QUANTUM BEAMS

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UK Accelerator Institutes Seminar

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ACKNOWLEDGEMENTS

→ *Thanks to the UK Accelerator Institutes (CI, JAI, ASTeC) and Ian Bailey , in particular, for inviting me to give this lecture*

→ *Thanks to my colleagues at Fermilab, ANL, Stanford and BNL (Jonathan Jarvis, Ihar Lobach, Sergei Nagaitsev, Valeri Lebedev, Alexander Valishev, Giulio Stancari, Alex Romanov, Kwang-Je Kim, Alex Halavanau, Zhirong Huang, Timur Shaftan)*

BACKGROUND

- *The title of this talk is deceptive!!!!*
- *Ian Bailey asked me to talk about 'quantum beams'*
- *As far as I know, taken singly without collisions, most beams are far from their quantum limits*
- *Limits appear when we consider colliding beams at extremely high intensities at high energies OR at extremely low intensities of a single charge with associated photon emission*
- *The title 'Quantum Beams' of this lecture is therefore meant to refer to physics of a single relativistic quantum -- either a charged particle or a photon or a collection of just a few of them*

BACKGROUND (cont'd)

- *I will first address briefly issues related high energy particle colliders*
- *I will then discuss issues related to phase-space manipulation and 'cooling' of a single charge or a few charges*
- *Finally, I will discuss quantum statistical aspects of photons emitted by a single charge or a few charged particles*
- *I am told by Ian that a number of talks will be solicited in early 2022 in this seminar series from colleagues at Fermilab, SLAC, BNL, CERN etc.*
- *I have already transmitted the relevant names and coordinates of speakers on these topics to Ian.*

→*Okay, onto the dreamland, my boyhood stomping ground…..!!!*

(I have earned my right in retirement to dream a bit after a long career of practical and successful projects)

Darjeeling!!! (8,000 ft) – my boyhood days!!

The Kanchenjunga range (28,000 ft) of the Himalayas in the backdrop, in northeast India, close to Nepal

Two significant experiences here in Darjeeling during my boyhood days inspired wonder and awe!!

(i) Experiencing Mountaineering/Trekking and (ii) Observing the soviet-launched man-made Sputnik with bare eyes in the clear Himalayan skies

OUTLINE

1. *Introduction: Background and a Skeptic's View*
2. *"Quantum-limited" Ultimate Beams for 5 TeV c.m. e-e+ Collider*
3. *Van der Meer's Optical Angel: "Optical Stochastic Cooling"*
4. *"Single Electron" in a Storage Ring*
5. *Radiation from a single electron: "Photon Statistics"*
6. *Outlook*

BACKGROUND and a Skeptic's View:

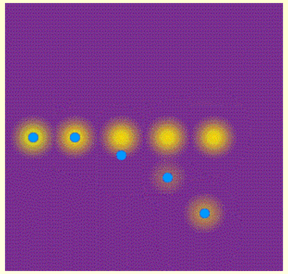
Photon emission from a single electron

Fundamental Issues of Electron-Photon Interaction

Each particle emits 'α' photons per turn, where α is the fine structure constant ~ 1/137

For small sample population, $N_s \sim 50 - 100$, the number of equivalent photons from sample and amplifier

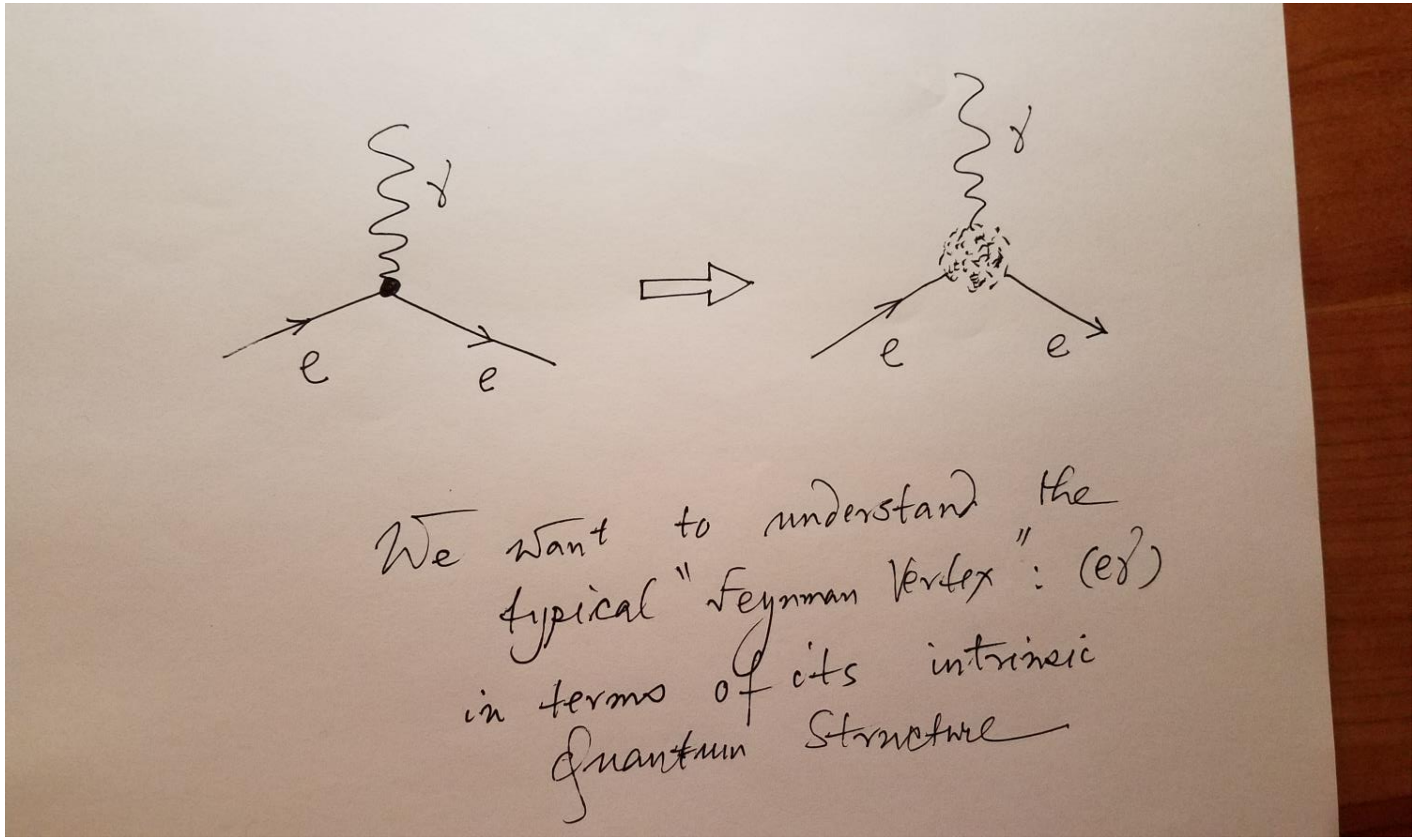
$$N_p \sim (0.5 - 1) + 1 \sim O(1).$$



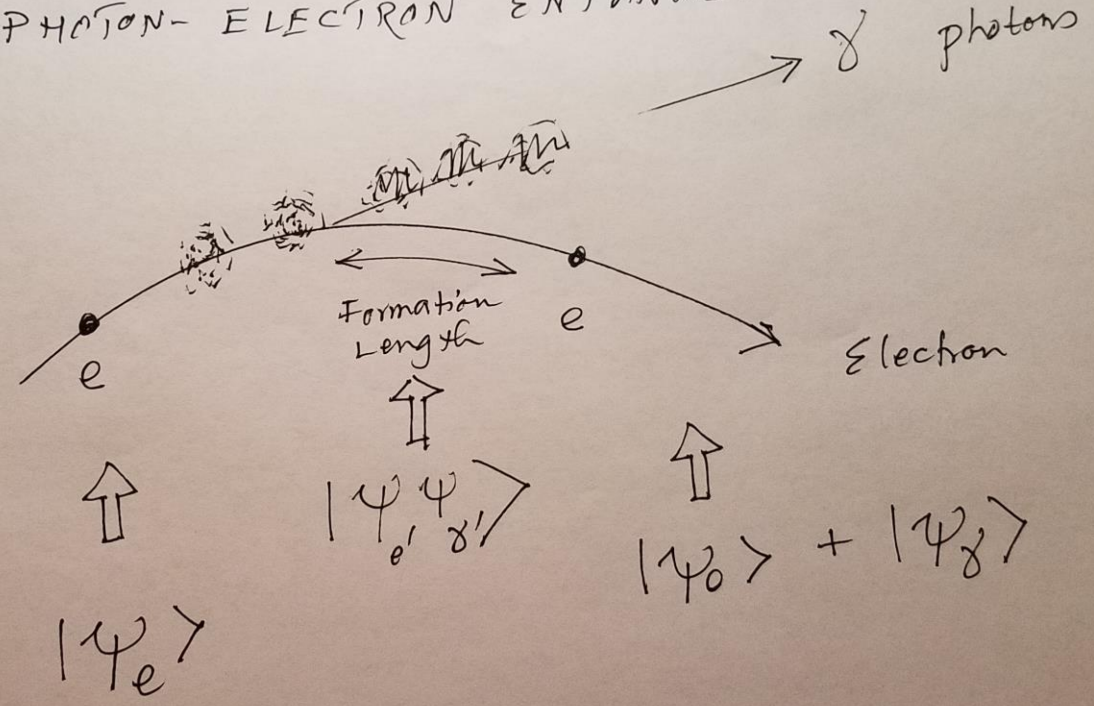
These few photons generate a field that is intrinsically non -classical and quantum mechanical. Small "degeneracy" parameter means small number of photons in a coherence volume. How does optical probing work in the quantum limit?

Quantum optics of radiation from accelerated ultra-short bursts of electrons is critical to taming particle beams to an "ordered" and "coherent" state comparable to a laser….this is very different for OSCILLATORS vs AMPLIFIERS!!

Understand the detailed quantum mechanical structure of the simple Feynman vertex



Weizsacker-Williams Virtual Quanta,
Formation Length,
PHOTON-ELECTRON ENTANGLEMENT



THIS QUESTION IS "UNSOLVED" TO DATE!!

Experiments very difficult and challenging due to the time-scales and laboratory noise involved. Theoretically, QED involves too many Feynman diagrams.

However creating and measuring enhanced 'radiation reaction' of a single electron is possible in a laboratory setting. This will be the topic of 'Van der Meer's Optical Angel: Optical Stochastic Cooling' later in the talk.

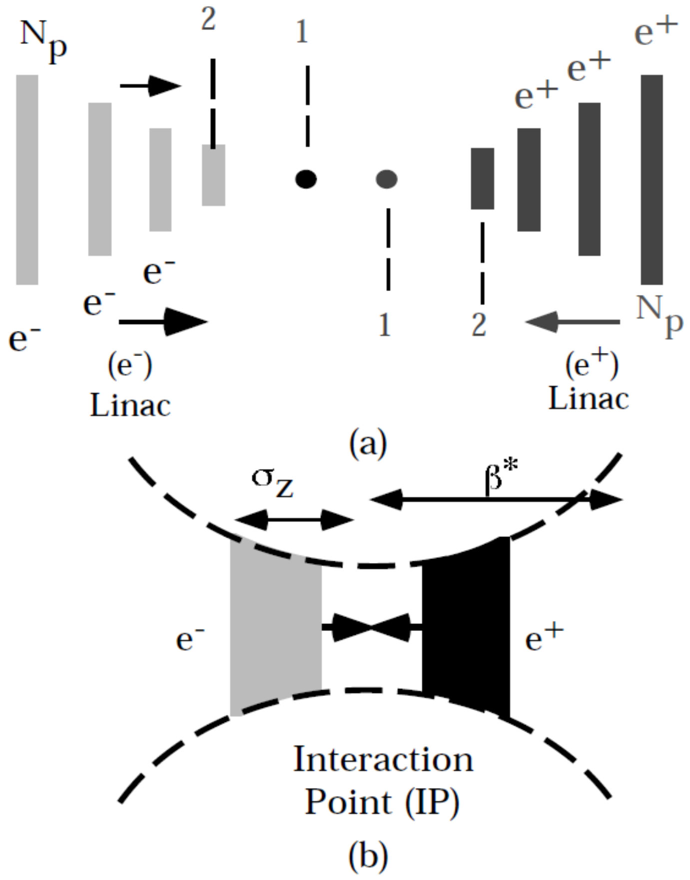
But first brief excursion into particle colliders…….

High Intensity, High Energy Collider Issues

- *In electron-positron linear colliders, quantum limits appear as 'radiative' effects of 'Beamstrahlung', coherent pair creation and strong interaction QCD backgrounds, but still far from the limits on 'final focus' spot size arising from the 'Oide' effect (statistical nature of emitted photons of synchrotron radiation arising from severe bending during final focus). These 'radiative' effects limit electron-positron linear colliders beyond 5 TeV c.m. energy*

- *In circular Lepton and Hadron Colliders, most limits arise either from energy loss due to synchrotron radiation requiring prodigious amount of electrical power (as in electron-positron circular colliders) or from classical nonlinear dynamical phenomena of phase-space diffusion and particle loss due scattering and classical nonlinear dynamics of resonances etc.*

A TYPICAL COLLIDER CONFIGURATION
at
INTERACTION POINT



'H': Luminosity enhancement due to 'beam self-pinching', high luminosity coming at the expense of high average beam power

$$L = \frac{fN^2}{4\pi\sigma_y^{*2}R} H$$

$$P_b = 2\left(\gamma mc^2\right)(Nf) = \eta P_w.$$

The 'radiative effects' at the IP affect the charged particle beam phase space (hence luminosity and collision kinematics) and generate undesirable backgrounds in the detector:

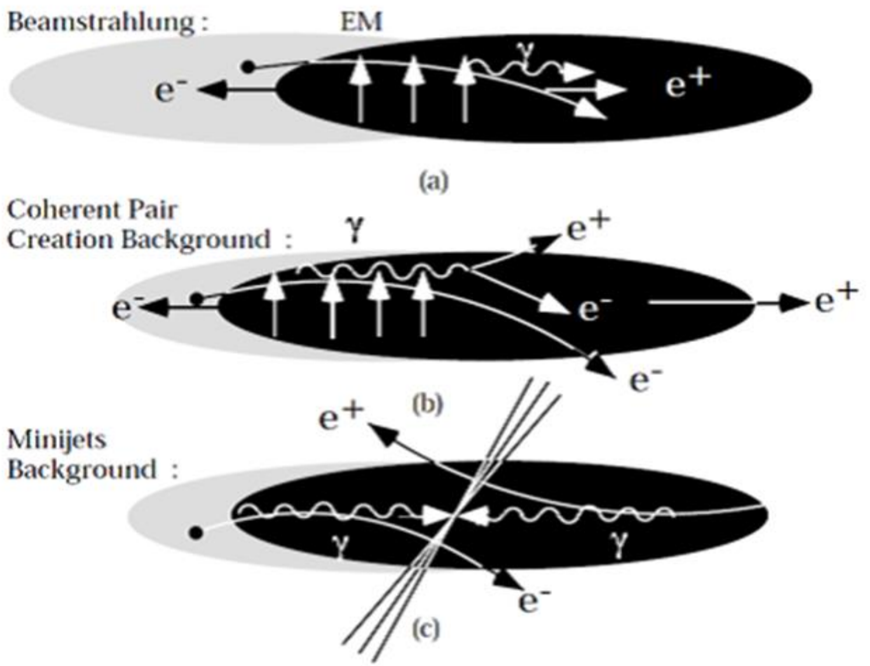
Υ 'Upsilon' parameter determines the ratio of the energy loss due to 'beamstrahlung' to the average particle energy in collision.

δ_B 'Delta B' parameter is the average energy loss of a beam particle to 'beamstrahlung'.

n_γ Finally, 'N-gamma' is the QCD hadronic background in terms of the hadronic cross-section. TYPICALLY: keep 'Upsilon' <0.3

$$\Upsilon >> 0.3$$
$$\delta_B > 0.1$$
$$n_\gamma >> 1 \quad .$$

$$\Upsilon = \frac{0.43 r_e^2}{\alpha}\left(\frac{\gamma N}{\sigma_z \sigma_y^*}\right)\left(\frac{2}{1+R}\right) .$$



Scaling of 'scaled' variables as a function of 'Upsilon' beamstrahlung parameter for a 5 TeV c.m. electron-positron collider at a luminosity: L = 10 E 35 cm-2 s-1 (round beams, horizontal normalized emittance 10 E -6 m-rad, beamstrahlung energy spread, 'Delta B' ~10%

$$\beta^*_{x,y} = \sigma_z \ \hat{\beta}_{x,y}$$

$$\sigma_z = (\lambda / 100) \ \hat{\sigma}_z$$

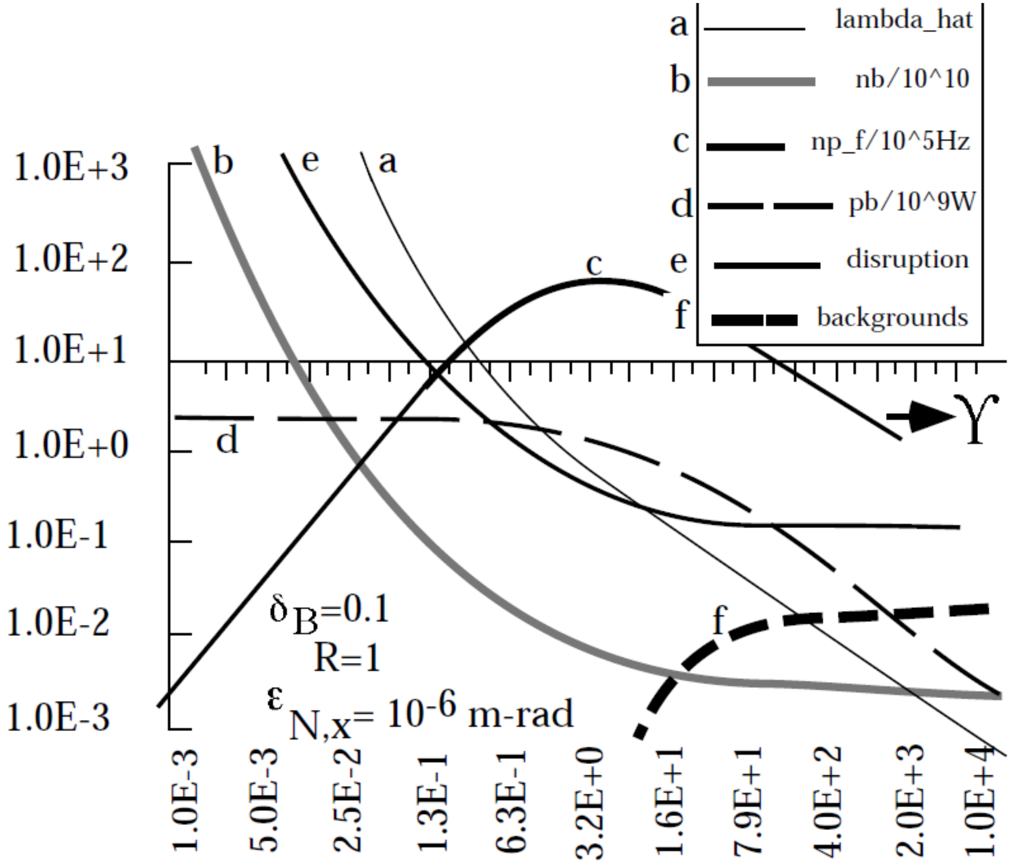
$$\gamma = 5\mathrm{x}10^6 \ \hat{\gamma}$$

$$L = \left(10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\right) \hat{L}$$

$$\varepsilon_{N,x,y} = \left(10^{-6}\,\mathrm{mrad}\right)\hat{\varepsilon}_{N,x,y}$$

$$R = \left(\sigma^*_x / \sigma^*_y\right)$$

$$\lambda(\mathrm{cm}) = (\hat{\gamma} / \hat{\sigma}_z)\hat{\lambda} \ .$$



$$N \sim 10^8 \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{1/2} \left(\frac{1+R}{R}\right) \hat{\lambda}^{3/2} \Upsilon$$

$$\delta_B \sim 0.5 \frac{\hat{\lambda} \Upsilon^{\,2}}{\left[1+(1.5\Upsilon)^{2/3}\right]^2}$$

$$f \sim 2.6\mathrm{x}10^7 \frac{R}{(1+R)^2} \frac{1}{\hat{\lambda}^2} \frac{1}{\Upsilon^2} \hat{L}$$

$$P_b \sim 2\mathrm{x}10^9 \frac{\hat{\gamma} \ \hat{L}}{(1+R)} \frac{1}{\Upsilon} \frac{1}{\hat{\lambda}^{1/2}} \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{1/2}$$

$$D_Y \sim 0.6 \ \Upsilon \ R \hat{\lambda}^{3/2} \left(\hat{\varepsilon}_x \hat{\beta}_x\right)^{-1/2} \ .$$

ULTIMATE 'Quantum-limited' BEAM for a SUPERCONDUCTING RF-BASED 5 TeV LINEAR COLLIDER

$L \sim 10^{35} cm^{-2} s^{-1}$	$N \sim 2.7 \times 10^{10}$
$f \sim 4.7$ kHz	$N_P \sim 20{,}000$
Spot Size :	1.3 nm x 505 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-8} m-rad
$\Upsilon \sim 2.3$	$\delta_B \sim 23\%$

ULTIMATE 'Quantum-limited' BEAM for a NORMAL COINDUCTING RF-BASED 5 TeV LINEAR COLLIDER

$L \sim 10^{35}\,cm^{-2}s^{-1}$	$N \sim 2.4 \times 10^{9}$
$f \sim 120$ Hz	$N_P \sim 225$
Spot Size :	0.5 nm x 40 nm
Normalized Emittance :	10^{-8} m-rad x 10^{-6} m-rad
$\Upsilon \sim 2.7$	$\delta_B \sim 27\%$

IT IS PREMATURE TO SPECULATE ULTIMATE BEAM for LASER-PLASMA or BEAM-PLASMA WAKEFIELD-BASED LINEAR COLLIDER UNTIL R&D HAS PROGRESSED FOR ANOTHER DECADE.

TODAY's Quantum-limited colliders reach 5 TeV c. m. energy at L = 10 E 35 cm-2 s-1 (round beams, horizontal normalized emittance 10 E -6 m-rad, beamstrahlung energy spread, 'Delta B' ~10%)

We continue to struggle to fund even a 250 GeV c.m. electron-positron collider today!!

"Radiative Regime of Linear Colliders, High Repetition Rate Free Electron Lasers and Associated Accelerating Structures", Swapan Chattopadhyay and Roger Jones, ***Nucl. Instrum. Meth. A* 657 (2011) 168-176**

"Advanced Accelerating Technologies: A Snowmass'96 Subgroup Summary", Swapan Chattopadhyay, David Whittum and Jonathan Wurtele, **Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High-Energy Physics (Snowmass '96), SLAC-PUB-9914**

Optical Stochastic Cooling (OSC)

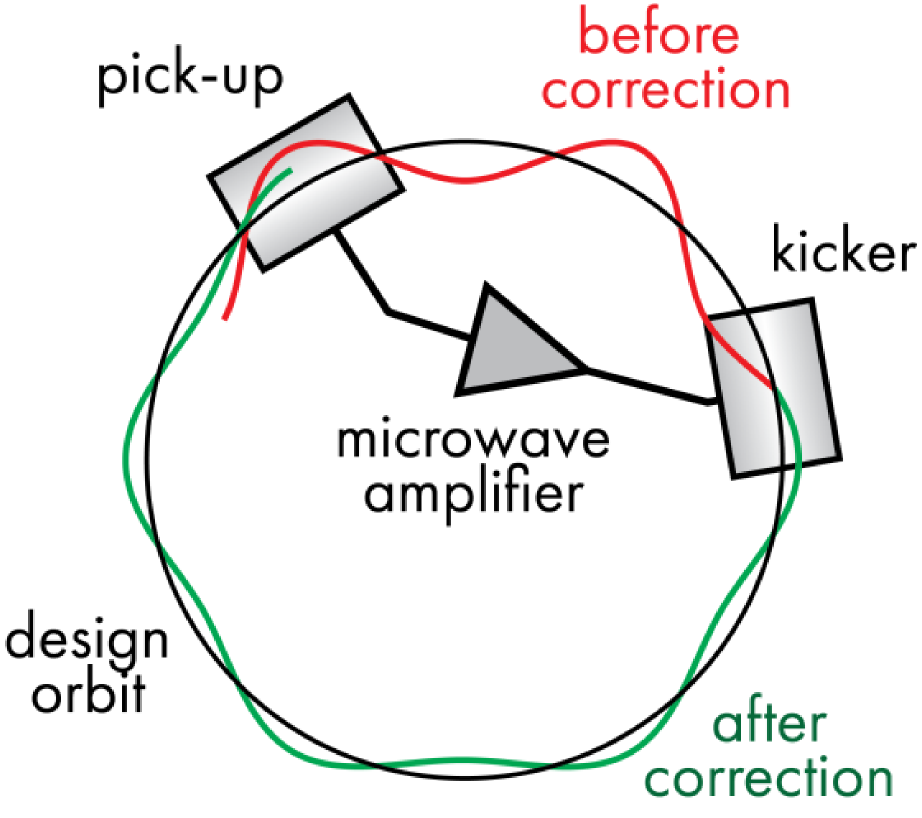
Van der Meer's Optical Angel

(or a Maxwell's Demon of Light!)

for a Single Electron

(CREDIT: Experimental data contribution from Jonathan Jarvis, Giulio Stancari and Valeri Lebedev of Fermilab)

SC: a powerful technique but limited to GHz BW



Simplified stochastic cooling system

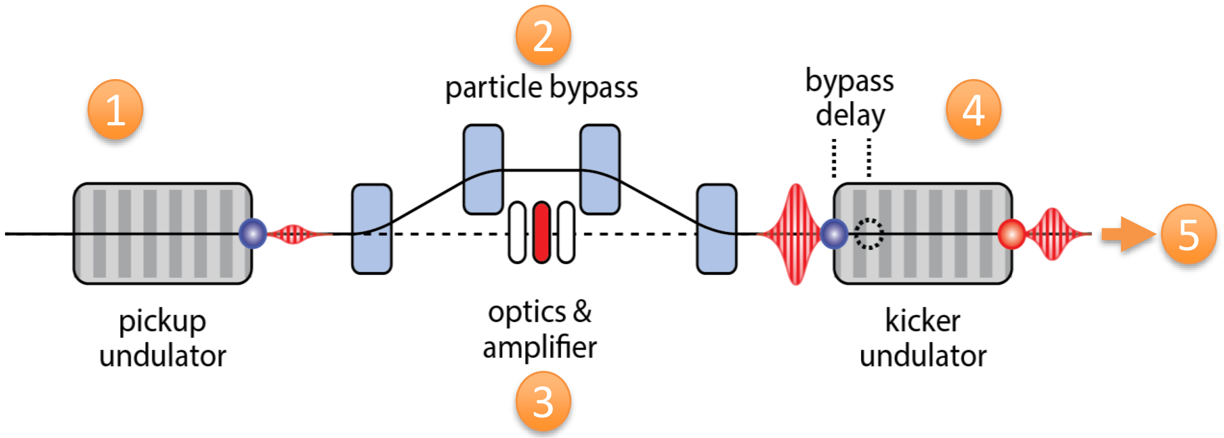
$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi\sigma_x{}^*\sigma_y{}^*}$$

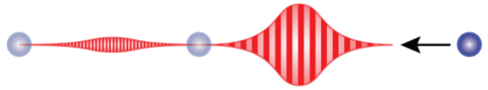
1984 Nobel: van der Meer/Rubbia
Enabled discovery of the W and Z Bosons of Electroweak Unification in the SppbarS collider

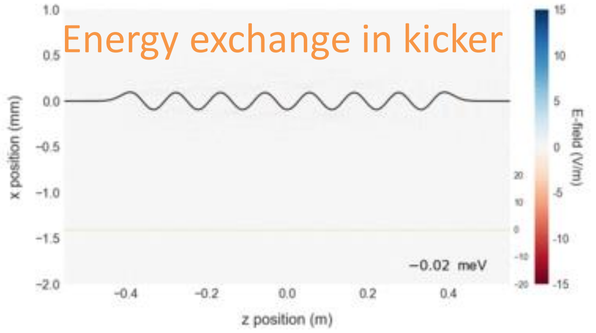
1) We can increase beam brightness if we have granular information about particle ensemble.

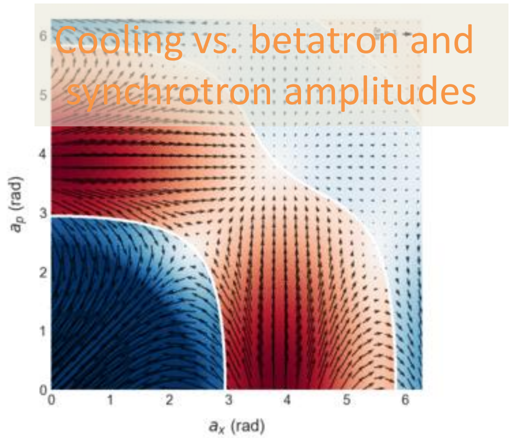
2) Bandwidth of feedback system controls cooling rate

OSC extends the SC principle to optical bandwidth









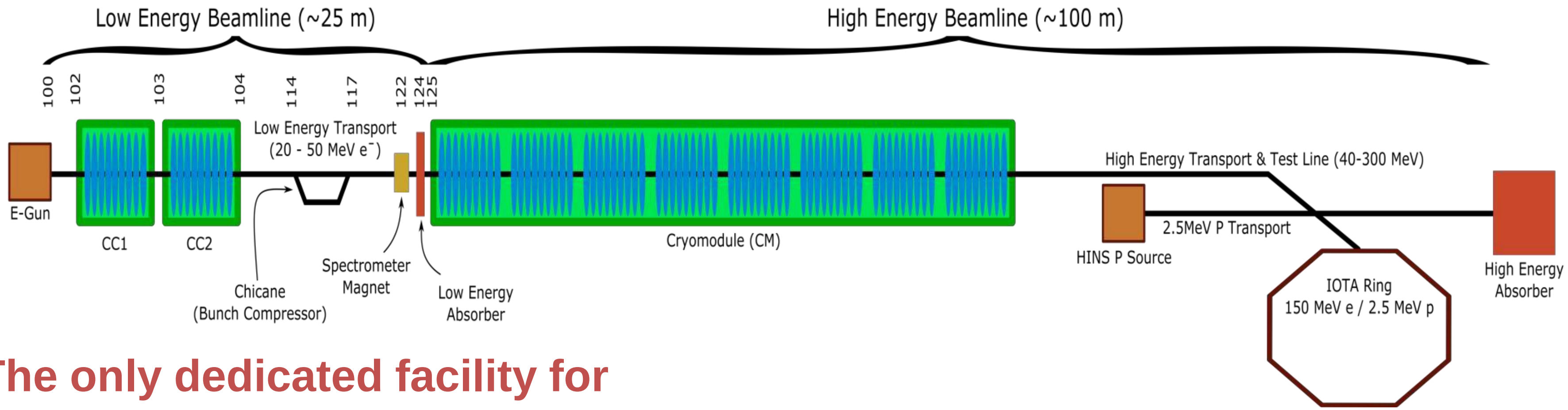
1. **Wavepacket generated**
2. **Particle delayed in bypass**
3. **Wavepacket amplified and focused**
4. **Corrective kick applied**
5. **Cooling accumulates over many passes**

10^3 – 10^4 increase in cooling rate over SC and extension into an energy range where no cooling solutions exist

[1] A.A.Mikhailichkenko, M.S. Zolotorev, "*Optical stochastic cooling*," Phy
Rev. Lett. 71 (25), p. 4146 (1993)
[2] M. S. Zolotorev, A. A. Zholents, "*Transit-time method of optical stochastic cooling*," Phys. Rev. E 50 (4), p. 3087 (1994)

IOTA/FAST Test Facility at Fermilab

- Establishes a unique capability world-wide for high and low intensity R$D



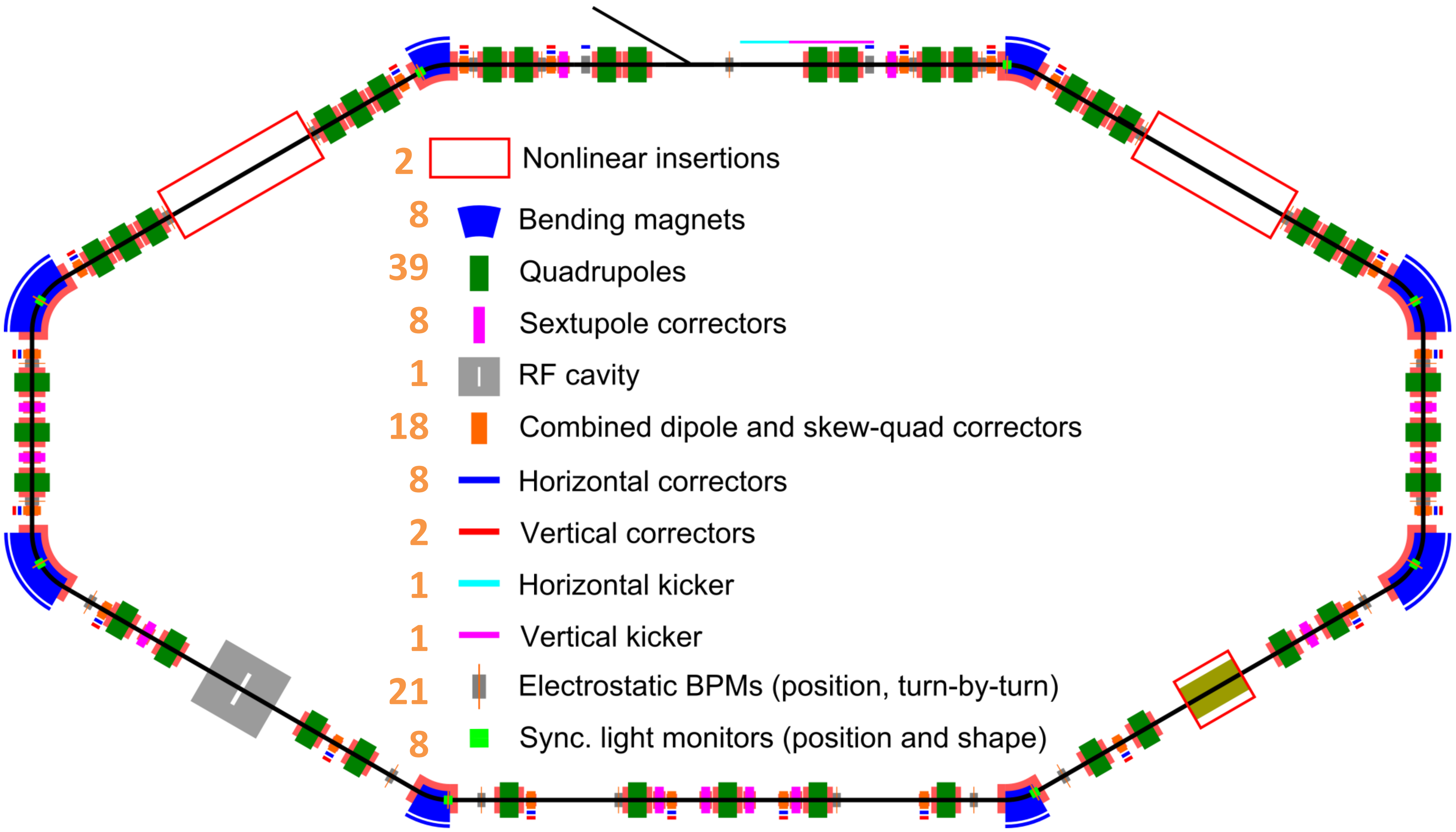
- The only dedicated facility for intensity-frontier accelerator R&D:

- ~30 Collaborating institutions

- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF

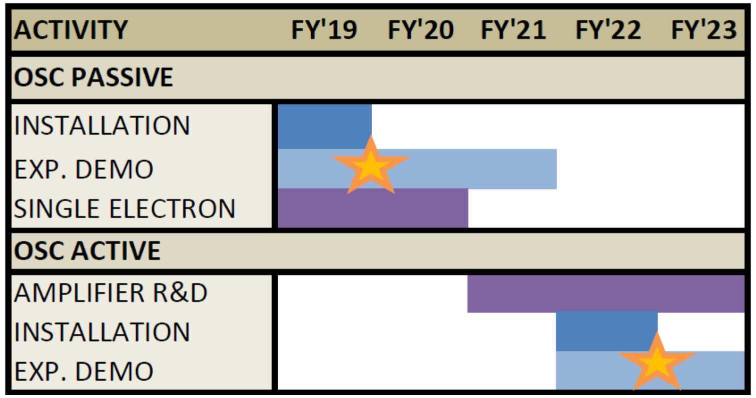
- Many opportunities for R&D with cross-office benefit in DOE/SC

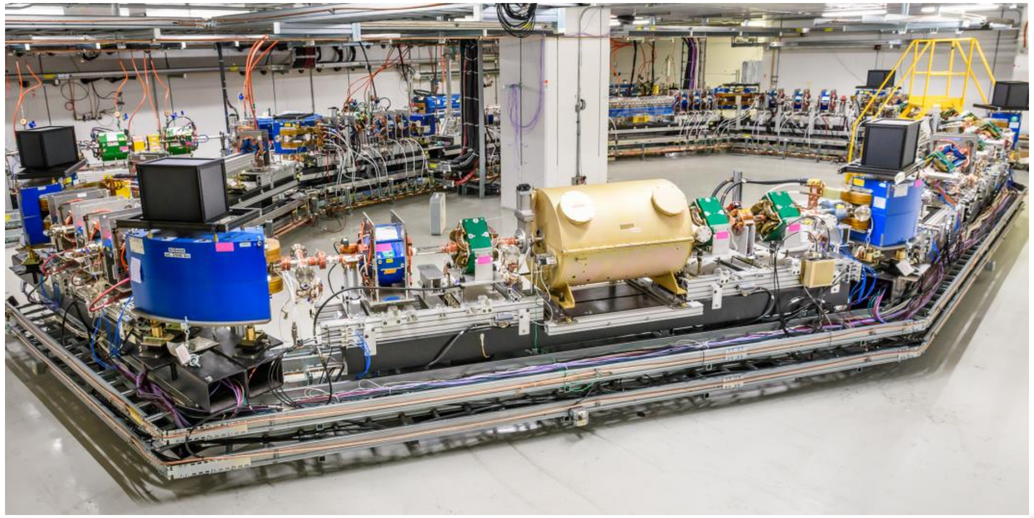
Fermilab Test Facility IOTA Layout - Elements

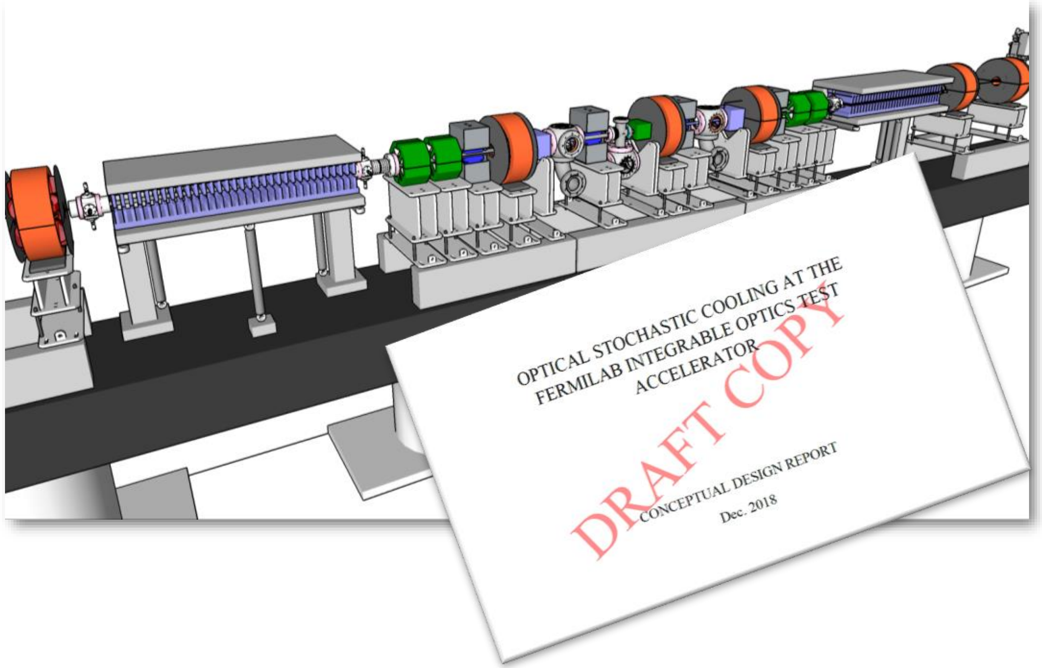


Worlds first OSC demonstration in ~Q4 FY'21

- Completing ~100 pg. CDR
- A low-emittance test lattice was successfully implemented and characterized in prep for OSC
- Proof of principal began in late FY'19
- Active OSC demo beginning in FY'21
- Facilitate pathfinder experiments towards use in EIC/future colliders

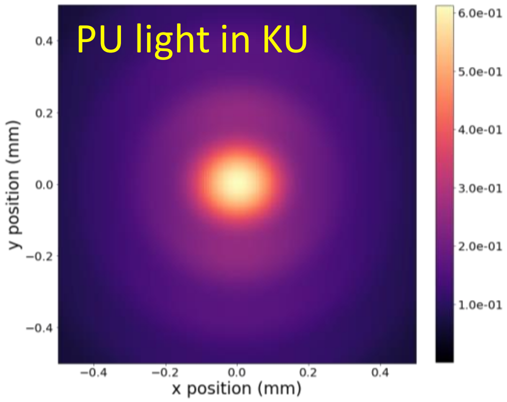




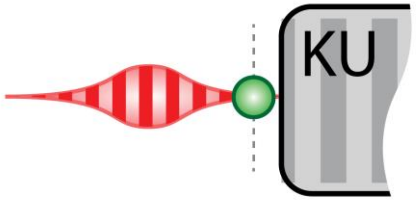


What makes ("simple") OSC challenging?

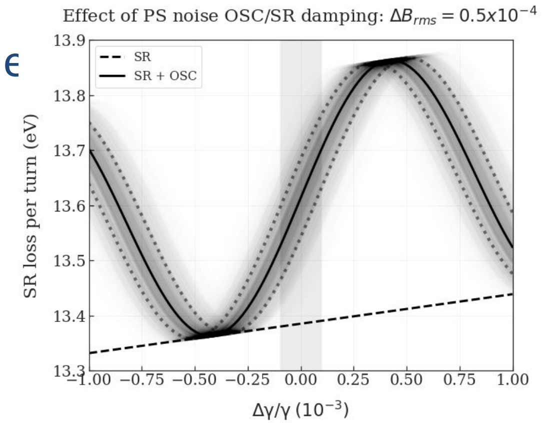
1. Beam and PU light must overlap through the KU
   – The undulator light is **~200 μm** wide
   – Want angle between light and beam at < **~0.1 mrad**



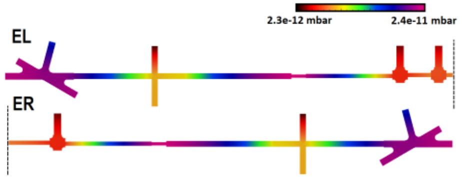
2. Beam and PU light must arrive ~simultaneously for maximum effect
   – Absolute timing should be better than **~0.3 fs**
   – The entire delay system corresponds to ~2000 fs



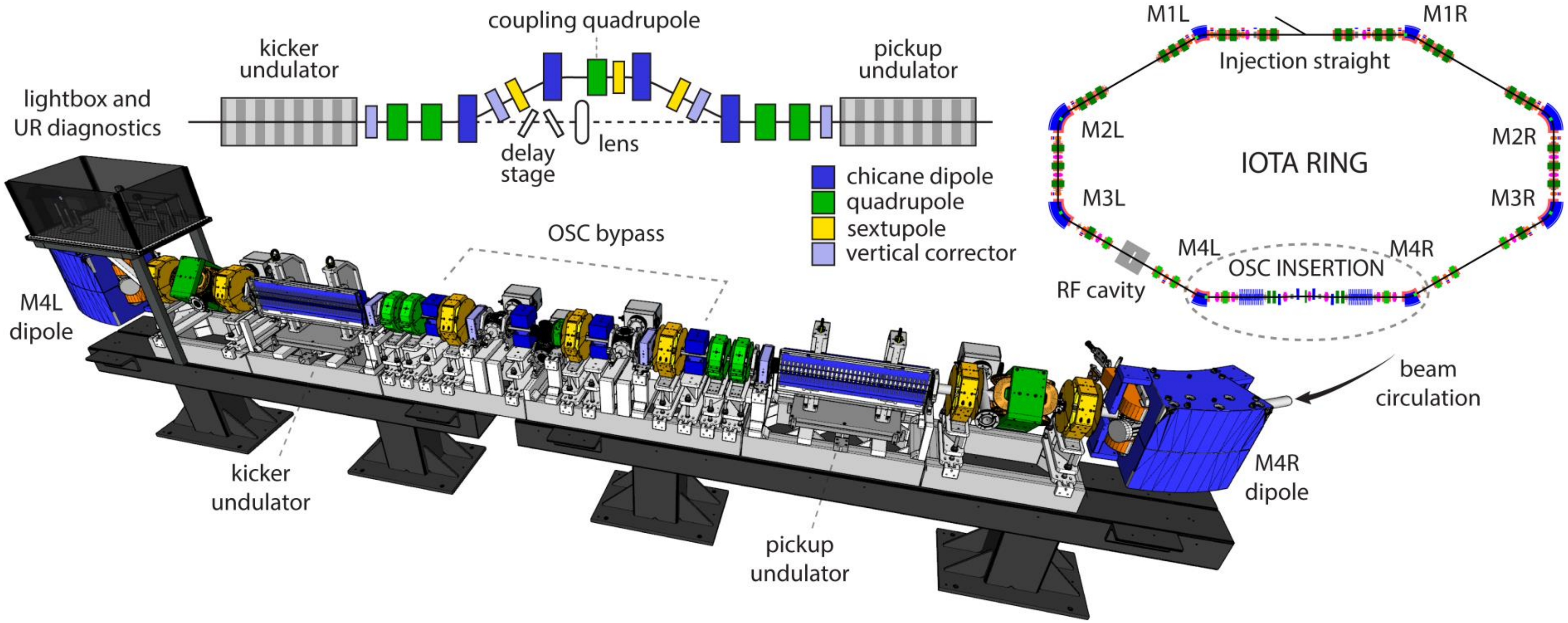
3. The electron bypass and the light path must be stable to much smaller than the wavelength
   – Arrival jitter at the KU should be better than **~0.3 fs**
   – This means total ripple+noise in chicane field must be at the **~mid 10^{-5}** level



4. Practical considerations of design and integration!



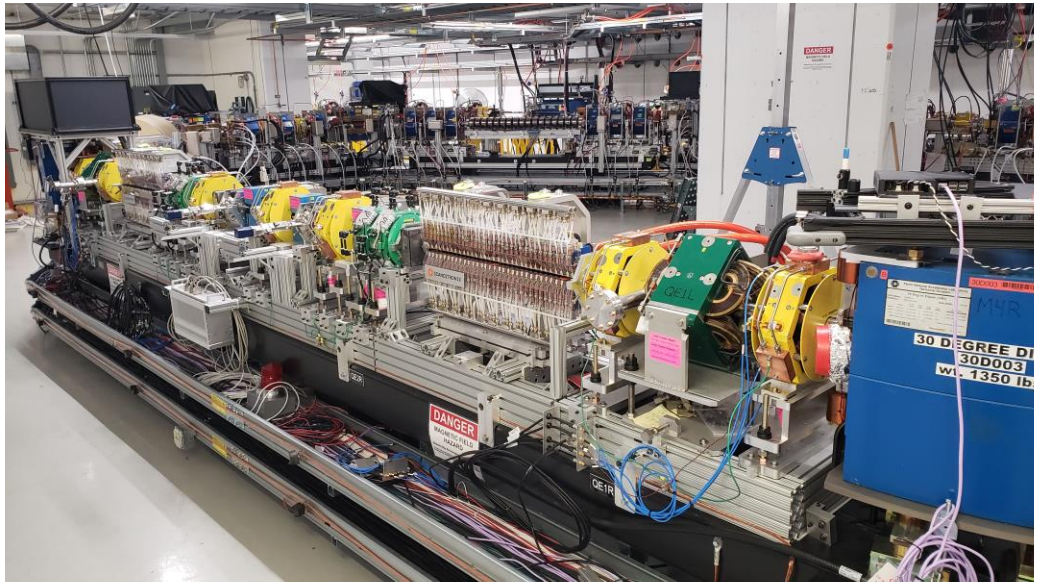
A staged approach for OSC at IOTA

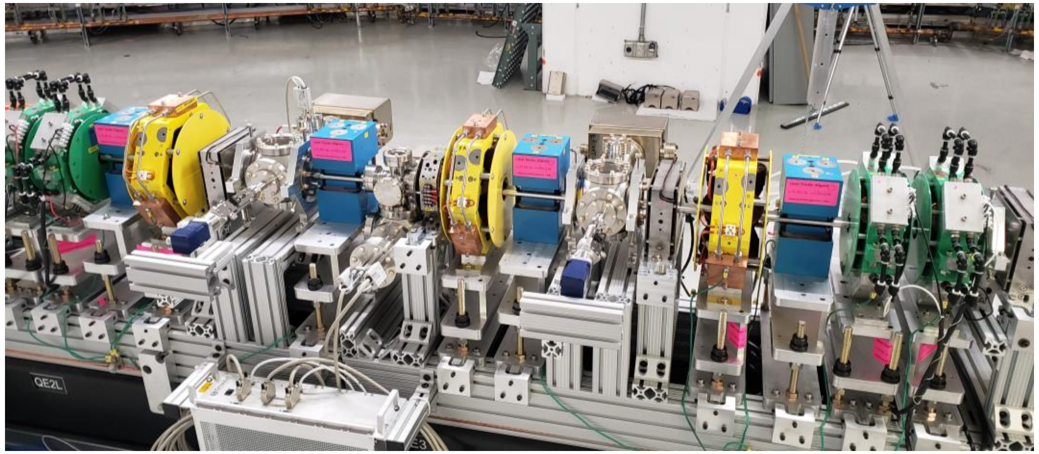


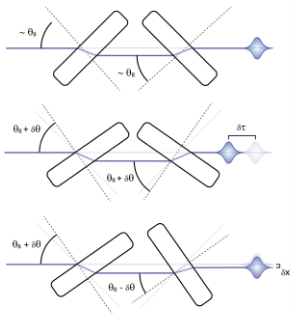
- **Non-amplified OSC (~1-μm)**: simplified optics with strong cooling to enable early exploration of fundamental physics; cooling rates, ranges, phase-space structure of cooling force, single and few-particle OSC
- **Amplified OSC (~2-μm)**: OSC amplifier dev., amplified cooling force, QM noise in amplification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

OSC apparatus successfully integrated in IOTA

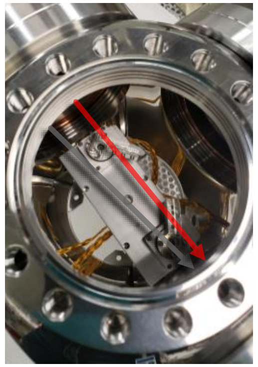
- Established and corrected OSC lattice to desired precision
- Achieved ~80% of theoretical max aperture and >20-min lifetime; more than sufficient for detailed OSC studies
- OSC chicane and the optical-delay stage were demonstrated to have the required control and stability for OSC
- Successfully validated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

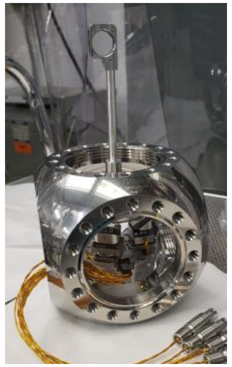




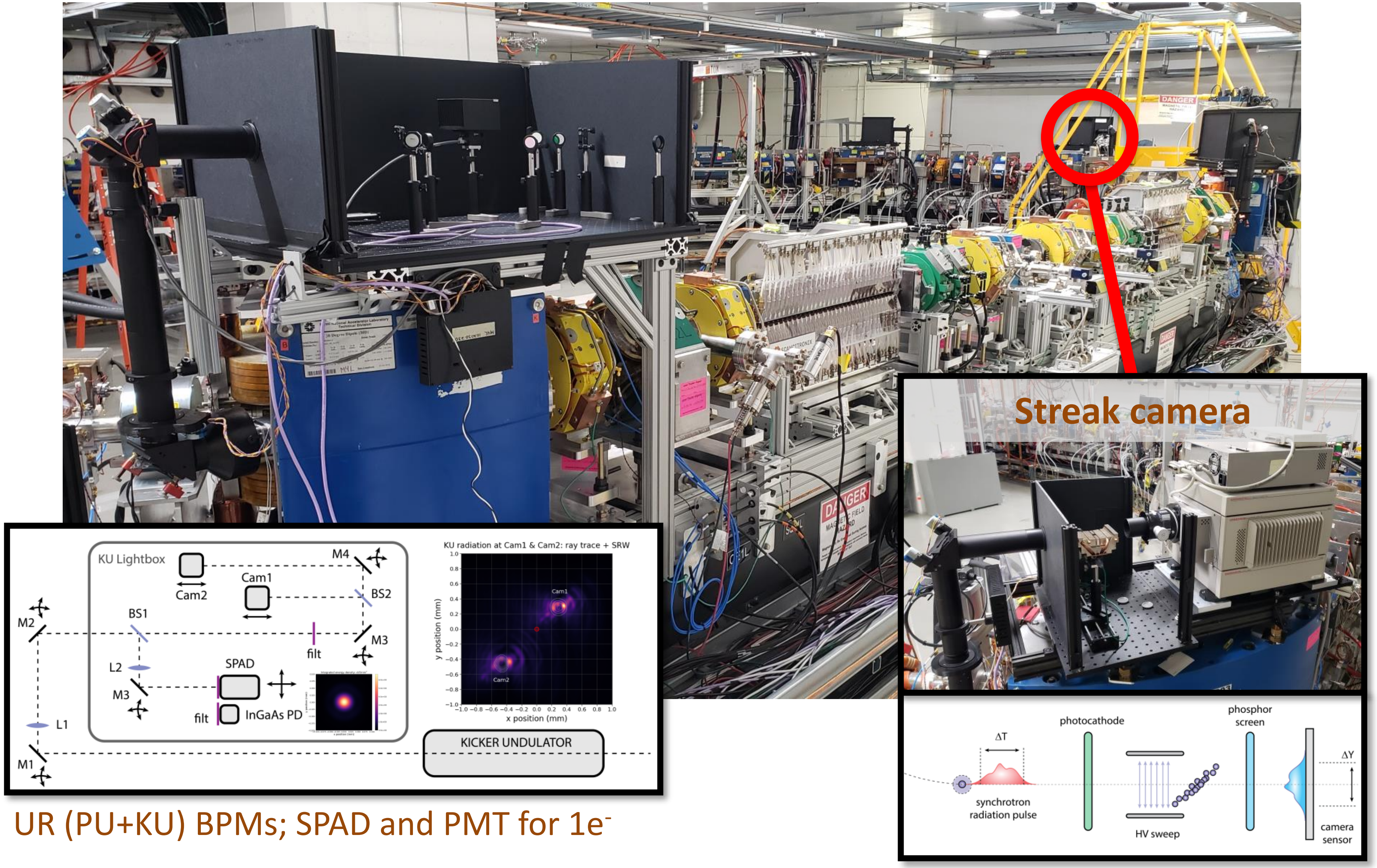


Delay stage





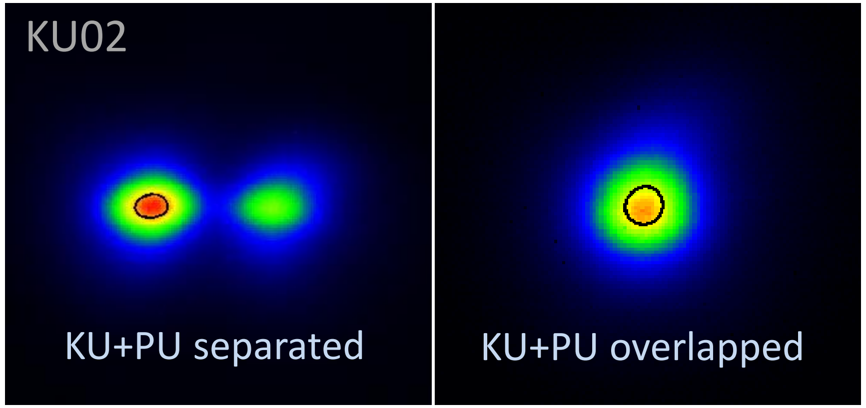
OSC is monitored via synchrotron-rad. stations

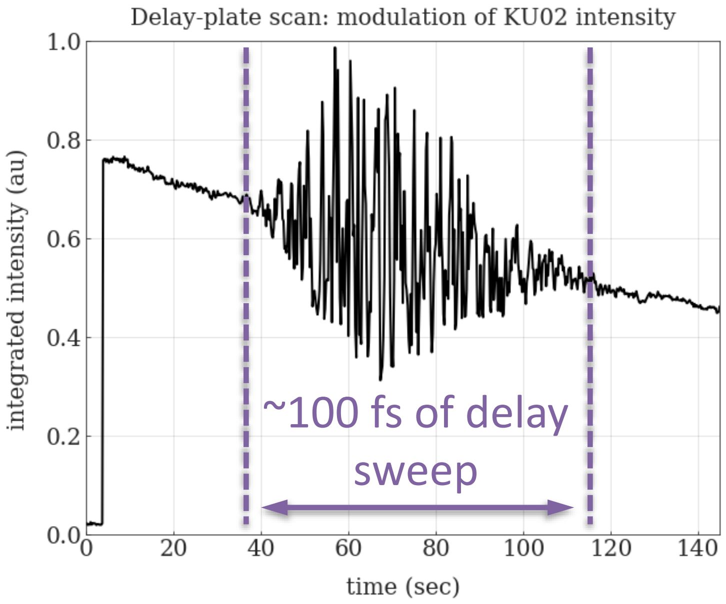


UR (PU+KU) BPMs; SPAD and PMT for 1e⁻

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

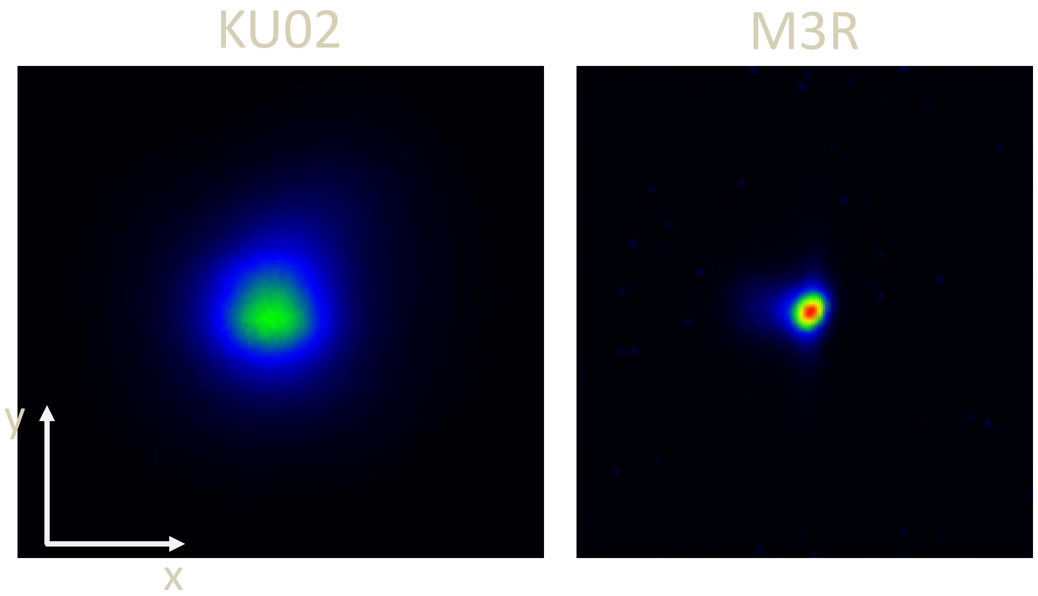
- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both 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 4/20/2021

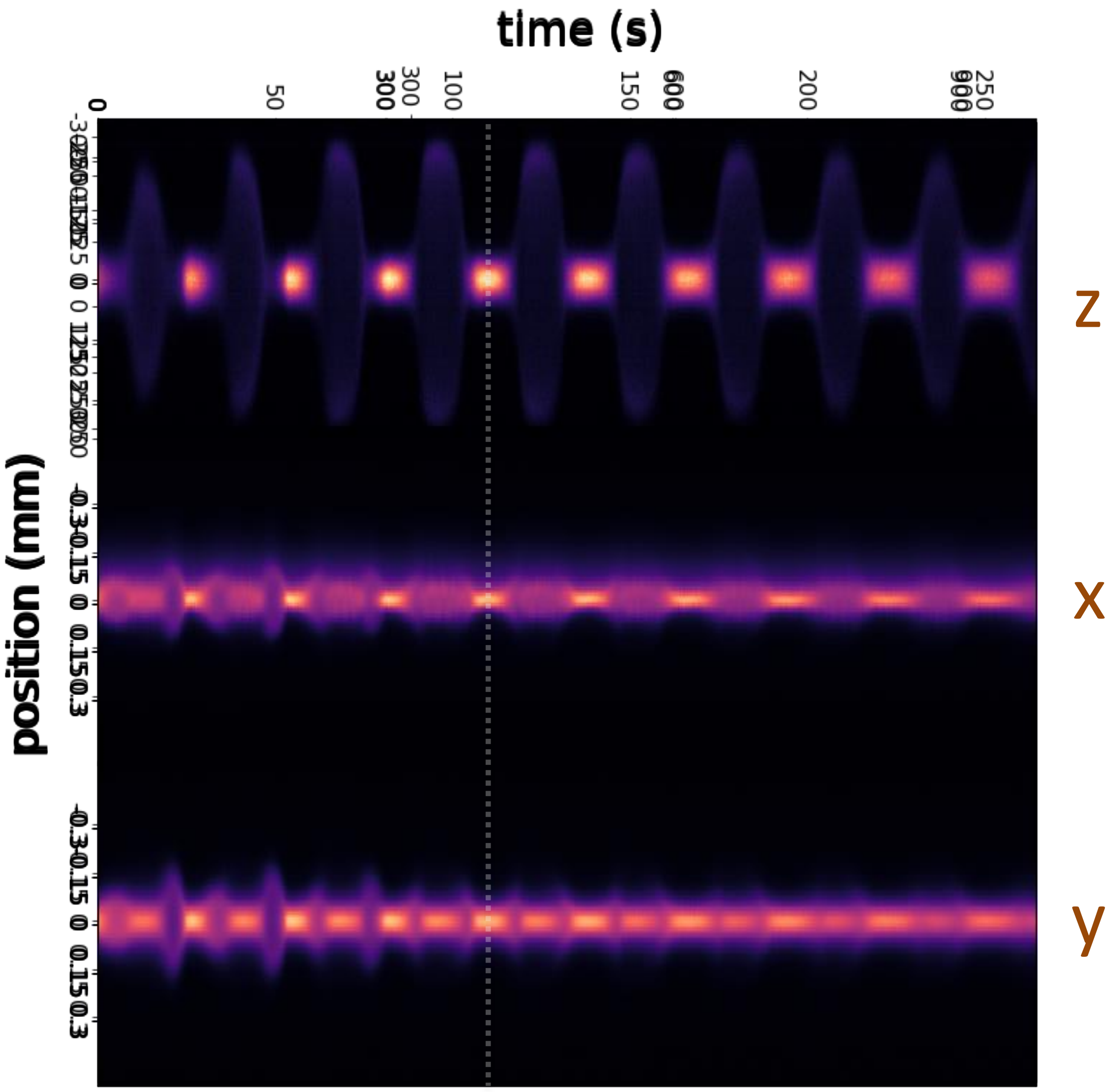


(movies not taken simultaneously but are representative)

- 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 (~10 nm?)

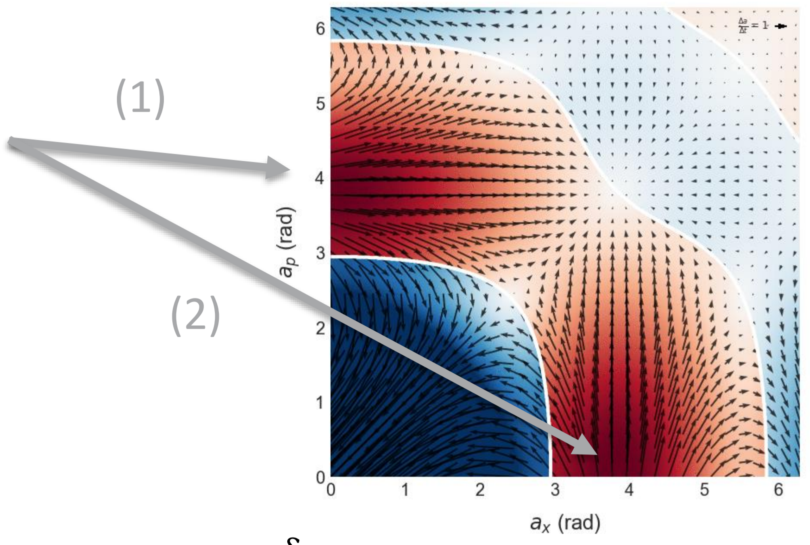
After much work… OSC was strong and stable: OSC ~10x stronger than longitudinal SR damping

- 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



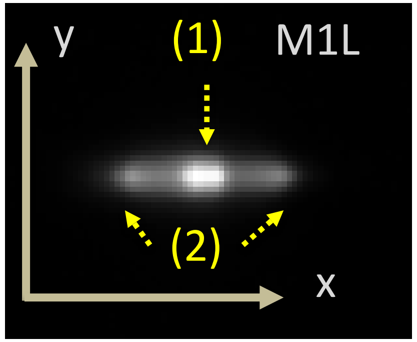
Clear observation of expected OSC zone structure

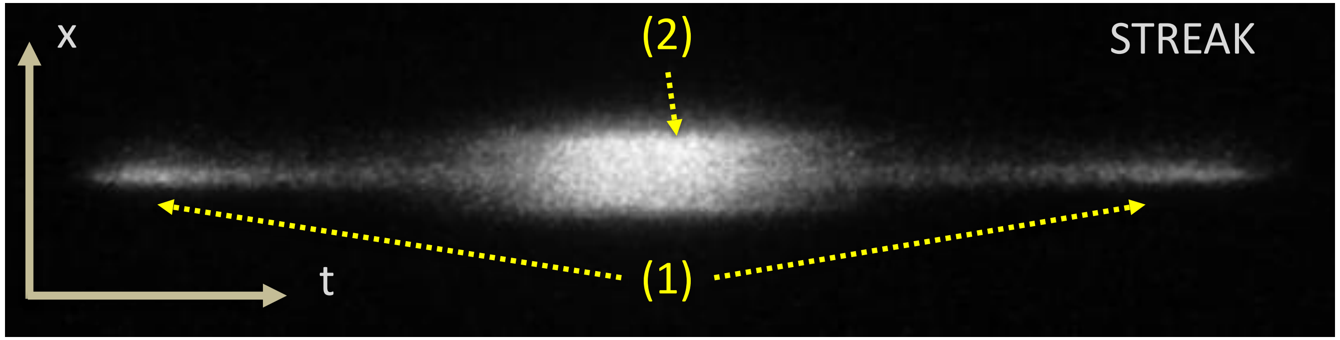
- (e.g) OSC in the 2D (s,x) configuration
- In “heating” mode, expect two high-amplitude attractors
- (1): high synchrotron amplitude, low betatron amplitude
- (2): high betatron amplitude, low synchrotron amplitude



$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$

2D Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net force



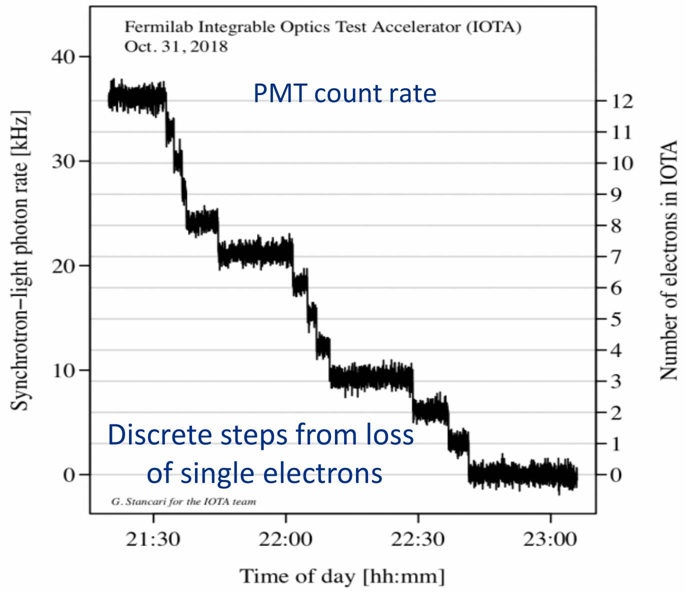


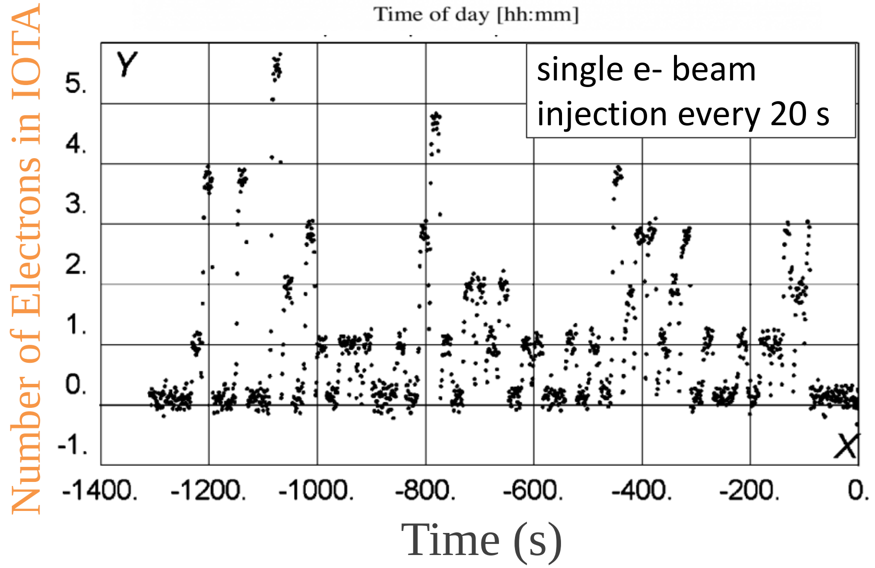
Quantum Science

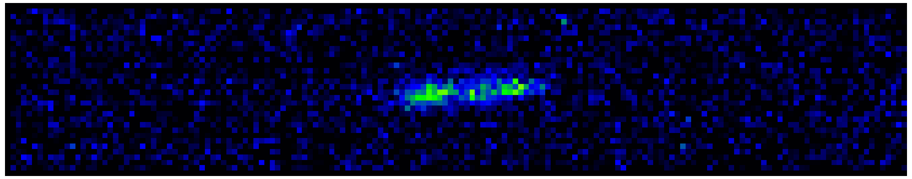
Can we go to the quantum limit for a "single" electron?

IOTA presents unique opportunities in QS

- IOTA demonstrated storage of a single relativistic electron for long periods of time (>10 minutes).
- High particle energy (100 MeV) enables observation of SR emission
- This opens the way to a wide variety of quantum experiments







Previous experiments with a single electron

- VEPP-3 storage ring in Novosibirsk in 1990s

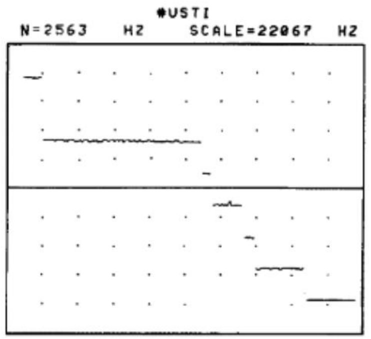
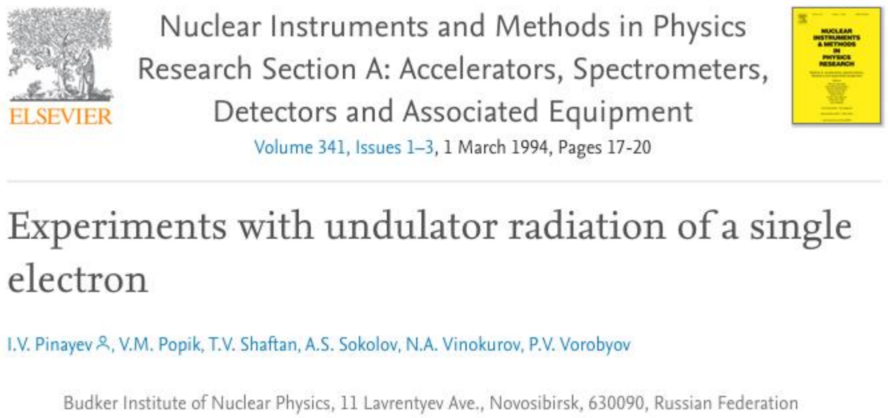


Fig. 3. The time dependence of the counts rate. One step corresponds to the blow out of one electron. (Vertical scale is 22 kHz, horizontal scale is 2560 s).



ELSEVIER

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment

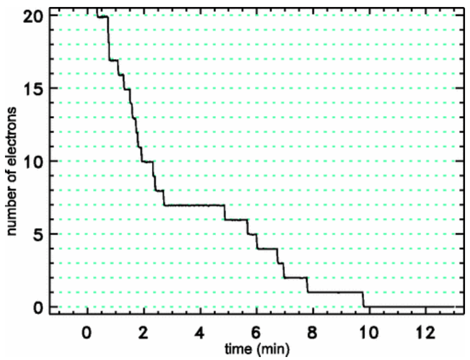
Volume 341, Issues 1–3, 1 March 1994, Pages 17-20

Experiments with undulator radiation of a single electron

I.V. Pinayev, V.M. Popik, T.V. Shaftan, A.S. Sokolov, N.A. Vinokurov, P.V. Vorobyov

Budker Institute of Nuclear Physics, 11 Lavrentyev Ave., Novosibirsk, 630090, Russian Federation

- Metrology Light Source in Germany in 2000s




Open Access

Operation of the Metrology Light Source as a primary radiation source standard

Roman Klein, Guido Brandt, Rolf Fliegauf, Arne Hoehl, Ralph Müller, Reiner Thornagel, Gerhard Ulm, Michael Abo-Bakr, Jörg Feikes, Michael v. Hartrott, Karsten Holldack, and Godehard Wüstefeld

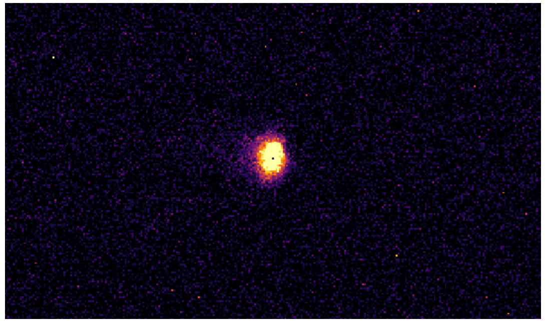
Phys. Rev. ST Accel. Beams **11**, 110701 – Published 20 November 2008

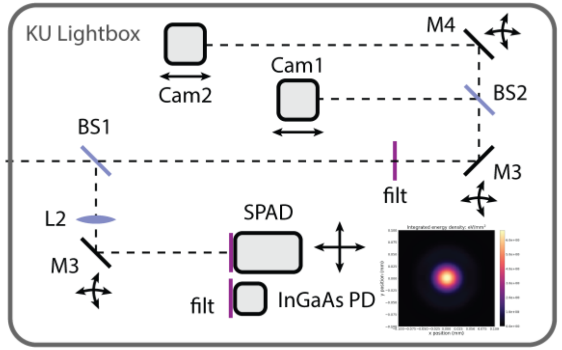
More

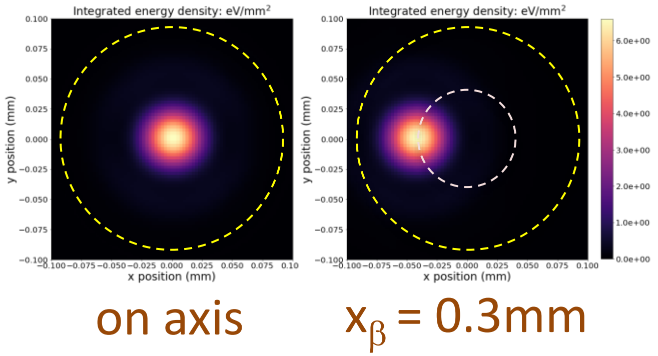
Article | References | Citing Articles (47) | PDF | HTML | Export Citation

IOTA enables single-electron OSC studies

- Can reliably inject and store a single electron in IOTA; **OSC system changes probability of photon detection in fundamental band**
- Fundamental (KU+PU) was focused on the active element of a SPAD (KU lightbox); demagnified so that betatron excitations up to ~0.3mm (~10 sigma) remain on SPAD's active element
- HydraHarp event timer captures every detected photon for both the SPAD and PMT (M3L lightbox) over many minutes; referenced to IOTA revolution marker with resolution of a few hundred ps, which is sufficient to observe OSC phenomena
- Performed full OSC delay scans and toggles of cooling/heating for 1D and 2D OSC configuration



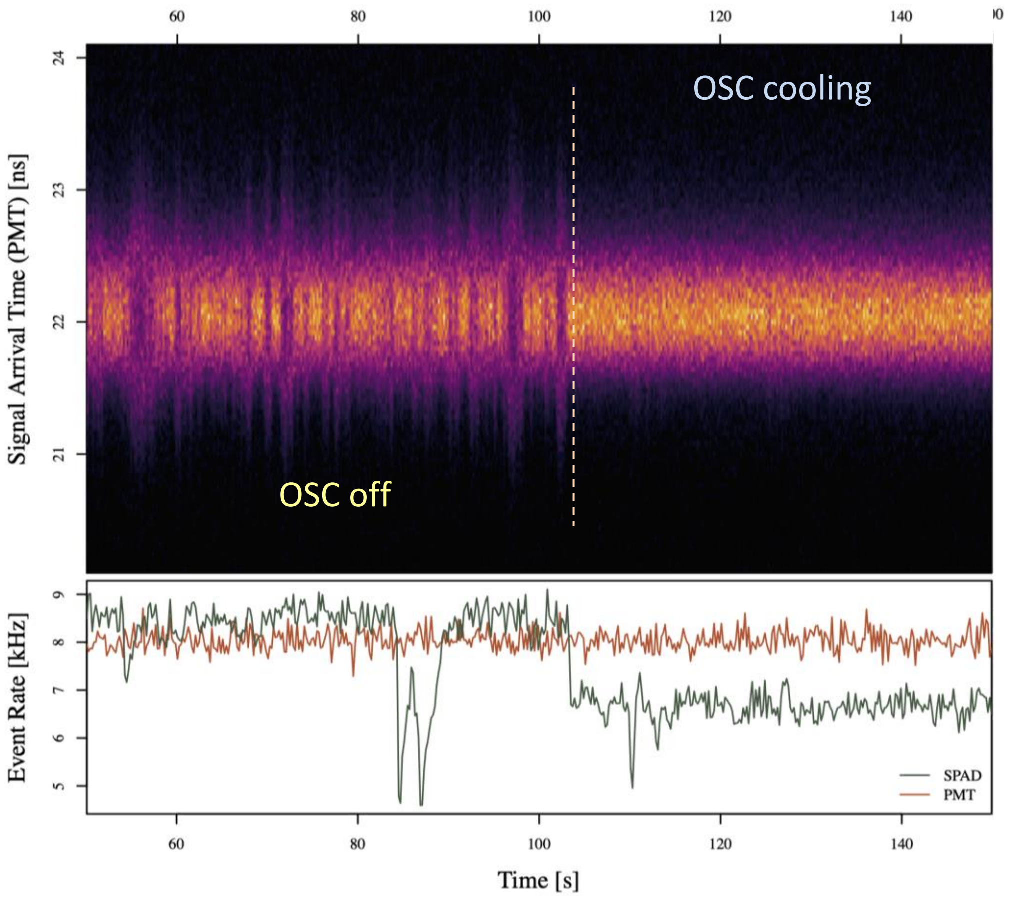




OSC for single electron is visible in photon timing

- Event data is binned in 40-ps intervals and integrated for 200-ms windows
- *Equilibrium bunch size with OSC off (~170 ps) is smaller than the system resolution
- Large excitations (gas scattering) are commonly observed with OSC off
- Synchrotron excitations are strongly damped with OSC in the cooling mode (1D)
- Observe projected turning points in the heating mode; amplitude corresponds to ~5 sigma (no OSC)

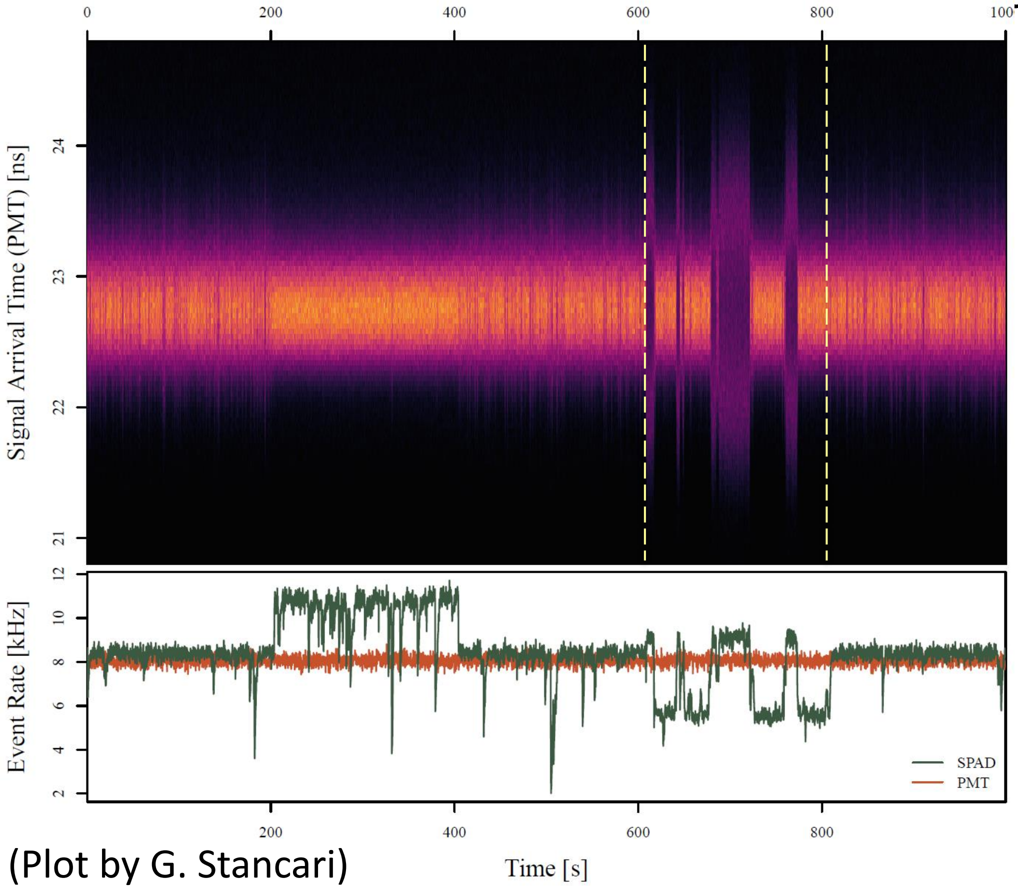
1D OSC configuration



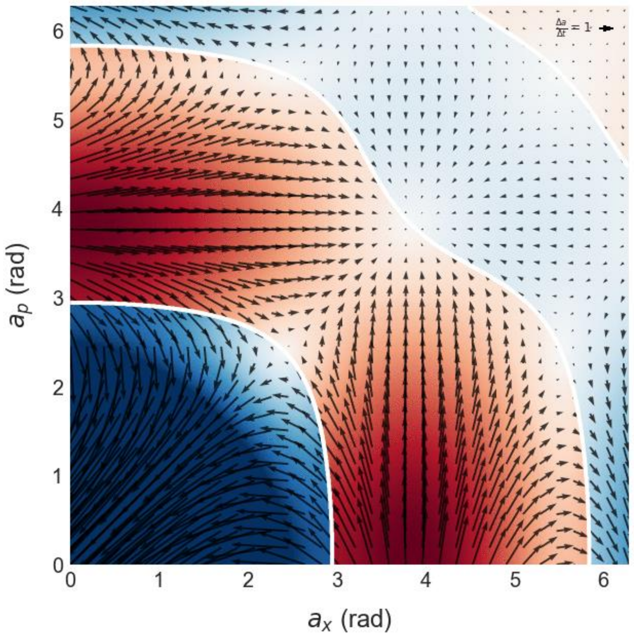
(Plots by G. Stancari)

Observe bistable transitions between attractors

- OSC in the 2D configuration (s,x)
- As with a beam, expect the same two attractors in heating mode…
- …but, single electron can only be in one attractor at a time!



(Plot by G. Stancari)



$$\frac{\delta p}{p} = -\kappa \sin\left(a_x \sin\psi_x + a_p \sin\psi_p\right)$$

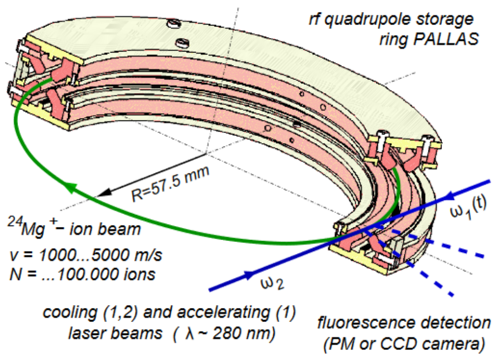
Cooling map integrated over betatron and synchrotron oscillations; arrows show mag. and dir. of net force

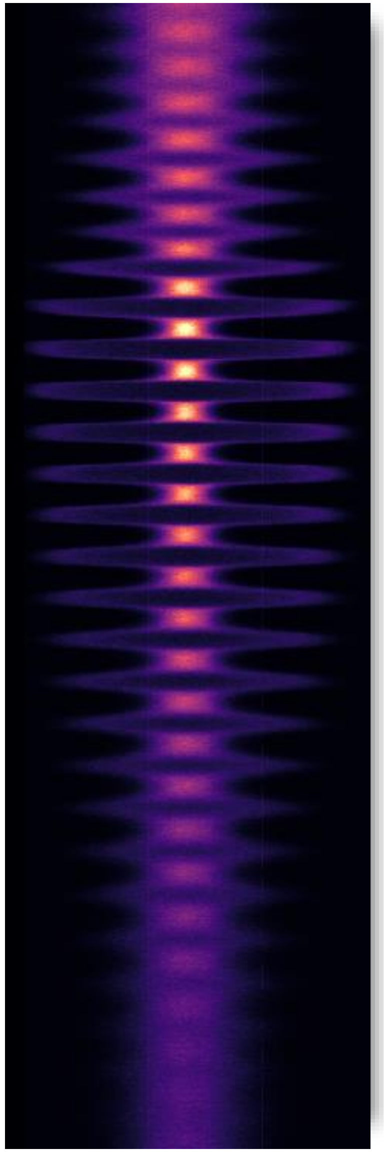
Conclusions:

- **OSC is at an intersection of fundamental beam-physics studies and the development of operational cooling systems**
- OSC has been successfully demonstrated and is the first beam-cooling technique to be realized experimentally in the optical regime: “OSC” of a single electron was definitively observed
- Established a strong foundation for development of amplified OSC
- Applications include:

(i) Beam cooling in a possible future Electron Ion Collider

(ii) “Frozen Crystalline Beams” enabled by OSC can act as Quantum Computers: e.g. ***Single Ions in a storage ring: towards Quantum Computers with large number of qubits***



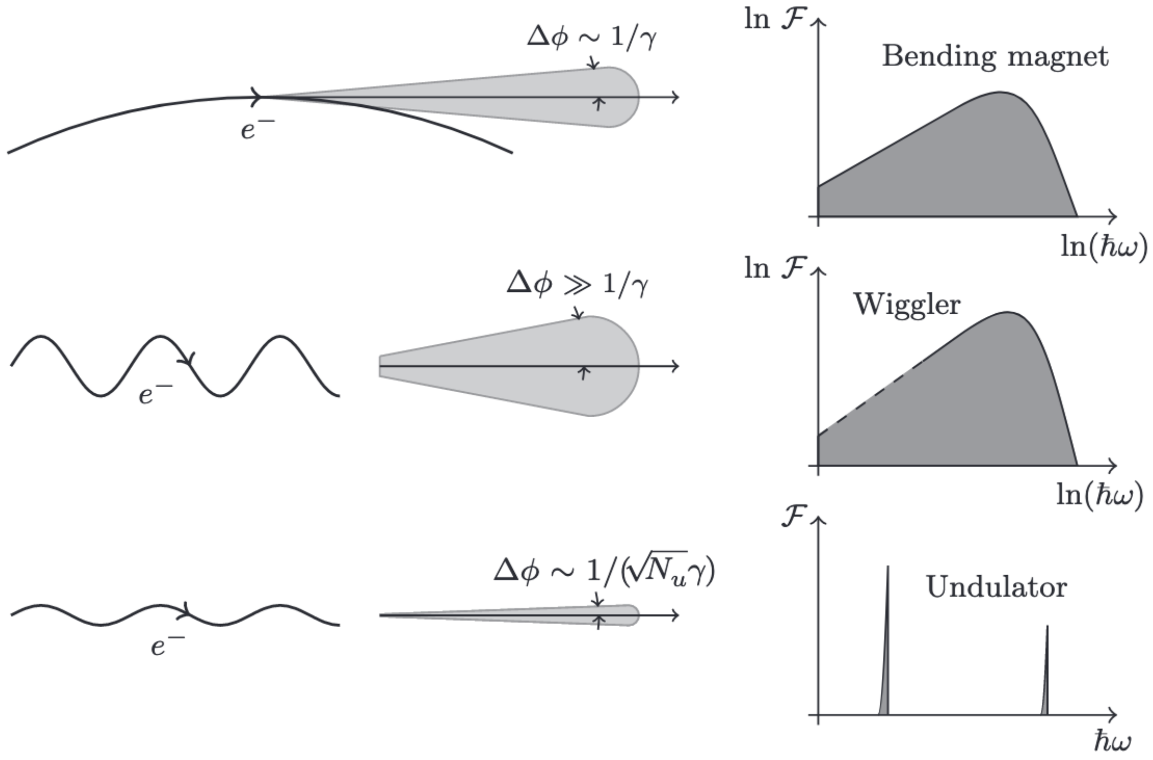


PHOTON STATISTICS

Courtesy: Ihar Lobach and Sergei Nagaitsev
Fermilab/ANL
Other investigators: Andy Charman (Berkeley)

A detailed and thorough investigation is planned for studying the quantum statistics of emitted photons from undulator radiation, both in multiple electron and single electron scenarios. A PhD thesis just got completed by Ihar Lobach (U Chicago) with preliminary results. Details should be described in future talks in this series, early next year.

Synchrotron light sources



*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

$$\lambda_1 = \frac{\lambda_\mathrm{u}}{2\gamma^2}\left(1 + \frac{K_\mathrm{u}^2}{2}\right)$$

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

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

Kinds of photon statistics

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

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

- $\boldsymbol{F = 1}$ – Poissonian light (very common)
  - laser radiation
  - radioactive decay

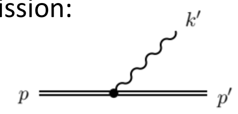
- $\boldsymbol{F > 1}$ – Super-Poissonian light (very common as well)
  - thermal light
  - any classical fluctuations of intensity
  - incoherent radiation by an electron bunch (Experiment #1)

- $\boldsymbol{F < 1}$ – Sub-Poissonian light (unusual! non-classical light)
  - Fock state (number state)
  - Parametric down-conversion

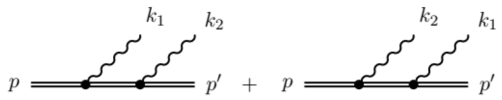
Description of single electron's undulator radiation in Quantum Electrodynamics

- 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

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

Two experiments to study statistical properties of undulator radiation in IOTA

- Experiment #1 with **many electrons** ($\sim 10^9$)
  - Fundamental harmonic, $\approx 1.16\ \mu\mathrm{m}$
  - InGaAs p-i-n photodiode
  - Feb-Apr 2019, Feb-Mar 2020

InGaAs p-i-n photodiode

- Experiment #2 with a **single electron**
  - Second harmonic, $450 - 800\ \mathrm{nm}$
  - Single Photon Avalanche Diode (SPAD)
  - Feb-Mar 2020 + Summer 2021

Single Photon Avalanche Diode (SPAD)

Turn-by-turn data in both experiments

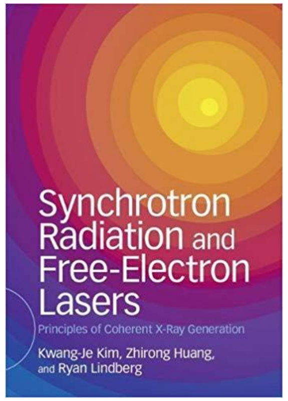
Theoretical predictions

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

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

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

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

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

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

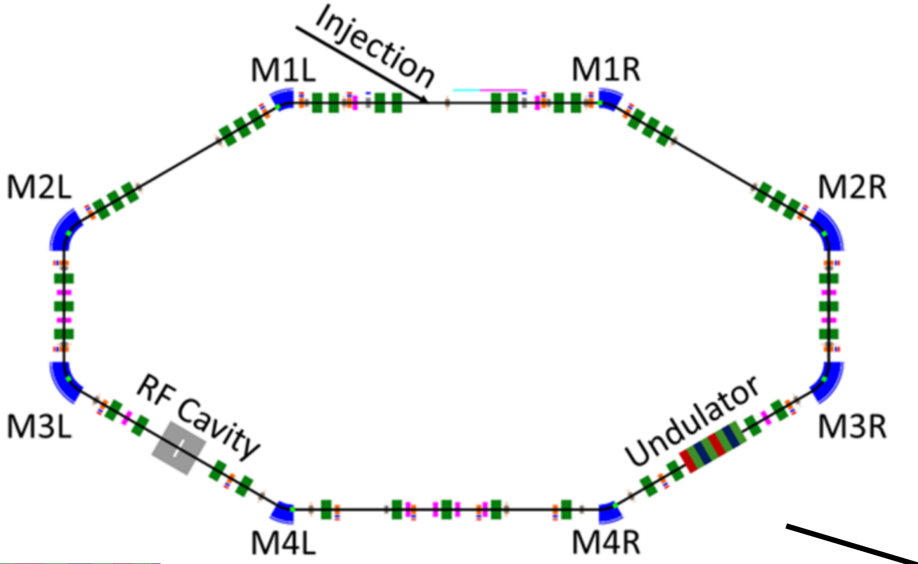
Open Access

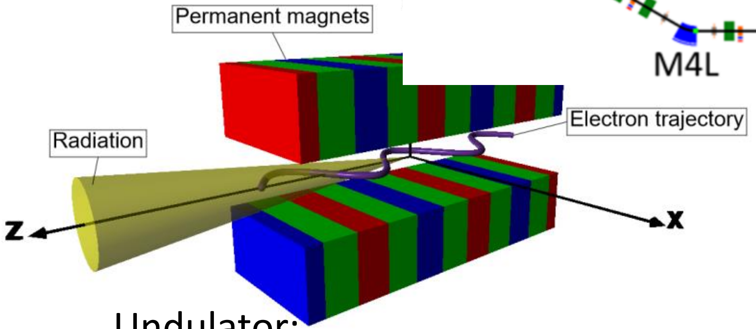
Statistical properties of spontaneous synchrotron radiation with arbitrary degree of coherence

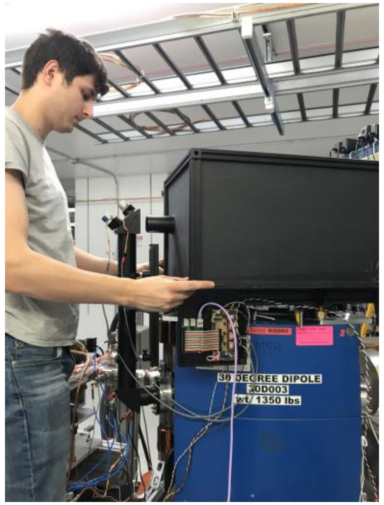
Ihar Lobach, Valeri Lebedev, Sergei Nagaitsev, Aleksandr Romanov, Giulio Stancari, Alexander Valishev, Aliaksei Halavanau, Zhirong Huang, and Kwang-Je Kim

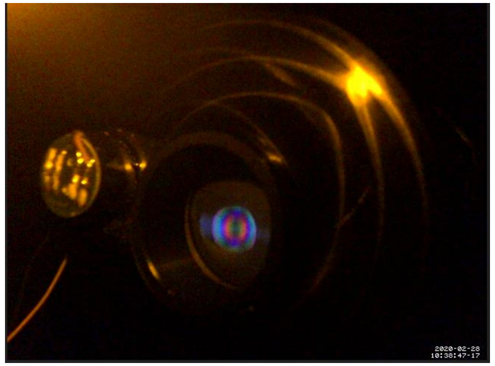
Phys. Rev. Accel. Beams **23**, 090703 – Published 11 September 2020

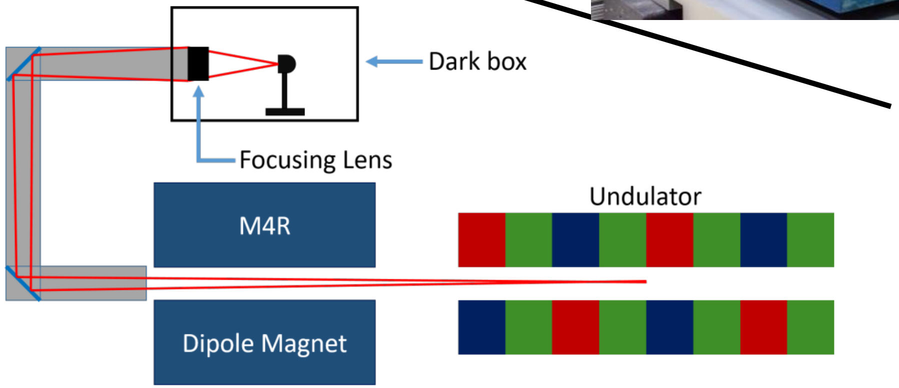
Layout of the undulator section in IOTA











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

Single Photon Avalanche Diode (SPAD) detector

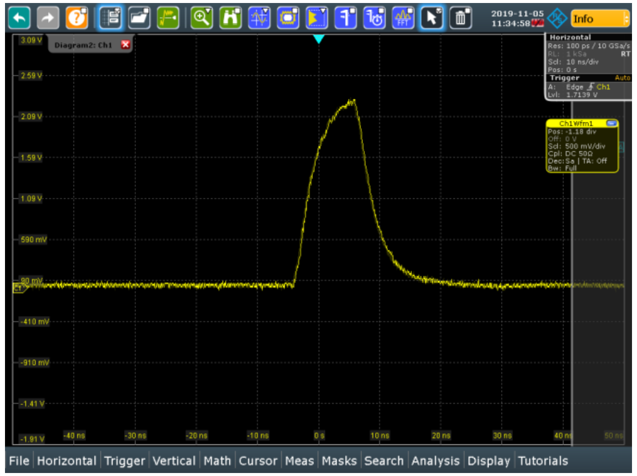
Excelitas SPCM-AQRH-10

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
Transit time spread (TTS)	0.35 ns

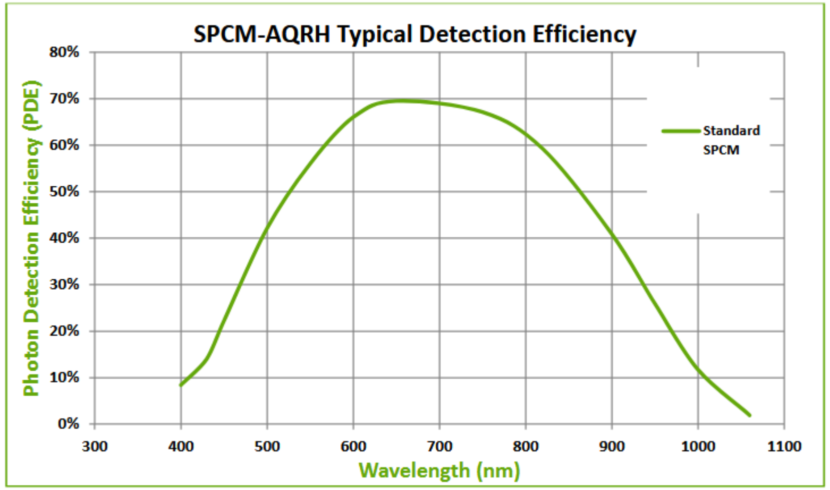
*with gating ≈4 Hz

*IOTA period is 133 ns

Each detection event creates a pulse of the same height and width:

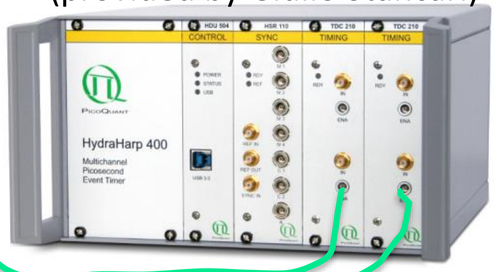


Typical Photon Detection Efficiency (PDE) vs. Wavelength



Design of the experiment with a single electron

Picosecond event timer
(provided by Giulio Stancari)



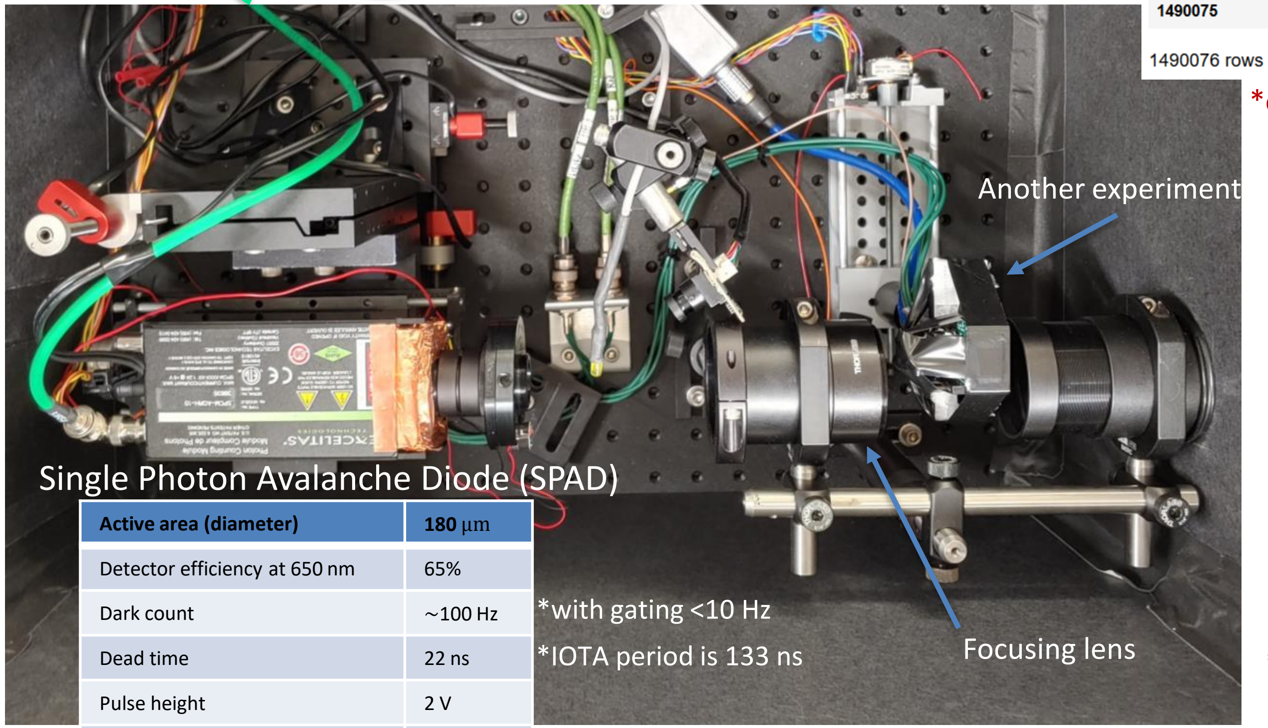
IOTA revolution marker

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



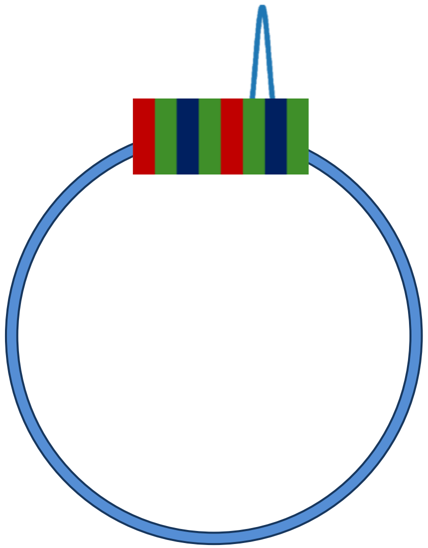
Active area (diameter)	**180 μm**
Detector efficiency at 650 nm	65%
Dark count	~100 Hz
Dead time	22 ns
Pulse height	2 V
Pulse length	10 ns

Undulator radiation

*the stepper motor translation stages were provided by Sasha Romanov

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 $\mathrm{var}(\mathcal{N})$

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

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 photon statistics in the single-electron case is Poissonian:

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

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

Super-Poissonian light:

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

Sub-Poissonian light:

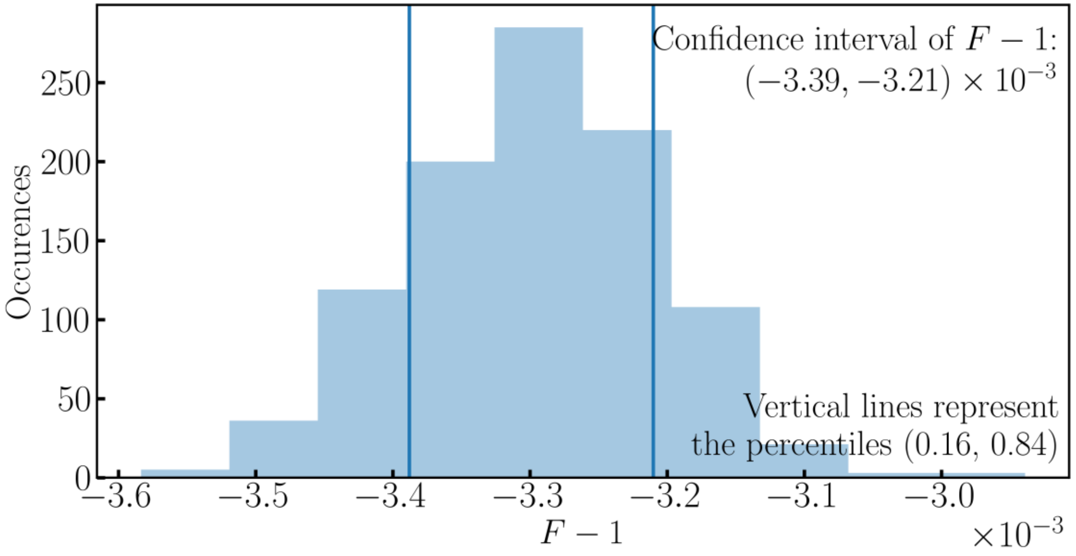
$$\mathrm{var}(\mathcal{N}) < \langle \mathcal{N} \rangle$$

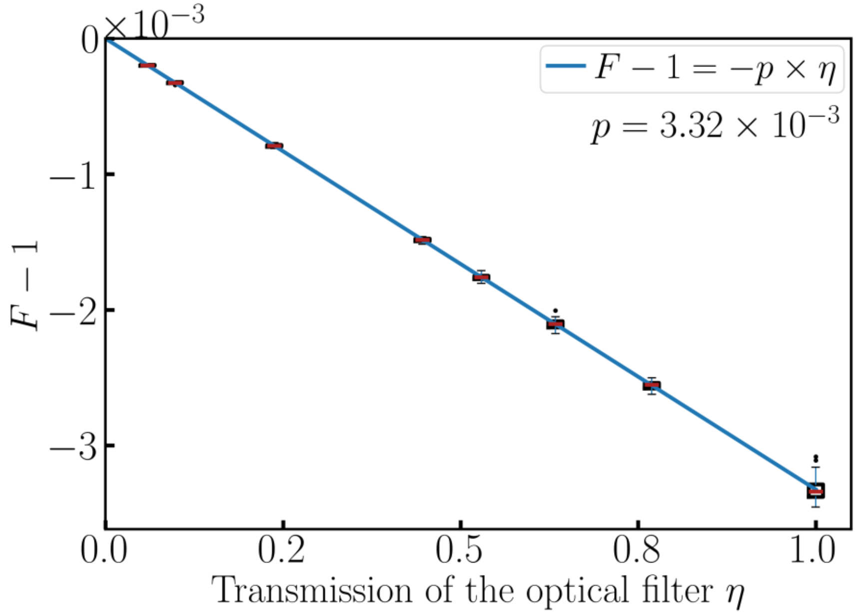
unusual – non-classical state of the radiated field

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

Fano factors with different neutral density filters

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

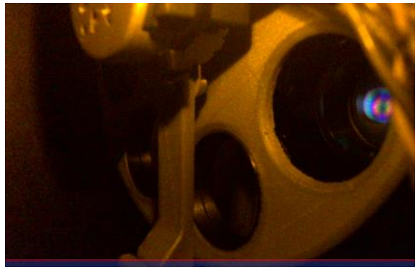




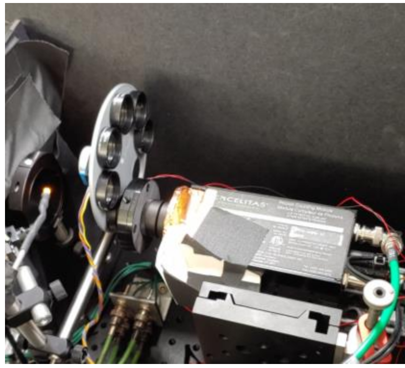
$$F_{measured} - 1 = \eta(F_{source} - 1)$$

η is the detection efficiency

Filter wheel:
(made by Sasha Romanov)



The measured Fano factor is less than 1!   Sub-Poissonian light?



Analysis of the statistical properties

- Our detector (SPAD) is binary:
  00000100000011000000000000100010000000011100000000…
- If our detector could see 0,1,2,3,… photons:
  00000100000011000000000000200010000000013100000000…
  0 - no detection, 1,2.. - photon(s) detected
- Poisson distribution

$$\Pr(k) = \frac{\lambda^k}{k!} e^{-\lambda}$$

- Bernoulli distribution

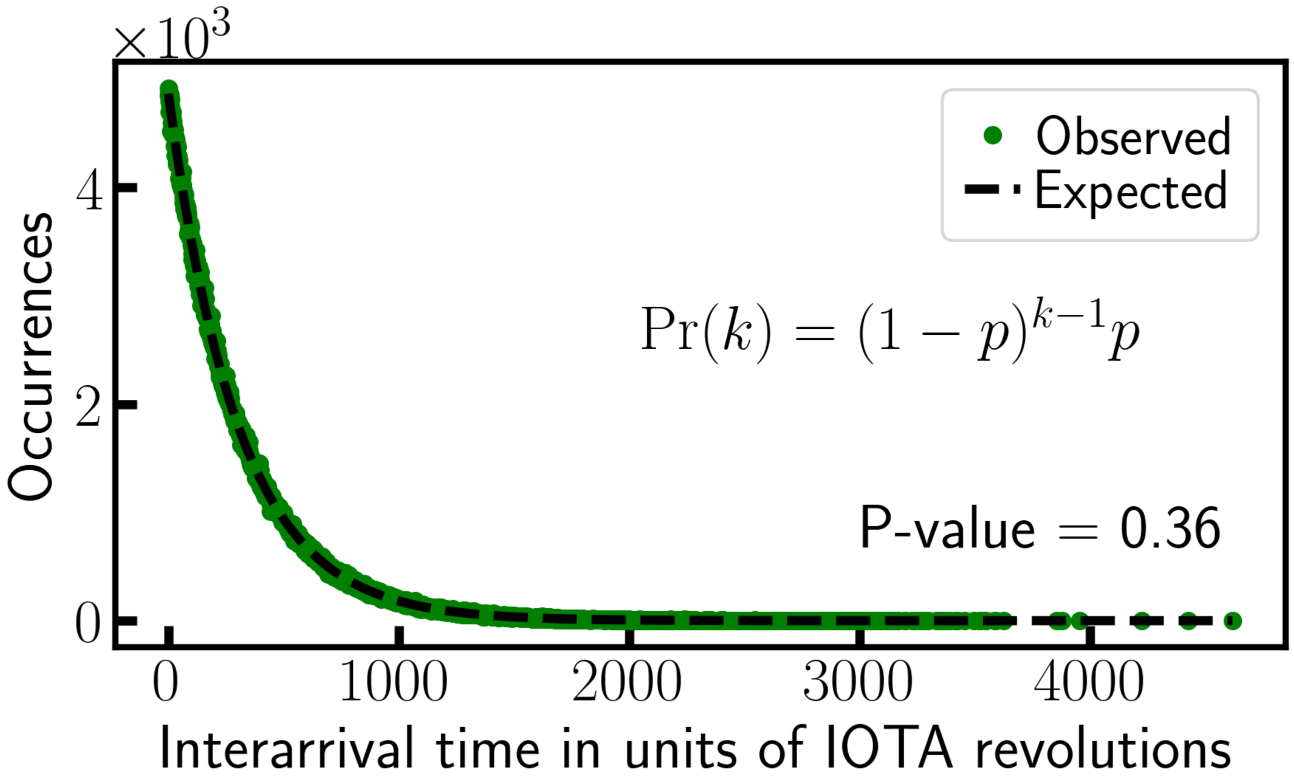
$$\Pr(k) = \begin{cases} 1-p, \text{if } k=0 \\ p, \text{if } k=1 \end{cases}$$

$$\boxed{\lambda e^{-\lambda} + \frac{\lambda^2}{2} e^{-\lambda} + \frac{\lambda^3}{6} e^{-\lambda} + .. = 1 - e^{-\lambda} = p}$$

- $F = \frac{\text{variance}}{\text{mean}} = \frac{\lambda}{\lambda} = 1$
- $F = \frac{\text{variance}}{\text{mean}} = \frac{p(1-p)}{p} = \boxed{1-p}$

Distribution of interarrival times

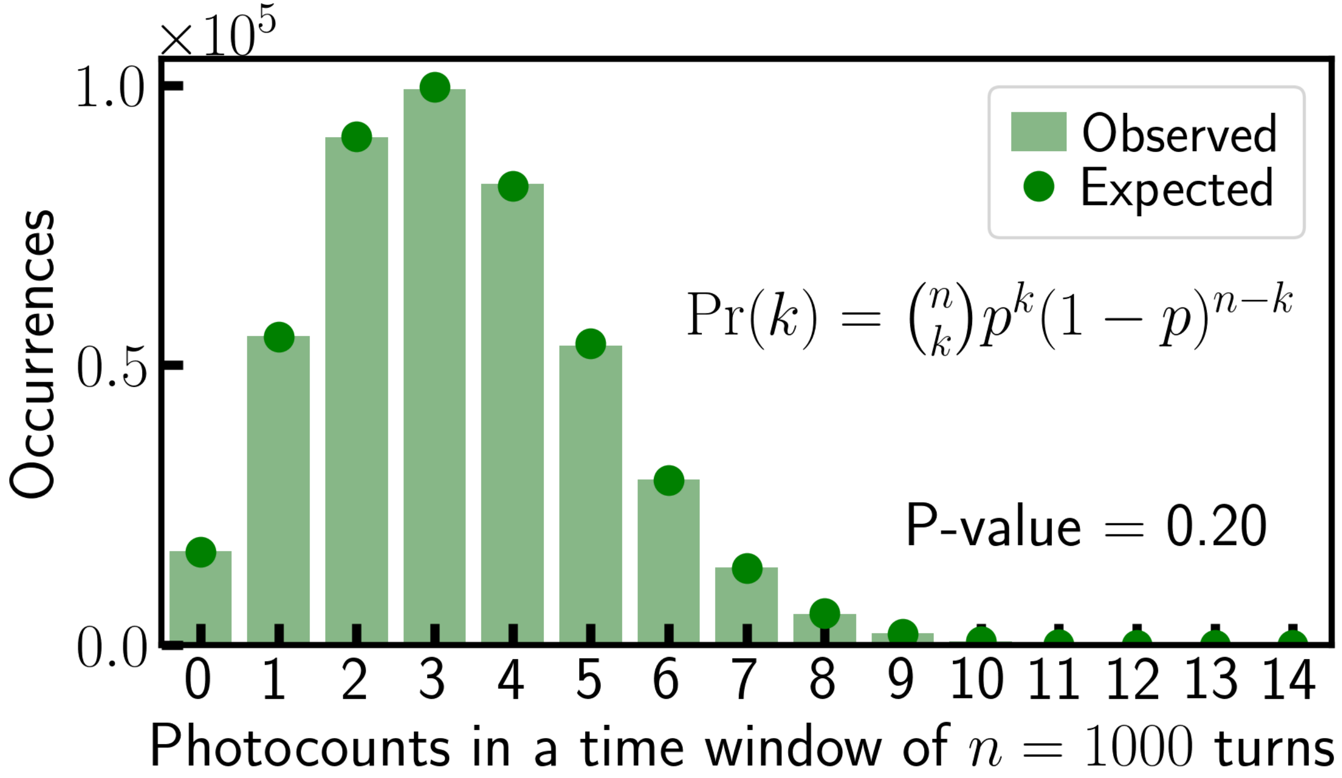
- Null hypothesis: geometric distribution



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

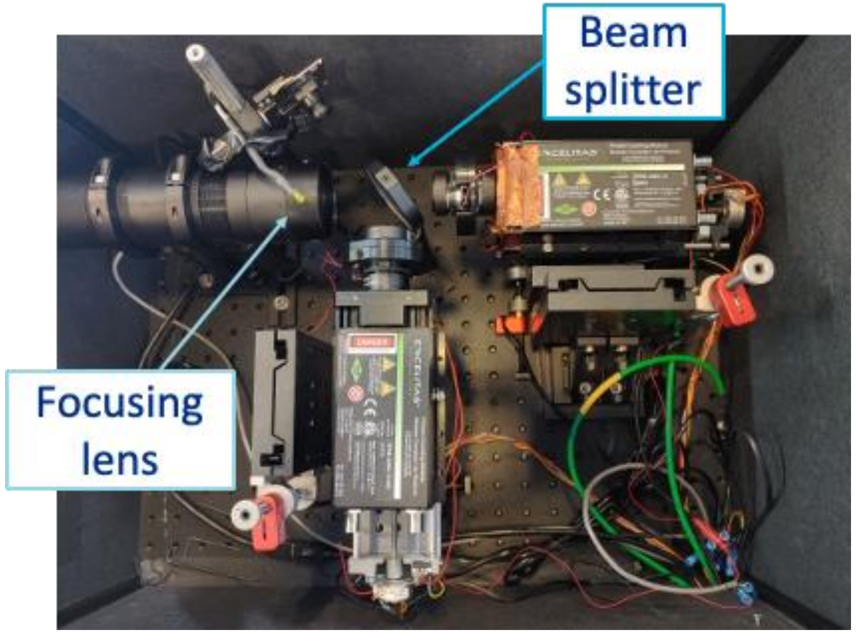
Distribution photocount in a time window

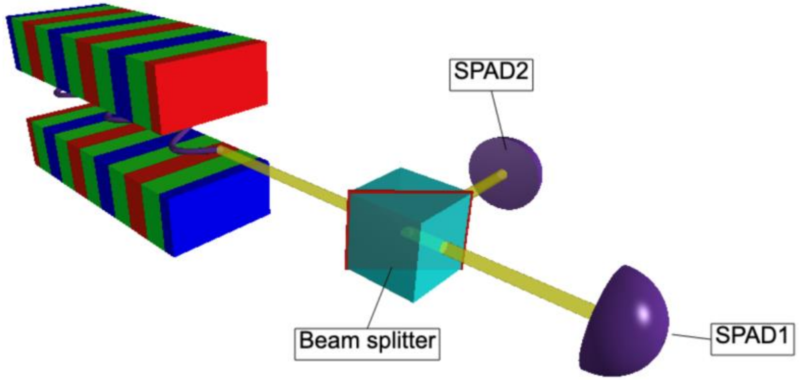
- Null hypothesis: binomial distribution



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

Two SPAD detectors
(very recent measurements)





Collected data:
000001000001100000000000200010000000112000000000...

- So far, no deviations from our expectations

Detector #1: ~30 kHz

Detector #2: ~15 kHz

Detector #1 & Detector #2: ~70 Hz

Featured in Physics Open Access

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

Conclusions

- Observation: Super-Poissonian fluctuations in undulator radiation intensity for many electrons, fully consistent with our model of classical and quantum fluctuations
- Suggests 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 a single electron in a ring and a binary photon detector, we have not yet observed any deviations from a random memoryless Bernoulli process
- The photocount arrival times can be used to study the synchrotron motion of a single electron and, thus, to infer some parameters, such as the synchrotron motion period as a function of amplitude and the rms rf phase jitter

MORE RESULTS TO COME IN THE COMING YEARS!!!!

Previous research about statistical properties of synchrotron radiation

Both theoretical and experimental results:

[1] M. C. Teich, T. Tanabe, T. C. Marshall, and J. Galayda, Statistical properties of wiggler and bending-magnet radiation from the Brookhaven Vacuum-Ultraviolet electron storage ring, Phys. Rev. Lett. **65**, 3393 (1990).

[2] V. Sajaev, *Determination of longitudinal bunch profile using spectral fluctuations of incoherent radiation*, Report No ANL/ASD/CP-100935 (Argonne National Laboratory, 2000).

[3] V. Sajaev, Measurement of bunch length using spectral analysis of incoherent radiation fluctuations, in *AIP Conf. Proc.*, Vol. 732 (AIP, 2004) pp. 73–87.

[4] F. Sannibale, G. Stupakov, M. Zolotorev, D. Filippetto, and L. Jägerhofer, Absolute bunch length measurements by incoherent radiation fluctuation analysis, Phys. Rev. ST Accel. Beams **12**, 032801 (2009).

[5] P. Catravas, W. Leemans, J. Wurtele, M. Zolotorev, M. Babzien, I. Ben-Zvi, Z. Segalov, X.-J. Wang, and V. Yakimenko, Measurement of electron-beam bunch length and emittance using shot-noise-driven fluctuations in incoherent radiation, Phys. Rev. Lett. **82**, 5261 (1999).

[6] K.-J. Kim, Start-up noise in 3-D self-amplified spontaneous emission, Nucl. Instrum. Methods Phys. Res., Sect. A **393**, 167 (1997).

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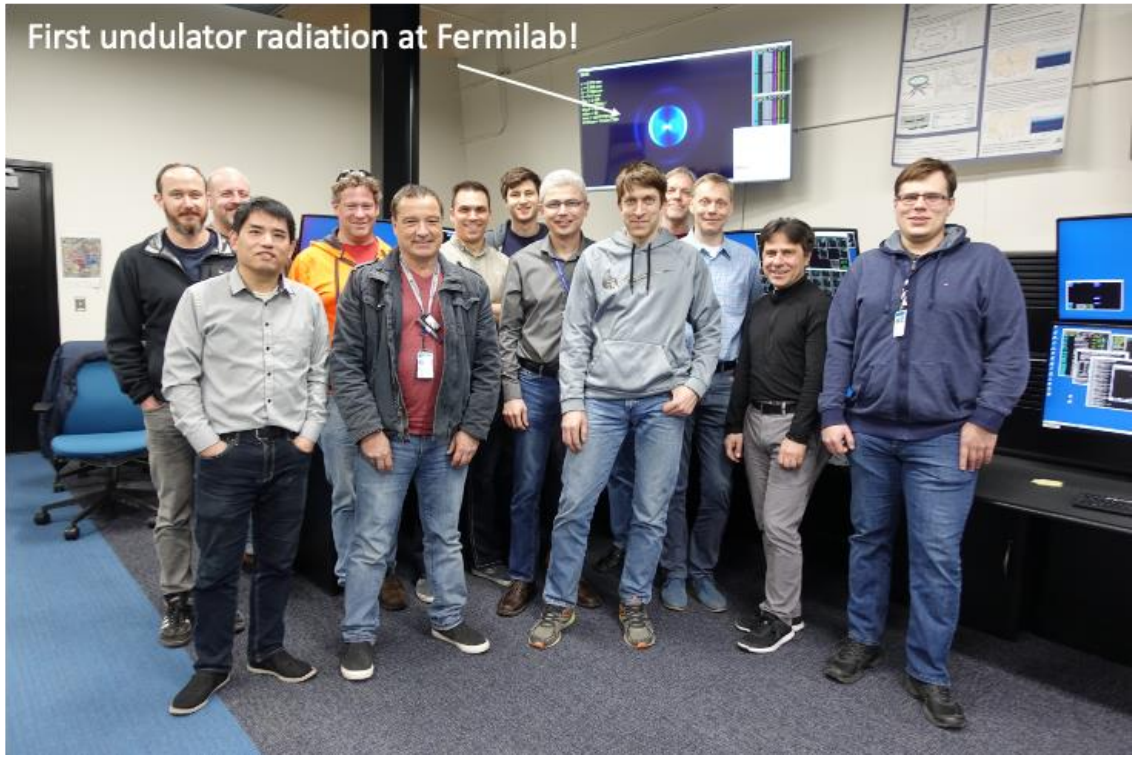
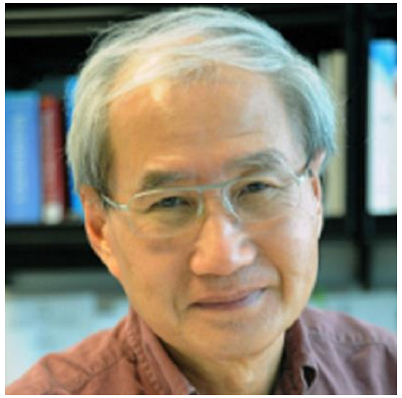
IOTA team and our collaborators



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Thank You!!!!