Using off Axis Undulator Radiation as a Longitudinal Electron Beam Diagnostic

Quinn Marksteiner
Nikolai Yampolsky
Heather Andrews
Sam Barber
Josh Coleman
Claudio Emma
Bricker Ostler
Bill Romero
Robert Ryne
Muhammed Zuboraj

8/2/2022

Los Alamos NATIONAL LABORATORY EST. 1943

NNSA National Nuclear Security Administration

Introduction

Basic Concept of Diagnostic

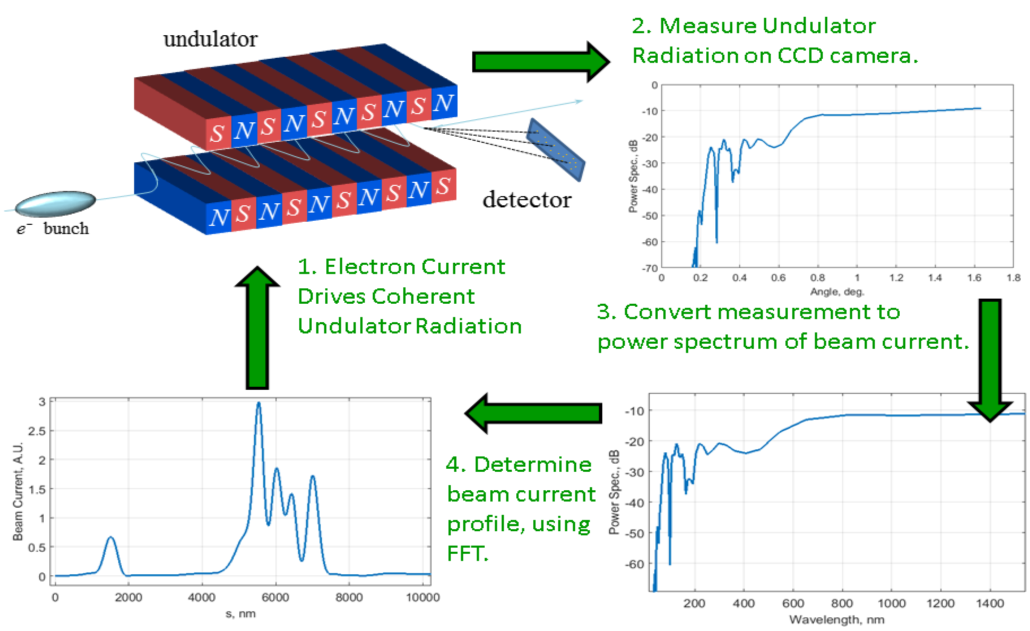


Figure 3: Illustration of the planned diagnostic. The current profile shown here is from particle in cell (PIC) simulations of BELLA [18].

- Use off-axis undulator to measure the temporal current profile of the BELLA electron beam.
- The electron bunch as a whole is coherent. Wavelengths that correspond to the coherent part of the bunch will radiate at an angle with respect to the undulator: $\lambda_0(\theta) = \frac{\lambda_w}{2\gamma^2}[(1 + a_w^2)\cos\theta + 2\gamma^2(1 - \cos\theta)]$ [1].
- By measuring the radiation at different angles, we will be able to determine the power spectrum of the electron bunch.
- Phase reconstruction methods can then be used to determine the temporal current profile of the electron beam.

[1] C.P. Neuman, W.S. Graves, and P.G. O'Shea, "Coherent off-axis undulator radiation from short electron bunches

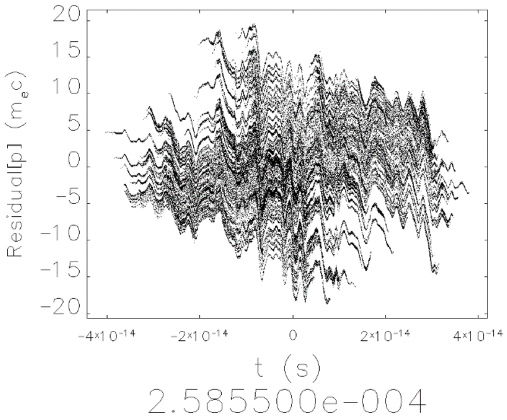
Why Off Axis Undulator Radiation?

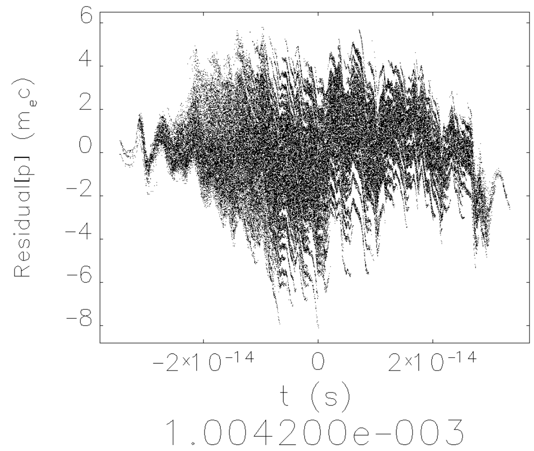
- There are other methods that generate coherent radiation from the electron bunch in order to measure its properties, including Coherent Transition Radiation (CTR) and bending magnet radiation. These other methods are much more perturbative to the electron beam than using a short, low K undulator, which is known not to spoil the emittance or energy spread of the electron beam.
- The transverse deflecting cavity method is a destructive measurement because the electron beam must be collected to determine the current profile.
- The electro-optic coupling method is single shot and non-destructive, but can only be used to measure temporal features greater than ~70 fs [2].
- If successful, the off-axis undulator radiation diagnostic will be a **single shot**, **non-destructive** measurement with **fs resolution**.
- Off axis undulator radiation is scalable to shorter bunch durations. There is no fundamental limit on the shortest bunch duration.

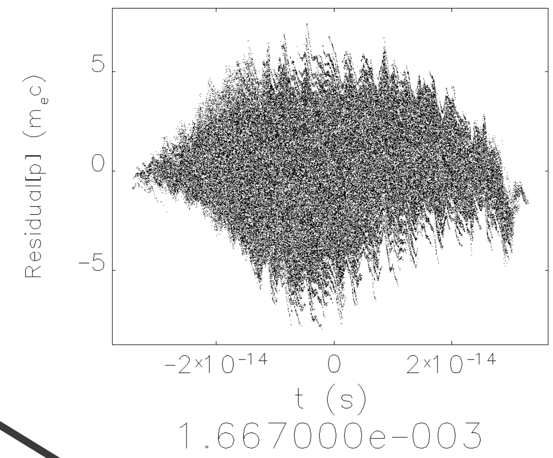
[2] I. Wilke, et al. Phys. Rev. ST-AB **14**, 120701 (2011)

Relevance to XFELs

The Microbunching Instability

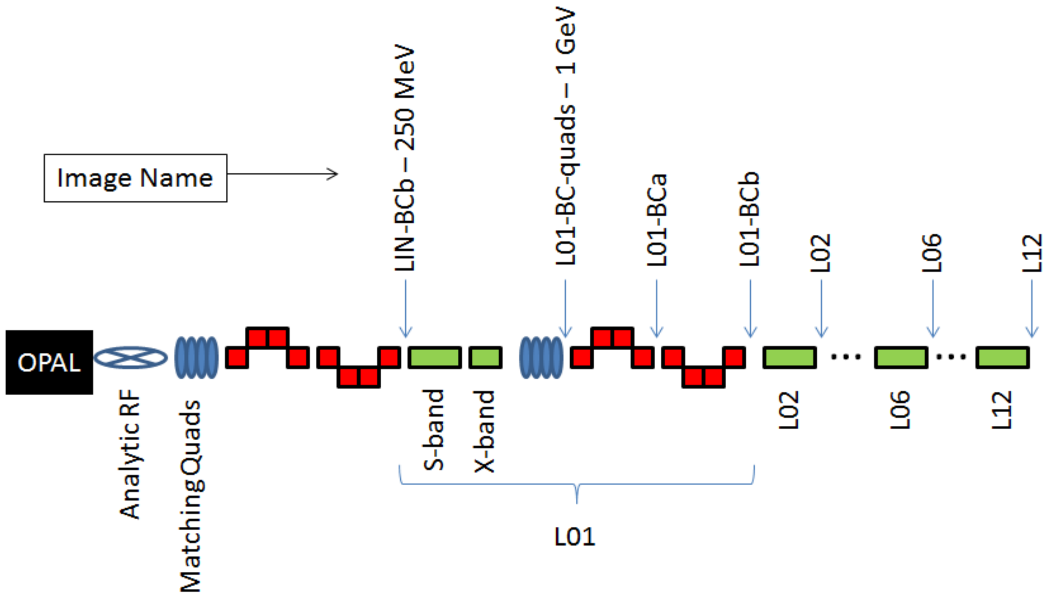


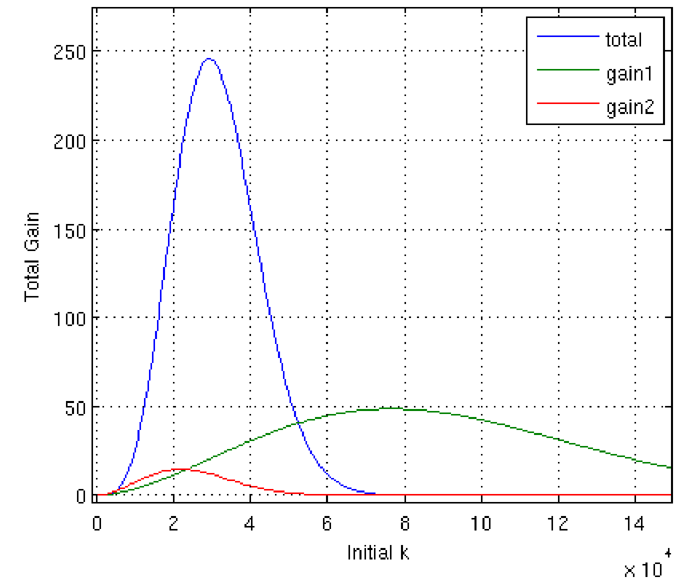




- At minimum final RMS energy, there is still some microbunching gain (~10).
- According to Elegant simulations, optimal laser heater heats beam to 6 keV, and has a final RMS energy spread (after chirp and bulk LSC are removed) of 1.05 MeV.
- Just meets requirement.

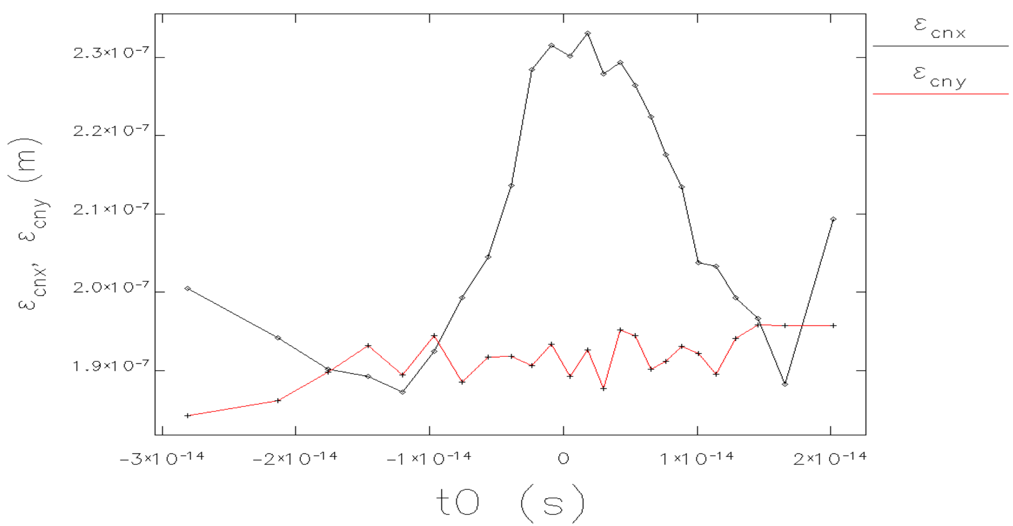
Diagnosing the Microbunching Instability





- MBI is a cascaded instability – initial random bunching is enhanced in each successive bunch compressing chicane.
- Our diagnostic will allow us to measure the evolution of MBI.
- Validate MBI models at other facilities, then use diagnostic to optimize MaRIE.

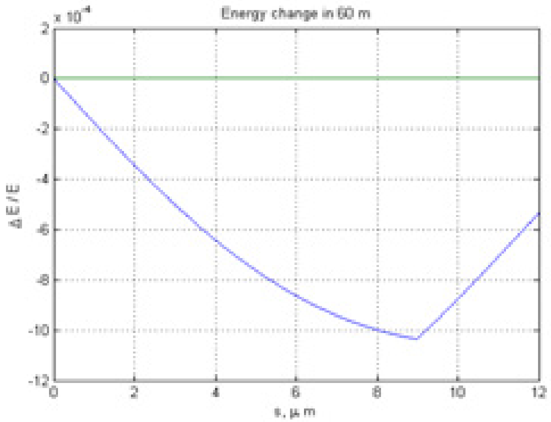
Diagnosing CSR from Bunch Compressors

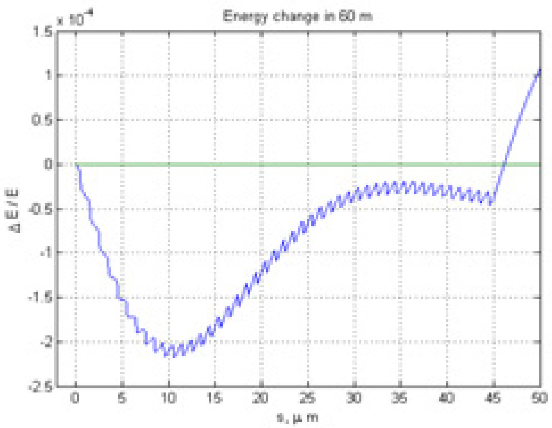


- Optimized double chicane increases slice emittance by only a small amount – from 0.19 μm to 0.23 μm.
- Projected emittance increases from 0.2 μm to 0.56 μm
- Measure change in longitudinal profile to validate CSR models.
- Compare projected emittance growth to photon output and coherence – need non-destructive to do this.

Resistive Wakes in Undulator Pipe

- Resistive wakes in undulator pipe leads to energy decay.
- Because this happens in undulator, and modifies different sides of beam with different energy, it can move parts of the beam out of FEL resonance.
- Depends on shape of electron bunch
- Our non-destructive diagnostic can allow us to correlate bunch profile with photon loss from resistive wake, and optimize to mitigate this effect.





Novel eSASE Concept to Improve FEL Performance

- Novel eSASE concept [1] could mitigate CSR, microbunching instability, and undulator wakes.
- Laser induced microbunches can be measured with our diagnostic.

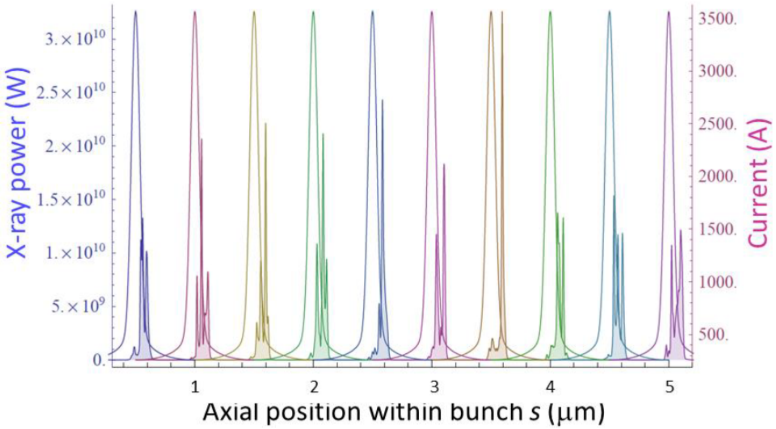
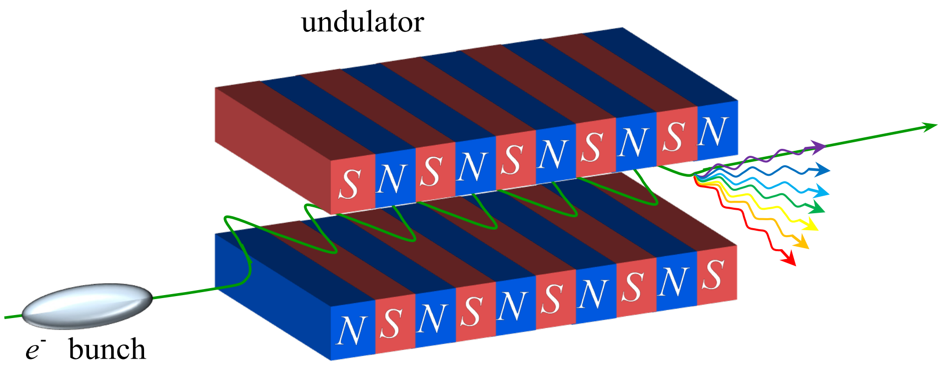


Figure 18. For this case, using a 1 μm laser, the 0.3 A X-rays slip ahead of the electrons by 90 nm over 3000 undulator periods. A compression ratio of only 6 was used for this figure (compression from 600 A to 3.6 kA), which generated relatively wider microbunches than a compression ratio of 10 would, allowing, in turn, shorter laser wavelengths without violating the slippage constraint.

General Idea

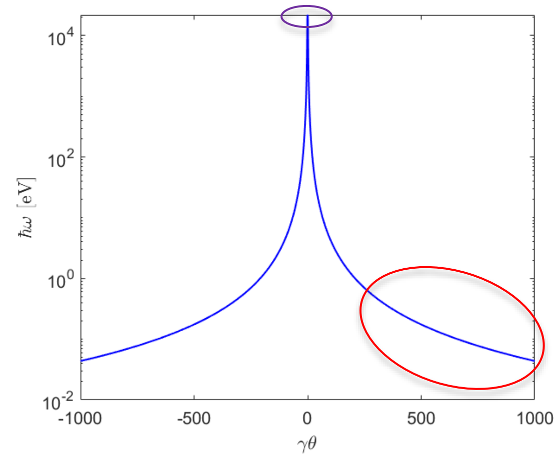
Coherent undulator radiation



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right) \sim \frac{\lambda_u \theta^2}{2}$$

no energy dependence!

Light sources

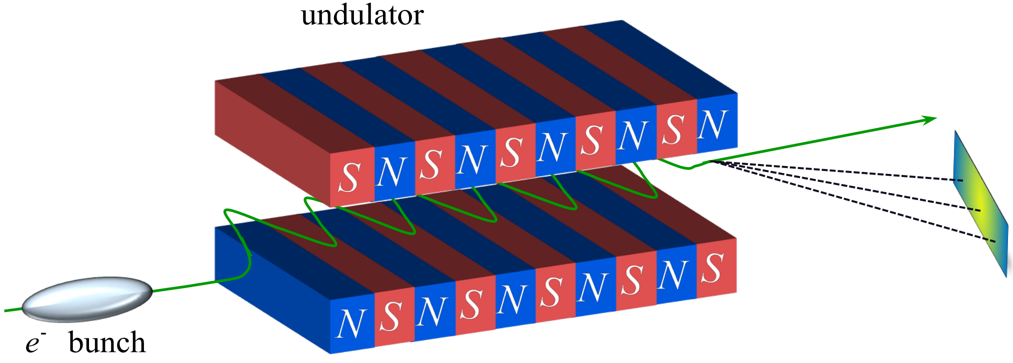


Coherent undulator radiation for few fs-long bunches

Single electron traveling through undulator emits synchrotron radiation. Radiation has strong dependence of frequency vs angle of emitted photons. Radiation from all electrons adds up in phase at low frequencies (large angles) – **coherent undulator radiation.**

Concept for diagnostics

1. Measure power flux at different angles



2. Find out Fourier spectrum of the bunch

$$\lambda = \frac{\lambda_u \theta^2}{2} \quad \Rightarrow \quad \theta = \sqrt{2\lambda/\lambda_u}$$

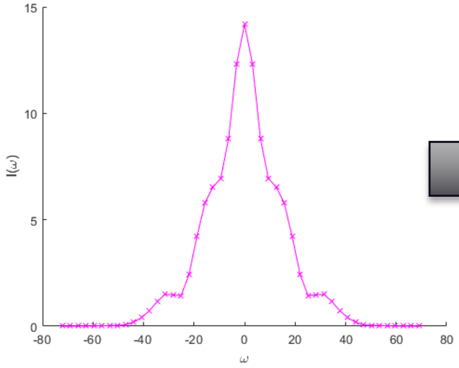
$$\left(\frac{dP}{d\omega}\right)_N = N^2 \left(\frac{dP}{d\omega}\right)_1 I(\omega)$$

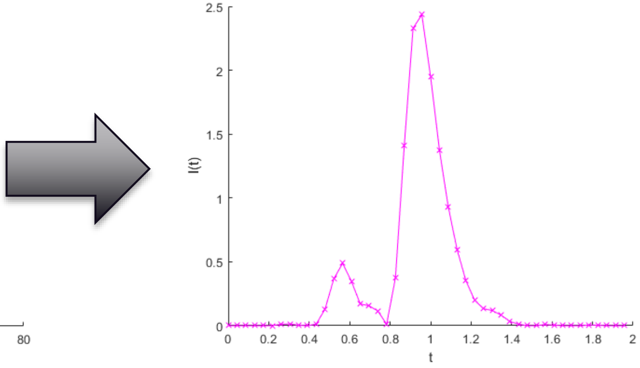
$$\frac{dP}{d\Omega} \propto \frac{dP}{d\omega} \propto |I(\omega)|$$

measure energy flux

get information about bunch spectrum

3. Reconstruct temporal bunch profile

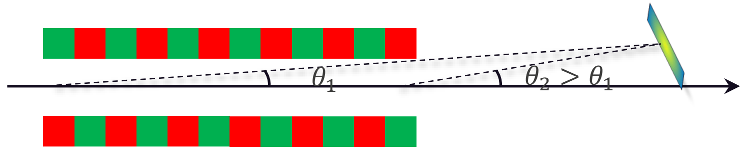




Eliminate chirp

<u>Geometrical optics:</u>

- Break radiation into an ensemble of rays
- Each ray is parametrized with its phase space coordinates
- Propagation of each ray follows linear optics



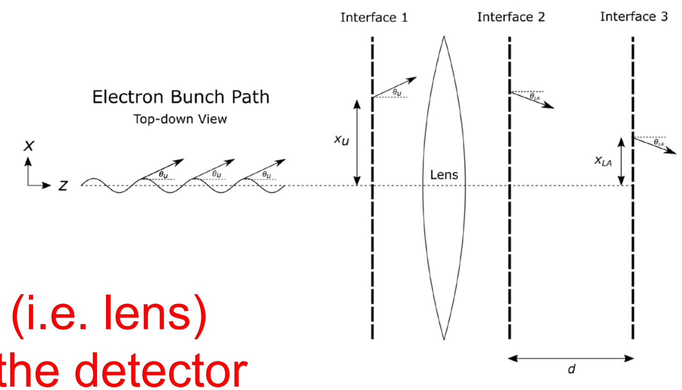
Type equation here.

$$\zeta = \begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} x \\ \theta \end{pmatrix} \qquad M_{drift} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \qquad M_{lens} = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \qquad M_{mirror} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

Rays with the same frequency (θ) have different transverse offset since they were emitted at different locations along the undulator

$$M = M_{drift} M_{lens} = \begin{pmatrix} 1 - d/f & d \\ -1/f & 1 \end{pmatrix}$$

$$x_f = (1 - d/f) x_i + d \cdot x_i'$$



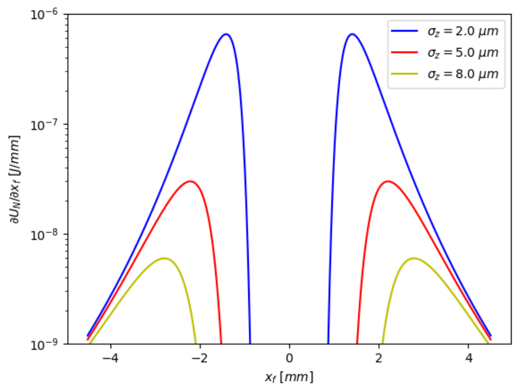
Use parabolic mirror (i.e. lens) to eliminate chirp at the detector

Expected energy flux at the detector

optics · coherent enhancement · Fourier spectrum

$$\frac{\partial U}{\partial x_f} = \frac{\partial \theta_i}{\partial x_f} \cdot \frac{\partial P_1}{\partial \theta} \cdot N^2 \cdot \frac{N_u \lambda_u}{c} \cdot |F(\theta)|^2$$

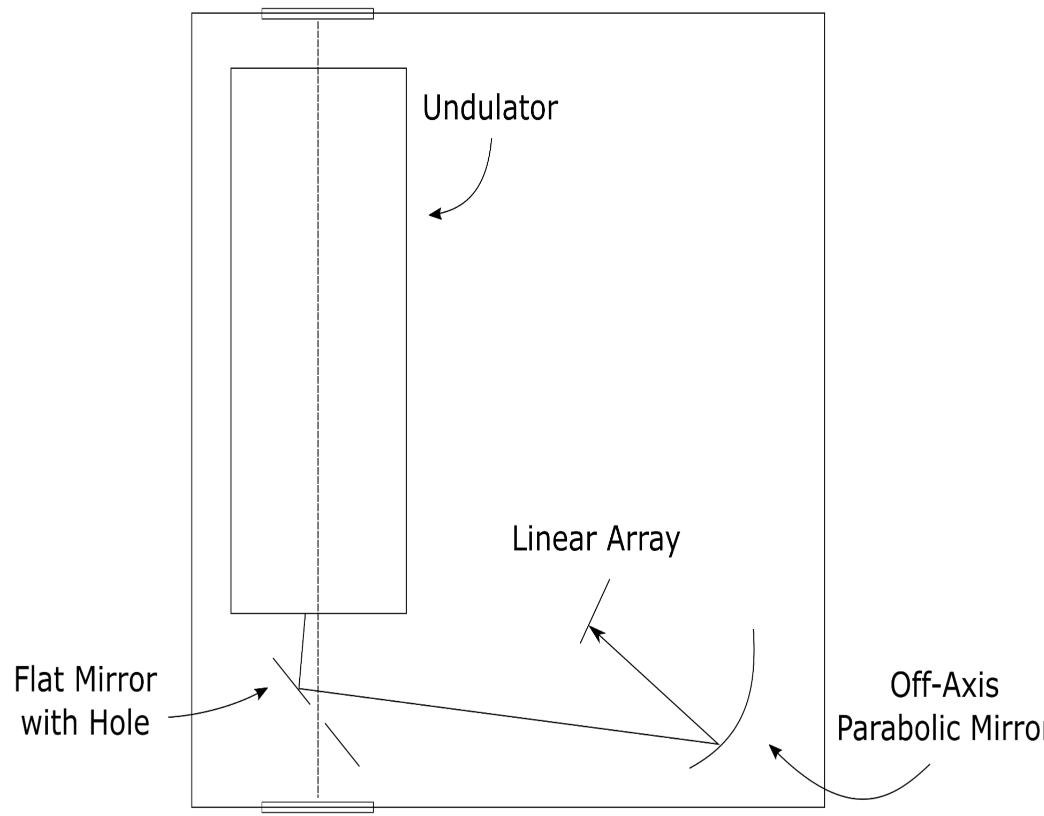
single electron radiation · emission time



Expected signal

Energy per pixel ~ few nJ
Total emitted energy ~ 6 mJ
Total detected energy ~ 1 mJ

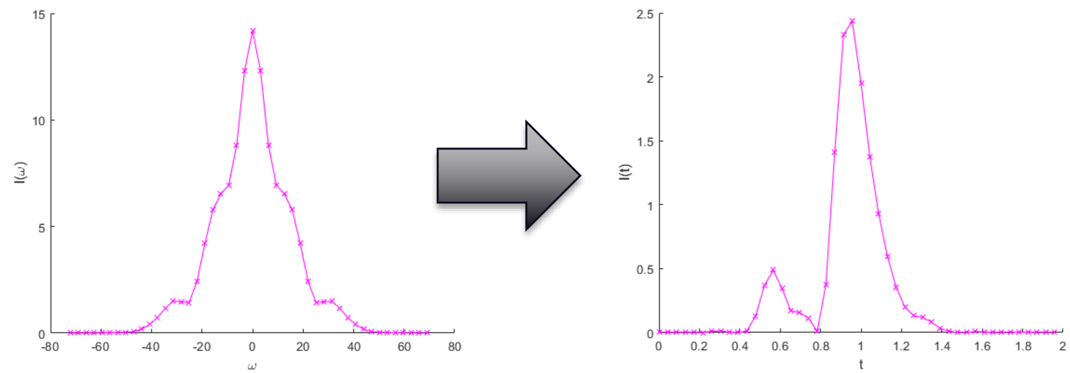
Current Experimental Setup (10/17/19)



Signal reconstruction

1D signal reconstruction

We have measured the Fourier spectrum of the signal and we need to reconstruct the signal in time domain. Information on phases is missing from the measurement.



$$F(\omega) = \int f(t) e^{i\omega t} dt \qquad |F(\omega)| \to f(t) \ ???$$

<u>Nonuniquiness of solution</u>

- $-f(t)$
- $f(t+\tau)$
- $f(-t)$
- Nontrivial differences, present in 1D

Commonly used reconstruction algorithms

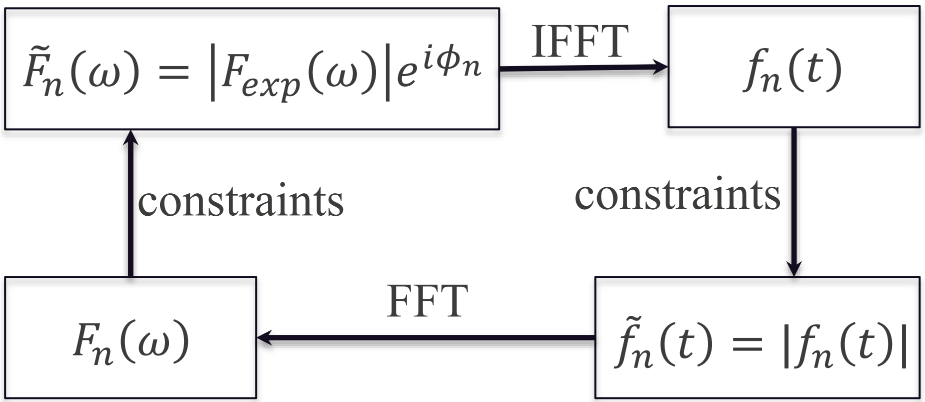
$$|F(\omega)| \quad \rightarrow \quad |F(\omega)|e^{i\phi(\omega)} \quad \rightarrow \quad f(t) = \frac{1}{2\pi}\int F(\omega)e^{i\omega t}d\omega$$

Kramers-Kronig relations

$$\phi(\omega) = \frac{2\omega}{\pi}\wp\int_0^\infty \frac{\ln|F(\omega')| - \ln|F(\omega)|}{\omega'^2 - \omega^2}\mathrm{d}\omega'$$

Unique solution, which may not coincide with original signal due to arbitrary invocation of causality

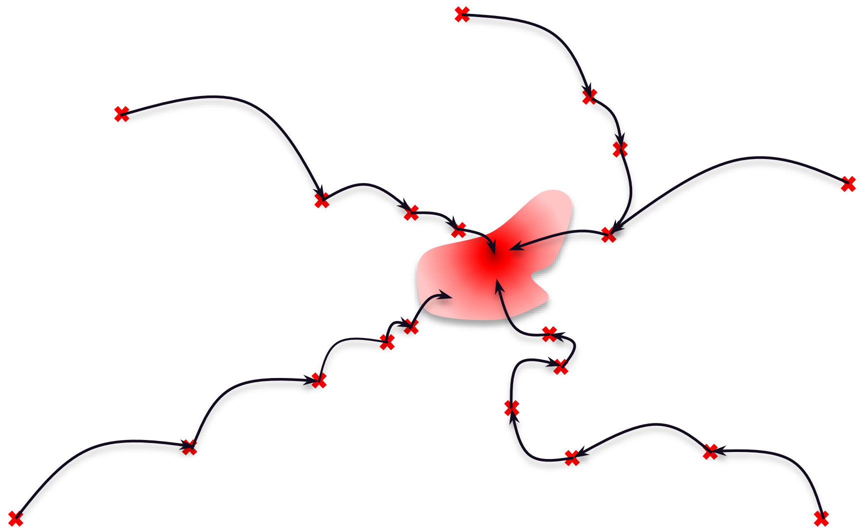
Gerchberg-Saxton algorithm



Multiple solutions, which depend on the initial choice of phases. All possible solutions are recovered (any given solution can be guessed from the beginning)

Reconstruction of the “most likely” solution

We would like to find all possible reconstruction (multiple GS algorithms with random initial conditions) and then find the most likely solution (averaging out all possible solutions)

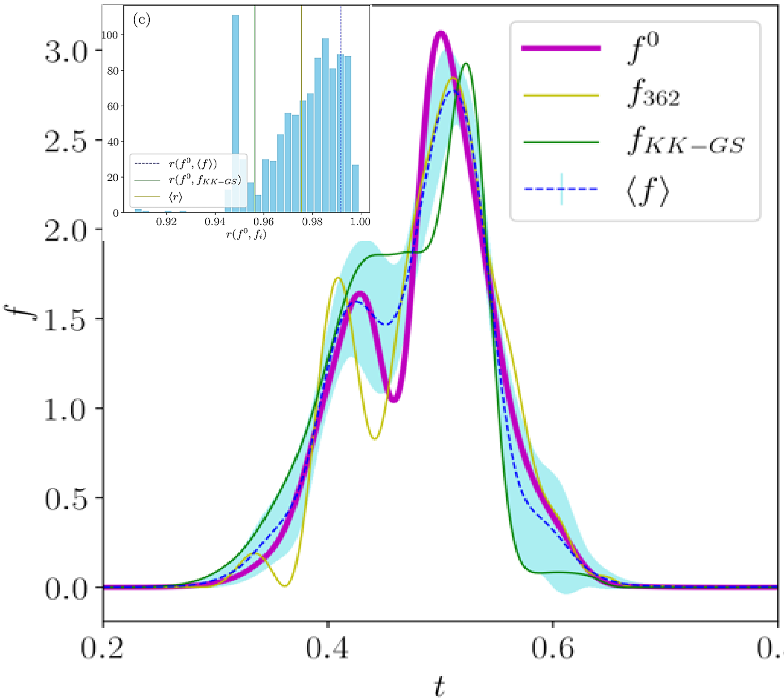


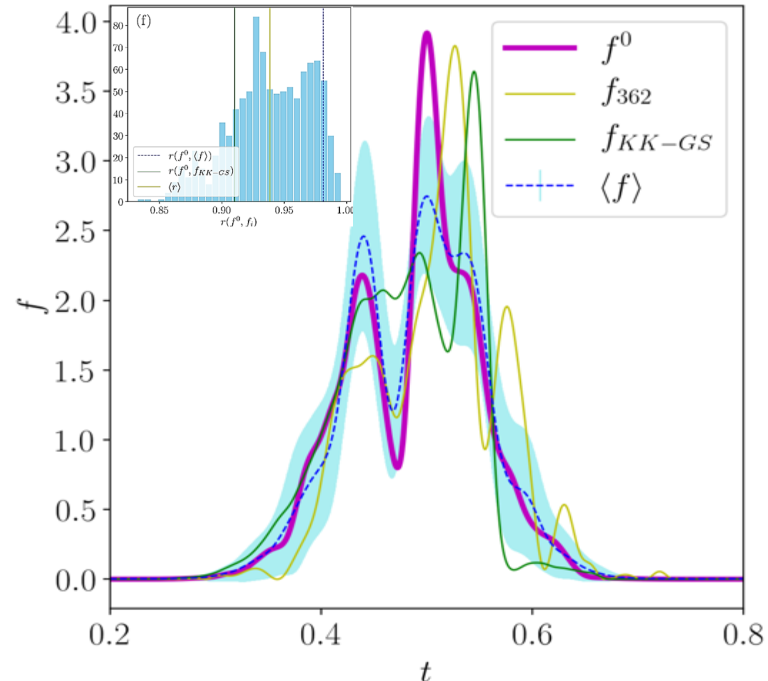
Innovations

- Use statistical analysis of GS solutions
- Introduce “error bar” caused by uncertainty in reconstruction
- Use autocorrelation function to eliminate time reversal and time shift uncertainty
- Use statistical analysis of convergence using multiple random initial signals
- Rigorous analysis of convergence in the presence of measurement noise

Average reconstructed solution vs individual reconstructions

Reconstruction is not perfect, but it recovers major trends of the original signal: width, amplitude, hills/valleys.

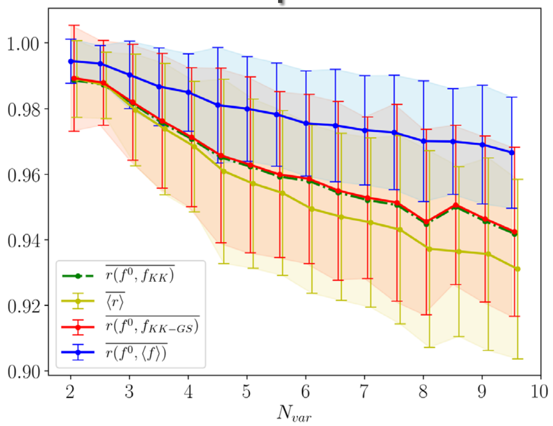




Average reconstruction provides a better fit than individual Gerchberg-Saxton and Kramers-Kronig reconstructions

Comparison of different algorithms

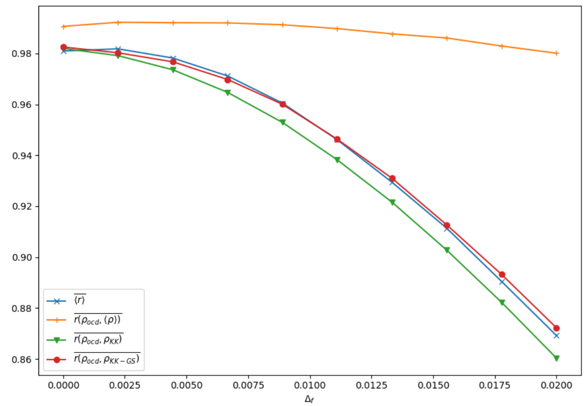
Noise-free performance

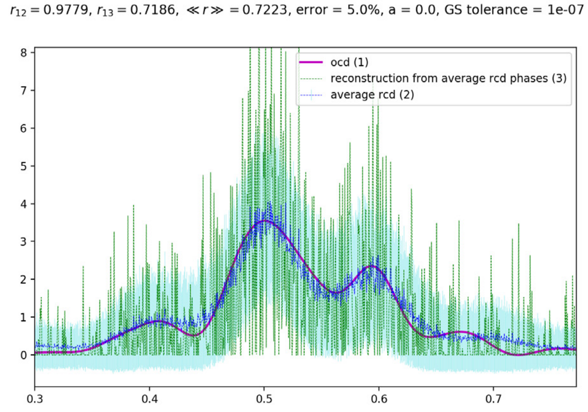


Average solution provides better reconstruction in statistical sense. The deviation from the original solution is about a factor of two smaller than for GS and KK algorithms.

Noise in measurements

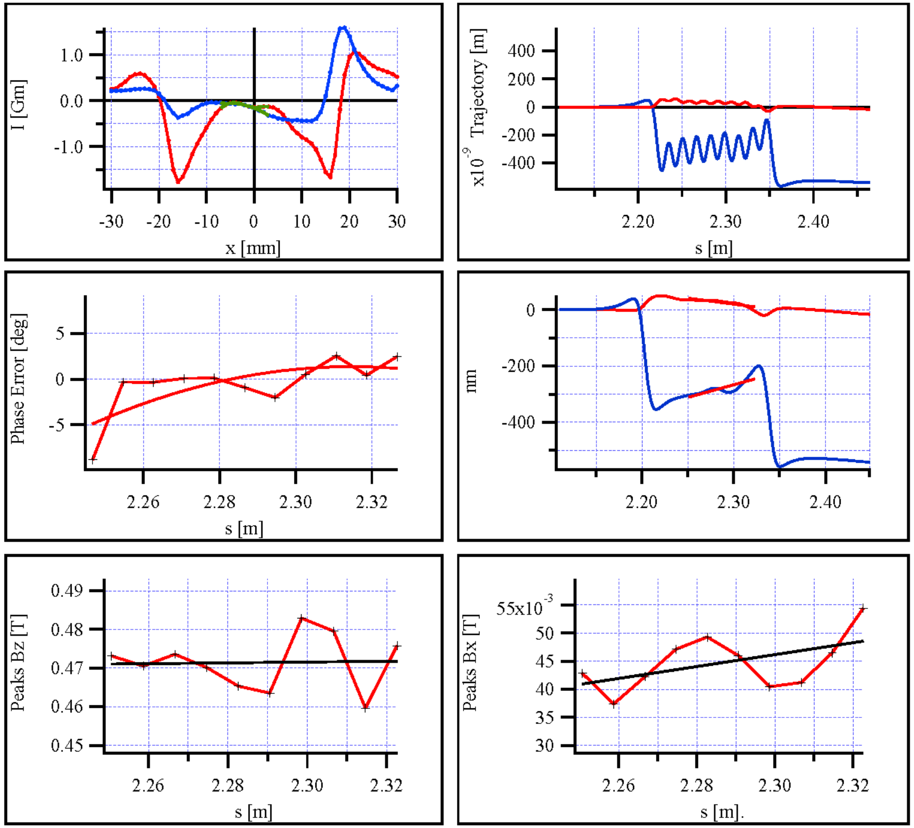
Real improvement comes when measurement noise is added. Averaging out beats the noise, while other algorithms quickly fail.





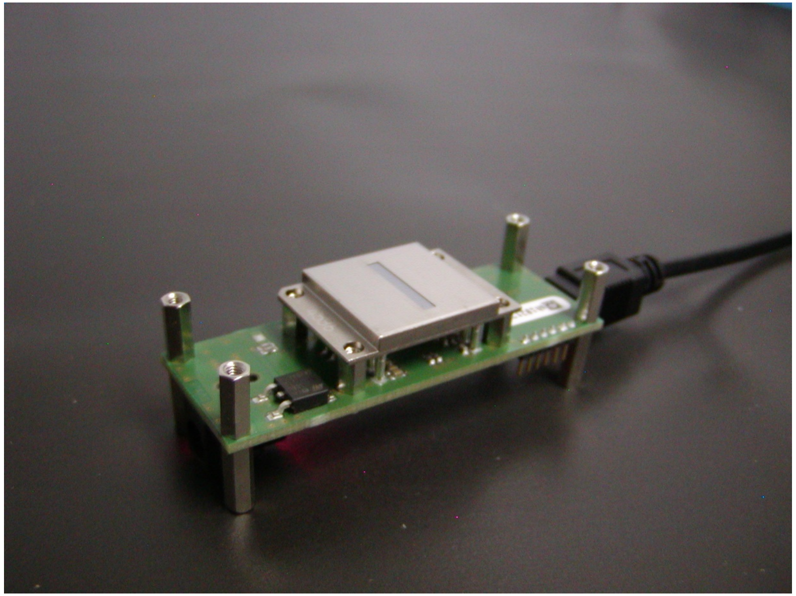
Experimental Progress

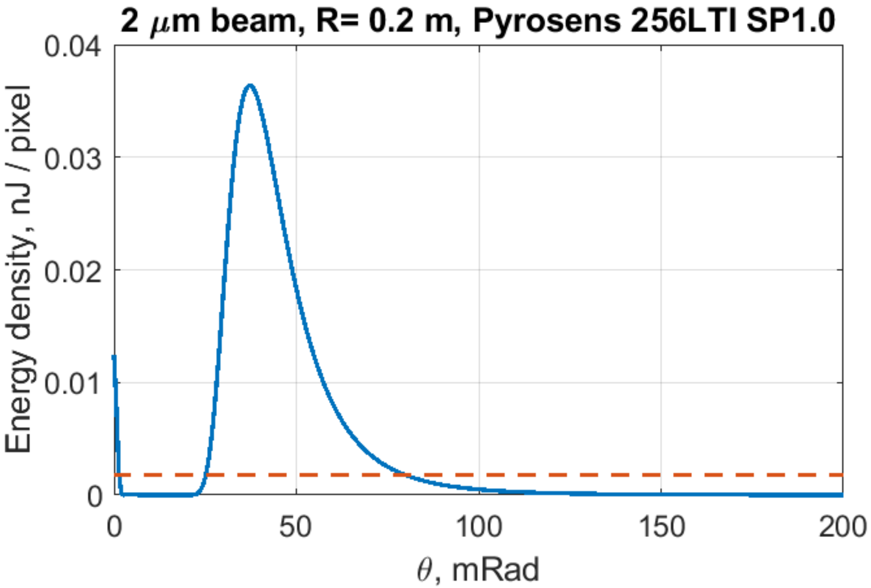
Undulator Fabricated and Delivered to Berkeley



Kyma Srl
S.S. 14 km 163,5 in Area Science Park – IT-34149 Trieste, Italy - VAT no.: IT-01131640326
Voice: +39.040.375.8796 – Fax: +39.040.375.8029 – E-mail: info@kyma-undulators.eu – web: www.kyma-undulators.eu

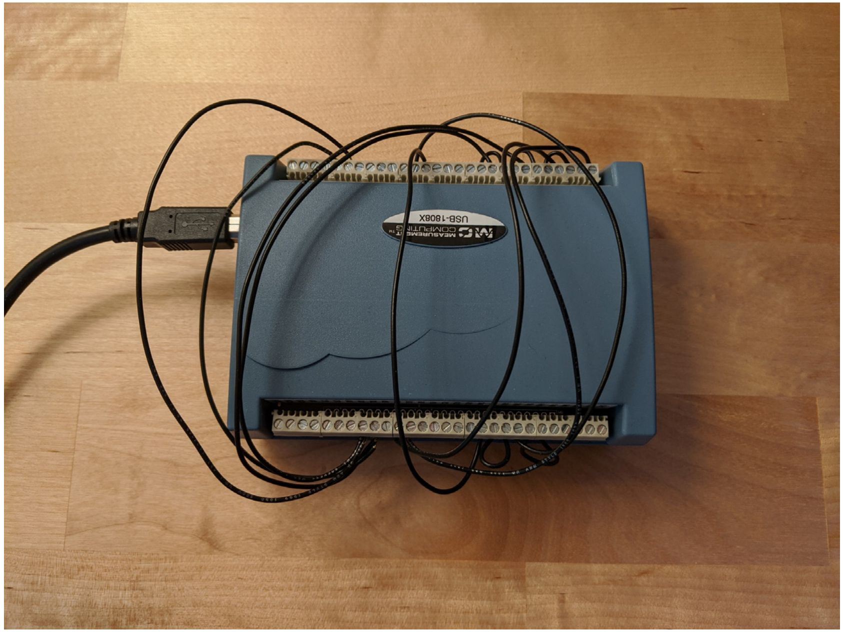
Pyrometer Predicted to Measure Signal Well Above Noise

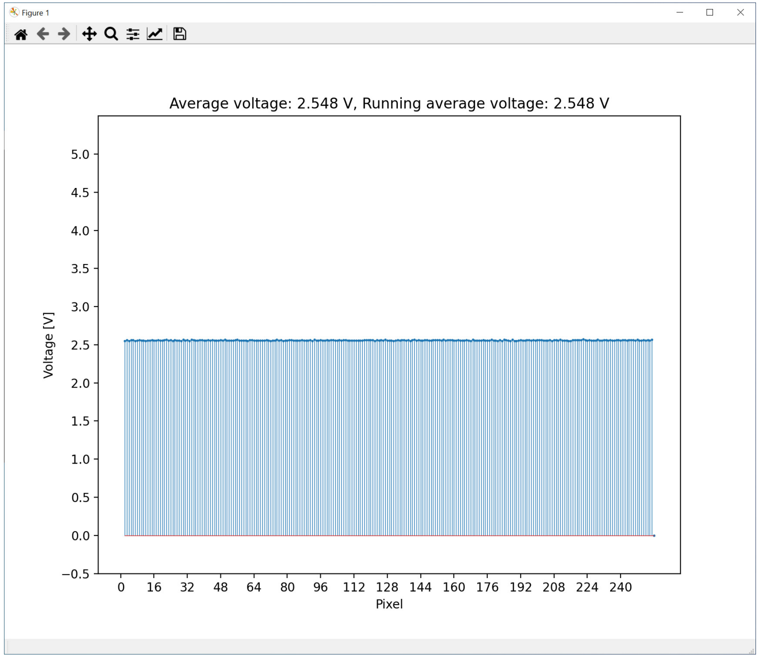




Pyrosens 256LTI SP1.0 has pixels that are 42 um x 1000 um. NEP (noise equivalent power) is 1.8 nW. Minimum integration time is 1 ms, which gives a "noise equivalent energy" of 1.8 pJ.

Pyrometer DAQ and Python Script



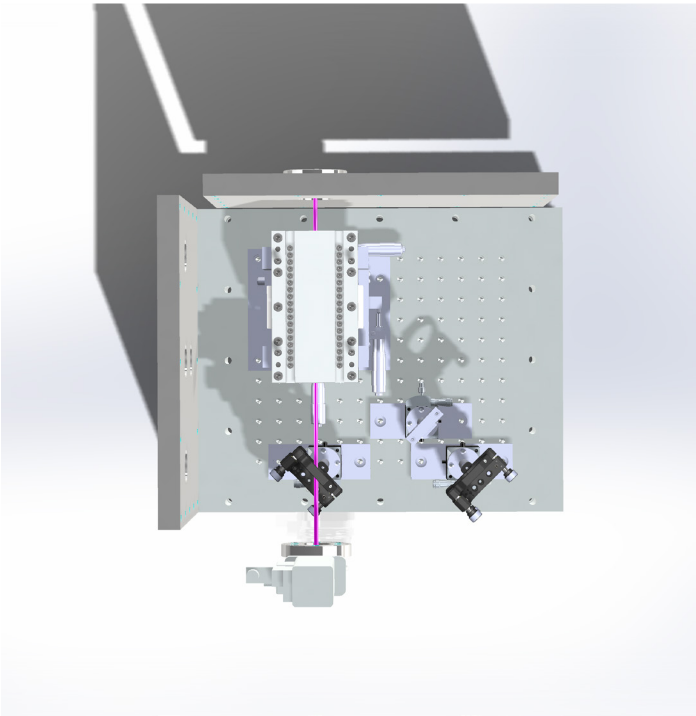


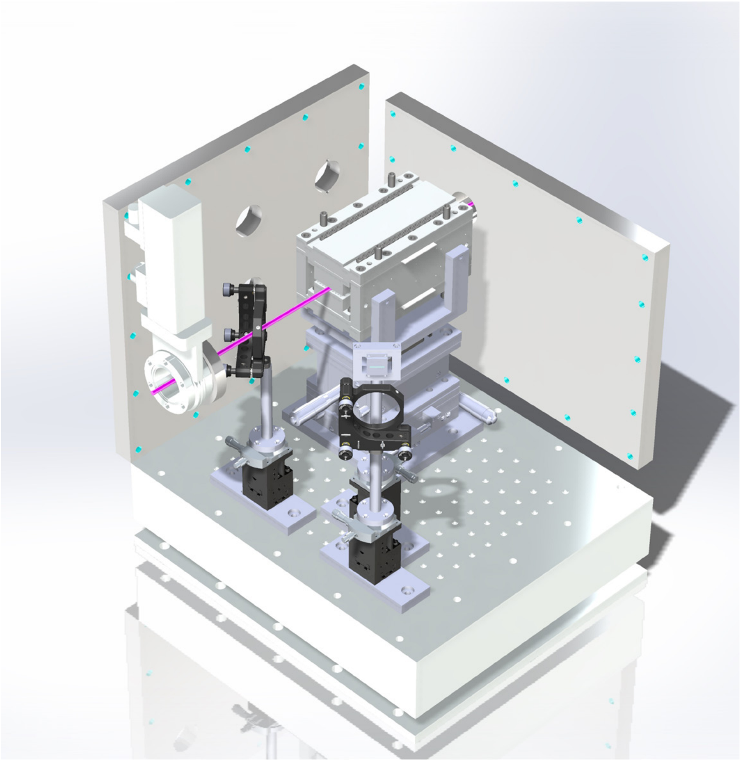
- Pyrometer came with an evaluation board that cannot trigger with BELLA experiment.
- We have developed a python script that interfaces with an DAQ board to interface between the pyrometer and BELLA.

Pyrometer Works in Vacuum

- Tested Pyrometer inside vacuum to verify that this is not an issue.
- Pyrometer did not break, and was able to detect IR signal.

Experimental Setup





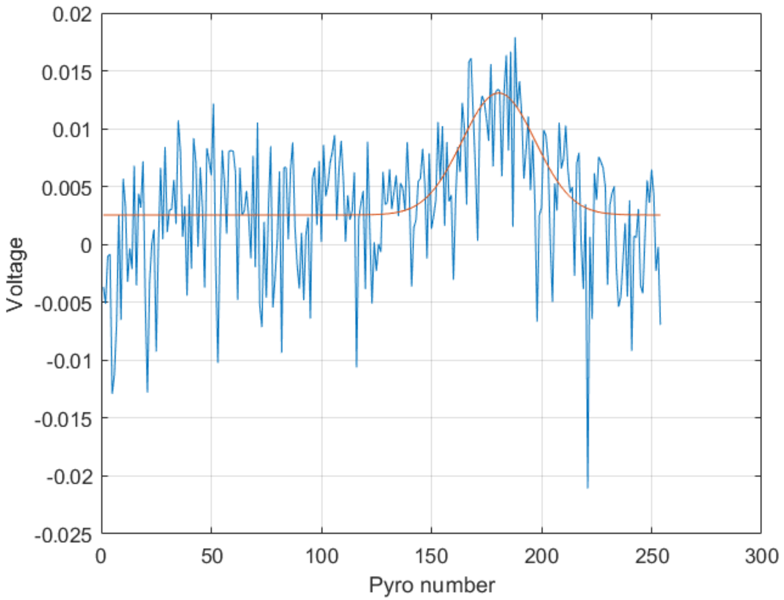
- Optics for final experiment: 1. separates IR from electron beam, 2. focuses beam onto pyrometer, and 3. eliminates chirp effect from finite undulator size.
- Most parts are here, a few in machine shop. Parts are at BELLA ready to test.

CTR Measurements at BELLA

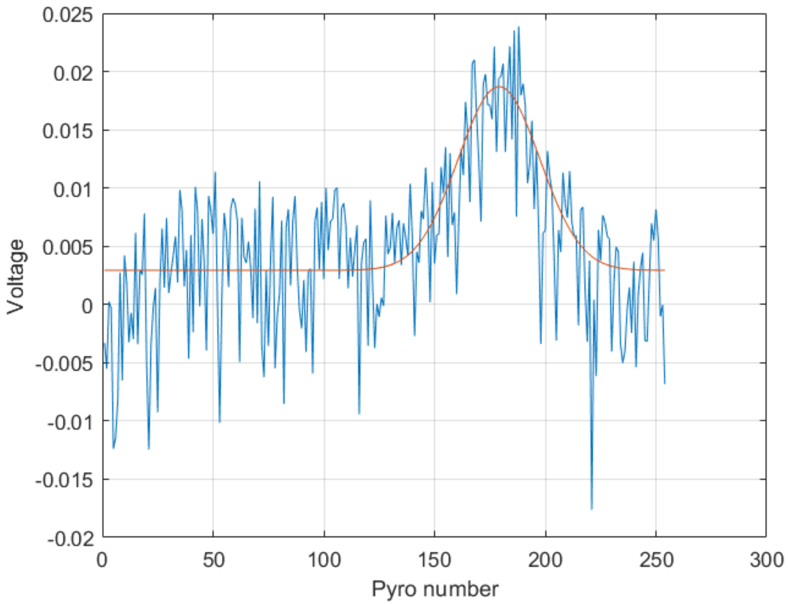
- Pyrometer is currently installed at BELLA, undulator has not yet been installed.
- We are measuring CTR signals that are (mostly) proportional to the bunch length of the signal.
- By scanning CTR signal vs. chicane strength, hope to extract information about pulse length and pulse shape.
- After this experimental campain, plan to install undulator and measure off-axis undulator signal

Short Pulse Pyrometer Tests

Laser Calibration of Pyrometer

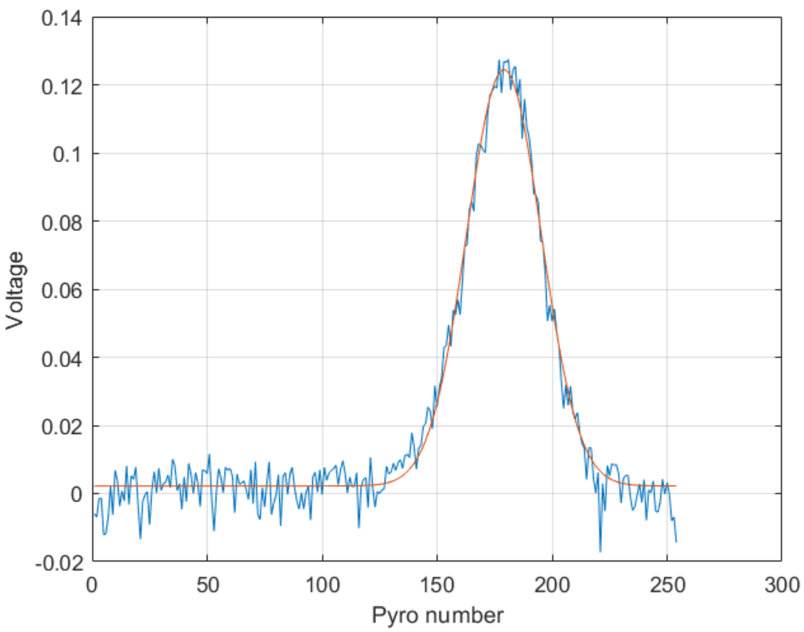


100 pulses in
1 ms, 26 nJ
total

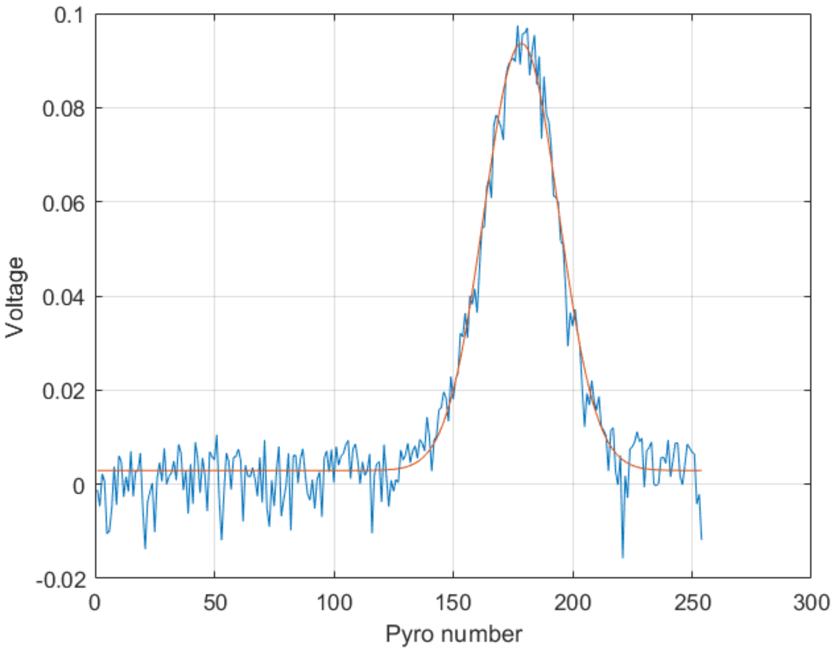


100 pulses in
1 ms, 44 nJ
total

Compare Long and Short Pulses

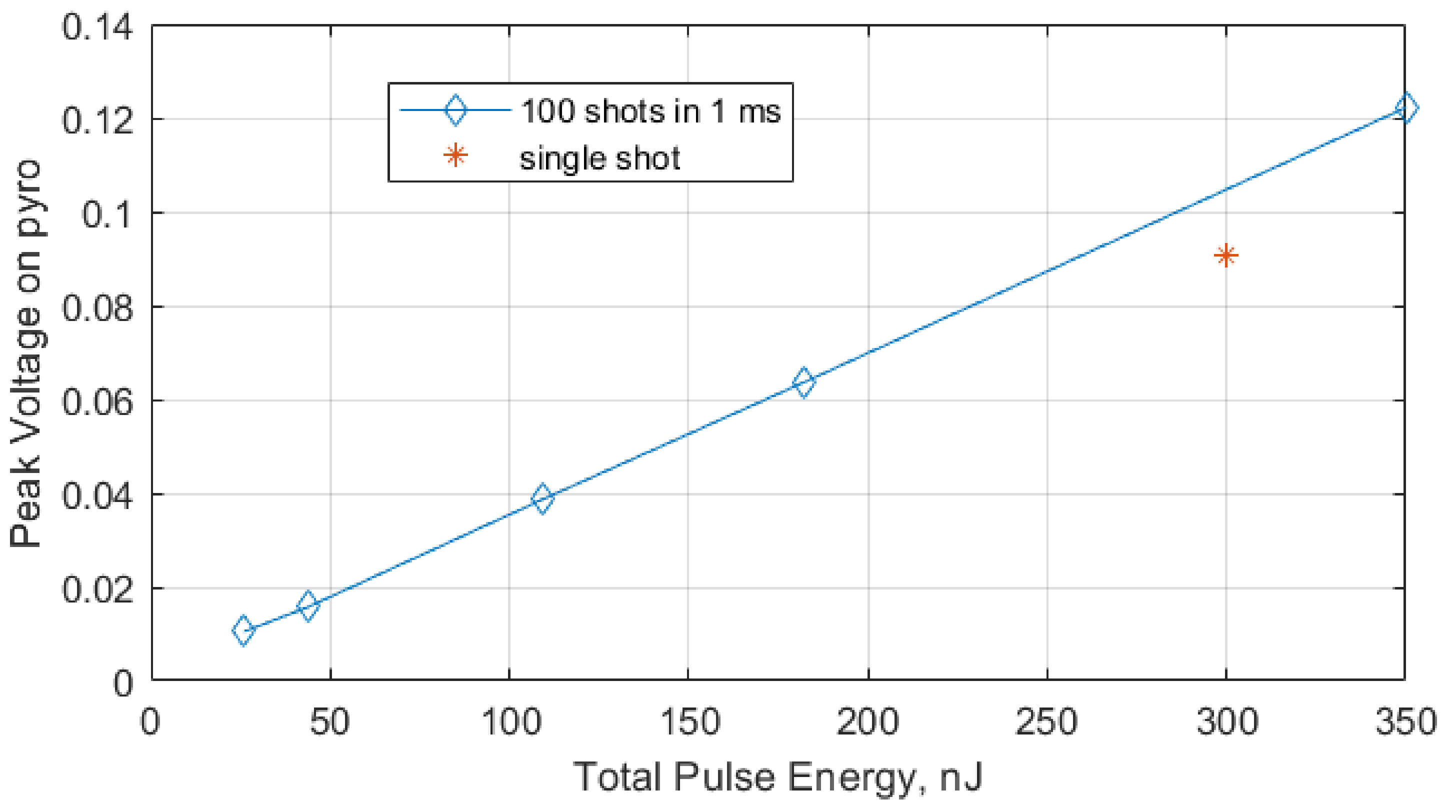


100 pulses in 1 ms, 350 nJ total



1 pulses in 1 ms, 300 nJ total

Calibration Does Not Change!



Conclusion

Conclusion

- We are developing a diagnostic that is single shot, non-destructive, with fs-resolution.
- This diagnostic would help us understand crucial physics issues in XFELs, including CSR, the microbunching instability, and resistive undulator wakes.
- Also would help develop advances accelerator / compression schemes such as eSASE.
- We have analytically and numerically modelled the generation of IR and the propagation to the pyrometer.
- We have found a way to numerically perform phase reconstruction in 1D.
- Experiment is developed: optics are designed and being built, pyrometer is working, undulator is at BELLA and has been tested.
- Currently performing CTR scans at BELLA using pyrometer, after plan to install undulator.