Fermilab

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

High Intensity Proton Stacking at Fermilab: 700 kW Running

Rob Ainsworth

HB2018

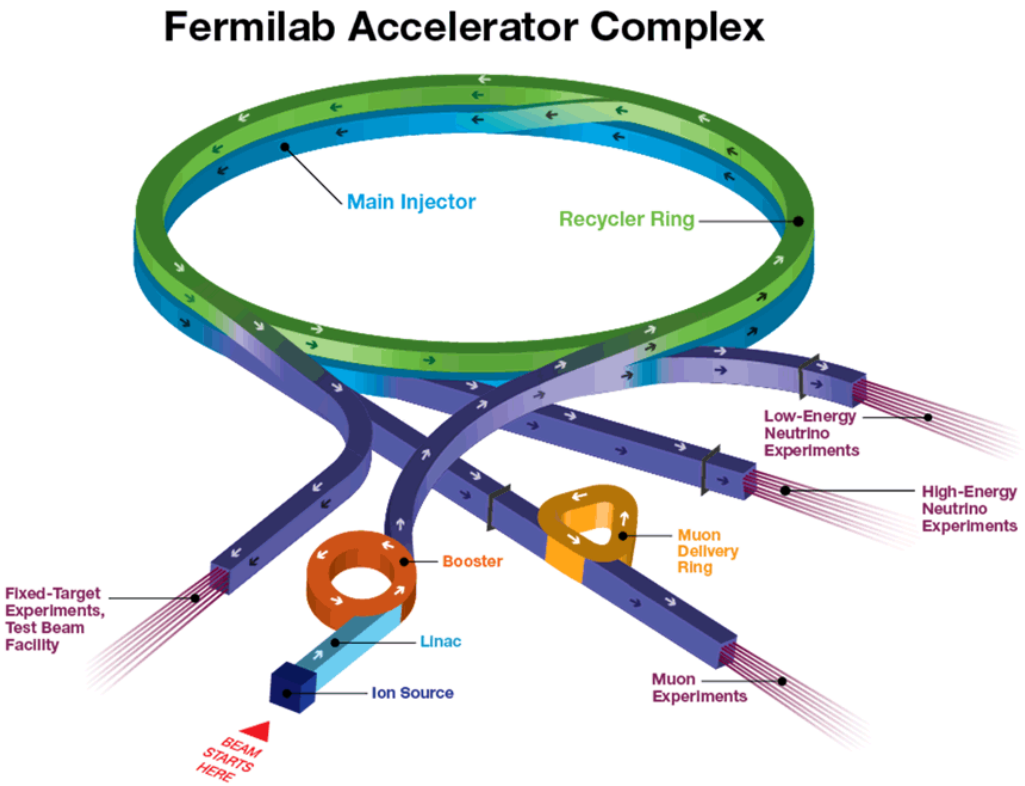
19th June 2018

Outline

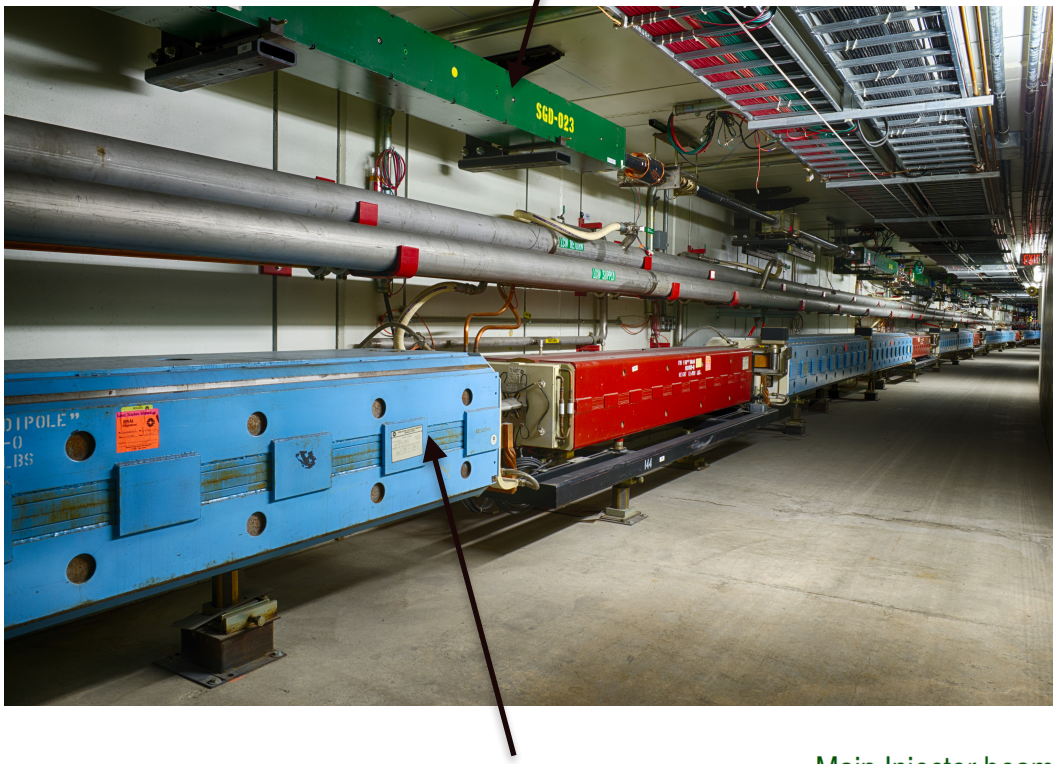
- Accelerator complex
  - Repurposed Recycler
  - Power evolution
- Slip-stacking
- Running in 2016 and issues
- Changes and Running in 2018
- Summary and future plans

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



Repurposed Recycler

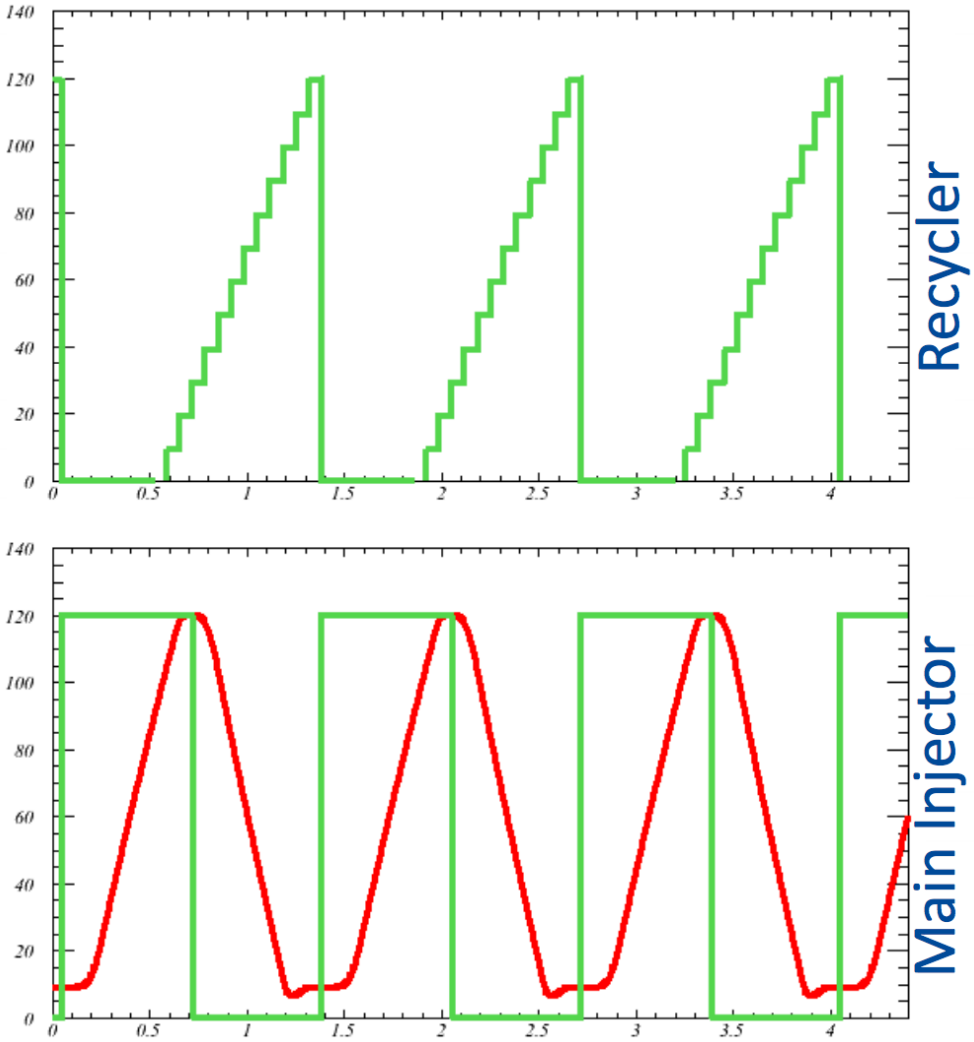


- Recycler is a permanent magnet storage ring
- Shares the tunnel with the Main Injector
- Originally named to recycle pbars from Tevatron which it never did!
- Eventually it stored and cooled pbars
- Contributed greatly towards increased Tevatron luminosity

Never designed for its current purpose

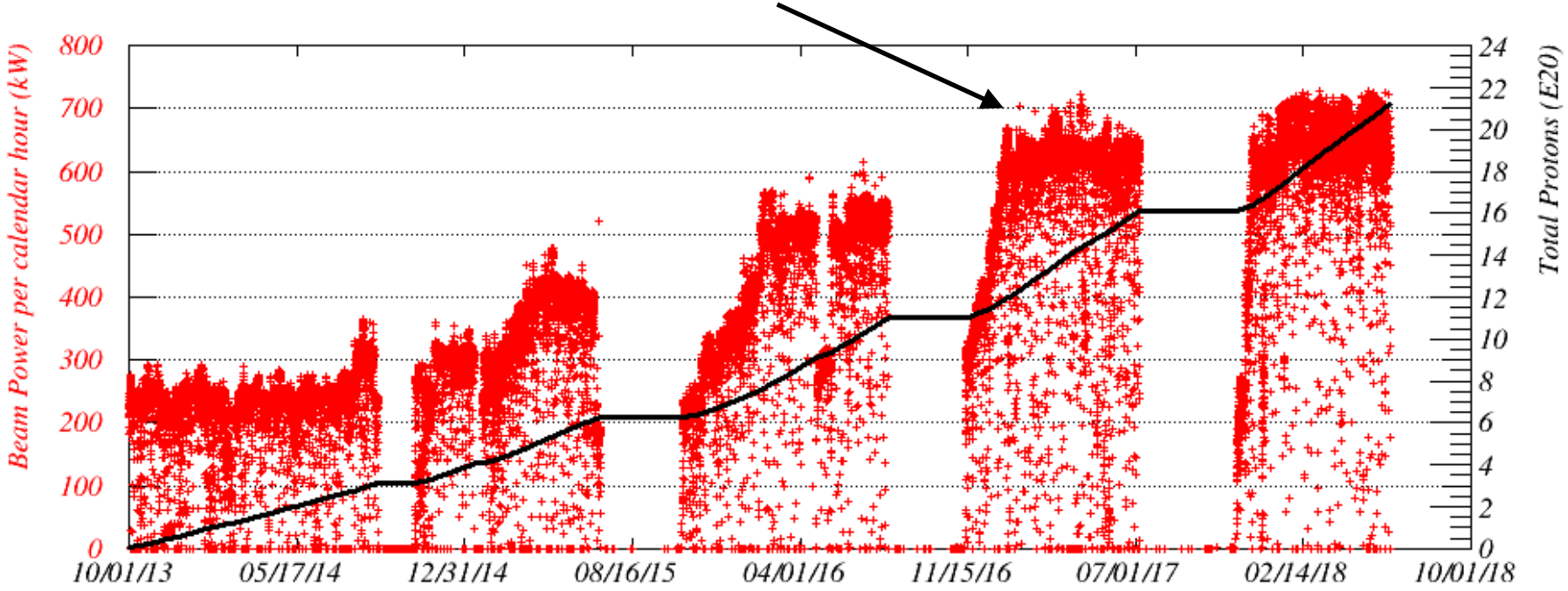
Scheme to increase beam power

- Slip-stack in the Recycler
- Increase the MI ramp rate (204 GeV/s to 240 GeV/s)
  - 2.2->1.33 s cycle time
- Achieve 700 kW with just a 10% increase in beam intensity from MI only



Power

Running 700 kW consistently since Jan 2017

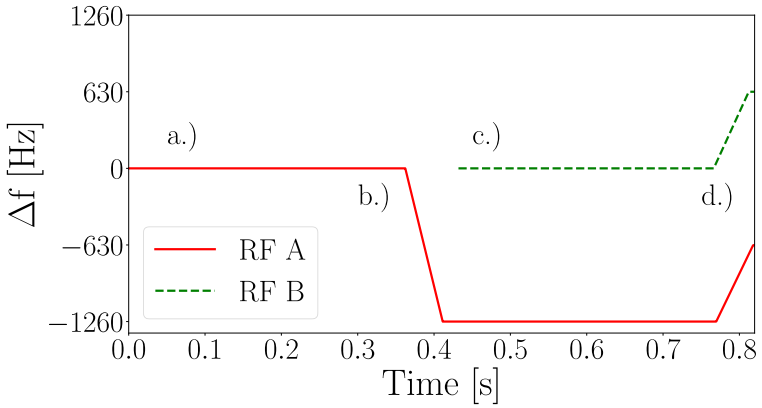


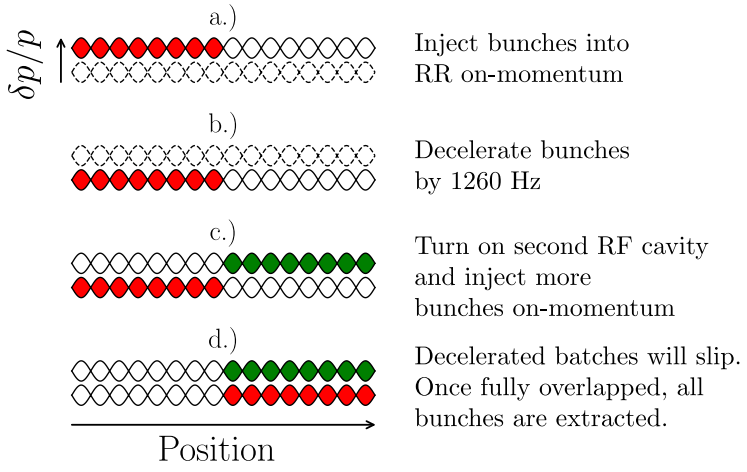
MI	RR	2+6	4+6	6+6
240kW	300kW	400kW	525kW	700kW

Slip stacking

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

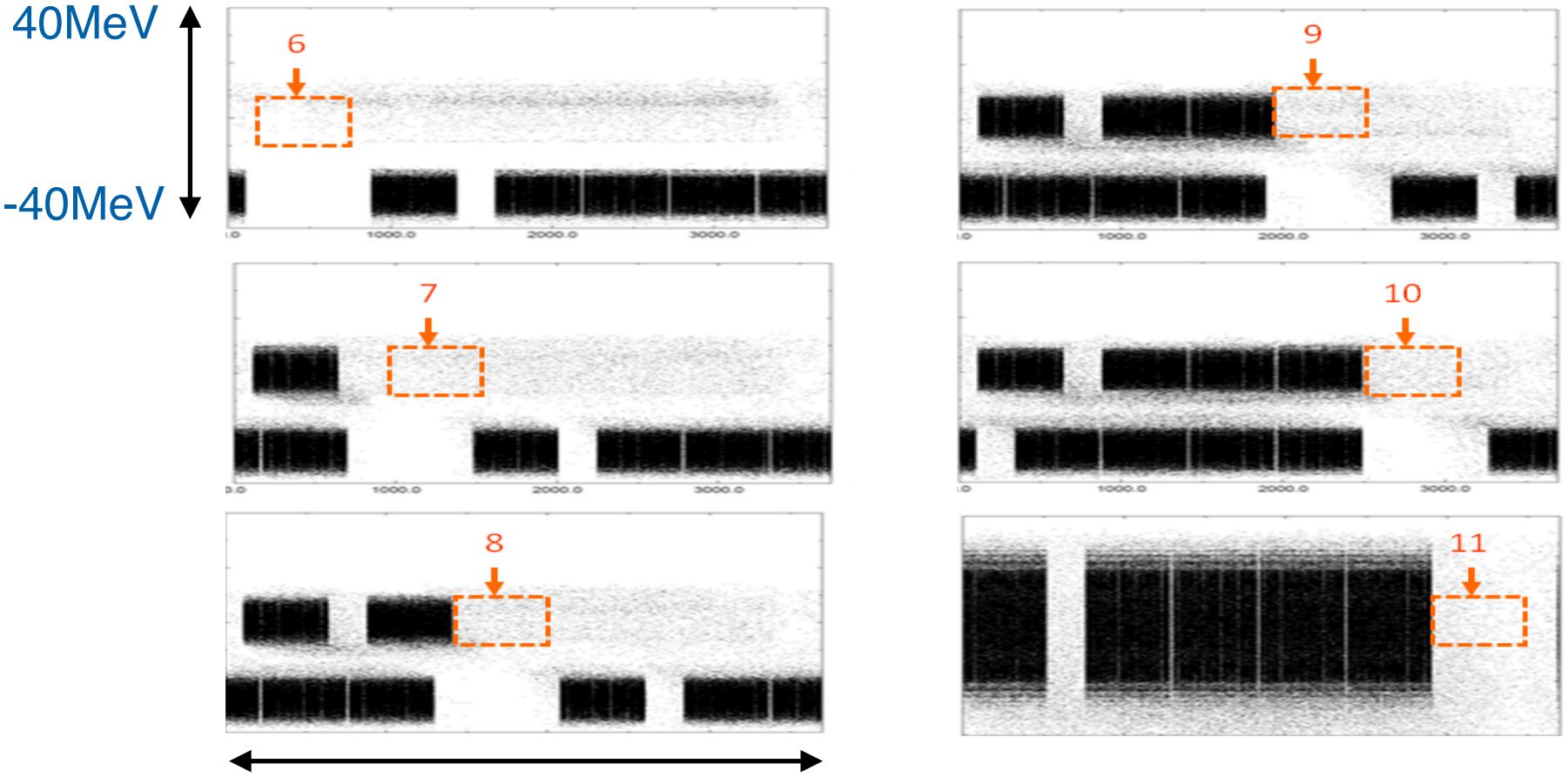
$$\Delta f = h_b f_b$$





Beam in the gap & un-captured beam

Simulation



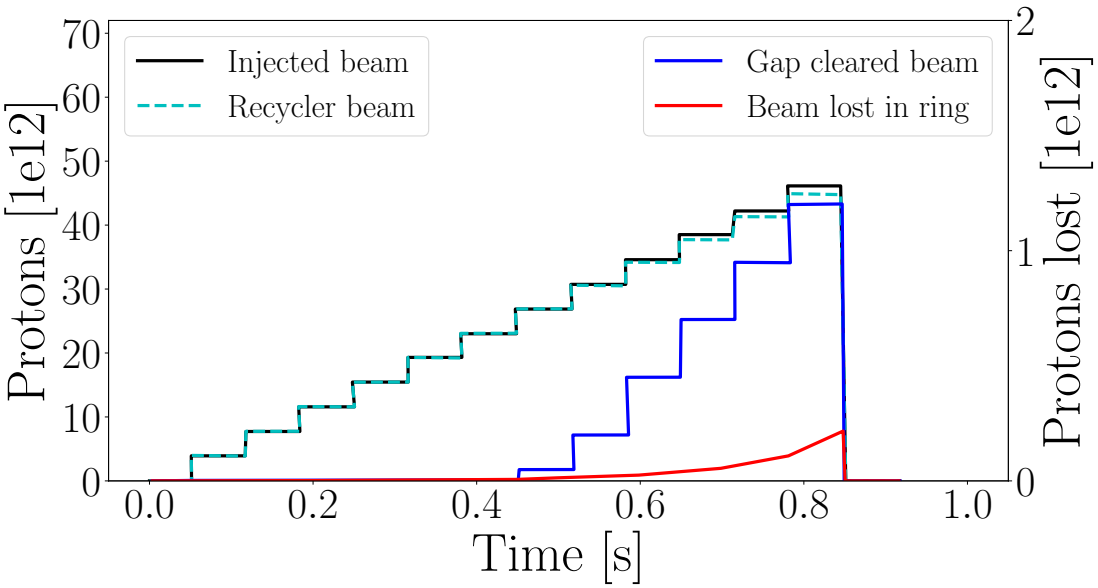
Gap clearing kickers fire before every injection sending beam to abort

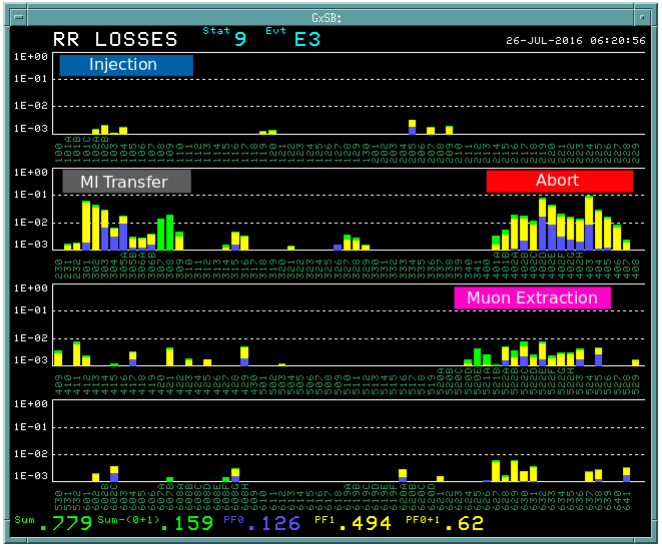
Fermilab

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

42E12 ppp

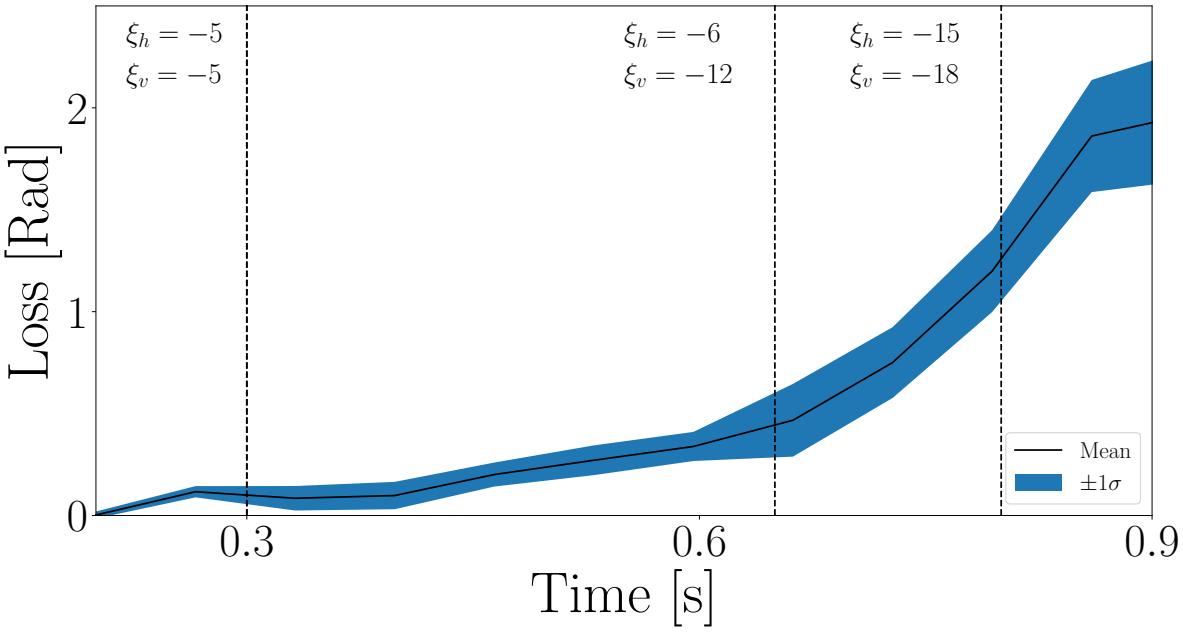




log scale

Fermilab

High Chromaticity running



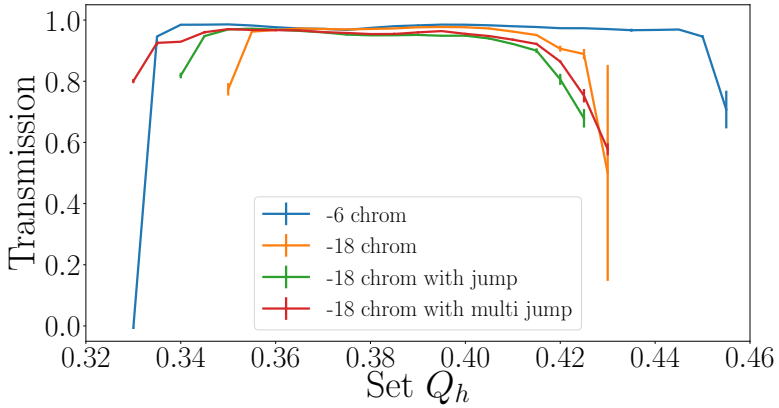
Exponential increase in losses as chromaticity increases

High chromaticity constrains tune space due to off-momentum beam

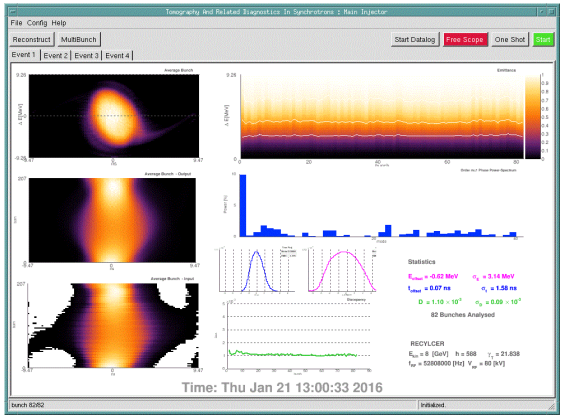
$$\Delta Q = \xi \delta p/p$$

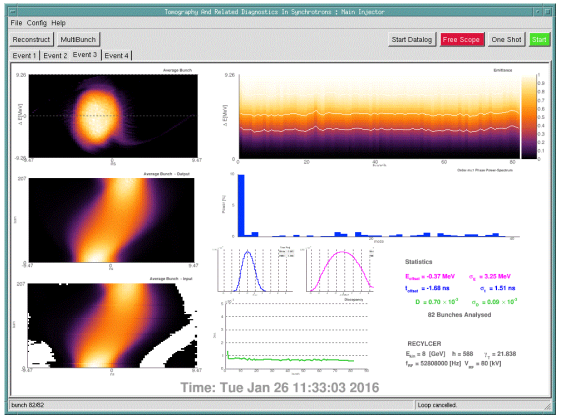
at -5, tune shift ~0.013

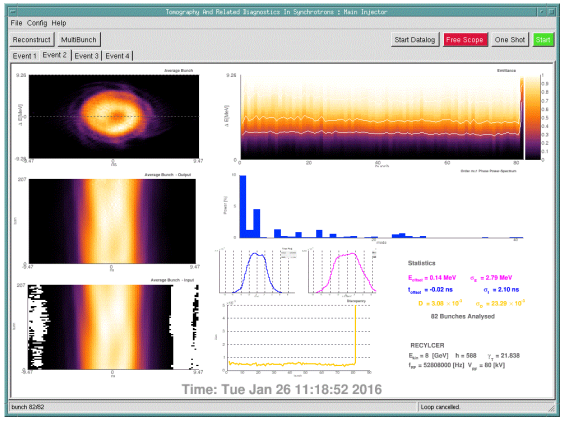
at -20, tune shift ~0.048

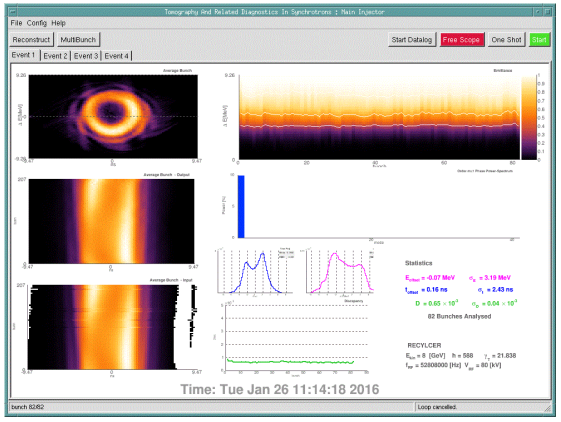


Injection phase offsets (Longitudinal Emittance dilution)









-allowed the final chromaticity to be reduced by 2-3 units

- resulted in more beam sent to abort (controlled)

Issues - 2016 shutdown

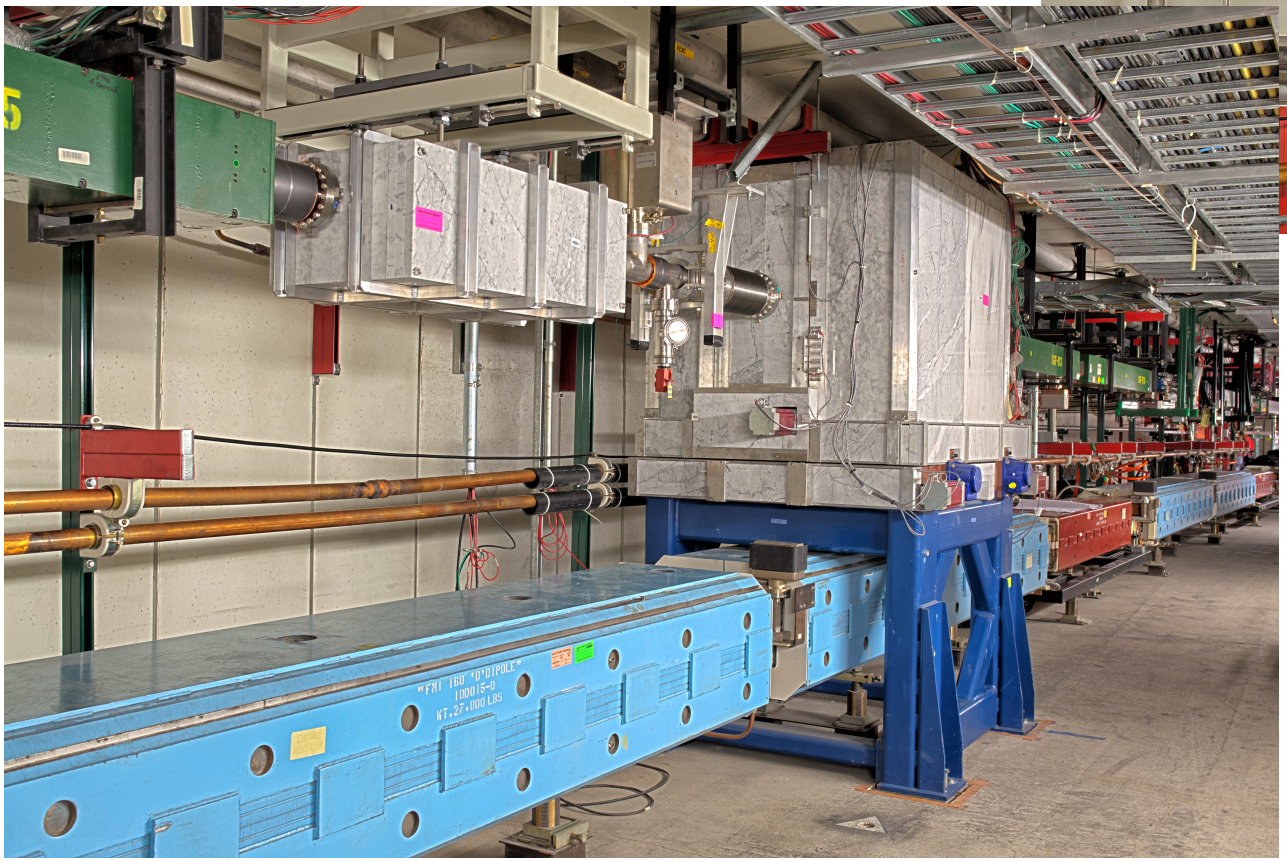
- Transverse losses are not controlled!

- No damper during slipping
  - Need high chromaticity for stability

Collimators

2 stage system

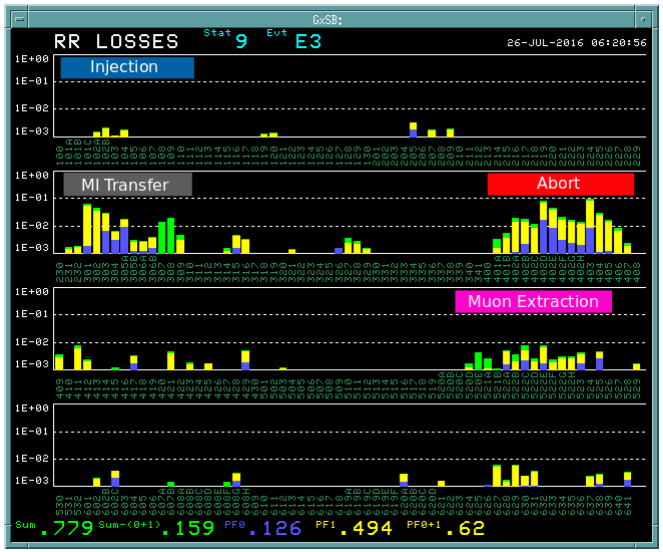
- primary scraping foil edge (vertical)
- two 20 ton secondaries



stainless steel vacuum liner is surrounded by steel absorber with marble shielding

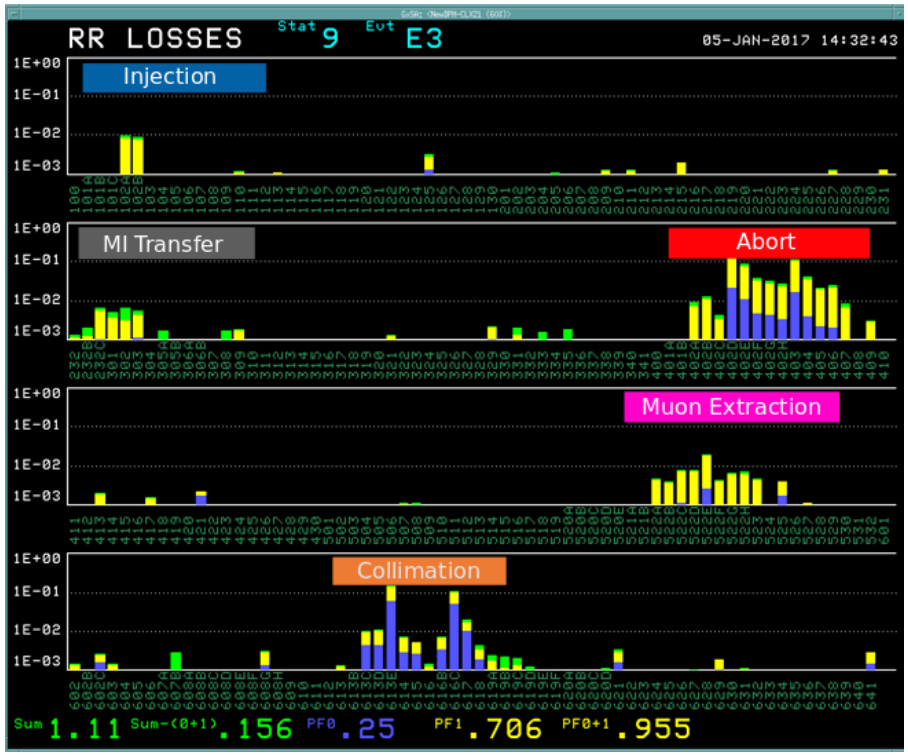
Fermilab

Collimation



42E12 ppp

45E12 ppp



Big improvement at MI Transfer Lambertson

Slip stack damper

- It was proposed that the bunches in the two beams perform the same motion
  - A lower bandwidth damper looking at the envelope could be sufficient

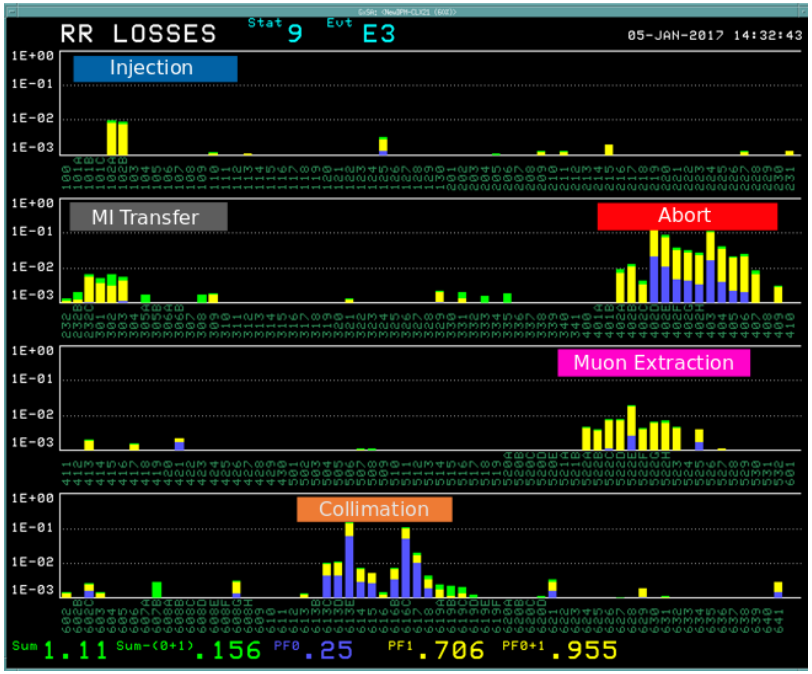
- Damper system developed based on Direct Diode Detection (3D) concept

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

Diode damper

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

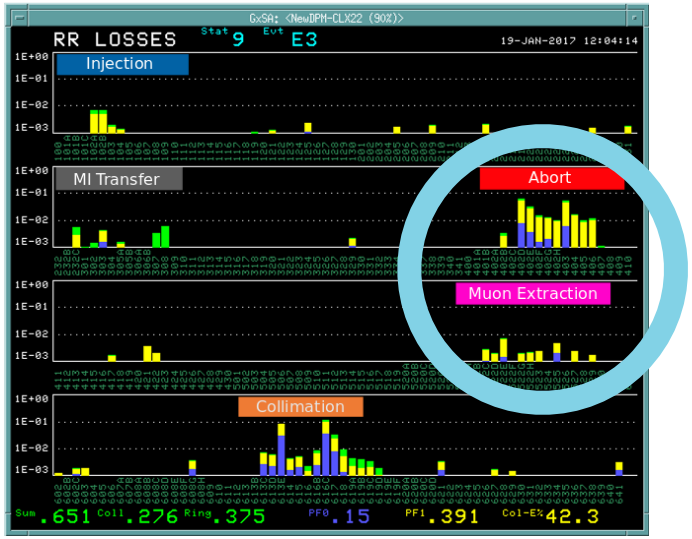
45E12 ppp



45E12 ppp

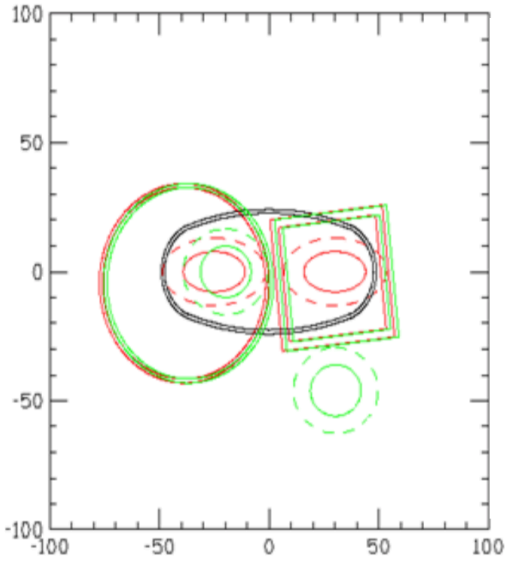
Aperture improvements

25 π mm mrad beam

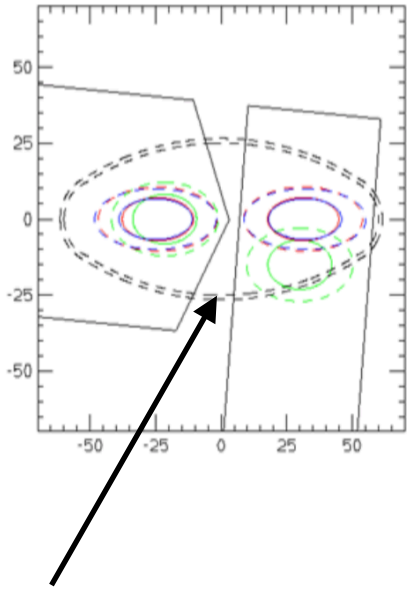


45E12 ppp

Old



New



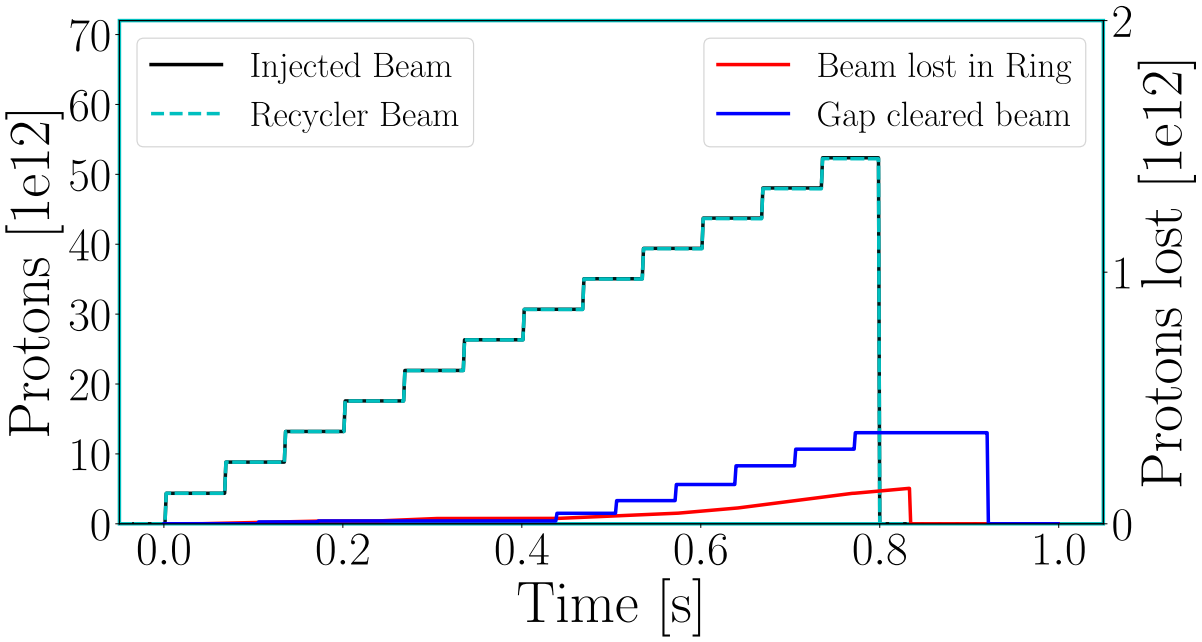
New bigger beam pipe

Replaced permanent magnet Lambertson with powered MLAW style

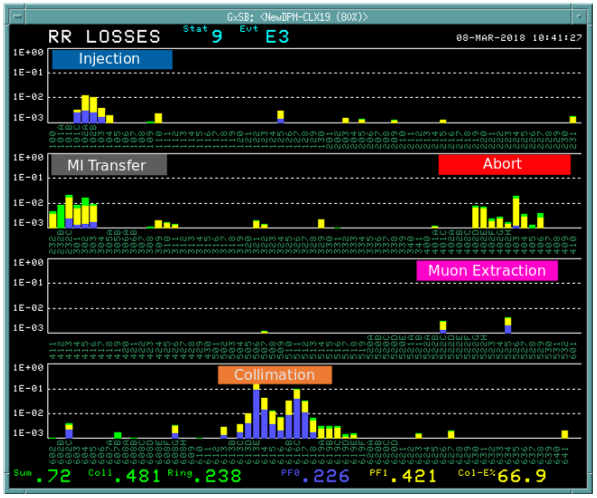
Fermilab

Typical 6+6 cycle - 2018

- Gap cleared beam reduced by a factor ~ 3
- large portion of ring losses go to collimators



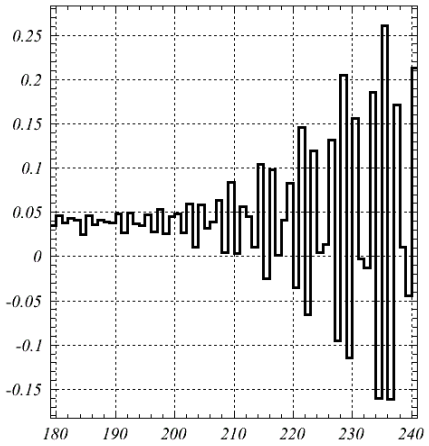
50E12 ppp



Instabilties

See Valeri's Talk on Thursday 8:30 THA1WE01

- Previously, a fast instability attributed to electron trapping in the gradient magnets was observed but was avoided by rotating the bunches

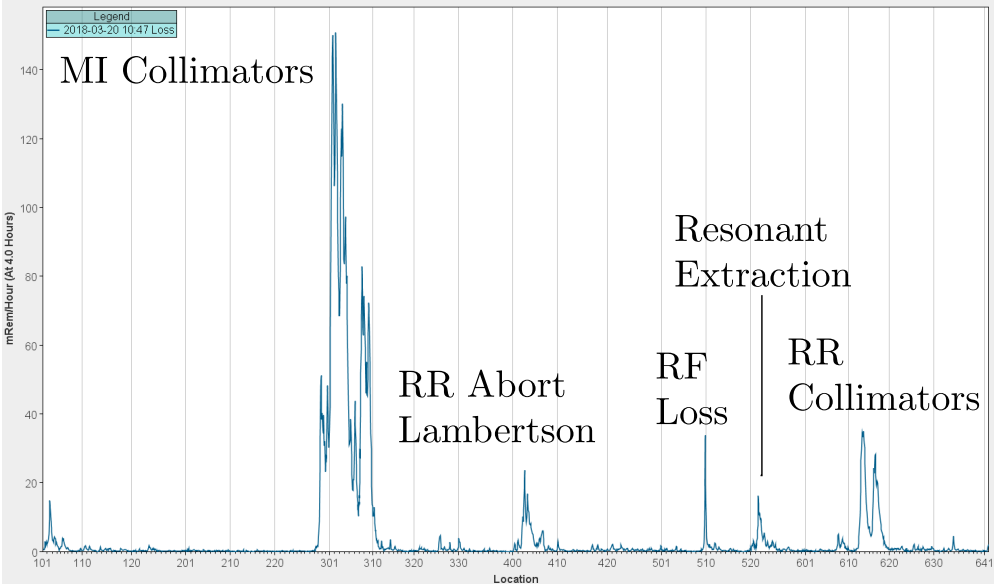


Observed on BPMs, growth rate 10-15turns

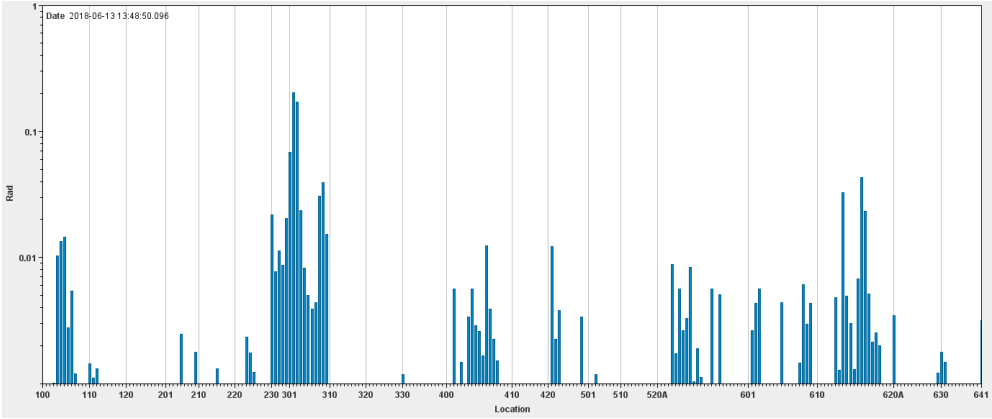
- Fast instability was not observed during commissioning this year
  - Conditioned vacuum pipe
  - Vacuum changes, TSPs -> Ion Pumps may have affected things too
- Tried to induce instability in RR with high intensity bunches (~6e10, -3,-3 chromaticity, short bunches) but observed nothing

Radiation Survey around Ring

DALE survey



Loss monitors



Fermilab

Summary and Future running

- Running 700kW consistently since Jan 2017
  - Added collimators
  - New damper during slip-stacking

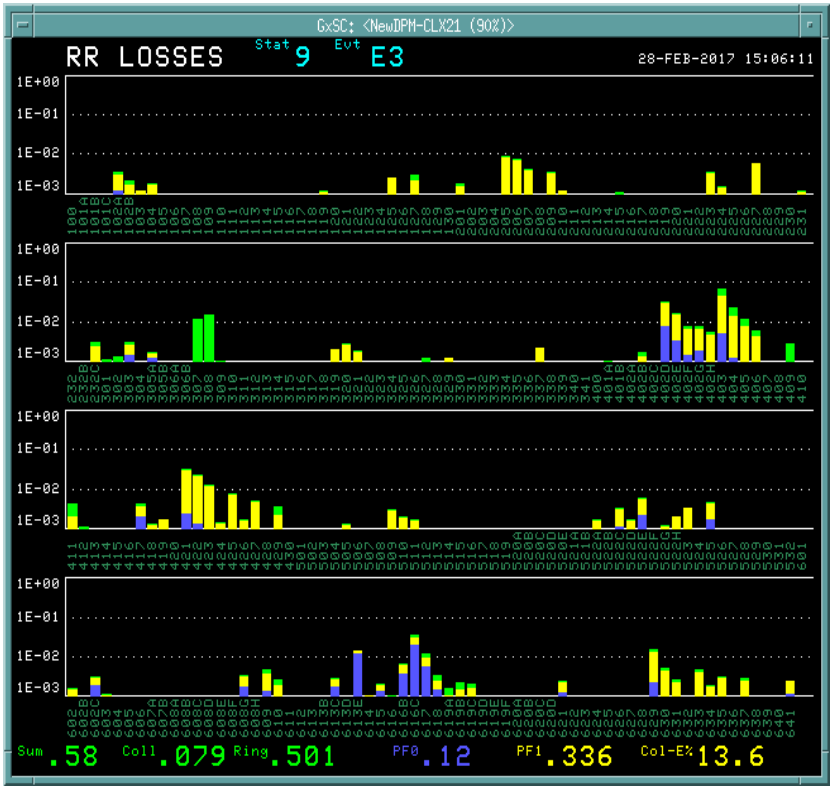
- Power limits
  - Current limit 54E12 (NuMI target limit). This corresponds to 777 KW with 1.33 sec cycle time.
  - MI is limited by the available RF power to 62E12 which corresponds to 892 KW with 1.33 sec

- Future plans
  - Recycler Lattice optimisation
  - Recycler Resonance compensation
  - 1.2 s ramp for MI (10% increase in power)
  - Gamma-t jump for MI

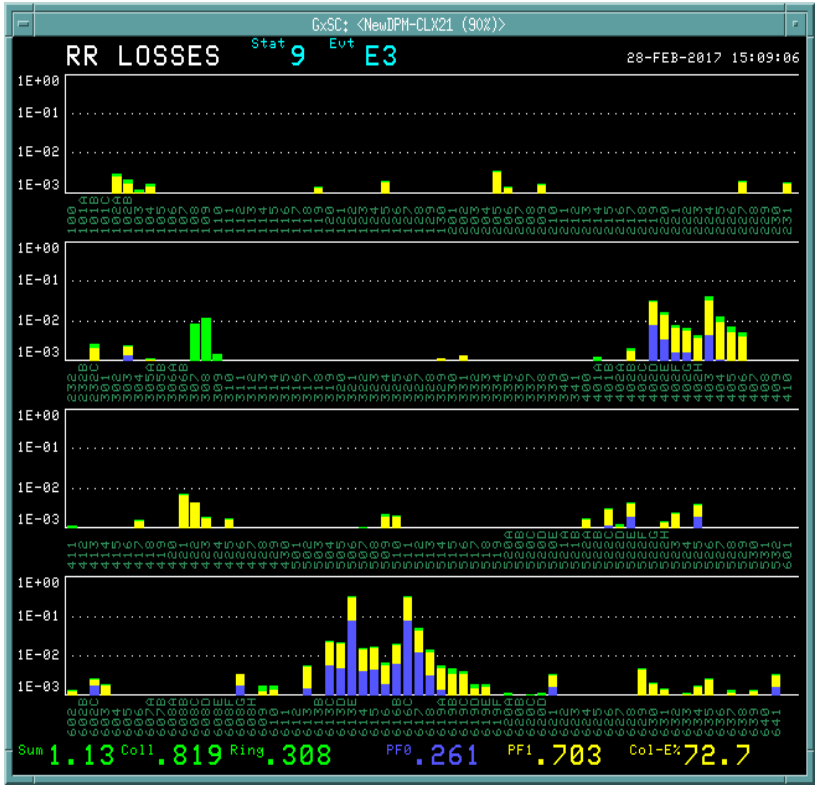
Back-up

Effect on RR collimators on losses with damper on

No Collimation, Damper ON

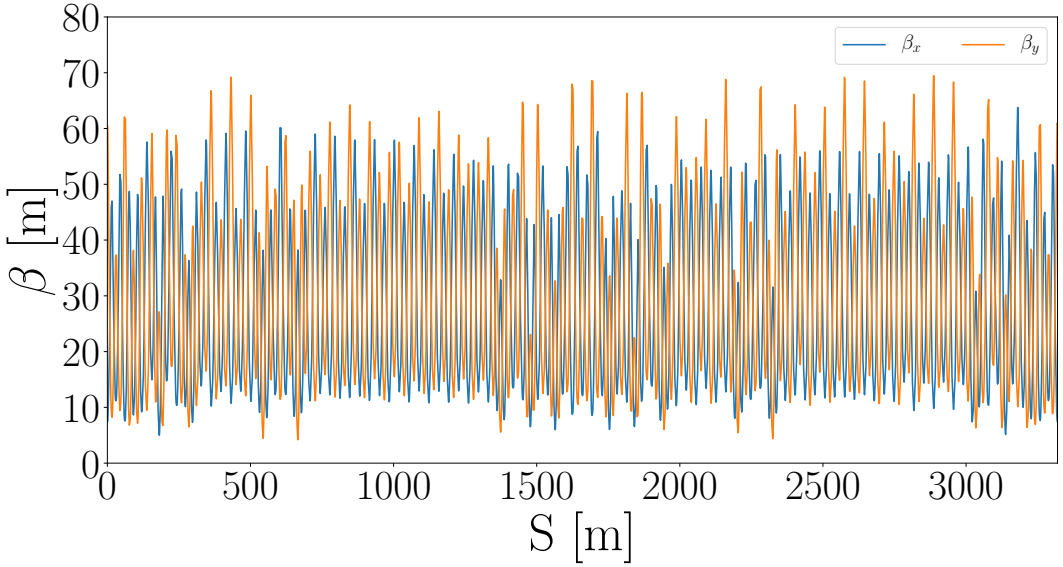


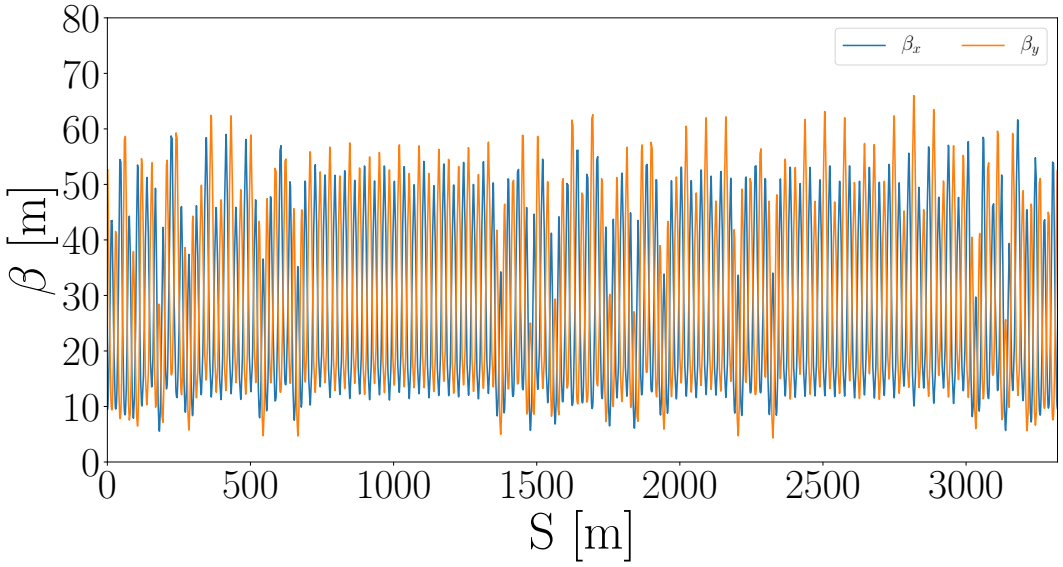
Collimation On, Damper ON



- We need the Recycler collimators even with the new damper!

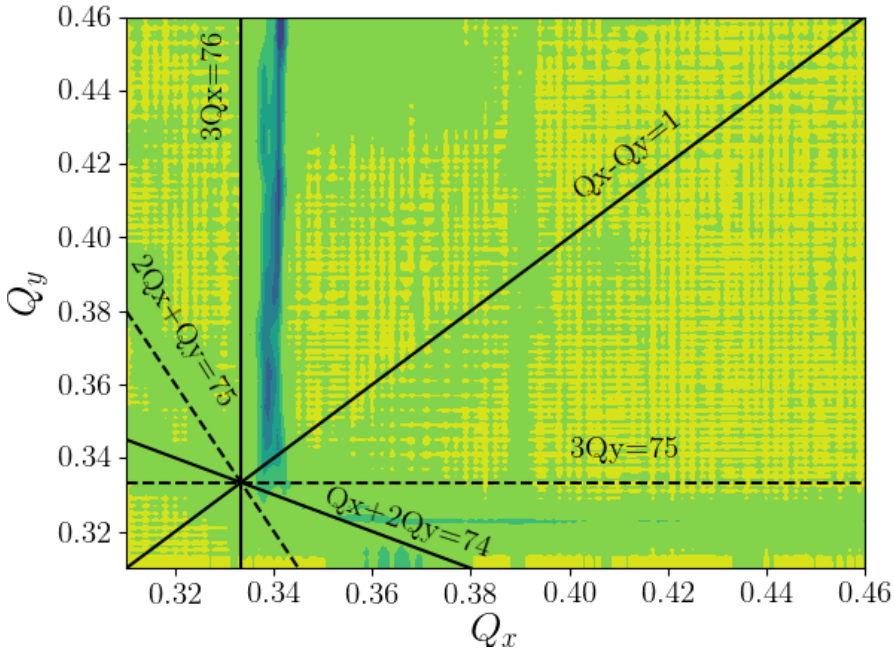
Lattice optimisation

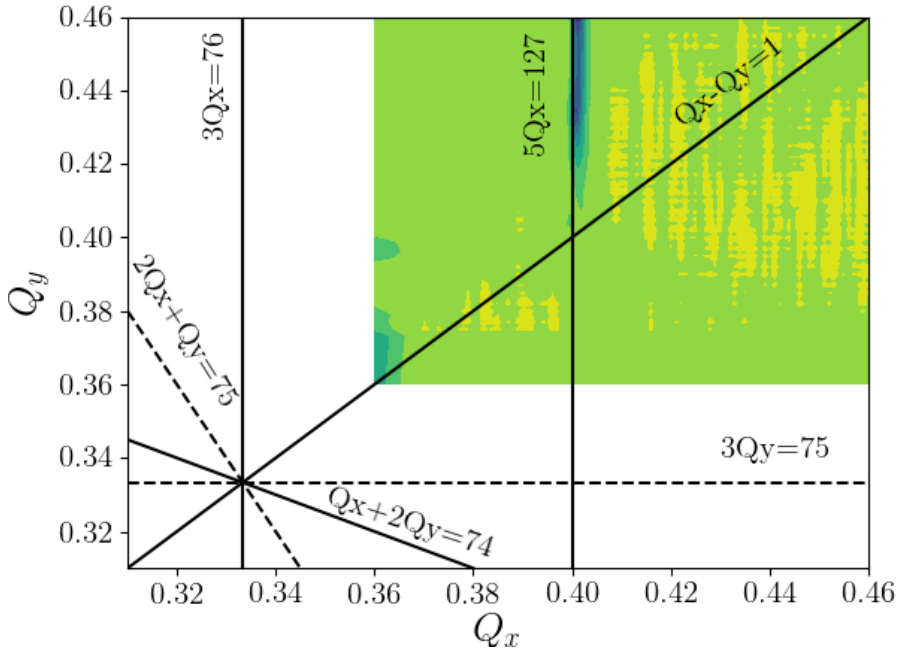


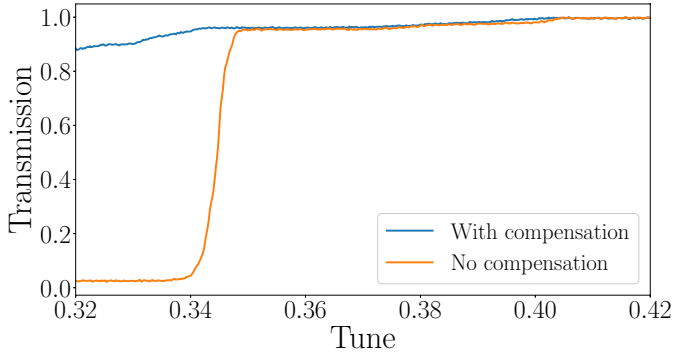


Fermilab

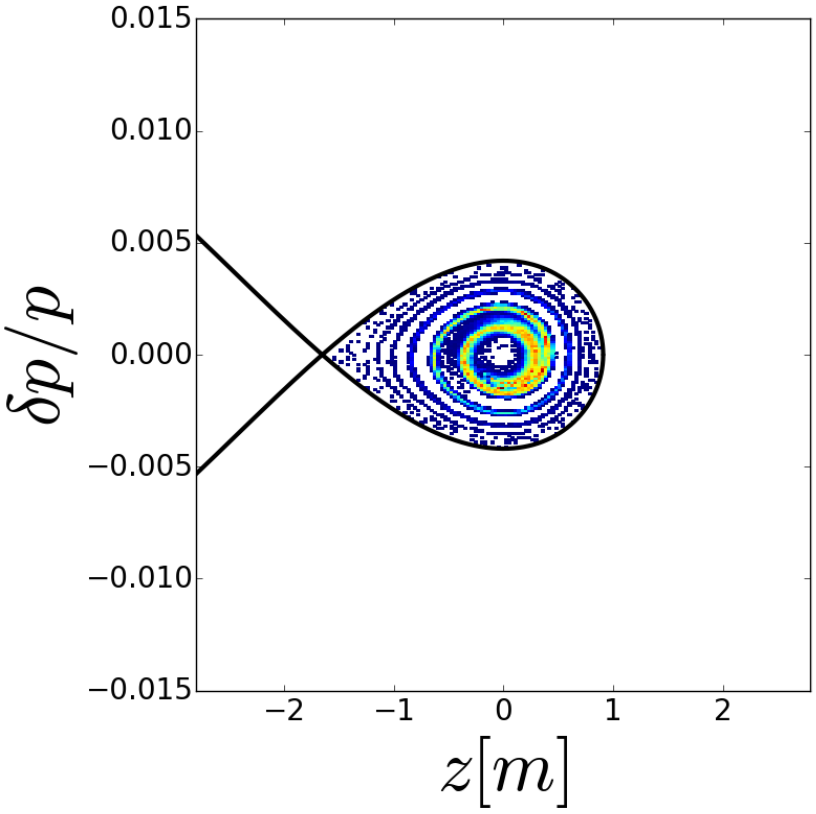
Resonance compensation

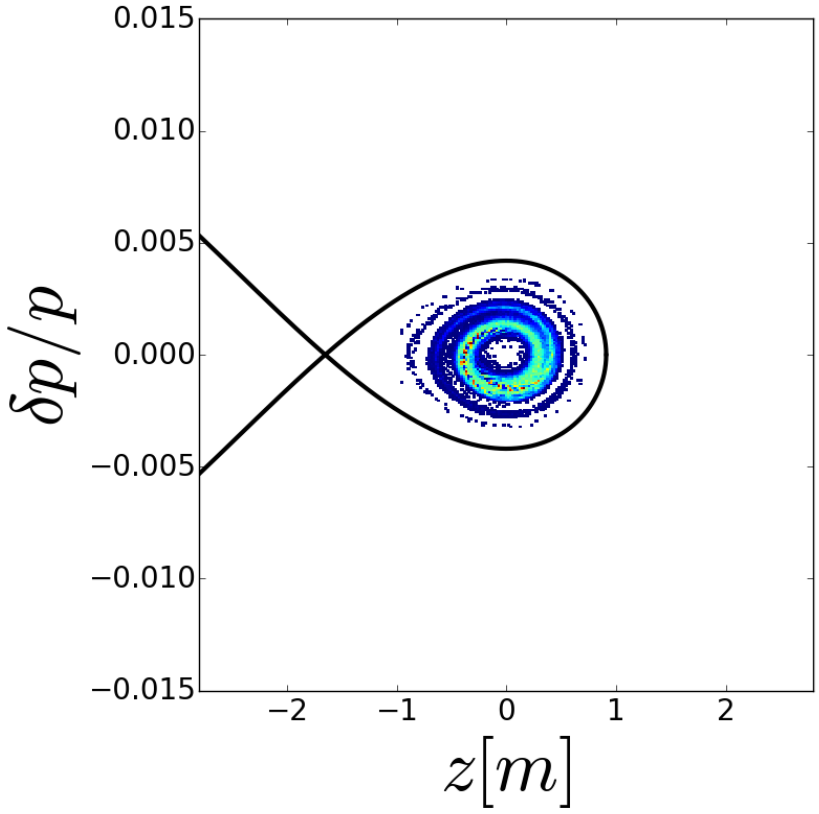






Gamma t jump


0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−2
−1
0
1
2
$\delta p/p$
$z[m]$


0.015
0.010
0.005
0.000
−0.005
−0.010
−0.015
−2
−1
0
1
2
$\delta p/p$
$z[m]$