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Stabilizing slip stacked beam in the Recycler and IOTA research program

Rob Ainsworth

APEC18

11th December 2018

Outline

- Damping instabilities related to slip stacking
  - Accelerator complex
  - Slip-stacking
  - Bunch by bunch damper system
    - Issues
  - Slip stack damper
- Pushing to high intensities
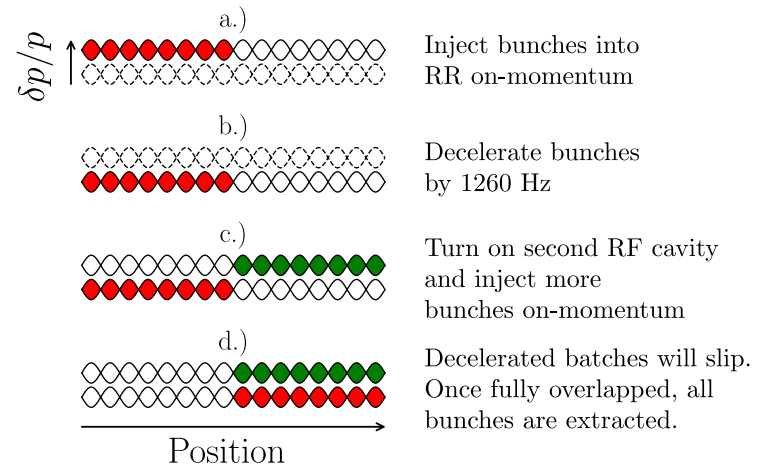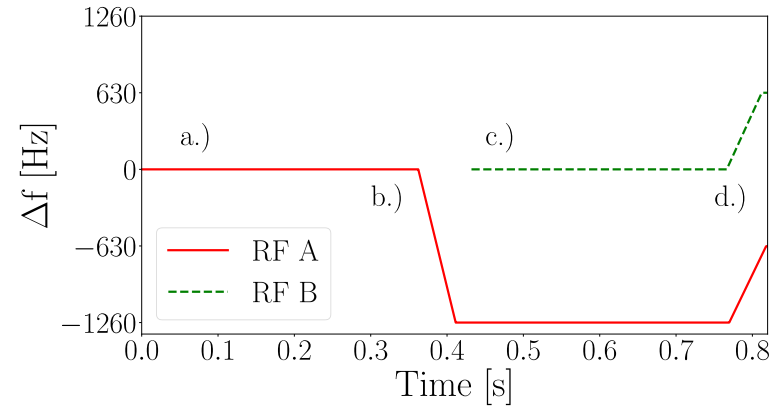 - Non linear integrable optics
  - FAST/IOTA

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Accelerator complex

- H⁻ linac
- Booster
  - h = 84
  - 15 Hz
  - 400 MeV -> 8 GeV
- Recycler
  - h = 588
  - Slip-stack 12 batches (double bunch intensity)
- Main Injector
  - 8 GeV -> 120 GeV

Fermilab Accelerator Complex
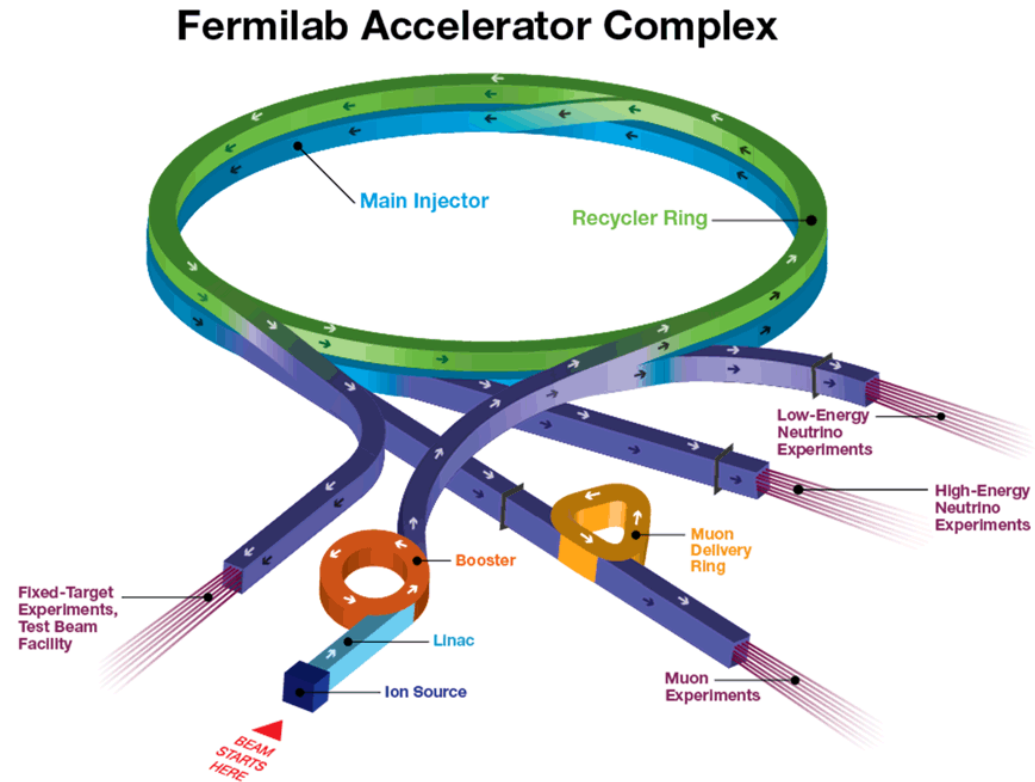
Slip stacking

- Slip-stacking allows us to double the intensity of the bunches in the Recycler

$$\Delta f = h_b f_b$$

Inject bunches into RR on-momentum

Decelerate bunches by 1260 Hz

Turn on second RF cavity and inject more bunches on-momentum

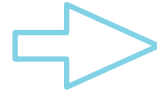Decelerated batches will slip. Once fully overlapped, all bunches are extracted.
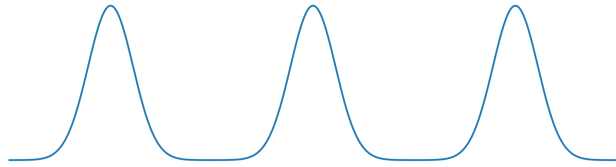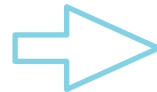
🔷 **Fermilab**
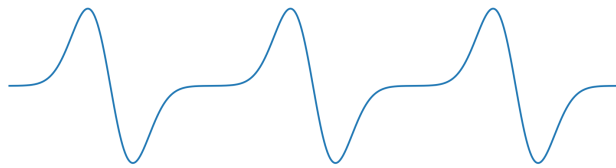
Resistive wall instability

- Impedance of beam pipe can lead to instability

- Can be stabilized with chromaticity

- Alternatively, with a damper system

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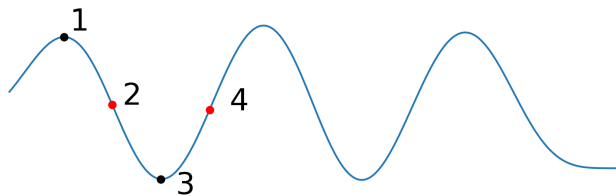
Bunch by bunch damper

Bunches time structure

As measured with stripline

70MHz Low Pass Filter

$$1 - 3 = Q$$
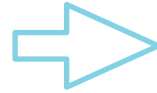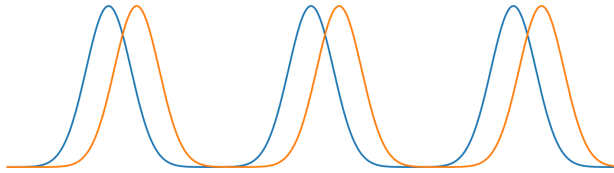
$$2 - 4 = I$$

Intensity x position

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Bunch by bunch damper during slip-stacking

Slip stacked bunches time structure

As measured with stripline

70MHz Low Pass Filter

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Bunch by bunch damper during slip-stacking

Slip stacked bunches time structure

As measured with stripline

70MHz Low Pass Filter

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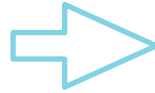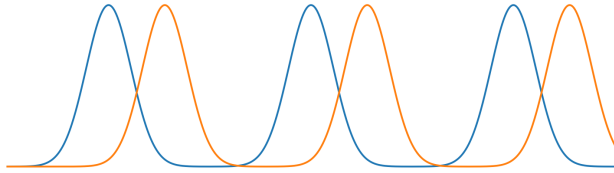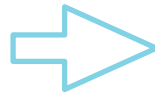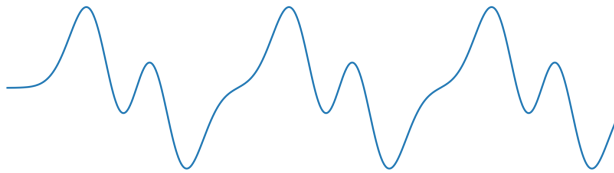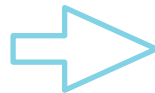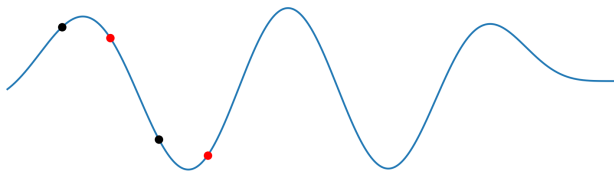
Bunch by bunch damper during slip-stacking
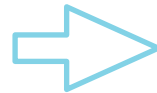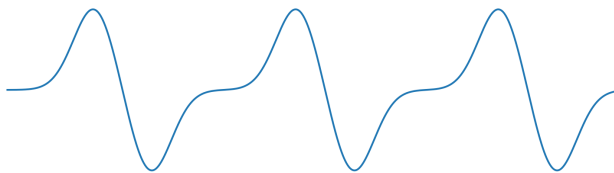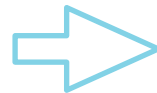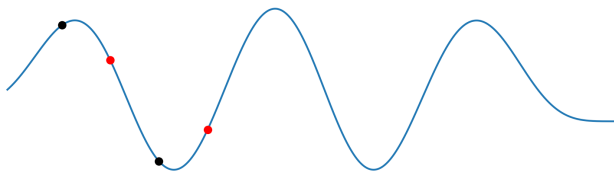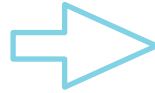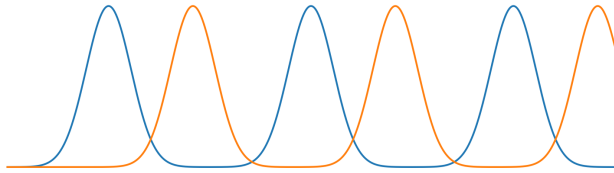
Slip stacked bunches time structure
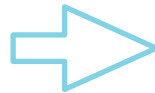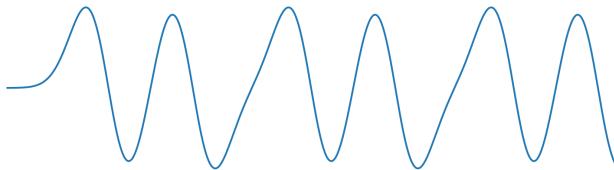
As measured with stripline
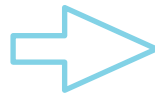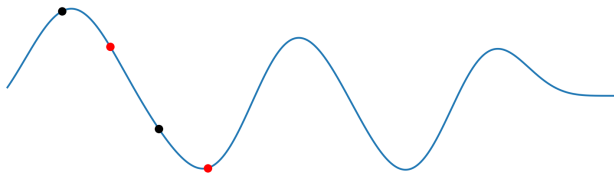
70MHz Low Pass Filter

No longer makes sense for slip stacked beam!

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Typical 6+6 cycle - 2016

- 6 batches injected and then decelerated
- Further 6 injected
    - Bunch by bunch damper systems turn off (cannot deal with slipping)
    - Chromaticity raised to control resistive wall instability
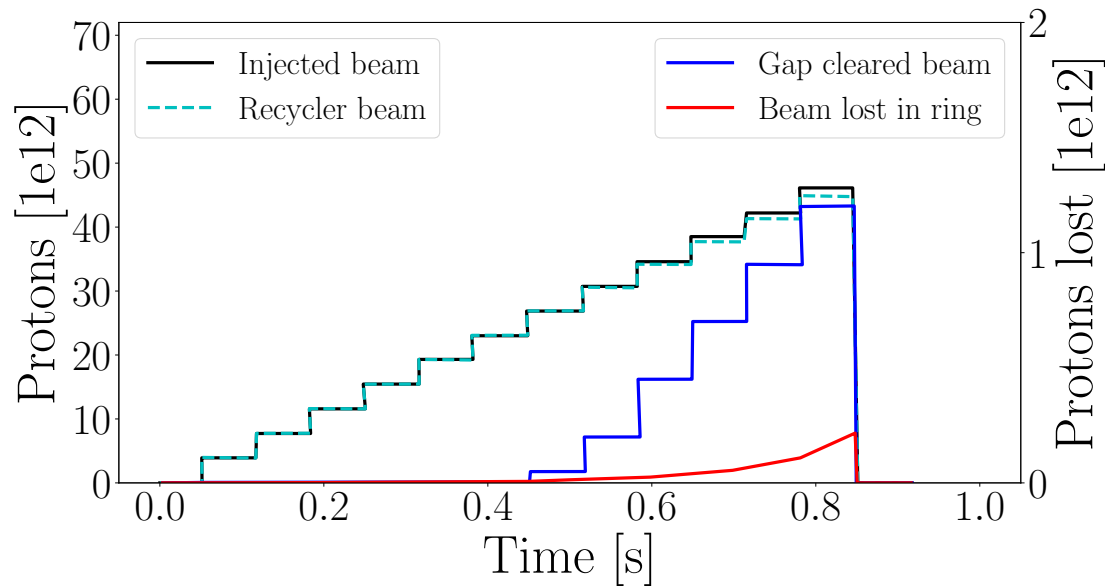
High Chromaticity running
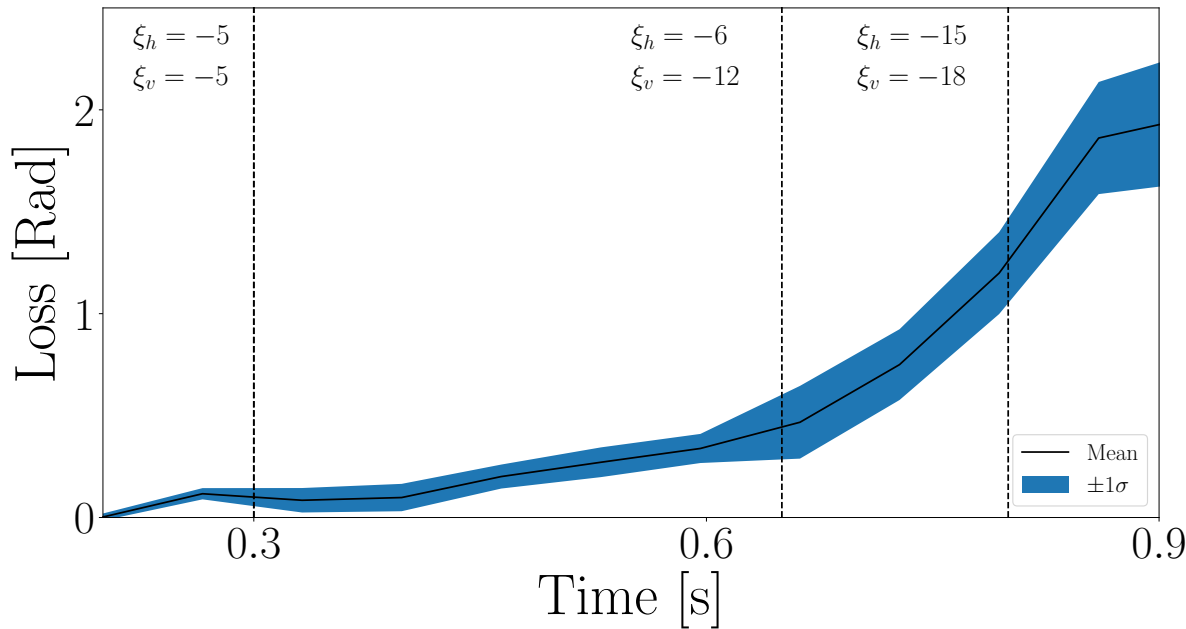
Exponential increase in losses as chromaticity increases

High chromaticity constrains tune space due to off-momentum beam

$$\Delta Q = \xi \delta p / p$$

at -5, tune shift ~0.013

at -20, tune shift ~0.048

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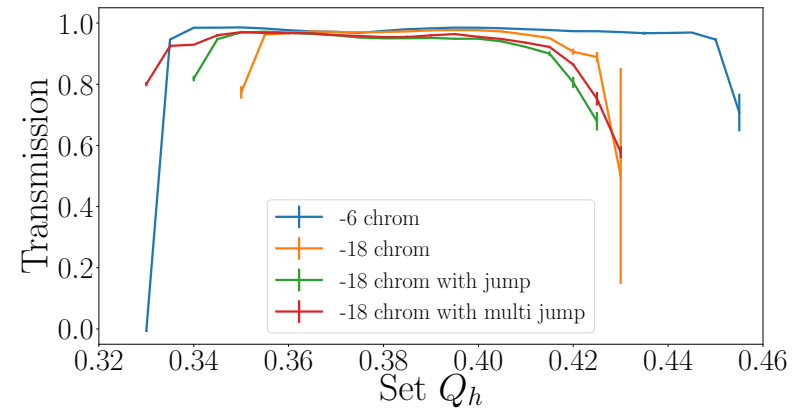
Slip stack damper

- For slip-stacking, the growth rate for the sum mode (bunches performing the same motion) is much larger than the difference mode
  - A lower bandwidth damper looking at the envelope could be sufficient
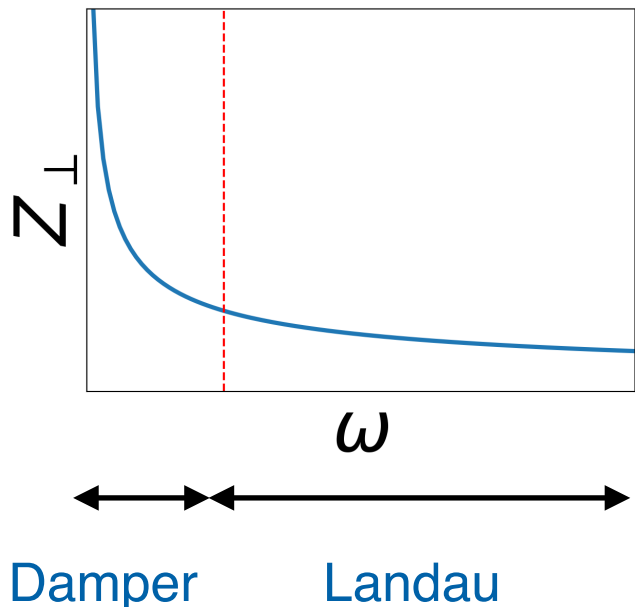
Coupled-beam and coupled-bunch instabilities

A. Burov[*]

Fermilab, P.O. Box 500, Batavia, Illinois 60510-5011, USA

A problem of coupled-beam instability is solved for two multibunch beams with slightly different revolution frequencies, as in the Fermilab Recycler Ring (RR). Sharing of the interbunch growth rates between the intrabunch modes is described. The general analysis is applied to the RR; possibilities to stabilize the beams by means of chromaticity and feedback are considered.
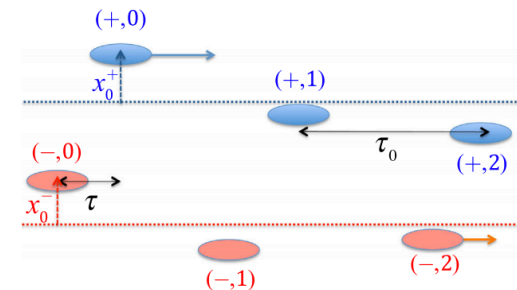
Diode damper

- Damper system developed based on Direct Diode Detection (3D) concept

- Bandwidth ~ 2.5 MHz

- System implemented in Jan 2017. The new damper system turns on during the cycle as the bunch by bunch dampers turn off.

HIGH SENSITIVITY TUNE MEASUREMENT BY DIRECT DIODE DETECTION

M. Gasior, R. Jones, CERN, Geneva, Switzerland
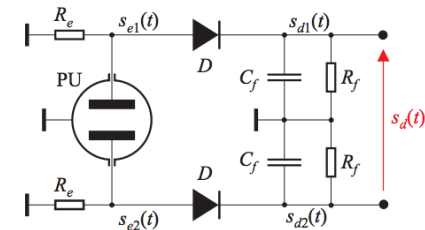
Figure 1: Direct Diode Detection principle.
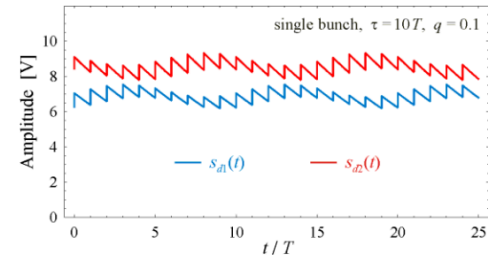
Figure 2: An example of peak detector voltages.
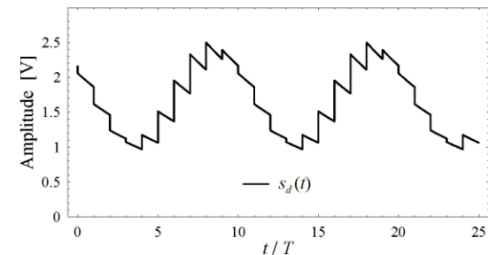
Figure 3: Difference of the signals in Fig. 2.

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Diode damper

Diode damper allowed final chromaticity to be reduced from -20 to -7

45E12 ppp   45E12 ppp
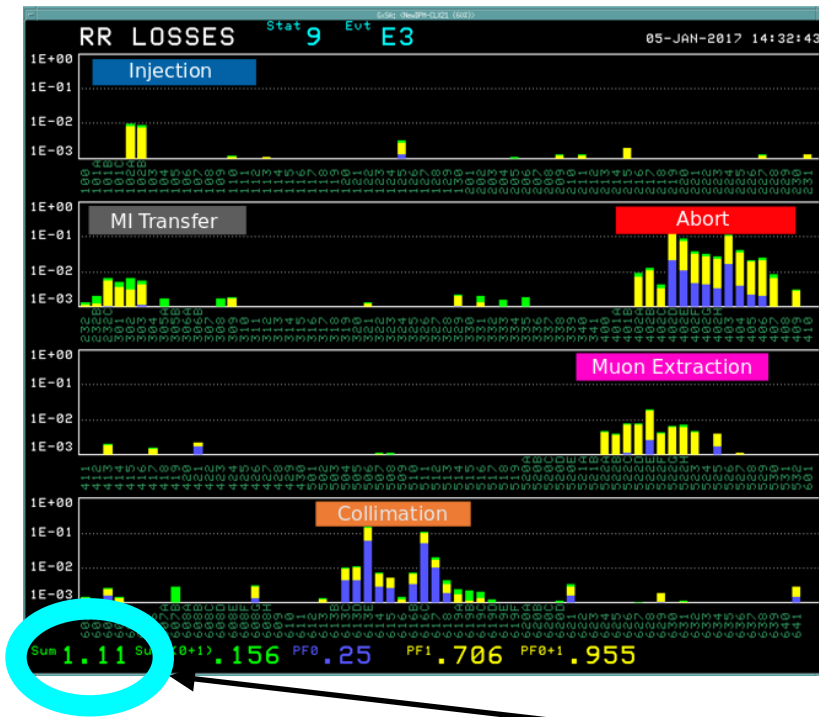
Loss sum reduced by factor of 2

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Damper questions

- The implementation of the new damper system allowed operation at much lower losses and was key to stable running for 700 kW operations
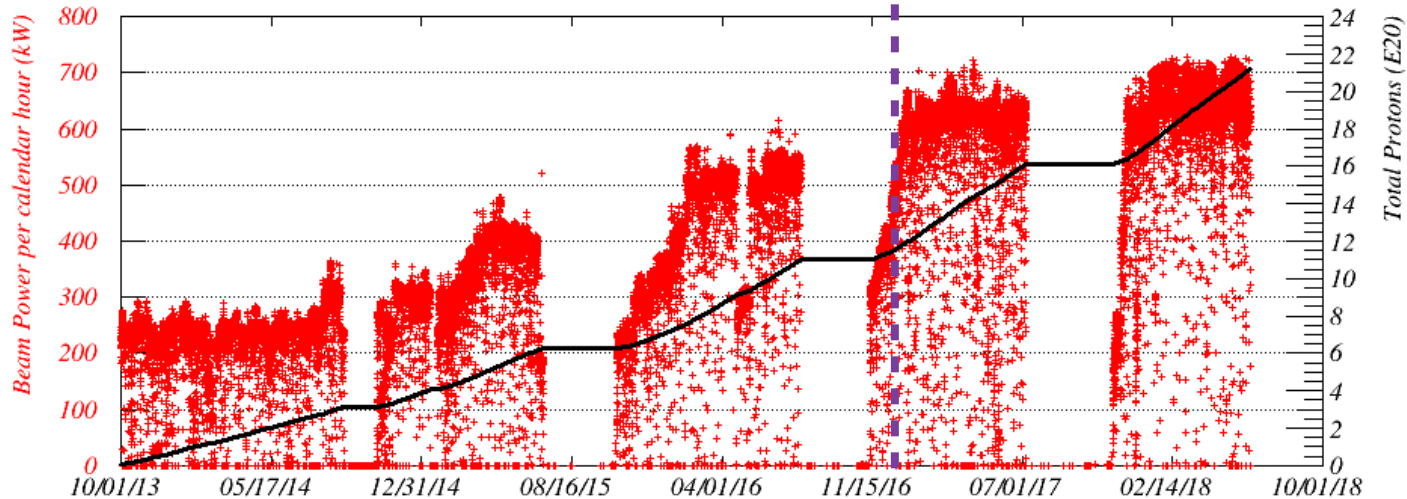
- Some questions remain
  - What is the maximum bandwidth the damper can operate at?
  - What is the max intensity for which Landau damping is sufficient for the higher frequency modes

Problems at higher intensity

- As intensity is increased, some concerns are
  - Coherent instabilties
  - Increased space charge effects

- Resonance compensation

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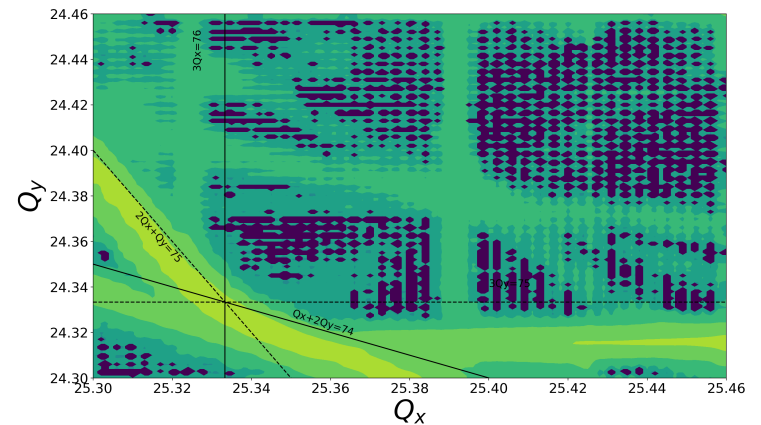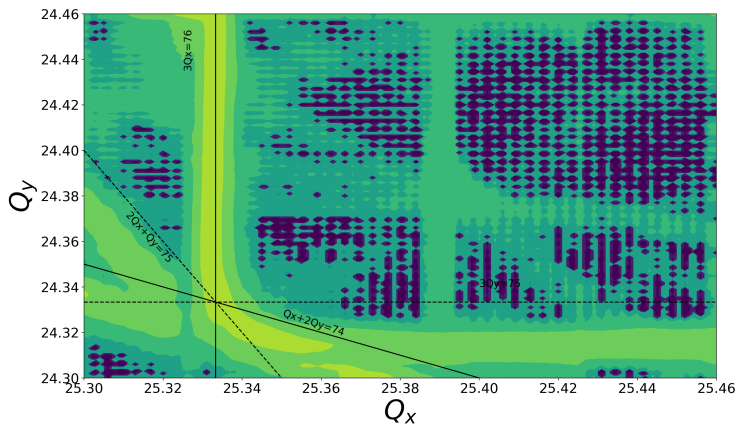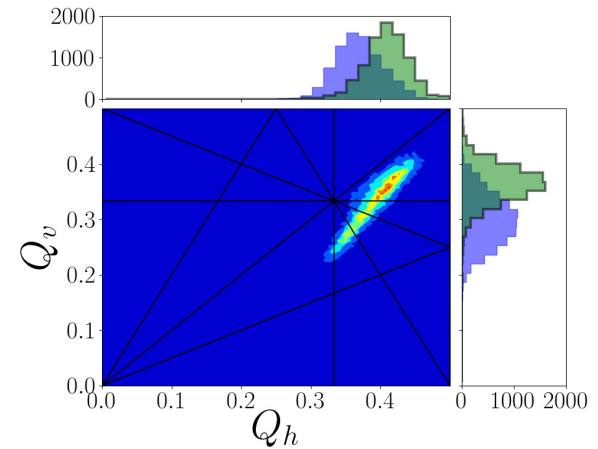
Beam Focusing in Accelerators
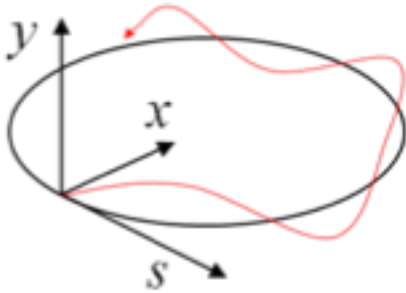
$$H(J_1, J_2) = \nu_x J_1 + \nu_y J_2$$

- Nonlinear terms are unavoidable and can be intentional/unintentional and can help/harm the beam:
  - Sextupoles are used for chromaticity compensation
  - Particles tunes are randomized with octupoles to enhance Landau damping for suppression of collective instabilities
  - At the same time most nonlinearities shrink stable region in the phase space by creating chaos for particles with high amplitudes
- Can we attempt to leave linear focusing behind?
  - Build machines that are nonlinear by design but stable (like Solar system)

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Motivation for Nonlinear Integrable Optics

- We want to build an optical focusing system that
    - A. Is strongly nonlinear = strong dependence of oscillation frequency on amplitude
    - B. Is 2D integrable and stable
    - C. Can be realized with magnetic fields in vacuum

- Mathematically, that means the system should
    - Possess **two integrals of motion**
    - Field potential satisfies the Laplace equation

- Practical **benefits** relevant to future HEP machines
    - Reduced chaos in single-particle motion, e.g. helpful for space-charge suppression
    - **Higher beam current and brightness** from strong immunity to collective instabilities via Landau damping

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Nonlinear Integrable Optics - Implementation

Danilov-Nagaitsev Solution (2010)

1. Remove time dependence from Hamiltonian thus making it an integral of the motion

   • Can be done with any nonlinear potential, for example <u>octupoles</u>

2. Shape the <u>nonlinear</u> potential to find a second integral

   • General solution was found, which satisfies the Laplace equation (Phys. Rev. ST Accel. Beams 13, 084002, 2010)

1 cm
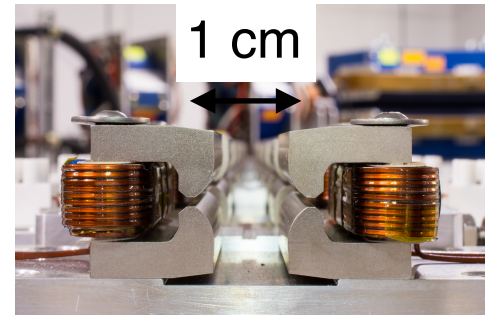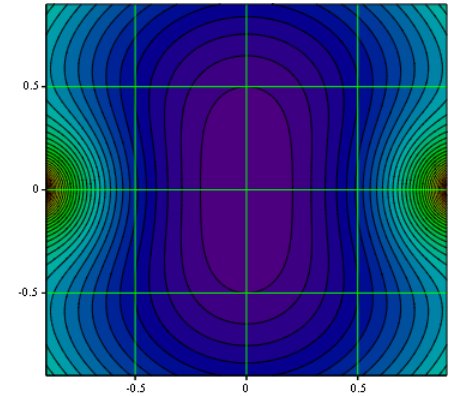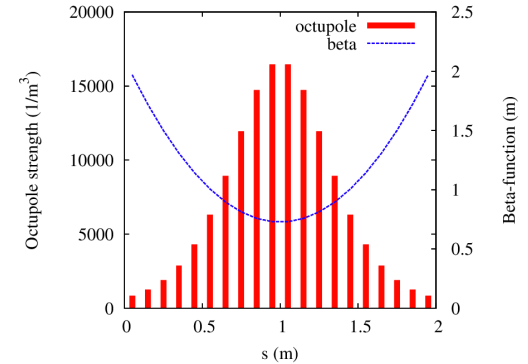
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Fermilab Accelerator Science and Technology
FAST facility – unique set of capabilities
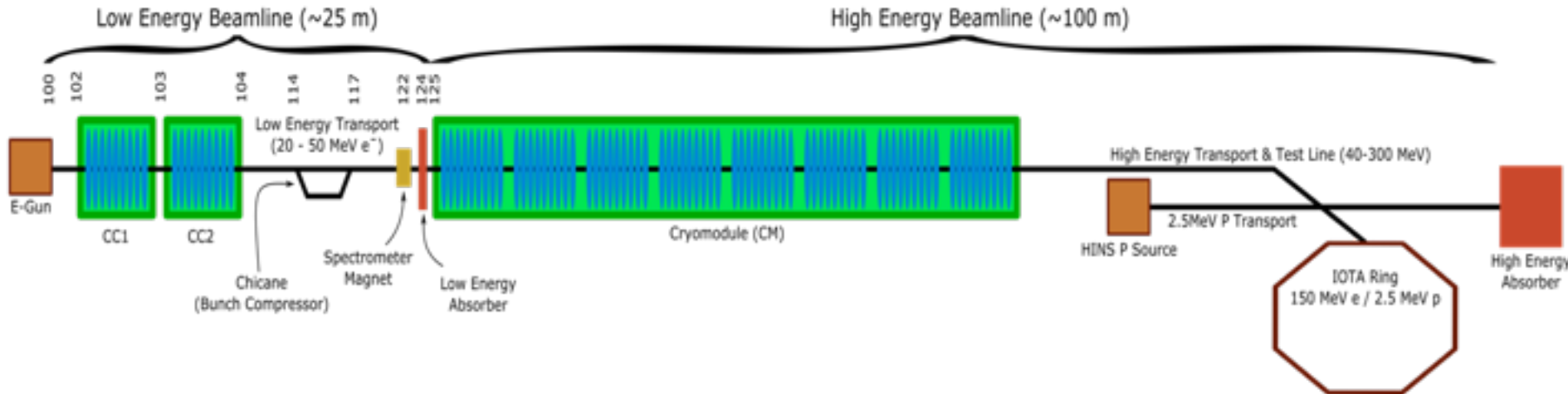
IOTA ring (completed 2018) – **the only accelerator R&D ring of its kind**
- Protons or electrons
- Highly flexible, precise

SRF electron linac (completed 2017)
- Full ILC beam parameters
- **World record SRF beam accelerating gradient > 31.5MV/m**

Proton RFQ (future addition – 2020)
- High current / high space-charge

Together – positioned to advance beam brightness and intensity

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Fermilab Accelerator Science and Technology
FAST facility – Injectors
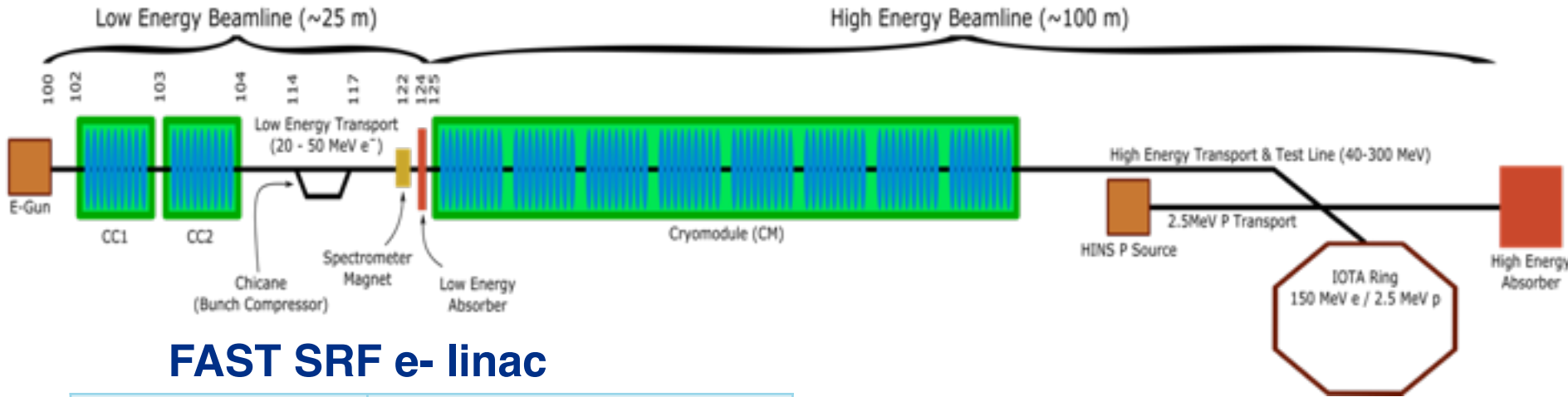
FAST SRF e- linac

Bunch charge	up to 2 nC
Gun gradient	45 MV/m
CC1 gradient	26 MV/m
CC2 gradient	15 MV/m
CM2 gradient	up to 31.5 MV/m
Beam energy	150 MeV (up to 300)
Bunch length	6-8 ps (rms)
Pulse length	1 ms
Bunch freq.	3 MHz
Rep. rate	1 Hz (5 Hz)

FAST proton injector (future)

Particles	proton
Kinetic Energy	2.5 MeV
Momentum	69 MeV/c
B (v/c)	0.073
RF Structure	325 MHz
Beam current	10 mA
Emittance	0.3 mm mrad
Rep. rate	1 Hz
Pulse length	1.5 µs
$\triangle Q_{sc}$ in IOTA	-0.5

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Centerpiece of FAST Integrable Optics Test Accelerator

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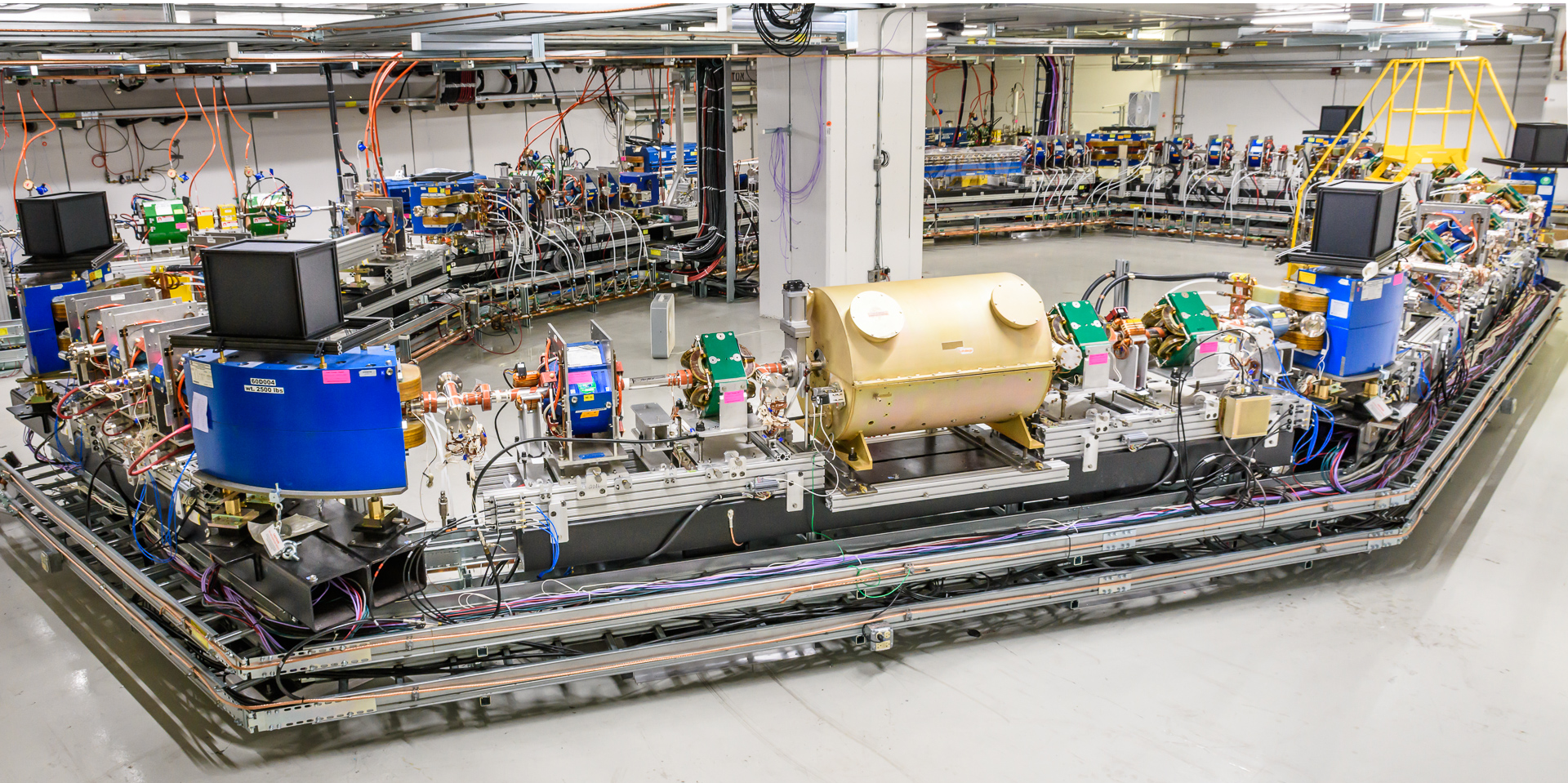
Integrable Optics Test Accelerator – Unique R&D Machine

- **Flexible**
  - Can operate with either electrons or protons
  - Easily reconfigurable – quick-change experimental equipment
  - Significant flexibility

- **Precise**
  - Precise control of the optics quality and stability
  - Comprehensive set of precision instrumentation
  - Set up for very high intensity operation (with protons)

- **Affordable**
  - Cost-effective solution, re-use existing parts whenever possible
  - Mostly based on conventional technology (magnets, RF)
  - Balance between low energy (low cost) and research potential

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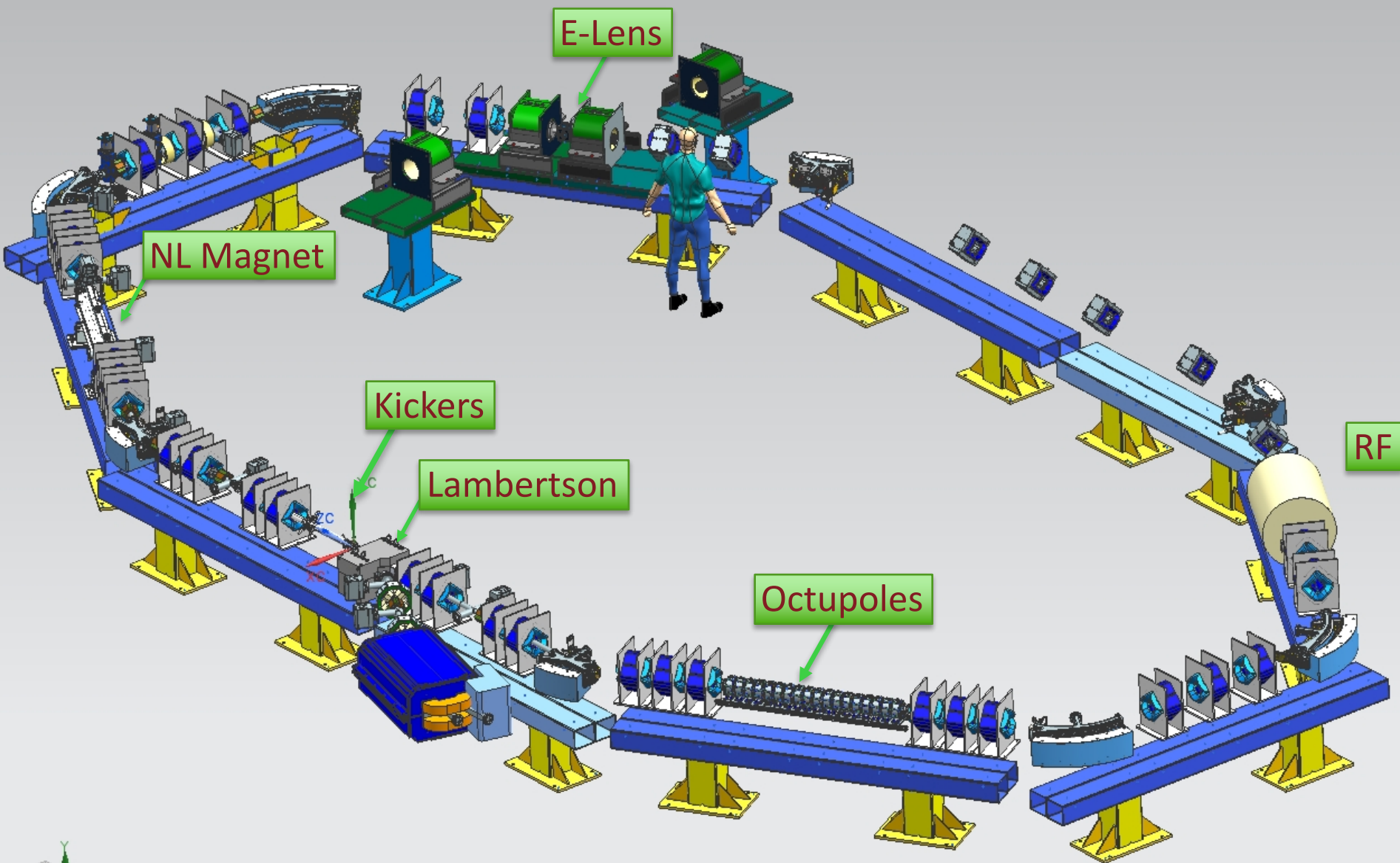
E-Lens

NL Magnet

Kickers

Lambertson

Octupoles

RF
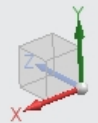
IOTA Parameters

	Electrons	Protons
Nominal kinetic energy	150 MeV	2.5 MeV
Nominal intensity	1×10^9	1×10^{11}
Circumference	40 m	
Bending dipole field	0.7 T	
Beam pipe aperture	50 mm dia.	
Betatron tune	3-5	
Beam size (rms, x,y)	0.05 - 0.5 mm	5 - 15 mm
Transverse emittance r.m.s.	0.04 mm	2 mm
Synchrotron Radiation damping time	0.6s, 5×10^6 turns	
Synchrotron tune	$2-5 \times 10^{-4}$	
Bunch length, momentum spread	12 cm, 1.4×10^{-4}	
Beam pipe vacuum	$2-4 \times 10^{-10}$ Torr	
Beam lifetime	1-10 hour	1-10 min

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FAST/IOTA Timeline

✔ 5 MeV e- beam 2015

✔ 50 MeV e- beam 2016

  - First experimental journal publication

✔ 300 MeV e- beam   2017

  - Beam accelerated in ILC-type CM

  - experimental program at FAST

✔ IOTA commissioned with e- 2018

  - 1st IOTA experiments began

• p+ beam in IOTA   2020

• Research   2018-2023

JINST 12 T03002 (2017)

IOTA (Integrable Optics Test Accelerator): facility and experimental beam physics program

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ABSTRACT: The Integrable Optics Test Accelerator (IOTA) is a storage ring for advanced beam physics research currently being built and commissioned at Fermilab. It will operate with protons and electrons using injectors with momenta of 70 and 150 MeV/c, respectively. The research program includes the study of nonlinear focusing integrable optical beam lattices based on special magnets and electron lenses, beam dynamics of space-charge effects and their compensation, optical stochastic cooling, and several other experiments. In this article, we present the design and main parameters of the facility, outline progress to date and provide the timeline of the construction, commissioning and research. The physical principles, design, and hardware implementation plans for the major IOTA experiments are also discussed.

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Accelerator Science at IOTA/FAST

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

   - Nonlinear Integrable Optics
     - Suppression of coherent instabilities
     - Impedance controlled (protons)
   - Optical Stochastic Cooling
   - Space-charge compensation

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

   - Radiation generation
   - High average current experiments
   - Complementary to FACET-II
   - Suitable for LCLS-II commissioning, MARIE and EIC R&D
   - Studies on the quantum nature of synchrotron radiation

Fermilab Integrable Optics Test Accelerator (IOTA)
Oct. 31, 2018

G. Stancari for the IOTA team

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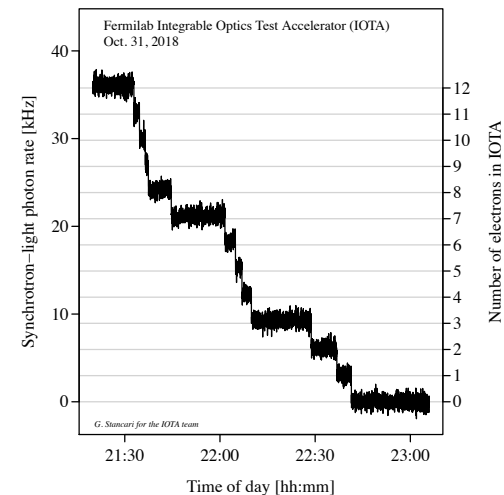
IOTA Accelerator and Beam Physics Roadmap

1. **Complete the construction of IOTA/FAST facility**
    1. Install and commission IOTA proton injector 2020*
2. **Conduct R&D in IOTA** with the goal to develop enabling technologies for next-generation facilities
    1. Nonlinear Integrable Optics (aim to improve beam stability / losses)
        – Phase I – e- beam 2018–2021
        – Phase II – p beam 2020–2022
    2. Optical Stochastic Cooling (enable p-beam cooling at high energy)
        – Without optical amplifier 2019–2021
        – With optical amplifier 2021–2023
    3. Space-charge Compensation (aim to reduce space-charge losses)
        – Using electron lens 2020–2023
        – Using electron column 2022–2023
3. **Expand IOTA/FAST collaboration**, establish AS User Facility 2019–2023

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Summary

- One of the major hurdles in running high intensity slip stacked beam was overcome with the implementation of a new damper system

- As the intensity is pushed higher, it will be harder to run with minimal losses
  - Coherent instabilities
  - Space charge effects

- A move to nonlinear integrable optics could pave the way for better stability at high intensity

- IOTA will aim to demonstrate this

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Backup

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Why Dedicated Facility?

- 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

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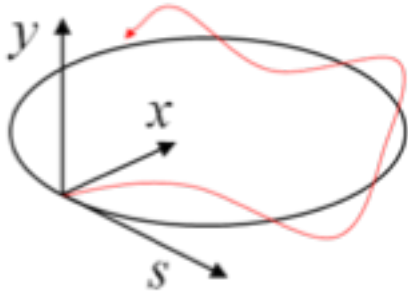
$$H = c\left[m^2 c^2 + \left(\mathbf{p} - \frac{e}{c}\mathbf{A}\right)^2\right]^{\frac{1}{2}} \qquad H' \approx \frac{p_x^2 + p_y^2}{2} + \frac{K_x(s)x^2}{2} + \frac{K_y(s)y^2}{2}$$

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

- Nonlinear terms are unavoidable and can be intentional/unintentional and can help/harm the beam:
  - Sextupoles are used for chromaticity compensation
  - Particles tunes are randomized with octupoles to enhance Landau damping for suppression of collective instabilities
  - At the same time most nonlinearities shrink stable region in the phase space by creating chaos for particles with high amplitudes
- It has been **experimentally demonstrated** that systems with one integral of motion are **more stable**:
  - 1/2-integer working point in colliders (KEK, 2004)
  - Crab-crossing at DAFNE (INFN/LNF, 2008)
  - Round colliding beams (BINP, 2011)

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Nonlinear Integrable Optics - Implementation

- Danilov-Nagaitsev Solution (2010)
    1. Remove time dependence from Hamiltonian thus making it an integral of the motion
        - Can be done with any nonlinear potential, for example <u>octupoles</u>
    2. Shape the <u>nonlinear</u> potential to find a second integral
        - General solution was found, which satisfies the Laplace equation (Phys. Rev. ST Accel. Beams 13, 084002, 2010)
- 2D Expansion of McMillan mapping
    - Two invariants of the motion
    - Implementation with <u>electron lens</u>
    - The steepest Hamiltonian

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