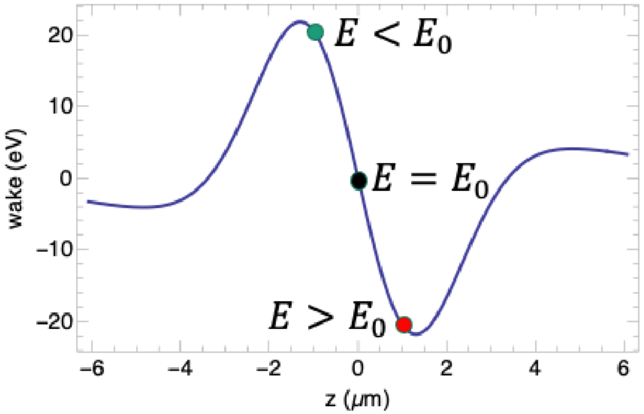
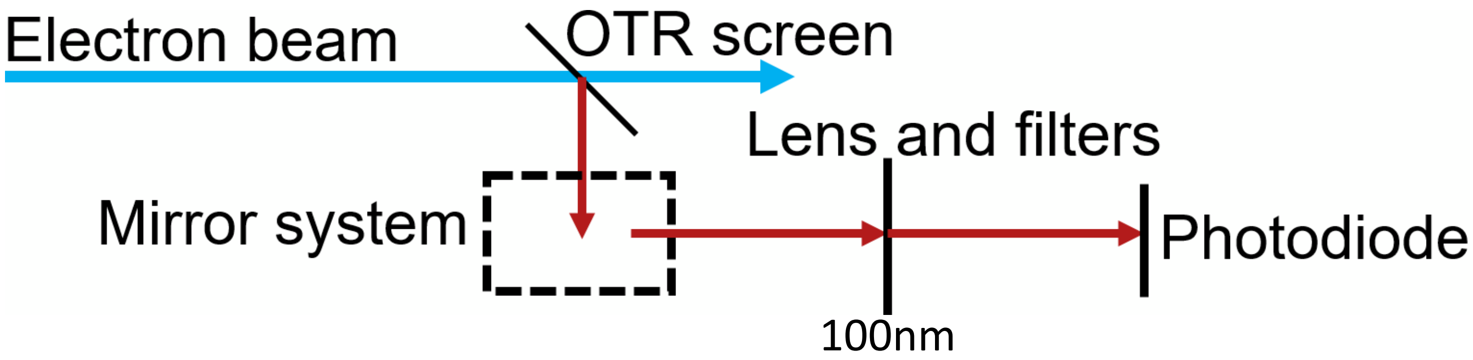
Noise in Intense Electron Bunches

S. Nagaitsev, J. Ruan, A. Lumpkin, R. Thurman-Keup, A. Saewert, S. Kladov, D. Broemmelsiek, J. Jarvis, Y.-K. Kim, Z. Huang

Bunch compression



$0 - 6\ \mu m$


Electron beam

OTR screen

Lens and filters

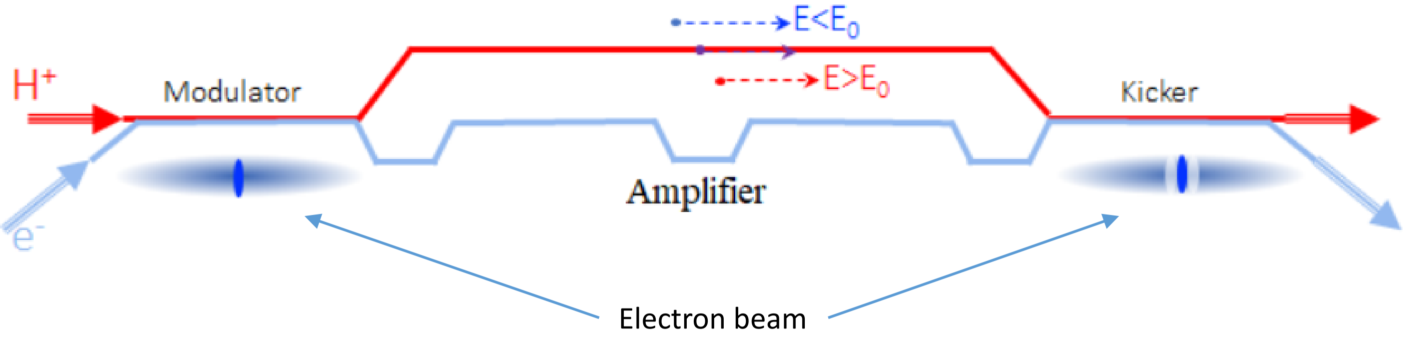
Mirror system

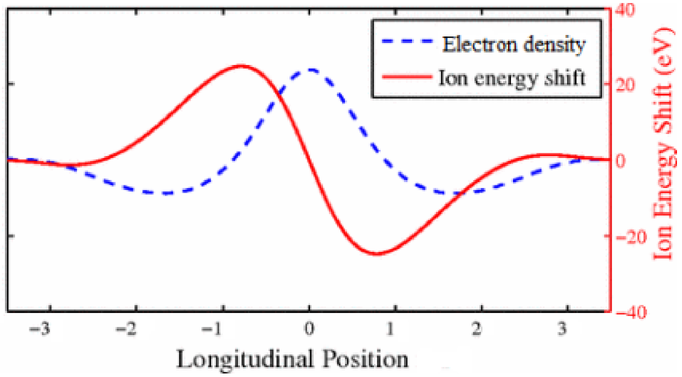
Photodiode

100nm

Similar method but with undulators – Optical stochastic cooling – already done

Introduction. Coherent Electron Cooling





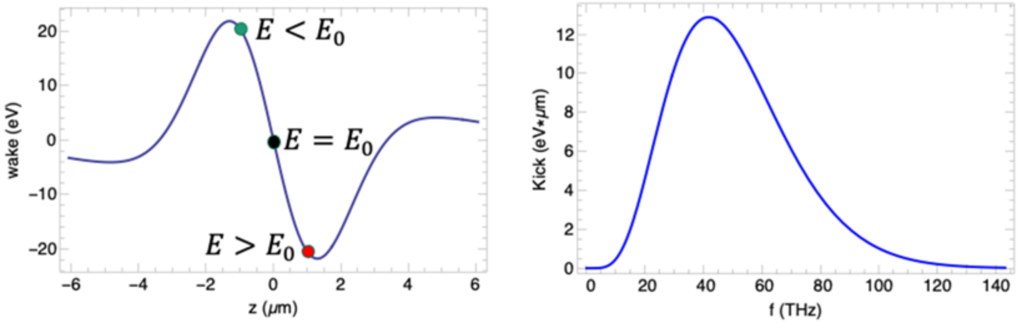
Noise:

Shot noise → $\sqrt{2}$ reduction

Above shot → may become not effective

Goal:

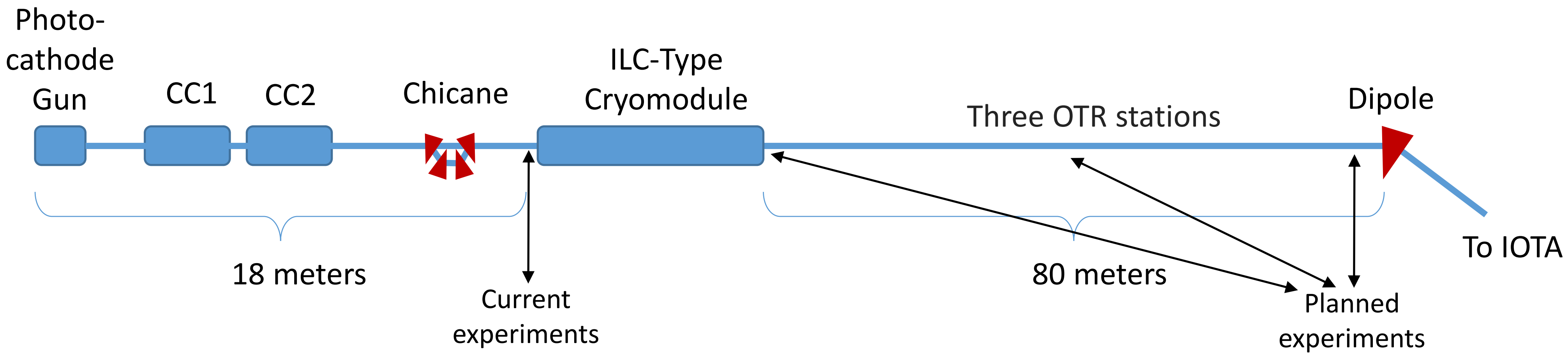
Determine how much noise we have and how to suppress it



Coherent Electron Cooling (CEC) kick at EIC

Introduction. EIC vs FAST parameters

	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	



Introduction. Microbunching instability

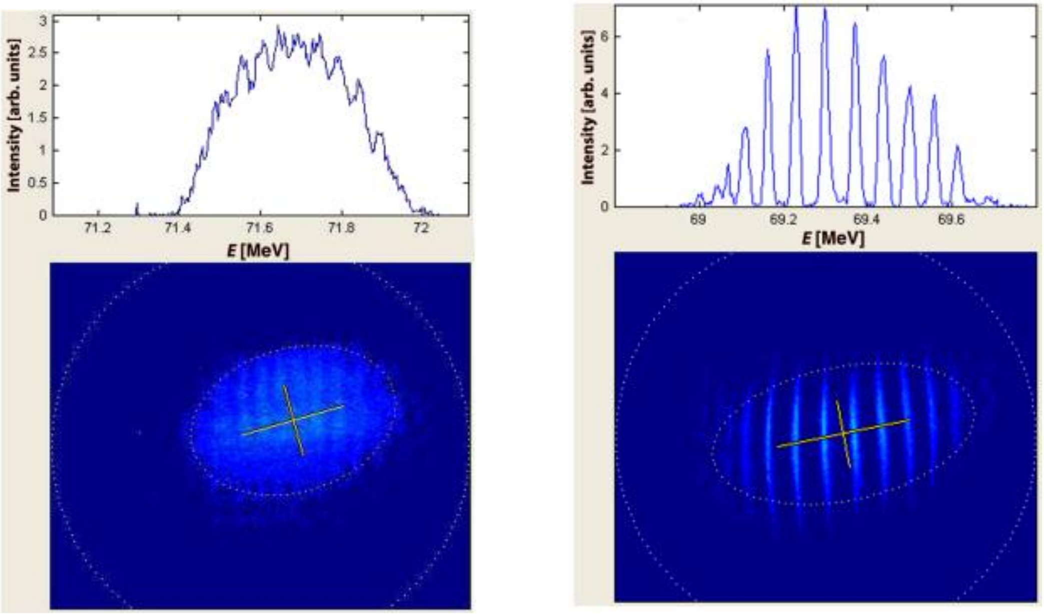
Without deliberate modulation is random

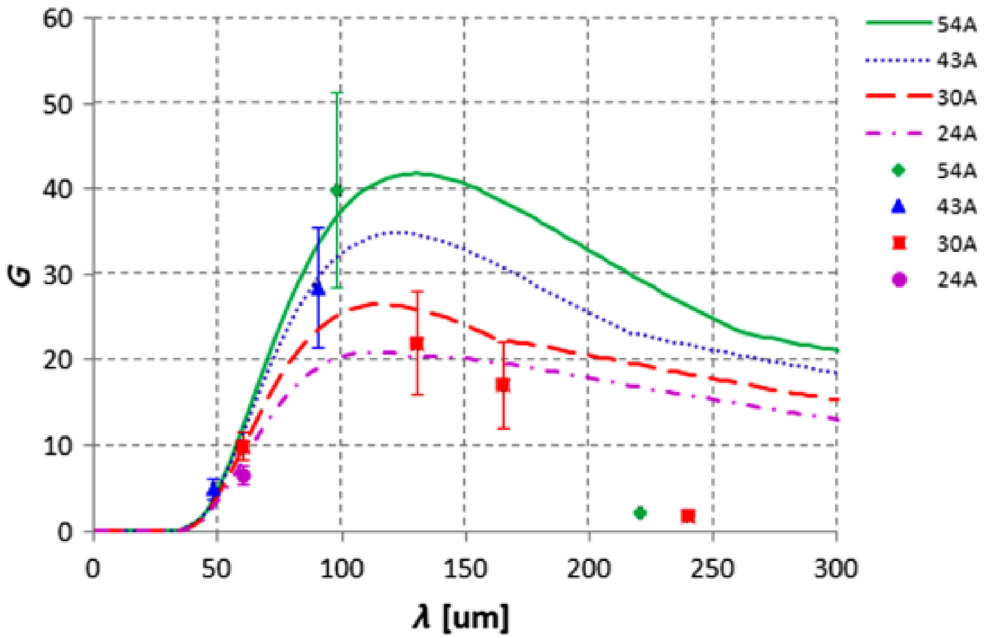
Initial distribution: $\rho(z) = \rho_{smooth}(z) + \frac{1}{2\pi}\int_{-\infty}^{\infty} \rho_{modulation}(k)e^{ikz}\,dk$

Each term in modulation spectrum is increased by gain

Need a physical mechanism that depends on longitudinal distribution

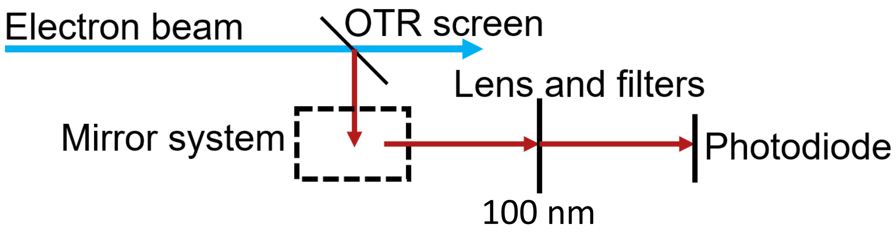
final distribution: $\rho(z) = \rho_{smooth}(z) + \frac{1}{2\pi}\int_{-\infty}^{\infty} \underbrace{G(k)\rho_{modulation}(k)}_{\text{Final } \rho_m(k) \to \rho_m(\lambda)}e^{ikz}\,dk$

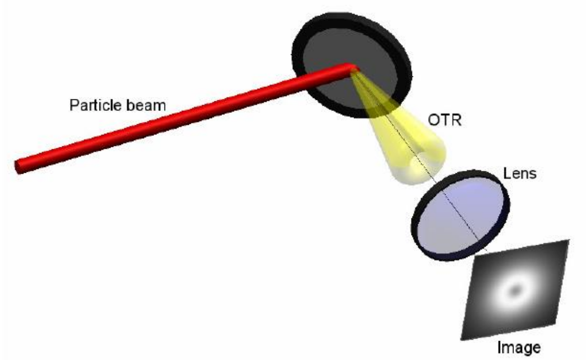


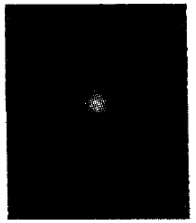


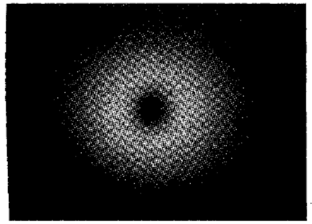
Microbunching instability produced by longitudinally modulated photocathode laser

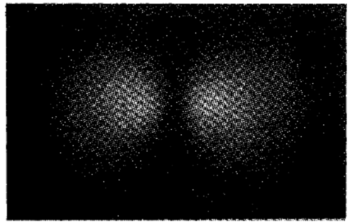
Experimental scheme. Transition Radiation





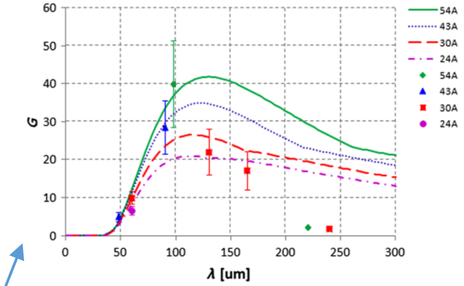

Near field observation


Far field observation


Far field observation of the horizontal polarization

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

For interesting parameters is small for microbunching instability



Radiation intensity:

$$\frac{d^2I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi\lambda^2}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\left(N + N(N-1)\left|\overbrace{\int \rho(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz}^{\rho_m(\lambda)}\right|^2 f(\sigma_x)f(\sigma_y)\right)$$

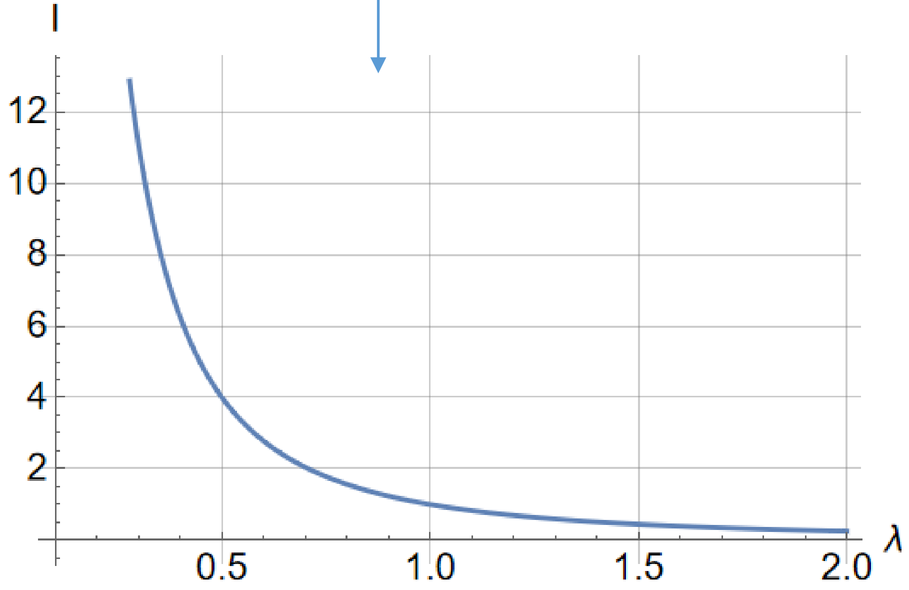
Incoherent term
N – number of particles

Coherent term

Dependence on longitudinal distribution

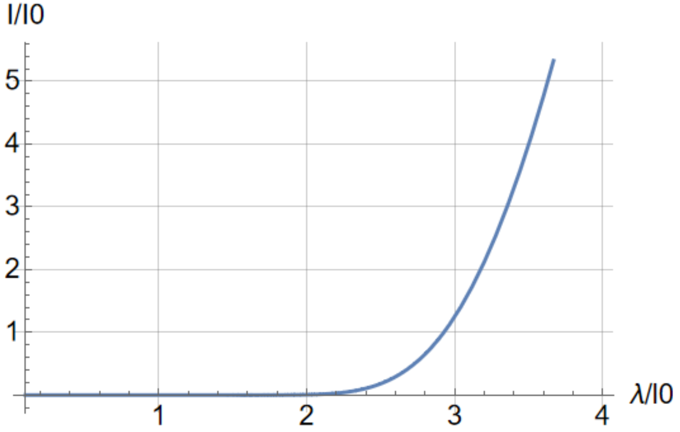
Spectrum “bricks”

$$\frac{d^2I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi\lambda^2}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\left(N + N(N-1)\left|\int\rho(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2 f(\sigma_x)f(\sigma_y)\right)$$



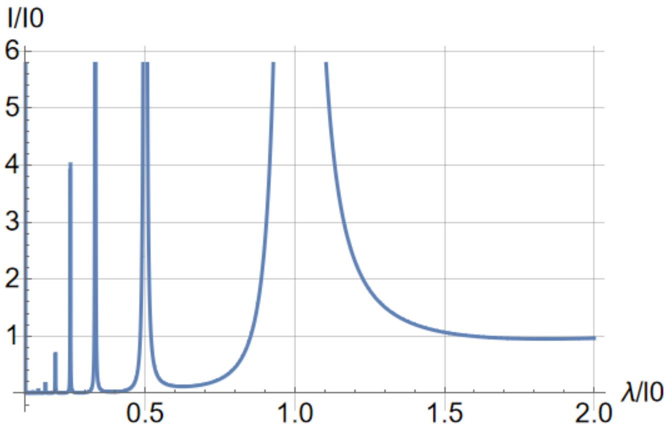
Micro-bunches are displaced randomly:

$$\frac{N(N-1)}{N_b}\left|\int\rho_{1_{norm}}(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2$$



Micro-bunches are ordered:

$$\frac{N(N-1)}{N_b^2}\left|\sum_{n=1}^{N_b}\exp\left(\frac{2\pi i\, n\, l_0}{\lambda}\right)\right|^2\left|\int\rho_{1_{norm}}(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2$$

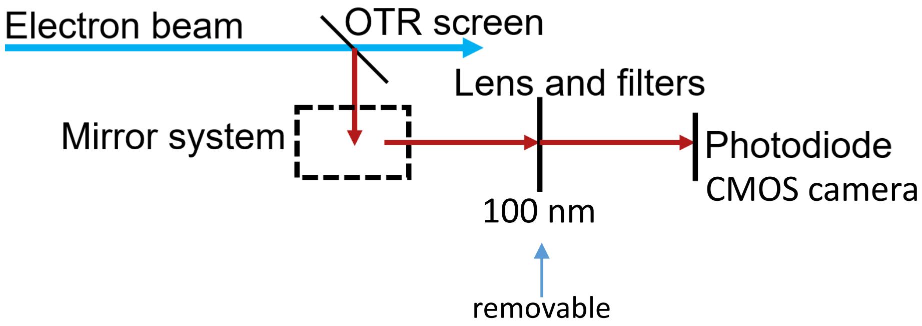


Theory conclusion. Signs of COTR. Experimental scheme. Methods

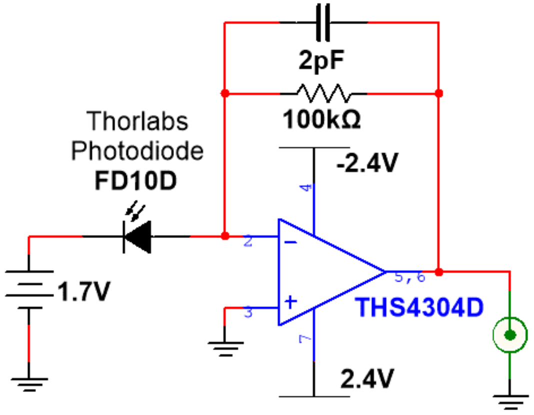
$$\frac{d^2I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi\lambda^2}\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\left(N + N(N-1)\left|\int \rho(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2 f(\sigma_x)f(\sigma_y)\right)$$

- Nonlinear dependence on beam charge
- Dependence on beam length

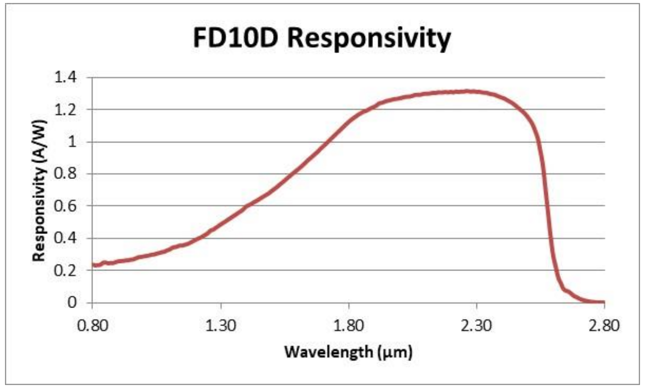
- Larger signal fluctuations for COTR


Electron beam
OTR screen
Lens and filters
Mirror system
Photodiode
CMOS camera
100 nm
removable

Two measurement methods to compare results:
Photodiode and CMOS camera



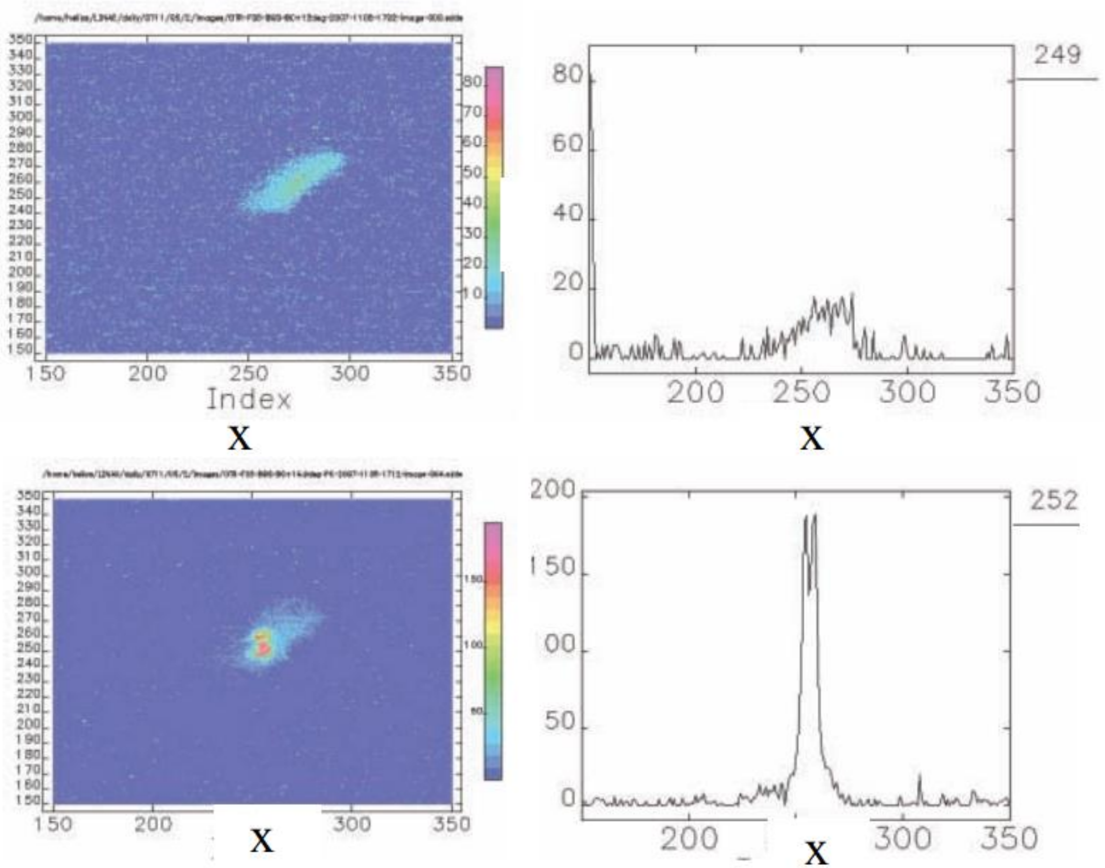
Photodiode amplifier circuit



Photodiode responsivity

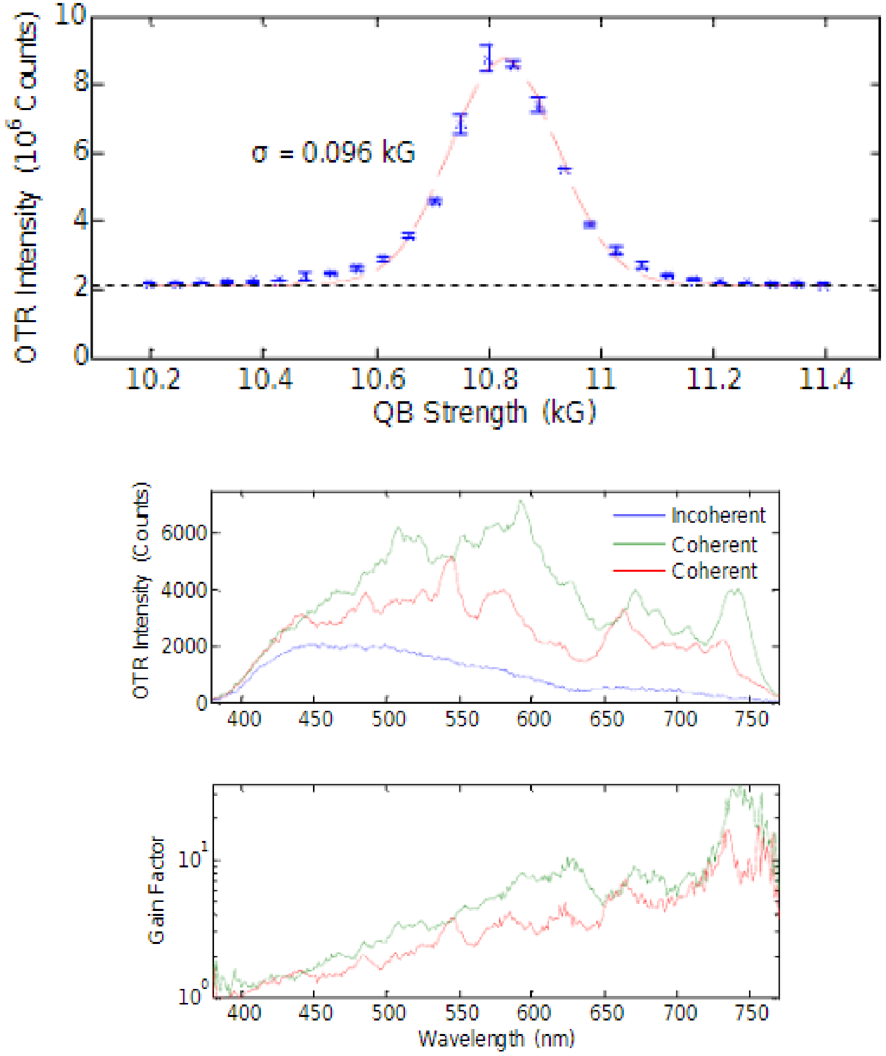
Background. Similar studies in the past

APS, Argonne National Laboratory



OTR images for uncompressed and compressed beams

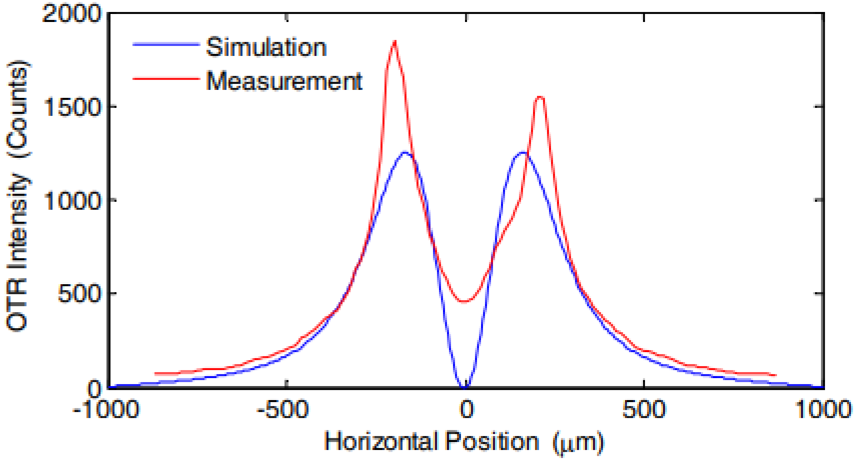
LCLS, SLAC



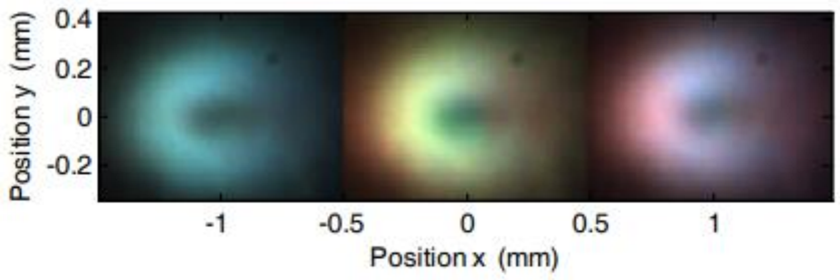
OTR power increase at specific chicane parameters

Background. Similar studies in the past

LCLS

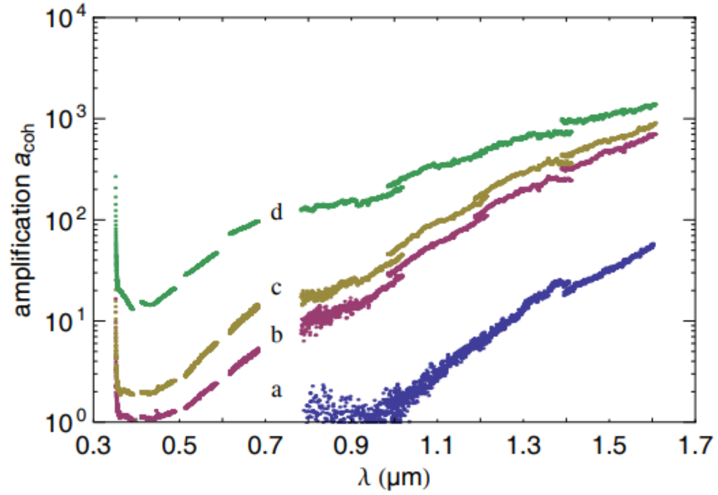


OTR angular distribution

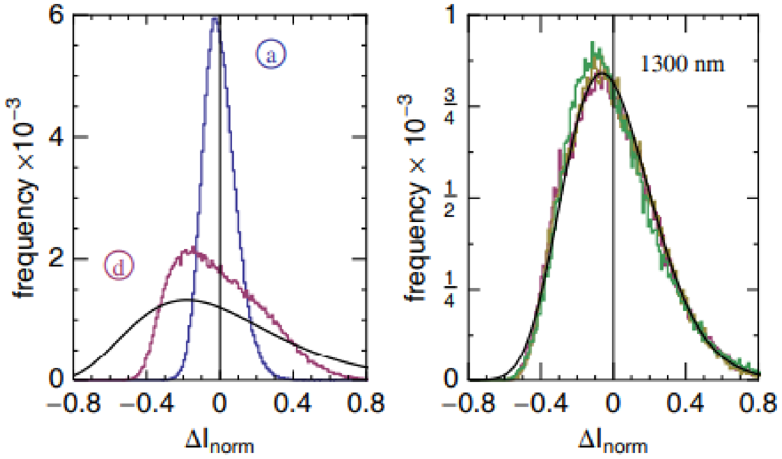


COTR fluctuations – each wavelength is produced randomly

FLASH, DESY

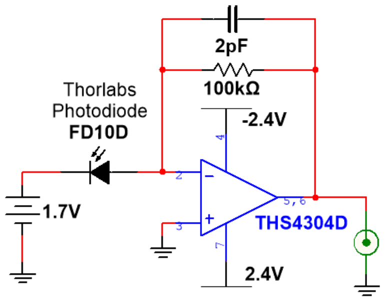


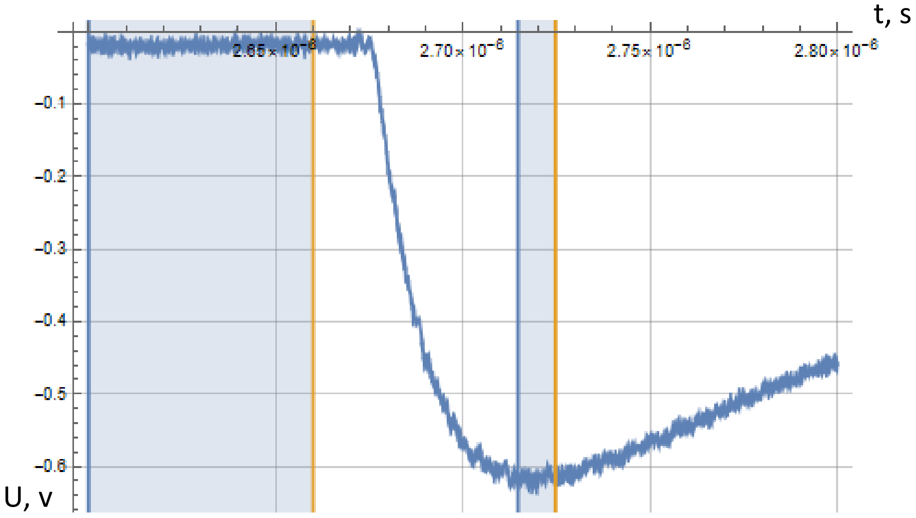
Amplification factors of coherent spectral intensity with respect to the incoherent level



Relative fluctuations histograms

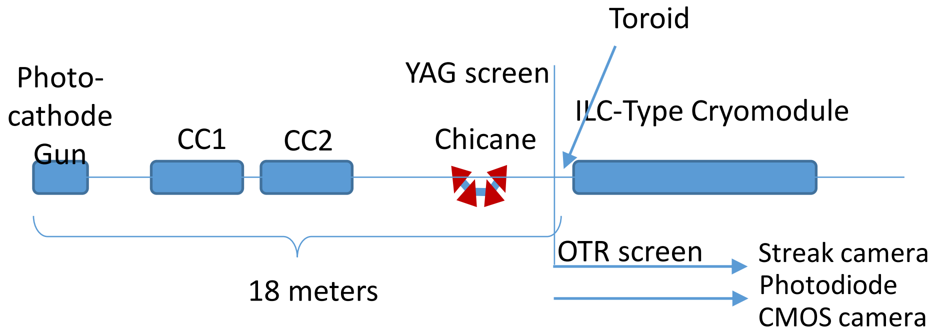
Signal and its evaluation. Bunch compression

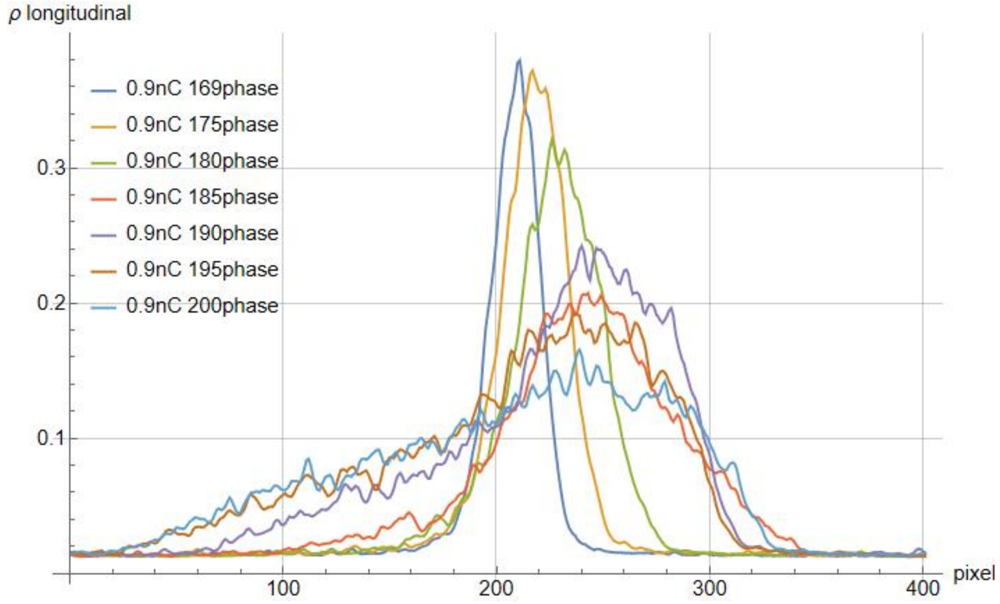




```
baseline: -0.019 ±0.004 || peak: -0.616 ±0.005 || answer: 0.597 ±0.007
```

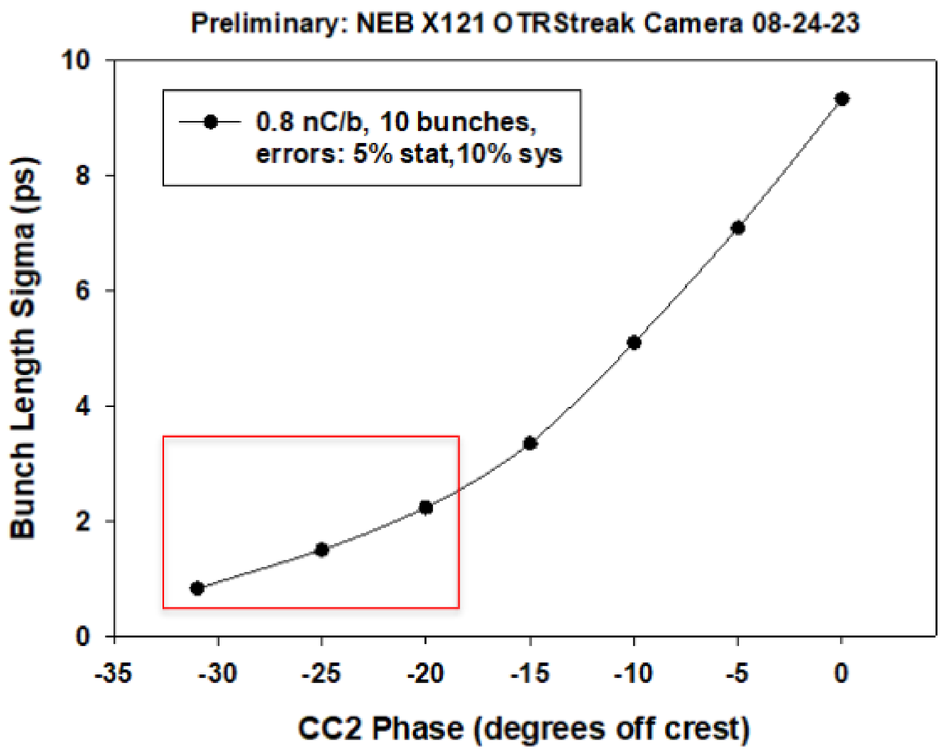
Usual signal on the scope (voltmeter) at the end of the amplifier circuit of the photodiode and its evaluation



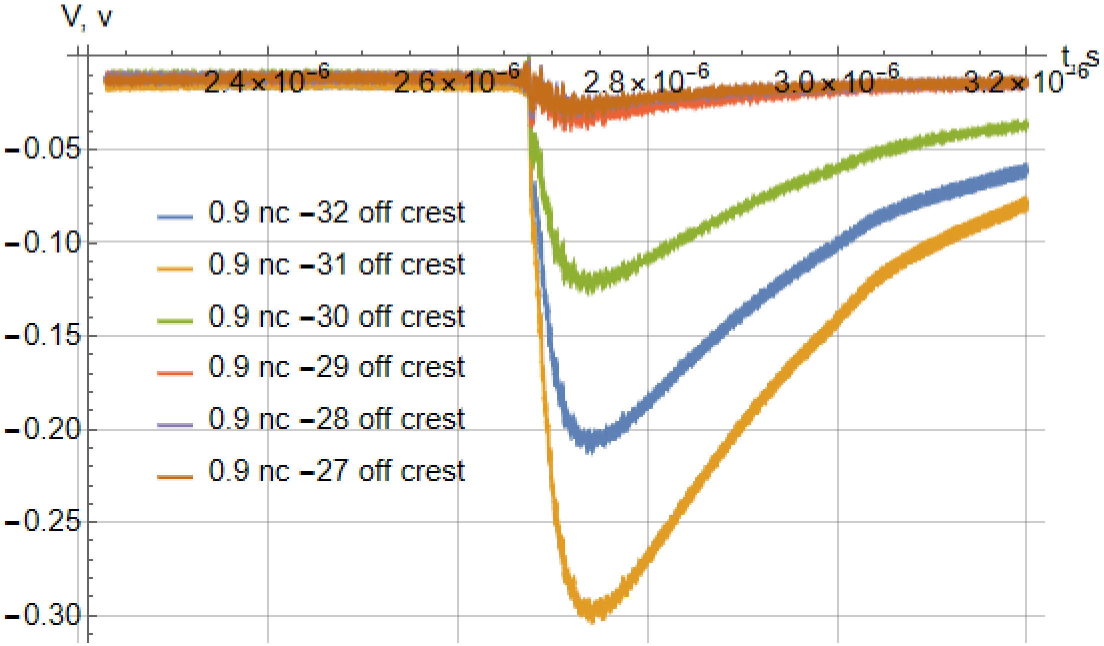


Longitudinal beam profile for different CC2 phases. Streak camera. “200phase” – on crest

Bunch compression. Main result

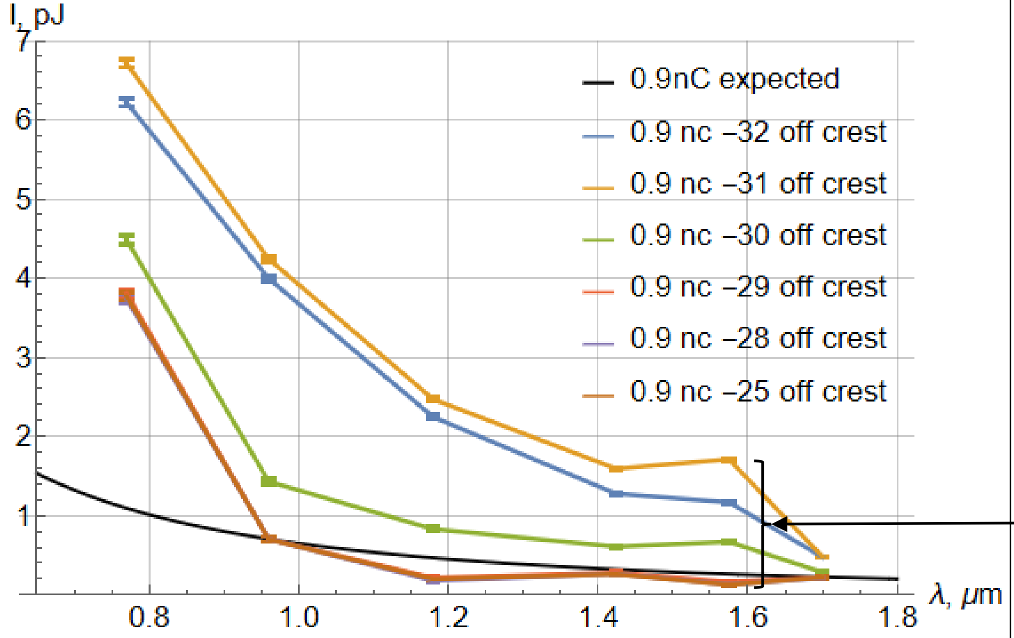


Beam length dependence on CC2 phase



OTR signal dependence on CC2 phase (bunch compression).
1570nm filter

Wavelength + compression dependence



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

- Total charge is conserved
- Beam is always steered well

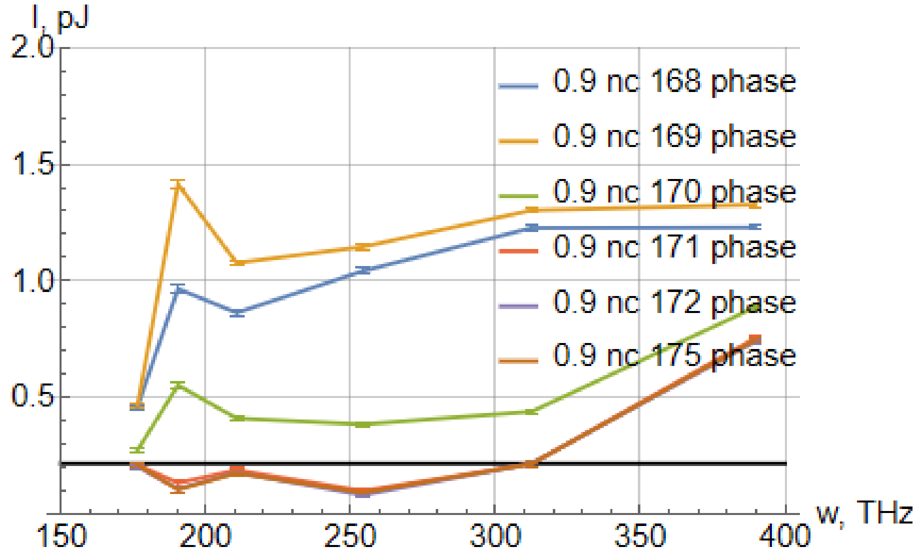
$$\frac{d^2 I}{d\Omega d\lambda} \sim \frac{1}{\lambda^2}\left(N + N(N-1)\left|\int \rho(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2\right)$$

20 times increase!

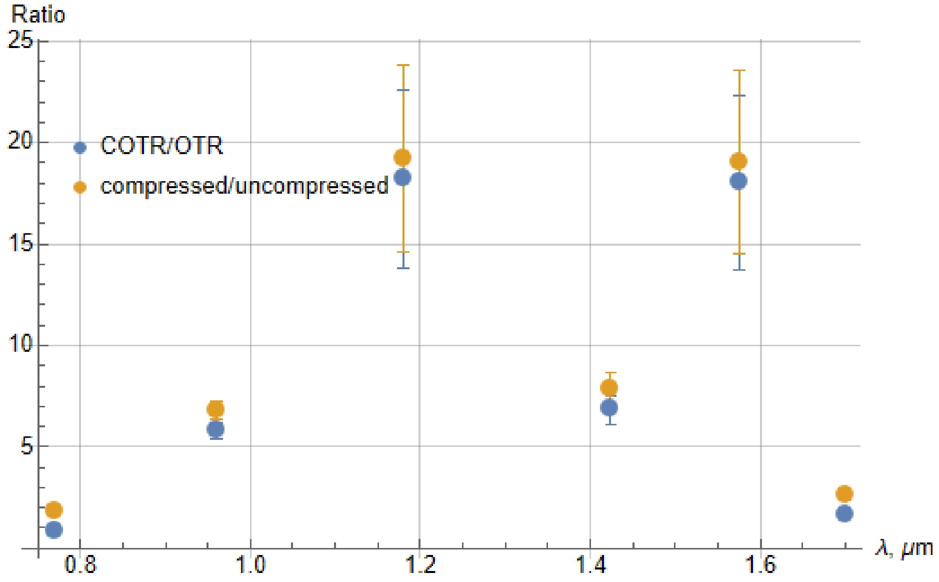
frequency dependence. Gain plot

$$\frac{d^2 I}{d\Omega d\lambda} = \frac{Z_0 q^2 c}{\pi\lambda^2}\frac{\beta^2 \sin^2\theta}{(1-\beta^2\cos^2\theta)^2}\left(\underbrace{N}_{\text{OTR}} + \underbrace{N(N-1)\left|\int \rho(z)\exp\left(\frac{2\pi i z}{\lambda}\right)dz\right|^2 f(\sigma_x)f(\sigma_y)}_{\text{COTR}}\right)$$

$$\frac{\text{compressed}}{\text{uncompressed}} = \frac{\text{OTR} + \text{COTR}}{\text{OTR}}$$

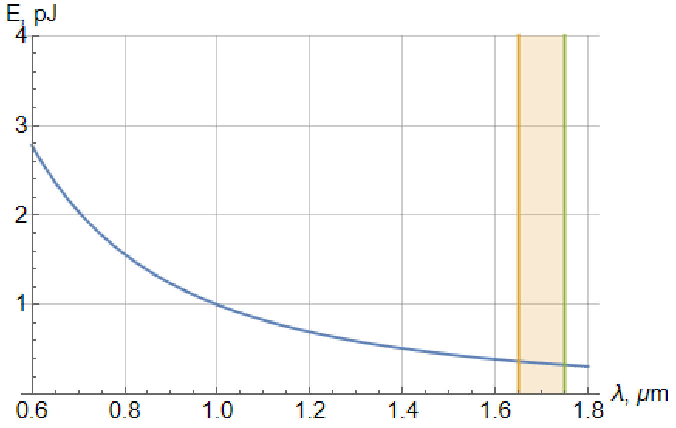


OTR energy per 100-nm BW dependence on frequency for different bunch lengths

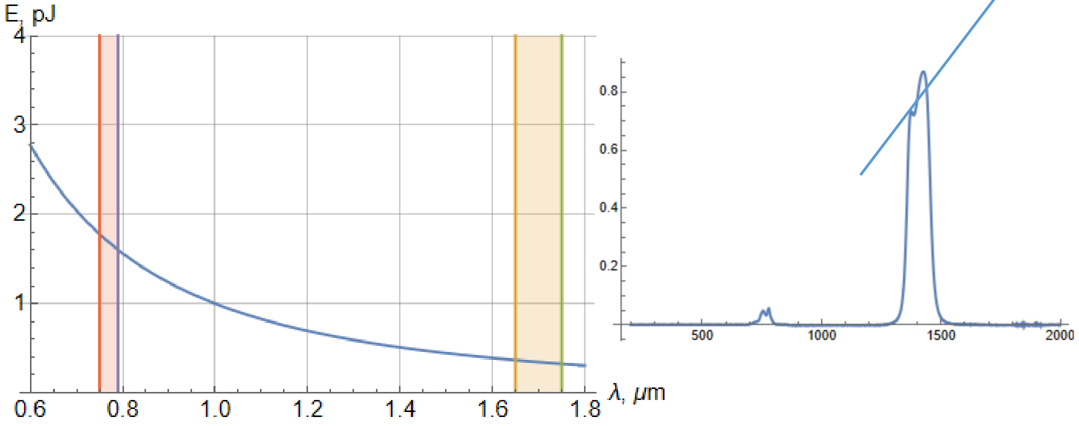


Q=0.9nC. Compressed/uncompressed ratios for 6 points in wavelength

Filter two-spots correction

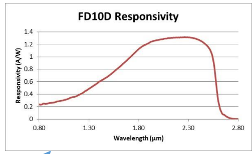


What we want the filter do – integrate over dashed area



What the filter does in practice – also integrates wrong area

$$I = \int_{w1}^{w2} \frac{dI}{d\lambda} q(\lambda)\, f(\lambda) d\lambda + \int_{c1}^{c2} \frac{dI}{d\lambda} q(\lambda)\, f(\lambda) d\lambda$$

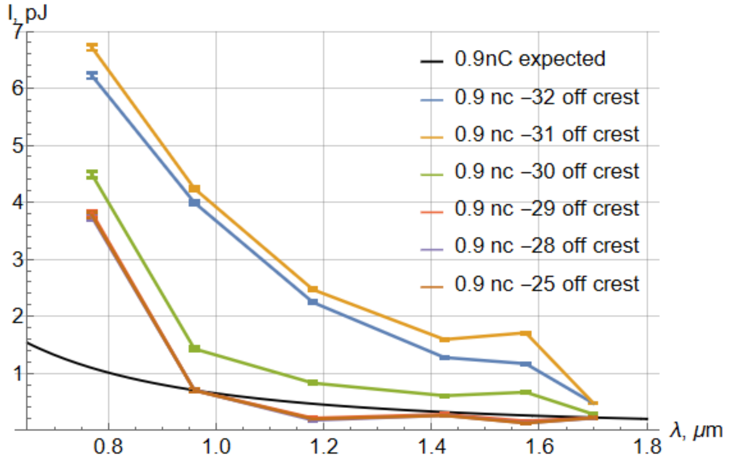


w1,w2 – wrong area
c1,c2 – correct area
$q(\lambda)$ - photodiode quantum efficiency
$f(\lambda)$ - filter transmission rate

We know the 1st term: $\int_{w1}^{w2} \frac{dI}{d\lambda} q(\lambda)\, f(\lambda) d\lambda$

->

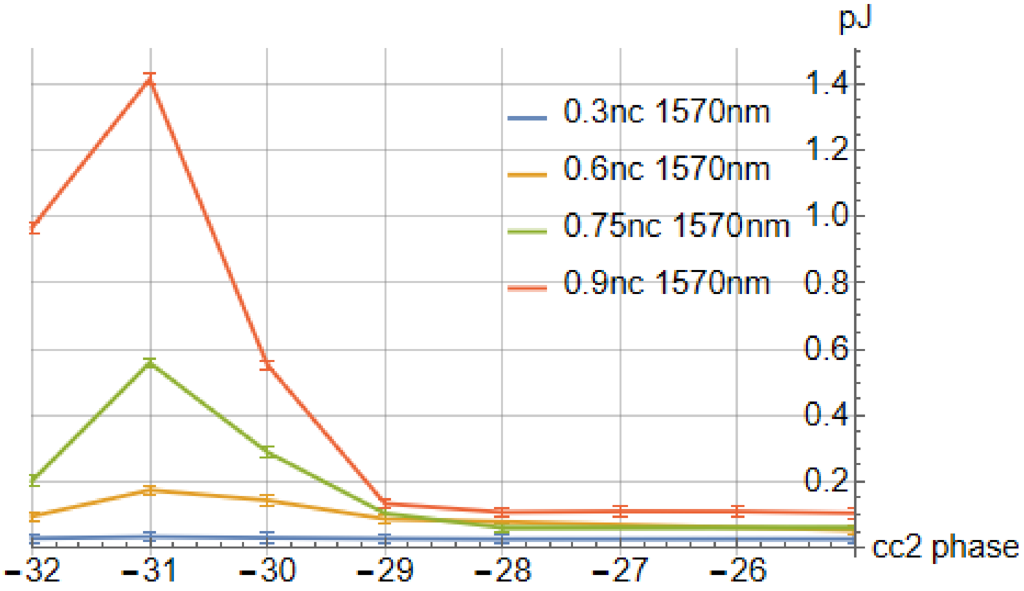
$$\left.\frac{dI}{d\lambda}\right|_{\lambda=1570nm} \approx I_{measured} - \int_{w1}^{w2} \left.\frac{dI}{d\lambda}\right|_{\lambda=770nm} q(\lambda)\, f(\lambda) d\lambda$$



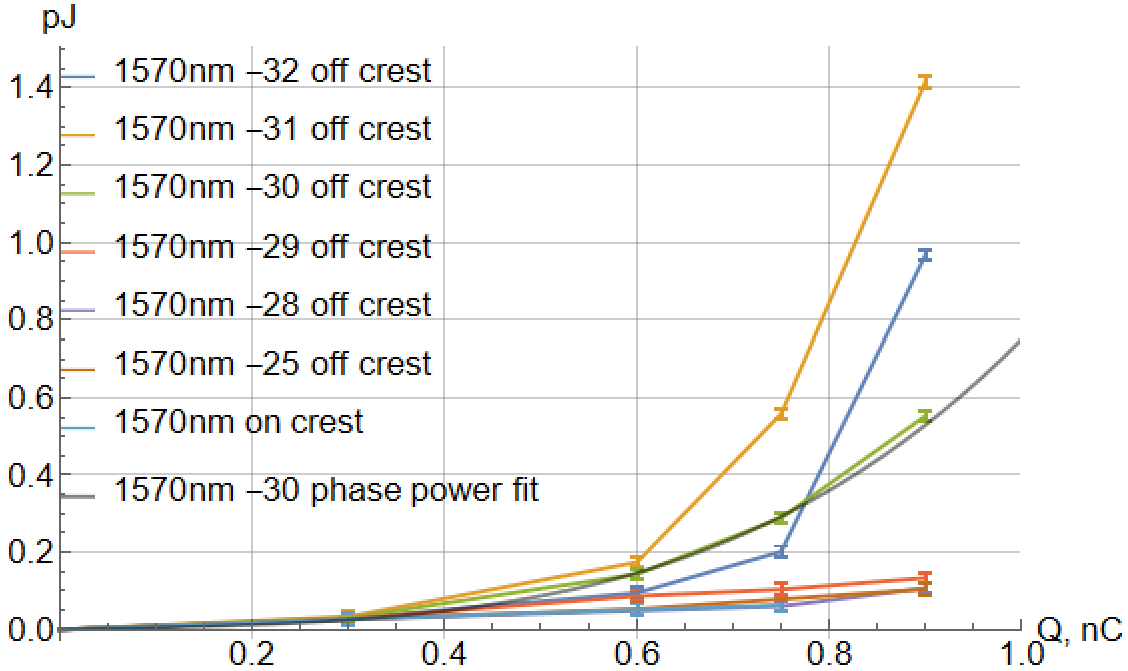
OTR energy per 100-nm BW dependence on wavelength for different bunch lengths

Charge + compression dependence

Nonlinear charge dependence ✓



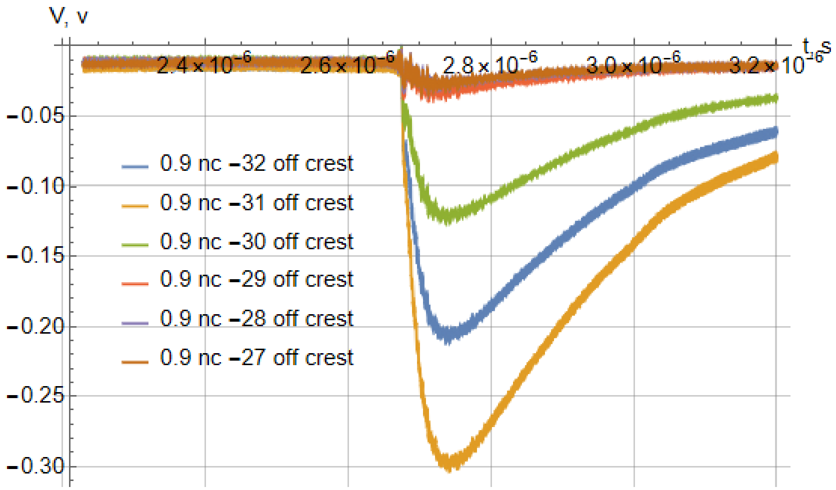
OTR energy per 100-nm BW dependence on CC2 phase for different charges
(complementary plot)



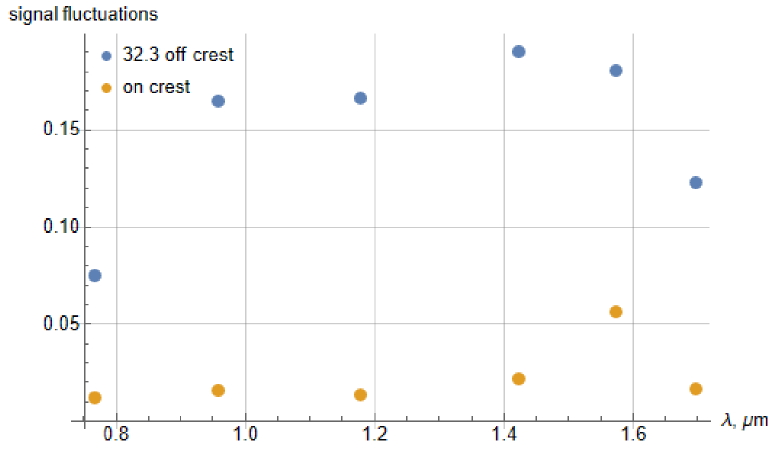
OTR energy per 100-nm BW dependence on beam charge for different CC2 phases

Larger fluctuations in microbunching area ✓

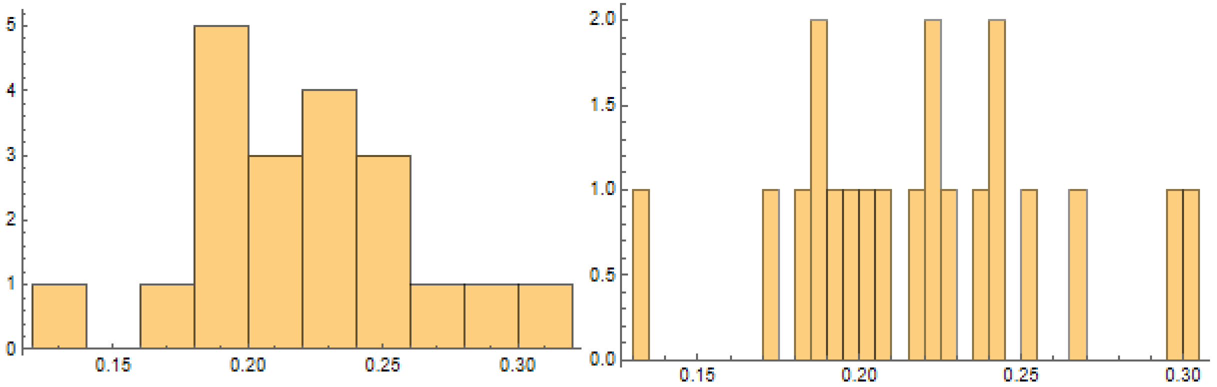
New data. Fluctuations



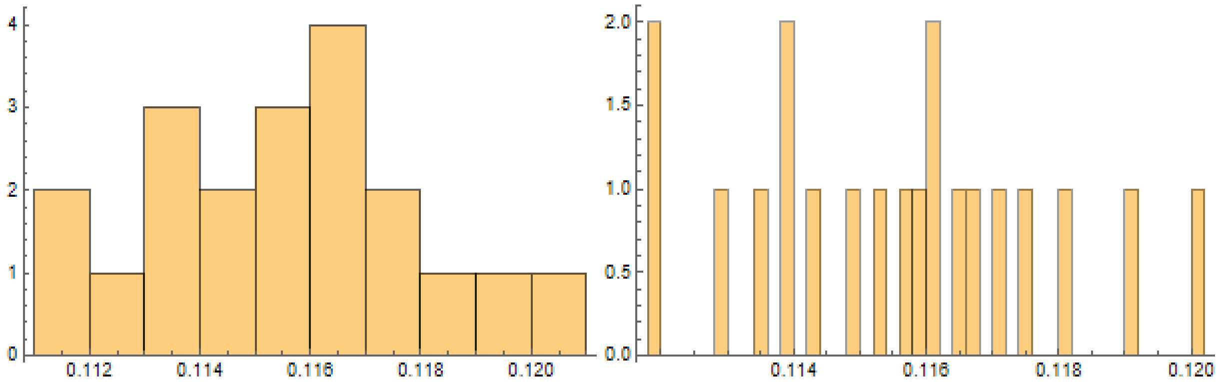
OTR signal dependence on CC2 phase (bunch compression). 1570nm filter



Relative signal fluctuations for 1.3nC

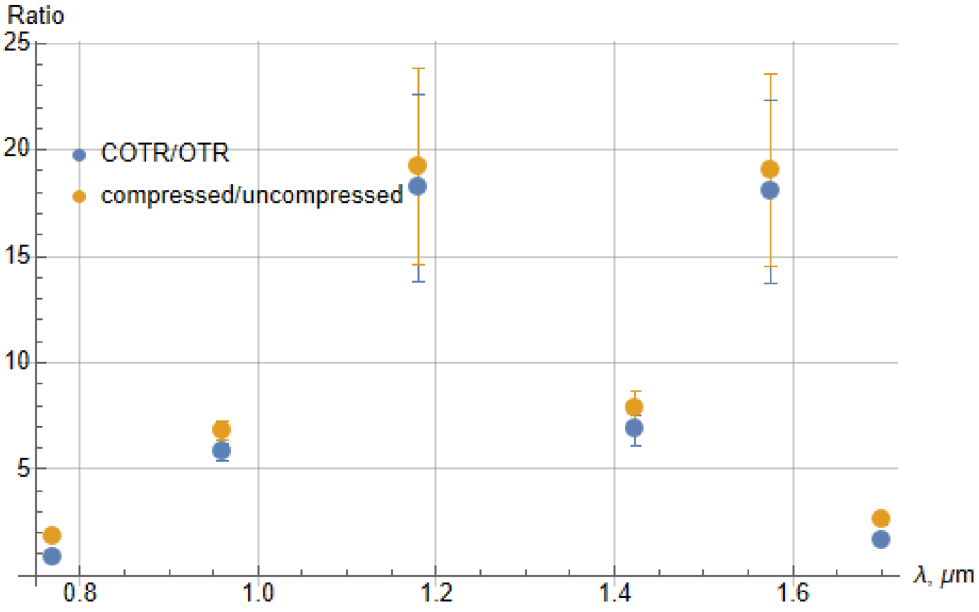


Signal histogram at 1424nm, 1.3nC, compressed

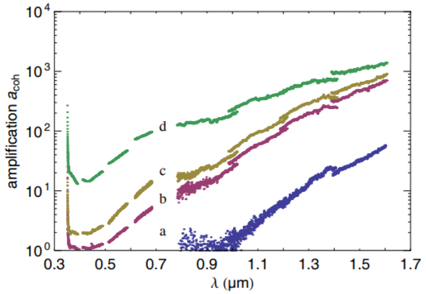


Signal histogram at 1424nm, 1.3nC, uncompressed

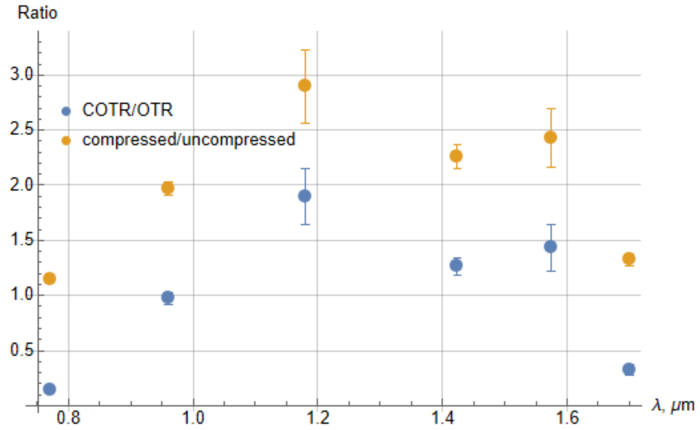
New data. gain verification



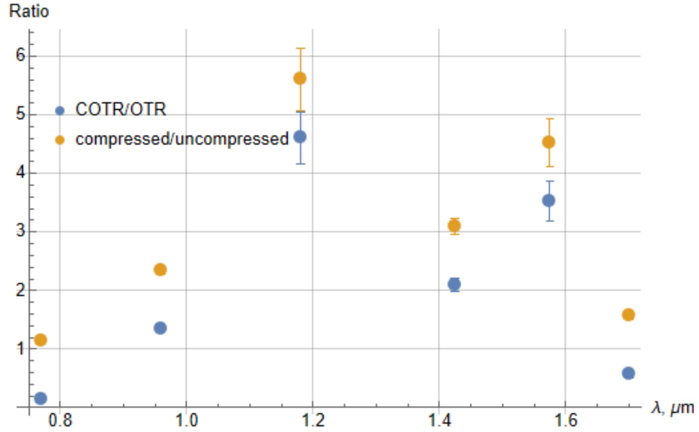
Old (August) data. Q=0.9nC. Good compression



FLASH data

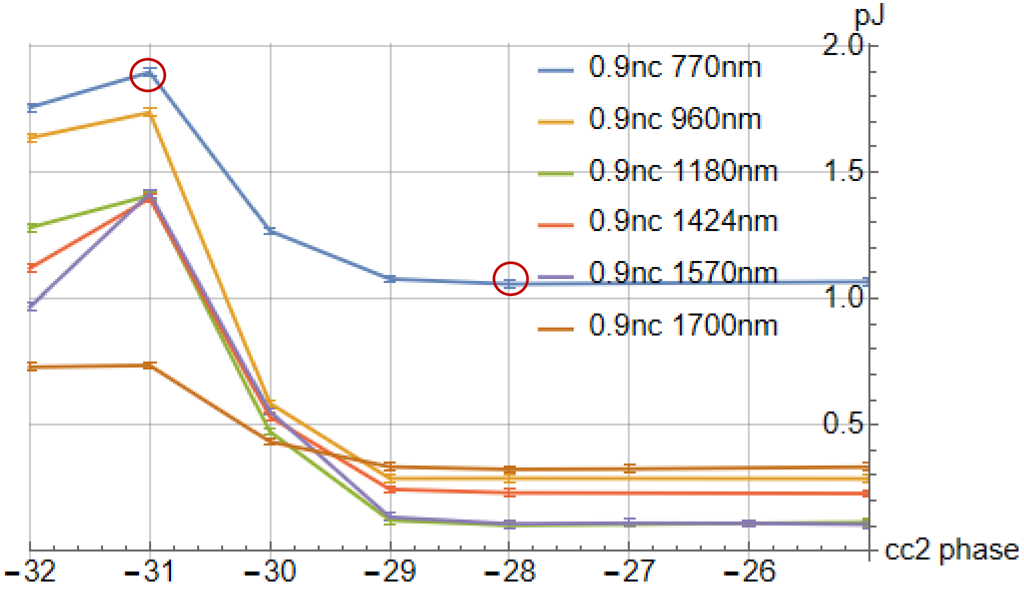


New data. Q = 0.63 nC. Worse compression

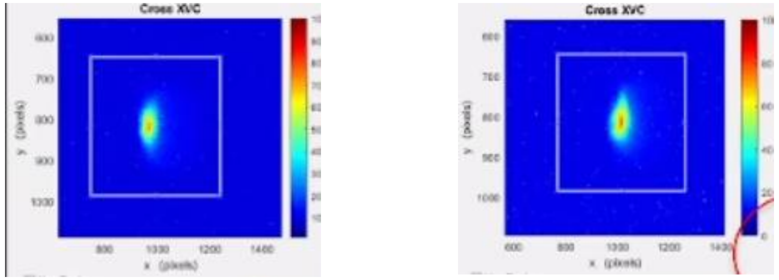


New data. Q = 1.3 nC. Worse compression

Test with CMOS camera

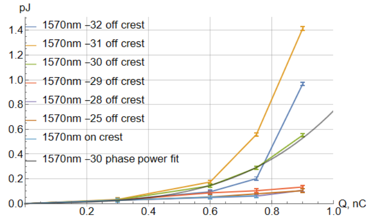


CMOS camera images were taken in 2 circled points



770 nm:
21% increase found on CMOS camera (0.6 nC) instead of 80% from the photodiode (0.9 nC)

Using the charge dependence fit:
~**70%** on CMOS vs **80%** on PD

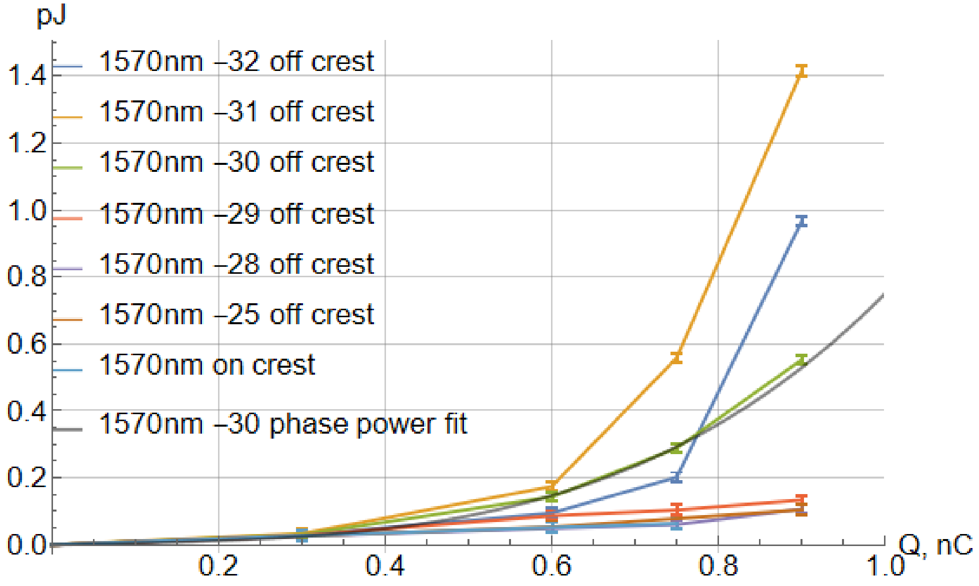


Signal is not visible by eye in 960nm.

OTR power conclusions

What signifies the Coherent Optical Transition Radiation (**COTR**):

- Dependence on beam longitudinal distribution, Large signal increase for some parameters (~20 times)
- Nonlinear (higher than linear) dependence on charge
- Larger relative fluctuations in COTR area



Future steps:

What can be done now:

- More measurements (CMOS camera, streak camera)
- New filters (> 1700nm)
- Calibrate the streak camera; CMOS camera
- Energy spectra without and with compression (might see energy modulation)

What can be done during the next runs:

- IRIS right after the vacuum window for the angular distribution measurements
- Manual generation of microbunching, including the transverse one
- Microbunching gain simulations for FAST

End of slide show, click to exit.

Thank you! Questions time.

Strange peak investigation (additional slide)