Beam Instrumentation at the Fermilab IOTA Ring

Nathan Eddy on behalf of the IOTA team

IBIC’18, September 9th, 2018

Malmo, Sweden

Outline

- Overview of the Fermilab Accelerator Science and Technology (FAST) facility
- Beam Instrumentation in the IOTA Ring & Commissioning
- Experimental Results from First Run
- Future Upgrades

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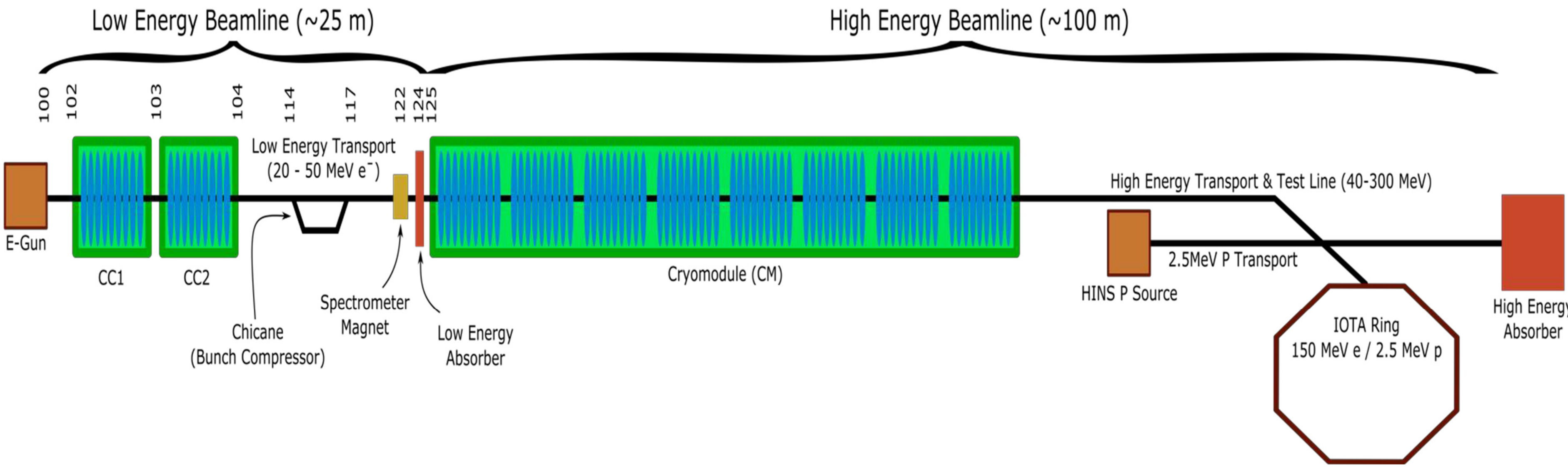
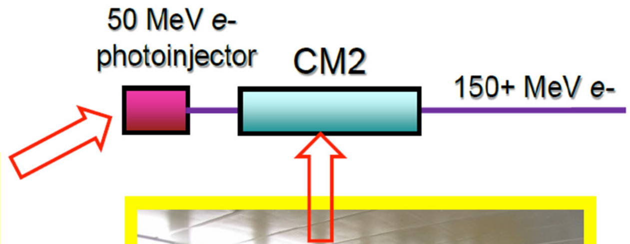
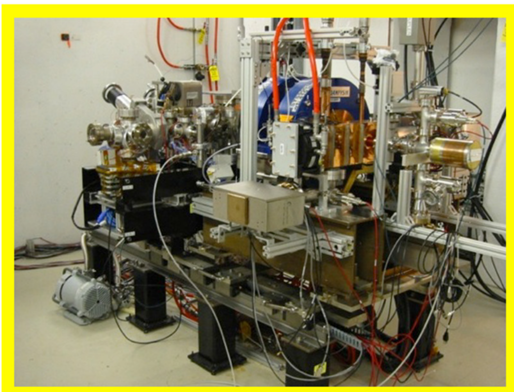
The FAST Facility



- FAST facility dedicated entirely for intensity-frontier accelerator R&D
- Superconducting electron linear accelerator (Electron Injector)
- Integrable Optics Test Accelerator (IOTA) Ring
- Proton Injector – under development

The Electron Injector (formerly ASTA)

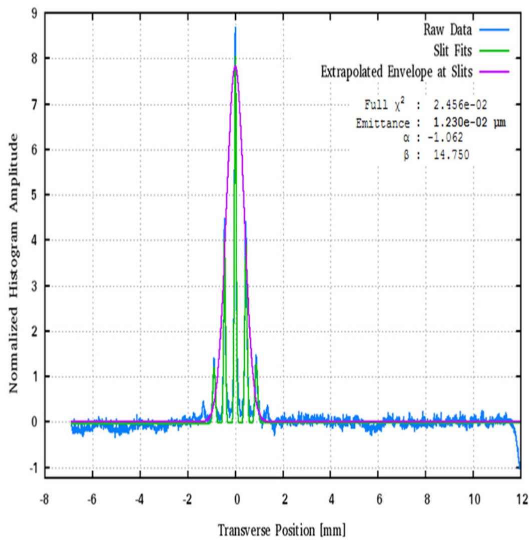


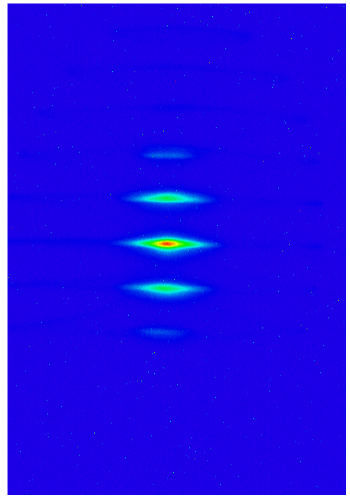


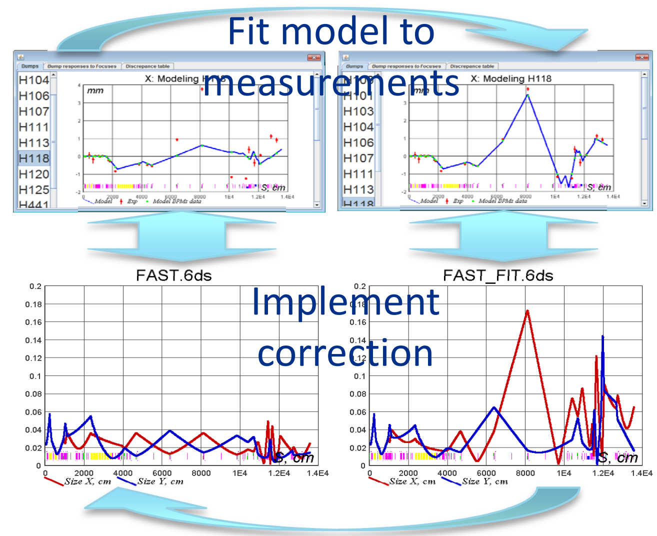
Parameter	FAST Value
Beam Energy to LE Absorber	20 – 50 MeV
Beam Energy to HE Absorber	100 – 300 MeV
Bunch charge	<10 fC – 3.2 nC
Bunch Frequency	0.5 – 9 MHz
Macropulse frequency	1 – 5 Hz
Macropulse duration	< 1 ms
Normalized emittance (0.1nC/bunch)	0.6 um
Number of trims (X & Y)	23 & 23
Number of BPMs	26
Quads (LE & HE)	14 & 22
Beam imaging stations	17
Crosses for insertion devices	20

- 2015 – first beam through the LE beamline to LE absorber
- October 2017 – **beam accelerated through ILC-type cryomodule to energy 150 MeV**
  - Propagated to point of injection to IOTA
- November 2017 – **beam accelerated to 301 MeV**
  - **Record ILC-type cryomodule acceleration of 255 MeV**
  - Over 31.5 MV/m
- August 2018 – Startup after long shutdown to install IOTA

Matching e-Beam Parameters for IOTA Injection







- Lattice matching for IOTA successful injection
  - Slit emittance from OTR screens
  - Lattice optics measurements using BPMs
- 6D parameter matching
  - Beta-functions in both planes
  - Twiss parameters alpha for both planes
  - Horizontal dispersion and its derivative

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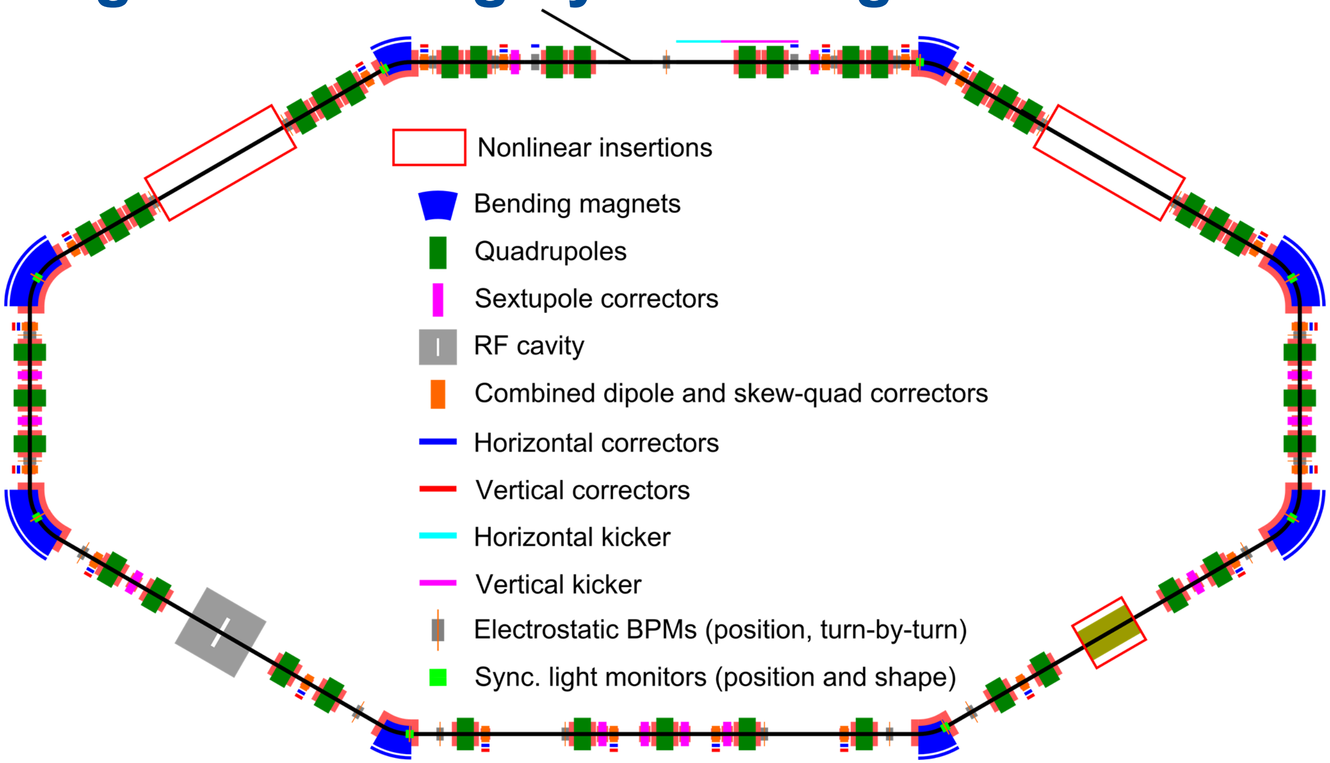
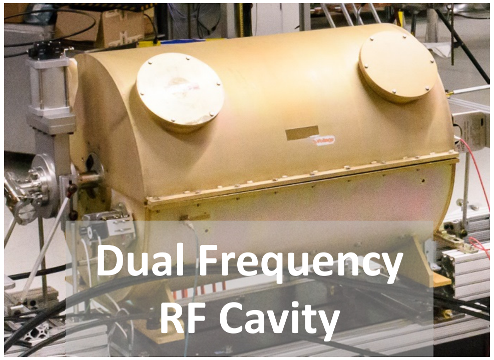
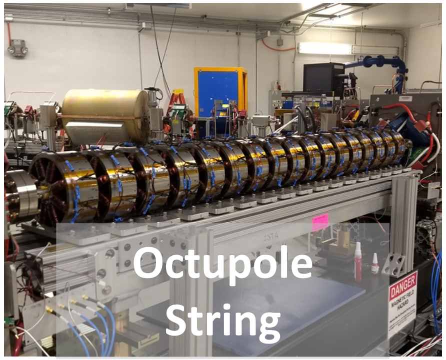
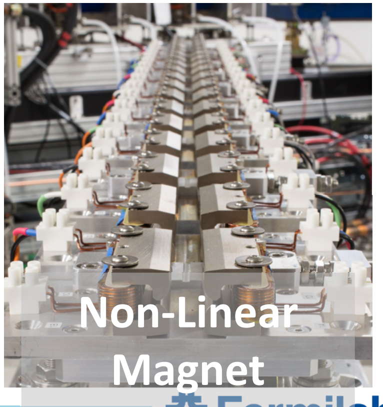
IOTA Designed as a Highly Reconfigurable R&D Ring









IOTA Experimental Plan

Phase I with electrons: 2018-2021

- Probe beam dynamics for Non-linear Integrable Optics (NIO)
  - Octupole string as NIO element
  - IOTA Non-Linear magnet as NIO element
- Optical Stochastic Cooling

Phase II with protons: 2020-2023

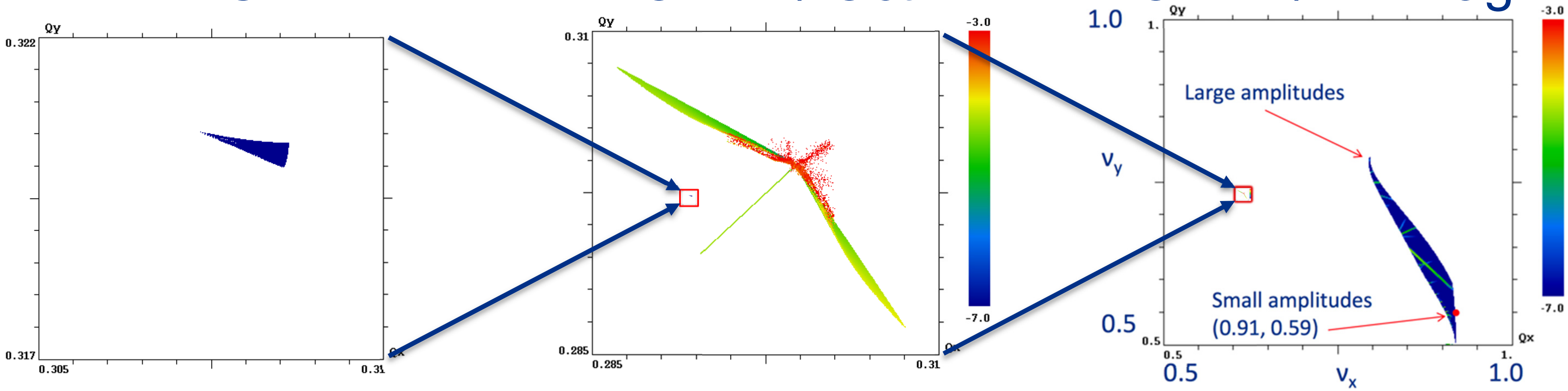
- Study NIO systems in high-intensity regime
- Study space-charge compensation methods in NIO systems

Goal: Reduce beam losses and improve immunity to coherent instabilities for bright beams

Non-linear Integrable Optics Potential Benefits

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

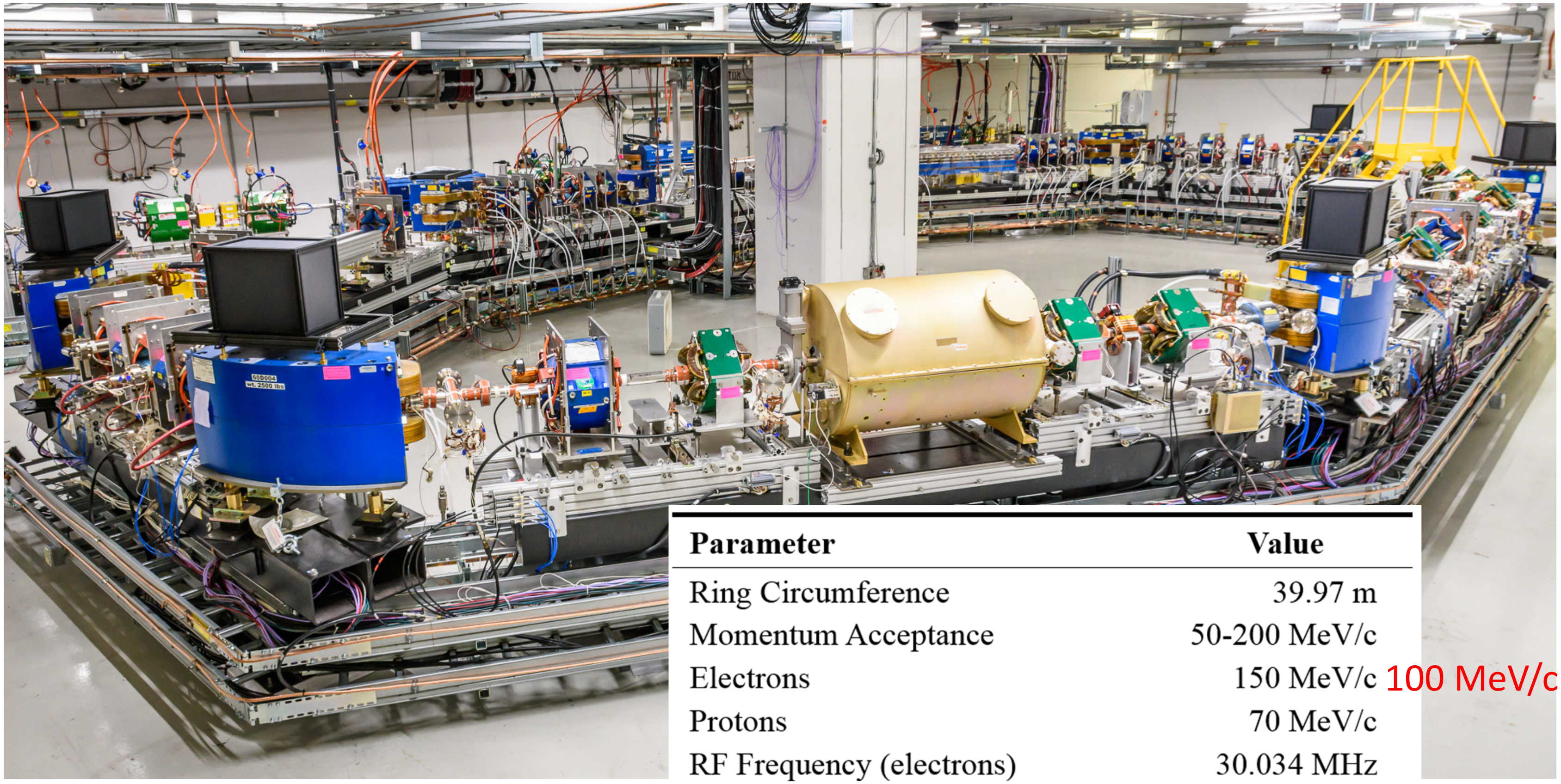
LHC | IOTA w/ Oct. | IOTA w/ NL mag.



$\Delta Q = 0.001$ | $\Delta Q = 0.025$ | $\Delta Q = 0.25$

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

IOTA Beam Parameters

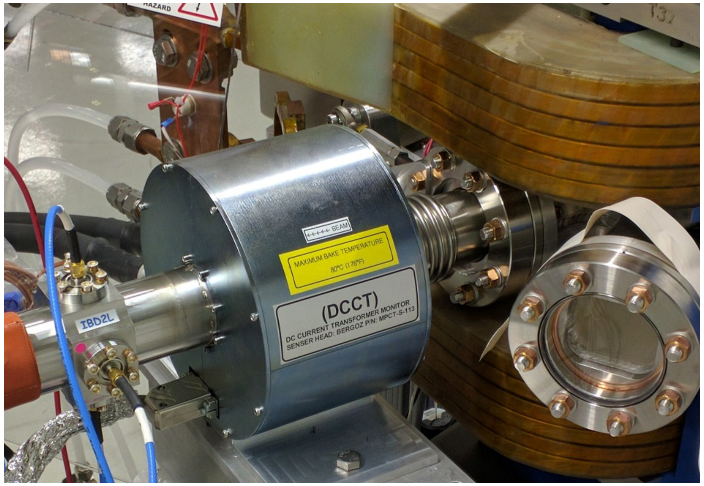


Parameter	Value	
Ring Circumference	39.97 m	
Momentum Acceptance	50-200 MeV/c	
Electrons	150 MeV/c	100 MeV/c
Protons	70 MeV/c	
RF Frequency (electrons)	30.034 MHz	
RF Frequency (protons)	2.19 MHz	
RF Voltage	1 kV	150-200V
Harmonic Number	4	
Bunch Length (electrons)	10-20 cm	>=20cm
Tune (horizontal, vertical)	5.3, 5.3	
Synchrotron Frequency	43 kHz	

Diagnostics in IOTA & Commissioning

- DCCT
- SyncLight System
- BPM System
- WCM
- RF longitudinal feedback System
- Transverse Feedback System

DCCT

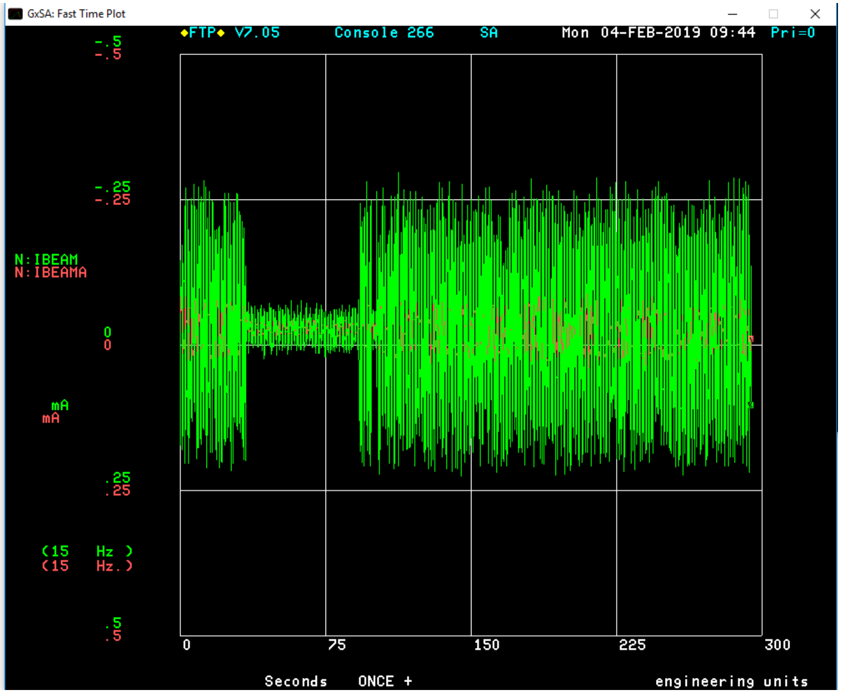


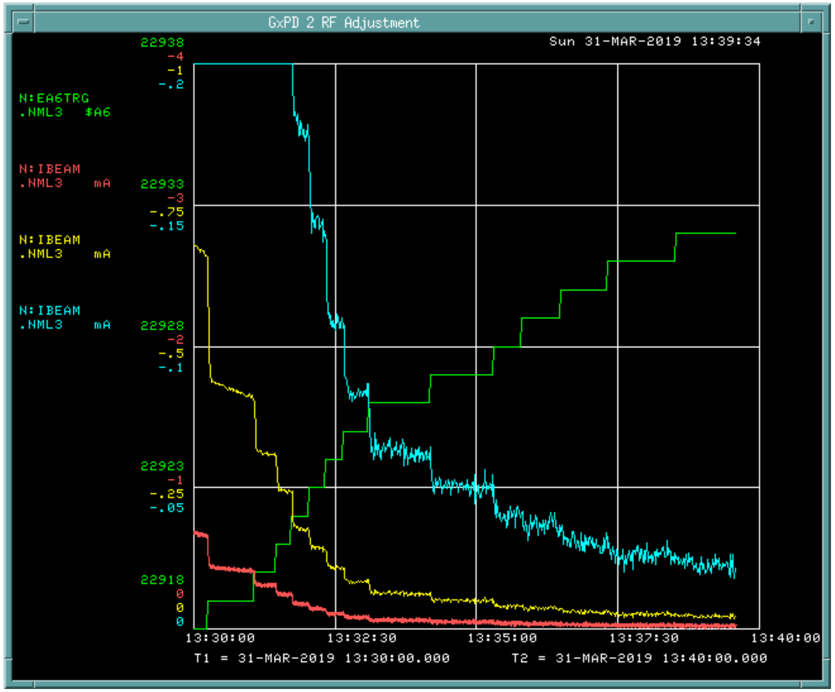
Bergoz MPCT-RH-113

Parameter	Value
Resolution	10μA rms
Linearity Error	< 0.1% Full Scale
Ripple RMS	< 0.2% Full Scale
Bandwidth	DC to 4.2 kHz

- Was purchased for Fermilab Booster R&D in 1999
  - Never operational
- Removed from the Booster in 2016
  - Signal cable was radiation damaged, not repairable
  - Bergoz was able to give us a new sensor head and calibrate it for the original electronics
- Installed as a late addition to the IOTA ring

DCCT Noise

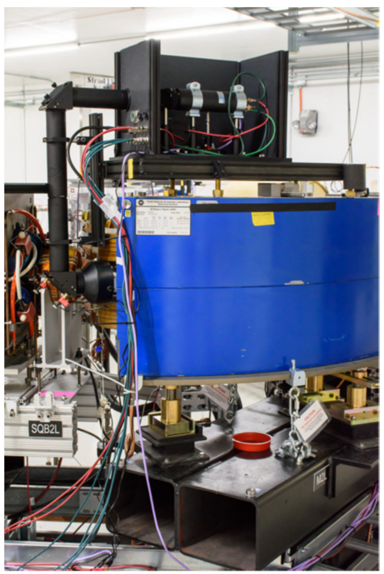


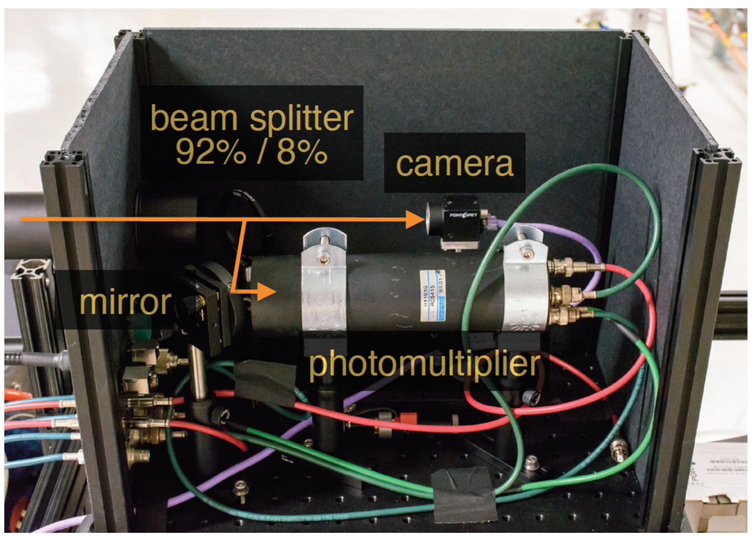


- Startup was plagued by 720Hz noise
- Investigation found correlation with RF cavity probe cable
- Was fixed by improving grounding between tunnel and racks
- At the end of the run, resolution was ~5uA

Synchroton Light (SyncLight) System

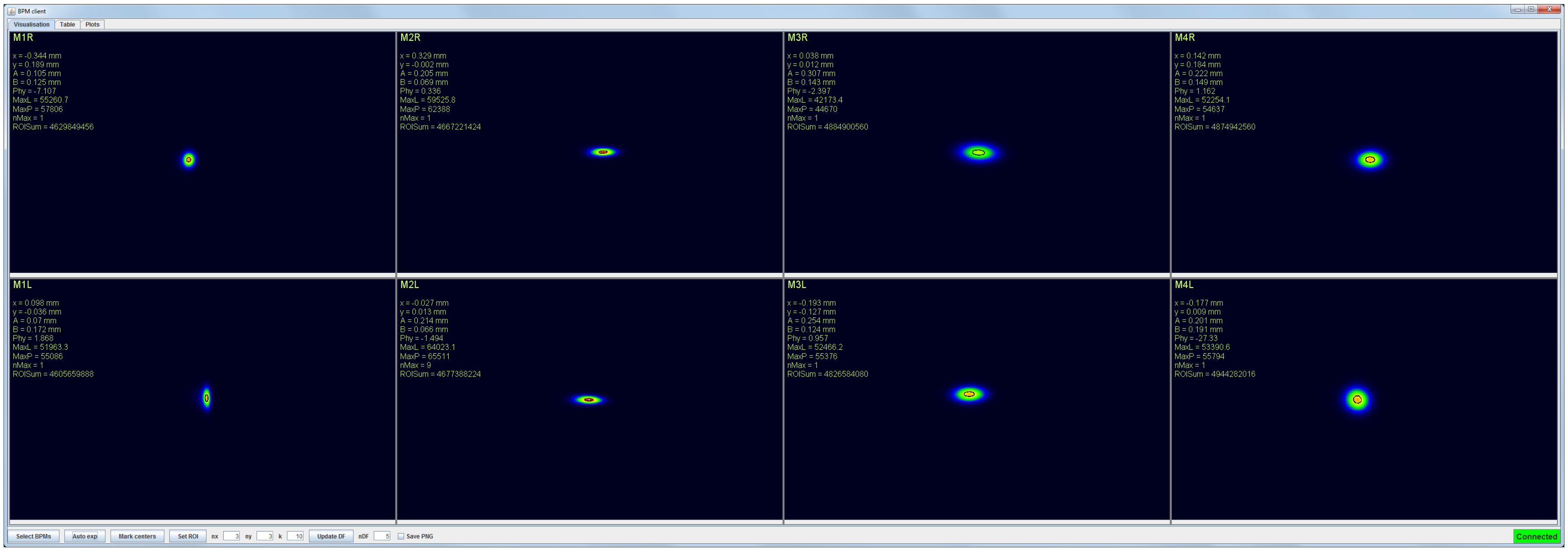
- There are 8 SyncLight systems – one installed at each dipole
- Each main bend has a base station with optics + camera
- A variety of customizations available – PMTs, diodes, etc.
- Installation began in September 2018
- All 8 stations operational in October 2018





Sync-Light Display

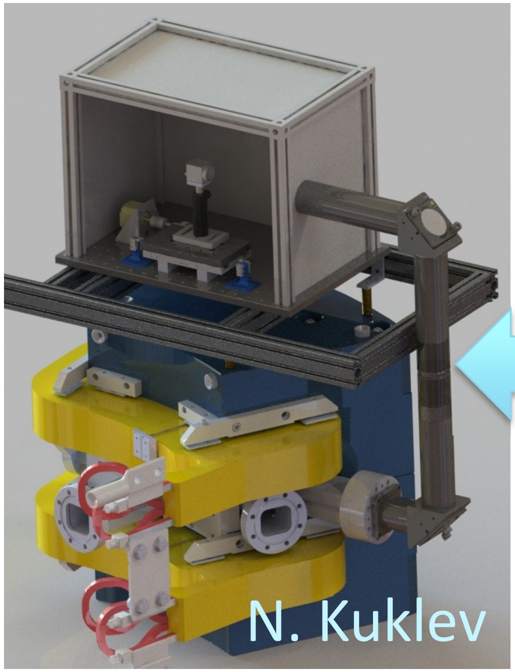
- Live control room readout through DAQ server cluster
  - Beam size, Positions, Intensity available



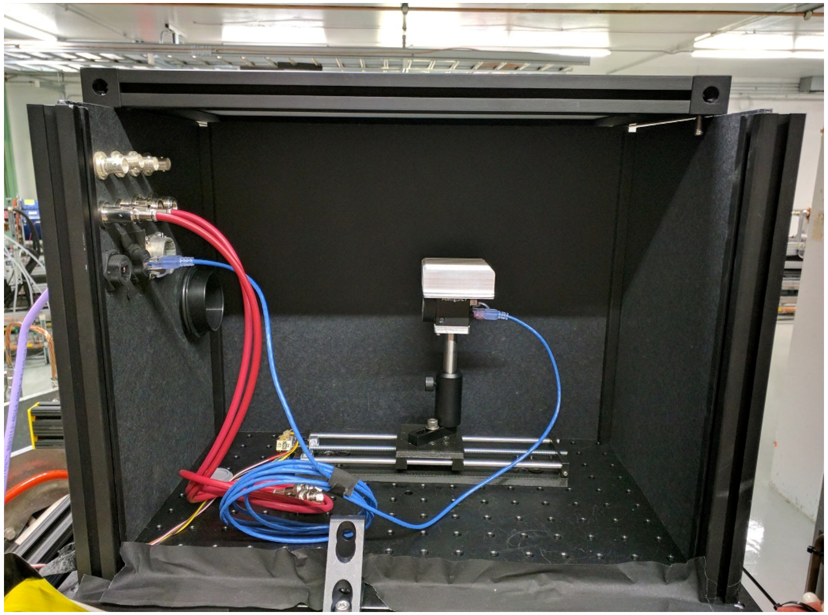
- Excellent precision for orbit measurement, <100nm statistical
- Strongest constraints on closed orbit optics

SyncLight Station Optimizations During Run

- Irises were removed to open aperture
- Had to motorize top and bottom mirrors for transmission optimization
- Passive heatsinks added to cool cameras for lower noise
- Installed stepper actuated focusing stages for all cameras

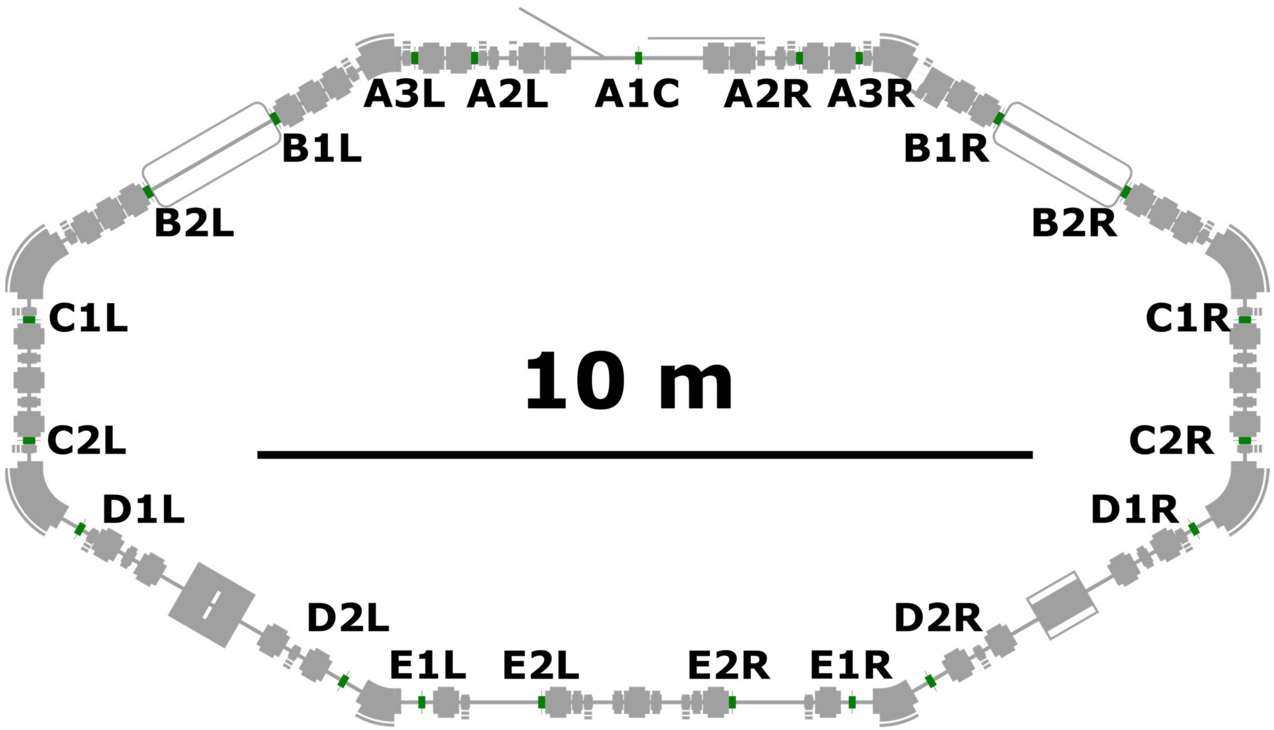


Iris &
lens



Beam Position Monitor (BPM) System

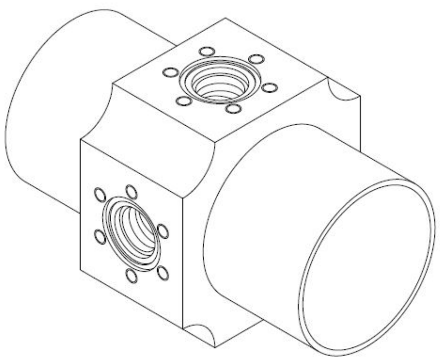
- 21 electrostatic button BPMs – 20 identical to linac pickups

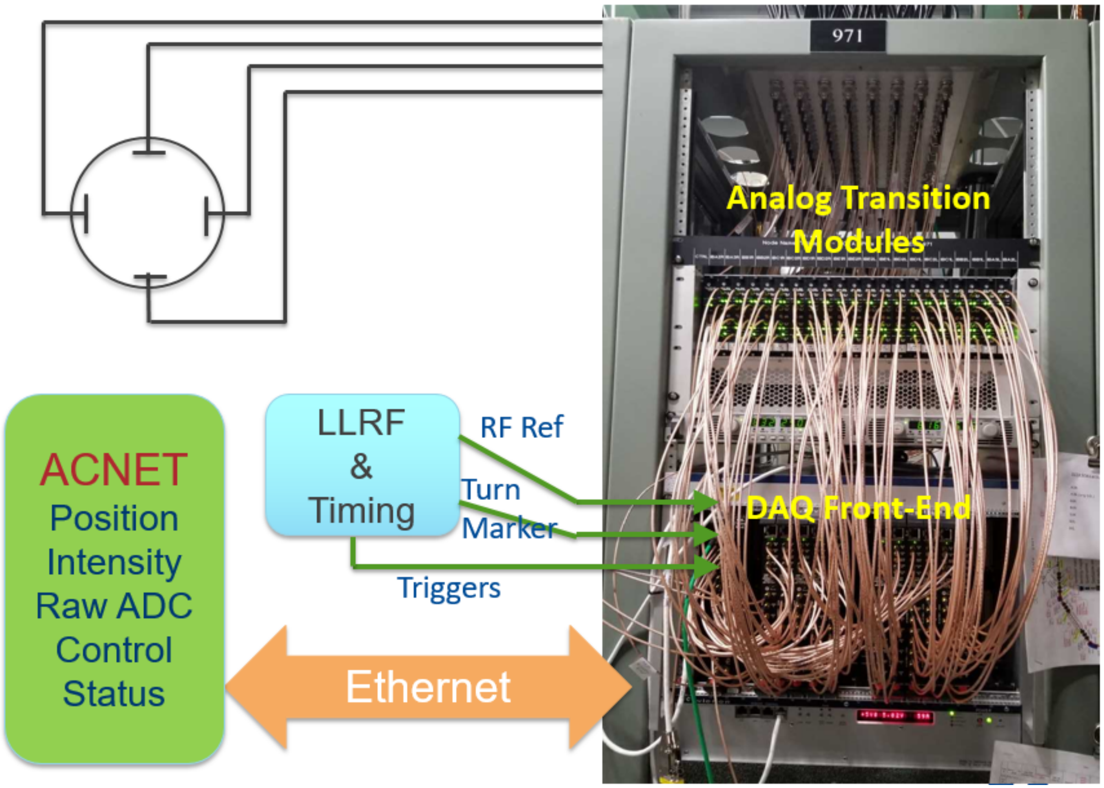


- Provide Turn-by-turn or Orbit (averaging) modes

BPM System Overview

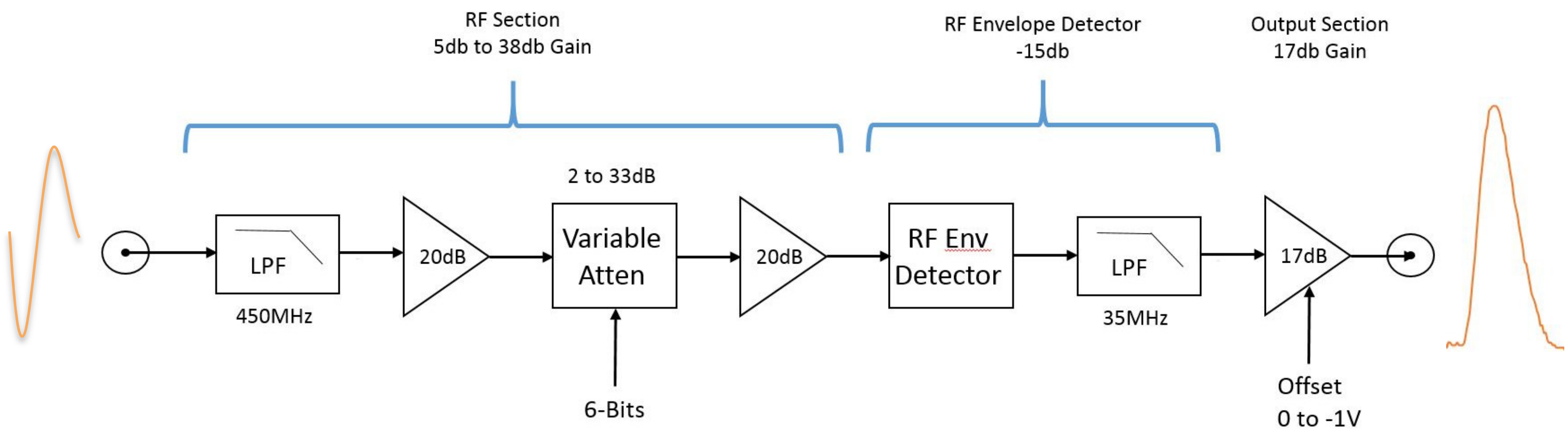
- Pickups, Analog Modules, Digitizers





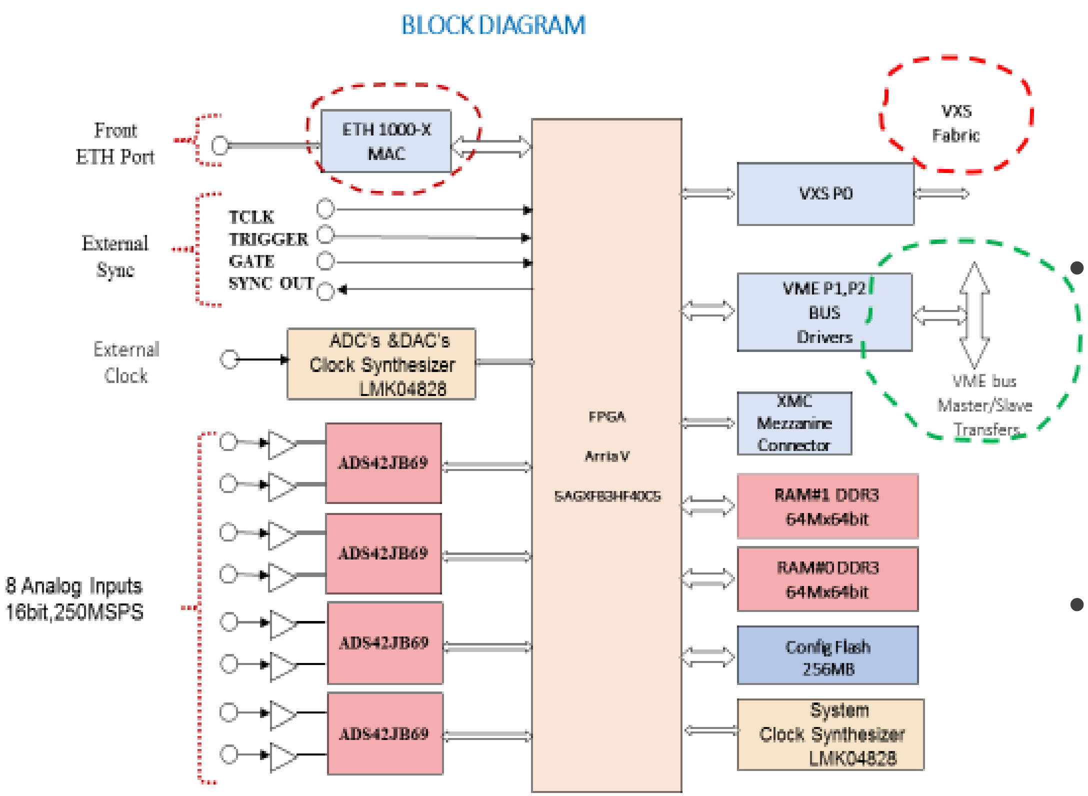
- Timing Module handles clock and trigger fanout
- Commercial VME x86 CPU Card

BPM Analog Transition Modules



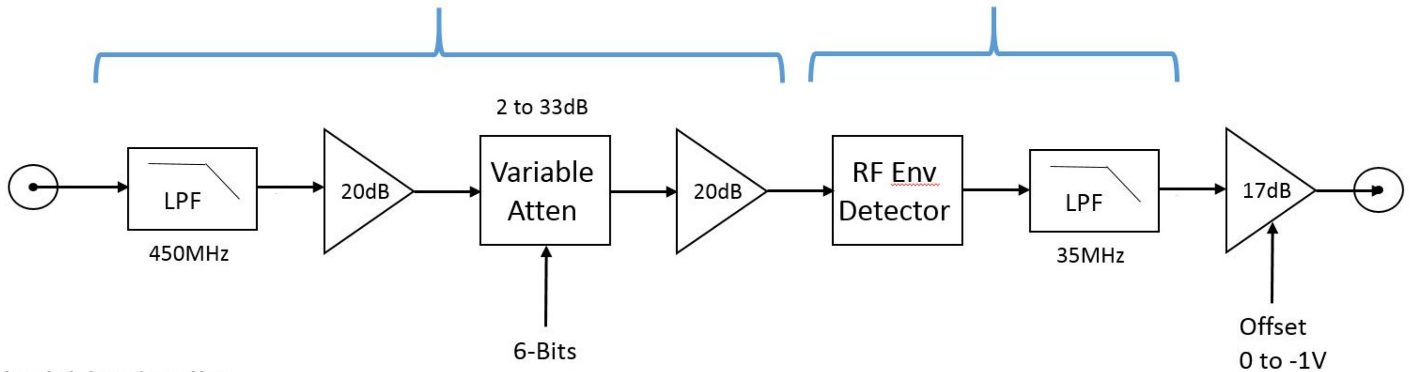
- Provide a signal conditioning before digitization for each bunch from the button electrode (Late Design Change)
  - Short doublet from button electrode (3ps to 1ns)
  - 30MHz RF Bucket -> 33ns
- RF Section – set signal level into RF Detector
- RF Detector – envelope option for ADL5511 plus LPF
- Output Section – Provide further gain and offset

BPM Processing

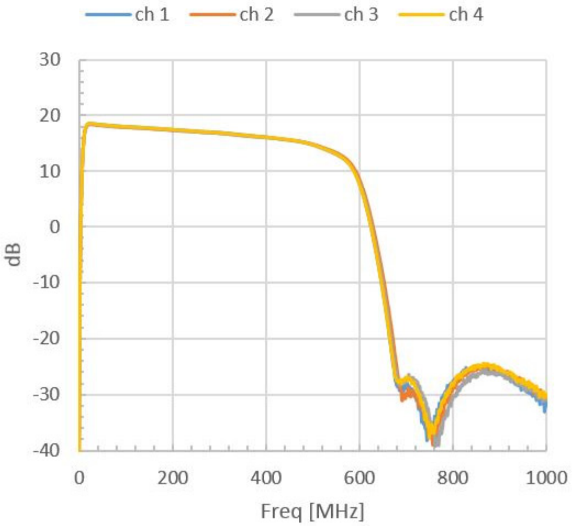


- New Custom Digitizer Modules
  - 250MS/s 16 bit ADCs
  - DC or AC coupled inputs
  - VME/VXS/GigE capable
- Custom firmware using Altera QSYS integrated system
  - ARM CPU, bus, interfaces
  - Perform calculations magnitude -> diff/sum linear fit
- Custom Timing Board
  - Clock and Trigger fanout
  - Upgraded during run provide serial trigger sync'd to turn
- Front-end switch from VxWorks -> real-time linux
  - Switch to x86 architecture
  - Ability to move to commercial server front-end

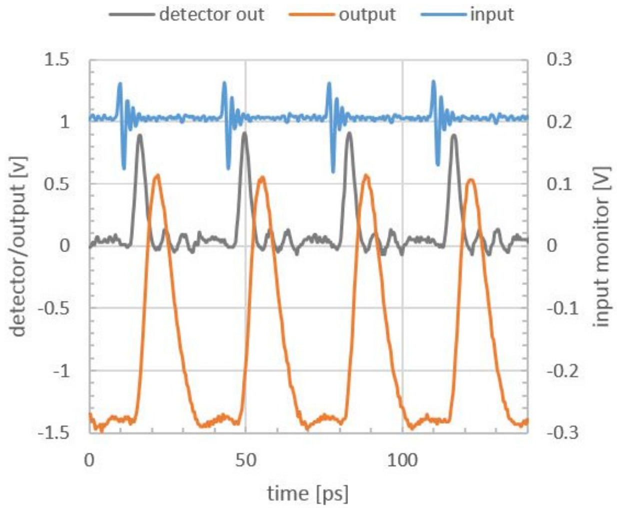
Analog Transition Module Testing



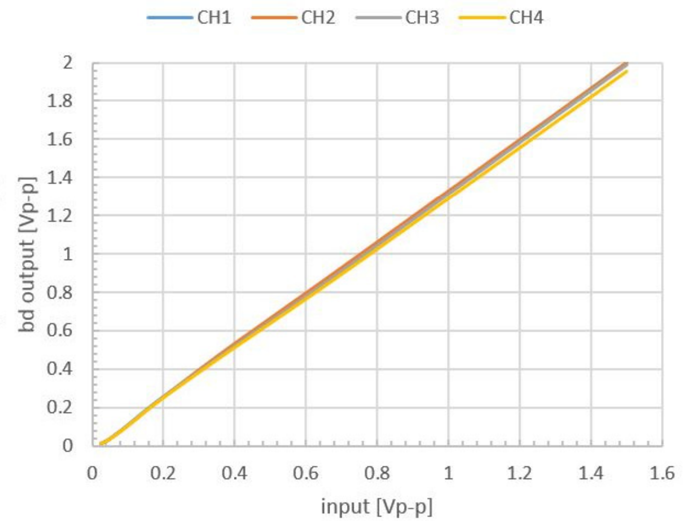
IOTA BPM Transition bd, input section response, measured from input to input monitor test point (-20db loss).



IOTA BPM transition bd, measured output signal with test signal from button viewed from input monitor (-20db loss).

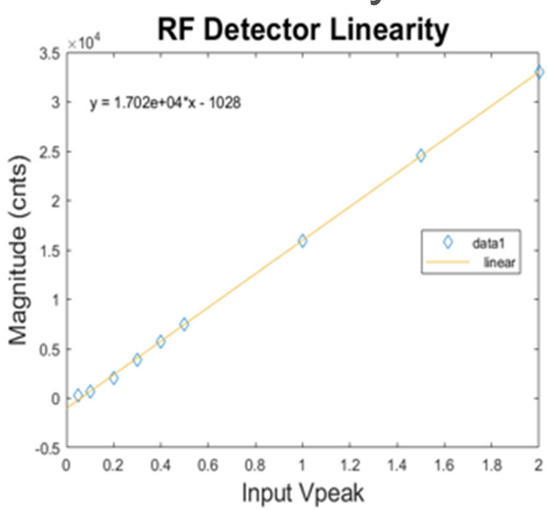


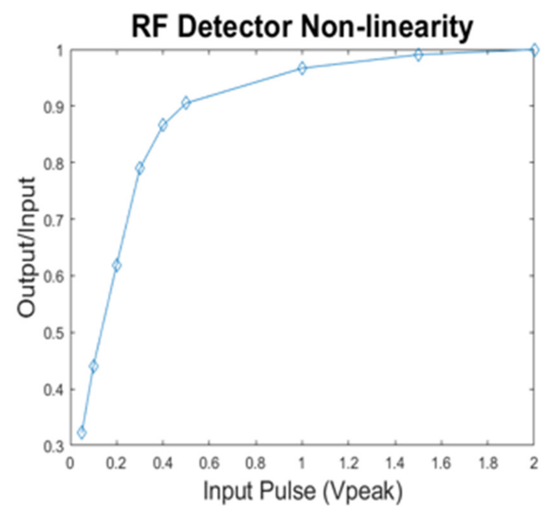
Transition bd linearity test using pulser and bpm button.



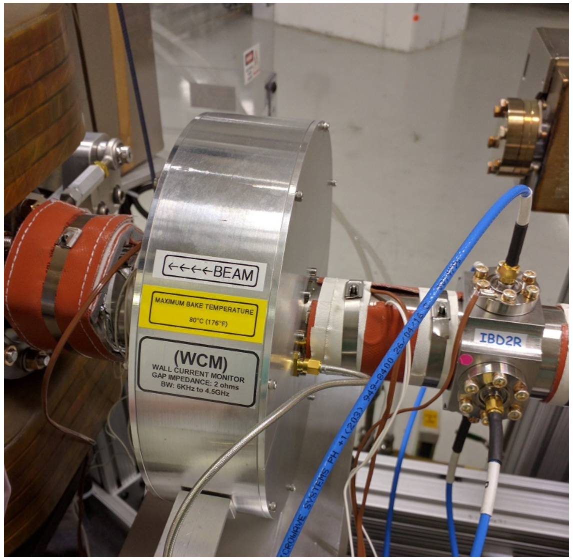
BPM Commissioning

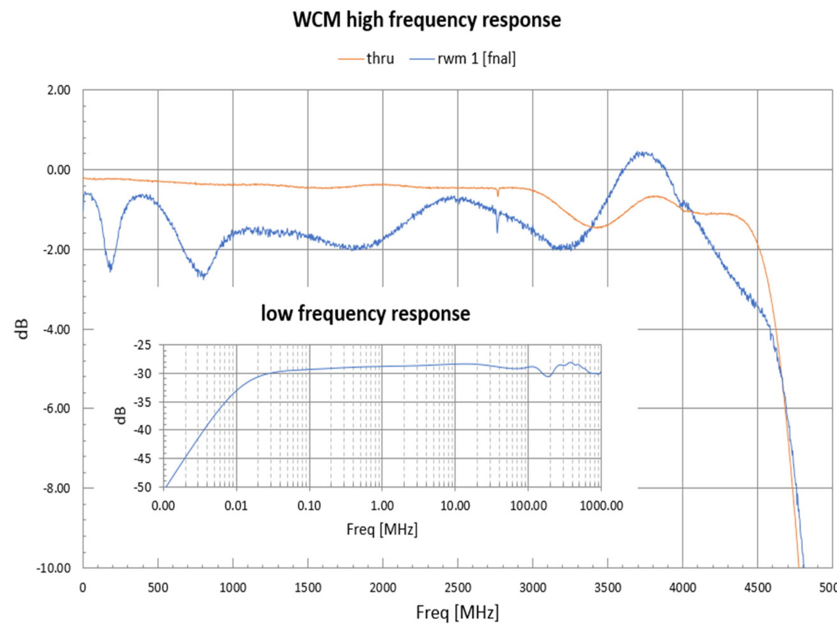
- Worked as expected on injection and getting beam stored in IOTA
- Growing pains with new front-end and controls interface
- Problems arose during stored beam measurements
  - Issues with TBT data due to Beam Quality (more later)
    - Signals much smaller than expected -> poor resolution
    - Put RF pre-amps in tunnel (only handful of bpms)
      - Able to measure smaller beam currents (~2 improvement on resolution)
    - Fit for Diff/Sum and switch to AC coupled inputs
  - RF Detector seriously limited orbit usefulness





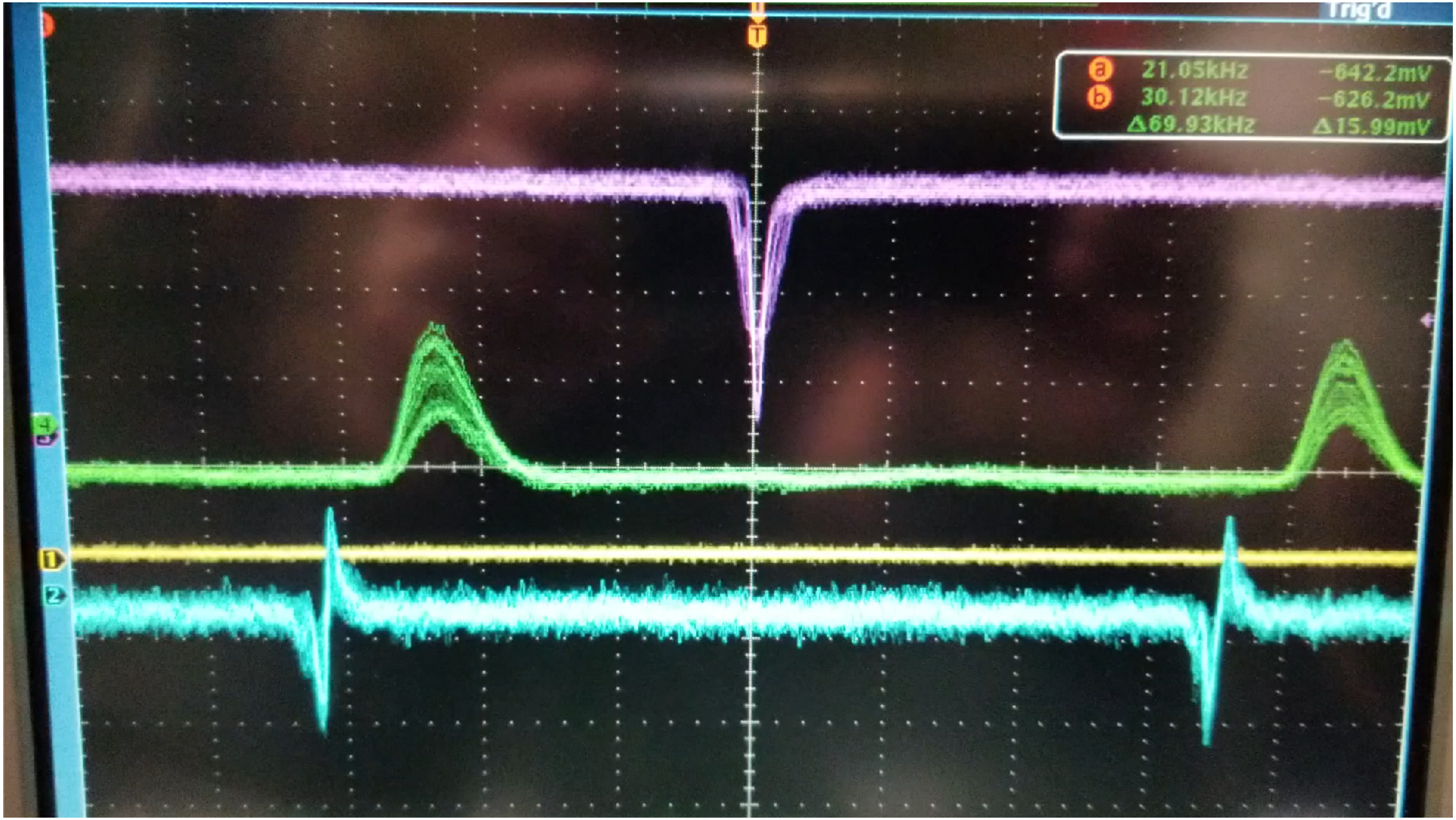
Wall Current Monitor





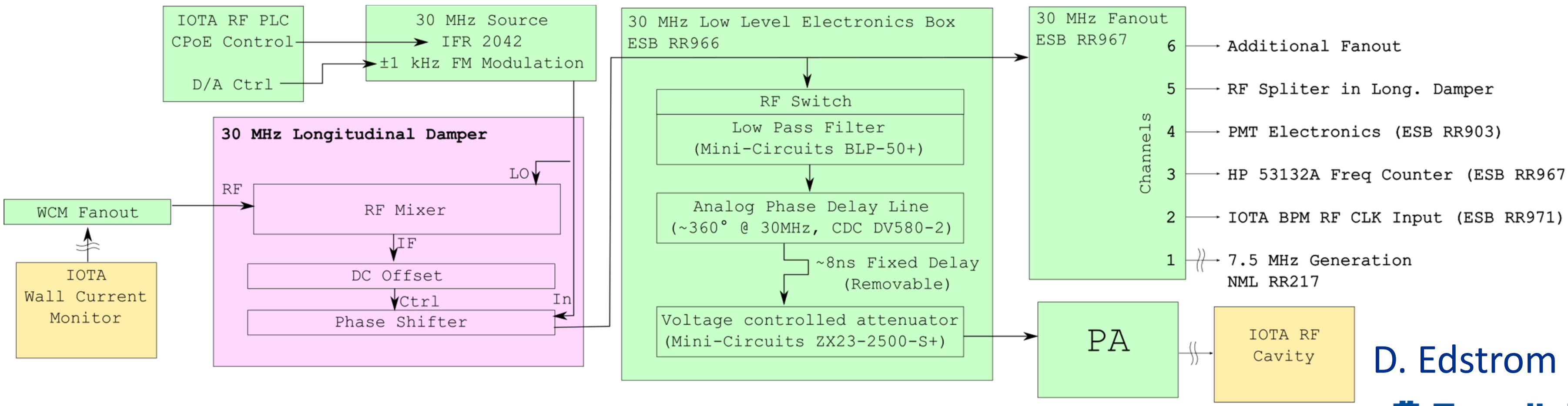
- Based upon a design developed for the EMMA ring
- Originally installed in the electron linac but replaced with toroid
- Like the DCCT somewhat of an afterthought…

BPM Stored Beam Investigations – December 2018



RF Feedback System

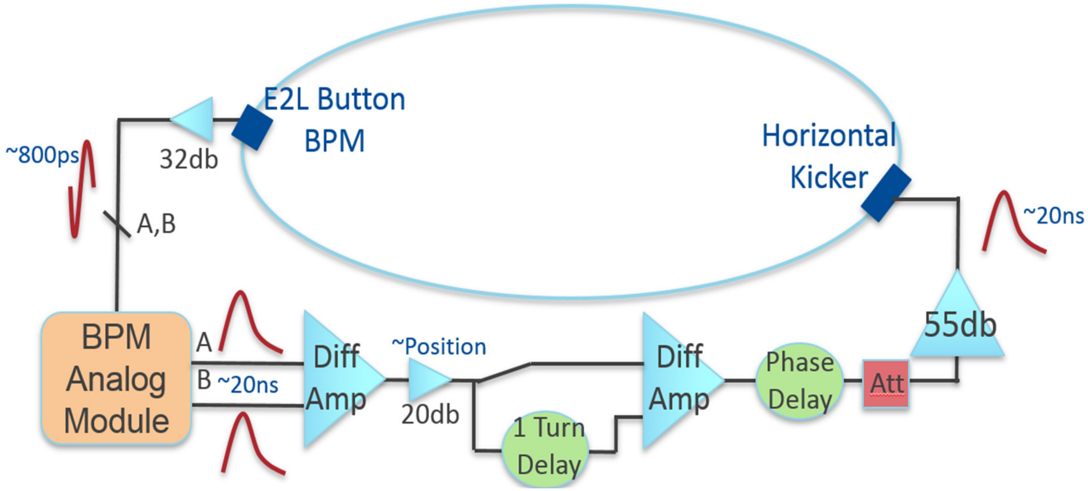
- Initial RF design relied on the relatively low Q factor (~100) to damp beam induced high-order modes
- After several months of investigations and tweaks to RF cavity and control led to design of a feedback system for RF control using the WCM
  - As a result maximum stored beam current increased up to 4.8 mA, 4 times the design value
  - Also improved phase stability and beam lifetime
  - Big improvement for BPM TBT measurements



D. Edstrom

Transverse Feedback System

- Designed and implemented in the last month of running
- Able to mimic transverse beam instabilities

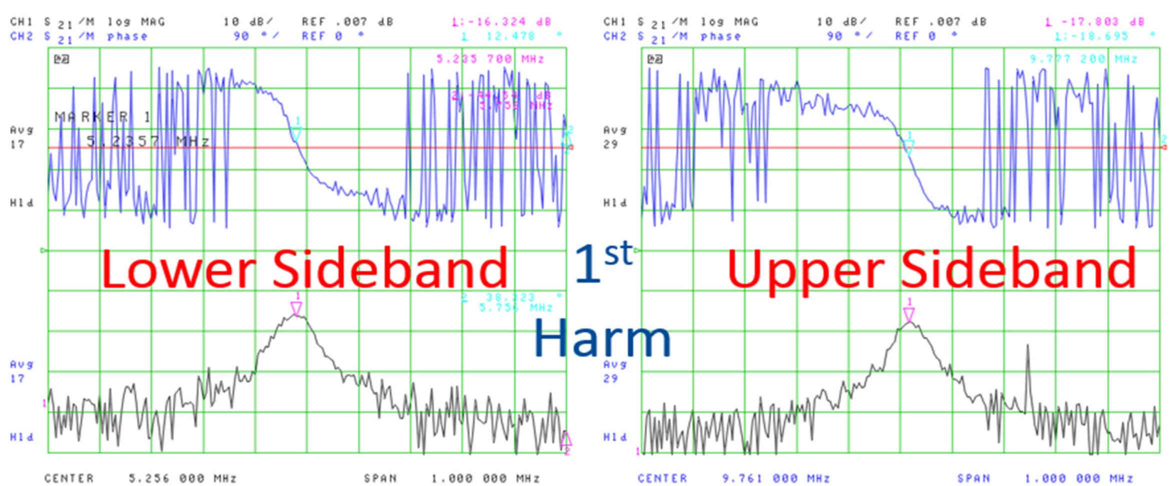


$$NumTurns = \frac{1}{RevT} * (T_{kick} + T_{feedback} + T_{pickup})$$

T_{pickup} *includes beam transit*

$$PhaseAdv = (NumTurns) * \nu_x$$

$$T_{kick} = 370ns$$
$$T_{feedback} = 125ns$$
T_{pickup} = 180-270ns



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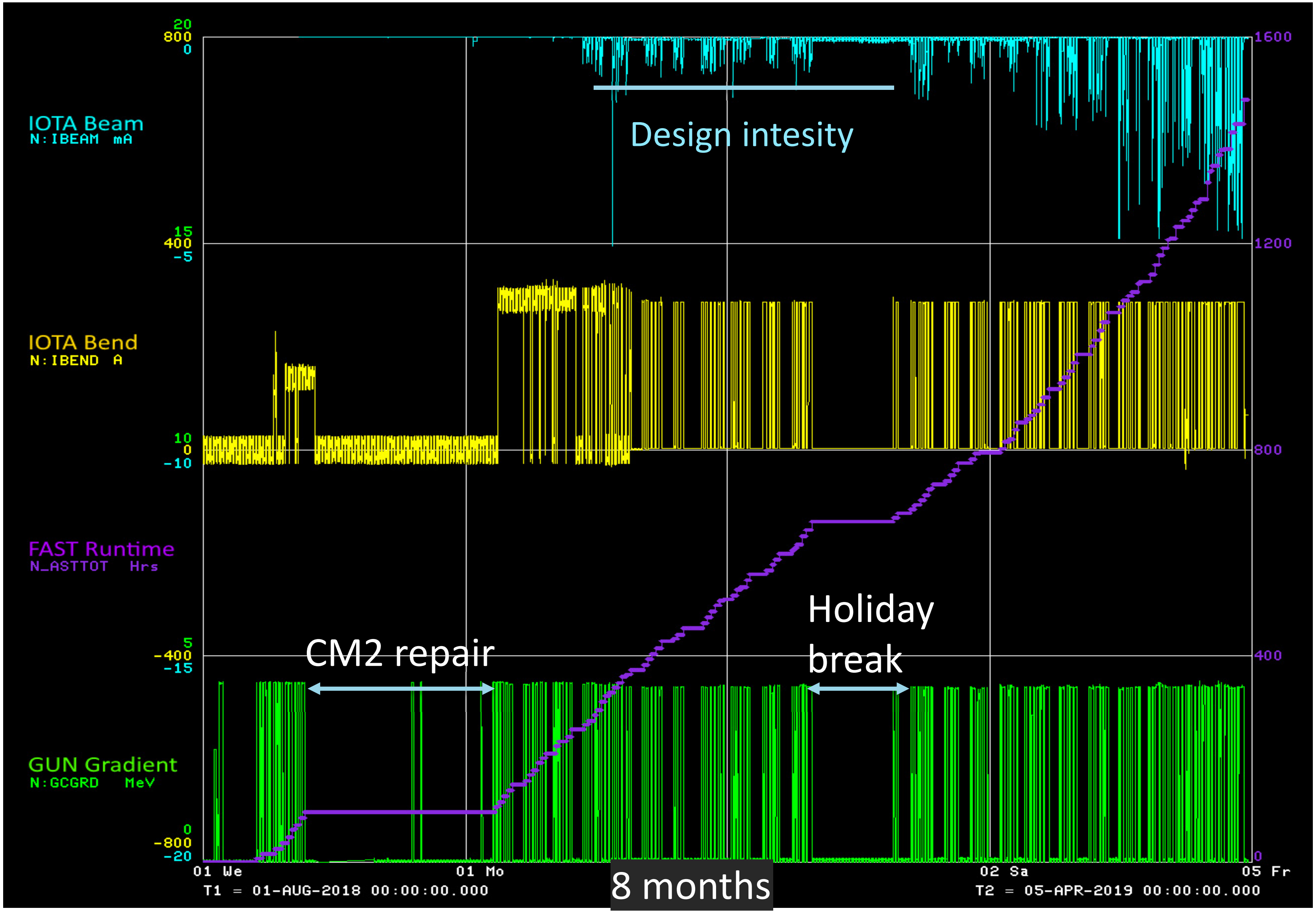
2018/19 IOTA/FAST Run – Total Beam Time 1477 h

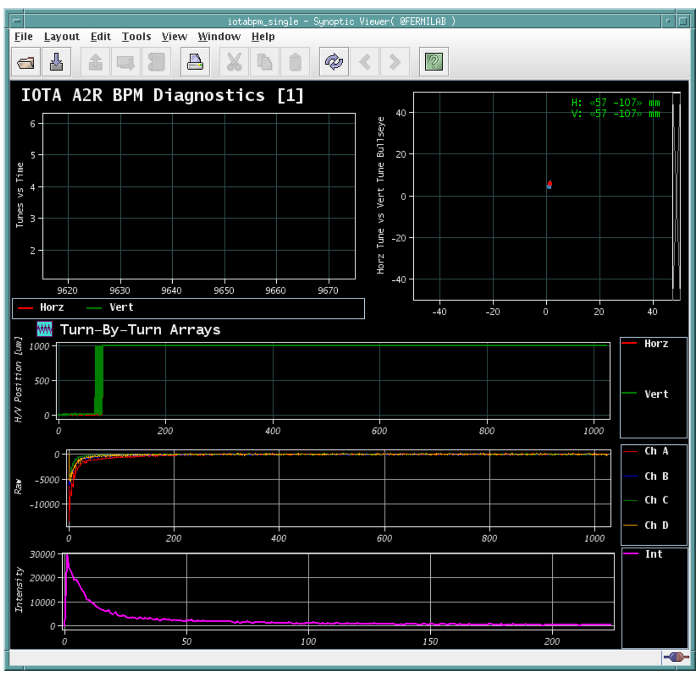


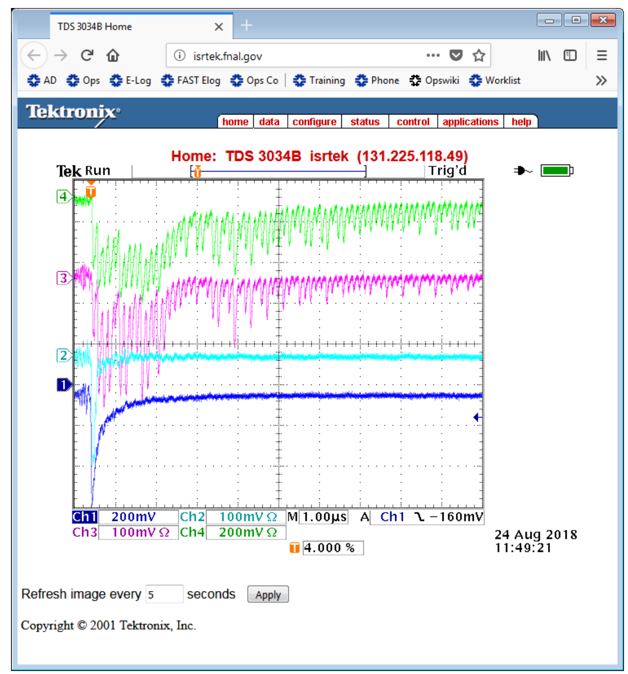
Results from First Run

- Beam Stored in IOTA
- Beam Captured in IOTA RF
- Beam Lifetime
- Single Electrons
- Octupole Experiments
- Landau Damping with Octupoles

50 MeV injection: first turns

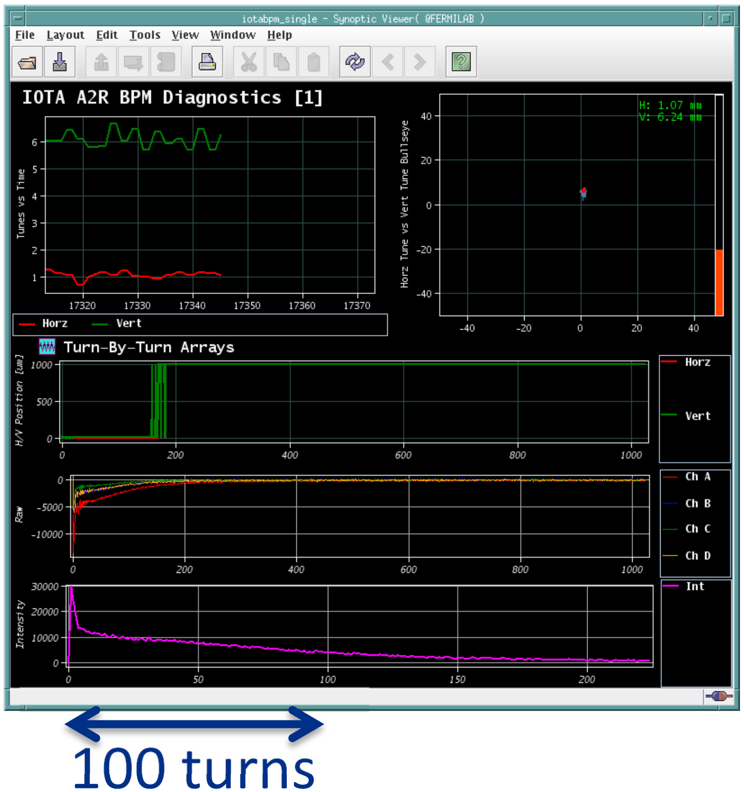
- Issues with Cryomodule and Ring RF Cavity
- After kicker timing was adjusted, pickups were used to trace beam through the first turns without big losses
- At this point response matrix was done to correct IOTA lattice and absolute readings from pickups were used to algorithmically correct closed orbit.

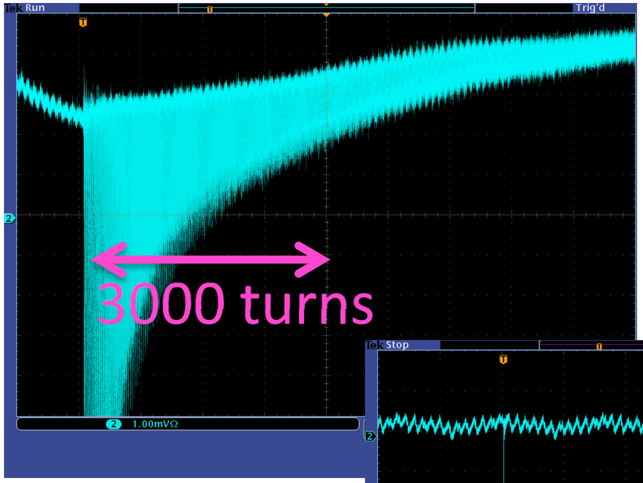




50 MeV injection: first turns

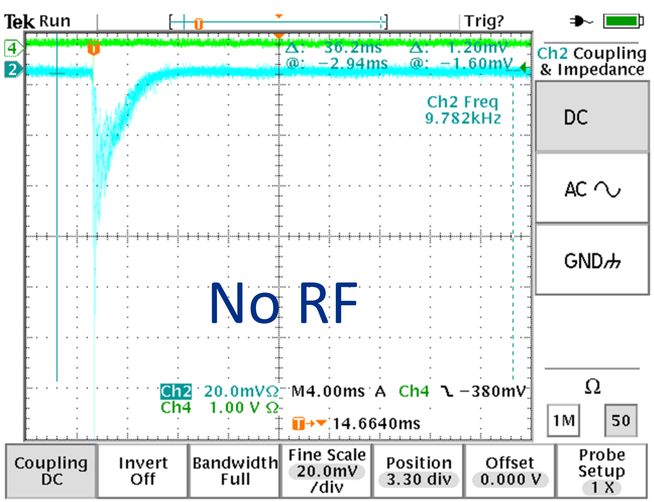
- Another correction was done based on data from the first 2 turns brought IOTA's lattice to stable condition and electron beam was captured into IOTA

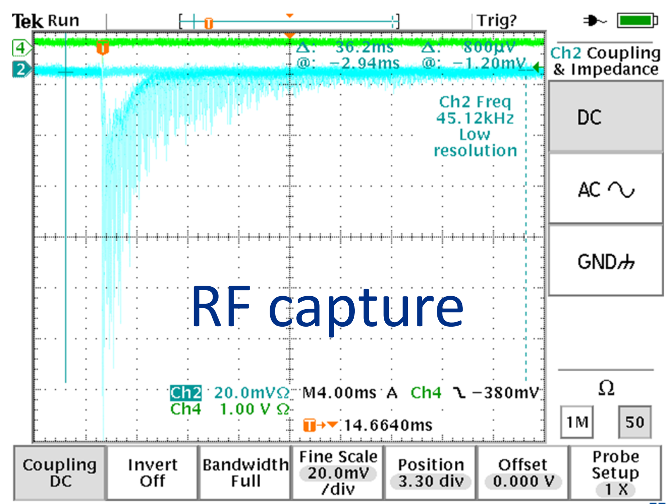




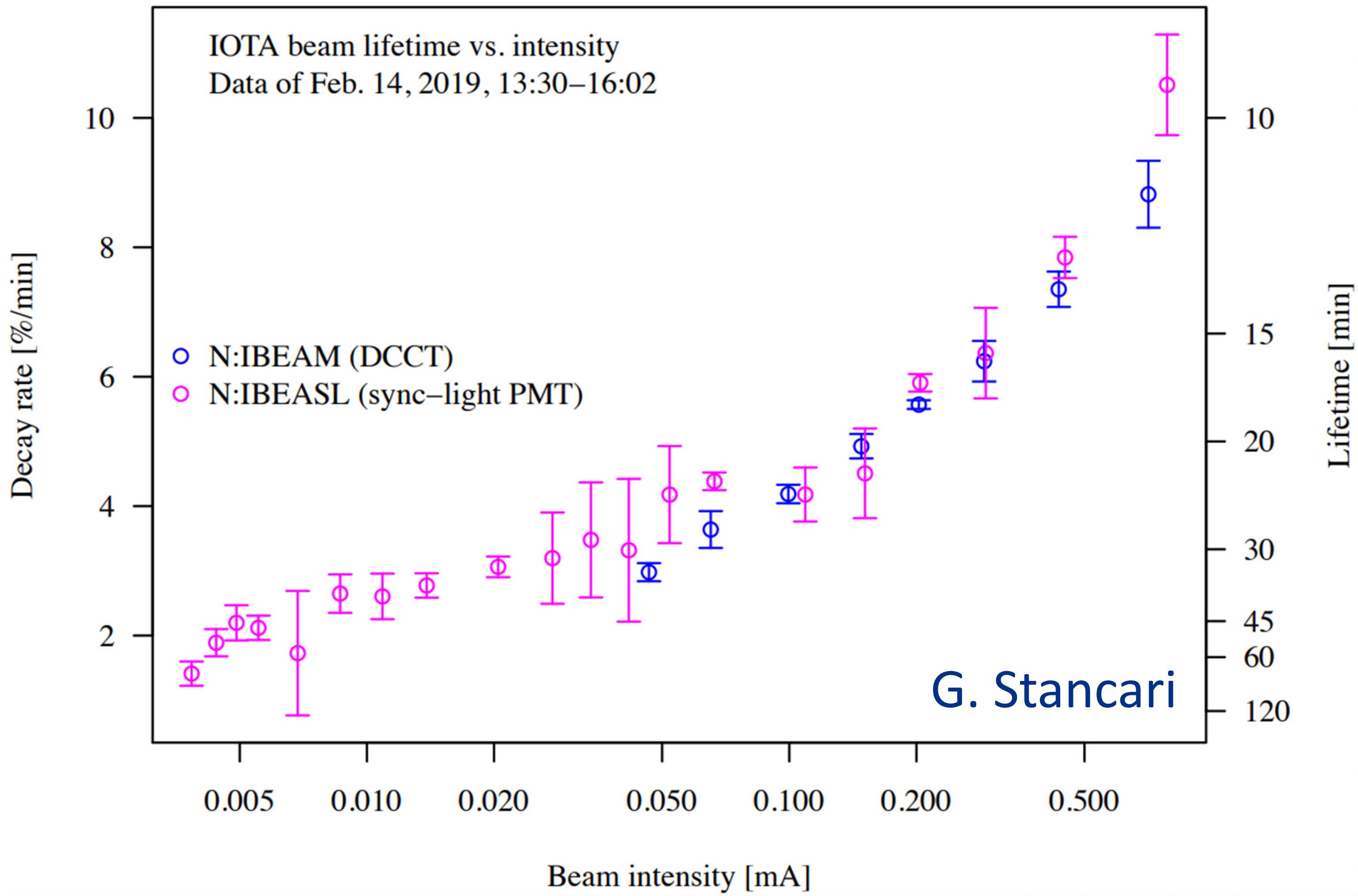
100 MeV RF Capture with RF

- Kicker had to be conditioned for maximum voltage (25kV)
- Capture procedure was similar to that used for the 50 MeV injection run
- RF capture required tuning two parameters
  - Timing scheme were introduced to control phase between the FAST and IOTA RF
  - RF frequency was scanned to match ring circumference





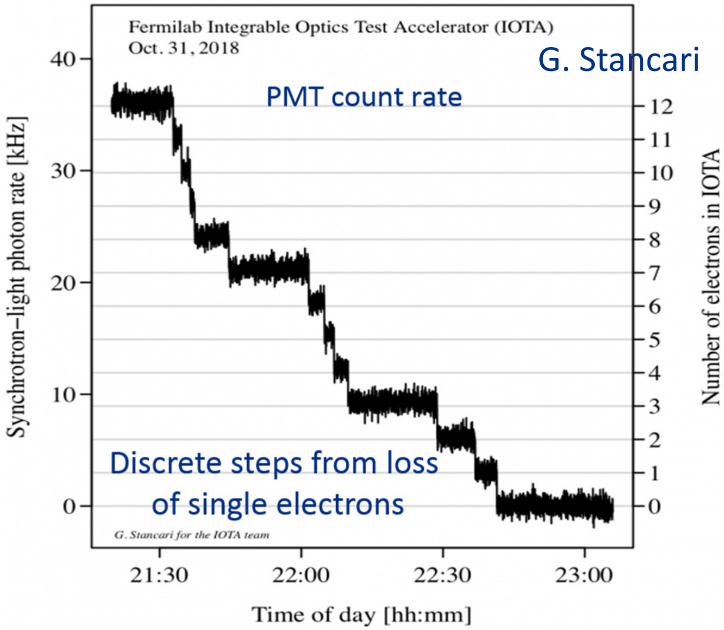
Lifetime

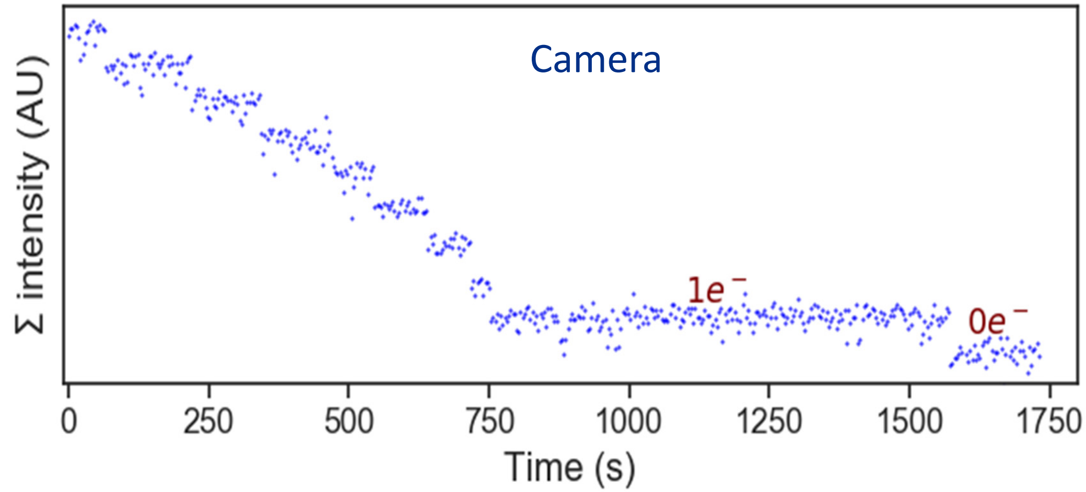


IOTA beam lifetime vs. intensity
Data of Feb. 14, 2019, 13:30–16:02
N:IBEAM (DCCT)
N:IBEASL (sync–light PMT)
Decay rate [%/min]
Lifetime [min]
Beam intensity [mA]
0.005
0.010
0.020
0.050
0.100
0.200
0.500
2
4
6
8
10
10
15
20
30
45
60
120
G. Stancari

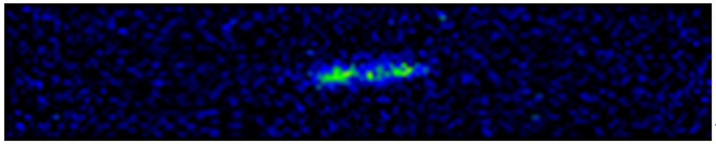
Single Electron Experiments

- Dynamic range from mA to single electron





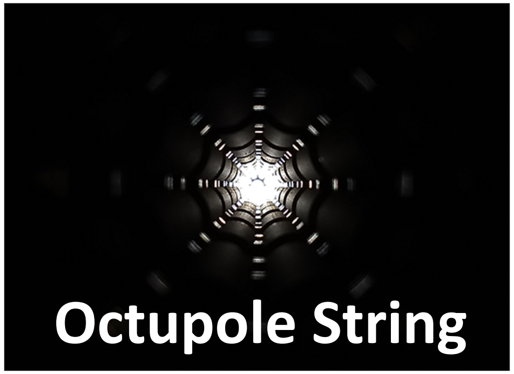
Single e Tomography!

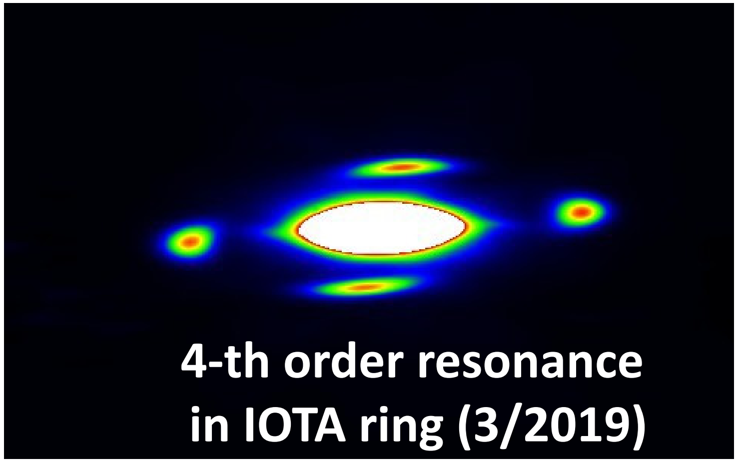


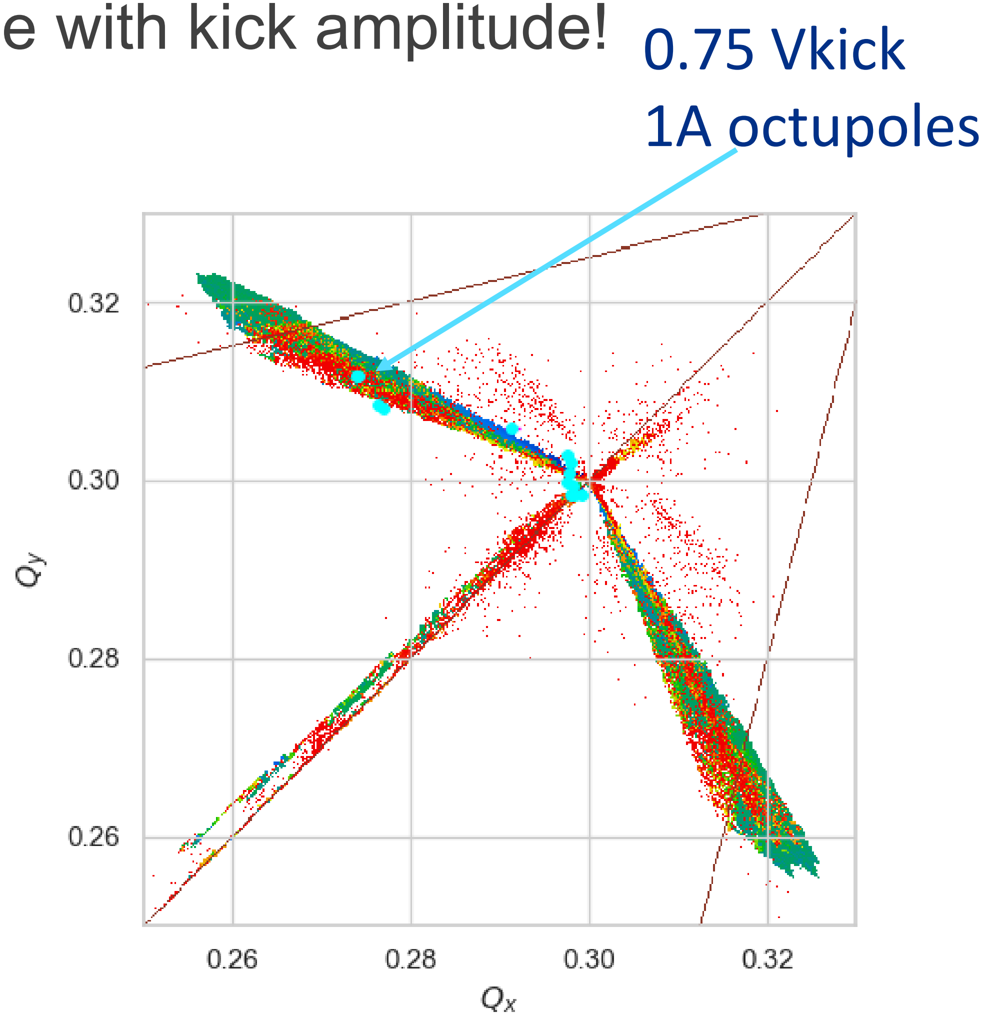
A. Romanov

First Results with Octupoles

- See expected tune change with kick amplitude!

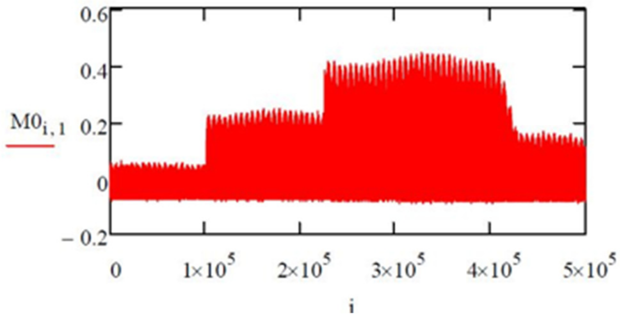




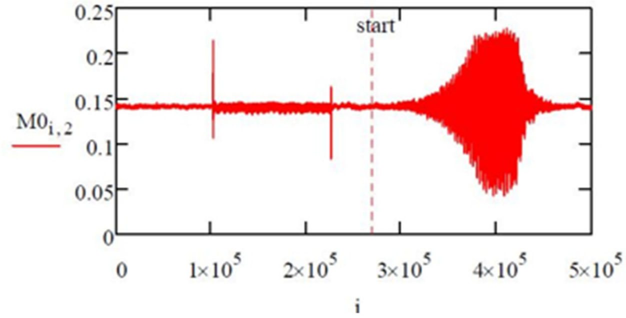


Octupoles and Landau Damping

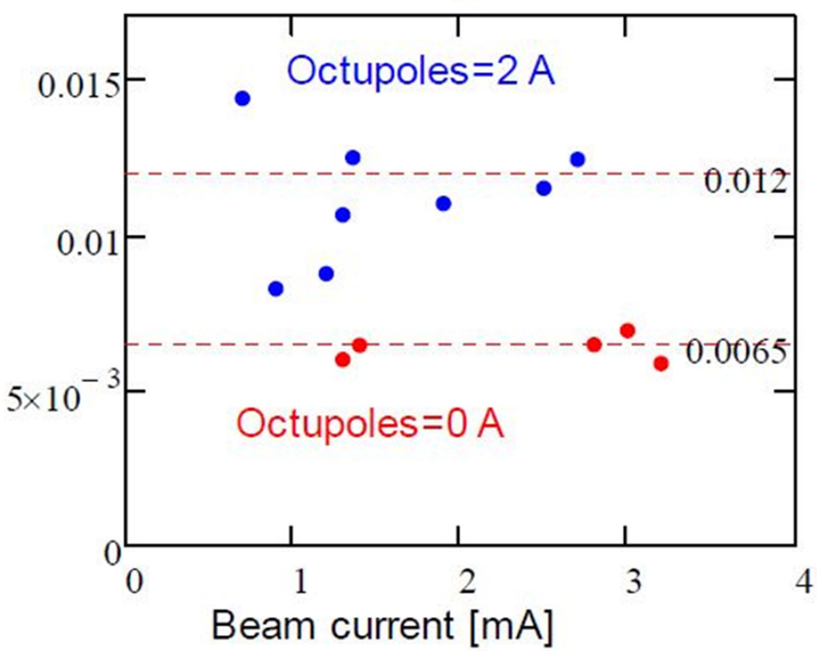
Sum Signal

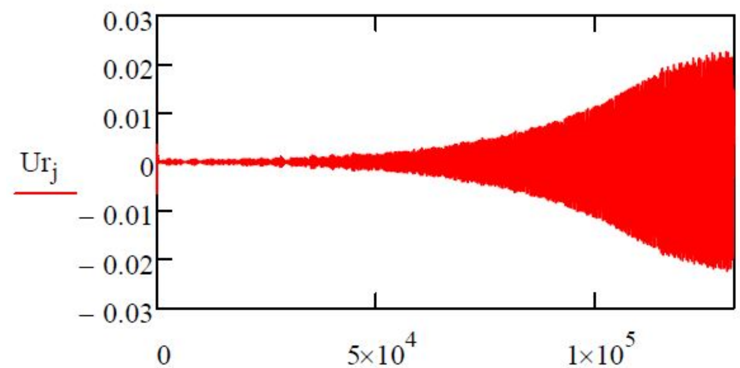


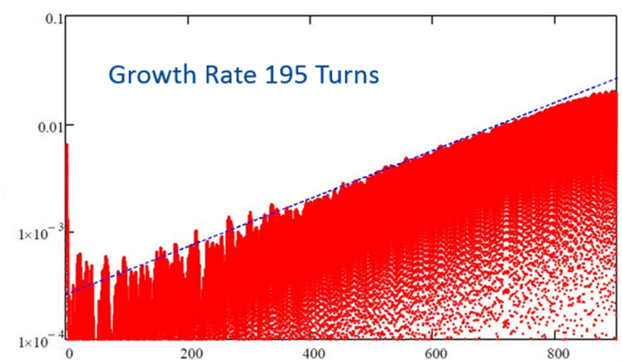
Kick Signal



Gain at instability threshhold





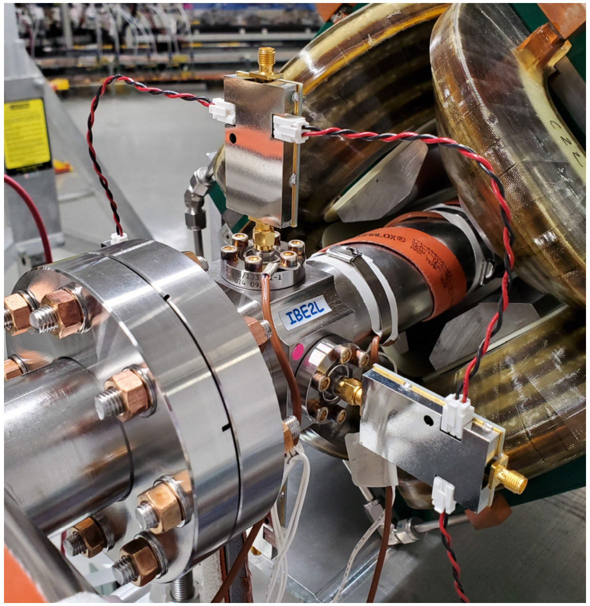


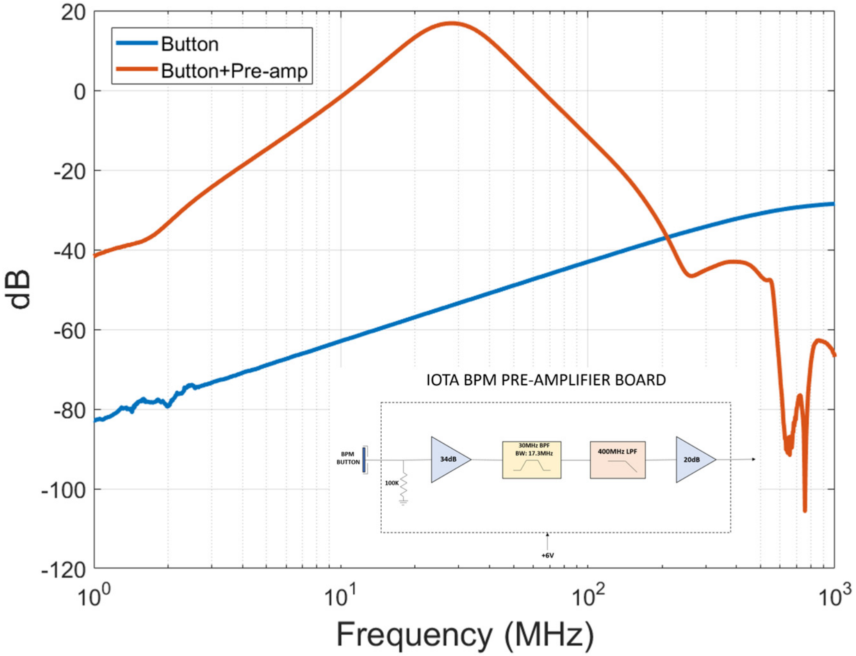
Future Upgrades

- BPM System
- SyncLight System
- Optical Stochastic Cooling
- Proton Injector
- Electron Lens

BPM upgrades

- Install high impedance pre-amplifiers at button electrode





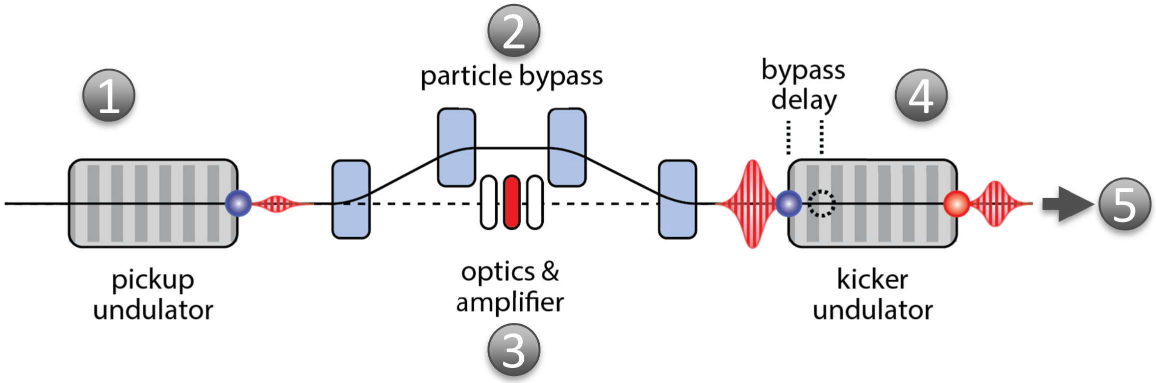
- Remove RF detector – linearity, bunch length, protons
- Implement floating point diff/sum linear fit in Digitizer
- Replace VME backplane with GigE readout/control

SyncLight Upgrades

- Install more remote controlled opto-mechanics
  - Beam splitters to serve multiple optical lines
  - Minimal need to disturb main camera for studies

- Investigating multi-anode PMT
  - Several vendors offer 8x8 detectors
  - Capable of providing Turn-by-Turn data with single electron

Optical Stochastic Cooling



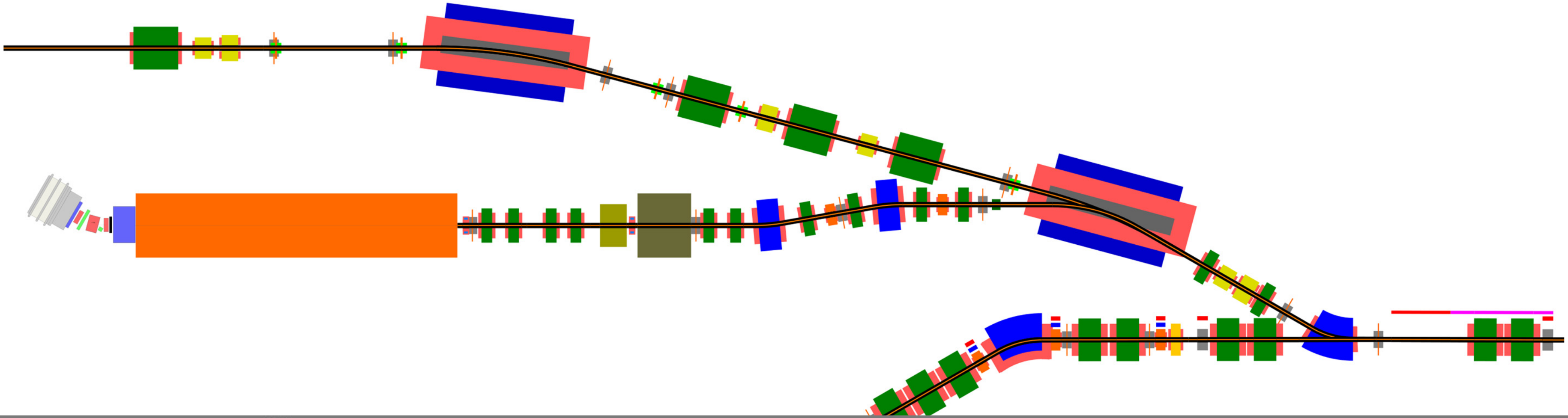
1. Wavepacket generated
2. Particle delayed in bypass
3. Wavepacket amplified and focused
4. Corrective kick applied
5. Cooling accumulates over many passes

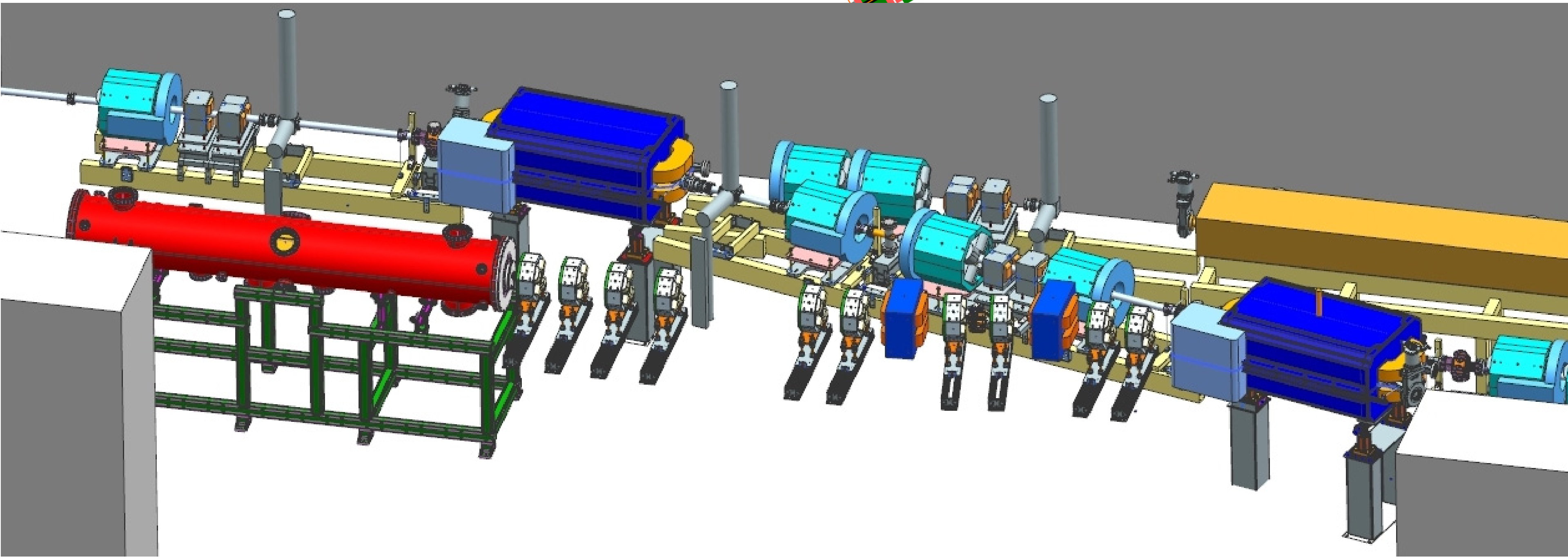
10^3 – 10^4 increase in cooling rate over SC and extension into an energy range where no operational cooling solutions exist

Minimal installation this fall
Full experiment ready early 2020

A.A.Mikhailichkenko, M.S. Zolotorev, Phys. Rev. Lett. 71 (25), p. 4146 (1993)
M. S. Zolotorev, A. A. Zholents, Phys. Rev. E 50 (4), p. 3087 (1994)

The IOTA Proton Injector





IOTA Proton Injector Plan

The HINS ("High Intensity Neutrino Source") was developed in 2008 as the front end of a pulsed "Project X" 8 GeV proton linac

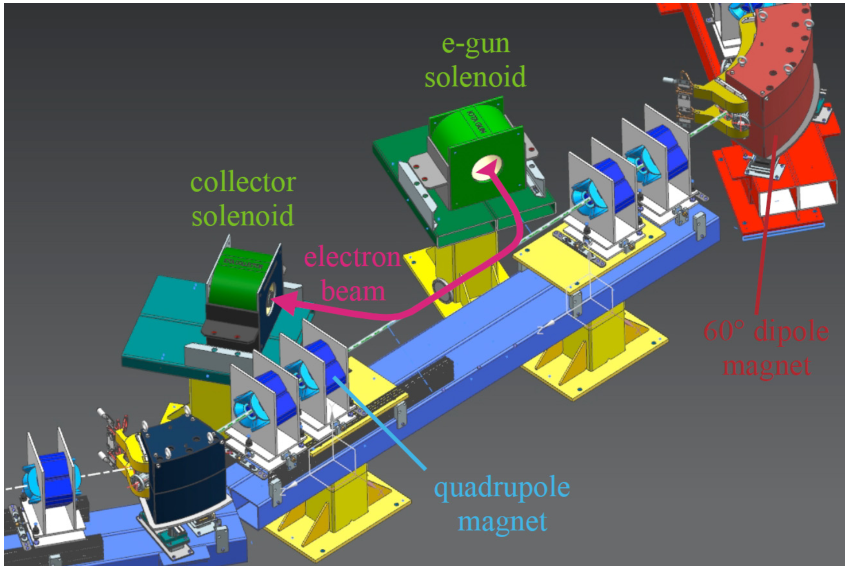
- Because of cooling problems, it never reached its design pulse rate but works well for IOTA parameters and available for our use
- Many components taken for use elsewhere after 10 years of storage

The plan

- Recommission ion source at present location ✓**in 2017**
- Relocate the source and RFQ to IOTA enclosure **2019**
- Build new RFQ RF system at FAST originally planned for 2019
- now 2020
- Commission injector 2020

Fermilab

Electron Lens



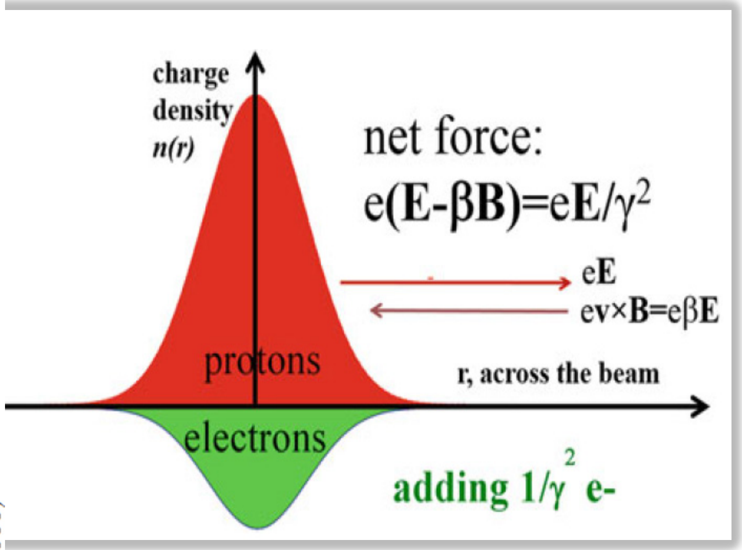
Another versatile tool:

- Novel nonlinear element for integrable optics (using space charge)

Research with stored protons:

- Space-charge compensation and Landau damping
- Electron cooling: extending performance of IOTA for space-charge studies; cooling studies in a NIO lattice

Installation in 2021 after p-injector



A. Burov, G. Foster, V. Shiltsev, FNAL-TM-2125 (2000)

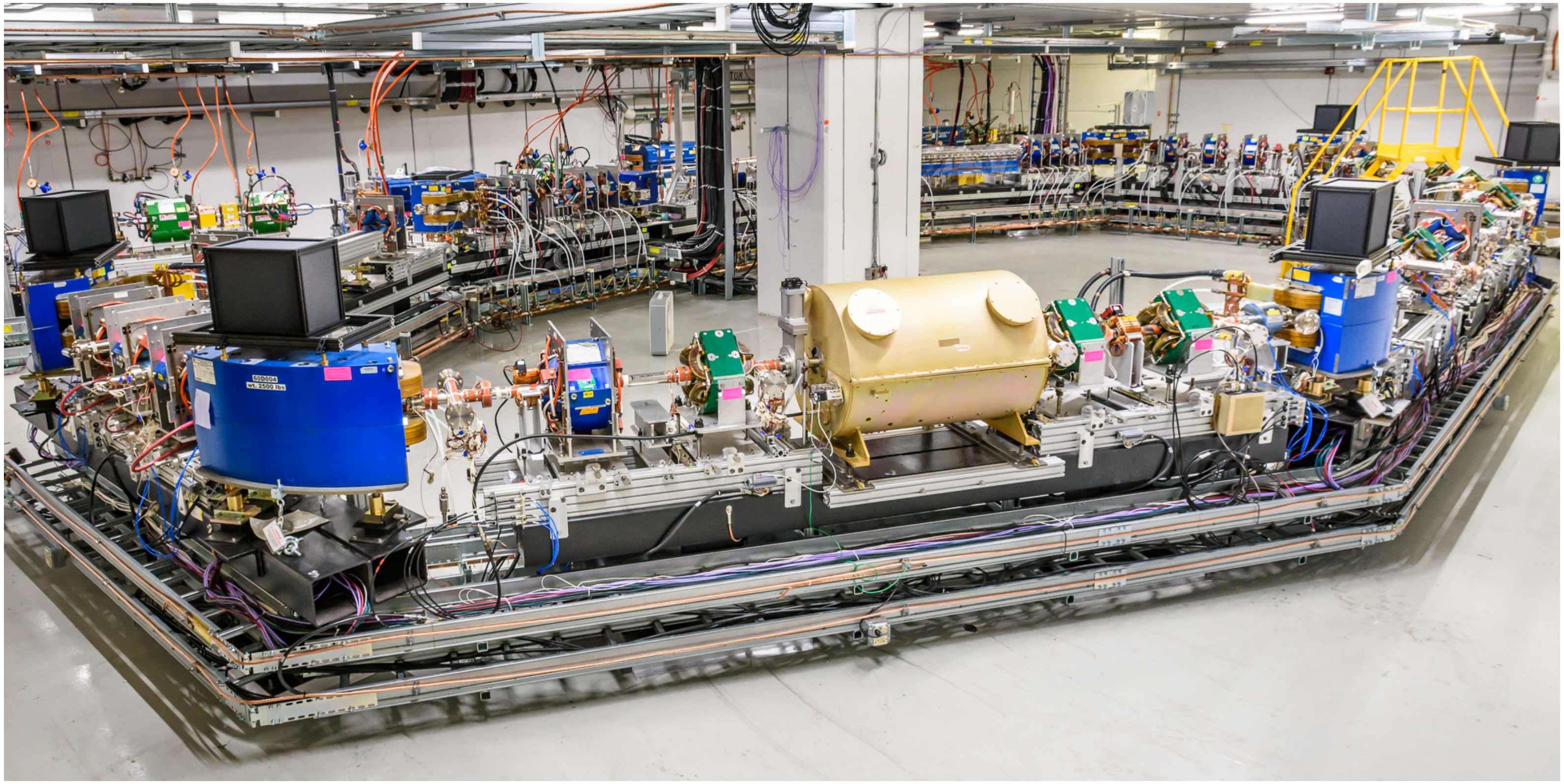
In Conclusion…

- IOTA/FAST is a unique R&D facility and the only one in the world dedicated to the future of intensity-frontier research

- IOTA has begun successful operations with electrons with exciting results

- The IOTA science program explores a wide variety of fundamental topics in accelerator and beam physics
  - Provides challenges for beam instrumentation!
  - In particular near concurrent electron and proton running

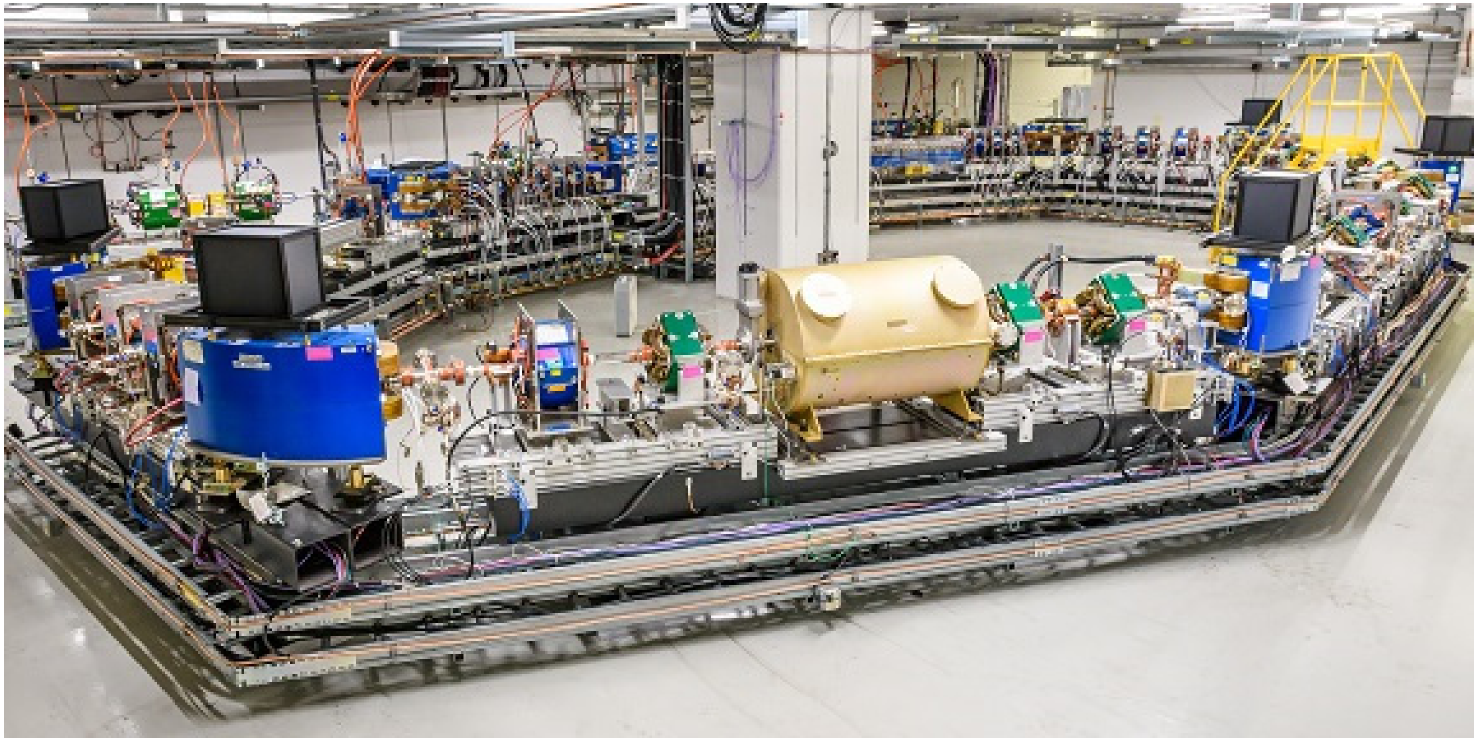
- IOTA also constitutes an excellent platform for technological developments that may be vital for realizing next-gen. facilities
  - Provides an excellent platform for new diagnostics
  - Such as non-invasive profile monitors



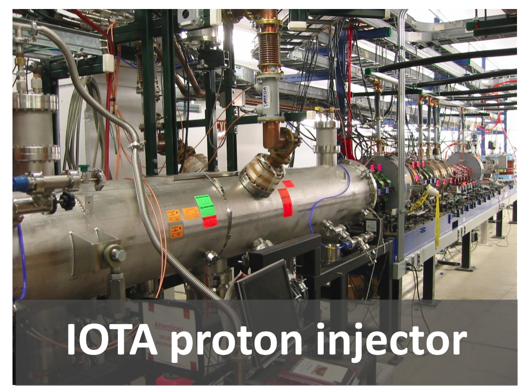
Thank you for your attention!

Backup Slides

IOTA successfully constructed and commissioned



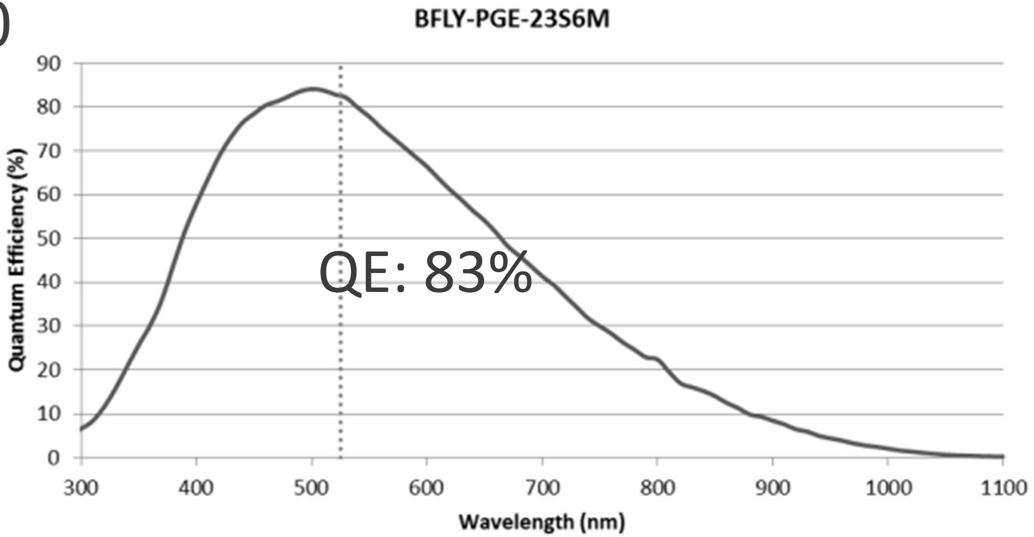
- Commissioned with electrons at 47 MeV and 100 MeV; charge achieved 600pC (design 160pC)
- Proton injector being completed in FY20; available for start of proton science program in **FY’21**



IOTA proton injector

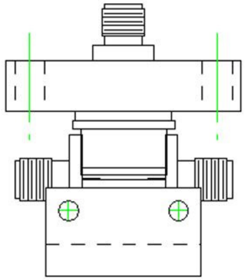
Camera Characteristics

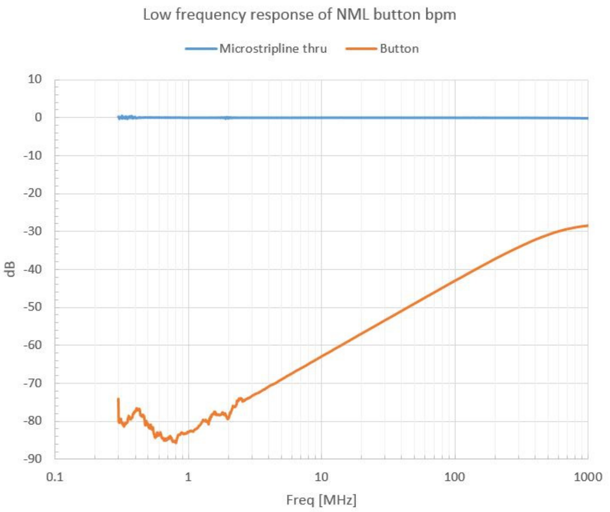
- IOTA is equipped wit 8 PoE cameras BFLY-PGE-23S6M-C from Point Grey (now Flir)
- Exposure Range: 0.019 ms to 32 seconds
- Sensor: Sony IMX249, CMOS, 1/1.2“
- Sensitivity Threshold (γ): 9.5
- Saturation Capacity (e-) 33106
- Rsolution: 1920 x 1200
- Pixel Size: 5.86 µm
- ADC: 12-bit



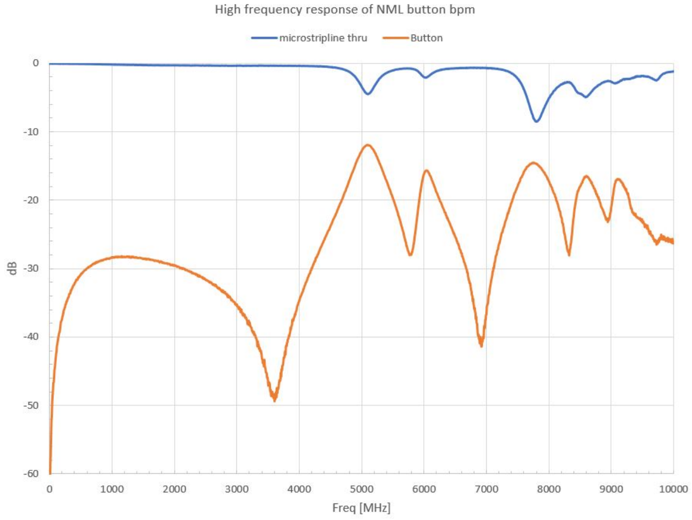
BPM Pickup Measurements

- Button response was measured using a test fixture with a strip line attached





- Each style was also measured via stretched wire and the response fit to a 2D polynomial to linearize the pin cushion effect of the buttons



BPMs

- Key (upgraded) specs for users:
  - GigE readout (<<1s)
  - 8k+ turns
  - <100um Turn-by-Turn resolution
  - <10um Orbit Resolution
  - Good linearity (or high sensitivity)

BPM System Upgrade Thrusts

- Analog Signal Conditioning Electronics
  - Resolution, Linearity, Bunch Length Dependence

- Digitizer Firmware Updates
  - Position calculation algorithm
  - Improve readout speed

- Front-end Software Updates
  - Features – data structure, status
  - Speed & reliability

Analog Signal Conditioning Electronics

- Current system based upon RF envelope electronics
  - Linearity issues especially for small signals
    - Can also have subtle effect on TBT data
    - Calibration can improve but not eliminate
  - Strong bunch length dependence

- Ideal solution is to remove RF envelope electronics
  - Have been exploring many different linear options
    - Involve tunnel electronics & modifications to existing modules
  - All candidates suffer worse TBT resolution (2+)
  - Will take ~3 months to implement new solution
    - Need to make decision soon (2-3 weeks)

Digitizer Firmware Updates

- Currently implement linear fit to calculate Diff/Sum
  - Less position sensitivity to timing
  - No background subtraction needed
  - works for AC coupled inputs

- Could implement polynomial calculation for position as well
  - Currently done at time of ACNET request
  - Would greatly improve ACNET response time

- Readout via GigE connection
  - Expect 10x improvement on readout speed

Front-end Software Updates

- Features
  - Data structures
    - Orbit readback
    - Large TBT data
  - Status information (timestamp, trigger type, error info)
- GigE readout of Digitizers
  - 10x faster readout of data from digitizer to CPU
- Improve user access
  - ACNET
  - Backdoor
  - Epics
    - has a lot of features needed already built in
    - Bigger undertaking but needed for PIP-II

Decision to Run at 100MeV

Pros:

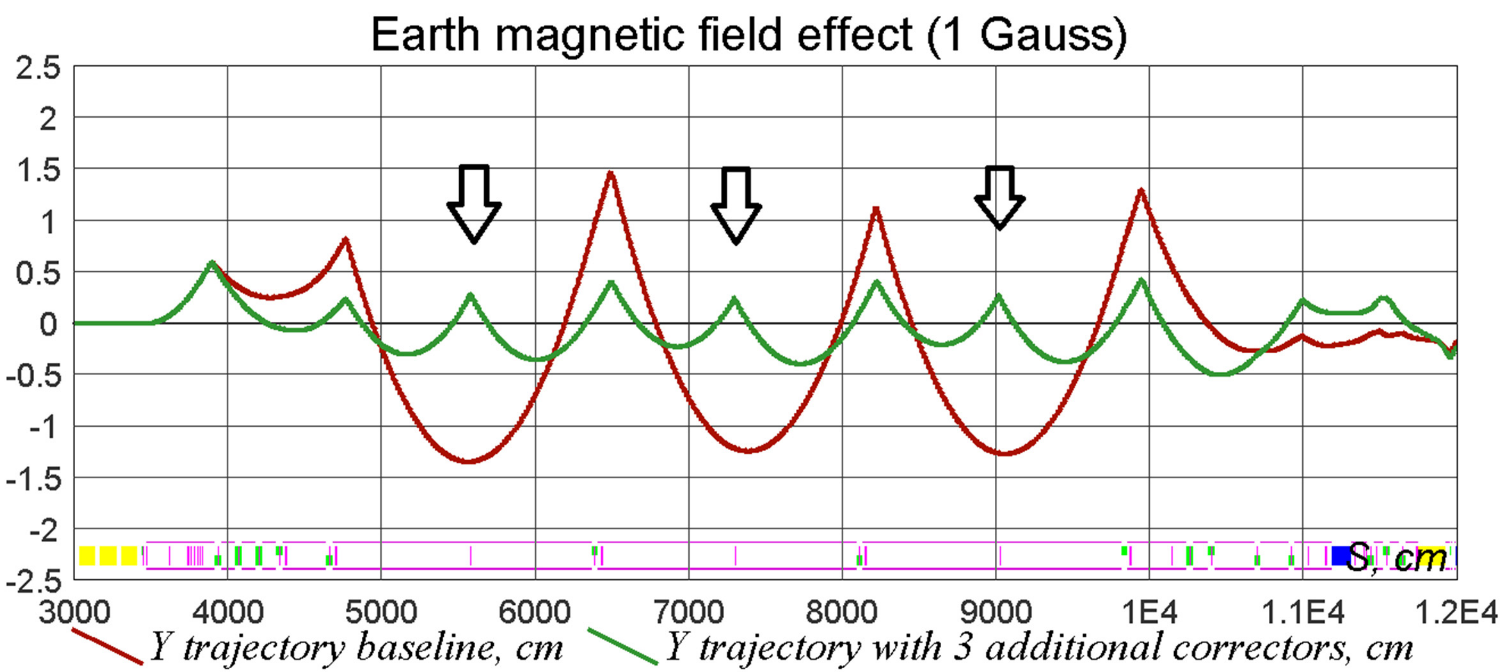
- Nonlinear dynamics is the same regardless of the beam energy
- Lower technical risks
  - Safer operation of the cryomodule that had just recovered from failure
  - Lower load on the power supplies
- Allowed to prepare for the Optical Stochastic Cooling experiment that will be demonstrated with 100 MeV electrons
  - Low-emittance diagnostics
  - Beam injection and dynamics

Cons:

- Stronger IBS increases emittance and energy spread

50 MeV injection: the Earth magnetic field

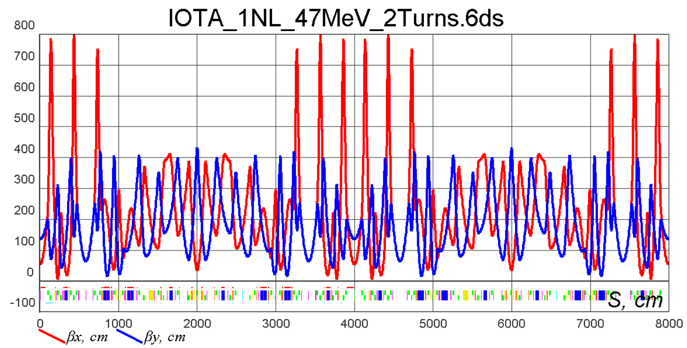
- One of the biggest constraints for the injection of the low-energy electrons is the Earth magnetic field that deflects beam in the long FODO section of the FAST linac.
  – Without additional correctors 50 MeV is close to the limit for the 2” beam pipe

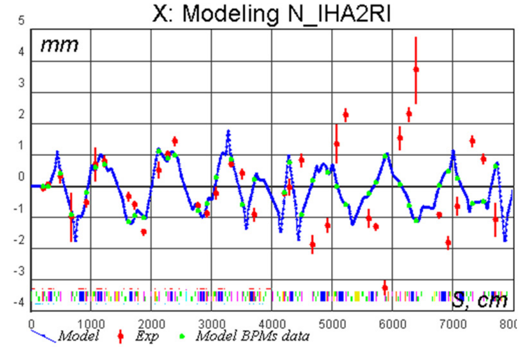


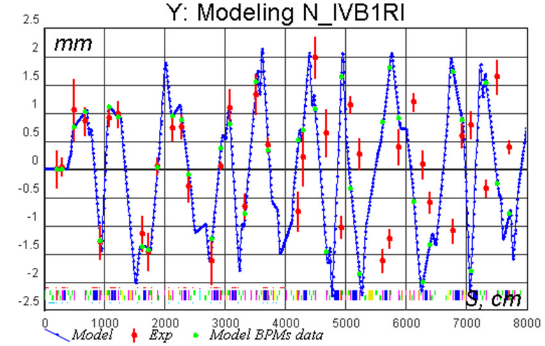
Betatron capture into IOTA

- Measured data: 21 BPMs x 20 trims
- Model adjusted to match measured data by tuning 39 quads

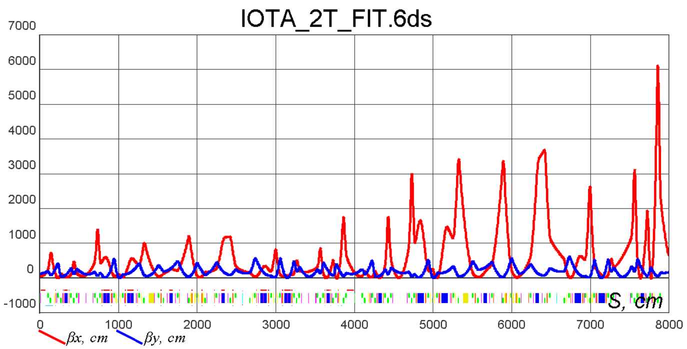
Model lattice and corresponding sample responses compared to measured

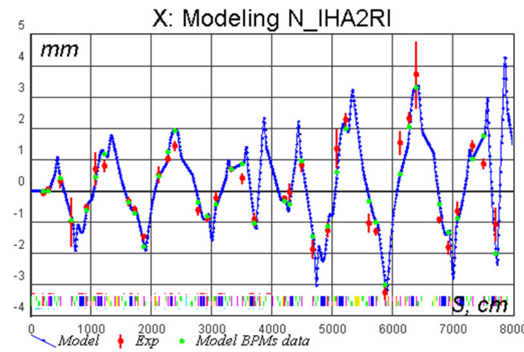


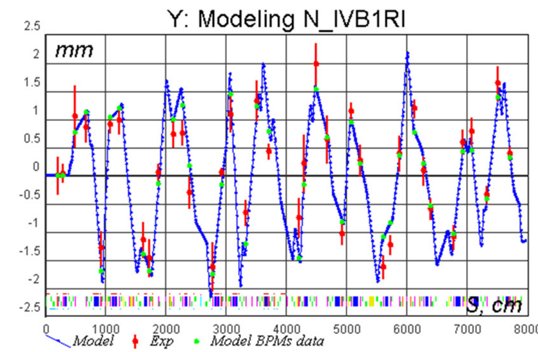




Fitted model has clear instability in X plane







- **First correction iteration made stable betatron lattice**

Lattice correction

- Simulations shows that with BPMs precision of 1um and better lattice can be corrected to required levels
  - Precision of the orbit measurements were limited to about 10um
    - Beam jitter because of main PS ripple
    - Suboptimal beam parameters for electrostatic pickups
- Resulting lattice precision
  - Good for experiments with octupoles and other studies
  - Not enough for precise studies of the DN-nonlinear magnet

Tomography method

Coordinate of the electron at turn *n* can be presented as

$$X_n = \sum a_i(n) Y_i e^{2\pi i\,(\psi_i + n\,\nu_i)}\,,$$

here Y_i are eigenvectors of the turn-matrix at the location of a monitor, ν_i are betatron tunes and $a_i(n)$ are mode amplitudes that typically have slow dependence on *n.*

For the IOTA at 100 MeV characteristic time of the amplitudes change (inverse decrements) are (6.7,2.4,0.9) s. Therefore for the frame rate of 1.3 fps amplitudes remain roughly the same.