ACE – Accelerator Capabilities Enhancement – MI RF

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January 30, 2023

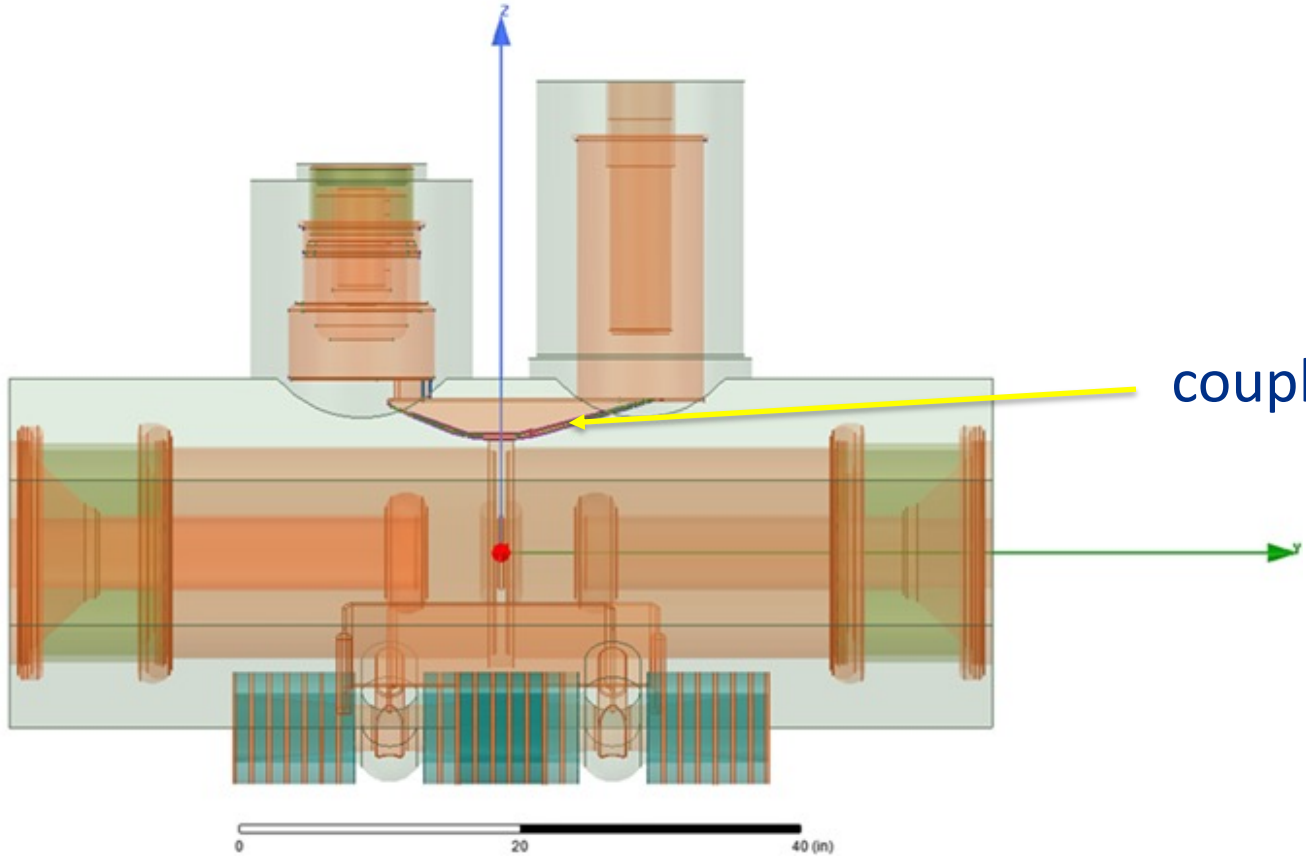
PIP-II – Accelerator Upgrades - Main Injector

Table 9.12: Power calculations of current RF cavities.

	PIP-II	Main Injector - Present Capability
Beam Intensity	7.5×10^{13} protons	6.24×10^{13} protons
Harmonic Number	588	588
Number of Filled Buckets	504	504
Frequency	52.808-53.104 MHz	52.808-53.104 MHz
Acceleration Ramp Slope	240 GeV/s	240 GeV/s
Beam Intensity	7.5×10^{13} protons	6.24×10^{13} protons
Main Injector Ramp Rate	1.2 s	1.2 s
Beam Power at 120 GeV	1.2 MW	998.8 kW
Beam Accelerating Power	2.88 MW	2.40 MW
Number of Accelerating Cavities	20	20
Cavity R/Q	104	104
Maximum Cavity Accelerating Voltage	235 kV/cavity	235 kV/cavity
Operating Peak Voltage	210 kV/cavity	210 kV/cavity
Accelerating Voltage Required: V$\sin\phi_2$	2.66 MV	2.66 MV
Total Accelerating Voltage Available	4.7 MV	4.7 MV
Total Operating Voltage	4.2 MV	4.2 MV
Cavity Power Loss	45.11 kW/cavity	45.11 kW/cavity
Total Apparent Power	240.5 kW/cavity	204.2 kW/cavity
Robinson Stability Factor	4	4

In table 9.12 of the PIP-II Final Design Report, it can be found that an individual Main Injector cavity needs to be able to supply 240 kW of power.

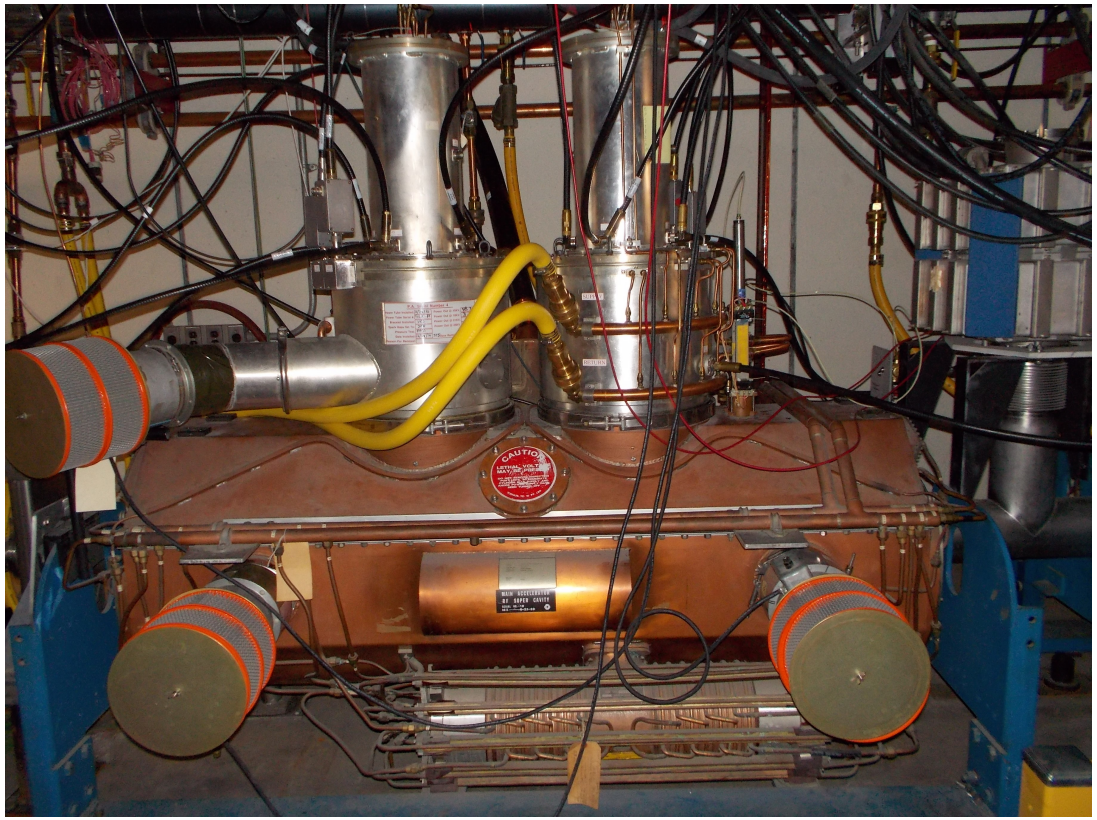
PIP-II – Accelerator Upgrades - Main Injector



Drawing by Ding Sun

Single Power Amplifier (PA) Main Injector (MI) cavity drawing. Coupling loop shows how cavity was always envisioned to be able to support dual PA operation.

PIP-II – Accelerator Upgrades - Main Injector



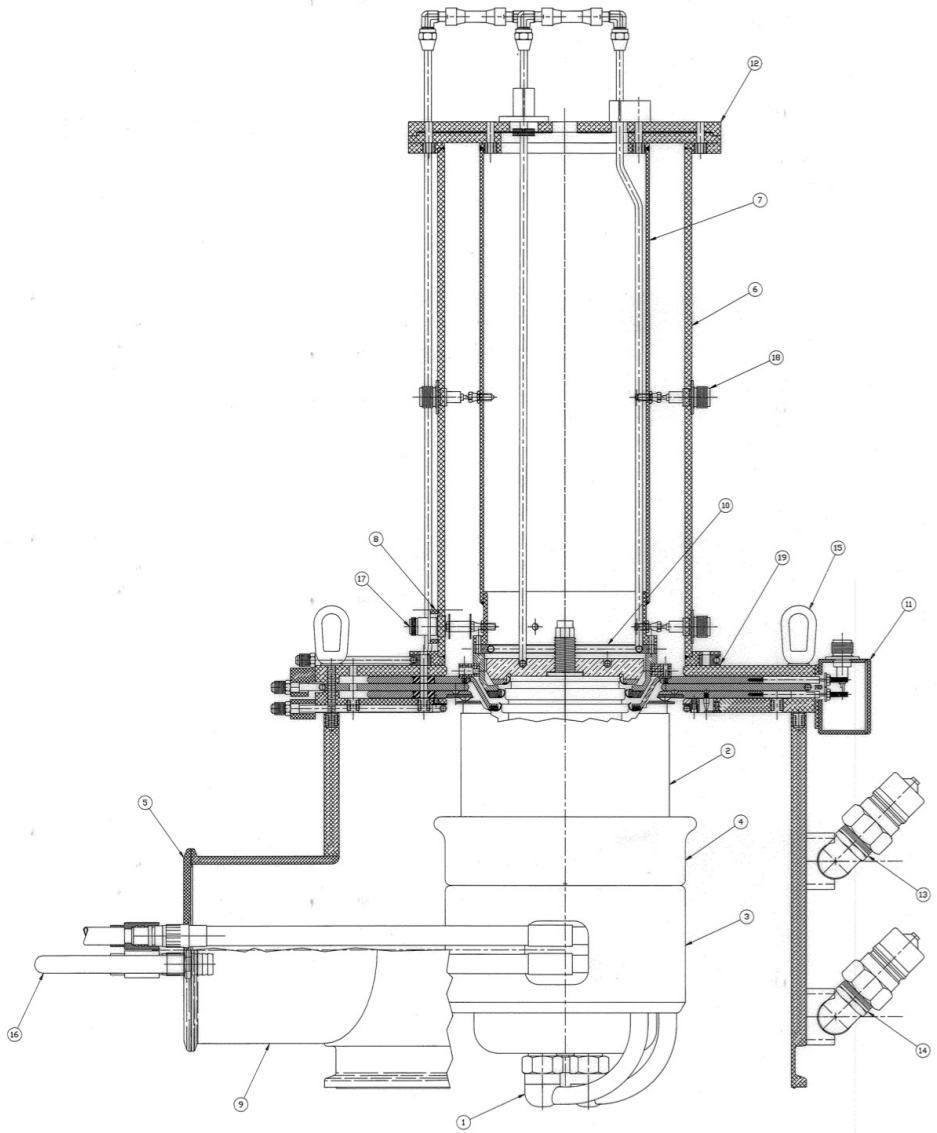
Station 5 of the Main Injector was upgraded to a Dual PA cavity and has operated in this mode for the last two years with beam intensities up to 5.4E13. It can supply 400 kW of power. The two PAs operate in a push-pull mode and easily surpasses the 240 kW needed for PIP-II operations. All twenty MI cavities will be updated to Dual PA operation.

PIP-II – Accelerator Upgrades - Main Injector

Dual Series Tube Modulator

PIP-II will also upgrade all the modulators to Dual PA operation.

PIP-II – Accelerator Upgrades - Main Injector



Main Injector Power Amplifiers

PIP-II will build a total of 40 new power amplifiers for the twenty Dual PA cavities.

PIP-II – Accelerator Upgrades - Main Injector

8 kW 53 MHz Solid State Amplifier

Each PA will have it's own 8 kW solid state amplifier after the the PIP-II Upgrade.

Solid State RF Amplifier

PIP-II – Accelerator Upgrades - Main Injector

Cable Pull

Each Dual PA requires additional cables pulled from RF gallery to the tunnel for operation of the additional power amplifier.

PIP-II – Accelerator Upgrades - Main Injector

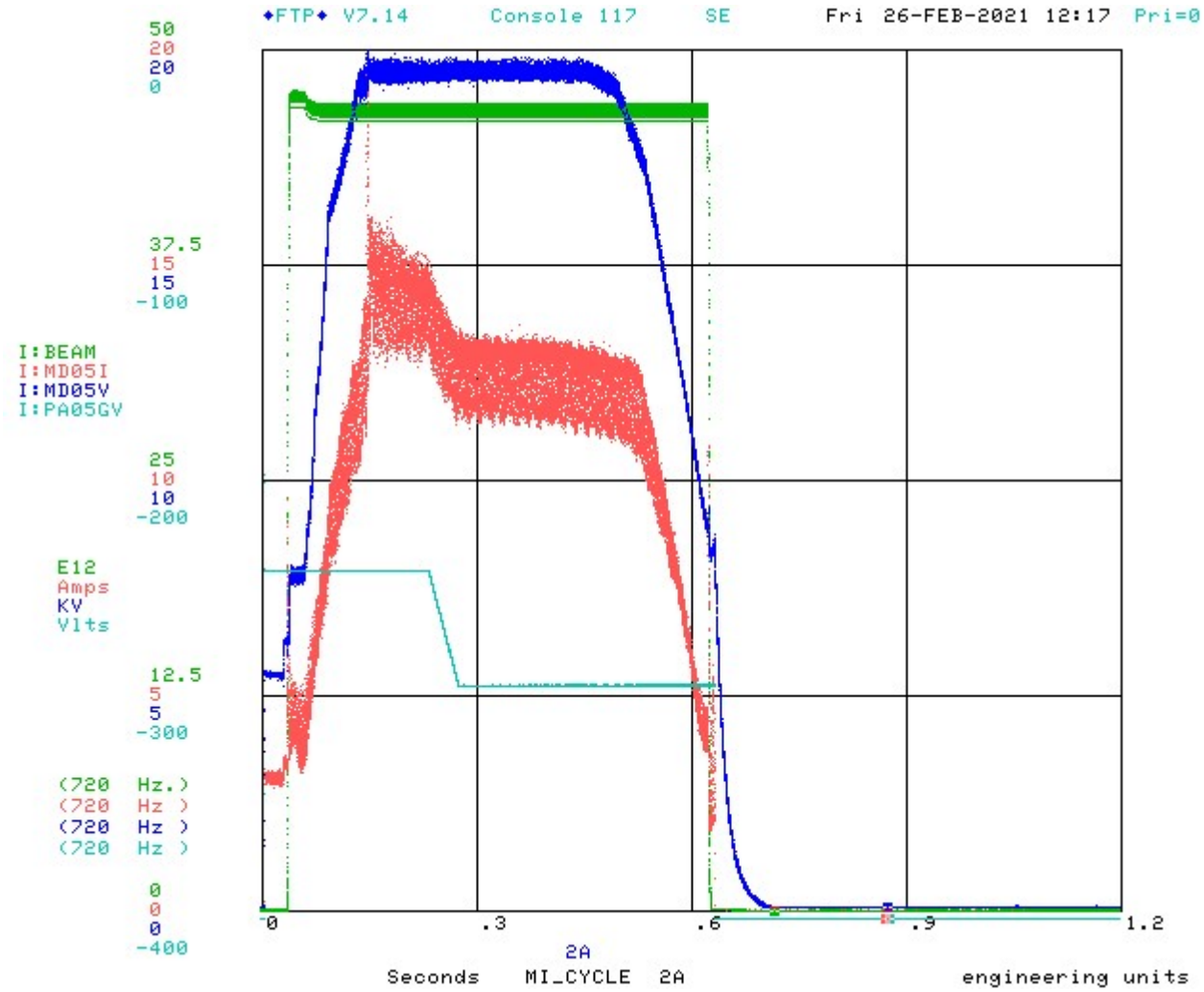


Figure 9.51: Main Injector upgraded RF cavity signals. (Green) Main Injector beam intensity, (Red) total plate current with two PAs, (Blue) PA anode voltage, (Cyan) PA grid bias voltage.

Operations of MI Station #5

Excerpt from PIP-II Final Design Report

ACE – Main Injector Enhancement

	ACE	PIP-II
Beam Intensity	7.5E13 Protons	7.5E13 Protons
Harmonic Number	588	588
Number of Filled Buckets	504	504
Frequency	52.808-53.104 MHz	52.808-53.104 MHz
Acceleration Ramp Slope	500 GeV/s	240 GeV/s
Beam Intensity	7.5e13 Protons	7.5e13 Protons
Main Injector Ramp Rate	0.65 s	1.2 s
Beam Power at 120 GeV	2.22 MW	1.2 MW
Beam Accelerating Power	6 MW	2.88 MW
Number of Accelerating Cavities	37	20
Cavity R/Q	104	104
Maximum Cavity Accelerating Voltage	240 kV/Cavity	235 kV/Cavity
Operating Peak Voltage	210 kV/Cavity	210 kV/Cavity
Accelerating Voltage Required: $V\sin\phi_s$	5.54 MV	2.66 MV
Total Voltage Available	8.9 MV	4.7 MV
Total Operating Voltage	7.8 MV	4.2 MV
Cavity Power Loss	45.11 kW/Cavity	45.11 kW/Cavity
Total Apparent Power	246.2 kVA/Cavity	240.5 kVA/Cavity
Robinson Stability Factor	4	4

Minimum bucket area after transition 1.8 eV-s

ACE – Main Injector Requirements

- Civil construction to add 17 Main Injector RF stations at MI-60
  - Additional chilled water capability
  - New electrical utilities
- Civil construction for three additional anode supplies
- Larger and improved cooling pond
- Removal of all NuMI items in the MI-60 tunnel straight section.
- 17 Main Injector cavities
- 34 200 kW power amplifiers
- 34 8 kW 53 MHz solid state amplifiers
- 17 dual series tube modulators
- 37 new bias supplies

ACE – Main Injector Requirements

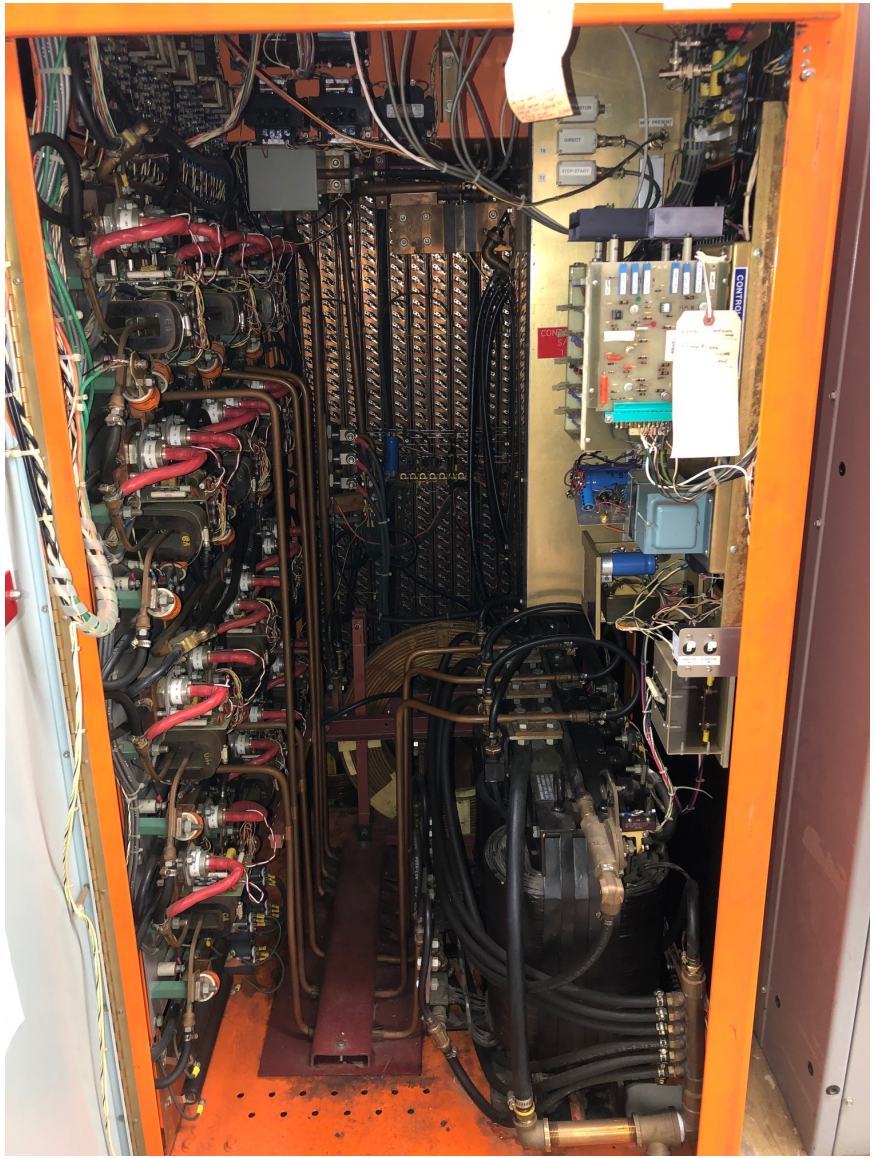
- Four new MI Solid State Longitudinal Damper Amplifiers
- PiRM for each station (IRM replacement)
- All new cable pulled for the 17 new stations
- LLRF would need to be updated to ARRIA 10 FPGA

ACE – Main Injector Requirements

MI Bias Supply

50-year-old design and numerous parts are outdated.

ACE would need 37.

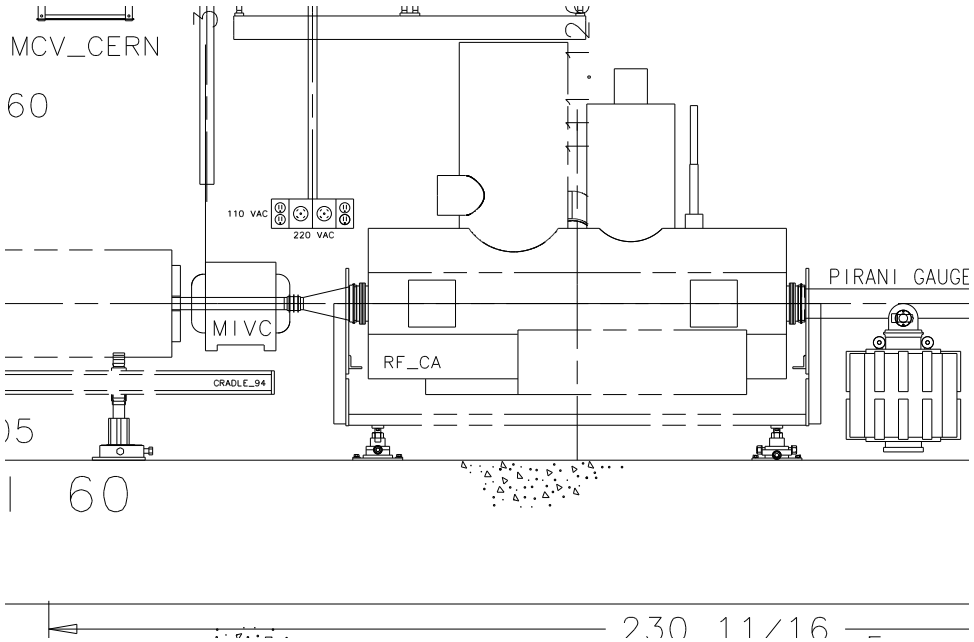


ACE – Main Injector Requirements

MI Anode Supplies

ACE would need an additional three.

ACE – Main Injector Requirements



17 Additional MI cavities

Arrangement between the quads in the tunnel.

ACE – Main Injector Requirements

MI-60 Electrical Utilities

Additional 13.8 kV utilities would need to be added for the anode supplies and stations.

ACE – Main Injector Requirements

MI-60 cooling pond – larger and needs to be improved.

ACE – Summary

- We have the power to accelerate at 500 GeV/s.
- Will require an additional 17 MI RF stations to maintain the same bucket area.
- Civil construction for additional RF gallery, penetrations, anode supplies, and transformers will be needed.

Backup Slides

ACE – Initial M&S Cost Estimates

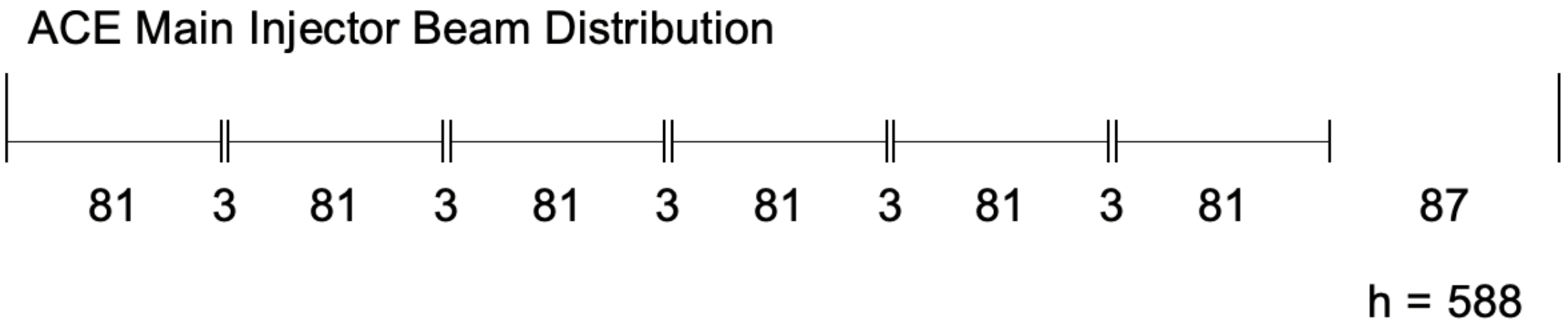
• Main Injector Bias Supply (41 @ $220 k)	$9.02 M
• Main Injector Cavities (18 @ $611 k)	$11 M
• Main Injector 200 kW Power Amplifiers (36 @ $44.2 k)	$1.59 M
• CPI Eimac Y567B vacuum tube (72 @ $27.76 k)	$2 M
• 8 kW 53 MHz Solid State Amplifier (56 @ $186 k)	$10.42 M
• Dual Series Tube Modulator (18 @ $142.9 k)	$2.57 M
• Solid State Amplifiers for Longitudinal Damper (4 @ $324K)	$1.3 M
• LLRF update	$40k
• PiRM (45 @ $2K)	$90k

ACE – Initial Labor Cost Estimates

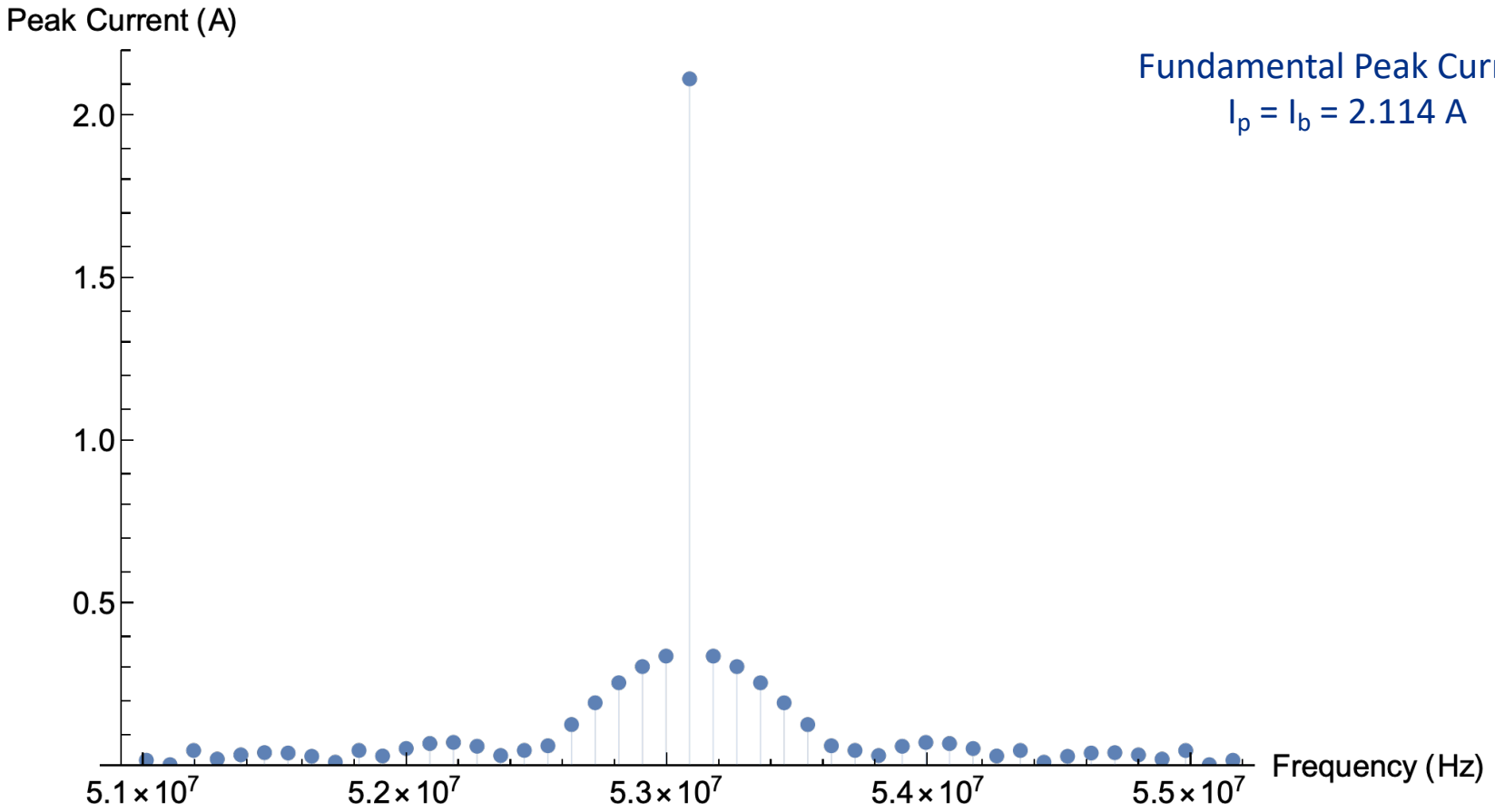
• MI Cavites	161,500 hrs
• Station Racks	28,339 hrs
• MI Cavity Installation	11,340 hrs
• Anode Supplies	24,000 hrs
• Power Amplifier assembly	7,200 hrs
• Modulator assembly	31,720 hrs
• Bias Supply assembly	82,000 hrs
• LLRF	12,000 hrs
• 8 kW Solid State driver testing and installation	2,000 hrs
• NuMI Removal	4,000 hrs
• PiRM install	2,000 hrs

(1,768 hrs = 1 FTE) Total of 366,099 hours = 207.1 FTE

ACE – Main Injector Enhancement – Beam Distribution



ACE – Main Injector Enhancement – 30 GeV Peak Current



Fundamental Peak Current
$I_p = I_b = 2.114$ A

ACE – Main Injector Enhancement – 30 GeV Robinson Stability

$\phi s = 39.8701$ deg

Beam Current (Ip) = 2.11426 A

Number of Cavities = 36

R/Q = 104 Ω

Q = 4700

Cavity Voltage = 240. kV

Cavity Power Loss per Cavity = 58.9198×10^3 W

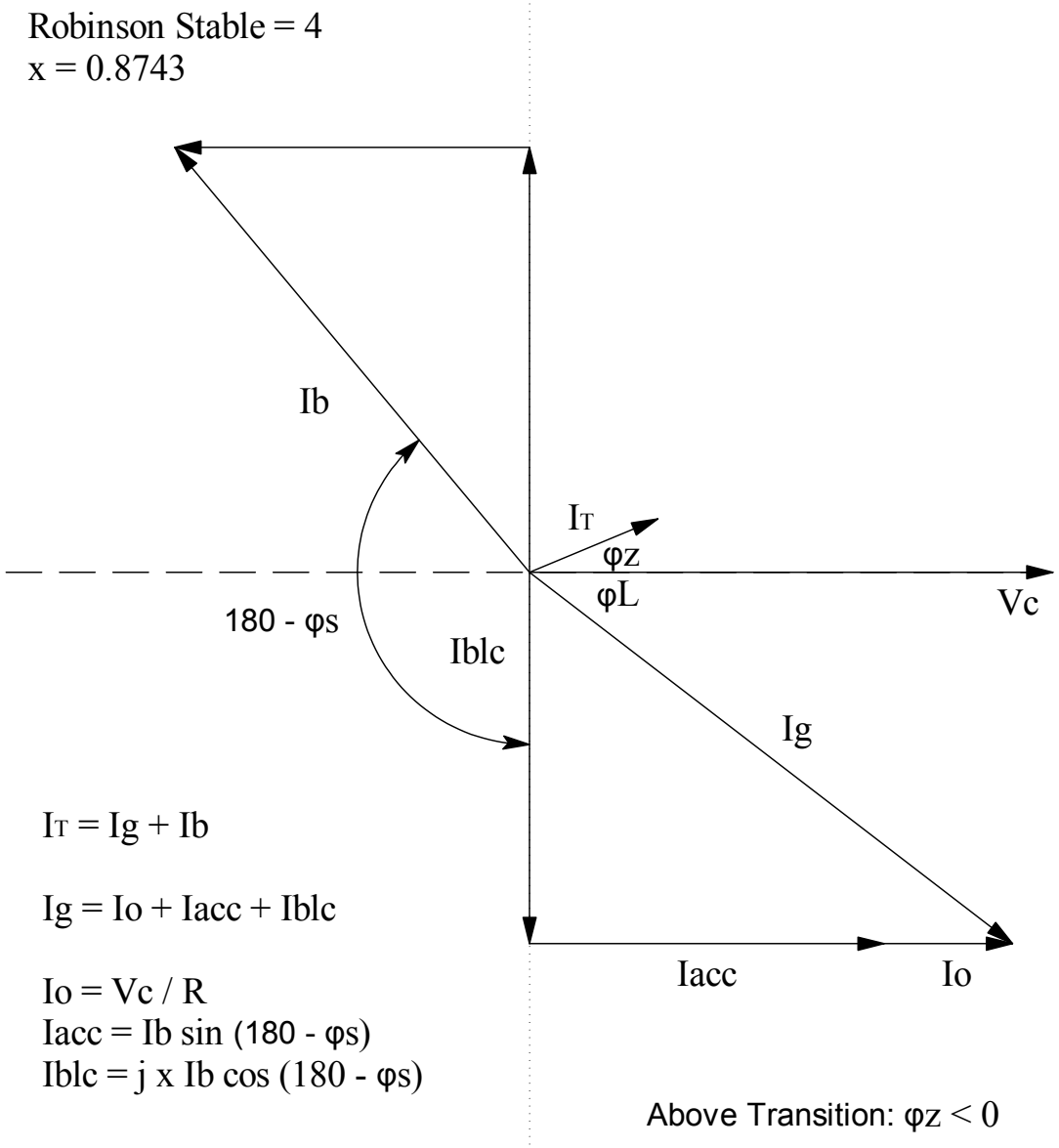
Total Apparent Power = 279.427×10^3 VA ∠ 37.5416 degrees

Total Current = 2.32856 A ∠ 37.5416 degrees

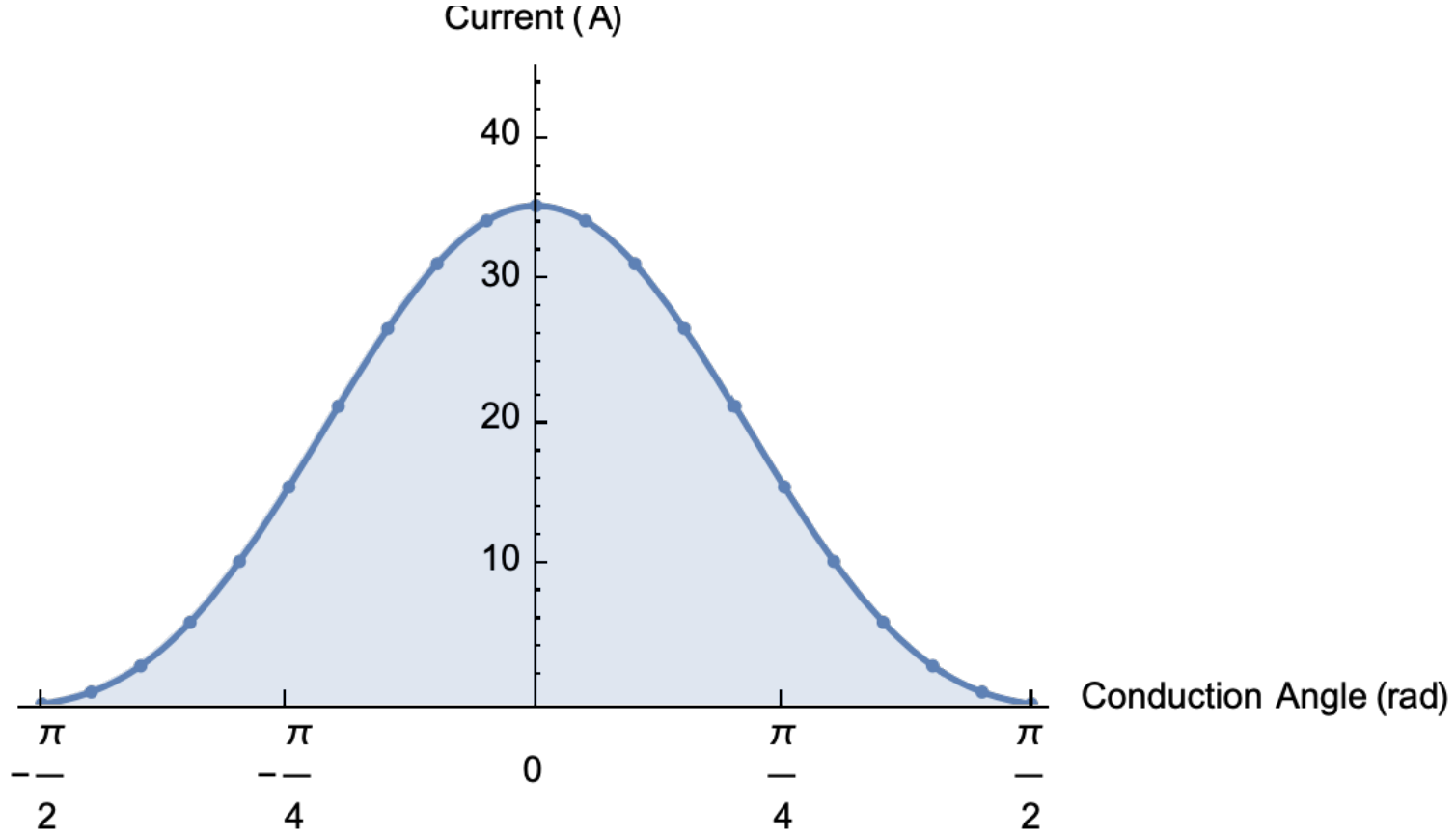
Percent of Induced Mode Compensated = 18.02 dB = 87.4397 %

Robinson Stable = 4.00762

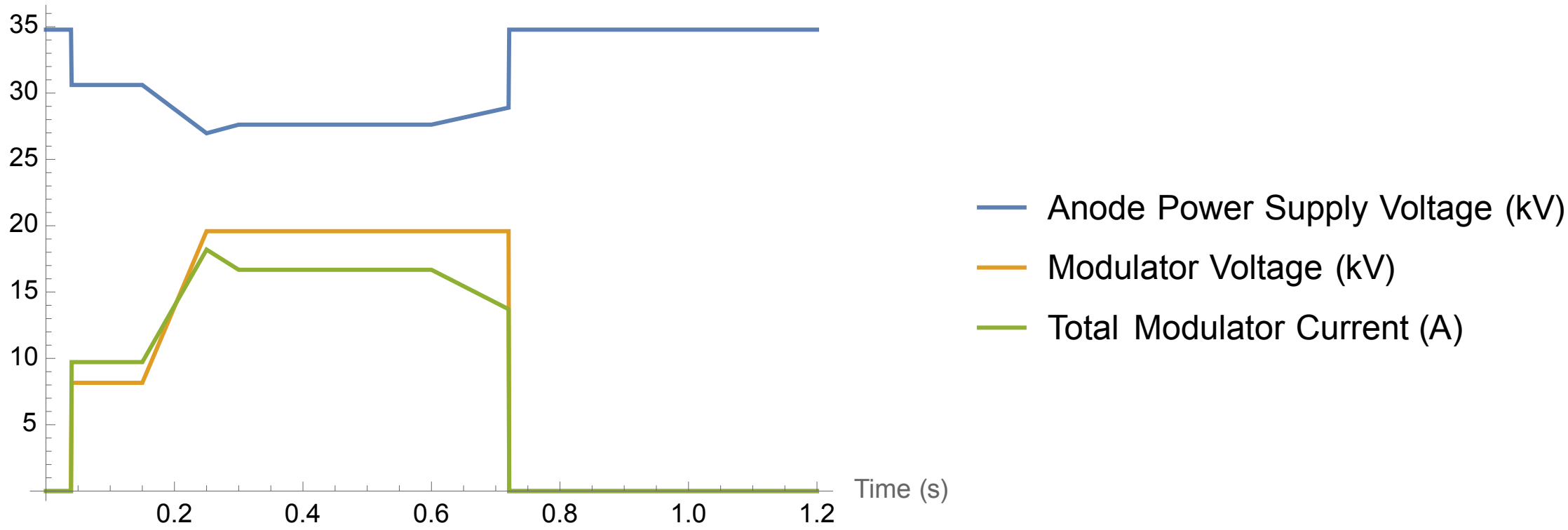
ACE – Main Injector Enhancement – 30 GeV Vector Diagram



ACE – Main Injector Enhancement – 30 GeV Vector Diagram



ACE – Main Injector Enhancement – Modulator



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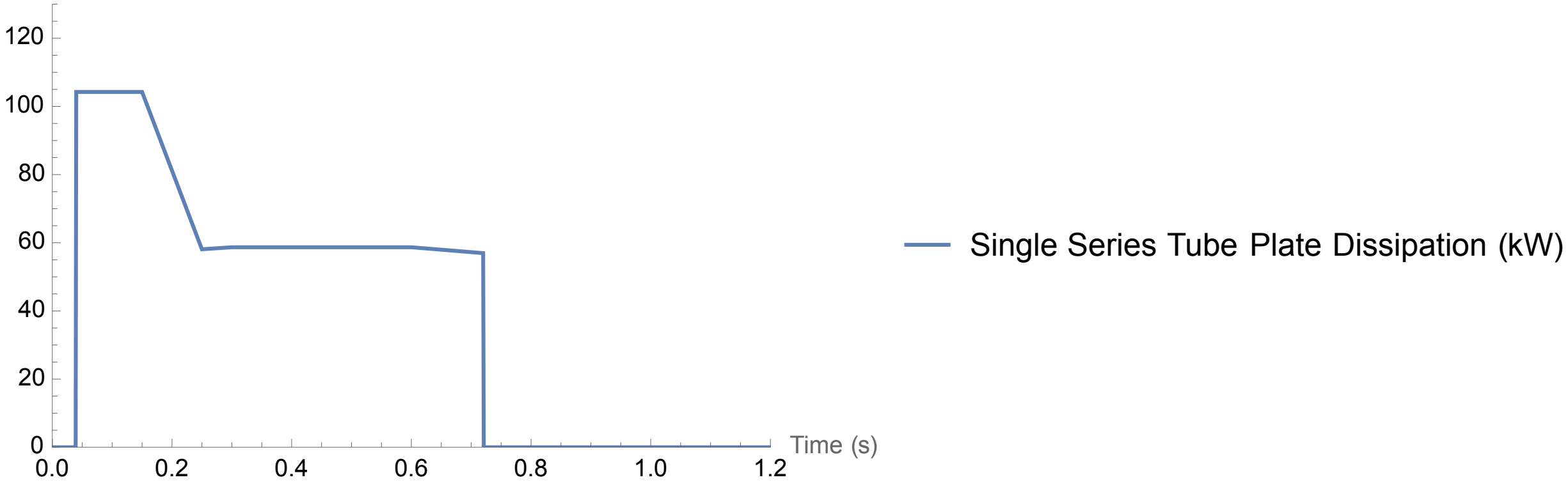
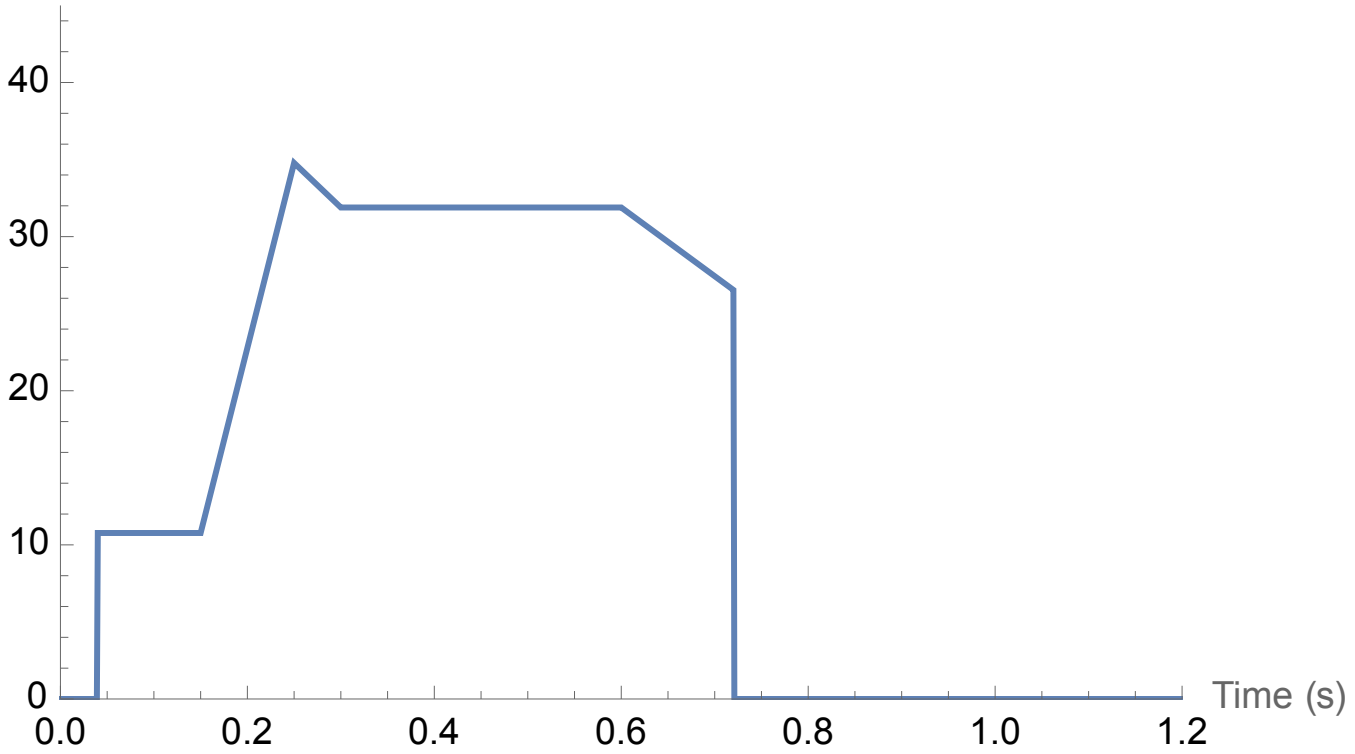
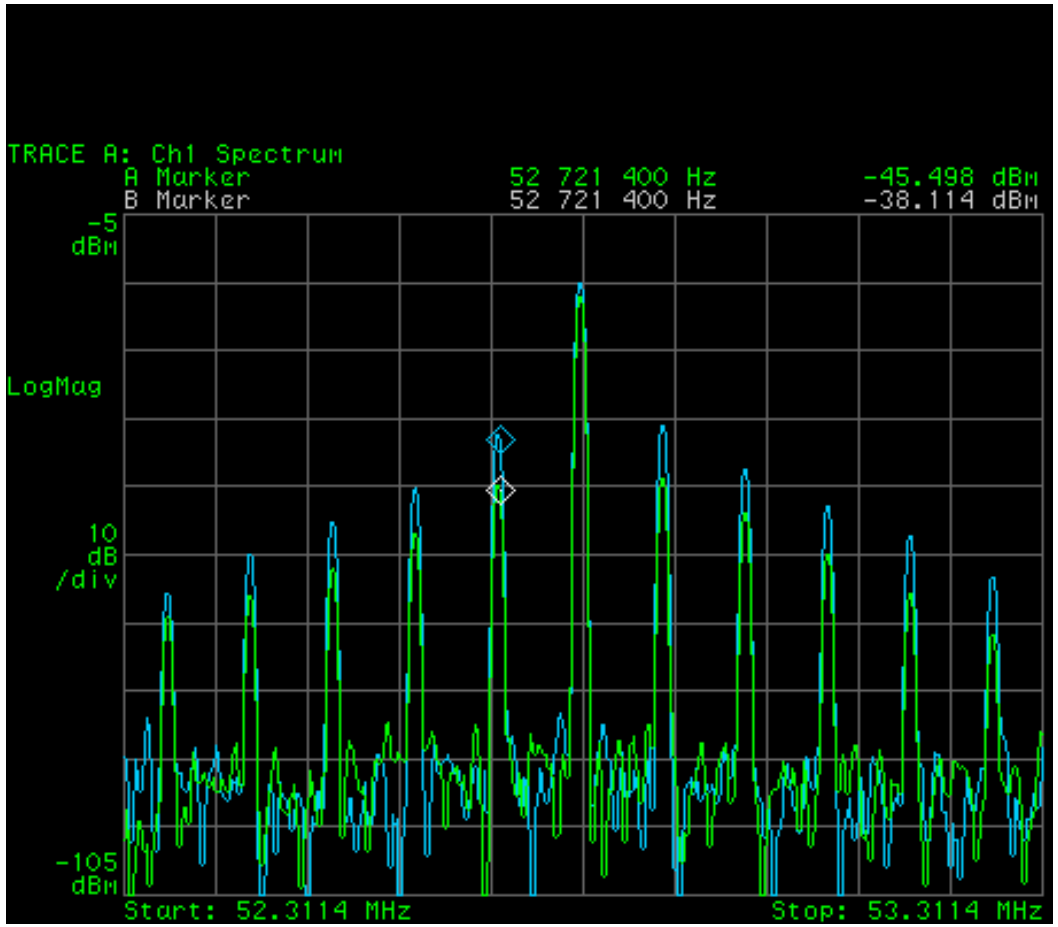


ACE – Main Injector Enhancement – Modulator



ACE – Main Injector Enhancement – BLC



Feedforward Beam Loading Compensation and Direct RF Feedback is used on each of the Main Injector stations to obtain a Robinson Stability factor of 4.