Berkeley
UNIVERSITY OF CALIFORNIA

Progress on Optical Stochastic Cooling in IOTA

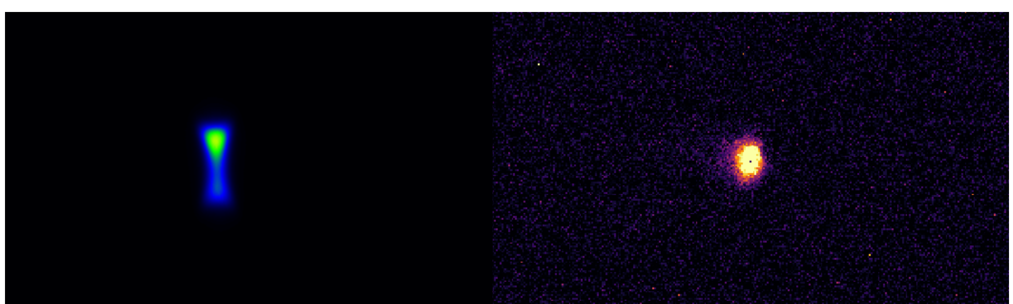
Swapan Chattopadhyay

UC Berkeley

(Fermilab, CERN)

May 14, 2024

UK Accelerator Institutes Seminar Series, Spring 2024



I dedicate this talk to our late colleague/my dearest personal friend

Mats Lindroos (1961-2024)

Mats had strong historical, personal, educational and collaborative connections with CERN as well as UK: Mats studied for his undergraduate degree at Oxford, was affiliated with the Cockcroft Institute and its associated universities (Liverpool, Lancaster and Manchester), and with ASTeC at Daresbury Lab. He worked in nuclear/particle/accelerators physics, contributed to rare isotope and radioactive beams, neutrino and muon facilities, and was one of the principal early motivators behind the European Spallation Source in Lund, Sweden. We will miss him dearly.

ACKNOWLEDGMENTS

1. Thanks to Prof. Philip Burrows (Oxford/JAI) and Dr. Emmanuel Tsesmelis (CERN/JAI) for inviting me to present this lecture

2. The entire research team at FAST/IOTA facility at Fermilab

3. Dr. Jonathon Jarvis, John Peoples Fellow and Department of Energy (DOE) Young Investigator at Fermilab, who is my mentee and the first author of the publication.

My sincere apologies to Phil Burrows and JAI for not being able to travel to Oxford for a period of time in May and deliver this lecture in person, due to unforeseen family circumstances. Not to mention the dinner at the high table in Jesus College offered by Phil Burrows will be a big miss! Thanks to Emmanuel for arranging the remote zoom presentation.

This lecture is based on the published article:

Experimental Demonstration of Optical Stochastic Cooling

J. Jarvis, V. Lebedev, A. Romanov, D. Broemmelsiek, K. Carlson, S. Chattopadhyay, A. Dick, D. Edstrom, Lobach, S. Nagaitsev, H. Piekarz, P. Piot, J. Ruan, J. Santucci, G. Stancari, A. Valishev*

***** *My mentee*

Nature **608,** 287 – 292 (2022) August 11, 2022 issue

+ Developments since 2022 to date.

Optical Stochastic Cooling

→ *"Maxwell's Demon" using Light*

OR IN OTHER WORDS.....

Relativistic charged particles cooled (i.e. "damped") via self-interaction with (i.e. feedback from) their own optical synchrotron radiation

OUTLINE

1. ***Maxwell's Demon*: a historical perspective**

2. ***Microwave "*Stochastic Cooling*" of Simon van der Meer***

3. **Optical Stochastic Cooling: *Maxwell's demon goes optical***

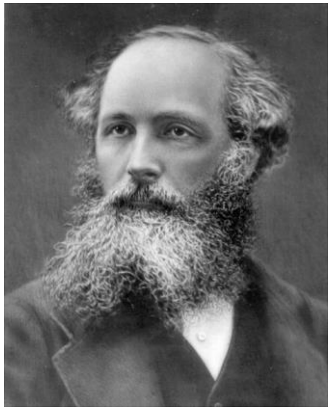
4. **Experimental Demonstration of OSC in IOTA ring at Fermilab**

4. **Question of a *"Single Electron" and its radiation***

6. **Further developments and Outlook**

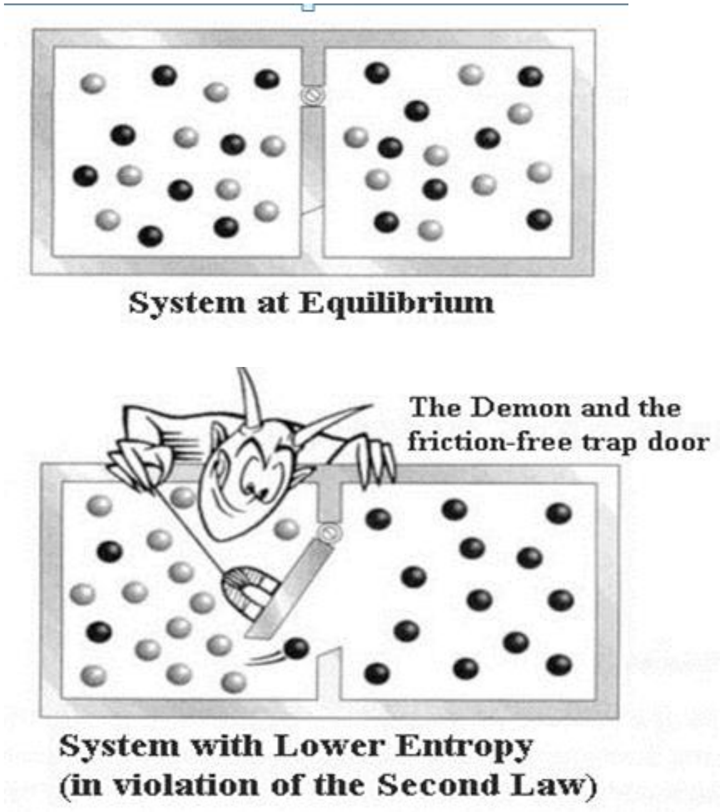
Maxwell's demon paradox

Maxwell first introduced the '*finite being*' in a letter to his school friend Tait (dated 11 December 1867) and repeated this argument in his 1871 treatise, Theory of Heat.



James Clerk Maxwell

"Second law of thermodynamics is statistical law and can't be applied to fluctuations of individual molecules"



William Thomson (Lord Kelvin) coined the term Maxwell's Demon

— implied that information can be converted to energy

Demon's exorcism

Smoluchowski (1914), Szilard (1929), Shannon (1948), Brillouin (1953) …

Rolf Landauer and Charles H. Bennett

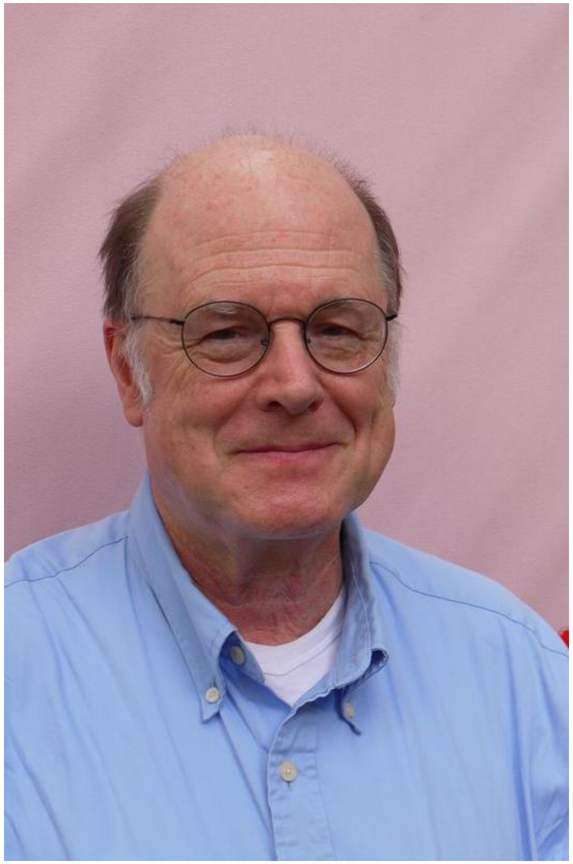
Discovered the fundamental law (Landauer's principle) governing the thermodynamics of information. "Irreversibility and Heat Generation in the Computing Process" (1961).

Proposed a reinterpretation of Maxwell's demon, attributing its inability to break the second law to the thermodynamic cost of destroying memory (1982).

SCIENCE

2023 Breakthrough Prize winners

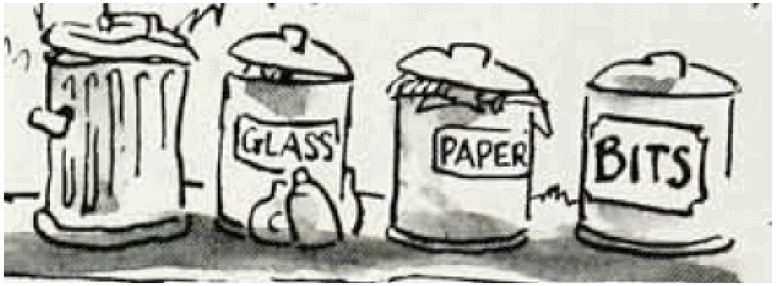
Charles Bennett, David Deutsch and Peter Shor



The Breakthrough Prizes, created in 2010 by a group of Silicon Valley entrepreneurs, are the most richly endowed awards in science, disbursing more than the Nobel prizes, dubbed the "Oscars of Science"

Demon's exorcism

Demon's inability to violate the Second Law of Thermodynamics arises from the cost of information erasure to entropy.

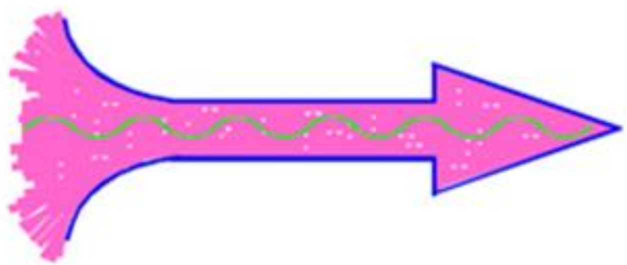


Let us speak of "BEAMS" !!

Particle and Light Beams are many-body statistical mechanical systems

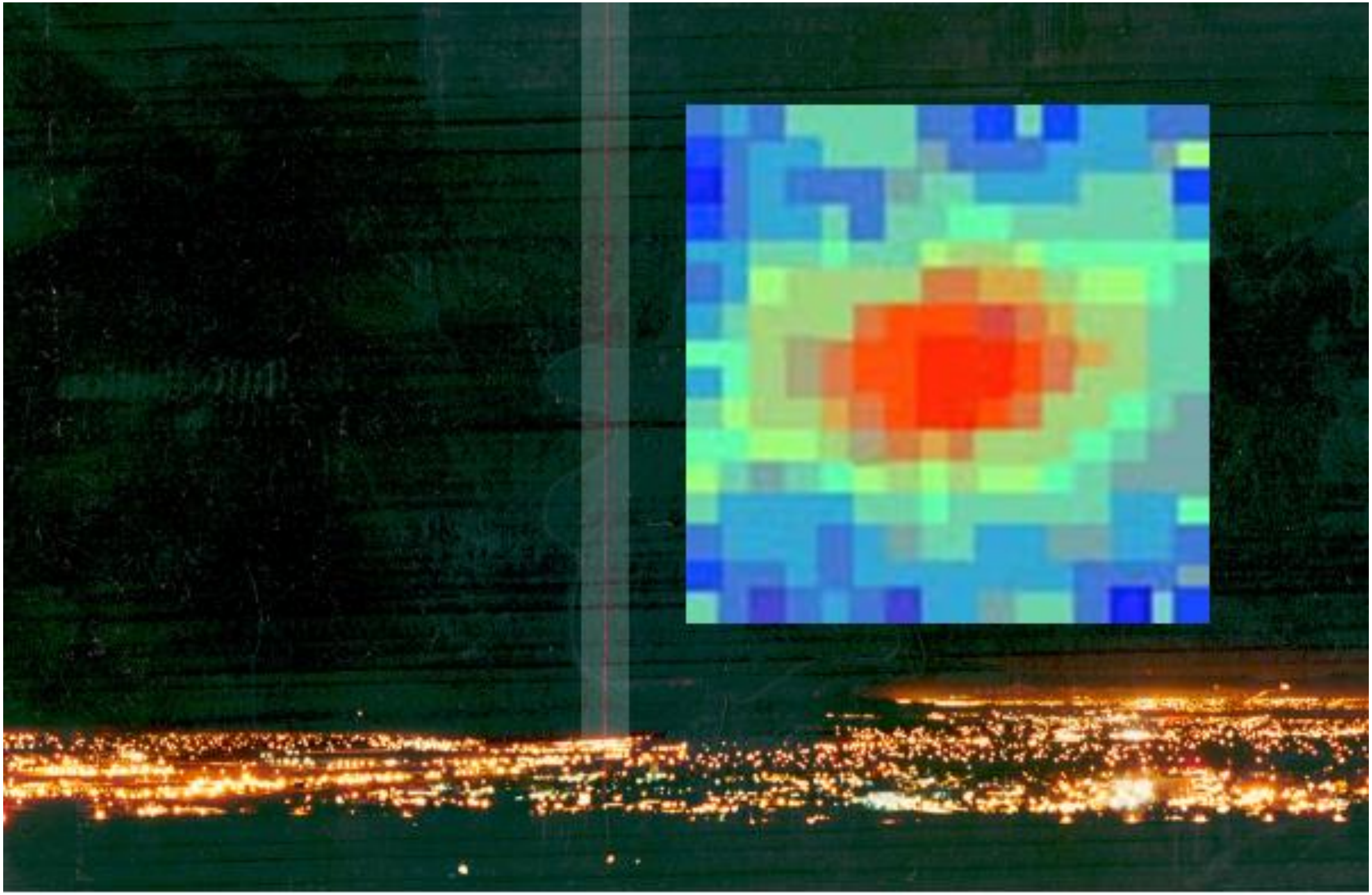
Beams

Directed and Focused Flow of Energy and Information



Beams of:

- Particles: electrons, protons, ions, …
- Ultraviolet, Visible, Infrared, X-ray, Photons; Radio Waves; Lasers

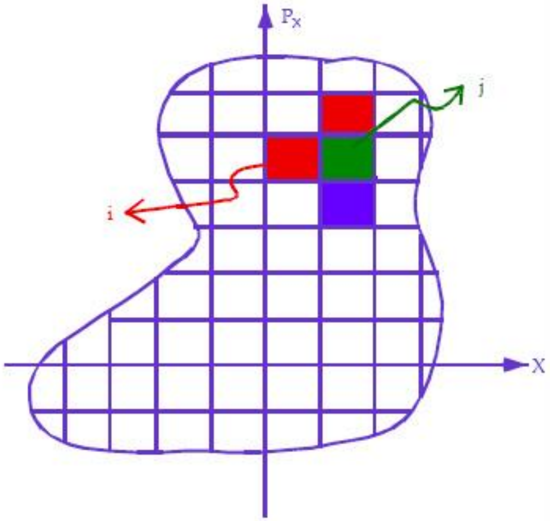


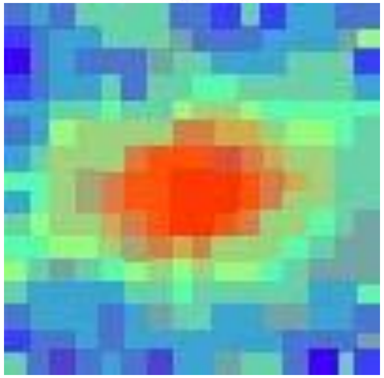
Sky-shine laser beam in California's Livermore valley

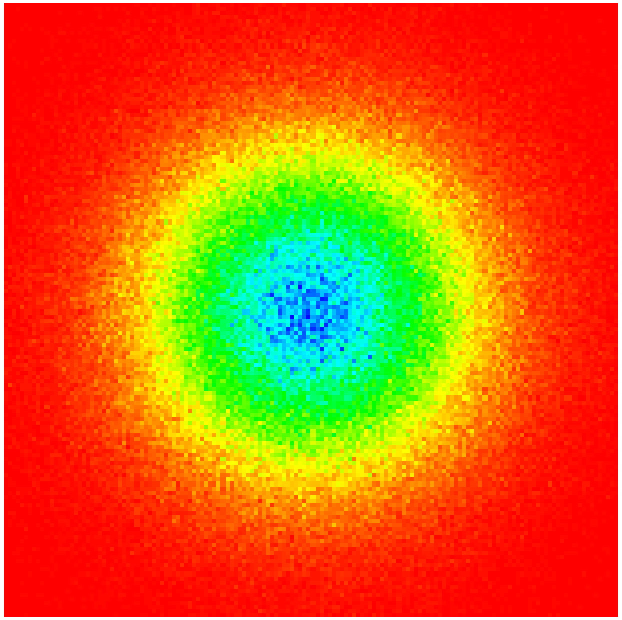
BEAMS:

• **Energy in a Beam**

• **Entropy & Information in a Beam: related to its phase-space volume**







Digression into Beam Dynamics:

Joseph Liouville, Henri Poincare and Simon van der Meer

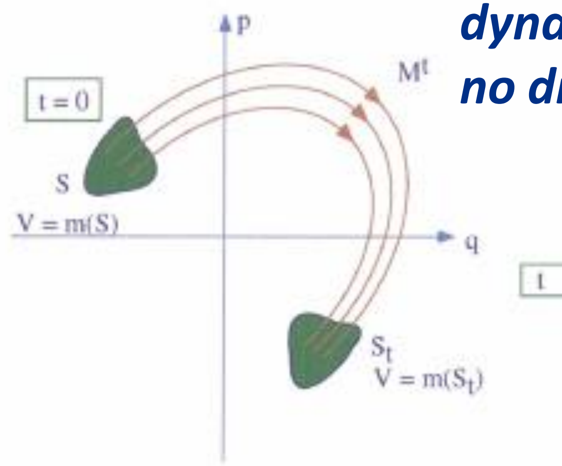
"BEAM" as a " Fluid Flow"

Joseph Liouville (France)

Important mathematical theorem, 1837 and 1838

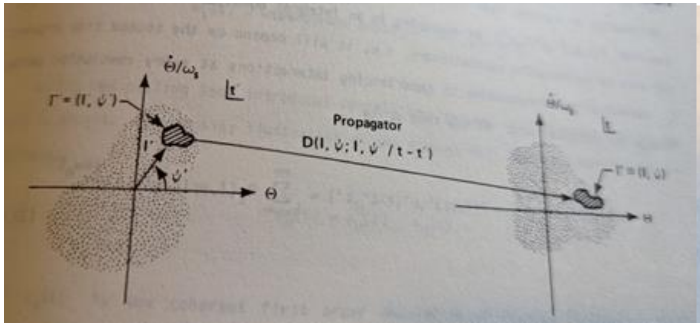
Under conservative Hamiltonian dynamics with no dissipation

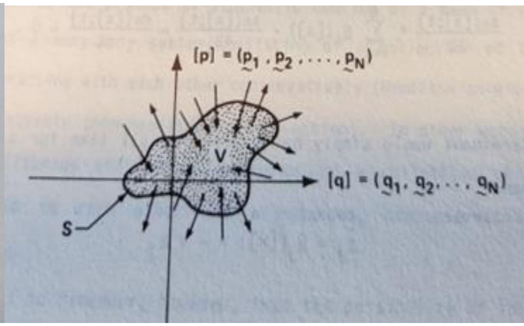
$$\frac{d}{dt}\left[m(s_t)\right]=0$$



Liouville looked at BEAMS as a <u>SMOOTH FLOW</u>, with only gentle deformations: dynamical volume is conserved.

Continuity Equation in phase-space



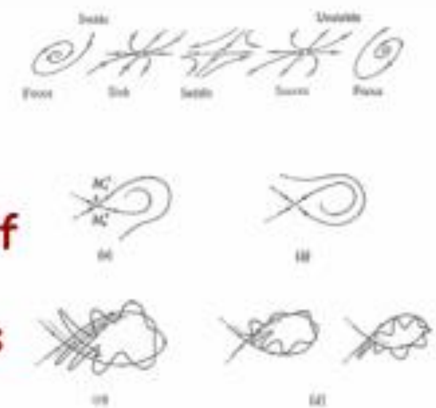


“BEAM” as a Geometry

Henri Poincaré (France)

Geometry and Topology of Phase Space, 1880’s, France

Poincaré looked at Phase-Space as full of geometrical and topological structures



Discrete dynamical points– elliptic, hyperbolic fixed points, strange attractors, sources and sinks,….

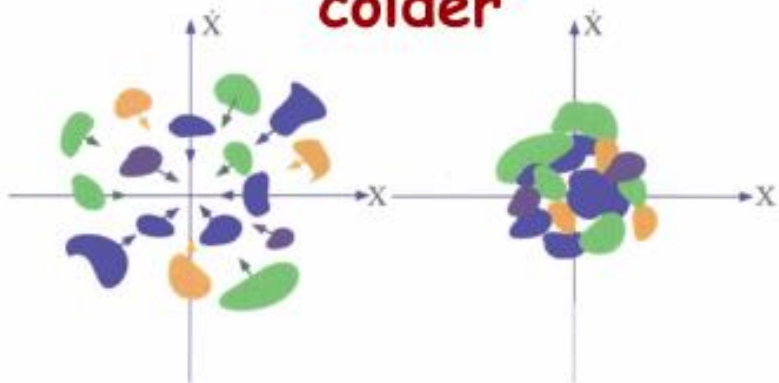
“Beam” as FLUCTUATIONS!

Simon van der Meer, Nobelist 1984

Stochastic Cooling

Both continuous fluid and discrete point particles, manifesting as fluctuations

BEAM is mostly empty and can be made more “compact” and “colder”



But we must be able to observe, record and correct FLUCTUATIONS!
Or in other words, you need to create a Maxwell’s Demon!

FLUCTUATIONS in BEAM DISTRIBUTION

$$\mathcal{F}(\vec{r},\vec{v};t) = \sum_{i=1}^{N} \delta\left[\vec{r} - \vec{r}_i(t)\right] \delta\left[\vec{v} - \vec{v}_i(t)\right]$$

$$f(\vec{r},\vec{v};t) = \langle \mathcal{F}(\vec{r},\vec{v};t) \rangle$$

$$\delta f(\vec{r},\vec{v};t) = \mathcal{F}(\vec{r},\vec{v};t) - \langle \mathcal{F}(\vec{r},\vec{v};t)\rangle = \mathcal{F}(\vec{r},\vec{v};t) - f(\vec{r},\vec{v};t)$$

with $\langle \delta f(\vec{r},\vec{v};t)\rangle = 0$.

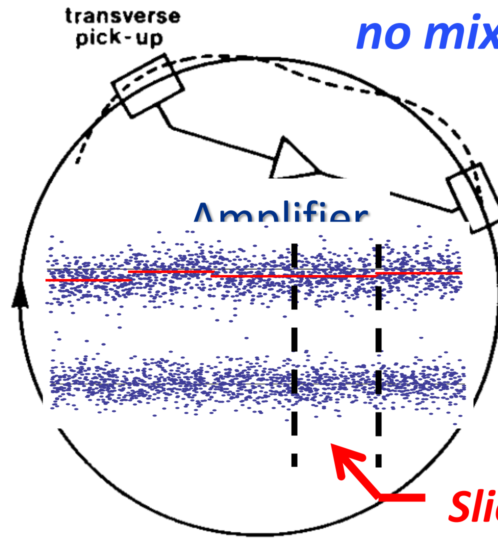
Stochastic cooling of HOT Anti-matter

Stochastic Damping of Betatron Oscillations in the ISR, CERN, 1972

Drawing is reproduced from van der Meer's Nobel Lecture

Simon van der Meer

Fluctuations



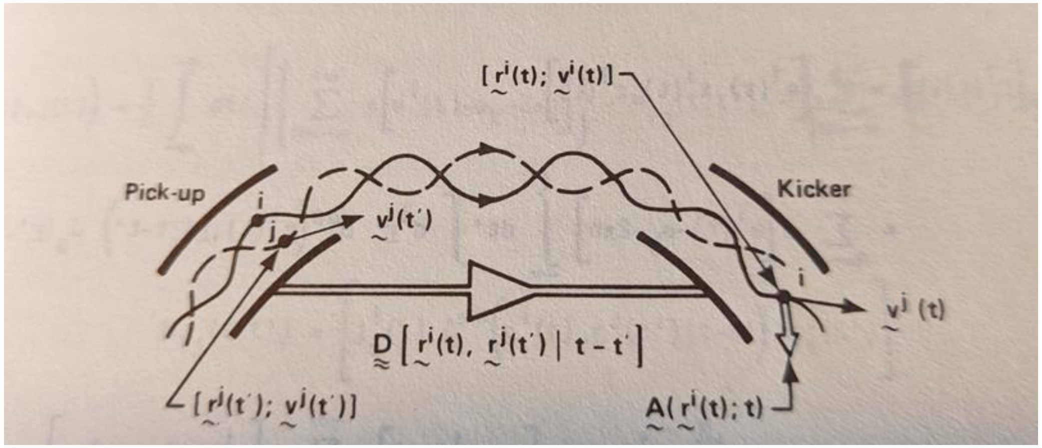
$$N_s = \frac{I_p}{e}\frac{1}{\Delta f}$$

Nobel Prize in 1984 shared with Carlo Rubbia "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction."

Bandwidth: few GHz

Single particle power: 10^{-19} Watts per charge

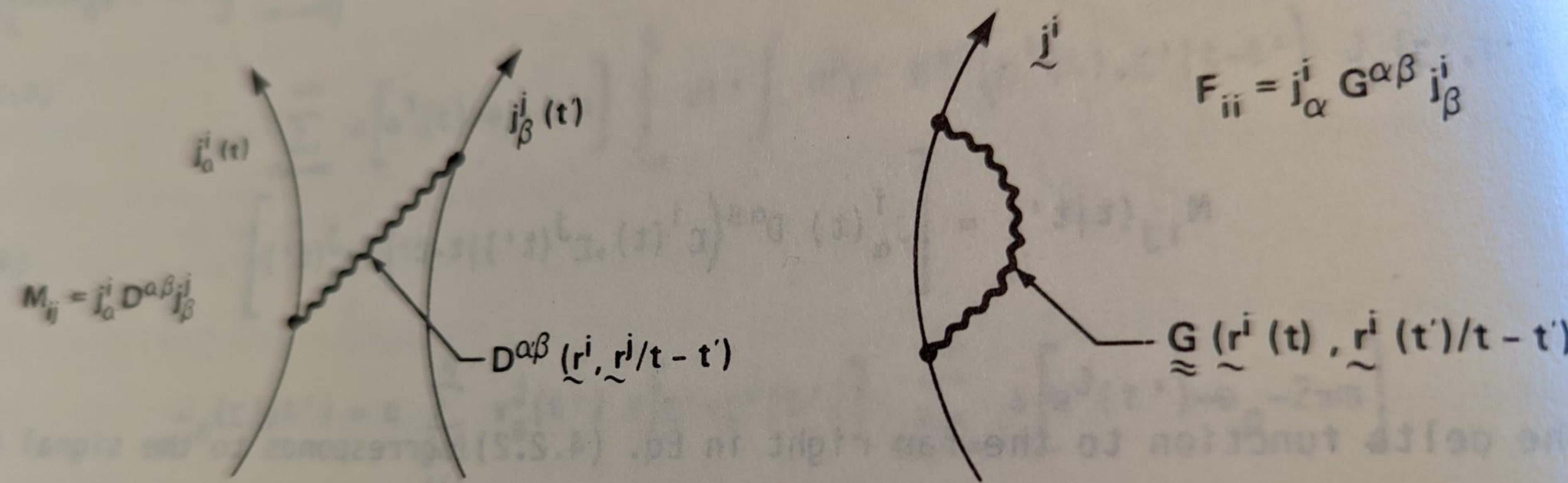
Detailed Dynamics



$$\mathcal{L}^{i}_{int} = \frac{q}{c}\, \underset{\sim}{v}^{i}(t) \cdot \underset{\approx}{A}^{ns}\left[\underset{\sim}{r}^{i}(t);t\right] = \frac{q}{c}\, v^{i}_{\alpha}(t)\; A^{\alpha}_{ns}\left[\underset{\sim}{r}^{i}(t);t\right]$$

$$V\Big(i(t),j(t)\Big) = \frac{1}{c}\int_{-\infty}^{+\infty} dt' \left[\left\{\sum_{n=-\infty}^{+\infty} \delta\left[\theta^{i}(t)-\theta_{k}-2\pi n\right]\right\} \cdot M_{ij}(t|t') \cdot \left\{\sum_{m=-\infty}^{+\infty} \delta\left[\theta^{j}(t')-\theta_{p}-2\pi m\right]\right\}\right]$$

$$M_{ij}(t|t') = \left[j^{i}_{\alpha}(t)\; D^{\alpha\beta}\Big(\underset{\sim}{r}^{i}(t),\underset{\sim}{r}^{j}(t')\,\Big|\,t-t'\Big)\; j^{j}_{\beta}(t')\right]$$



Propagator of interaction potential

Propagator of self-interaction force only

$$\frac{\partial}{\partial \vec{I}_i} \cdot [\dot{\vec{I}}_i - \vec{G}(i,i)] = - \frac{\partial}{\partial \vec{\psi}_i} \cdot [\dot{\vec{\psi}}_i - \vec{H}(i,i)] \quad .$$

In terms of a general coordinate $\vec{x}_i \equiv \{\vec{I}_i, \vec{\psi}_i\}$ and generalized self-force $\vec{F}_x(i,i)$, one has

$$\frac{\partial}{\partial \vec{x}_i} \cdot [\dot{\vec{x}}_i - \vec{F}_x(i,i)] = 0 \quad .$$

STOCHASTIC COOLING:

An enabling technology invented by Simon van der Meer for colliders. A powerful technique but limited to GHz BW.

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

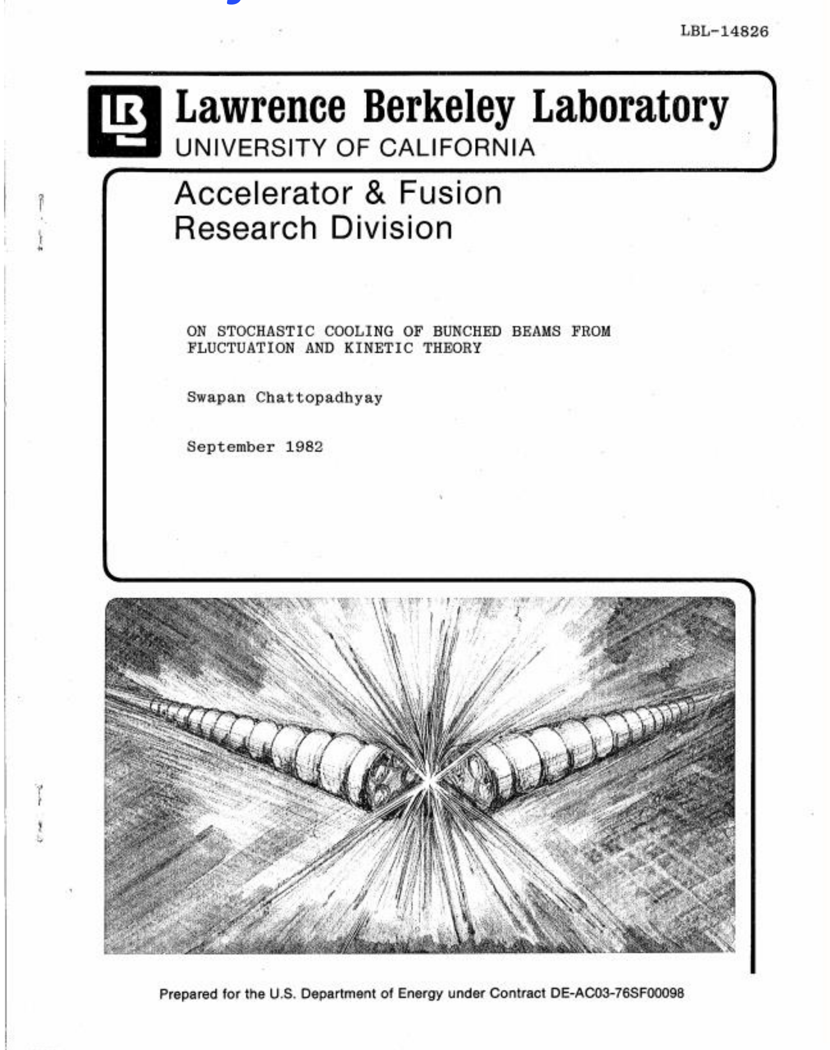
1984 Nobel: Simon van der Meer/Carlo Rubbia: Enabled discovery of the W and Z Bosons of Electroweak Unification in the SppbarS collider

Simplified stochastic cooling system

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

2) Bandwidth of feedback system controls cooling rate

In my ancient past, my 1982 PhD dissertation from University of California at Berkeley: *"On Stochastic Cooling of Bunched Beams from Fluctuation and Kinetic Theory"*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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion
Research Division

ON STOCHASTIC COOLING OF BUNCHED BEAMS FROM
FLUCTUATION AND KINETIC THEORY

Swapan Chattopadhyay

September 1982

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

In the period 1982-1984, I had the unique opportunity and good fortune to work with Simon van der Meer himself (before he got the Nobel Prize!!)

S. van der Meer*:

* Nobel prize lecture, 1984

"Such a system resembles Maxwell's demon, which is supposed to reduce the entropy of a gas by going through a very similar routine, violating the second law of thermodynamics in the process.",

J.C. Maxwell,
Theory of Heat (1871)
Limitations of the Second Law of Thermodynamics

This is only one of the instances in which conclusions which we have drawn from our experience of bodies consisting of an immense number of molecules may be found not to be applicable to the more delicate observations and experiments which we may suppose made by one who can perceive and handle the individual molecules which we deal only in large masses.

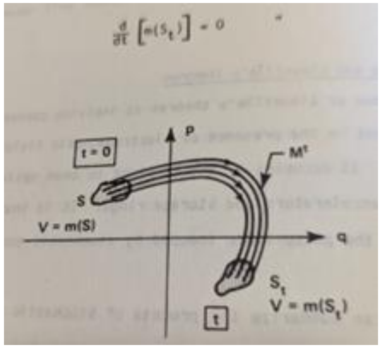
Violates Liouville theorem: a Misconception!!!!

Joseph Liouville:

French Mathematician

1837: Conservation of Phase-Space Volume of a dynamical system under conservative forces

1838: Phase-space can be “damped” or “inflated” when there is dissipation or amplification



Stochastic Cooling Feedback system

= Non-Hermitian Dissipative term in the Hamiltonian fully satisfying “Liouvillian flow”

$$\rho([x];t) = \rho(M^{-1}([x],t);0)\ \frac{d\{M^{-1}([x])\}}{d\{[x]\}}$$

$$M^t: \quad [a] \rightarrow [x]$$

$$[x] = M([a];t)$$

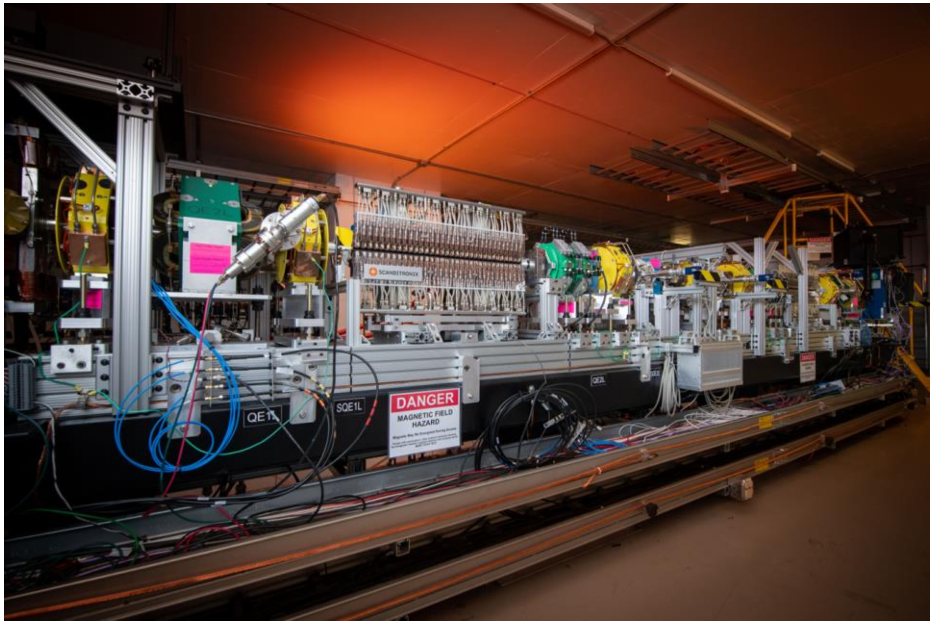
$$\frac{d\{M^{-1}([x])\}}{d\{[x]\}} \equiv J$$ is the Jacobian determinant of the mapping

Optical Stochastic Cooling (OSC)

Van der Meer's Optical Angel

(or a Maxwell's Demon of Light!)

Going down to even a Single Electron!



Optical wavelength of a ‘micron’ scale, can sample a beam both longitudinally and transversely, thus giving a richer granular phase-space information than microwaves (cm.)

PHYSICAL REVIEW LETTERS

Optical Stochastic Cooling

A. A. Mikhailichenko and M. S. Zolotorev

20 December 1993

Max Zolotorev

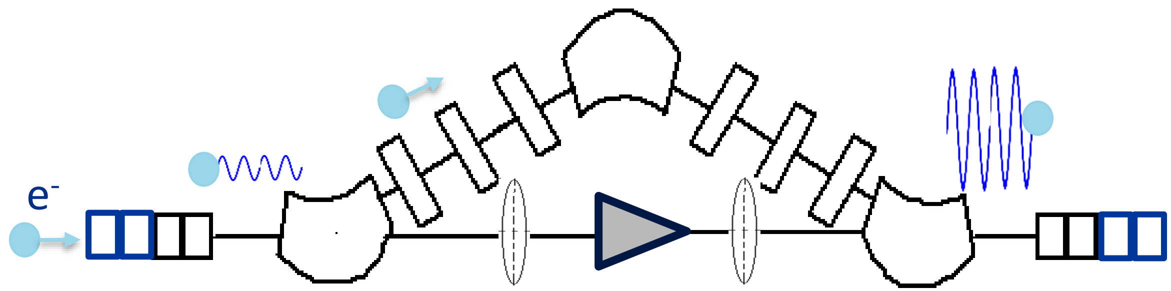
$$\Delta f \leq 5\,\mathrm{THz}$$

Alexander Mikhailichenko

The method has applications in electron-positron cooling, electron-ion high luminosity colliders as well as potential application in muon cooling and studying coherent emission from a single electron.

OSC Principle and Limitations

Delay adjustment using bypass



Light signal is produced in undulator

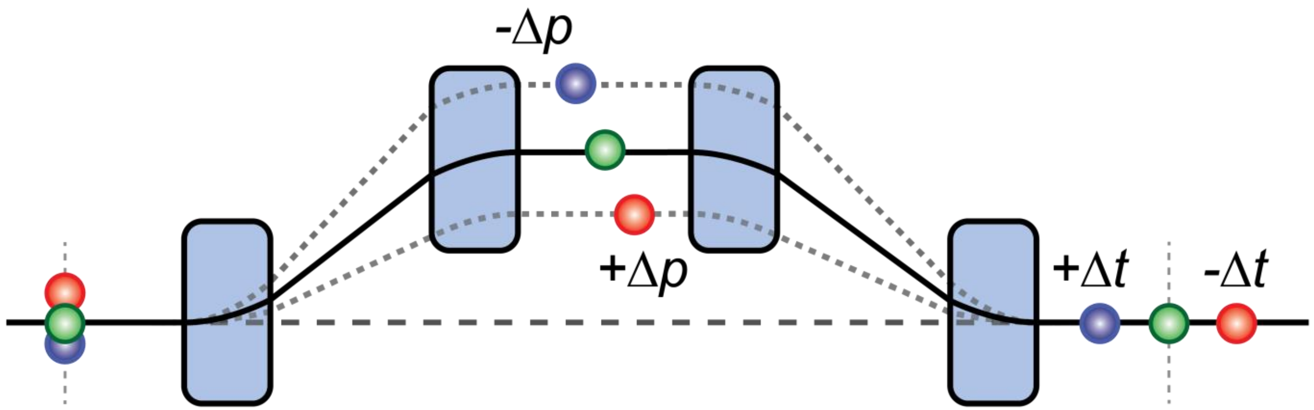
Light signal amplifier

Amplified light signal is used in undulator to correct the offset

- **Amplifiers are available only for several IR wavelengths**
- **Amplifier and refractive lenses limit bandwidth of the system**

Zolotorev, Zholents, *“Transit-time method of optical stochastic cooling”*, Phys. Rev. E, 1994

A particle's momentum error maps to temporal delay



- Lower (higher) energy particles take a longer path through the bypass and thus arrive at the entrance to the KU later (sooner) than the reference particle
- There are also contributions from the transverse elements of the mapping depending on the dispersion at the exit of the PU undulator

$$c\Delta t \sim (\underbrace{M_{51}D + M_{52}D'}_{\text{transverse}} + \underbrace{M_{56}}_{\text{longitudinal}})\frac{\Delta p}{p} + \text{Nonlinear terms}$$

Particle's dynamical Phase-space gets mapped onto the radiation that it emits:

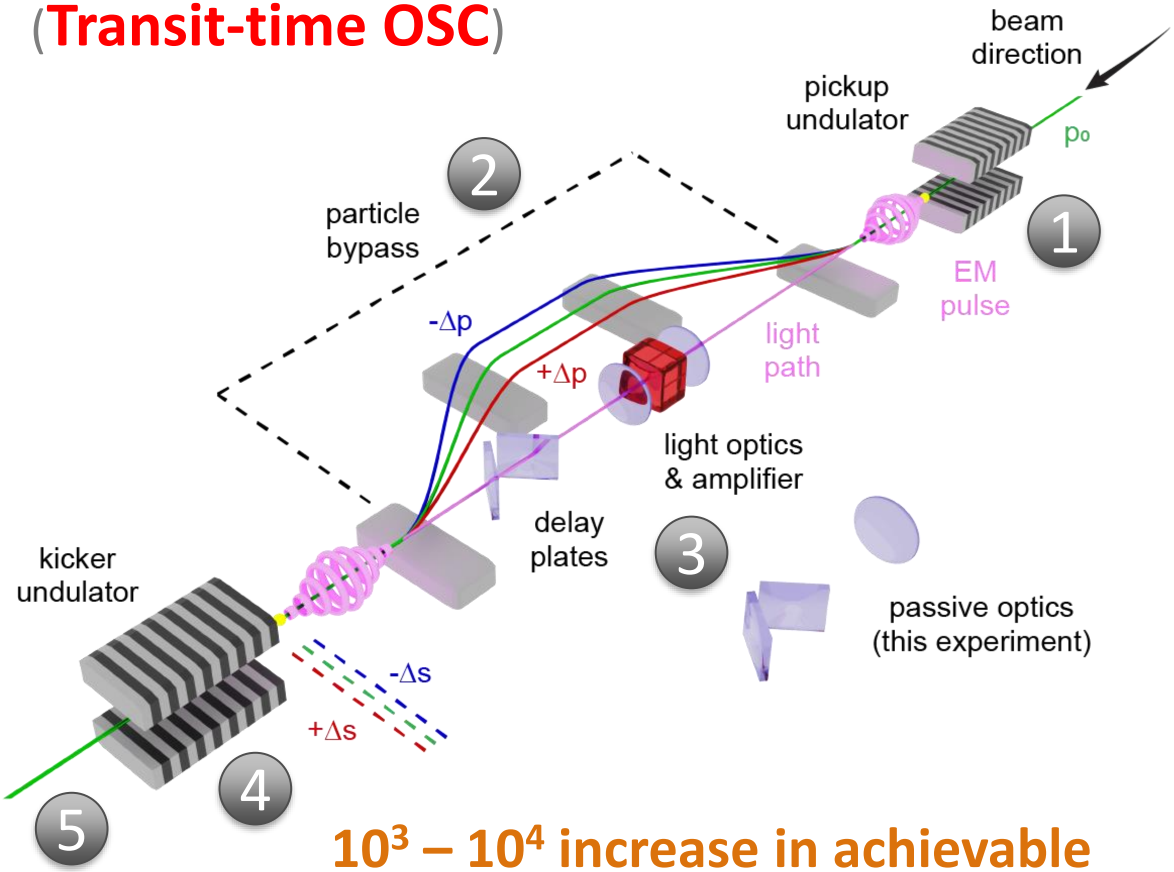
(**r**, **p**, t, E) → (**r**, **k**, t, f)

Typically a complex 'nonlinear' dynamical 'transformation, represented by a 'symplectic Lie map'

Emitted photons carry dynamical information *about the particle's phase*-space !!

OSC extends the SC principle to optical bandwidth

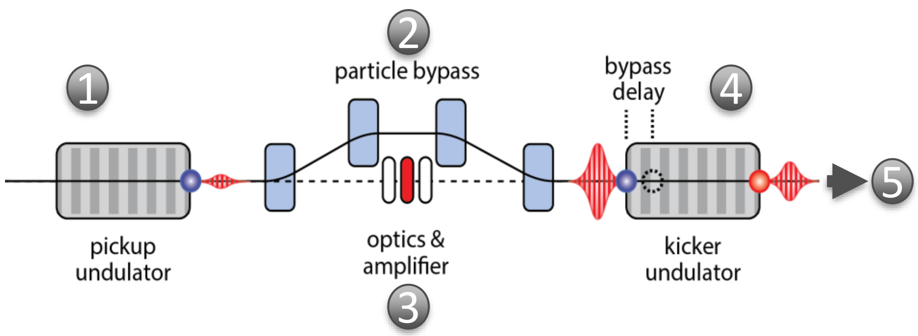
(**Transit-time OSC**)



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

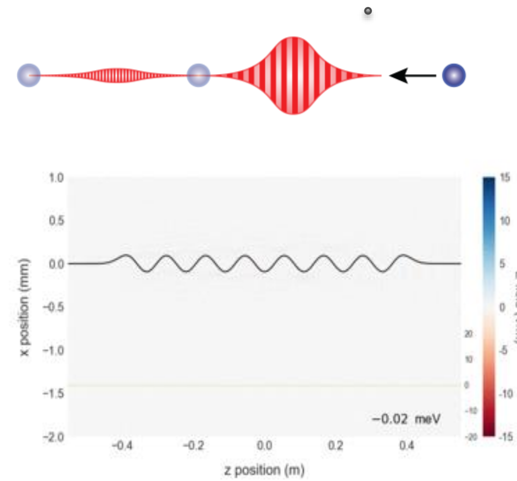
1. **Each particle generates EM wavepacket in pickup undulator**
2. **Particle's properties are "encoded" by transit through a bypass**
3. **EM wavepacket is amplified (or not) and focused into kicker und.**
4. **Induced delay relative to wavepacket results in corrective kick**
5. **Coherent contribution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

OSC extends the SC principle to optical bandwidth



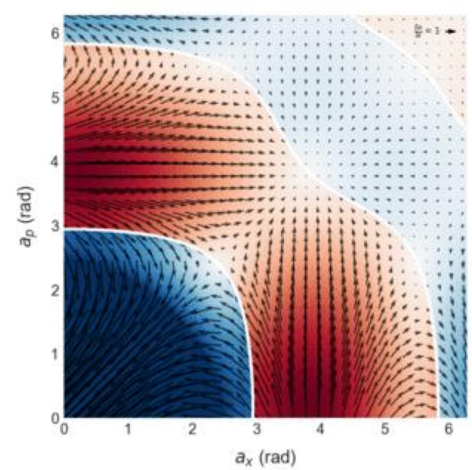
1. **Wavepacket generated**
2. **Particle delayed in bypass**
3. **Wavepacket amplified and focused**
4. **Corrective kick applied**
5. **Cooling accumulates over many passes**

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



Energy exchange in kicker

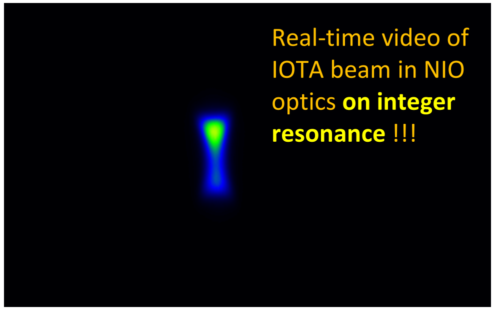
Cooling vs. betatron and synchrotron amplitudes

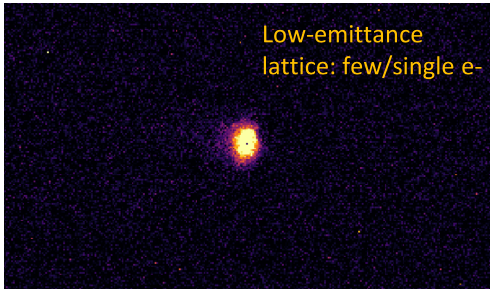


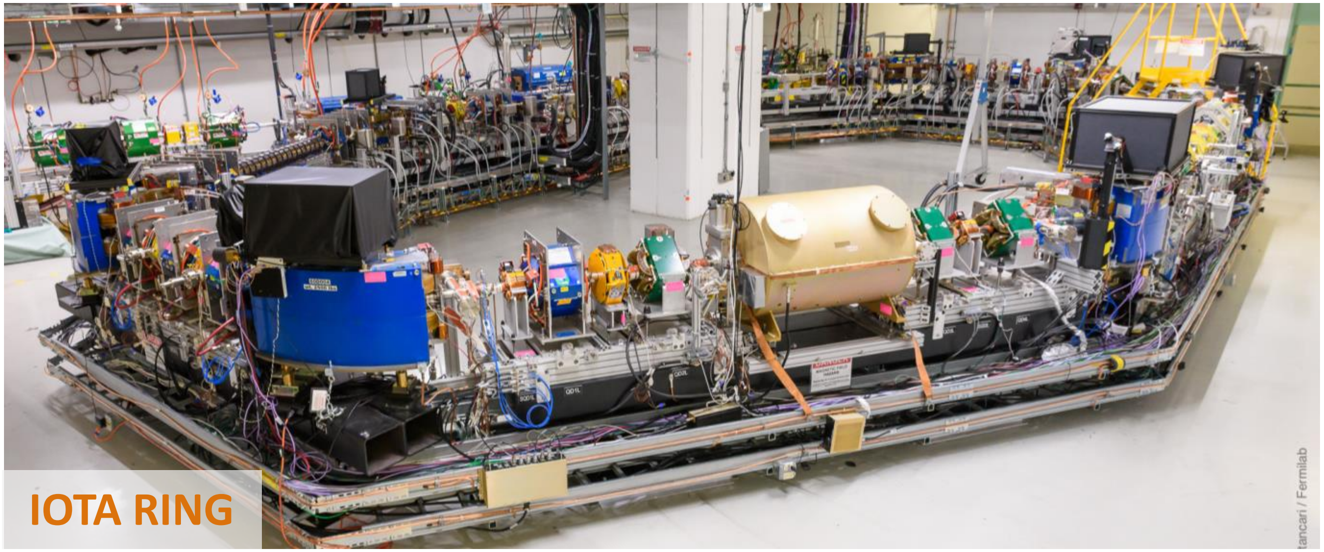
IOTA/FAST: Scientific Program

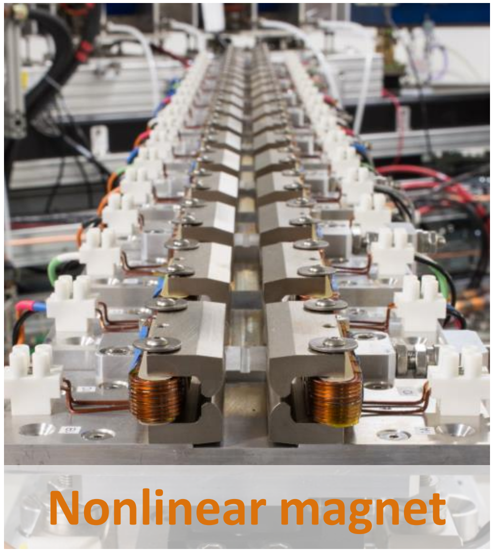
→ Advanced beam cooling; Optical Stochastic Cooling: **OSC demonstration → ACHIEVED!!**

→ Photon and Quantum Science with a single electron → **NEXT ADVENTURE!!** after experiments with protons are finished.

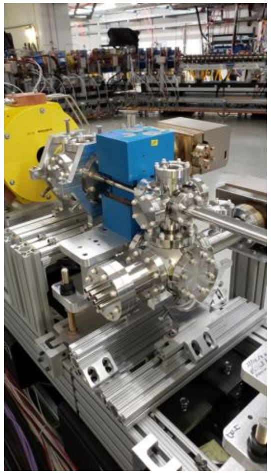


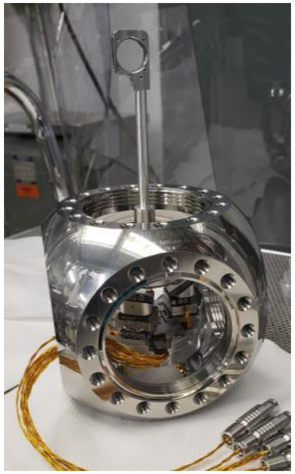


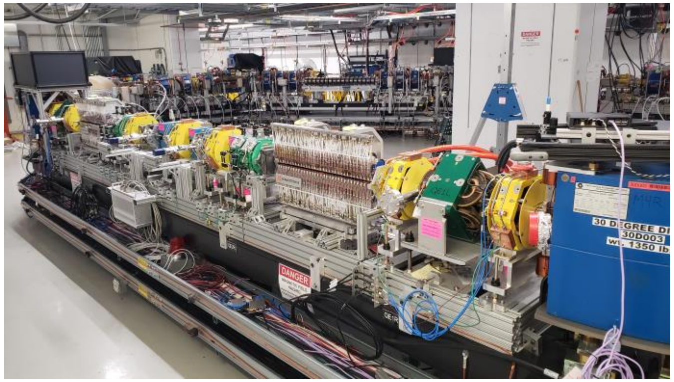


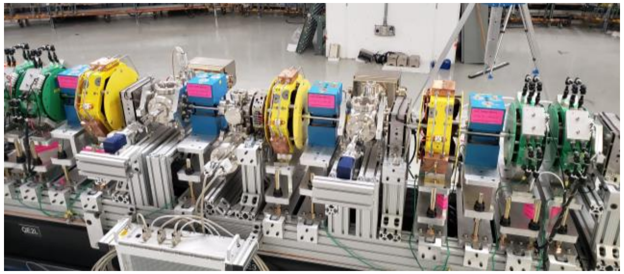


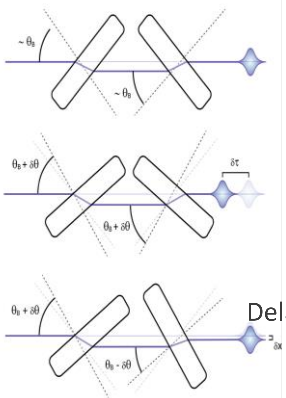
OSC apparatus and hardware successfully integrated in IOTA

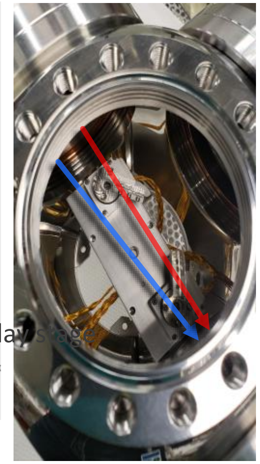


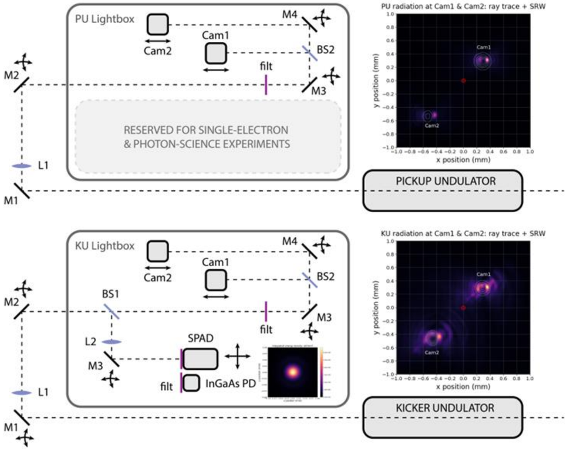


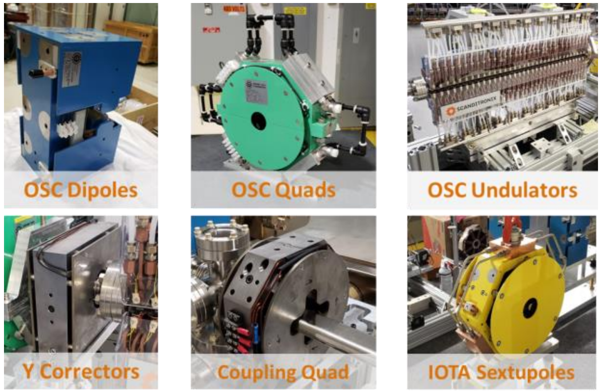




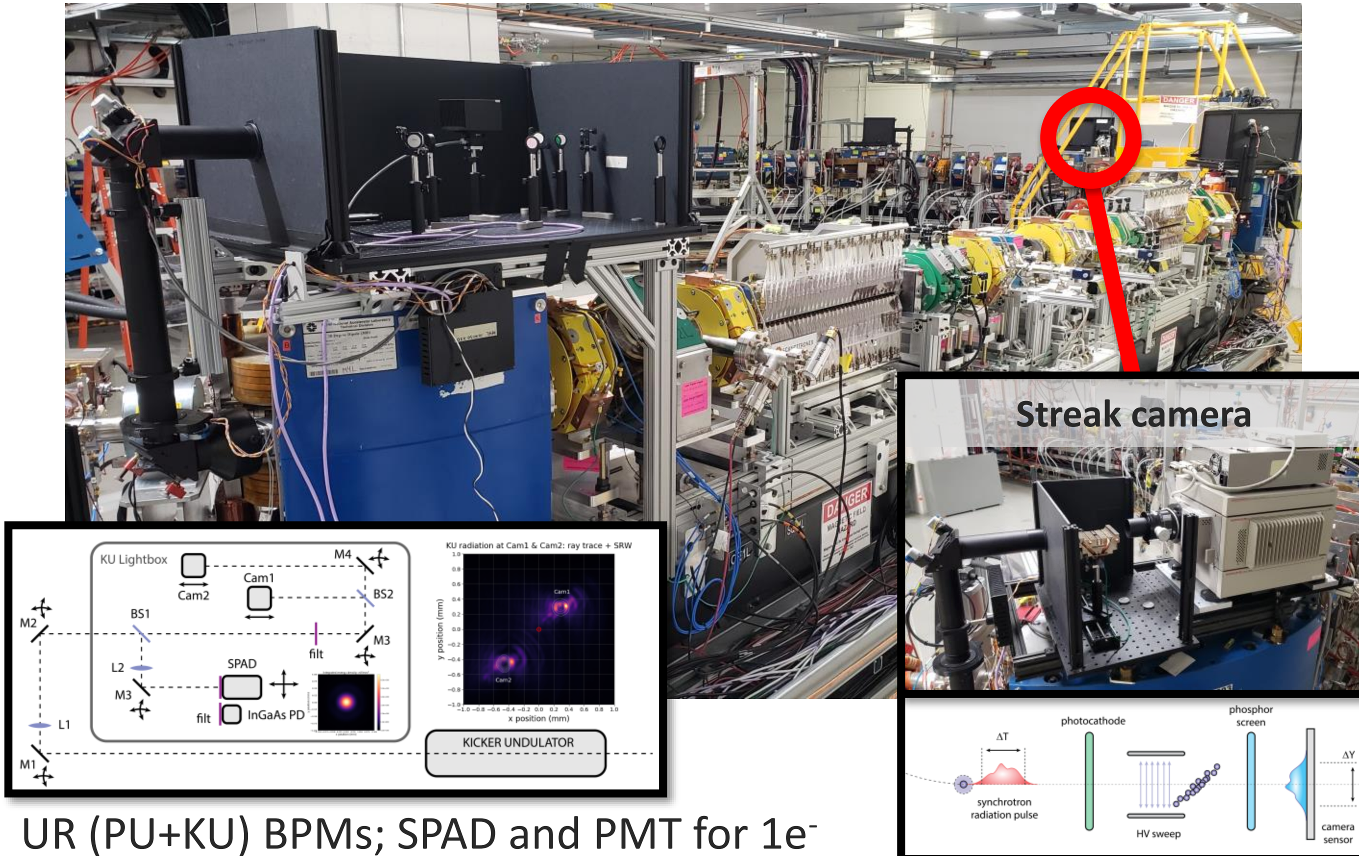








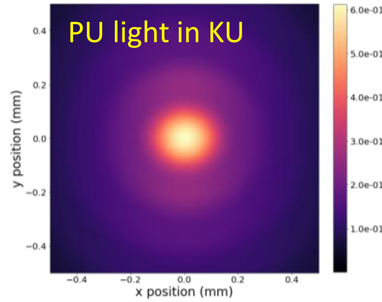
OSC is monitored via synchrotron-rad. Stations

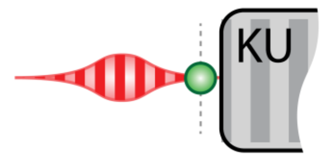


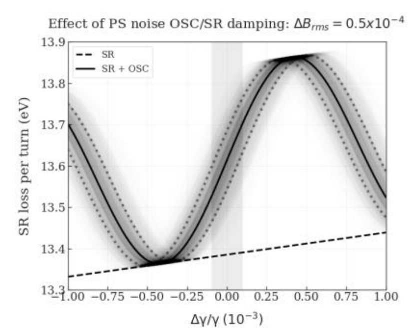
UR (PU+KU) BPMs; SPAD and PMT for 1e$^-$

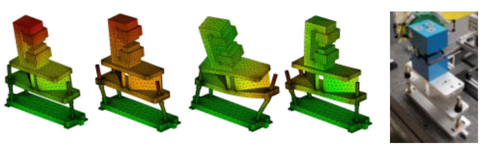
What makes (“simple”) OSC challenging?

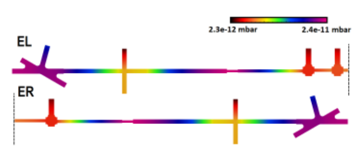
1. Beam and PU light must overlap through the KU
   - The undulator light is ~200 μm wide
   - Want angle between light and beam at < ~0.1 mrad
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than ~0.3 fs
   - The entire delay system corresponds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



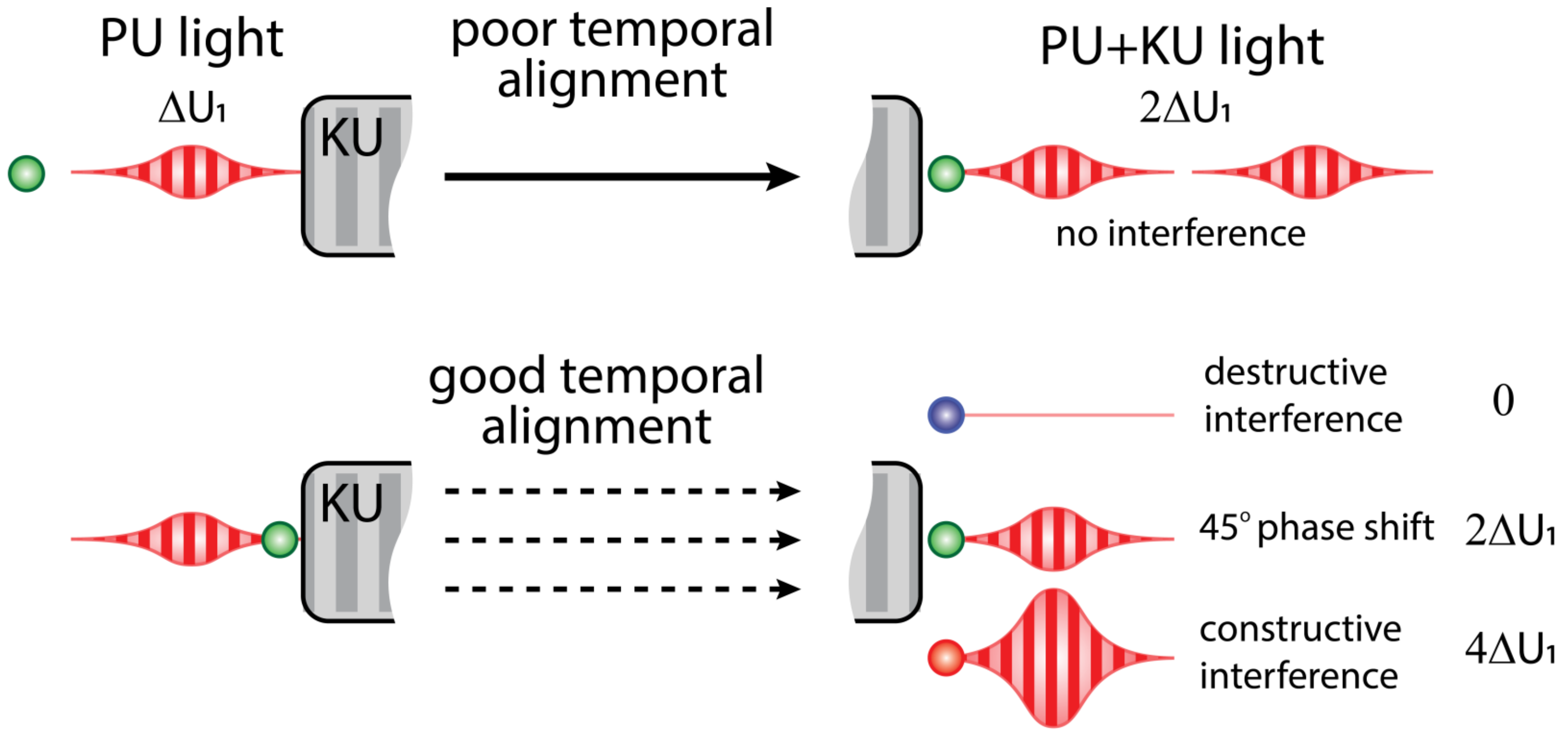








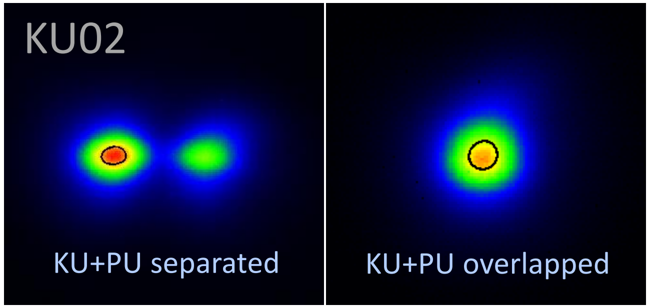
OSC energy exchange has the character of interference

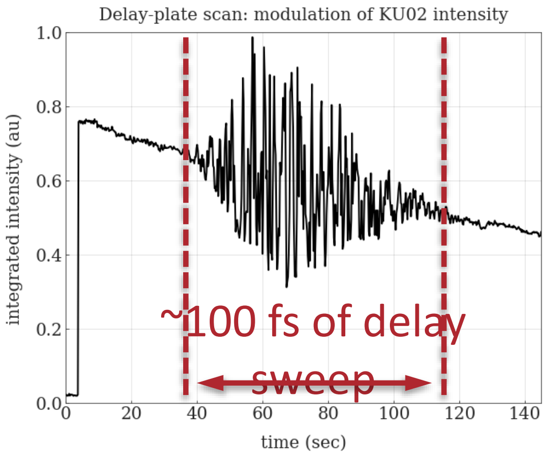


- Matching optical delay and particle-bypass delay will produce interference between the PU and KU radiation
- Amount of light emitted then depends strongly on the delay change due to the particle’s momentum (and trajectory) error
- Neighboring particles add a random contribution that produces diffusion

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

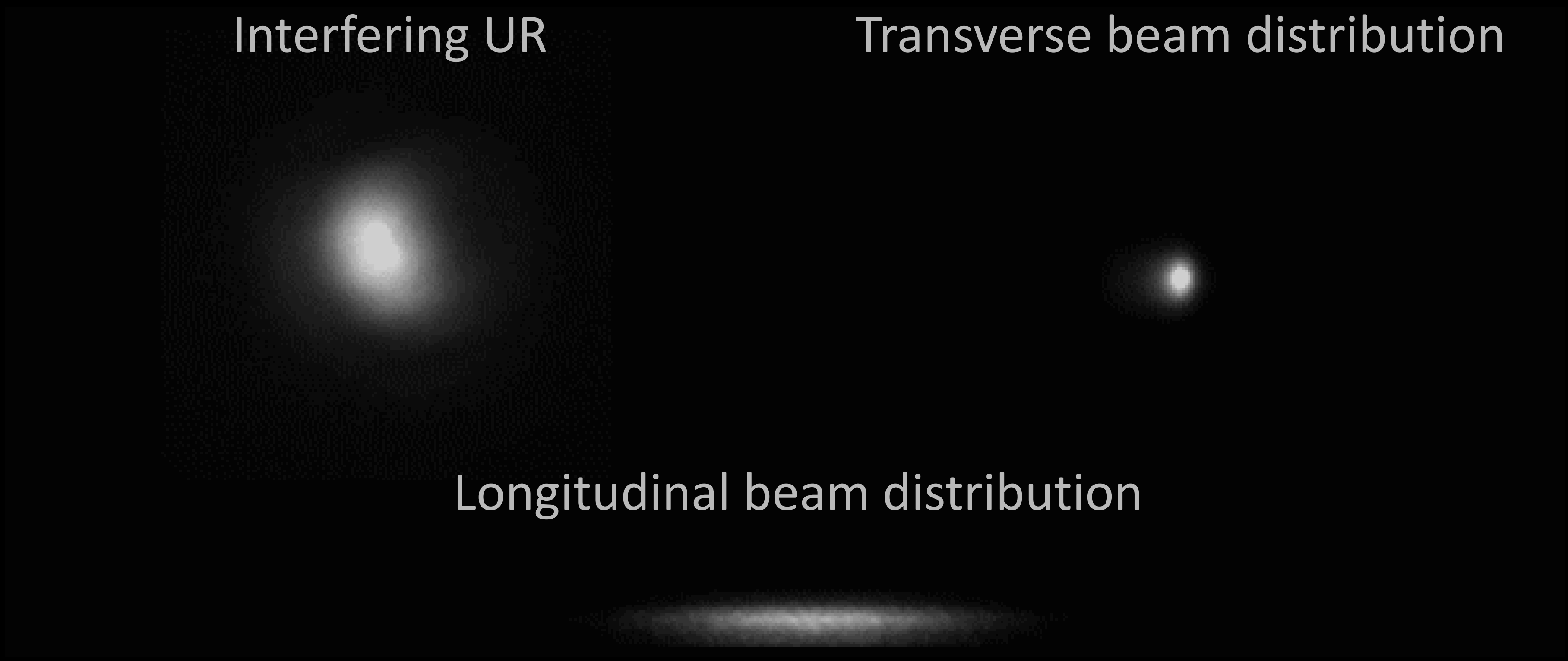
- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- In-vacuum light optics and closed-orbit bumps were used to maximally overlap the coherent modes of the undulators, first on the detectors and then inside the kicker undulator
- This coherent-mode overlap, in both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

Delay scan with OSC in the 3D configuration



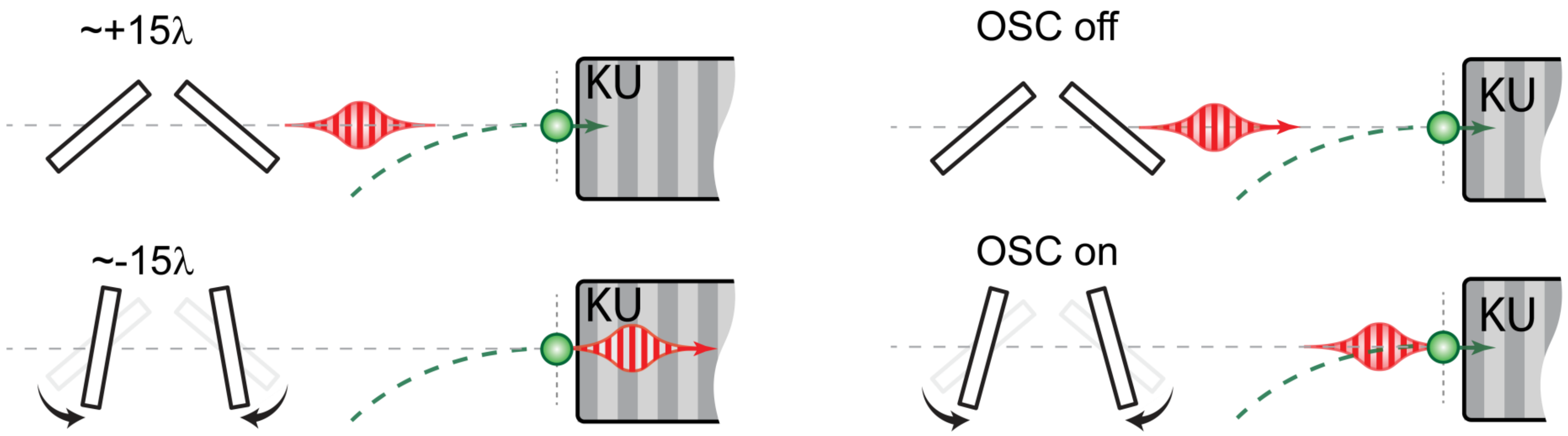
Video @ ~15x realtime

Delay-scan rate ~0.03λ/s

After much work… OSC was strong and stable

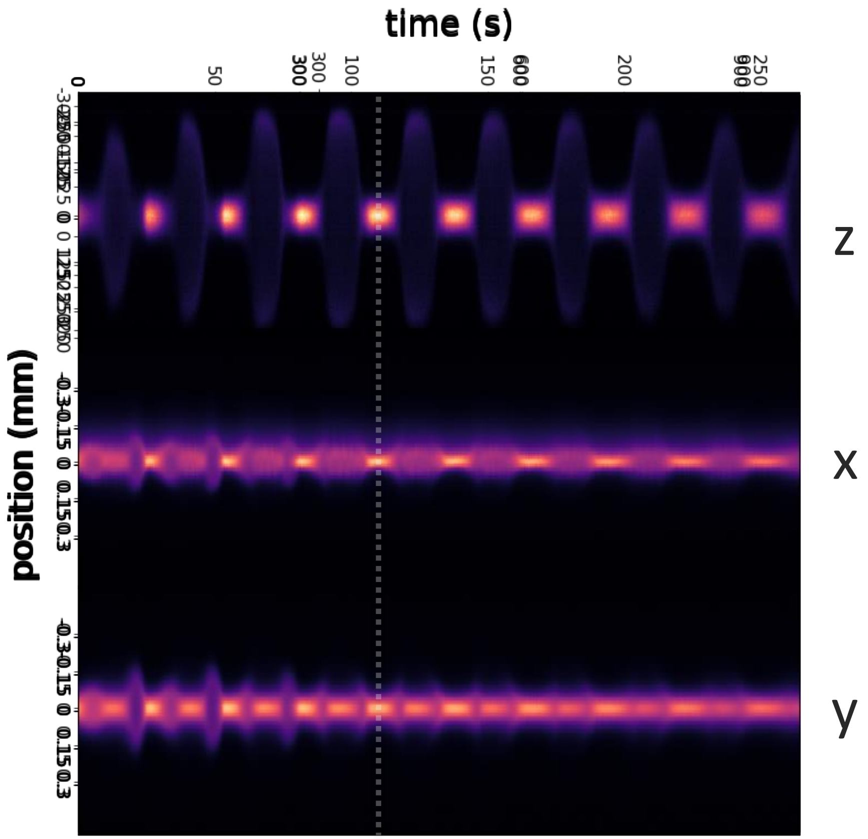
- **OSC was achieved and characterized in 1D, 2D and 3D configurations**
  - 1D: lattice decoupled and bypass quad set to null transverse response to OSC (some residual due to dispersion @ SR BPM)
  - 2D: lattice decoupled and bypass coupling to nominal
  - 3D: lattice coupled and bypass to nominal
- OSC system is reoptimized for each configuration
- Two primary measurements:

SLOW DELAY SCANS (~0.03 λ/sec) **FAST TOGGLES (~15 λ/sec)**

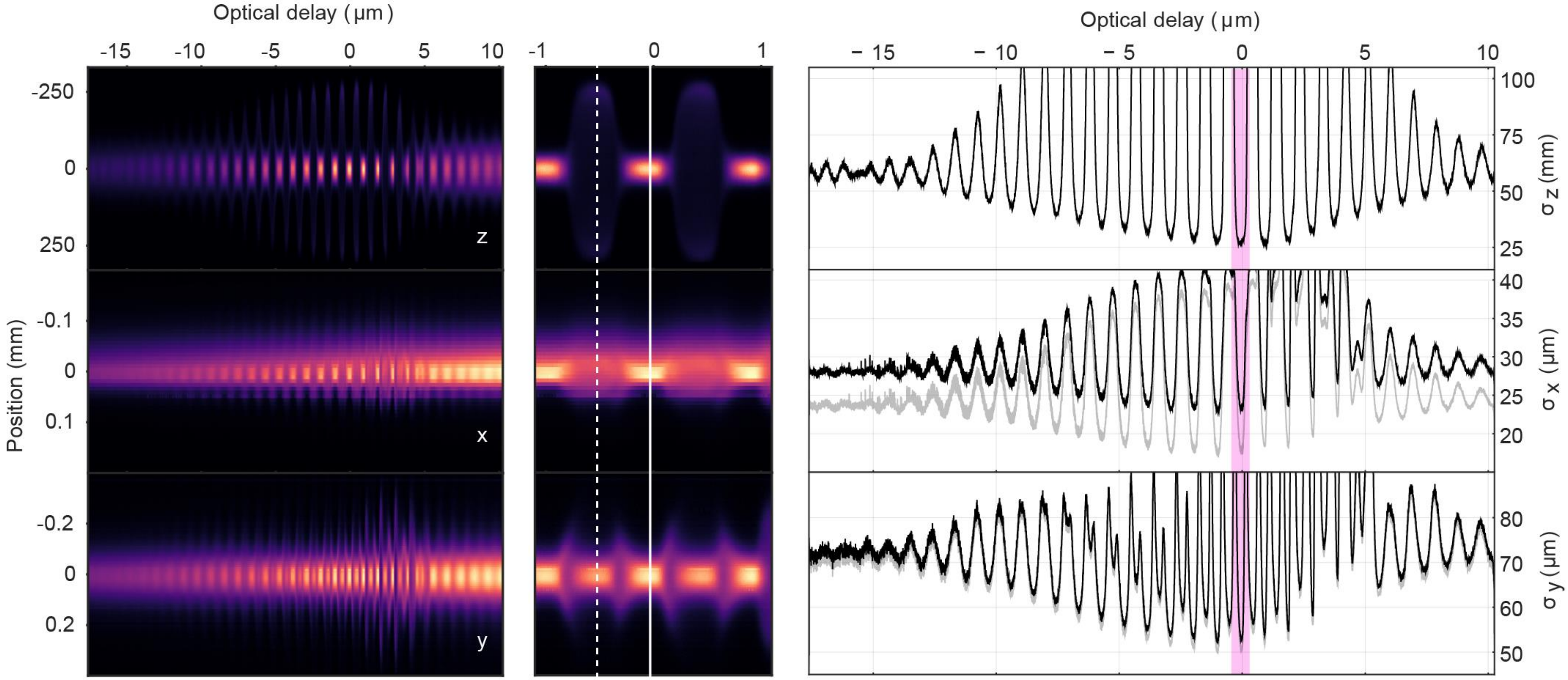


After much work… OSC was strong and stable: OSC ~10x stronger than longitudinal SR damping

- 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



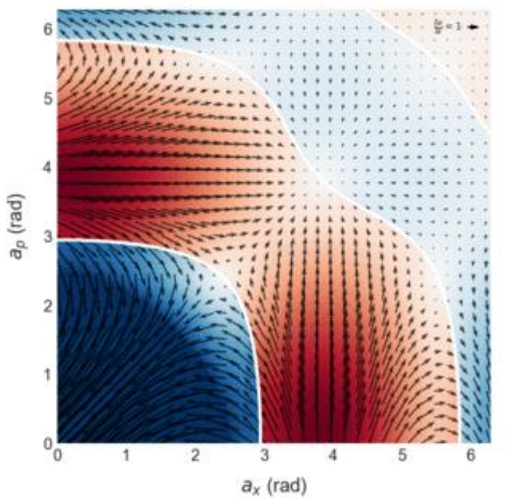
Delay scans show expected OSC structure



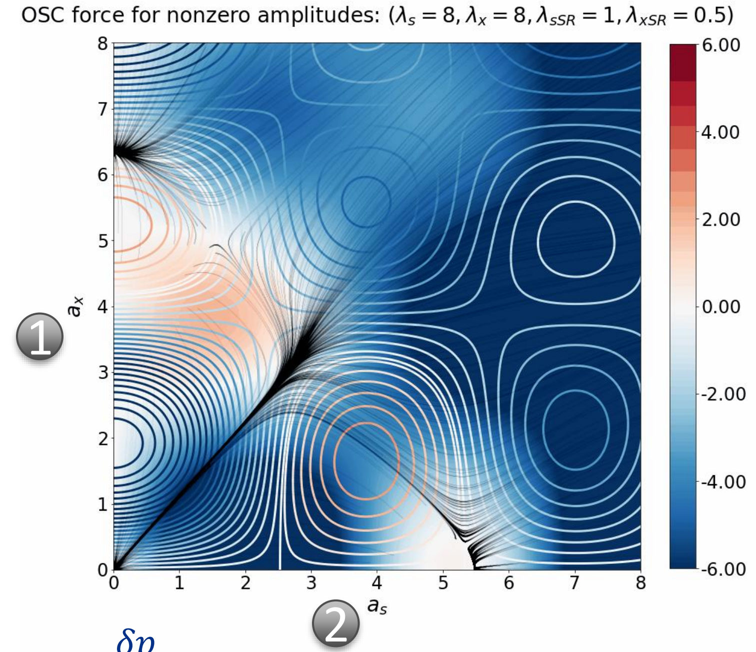
- Delay scan over entire OSC overlap region (~30λ)
- OSC alternates between cooling and heating modes
- Strong simultaneous cooling is observed for all three planes
- Envelope corresponds to ~20-THz bandwidth (**~2000x greater than conventional stochastic cooling**)

Clear observation of expected OSC zone structure and **"attractors" in phase space**

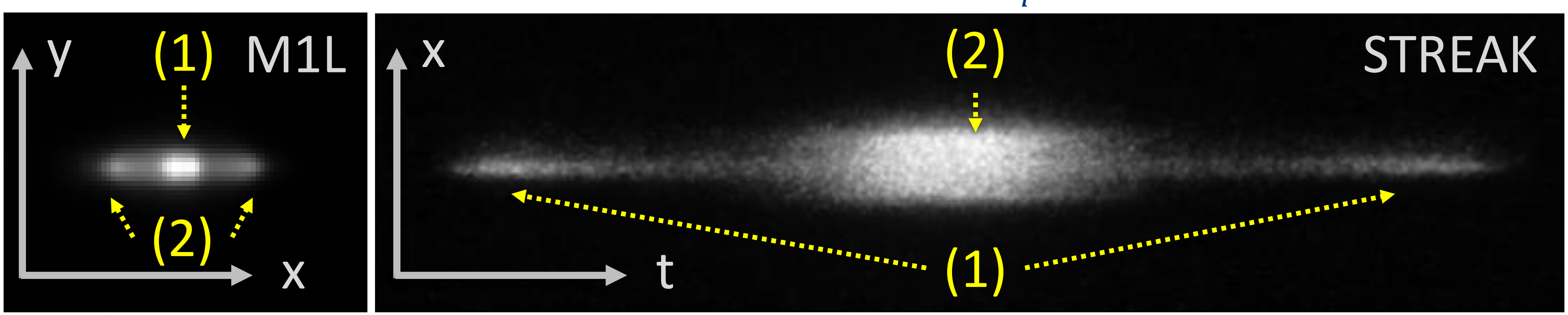
- In "heating" mode, expect **two high-amplitude attractors**



(Sweeping through optical delay)

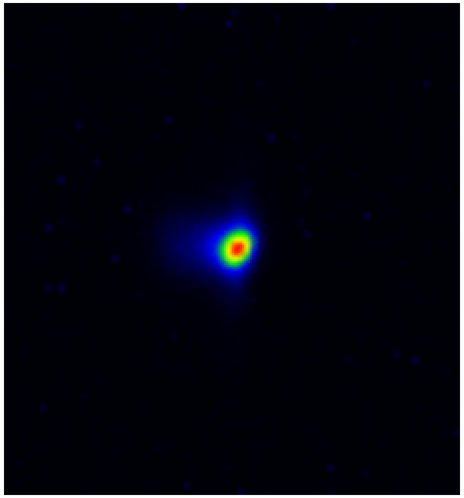


$$\frac{\delta p}{p} = -\kappa \sin(a_x \sin\psi_x + a_s \sin\psi_s)$$



Transverse and longitudinal projections for heating mode of 2D OSC

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-100s nm?)

OSC Ring and Beam Parameters

Fluctuation Power from a single electron : <10 E -19 Watts

Design momentum, p_0	(MeV/c) 100
Revolution frequency	(MHz) 7.50
RF frequency	(MHz) 30.00
Momentum compaction	$4.91 \cdot 10^{-3}$
Rms momentum spread, σ_p/p_0	$0.986 \cdot 10^{-4}$
Horiz. emitt.: x-y uncoupled, ε_0	(nm) 0.857
Total bypass delay	(mm) 0.648
Nominal rad. wavelength, λ_r	(nm) 950
Maximum OSC kick per turn	(meV) 60
Horiz. cooling acceptance, ε_{max}	(nm) 72
Long. cooling acceptance, $(\Delta p/p)_{max}$,	$5.7 \cdot 10^{-4}$
Bandwidth of the OSC system	(THz) 19
Sum of emittance OSC rates	(s^{-1}) 38 ←
SR emitt. damping rates, [z,x,y]	(s^{-1}) 2.06, 0.94, 0.99 ←

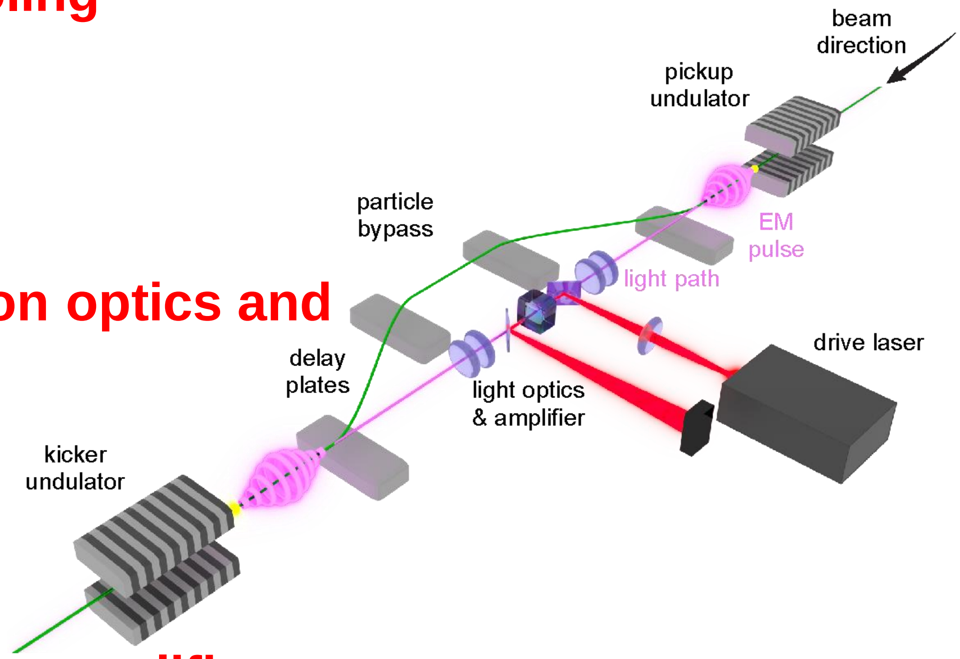
OSC is 38 X faster than natural Sync. Rad. Damping!!!

Progress since 2022:

Amplified OSC system
New Bypass Design
Bypass Optimization
Laser Amplifier
All-fiber Pump Laser
Iterative Design Process
Updated Light Optic Design

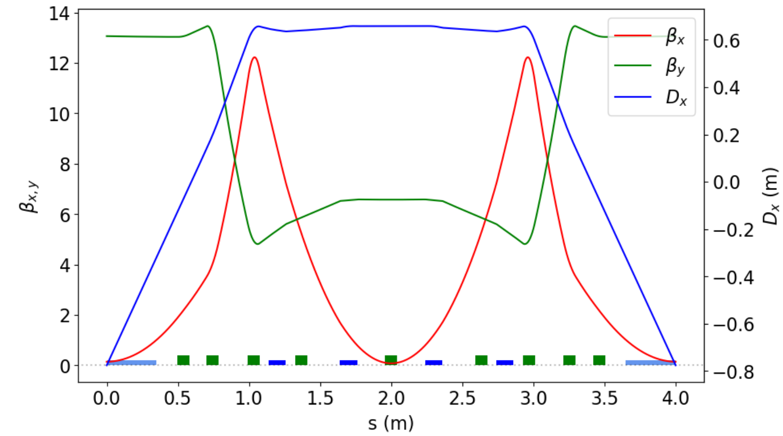
Amplified OSC concept is now under conceptual development

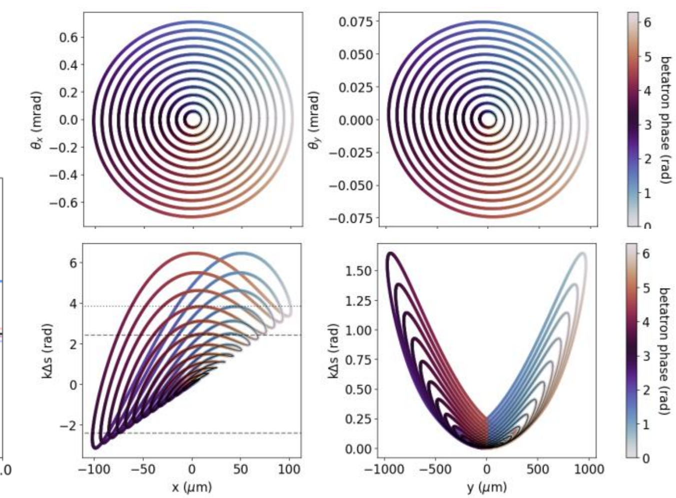
- **Higher-delay system (6mm vs 0.6mm – provides optics budget and stronger cooling**
- **More complex bypass**
- **Good matching between electron optics and light optics**
- **Telescopic in-vacuum optics**
- **Longer wavelength for high gain amplifier compatibility**
- **Power gain ranging from 0dB to >40dB (cooling time ~ 1 ms)**

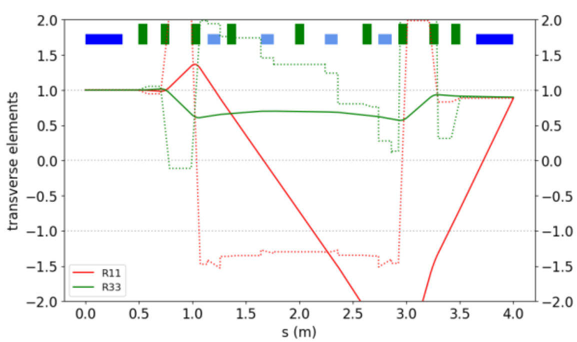


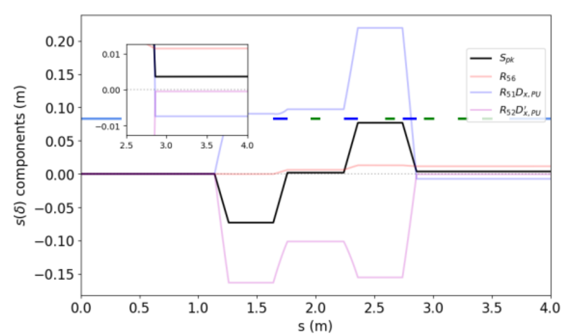
Extensive bypass optimization effort

- To meet needs of all operational modes while still being physically "realizable."
- Extensive multi-objective optimization campaign using cpymad (i.e. MADX) with genetic algorithms (CNSGA) in Xopt and Pymoo; many millions of variations considered
- Optimization on critical performance parameters for OSC (mappings, rates, ranges, etc…)



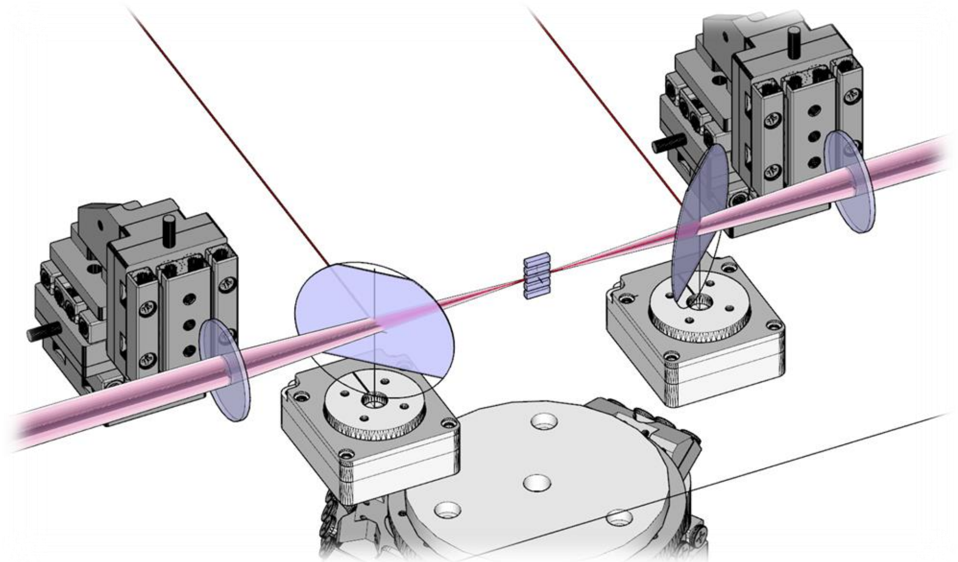


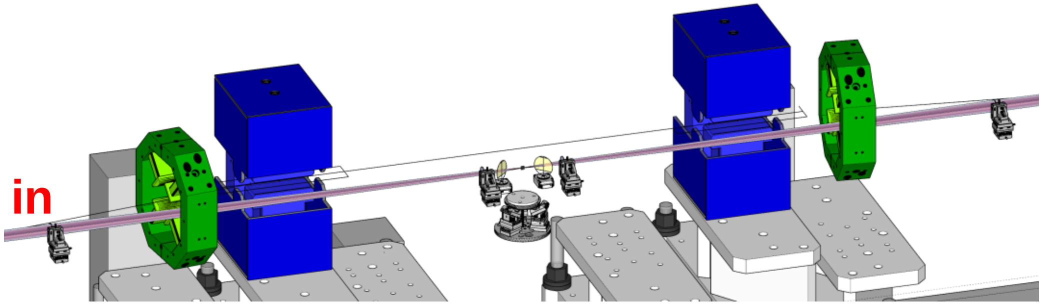




Overall light-optics design is relatively mature

- Positive-identity, telescopic optics with depth-of-field suppression; four lenses
- All lenses independently controllable in (x, y, z) dimensions
- MgF_2 optics for low group-velocity dispersion (minimize pulse spreading) and good manufacturability
- Delay plates are also dichroic mirrors for coupling pump laser in and out of the system
- Amplifier crystals on 6-DoF hexapod

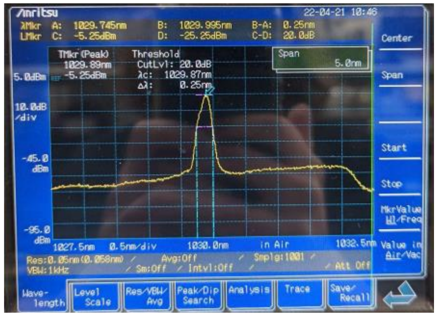




New, all-fiber pump laser from Optical Engines

- Originally developed for **next-gen laser notcher**
- New system was **tested** at manufacturer under conditions required **for amplified OSC experiment**
- Demonstrated: ~200-ps pulses @ 7.5 MHz; ~33 uJ/pulse (250-W avg output) – **i.e. can pump every turn**
- Clean spectrum, σ_λ**~0.1nm**, under operational conditions
- Performance limited by heating of fiber and mirror
- Arbitrary turn-by-turn programmability enabling **advanced beam control**

Original laser system for FNAL linac laser notcher



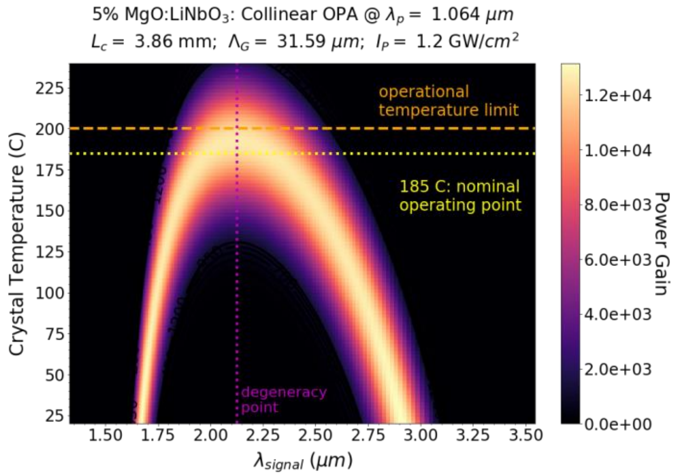
OE spectral measurement @250W

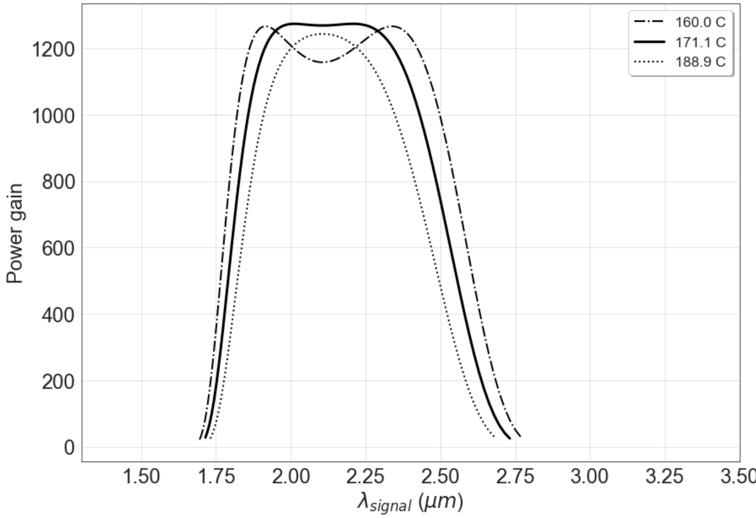
OSC amplifier based on MgO : PPLN Crystals and Chips

(Magnesium-doped Periodically Poled Lithium Niobate)

High-efficiency wavelength converter at visible and mid-IR wavelengths

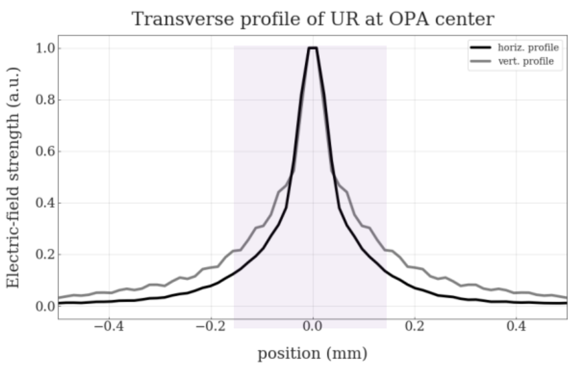
Crystal temperature / gain vs. wavelength →

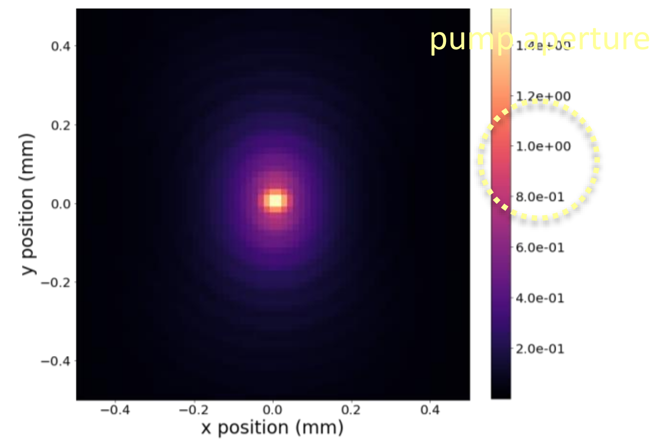


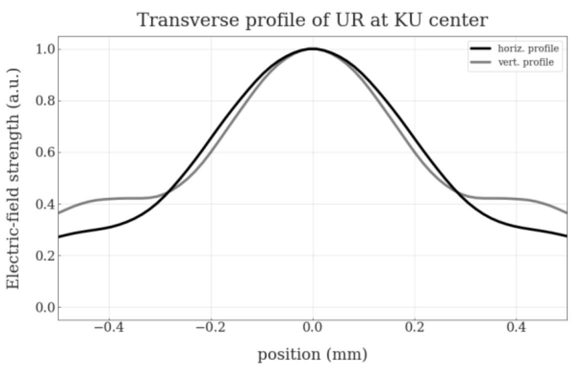


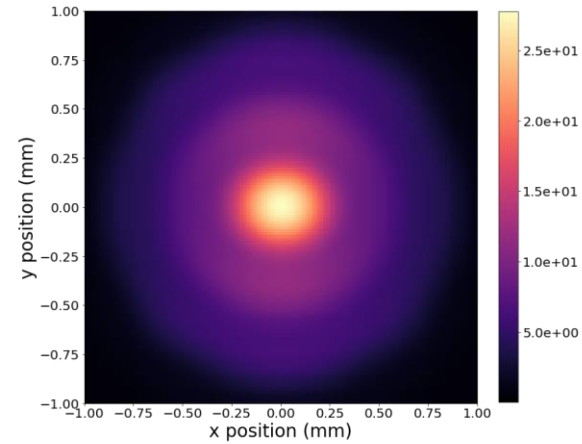
- Amplifier must be "single pass" (low delay)
- Also needs low group velocity dispersion and widest gain bandwidth possible
- A PPLN OPA operating near "degeneracy" should meet all requirements
- Operation at max temperature possible to reduce photorefractive effect (damage); ~185 C
- Accounting for all delay needs, a 3.86-mm crystal length is possible: ~40dB of gain for expected pump intensities.

OSC simulations underway for integrated optical system



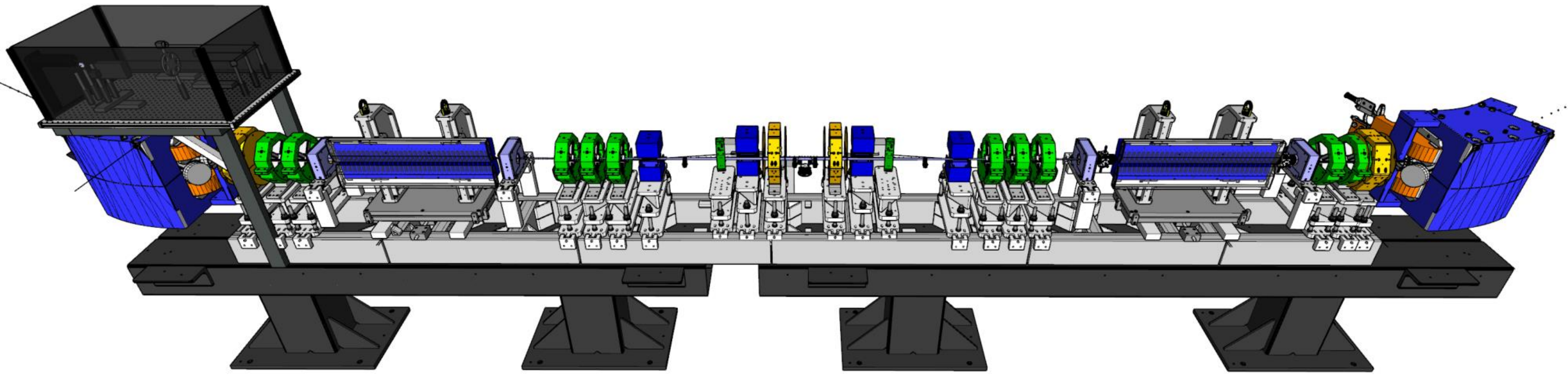




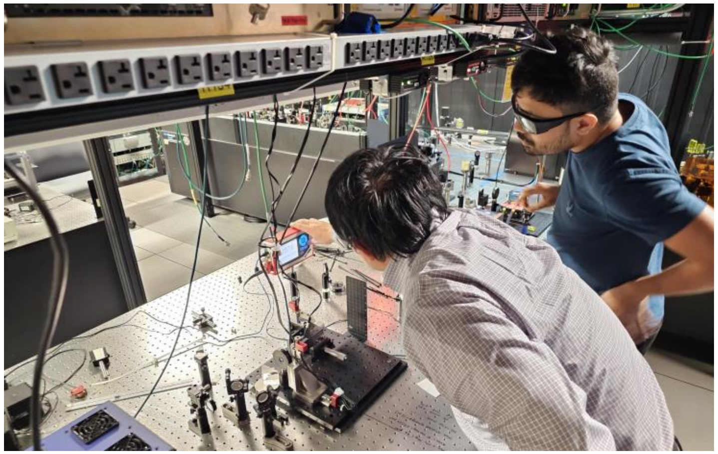


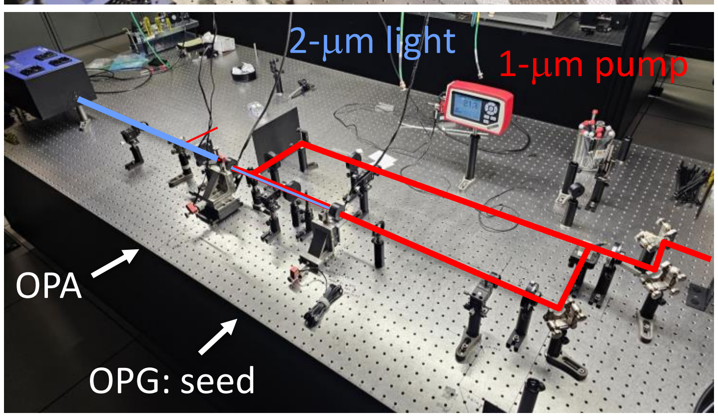
Iterative design process for integrated system is underway:

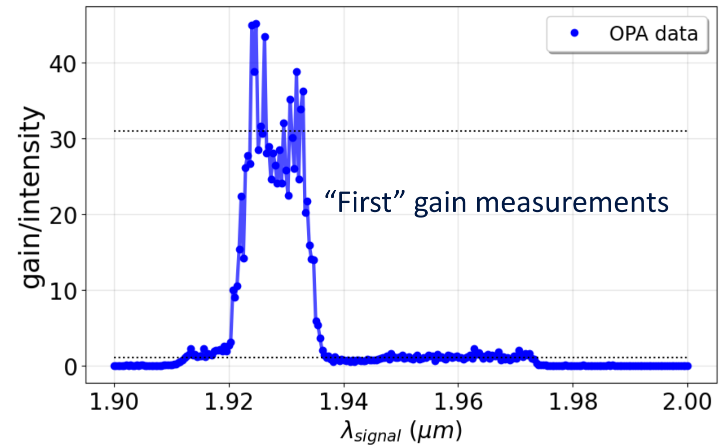
Bypass optimization, new undulators, new quadrupoles, multifunction correctors, bypass sextupoles, new vacuum envelope, new permanent magnet chicane dipoles with trims

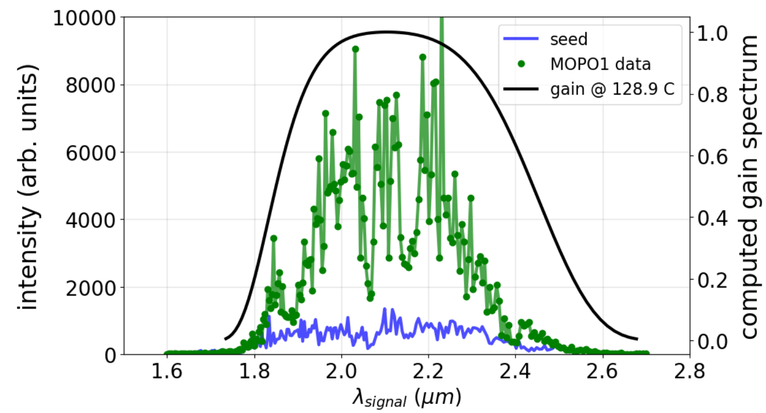


Prototyping amplifier and entire optical system in FAST laser lab



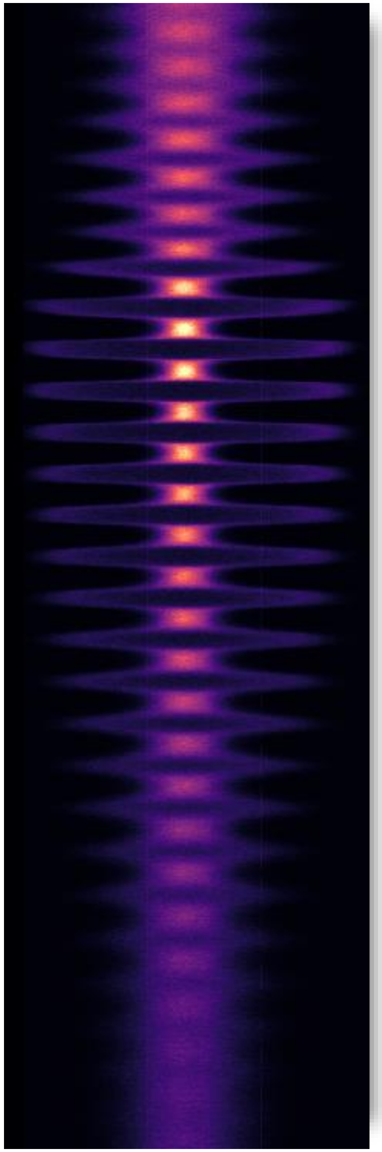




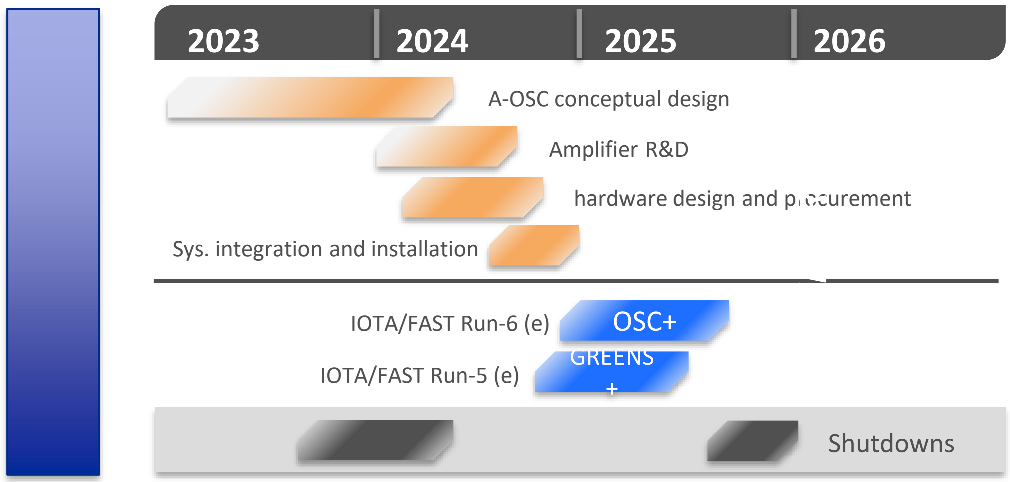


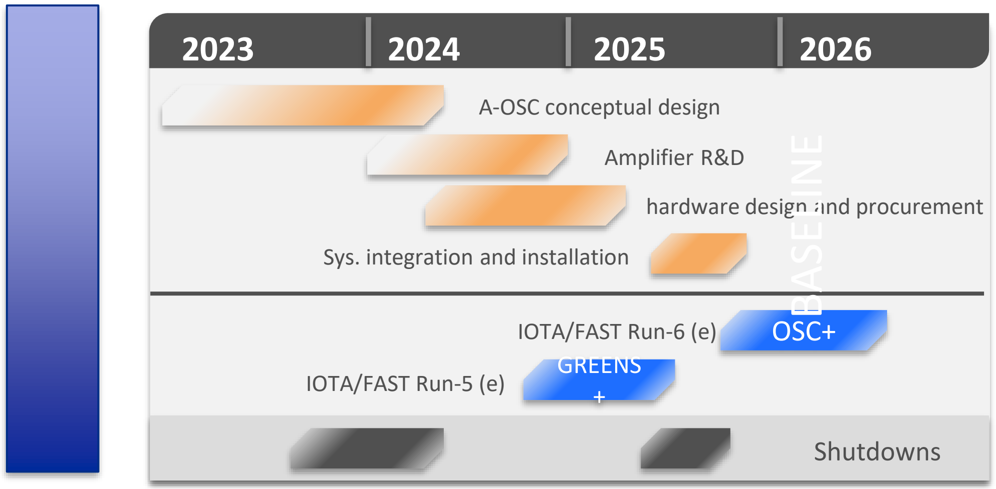
SUMMARY of Achievements to date:

- Comprehensive, systematic studies of the non-amplified OSC physics were carried out during IOTA Run #3; full analysis of the data performed and published in Nature journal
- This is the first experimental demonstration of a stochastic cooling technology in the optical regime
- Successfully demonstrated OSC in 1, 2 and 3 dimensions
- "OSC" of a single electron was definitively observed
- Establishes a strong foundation for development of our new amplified OSC experiment: validated many critical subsystems and concepts; gathered excellent operational experience and learned many valuable lessons



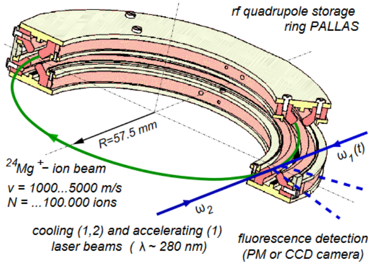
Summary and Timeline:
(Accelerated vs. delayed depending on Fermilab priorities)





Speculative applications:

- 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
- Applications include:
  - (i) Beam cooling in a possible future Electron Ion Collider
  - (ii) Beam Cooling in a future possible Muon Collider
  - (iil). Single Ions in a storage ring: towards Quantum Computers with large number of qubits: e.g. “Frozen Crystalline Beams” enabled by OSC can act as Quantum Computers:

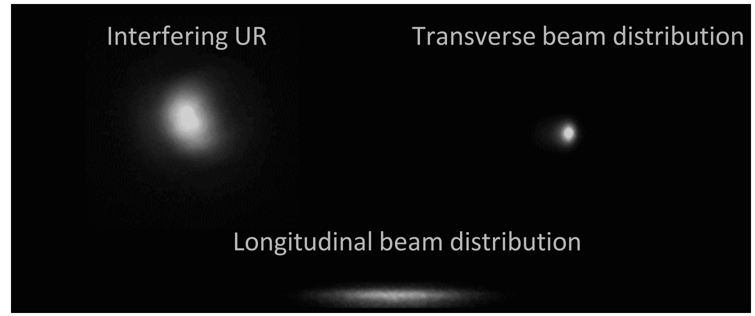


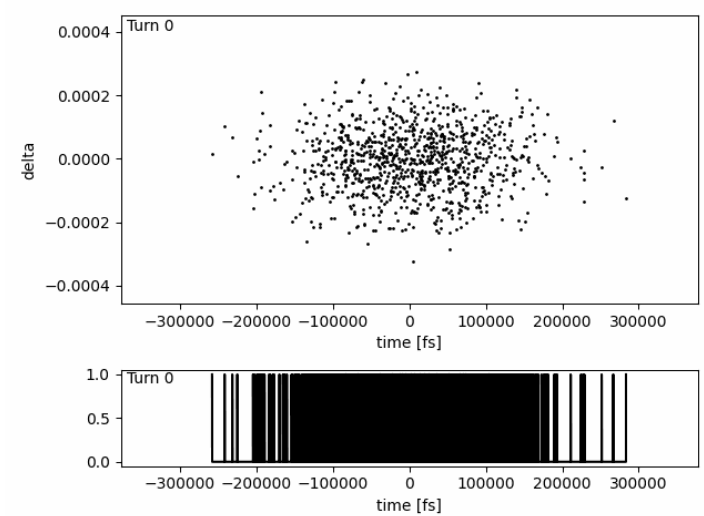
OSC systems as a flexible tool for advanced beam manipulation

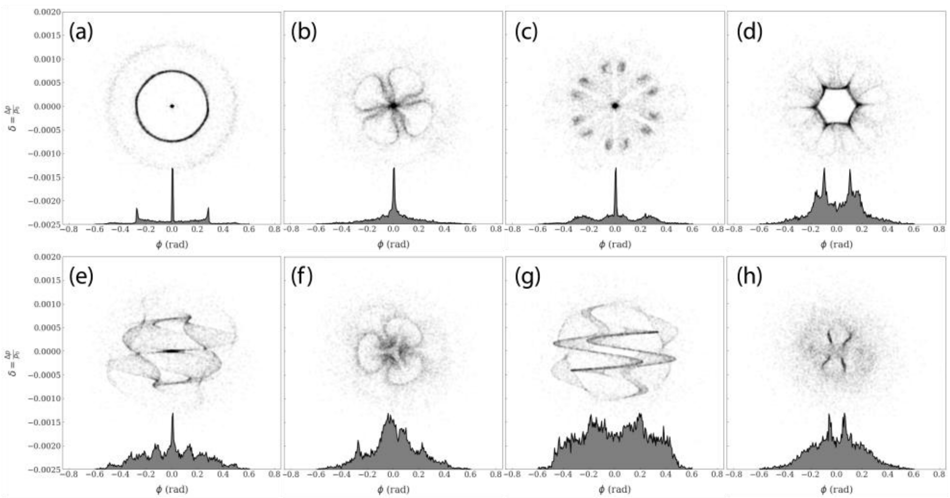
- **The OSC force is very powerful and can be structured in space and time with tremendous freedom (delay, gain, optics, mapping, etc…).**

- **The amplified-OSC system is being designed to enable a robust program in exploring "distributions on demand"**

- **Will develop and test advanced control systems using Reinforcement Learning + surrogate models**



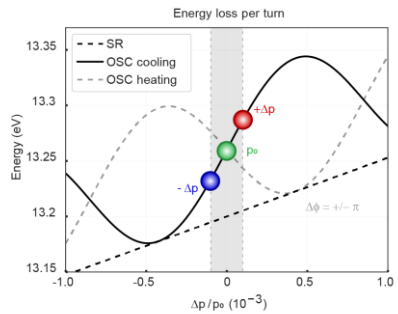




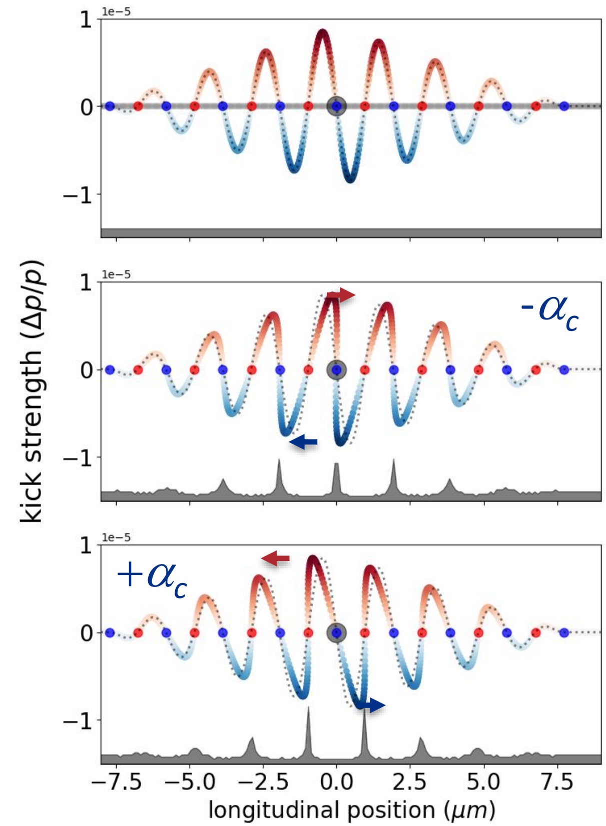
Optical Stochastic Crystallization: Targeting the first SSMB demonstration

- **Standard OSC** maps particles' energy deviations onto appropriate energy corrections; **creates attractors in momentum**

- **OSX creates attractors in both momentum and longitudinal position simultaneously; these are locked to the beam structure itself**



OSC bypass mechanism



Quantum Science

Can we go to the quantum limit of photon emission from a "single" electron or positron?

Three fundamental questions:

→ ***Photon statistics***

→ ***Quantum Optics of Radiation from a free charge***

→ ***Quantum entanglement between photon and electron/positron***

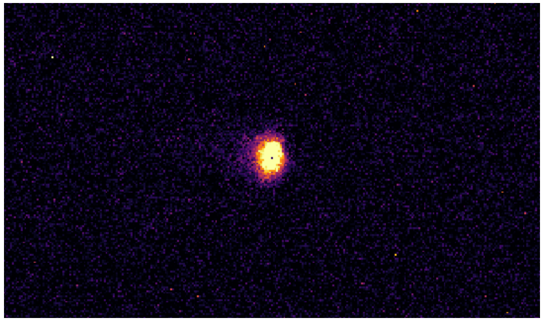
→ ***"Cheshire Cat" exchange between 'electron' & 'positron'***

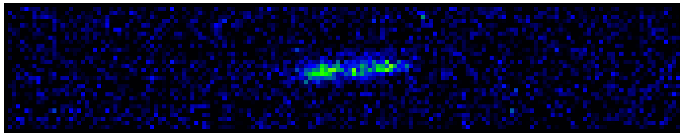
→ ***Radiation does not discriminate between positive and negative charges i.e. one cannot tell from emitted radiation alone whether it came from an 'electron' or a positron***

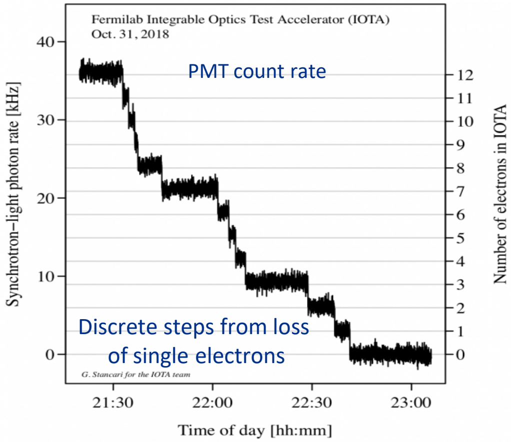
→ ***Yet, emitted photons are fundamentally entangled with the 'charge'!***

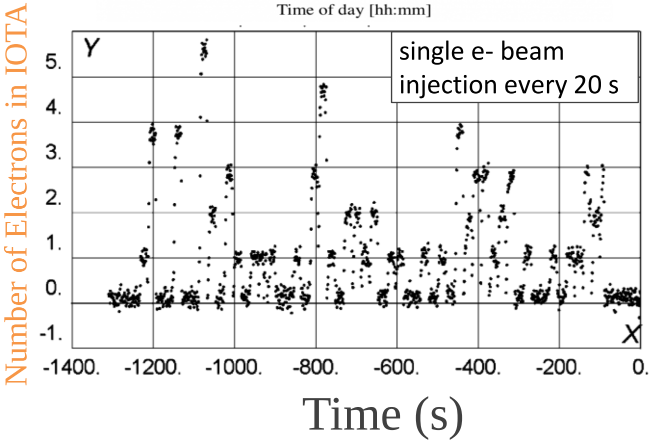
IOTA has succeeded in storing a single electron in the ring for several minutes!

- 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



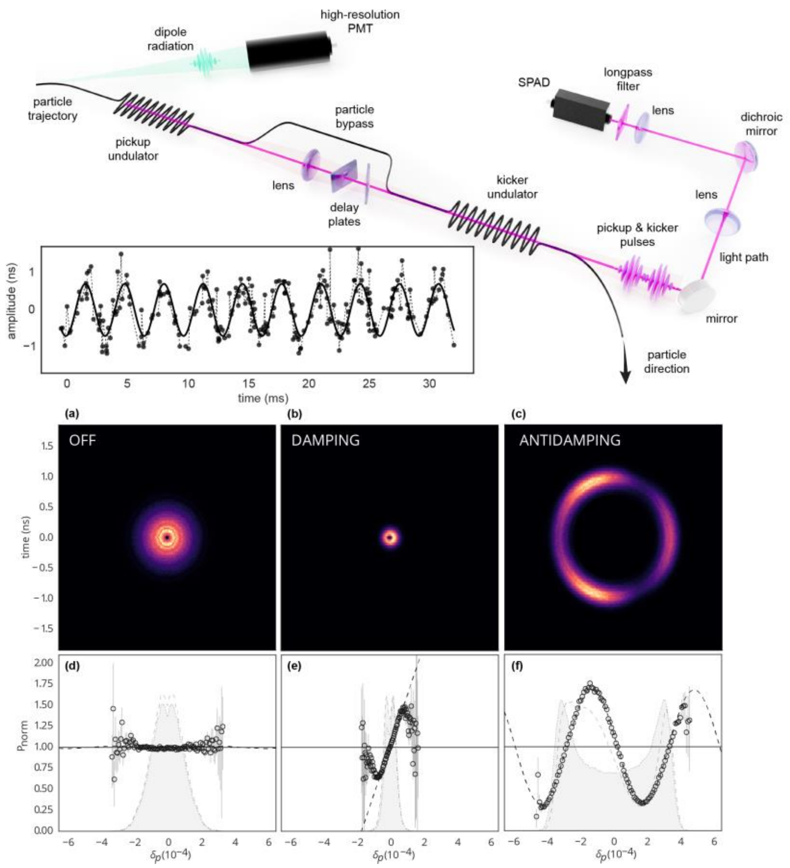






Single-electron OSC also produced outstanding results

- First closed-loop interaction of a single relativistic particle with its own radiation field
- Successfully resolved the underlying OSC physics using a single electron as the probe
- Observe expected modulation of photon-emission probability due to the OSC system
- Used the OSC force to freely manipulate the single-particle action
- Excellent agreement between system performance with single particle and with beam
- Manuscript in preparation



PHOTON STATISTICS

$\alpha \sim 1/137 \Rightarrow$ 1 PHOTON (γ) every 130 - 140 turns approximately

1, 2, 3, ... , n, ... , 130, . . ., 137, ...

γ

No 'γ'
But field ?
$\vec{E}(t)$, $\vec{B}(t)$?

$$\langle E^-(r',t') E^+(r,t) \rangle = Tr\left\{ E^-(r',t') E^+(r,t) \rho_{ph} \right\}$$

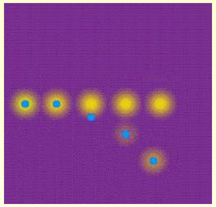
$$E^-(r,t) = \left(E^+(r,t) \right)^\dagger$$

$$\rho_{ph} = Tr_e \left\{ \rho_f \right\}$$

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



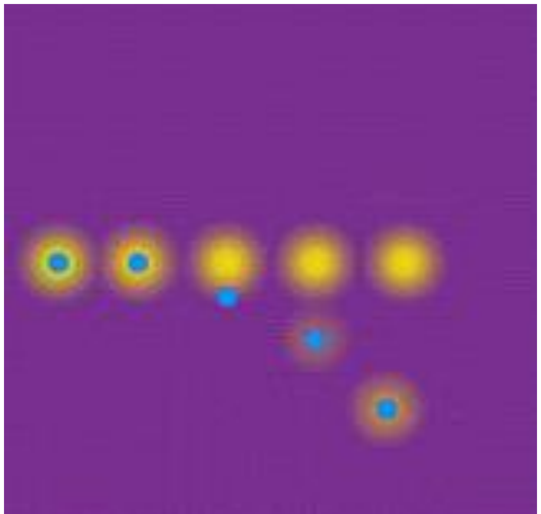
$N_p \sim (0.5 - 1) + 1 \sim O(1)$.

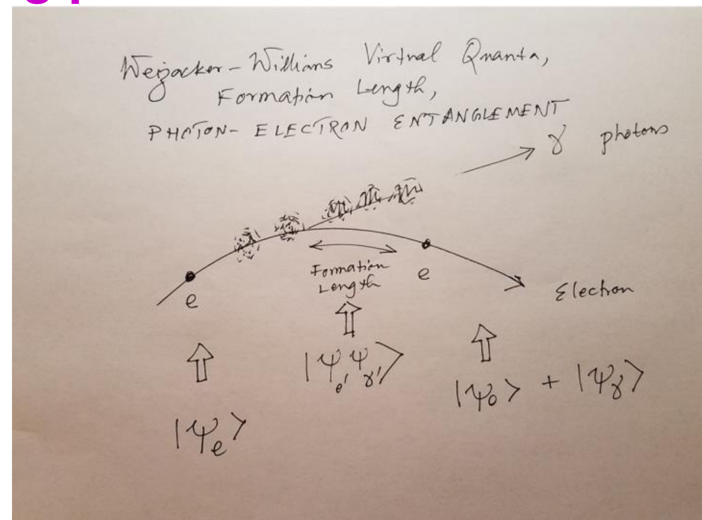
These few photons generate a field that is intrinsically non - classical and quantum mechanical. Small "degeneracy" parameter means small number of photons in a coherence volume. How does optical probing work in the quantum limit?

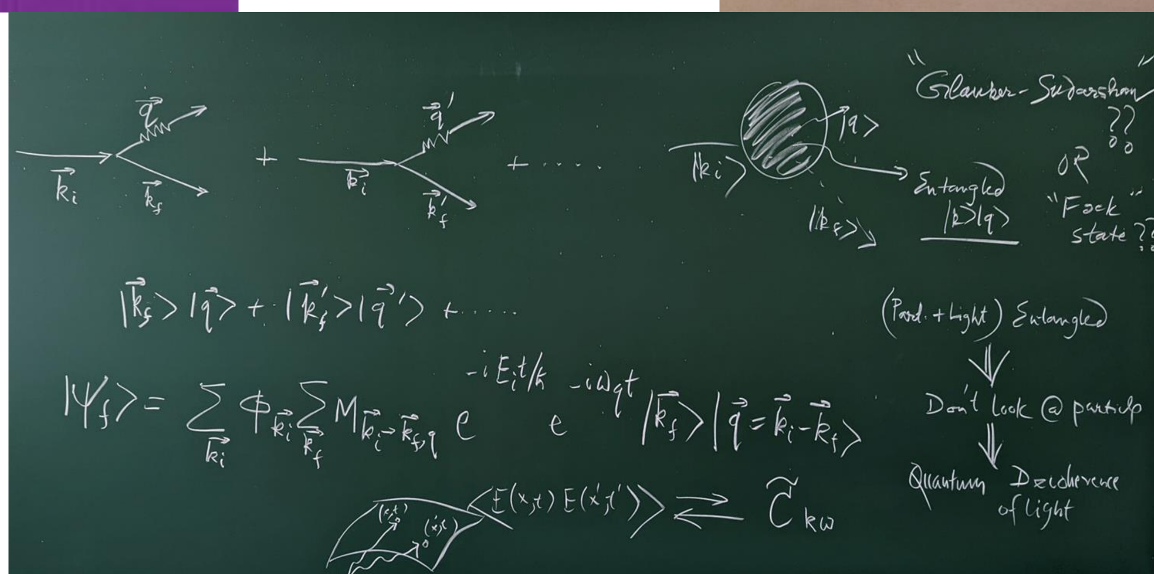
Quantum optics of radiation from accelerated ultra-short bursts of electrons is critical to taming particle beams to an "ordered" and "coherent" state comparable to a laser….this is very difficult!!

Electron-Photon Entanglement Entropy-

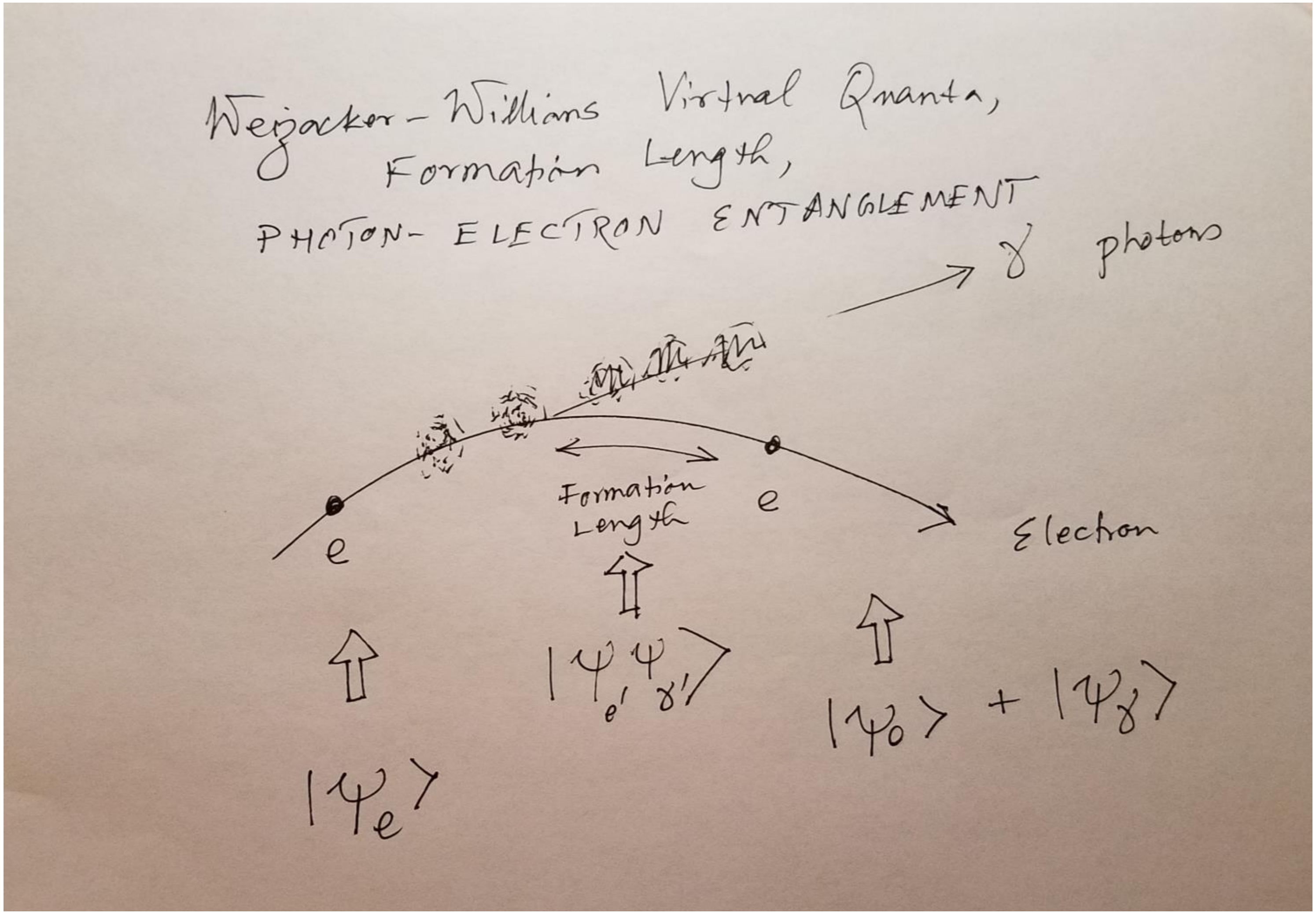
Self-Entanglement of electron, its charge and emitted photon
→ coherence of light is fundamentally tied to the coherence and entanglement of the emitting particle







Virtual Quanta and Formation Length: Electron-Photon “entangled” bi-partite wavefunction



$$H_A \otimes H_B. \rightarrow \quad |\psi\rangle_A \otimes |\phi\rangle_B \qquad |\psi\rangle_{AB} = \sum_{i,j} c_{ij} |i\rangle_A \otimes |j\rangle_B$$

Personal observation on electron-photon entanglement entropy:

T. (dS) . (dt) ~ h (fundamental unit of action)
dS ~ k ln (W) a la Boltzmann

State ‘1’: “dressed” electron and no photon: I0>
State ‘2’: “bare” electron and photon: I1>

→ W = 2

T k ln(2) (dt) ~ h → using temperature of oscillating electron in the field of radiation, one can estimate the ‘formation length’ and emission time of photons (dt).

Use temperature equivalent to electron rest energy to estimate entropy of electron-photon entanglement prior to emission.

THESE QUESTION ARE "UNSOLVED" TO DATE!!
(Future Research)

Experiments very difficult and challenging due to the time-scales and laboratory noise involved. Theoretically, QED a la Feynman, treats electron-photon vertex as just a point interaction in energy-frequency domain, but probing of quantum entanglement of electrons and photons in real time in the radiation process itself is very difficult.

Space-*time real, "virtual" particles* → Feynman diagrams

Real particles, space-*time "virtual" → ?? "emergence of trajectory" via continuous entanglement of "soft" photons*

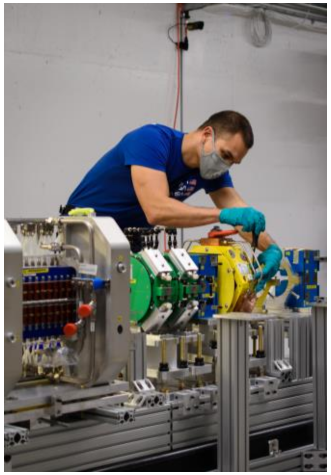
A detailed and thorough investigation is planned for studying the quantum statistics of emitted photons both in multiple electron and single electron scenarios. A PhD thesis just got completed by Ihar Lobach (U Chicago) with preliminary results.

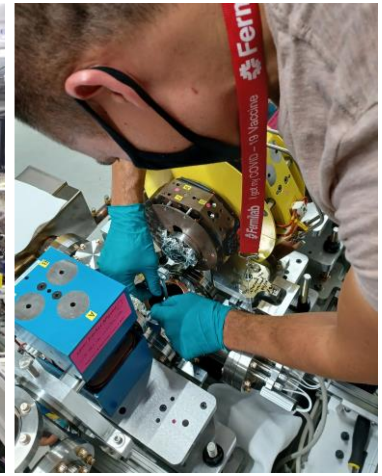
A final frontier will be studying experimentally the electron-*photon "entanglement" in* the process of radiation i.e. catching the electron in the act of emitting a photon, and *"Cheshire Cat" exchange experiment*

QUANTUM OPTICS of RADIATION from FREE CHARGES (vs. ATOMS/Quantum Dots)

Thank You!

A huge CREDIT and "thank you" to the IOTA team





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