Booster 15Hz Operation

John Reid
March 4, 2014
• Brief History of Booster RF systems
• RF system description
• Modifications over the years
• Booster Solid State RF upgrade project.
• Upgrades required to achieve 15 Hz beam operation.
• Booster RF cavity
• Other RF issues.
• Summary
Brief History

- Booster cavity design started at Lawrence Radiation Laboratory in the 1960’s.
- Comprehensive study to evaluate ferrite toroid manufactures with specific properties suitable for electronic tuning a coaxial accelerating cavity over a frequency range of 30Mhz to 52.8MHz. Toroid size: 8” OD x 5” ID x 1” thick.
- Settled on NiZn toroids manufactured by Stackpole \(\mu=12\) & & Toshiba \(\mu=40\).
- Production cavities & tuners built by GE in Schenectady, NY
July 1970 Flatbed semi delivering Booster RF cavity pair with original one piece girder to X-Gallery.
July 1970 – Single one piece girder with two RF cavities at x-gallery high-bay – ready to be lowered into Booster staging area.
RF System Description

- Normally 19 High level RF stations installed and operational but with current cavity refurbishment only have 17 stations active.

- Typical RF station consists of a fast slewing 0 to 2500 Amp Ferrite Bias Supply, 30 kV Series tube modulator, 150 kW power amplifier, RF cavity with 3 tuners + HOM dampers, & local station controls.
  - 10 stations in the West Gallery run off one outdoor anode supply.
  - 9 stations in the East Gallery run off another outdoor anode supply.

- All 19 stations are upgraded with 4kW Solid state driver assembly, new 30kV Series Tube Modulators, new 150 kW Power Amplifiers (St 12 upgraded in 2001 (prototype) and St 19 in 2005).

- Booster cavity parameters
  - Frequency sweep – 30 to 52.813 MHz, present sweep 37 to 52.8 MHz due to 400MeV Linac upgrade.
  - Q at injection (37MHz) ~ 325, Q at extraction (52.8MHz) ~ 1250
  - Peak accelerating voltage per cavity ~ 50 kv

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Modifications / Upgrades – Early Years

- **Booster RF cavities were modified in the mid to late 70’s with the following upgrades:**
  - Upgraded spark detection system.
  - Monolithic RF coupling capacitor with metalized interface to copper spinning's for coupling PA output to RF cavity.
  - Girders split into two separate structures to facilitate change-out.
  - Tuners rebuilt using new lower loss ferrite to replace M4C21A:
    - Replaced 10 Toshiba M4c21 cores (mu=40) with 10 Toshiba M4D21a cores (mu=20) in each tuner.
    - 18 Stackpole CeraMag 14 material toroids (mu=12) remain unchanged.
  - Cavities:
    - Tuners removed for rebuilding
    - All components thoroughly cleaned
    - Electrical joints tin plated
    - Mode damper mounts add

Fermilab

J. Reid

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Installed Pair of Booster RF Cavities
Typical Booster RF Station

Ferrite Bias Supply  Modulator  Control Rack  SSD Controls  Ferrite Bias Supply  Modulator

Original Booster RF Station  Upgraded RF Station with SSD + New Modulator
Booster RF Cavity
• **Modulators**
  – Relics of the past, outdated from day one. Use technology from the 50’s.
  – Very few PC boards, mostly point to point wiring.
  – Use a number of glass vacuum tubes, some getting harder to find.

• **Ferrite Bias Supplies**
  – Replaced original Ling power supplies with FNAL design units in the early to mid 70’s due to original Ling power supply poor pulsing performance, both electrically & mechanically.

• **Power Amplifiers**
  – Consist of three sections
    • 6 water cooled 4CW800F tubes - distributed amplifier – life ~9-12 months
    • 14 water cooled 4CW800F tubes - Cascode amplifier –life ~9-12 months
    • 1 water cooled Y-567B tube – Power module – life ~ 36 months
  – Typical repair time for original Booster Power amplifier was ~ 60 man hours and cost of 4CW800F’s getting extremely high.
Original Modulators
Original Modulators
Monolithic PA Anode Coupling Capacitor
Preparing for 15 Hz RF System Operation

- **Booster RF presently running at ~ 7.5 Hz.**
- **To satisfy program demands, need to run 15 Hz continuous.**
- **Booster RF reliability has been a significant matter for discussion over the last 12 + years.**
  - RF system never capable of operating at a continuous 15 Hz, only ran in burst mode at moderate duty factor.
  - Increased demands on the duty factor started with the beginning of MiniBooNE operations in 2002
  - NuMI/MINOS demands have greatly increased the demands on Booster.
  - Original equipment > 40 years old.
  - Need to maintain a minimum of 900Kvolts / turn ~ 50kV/ station
  - Spare Station 19 acts as hot spare to compensate for a down station.
Modifications to Achieve 15 Hz

• **Required Modifications for 15Hz operation,**
  – Completed the Solid State Driver Upgrade project, March 2013.
  – Reconnect the ferrite cone cooling lines which were disconnected many years ago due to low duty factor operation.
  – Install new copper clad skins on tuner cone castings.
  – Machine cavity tuner interface surfaces flat and parallel for good high power RF connections.
    • This requires removing cavities from tunnel and cycling tuners & cavities through a rebuilding process.
    • All cavities are run through the MI-60 test station and tested at a 15 Hz rate for a minimum of 168 hours of which 120 hours at full gradient before reinstallation in Booster tunnel.

• **Would like to have a second high power test stand at F0 to do long term testing of a refurbished cavity**
Solid State Driver Upgrade Program

• Upgrade Program
  – Build 22 new FNAL designed modulators (identical to MIRF).
  – Build 22 new FNAL designed 150kW power amplifiers
  – Build 22 new FNAL designed 4kW solid state driver amplifier assemblies.
  – Replace all RF station cabling to the tunnel (HV, ½” Heliax,
  – & all control cables.

• Present Status
  – Completed solid state driver upgrade project in March 2013.
  – Final project cost was under original cost estimate.
1 kWatt Solid State RF Module
1 kW SS RF Amplifier Module

Each ckt board contains two MRF-151G MOSFETs producing ~250 watts per channel

4-way combiner

Water cooling
Booster St 12 Amplifier

New 150 kW power amplifier on station 12’s cavity
Solid State Driver Amplifier Racks
New Modulators
Additional Scheduled Booster RF Upgrades - PIP

- **Anode Power Supplies**
  - Two new power supplies to replace original 1970 power supplies
    - Includes new 13.8kV Step Start VCB contactors
    - New 2MVA transformers
    - New outdoor DC Cabinets with HV components
    - New controls
    - Completion in FY15-FY16

- **Ferrite Bias Supplies**
  - Replace marginal Main Rectifier Transformer & SCR packages in 10 West Gallery Supplies.
  - Project started in FY14 and scheduled to be complete in FY15.
  - Completion does not limit prior 15 Hz operation.

- **Build 3 new Booster Cavities with slightly larger aperture 3.25”**
  - Would install cavities for NEW Booster Stations 21 and 22.
  - Preliminary design considerations based on modeling (Simulation from M. Hassan in TD) is underway.
Cavity Refurbishment

- Completed 9 of 19 cavities with the 10th cavity currently running in the MI-60 testing.
  - The first two cavities that were refurbished had to be redone after a number of months of operating time in the machine due to tuner stem arcing.
  - All other refurbished cavities have run to date without problems.
  - On-going learning process as additional rebuild issues arise.
    - Cavity end flange (pie tin) vacuum leaks.
    - Water cooling tube leaks on center casting.
    - Concentricity of center casting in outer shell.
- Takes about 8-12 weeks per cavity for refurbishment.
- Some cavities are more radioactive than others (upstream cavities are the most radioactive) with a few of them Class 3.
- Rebuilding tuners takes the most time.
- Have procured & tested additional 200 low mu ferrites and waiting on the vendor to finalize high mu (mu=20) toroids.
  - With the procurement of low and high mu toroids + cone castings, an additional 10 tuners can be built which would accelerate our turnaround time and supplement our tuner spares.
## Cavity Installation Schedule

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Standard Booster Cavity Bore - 2.25”
Booster Cavity Ferrite Tuner housing with Ferrites only
Tuner Cones

Bare copper castings with single turn cooling loop

5 mil Cu clad stainless skins
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Check Stem connection to center casting 7/3/13

All three flanges need copper fill welded.

Flatten all three tuner flanges on cavity 16-Jul
Clean cavity 23-Jul

Electrical test of Bottom tuner 11/July 1st
Electrical test of Back tuner 29/July 26
Electrical test of Front tuner 10/July 26

Installed refurbished tuner Back 29/July 26 Has a .030 copper shim with no lip.
Both cones have new brazed cooling cones.

Installed refurbished tuner Bottom 11/July 24 Has a .062 with .030 lip.
Both cones have new brazed cooling cones.

Installed refurbished tuner Front 10/July 25 Has a .015 with no lip.

Install plumbing 5-Aug

Vacuum leak check cavity 6-Aug
All electrical bus bars are connected.

Vacuum leak check cavity final assembly of cavity with Blocker + PA 5-Aug

Date moved into test cave 6-Aug

Date start of electrical testing 7-Aug

Date Finished of electrical testing 31-Aug

Date shipped to Booster 4-Sept

Date installed in tunnel 11-Sept

Installed into St Number 31

Cavity traveler + detailed logbook entries keeps good documentation for refurbishment process.
Other RF Issues

- Increase mode damper power dissipation (load).
- Replace old rf sum balancing circuit with new global amplitude & phase regulator circuits so amplitude and phase of “A” stations and “B” stations track the request.
- Rebuild prototype Booster rf cavity using spare production center castings (inner & outer) to achieve a good operational spare. Start Jan 1, 2011.
- Need to get acceptable mu=20 toroids from vendor before starting assembly of 10 spare tuners.
- Add direct RF feedback to each station to reduce beam loading effects for added stability under possible higher beam currents.
• Continue to refurbish Booster RF cavities & tuners shooting for an 8 week turnaround.

• Implement Global Amplitude & Phase control.

• Finish assembly of one additional girder assembly with cavity assembled (referred to as cavity 20) from out of tolerance center casting and select components from the original welded prototype cavity. Bare cavity is complete but waiting on new tuners for assembly.

• Procure spare tuner cones.

• Build 10 additional spare tuners (TD) to supplement our current 4 spares.

• Install diagnostic measuring devices on a couple of the existing RF cavities in the tunnel to track thermal heating.

• Replace old rf sum balancing circuit with new global amplitude & phase regulator circuits so amplitude and phase of “A” stations and “B” stations track the request.

• Increase mode damper power dissipation (external loads).