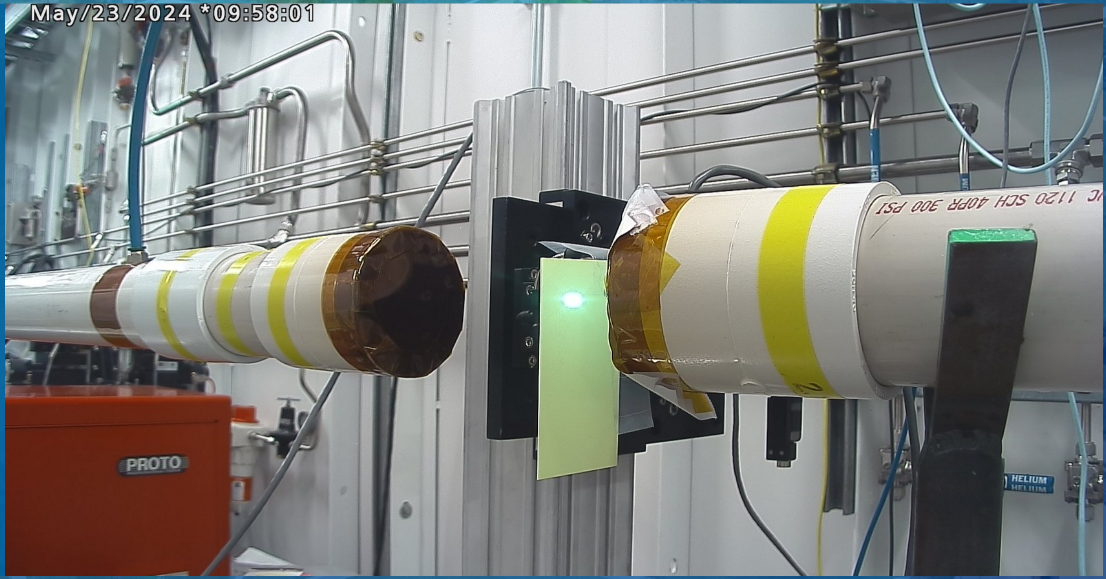
APS-U COMMISSIONNING

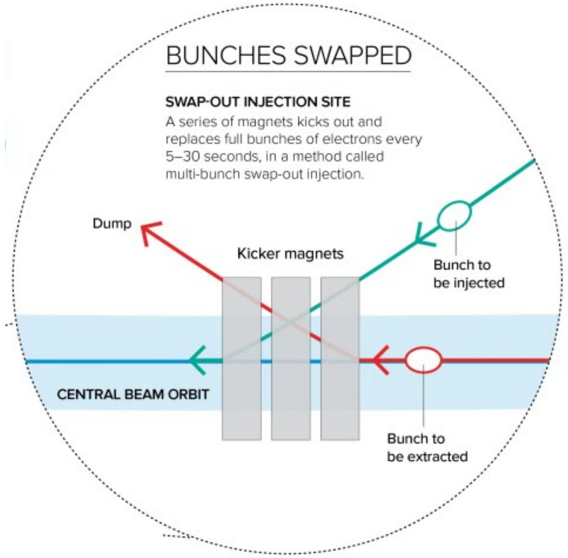


Vadim Sajaev on behalf of APS-U Commissioning Team
Accelerator Systems Division, APS

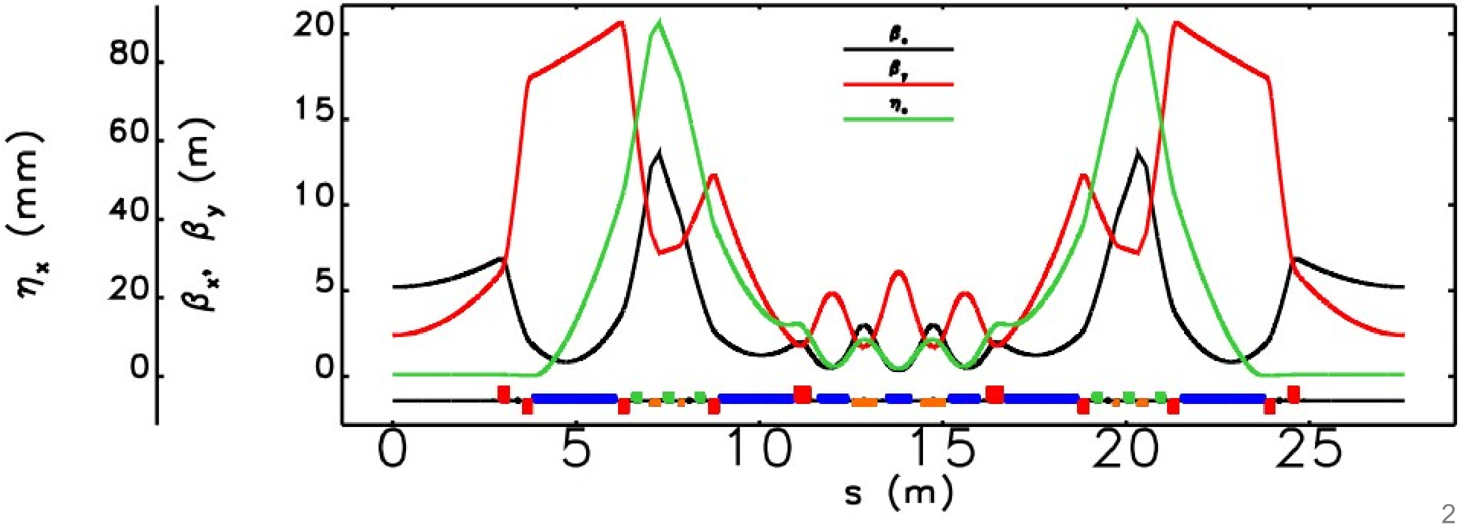
Accelerator Middle Layer workshop, DESY, June 19, 2024

APS-U utilizes hybrid 7-bend achromat lattice

- New storage ring has natural emittance of 42 pm and increases photon brightness by a factor of 500 compared to old APS
- Injection is in horizontal plane, single-bunch, on-axis swap-out
  - The same kickers are used to place injected bunch on axis and to extract stored bunch
  - Injectors were not upgraded
- Superconducting passive bunch-lengthening cavity is used to improve lifetime
- APS dark time started April 24, 2023
- Commissioning of new ring started April 10, 2024



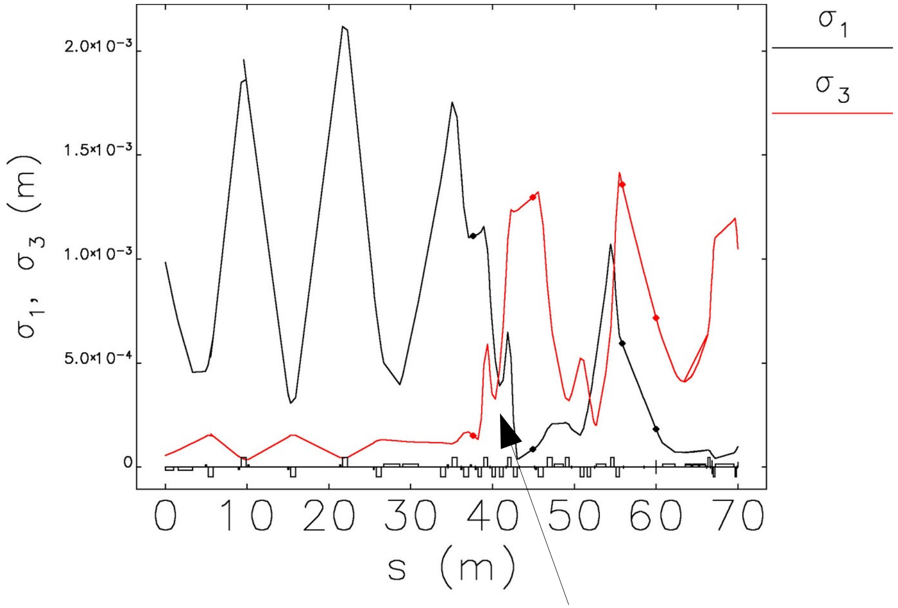
Lattice functions for one sector



BTS commissioning turned out much harder than expected

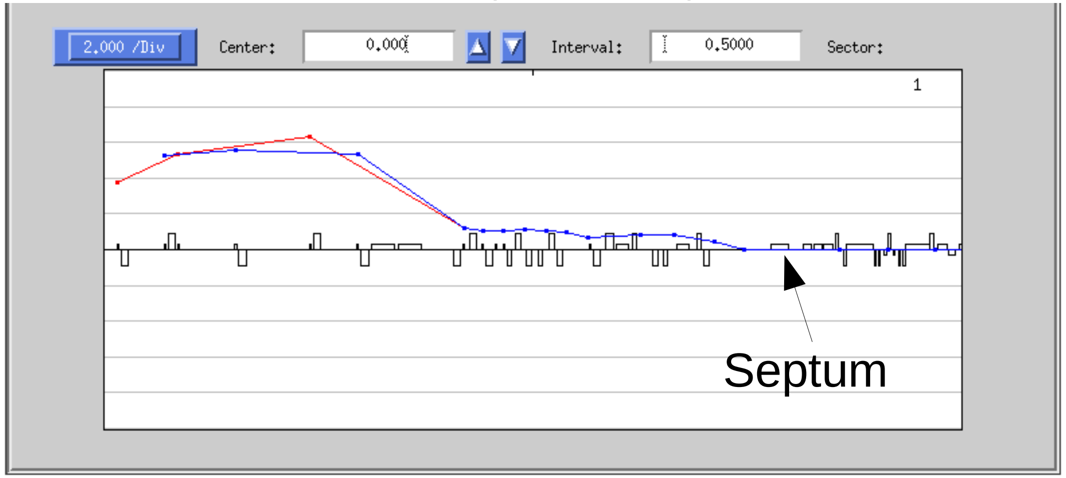
- Single pulsed septum magnet and 3 fast kickers place injected beam on axis
  - All within one straight section
- Horizontal gap between septum magnet and kicker blade is 2.8 mm
  - Horizontal beam size in Booster is 0.6 mm rms
  - Emittance exchange is used to flip the beam to fit in 2.8-mm horizontal gap
- Threading program could not bring beam through the gap; various optimizations also failed

Beam sizes in BTS



Emittance exchange

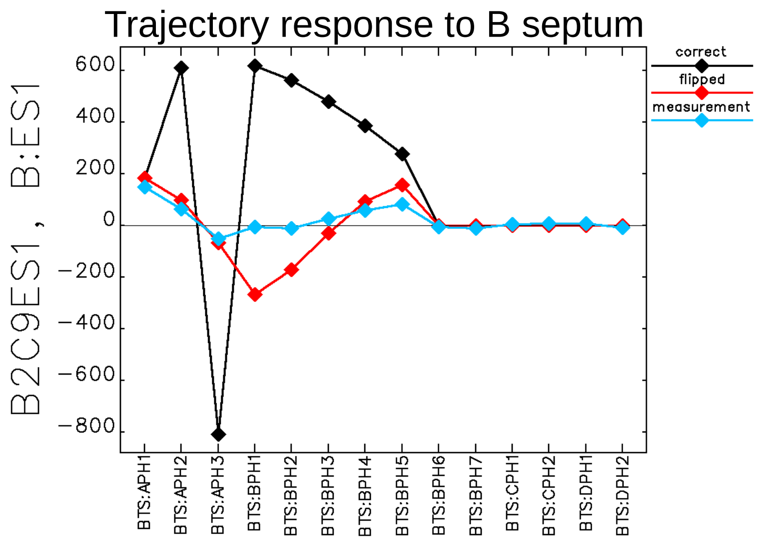
BPM sum signal along BTS

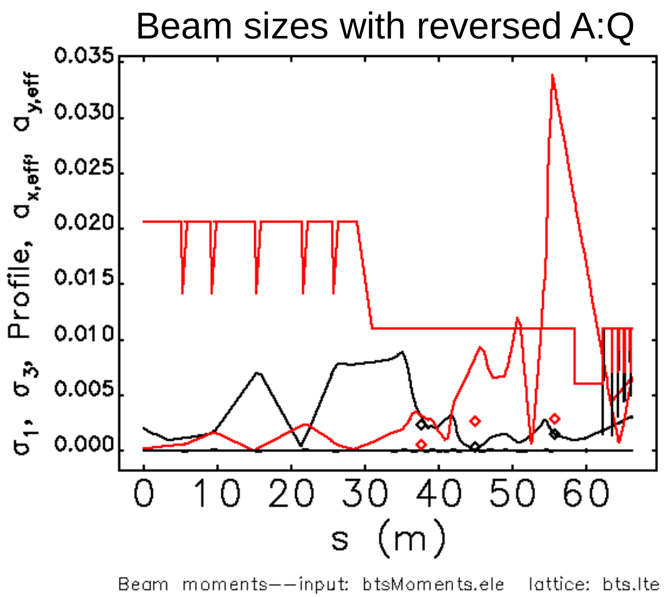


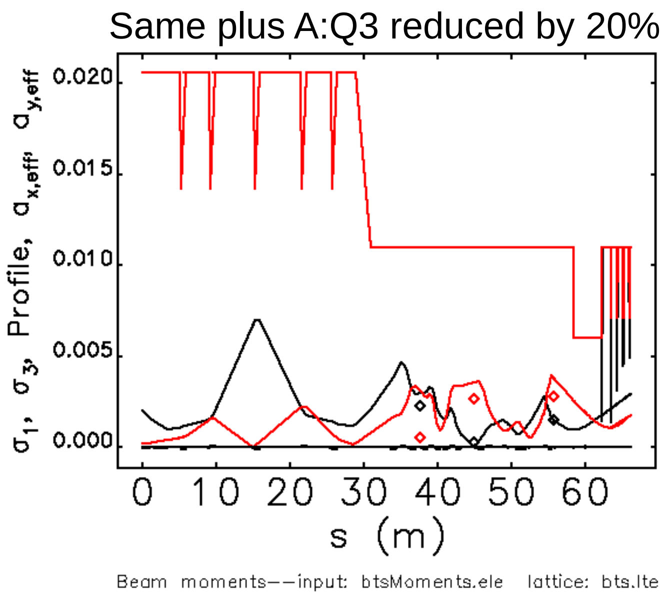
Septum

Investigation revealed 5 old quads connected with opposite polarity

- Response to booster septum resembled reversed polarity of A:Q quadrupoles
- Reduction of a single A:Q3 quad by 20% improved BTS transmission significantly
  - Beam size calculations with reversed A:Q quads confirm the loss location and improvement due to A:Q3 change







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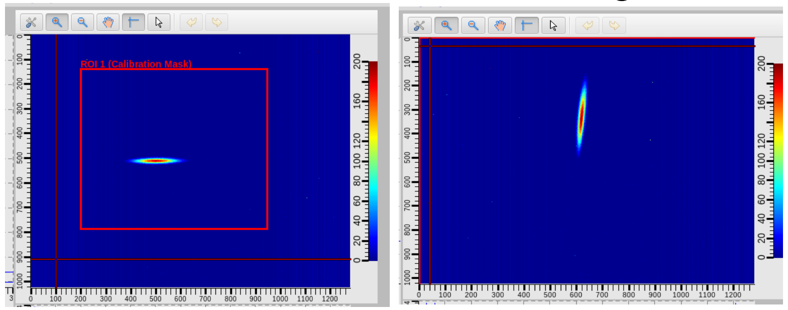
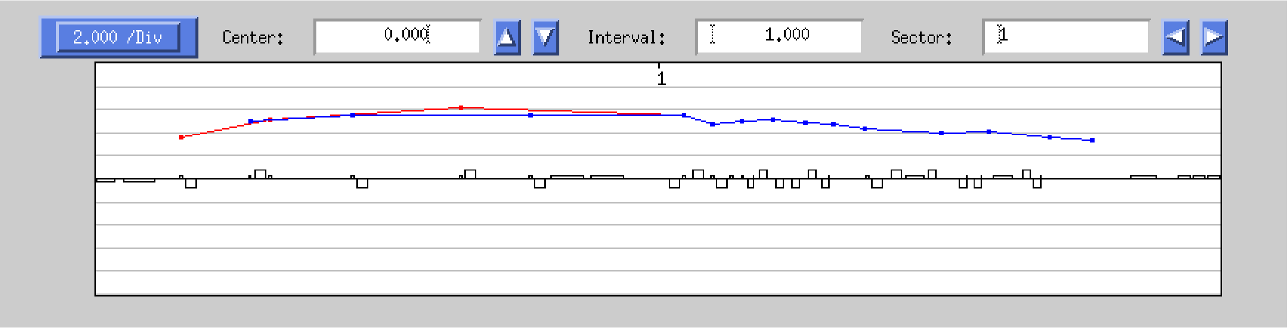
Fixing quad polarity fixed all BTS problems

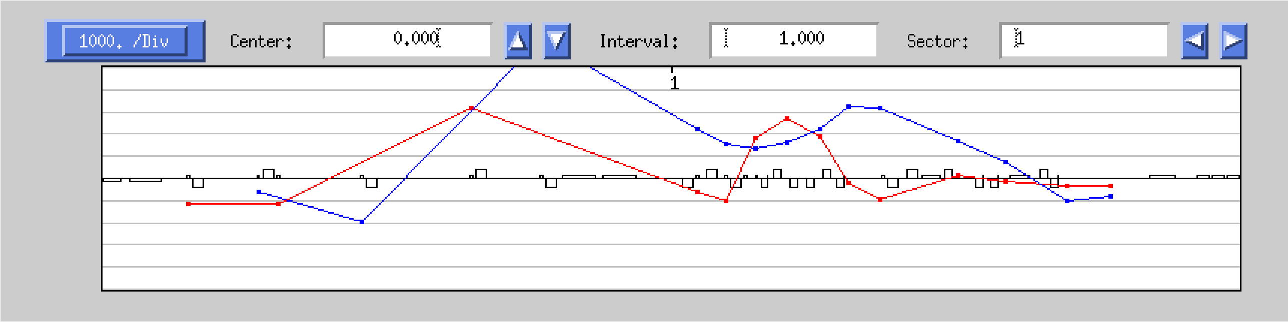
- Old APS was designed to operate on positrons
- BTS lattice reuses 5 old APS quadrupoles designed for positrons
- When these quadrupoles were connected to new power supplies, they were connected the "positron way"
- After reversing quad polarity, trajectory correction program brought beam past septum/kickers in a few iterations

Measured beam image before and after emittance exchange





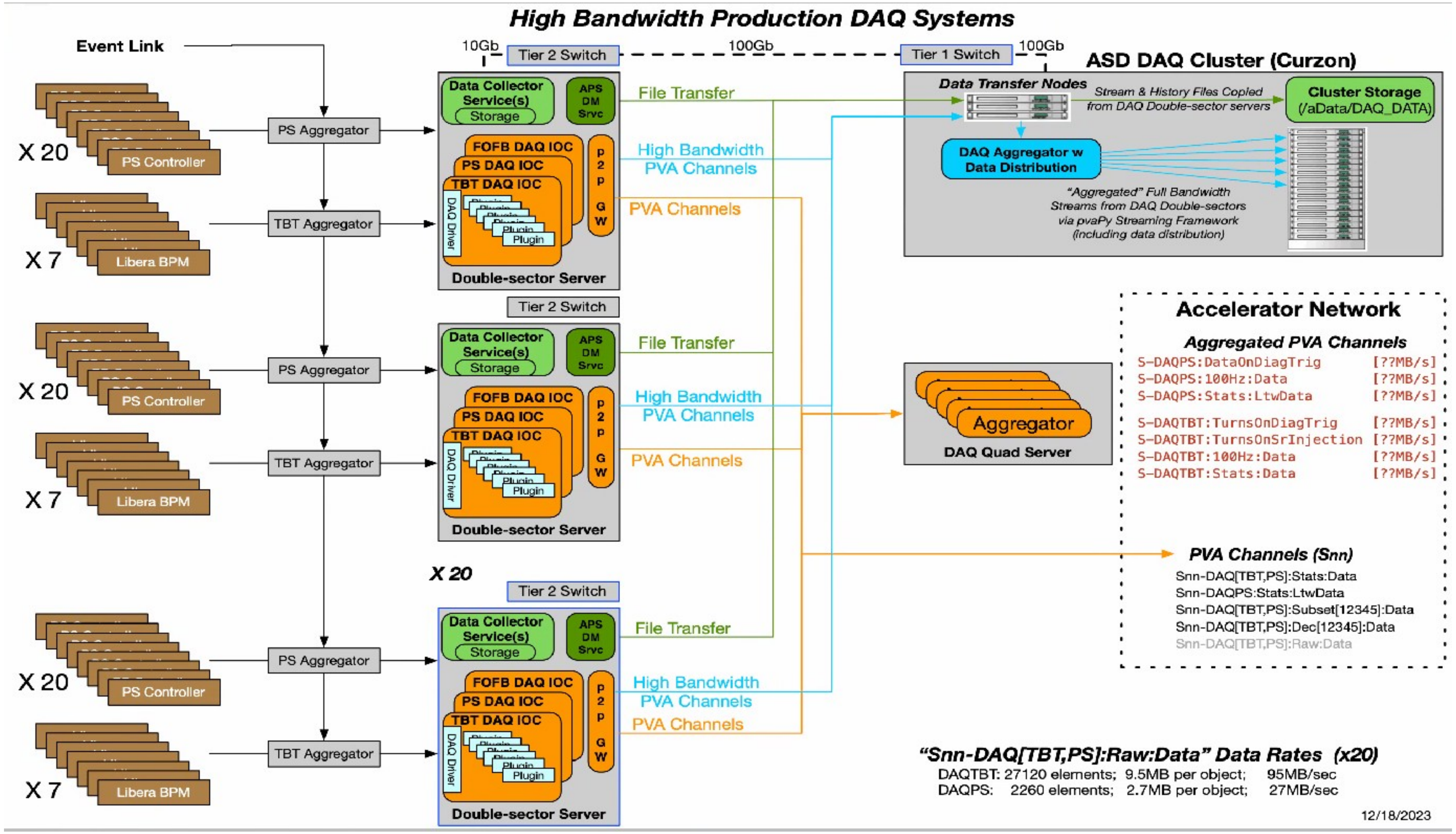
BPM sum signal in BTS



Trajectory in BTS

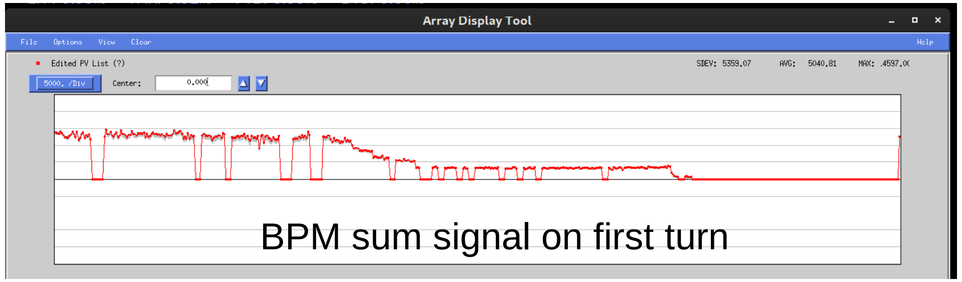
Data Acquisition System (DAQ)

- Commissioning relied heavily on BPM turn-by-turn data provided by DAQ system
- DAQ provides synchronized data from many sources and a way to save the data in SDDS format

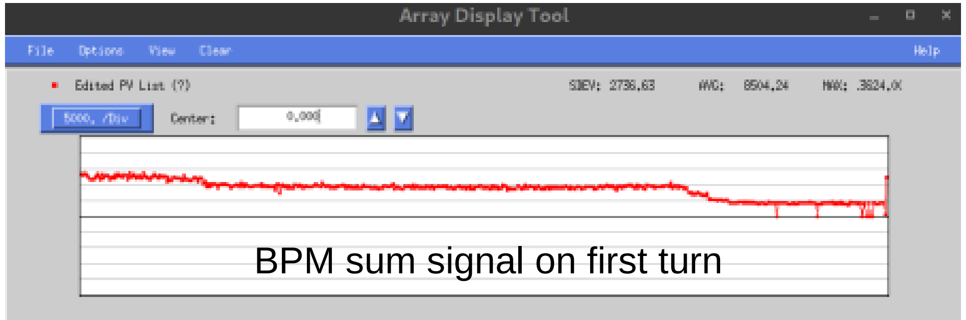


Well-aligned machine resulted in quick first turn

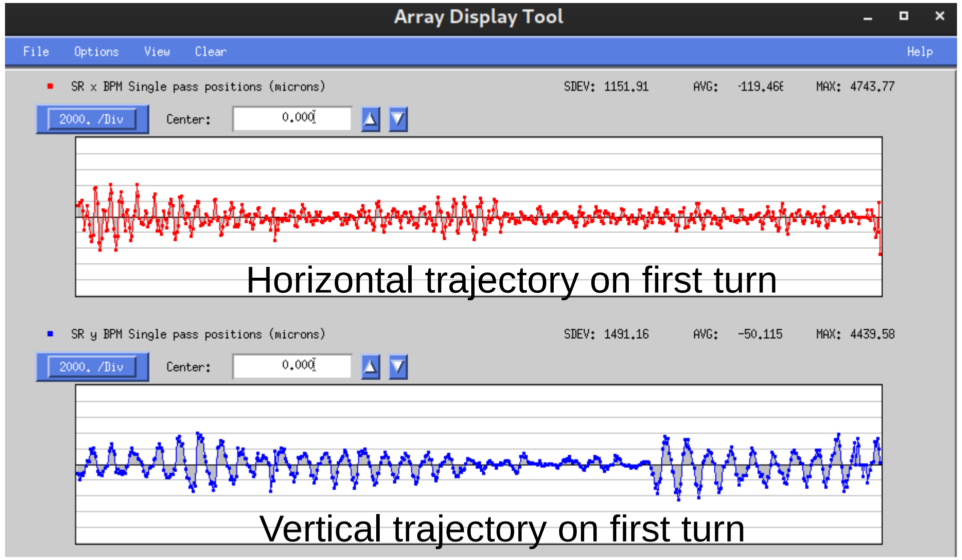
- After adjusting injection conditions, the beam went all the way to sector 28 (out of 40)
  - Starting conditions: RF off, sextupoles off



- Adjustment of correctors in storage ring brought the beam all the way to the end of turn one!!!



- Further corrector adjustment resulted in 100% transmission through first turn



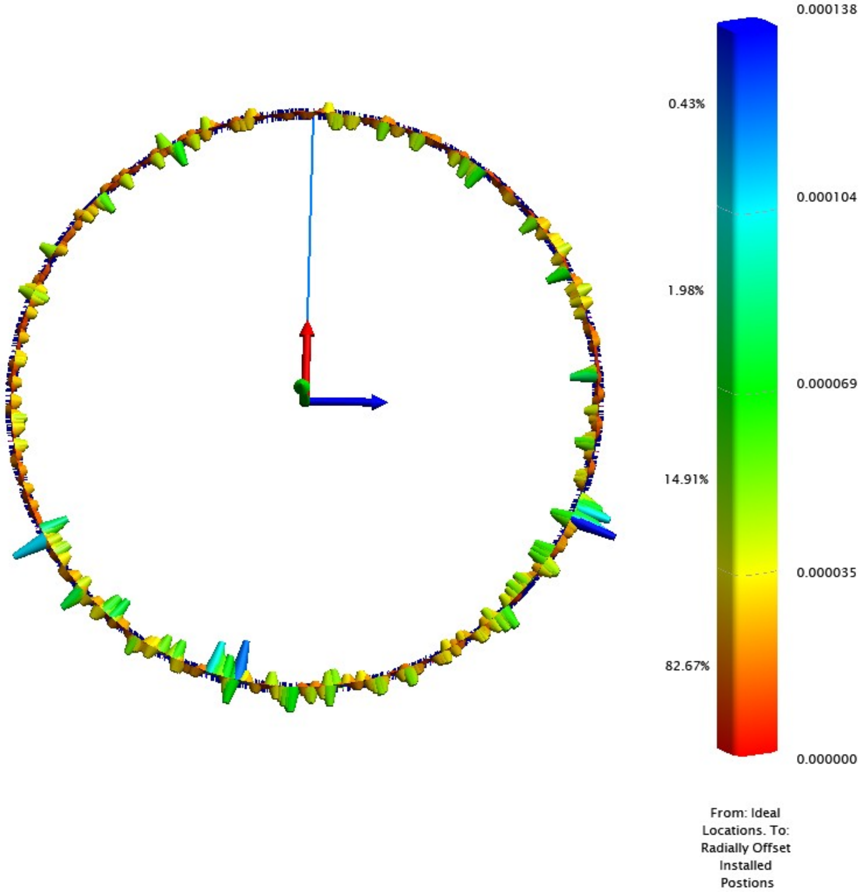
- No automated correction was used – it was quicker to vary a few knobs

Final alignment is better then requirements

- Magnets on modules (girders) were aligned in the lab, then entire modules transported to the tunnel
- Modules were aligned once, second pass was skipped due to lack of time
  - A few worst offenders were realigned

	Requirements	As installed
Element to element	30 μm rms	15 μm rms
Module to module	+-100 μm	X: 50 μm rms Y: 35 μm rms

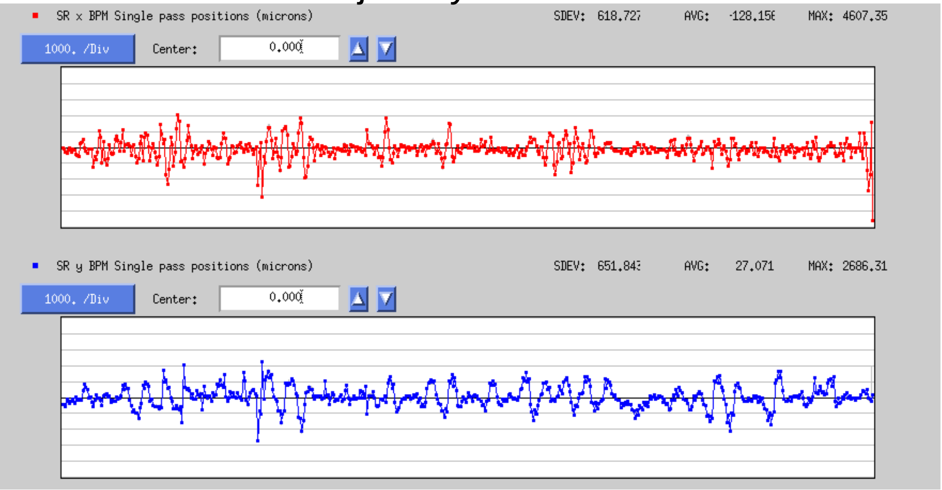
Radial misalignment of modules



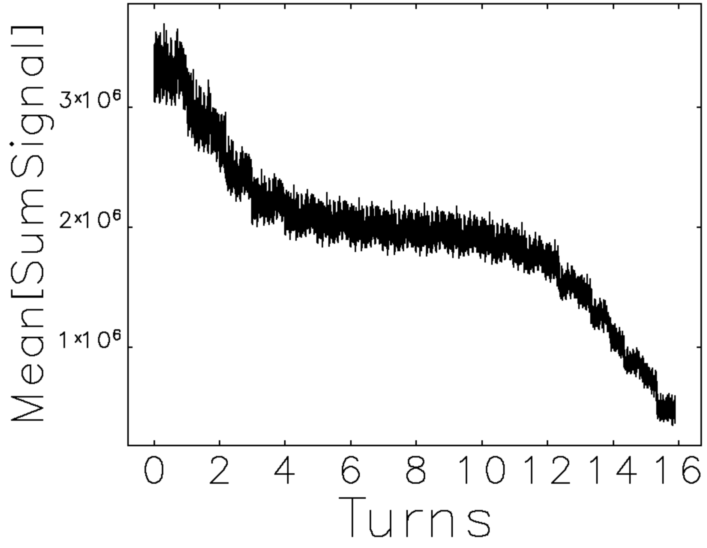
Struggle getting multiple turns despite quick first turn

- First-turn threading corrected trajectory well but could not result in second turn (simulations predict 5-10 turns)
  - Automated way of getting many turns failed
- The beam is clearly lost around septum
- Large orbit bumps around septum (> 2 mm) allowed to get ~5 turns
- Measured tunes based on differential trajectories: horizontal was good, vertical was high by 1 unit – corrected
- Tweak fest ensued, resulted in 15 turns

First-turn trajectory is within +-2 mm



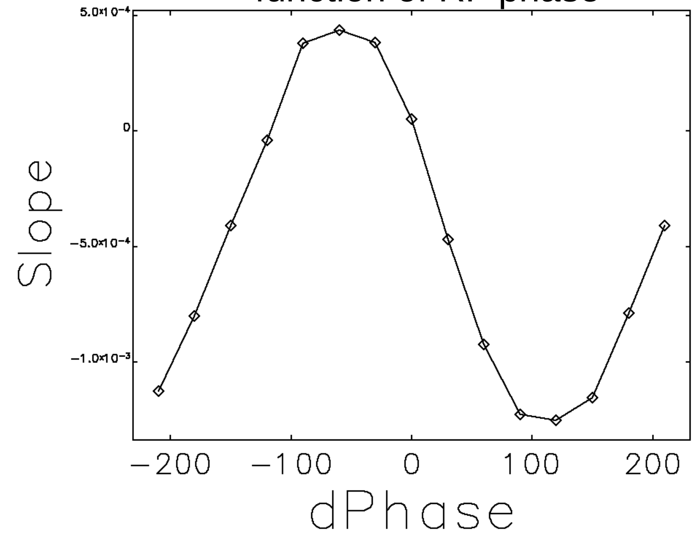
BPM sum signal showing 16 turns

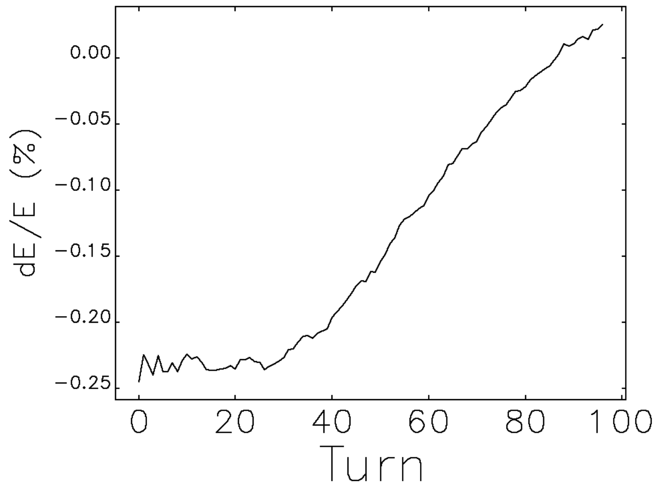


Wild optimization found condition with"almost" stored beam

- Turned on RF, scanned and set rf phase – resulted in 80 turns
- Turned on sextupoles
- Bayesian optimization of everything resulted in 40 μA with lifetime of 4 sec
  - BTS exit trajectory and quads
  - Position and angle closed orbit bump at SR septum
  - SR Tunes
  - The optimization still wanted large orbit at septum
- Tunes are 1 unit off, and lifetime is too short and could not be increased

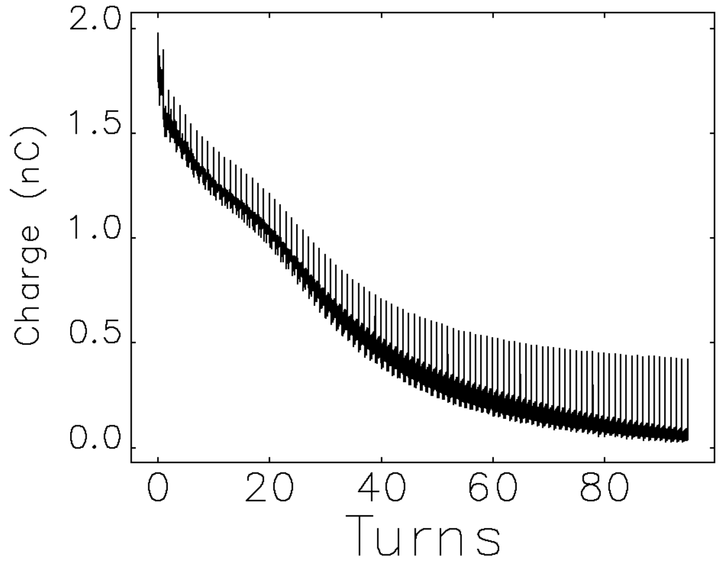
Turn-by-turn dE/E slope as a function of RF phase





Beam energy measurement using trajectory works well

Bunch charge showing 80 turns



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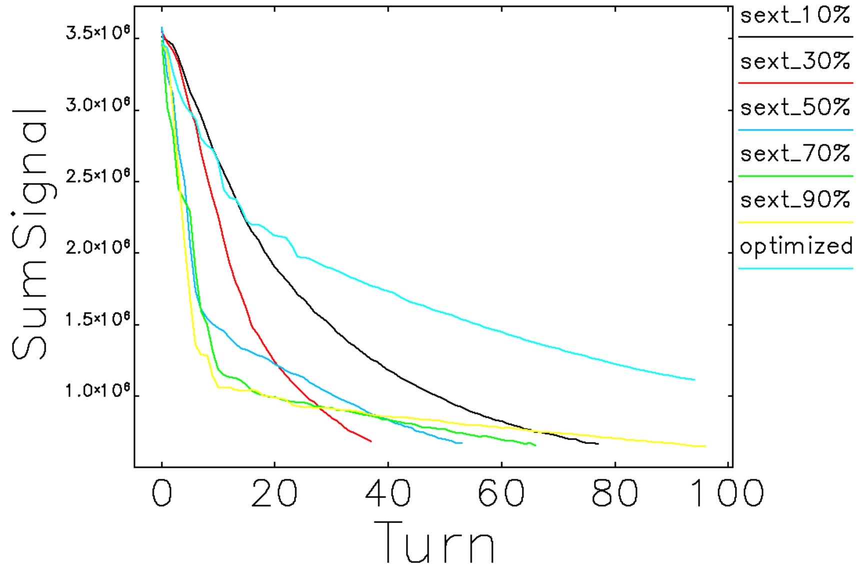
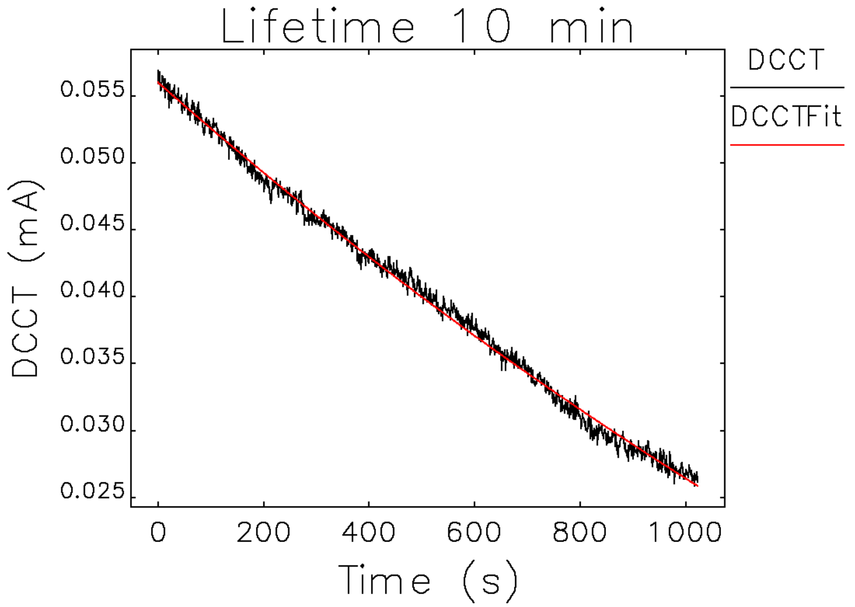
Stepped back and let automated commissioning work its magic

- Conditioned magnets to design values, set sextupoles to zero and started from scratch
  - Large orbit bump found previously was preserved as target for orbit correction
  - Discarded all other previous changes
- Used automated commissioning tools to ramp sextupoles
  - Trajectory correction
  - Quasi-closed orbit correction
  - Trajectory-based tune measurement (by-sector NAFF worked well)
- At 90% of sextupole strength got stored beam (50 µA, 20% efficiency, 10 min lifetime)
  - Took short time, but relied on previously found large orbit bump in septum location
- Further optimization resulted in 70% injection efficiency





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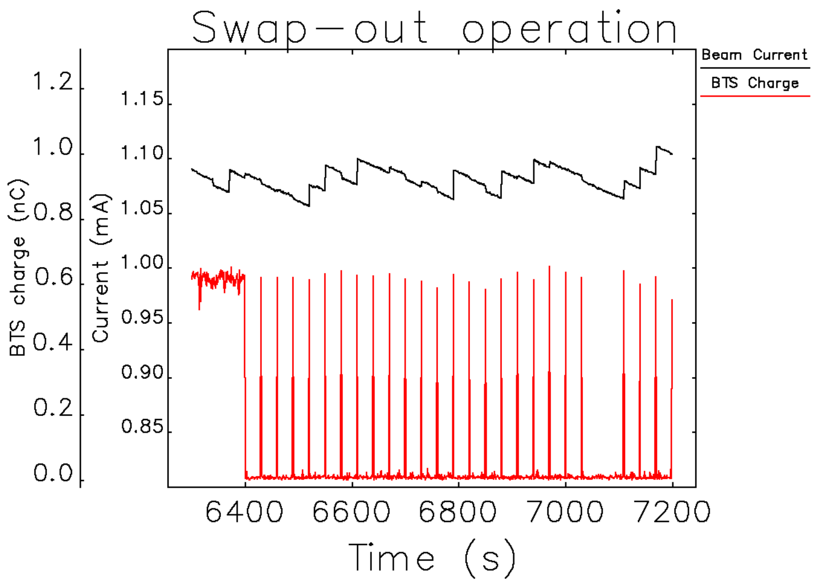
Multi-bunch swap-out

- Through various optimizations achieved consistent 70% injection efficiency
- Pre-requisites for swap-out: operating decoherence and fan-out kickers, validated swap-out permissive software
- Swap-out program detects the weakest bunch and replaces it with the new bunch at defined time interval
- Swap-out has been running ever since



12-bunch 30-second swap-out

APS-U has 3 types of kickers:

Injection kickers	Fired at injection H plane 3 mrad; 11 ns pulse	Place injected bunch on axis, extract stored bunch to dump
Decoherence kicker	Fired 250 turns prior to injection V plane 0.2 mrad; 11 ns pulse	Blows up beam size of extracted bunch
Fan-out kicker	Fired at fast beam abort V plane 0.1 mrad; 5 µs pulse	Spreads out stored bunches over beam dump surface

M. Borland and J. Calvey run swap-out

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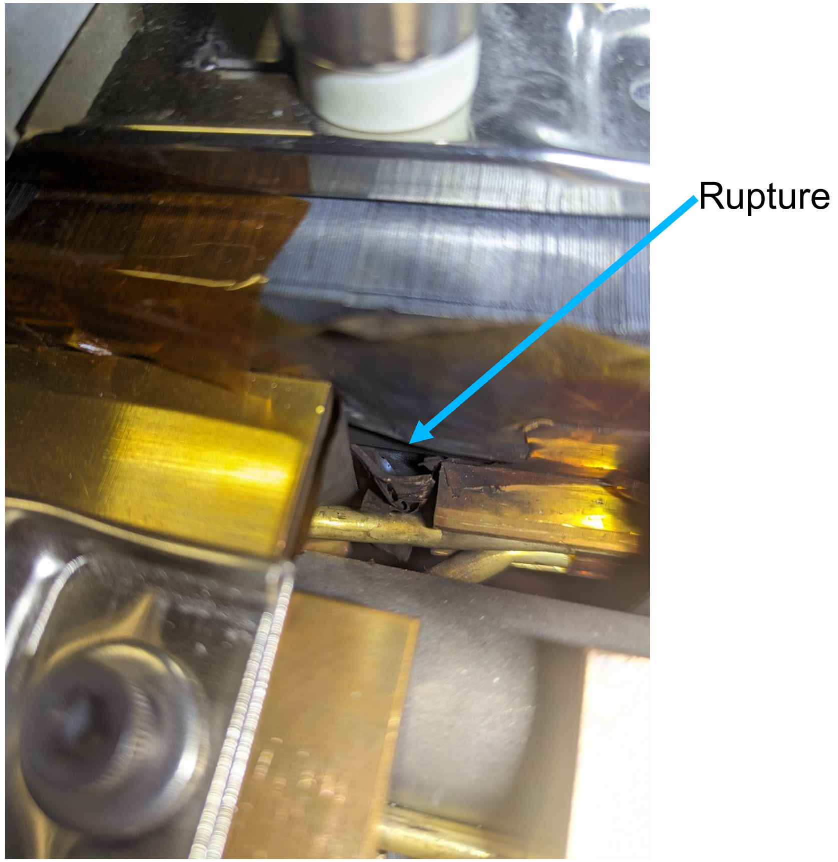
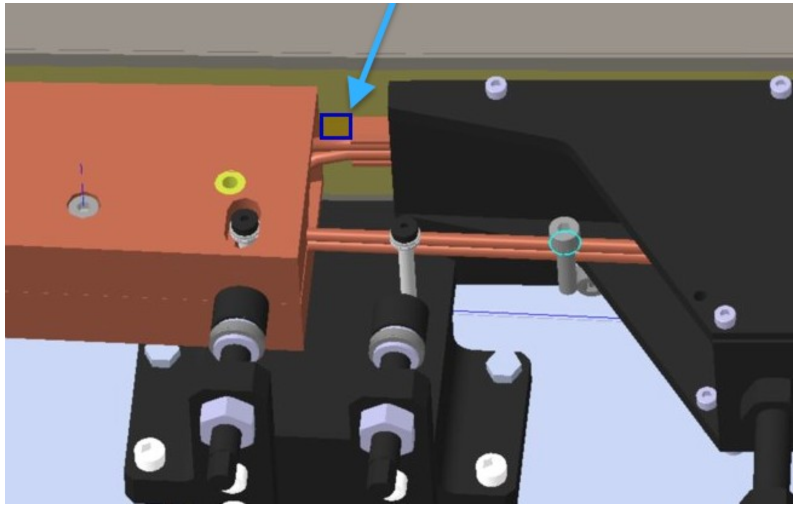
Septum #1 failed on May 2

- A 1-mm thin copper bus is the main current conductor of the pulsed septum magnet
- It is firmly supported along the entire length of the 1.5-m long magnet with the exception of a small 16 mm gap
- After ~1M pulses, the copper bus ruptured at the location of that gap
- A spare septum magnet was modified to eliminate the gap and installed; beam was back on May 12

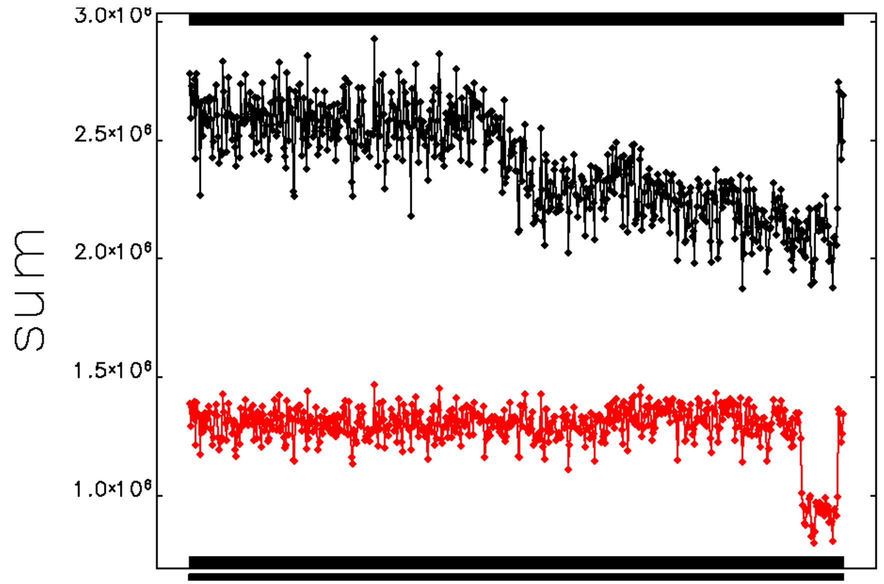


Rupture location, 16 mm gap



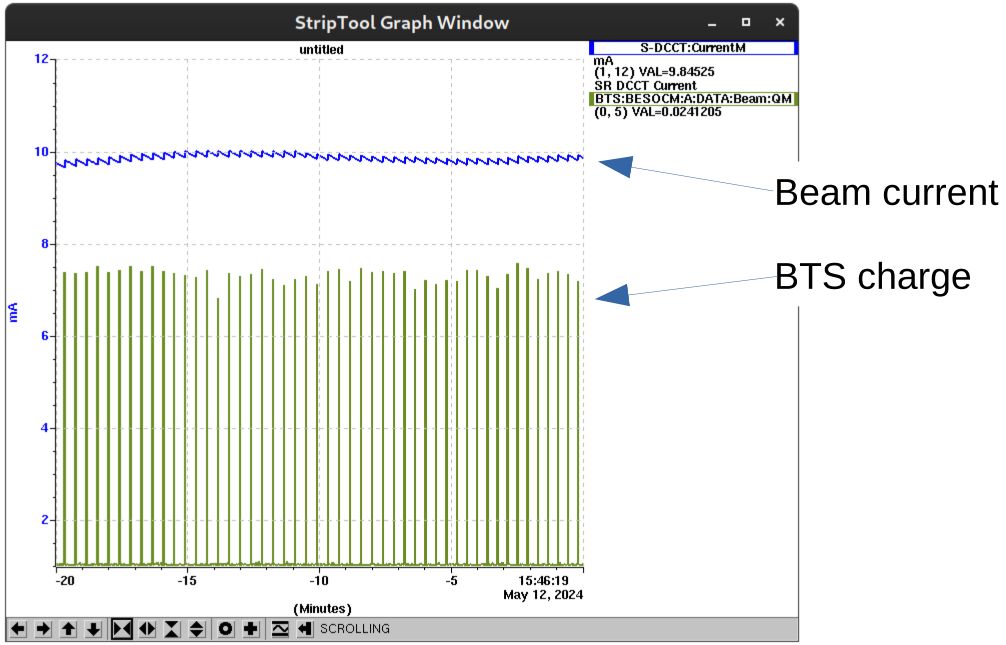
Operation resumed May 12 – 10 mA multi-bunch

- Prerequisite for muti-bunch 10 mA operation: positioning of 5 collimators serving as the whole beam dumps
  - Collimators placed at design position, then adjusted
- One benefit of multi-bunch operation – start of overnight vacuum conditioning so that physicists can switch from 24- to 16-hour days
- The commissioning team was pretty tired at this moment



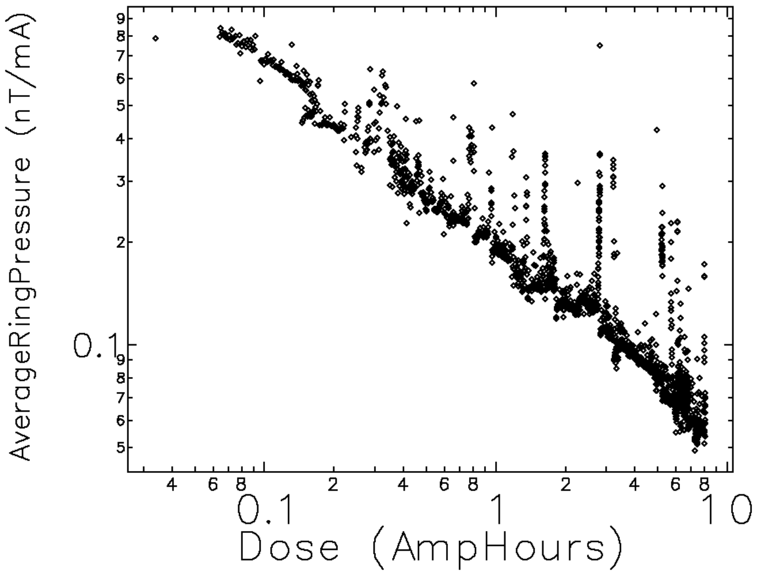
BPM sum signal over 1 turn showing beam loss during beam dump: distributed beam loss without collimator (black) and localized beam loss with collimator inserted (red).
Turn 98 after beam dump command is shown

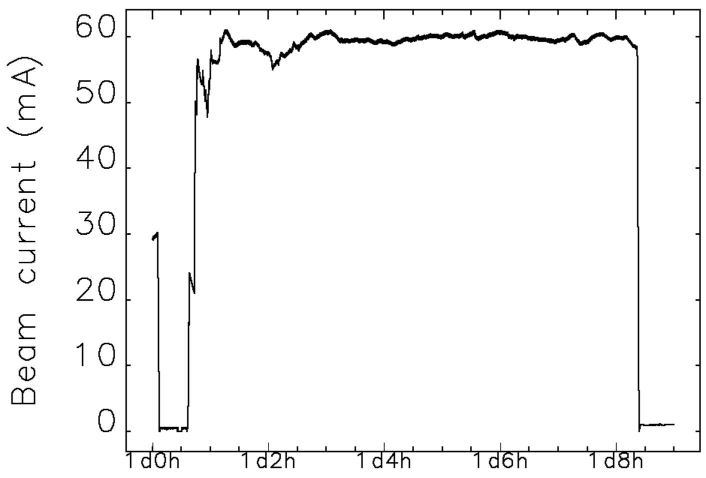
Swap-out running at 10 mA



Vacuum conditioning is going well

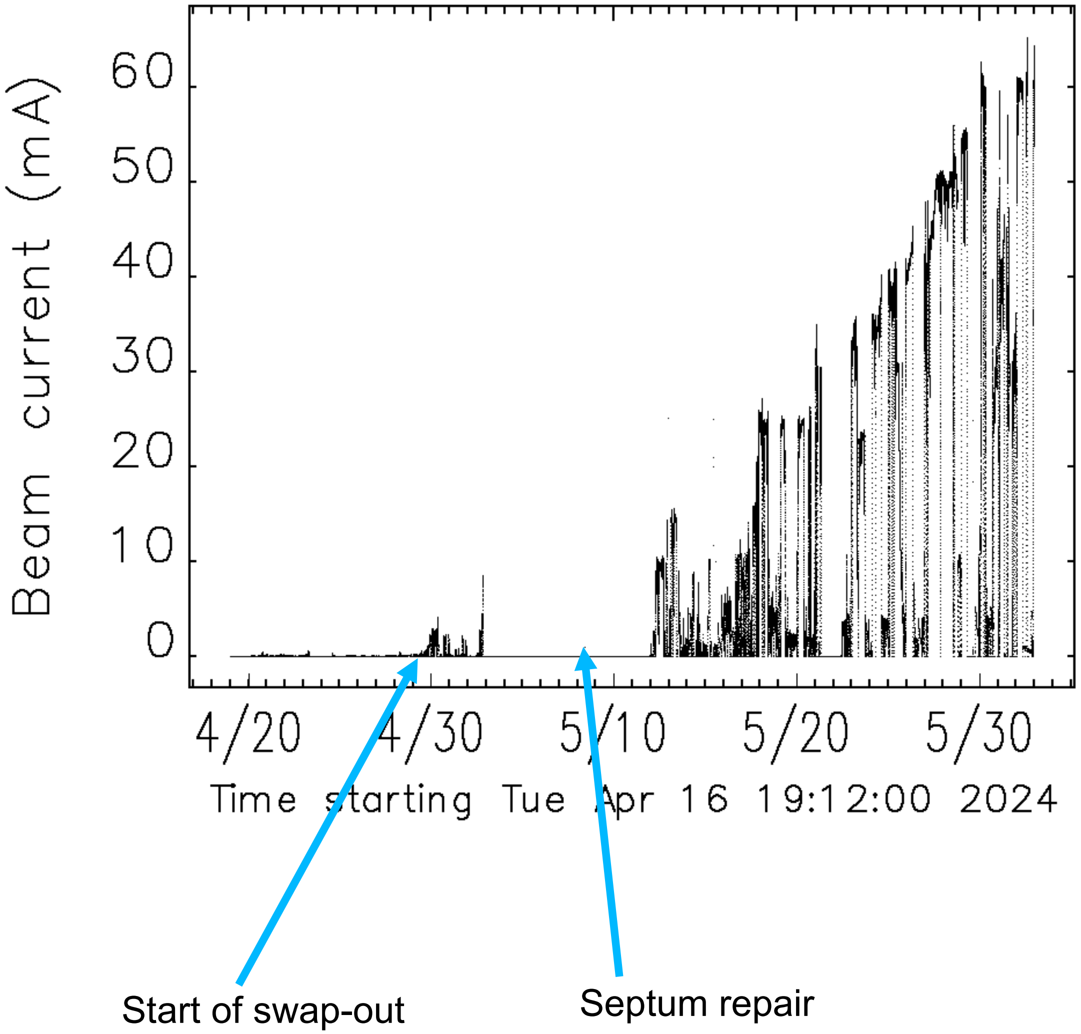
- Vacuum conditioning is required to improve vacuum before opening beamline shutters to reduce bremsstrahlung radiation
- Vacuum conditioning was planned to be performed at nights by operators
- Main challenge – to train operators to run the new ring
  - Need to provide simple enough software and simple enough instructions
  - Need to train operators on that software
  - This step was missing from commissioning plan
- Delayed vacuum conditioning start by 5 days because of that





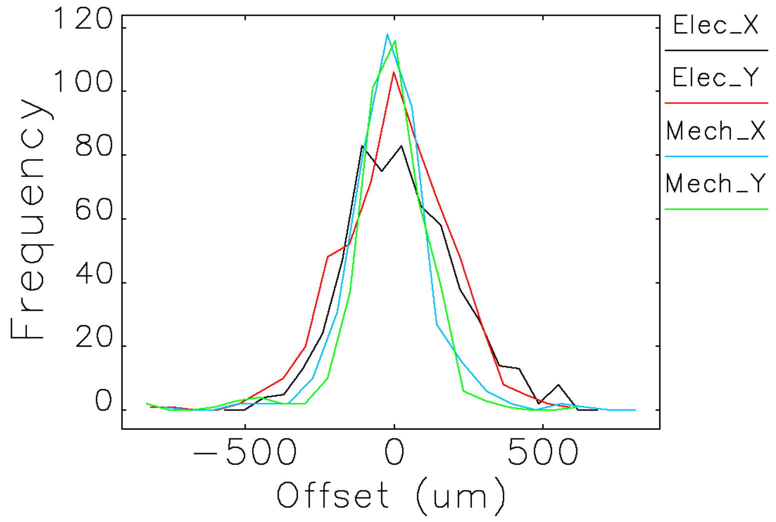
Beam current ramping

- APS-U objective beam current target is 200 mA, to be achieved one year after commissioning
- Beam current is increased mainly during vacuum conditioning shifts at night
- Day-time studies are typically performed with lower beam current
- Between May 12 and June 2, beam current was increasing at an average rate of about 2.5 mA per day

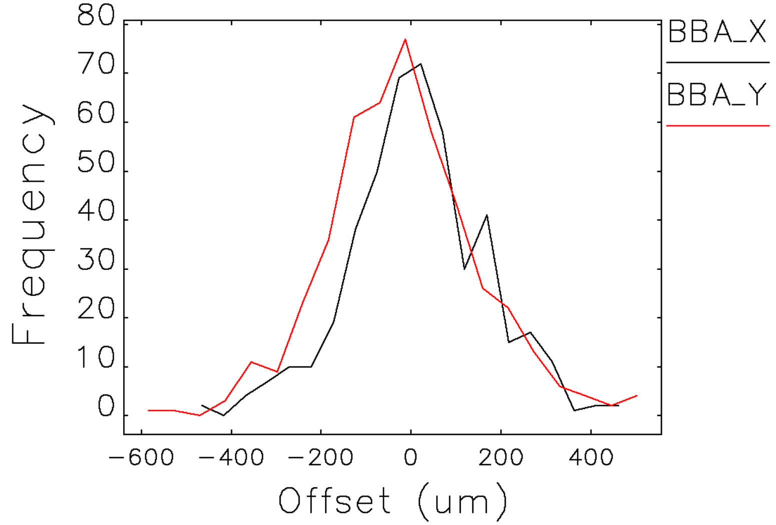


Residual BPM offsets are much better than requirements

- Based on simulations, BPM offset errors are one of main sources of commissioning complications
- 10 out of 14 BPMs per sector were surveyed prior or during installation
- All BPMs were electrically characterized in the tunnel
- Mechanical and electrical offset errors were included in the initial database
- Residual offset errors are measured beam-based



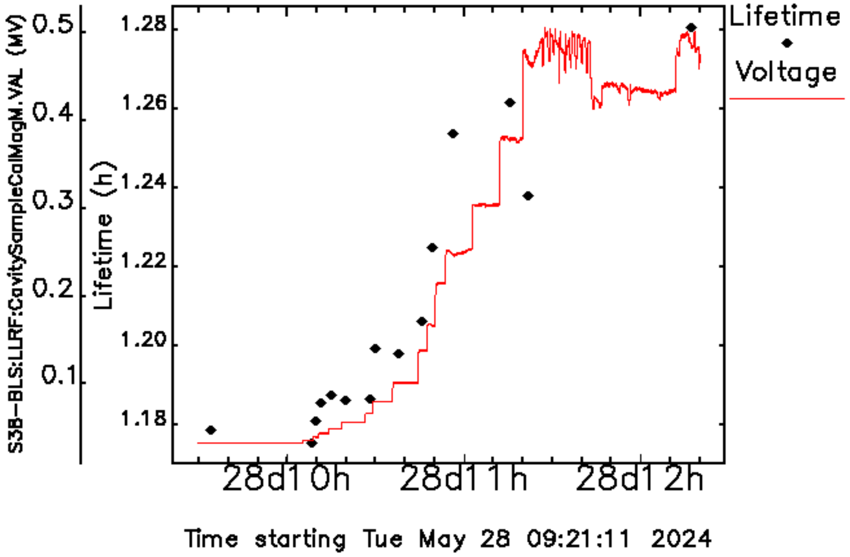
	Electrical	Mechanical	Total	BBA
X (µm rms):	190	150	240	150
Y (µm rms):	190	150	240	170
Requirements (µm rms):				500

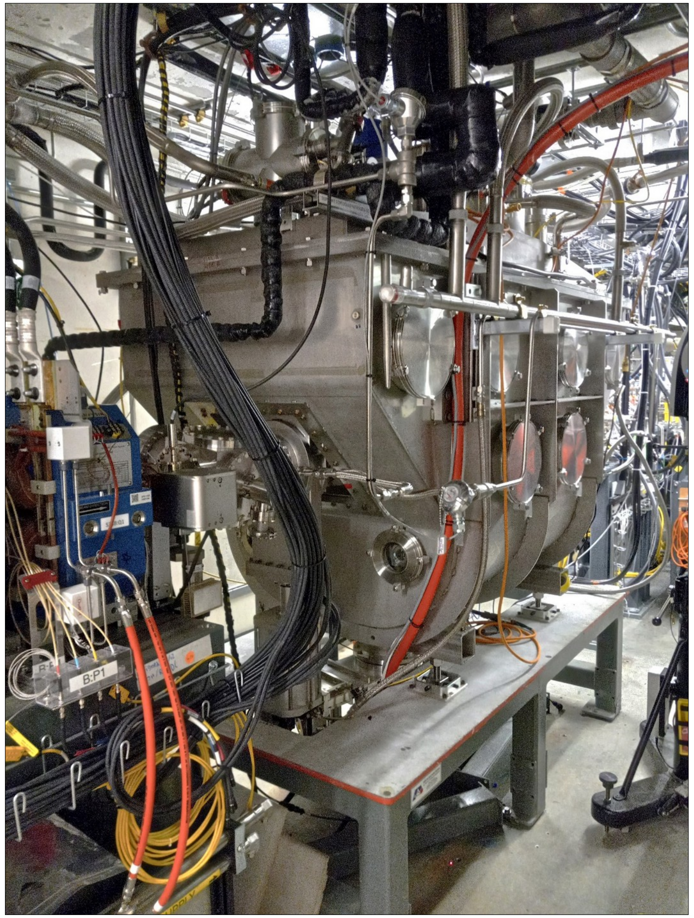


Bunch lengthening cavity

- Bunch lengthening cavity (BLS) was briefly tested with 50 mA beam
- BLS was tuned to generate 0.5 MV
- Small lifetime improvement was observed
  - Lifetime is presently dominated by gas scattering

Cavity voltage and beam lifetime





BLS Cryomodule installed and cooled down

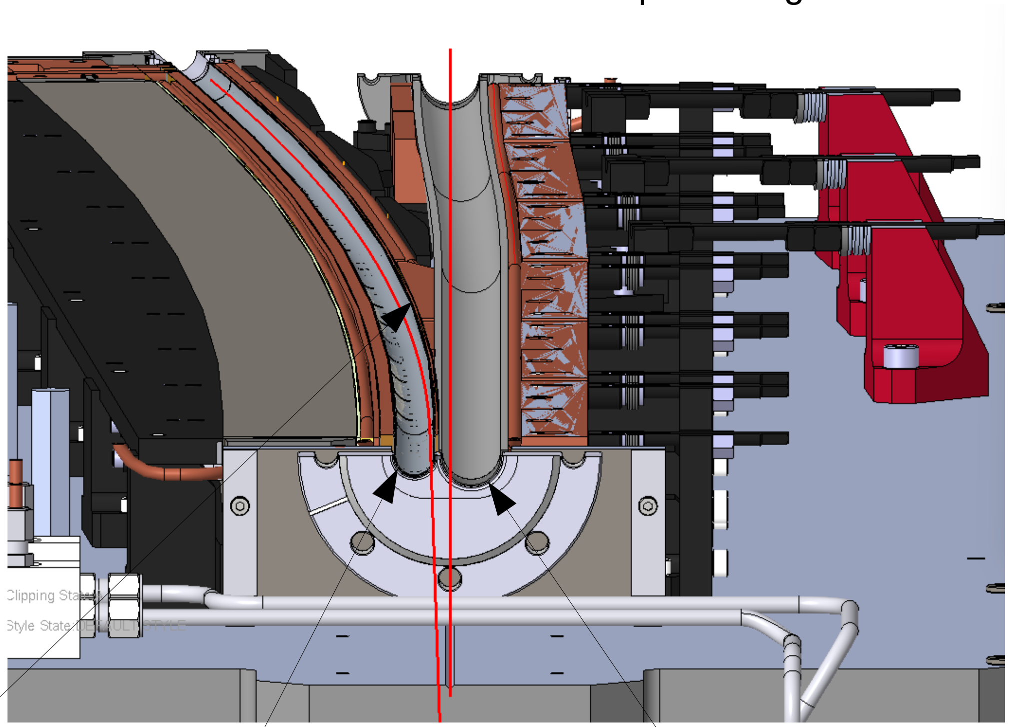
Vacuum leak opened in septum #2 on June 2

- A leak opened in the downstream flange of the septum magnet vacuum chamber
- There were indications that magnet pulsing leads to mechanical motion that puts stress on vacuum weld
- Attempts to mechanically stabilize components around the septum and fix the leak in place failed
- Septum #1 was fixed by that time and installed back June 14

Reason for large orbit bump around septum was found

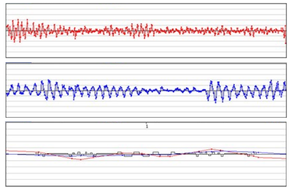
- Explanation of large orbit bump around septum was found while installing septum #1 back
- Survey showed that the stored beam tube was deformed such that its inner surface was touching the design beam orbit at 0.8 m upstream of the septum exit (instead of being 3 mm away from the orbit)
  - Something wrong with wedges used to deform the tube
- Could not be fixed in place
  - Septum was pivoted 1.5 mrad around its exit to provide more clearance 0.8 m upstream
- The beam was back June 15

Horizontal cross-section of the septum magnet

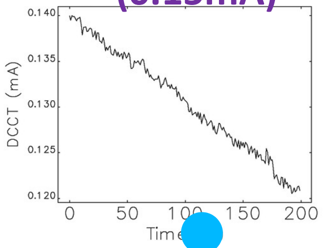


Commissioning timeline

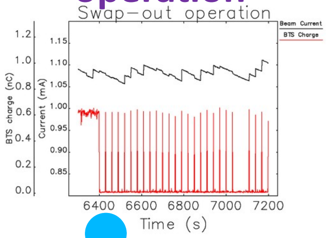
First turns



Stored beam (0.15mA)



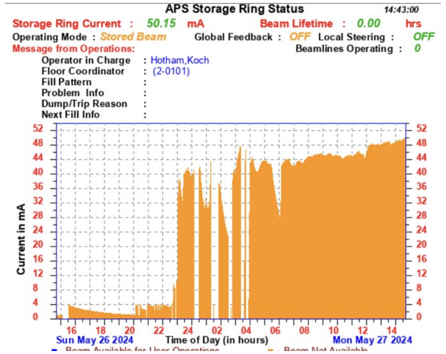
Swap-out operation



10 mA

25 mA

50 mA



First light at user beamline @ 50 mA

April 10	April 13	April 18	April 20	April 29	May 2	May 12	May 17	May 25	May 27	June 2	June 15	June 17	June 19

Machine studies | Radiation studies | Machine studies | Septum failure | Machine studies | Septum failure | Machine studies | Beamline commiss / Machine studies

- April 10 – Machine studies
- April 13 – Radiation studies
- April 18 – Machine studies
- April 20
- April 29
- May 2 – Septum failure
- May 12 – Machine studies
- May 17
- May 17
- May 25
- May 27
- June 2 – Septum failure
- June 15 – Machine studies
- June 17
- June 19 – Beamline commiss; Machine studies

DOE authorizes start of commissioning

Vacuum conditioning started

Diagnostics beamline shutter opened with swap-out

The team is very proud of successful commissioning


Yine Sun


Michael Borland


Jeff Dooling

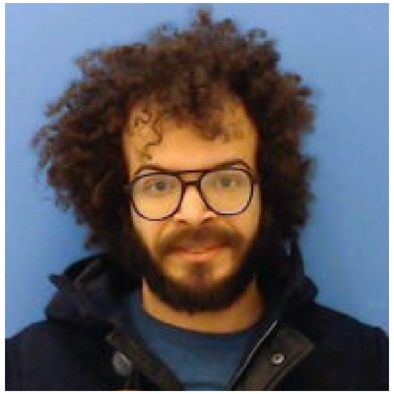

Joe Calvey


Vadim Sajaev


Kathy Harkay


Louis Emery


Nikita Kuklev


Osama Mohsen

Beamline commissioning phase started June 19

- Most of the SR commissioning tasks are completed
- Remaining tasks will be worked on in parallel with beamline commissioning
- Beamline commissioning will take about 2 months as beamlines will be brought online one by one
- With exception of septum problems, the commissioning went really well