EXPERIMENTAL STUDIES OF OCTUPOLE HENON-HEILES QUASI-INTEGRABLE SYSTEM

(AND OTHER THINGS)

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BUDKER SEMINAR

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Outline

- Introduction - bio, and motivation for the work

- Projects in detail:
  - Synchrotron radiation diagnostics
  - Octupole Henon-Heiles System

- Discussion + Q/A

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- Introduction

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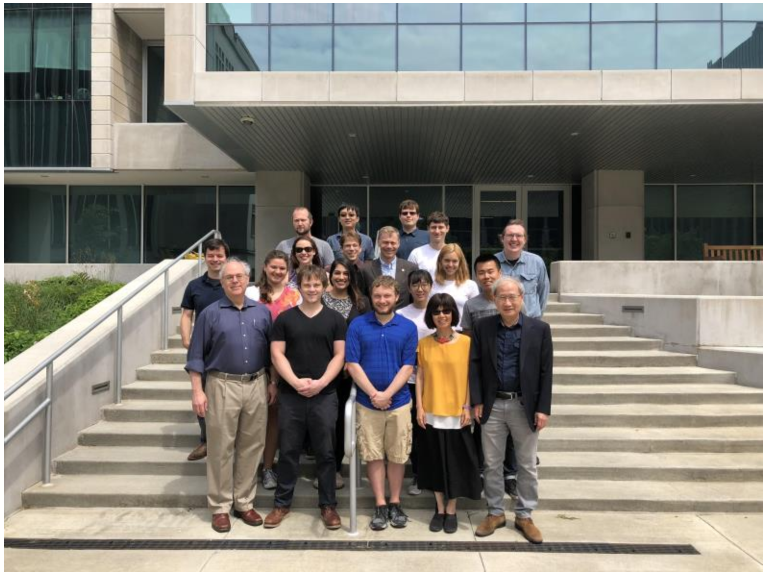
Intro – bio sketch

- Graduate student, physics, University of Chicago (year 5)
  - Graduation next Spring
- BSc (2012), MSc (2014) in physics, University of Victoria
- Member of UChicago accelerator group, and Centre for Bright Beams
- Co-advisors:

  Dr. Young-Kee Kim
  Dr. Alexander Valishev



Intro – NIO

- Key principle of accelerator design: 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
  - Coulomb self-interaction inside beam, and with environment
  - Intentionally introduced multipole magnets (e.g. sextupoles to correct chromaticity)

- All are aberrations to the initially decoupled system of two linear oscillators

Intro – NIO

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

- Nonlinearities result in dependence of oscillation frequency (tune) on amplitude
- Explicit time-dependence of multipoles produces resonances
- Coupling between x and y further complicates the dynamics
- Ultimately, chaos and loss of stability
  - Beam quality degradation (blow-up)
  - Particle loss
- Called single particle stability or Dynamical Aperture

Intro – NIO

- Another problem - whole beam can become unstable if resonantly excited
  - Via external fields or self-interaction through environment

- Instabilities can be suppressed by
  1. External damping system – most common solution
  2. Landau damping – intrinsic 'immune system', related to the spread of betatron oscillation frequencies.
     Larger spread = stronger suppression of collective instabilities

- Examples of Landau damping:
  - CERN PS: instabilities found in 1959, mitigated by octupoles
  - LHC: 336 octupoles @ 500A to create 0.001 tune spread

Intro – NIO

- So...nonlinearities:
  - Are intrinsic to charged particle beams, scale with brightness
  - Ruin beam quality and particle stability
  - And yet, must be introduced to maintain immunity to coherent instabilities through Landau damping

- Are there 'good' kinds of nonlinearities? YES

Intro – NIO

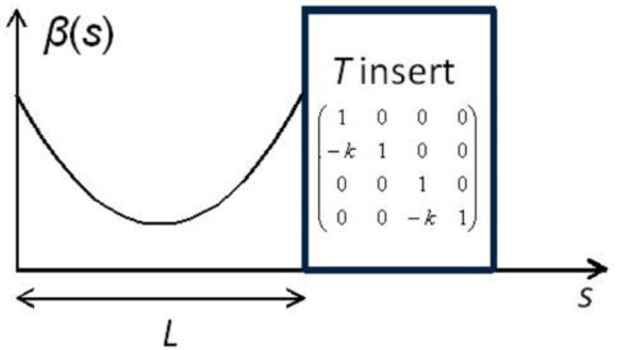
- Electron lenses in 1D (McMillan,1967) and 2D (Perevedentsev and Danilov, 1990)
  - Require non-Laplacian potentials to realize (i.e. not magnets)
  - Implemented in Tevatron, RHIC, others…

- Danilov, Nagaitsev (2010) – nonlinear lattice with 2 invariants that **can be implemented with Laplacian potentials**
  - *Phys. Rev. ST Accel. Beams 13, 084002 (2010)*

Intro – NIO

Recipe:

- Start with an axially-symmetric *linear* lattice (FOFO) with the element of periodicity consisting of
    a. Drift L (equal βs)
    b. Axially-symmetric focusing block "T-insert" with phase advance n × π



- Add special nonlinear potential *V(x,y,s)* in the drift

Intro – NIO

Briefly:

- Start with a Hamiltonian $$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + K(s)\left(\frac{x^2}{2} + \frac{y^2}{2}\right) + V(x,y,s)$$
- Choose s-dependence of nonlinear potential V such that *H* is time-independent in normalized variables

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + \beta(\psi)V\left(x_N\sqrt{\beta(\psi)}, y_N\sqrt{\beta(\psi)}, s(\psi)\right) \qquad z_N = \frac{z}{\sqrt{\beta(s)}},$$

$$H_N = \frac{p_{xN}^2 + p_{yN}^2}{2} + \frac{x_N^2 + y_N^2}{2} + U\left(x_N, y_N, y\right) \qquad p_N = p\sqrt{\beta(s)} - \frac{\beta'(s)z}{2\sqrt{\beta(s)}},$$

- Makes *H* an integral of motion under certain conditions
- No requirements on *V* – can use any conventional magnet
  - But some better, i.e. octupoles $$U = \kappa\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3y_N^2 x_N^2}{2}\right)$$
- It is possible to derive another integral of motion (quadratic in momentum). See paper for details.

Intro – NIO

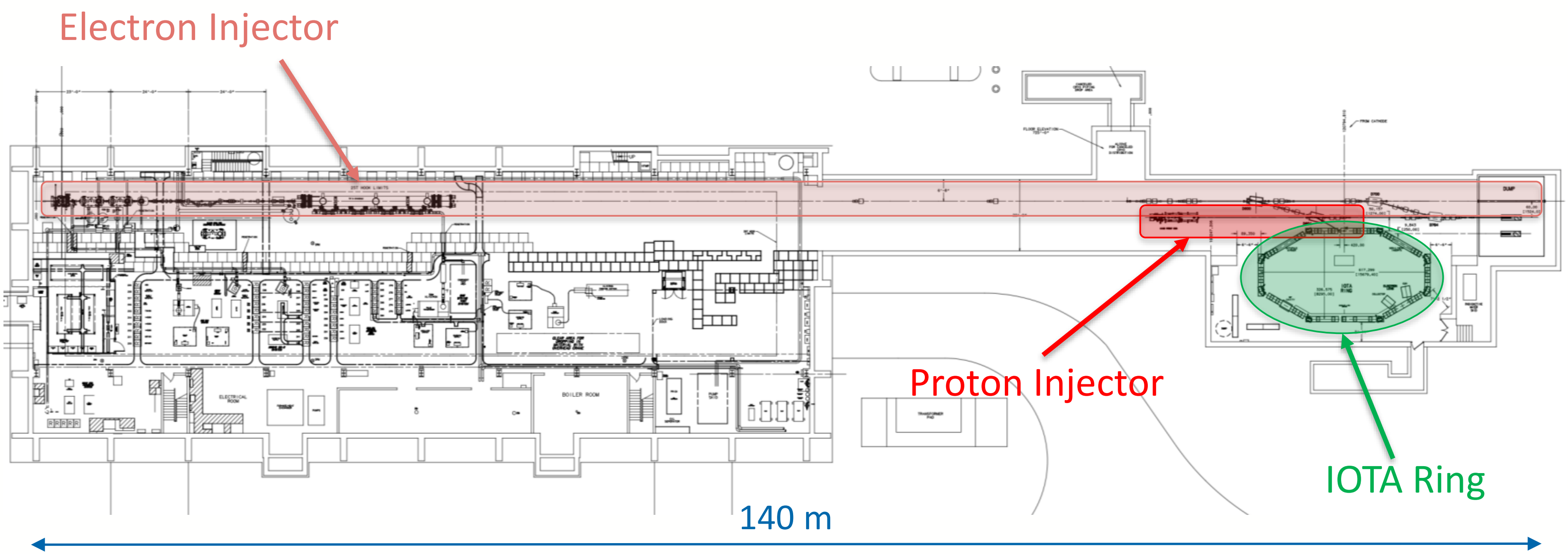
- In summary, NIO:
  - Relies on carefully crafted lattice + non-linear magnets
  - Provides immunity to collective instabilities
  - Maintains large dynamic aperture = fewer particle losses
  - Easy to implement and cost effective

- Works great in simulations

- Want experimental verification – my thesis project

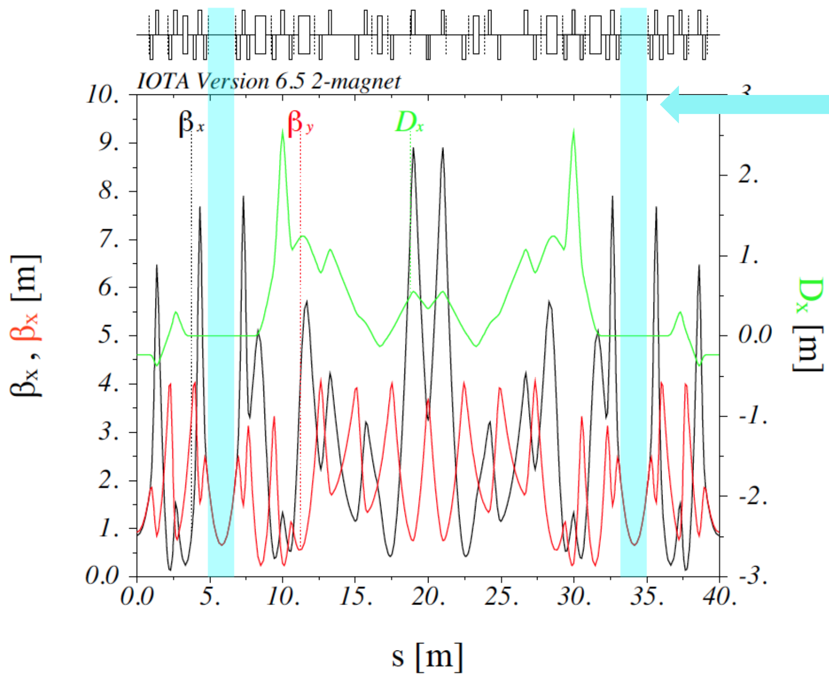
Intro – IOTA

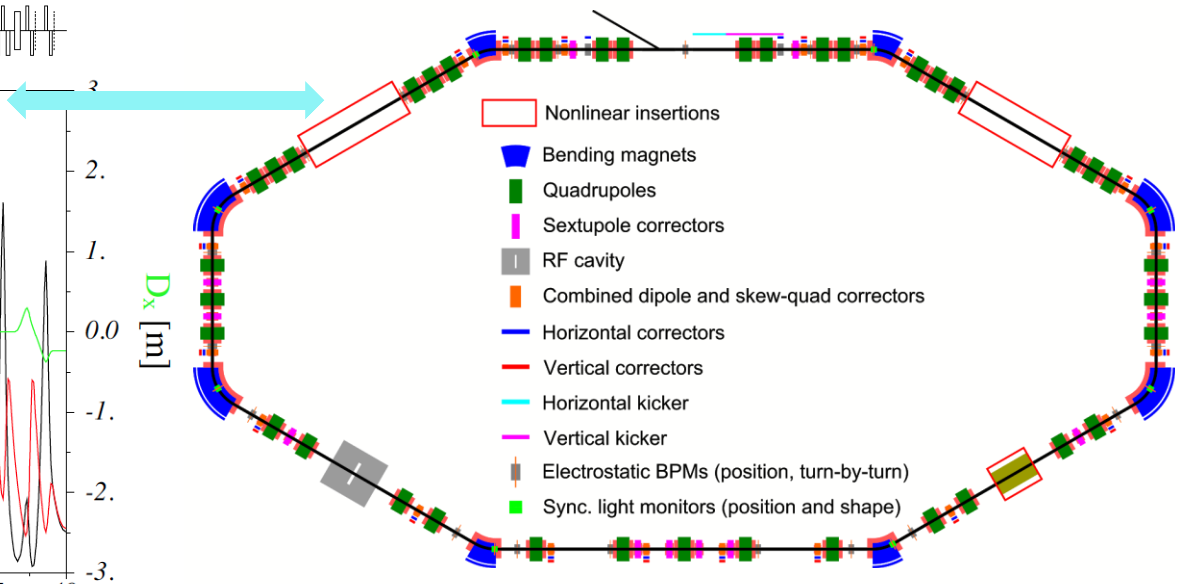
- Given lattice requirements, a special ring is necessary
  - It was built as part of FNAL FAST facility, called The Integrable Optics Test Accelerator (IOTA)



Intro – IOTA

- Has 2 nonlinear sections, and space for other experiments
- Satisfies the T-insert and other conditions





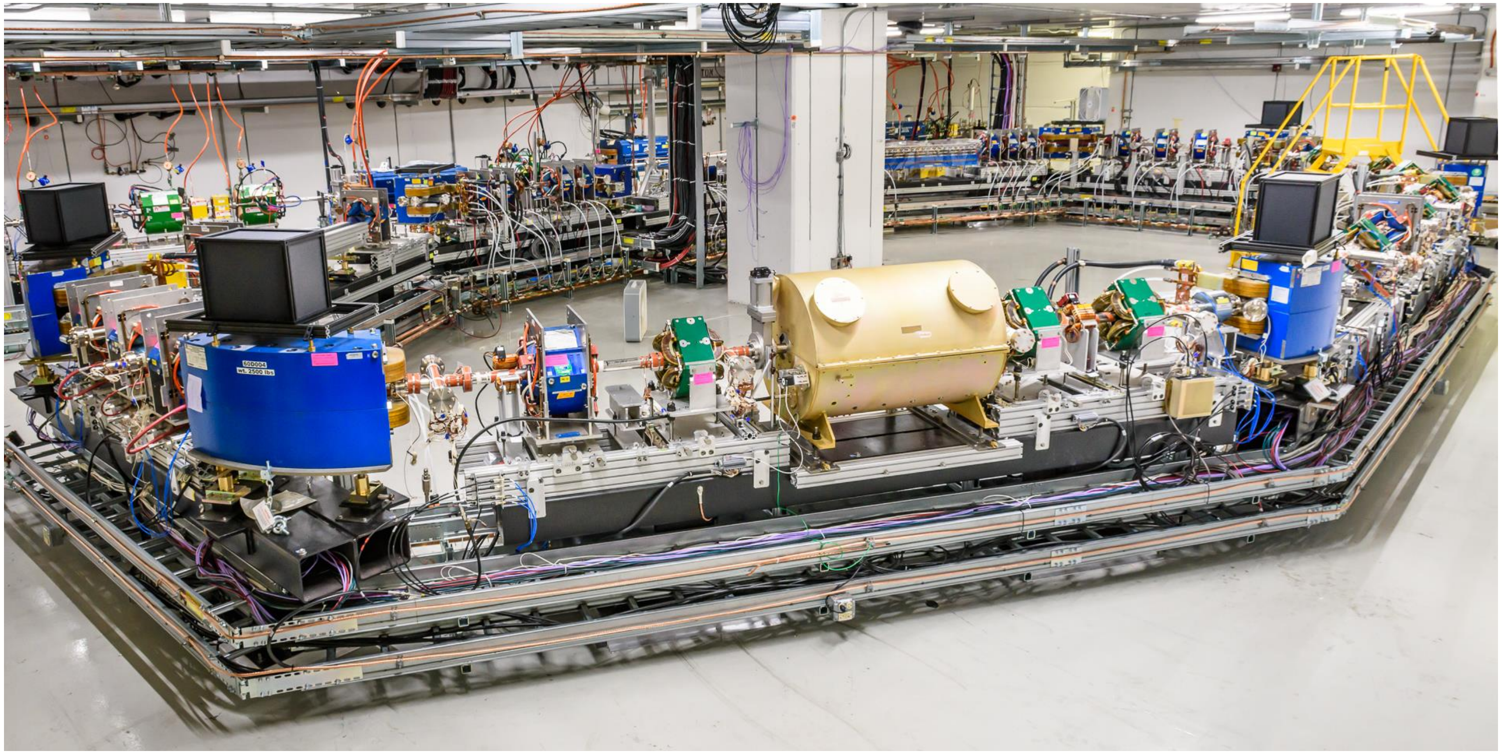
Intro – IOTA

Nominal kinetic energy	e^-: 150 MeV, p+: 2.5 MeV
Nominal intensity	e^-: 1×10^9, p+: 1×10^{11}
Circumference	40 m
Bending dipole field	0.7 T
Beam pipe aperture	50 mm dia.
Maximum b-function (x,y)	12, 5 m
Momentum compaction	-0.02 ÷ 0.1
Betatron tune (integer)	3 ÷ 5
Betatron tune chromaticity	-15 ÷ 0
Transverse emittance r.m.s.	e^-: 0.04 μm, p+: 2μm
SR damping time	0.6s (5×10^6 turns)
RF V,f,q	e^-: 1 kV, 30 MHz, 4
Synchrotron tune	e^-: 2×10^{-4} ÷ 5×10^{-4}
Bunch length, momentum spread	e^-: 12 cm, 1.4×10^{-4}
Beam lifetime	e^-: 1 hour, p+: 1 min

Intro – IOTA

- Beam first circulated in August 2018

- Scientific program started in December 2018



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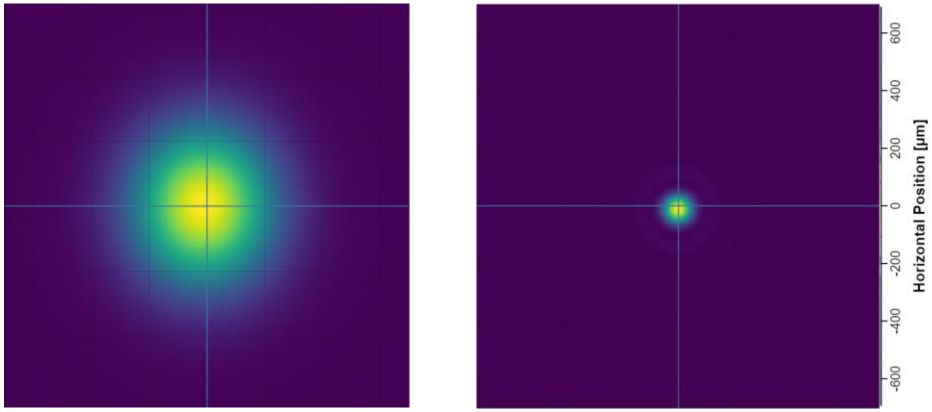
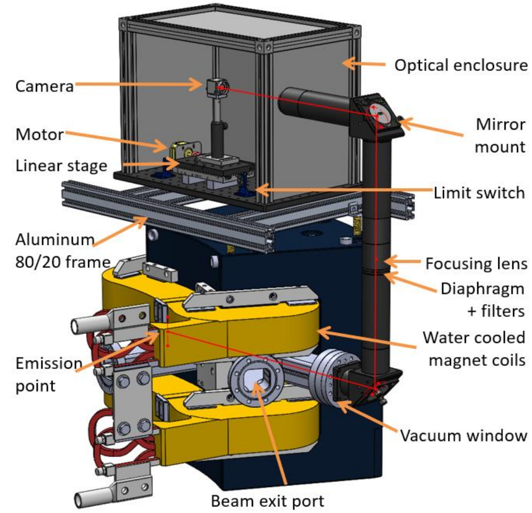
SyncLight

- Good knowledge of beam parameters is critical to the research program
- Multiple development efforts:
  - Beam position monitors - AD instrumentation group
  - Synchrotron light detectors (SyncLight) – in house
- At IOTA energy and emittance, have the luxury of simple optical setup - critical wavelength near visible light!
  - Cheap optics
  - Compact 1 lens layout
  - CCD detectors

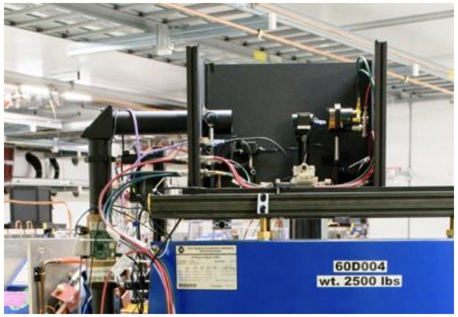
SyncLight

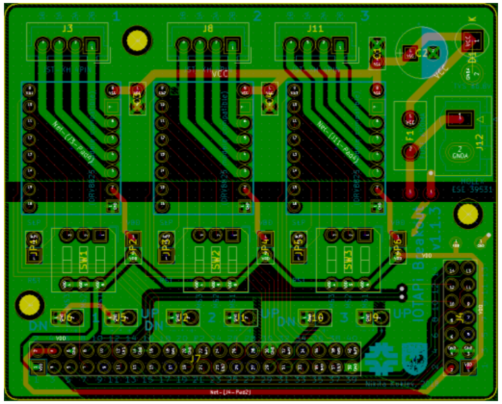
- Participated in many aspects of design and assembly
  - Synchrotron Radiation Workshop (SRW) optical simulations





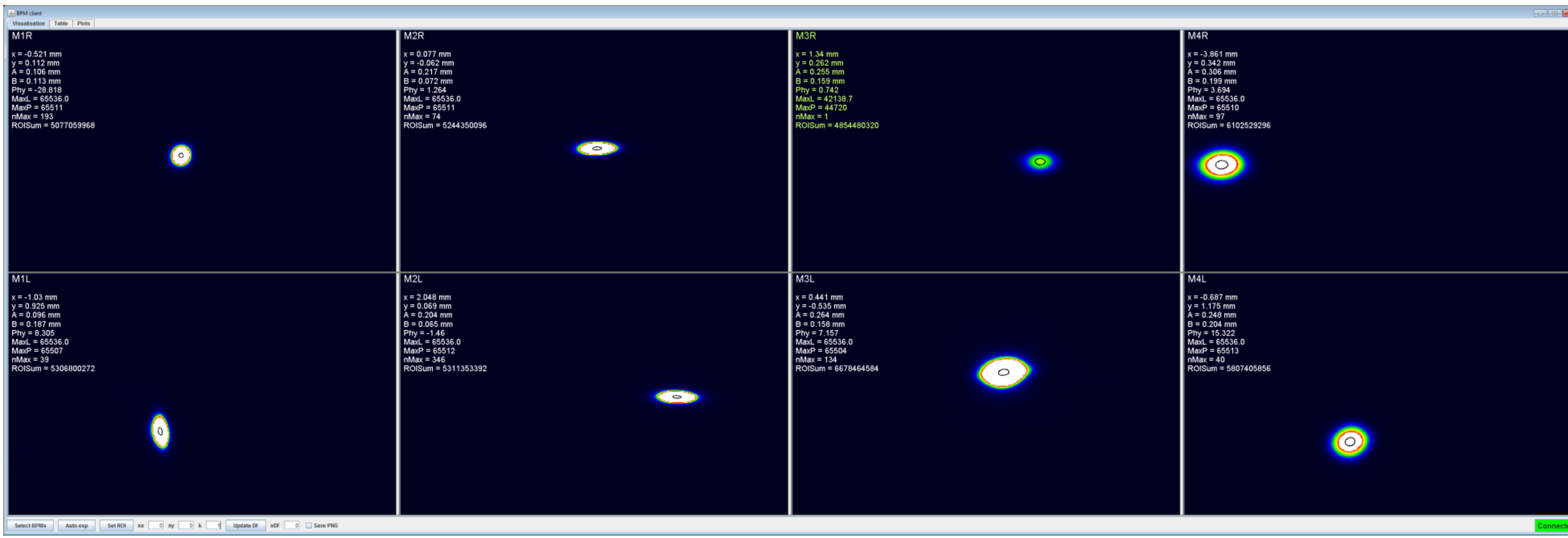
  - Solidworks/NX mechanical CAD
  - Control electronics design
  - Software development and integration
  - Final assembly





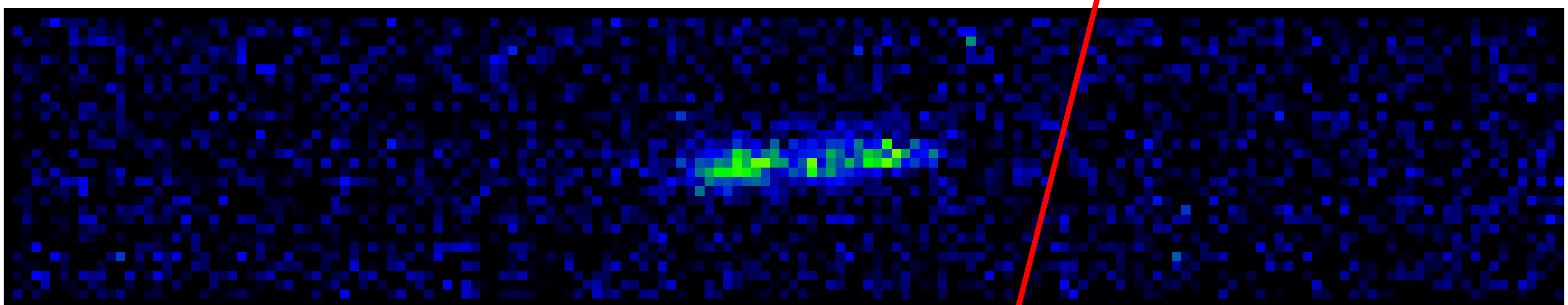
Sync-Light

- Performance:
  - Resolution of O(10-100nm), depending on current
  - Near full rate (20-40FPS) acquisition, fitting and noise subtraction

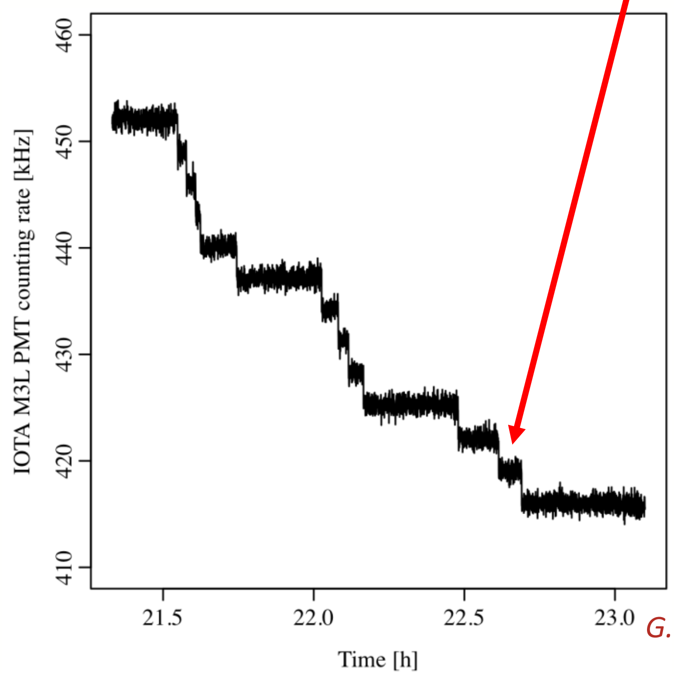


Sync-Light

– Dynamic range from mA down to single electron



A. Romanov



G. Stancari

SyncLight

- It has proven to be a reliable tool for closed orbit measurements, and served as base for other experiments

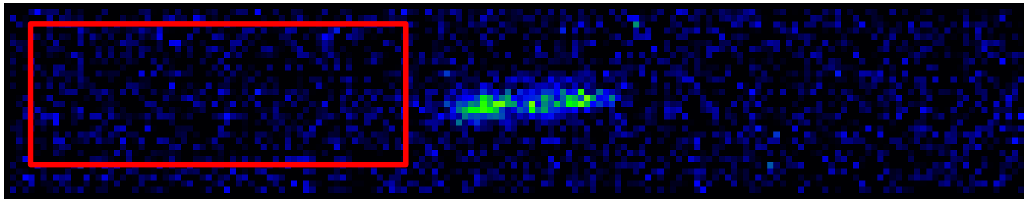
- Current efforts focus on:
  – Functionality improvements
  – Increasing low light sensitivity
  – Turn-by-turn (TBT) data

Functionality improvements

- Experiments have different requirements for wavelength, polarization, and optics
  - Currently, stations physically reassembled for each case
  - Want to add standard ways to address this – filter wheels, flipper mirrors, etc.
  - To save on cost, integrate with current stepper control
  - Requires control board redesign, in progress…

SyncLight

Increased low light sensitivity

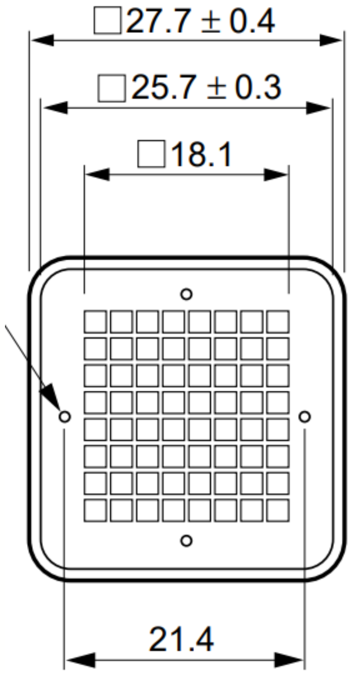


- At very low currents, noise becomes limiting factor
  - Want to (more) reliably distinguish signals at ~few electron level
  - Our cameras are already almost as good as it gets for normal CCDs

- Solutions
  - Fancy CCDs – deep depletion, etc = $$
  - Temperature control (lowers dark current) – in progress
  - Intensified camera – have one, but old and needs driver work

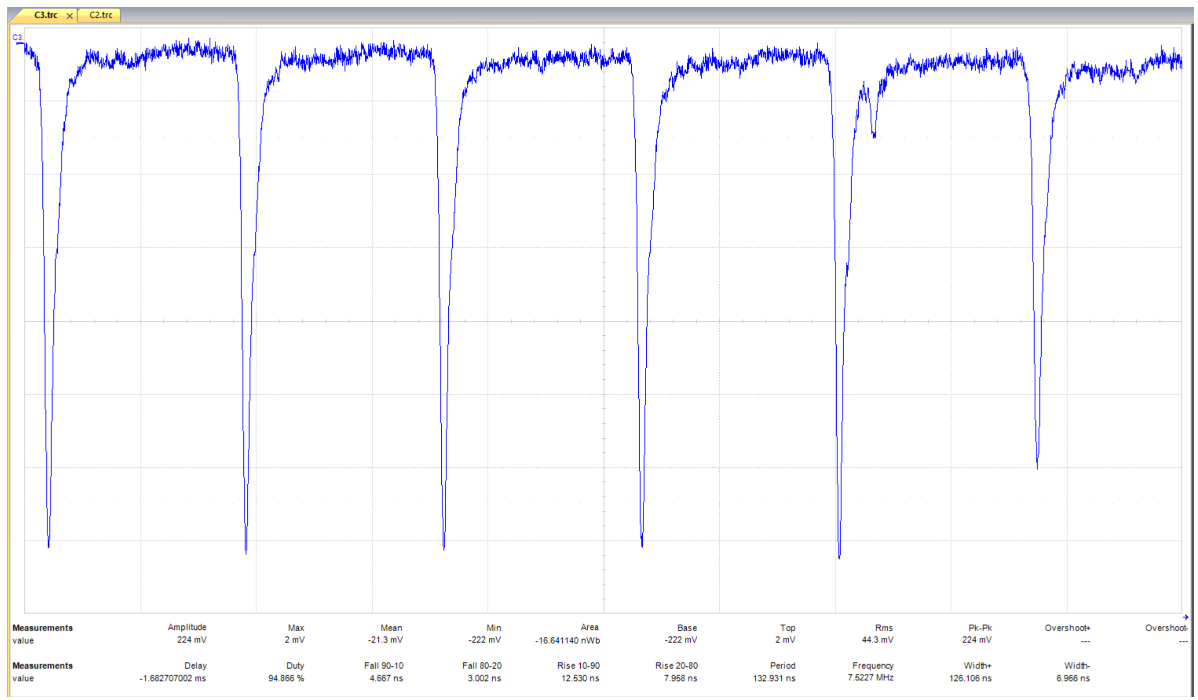
TBT data

- CCDs are not good for TBT data
  - 19μs smallest exposure = 100's of turns
- Solution – multi-anode PMTs
  - G. Stancari currently testing a 4x4 MCP-PMT procured by V. Shiltsev, with promising results
  - Found many 8x8 (R5900-00-M64) from MINOS, about to be decommissioned and available for free
- There is a wealth of info in TBT 2D profiles
  - Beta mode beatings
  - Single electron tracking



TBT data

- Challenge – DAQ
  - Need >2.5GS/s, ~1GHz BW, 64 channel simultaneous acquisition
  - Care about cross-calibration and bit depth
  - Means $$$$$$
- Ideas:
  - Adapt boards from another detector system (LAPPD)
  - Smart channel mux (impact unclear)
  - Pay ☹



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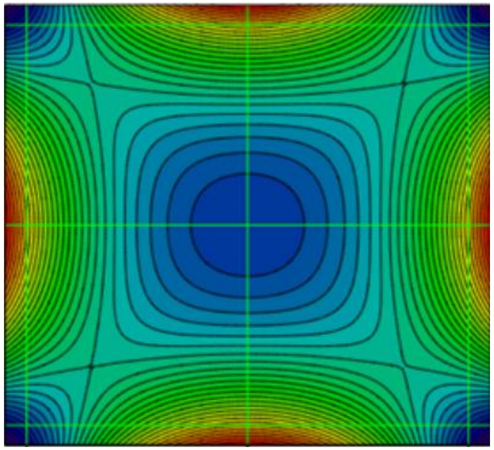
Octupole Henon-Heiles

- Lowest order multipole of D-N potential is a 'continuous' octupole



$$U = \kappa\left(\frac{x_N^4}{4} + \frac{y_N^4}{4} - \frac{3y_N^2 x_N^2}{2}\right)$$

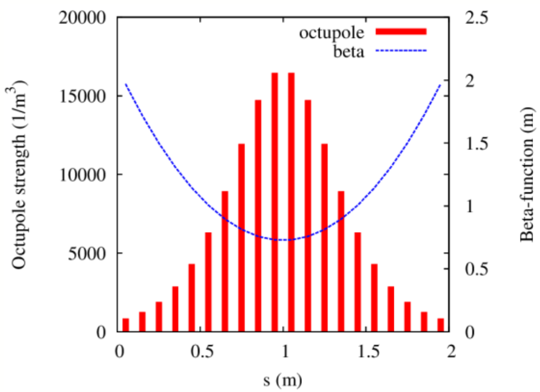
$$H = \frac{1}{2}(p_x^2 + p_y^2) + \frac{1}{2}(x^2 + y^2) + \frac{k}{4}\left(x^4 + y^4 - 6x^2 y^2\right)$$

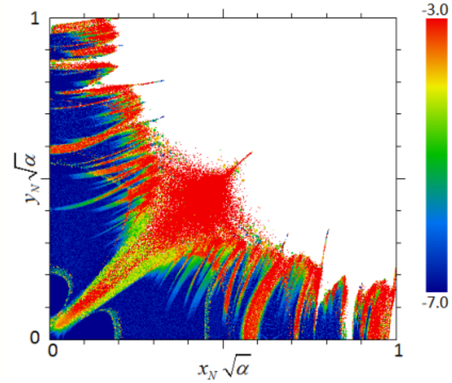
- A type of Henon-Heiles system
  - First studied in context of star dynamics

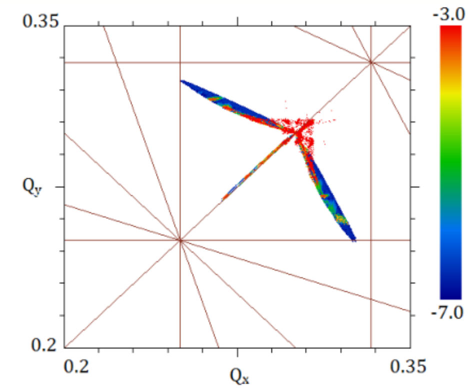
- Single invariant, *H* (for limited number of initial conditions)

Octupole Henon-Heiles

- Preliminary simulations done by S. Antipov
- Showed promising results with an approximate potential
  - 20 slices, 0.3 phase advance = 0.08 tune spread







- Low requirements on field quality and alignment
  - 10% field error, or 0.5mm misalignment = 10% tune spread reduction
  - IOTA is expected to be significantly better on optics, and we can get away with cheaper alignment techniques
- Working on repeating simulations on updated lattice

S. Antipov, S. Nagaitsev, A. Valishev, "Single-Particle Dynamics in a Nonlinear Accelerator Lattice: Attaining a Large Tune Spread with Octupoles in IOTA", JINST 12 (2017) no.04, P04008.

Octupole Henon-Heiles

- My work – experimental demonstration

- Goals:
  - Demonstrate the implementation of Octupole Henon-Heiles system (i.e the Hamiltonian, Poincaré surfaces of sections)
  - Measure significant tune spread consistent with theoretical predictions, without large losses in dynamic aperture
  - Study boundary layer behavior near separatrices and resonances (can we cross some without losing the beam?)

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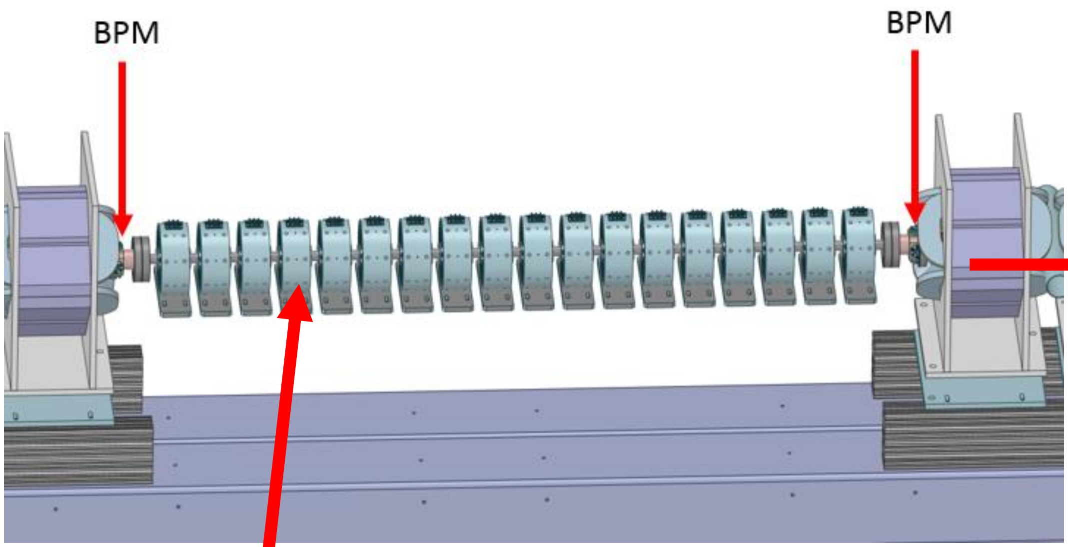
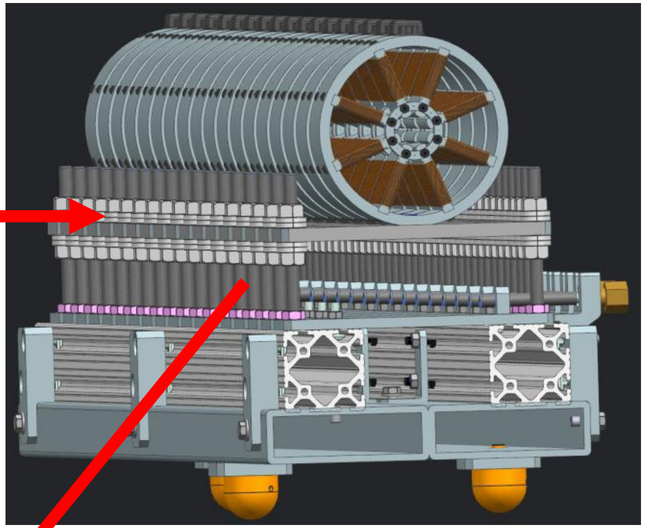
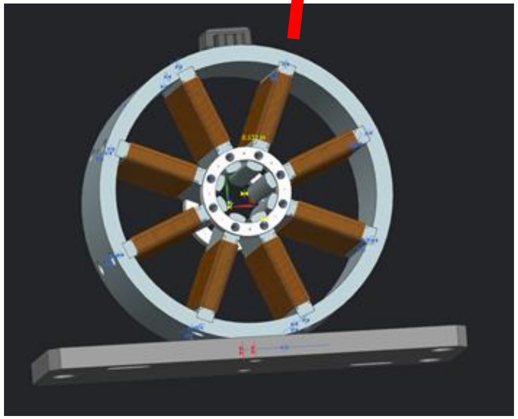
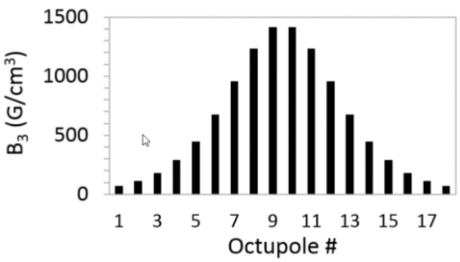
Octupoles

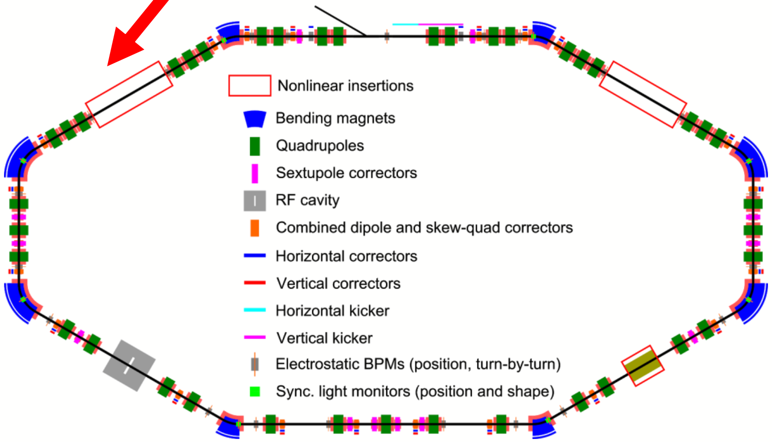
- Nominal design - physical insert of 18 octupoles









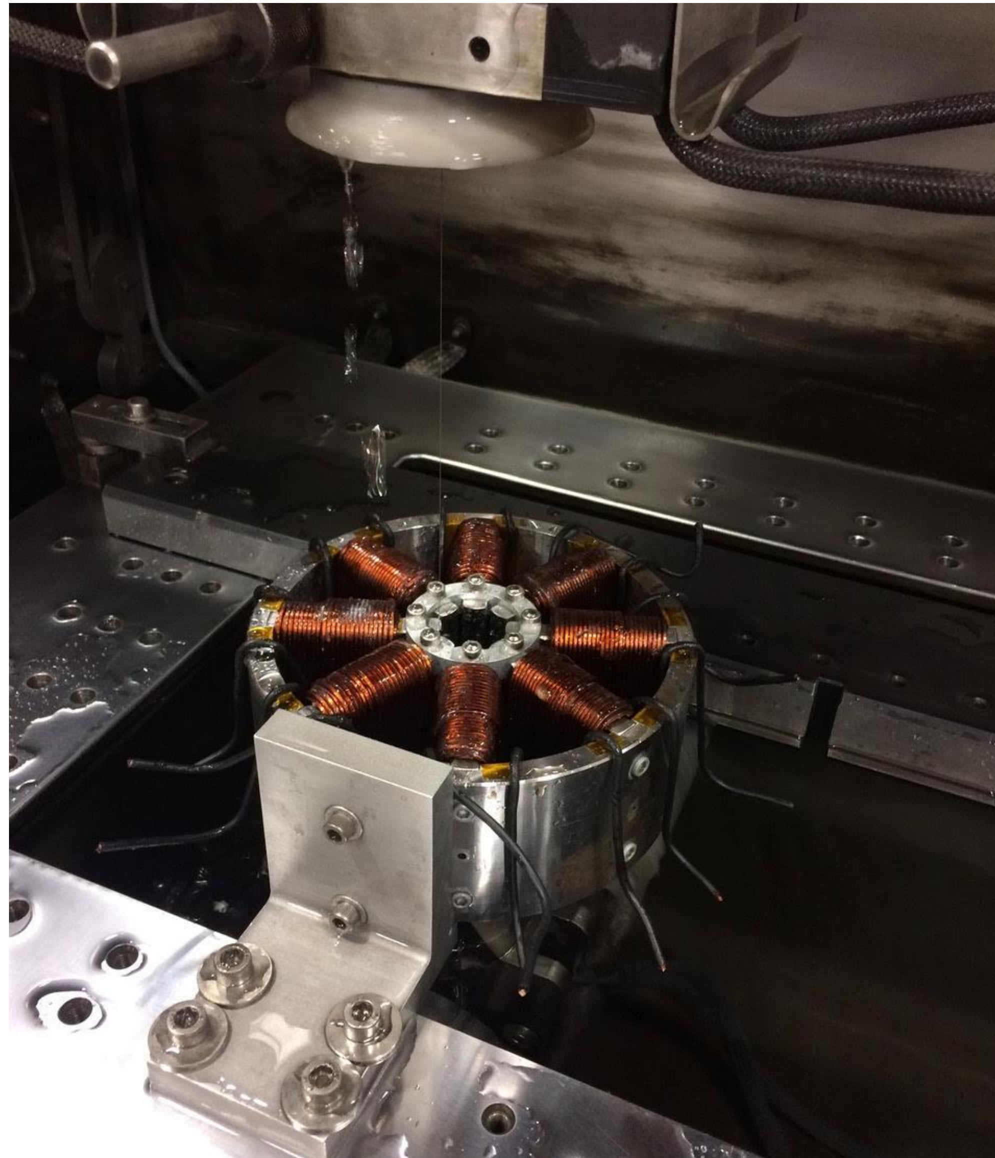


Octupole Henon-Heiles

- Initial manufacturing done in 2015, but several quality control and dimensional issues discovered later
- Required disassembly and re-machining of poles
- A long and costly process, done over fall of 2018

Octupole Henon-Heiles

- Wire EDM in progress

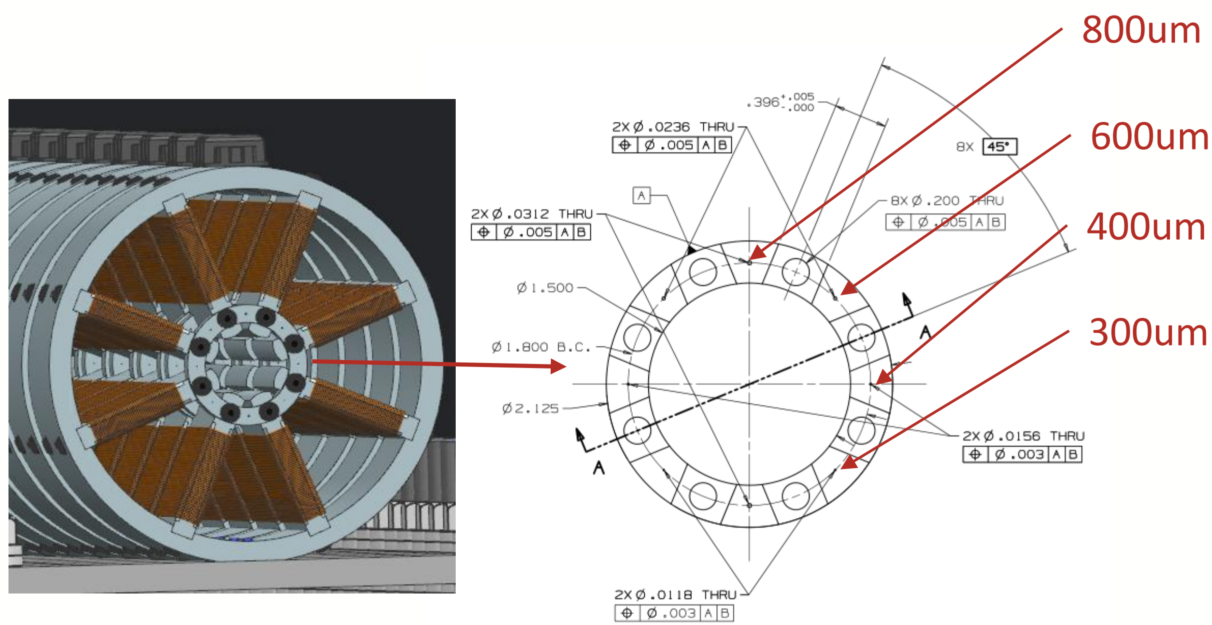


Octupole Henon-Heiles

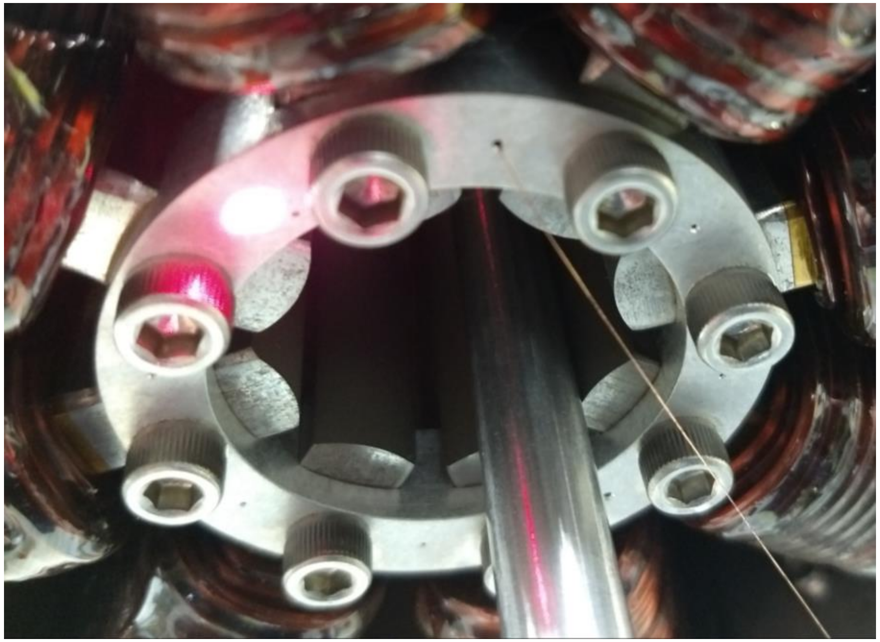
- Why was assembly a problem?
  - Issues discovered last minute – shorted coils, cracked epoxy, etc…
  - Required individual, manual refurbishment
  - ~5-8 hours per magnet

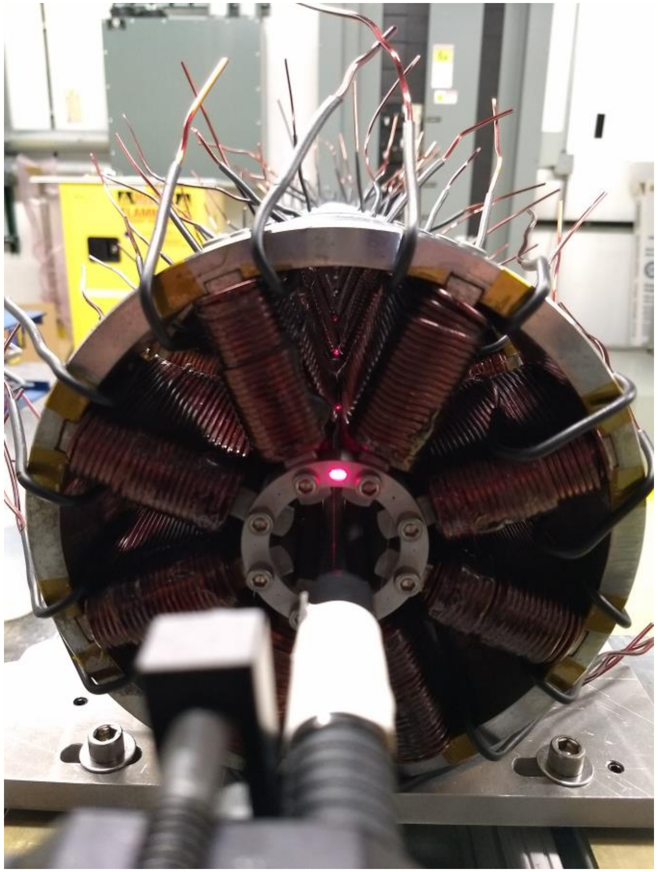
Octupoles

- Alignment:
  - Rough first pass with simple precision ground tube/by eye
  - Final alignment with BeCu wire, and laser
  - Goal <500um, think it was achieved

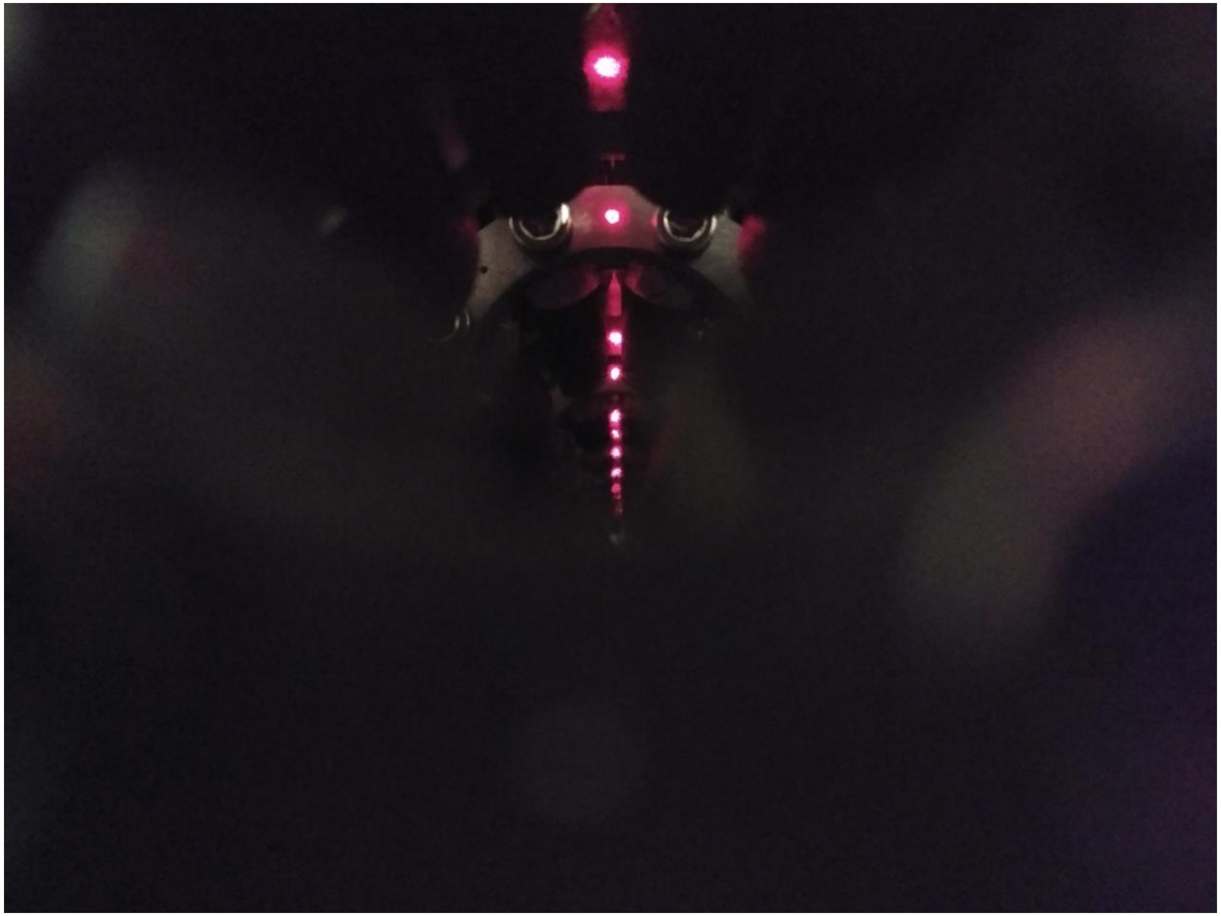


Octupole Henon-Heiles



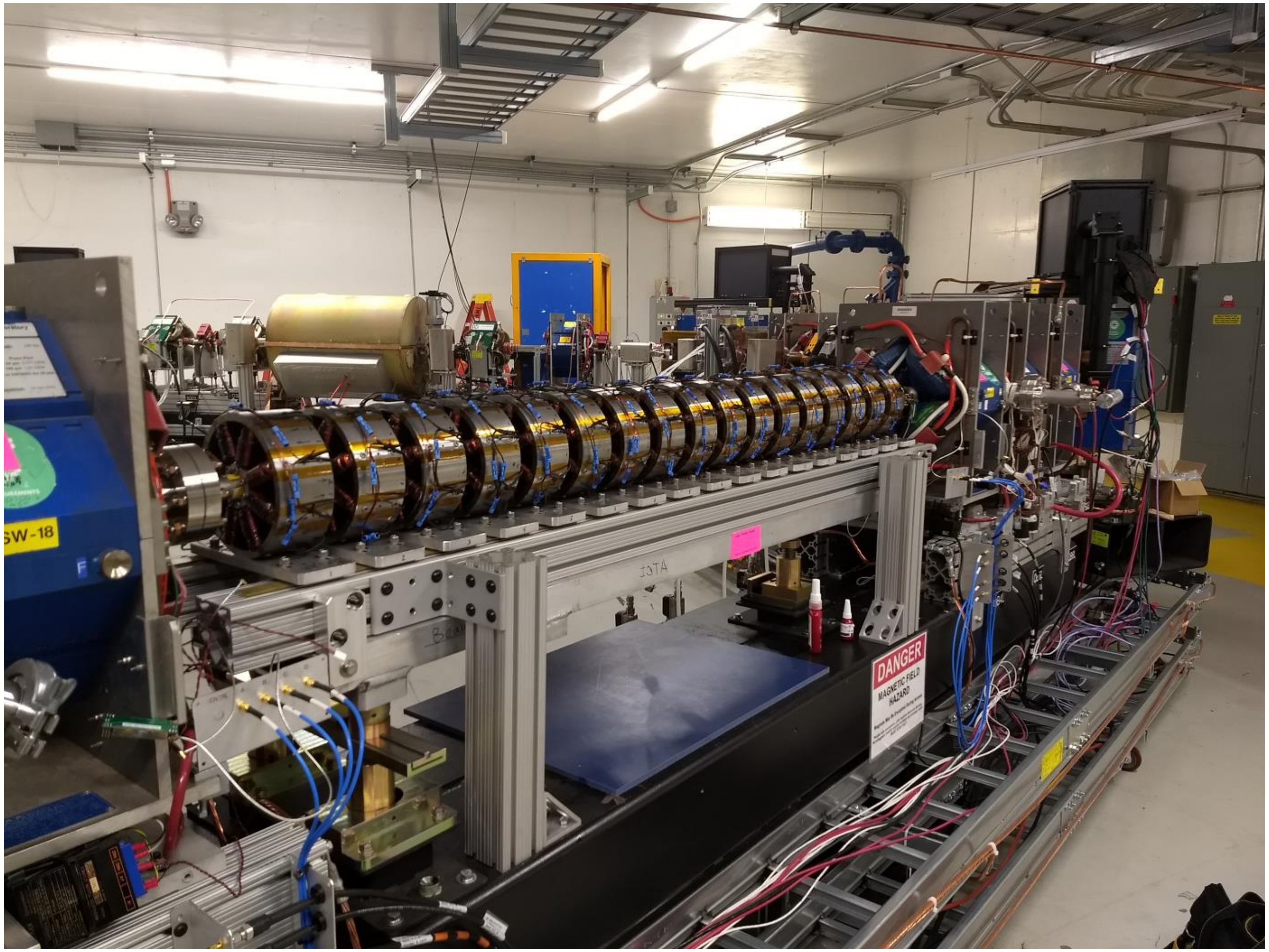


Octupole Henon-Heiles



Octupoles

- Final installation completed early January, with 17 octupoles



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Octupole Henon-Heiles

- Commissioning goals:

  Insert:
  - Ensure that insert generates the desired field distribution
  - And is centered *relative to the reference orbit*

  IOTA:
  - Verify correct optics in the ring (β, $Q_{x,y}$)

- All these can be accomplished with beam-based diagnostics

- (Took very well timed beam-based diagnostics USPAS class)

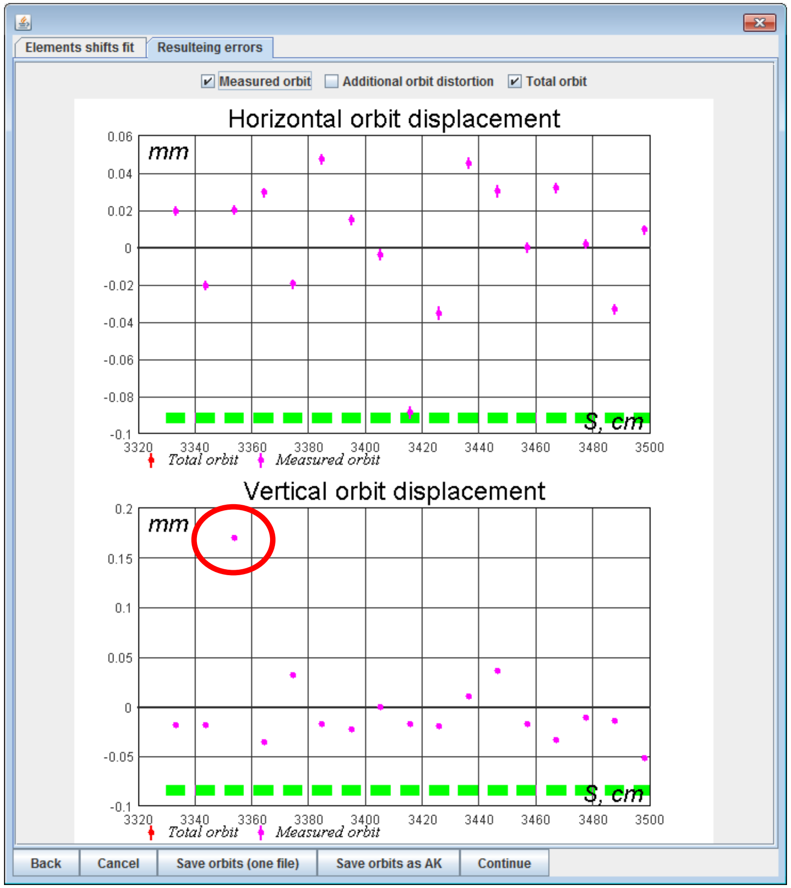
Octupole Henon-Heiles

- For lattice optics:
  - LOCO and more LOCO (A. Romanov's tool 6dsim)
  - Dependent on accuracy of available BPMs and eliminating sources of drift/noise in power supplies
  - A continuing effort…

Octupole Henon-Heiles

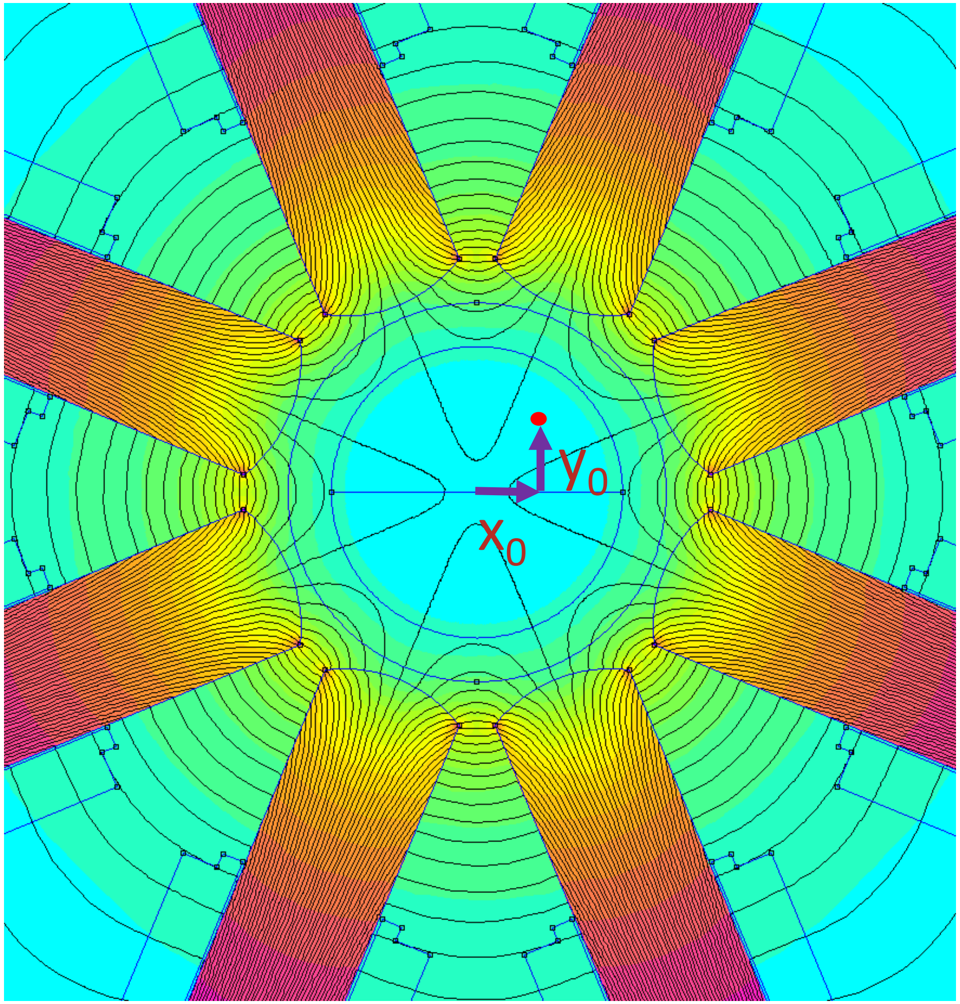
For centering, several approaches available:

- Rough alignment check - pretend they are quads, do orbit response ('centering') measurements
  - Initial results identified a single outlier, oq15
  - Cause traced to intermittent ground fault, was cleared, but problem has returned later, still under investigation



Octupole Henon-Heiles

- More systematic way: scan each oq with local bumps
- Off-center orbit will produce feed-down effects that can be detected



Octupole Henon-Heiles

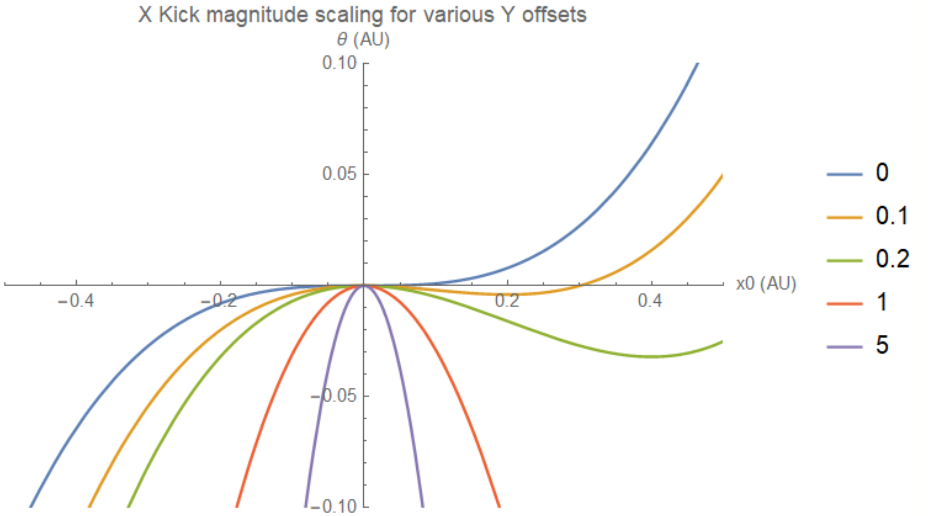
- Can consider two types of linear optics responses:
  - Dipole kicks
  - Quadrupole focusing

$$B_y = x^3 - 3\,x\,y^2$$

$$B_y = x^3 + 3\,x_0\,x^2 - 3\,x\,y^2 - 3\,x_0\,y^2 - 3\,x\,y_0^2 - 6\,x\,y\,y_0 - 3\,x_0\,y_0^2 - 6\,x_0\,y\,y_0 + 3\,x_0^2\,x + x_0^3$$

- For example: horizontal orbit scan gives linear + cubic kick

- NB: if coils counts are asymmetric, that will produce current dependent feed-down too!



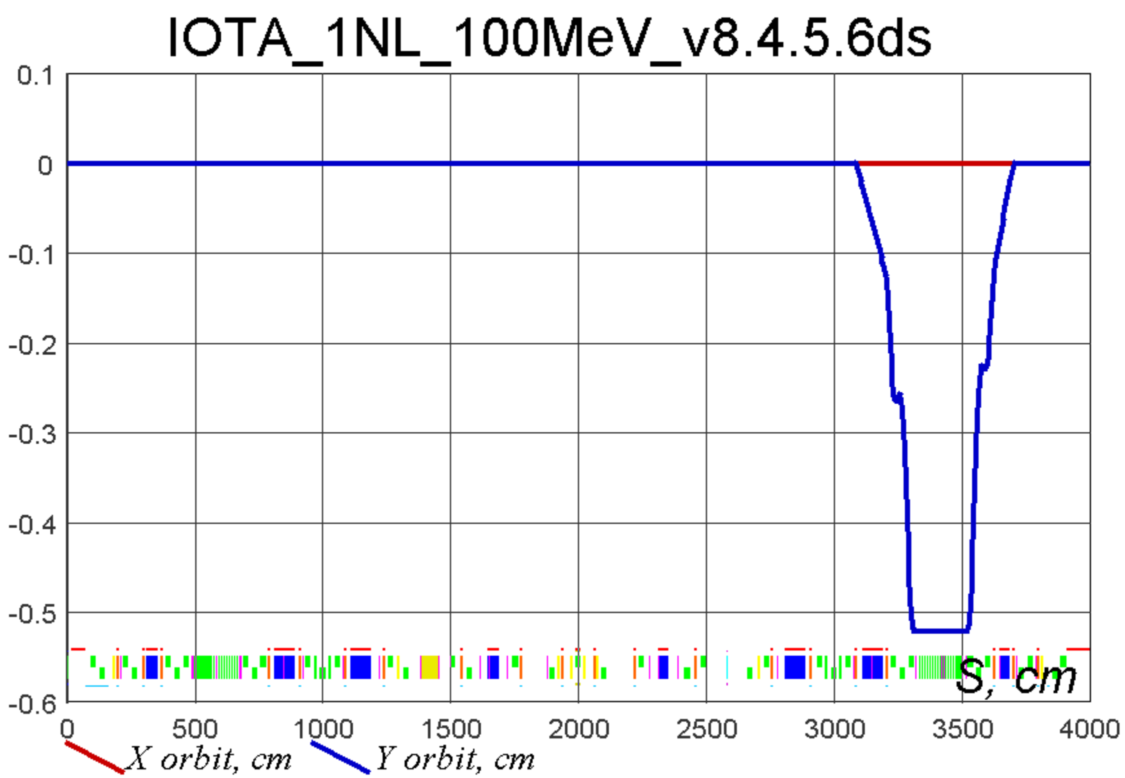
Octupole Henon-Heiles

- Dipole field affects closed orbit
  - Can detect with SyncLight and BPMs in orbit mode
  - Main source of uncertainty - slow system drift (second-minute scale)
  - Luckily, drifts mostly in horizontal plane
    - O(30nm) in X, O(2nm) in Y

- Quadrupole component affects tunes, only seen during kicks
  - Detectable with BPMs in TBT mode
  - Relies on tune calculation accuracy, and hence BPM TBT noise
  - ~100um accuracy, current dependent below 1mA

Octupole Henon-Heiles

- Decided to do closed orbit (dipole) scans first
- Bumps computed with 6dsim (i.e. 6D closed orbit)
  - (NB for horizontal bump due to dispersion)



Octupole Henon-Heiles

- Data collection via Python->Java->ACNET pipeline
  - Loop: change correctors-change octupole-collect X/Y/sX/sY

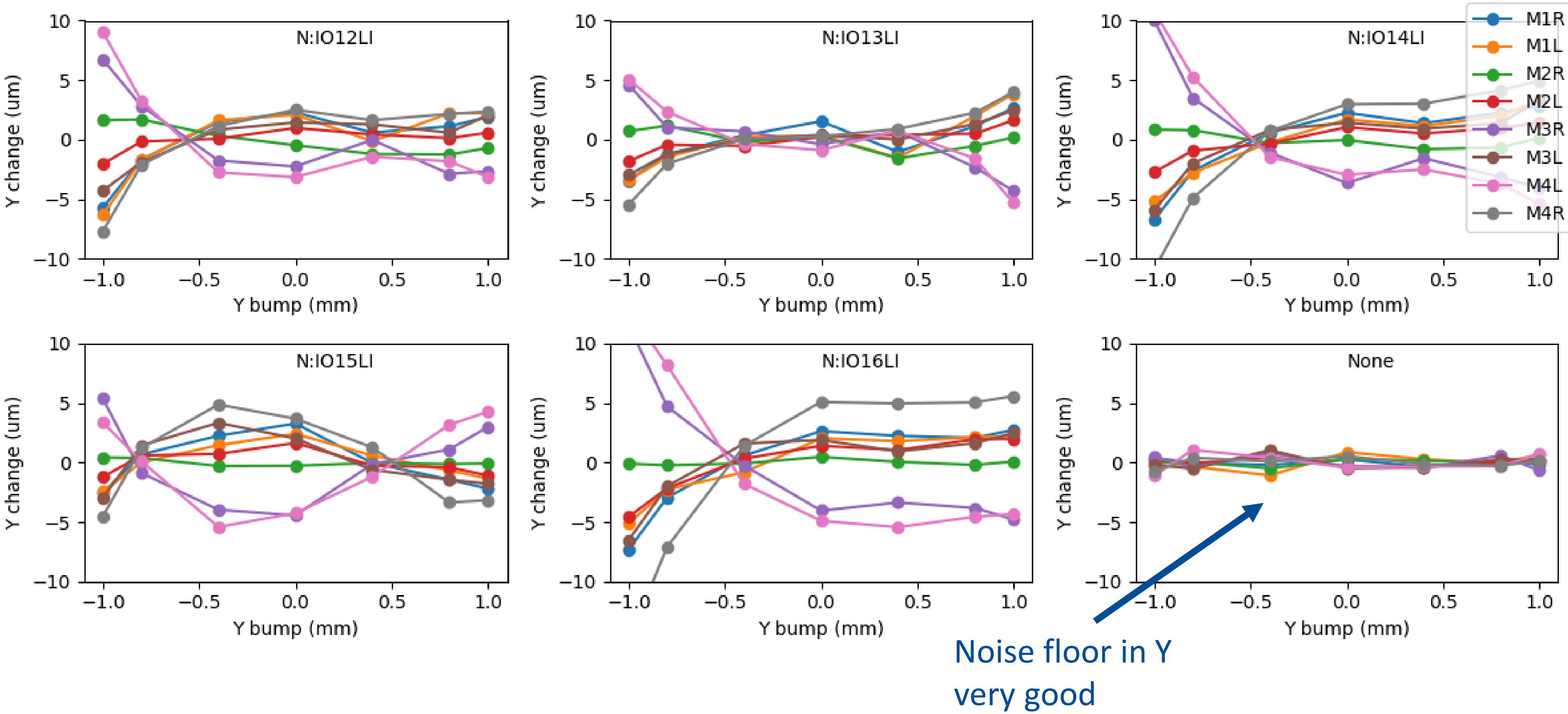
- Spent A LOT of time fighting ACNET and various bugs

```
---DOING OFFSET: (-1, -1)
N:IVA2LI shift is 0.15 A (abs: 0.231634521484375 A)
N:IVB1LI shift is 0.304 A (abs: 0.560500244140625 A)
N:IVB2LI shift is 0.462 A (abs: 0.77602587890625 A)
N:IVC1LI shift is 0.104 A (abs: 0.367214111328125 A)
{'N:IVA2LI': 0.231634521484375, 'N:IVB1LI': 0.560500244140625, 'N:IVB2LI': 0.77602587890625, 'N:IVC1LI': 0.367214111328125}
-Setting devices
SET - N:IVA2LI -> 0.231634521484375...OK
SET - N:IVB1LI -> 0.560500244140625...OK
SET - N:IVB2LI -> 0.77602587890625...OK
```

- Now, working reliably but needs extensive (>1hr) beam time

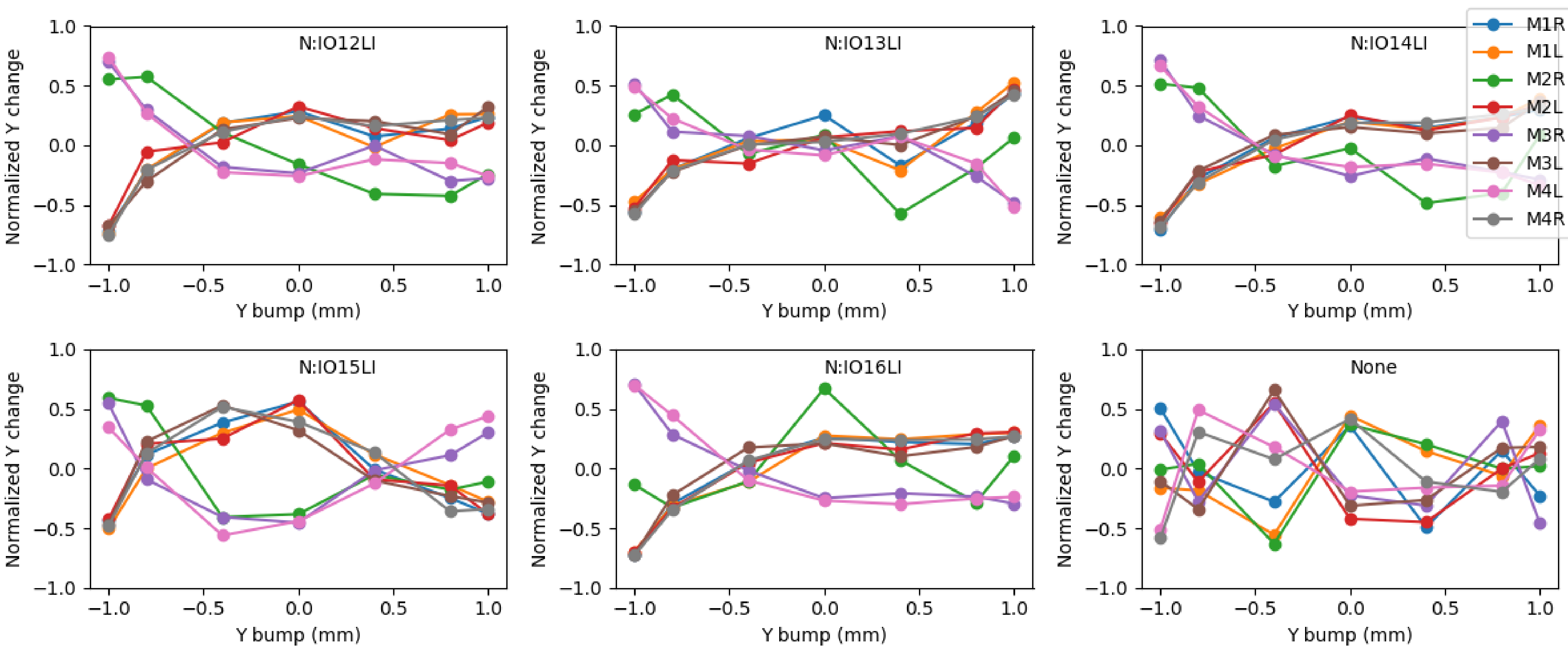
Octupole Henon-Heiles

- Preliminary data acquired during last two weeks
- Indicates generally good agreement between octupoles, except #15



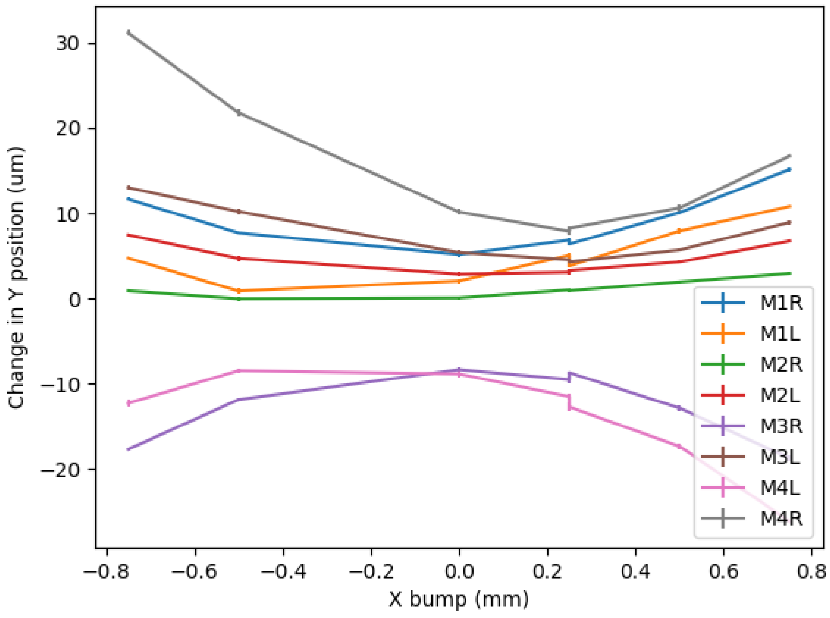
Octupole Henon-Heiles

- Normalizing helps see the good inter-camera agreement

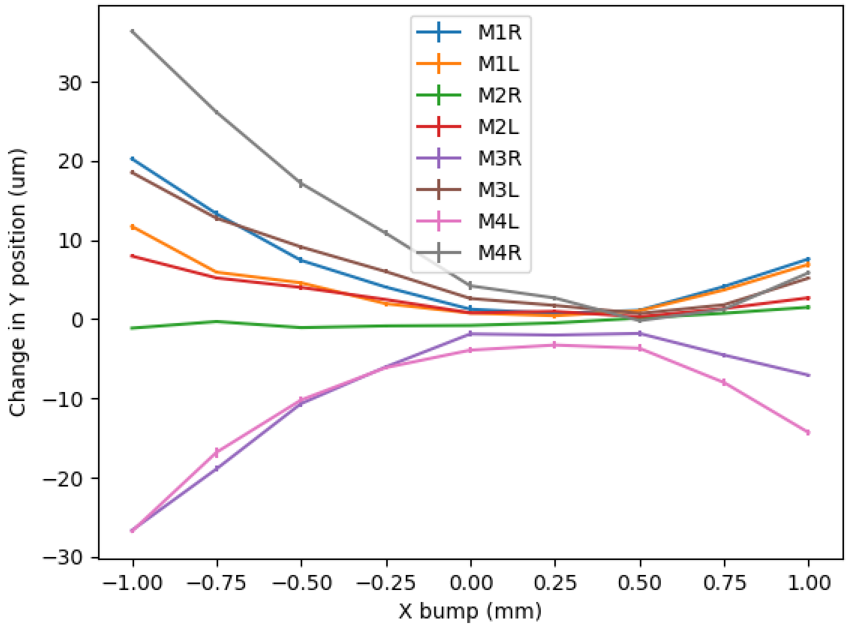


Octupole Henon-Heiles

- Other 'scan' direction can determine X offset
- Working on reliable quantification



OQ16



OQ15

Octupole Henon-Heiles

- Questions to answer:
  - What is the resolution of these scans?
    Simulations are not likely to be useful due many systematics
    Also, depends on bump accuracy
    -> Hope to answer once we have full 17 octupole scan
  - Will tune scans be better?
    -> Plan to do some this week!
  - What can we do to improve the performance?
    -> Implement local bump that ‘threads’ the centers
    -> Rebalance octupole strengths to best preserve the invariant

Outline

- Introduction
- Projects in detail:
  - Synchrotron radiation diagnostics
  - Octupole Henon-Heiles System
    - Physics motivation
    - Design and assembly
    - Commissioning
    - Data collection
- Discussion + Q/A

Octupole Henon-Heiles

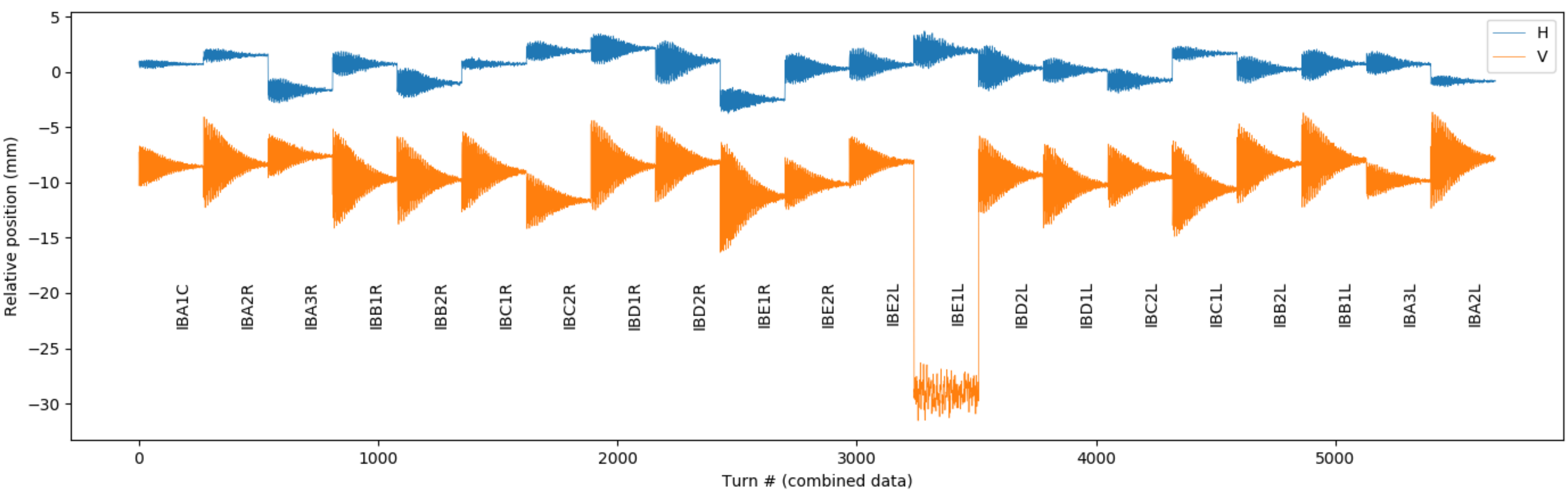
- Several early attempts to measure tune shifts

- Procedure:
  - Do vertical or combined (H/V) kicks with insert at –2A/0/+2A
  - Acquire TBT BPM data, do NAFF (Numerical Analysis of Fundamental Frequencies) tune fitting
  - Repeat for various kick magnitudes
  - (optionally) Monitor beam lifetime and compare max kick amplitudes to measure dynamic aperture reduction

Octupole Henon-Heiles

Disclaimer: this is VERY preliminary data

- Raw BPM outputs (2mA current, 0.5kV V kick, 2kV H kick):



- Note decoherence in ~300 turns due to large chromaticity

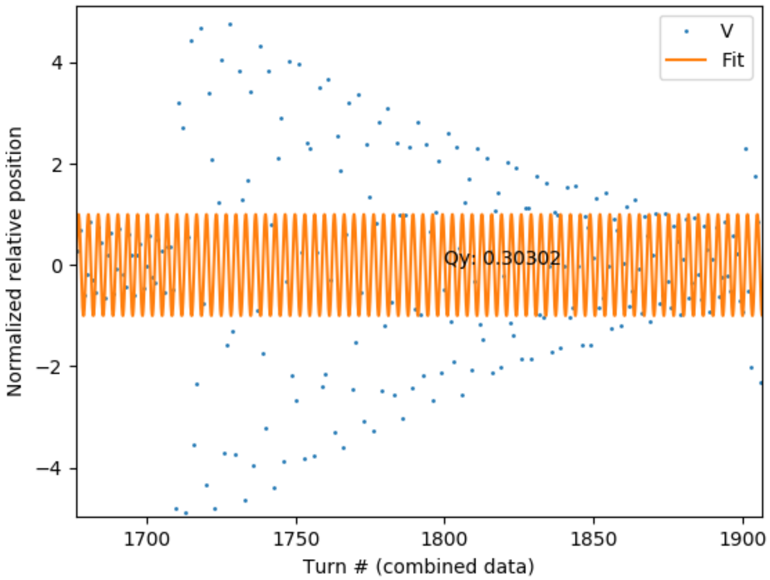
Octupole Henon-Heiles

Disclaimer: this is VERY preliminary data

- Detrend, normalize, apply NAFF
- Extract top harmonics

- Ex: Qy = 0.30302
  Qx = 0.29774

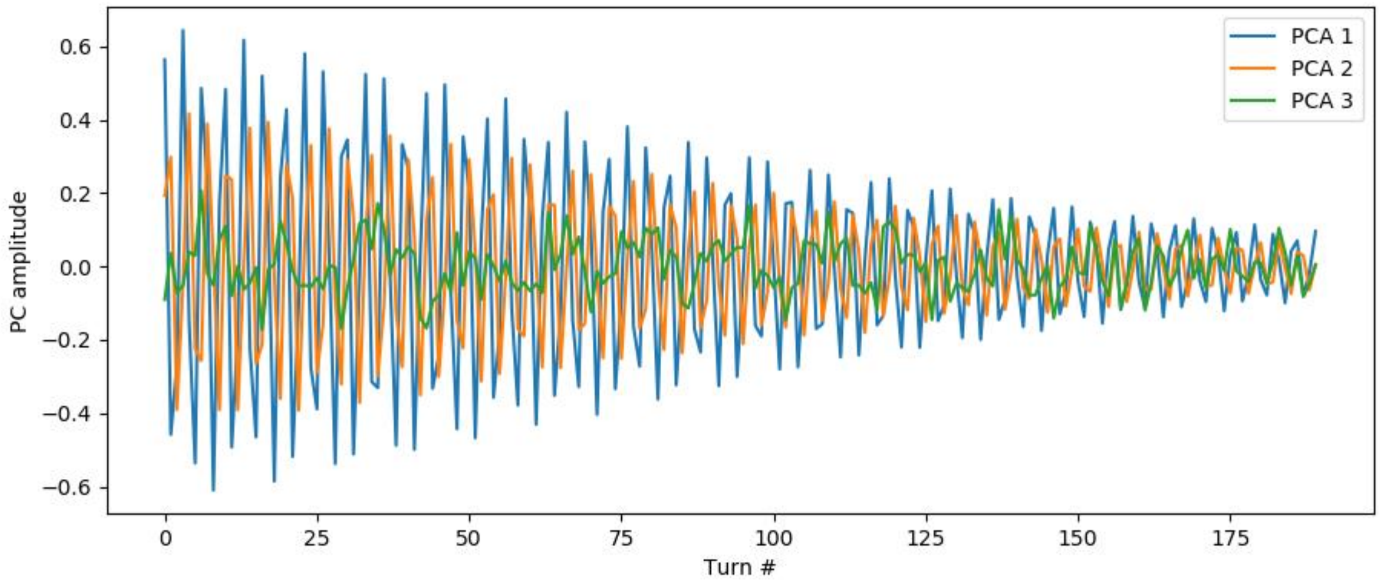
- Very simplistic approach,
  need to add envelope function



Octupole Henon-Heiles

Disclaimer: this is VERY preliminary data

- Preprocessing data to decompose modes can help things
- Using same tool as for Tevatron (by A. Petrenko)
  - But also developing ways to integrate methods into own processing pipeline



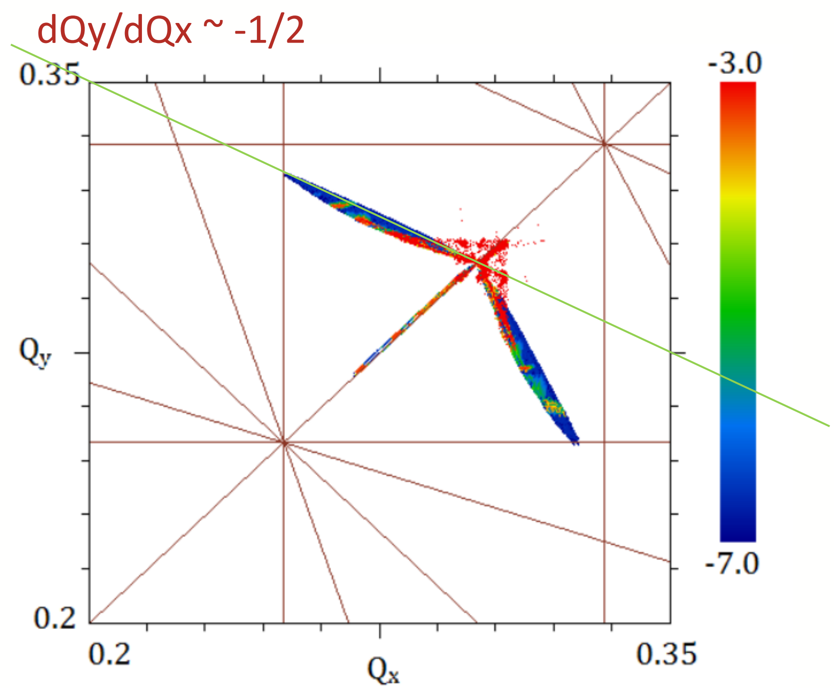
Octupole Henon-Heiles

Disclaimer: this is VERY preliminary data

- Comparing frequencies between on/off cases can demonstrate tune shift trends

- Latest data gives -1/2 slope (expect a bit different, Ax != 0)
  - $\Delta Qy = +0.007$
    $\Delta Qx = -0.014$

- Tune spread magnitude is lower than last week….
- Likely due to optics changes, investigating this week



Octupole Henon-Heiles

- Questions to answer:
  - What is the best experimental working point?
    We can slide up/down Qx=Qy easily, but are limited by ¼ resonances
  - How can we improve measurement accuracy?
    Determine correct envelope function, combine H/V data (if coupled)
    BPM improvements? (Like done earlier today)

Conclusion

- Progress has been made on a number of projects
- SyncLight
  - System commissioned and used extensively during this run
  - Many upgrades in the pipeline to extend dynamic range and provide TBT data
- Octupole Quasi-Integrable System
  - Insert finished, assembled, and installed into the ring
  - Commissioning ongoing, with simultaneous first studies
  - Data promising, will now pursue maximizing tune spread
- Other things
  - Open sourcing our tools though tech transfer office
  - Learning to operate and control the machine

Q/A

THANK YOU FOR YOUR ATTENTION