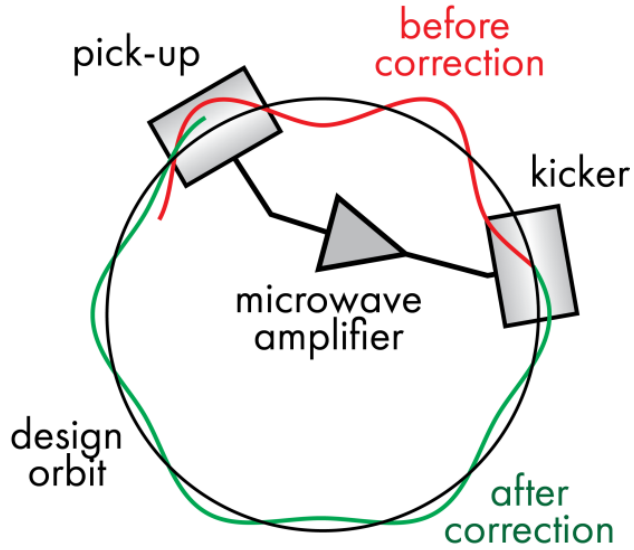
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Using synchrotron radiation to understand and manipulate particle beams

Sergei Nagaitsev
Fermilab/U.Chicago
Nov 17, 2022

Stochastic Cooling: an enabling technology for colliders



(simplified stochastic cooling system)

$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi\sigma_x{}^*\sigma_y{}^*}$$

1984 Nobel: van der Meer/Rubbia

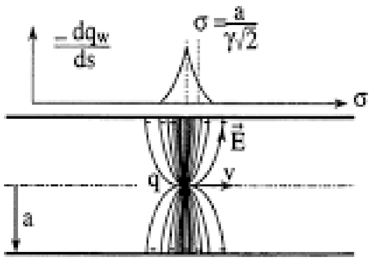
Simon van der Meer (COOL 1993 workshop, Montreux):

"How then can cooling work? It must necessarily be through deformation of phase space, such that particles move to the center of the distribution and (to satisfy Liouville) the empty phase space between the particles moves outwards. Clearly, the fields that do this must have a very particular shape, strongly correlated with particle position. In fact, at least two conditions must be satisfied:

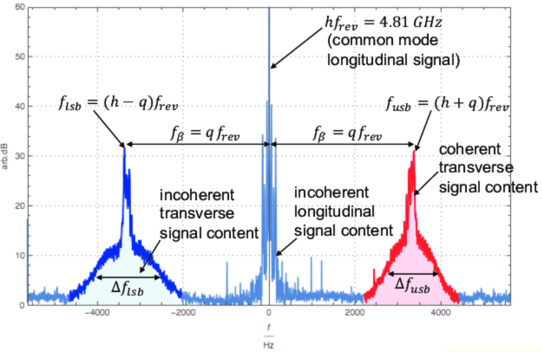
1. The field that cools a particular particle must be correlated with the particle's phase-space position. **In short, the field must know where each particle is.**
2. The field that pushes a particular particle towards the centre should preferably push the empty phase-space around it outwards. **It should therefore treat each particle separately.**

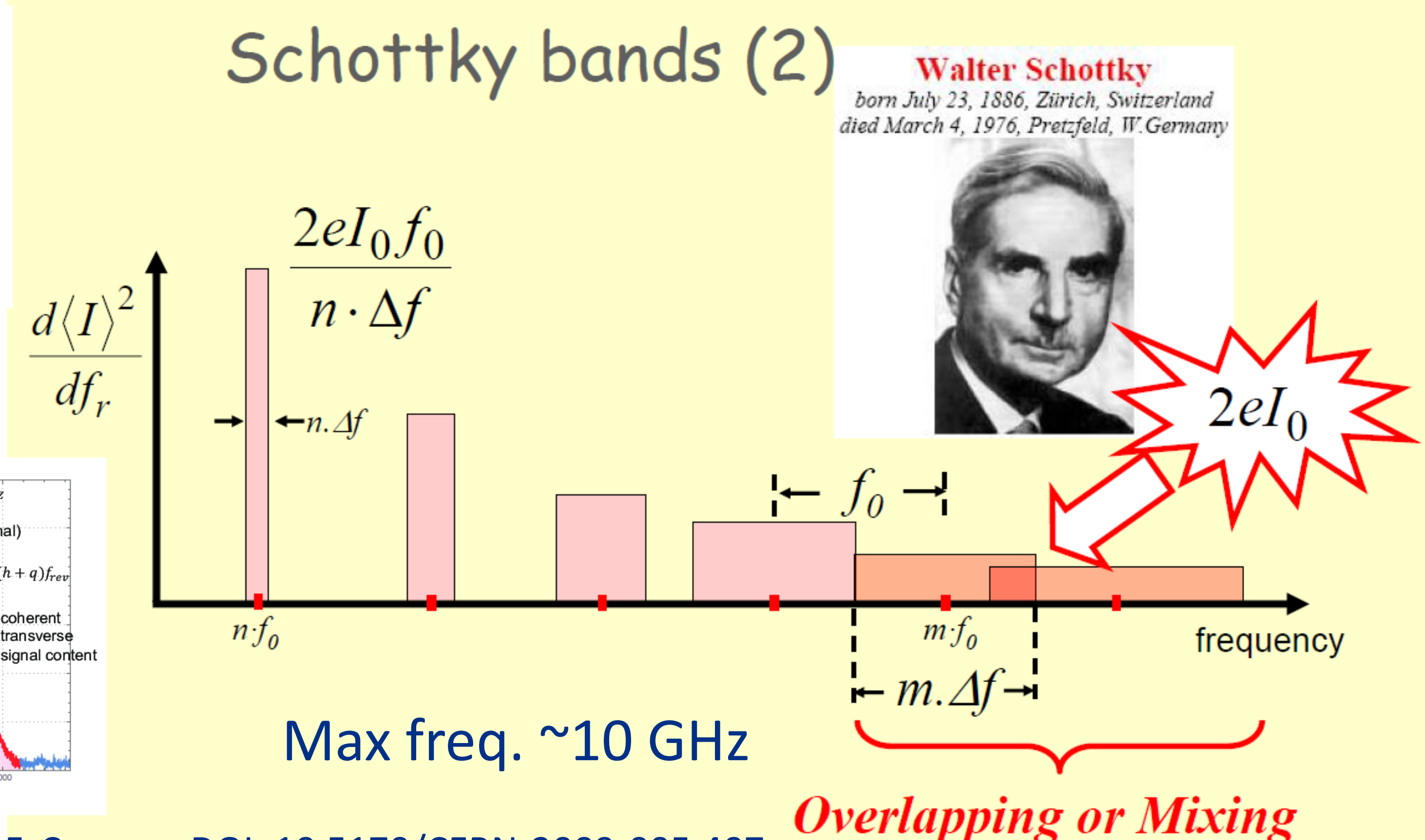
With stochastic cooling, these two conditions are clearly corresponding to the function of the pickup and kicker. **Both must be wide-band in order to see individual particles as much as possible**."

Schottky noise in rings



Typical LHC beam Schottky signals (credit: T. Lefevre)



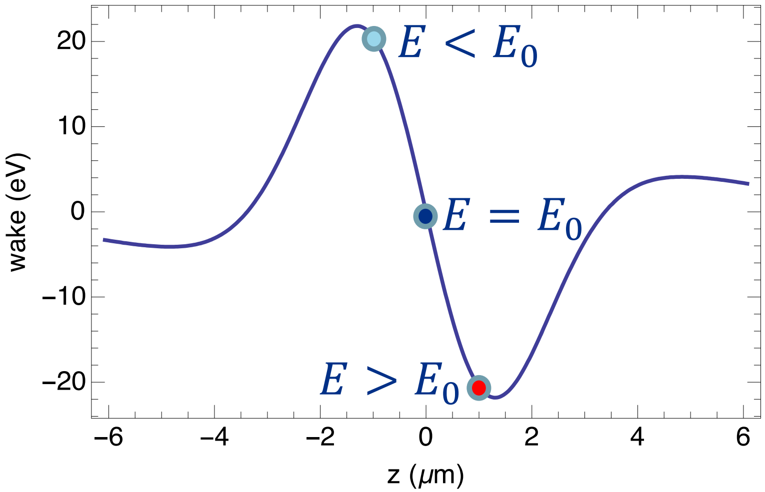


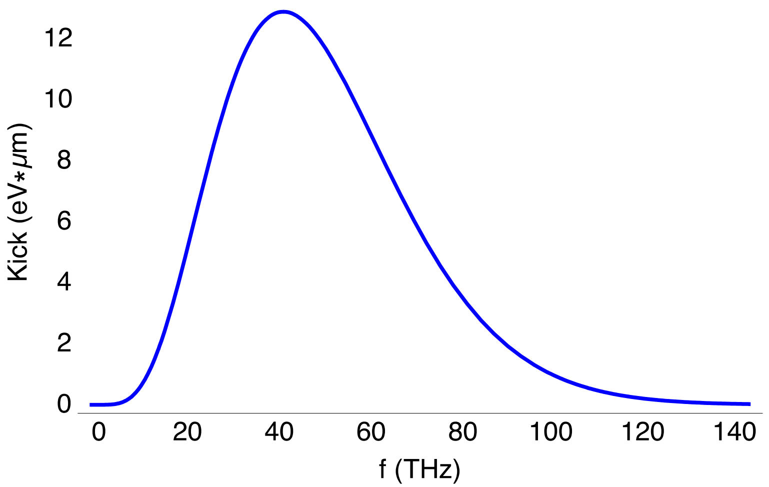
Max freq. ~10 GHz

F. Caspers, DOI: 10.5170/CERN-2009-005.407

First observed in n 1972 in the CERN–ISR (Intersecting Storage Rings) followed in the same year by the first publication of the stochastic cooling idea by Simon van der Meer.

Beam cooling in the proposed EIC





Case	100 GeV	275 GeV
Proton Bunch Length (cm)	7	6
Electron Normalized Emittance (x/y) (mm-mrad)	2.8 / 2.8	2.8 / 2.8
Electron Bunch Charge (nC)	1	1
Electron Bunch Length (mm)	14	7
Electron Fractional Energy Spread	1e-4	1e-4
Modulator/Kicker Length (m)	39 / 39	39 / 39
Amplifier Drift Lengths (m)	43	43
Proton Horizontal Dispersion in Modulator & Kicker (m)	1.108	1.36
Horizontal / Longitudinal IBS Times (hours)	2.0 / 2.5	2.0 / 2.9
Horizontal / Longitudinal Cooling Times (hours)	1.8 / 2.3	1.9 / 3.0

The proposed bandwidth is ~ 40 THz

Electron and photon interference in a storage ring

Using Fluctuations to Measure Beam Properties

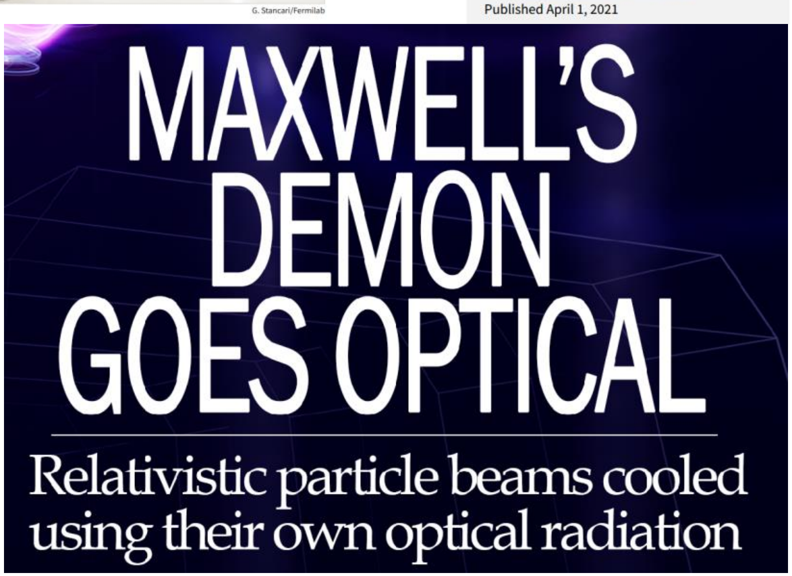
April 1, 2021 • *Physics* 14, s41

A new way of measuring a vital property of electron beams helps prepare researchers for next-generation synchrotron light sources.

G. Stancari/Fermilab

Measurements of undulator radiation power noise and comparison with *ab initio* calculations
Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim
Phys. Rev. Accel. Beams 24, 040701 (2021)
Published April 1, 2021

Transverse Beam Emittance Measurement by Undulator Radiation Power Noise
Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim
Phys. Rev. Lett. 126, 134802 (2021)
Published April 1, 2021



I. Lobach,
UChicago
Ph.D. 2021
2022 Faraday Cup

J. Jarvis,
Fermilab

V. Lebedev,
Fermilab

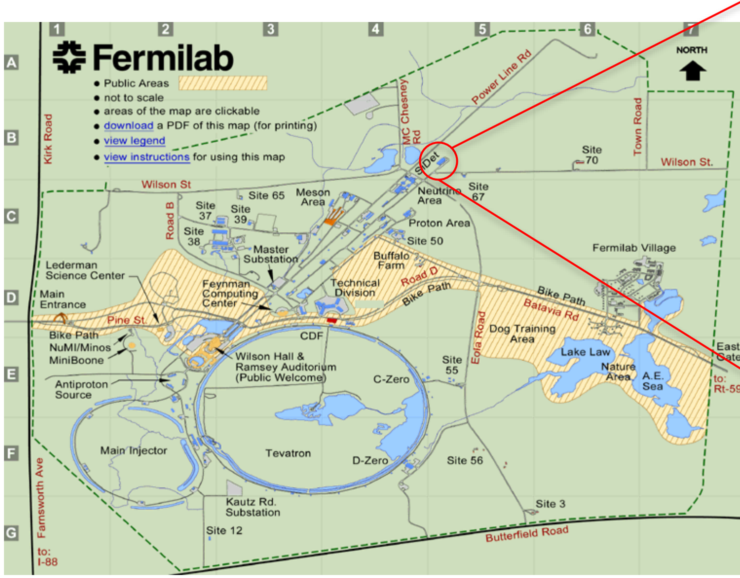
J. Jarvis et al., "First Experimental Demonstration of Optical Stochastic Cooling", ***Nature*** volume 608, pages 287–292 (2022)

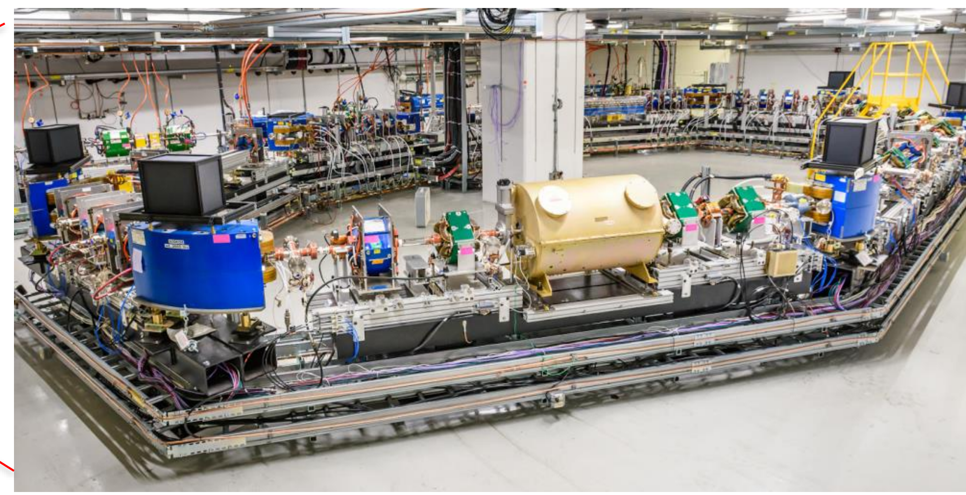
Synopsis

1. Undulator radiation fluctuations for many electrons
2. Undulator radiation: quantum fluctuations for a single electron
3. Optical Stochastic Cooling demonstration

Fermilab's Integrable Optics Test Accelerator (IOTA)

First beam Aug 21, 2018





Circumference: 40 m (133 ns)

Electron energy: 100-150 MeV

Primary purpose of IOTA: accelerator science and technology research

Integrable Optics Emerges

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **13**, 084002 (2010)

Nonlinear accelerator lattices with one and two analytic invariants

V. Danilov
Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830, USA

S. Nagaitsev
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
(Received 3 March 2010; published 25 August 2010)

HB 2010 FERMILAB-CONF-10-390-AD

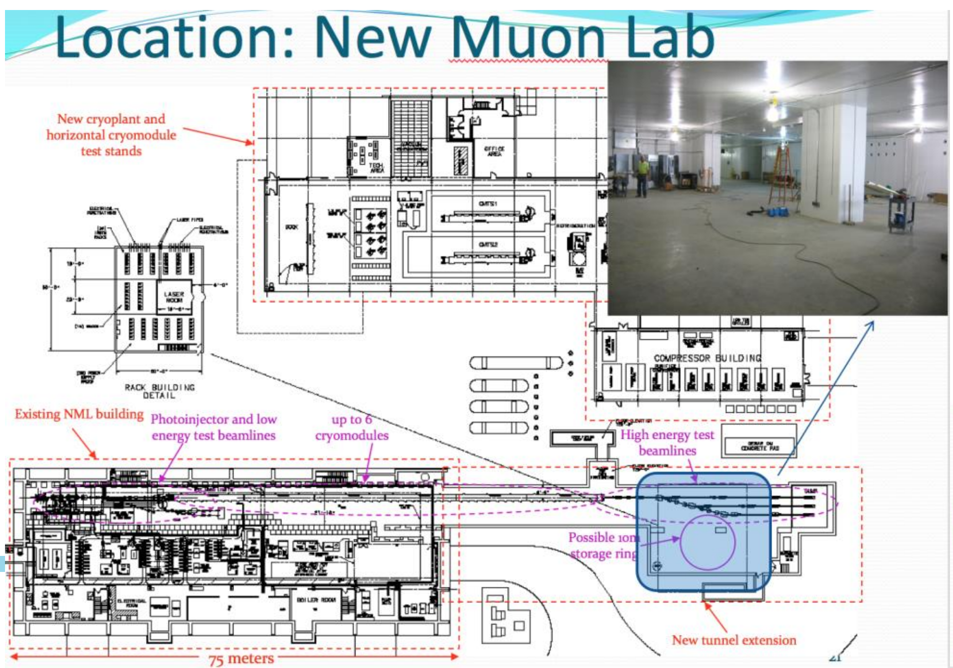
NONLINEAR OPTICS AS A PATH TO HIGH-INTENSITY CIRCULAR MACHINES*

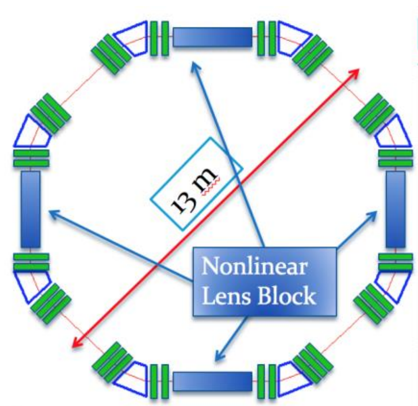
S. Nagaitsev#, A. Valishev FNAL, Batavia, IL 60510, U.S.A
V. Danilov SNS, Oak Ridge, TN 37830, U.S.A.

PAC'11 FERMILAB-CONF-11-114-AD-APC

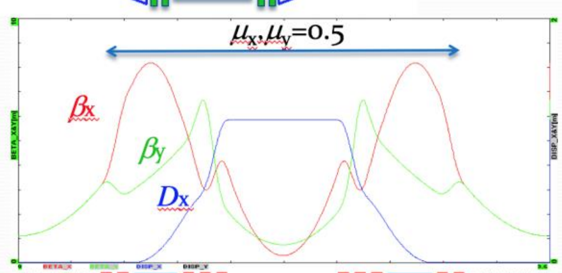
RING FOR TEST OF NONLINEAR INTEGRABLE OPTICS

A. Valishev, S. Nagaitsev, V. Kashikhin FNAL, Batavia, IL 60510, U.S.A.
V. Danilov SNS, Oak Ridge, TN 37830, U.S.A.



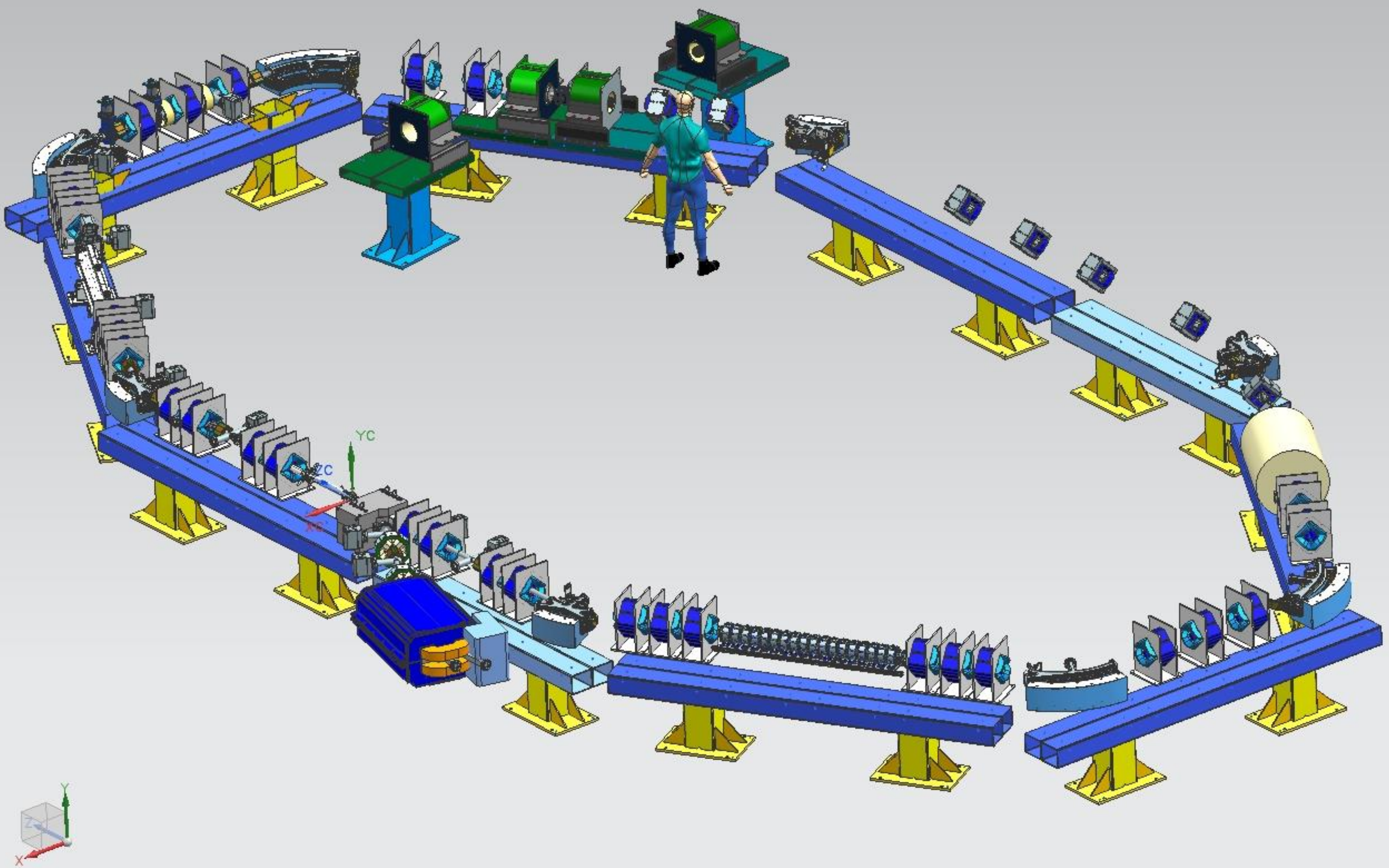


e- Energy	150 MeV
Circumference	38 m
Dipole field	0.5 T
Betatron tunes	Qx=Qy=3.2 (2.4 to 3.6)
Radiation damping time	1-2 s (10^7 turns)
Equilibrium emittance, rms, non-norm	0.06 μm



Nonlinear lens block	
Length	2.5 m
Number of elements	20
Element length	0.1 m
Max. gradient	1 T/m
Pole-to-pole distance (min)	~ 2 cm

IOTA Layout



Acknowledgments

- I. Lobach, V. Lebedev, A. Romanov, G. Stancari, A. Valishev, A. Halavanau, Z. Huang, and K.-J. Kim (Experiments 1 and 2)
  – U.Chicago, Fermilab, SLAC, ANL

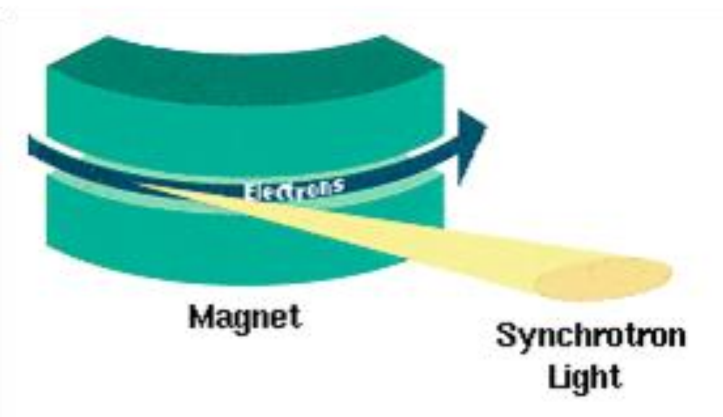
- J. Jarvis, V. Lebedev, A. Romanov, D. Broemmelsiek, K. Carlson, S. Chattopadhyay, A. Dick, D. Edstrom, I. Lobach, H. Piekarz, P. Piot, J. Ruan, J. Santucci, G. Stancari, A. Valishev (Experiment 3)
  – Fermilab, U.Chicago, NIU

Synchrotron light sources

When the trajectories of high-energy electrons are bent by magnetic field, they emit radiation

Sources of magnetic field:

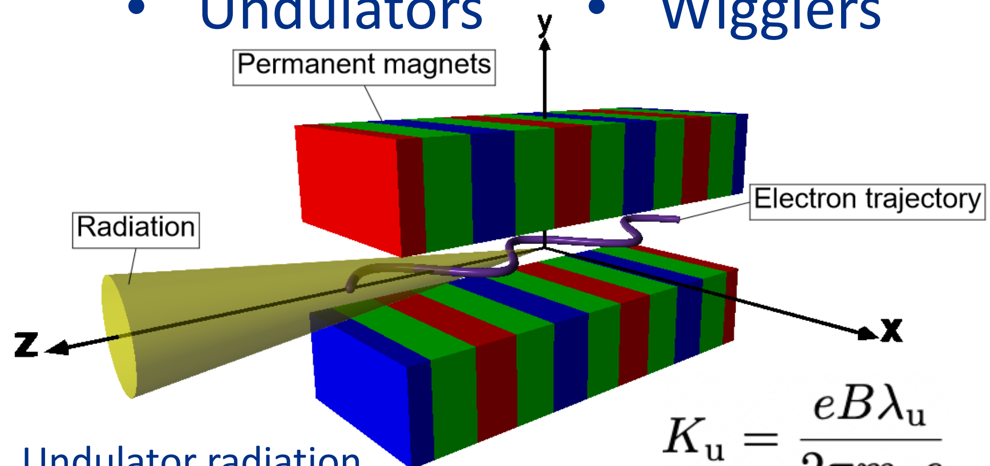
Bending magnets



https://commons.wikimedia.org/wiki/File:Syncrotron.png

Insertion devices:

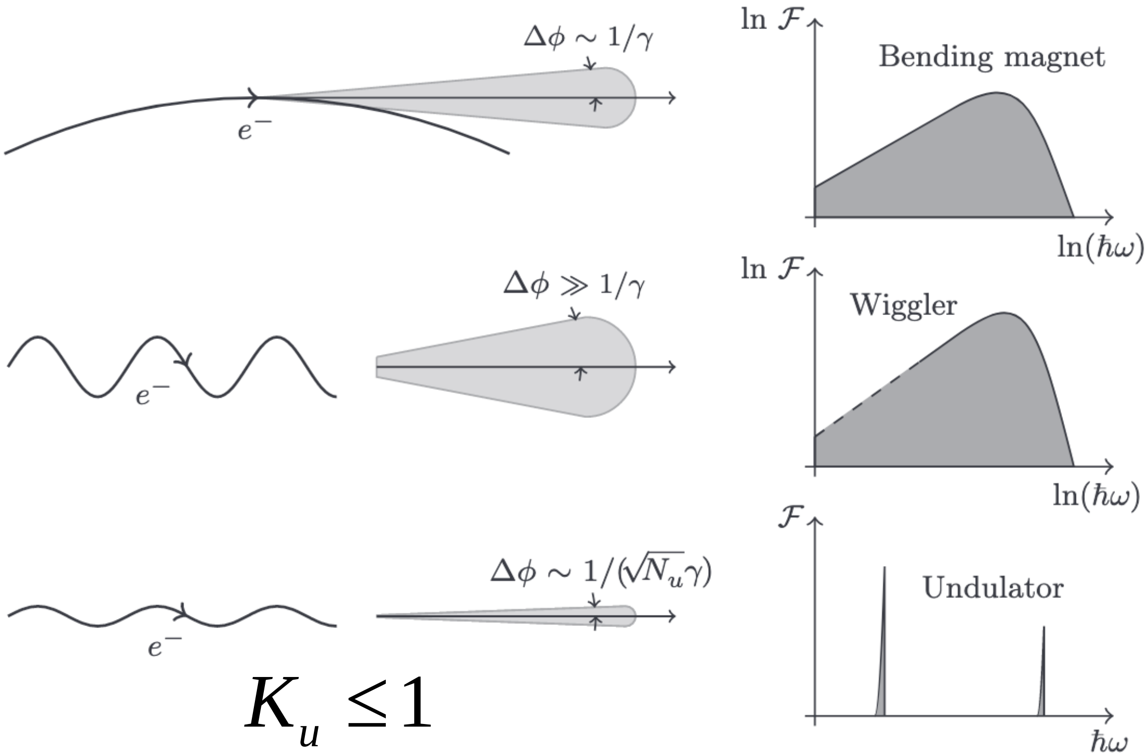
- Undulators
- Wigglers



Undulator radiation

$$K_{\mathrm{u}} = \frac{eB\lambda_{\mathrm{u}}}{2\pi m_e c}$$

Synchrotron light sources



$$K_u \leq 1$$

*K.-J. Kim, Z. Huang, R. Lindberg, "Synchrotron Radiation and Free-Electron Lasers", Cambridge University Press 2017

$$\gamma = \frac{E}{m_e c^2}$$

$\mathcal{F}$ is the spectral photon flux

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2}\right)$$

λ_u is the undulator period length,
N_u is the number of undulator periods,
K_u is the undulator strength parameter,

$$K_u = \frac{eB\lambda_u}{2\pi m_e c}$$

Quantum fluctuations

- For an undulator with N_u >> 1, the radiation wavelength

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K_u^2}{2}\right)$$

determines the photon energy, $\frac{hc}{\lambda_1}$

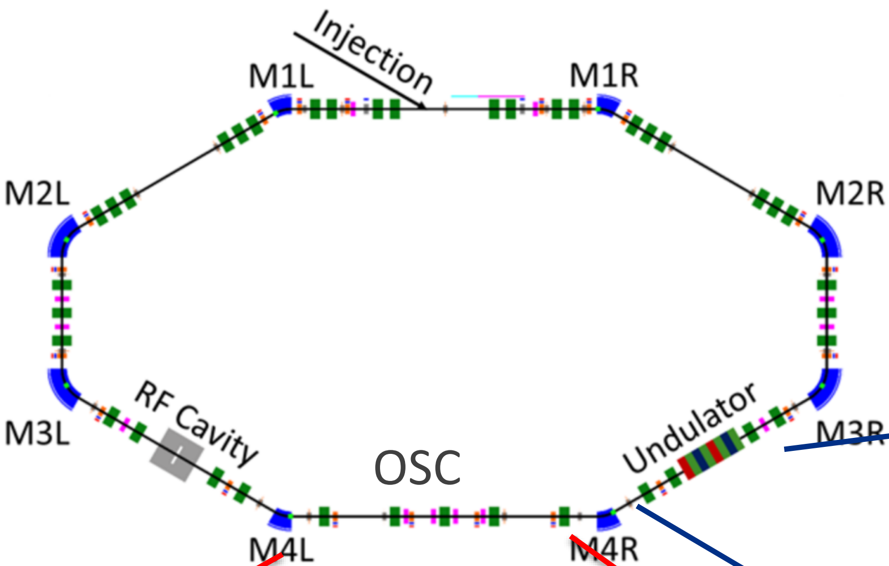
- From the Larmor's classical formula we have the average energy loss

$$\Delta E = \frac{2r_e e^2 E_0^2}{3m_e^3 c^4}\int_0^{N_u\lambda_u} B_y^2(s)\,\mathrm{d}s = \frac{4\pi^2\gamma^2 N_u K_u^2 r_e m_e c^2}{3\lambda_u}$$

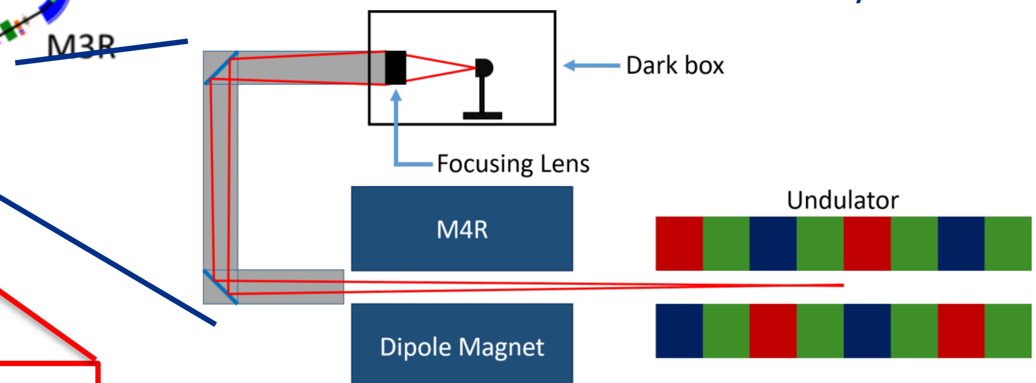
$$\Delta E = \frac{hc}{\lambda_1} \Rightarrow N_u \approx \frac{1}{\alpha K_u^2}$$

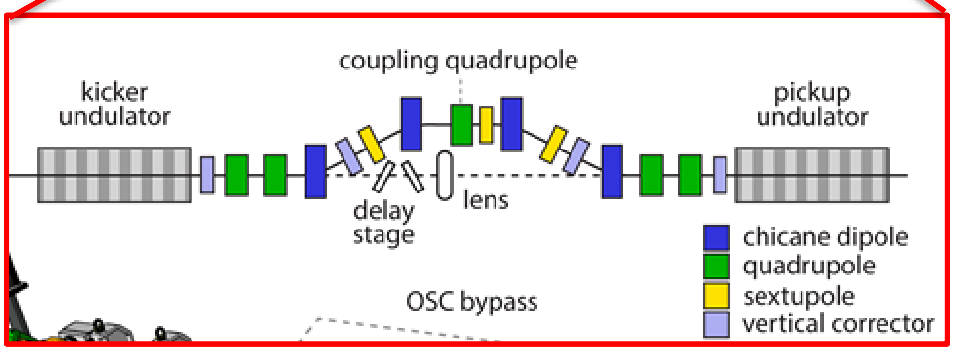
$$\alpha^{-1} \approx 137$$

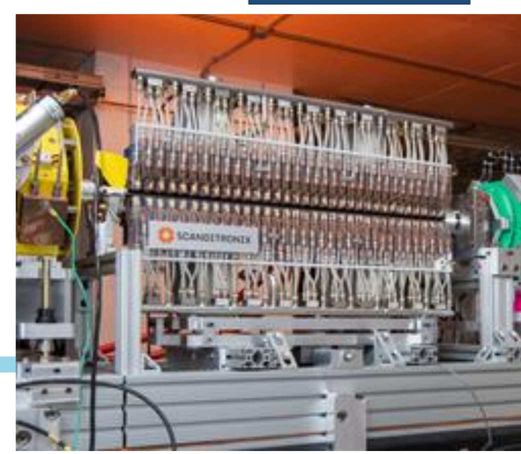
Layout of the undulator and OSC sections in IOTA



Undulator courtesy of SLAC







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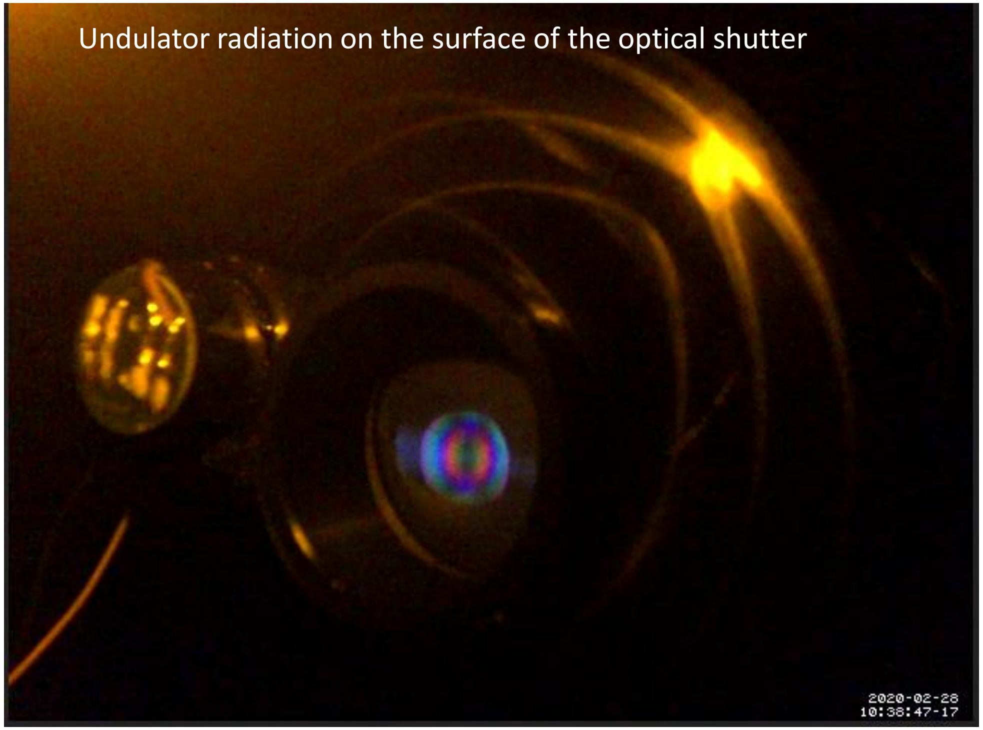
Parameters of the SLAC undulator in IOTA



Undulator:

- Number of periods: $N_\mathrm{u} = 10.5$
- Undulator period length: $\lambda_\mathrm{u} = 55\ \mathrm{mm}$
- Undulator parameter (peak): $K_\mathrm{u} = 1$
- Fundamental of radiation: 1.16 um
- Second harmonic: visible light

$$K_\mathrm{u} = \frac{eB\lambda_\mathrm{u}}{2\pi m_e c}$$

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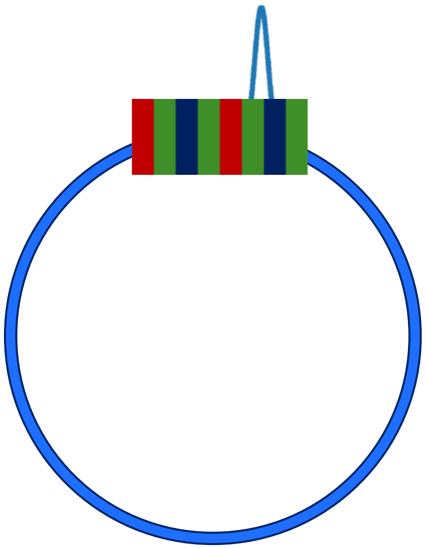
Experiment #1 --- many electrons ($\sim 10^9$)

Fundamental of the undulator radiation 1.16 um



InGaAs p-i-n photodiode

Revolution number	Number of photocounts, N
0	9994352
1	9997379
2	10002465
3	9999482
4	9996153
...	...
11273 1.5 ms	10000362

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N}^2 \rangle - \langle \mathcal{N} \rangle^2$$

Particle loss is negligible during 1.5 ms

The initial goal was to systematically study var($\mathcal{N}$) as a function of the electron bunch parameters (charge, size, shape, divergence)

Then, we realized that we could reverse this procedure and infer the electron bunch parameters from the measured $\mathrm{var}(\mathcal{N})$

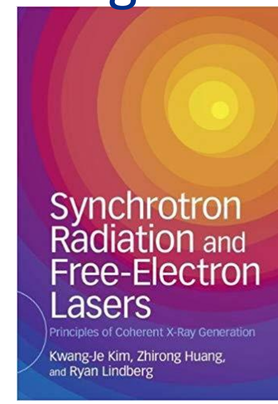
Theoretical predictions

$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle \mathcal{N}_{\mathrm{ph}} \rangle + \frac{1}{M} \langle \mathcal{N}_{\mathrm{ph}} \rangle^2$$

Discrete quantum nature of light (Poisson fluctuations)

Turn-to-turn variations in relative electron positions and directions of motion

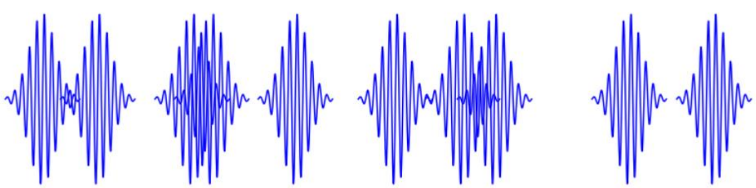
Page 28:



M is conventionally called the number of coherent modes

Simplified 1D model:

Pulses emitted by the electrons:



$$W \propto \int \mathrm{d}t \left| \sum_{i=1}^{n_e} E(t - t_i) \right|^2 = \int \mathrm{d}\omega \, |E(\omega)|^2 \left| \sum_{i=1}^{n_e} e^{-i\omega t_i} \right|^2$$

The set of arrival times of the electrons $\{t_i\}$ is different during every revolution in the ring. Hence, the radiated energy W fluctuates from turn to turn. $\sigma_t = \sqrt{\langle t_i^2 \rangle - \langle t_i \rangle^2}$

$$|E(\omega)|^2 \propto e^{-\frac{(\omega-\omega_0)^2}{2\sigma_\omega^2}} \Rightarrow M = \sqrt{1 + 4\sigma_\omega^2 \sigma_t^2}$$

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General case

$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle\mathcal{N}_{\mathrm{ph}}\rangle + \frac{1}{M}\langle\mathcal{N}_{\mathrm{ph}}\rangle^2$$

In general, M is a function of

- Detector's angular acceptance
- Detector's spectral sensitivity, polarization sensitivity
- Spectral-angular properties of the radiation (undulator or bending magnet)
- Electron bunch density distribution over x, y, z, x', y', δ_p

We accounted for this part for the first time

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Measurements of undulator radiation power noise and comparison with *ab initio* calculations

Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim

Phys. Rev. Accel. Beams **24**, 040701 – Published 1 April 2021

Physics See synopsis: Using Fluctuations to Measure Beam Properties

The obtained expression is very complex and includes a multidimensional integral:

$$\frac{1}{M} = (1 - 1/n_e)\frac{\sqrt{\pi}}{\sigma_z^{\text{eff}}}\frac{\int \mathrm{d}k\mathrm{d}^2\boldsymbol{\phi}_1\mathrm{d}^2\boldsymbol{\phi}_2\mathrm{d}^2\boldsymbol{r}'\mathcal{P}_k(\boldsymbol{r}',\boldsymbol{\phi}_1-\boldsymbol{\phi}_2)\mathcal{I}_k(\boldsymbol{\phi}_1,\boldsymbol{r}')\mathcal{I}_k^*(\boldsymbol{\phi}_2,\boldsymbol{r}')}{\langle\mathcal{N}_{\text{s.e.}}\rangle^2}, \quad (2)$$

with

$$\mathcal{P}_k(\boldsymbol{r}',\boldsymbol{\phi}_1-\boldsymbol{\phi}_2) = \frac{1}{4\pi\sigma_{x'}\sigma_{y'}}e^{-\frac{(x')^2}{4\sigma_{x'}^2}-\frac{(y')^2}{4\sigma_{y'}^2}}e^{-ik\Delta_x(\phi_{1x}-\phi_{2x})x'-ik\Delta_y(\phi_{1y}-\phi_{2y})y'}e^{-k^2\Sigma_x^2(\phi_{1x}-\phi_{2x})^2-k^2\Sigma_y^2(\phi_{1y}-\phi_{2y})^2}, \quad (3)$$

$$\mathcal{I}_k(\boldsymbol{\phi},\boldsymbol{r}') = \sum_{s=1,2}\eta_{k,s}(\boldsymbol{\phi})\mathcal{E}_{k,s}(\boldsymbol{\phi})\mathcal{E}_{k,s}^*(\boldsymbol{\phi}-\boldsymbol{r}'), \quad (4)$$

$$\langle\mathcal{N}_{\text{s.e.}}\rangle = \sum_{s=1,2}\int \mathrm{d}k\mathrm{d}^2\boldsymbol{\phi}\eta_{k,s}(\boldsymbol{\phi})|\mathcal{E}_{k,s}(\boldsymbol{\phi})|^2, \quad (5)$$

where $s = 1, 2$ indicates the polarization component, n_e is the number of electrons in the bunch, $k = 2\pi/\lambda$ is the magnitude of the wave vector; $\boldsymbol{\phi} = (\phi_x, \phi_y)$, $\boldsymbol{\phi}_1 = (\phi_{1x}, \phi_{1y})$ and $\boldsymbol{\phi}_2 = (\phi_{2x}, \phi_{2y})$ represent angles of direction of the radiation in the paraxial approximation. Hereinafter, x and y refer to the horizontal and the vertical axes, respectively, and

$$\sigma_z^{\text{eff}} = 1\Big/\left(2\sqrt{\pi}\int\rho^2(z)\mathrm{d}z\right) \quad (6)$$

where $\rho(z)$ is the electron bunch longitudinal density distribution function, $\int\rho(z)\mathrm{d}z = 1$, and σ_z^{eff} is equal to the rms bunch length σ_z for a Gaussian bunch; $\boldsymbol{r}' = (x', y')$ represents the direction of motion of an electron at the radiator center, relative to a reference electron; $\sigma_{x'}$ and $\sigma_{y'}$ are the rms beam divergences, $\sigma_{x'}^2 = \gamma_x\epsilon_x + D_{x'}^2\sigma_p^2$, $\sigma_{y'}^2 = \gamma_y\epsilon_y$; $\Sigma_x^2 = \epsilon_x/\gamma_x + (\gamma_x D_x + D_{x'}\alpha_x)^2\beta_x\epsilon_x\sigma_p^2/\sigma_{x'}^2$, $\Sigma_y^2 = \epsilon_y/\gamma_y$, $\Delta_x = (\alpha_x\epsilon_x - D_x D_{x'}\sigma_p^2)/\sigma_{x'}^2$, $\Delta_y = \alpha_y/\epsilon_y$, where α_x, β_x, γ_x, α_y, β_y, γ_y are the Twiss parameters of an uncoupled focusing optics in the synchrotron radiation

$$\mathcal{E}_{k,s}(\boldsymbol{\phi}) = \sqrt{\frac{\alpha k}{2(2\pi)^3}}\int \mathrm{d}t\boldsymbol{e}_s(\boldsymbol{k})\cdot\boldsymbol{v}(t)e^{ickt-i\boldsymbol{k}\cdot\boldsymbol{r}(t)}$$

- Transversely Gaussian beam
- Arbitrary longitudinal density distribution

- Assumes known Twiss-functions

The code for numerical computation is available at https://github.com/IharLobach/fur

A remark about the quantum contribution

$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle\mathcal{N}_{\mathrm{ph}}\rangle + \frac{1}{M}\langle\mathcal{N}_{\mathrm{ph}}\rangle^2$$

Quantum — Classical

At negligible electron recoil the radiated field is in a **coherent state**:

PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Coherent and Incoherent States of the Radiation Field*

Roy J. Glauber

$$|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2}\sum_n \frac{\alpha^n}{\sqrt{n!}}|n\rangle$$

$$\mathrm{var}(n) = \langle\alpha|\left(\hat{a}^\dagger\hat{a} - \langle n\rangle\right)^2|\alpha\rangle = |\alpha|^2 = \langle n\rangle$$

A unified description leading to the above expression is possible withing the framework of **quantum optics using the density operator formalism**:

Open Access

Statistical properties of spontaneous synchrotron radiation with arbitrary degree of coherence

Ihar Lobach, Valeri Lebedev, Sergei Nagaitsev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim

Phys. Rev. Accel. Beams **23**, 090703 – Published 11 September 2020

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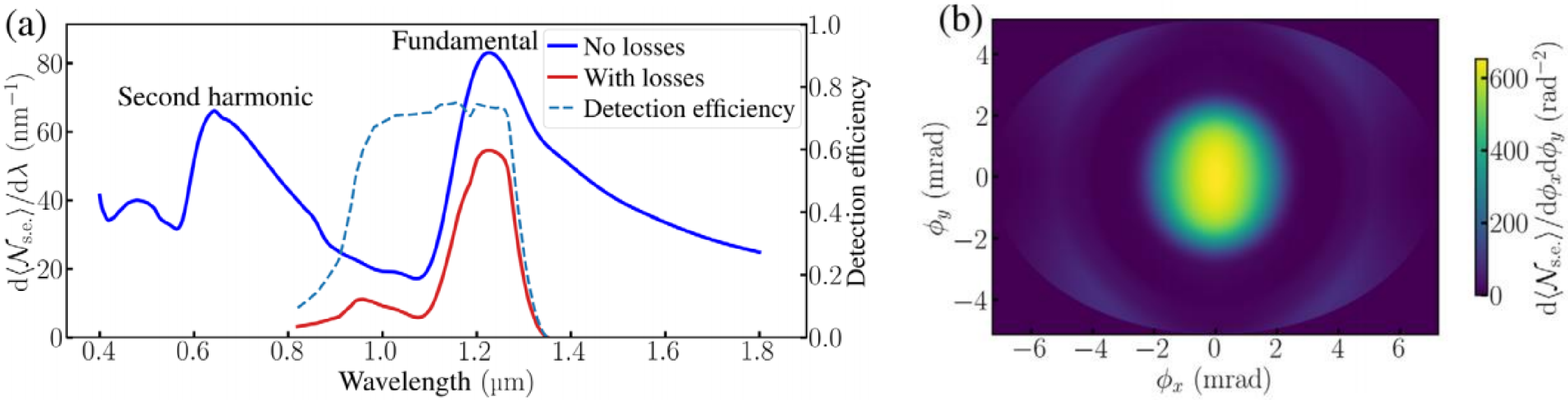
More

Details about Experiment #1 --- many electrons (10^9) Spectral-angular radiation distribution



In Experiment #1:

#1	Detect the fundamental (≈ 1.16 um). InGaAs p-i-n photodiode
#2	Wide band (≈ 0.14 um FWHM). Large acceptance angle > $1/\gamma$

(We use a focusing lens)

Simulated total intensity: 9.1×10^{-3} photoelectrons/electron

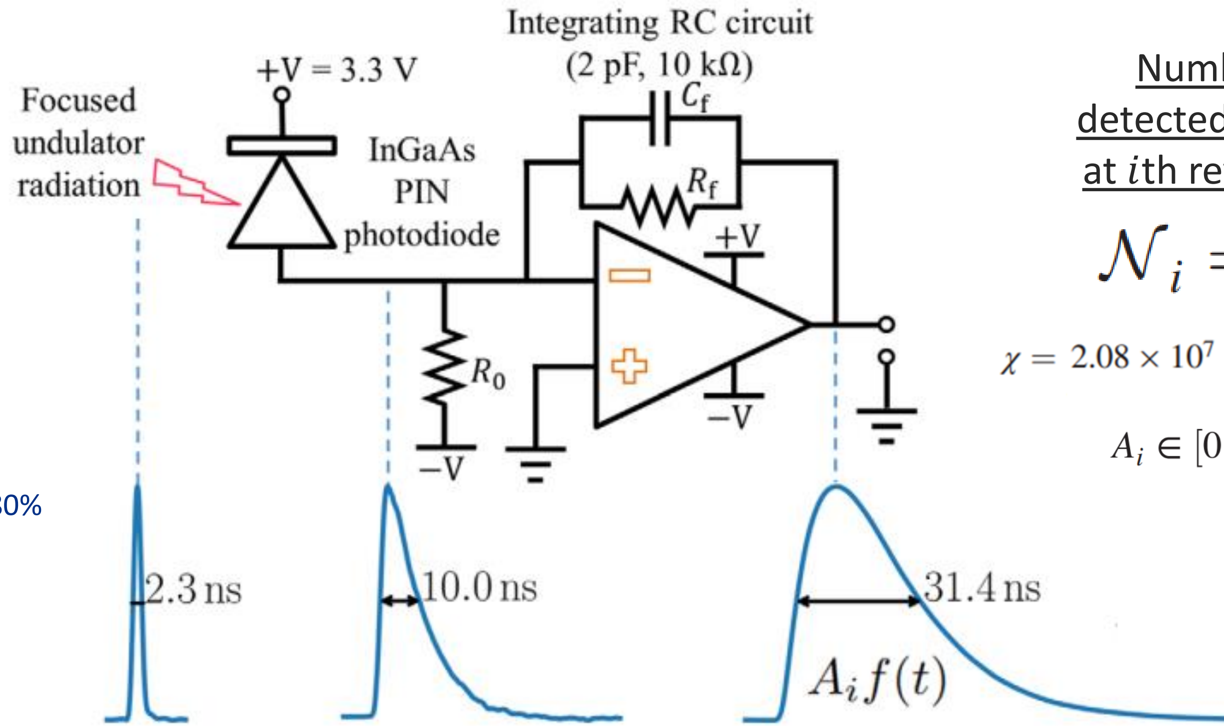
Measured: 8.8×10^{-3} photoelectrons/electron

Details about the apparatus

InGaAs PIN photodiode

Sensitive area: Ø1mm
Quantum efficiency at 1.16 μm: 80%

*the circuit was built by Greg Saewert



Number of detected photons at ith revolution:

$$\mathcal{N}_i = \chi A_i$$

$\chi = 2.08 \times 10^7$ photoelectrons/V

$A_i \in [0, 1.2]$ V

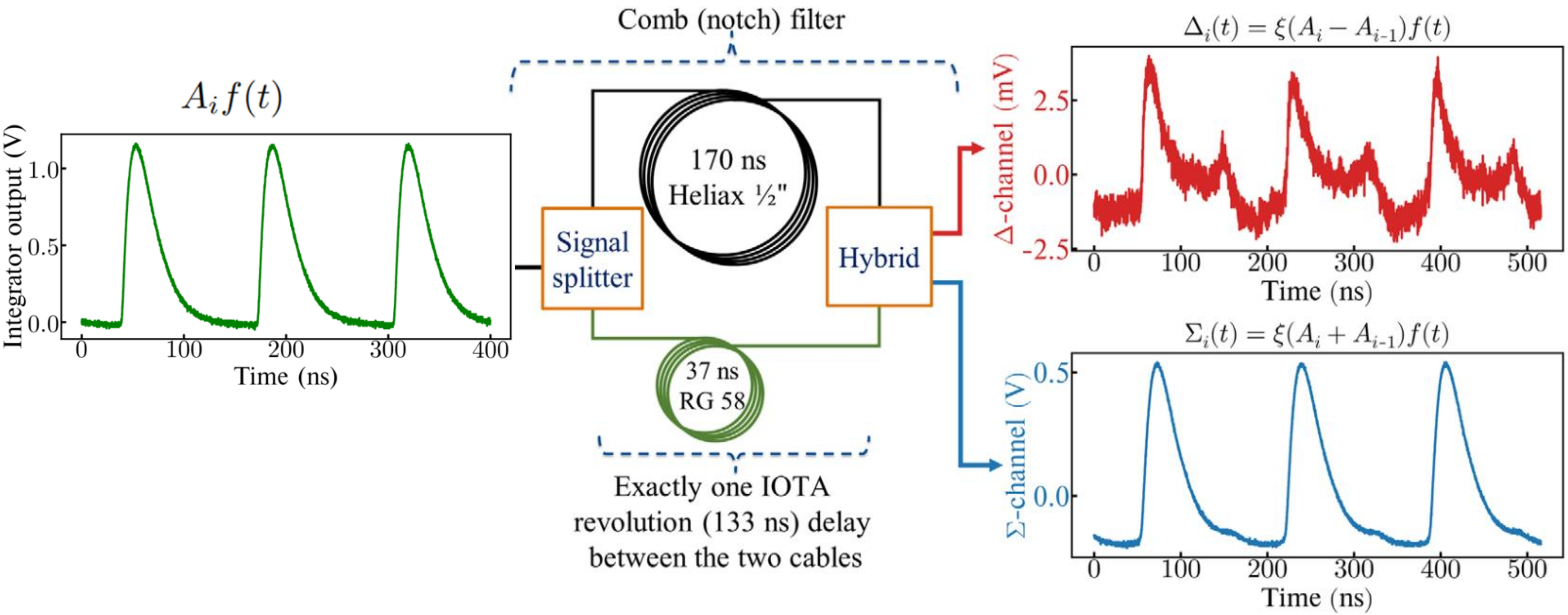
*Many thanks to Mark Obrycki, Peter Prieto, David Johnson, Todd Johnson and Greg Saewert for the equipment for the setup and for their help during our detector tests.

> The expected relative fluctuation of A_i was very small $10^{-4} - 10^{-3}$ (rms).
> It was a big challenge to measure it.

*comparable to the resolution of our 8-bit scope

Comb (notch) filter

The components were provided by B.J. Fellenz, K. Carlson, and D. Frolov

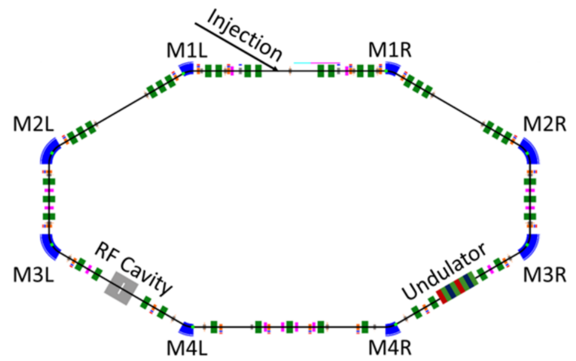


Our comb filter had some imperfections:

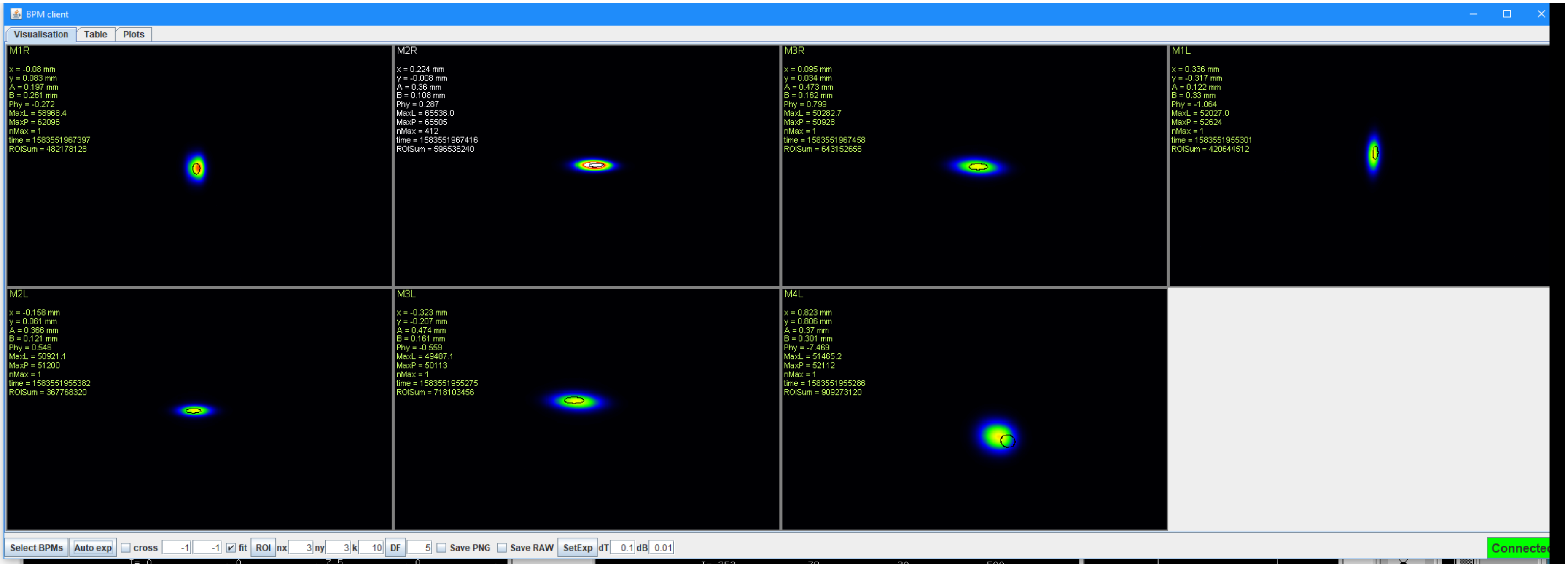
- Cross-talk (< 1%)
- Small reflected pulse in one of the arms

*they could be taken into account and did not affect final results

Measurement of transverse bunch size: 7 synclight stations

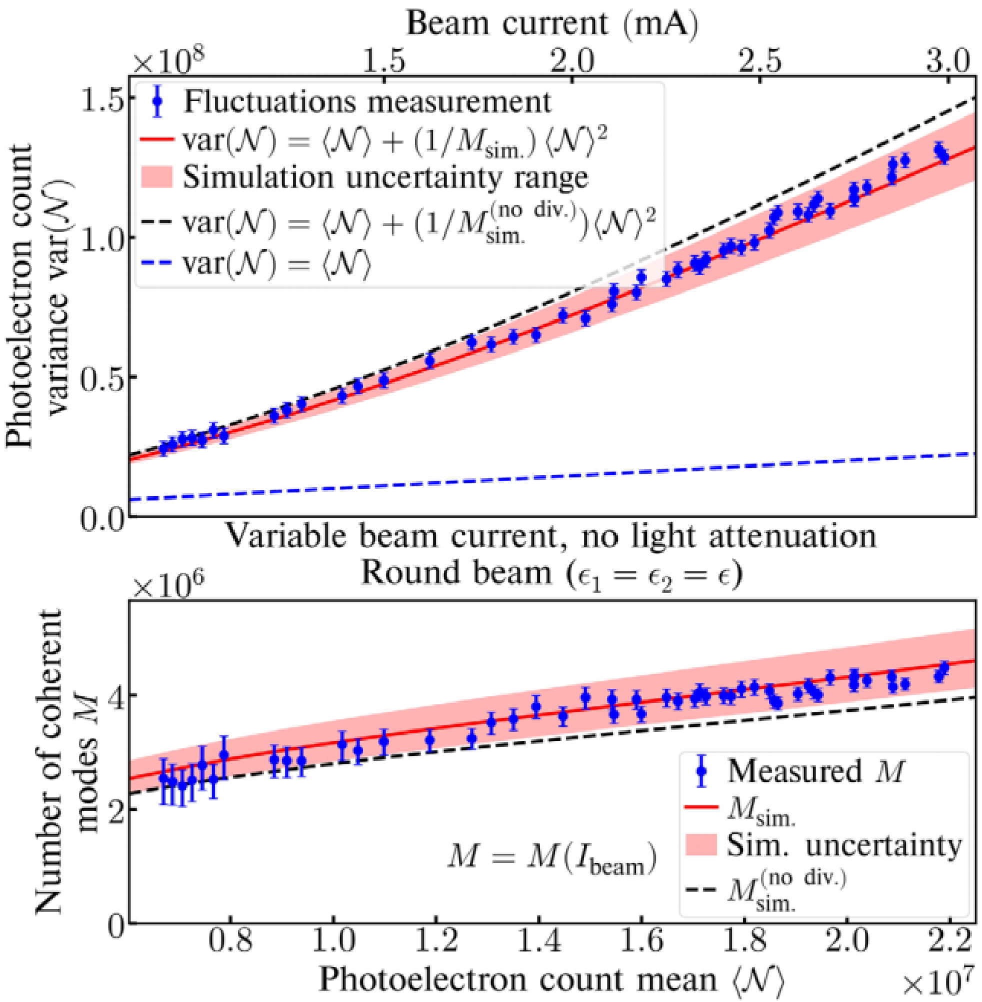


Bending magnet radiation (not undulator)



*built by A. Romanov, J. Santucci, G. Stancari, N. Kuklev, …

Measurements and simulations



$$M = M(\epsilon_x, \epsilon_y, \sigma_p, \sigma_z^{\mathrm{eff}})$$

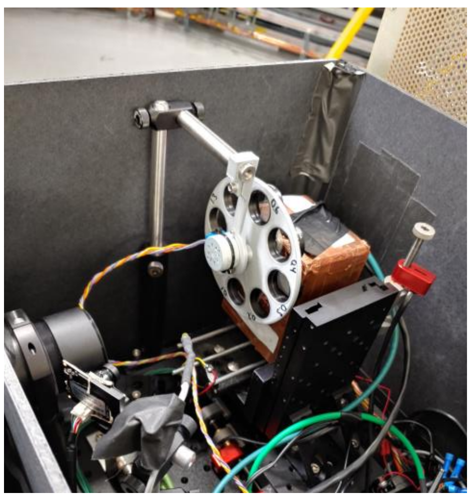
For the simulation,

- ϵ_x and ϵ_y were estimated using bending magnet synchrotron radiation monitors and known Twiss functions.
- σ_z^{eff} and σ_p were estimated using the wall-current monitor signal

Note that the simulation with beam divergence taken into account agrees better

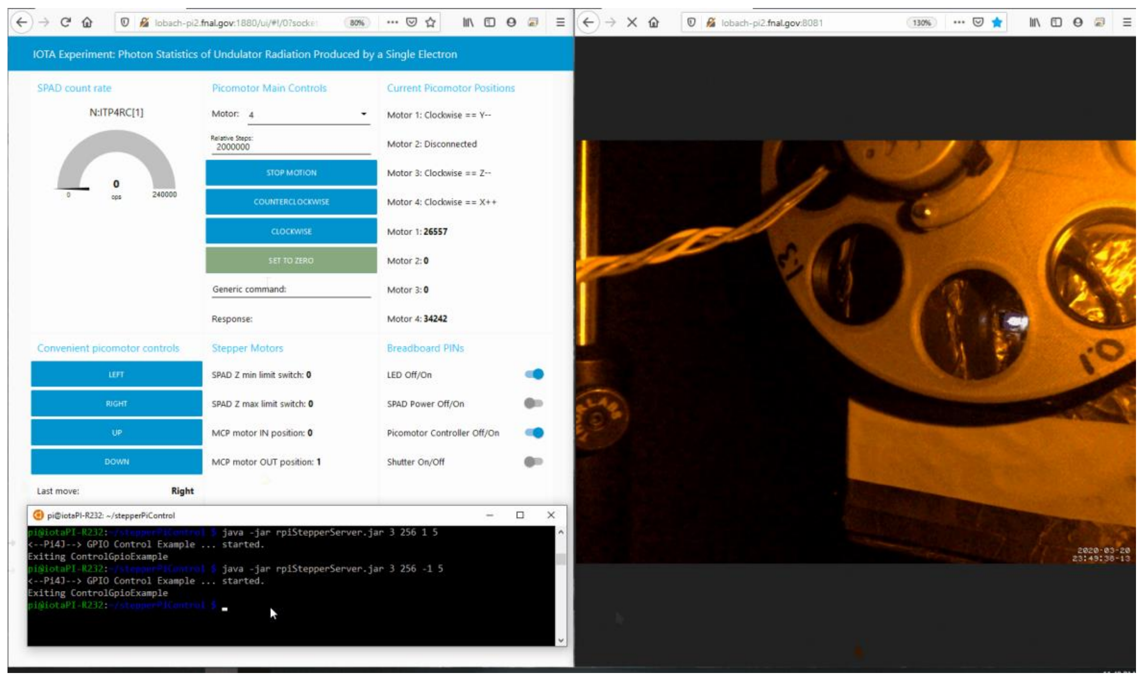
Neutral density (ND) filters

- ND filter is a filter that has constant attenuation in a wide spectral range
- ND filter does not change the number of coherent modes M, however, it does change the average number of detected photons $\langle \mathcal{N} \rangle$



The filter wheel was built by Sasha Romanov

Remote controls for the apparatus



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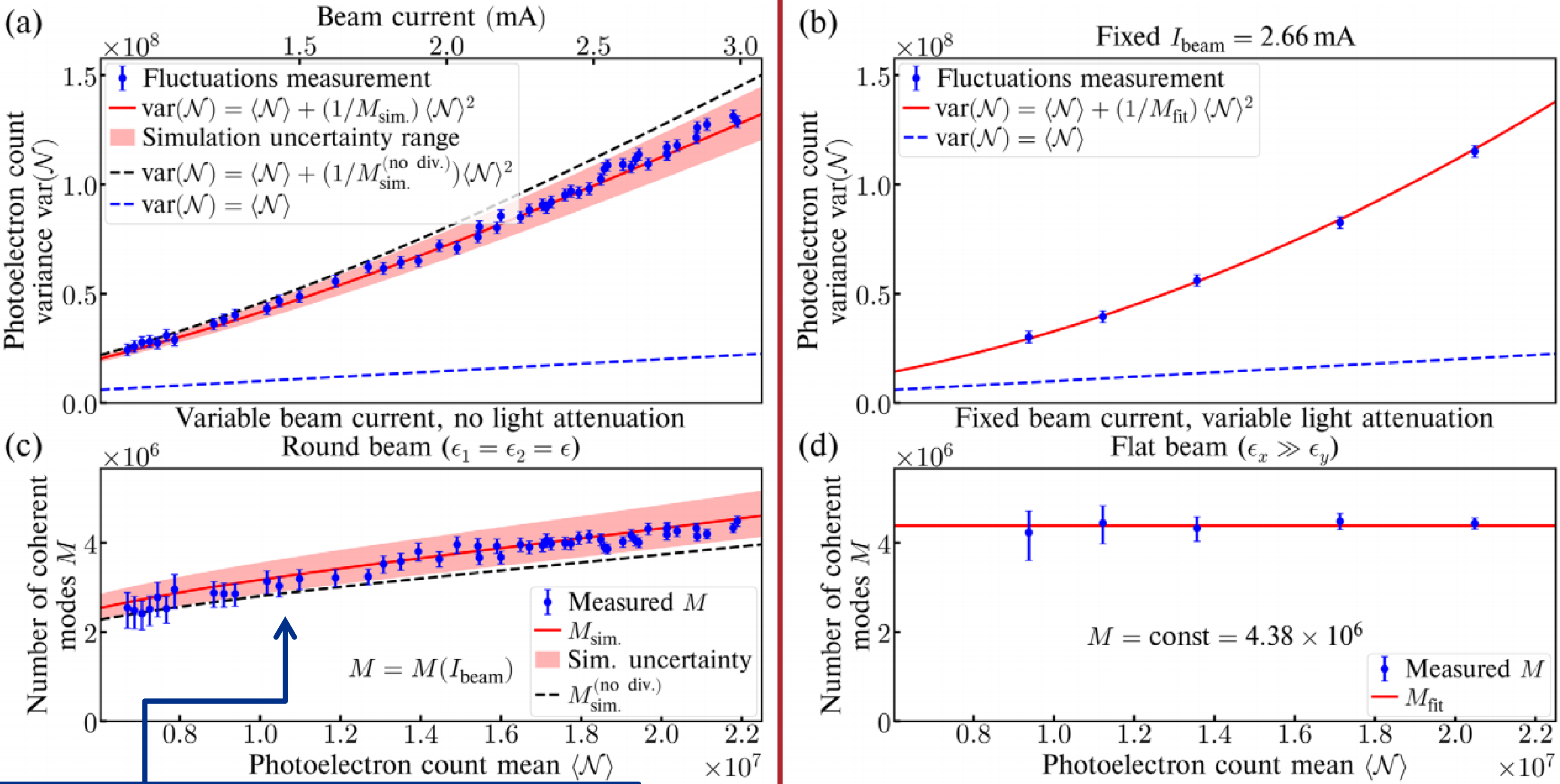
Measurements with ND filters (right-hand side)



ϵ_x, ϵ_y, σ_z^{eff}, σ_p change with the beam current due to intrabeam scattering and interaction of the bunch with its environment. Therefore, M changes too.

Reconstruction of transverse emittances from the measured $\mathrm{var}(\mathcal{N})$

Featured in Physics | Editors' Suggestion | Open Access

Transverse Beam Emittance Measurement by Undulator Radiation Power Noise

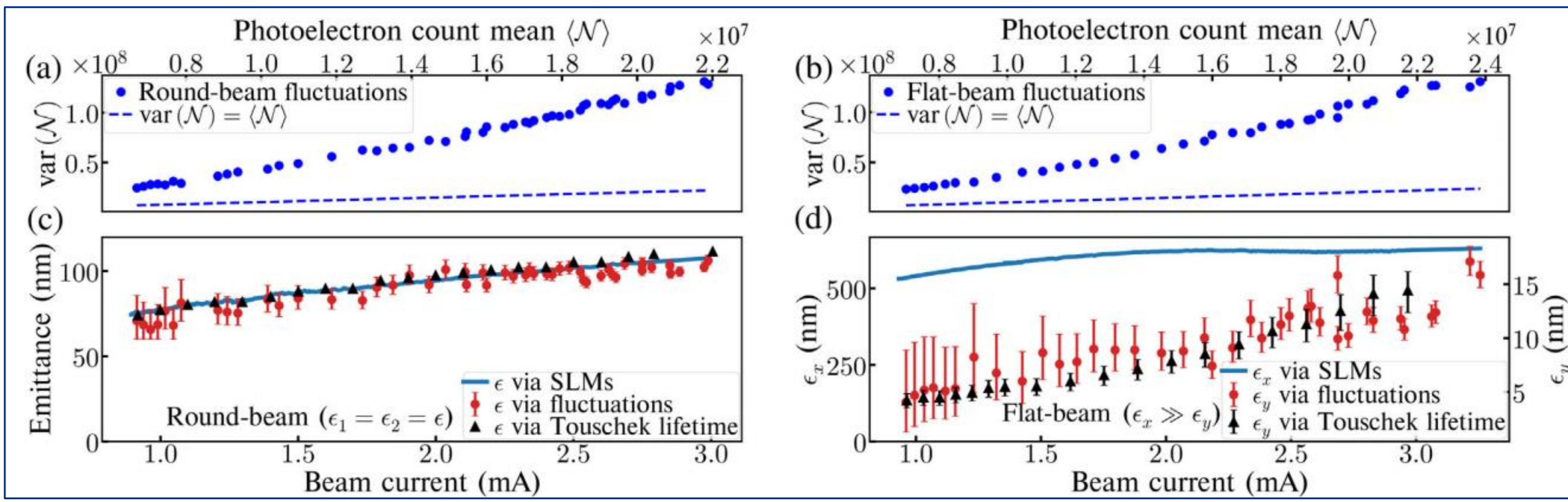
Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim

Phys. Rev. Lett. **126**, 134802 – Published 1 April 2021

Physics See synopsis: Using Fluctuations to Measure Beam Properties

We verified our method with a “round” beam, whose emittances could be independently measured by synchrotron radiation monitors, (a) and (c):

Then, we used our fluctuations-based method to **measure the unknown small vertical emittance of a “flat” beam**, (b) and (d):



Strong coupling

Uncoupled

Limitations (or strengths?)

- The fluctuations must not be dominated by the Poisson noise

$$\langle \mathcal{N} \rangle \lesssim \frac{1}{M} \langle \mathcal{N} \rangle^2 \quad \Rightarrow \quad \frac{\langle \mathcal{N} \rangle}{M} = \alpha \left(\frac{\pi}{2}\right)^{\frac{3}{2}} F_h(K_\mathrm{u}) \frac{\gamma^2 N_\mathrm{u}^2 n_e}{\sigma_x \sigma_y \sigma_z k_0^3} \gtrsim 1$$

- M must be sensitive to changes in σ_x, σ_y (ϵ_x, ϵ_y)

$$\sigma_x, \sigma_y \gtrsim \sqrt{2L_\mathrm{u}\lambda_0}/(4\pi)$$

The sensitivity of this technique improves with shorter wavelength. Therefore, this technique may be particularly beneficial for existing state-of-the-art and next-generation low-emittance high-brightness ultraviolet and x-ray synchrotron light sources. For instance, this technique could measure $\epsilon_x \approx \epsilon_y \approx 30$ pm in the Advanced Photon Source Upgrade at Argonne.

Experiment #1: Conclusions

- We have observed super-Poissonian fluctuations in undulator radiation intensity for many electrons, fully consistent with our model of classical and quantum fluctuations.
- We proposed and demonstrated a fluctuations-based technique to measure electron beam emittances, which can be particularly useful for state-of-the-art and next-generation x-ray synchrotrons.

Experiment #2 --- a single electron in the ring

Next step is a single electron because it is free from any collective effects. It is a very repeatable and well controlled system to study possible deviations from Poisson statistics.

Goal #1 Verify that the photostatistics in the single-electron case is Poissonian:

$$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N} \rangle + \frac{1}{M}\langle \mathcal{N} \rangle^2$$

$$\frac{1}{M} \propto (n_e - 1)$$

Super-Poissonian light:

$$\mathrm{var}(\mathcal{N}) > \langle \mathcal{N} \rangle$$

Sub-Poissonian light:

$$\mathrm{var}(\mathcal{N}) < \langle \mathcal{N} \rangle$$

unusual – non-classical state of the radiated field

Goal #2 Use the photocount arrival time information to study the synchrotron motion of a single electron

Kinds of photon statistics

- The **Fano factor** is a measure of photon statistics:

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

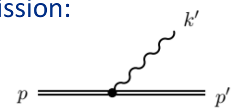
- $\boldsymbol{F = 1}$ – Poissonian light (very common)
  - laser radiation
  - radioactive decay
- $\boldsymbol{F > 1}$ – Super-Poissonian light (very common as well)
  - thermal light
  - any classical fluctuations of intensity
  - incoherent radiation by an electron bunch (Experiment #1)
- $\boldsymbol{F < 1}$ – Sub-Poissonian light (unusual! non-classical light)
  - Fock state (number state)
  - Parametric down-conversion

Ugo Fano
(1912-2001)

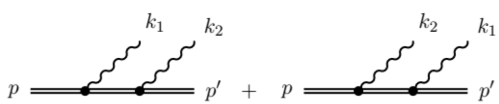
Description of single electron's undulator radiation in Quantum Electrodynamics

- Important parameter: electron recoil $\chi = \frac{E_{photon}}{E_{electron}}$ (in IOTA, $\chi \sim 10^{-8}$)
- $\chi \gtrsim 0.001$, Dirac-Volkov model
  (quantum electron + quantized radiation + classical undulator field)

Single-photon emission:



Two-photon emission:



Correlation, quantum entanglement between photons is possible:

PHYSICAL REVIEW A **80**, 053419 (2009)

Correlated two-photon emission by transitions of Dirac-Volkov states in intense laser fields: QED predictions

Erik Lötstedt*
Max-Planck-Institut für Kernphysik, Postfach 103980, 69029 Heidelberg, Germany

*would be observable at FACET-II with an optical undulator

- $\chi \lesssim 0.001$, Glauber's model
  (classical electron + quantized radiation)

PHYSICAL REVIEW VOLUME 131, NUMBER 6 15 SEPTEMBER 1963

Coherent and Incoherent States of the Radiation Field*

Roy J. Glauber
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received 29 April 1963)

Photons are not correlated

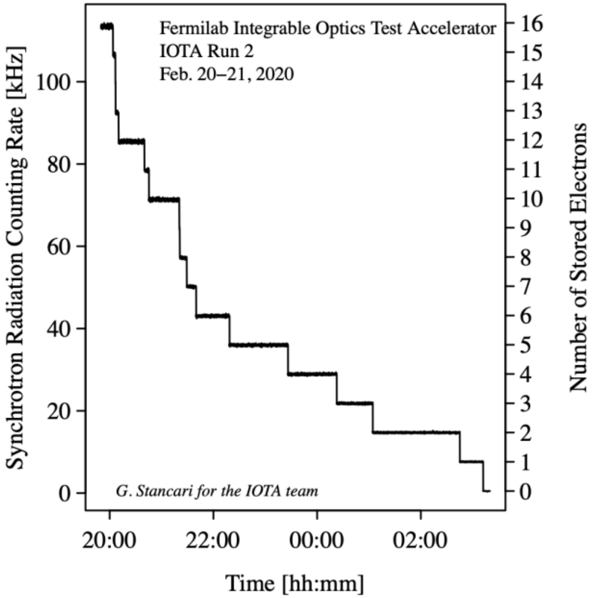
However, it does not explain this paper:
Teng Chen and John M. J. Madey
Phys. Rev. Lett. 86, 5906, 25 June 2001

Poissonian photostatistics

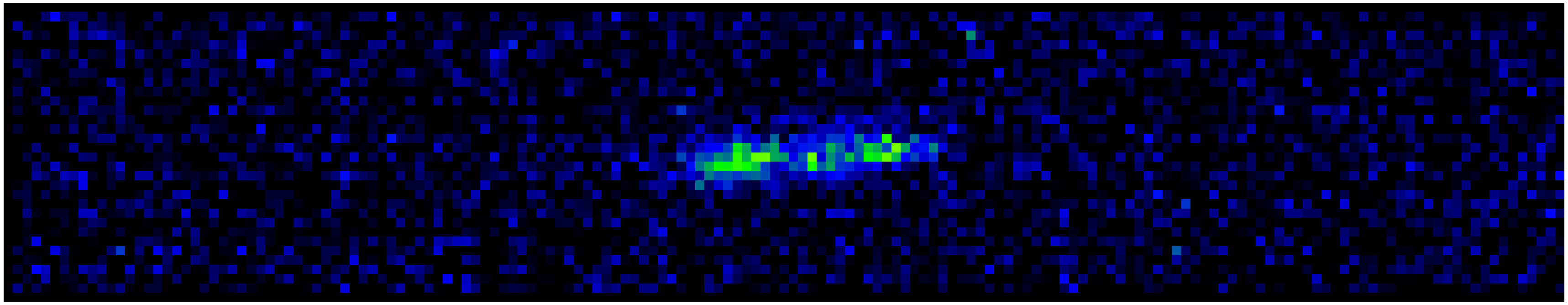
$\mathrm{var}(\mathcal{N}) = \langle \mathcal{N} \rangle$

Obtaining a single electron in the ring

- Injecting very low current from linac
- Changing RF voltage quickly to scrape electrons
- The number of electrons is easily determined by looking at photocounts rate
- Lifetime ≈1-2 hours



- Real time footage of **one electron** from M2R camera after specially developed noise cancellation algorithms (bending magnet radiation)
  - Clearly visible “stopping” points are due to integration time of less than damping time



*adapted from Sasha Romanov’s presentation at the workshop “Single-electron experiments in IOTA”

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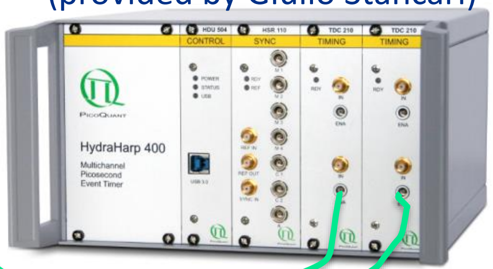
Design of the experiment with a <u>single electron</u>

Picosecond event timer
(provided by Giulio Stancari)



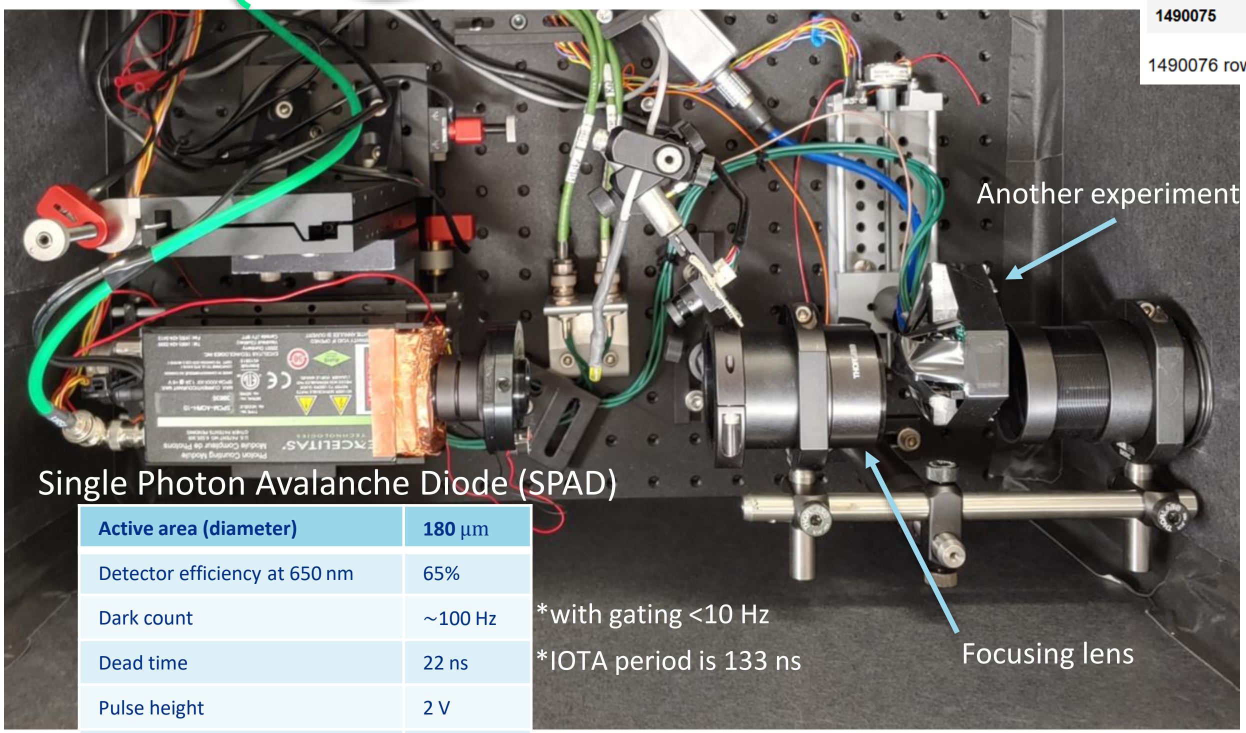
IOTA revolution marker

Record all events for 20 sec – 2 min

	Revolution number	Detection time relative to IOTA revolution marker, ps
0	51	62977.0
1	171	64337.0
2	239	62389.0
3	598	63454.0
4	999	64303.0
...	...	...
1490071	450123392	63592.0
1490072	450123677	62846.0
1490073	450123880	62373.0
1490074	450123931	62842.0
1490075	450124364	62746.0

1490076 rows × 2 columns

*on average one detection per 304 revolutions



Active area (diameter)	**180 μm**
Detector efficiency at 650 nm	65%
Dark count	~100 Hz
Dead time	22 ns
Pulse height	2 V
Pulse length	10 ns

*with gating <10 Hz

*IOTA period is 133 ns

Undulator radiation

*the stepper motor translation stages were provided by Sasha Romanov

Analysis of the statistical properties

*on average one detection per 304 revolutions
*Probability to detect a photon(s) in one revolution: $p = 0.00330$

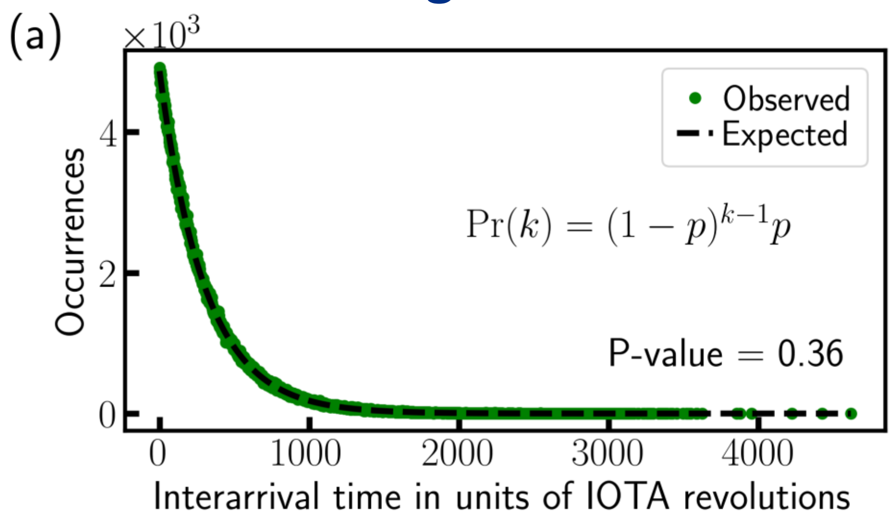
Collected data (binary detector):

000001000000110000000000001000100000000011100000000…

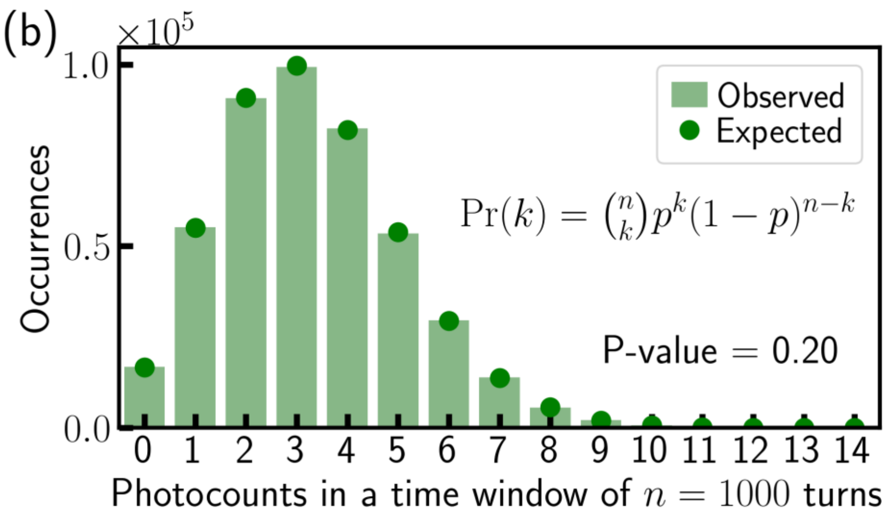
0 - no detection, 1 – one or more photons detected

~~Poisson distribution~~ → **Bernoulli trials**: $\mathrm{var}(\mathcal{N}) = (1-p)\langle\mathcal{N}\rangle$

Distribution of interarrival times: geometric



Distribution of photocounts in a time window: binomial



P-value – for hypotheses testing (χ^2 goodness of fit test)

Experiment #2: Conclusions

- In our experiment with a single electron and a single binary photon detector we did not observe any statistically significant deviations of the undulator radiation photostatistics from a memoryless Bernoulli process. Our observations directly confirm that at negligible electron recoil, synchrotron radiation produced by a single electron is in a coherent state as predicted by Glauber.

PAPER • OPEN ACCESS

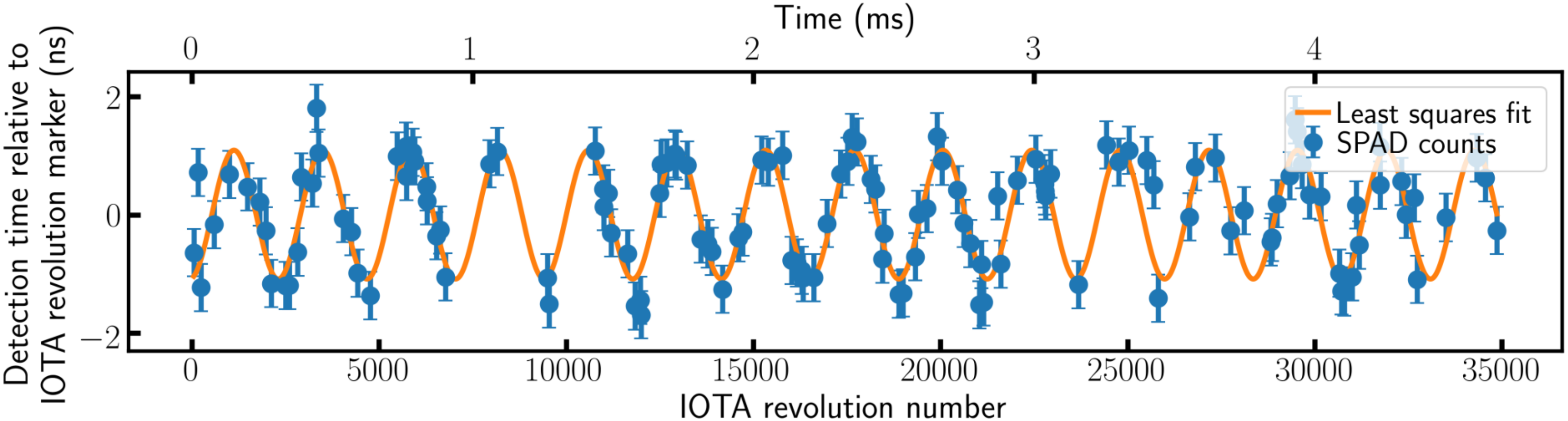
Single electron in a storage ring: a probe into the fundamental properties of synchrotron radiation and a powerful diagnostic tool

I. Lobach[1], S. Nagaitsev[1,2], A. Romanov[2] and G. Stancari[2]

Published 8 February 2022 • © 2022 The Author(s)

Journal of Instrumentation, Volume 17, February 2022

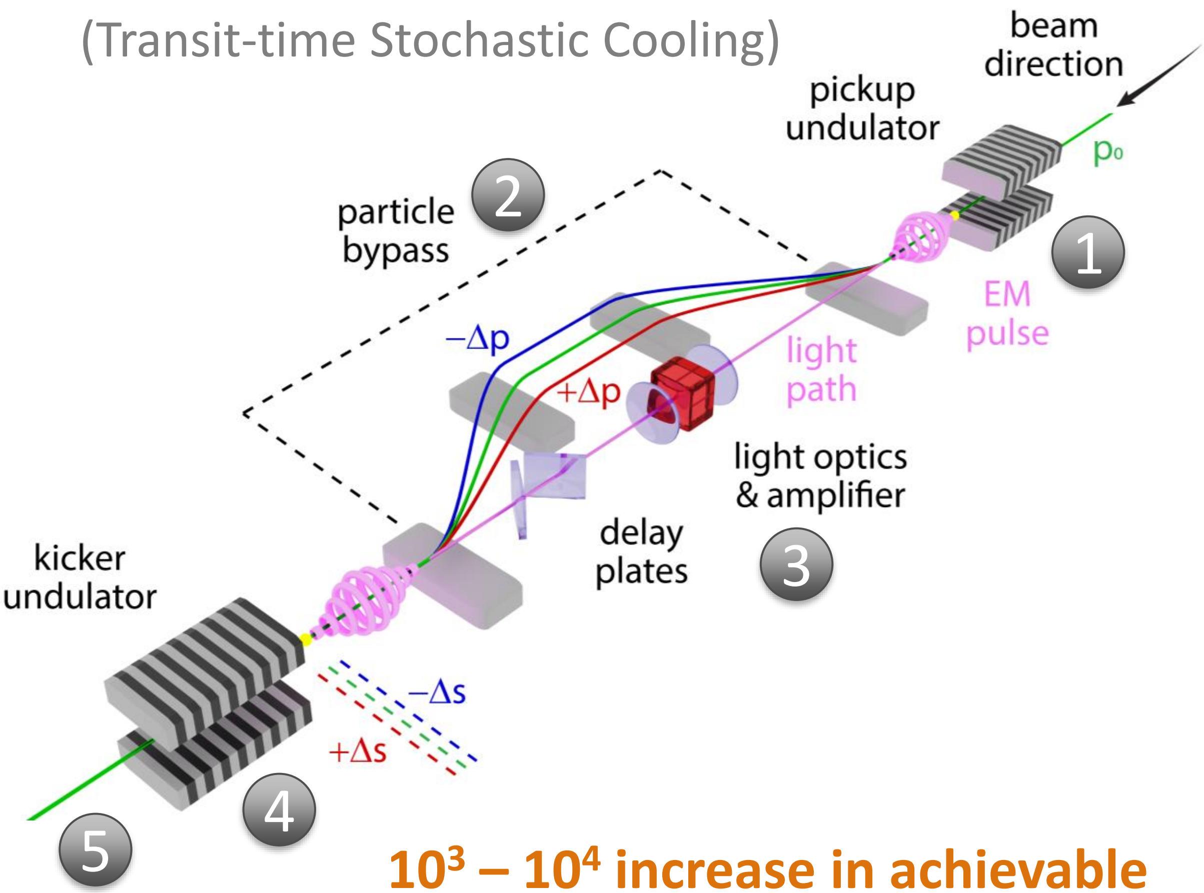
A possible diagnostics tool: Synchrotron motion of a single electron



- The SPAD's timing resolution is ≈ 0.4 ns (the error bars)
- The outliers could also be the dark counts

Experiment #3 -- optical stochastic cooling

(Transit-time Stochastic Cooling)



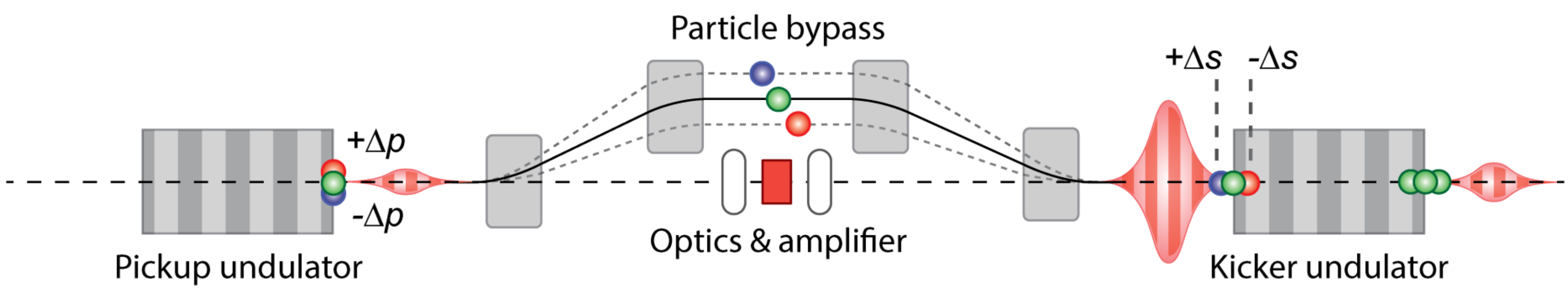
10^3 – 10^4 increase in achievable stochastic cooling rate (~10s of THz BW vs few GHz)

1. Each particle generates EM wavepacket in pickup undulator
2. Particle's properties are "encoded" by transit through a bypass
3. EM wavepacket is amplified (or not) and focused into kicker und.
4. Induced delay relative to wavepacket results in corrective kick
5. Coherent contribution (cooling) accumulates over many turns

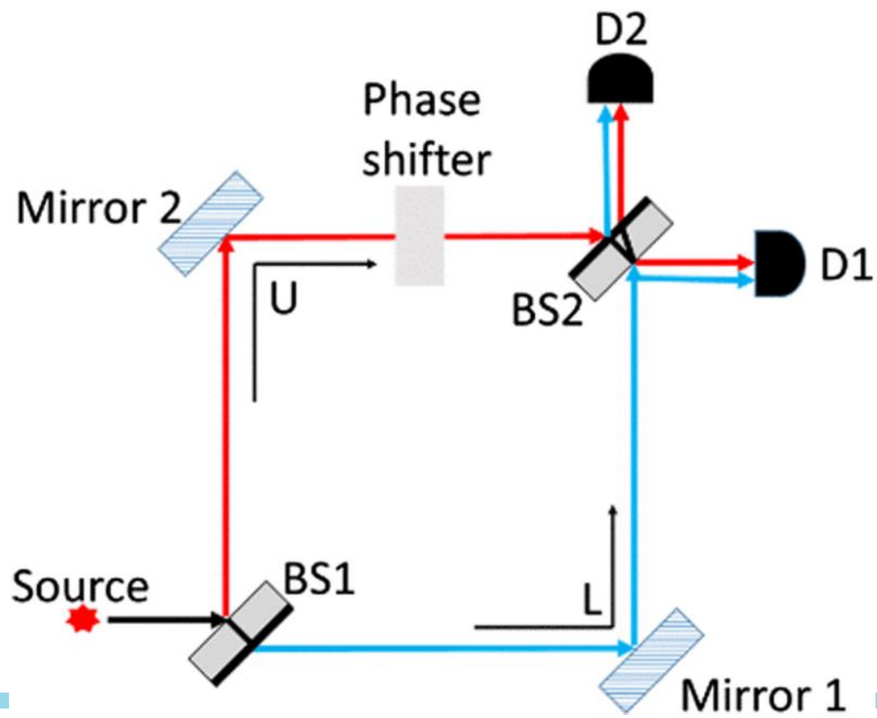
A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phys. Rev. Lett. 71 (25), p. 4146 (1993)

M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

OSC as interference

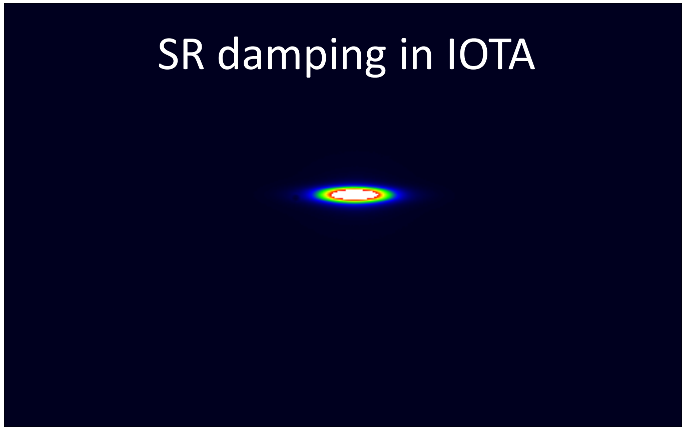


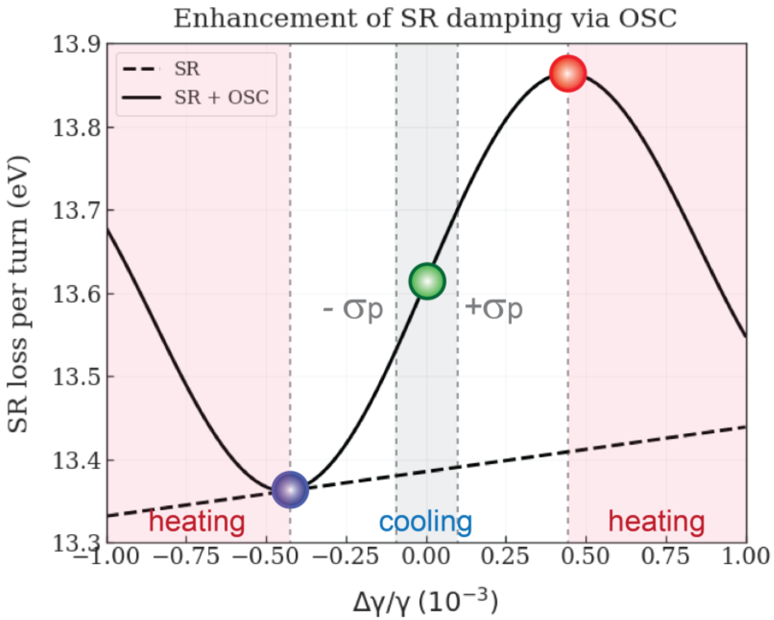
Mach-Zehnder Interferometer

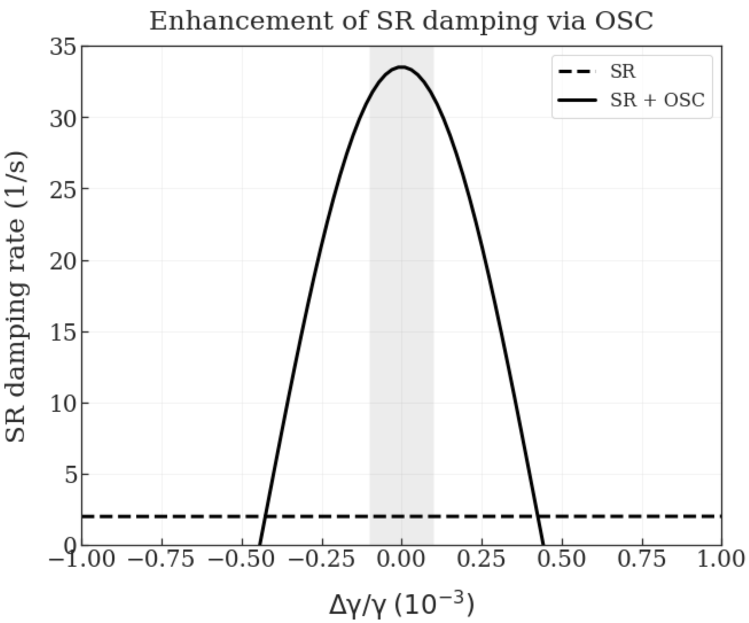


"Interference" of UR greatly amplifies SR damping

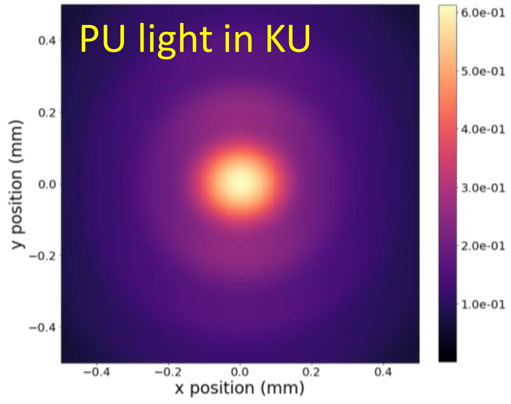
- SR-damping rate goes as ***dU/dE***
- UR interference produces large ***dU/dE*** for small deviations in ***E***
- IOTA's OSC was designed to dominate SR damping by ~10x without any optical amplification ($\tau_{\varepsilon s}$~50 ms, $\tau_{\varepsilon x/y}$~100 ms)



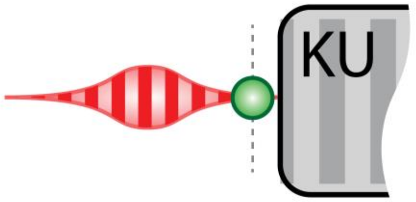




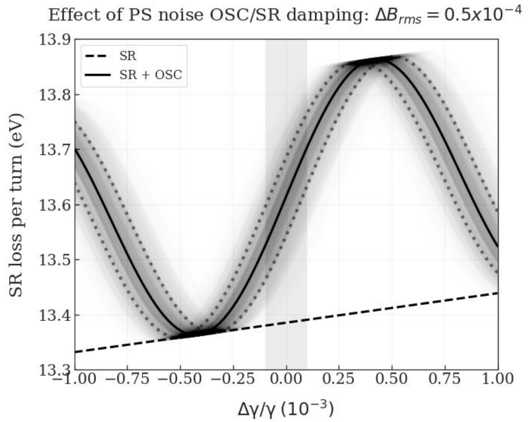
What makes ("simple") OSC challenging?

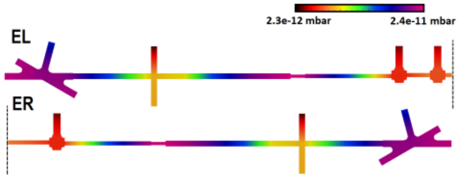


1. Beam and PU light must overlap through the KU
   - The undulator light is **~200 μm** wide
   - Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than **~0.3 fs**
   - The entire delay system corresponds to ~2000 fs



3. The electron bypass and the light path must be stable to much smaller than the wavelength
   - Arrival jitter at the KU should be better than **~0.3 fs**
   - This means total ripple+noise in chicane field must be at the **~mid 10^{-5}** level
4. Practical considerations of design and integration!





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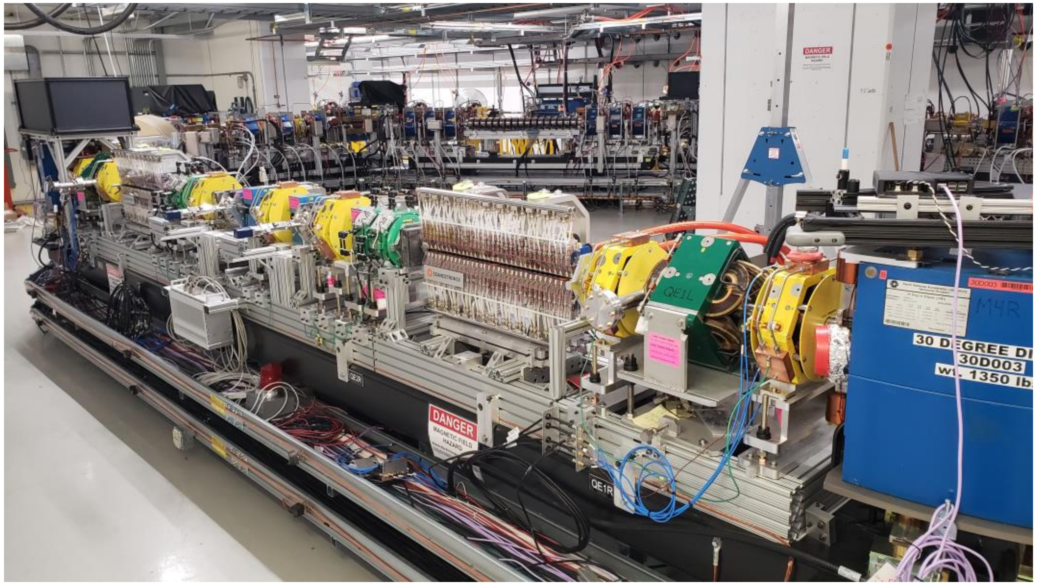
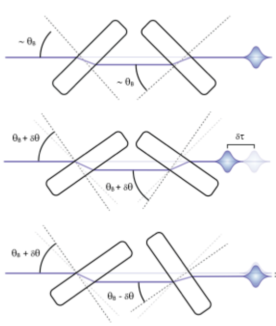
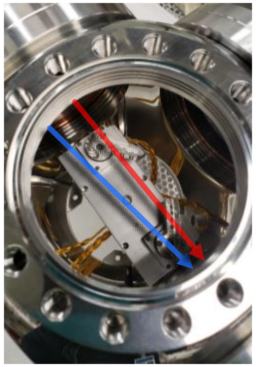
OSC apparatus successfully integrated in IOTA

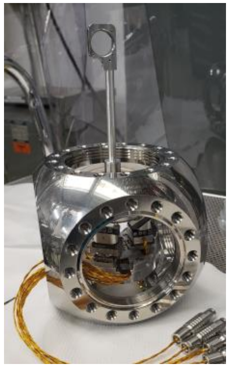
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and ~20-min lifetime; sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated all diagnostic and control systems

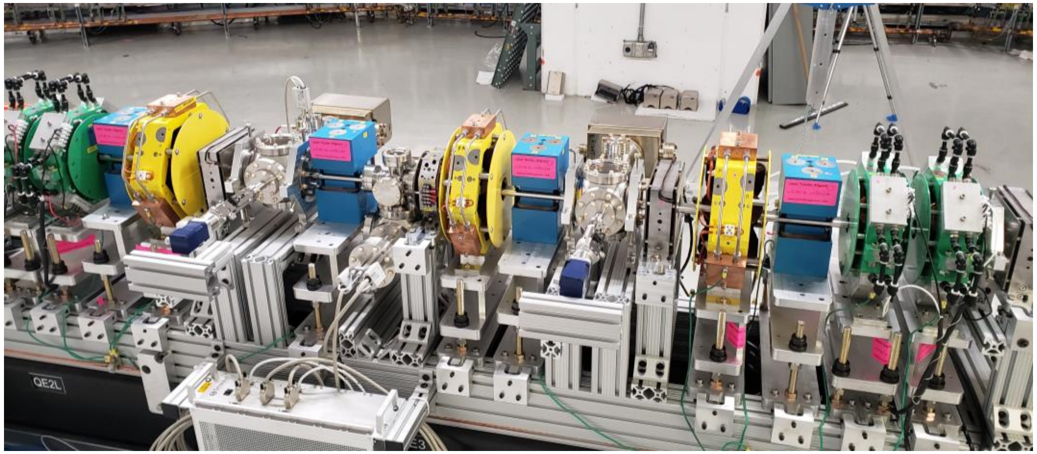




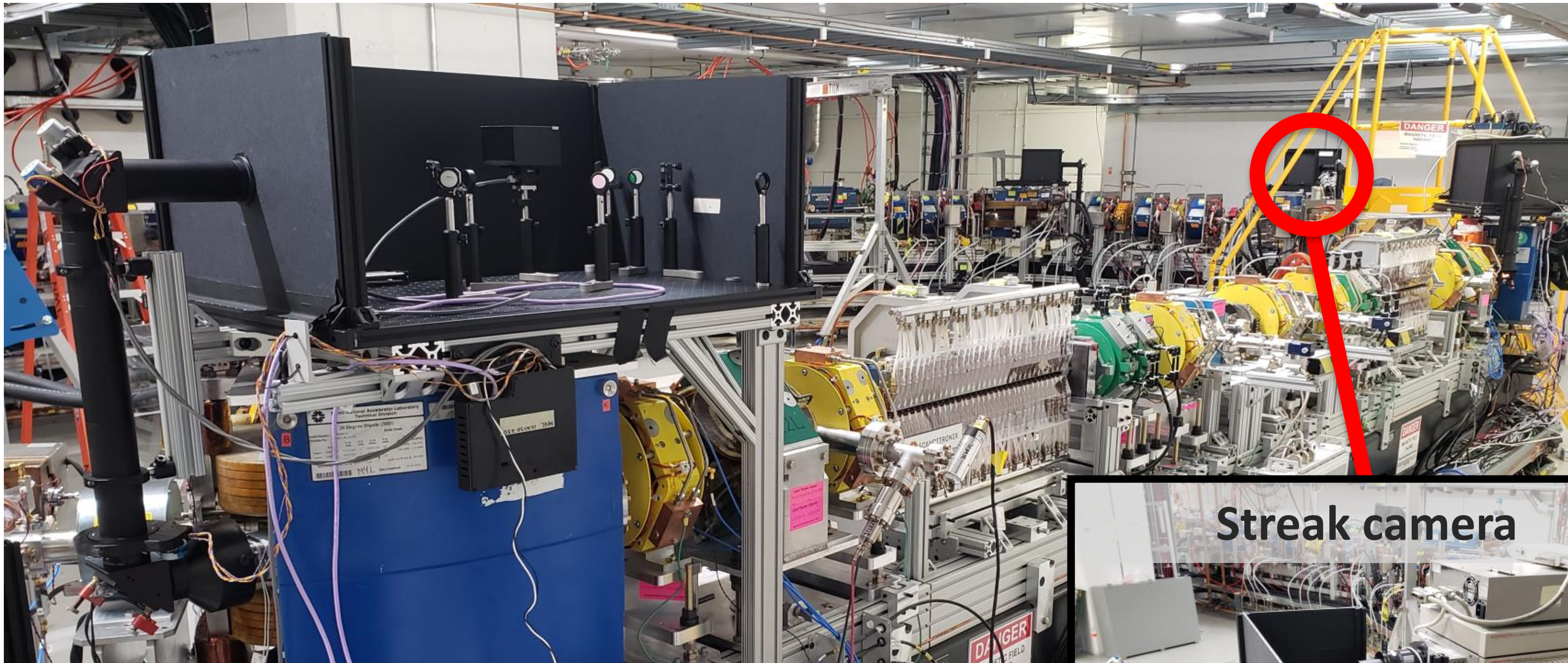
Delay stage

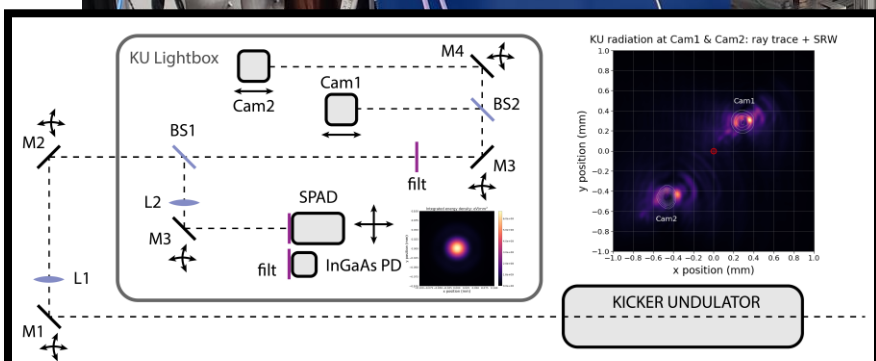


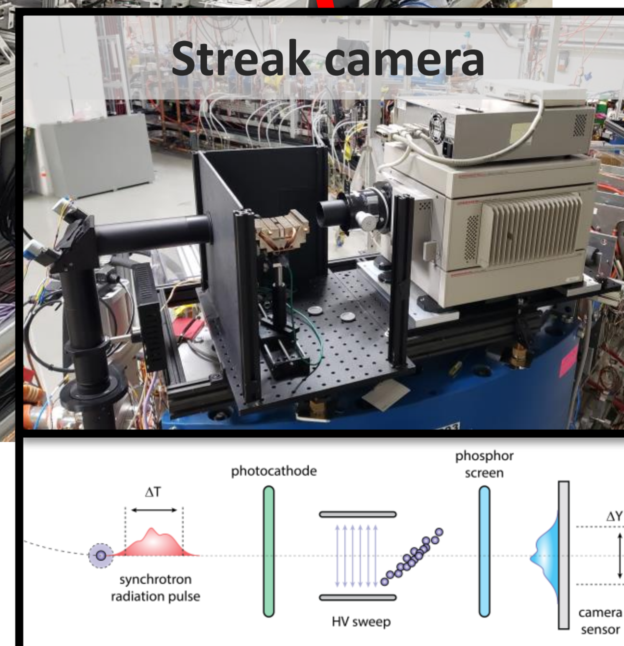




OSC is monitored via synchrotron-rad. stations



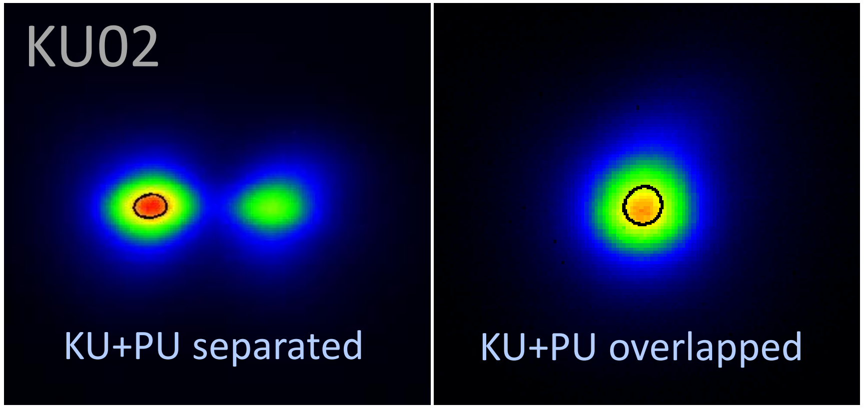


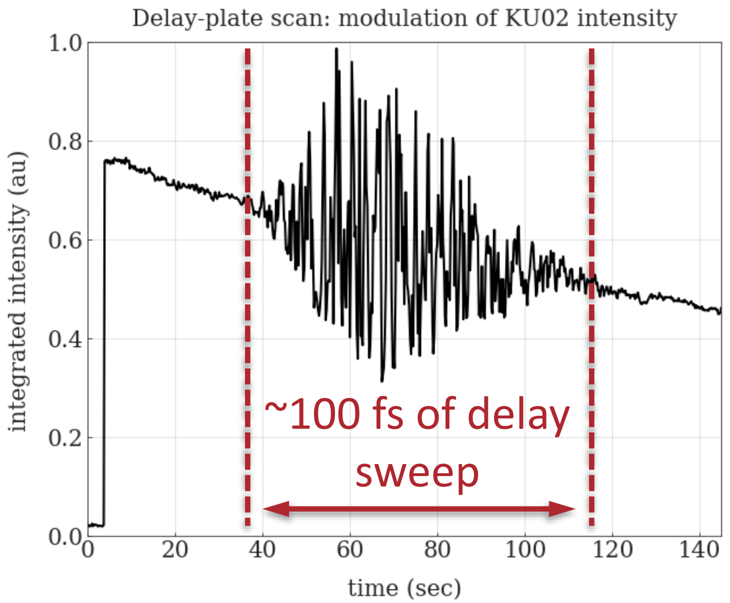


UR (PU+KU) BPMs; SPAD and PMT for 1e$^-$

On 04/20/21, interference was observed at full undulator power

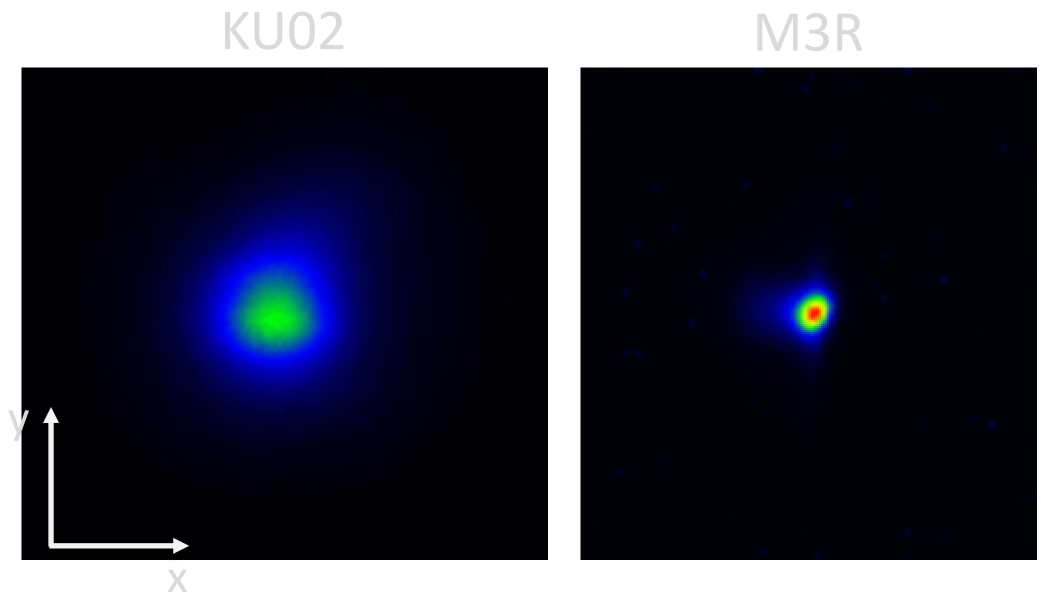
- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both space and time, is the fundamental requirement for producing OSC
- When this condition was met, synchrotron-radiation cameras throughout IOTA were monitored for a definite effect on the beam….





Delay scan through entire wavepacket-overlap region

Observed strong UR modulation and cooling/heating on 4/20

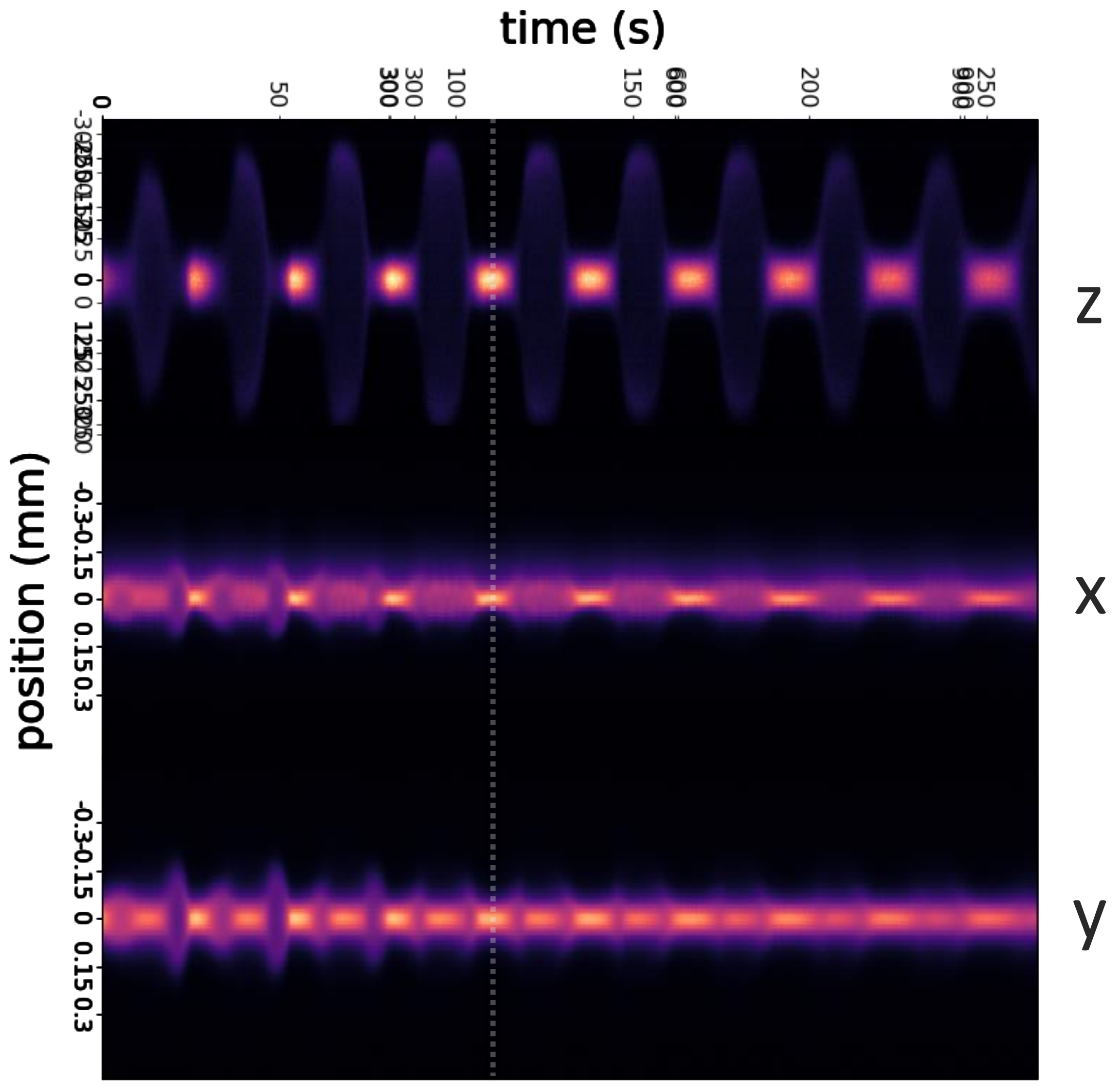


(movies not taken simultaneously but are representative)

- Bypass and optical delay are fixed in the movies above
- **FNAL Main Injector ramp was sweeping beam across OSC zones**
- Regulation upgrades resulted in excellent stability of OSC (~10s nm?)

After much work… OSC was strong and stable

- 1D: lattice decoupled and bypass quad set to null transverse response to OSC; some residual due to dispersion @ SR BPM
- 2D: lattice decoupled and bypass coupling to nominal
- 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration
- Delay system is scanned at a constant rate of 0.01deg/sec
- Corresponds to ~one wavelength every 30 sec



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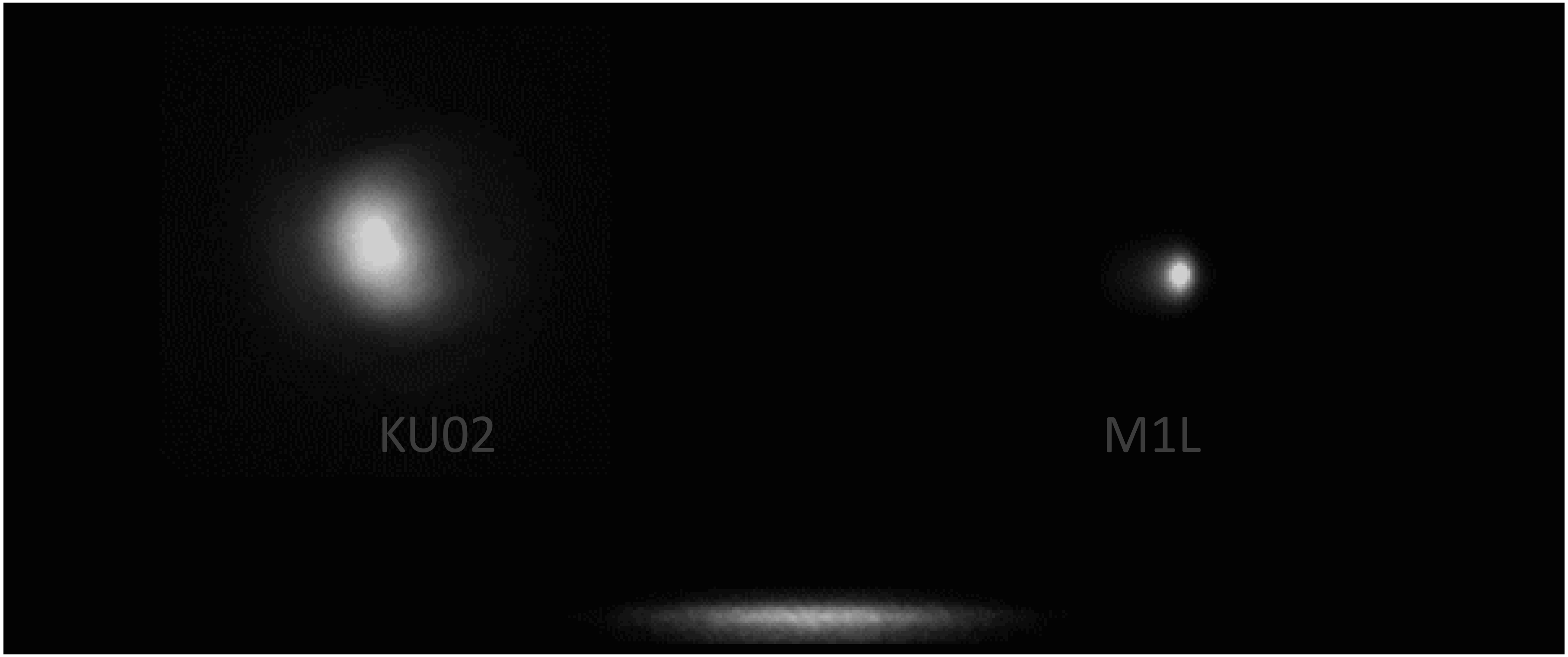
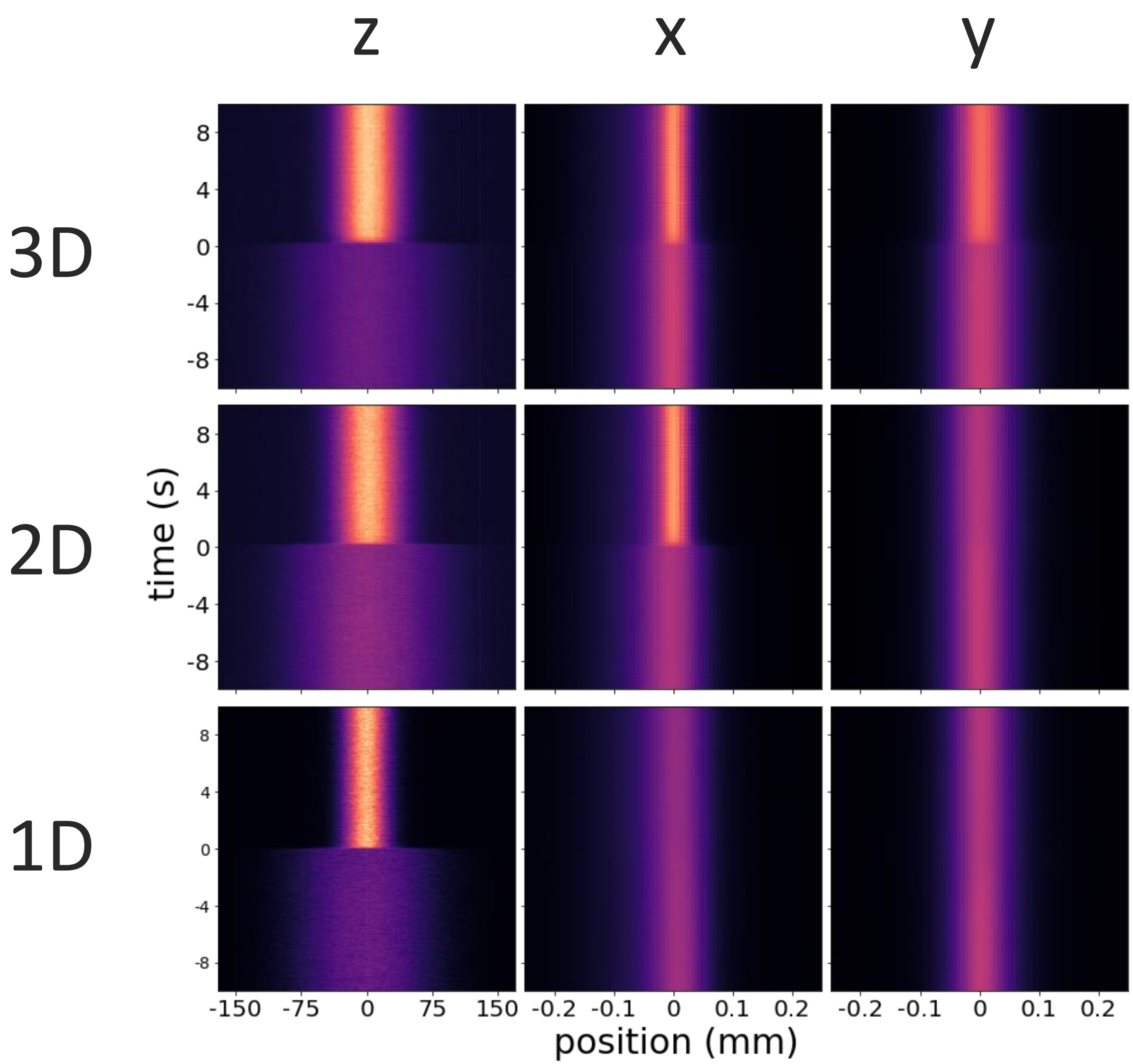
Delay scan with OSC in the 3D configuration



STREAK

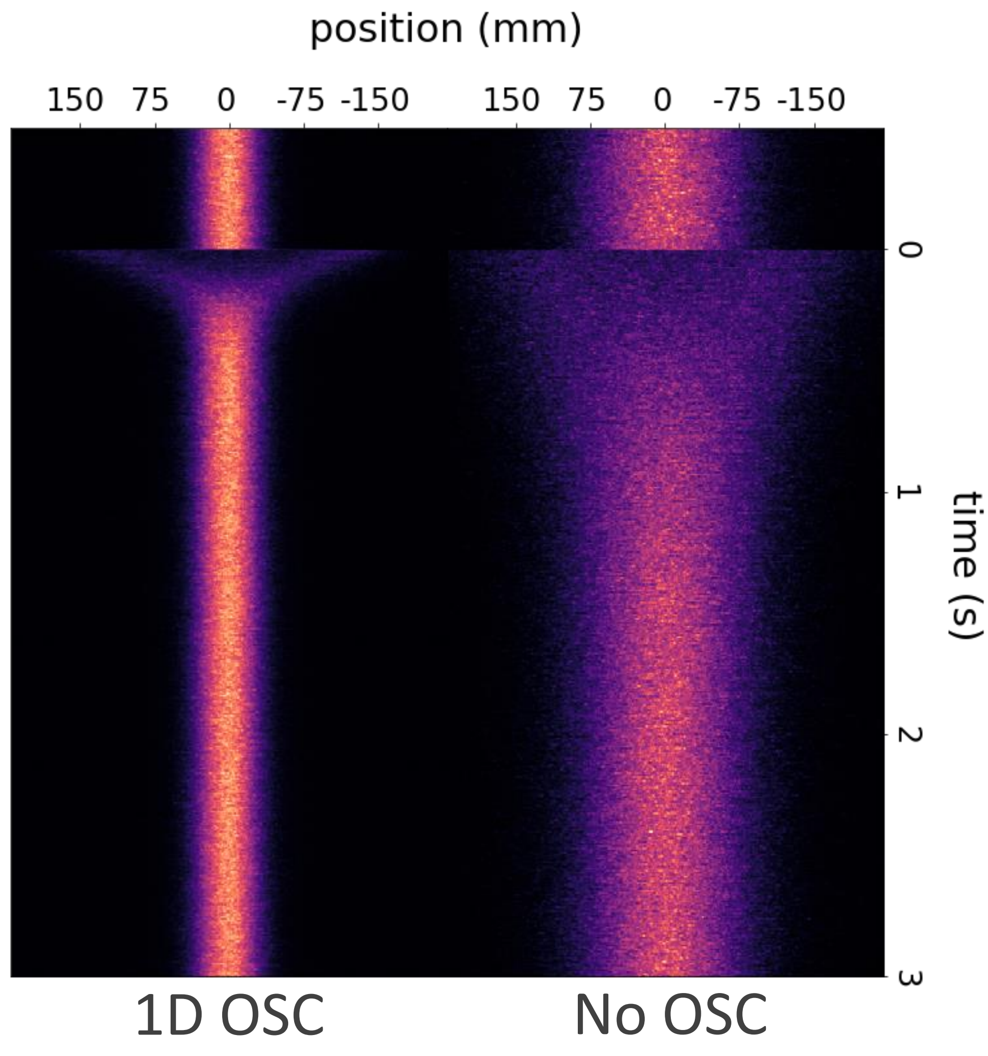
OSC Cooling configurations at a glance…

- OSC toggles "quickly" place the system in a cooling or heating mode
- OSC system initially detuned longitudinally by ~30 wavelengths; i.e. OSC off
- Delay plates are then snapped at max speed (15λ/s) to the orientation for optimal cooling
- OSC system would remain stable over the beam lifetime.



Total OSC ~9x stronger than longitudinal SR damping

- Can estimate OSC strength relative to synchrotron-radiation damping via:
  - **Equilibrium sizes**
  - **Direct "fast" measurements of damping after a kick**
- Sizes: full takes all relevant effects into consideration (e.g. IBS, gas scattering, cooling range, etc…)
- Direct/fast: Placed system in the 1D cooling mode and "kicked" beam longitudinally with RF phase jumps
- Initial analysis gives total emittance cooling rate of **~9x** SR damping (z) for both methods



(Streak camera projections)

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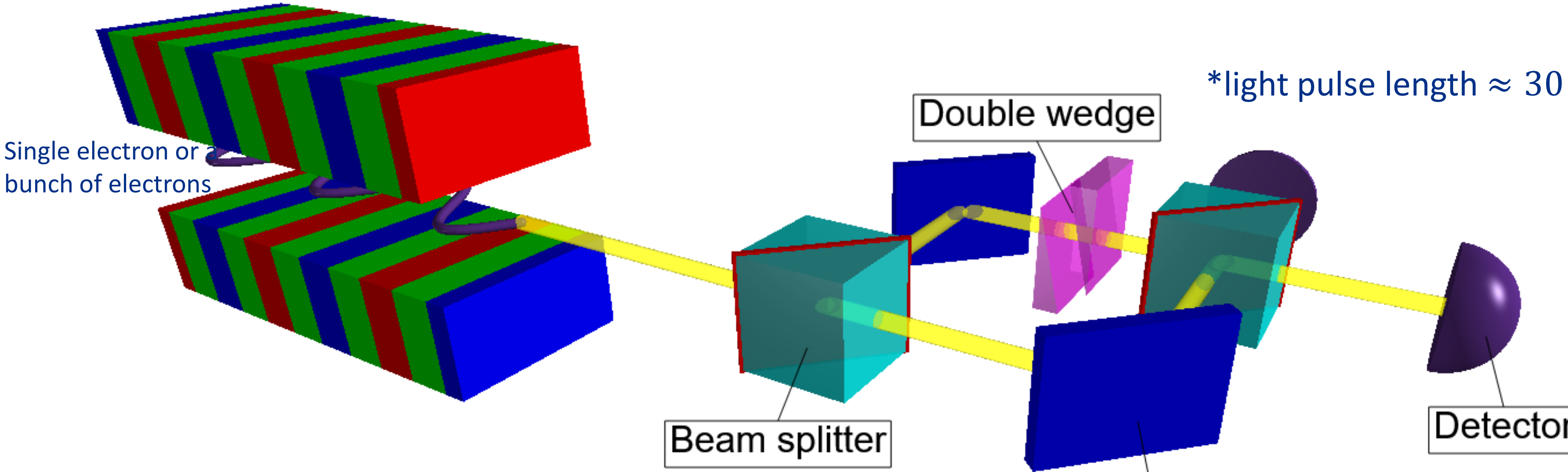
Experiment #3: Conclusions

- Our first ever demonstration of stochastic beam cooling at optical frequencies serves as a foundation for more advanced experiments with high-gain optical amplification and advances opportunities for future operational OSC systems with potential benefit to a broad user community in the accelerator-based sciences.
- May offer a feasible method for cooling hadrons at energies below ~4 TeV (e.g. at the EIC). May also enhance the existing synch radiation facilities.

Future experiments

Future experiments: Mach-Zehnder interferometry

- Interference of the photons in emitted photon pairs with two detectors:



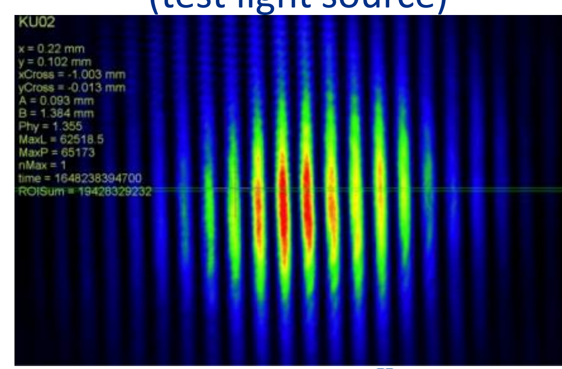
*light pulse length ≈ 30 fs

- **Mach–Zehnder interferometer:**
  - **Output 1:** $E(t) - E(t + \delta t)$
  - **Output 2:** $E(t) + E(t + \delta t)$

In some sense, this is a measurement of the light pulse shape in time domain

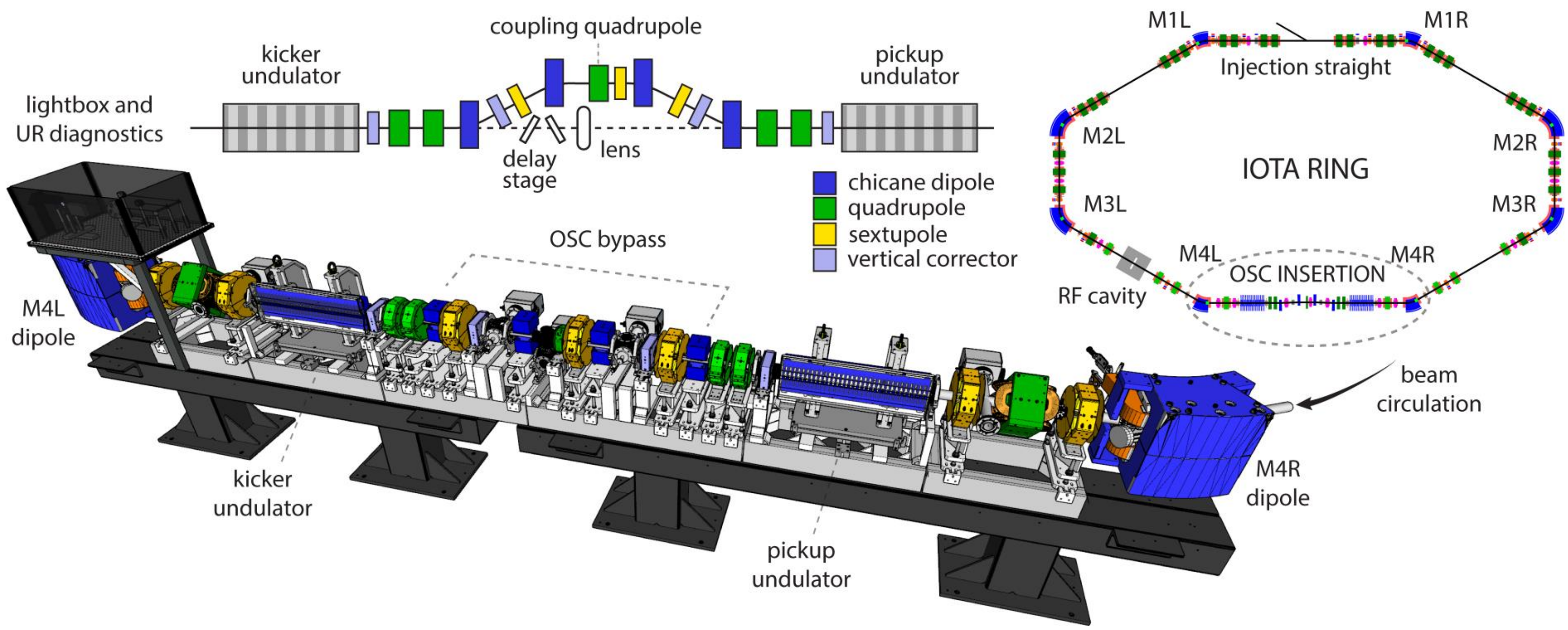
This experiment is currently under preparation

MZ fringes with a HeNe laser (test light source)



Fermilab

A staged approach for OSC at IOTA



- **Non-amplified OSC (~1-μm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-μm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification + effect on cooling, active phase-space control for improved cooling

Summary

- Observed super-Poissonian fluctuations in undulator radiation intensity, fully consistent with our model of classical and quantum fluctuations.
- Proposed and demonstrated a fluctuations-based technique to measure electron beam emittances, which can be particularly useful for state-of-the-art and next-generation x-ray synchrotrons.
- For the first time, observed 6D OSC, fully consistent with our predictions. Our OSC demonstration is at an intersection of fundamental beam-physics studies and the development of operational cooling systems.
- Established a strong foundation for development of amplified OSC experiment: validated many critical subsystems and concepts; gathered excellent operational experience and learned many valuable lessons