Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Accelerator Physics
Beam Physics in Synchrotrons

Rob Ainsworth

User's meeting

10 August 2020

Outline

- Grand challenges of accelerator and beam physics
- How to increase intensity
  - Space charge issues
  - Mitigations in FNAL complex
  - Looking to the future – IOTA
  - Instabilities

- How to improve beam quality
  - Optical Stochastic cooling

Accelerator and Beam Physics Grand Challenges

- Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

- Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?

- Grand challenge #3 (beam control): How do we measure and control the beam distribution down to the level of individual particles?

- Grand Challenge #4 (beam prediction): How do we develop predictive “virtual particle accelerators”?

Grand Challenge #1

- Grand challenge #1 (beam intensity): How do we increase beam intensities by orders of magnitude?

- Important for FNAL accelerator complex as we try to increase beam power in the future

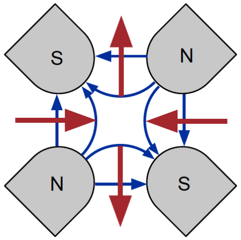
- Why is this a challenge?
  - Space charge - repulsive force between particles in a bunch
  - Instabilities

- But first, a quick intro to linear focusing and resonances

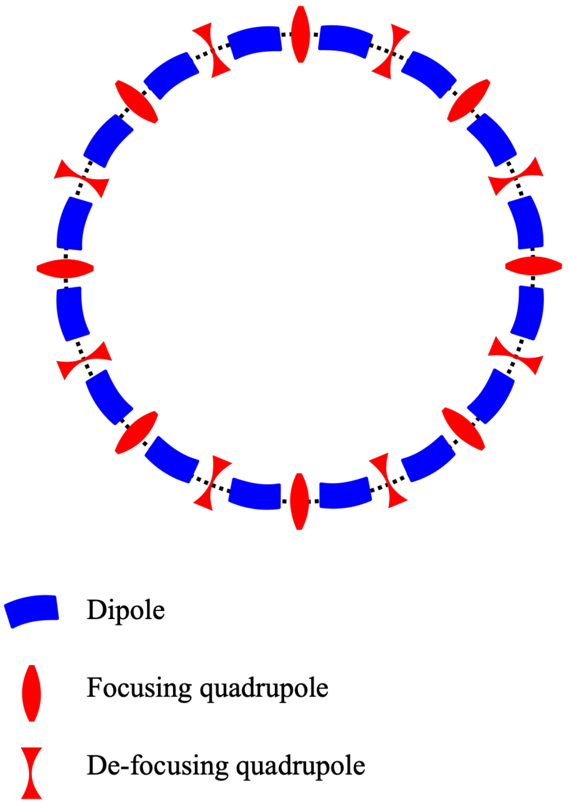
Linear focusing

- Dipole magnets to steer the beam

- Quadrupole magnets to focus the beam



- Quads focus in one plane and de-focus in the other

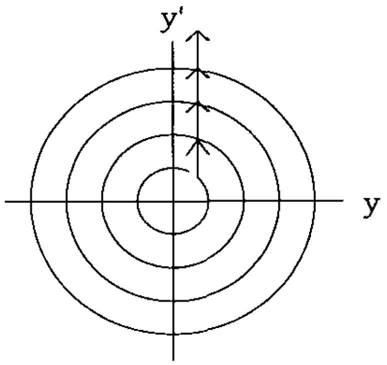


Betatron tune

- Alternating focusing means the beam oscillates as it goes around the ring
- **Betatron tune - The number of oscillations the beam makes in one revolution**
- For example, In the Fermilab Recycler, the horizontal tune is 25.44 and the vertical tune is 24.39
- The fractional part is very important!

Integer resonance

- Suppose the fractional part was zero i.e. the tune is an integer

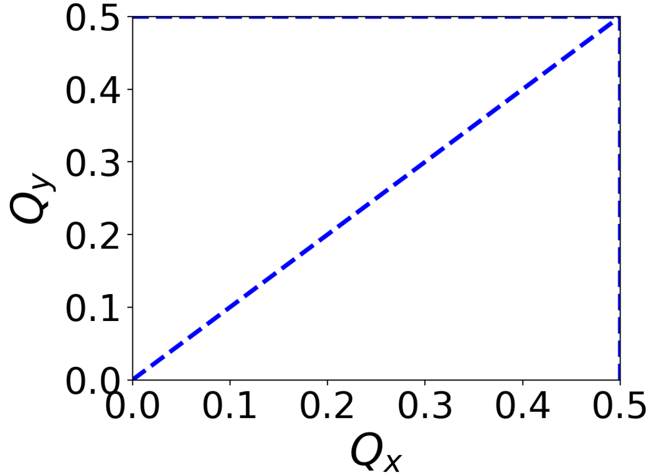


ν_v = integer

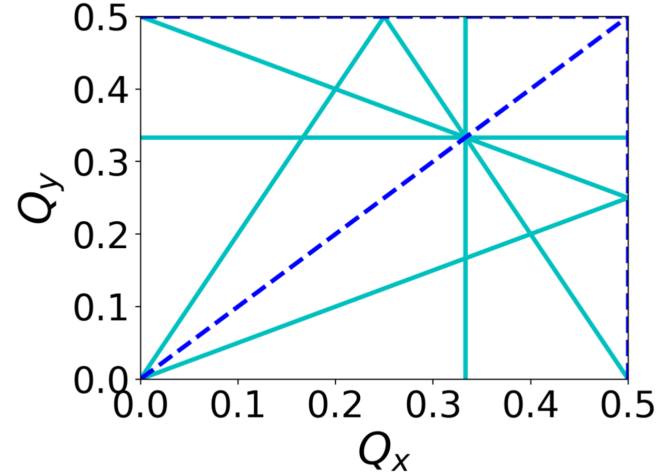
- If we have an error in a dipole magnet
- Particle would receive same kick every revolution
  - Eventually hit the beam pipe
  - Irradiate accelerator components

Resonances – many more possible

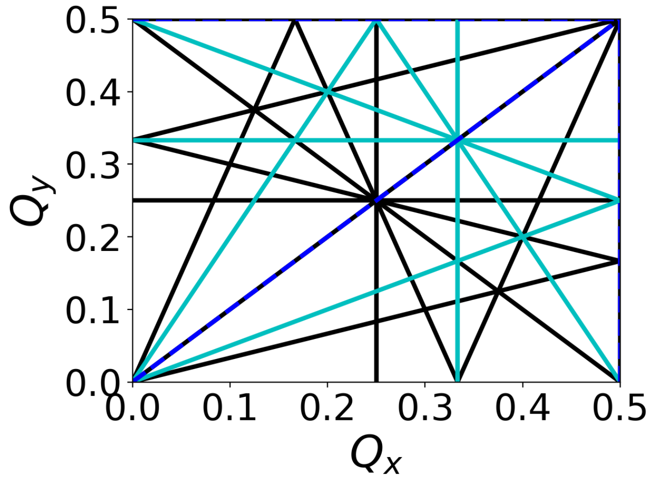
2nd order



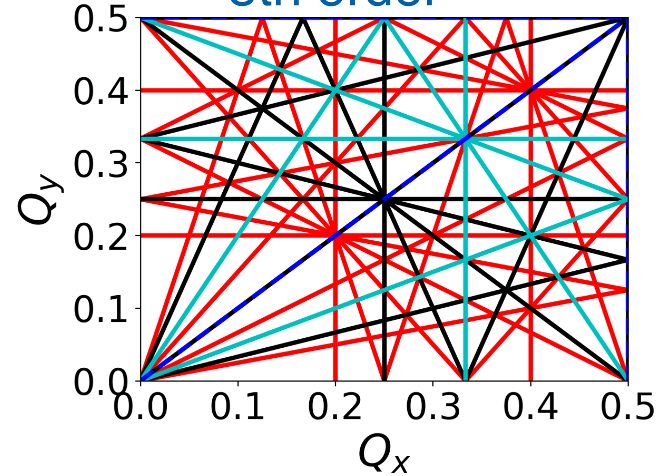
3rd order



4th order



5th order

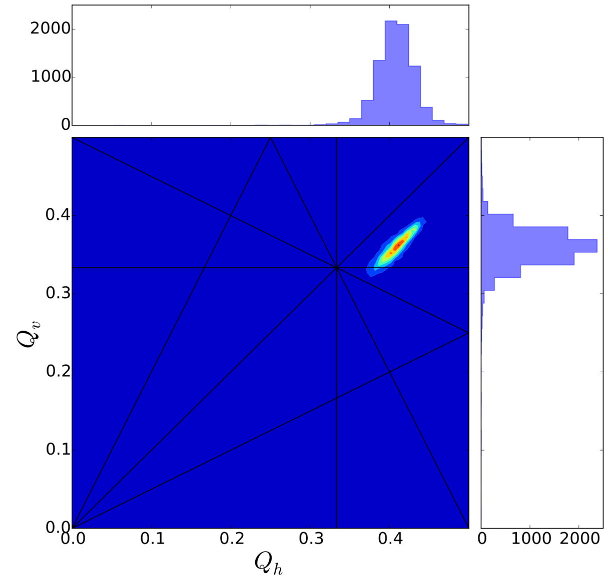


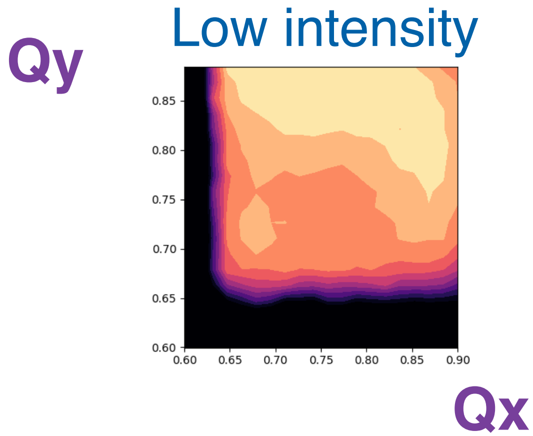
Fermilab

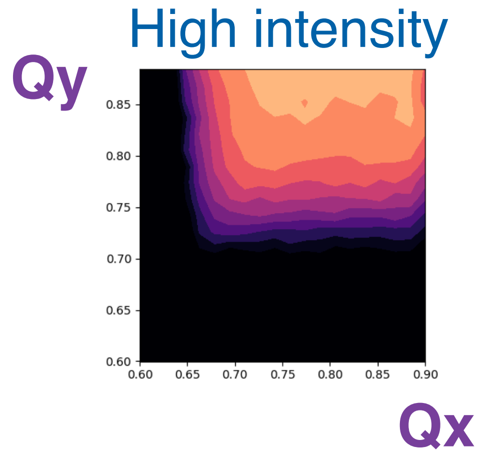
Intensity issues from space charge

Space charge

- Inside a bunch, each there is a spread of tunes
- Space charge increases this spread with intensity
  - More likely for particles to cross resonant lines
  - Reduction in available tune space







Example measurements In Booster

- effect of half-integer resonance

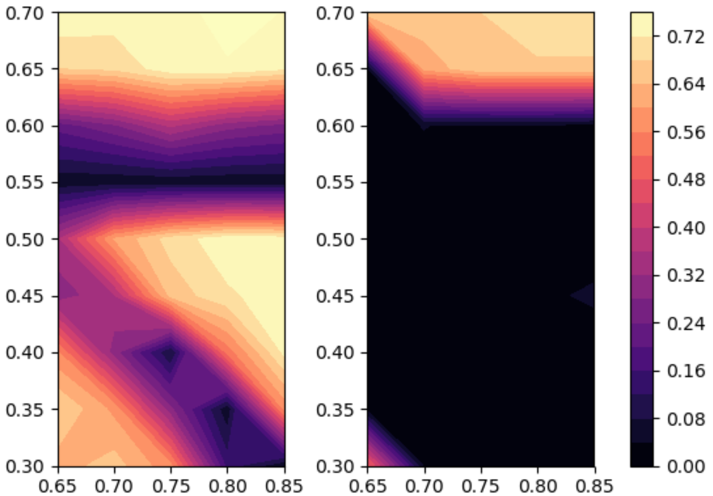
Difficult to compensate space charge

Actively trying to correct resonant lines in FNAL complex

Half integer correction in the FNAL booster

- The half integer resonance can be compensated using quadrupoles at appropriate locations

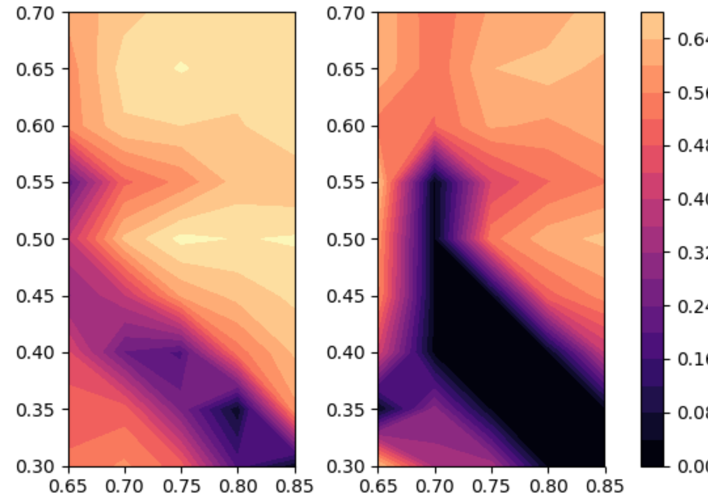
Before Correction



Early transmission

Late transmission

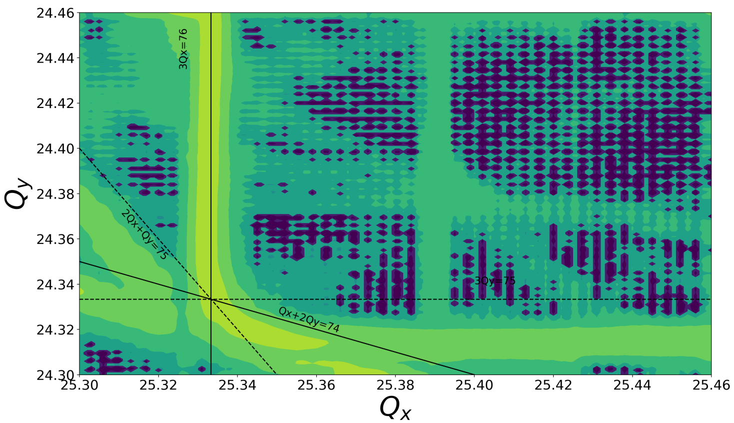
After Correction



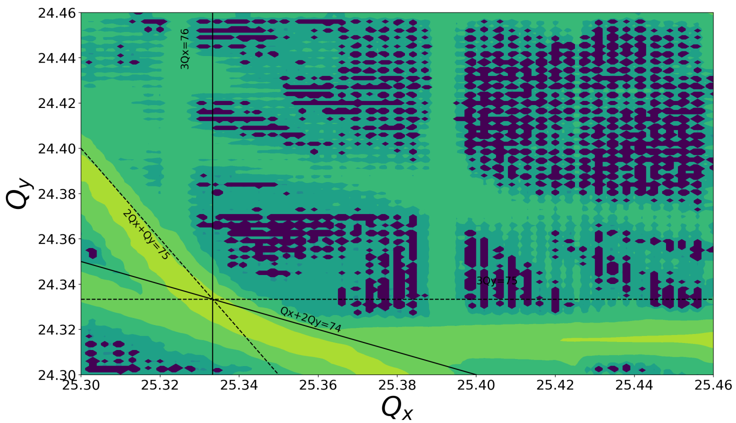
Third order compensation in FNAL Recycler

- Third order resonances can be compensated using sextupoles at appropriate locations

Before Correction



After Correction



- Side-effects – May make other lines stronger

Is there a better way?

- Compensating resonances is tricky
  - May drive other resonances
  - Multiple lines

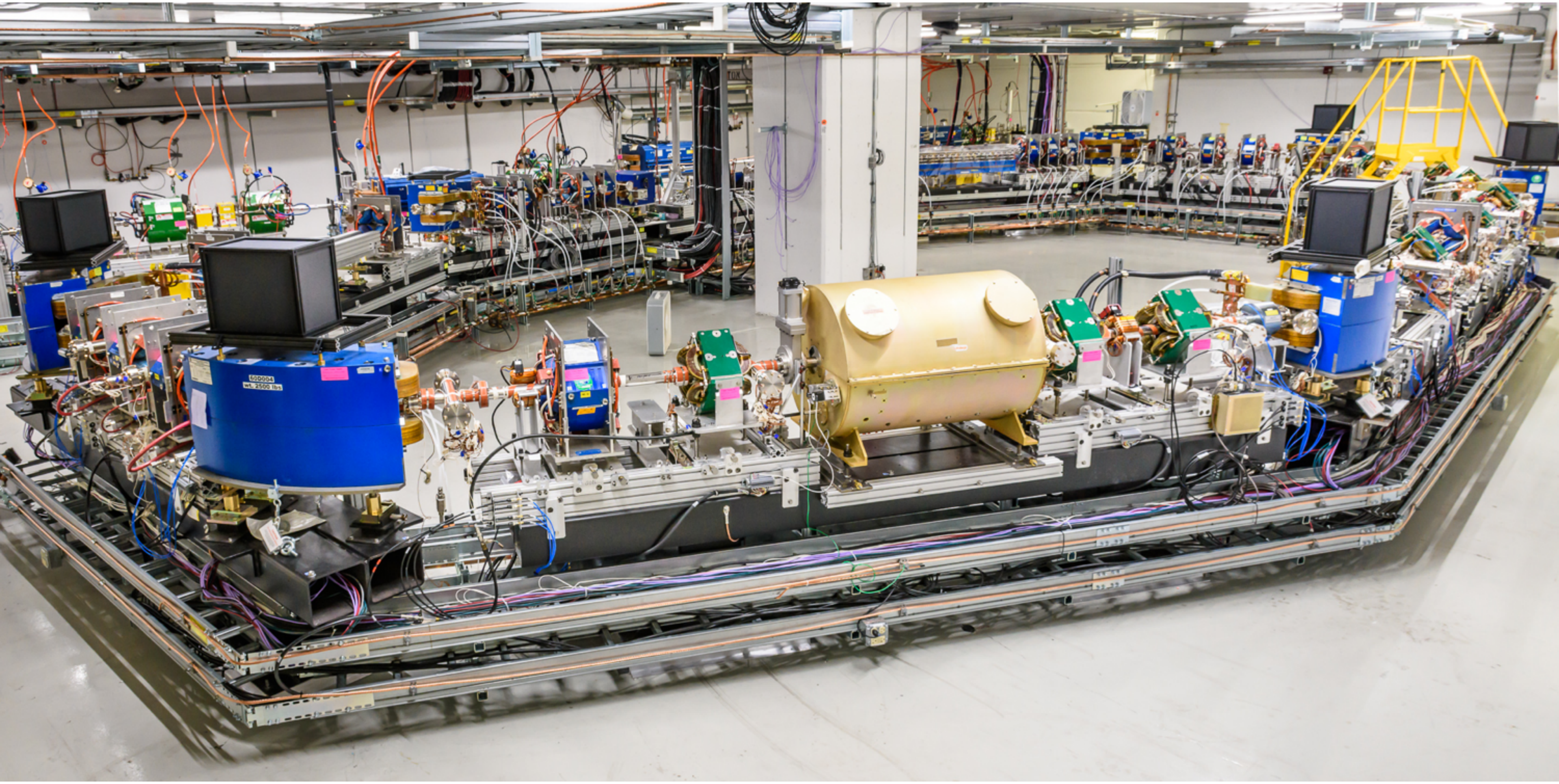
- Is there a better way?
  - Rethink how we design our accelerators
  - Move away from linear focusing to a non linear approach

- Such an approach is being tested here at FNAL
  - Nonlinear integrable optics

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

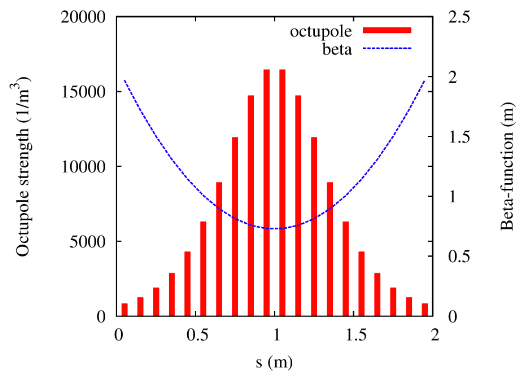
Integrable Optics Test Accelerator (IOTA)

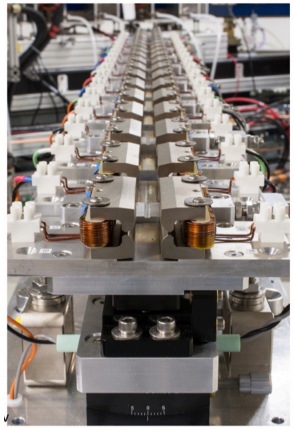


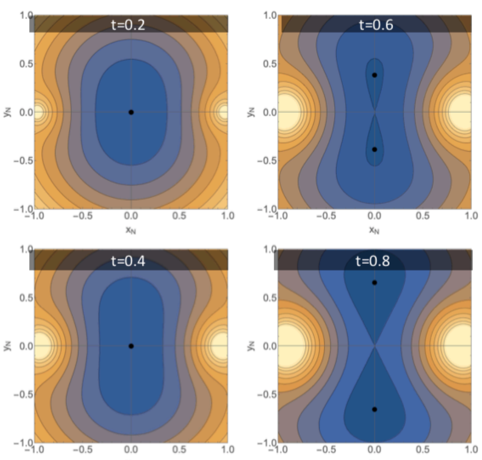
Nonlinear integrable optics at IOTA

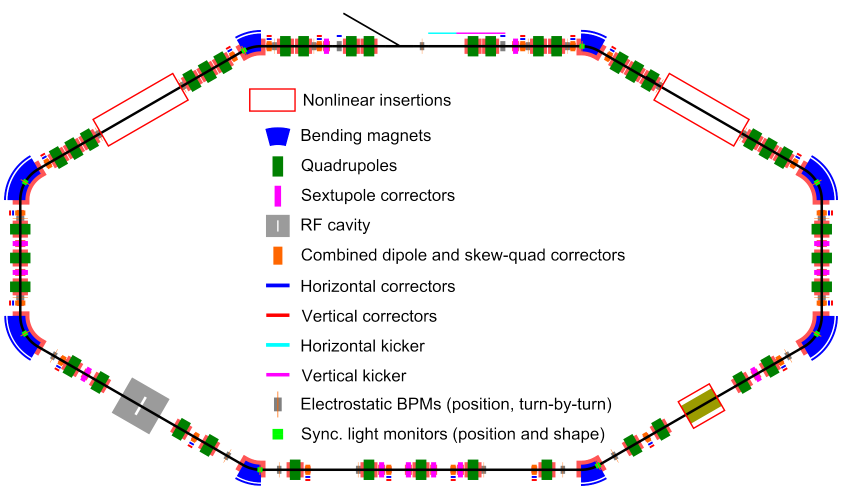
- Take a linear lattice and add a non-linear insert

- Recent run tested two inserts
  - a quasi-integrable insert implemented as octupole string
  - insert with 2 invariants, aka Danilov-Nagaitsev or Elliptic potential

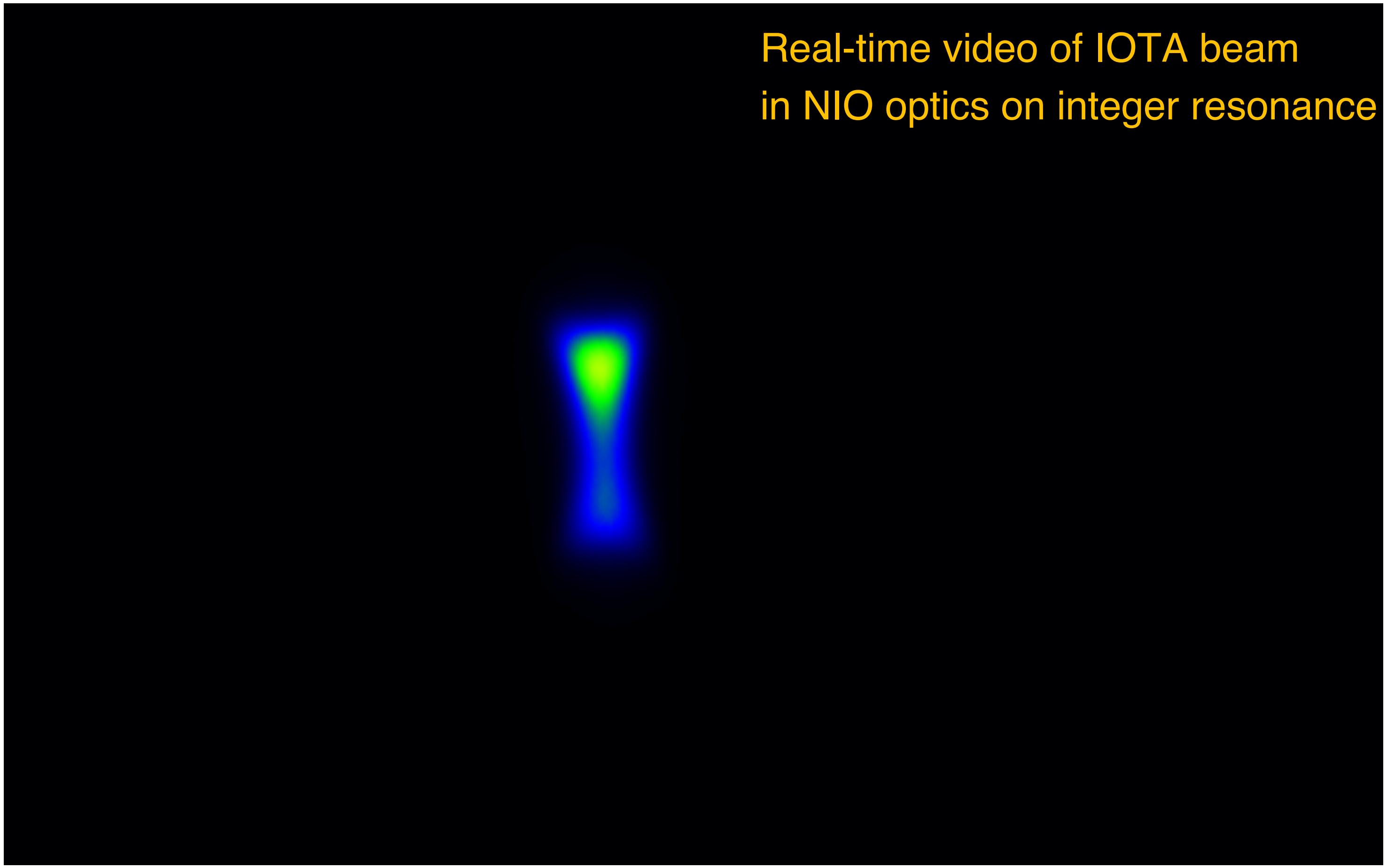








Stable beam on the integer



Instability Studies

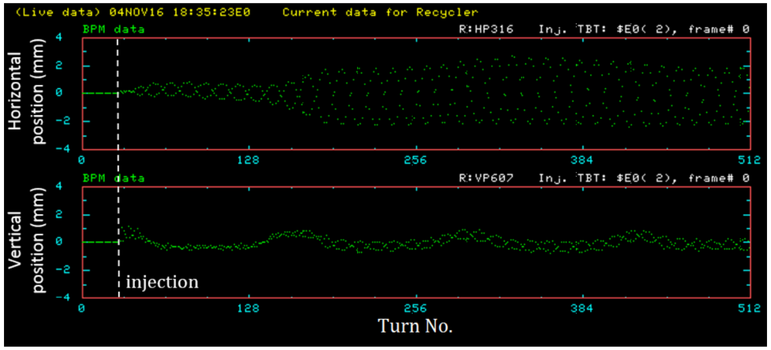
We see instabilities everyday operationally

Some are protected by feedback systems but not all

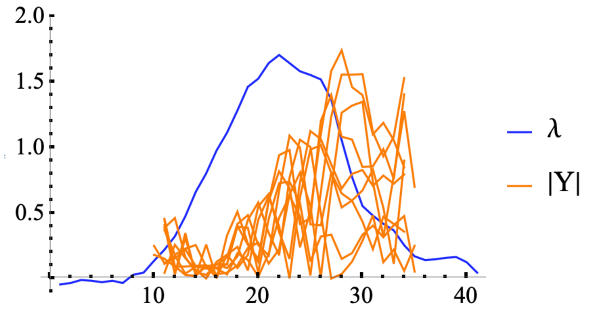
Important to study to develop mitigation strategies

Instabilities Studies

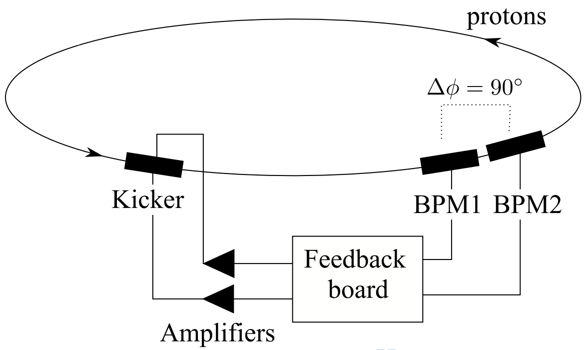
- Electron cloud instabilities
  - Proton bunch interacting with electrons inside the vacuum chamber
  - An issue during commissioning of Recycler



- Instabilities in the presence of strong space charge
  - Prediction of new instability – Convective instability (A. Burov)
  - Observed in dedicated booster studies

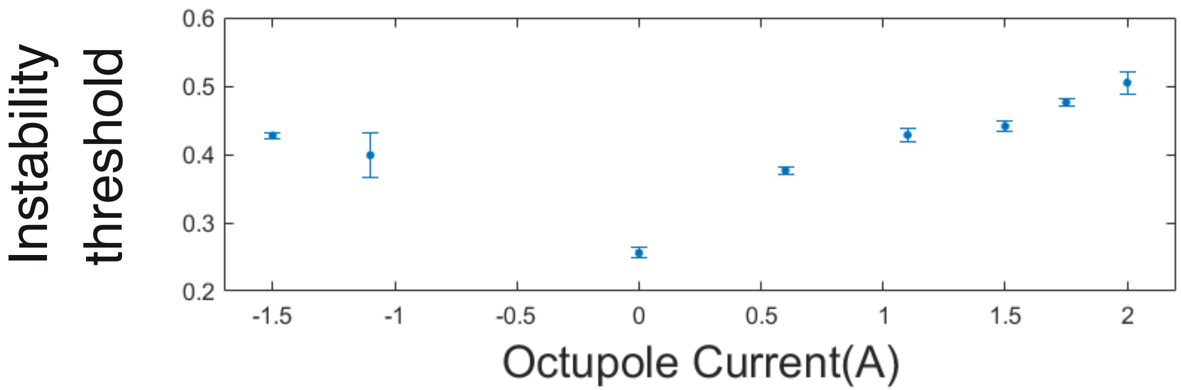


- Dedicated experimental research program(ECA) beginning soon
  - Excite instabilities in a controlled way
  - Will explore how instabilities depend on space charge



Instabilities – IOTA can help with that too!

- Non-linear integrable optics can help with coherent instabilities
- A coherent instability requires many of the particles to be working collectively
- The large tune spread from nonlinear integrable optics helps damp this
- Studies on-going at IOTA
  - Observed factor of 2 increase in the threshold with octupole insert on



Grand challenge #2

- Grand challenge #2 (beam quality): How do we increase beam phase-space density by orders of magnitude, towards the quantum degeneracy limit?

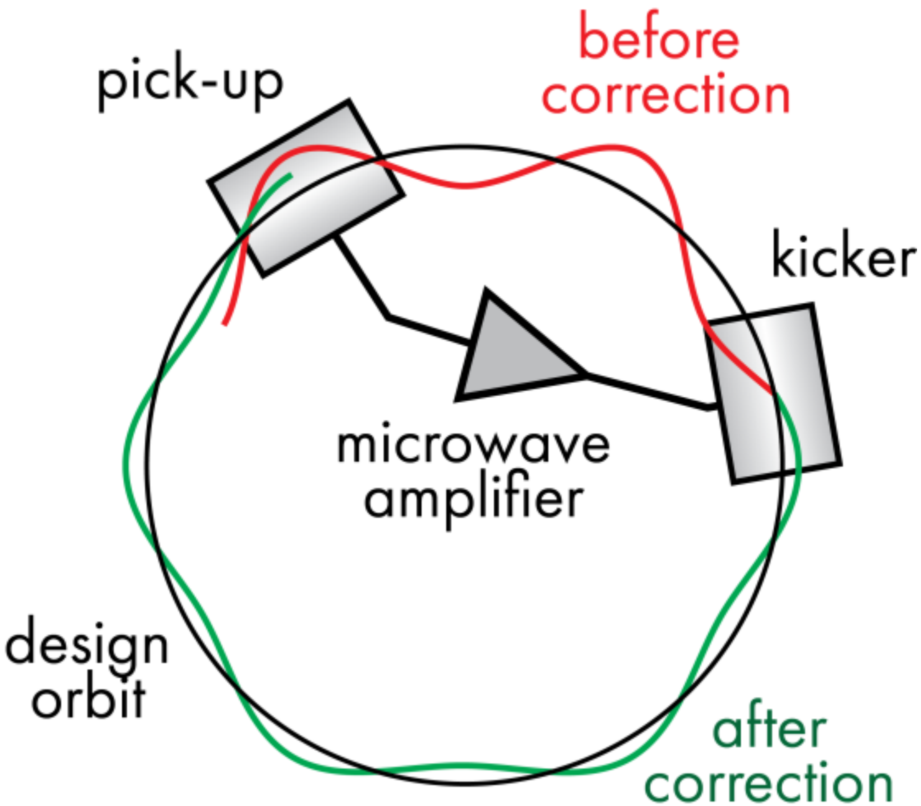
$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi \sigma_x{}^* \sigma_y{}^*}$$

Decrease beam size

Improving beam quality with cooling

Fermilab

SC: a powerful technique but limited to GHz BW



Simplified stochastic cooling system

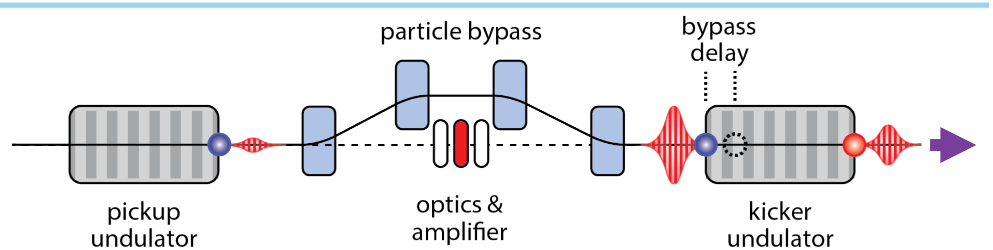
$$\mathcal{L} \sim \frac{f N_b N^2}{4\pi\sigma_x{}^* \sigma_y{}^*}$$

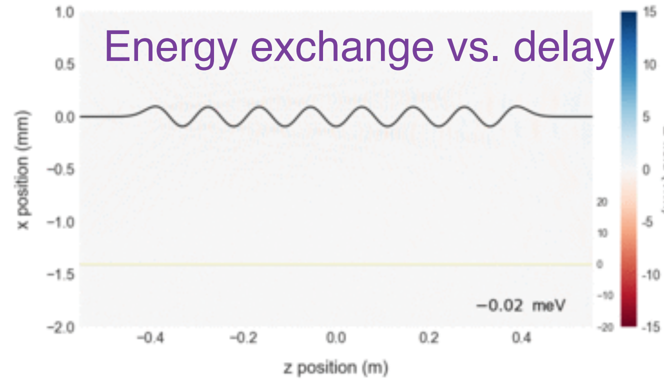
1984 Nobel: van der Meer/Rubbia

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

2) Bandwidth (time resolution) of feedback system controls cooling rate

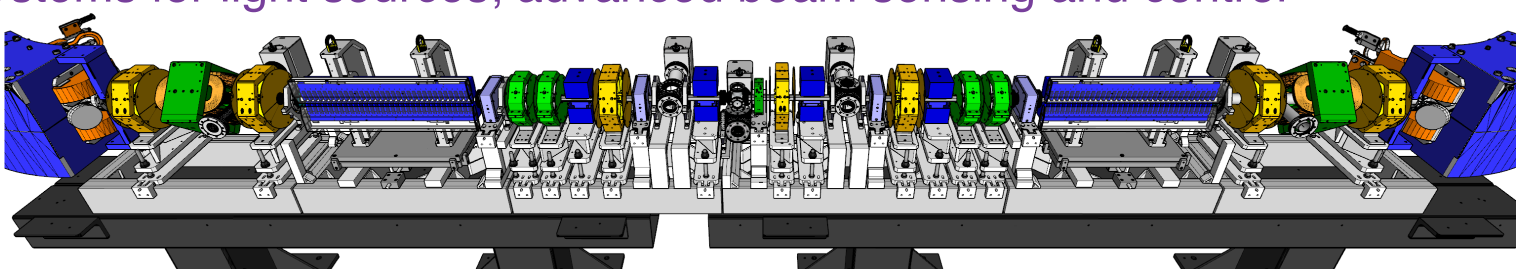
OSC extends the SC principle to optical bandwidth





- Microwave hardware of SC replaced with undulators, lenses and amplifiers
- Potential for $10^3 – 10^4$ increase in cooling rate over SC (~10 THz vs few GHz)

- **OSC is at an intersection of fundamental beam-physics studies and pathfinding for operational systems in cooling, control and sensing**
- Potential applications: direct cooling of high-energy hadrons (~0.25-6 TeV); perf. enhancement in med.-energy ring coolers; specialized SR-damping systems for light sources; advanced beam sensing and control

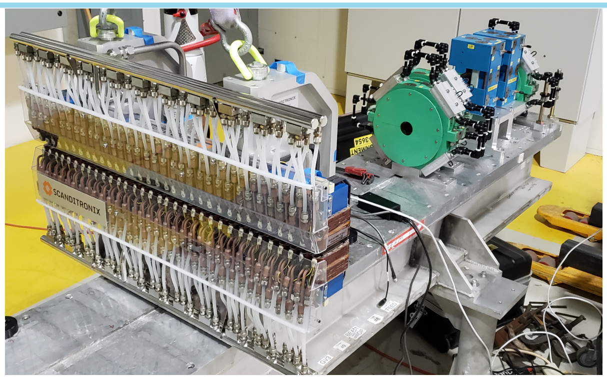


Fermilab

OSC program @ IOTA takes a staged approach

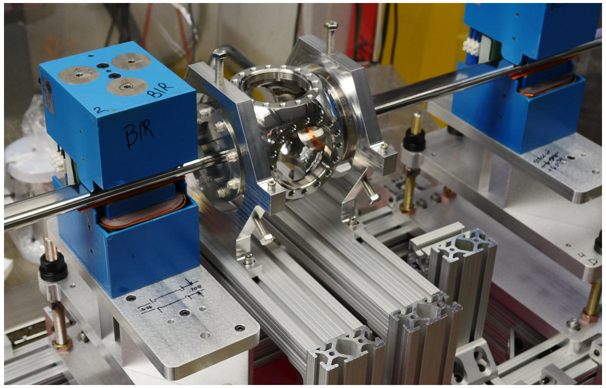
Phase I: Non-amplified OSC

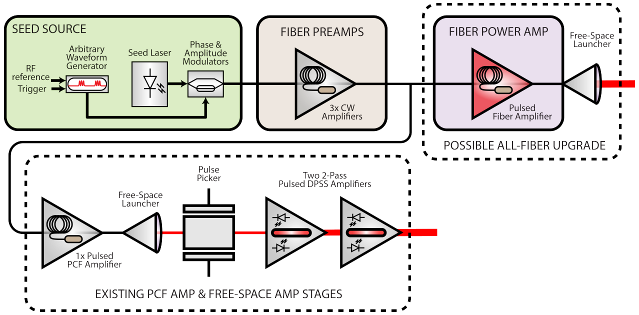
- Explore OSC physics decoupled from technological challenges related to high optical gain
- Includes OSC studies with a single electron in IOTA
- OSC elements are nearing completion and systems are being integrated
- **Experiments begin in ~Sep ’20 (world’s first demo)**



Phase II (ECA): Amplified OSC and advanced control/sensing

- Develop a high-gain (1000x) amplified-OSC system at IOTA; leverages previous FNAL/DOE investments in Linac-Laser-Notcher system
- Develop specialized Machine-Learning systems and diffractive optics for advanced sensing and control
- Focus on conceptual and technological paths towards operational systems
- **Amplified-OSC experiments beginning in ~FY’22/23**





Summary

- Increasing intensity involves many challenges
  - Space charge effects, instabilities are just a few examples

- Looking to the future
  - IOTA is testing a novel method to redefine how we build our machines
  - World's first OSC demonstration this year
    - New cooling method to improve beam quality

- Thanks to J. Eldred, J. Jarvis, S. Nagaitsev and A. Valishev for slides

Backup slides