Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Accelerator research at Fermilab's IOTA/FAST facility

Alexander Valishev

MSU/FRIB Seminar

19 November 2021

Fermilab and accelerators

Fermilab is America's particle physics and accelerator laboratory

We bring the world together to solve the mysteries of matter, energy, space and time.

- Our vision is to solve the mysteries of matter, energy, space and time for the benefit of all. We strive to:
  - lead the world in neutrino science with particle accelerators
  - lead the nation in the development of particle colliders and their use for scientific discovery
  - advance particle physics through measurements of the cosmos
- Our mission is to drive discovery by:
  - building and operating world-leading accelerator and detector facilities
  - performing pioneering research with national and global partners
  - developing new technologies for science that support U.S. industrial competitiveness

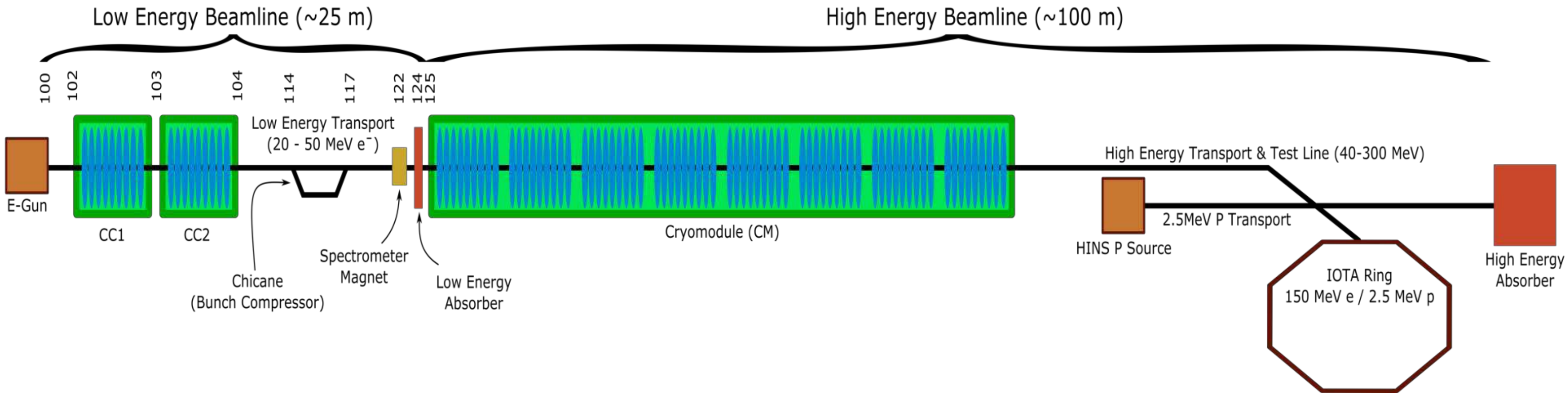
Why Dedicated Facility?

FAST = Fermilab Accelerator Science and Technology

- Need for experimental beam physics research especially in circular accelerators
  - Many challenges on the way to higher beam intensity and brightness
- Difficult to conduct R&D in main complex
  - Production machines must operate 24/7 for HEP users
  - Disruptive studies – opportunities limited by time, impact on operations
  - Hardware modifications expensive and time consuming
- Dedicated R&D facility is an efficient way to conduct proof-of-principle experiments, train researchers

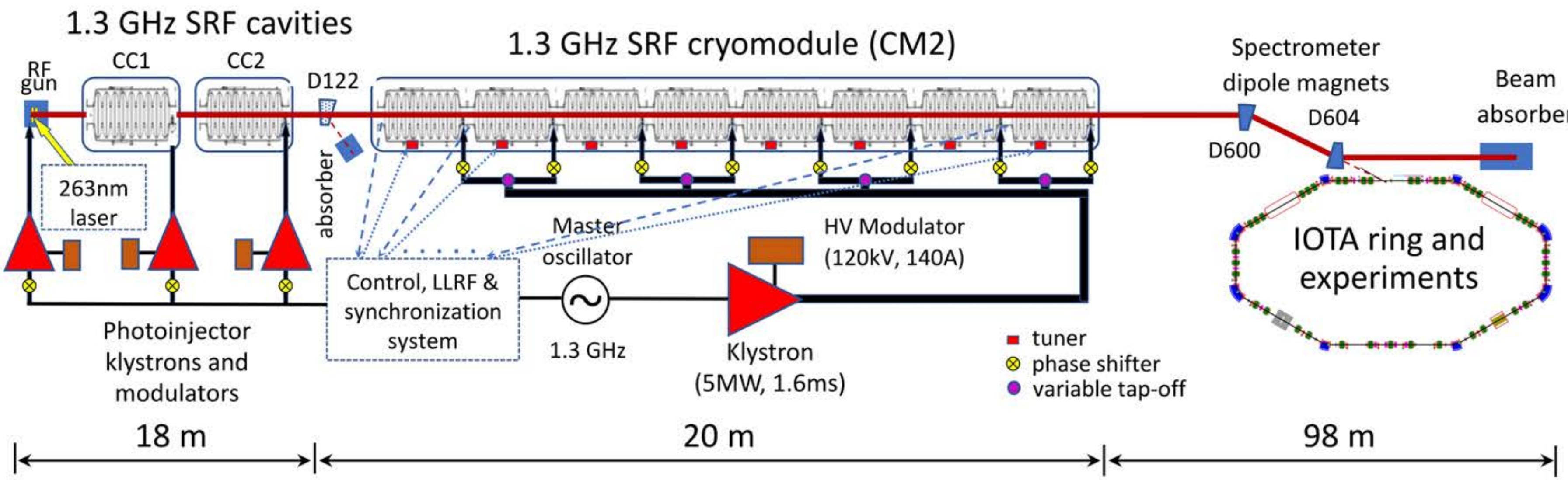
IOTA/FAST facility established as center for accelerator and beam physics

- **Facility establishes a capability at FNAL, unique in the world, to address frontier topics in Accelerator and Beam Physics**



- **The only US dedicated facility for intensity-frontier accelerator R&D**
- Flexible, small-scale machines and efficient operation model
- Driven by research needs of future HEP accelerators
- Operates as collaboration, ~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

IOTA/FAST accelerators – present configuration



Electron beams are supplied to IOTA from FAST, 1.3 GHz Superconducting RF electron linear accelerator

- Beam energy to IOTA: 40-300 MeV
- Bunch charge: 1e- to 3 nC (160 pC nominal)
- Injection frequency: up to 5 Hz

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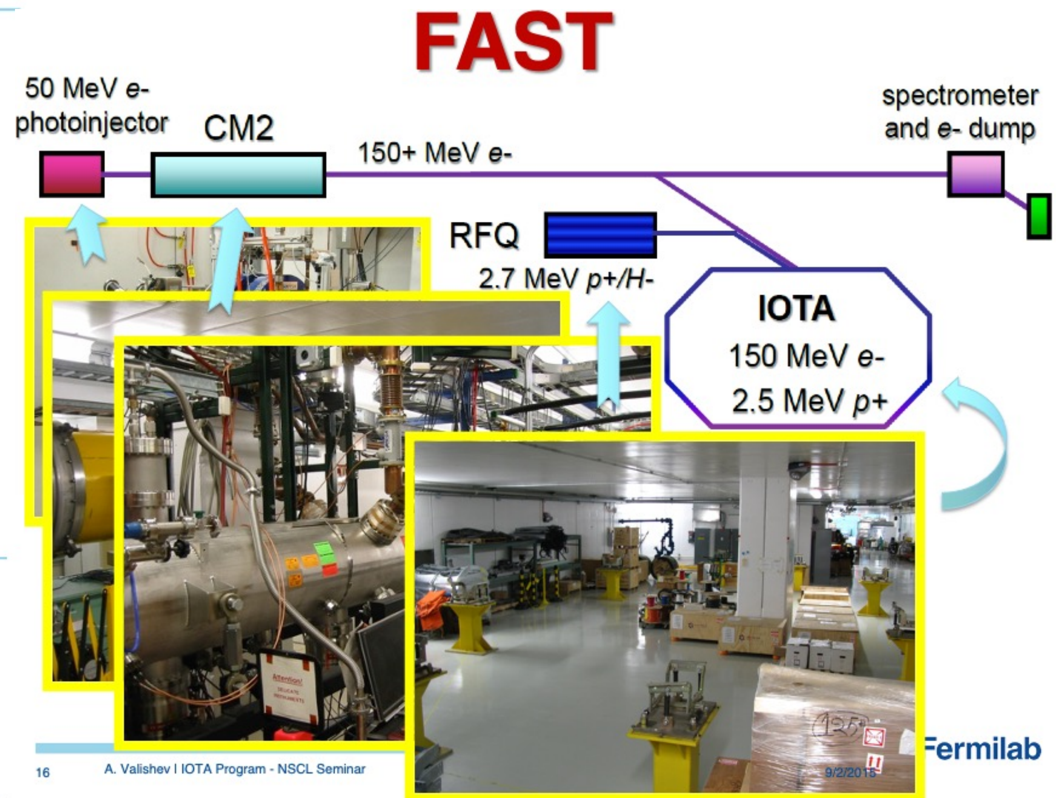
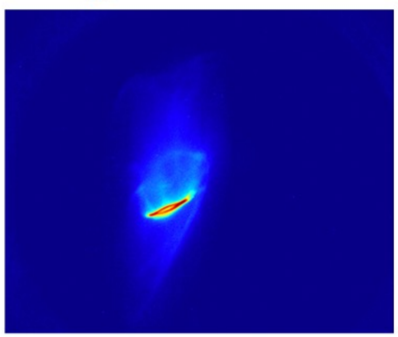
Experimental Beam Physics Program at Fermilab's IOTA Ring

Alexander Valishev
NSCL Seminar
2 September 2015



First Electrons Through Photoinjector!

- Sign-offs Wednesday, 25 March
- Electrons beyond the gun - Wednesday, 25 March
- Beam after CC2, towards end of line – Thursday, 26 March
- Electrons seen at low energy beam absorber (~20 MeV) – Friday morning, 27 March



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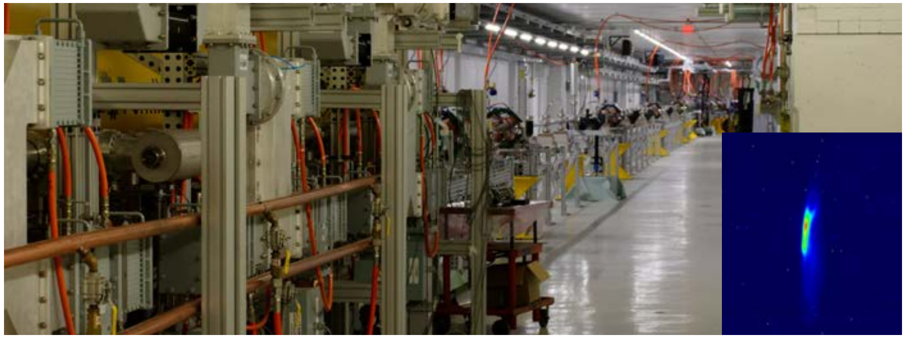
19 A. Valishev I IOTA Program - NSCL Seminar 9/2/2015

FAST SRF linac has successfully met design goals

- Commissioned to full design energy of **300 MeV**; ~90% up-time eff.
- World-record beam acc. by ILC-type CM: **>31.5MV/m** (~250MeV gain)
- Successful beam delivery to IOTA
- Active & expanding scientific program with new results in:
  - HOM excitation in SRF cavities & effects on beam emittance
  - Advanced beam diagnostics using synchrotron radiation
  - Machine learning algorithms for optimization of accelerator controls
  - 4D phase-space tomographic reconstruction of the beam
  - Flat-beam transformations of high-intensity magnetized beams



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IOP Institute of Physics
Published in partnership with: Deutsche Physikalische Gesellschaft and the Institute of Physics

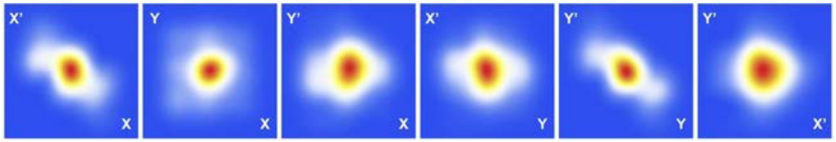
PAPER

Record high-gradient SRF beam acceleration at Fermilab

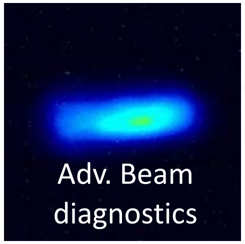
D Broemmelsiek, B Chase, D Edstrom, E Harms, J Leibfritz, S Nagaitsev, Y Pischalnikov, A Romanov, J Ruan, W Schappert, V Shiltsev, R Thurman-Keup and A Valishev
Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510, United States of America

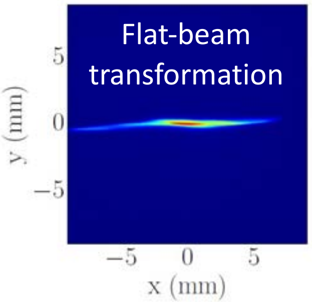
Submacropulse electron-beam dynamics correlated with higher-order modes in Tesla-type superconducting rf cavities

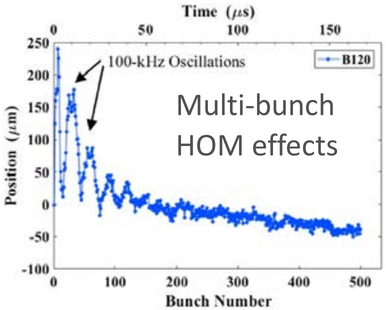
A. H. Lumpkin, R. Thurman-Keup, D. Edstrom, J. Ruan, N. Eddy, P. Prieto, O. Napoly, B. E. Carlsten, and K. Bishofberger
Phys. Rev. Accel. Beams **21**, 064401 – Published 4 June 2018



Tomographic reconstruction of 4D phase space







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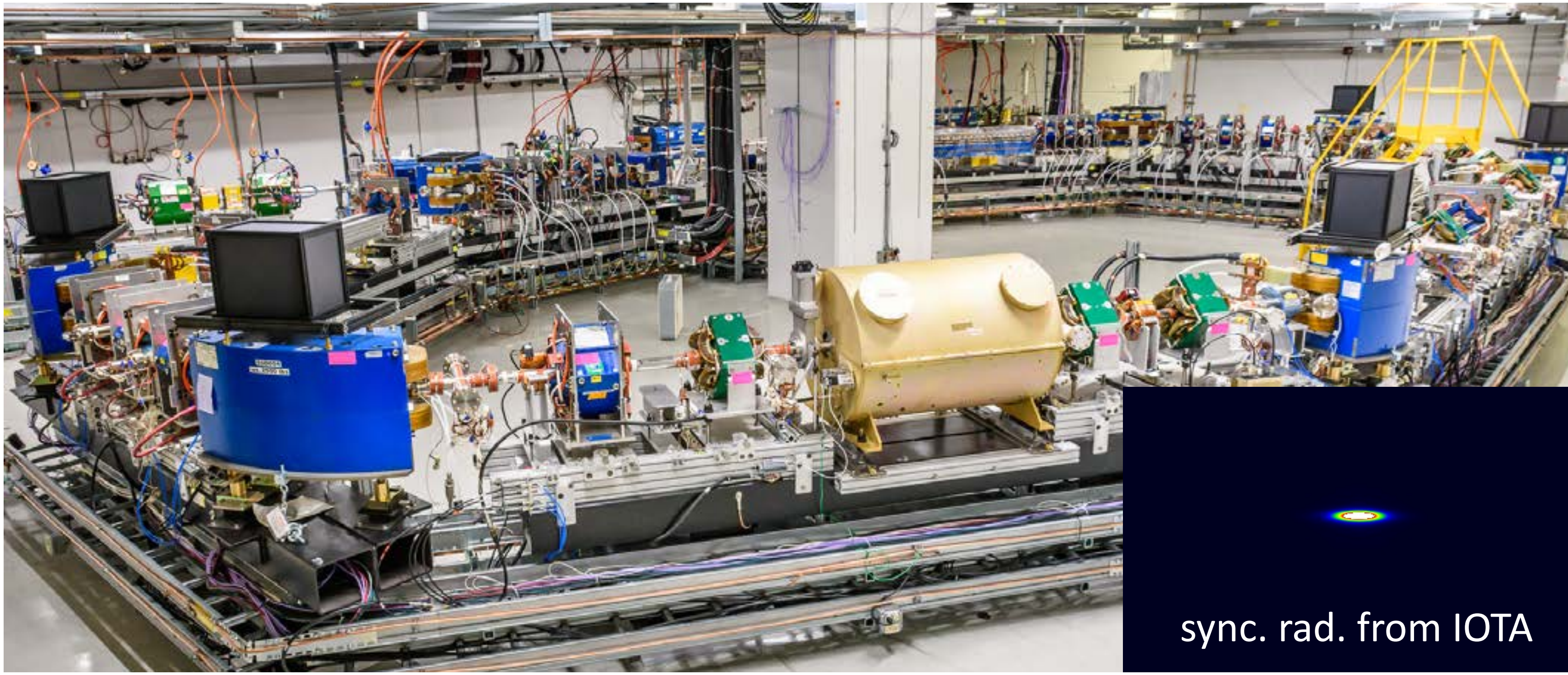
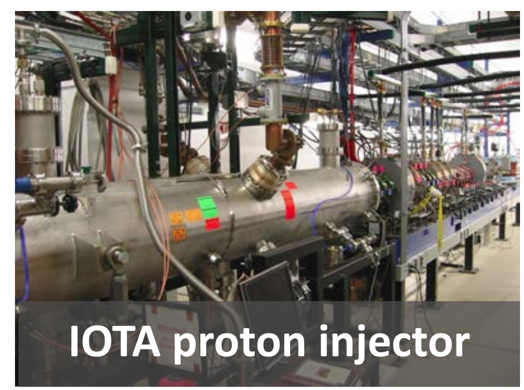
IOTA successfully constructed and commissioned



- Commissioned with electrons at 47 MeV and 100 MeV; design charge achieved ~100pC
- Proton injector being completed; available for start of proton science program in 2020



IOTA/FAST Strategic Goals

- **Complete the FAST facility construction and commissioning**
  1. Assemble and commission the IOTA proton injector
  2. Commission IOTA with proton beams
  3. Complete the commissioning of FAST SRF linac
- **Plan and execute the experimental program at IOTA and in the injector machines**
  1. Conduct high-priority research in IOTA
  2. Develop IOTA experimental capabilities
  3. Allow concurrent experiments in IOTA and FAST as afforded by resources
- **Expand the IOTA/FAST Collaboration**
  1. Establish efficient facility operations
  2. Develop the collaborative proposal-driven framework
  3. Establish FAST as training center

Quick Introduction to Beam Physics in Circular Machines

Physics of *Circular* Accelerators

Historically, the development of rings was about two things

1. Beam Energy
   - Mostly related to technology of magnets
   - Related aspects
     - Acceleration / RF power
     - Machine protection / collimation

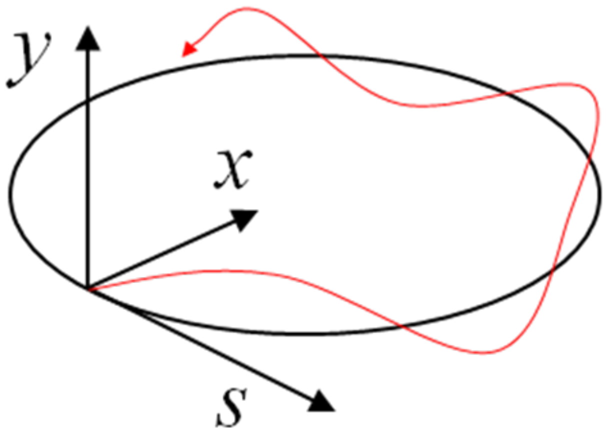
$$R = \frac{pc}{eB}$$

$$\frac{2\pi}{C}\frac{pc}{eB} = 0.66$$

packing factor

2. Beam intensity and brightness
   - Luminosity for colliders
   - Number of particles for fixed target experiments
   - Brightness for light sources
   - Cost of construction

Beam Focusing in Accelerators



$$H = c\left[m^2c^2 + \left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2\right]^{\frac{1}{2}} \qquad H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

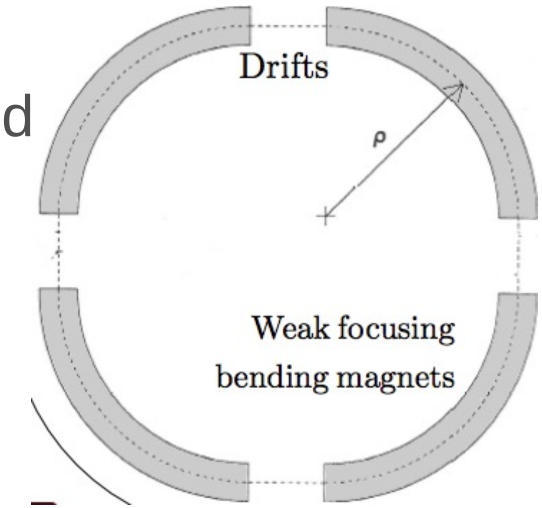
$$K_{x,y}(s+C) = K_{x,y}(s)$$

- Equilibrium orbit – closed circular trajectory of the particle with ideally matched energy
- Beam – particles which have a spread in coordinates, momenta (both transverse x,y) and longitudinal (s)
  - Beam emittance – volume in phase space
- Need to contain beam particles
  - Focusing with Lorentz force from magnets and accelerating structures
    - Longitudinal focusing – synchrotron principle (Veksler 1944, McMillan 1945)

Transverse Beam Focusing – Weak Focusing

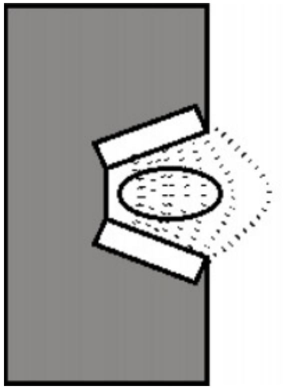
Weak focusing (betatron, early synchrotrons)

- Bending magnet does the focusing
- Azimuthally uniform transverse magnetic field
- To satisfy the Maxwell equations



$$x'' + (1-n)x = 0$$
$$y'' + n\,y = 0$$

- Stability criterion $$0 < -\frac{\rho}{B_0}\frac{\partial B_y}{\partial x} < 1$$
- Betatron tune and betatron function



$$x = \sqrt{J_x \beta_x}\cos\left(Q_x \frac{s}{\rho}\right) \quad Q_x = \sqrt{1-n} \quad \beta_x = \frac{\rho}{\sqrt{1-n}}$$

- RMS Beam size $\sigma_x = \sqrt{\varepsilon_x \beta_x}$
  - Beta-function – determined by focusing properties
  - Emittance – intrinsic beam property

Limitations of Weak Beam Focusing

- No room for insertion devices – all circumference occupied by gradient magnet
- Cannot achieve small beam size
  - Limited beam brightness
  - Requires huge beam aperture = cost

$$\beta_x = \frac{\rho}{\sqrt{1-n}} = \frac{\rho}{Q_x}$$

Dubna Synchrophasotron 1957

- E=10 GeV, Protons
- ρ = 30 m
- Vacuum chamber 2 × 0.36 m
- Magnet weight 36,000 ton

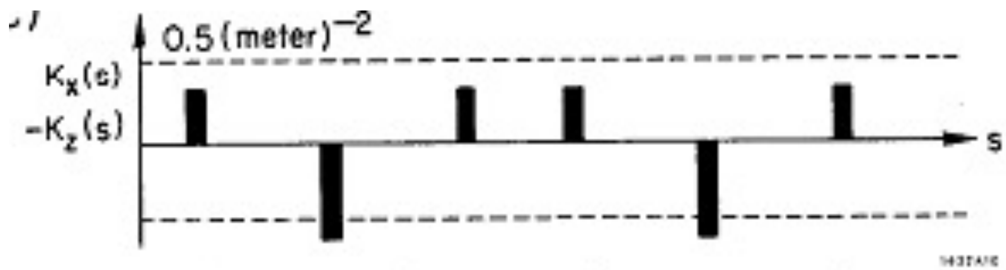
Transverse Beam Focusing – Strong Focusing

- a.k.a alternating-gradient focusing
  - N.Christofilos (1949, unpublished);
  - Courant, Livingston, Snyder (1952)
- 28GeV CERN PS (1958), 30GeV BNL AGS (1960)

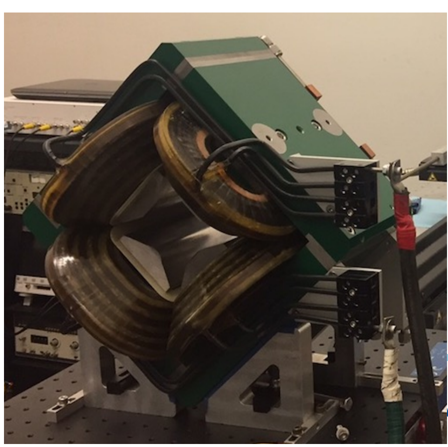
$$\begin{cases} x'' + K_x(s)x = 0 \\ y'' + K_y(s)y = 0 \end{cases}$$

$$K_{x,y}(s+C) = K_{x,y}(s)$$

piecewise constant alternating-sign functions



--Magnet lattice and focussing functions in the normal cells of a particular guide field.



- Quadrupole is focusing in one direction and defocusing in cross-plane $\varphi(x,y) \propto x^2 - y^2$
- A combination of quadrupoles with alternating signs can be made stable in both x and y

Strong Focusing - Features

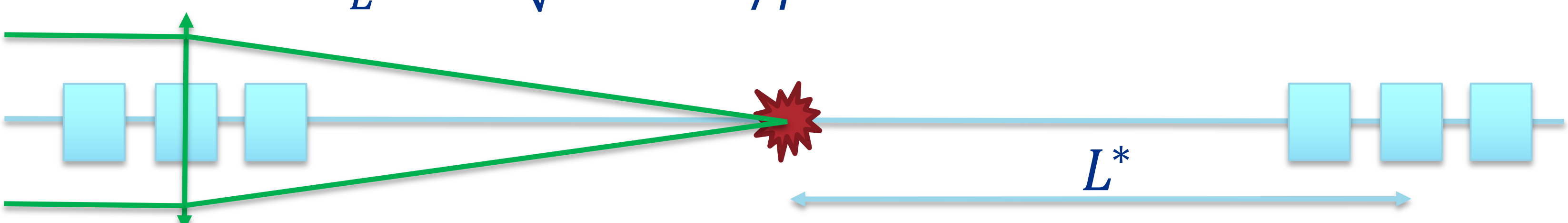
- Betatron tune can be made large
  - e.g. Tevatron Q=20.58, LHC Q=64.31
- Beta-function and consequently beam size can be small
- Beam size varies along the ring – there are maxima and minima

$$x'' + K_x(s)x = 0 \quad x = \sqrt{J_x\beta_x(s)}\cos\phi_x(s) \qquad (\sqrt{\beta})'' + K(s)\sqrt{\beta} = \frac{1}{\sqrt{\beta}^3}$$

$$y'' + K_y(s)y = 0$$

- For example, in the final focus of a collider $\beta(s) = \beta^* + \frac{s^2}{\beta^*}$
- For LHC $\sigma^* = \sqrt{\varepsilon\beta^*} \approx 17\mu m$

$$\sigma_L = \sigma^*\sqrt{1 + L^{*2}/\beta^{*2}} \approx 2\, mm$$



Strong Focusing - Limitations

- The key principle of everything we considered so far – linear focusing

$$H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

- What about higher order terms?
  - Imperfections in magnet construction
  - Chromatic aberrations ∝ quadrupole gradient

$$F \propto \frac{e}{(p_0 + \Delta p)c} \frac{\partial B_y}{\partial x} x$$

  - Coulomb self-interaction inside beams
  - E/M interaction of beam with environment (image charges, etc)
  - E/M interaction between beams
  - Intentionally introduced multipole magnets (e.g. sextupoles to correct chromaticity)
- All are aberrations to the initially decoupled system of two linear oscillators
  - Since the 60ies, thousands of papers on mitigation
  - Accelerator physics on crossroads of plasma, nonlinear dynamics, etc.

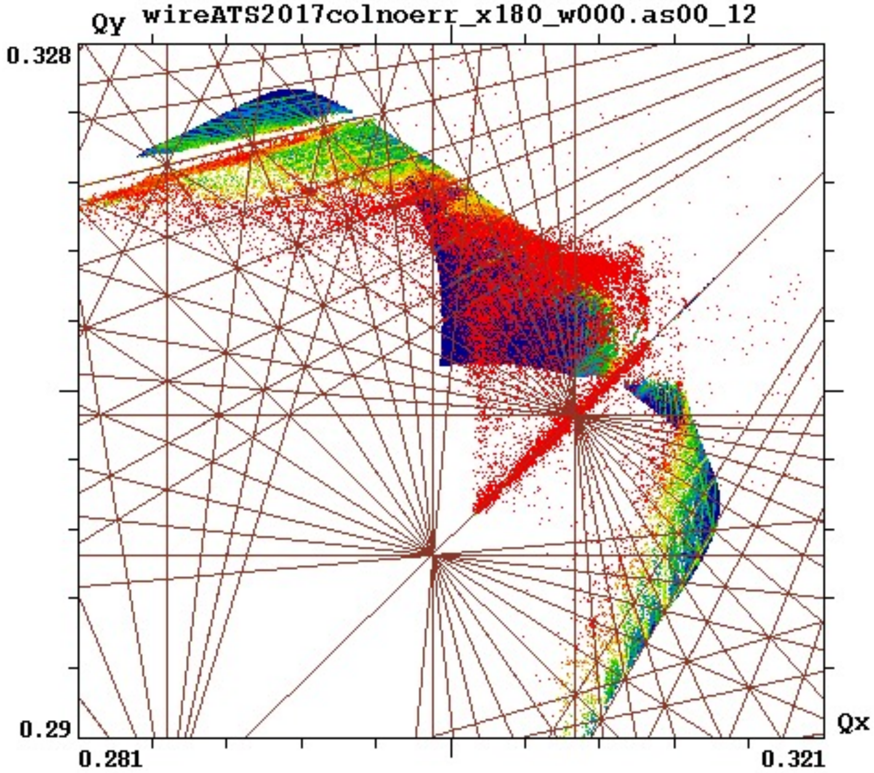
Aberrations of Linear Focusing

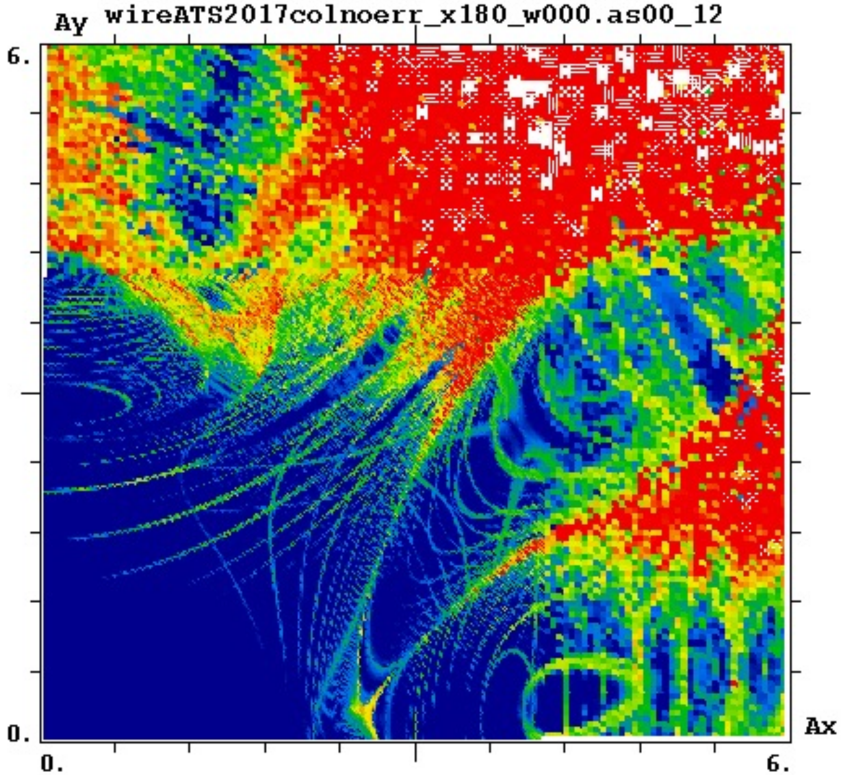
$$x'' + K_x(s)x = S(s)x^2 + O(s)x^3 + \cdots$$

- Nonlinearities result in dependence of oscillation frequency (tune) on amplitude
- Explicit time-dependence of multipole coefficients results in resonances
- Coupling between x and y further complicates the dynamics
- Ultimately, chaos and loss of stability
  - Beam quality degradation (blow-up)
  - Particle loss from accelerator

Example of Single Particle Limitations – HL-LHC

- Nonlinearity caused by E/M interactions between colliding beams (also referred to as beam-beam)
- Note that frequency spread ∝ beam brightness
  - Characteristic spread 0.02 for LHC





- Frequency Map Analysis invented by J.Lascar for analysis of motion of Solar system

Collective Instabilities

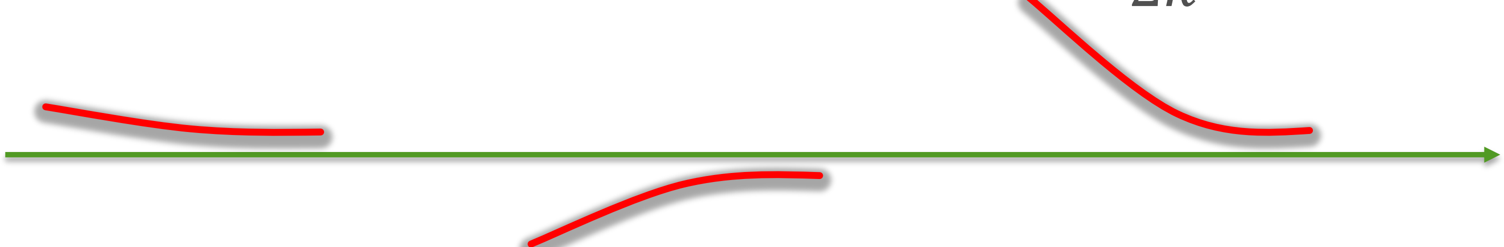
In addition to the single-particle chaos, the beam can become unstable as a whole if resonantly excited by external field or via self-interaction through environment

- Simple example: beam breakup instability
  - Two particles – leading (head) particle and trailing (tail) particle
  - Head particle motion

$$x_1'' + k^2 x_1 = 0, x_1 = a_1 \cos ks$$

  - Head particle through interaction with environment leaves E/M wake acting on tail particle

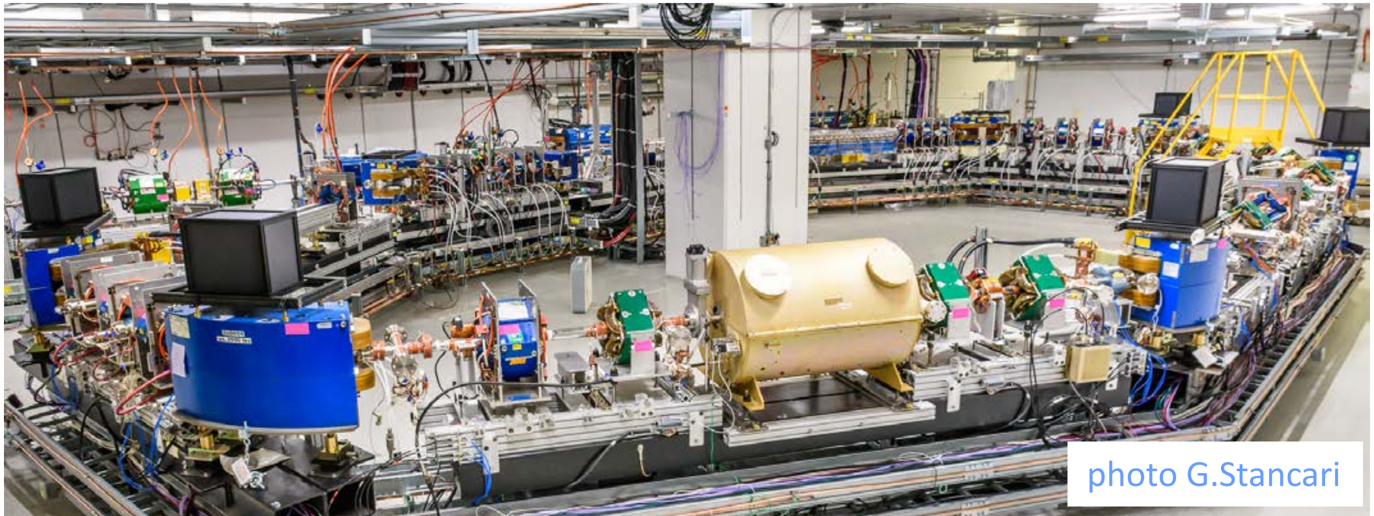
$$x_2'' + k^2 x_2 = W x_1, x_2 = a_2 \cos ks + \frac{W a_1 s}{2k} \sin ks$$



Intermediate Summary

- Historical development of circular accelerators saw a major paradigm change – from weak to strong focusing
  - Opened way to orders of magnitude gains in energy and brightness
- All machines since 1960s are built around concept of linear focusing
  - Nonlinear aberrations ruin beam quality and particle stability
  - Nonlinear aberrations are intrinsic to charged particle beams and scale with beam brightness
  - Nonlinearities must be introduced to maintain beam's own immunity to coherent instabilities through Landau damping
- Time for a major paradigm change to leave the linear focusing
  - Let us build machines that are nonlinear by design but stable (like Solar system) ➜ IOTA

Integrable Optics Test Accelerator



- Easily reconfigurable
  - Support many experiments
- Flexible
  - Protons or electrons
- Small
  - Low cost of operation

Parameters if IOTA operation with electrons	
Momentum	50-150 MeV
Perimeter	40 m
RF voltage	300 V
RF frequency	30 MHz
3 Experimental sections	2x180 cm, 1x150 cm
Main vacuum chamber aperture (R)	25 mm
Lambertson and kickers aperture (R)	20 mm
Electrons bunch	10^9 e, 160 pC, 1.2 mA

Accelerator science at IOTA/FAST

I. **IOTA Ring** – **priority research focused on high-intensity *proton* rings**, driven mostly by Fermilab

- Nonlinear Integrable Optics
- Optical Stochastic Cooling
- Space-charge compensation
- Suppression of coherent instabilities

Near-term, high-impact science with electrons (Nonlinear Integrable Optics, Optical Stochastic Cooling)

High-impact science with protons (Space-charge compensation, Suppression of coherent instabilities)

II. **FAST e- Linac and IOTA** – **opportunities concurrent with main IOTA program**, driven mostly by external partners

- Radiation generation
- High average current experiments (ILC-like electron beams)
- Collaboration with the FACET-II team
- EIC R&D
- Quantum science: single and few-electron experiments

Research focused on beam intensity in rings

Key components of this research topic are

- **Suppression of coherent instabilities via Landau damping**
  - Can be studied with *both* **electrons and protons**
  - Possible technologies
    - Nonlinear Integrable Optics
    - Electron Lenses

COLLIDING BEAMS: PRESENT STATUS; AND THE SLAC PROJECT*

B. Richter

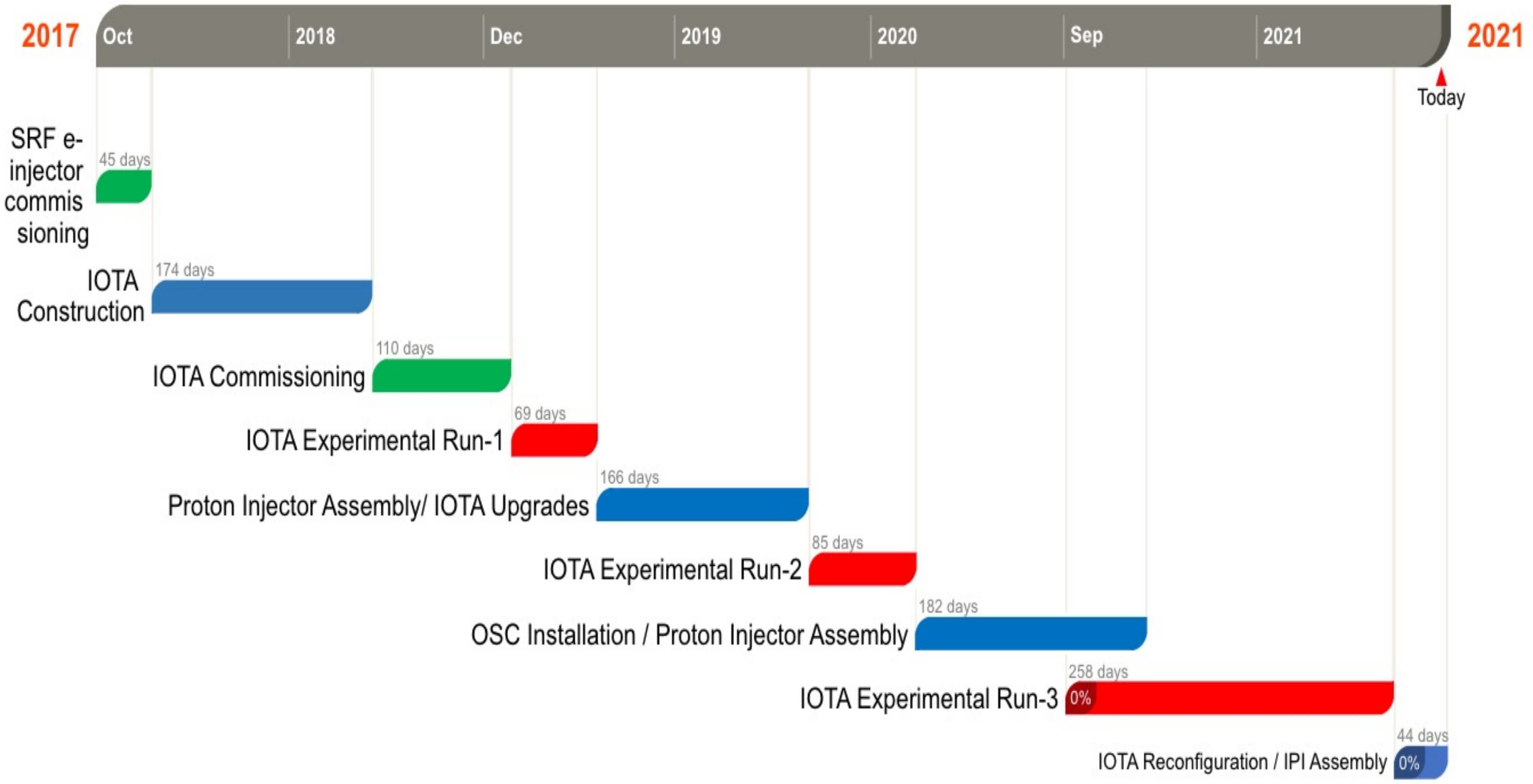
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

The discovery in the early '60's at the Princeton-Stanford ring of what was thought to be the resistive wall instability brought the realization that circular accelerators are fundamentally unstable devices because of the interaction of the beam with its environment. Stability is achieved only through Landau damping and/or some external damping system.

- **Mitigation of space-charge effects**
  - **Requires proton beam in IOTA**
  - Possible technologies
    - Nonlinear Integrable Optics
    - Electron Lenses
    - Electron columns

IOTA/FAST timeline

Experimental runs interleaved with periods of construction, maintenance, and experiment assembly



Research in IOTA/FAST experimental run 2

Broad program: in all 9 experiments took data over 60 shifts and produced relevant results. Engagement of outside collaborators (CERN, SLAC, Jlab, Uchicago, NIU) and 6 graduate students.

1. Nonlinear Optics Measurements and Correction in the IOTA Ring	PI M.Hofer (R.Tomas), CERN
2. Study of Intrabeam Scattering	V.Lebedev, FNAL
3. Nonlinear Integrable Optics in Run 2	A.Valishev, FNAL
4. Angular Measurement of Photons from Undulator Radiation in IOTA's Single Electron Mode	E.Angelico (H. Frisch/S. Nagaisev), UChicago
5. Measurement of Spontaneous Undulator Radiation Statistics Generated by a Single Electron	S.Nagaitsev, I. Lobach, FNAL/UChicago
6. Fluctuations in undulator radiation	I.Lobach (S. Nagaitsev/G. Stancari), UChicago
7. Instability thresholds and integrable optics	N.Eddy, FNAL
8. Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities	A.Lumpkin, FNAL
9. Generation, Transport and Diagnostics of High-charge Magnetized Beams	P.Piot, NIU/ANL

Nonlinear Integrable Optics

Nonlinear Integrable Optics in IOTA

We aim to build an optical focusing system that

a. Is strongly nonlinear = strong dependence of oscillation frequency on amplitude
b. Is integrable and stable
c. Can be realized with magnetic fields in vacuum

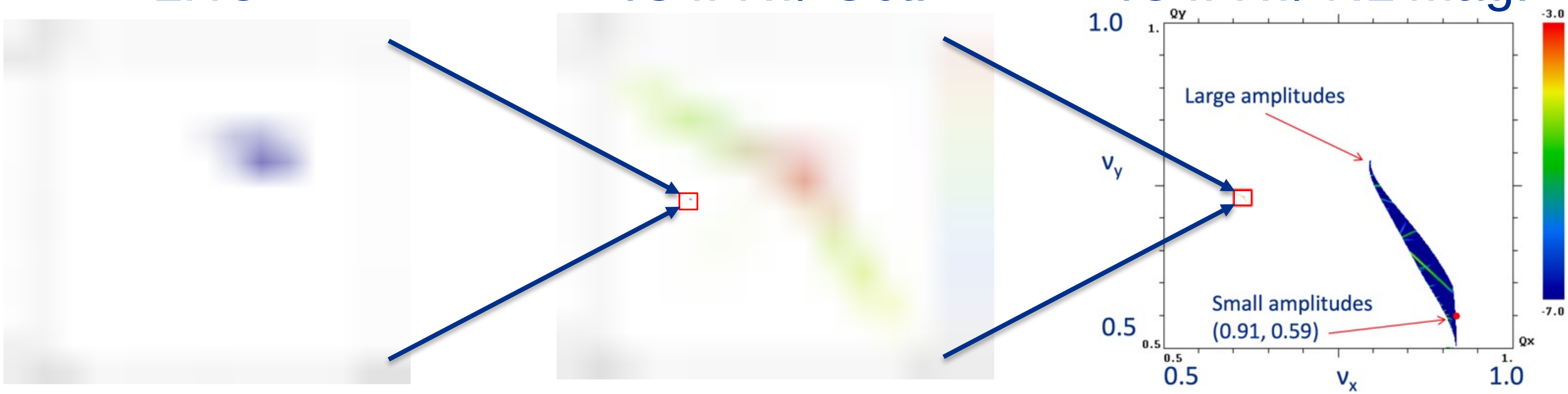
Goals

1. Experimentally demonstrate viability of theoretical concepts
2. Establish limits of applicability
   - Are requirements to implementation tolerances supported by present-day technology?
3. Develop practical solutions for circular accelerators pushing the envelope in beam brightness without significant cost increase

NIO could yield important benefits for future HEP machines

- **Reduced chaos in single-particle motion:** e.g helpful for space-charge suppression
- **Strong immunity to collective instabilities via Landau damping:** provides for higher beam current and brightness
- **Low cost:** brighter beams produce a cascade of cost savings throughout the design, engineering and construction of accelerators

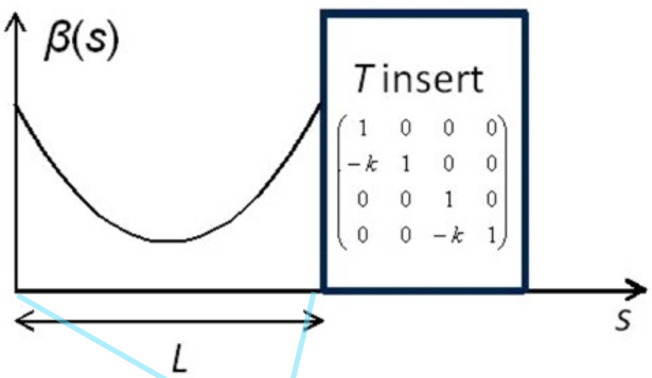
LHC | IOTA w/ Oct. | IOTA w/ NL mag.

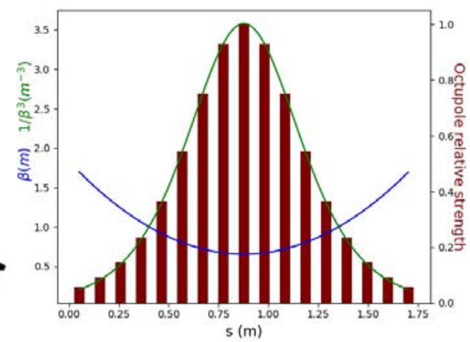


ΔQ = 0.001 | **ΔQ = 0.025** | **ΔQ = 0.25**

Fig. of merit is “tune spread” (ΔQ): the spread in oscillation freq. for beam particles

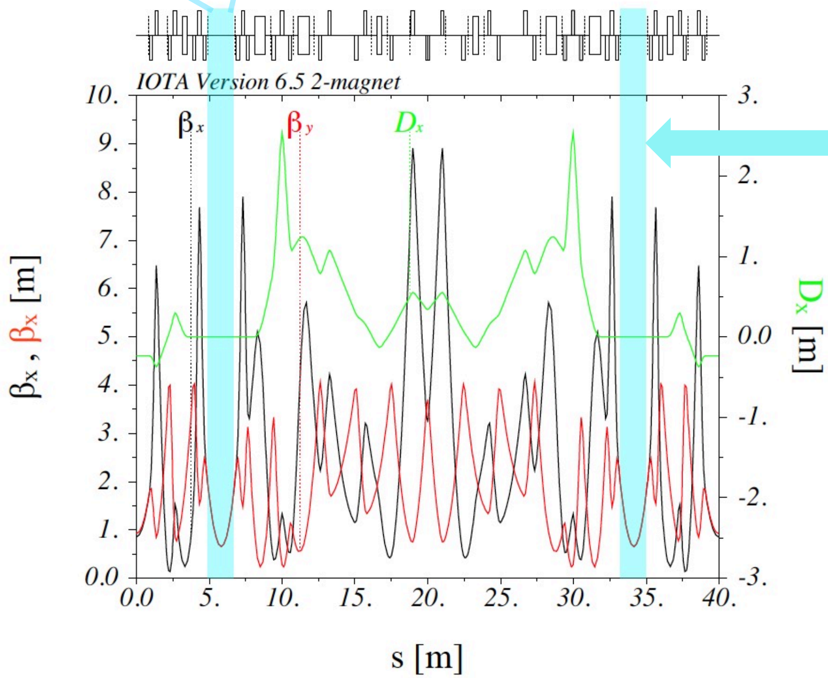
Implementation of NIO in IOTA

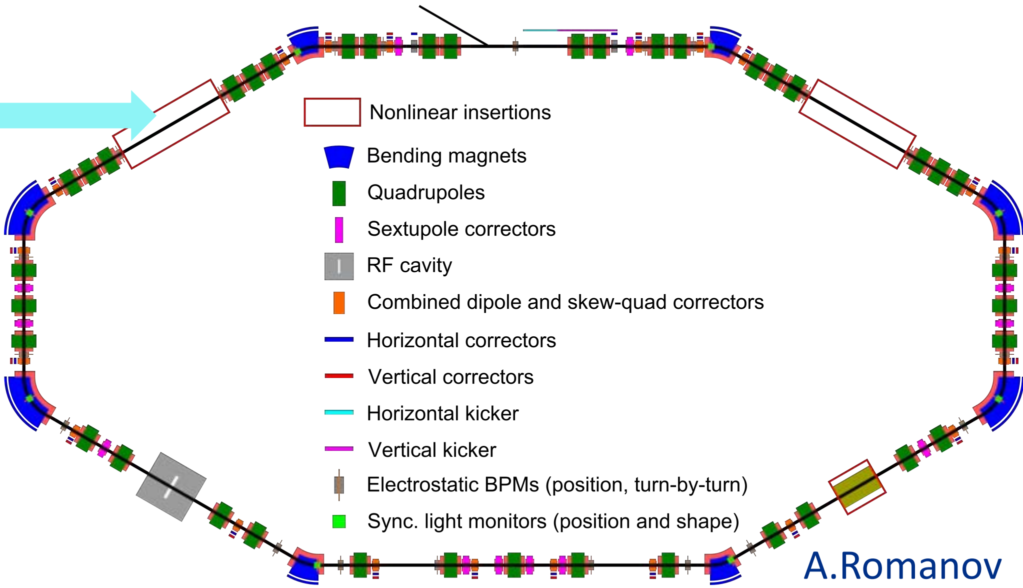




Practical requirements:

- Round axially-symmetric linear lattice (FOFO)
  - $2\pi \times n$ phase advance
- Drift with $\beta_x=\beta_y$, no dispersion



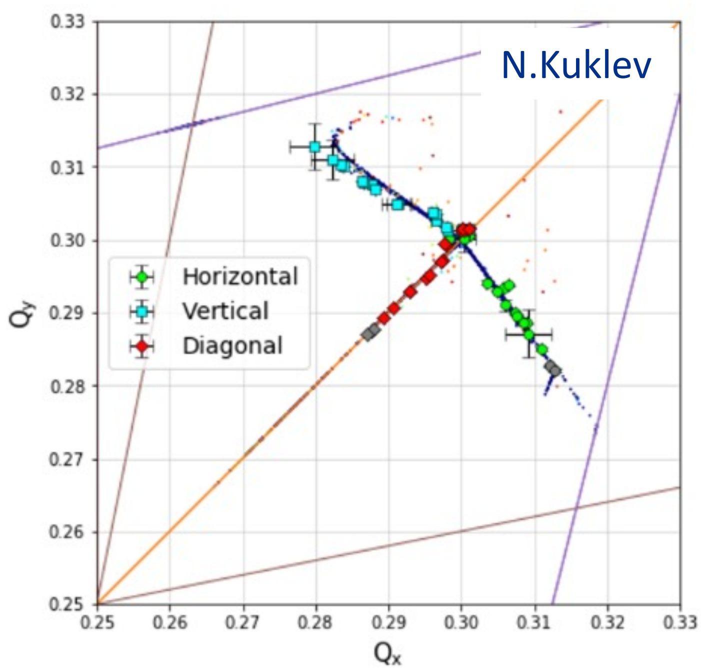


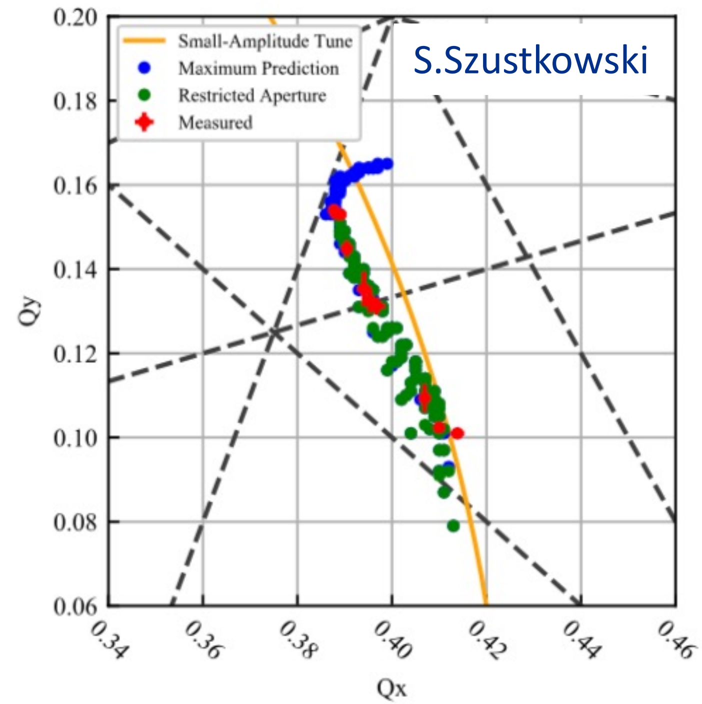
A.Romanov

NIO results – amplitude-dependent tune shift

Performance close to maximum prediction achieved for two types of NIO implemented in IOTA

- ΔQ =0.04 for quasi-integrable system implemented with octupoles
- ΔQ =0.08 for NIO with 2 invariants of motion

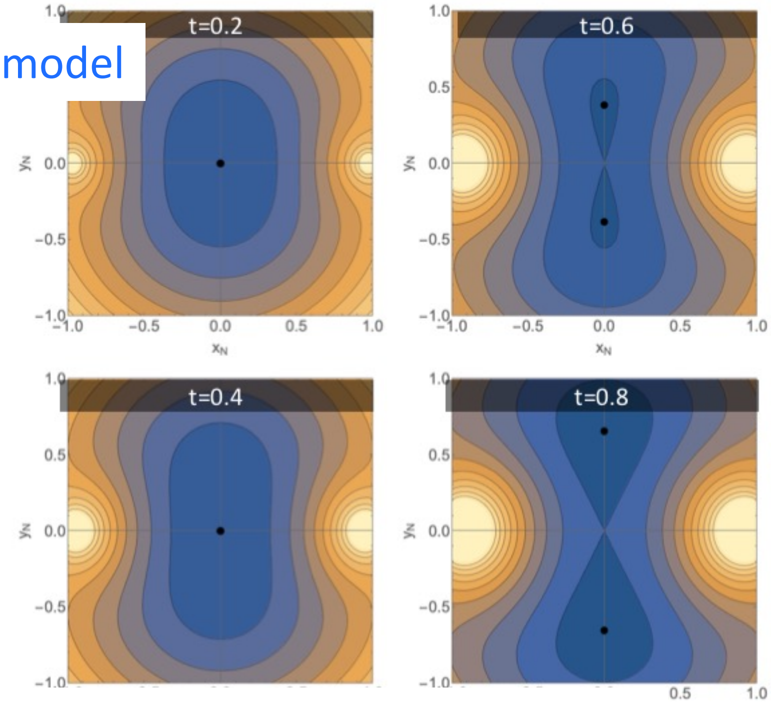




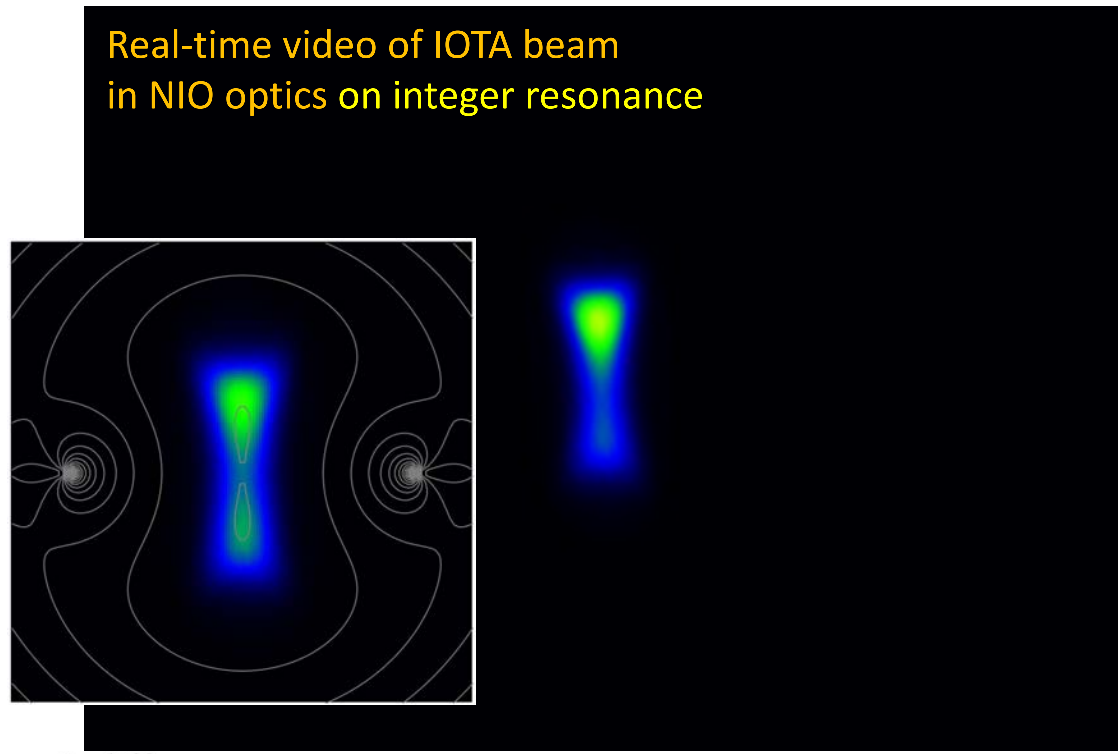
Fermilab

Phase-space topology, beam on integer resonance!

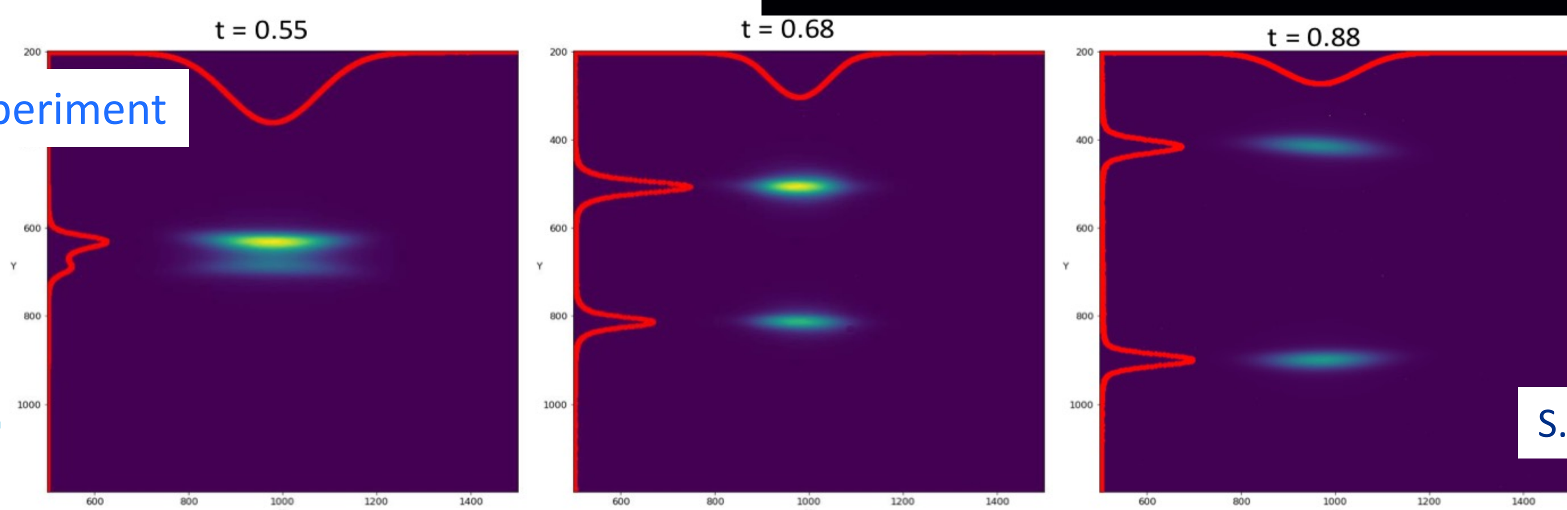
model



Phys. Rev. Accel. Beams **23**, 064002 (2020)



experiment



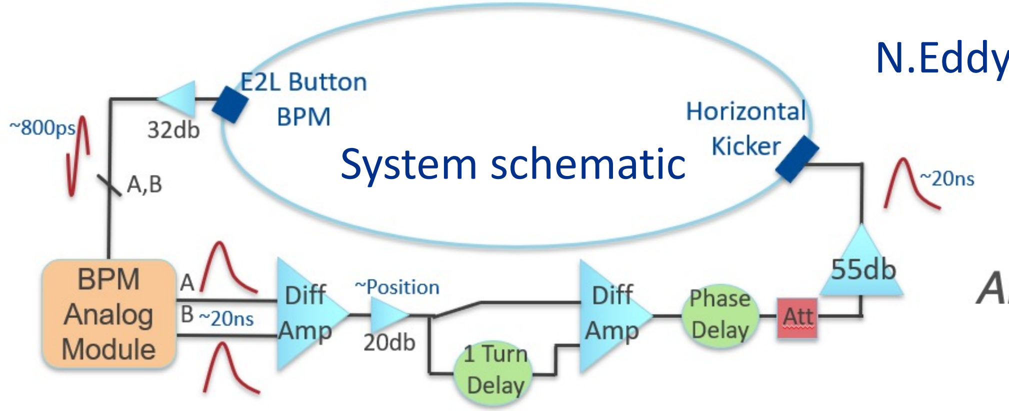
S.Szustkowski

Practical benefit of NIO – Improvement of coherent stability via Landau damping

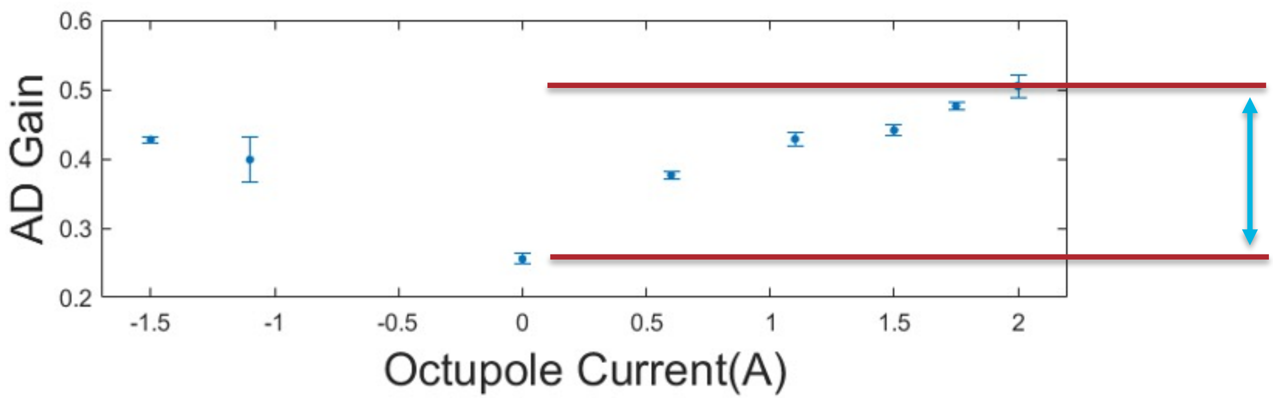
Experiment:

- Artificially induce controlled instability with feedback system
- Study the effect of NIO on instability threshold

N.Eddy



$$AD\ Gain = \frac{10^{-\frac{atten}{20}} * Ibeam}{\sigma_z \sqrt{2\pi}}$$



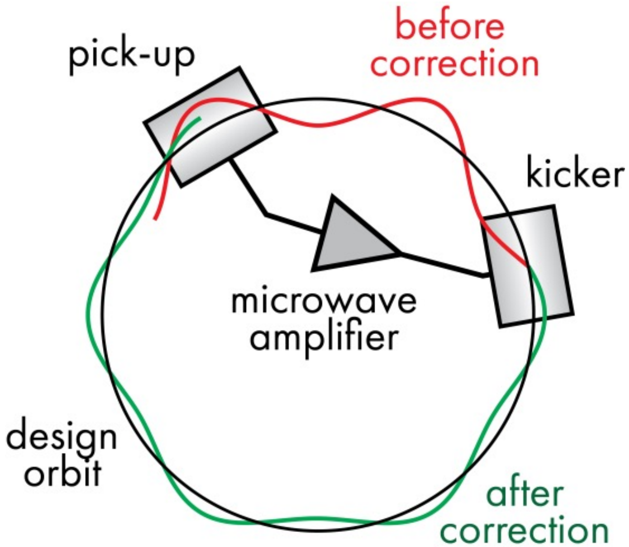
2x increase of stability threshold !!!

Research in IOTA/FAST Experimental Run 3

Unlike Run-2, the program of Run-3 was focused on OSC. Beam time and resources were allocated to small number of other experiments.

1. Optical Stochastic Cooling Experiment: Apparatus Commissioning	PI J.Jarvs, FNAL
2. Optical Stochastic Cooling Experiment: Demonstration Experiment	J.Jarvis, FNAL
3. Optical Stochastic Cooling Experiment: Systematic Studies of OSC Concepts	J.Jarvis, FNAL
5. Measurement of Spontaneous Undulator Radiation Statistics Generated by a Single Electron	S.Nagaitsev, I. Lobach, FNAL/UChicago
6. Fluctuations in undulator radiation	I.Lobach (S. Nagaitsev/G. Stancari), UChicago
8. Investigations of Long-range and Short-range Wakefield Effects on Beam Dynamics in TESLA-type Superconducting Cavities	A.Lumpkin, FNAL
9. Elegant- and ACL-Based Trajectory Tuning for the FAST Facility	J.Ruan, FNAL

Beam cooling has been essential for colliders



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

1984 Nobel: van der Meer/Rubbia

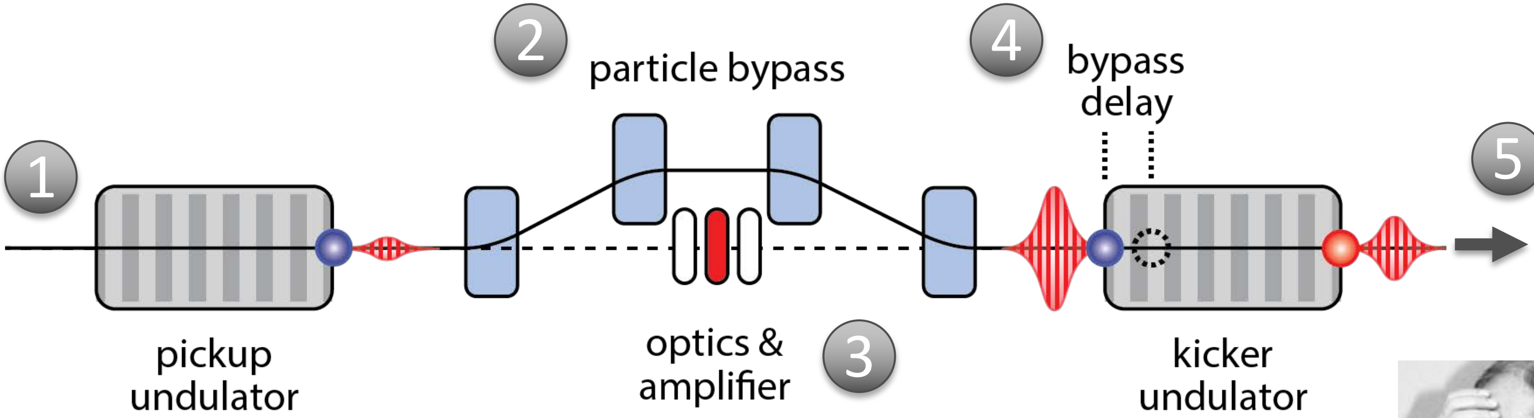
Simon van der Meer (COOL 1993 workshop, Montreux):

"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**."

Optical Stochastic Cooling extends the SC principle to optical bandwidth



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

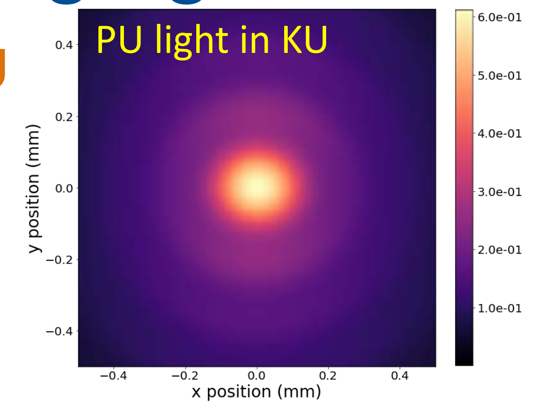
10^3 – 10^4 increase in cooling rate over stochastic cooling (~10s of THz BW vs few GHz)

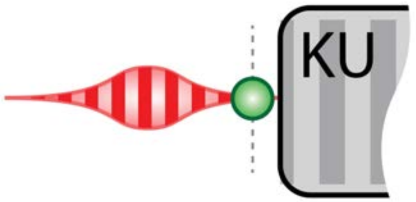
A.A.Mikhailichkenko, M.S. Zolotorev, Phys. Rev. Lett. 71 (25), p. 4146 (1993)

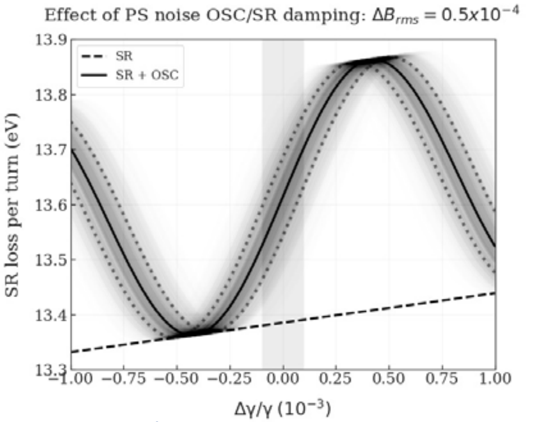
M. S. Zolotorev, A. A. Zholents, Phys. Rev. E 50 (4), p. 3087 (1994)

What makes ("simple") OSC challenging?

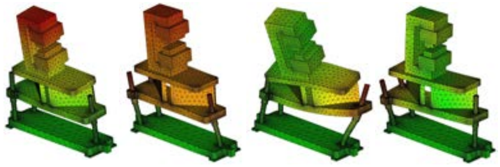
1. Beam and PU light must overlap through the KU
   - The undulator light is **~200 μm** wide
   - Want angle between light and beam at < **~0.1 mrad**
2. Beam and PU light must arrive ~simultaneously for maximum effect
   - Absolute timing should be better than **~0.3 fs**
   - The entire delay system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

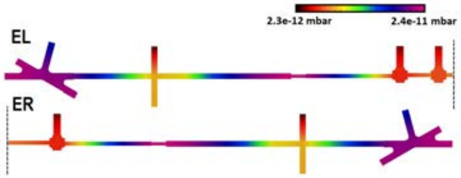






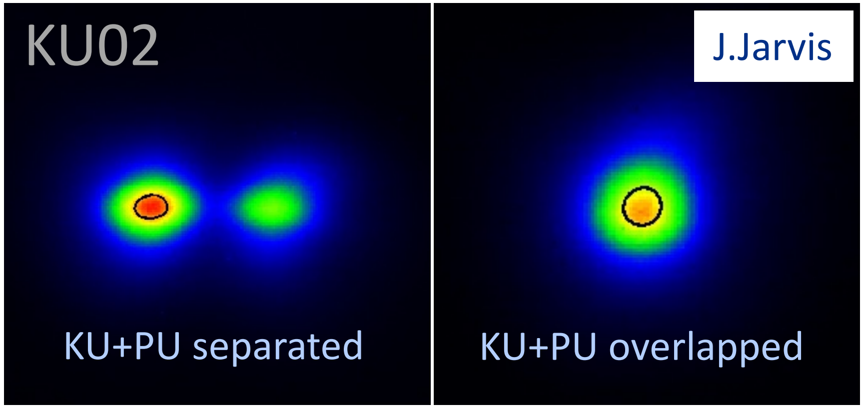
J.Jarvis

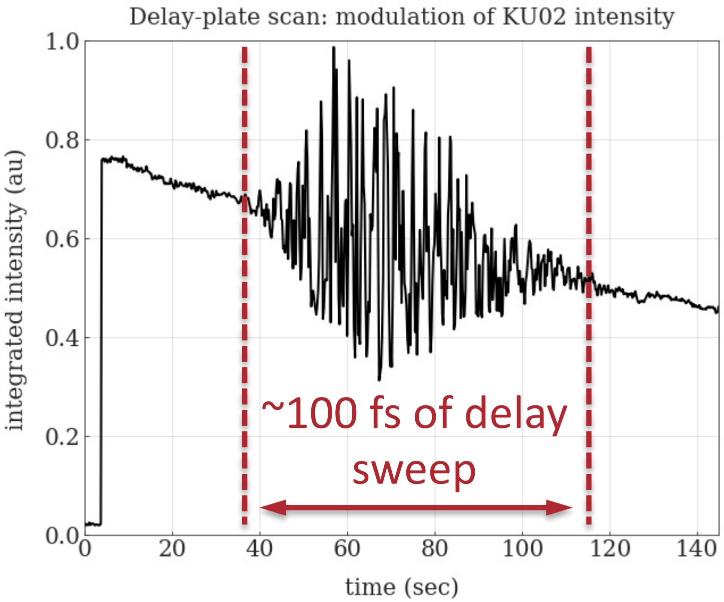




April 20, 2021: first interference at full undulator power in IOTA

- The undulators were brought to their nominal, high-power setting ($\lambda = 950$ nm)
- The in-vacuum light optics and specially designed 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….

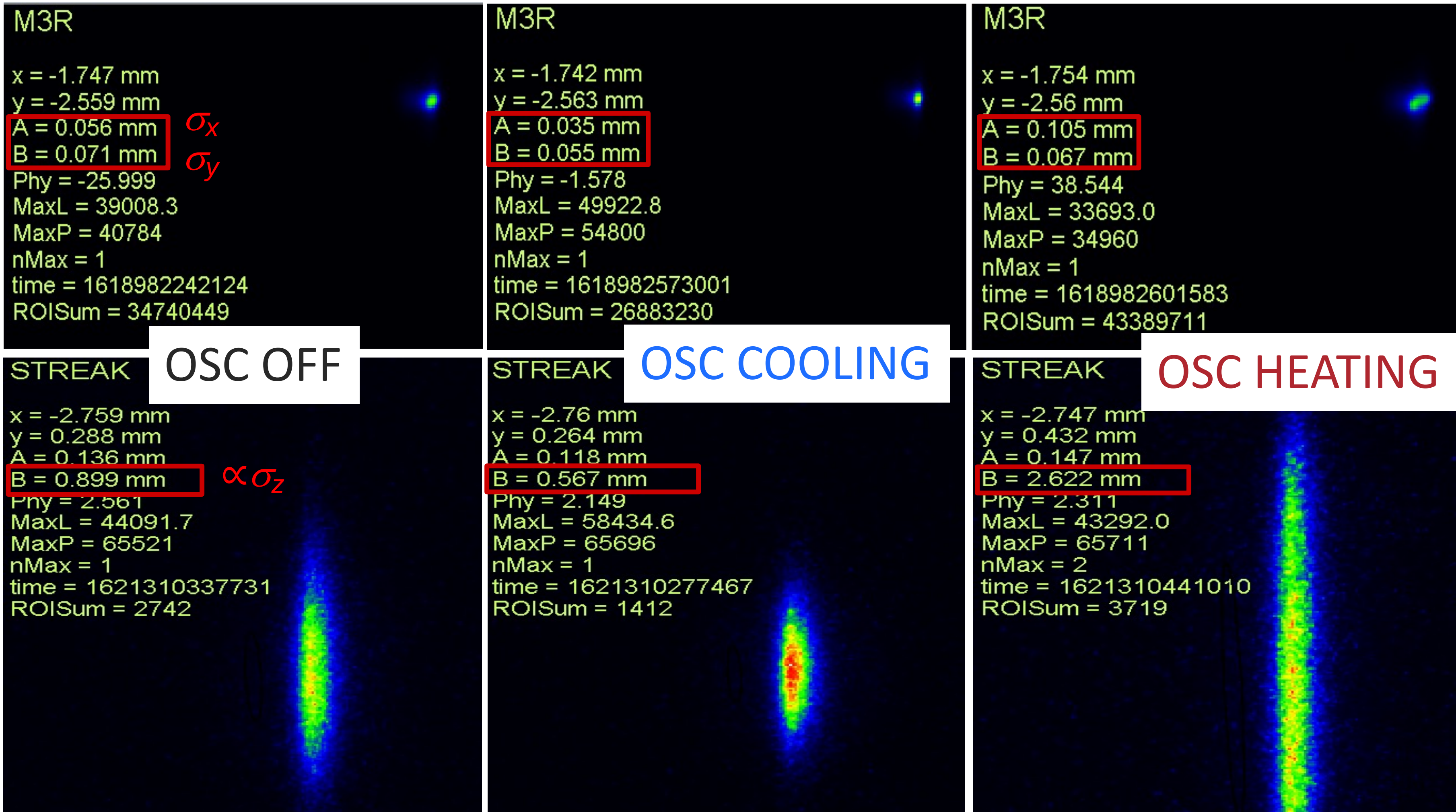




Delay scan through entire wavepacket-overlap region

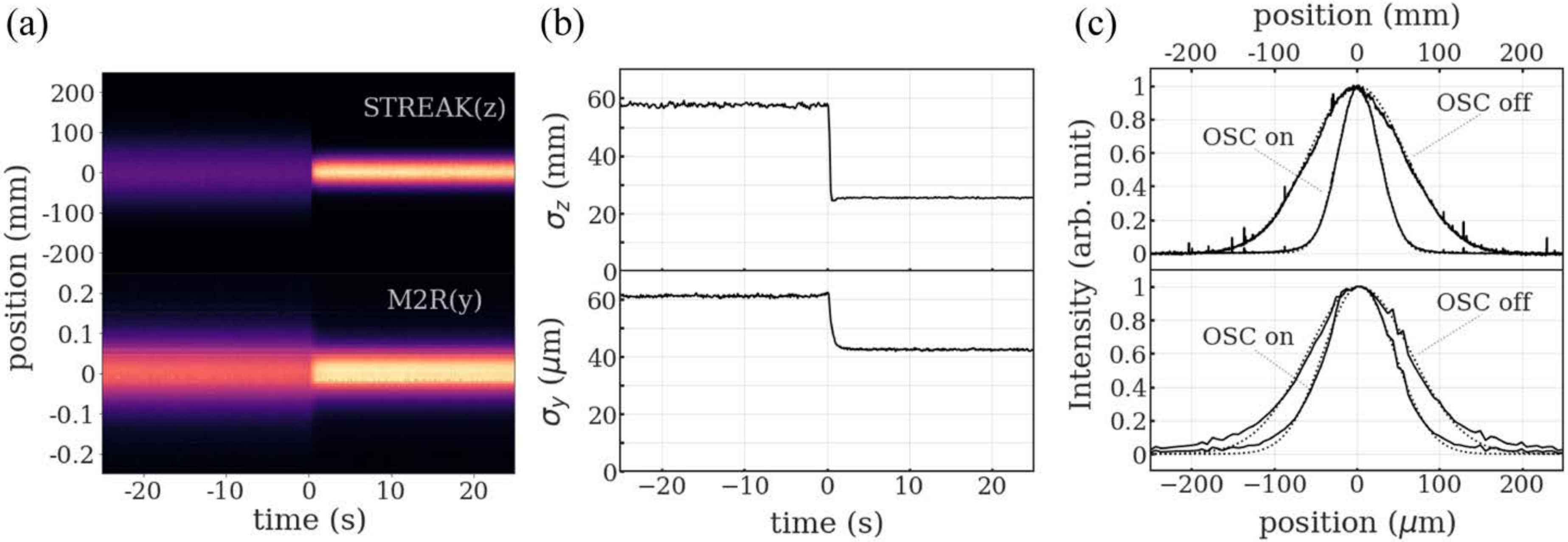
6D cooling/heating relative to no-OSC case

- **No significant beam loss has been observed during cooling or heating**
- Changing the delay system by a half wavelength inverts the cooling/heating zones



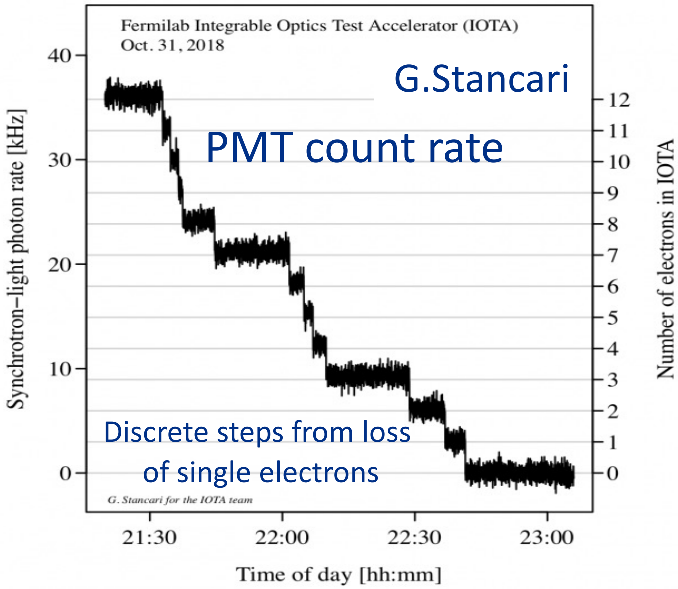
J.Jarvis

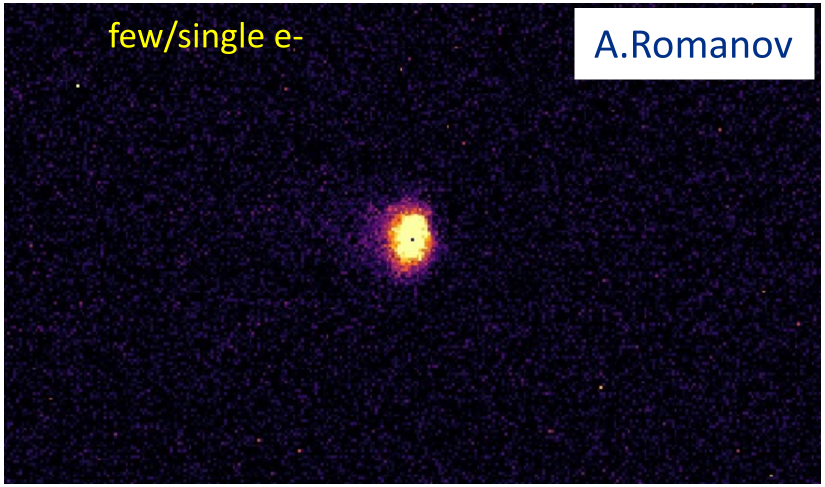
6D cooling relative to no-OSC case



Unique opportunities in quantum science

- We have demonstrated storage of a single relativistic electron for long periods of time (>10s of minutes).
- OSC enables unique, closed-loop studies of a particle interacting with its own radiation
- Collaboration with Berkeley on QM exp/theory for single-particle OSC
- New capabilities expected to come online at IOTA: High-speed, spatially resolved, single-photon detection (LAPPD); quantum-optical measurement systems, e.g. HOM interferometry



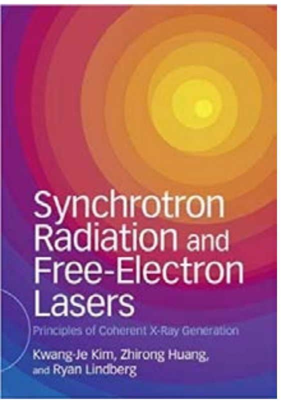


A.Romanov THXB01

Studies of statistical properties of undulator radiation

- Two collaborative experiments
  - Many - 10^9 electrons
  - Single electron

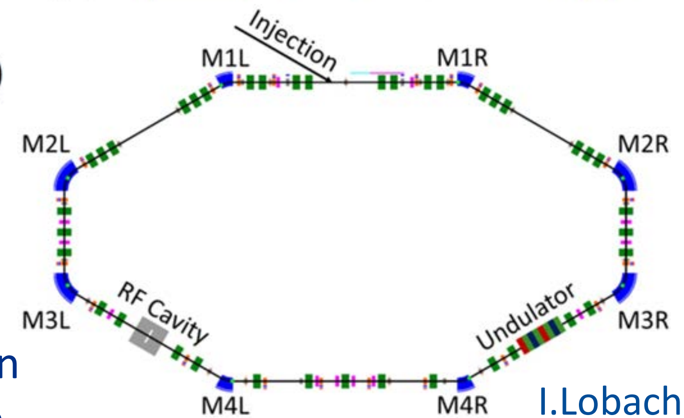
$$\frac{1}{M} \propto (1 - 1/n_e)$$



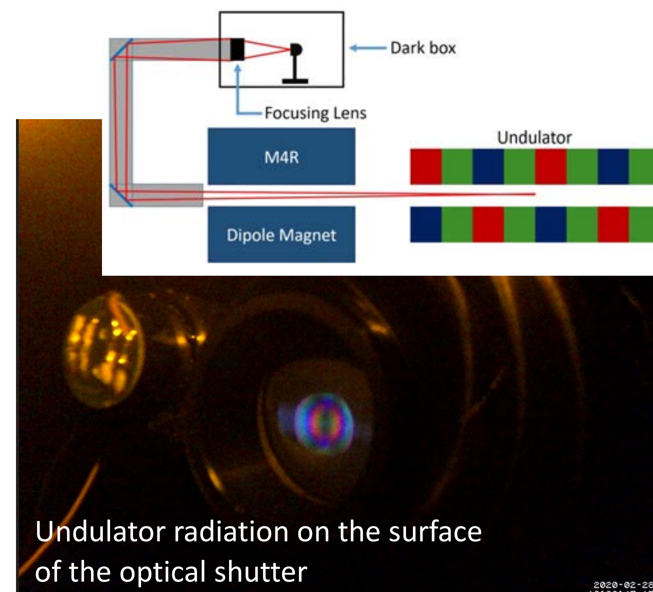
$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle \mathcal{N}_{\mathrm{ph}} \rangle + \frac{1}{M} \langle \mathcal{N}_{\mathrm{ph}} \rangle^2$$

Discrete quantum nature of light

Turn-to-turn variations in relative positions of the electrons



I.Lobach



Observed super-Poissonian fluctuations for many electrons, consistent with model of classical and quantum fluctuations

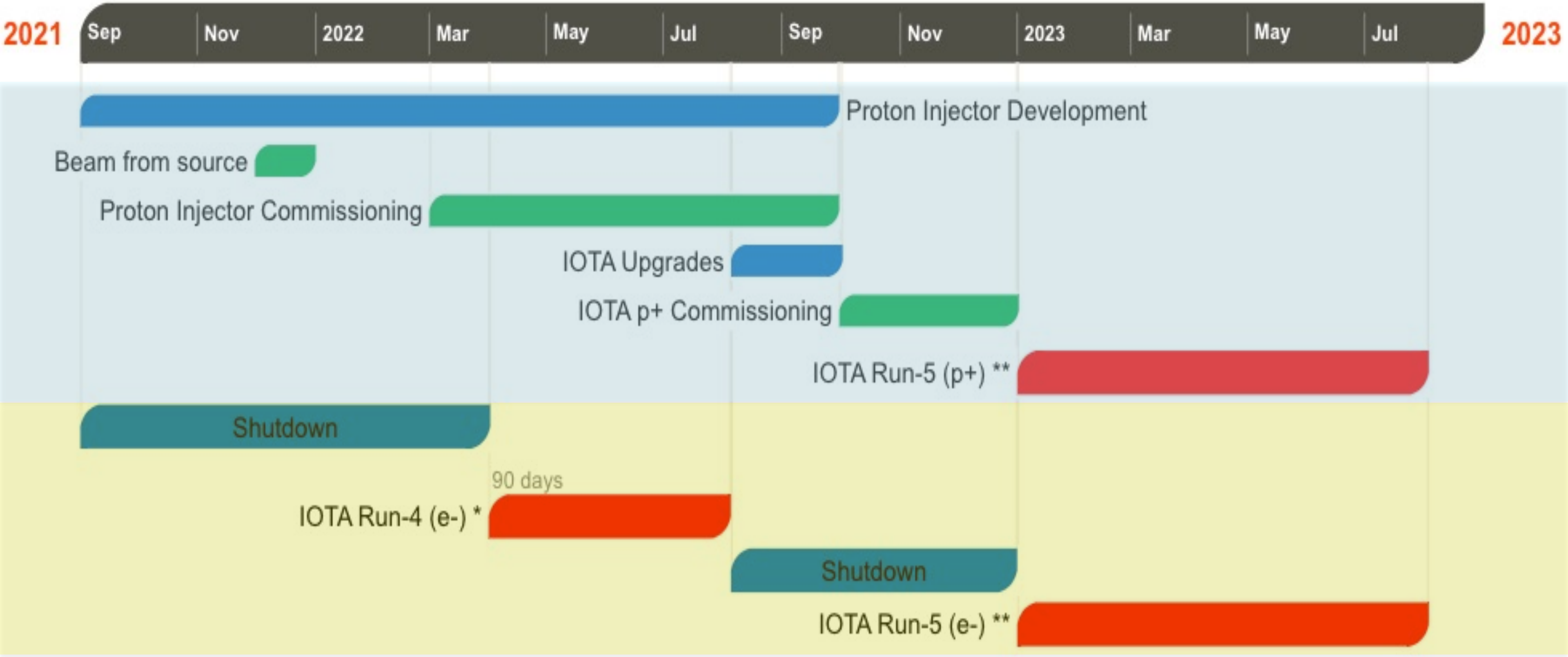
- Developed an absolute measurement (no free parameters or calibration) of a small vertical emittance unresolvable by a conventional SR beam size monitor

Phys. Rev. Lett., 126, 134802 (2021)

Phys. Rev. Accel. Beams, 24, 040701 (2021)

Phys. Rev. Accel. Beams, 23, 090703 (2020)

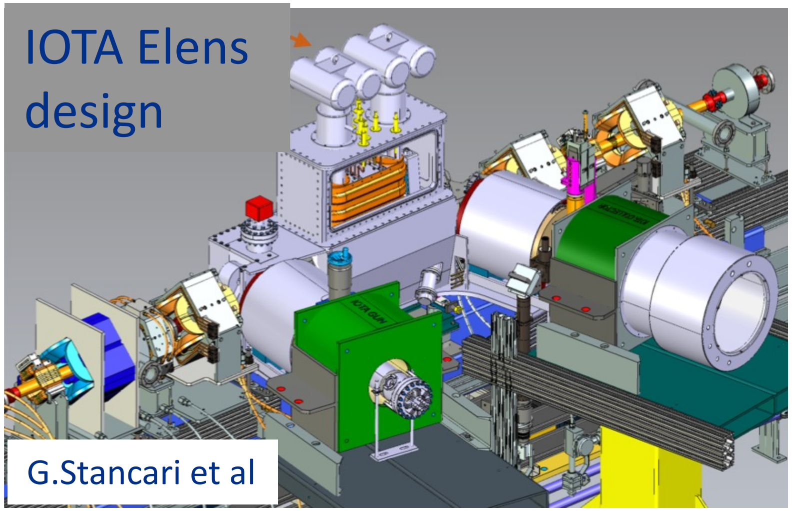
Future Vision



– Run-2 was cut short on March 21, 2020 due to Illinois stay-at-home order. Completion of high-impact NIO research requires e- run
– IPI commissioning can be done in parallel with e- operations
* Run-4 length minimum 3 months
** Run-5 may be separate for e- and p+

Electron lenses

Electron lens = magnetically confined electrons acting on the circulating beam is a versatile tool for beam physics (Tevatron, RHIC, HL-LHC)



In IOTA:

- With electrons
  - Nonlinear element for IO
  - Tune spread for Landau damping
- With protons
  - Space-charge compensator
  - Electron cooler

G. Stancari et al 2021 JINST 16 P05002

ICFA Beam Dynamics Newsletter #81

Summary

- IOTA/FAST is a unique R&D facility dedicated to accelerator science research. Over the last five years IOTA saw remarkable progress in construction, commissioning and first research with electron beams
  - 2017: FAST e- linac World record accelerating gradient for ILC-type cryomodule
  - 2018: IOTA completed and commissioned with electrons
  - 2019-20: First demonstration of Nonlinear Integrable Optics
  - 2021: First demonstration of Optical Stochastic Cooling
  - Growing portfolio of collaborative experiments
- Future research has strong potential (protons, OSC, E-Lens)
- IOTA is an excellent platform for technological developments, synergistic research and training
  - We welcome collaboration!