Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

FAST/IOTA Progress and Research Program

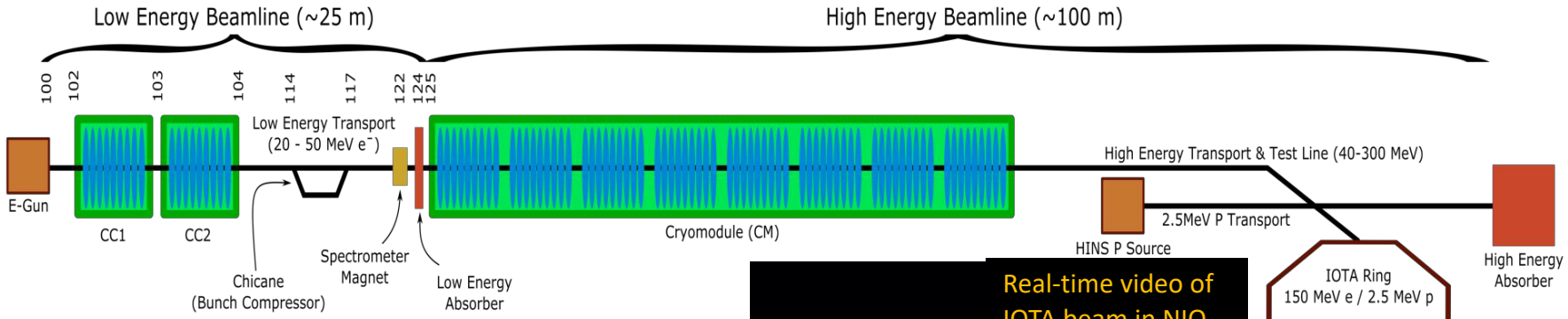
Alexander Valishev

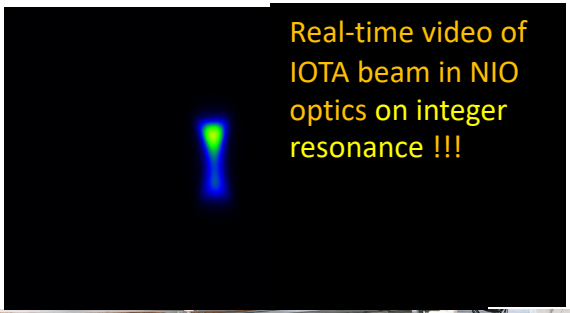
2020 Fermilab Accelerator Advisory Committee Review

9 December 2020

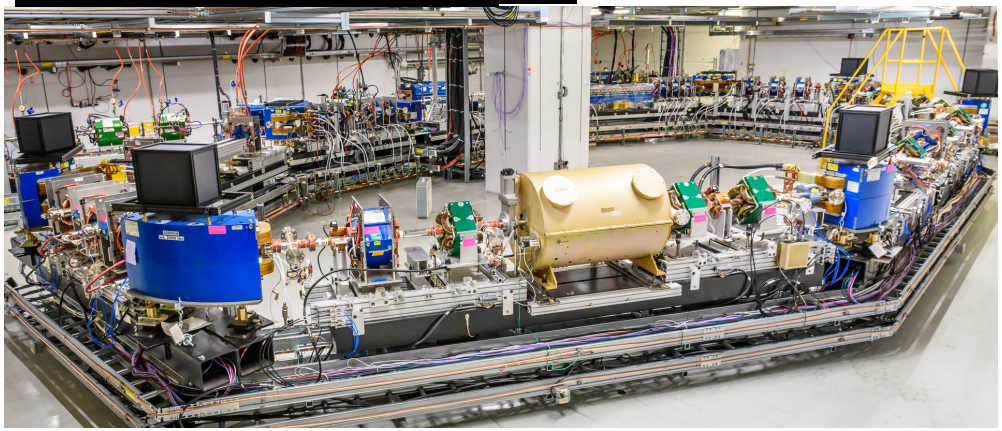
IOTA/FAST Facility: a center for Acc. and Beam Physics

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

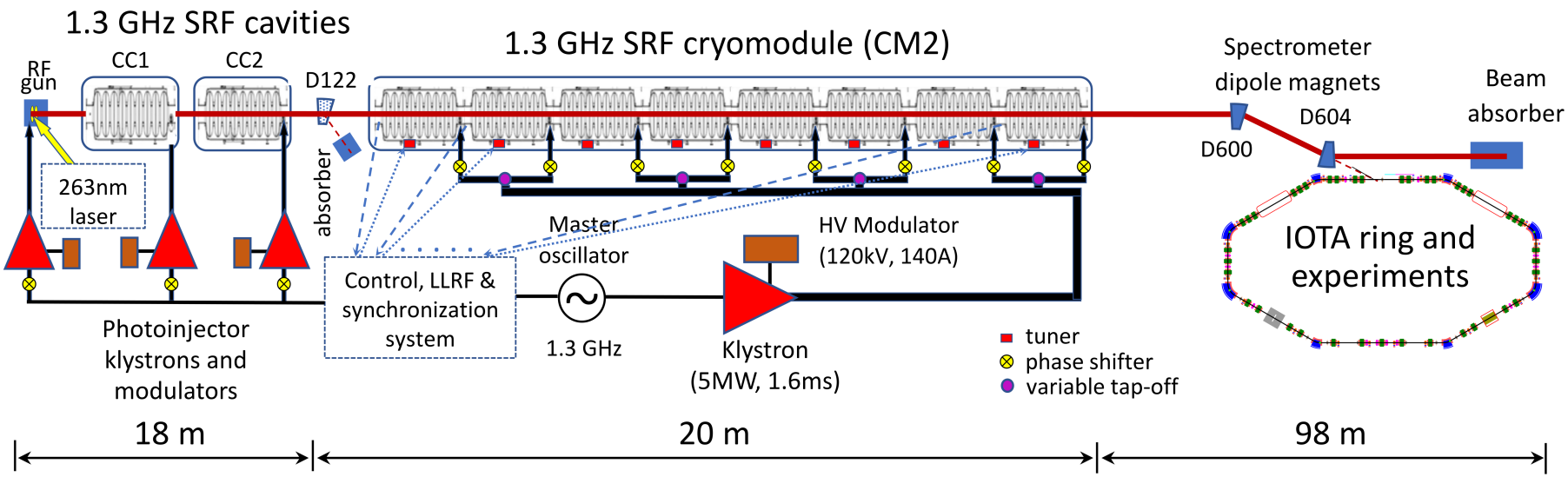




- **The only dedicated facility for intensity-frontier accelerator R&D; ranked as top facility ("Tier 1") for acc. & beam physics thrust by recent GARD review**
- ~30 Collaborating institutions
- Nat. Lab Partnerships: ANL, BNL, LANL, LBNL, ORNL, SLAC, TJNAF
- Many opportunities for R&D with cross-office benefit in DOE/SC



IOTA/FAST Accelerators



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

- Beam energy: 40-300 MeV
- Bunch charge: 1e- to 3 nC (160 pC nominal)
- Pulse frequency: up to 5 Hz (83 MHz train)

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

Current Priorities

In developing the priorities and schedules we balance present research capabilities, potential impact and available resources

I. **IOTA research focused on beam intensity and brightness in proton rings mostly driven by the development of Fermilab's high-energy neutrino program**
   - Prerequisite is the completion of the proton injector and IOTA commissioning with protons
   - Research that can be done with present capabilities

II. **High-impact science aligned with GARD mission**

III. **Collaboration-driven research seeding potentially high-impact directions**

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

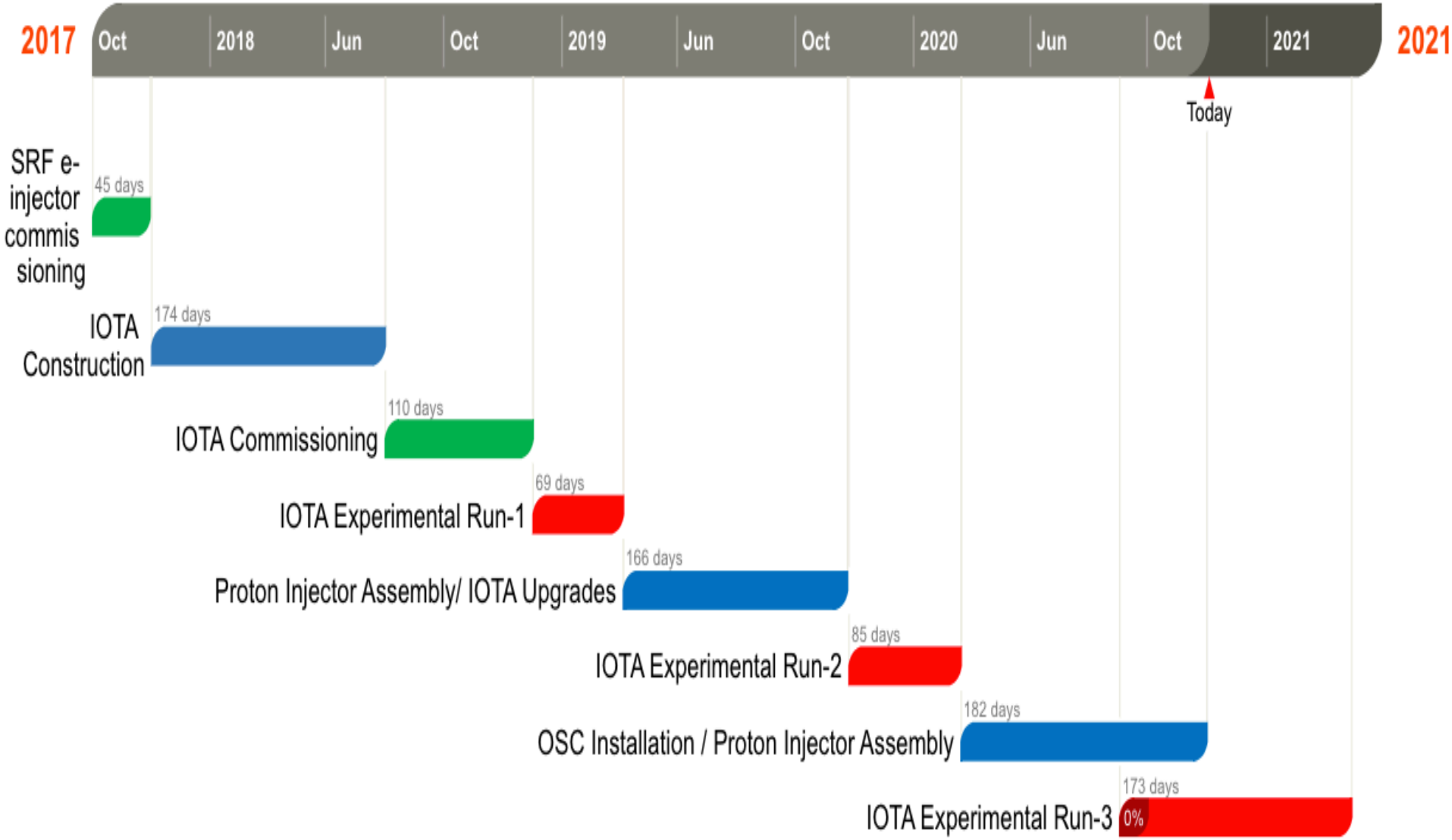
II. High-Impact GARD Research

- **Nonlinear Integrable Optics**
  - Can be studied with electrons
  - Several options for implementation: octupole lenses, elliptic-potential magnet, electron lenses
- **Optical Stochastic Cooling**
  - Uses electron beam
- **Development of novel beam instrumentation**
  - Large dynamic range halo monitoring
- **SRF acceleration: beam intensity and brightness**
  - Achievement of ILC beam acceleration and beam parameters

III. Collaboration-Driven Research & Development

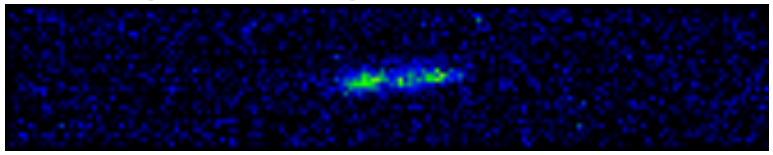
- **Radiation generation**
- **Electron-Ion Collider R&D**
- **Collaboration with other beam facilities and projects**
  - FACET-II and other accelerator test facilities
  - LCLS-II
  - PIP-II
- **Quantum science**
- **Education and training**

IOTA/FAST Timeline



Research in IOTA/FAST Experimental Run 1

IOTA operations in 2019/20 was mostly focused on commissioning however Run-1 produced great physics

- Record-high nonlinear amplitude-dependent tuns shift ΔQ=0.05 demonstrated in NIO
- Promising results on instability suppression via Landau damping
- Measurements of fluctuations in undulator radiation (with U.Chicago, ANL and SLAC)
- Reliable and reproducible storage of single electrons
  - Unique quantum probe 
  - First 3-dimensional tracking of a single particle in accelerator FERMILAB-PUB-20-652-AD
- Seed research on detection of edge-radiation interference (with SLAC)
  - Resulted in a DOE ECA (B. O'Shea, SLAC 2020)
- Generation and transport of high-charge magnetized beams (with NIU, Jlab)

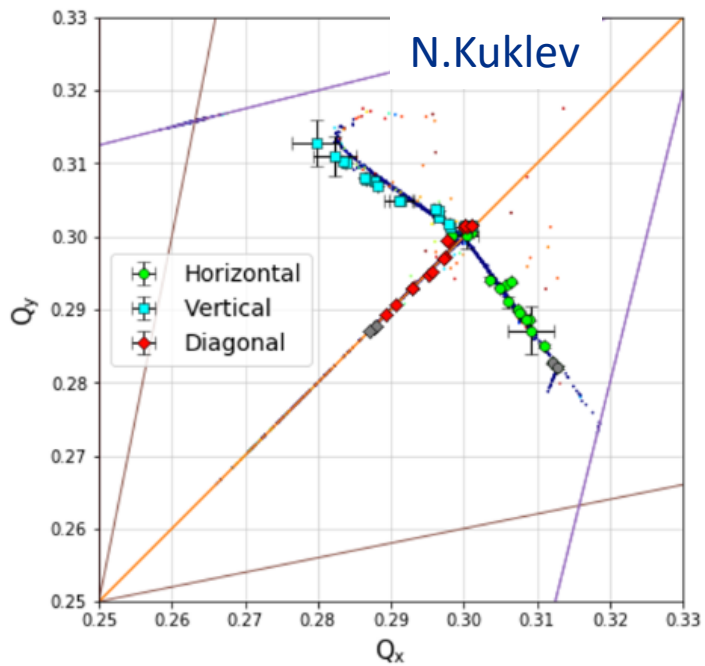
Research in IOTA/FAST Experimental Run 2

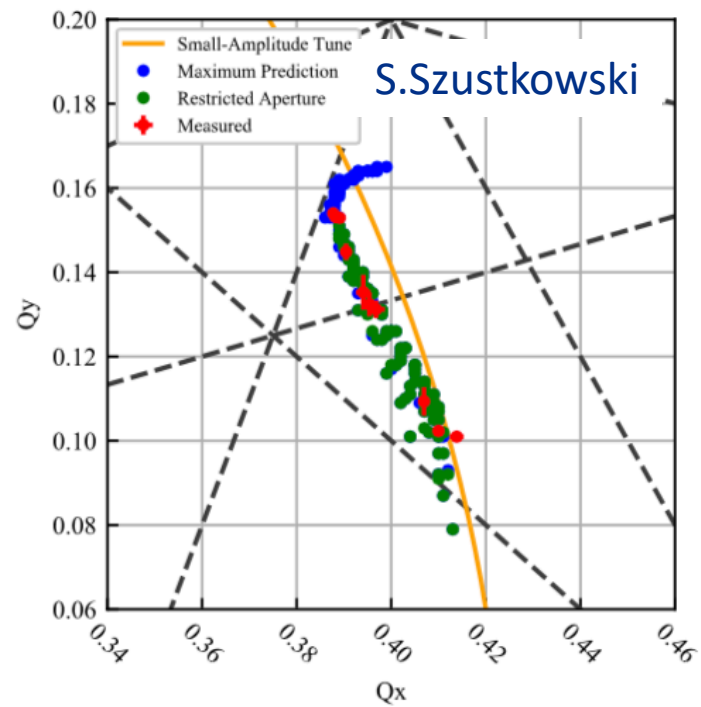
Broad program and systematic approach: in all 9 experiments took data over 60 shifts and produced excellent results. Engagement of outside collaborators (CERN, SLAC, Jlab, Uchicago, NIU, ANL) and 6 graduate students.

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

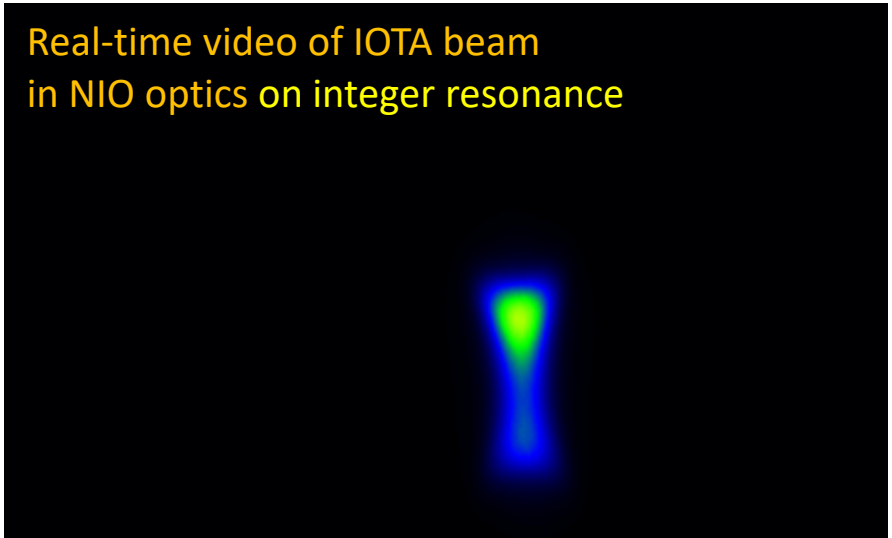
NIO Results – Amplitude-Dependent Tune Shift

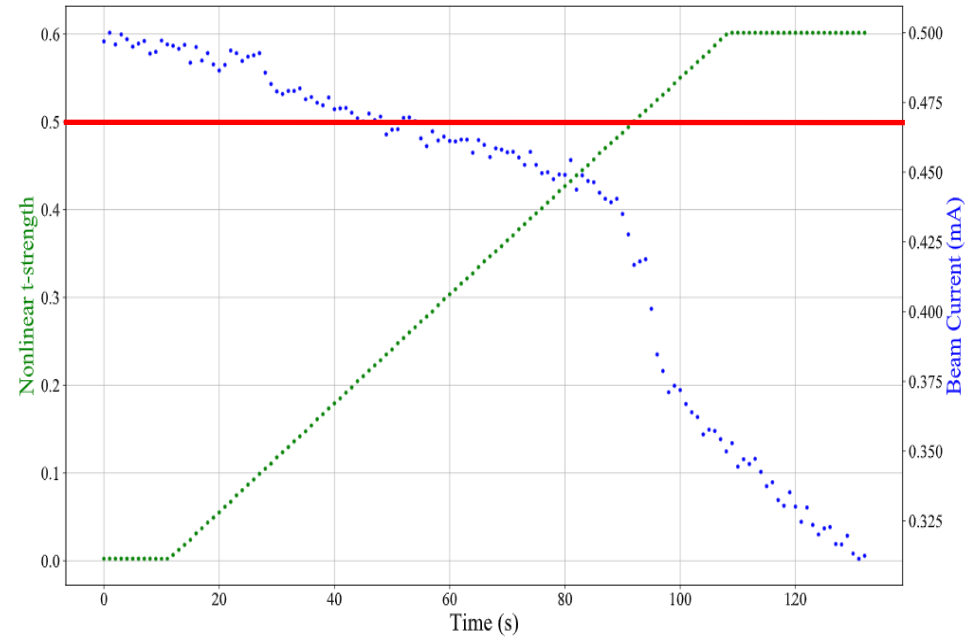
- Performance close to maximum prediction achieved for both types of NIO
  - ΔQ =0.04 for quasi-integrable octupole system
  - ΔQ =0.08 for NIO with 2 invariants of motion
  - Clear improvement vs single octupole

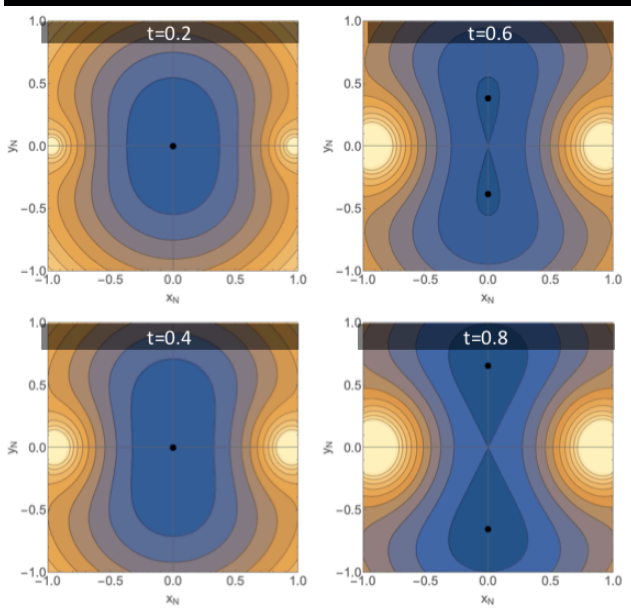


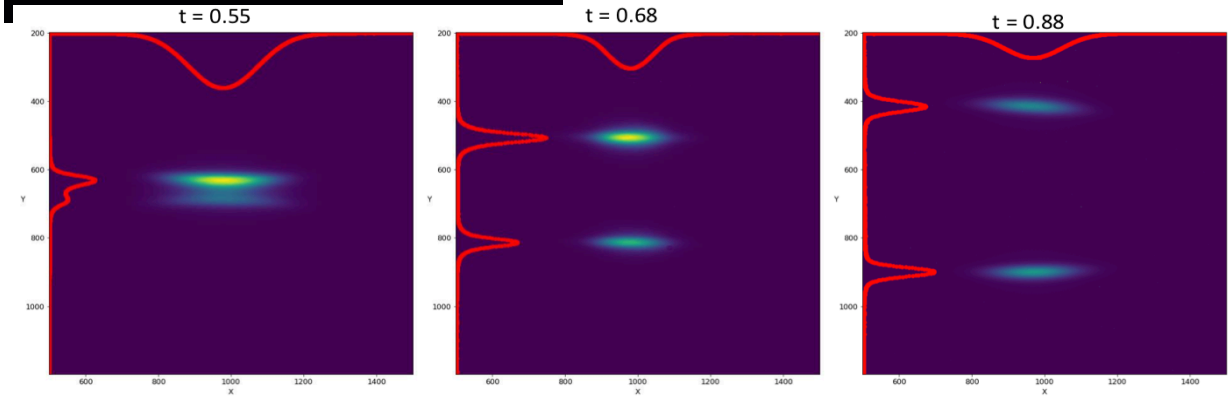


Run-2 Highlight – Beam on Integer !!!



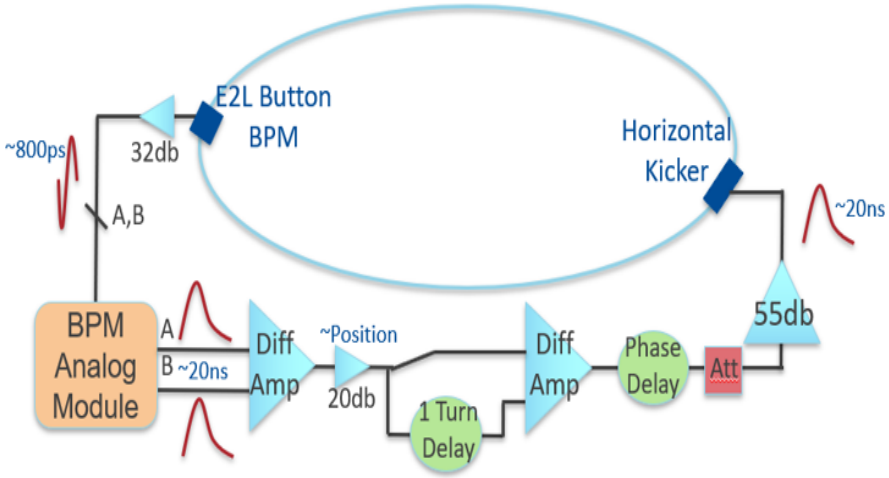


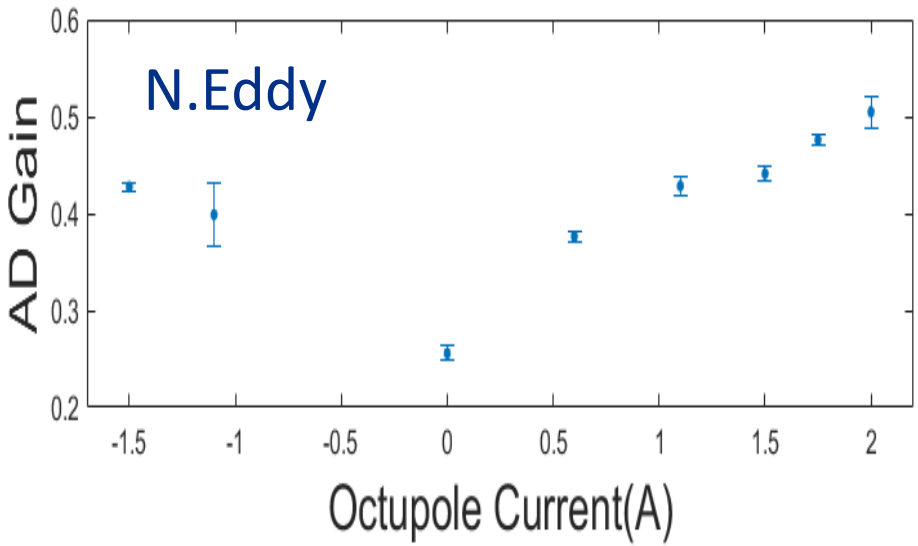




Improved Landau Damping with NIO

- Instability was induced with anti-damper
  - Demonstrated 2x increased stability (damper gain) with NIO





This research direction is now strengthened by a DOE ECA to R.Ainsworth "Ensuring bunch stability in multimegawatt accelerated particle beams"

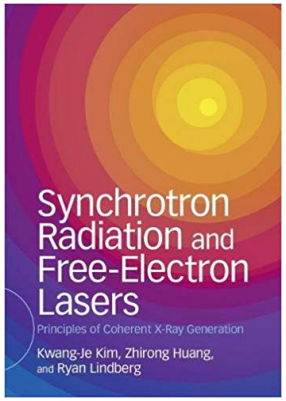
- New 'waker' system is implemented in Recycler
- Later to be moved to IOTA for experiments with proton beams

Studies of Statistical Properties of Undulator Radiation

I. Lobach, E. Angelico, UChicago, S. Nagaitsev, G. Stancari, V. Lebedev, A. Romanov, A. Valishev, J. Santucci, Fermilab, A. Halavanau, Z. Huang, V. Yakimenko, SLAC, A. Murokh, Radiabeam, K. J. Kim, ANL, T. Shaftan, BNL

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

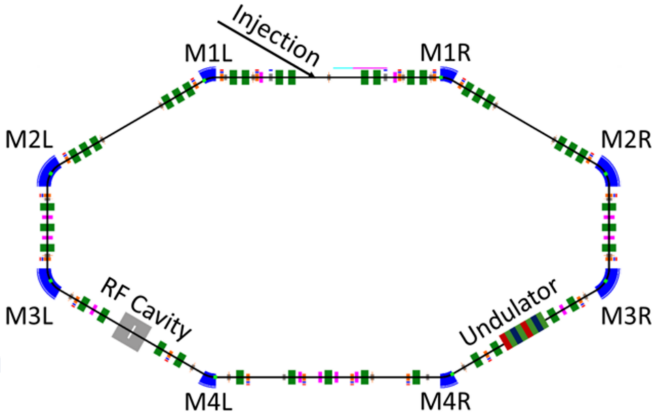
$$\frac{1}{M} \propto (1 - 1/n_e)$$

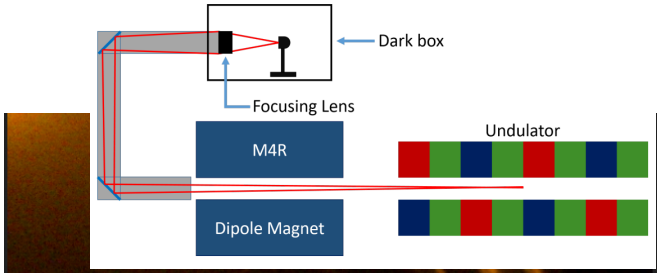


$$\mathrm{var}(\mathcal{N}_{\mathrm{ph}}) = \langle \mathcal{N}_{\mathrm{ph}} \rangle + \frac{1}{M} \langle \mathcal{N}_{\mathrm{ph}} \rangle^2$$

Discrete quantum nature of light

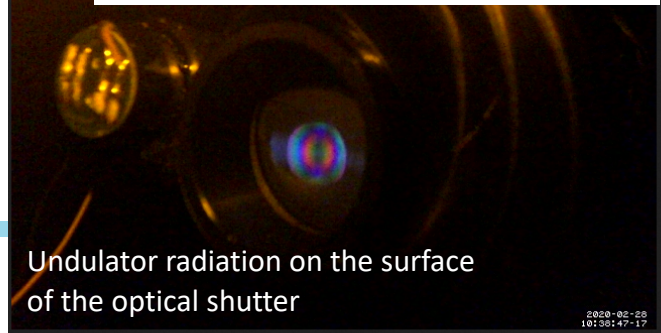
Turn-to-turn variations in relative positions of the electrons





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

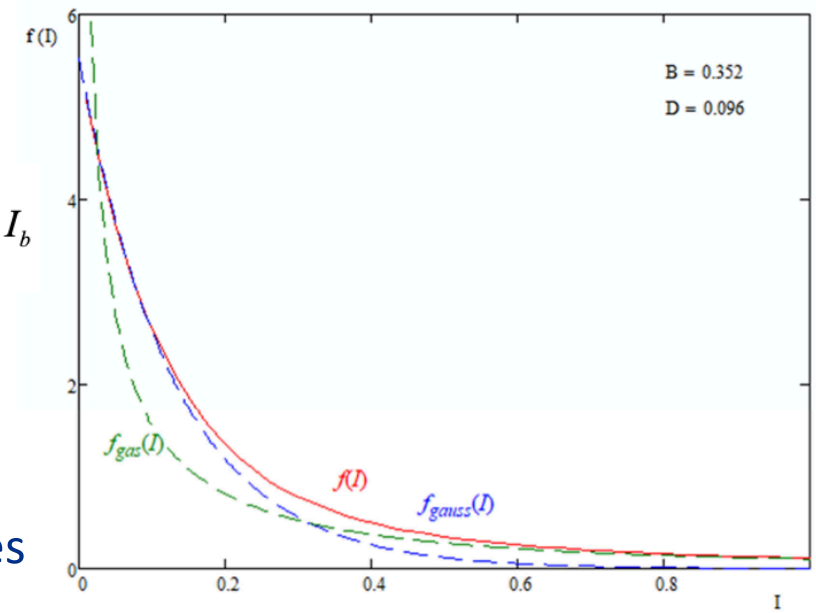


Undulator radiation on the surface of the optical shutter

Particle Scattering in the Residual Gas

- Fundamental processes affecting beam lifetime and emittance
  - Touschek effect
  - Multiple IBS
  - Scattering in the residual gas
- Performed beam measurements in IOTA in a wide range of intensities from μA to 4mA
  - Refined models and calculations

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial \hat{I}}\left(\hat{I} f\right) + D_{SR}\frac{\partial}{\partial \hat{I}}\left(\hat{I}\frac{\partial}{\partial \hat{I}}\right) + \hat{B}\left(\int_0^{I_b} W(\hat{I},\hat{I}') f(\hat{I}',t)\mathrm{d}\hat{I}' - f\right), \quad I < I_b$$



Gas scattering increases the Gaussian core width by 1.35 times
The core includes 72% of particles
However rms emittance exceeds ε_{SR} by 20 times

Generation and Transport of Magnetized Beams

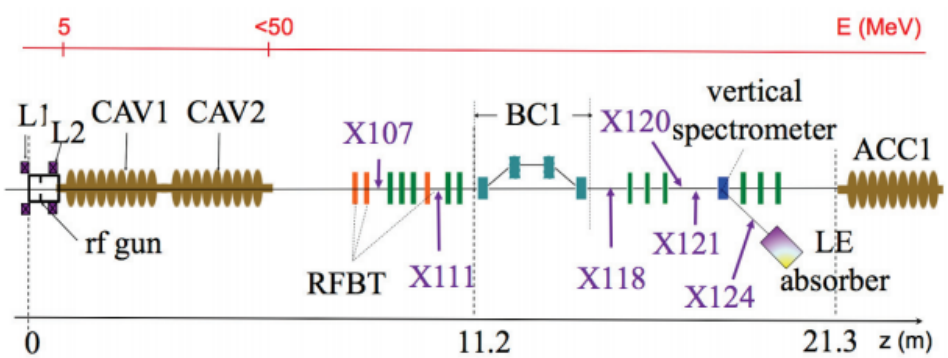
Flat beams with large emittance ratio can have a variety applications

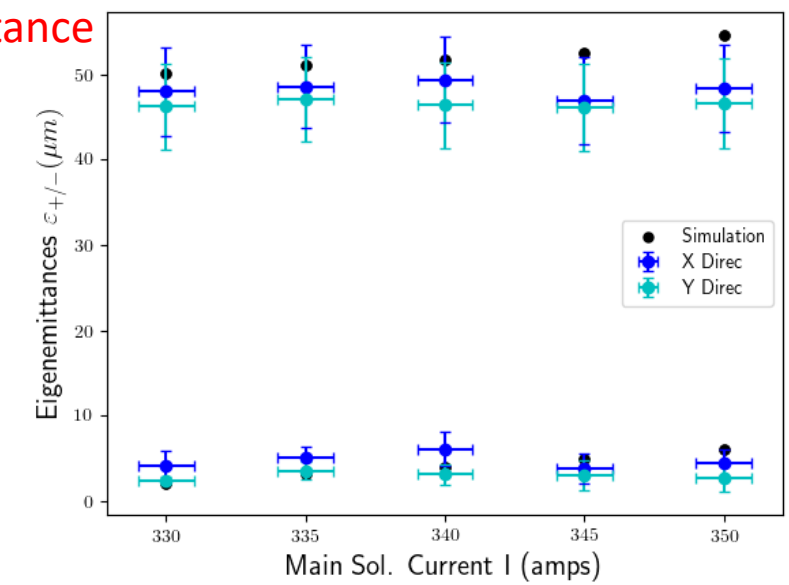
- This study is motivated by magnetized electron cooling

$$\varepsilon_{n,\mathrm{eff}} = [(\gamma\mathcal{L})^2 + \varepsilon_{n,u}^2]^{1/2}.$$

Effective emittance Magnetization Uncorrelated Emittance

$$\epsilon_{\pm} = \sqrt{\epsilon_u^2 + \mathcal{L}^2} \pm \mathcal{L}$$





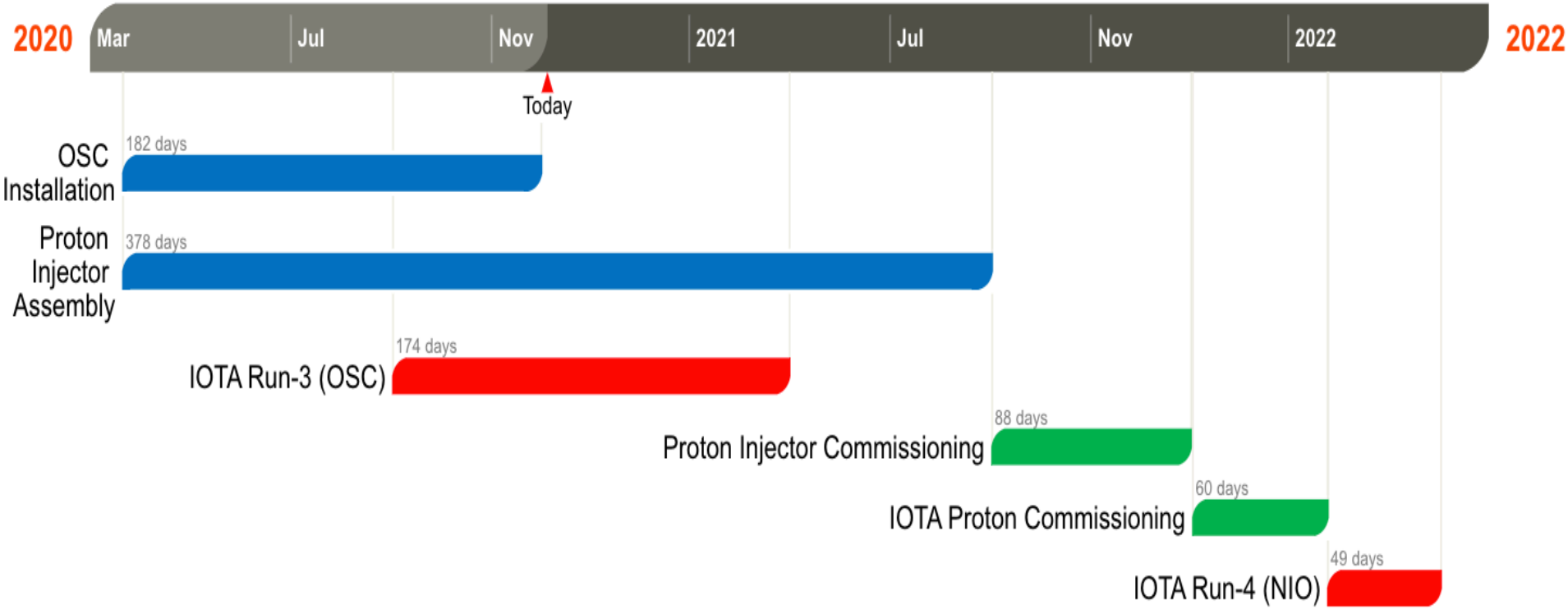
Generated flat beams and characterized emittances for up to 3.2nC, 45MeV bunches

Selected IOTA/FAST Run 2 Outcomes

IOTA/FAST Scientific Committee encourages a vibrant scientific program by working with experimenters to establish resource and schedule priorities, ensure adequate planning of experiments, and document research while keeping the process simple.

- Virtual Collaboration Meeting was held in June
- Each of the experiments produced a report (internal note)
- Publications:
  - JINST special issue on IOTA initiated
  - paper published: Phys. Rev. Accel. Beams 23, 090703
  - papers submitted: PRL, 2x PRAB
  - 3 papers in preparation
- 2 PhD students graduated
  - E. Angelico, U.Chicago
  - S. Szustkowski, NIU
- Collaborating European student received a Marshall Plan Scholarship

Future Vision



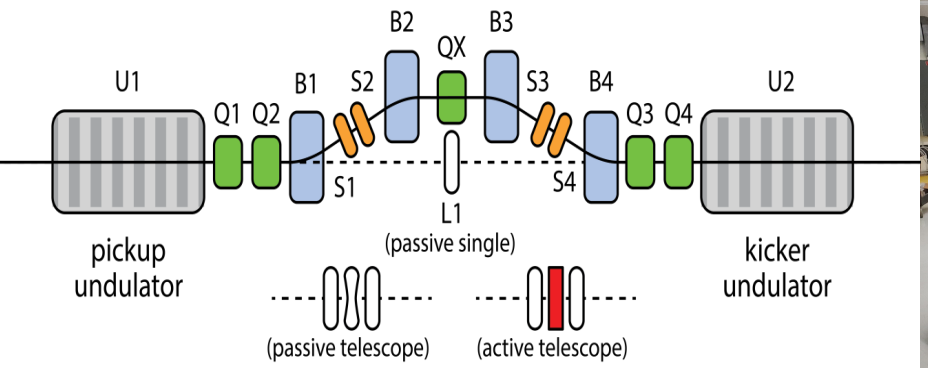
IOTA/FAST schedule was and continues to be impacted by covid-19

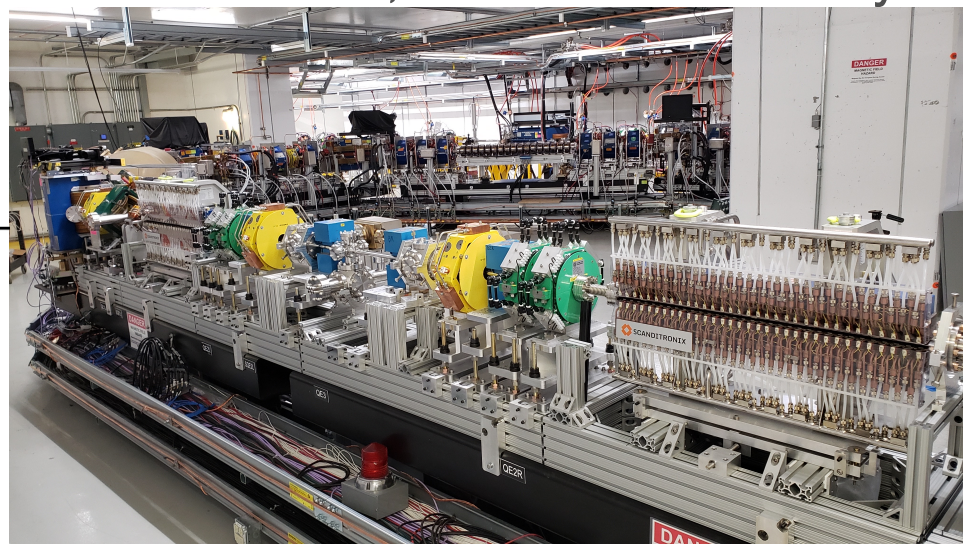
- Run-2 was cut short on March 21, 2020 due to Illinois stay-at-home order
- OSC installation and Proton Injector work was stalled until June
- Slow recovery

Run-3 (2020/21) – Optical Stochastic Cooling

IOTA was reconfigured to operate for the proof-of-principle OSC demonstration

- 100 MeV electrons, ultra-small emittances, low beam intensity



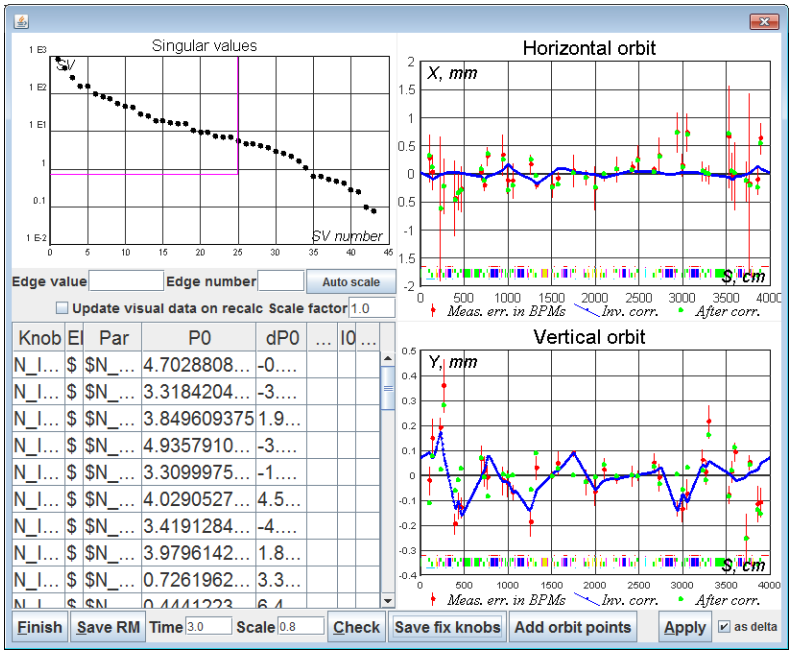


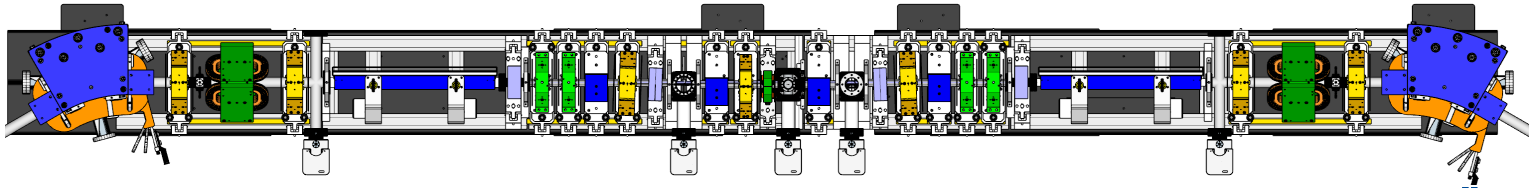
- 5 m straight rebuilt
- 1st experiment seeks to demonstrate passive cooling (no optical amplifier). Expected OSC damping rate 20 to 40x SR with beam of 10^5 e^-.

ECA awarded to J.Jarvis for "The development of next-generation particle beam cooling and control with optical stochastic cooling"

Commission OSC lattice and systems beginning ~DEC. ’20

- Anticipate ~1 month of commissioning activities
- Injection, tuning, capture, LOCO + manual adjustments until good agreement with model
- Exercise all diagnostics and control systems w/o OSC
- Characterize non-OSC beam dynamics w/ OSC lattice across all regimes

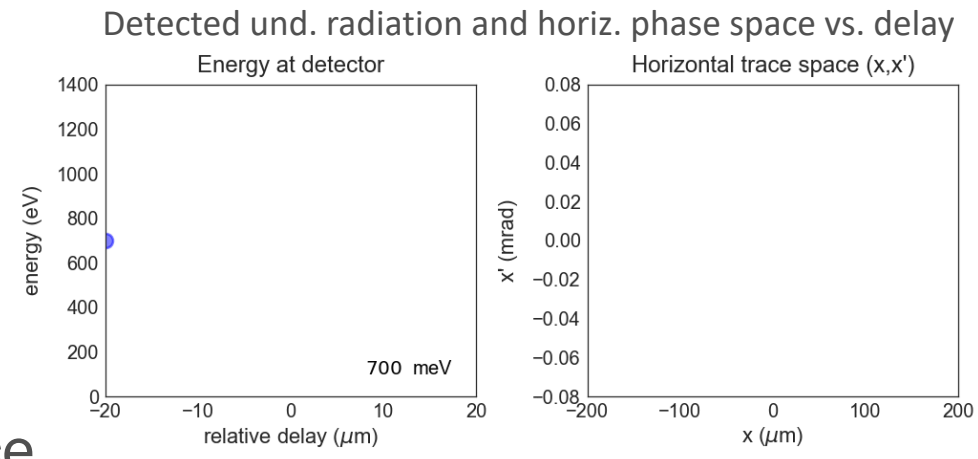




Experimental program executed in several phases

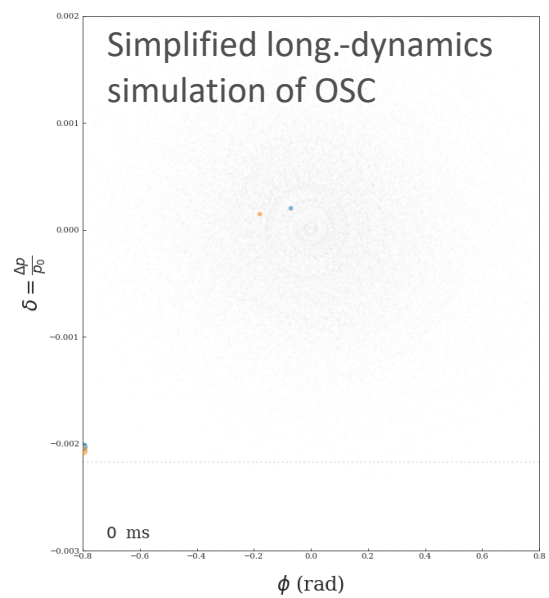
Ph1: Demonstration Experiment

- ~1e3 to ~1e5 particles
- fine alignment of PU/KU radiation
- delay scan + UR interference on diode detector
- beam image in SR diagnostics



Ph2: Systematic Studies

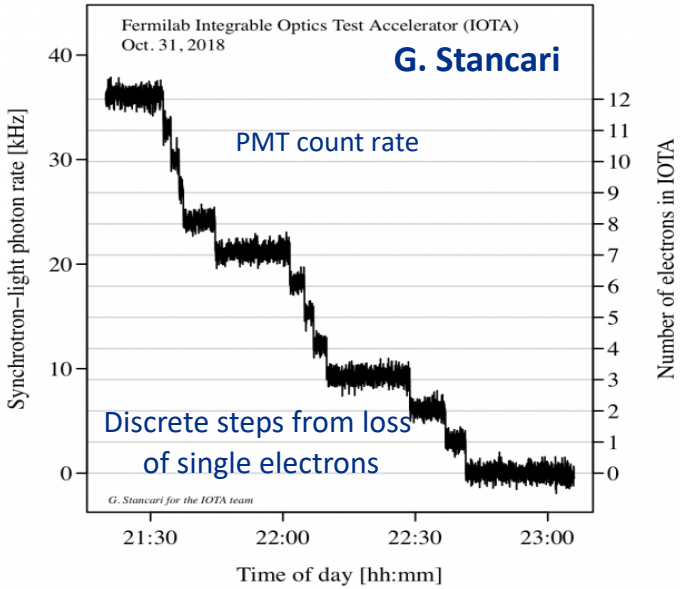
- Systematic examination of rates, ranges, coupling, nonlinearities, etc…
- All regimes: $N_e = [1, \sim 10^6]$
- Basic "phase-space control"

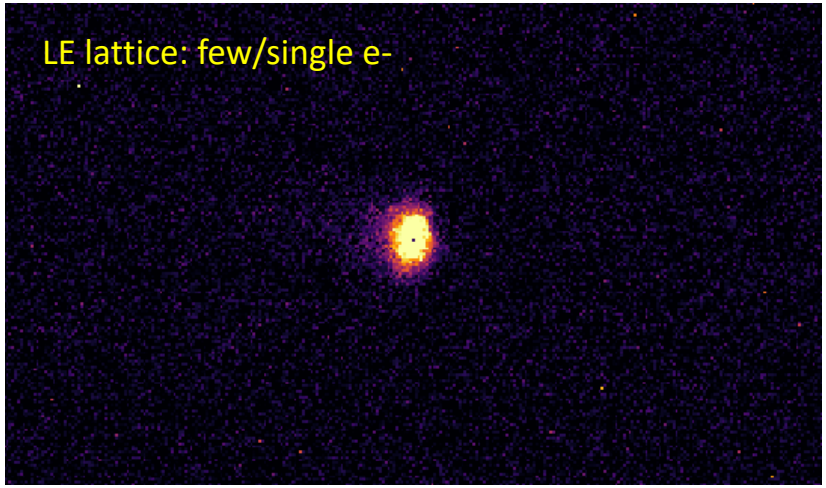


Experimental program executed in several phases

Ph3: Single/few Electron OSC and Advanced Concepts

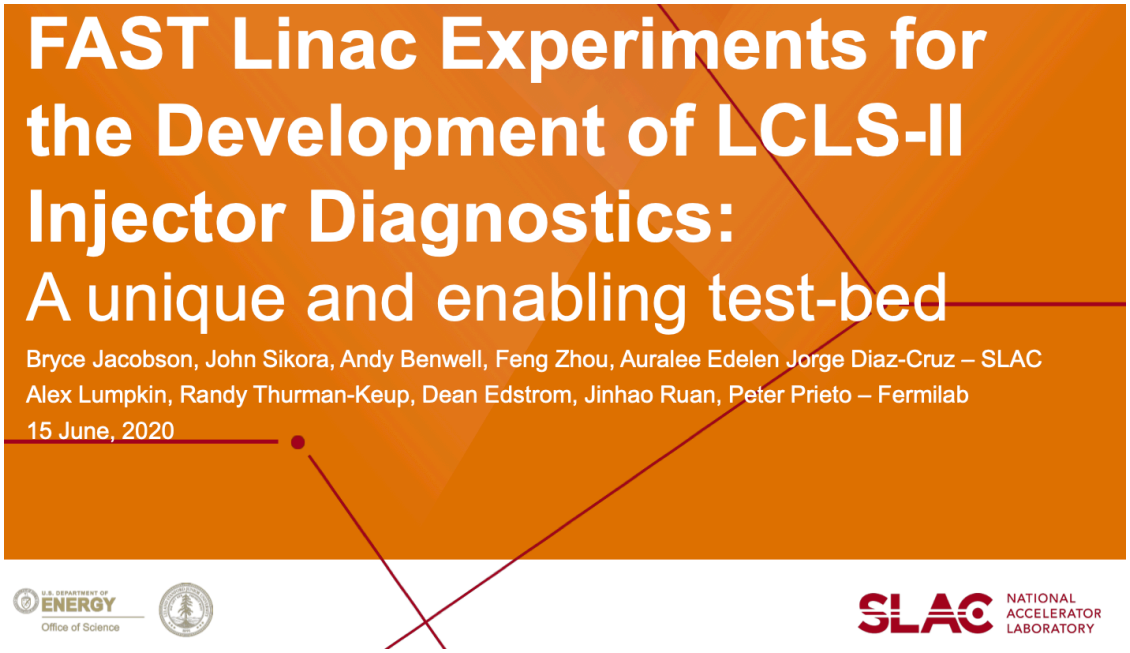
- Installation of improved imaging diagnostics
- Controlled modulation of emission probability due to UR interference
- Manipulation of single electron; transfer between different OSC cooling zones
- Active modulation of optical, RF, magnetic systems to manipulate beam structure using OSC





Run-3 Development of HOM Diagnostics at FAST

- Higher Order Modes impact beam quality
- LCLS-II seeks to develop instrumentation to aid in commissioning and FEL optimization



IOTA Proton Injector – Overview

Parameters & Timing:

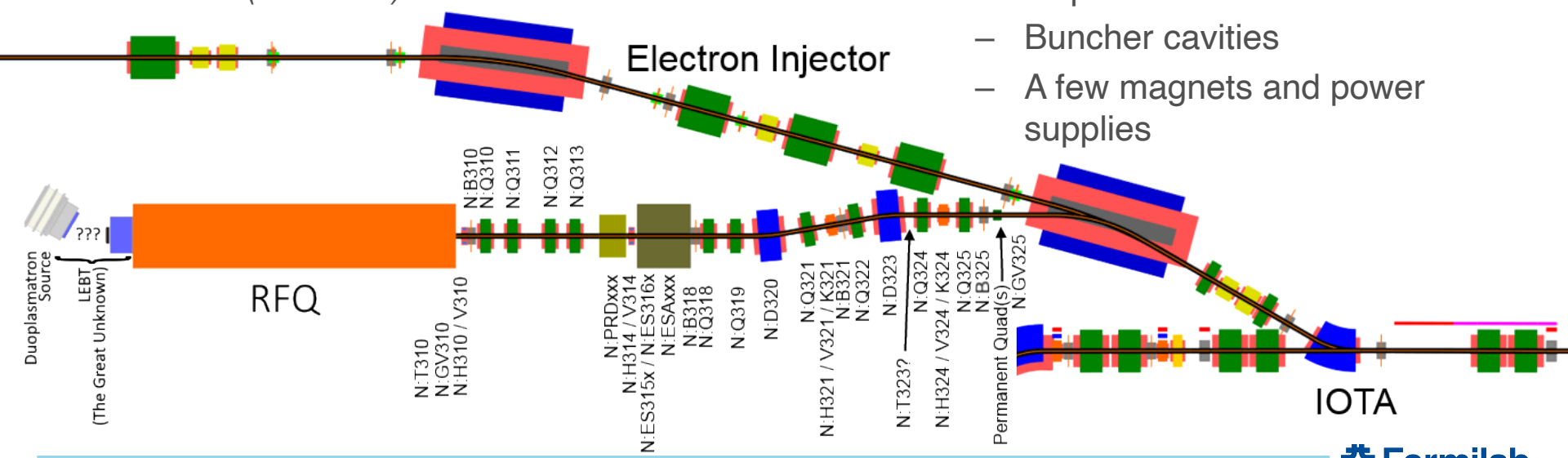
Parameter	Nom	Min	Max	Units
Beam Energy	2.5	2.4	2.8	MeV
Total Beam Current	5	1	10	mA
Pulse Length	2	1	50	µs
Repetition Freq	< 0.1	--	1	Hz
Transverse Emit (rms norm)	0.24	0.1	0.3	µm
Energy Spread (rms)	0.5	0.2	0.6	%
Bunch Structure	325	324.9	325.1	MHz
IOTA RF Frequency	2.2	2.1	2.3	MHz
IOTA Transit Time	1.8	1.7	1.9	µs

Brief History

PrX High Intensity Neutrino Source (HINS) concludes in 2012

- Usable components are appropriated from HINS for PIP-II
- Remainder of HINS is given to FAST (2015)
  - 50 kV Duoplasmatron source
  - 325 MHz RFQ with broken cooling loop
  - Buncher cavities
  - A few magnets and power supplies

Current Lattice (300 – 325):

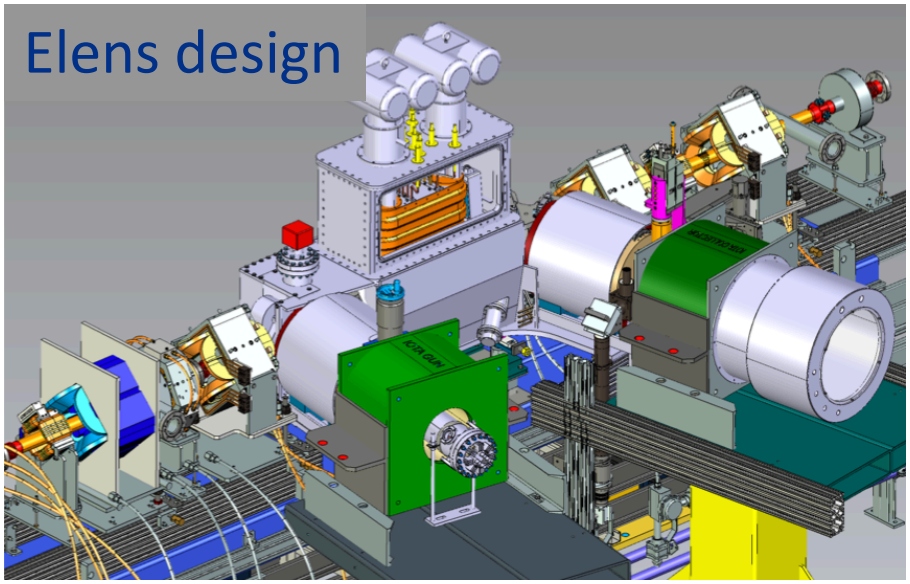


IOTA Proton Injector – Summary

- Significant work still remains
  - Contingent on run schedule and lab resources
    - Same Place / Same IOTA/FAST Personnel
    - Support department staff higher priority engagements
  - Most pieces in-hand, on-order now except…
    - HLRF Charging supply work in progress at A0
    - Fixed-Price Contracts for infrastructure systems being pursued or finalized
    - Odds & Ends (especially RF & MS)
  - Protons in late 2021 is an optimistic estimate
    - But it fits with the current run schedule

Research Beyond Run-3

- Nonlinear Optics and Space Charge
  - Theory and simulations campaign (together with LBNL)
  - Beam halo monitor (together with NIU and UC Davis)
    - Prototype was ready in May for test at UC Davis Crocker Lab, now postponed until January-February 2021
- Nonlinear Optics and Coherent Beam Instabilities
- Active OSC
- Electron Lenses
  - NIO with electrons
  - Space charge compensation
  - Electron cooling with NIO
- Quantum Science
  - Ion crystals in IOTA



Reference Material

- FAST Website https://fast.fnal.gov
- FAST Indico https://indico.fnal.gov/category/373/
- 2020 Collaboration Meeting https://indico.fnal.gov/event/43231/
- IOTA E-Lens wiki https://cdcvs.fnal.gov/redmine/projects/iota-e-lens/wiki
- IOTA Fluctuations in Synchrotron Radiation wiki https://cdcvs.fnal.gov/redmine/projects/fur/wiki
- IOTA/FAST Scientific Committee wiki https://cdcvs.fnal.gov/redmine/projects/ifsc/wiki

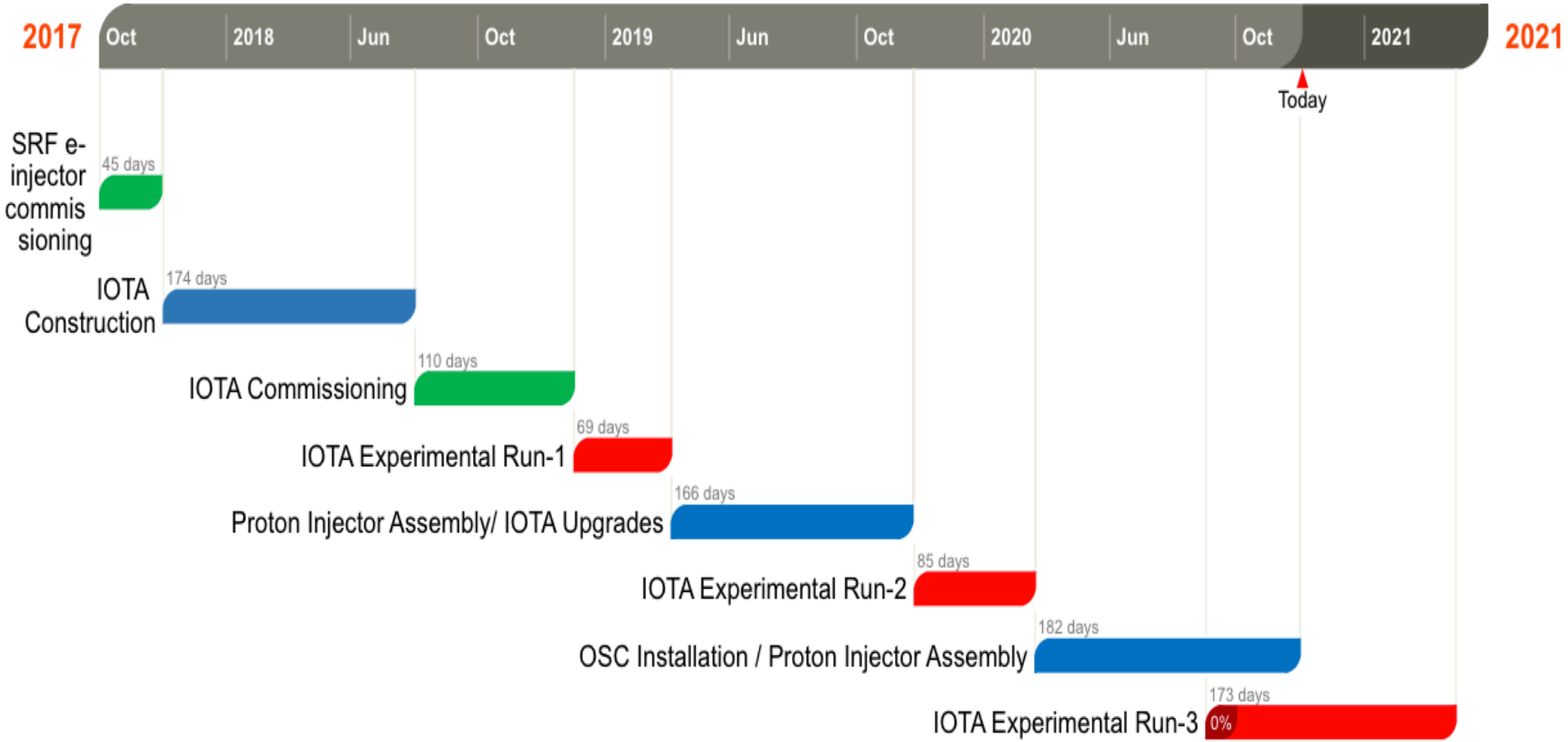
Summary

- IOTA/FAST has a very strong research portfolio addressing both medium and long-term mission of accelerator science
  - Support GARD Accelerator and Beam Physics thrust
  - Support three ECA projects (2x FNAL, 1 LBNL)
  - Several collaborative experiments
- Short term goals are well defined, and priorities established based on the available resources and science impact
- We have a very strong and focused team, work with collaborators to strengthen the research and develop long-term vision and path for IOTA/FAST

Extra Slides

Approach to Realization of the Strategy

- Balance priorities and resources
- Interleave facility development with beam runs
- Staged approach to research



Research Staging

Nonlinear Integrable Optics

- Phase I – research concentrates on the academic aspect of single-particle motion stability using electron beams
  - Run-1 2019, Run-2 2020
- Phase II – intense-beam studies with protons
  - 2022 and beyond

Optical Stochastic Cooling

- Without optical amplifier
  - Run-3 2020*
- With optical amplifier
  - 2022 and beyond

Transitioning to Stable Research Operation Model

Resources

- Until 2019, most resources were directed to installation and commissioning of IOTA – including the scientific staff
- Some limited resources were dedicated to research
- Transitioning to research-focused model – most resources support research/experimental program
- Established distinct groups for Research and Operations

Beam Operations

- Commissioning dominated operations periods until 2019 (research was parasitic to commissioning) (only operated for 2-4 months at a time)
- Transitioning to 6 months operation per year, 2 shifts/day (use 3rd shift as contingency)

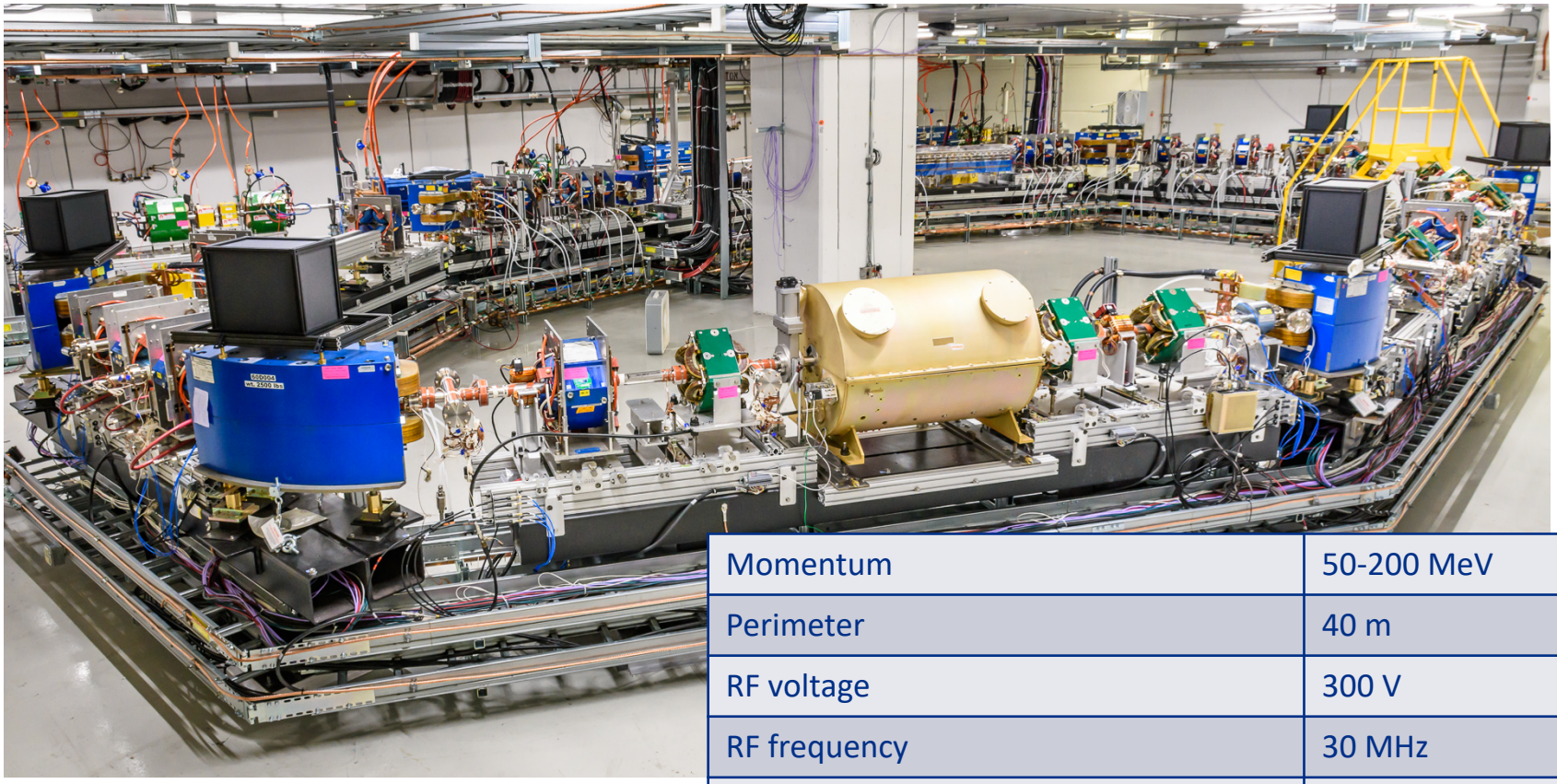
Planning

- Research was and will continue to be dominated by GARD thrusts
- Developing collaborative framework (IOTA/FAST Scientific Committee)

IOTA/FAST Workforce Organization

- FAST Facility Dept – Accelerator development, maintenance and operations
  - Research support personnel
  - **Need to increase operations staff**
- Accelerator Research Dept – Planning and execution of research program
  - Scientific staff
  - Currently 2 graduate students (U.Chicago)
  - **Need for more students, postdocs**
- Support Depts (on-demand) – Mechanical Support, Electrical Engineering, Controls, Instrumentation
  - Effort is shifted around to support FAST/IOTA and other laboratory activities – very efficient and eliminates ”Standing-Army” issues
- Collaborators

IOTA With Electrons

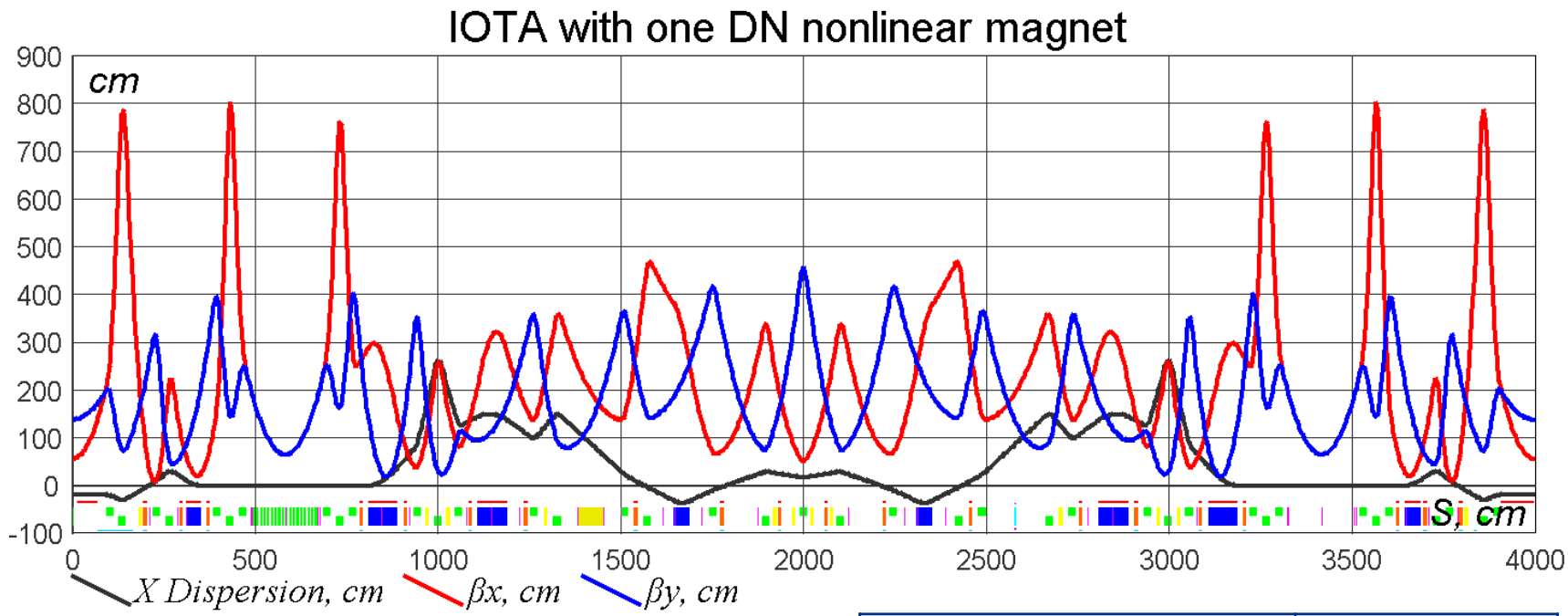


Momentum	50-200 MeV
Perimeter	40 m
RF voltage	300 V
RF frequency	30 MHz
3 Experimental sections	2x180 cm, 1x150 cm
Main vacuum chamber aperture (R)	25 mm
Lambertson and kickers aperture (R)	20 mm
Electrons bunch	10^9 e, 160 pC, 1.2 mA

IOTA Main Components

Lambertson magnet		1	Horizontal, injection in vertical plane
Kickers		1 hor. & 1 vert.	Horizontal for studies only
Main dipoles		4x60 deg & 4x30 deg	Powered in series with Lambertson
Quads		39	Powered in pairs with individual shunts
Trims	Hor.	8	In main dipoles
	Vert.	2	For injection bump
	Hor.	20	Combined correctors
	Vert.	20	
Skew-quads		20	
Pickups		21	Turn-by turn position
Sync. light monitors		8	Shape and position
RF		1	Dual frequency
Solenoid		1	For electron and McMillan lenses
Sextupoles		12	In six families
DCCT		1	Precision calibrated DC beam current
Wall current monitor		1	Bunch currents and longitudinal shape

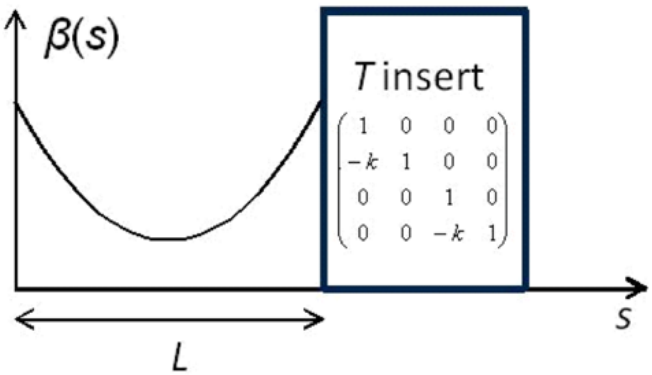
IOTA Lattice Configuration

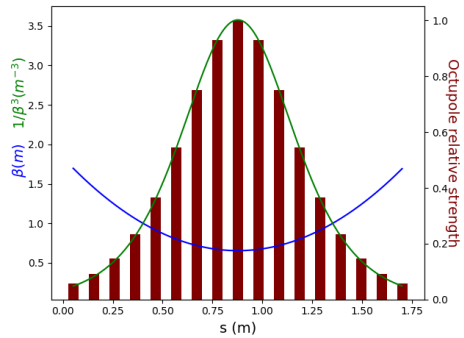


Parameter	Max error
Betas at the insertion	1%
Beta beating	3%
Dispersion	1 cm
Closed orbit at insertion	0.05 mm
Phase advance between insertions	0.001

Momentum	100 MeV
Tunes, x,y	5.3, 5.3
Mom. comp.	0.0756
RMS emit. (x, x&y-coupled)	(42.8, 11.2) nm
Damp. times (x,y,x&y-coupled,s)	(6.7,2.4,3.5,0.90) s
Energy spread	8.4 E-5
Bunch length @300V	10.6 cm
Sync. Tune @300V	3.8 E-4

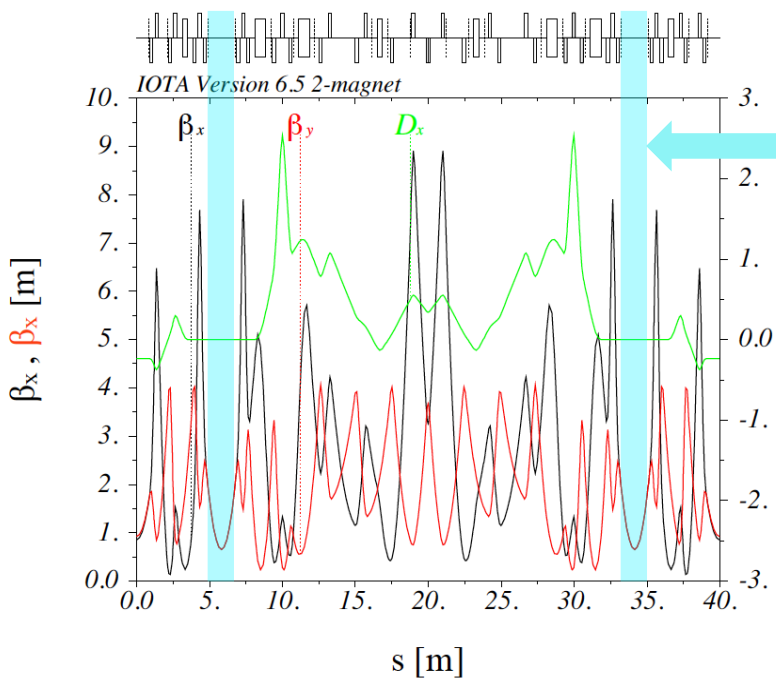
Implementation of NIO in IOTA

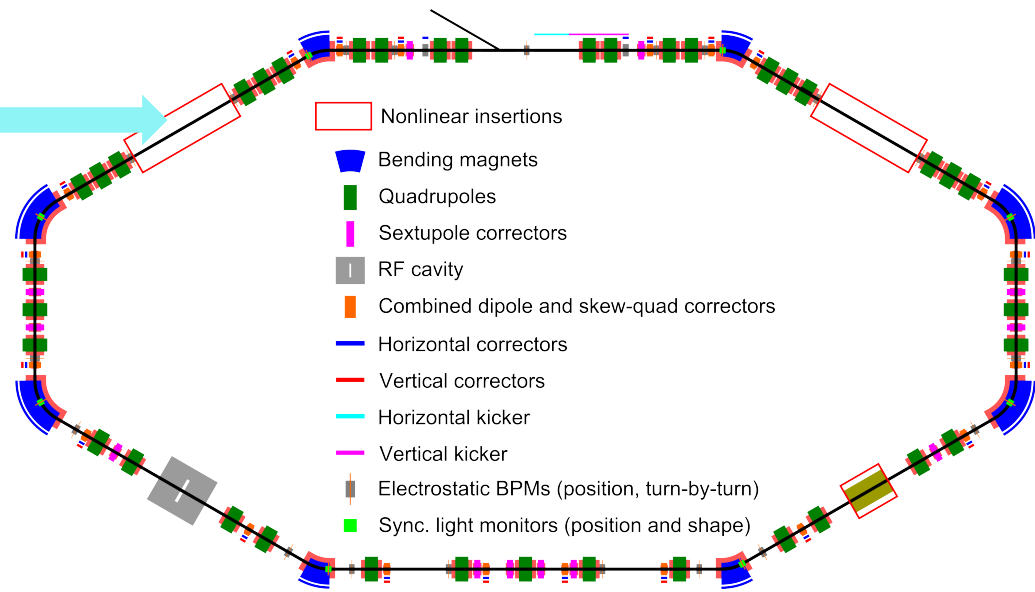




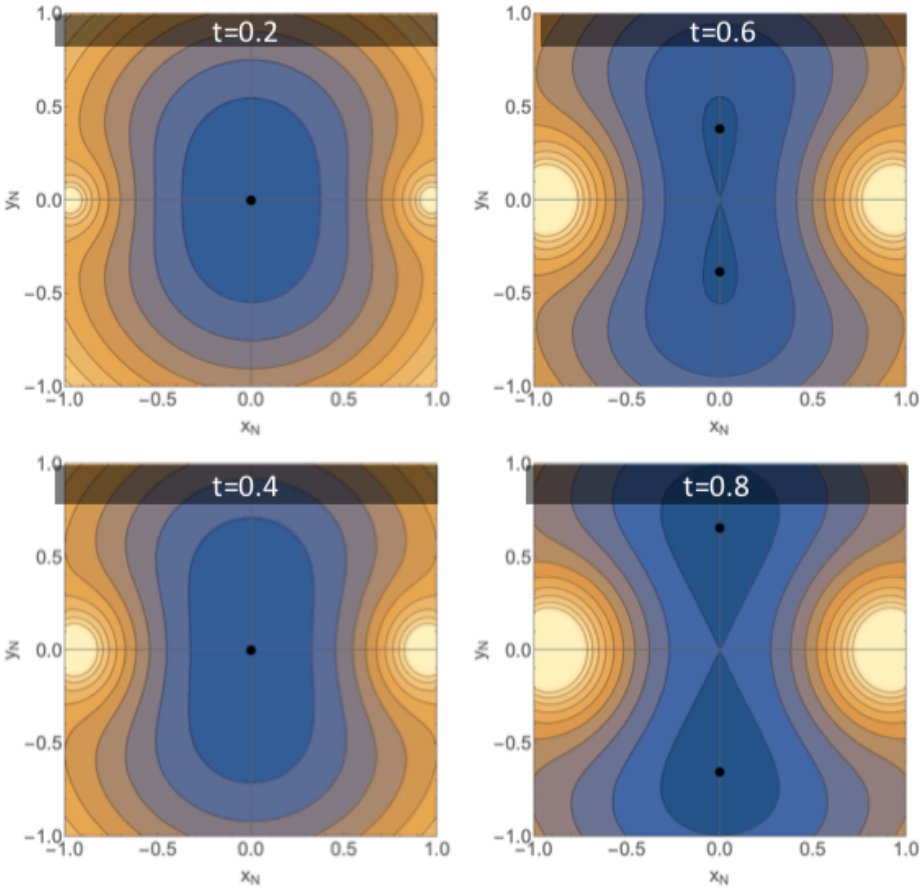
Practical requirements:

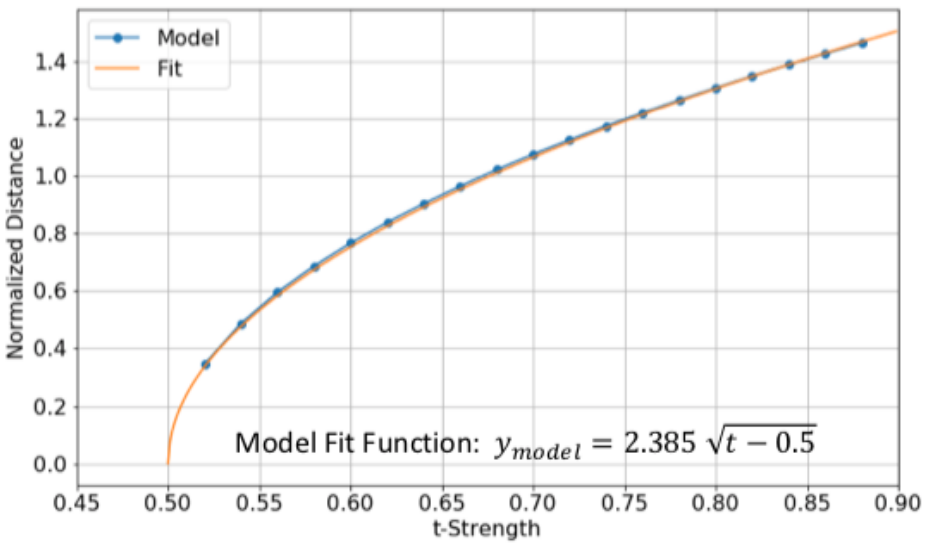
- Round axially-symmetric linear lattice (FOFO)
  - 2π x n phase advance
- Drift with $\beta_x=\beta_y$, no dispersion





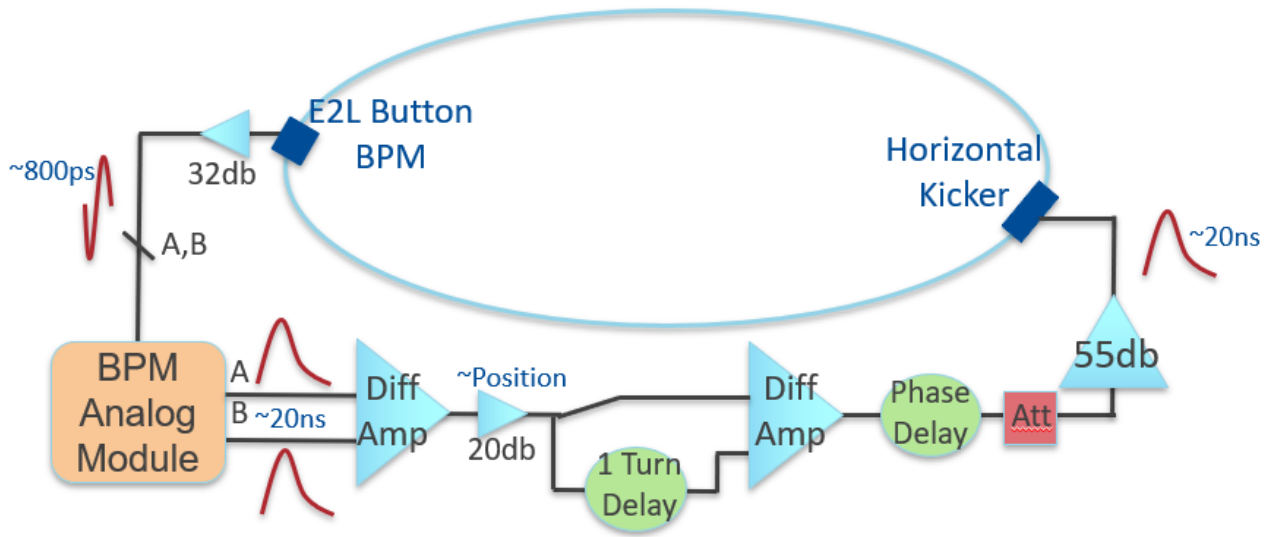
DN System – Phase Space Topology





Feedback System Overview

- Use horizontal button electrodes on E2L bpm with 32db RF pre-amplifier on each button
- BPM analog module based upon RF envelope detector conditions fast doublet into longer pulse – provides 32db of programmable gain control
- Implement 1 turn notch filter delay and phase delay with cable



Instability Threshold Study

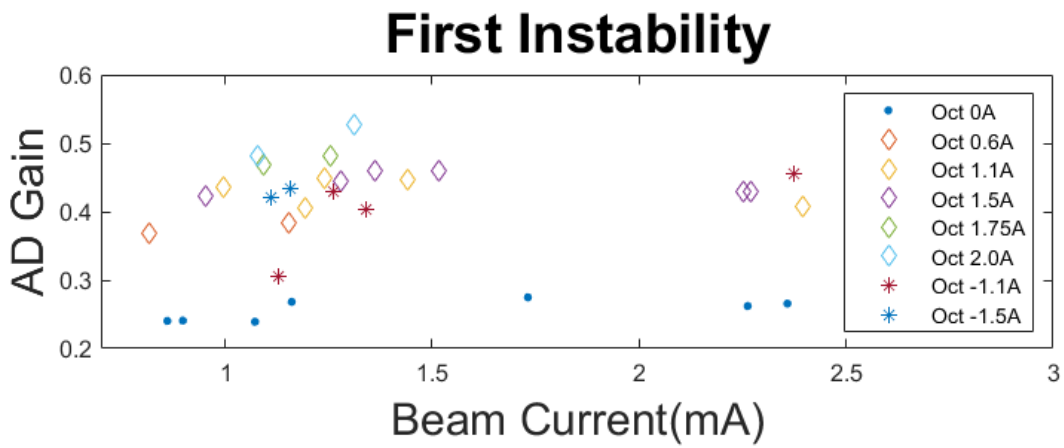
- Study the gain threshold for fast instability as a function of beam current and octupole current
- With nominal emittance (~160-170um), step the feedback gain until a fast instability occurs (>10% beam loss)

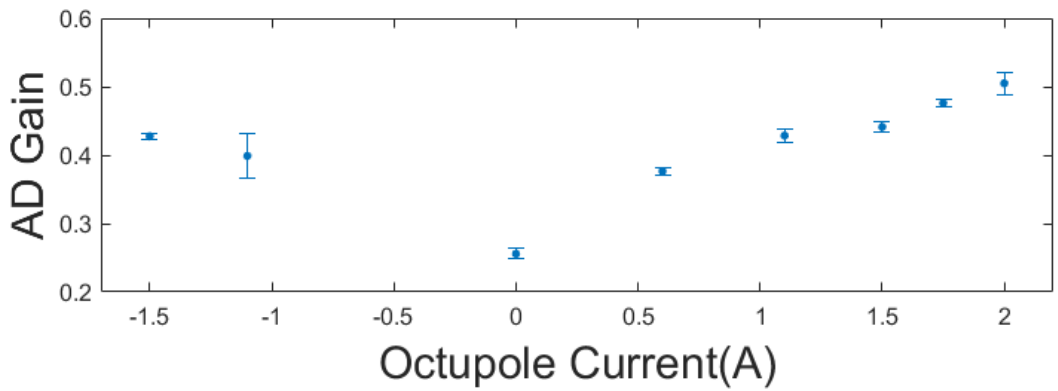
$$AD\ Gain = \frac{10^{-\frac{att_{db}}{20}} * Ibea_m}{\sigma_b \sqrt{2\pi}}$$

- The analog module attenuators were stepped in 1-2db steps until a fast instability occurred
- After each instability, wait for synchrotron radiation damping to restore beam to nominal emittance

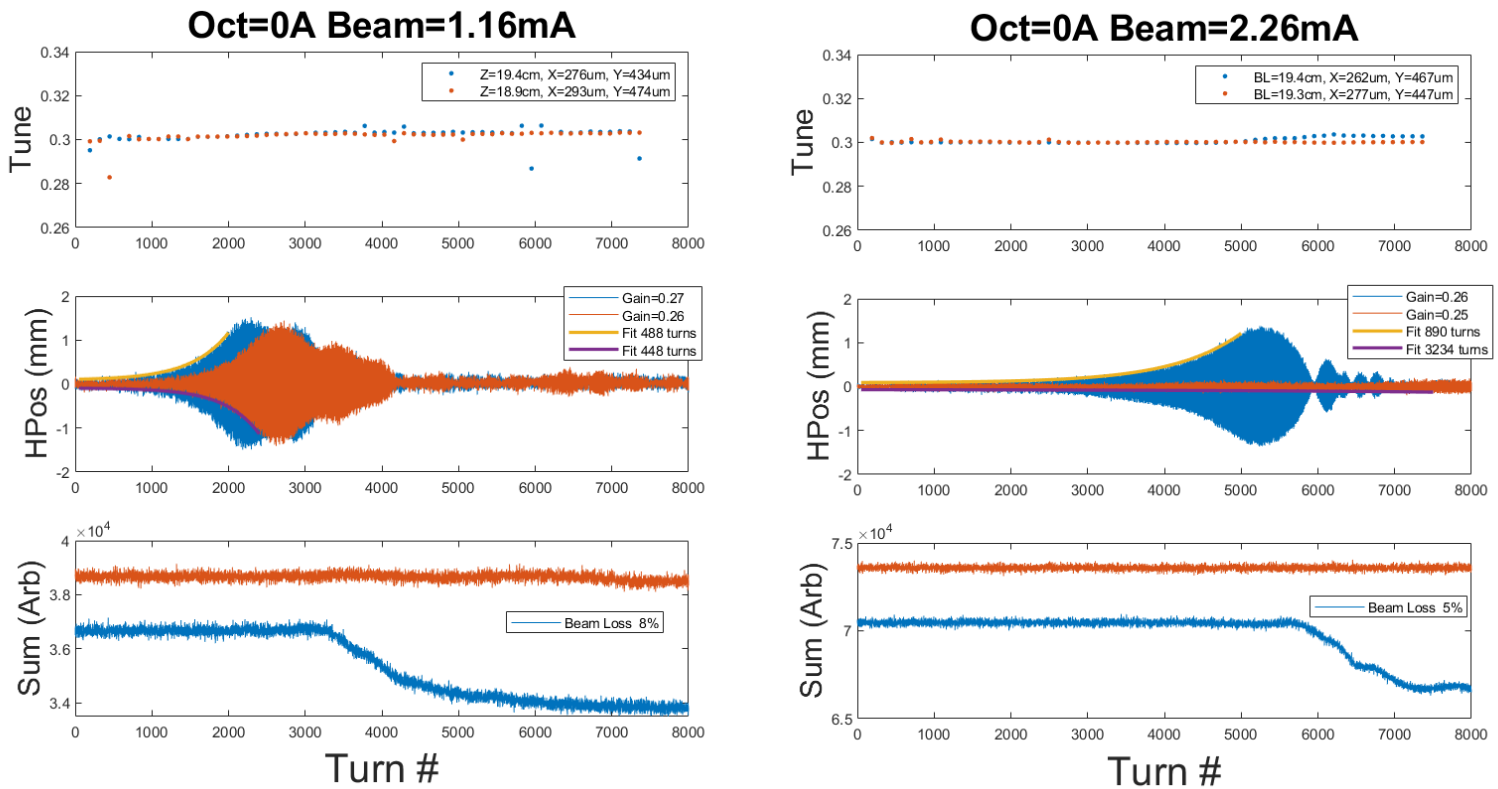
Instability Threshold vs Octupole Current

- Landau damping is sensitive to tails in the beam distribution which are scraped away during an instability with beam loss
- For threshold instability, just the first loss event per store is used
- Observe increase in the threshold with octupole
- At 2A see factor of 2 increase in agreement with Run I



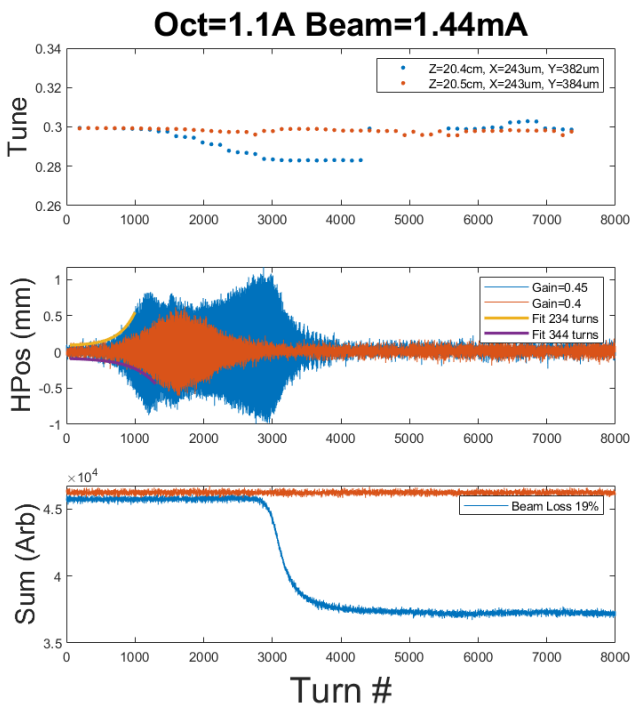


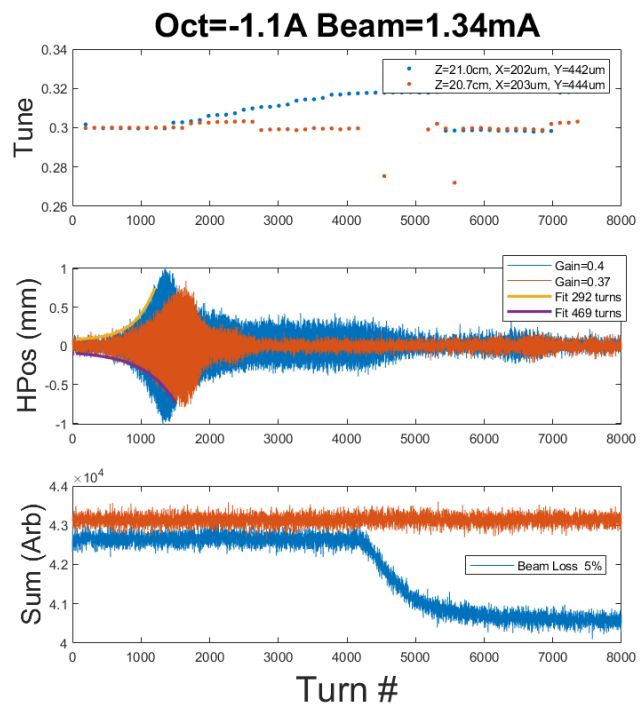
TBT Data Analysis – Octupoles Off



- Measure tune, gain, growth rate, and loss

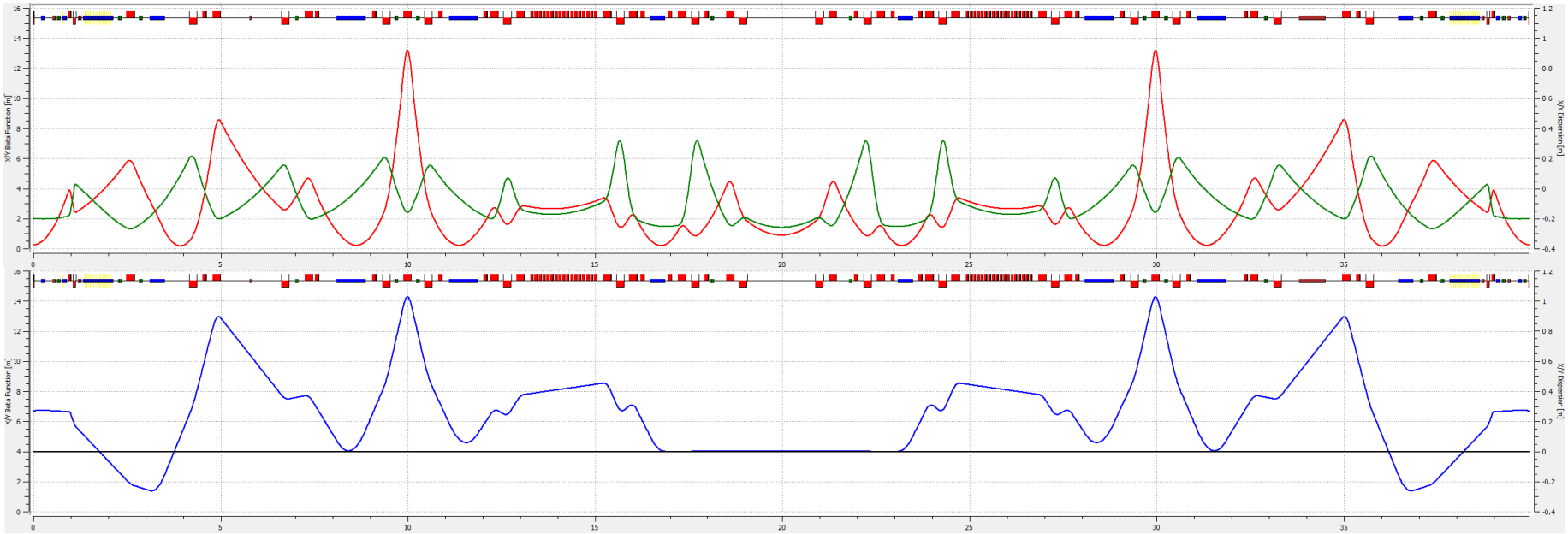
TBT Data Analysis – QI Octupoles On





- Tune shift direction dependent on octupole sign
- Only see beam loss when tune shifts (always at 0.02 change)

OSC-lattice design for 950nm

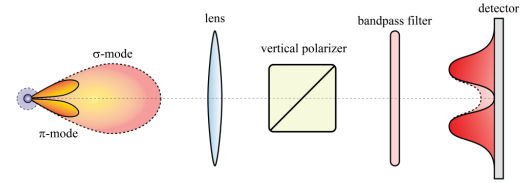


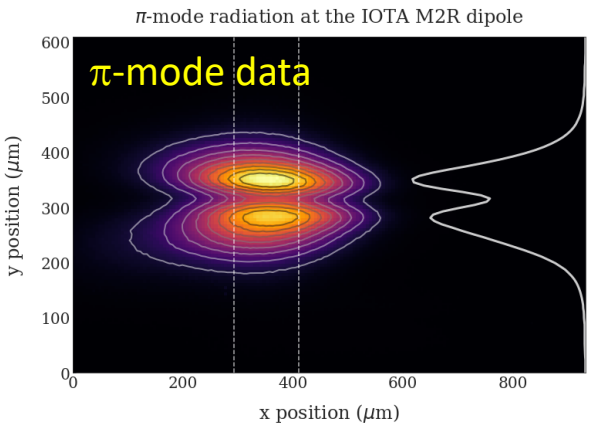
Betas start, x,y	25, 200 cm
D_x start	27 cm
Tunes, x,y	5.42, 2.42
Mom. compaction factor	0.00172
Mode emittances	0.426 / 0.423 nm
Natural chromaticity (x,y)	-10.2 / -8.1

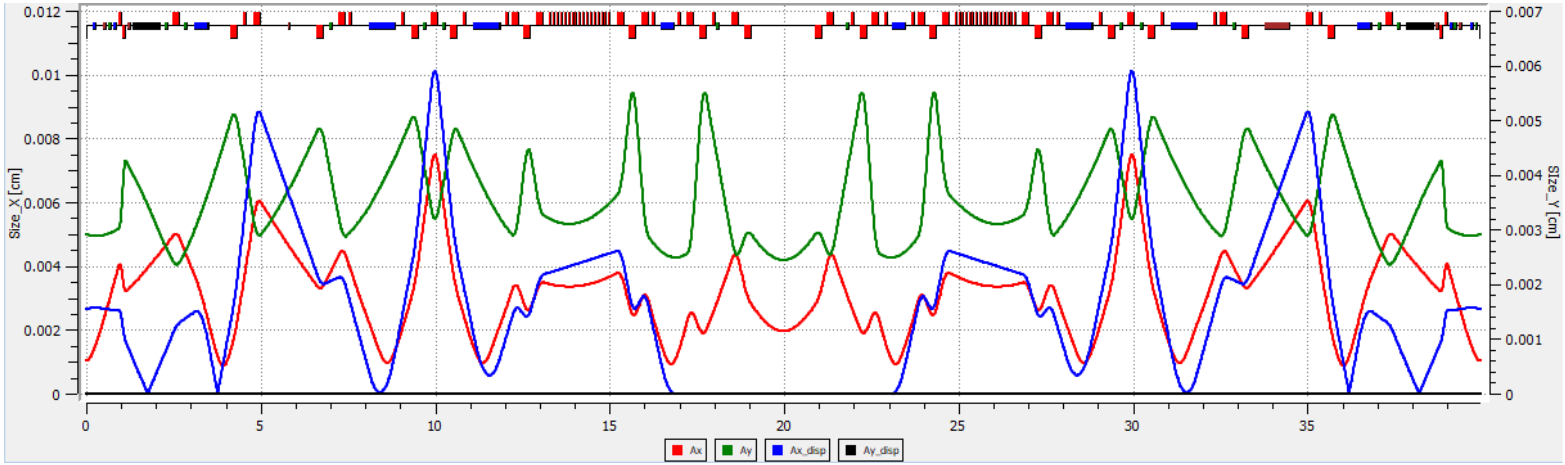
Energy drop	12.7 eV
Bunch length @70V	3.9 cm
Energy spread	0.99 E-4
Sync. Tune/freq. @70V	2.72 E-5 / 204 Hz
Emitt. damp. times (x,y,s)	(1.056,1.056,0.519) s
Chrom. from OSC sextupoles	29.2 / -20.9

Expanding IOTA's emittance diagnostics for OSC

- Want several ways to measure the evolution of small emittances (~0.5 nm)
  - Direct imaging ~50 μm)
  - π-mode imaging (~5-μm to <100μm)
  - sync-rad. interferometry (~10-100's μm)
- **Tested π-mode prototype in run #1**
- Some additional calibration measurements and simulations needed







Organization

Accelerator Division

Mike Lindgren, Head

Mary Convery, Deputy

Office of the CRO

Luciano Ristori, CRO

Sergei Nagaitsev, Head of Accel Science Programs

AD Accelerator S&T sector

A. Valishev, Head
(S. Nagaitsev), Accel. science lead

FAST Facility Dept.

D.Broemmelsiek, Head

Develop, operate, maintain FAST facility

Support the IOTA/FAST experimental program

Accelerator Research Dept.

G.Stancari, Head

Develop and carry out IOTA/FAST experimental program

Accelerator Physics Support Dept.

R&D in support of Fermilab's complex operations

R&D for future facilities

Accelerator Education

PhD program
Summer internships
USPAS