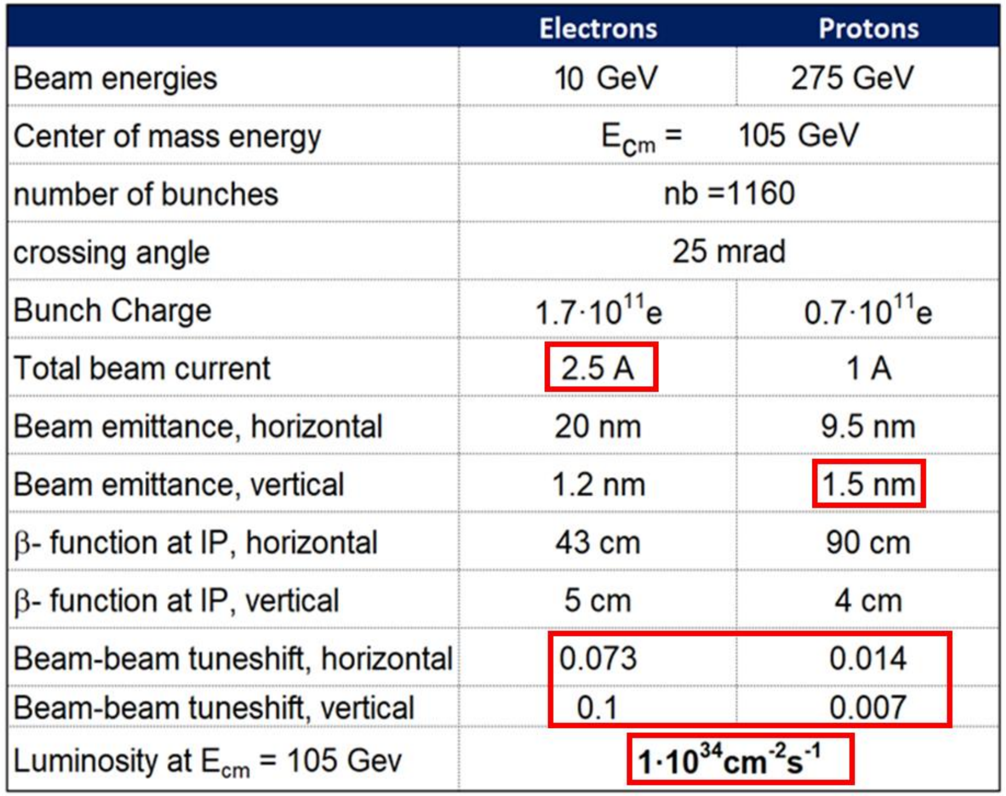


Electron-Ion Collider

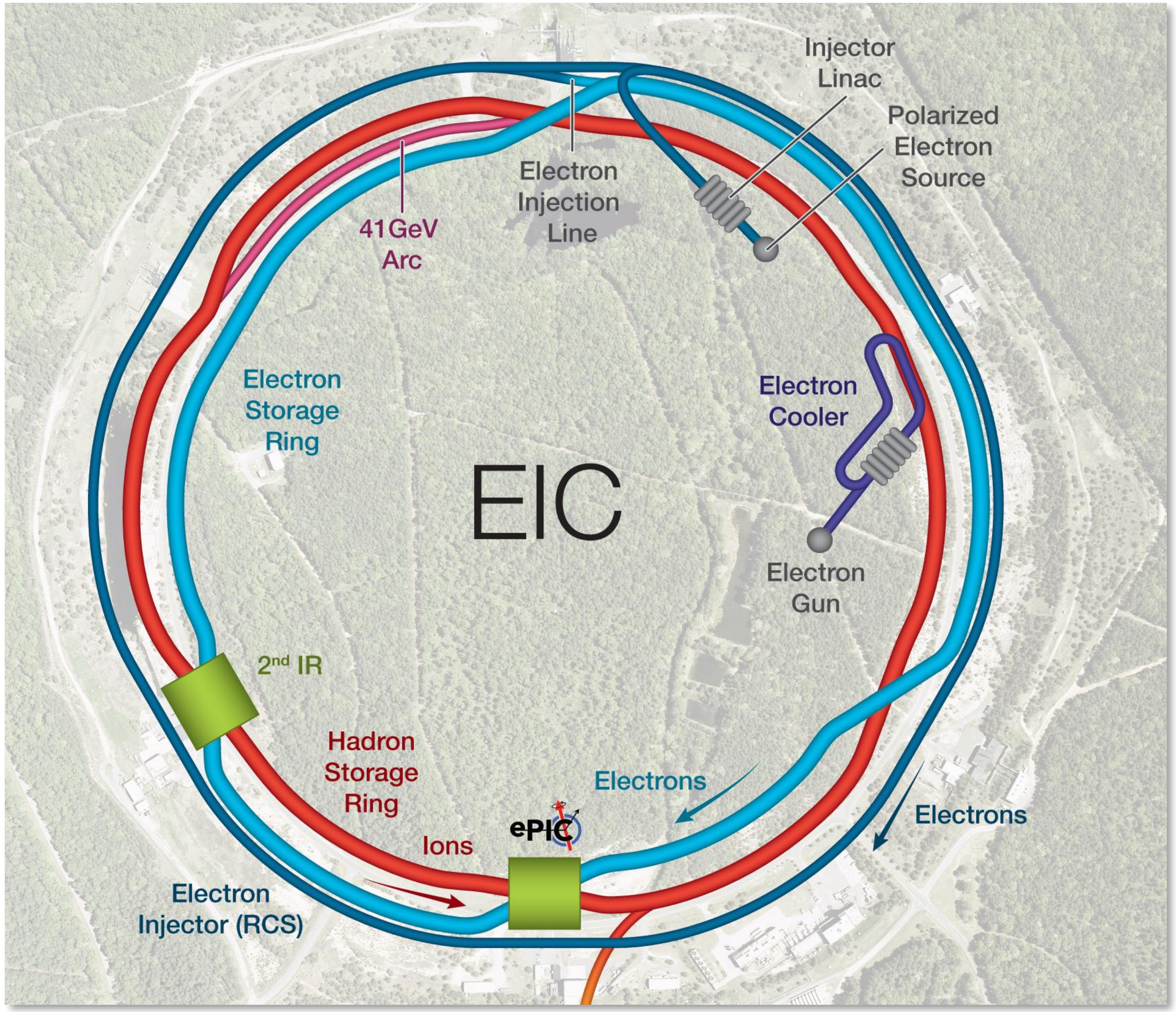
- High luminosity: L = 10^{33} to 10^{34} cm^{-2}sec^{-1} - a factor 100 to 1000 beyond HERA



	Electrons	Protons
Beam energies	2.5 - 18 GeV	41- 275 GeV
Center of mass energy range	E_{cm} = 20-140 GeV	



	Electrons	Protons
Beam energies	10 GeV	275 GeV
Center of mass energy	E_{cm} = 105 GeV	
number of bunches	nb =1160	
crossing angle	25 mrad	
Bunch Charge	$1.7\cdot10^{11}$e	$0.7\cdot10^{11}$e
Total beam current	2.5 A	1 A
Beam emittance, horizontal	20 nm	9.5 nm
Beam emittance, vertical	1.2 nm	1.5 nm
β- function at IP, horizontal	43 cm	90 cm
β- function at IP, vertical	5 cm	4 cm
Beam-beam tuneshift, horizontal	0.073	0.014
Beam-beam tuneshift, vertical	0.1	0.007
Luminosity at E_{cm} = 105 Gev	**$1\cdot10^{34}$cm^{-2}s^{-1}**	



Beam Cooling

Transverse momentum energy growth:

Source: longitudinal degree of freedom.

Coupling to transverse degree **processes**:

- Scattering (intra-beam, beam-beam, residual gas)
- Improper bending and/or focusing at injection
- Interaction with beam's environment (e.g. wake fields)
- Space-charge effects
- Secondary and tertiary beams

Necessary: $\langle p_\perp \rangle \sim 10^{-4} \langle p_\parallel \rangle$

Cooling is a reduction in the phase space occupied by the beam (for the same number of particles)

- The figure of merit – beam emittance

$$\varepsilon_{x,n} = \beta\gamma \left(\left\langle x^2 \right\rangle \left\langle \theta_x^2 \right\rangle - \left\langle x\theta_x \right\rangle^2 \right)^{1/2}$$

$$\theta_x = \frac{p_x}{\beta\gamma Mc}$$

Beam Cooling

- At 275 GeV, IBS times are: H/L = 1.5/4 hours
- IBS heating rate scales as $\lambda_{\perp} \sim \frac{1}{\gamma^{1.5}}$

|Thus, the hadron cooling system must provide ~1-2 hour horizontal cooling time to prevent emittance blowup and conserve luminosity

  - We are calling it Strong Hadron Cooling

Two basic methods employed for hadron cooling today:

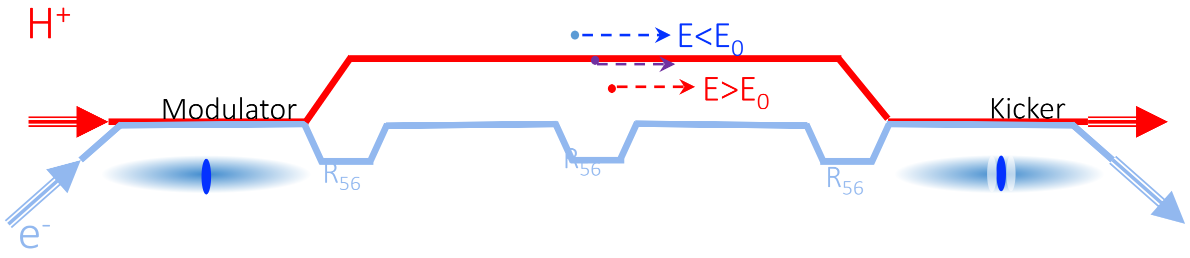
Electron cooling – energy exchange

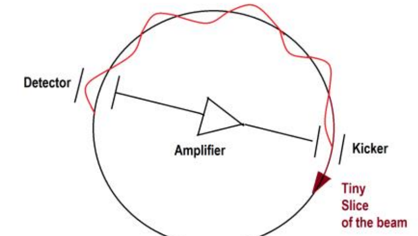
- Many low-energy proton/ion rings.
- Highest hadron beam energy to date - 8.9 GeV at Fermilab
- Cooling rate: $\lambda_{\perp} \sim \frac{1}{\gamma^{2.5}}$

Stochastic cooling (1984 Nobel Prize in Physics)

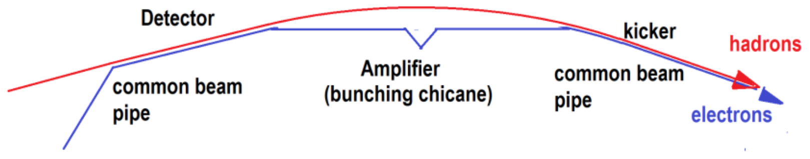
- CERN, Fermilab, GSI, RHIC, etc.

Optical Stochastic cooling

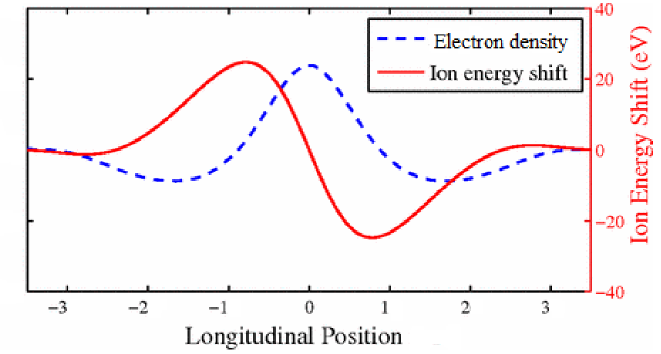




conventional



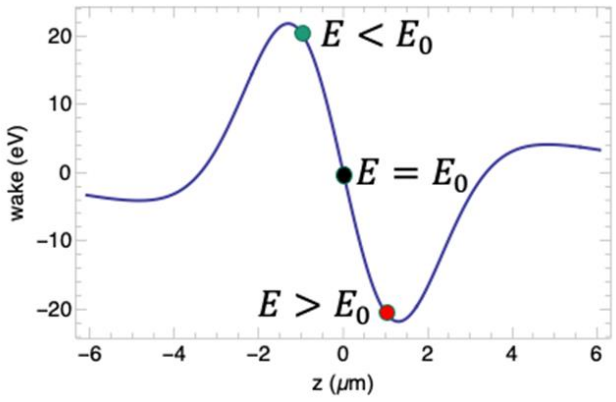
Optical (CEC)

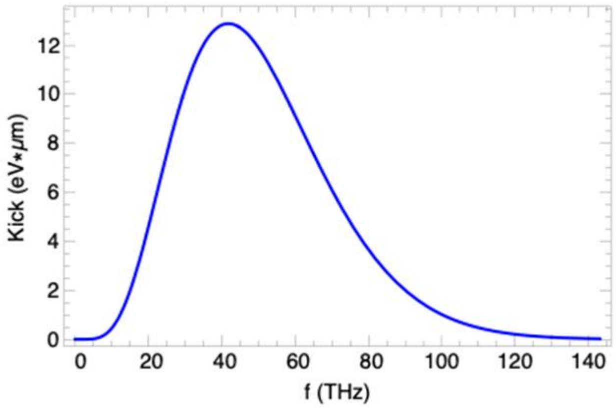


Concept:

Coherent electron cooling with microbunching amplification

- Type of stochastic cooling based on transit time between the modulator and the kicker
- Typical bandwidth of ~**40 THz** (conventional SC ~**10 GHz**)
- This is a longitudinal-only cooling scheme. Cooling in x and y requires coupling/sharing of cooling.
- Achievable cooling times of about 1 hour for 275 GeV protons





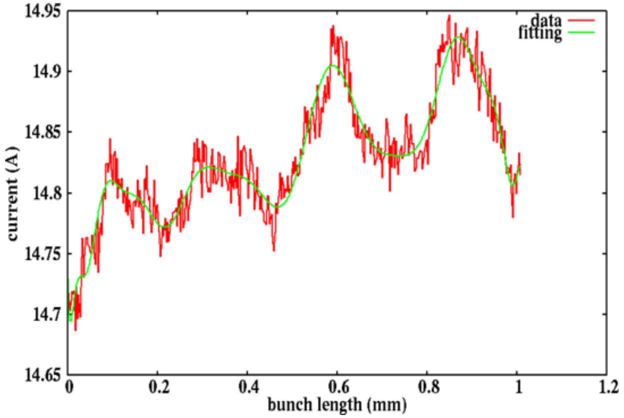
Electron beam noise

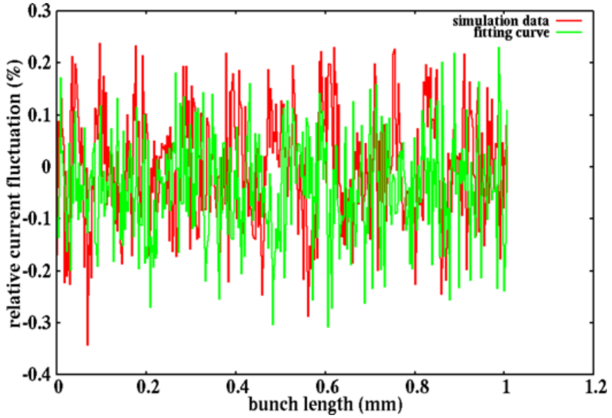
Noise = beam density fluctuations above (Poissonian) **shot noise**, *F* = 1

$$\boxed{F = \frac{\mathrm{var}(\mathcal{N})}{\langle \mathcal{N} \rangle}}$$

Fano factor

|We would like to confirm that for the ERL electron bunches <u>$F < 2$ at $\lambda \sim 3\mu m$</u>



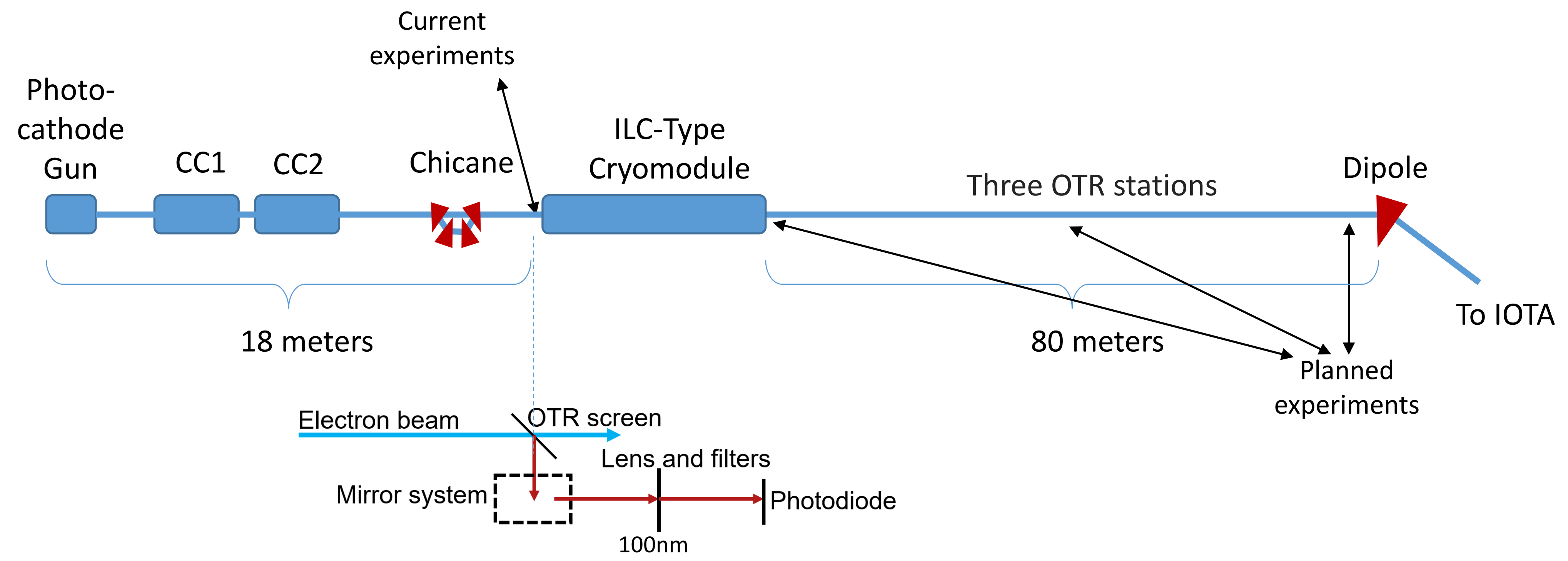


- IMPACT simulation (LBNL): energy spread, emittance, and bunch length matched well to GPT results
- Observed > 250 um modulation with noise amplitude 2x shot noise. It will not be amplified in the cooler.
- 250 um modulation will not affect the diffusion rate
- Current fluctuation through the linac and the merger is close to the shot noise level

Experiment. EIC and FAST

Beam spectrum ↔ Transition Radiation (TR) spectrum

	FAST	**EIC (100 GeV)**	**EIC (275 GeV)**	**Current experiment**
Electron beam energy	50 – 300 MeV	50 MeV	137 MeV	32 MeV
Bunch charge	0 – 3 nC	1 nC	1 nC	0.2 – 1.1 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	0.15-5 mm
Drift section (amplifier)	80 m	100 m	100 m	



Current experiments

Photo-cathode Gun

CC1

CC2

Chicane

ILC-Type Cryomodule

Three OTR stations

Dipole

To IOTA

18 meters

80 meters

Planned experiments

Electron beam

OTR screen

Lens and filters

Mirror system

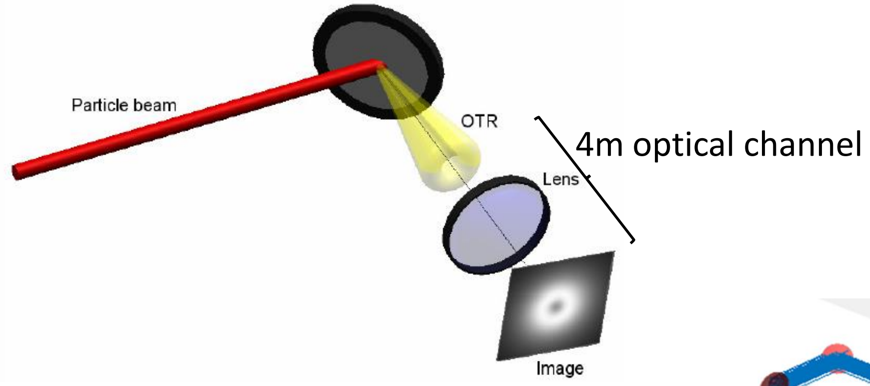
Photodiode

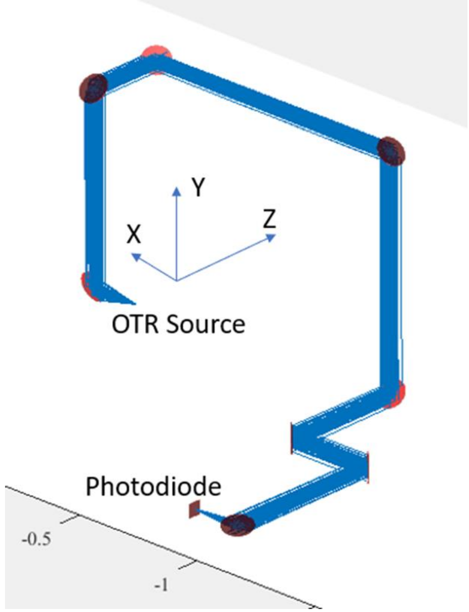
100nm

Optical Transition Radiation. Its registration

$$\frac{dI}{dwd\Omega} = \frac{Z_0 e^2}{4\pi^3}|n\times\beta|^2\left[\frac{1}{1-(\beta n)^2}\right]^2$$

- One particle

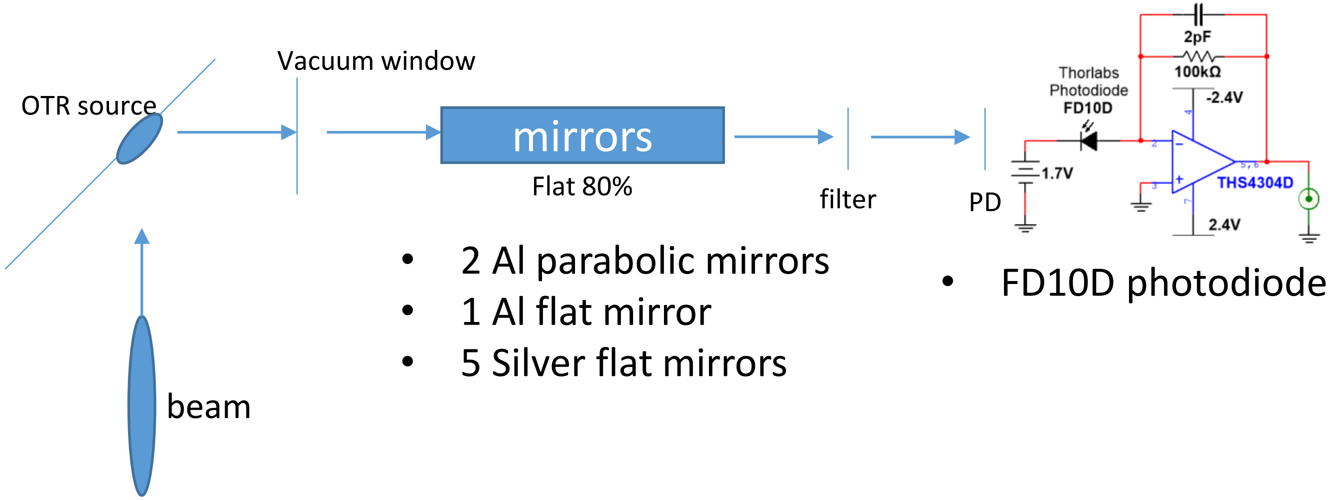




- Beam size dependence is determined by the PD size ($\gamma \gg 1$)

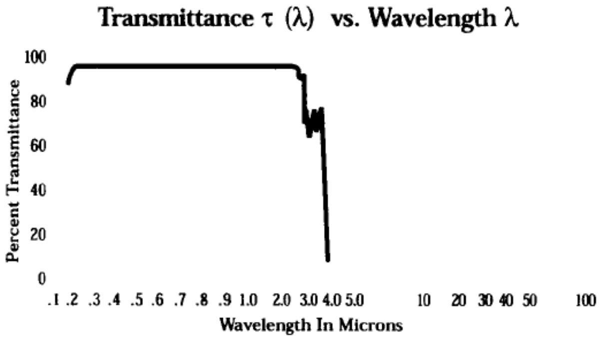
$$\frac{dI}{dwd\Omega} \sim N\left(1-\exp\left(-\frac{a^2}{2\sigma^2}\right)\right)$$

- SiO2 (fused silica) glass vacuum window

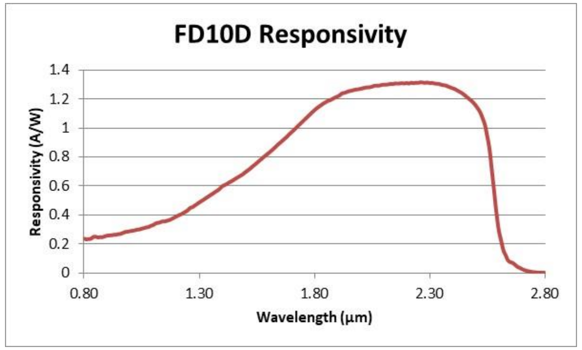


- 2 Al parabolic mirrors
- 1 Al flat mirror
- 5 Silver flat mirrors

- FD10D photodiode



Vacuum window transmittance

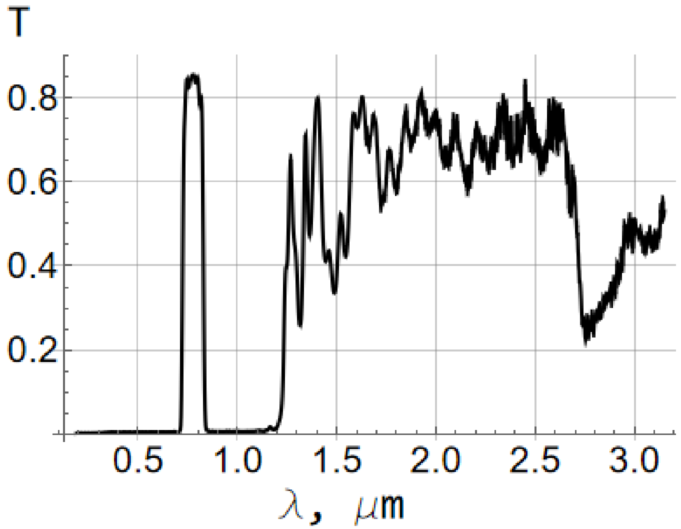


Photodiode responsivity

Data Analysis Flow

Transitions:

- Vacuum window
- Flat and parabolic mirrors
- Filters
- PD responsivity



Filter transmission example

Pass OTR through the light channel (Theory and Experiment)

Compare voltage $U(\lambda)$ for a set of filters (set of single values)

Discrete Homogeneous Fredholm Integral Equation

$$\int T(n,\lambda)\frac{dI}{d\lambda}d\lambda = U(n)$$

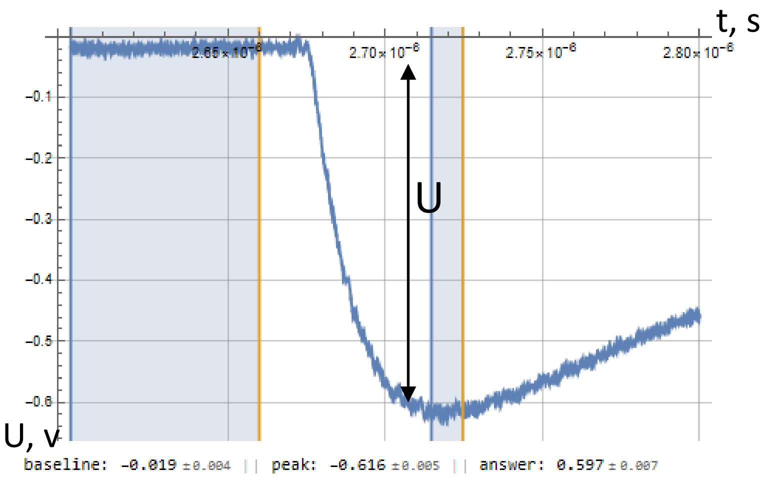
System of integral equations

If filters are <u>narrow-band</u>:

- Integrals are easily evaluated → unique solution

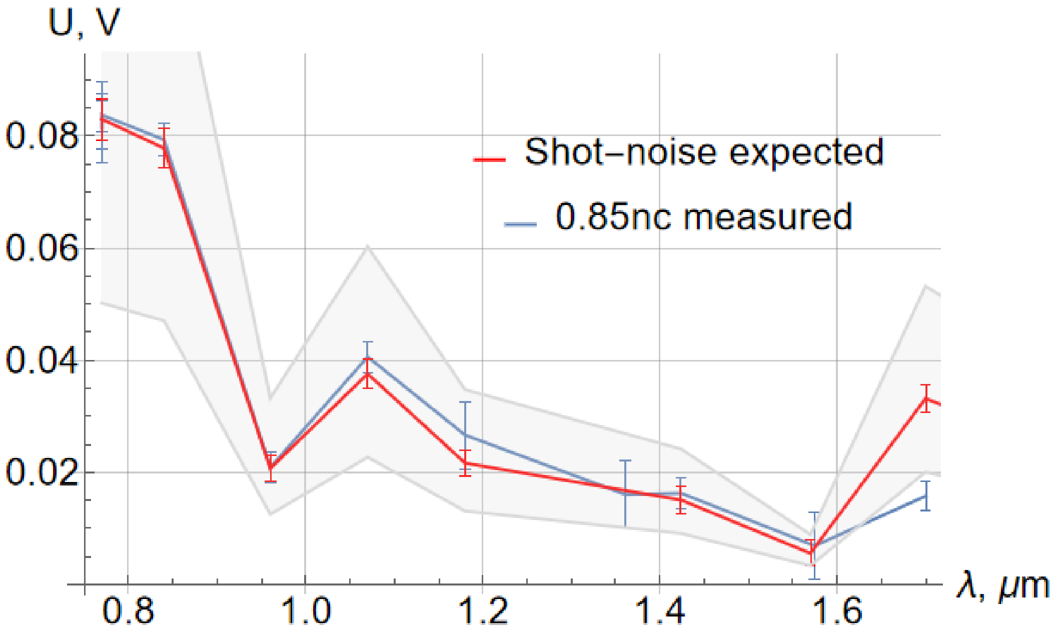
In <u>reality</u>:

- Ambiguous, guessed solution



Averaged scope data (voltage) example

OTR power Theory and Experiment comparison. Low noise



Predicted and Experimental $U(\lambda)$ comparison. 9 filters

⬇

Noise in the system is $\underline{F\ = 1 \div 1.62}$

$$\frac{d^2I}{d\omega d\Omega} = \frac{d^2I_1}{d\omega d\Omega}\left[N + N^2\left|\int \rho(z)\exp\left(iw\frac{z}{c}\right)\,dz\right|^2\right]$$

Incoherent term

N – number of particles

Coherent term

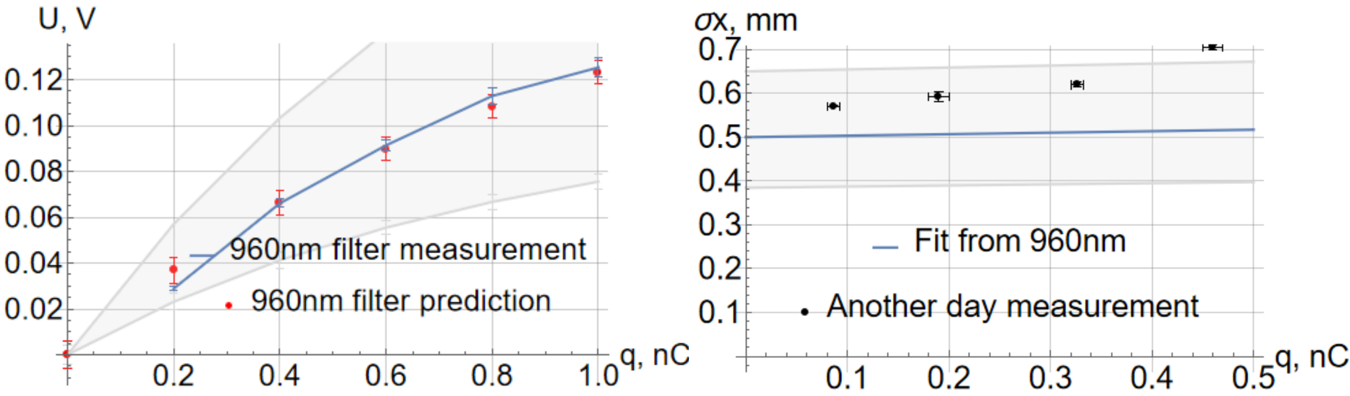
$$\frac{\text{Red}}{\text{Gray}} - 1 = N\left|\int \rho(z)\exp\left(iw\frac{z}{c}\right)dz\right|^2$$

$$\int \rho(z)\exp\left(iw\frac{z}{c}\right)dz = \sqrt{\frac{\text{Red}}{\text{Gray}} - 1}\,\frac{1}{\sqrt{N}} = \frac{\int \rho(z)\exp\left(iw\frac{z}{c}\right)dz}{\int \rho(z)\exp\left(i0\frac{z}{c}\right)dz}$$

Shot-noise: $\frac{\int \rho(z)\exp\left(iw\frac{z}{c}\right)dz}{\int \rho(z)\exp\left(i0\frac{z}{c}\right)dz} \approx \frac{1}{1.129\sqrt{N}}$

$$F = \sqrt{\frac{\text{Red}}{\text{Gray}} - 1}\,\frac{1.129}{\sqrt{N}}$$

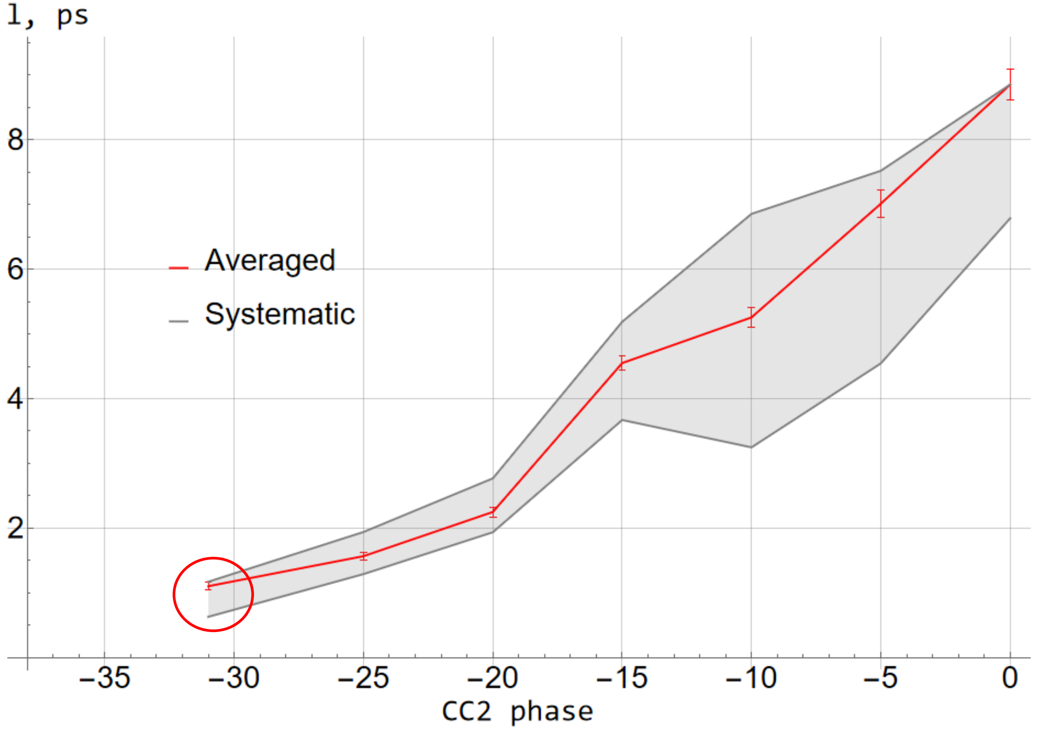
35% σ error → 50% U error → 62% F error



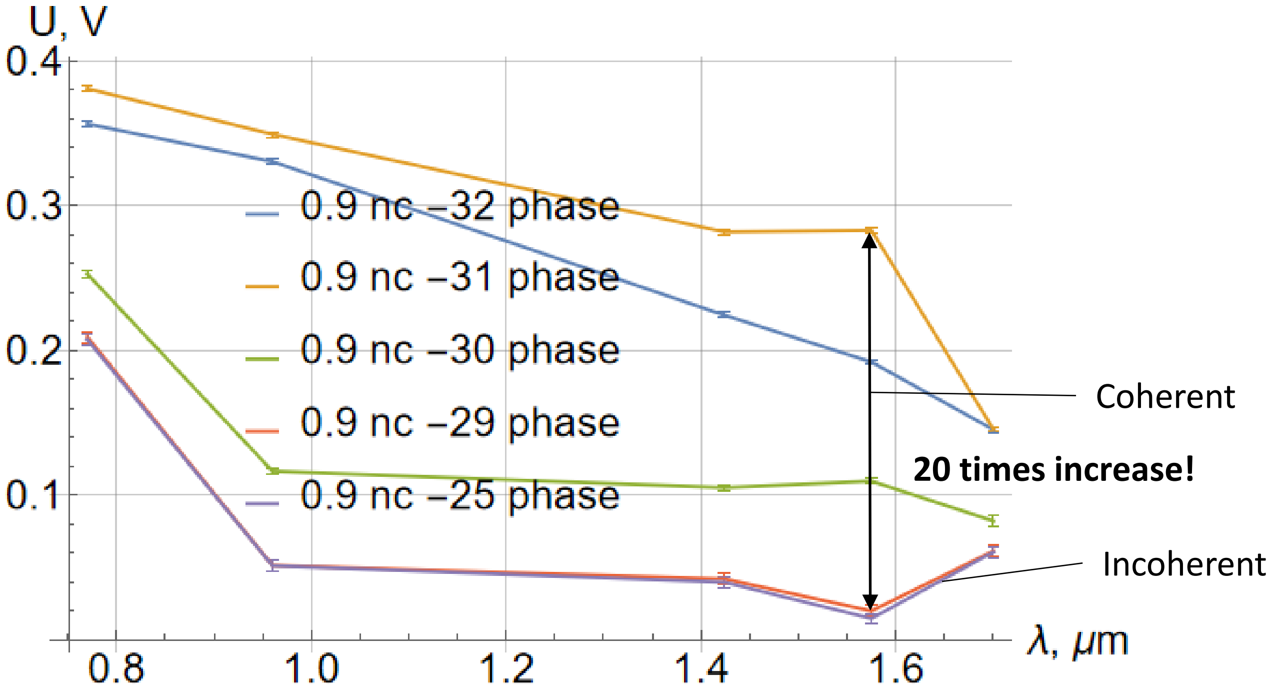
Beam size measurement error in work. Example

Bunch compression

$$\frac{d^2I}{d\omega d\Omega} = \frac{d^2I_1}{d\omega d\Omega}\left[N + N^2\left|\int \rho(z)\exp\left(iw\frac{z}{c}\right)\,dz\right|^2\right]$$



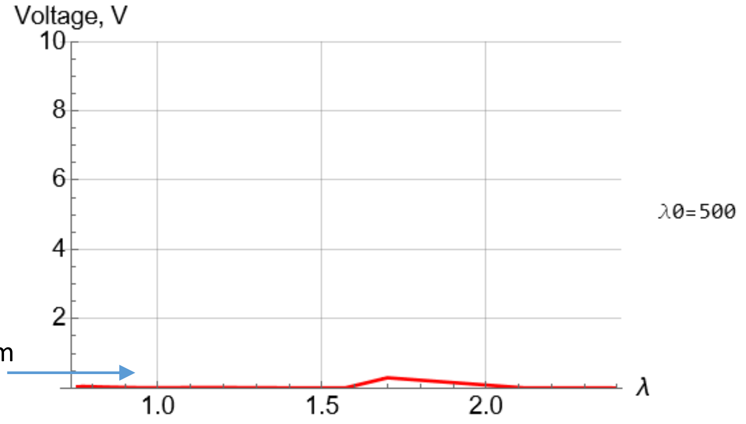
Beam length dependence on CC2 phase.
Interesting region is circled red



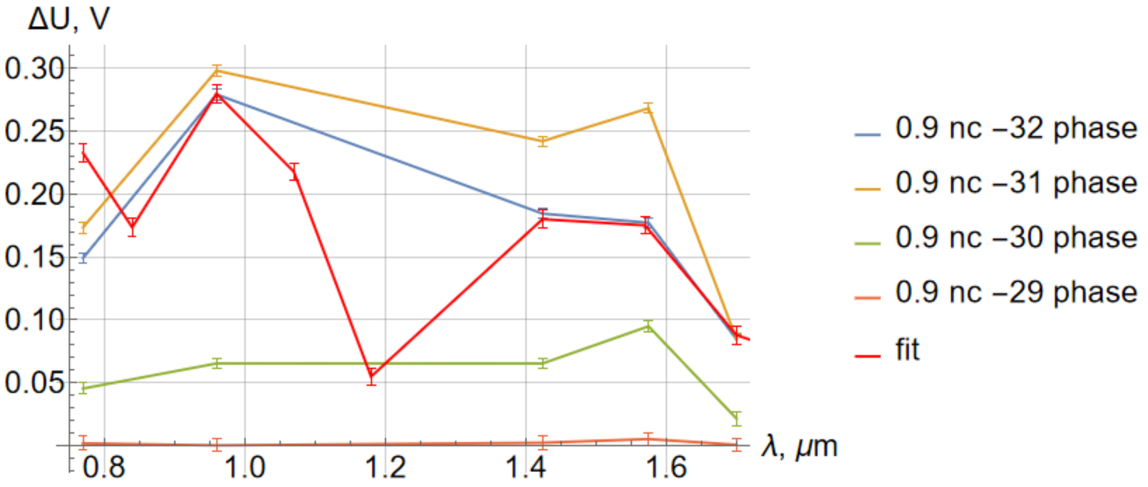
OTR energy per 100-nm BW dependence on wavelength
for different bunch lengths

Fano factor of $\langle F(\lambda)\rangle \sim 3$

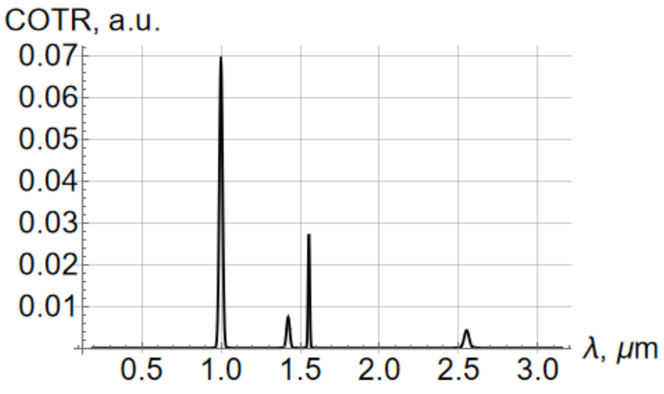
Elevated noise



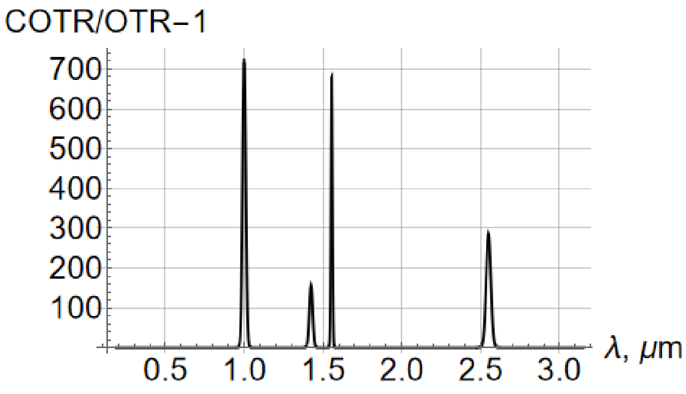
Is the largest only at 960nm



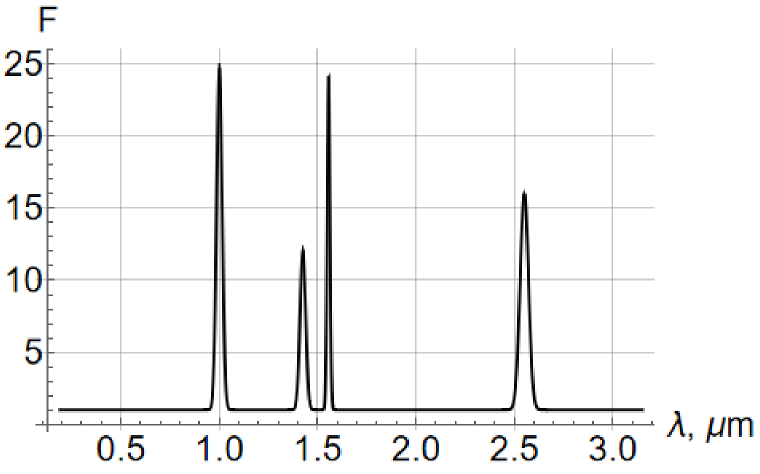
An attempt to fit the elevated noise picture



Additional OTR spectrum when the beam is compressed



$$N\left|\int \rho(z)\exp\left(2\pi i\frac{z}{\lambda}\right)dz\right|^2$$

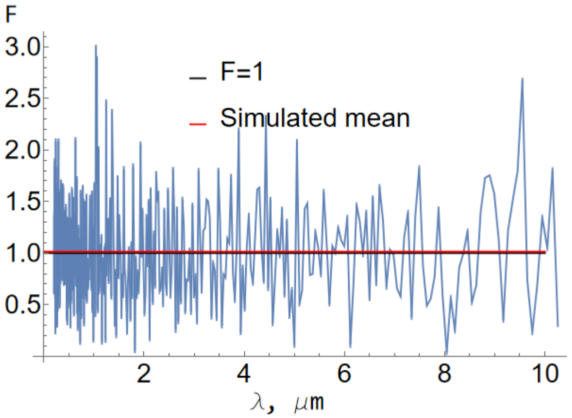


Fano factor

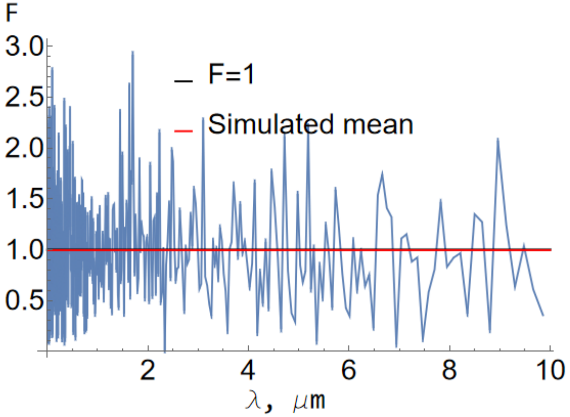
- No COTR at < 0.9 μm
- Peak at 1.5-1.6 μm
- Peak at 0.9-1 μm

Simulations

- ImpactX
- Cross-checked with ASTRA



Uncompressed beam

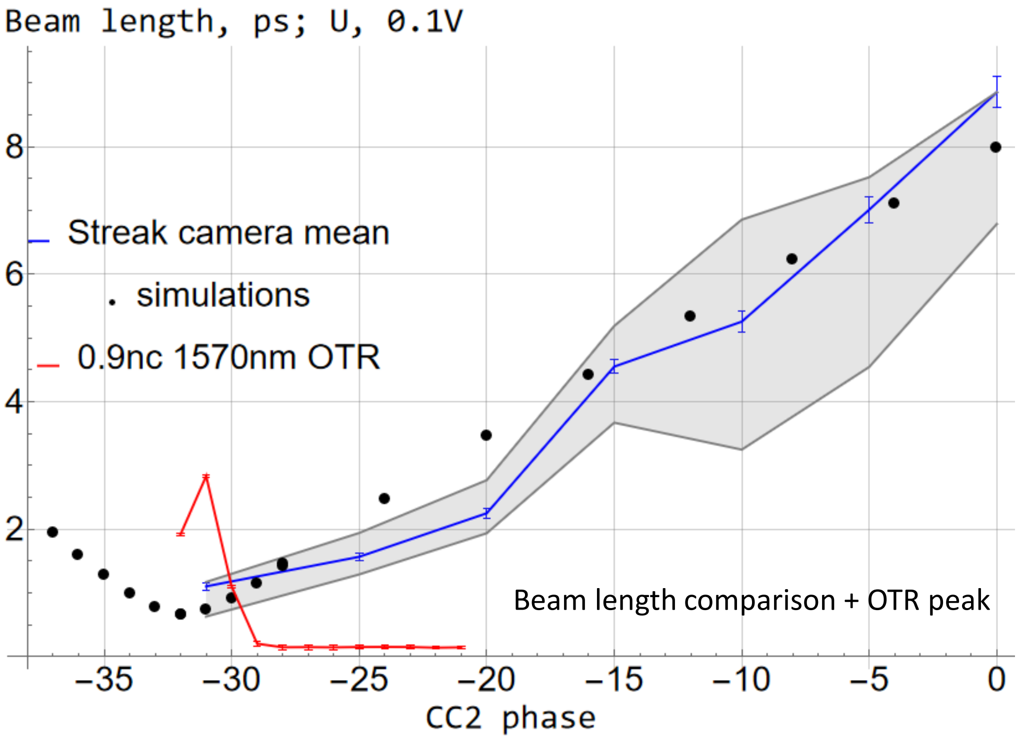


Compressed beam

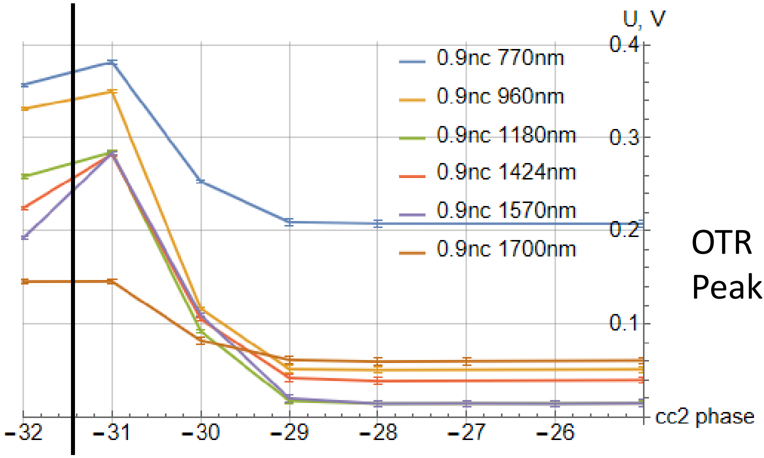
- No microbunching?

Need more accuracy

- Gain plot (with initial distortion) shows the same



Beam length comparison + OTR peak



OTR peak on multiple filters.
Peak ~31.4 (from symmetry)

Next steps

Data analysis:

- Fit the elevated noise automatically

- Fit the vacuum window transmission lower edge

Simulations

- Regular tracking:

Beam length vs cc2 phase for the high energy channel

- Microbunching:

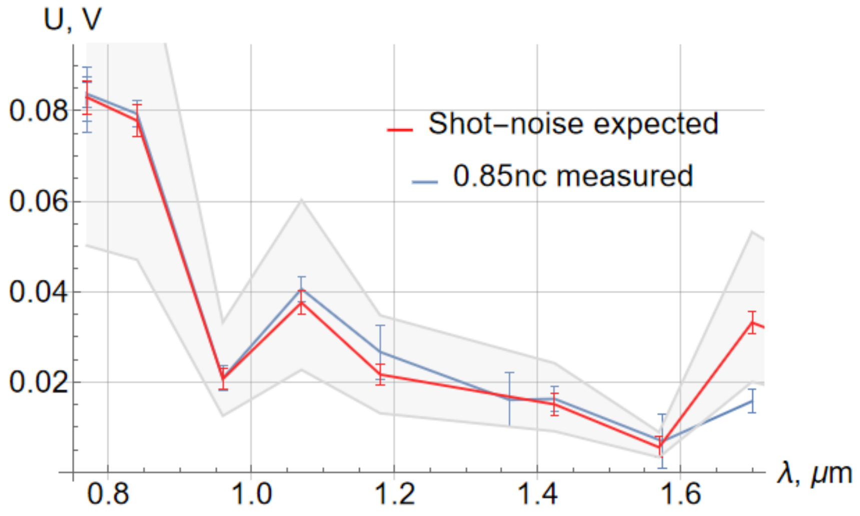
Increase accuracy and compare with other tools like GPT

Experiment:

- Perform the experiment with ultimate control of the beam size

- Create additional measurement stations in the high energy line

- Try other filters / neutral density filters to improve the data



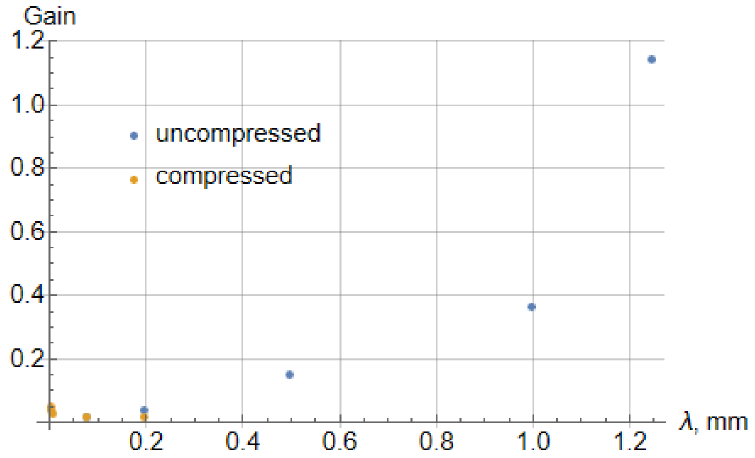
Noise in the system is $\underline{F = 1 \div 1.62}$

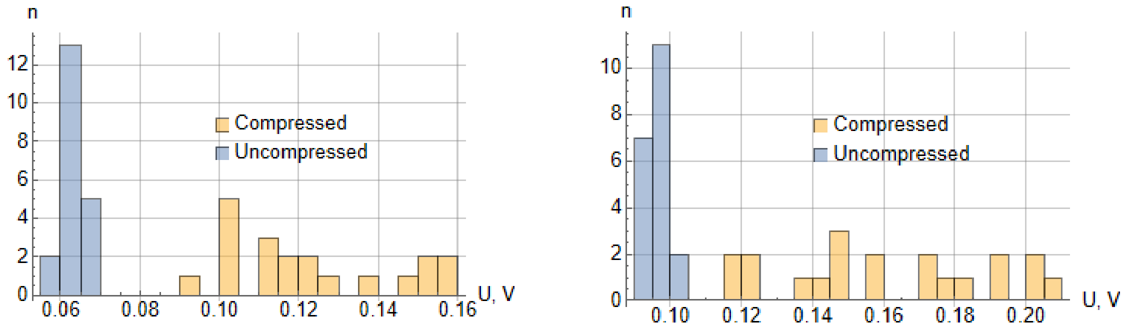
End of slide show, click to exit.

Thank you! Questions time.

EIC features

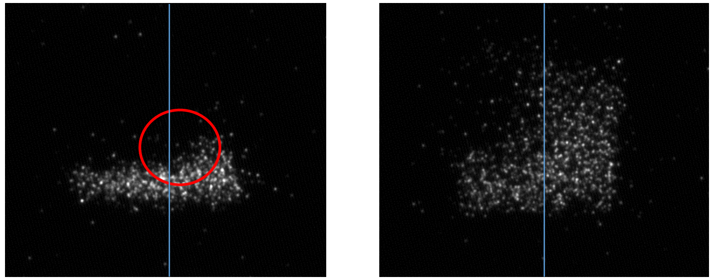
- Large range of center-of-mass energies E_{cm}= 29 to 140 GeV/u
- Polarized beams with flexible spin patterns
- Favorable condition for detector acceptance such as p_T =200 MeV/c
- Large range of hadron species: protons ….Uranium
- Collisions of electrons with polarized protons and light ions (^{3}He, d,…)





Signal fluctuations measurements

Possible discrepancy in beam length experiment vs simulation explanation



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