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Proton Expectations

Paul Derwent

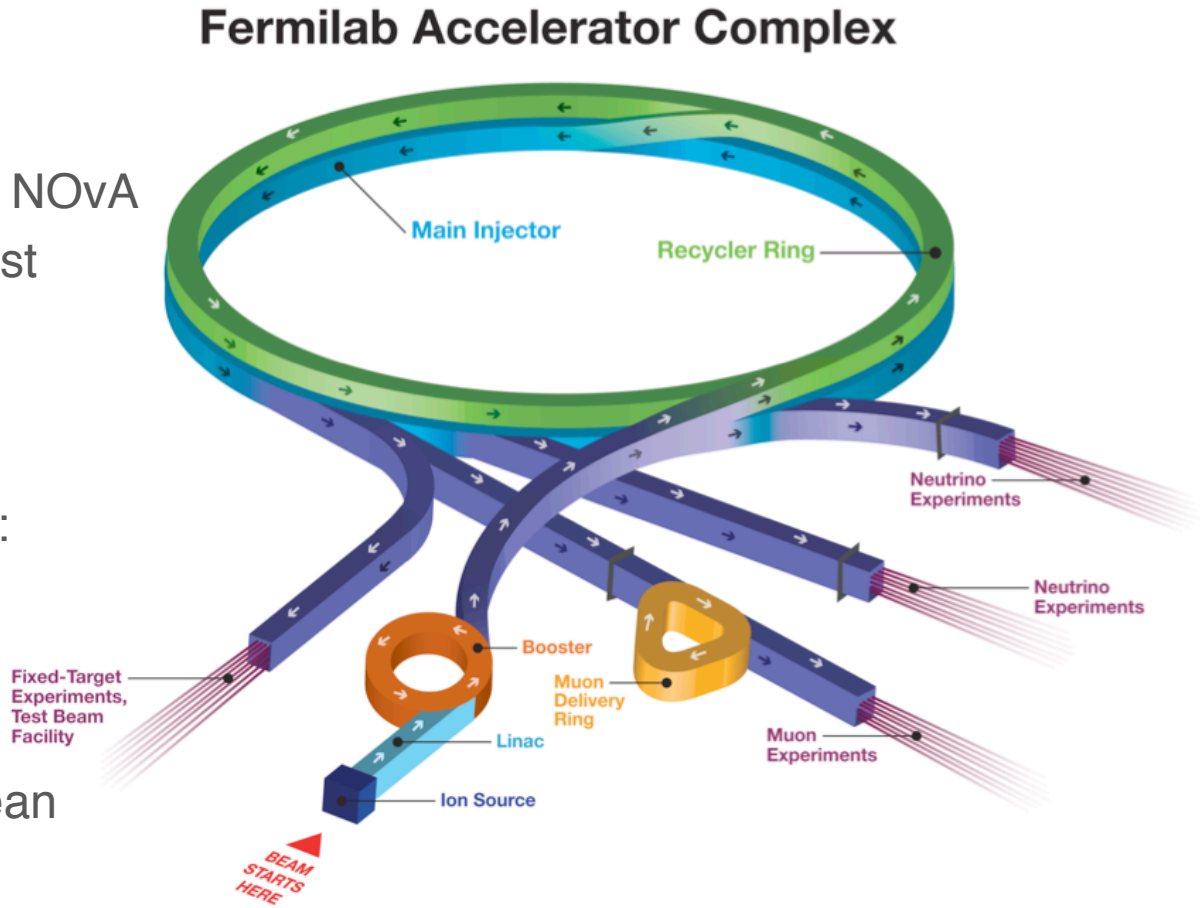
Fermilab Institutional Review

February 10-13, 2015

Fermilab Accelerator Complex

- Linac: MTA (MAP program)
- BNB: MicroBooNE
- NuMI: MINOS+, MINERvA, NOvA
- Fixed Target: SeaQuest, Test Beam Facility, M-Center
- Muon: g-2, Mu2e (future)

- Also, test and R&D facilities:
- ASTA (ILC CM)
- PXIE (PIP-II)
- CMTF (LCLS-II)
- Various cryo test stands, clean rooms



Proton Requests

- NuMI Program
  - NOvA 3.6e21 POT, 120 GeV (NOvA TDR, p. 1-2)
- BNB Program
  - MicroBoone 6.6e20, 8 GeV (MicroBoone TDR, p. 8)
- Muon Campus Program
  - g-2 3e20, 8 GeV (g-2 TDR p. 120)
  - Mu2e 3.6e20, 8 GeV (Mu2e TDR p. 3-44)
- SY120 Program
  - SeaQuest 5e18, 120 GeV (E906 Proposal, p. 25)
  - Test Beam Facility: various

Interactions and Constraints

- build TIMELINE – sequence of accelerator cycles to distribute beam to experiments
  - NuMI: minimum of 1.333 seconds (MI ramp), 20 Booster Ticks (15 Hz)
    - can send beam to BNB or Muon Campus during cycle
    - 12 Booster batches is TDR
  - SY120: 5.867 seconds (4 second spill)
    - can send beam to BNB during cycle
    - cannot send beam to NuMI or Muon Campus during cycle
  - Muon Campus:
    - Cycles in the Recycler Ring around the beam for NuMI
  - BNB: limited to 5 Hz
    - maximum rate for the current horn design
    - but can run under the SY120
- important in distribution of protons between the programs

Beam to Muon Campus

- Recently discovered issues with Muon Campus beam delivery models as described in TDRs
  - Timing and clock events: 7 not 8 available Booster ticks in the Recycler Ring
  - Task Force (led by E. Prebys) assigned to document and understand the issues:
    - Preliminary report at the PPMG Thursday February 5th
    - Simple Answer: RR Slip Stacking takes 13 ticks
    - Experiments have realistic proposals for 21 tick timelines
      - 20 tick timelines have significant impacts on both experiments
    - Provided several options with impacts to the PPMG
    - Discussions ongoing
  - Discovery has led to changes in process of discussion and approval (see S. Geer presentation)

Current high power operation and plans

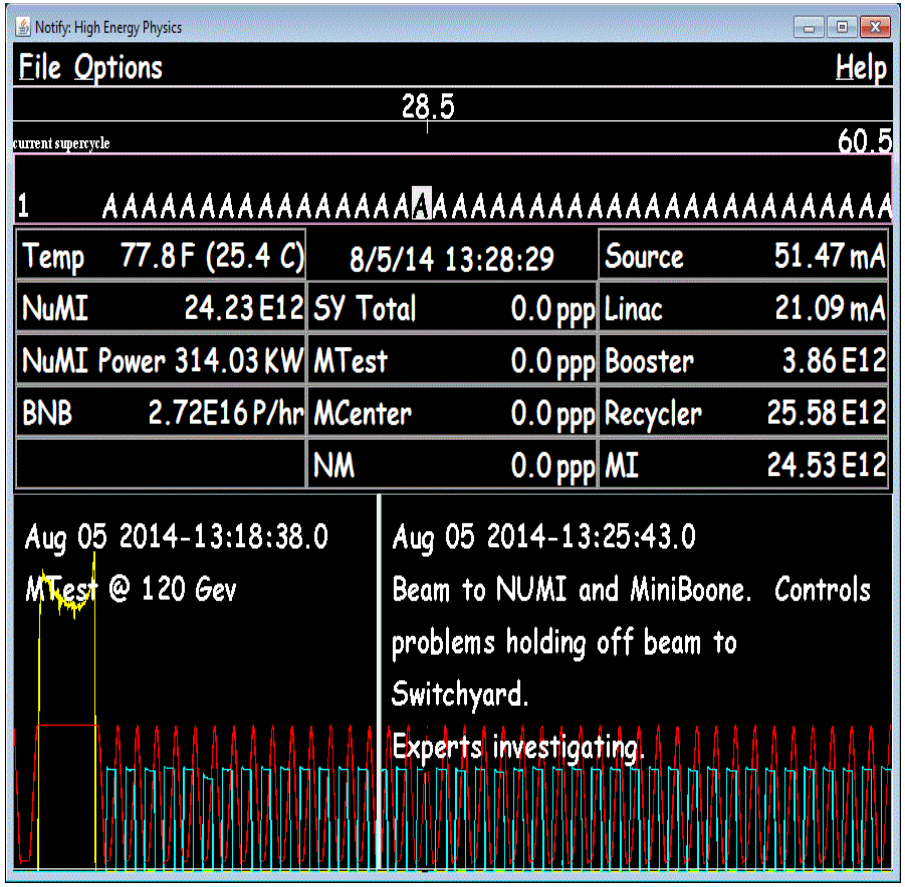
- We are delivering 2.5E13 ppp every 1.333sec by using the Recycler as a proton stacker (6 batches, no slip stacking)
  - 350 kW beam power (315 kW with SY120)
  - Booster limited to ~7.5 Hz pulses with beam by RF Cavities
- Working on commissioning 2+6 operation, achieving 450 kW of beam power.
  - Requires 6 Hz Booster operation (8 pulses, 1.333 seconds)

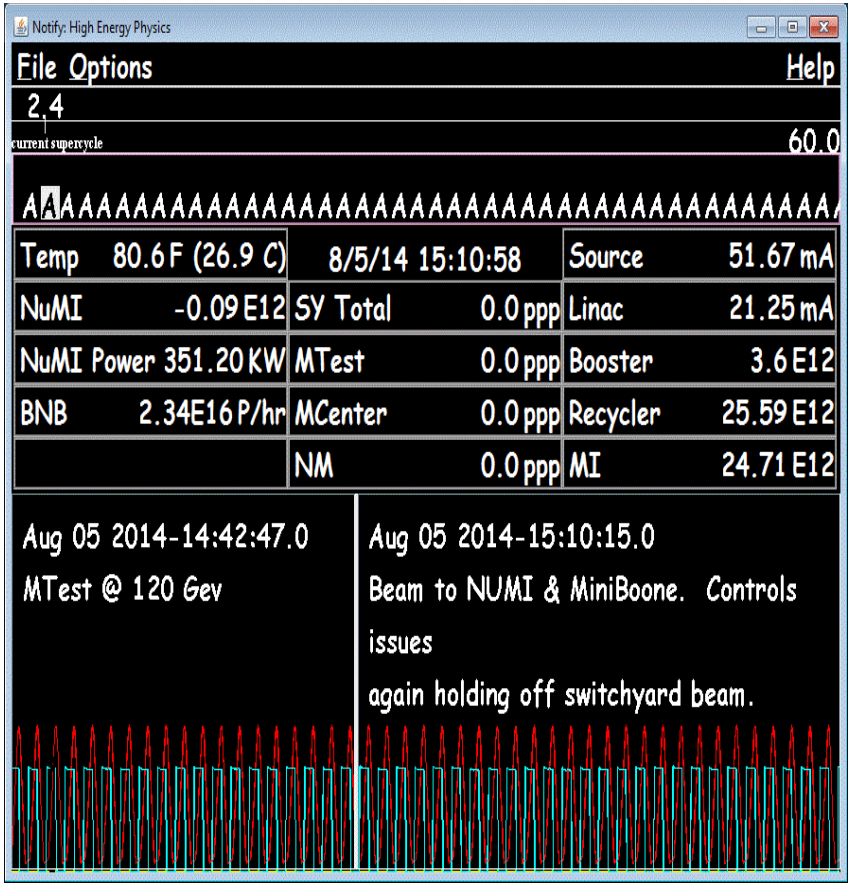
- Gradually increase the number of the slipped stacked batches.
  - We can test 4+6 operation (7.5 Hz 10 pulses, 1.333 second)

- January 2015 review of PIP & 700 kW operation, conducted by J Kogut (https://indico.fnal.gov/conferenceDisplay.py?confId=9236)
  - Well received, awaiting final report but already working towards addressing recommendations
  - “PIP is well defined, achievable. Impressive Progress”
  - “Aperture restrictions are being well-addressed in RR”
  - “Loss reduction is risk-fraught process - need to have a plan with planned results - compare as you go”

MI Beam power with and without SY120

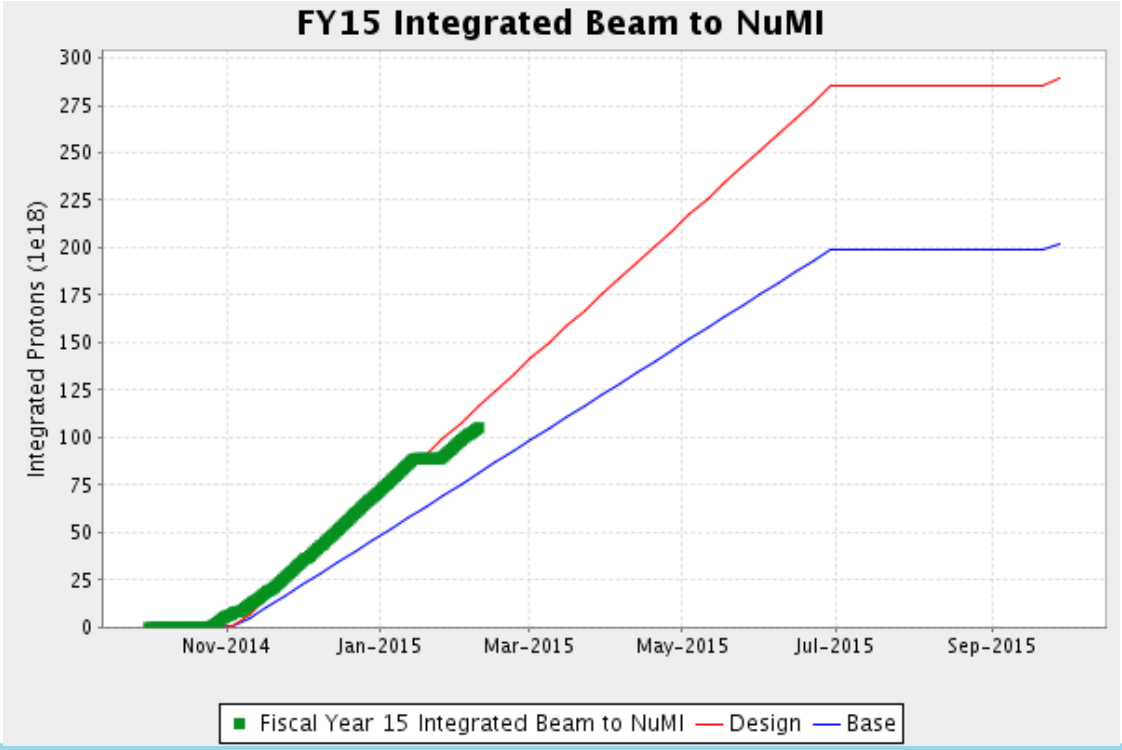
350 kW with ½ intensity





Accelerator Operations

- FY15Q1 Statistics
  - NuMI POT – 7.5 x 10^{19} protons
  - NuMI Operating Hours – 1408 hours
  - NuMI Projected Hours – 1200 hours
  - Percent Uptime (operating/scheduled) – 87%
  - Hours for Switchyard – 1120 hours



Intensity Improvements

- How do we get more flux from the Booster?
  - Proton Improvement Plan (PIP)
    - 15 Hz Beam Cycles
    - Lower losses per cycle

- How do we get to 700 kW from MI?
  - Establishment of 12 batch slip stacking in the Recycler
    - Operational Slip Stacking in the RR
    - 9 Hz operation in the Booster

PIP Goals and Scope (Established in 2011 – Stuart Henderson)

Goals:

- Increase the beam repetition rate from the present ~7 Hz to 15 Hz
- Eliminate major reliability vulnerabilities and maintain reliability at present levels (>85%) at the full repetition rate
- Eliminate major obsolescence issues
- Increase the proton source throughput, with a *goal* of reaching >2E17 protons/hour
  - Presently operating at <1E17 protons/hour
- Ensure a useful operating life of the proton source through at least 2025
  - Now extended to 2030 to accommodate the PIP-II schedule

- PIP is NOT a Project but a campaign of many activities scheduled around the on-going 24/7 operations by the same people
- It is managed like a project
  - budget, schedule, WBS, milestones, project controls..

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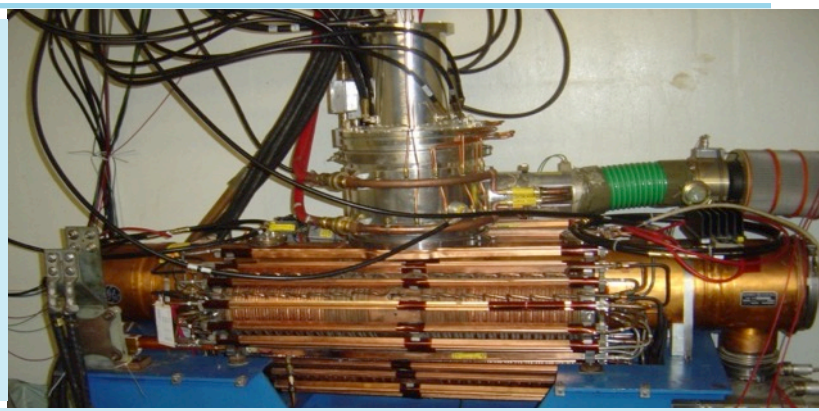
Booster Operation at 15 Hz

- Booster is a resonant machine at 15 Hz
  - but not all pulsed devices were designed for 15 Hz
  - Proton Plan (2004-2009) brought everything but the RF cavities to 15 Hz capability
    - RF Cavities sparked and Tuners overheated at higher frequencies
- Booster has 22 slots for RF cavities
- Requested Intensities (4.3e12) require ≥ 17 cavities
- We now have 20 cavities on hand
  - At any given time: 17 are installed, 2 are out for repair
  - each cavity requires 3 tuners. Tuners require 3 weeks to rebuild during the multi-week refurbishment process.
- Our plan is to have 17 15 Hz capable cavities before this summer's shutdown (July 2015).
- Complete all 20 by January 2016

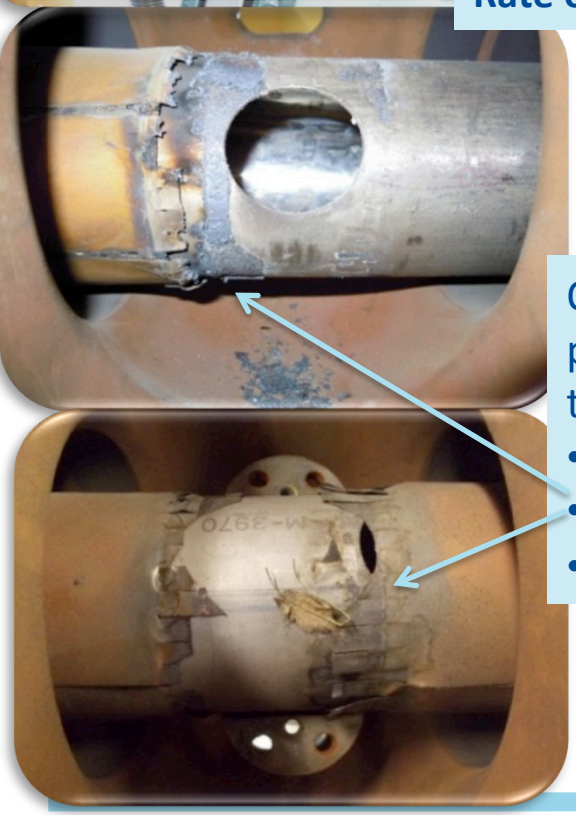
PIP – Booster Cavity Refurbishment

Cavity work: 2 – 4 weeks
Tuner work: 4 weeks
Tuner installation: 1+ week
RF testing: 1+ week
Potential delays: vacuum and water complications
Rate of repair improved by 1.5 wk



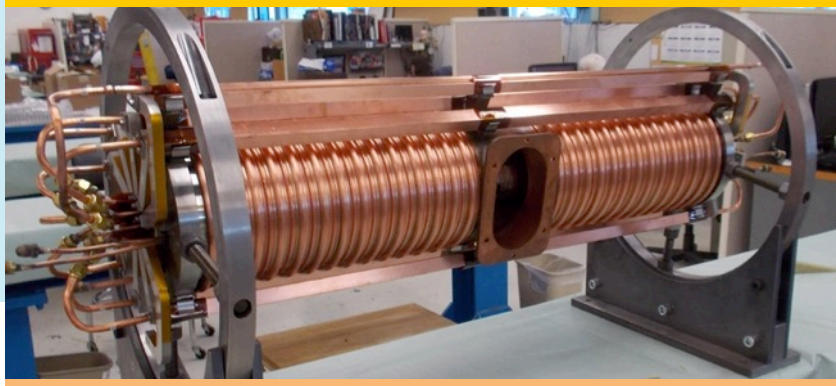
Additional 20th cavity being tested 15 Hz (salvaged original cavity – major rebuild)

After 2+ years vendor able to produce suitable ferrite for new tuners



Old cavities had many problems - especially the tuners:

- Water Leaks
- Burnt RF Fingers
- Connection Flange



First new tuner – built & tested

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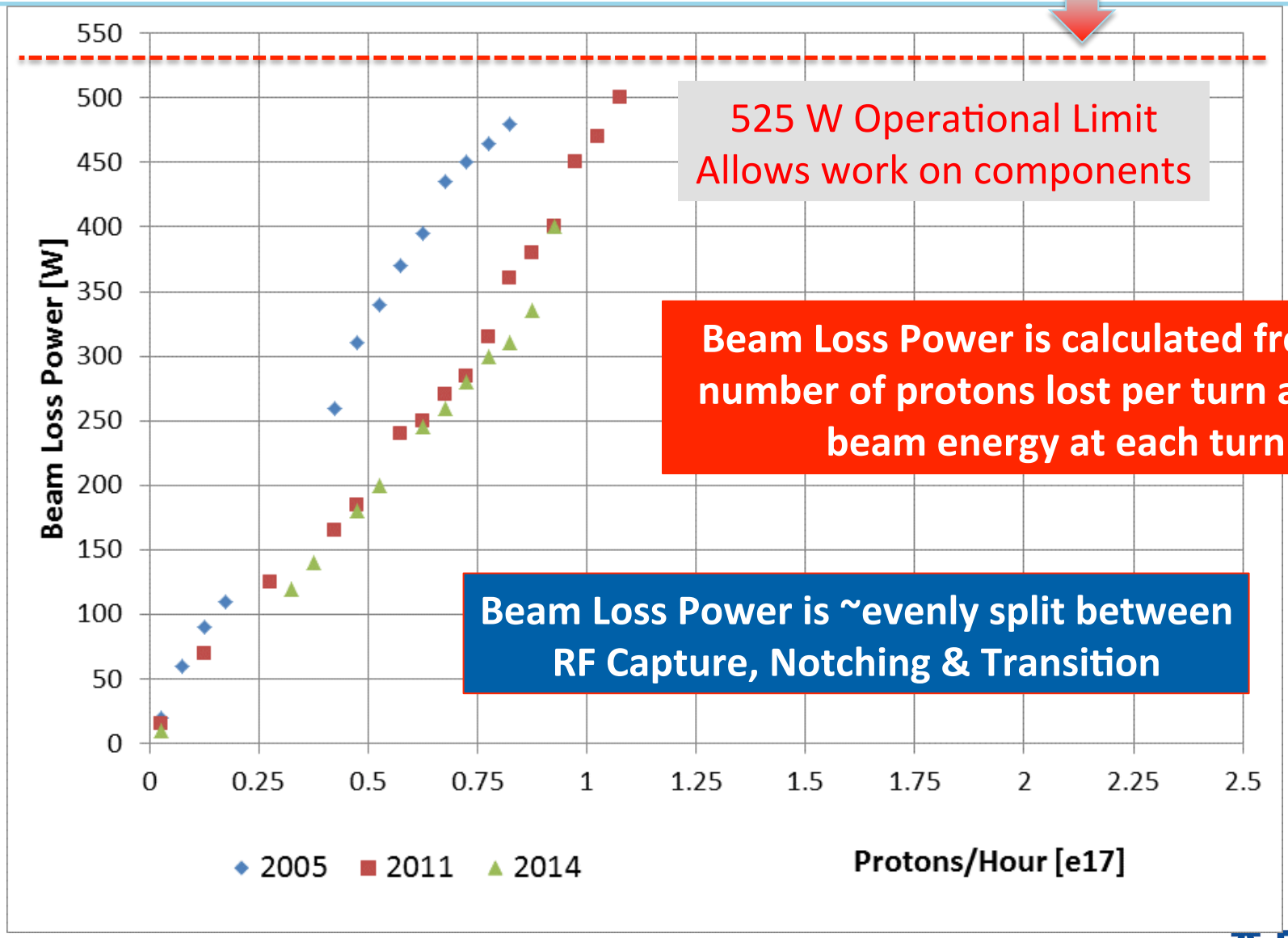
Beam Loss Power : Ramp intensity as understand losses

- If nothing done, the Beam Loss Power would become nearly 1 kW at 15 Hz and we will not run beam with such losses.
  - need to maintain the accelerator
  - 15-Hz operation by itself does NOT increase the proton flux.

- Reduction of losses requires Accelerator Physics and Engineering, not a simple replacement of components.
- Our strategy to reduce losses: focus of January review
  - Move beam notching system to linac (30% loss reduction)
  - Reduce losses at RF capture (several ideas)
  - Eventually, reduce losses at transition
  - Revisit our understanding of the operational limits
    - Global power loss and local normalized loss

Beam Losses -- Historical Look



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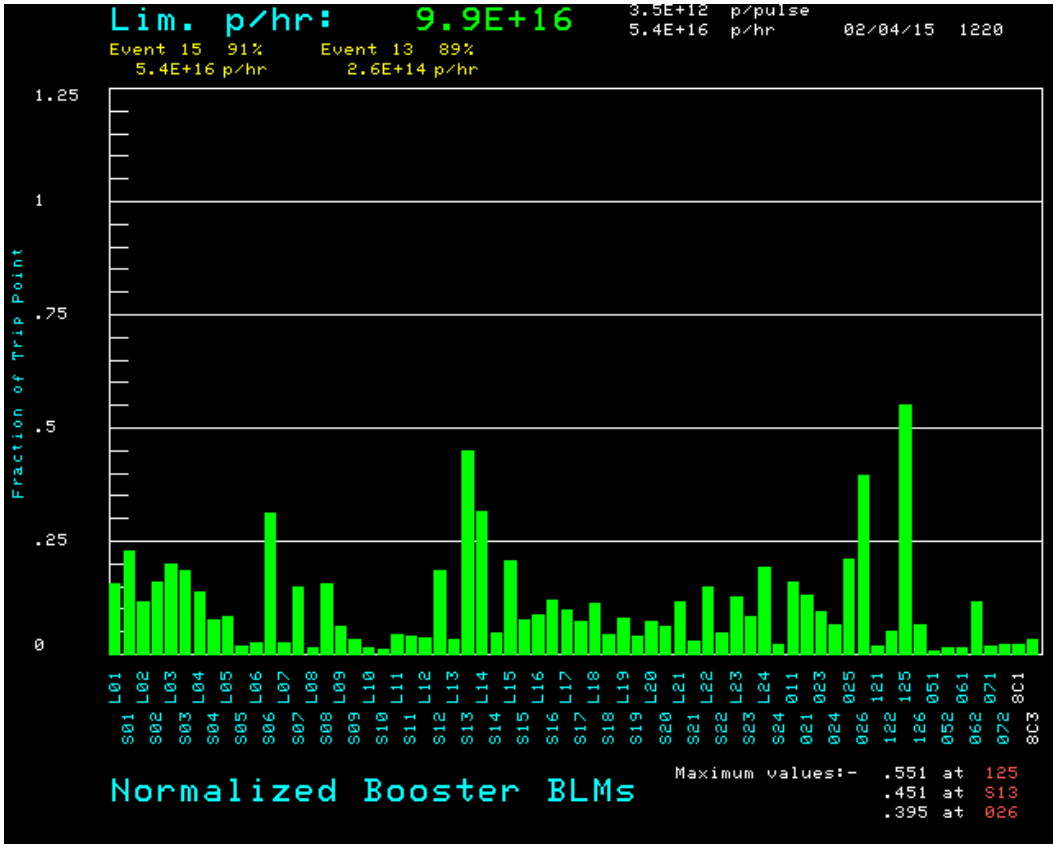
Beam Losses: Operational Look

- Normalized Loss Monitor Value, based on location, hardware, repair frequency to define operational limits
  - in example below, Power Loss ~237 W, Flux Limit ~1e17/hour, Flux 5.4e16/hour



Intensity Improvements

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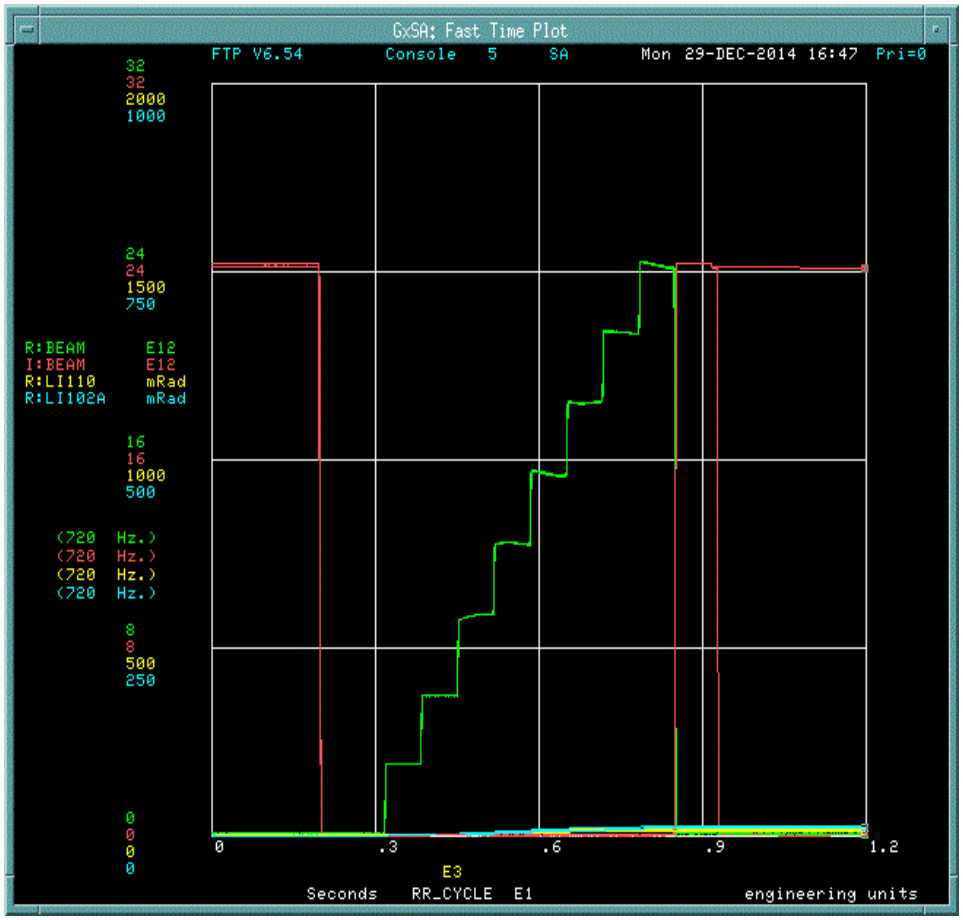
- How do we get to 700 kW from MI?
  - Establishment of 12 batch slip stacking in the Recycler
    - Operational Slip Stacking in the RR
    - 9 Hz operation in the Booster

MI/RR Roadmap to 700 KW

- *Switch to 2+6 Operation-Feb. 2015 (same power 350 KW)*
  - Main Injector Department
    - Optimize slip stacking in RR
    - Commission MI collimators
  - Proton Source Department
    - Reliable 6 Hz operation
    - Provide 3.2E12ppb with the proper longitudinal emittance and dp/p
- *Provide 450 KW with 2+6 operation-March 2015*
  - Main Injector Department
    - Minimize losses
  - Proton Source Department
    - Reliable 6 Hz operation
    - Provide 4.3E12ppb with the same longitudinal emittance and dp/p

6+2 RR Operation (Beam Study 10 Turns)



- **Have demonstrated 2+6 Slip stacking with 2.4E13 (current MI/RR intensity) and good efficiency!**

2+6 operation; beam

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MI/RR Roadmap to 700 KW

- *Demonstrate 4+6 operation by achieving 560 KW operation of at least one hour.-May 2015*
  - Main Injector Department
    - Commission 4+6 operation with 4.3E12 ppb and 95% overall efficiency.
  - Proton Source Department
    - Reliable 7.5 Hz operation
    - Provide 4.3E12 ppb with the proper longitudinal emittance and dp/p
- Switch to 4+6 operation providing 560 KW of beam power-October 2015

MI/RR Roadmap to 700 KW

- Switch to 6+6 operation (same power 560 KW)-Jan . 2016
  - Main Injector Department
    - Commission 6+6 operation with 3.6E12 ppb and 95% efficiency
  - Proton Source Department
    - Reliable 9 Hz operation
    - Provide 3.6E12 ppb with the proper longitudinal emittance and dp/p.
- Achieve 700 KW with 6+6 operation-Feb. 2016
  - Main Injector Department
    - Commission 6+6 operation with 4.3E12ppb and 95% efficiency
  - Proton Source Department
    - Reliable 9 Hz operation
    - Provide 4.3E12 ppb with the proper longitudinal emittance and dp/p

Peak Hourly Flux and Uptime Models

For POT projections, need models for

Peak Hourly Flux (best performance possible)

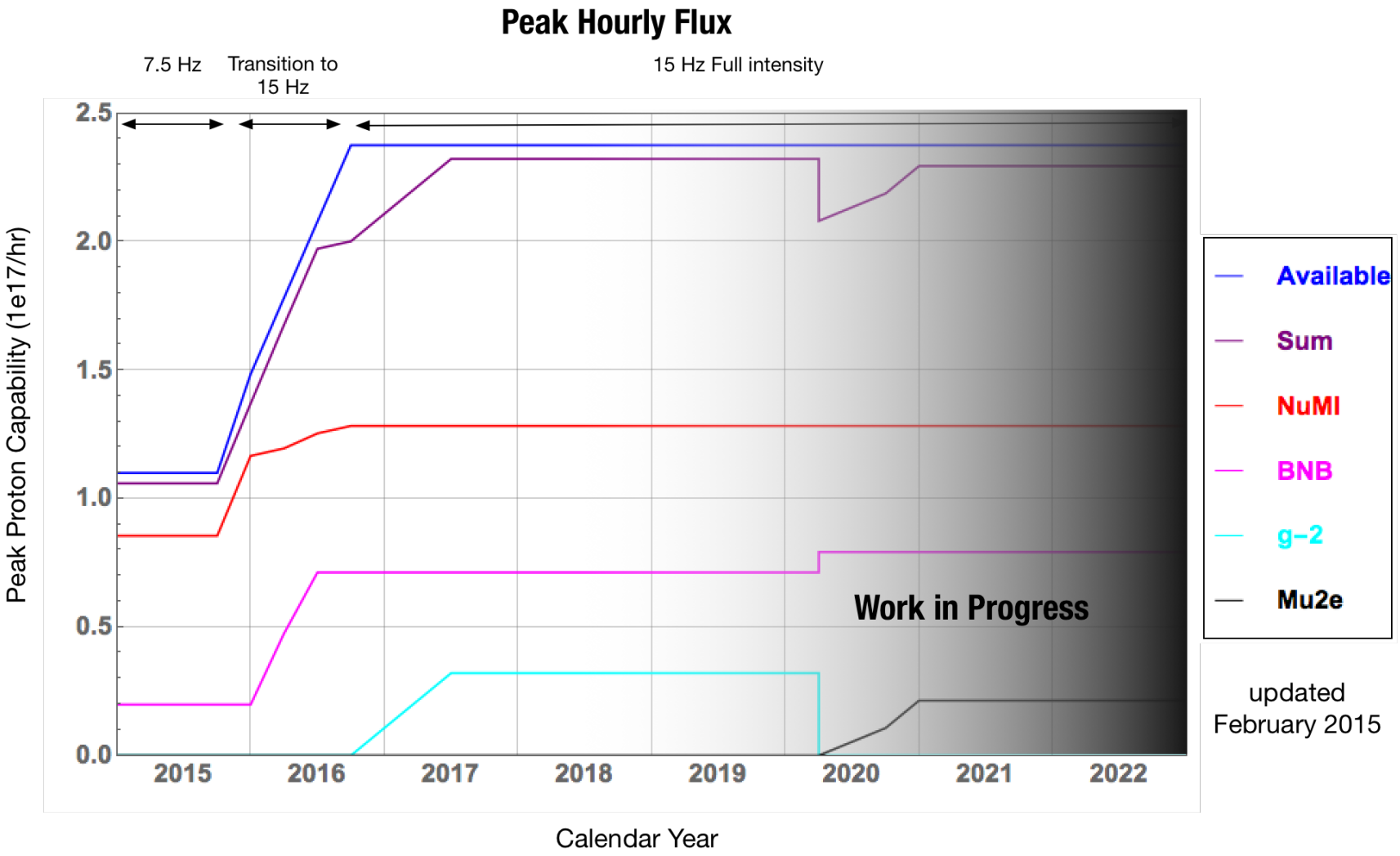
Uptime and Average Performance: based on FY14 & FY15

Discussions with Program Planning, the Proton PMG, Accelerator Division, and the experiments to define the model

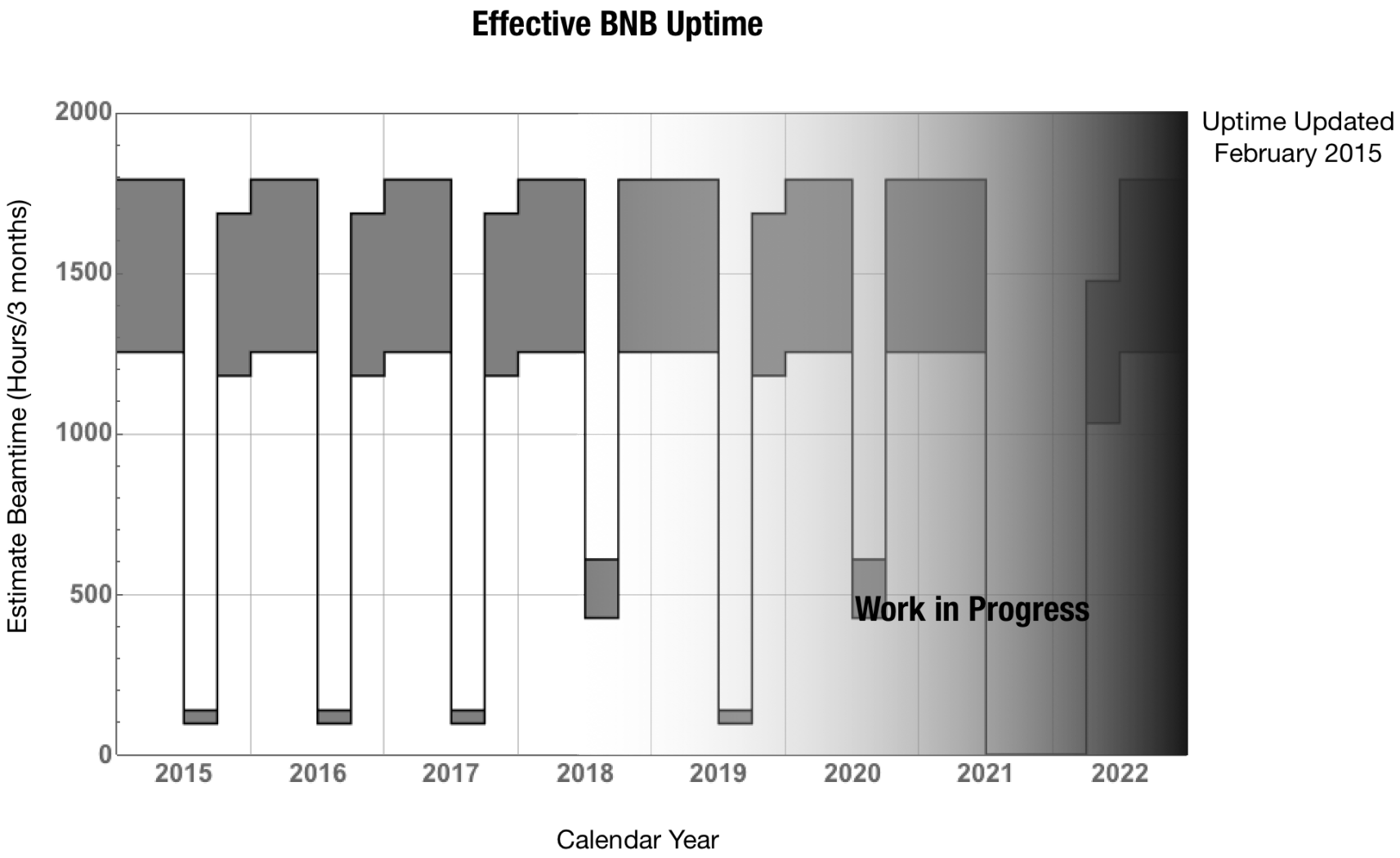
Details are available in backup slides

Peak Hourly Flux

Steve Geer will discuss in more detail



Uptime projections Steve Geer will discuss in more detail

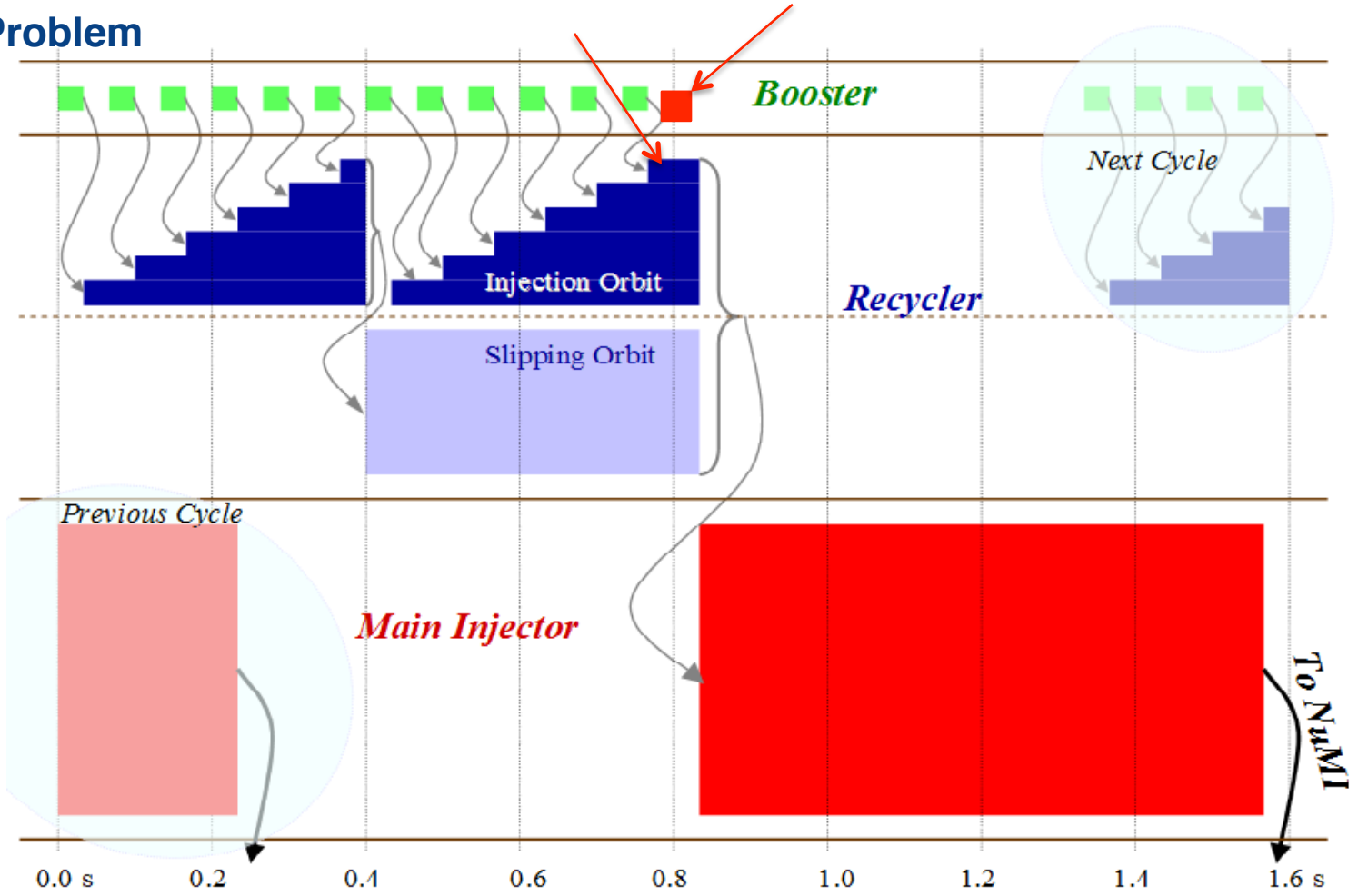


Extra slides

12th batch to Recycler requires an *entire tick* to slip into place, followed by a transfer and a clearing kicker

The Recycler cannot be ready for this batch. It can only go to studies or the BNB line (or be skipped entirely)

(First) Problem



So in a 20 tick timeline, 8 ticks ➔ 7 ticks

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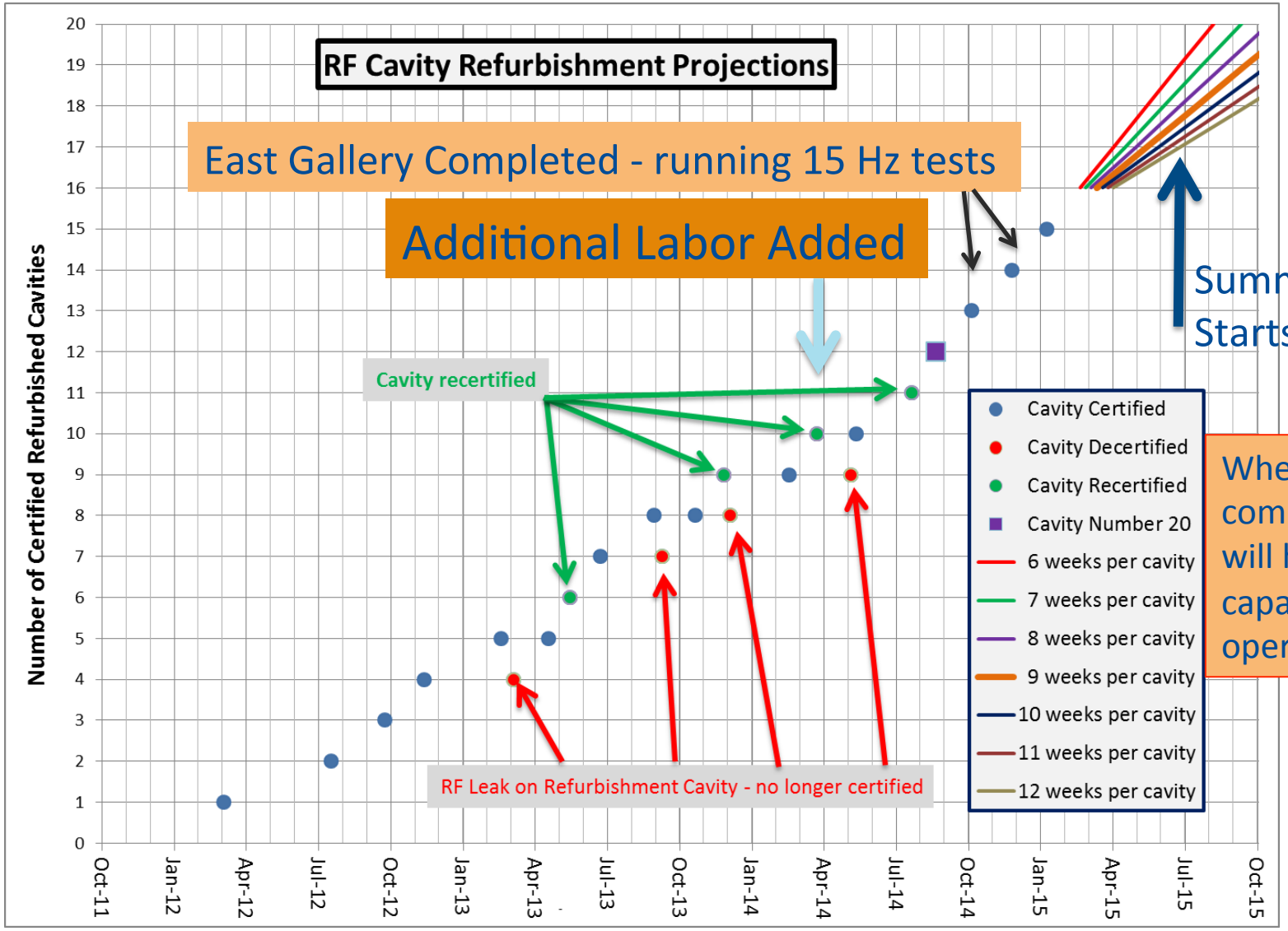
Booster RF cavities

July 1970 Flatbed semi delivering Booster RF cavity pair

Cavities built by GE

PIP – Booster Cavity Refurbishment

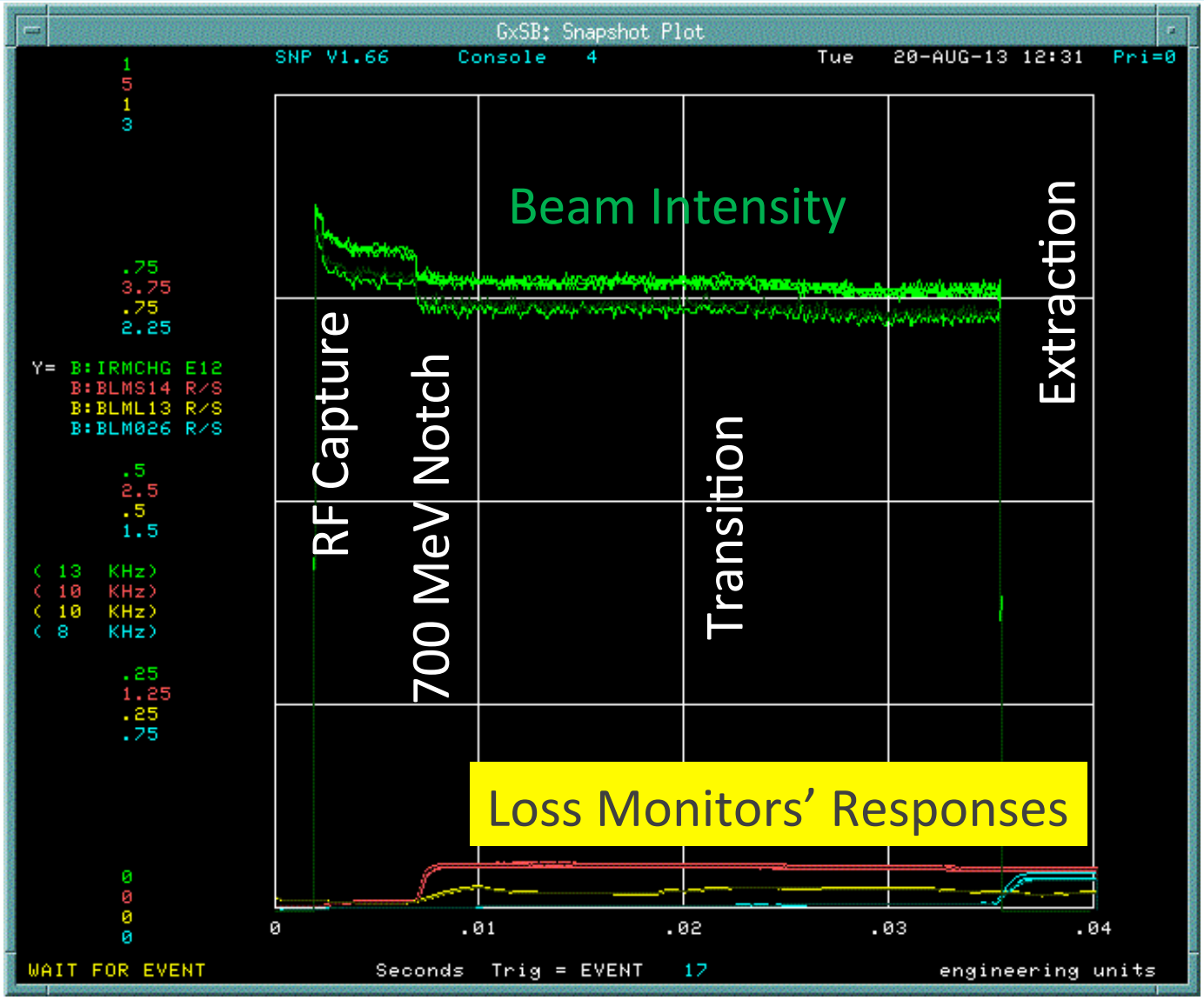
Goal is to have all installed stations (17) refurbished at run at 15 Hz before summer shutdown.



When PIP completed, Booster will have 22 stations capable of 15 Hz operations.

Updated January 8, 2015 by K Gollwitzer

Beam and Losses through Cycle



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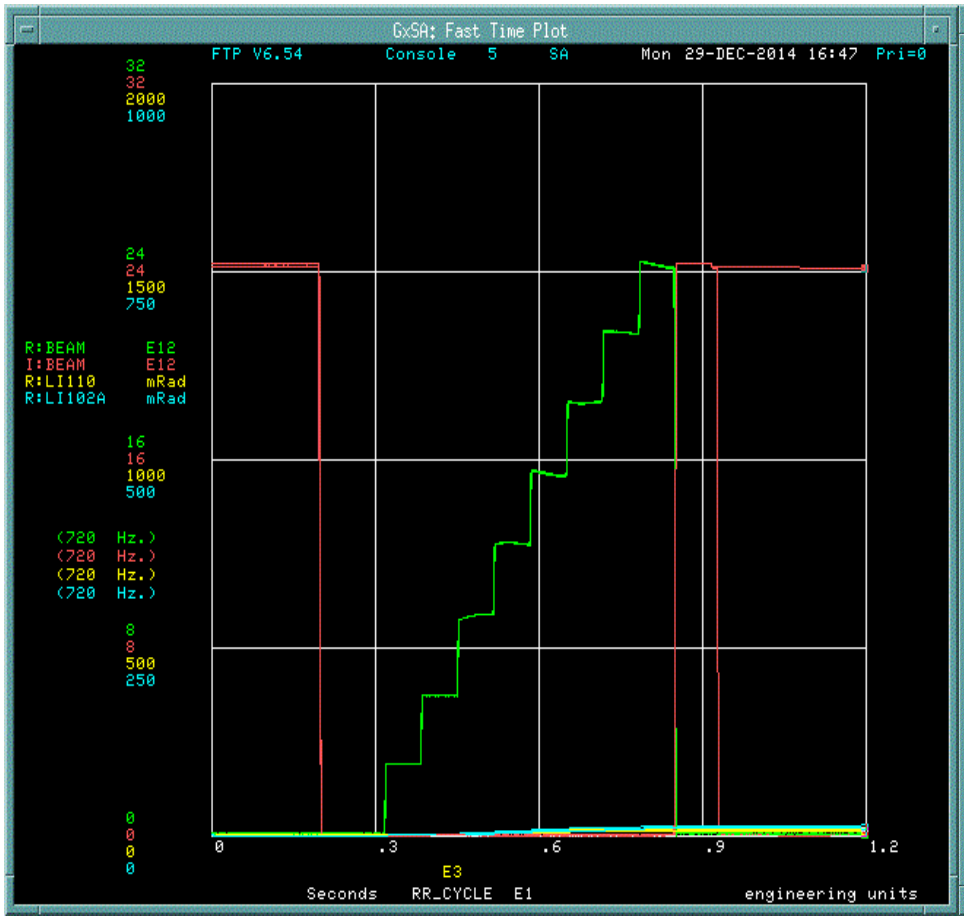
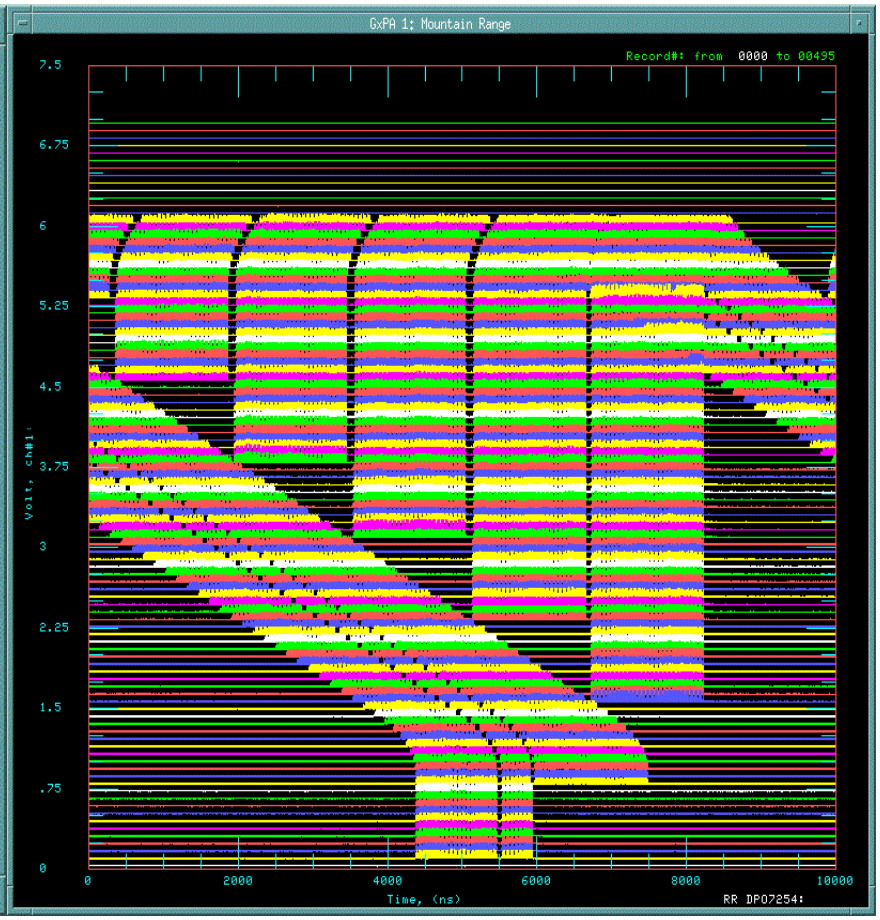
6+2 RR Operation (Beam Study 10 Turns)





2+6 operation; beam

2+6 operation; mountain range

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Peak Hourly Flux and Uptime Models

For POT projections, need models for

Peak Hourly Flux (best performance possible)

Uptime and Average Performance

- Peak:
  - based on 4.4e12 per Booster pulse
  - 15 Hz Booster operation
  - SY120: 1 event per supercycle (10% of timeline)
  - NuMI: 1.33 second cycles, 9 Hz
  - g-2: 2.25 Hz
  - Mu2e: 2 Hz
  - BNB: fill in, up to 5 Hz limit
  - 2016 ramp intensity as understand and mitigate losses
- Upper Bound: FY14 as model (saw ~-2.5% lower in NuMI than BNB)
  - 85% for BNB, 82.9% for NuMI, 80.8% for g-2
- Lower Bound: Major equipment failure
  - BNB/NuMI: Target / Horn 4 weeks (9/13 ~70% in quarter)
  - g-2: Target/PMAG/Li Lens 2 weeks (11/13 ~85% in quarter)
- Shutdowns:
  - FY16/17: 12 weeks
    - MI TSP->IonPump
    - Muon Campus work
  - end effects included
    - lower intensity for cool down
    - lower intensity on startup

Calculations and Assumptions

- **Booster Assumptions**
  - The Booster will achieve 15 Hz beam operations in Q4 of 2015.
  - Peak Pulse intensity is 4.4e12, leading to a maximum hourly flux of 2.38e17/hour.
  - Maximum flux will take ~year of commissioning effort and will be reached in Q4 2016.
- **NuMI Assumptions**
  - 12 Batch RR slip stacking with a 1.33 second cycle will start in Q4 2015 at 4e12 per Booster batch.
  - Through the course of 2016 it will ramp up to full intensity of 4.4e12.
  - SY120 continues to take 10% of the timeline, leading to a maximum flux of 1.28e17/hour.
  - Continues through 2023

Calculations and Assumptions

- **BNB Assumptions**
  - Runs at 1.25 Hz through 2015, ramping up in 2016 to 4.5 Hz at 4.4e12.
  - Saturate the flux (with a maximum of 5 Hz due to horn restrictions) in future years – concurrent with g-2 it corresponds to 0.71e17/hour, concurrent with mu2e it corresponds to 0.79e17/hour
  - Continues through 2023
- **g-2 Assumptions**
  - Turns on in Q1 2017, taking 2 quarters to get to full intensity.
  - Full intensity corresponds to 3 Booster cycles every 1.33 sec NuMI cycle at 4.4e12.
  - SY120 continues to take 10% of the timeline (g-2 and SY120 are not compatible as they both need the P1 line), leading to a maximum flux of 0.32e17/hour.
  - Turns off in Q3 of 2020 – 3 years at full intensity

Calculations and Assumptions

- **Mu2e Assumptions**
  - Turns on in Q3 of 2020, taking 2 quarters to get to full intensity.
  - Full intensity corresponds to 3 Booster cycles every 1.33 sec NuMI cycle at 4.4e12.
  - SY120 continues to take 10% of the timeline (mu2e and SY120 are not compatible as they both need the P1 line), leading to a maximum flux of 0.21e17/hour.
  - Continues through 2023
- **SY120 Assumptions**
  - 1e13 once per minute, which is ~10% of the available MI cycle time
  - Maximum flux of 0.006e17/hour (which is why it is hard to see on the plot)
  - Continues through 2023

POT Projections: Uptime

- Upper Bound: FY14 as model (saw ~-2.5% lower in NuMI than BNB)
  - 85% for BNB, 82.9% for NuMI, 80.8% for g-2
- Lower Bound: Major equipment failure
  - BNB/NuMI: Target / Horn 4 weeks (9/13 ~70% in quarter)
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- Shutdowns:
  - FY16/17: 12 weeks
    - MI TSP->IonPump
    - Muon Campus work
  - end effects included
    - lower intensity for cool down going in
    - lower intensity on startup

POT Projections: Method

- Protons/Hour
  - Booster capability at 15 Hz
    - Peak 4.3e12 per pulse, average 4.2e12 per pulse
    - FY16: Ramp through year to maximum flux of 2.32e17/hour
    - FY17: 2.32e17/hour
  - NuMI: 9 Hz capability, 90% of timeline (10% to SY120)
    - FY16: start at 4e12, ramp to peak
    - FY17: full capability, 1.25e17/hour
  - g-2: turns on January 2017, 2 quarters to full intensity
    - 3 Booster cycles/1.33 sec NuMI cycle at peak
    - 90% of timeline (10% to SY120)
  - BNB: Saturate available flux, giving NuMI & g-2 priority

POT Projections: FY16 & FY17

	NuMI (e20)	BNB (e20)	g-2 (e20)
FY16 Range	4.2 – 6.0	1.4 – 2.1	0
FY16 Target	4.8	1.7	
FY17 Range	4.7 – 6.8	2.7 – 3.9	0.72 – 0.85
FY17 Target	5.4	3.1	0.76

Range: lower to upper bound as described in previous slides

Target: (2 * lower + upper)/3

metric used in previous years

Accelerator Summer Shutdown

- Shutdown begins July 2015
  - Expect start date to be locked in by the end of January
  - Duration planned for 12 weeks
  - Major work
    - First of three phases in the TSP2IP project
      - Replaces Recycler TSPs with Ion Pumps
      - BV523 – BV100
    - Installation of the RR52 line
      - Beam extraction from Recycler to P150
    - Muon Campus AIPs in F-Sector
      - Remove lambertson and C-magnet
      - Replace with dipoles
    - General shutdown maintenance

Accelerator Summer Shutdown

- Shutdowns in 2016
  - Estimate 10-12 weeks
  - Complete phase two of TSP2IP project
  - Install RF cavities in MI-30
  - Rework MI-30 extraction
  - General shutdown maintenance
- Shutdowns in 2017
  - Estimate 8-10 weeks
  - Complete phase three of TSP2IP project
  - General shutdown maintenance

Issues with MI/Recycler

- Recycler vacuum
  - The Recyler TSP-based vacuum system, exceeded design lifetime; not suitable for a proton machine.
  - Developed a plan for replacement of ~400 TSPs with IPs. Will take 3 long shutdowns (lots of cutting and welding).
- Corrosion of the MI beam pipe.
  - Address the corrosion of the MI beam pipe at the collimation region.
- Recycler collimators
  - Recycler has no collimators; we are working on design a collimations system

Plan for RR Vacuum *

- Replace all Recycler TSPs with Ion Pumps.
- Starting with the FY15 shutdown we plan to replace ~1/3 of Recycler Ring TSPs.
- The bake-out capability in the RR will be maintained.

RR TSP

RR Ion pump

Replacing corroded MI pipe at collimation region

- Started replacing the MI beam pipe at the MI-30 collimation region with a 2205 duplex stainless pipe with higher corrosion resistance.