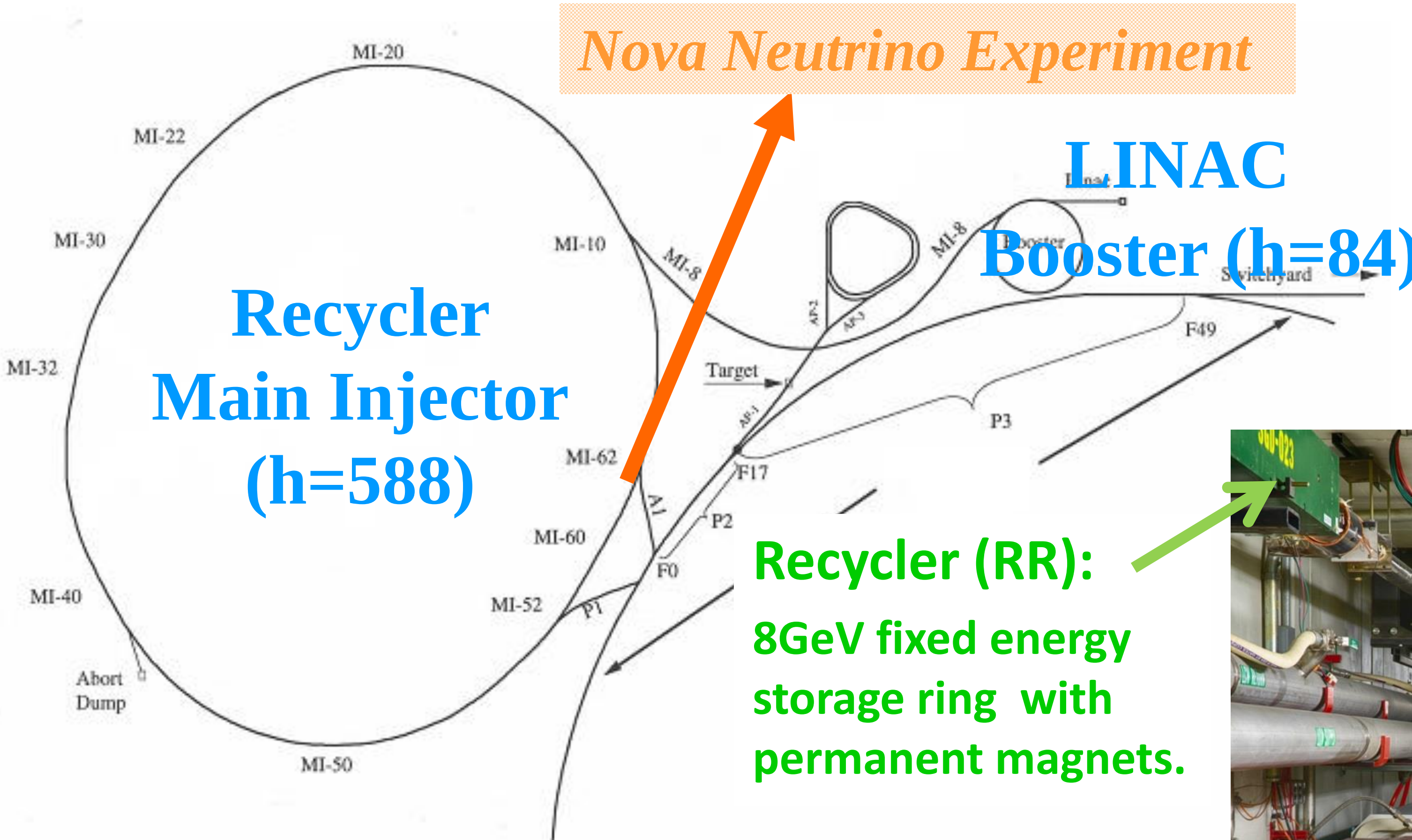
Booster upgrade for 700kW operation

November 11, 2014

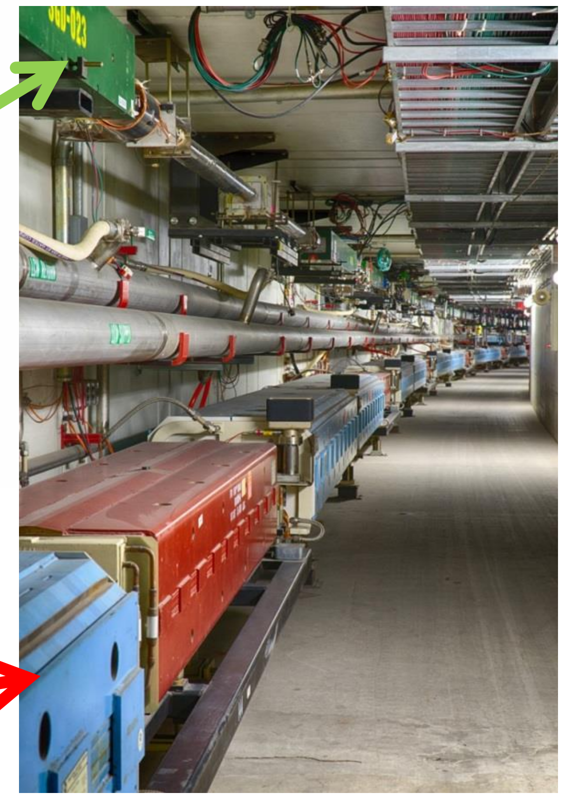
Kiyomi Seiya (Fermilab)

700 kW operation for Nova experiment



Recycler (RR):

8GeV fixed energy storage ring with permanent magnets.



400kW: Booster → MI

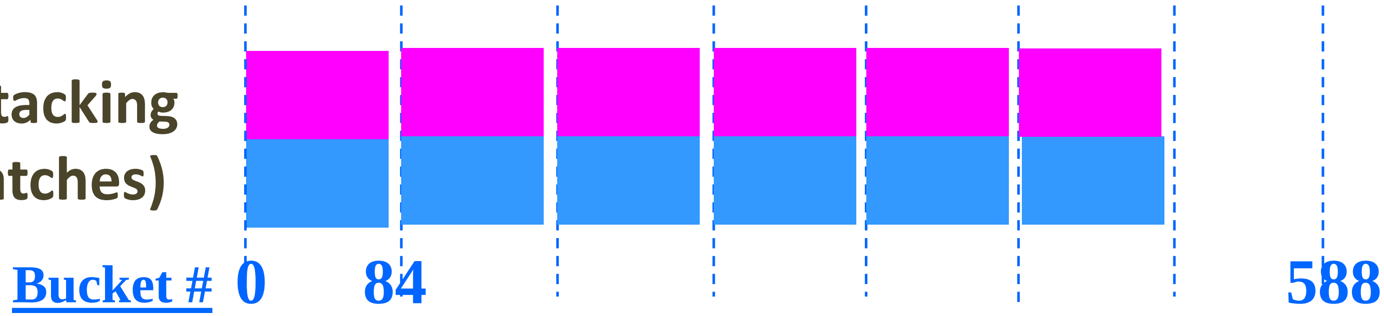
700kW: Booster → RR → MI

Main Injector (MI):

8GeV –120GeV

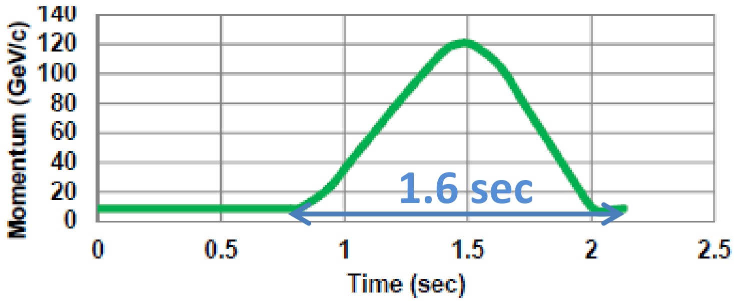
400 kW to 700 kW

**Injection & Slip stacking
(0.8 sec for 12 batches)**



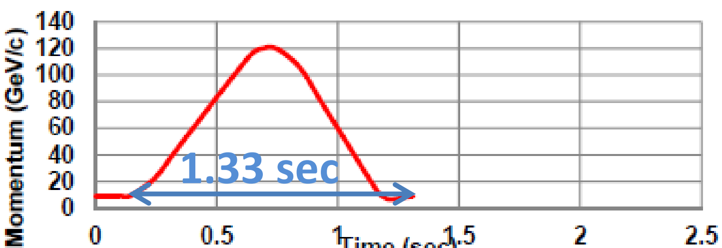
11 booster batches every 2.2sec

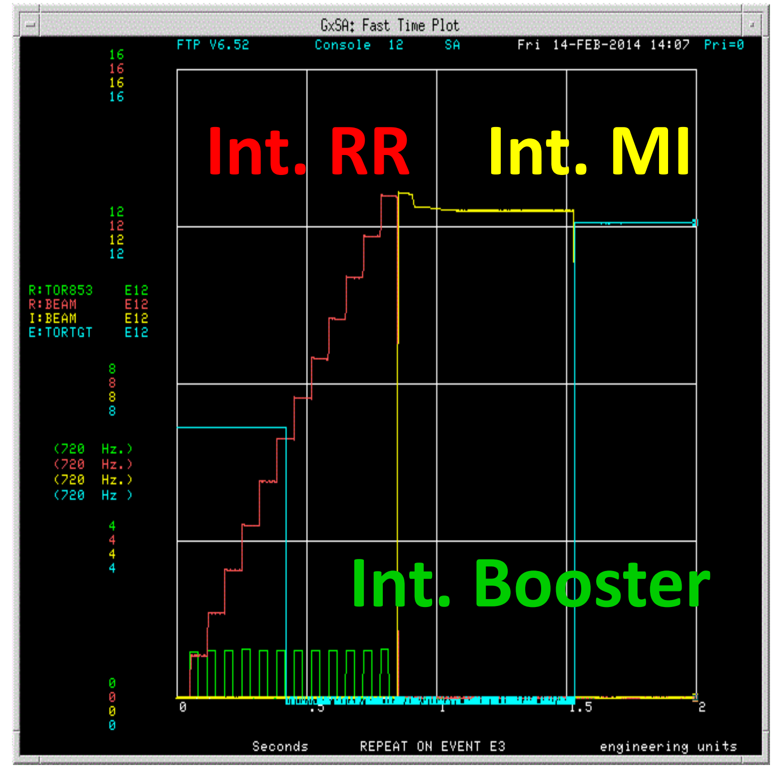
400kW



12 booster batches every 1.33sec

700kW

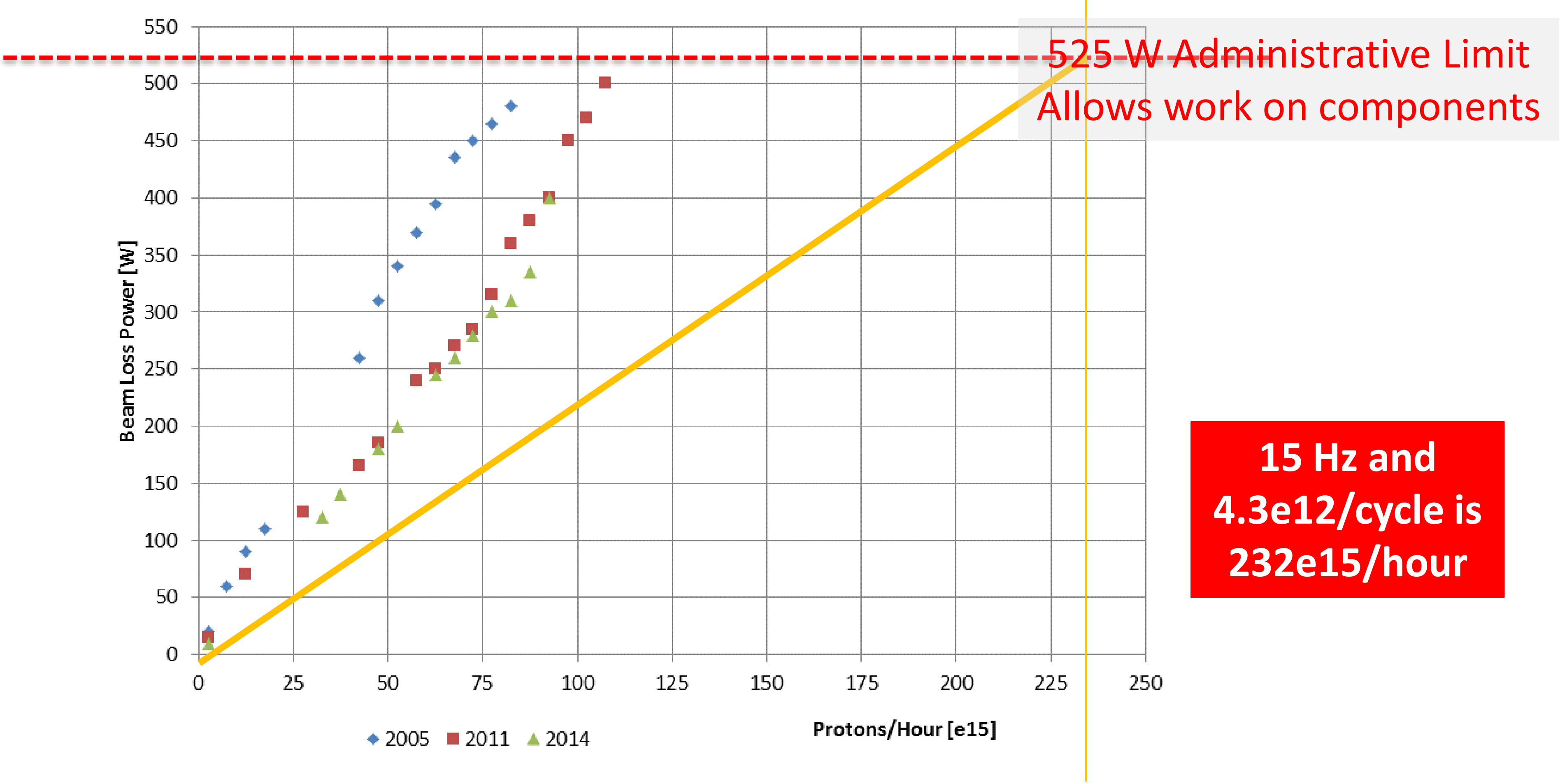




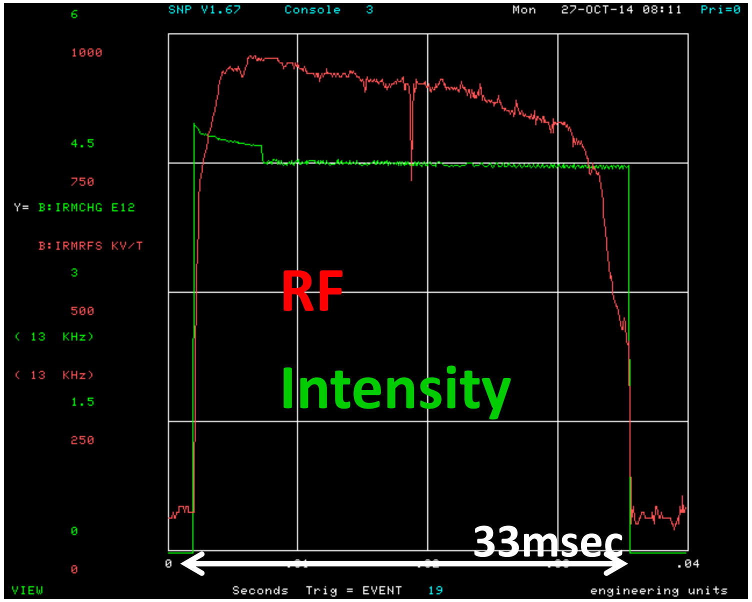
J. Eldred, "Slip-Stacking Dynamics and the 20 Hz Booster“, MOPAB12
J. Eldred, “New Intensity Induced Fast Transverse Instability in Fermilab Recycler.“, TH04LR04

Requirement for the Booster operation

- 4.3E12 ppp with 81 bunches to Recycler
- 9Hz to FULL 15Hz operation for entire Fermilab exp. program.
- Delivering 2.3E17 protons/hour (at 15 Hz) in 2016

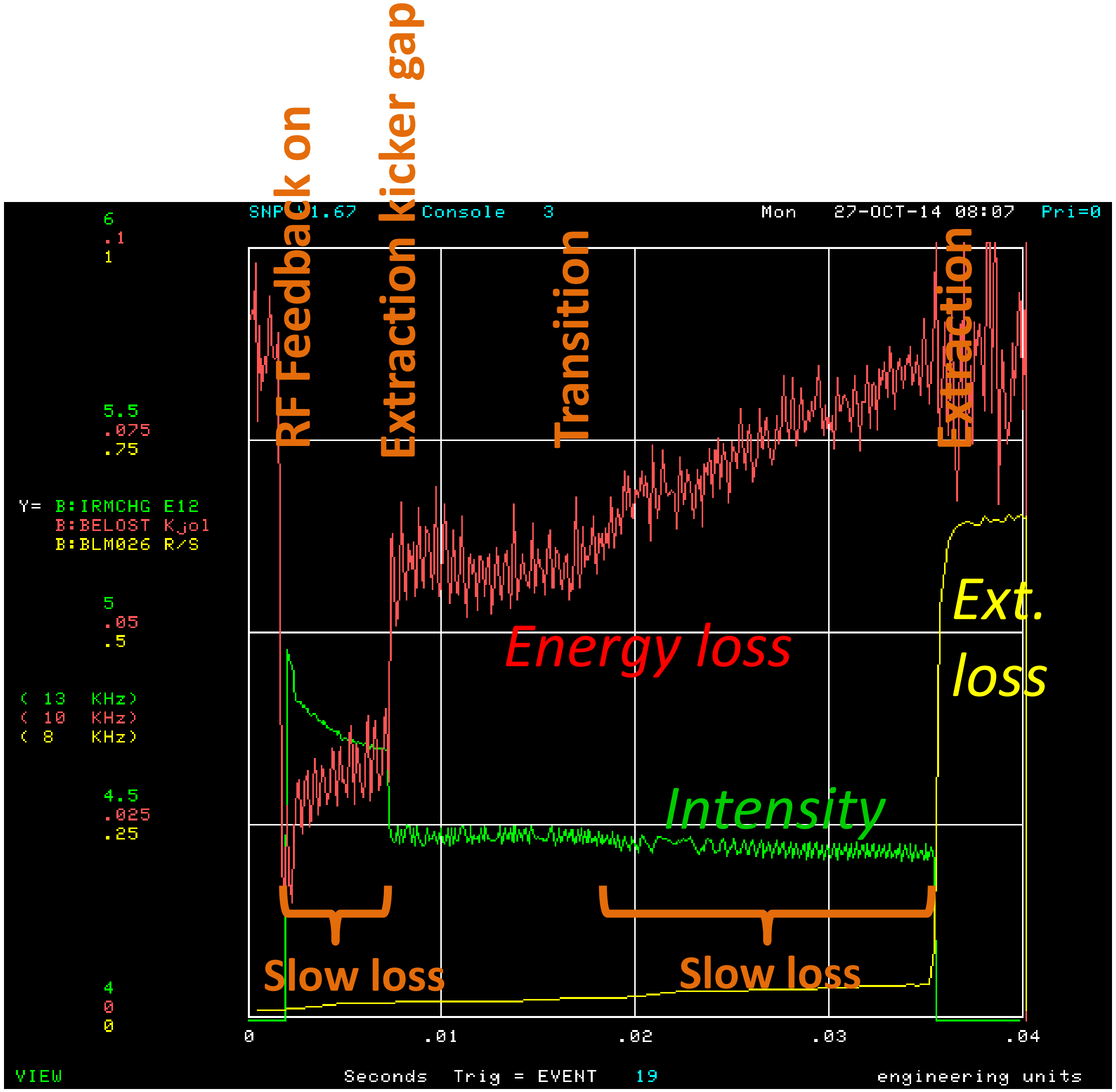


Operation status and beam loss



Int. at Injection: 5.0E12 ppp
Int. at Extraction: 4.5E12 ppp
Efficiency: 90%

Energy: 400 MeV – 8GeV
RF freq. : 37.9 – 52.8MHz



Beam loss/cycle = 0.075 kJ → 1125W
(525 W Administrative Limit)

Booster upgrade and beam studies

Injection

- **Aperture scan and Magnet move**
- **Injection rf capture**
- Harmonic cavity (*)

Notch

- **Cogging**
- Laser notch (*)

Transition

- RF refurbishment (*)

Slow loss

- Transverse bunch by bunch damper
- **LOCO orbit control**
- **Tune measurements and control**

Extraction

- Notcher (*)

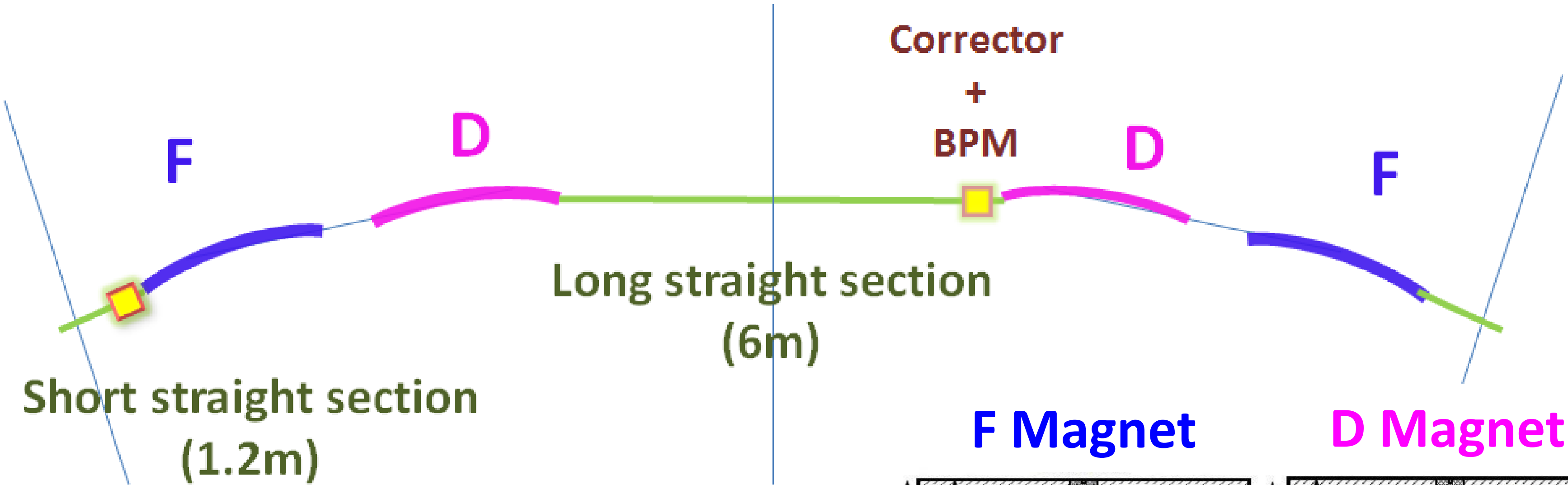
Loss control

- **Total loss monitor (TLM)**
- Notch absorber(*)
- Collimator(*)

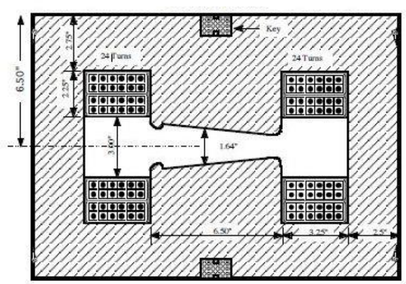
LLRF and Instrumentations

* R. Zwaska,
"Enhancement of the Fermilab Booster to reduce Losses and Extend the Lifetime: The Proton Improvement Plan", TU01AB03

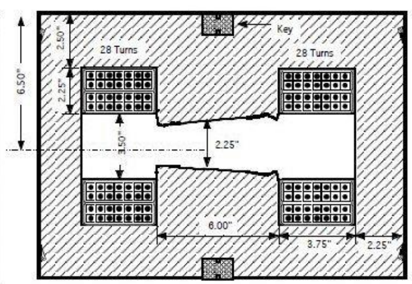
Booster FDOODF lattice



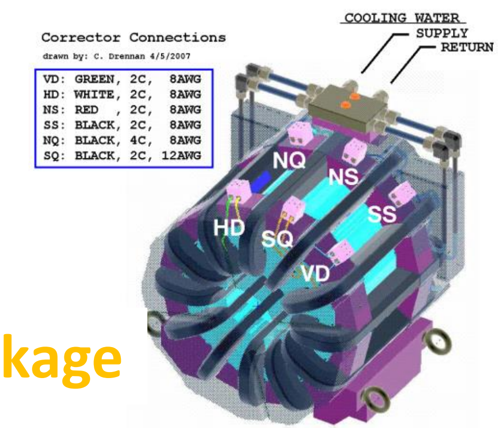
F Magnet



D Magnet

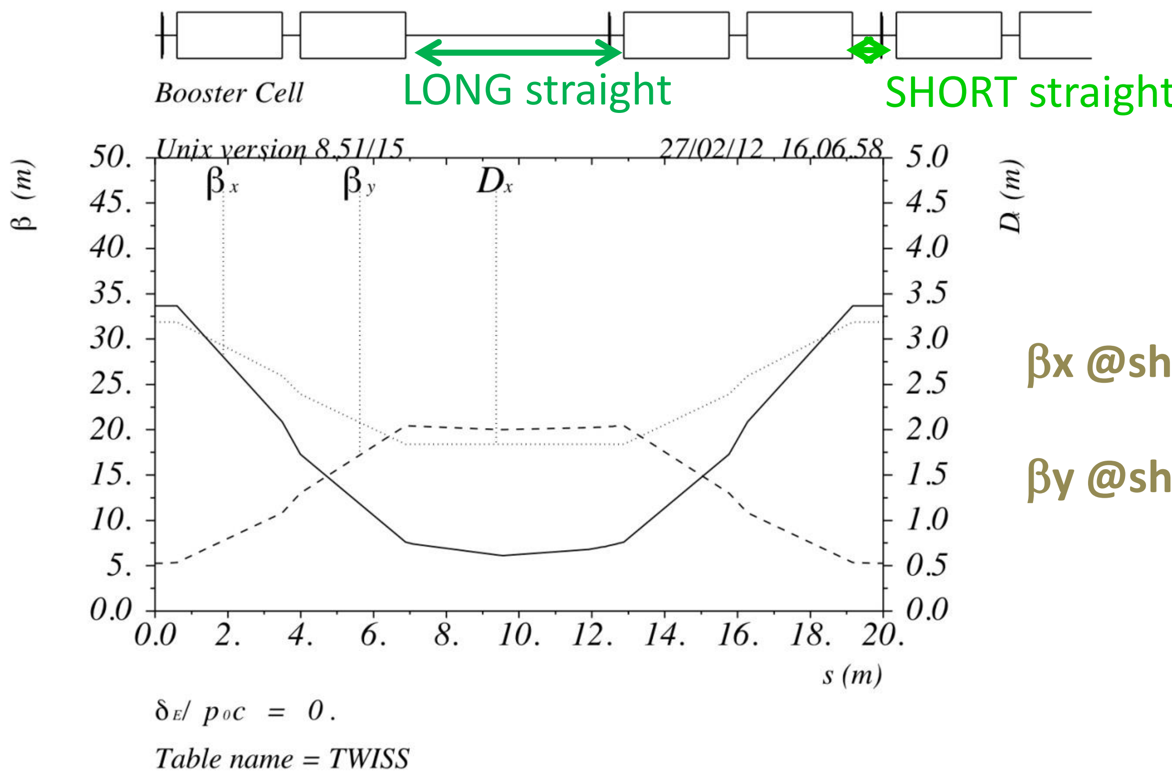


- FDOODF x 24 periods
- Combined function magnets: F, D
- Corrector packages at short and log
- Corrector package (12 poles) includes
  H & V dipoles, quad, skew quad, sextupole, skew sextupole and H & V BPMs.



Corrector Package

H/V beam size at short and long straight sections



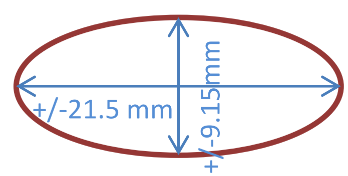
βx @short = 33.7 βx @long = 6.1

βy @short = 5.3 βy @short = 20.4

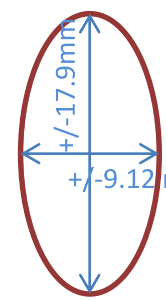
beam size

H_emittance(95%) = 14π mmmrad
V_emittance(95%) = 16 π mmmrad

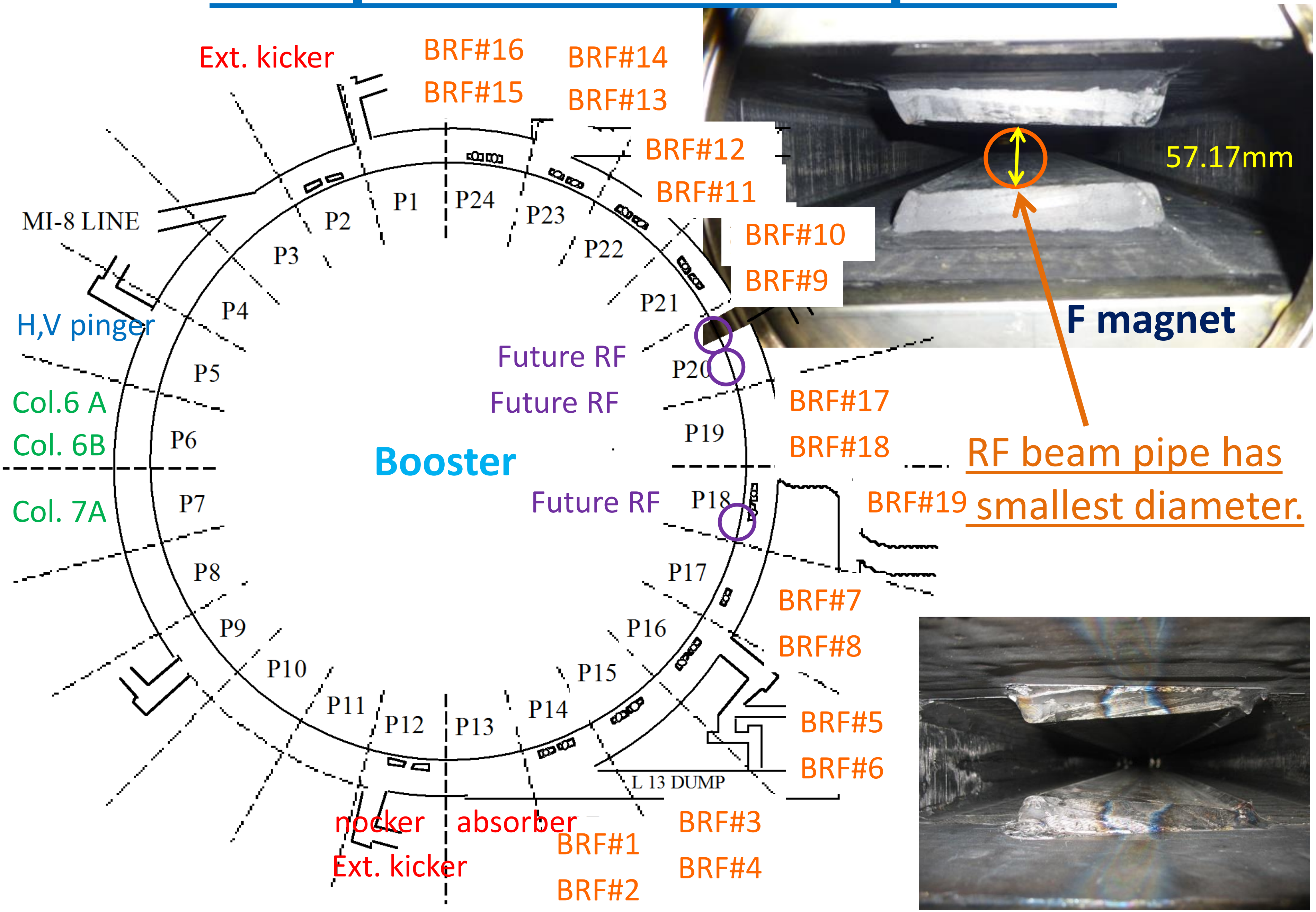
@ SHORT straight



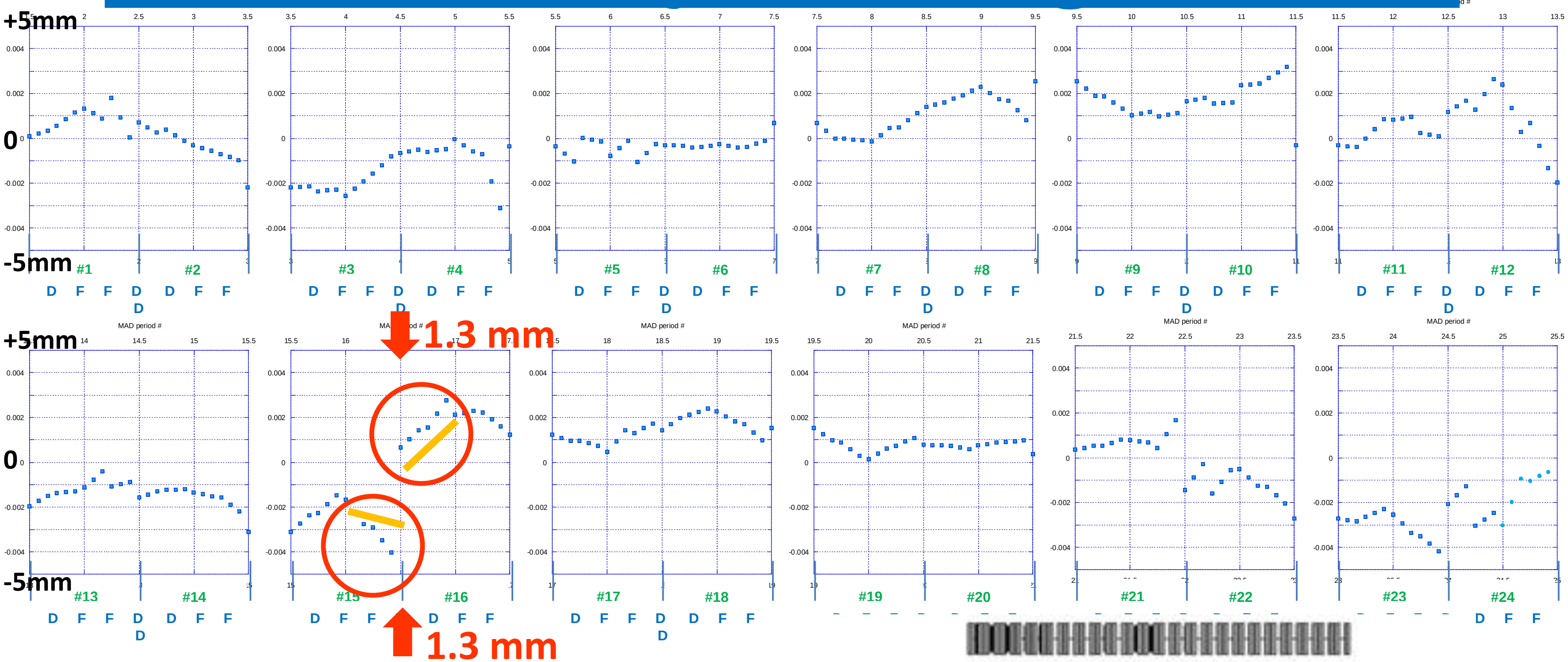
@ LONG straight



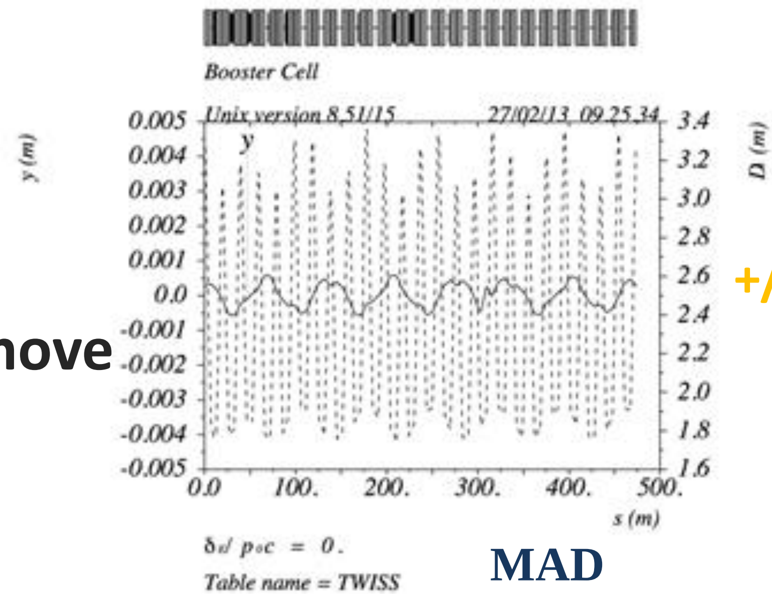
Components restrict aperture



Vertical survey and Magnet move



Calculated vertical orbit difference between before and after magnet move

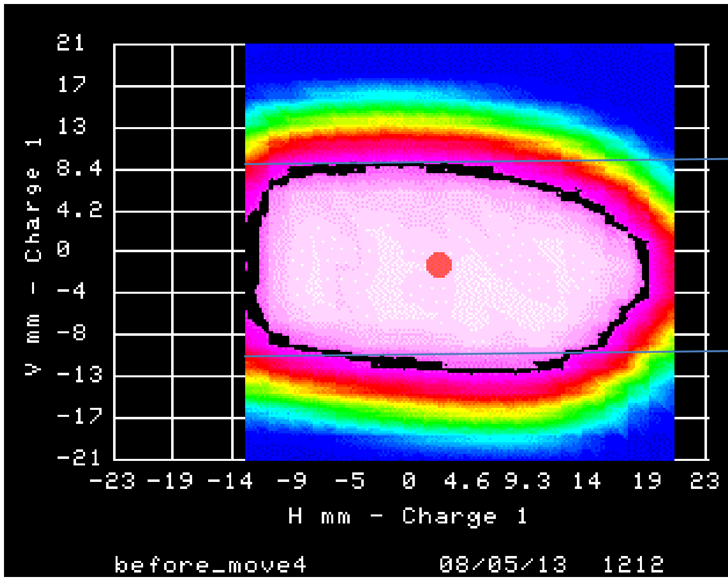


+/-0.6mm

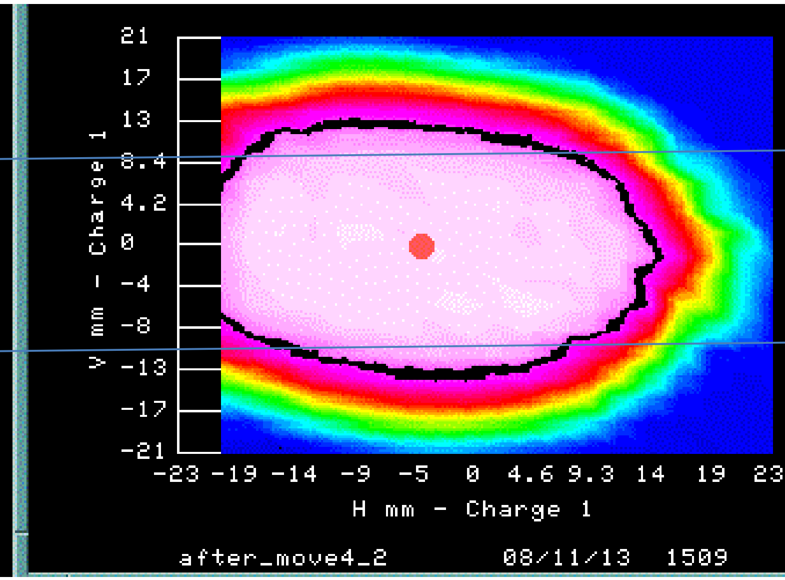
MAD

Aperture scan at L16

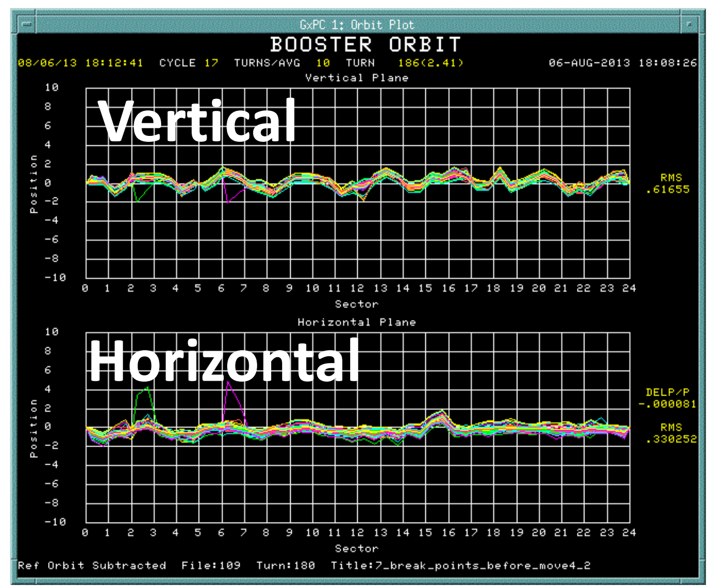
Before Move4



After Move4

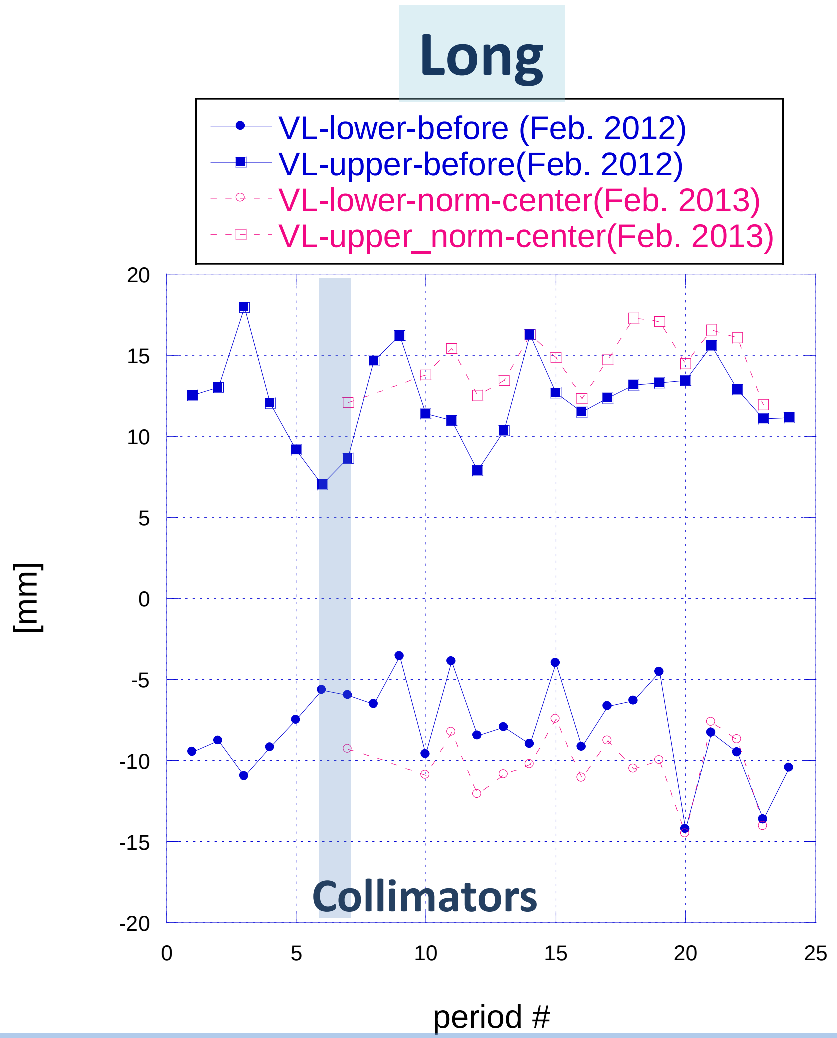


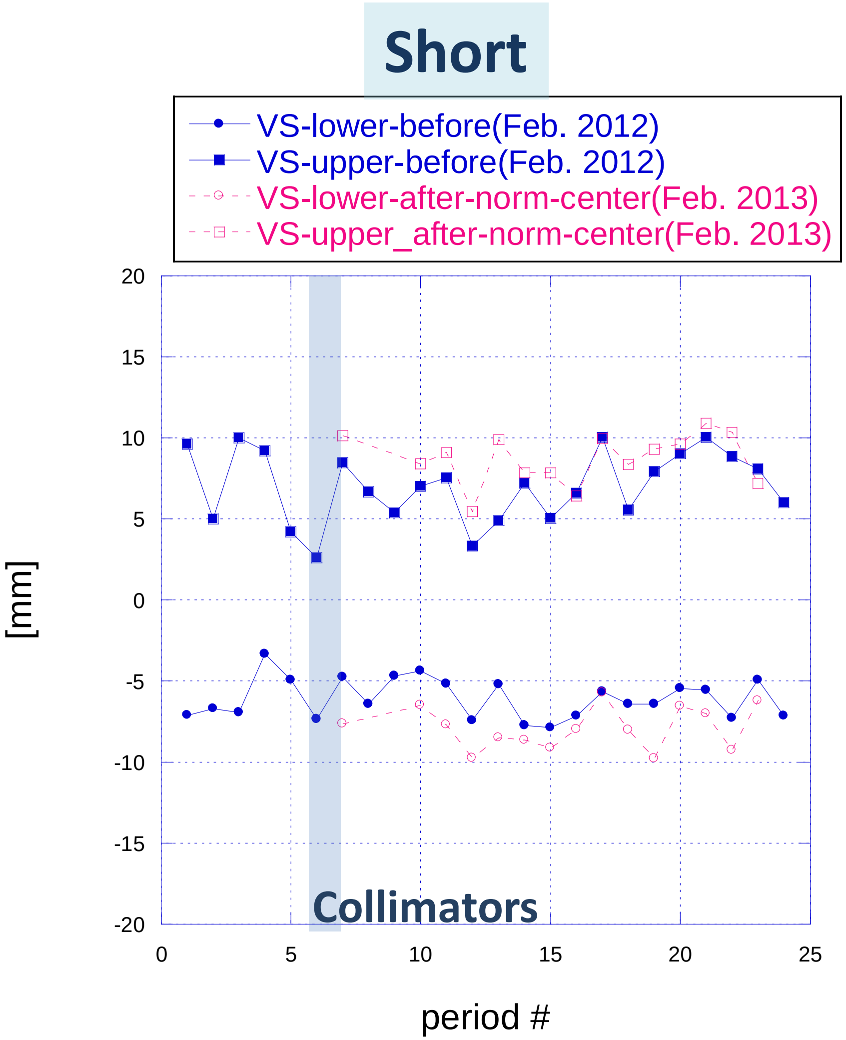
Orbit difference between before and after Move4



+/-0.8mm

Aperture (90%) before and after alignment

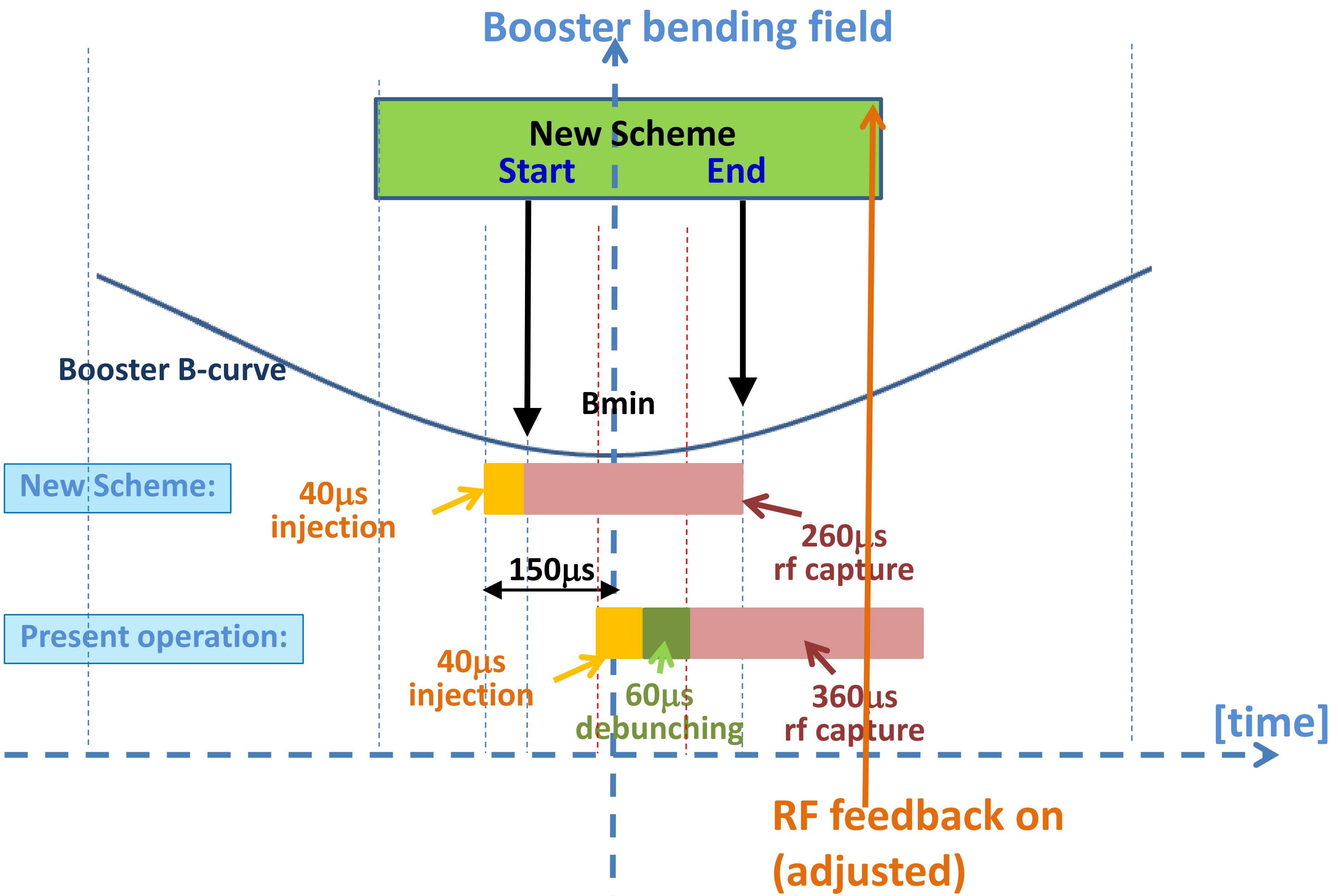




The next step will be

optimizing the collimator settings

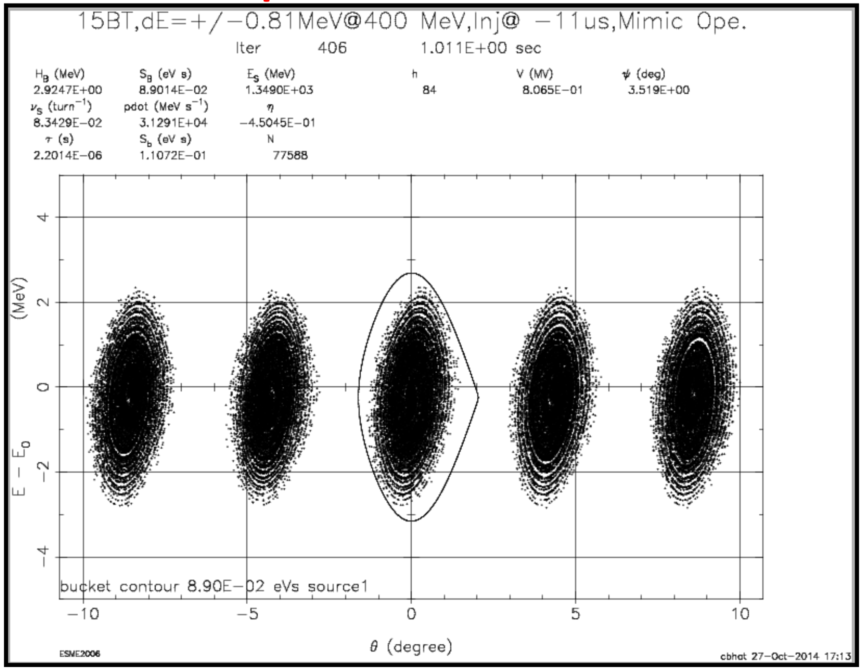
Injection rf capture



Injection rf capture simulation

dE/E @ Inj= ±0.8 MeV (Measured)

Operational Scheme



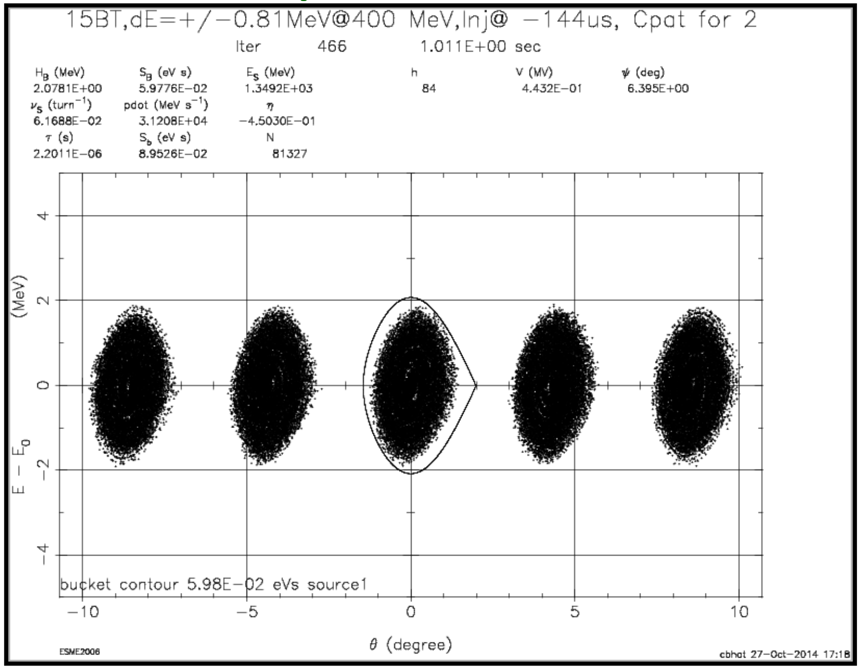
Vrf (@400 μs) = 0.81 MV

Bucket Area = 0.09 eVs

ε_l = 0.07 eVs

~4% Beam loss

Proposed Scheme:



Vrf (@400 μs) = 0.44 MV

Bucket Area=0.06 eVs

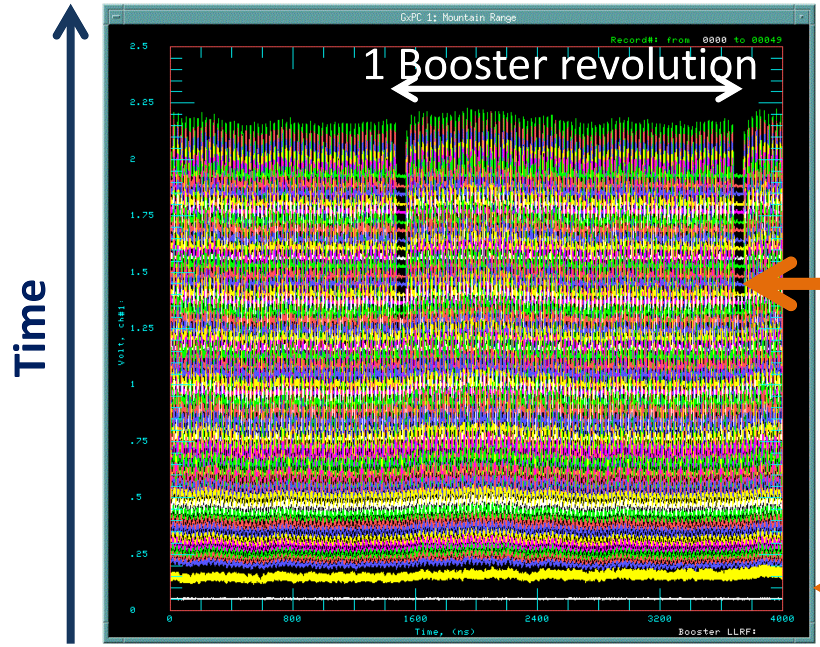
ε_l = 0.05 eVs

No Beam loss

~30% lower rf power on average over the cycle

Preparing timing and rf curves for the beam studies.

Beam at Booster Injection



Notch @ 700MeV

→ 81 bunches + 3 empty buckets

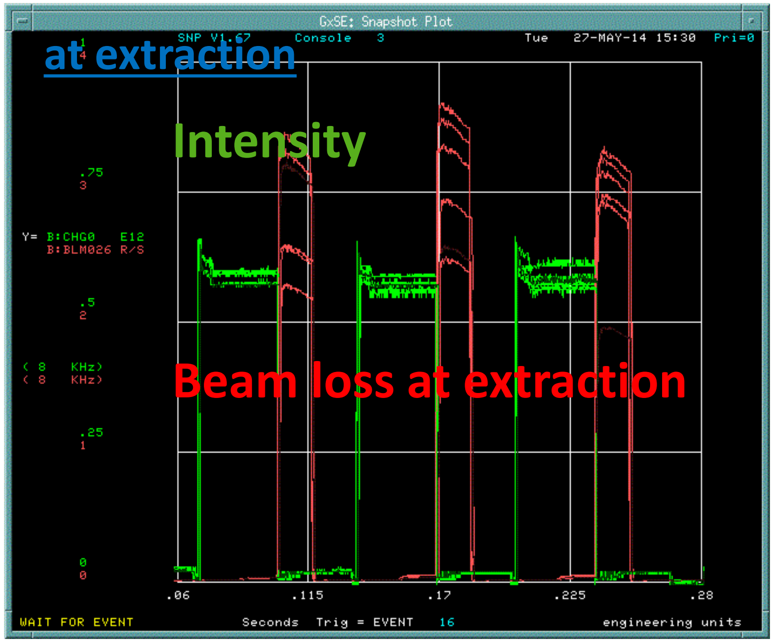
Adiabatic capture with 37MHz RF

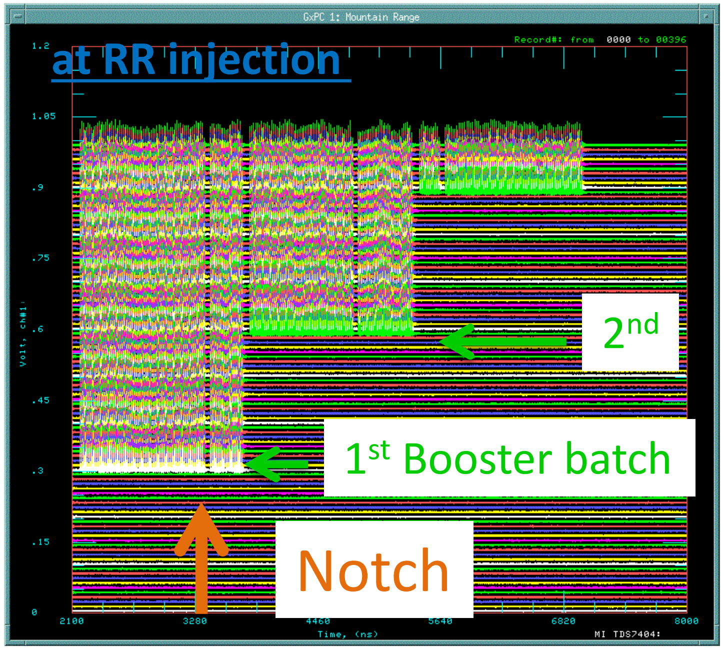
→ 84 bunches

Injection from LINAC @ 400MeV

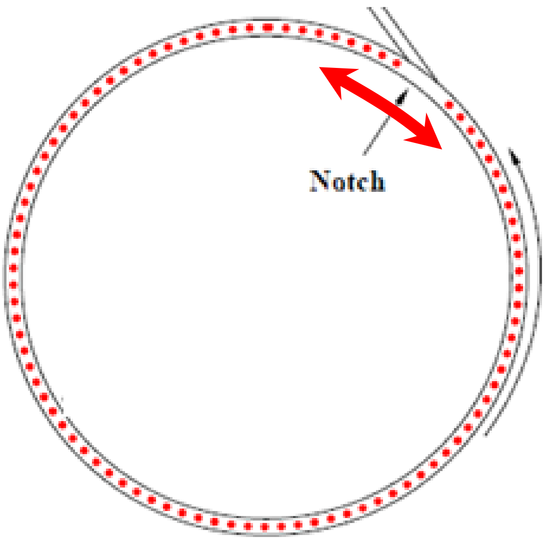
Beam w/o cogging

Lost 3 bunches every Booster extraction.





Revolution frequency control with Radial Cogging

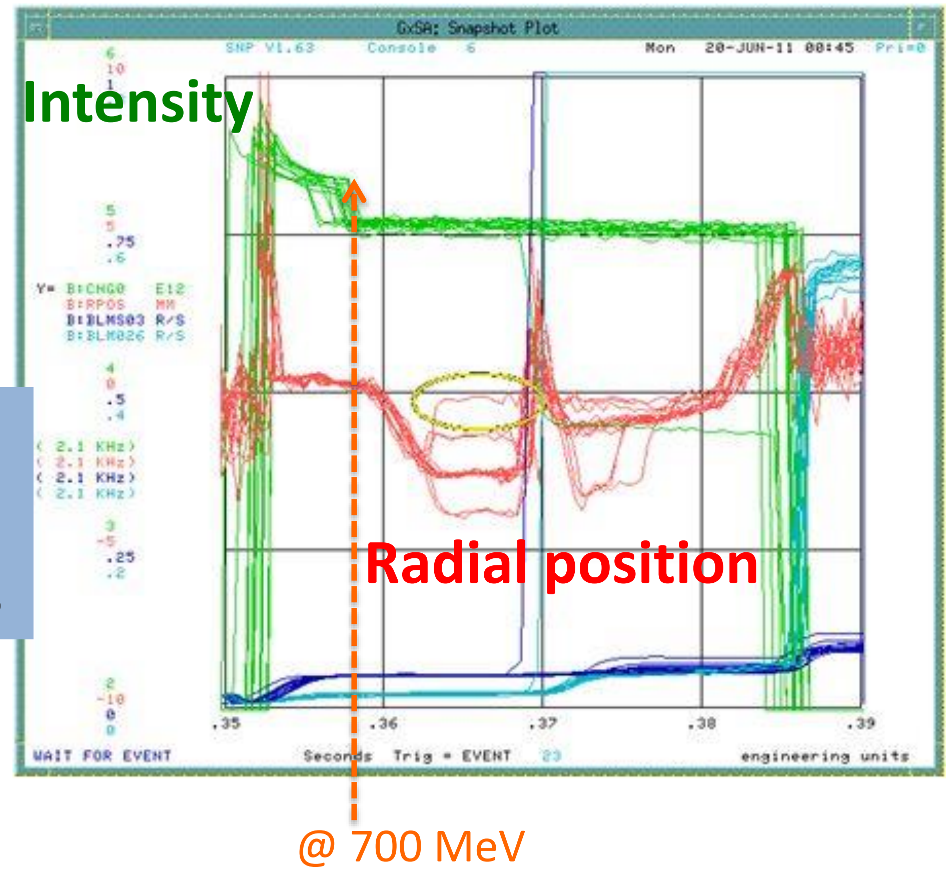


$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{\Delta P}{P} - \underline{\frac{\Delta L}{L}}$$

Path length (radial position) of the beam

Creates notch at 700MeV.

Moves orbit before/after transition.



Magnetic Cogging using 48 dipole corrector magnets

$$\frac{\Delta f_{rev}}{f_{rev}} = \frac{1}{\gamma^2}\frac{\Delta P}{P} - \frac{\Delta L}{L}$$

Fixed with RPOS feedback

$$= \frac{1}{\gamma^2}\frac{\Delta B}{B}$$

Changed by dipole corrector
Dipole corrector: 0.009[T-m] @ 24.4[A]

$$\frac{\Delta B\ell_{max}}{B \times 2\pi\rho} = \frac{0.009[T \cdot m] \times 48 \times 10[A]/24.4[A]}{0.042[T] \times 2\pi \times 75.75[m]}$$

$$= \mathbf{0.0088}$$ (Assuming 10[A] change)

B field error ~1% can be compensated.

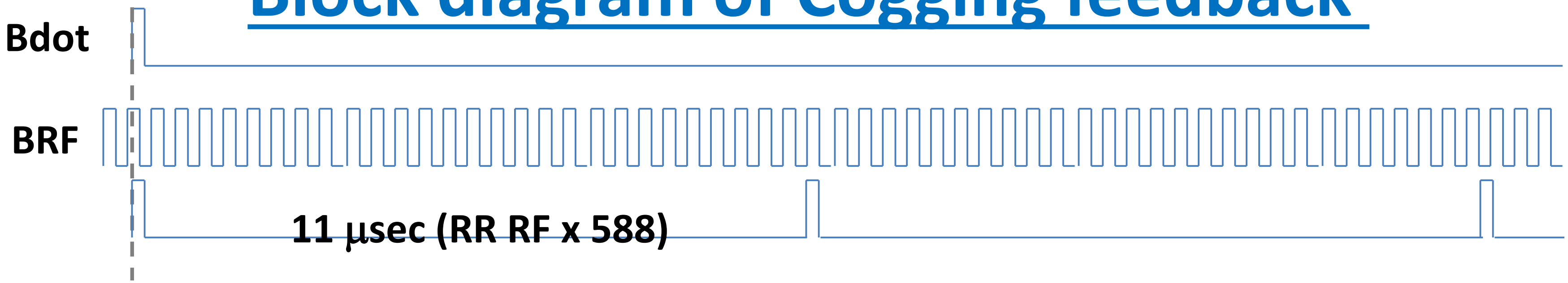
Keeps beam on central orbit and save aperture.

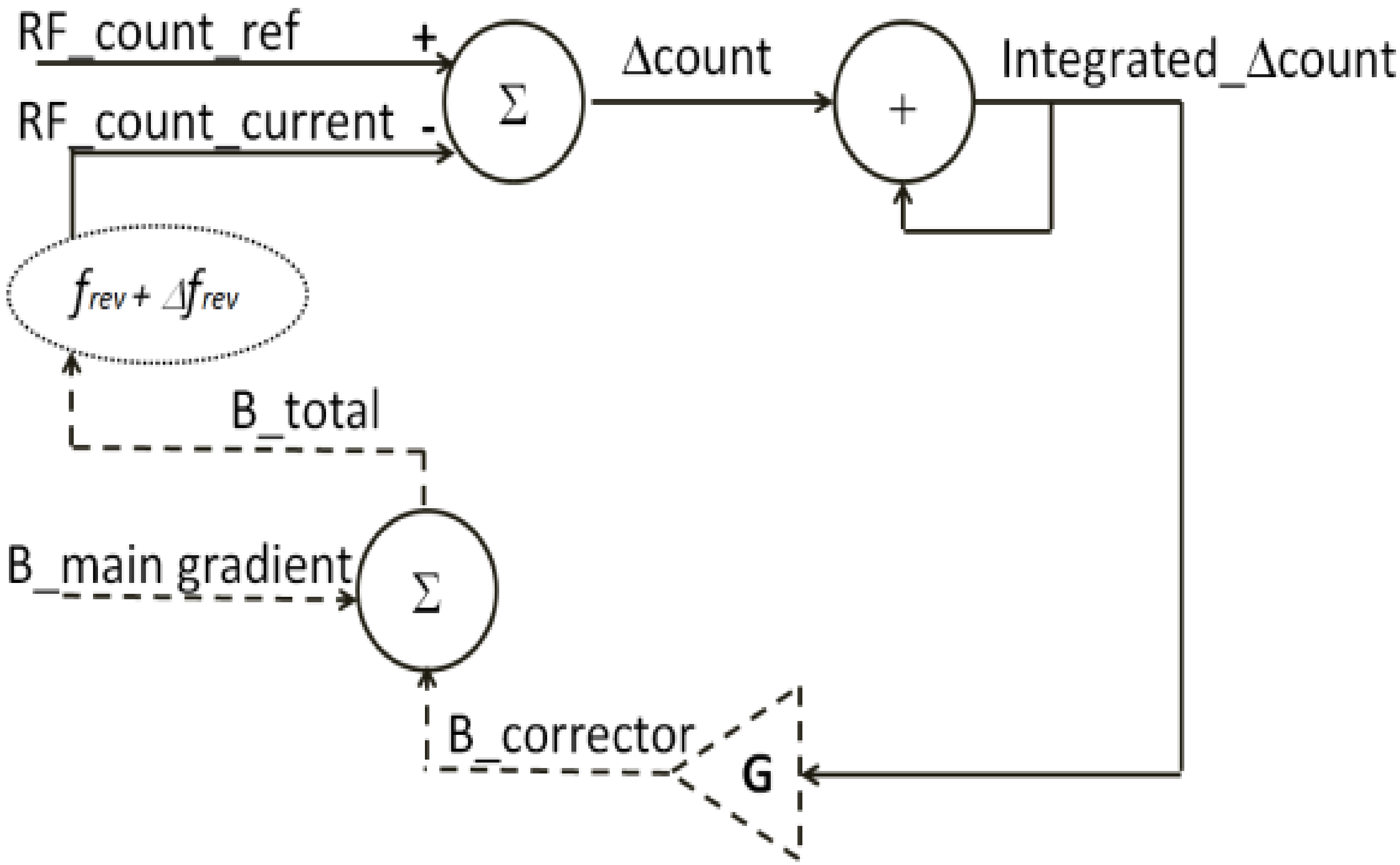
Creates notch anytime after injection

→ reduce beam power loss by 40%.

→ no loss with LINAC notch.

Block diagram of Cogging feedback

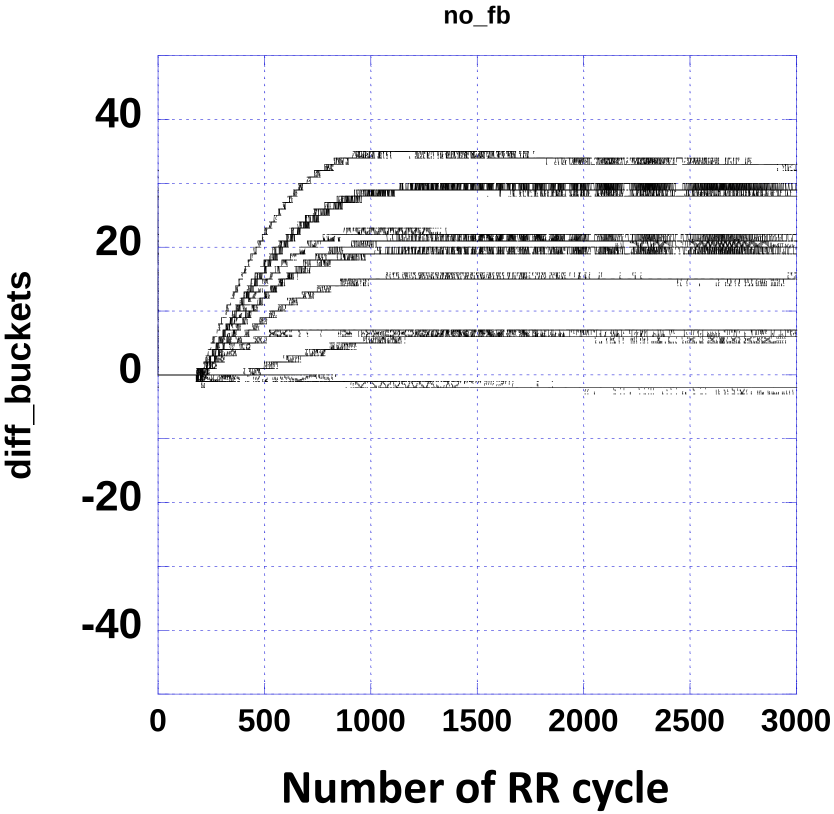




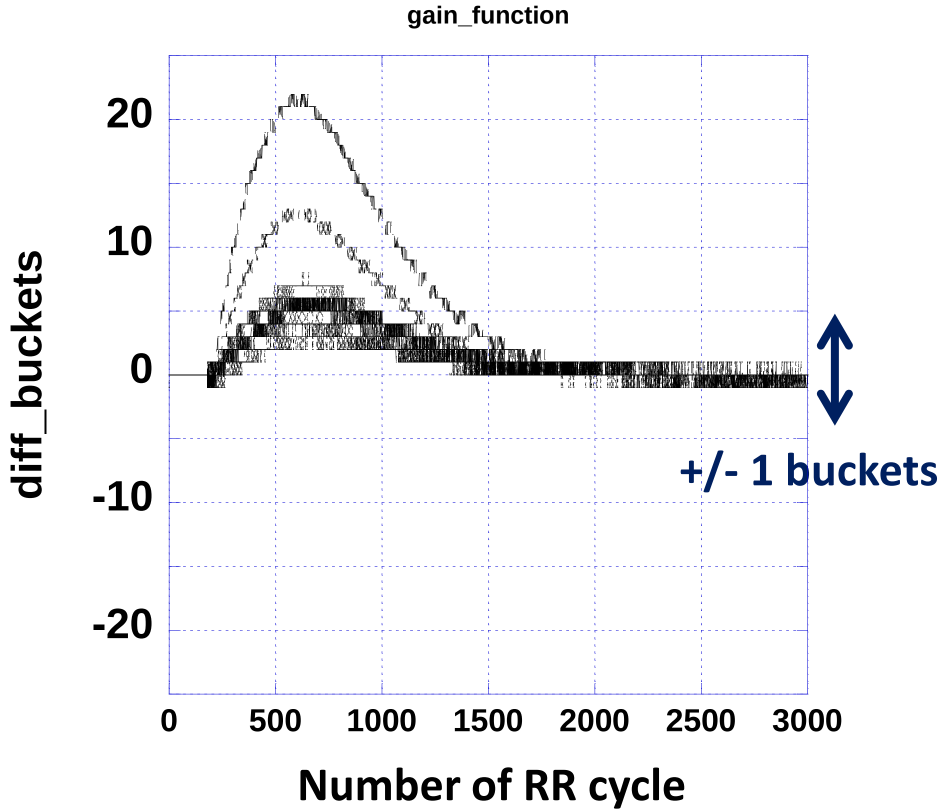
Integrated diff. bucket count has to be '0' at the end of cycle.

Optimization of the cogging feedback gain

without feedback



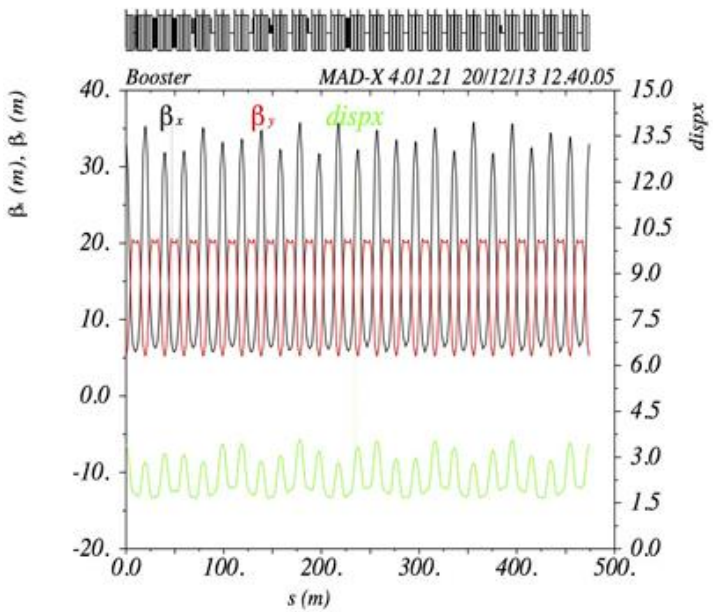
with feedback



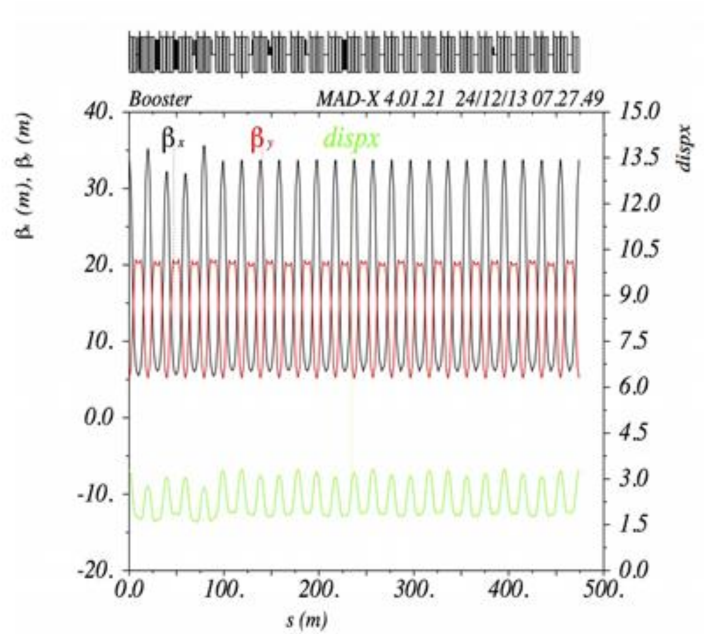
The resolution of the final bucket error will be reduced to +/- 0.5 bucket.
New cogging is going be operational by the end of this year.

Beam optics correction

Beta beating with injection bump



Ideal lattice



- Most of the beta errors come from the extraction bump at Long 3.
- Beta beating can be corrected with quad and skew quad.

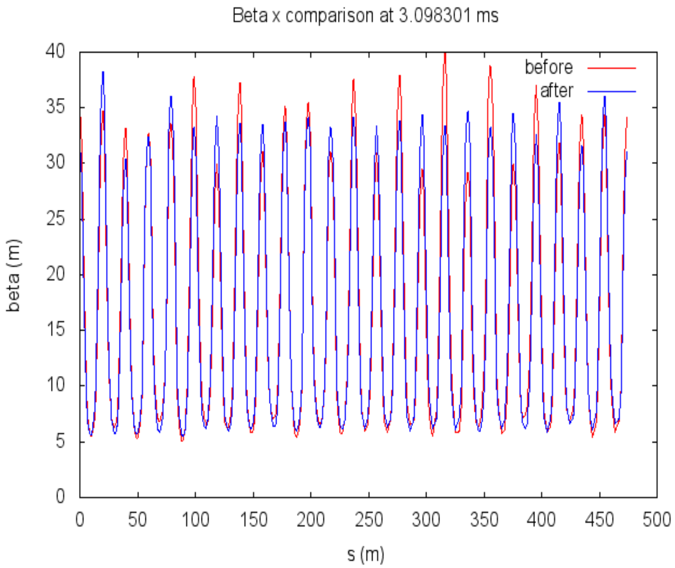
Beam optics correction with LOCO (Linear Optics from Closed Orbit)

- LOCO calculate quad and skew quad strength that make the measured lattice closer to the ideal lattice.
- Make a single kick with each dipole corrector and measure every BPM response.
- Change the kick angle by changing the dipole current.
- Calculate dx/dθ.

$$\chi^2 = \sum_{i,j} \left[\left(\frac{\Delta x_i}{\Delta \theta_j} \right)_{\text{measured}} - \left(\frac{\Delta x_i}{\Delta \theta_j} \right)_{\text{model}} \right]^2 \frac{1}{\sigma_{ij}^{\;2}}$$

- LOCO also calculates the rolls and calibrations of every BPM and dipole corrector.

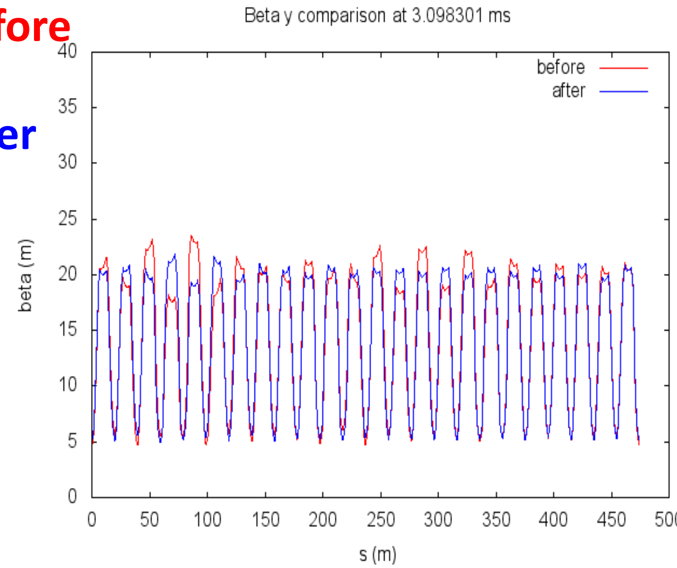
Measured H beta at injection



before

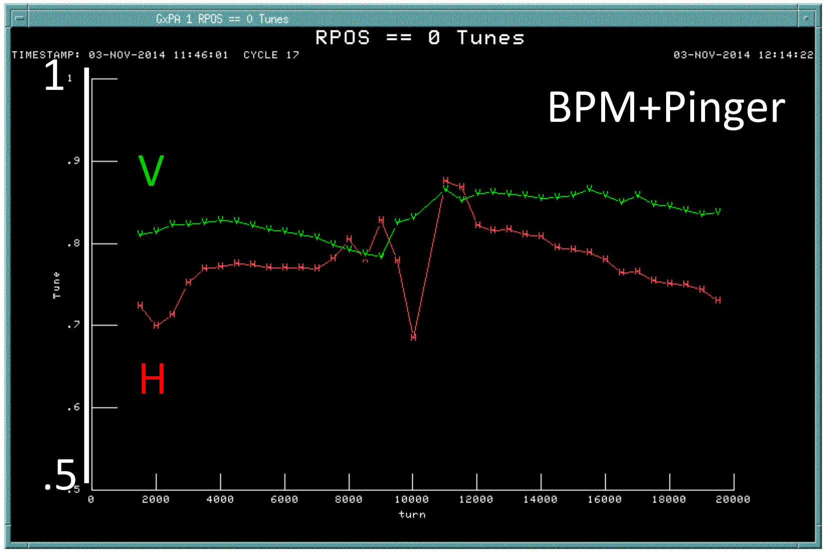
after

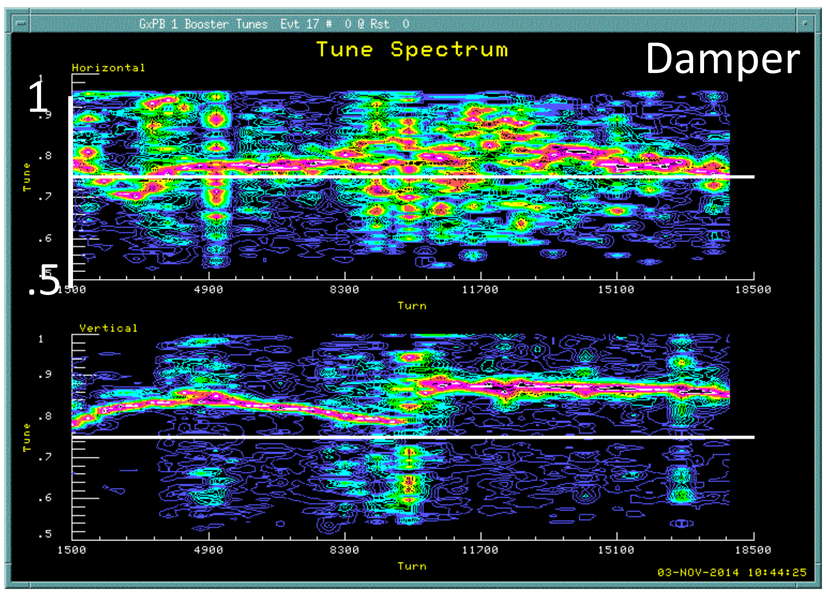
Measured V beta at injection



The beta errors were reduced around the ring.
Studies are continuing to incorporate these corrections into the operational lattice.

Tune measurement and control



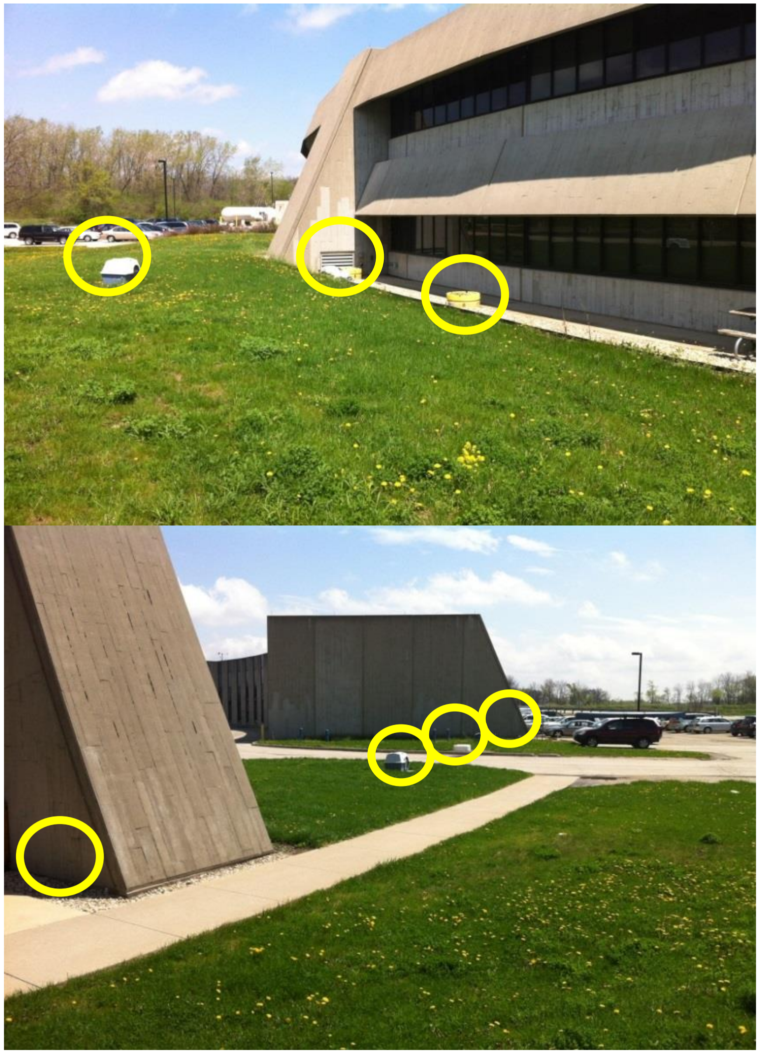


- Tune is able to measure with BPM turn by turn data from injection to extraction with exciting an oscillation every 500 turns using pinger.
- Tune bump with quadrupoles for a time slot.
- The coupling was corrected with skew quadrupoles.
- Present tune monitor excites large amount of oscillation and can cause beam loss.
- New tune meter uses horizontal bunch by bunch damper.

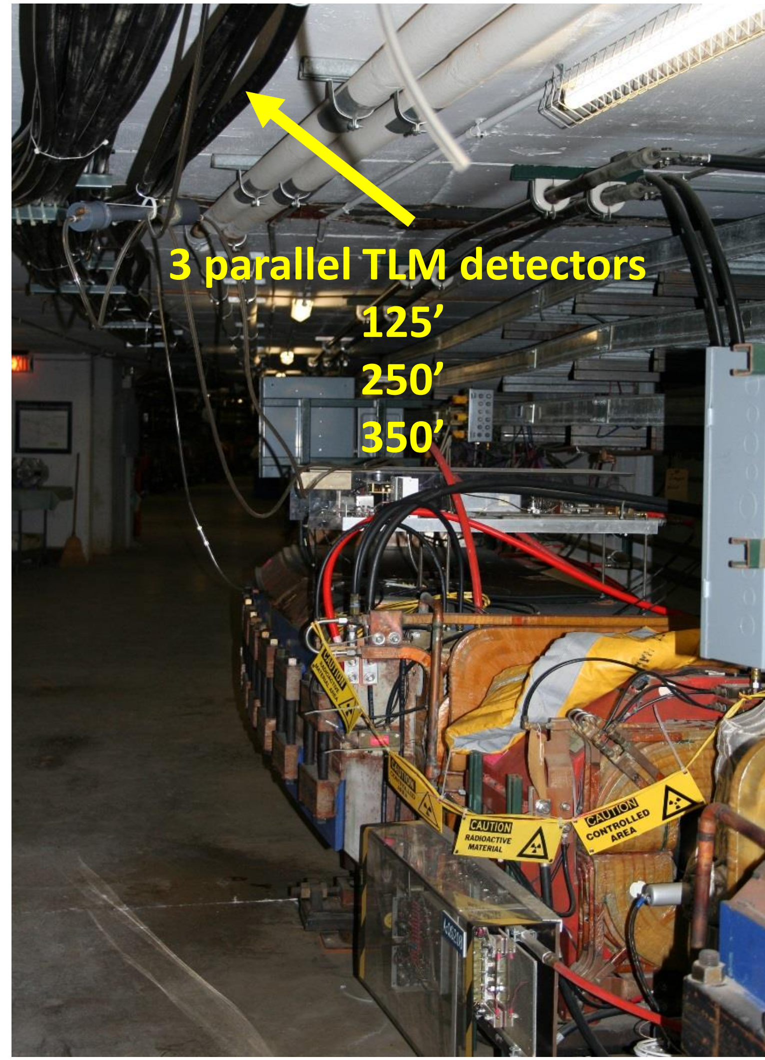
Plan: Tune and coupling corrections at high intensity using new tune meter.

Radiation safety system with TLM (Total Loss Monitor)

Chipmunks (Ion gas monitor)



TLM (long detector)



Radiation safety system with TLM (Total Loss Monitor)

Chipmunk (Ion gas monitor):

Covers discrete locations

High cost

Small dynamic range

Can’t be installed in the tunnel because of the radiation damage.

TLM

Coaxial cable filled with $ArCO_2$ gas.

Single detector can cover very large region.

Relatively inexpensive.

The detectors are in the tunnel and all electronics are outside.

Beam studies to characterize TLM response under a wide variety of beam loss conditions are ongoing.

LLRF and Instrumentation upgrades

Motivation

- **Booster has been operating since 1971 and many low level modules were developed in the 1980's and have component obsolescence issues.**
- **Upgrades will provide more precision and flexibility.**

Longitudinal Damper

8 mode dampers after transition.

LLRF

Phase lock to the MI/RR

LLRF frequency source

Phase shift

BPM

Capable to measure 200 MHz injection beam

Summary

Injection

- **Aperture scan and Magnet move**
- **Injection rf capture**
- Harmonic cavity

Notch

- **Cogging**
- Laser notch

Transition

- RF refurbishment

Slow loss

- Transverse bunch by bunch Damper
- **LOCO orbit control**
- **Tune measurements and control**

Extraction

- Notcher

Loss control

- **Total loss monitor**
- Notch absorber
- Collimator

LLRF and Instrumentations

The Booster cycle rate of 15 Hz and averaging 4.3E12 protons per pulse will be completed by 2016.

The beam loss has to be reduced by half compared to the present situation.

The ongoing PIP beam studies along with hardware and software upgrades are critical.