Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Fermilab Accelerator Complex: Status, Progress, and Upgrade Plans

Phil Adamson
Fermilab
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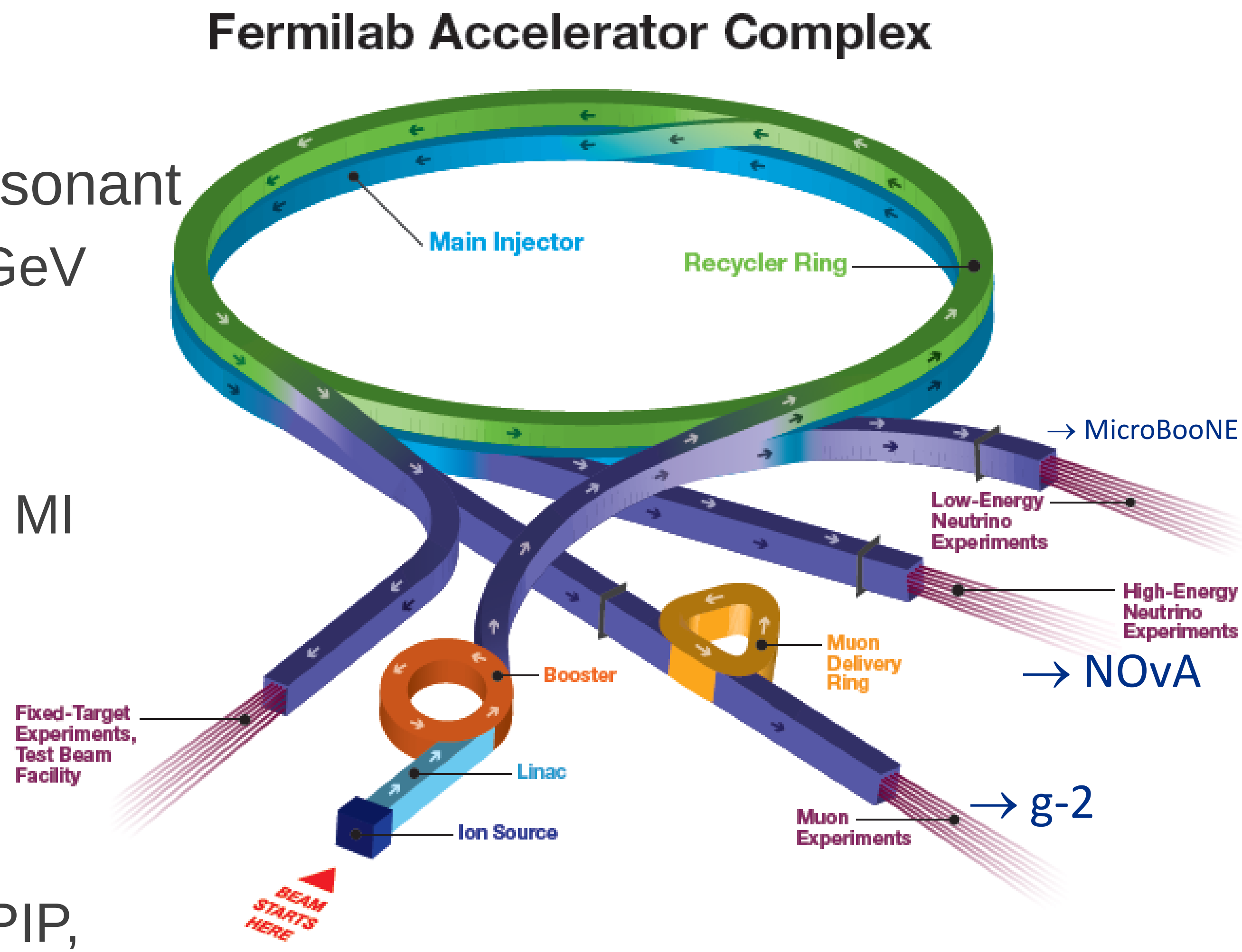
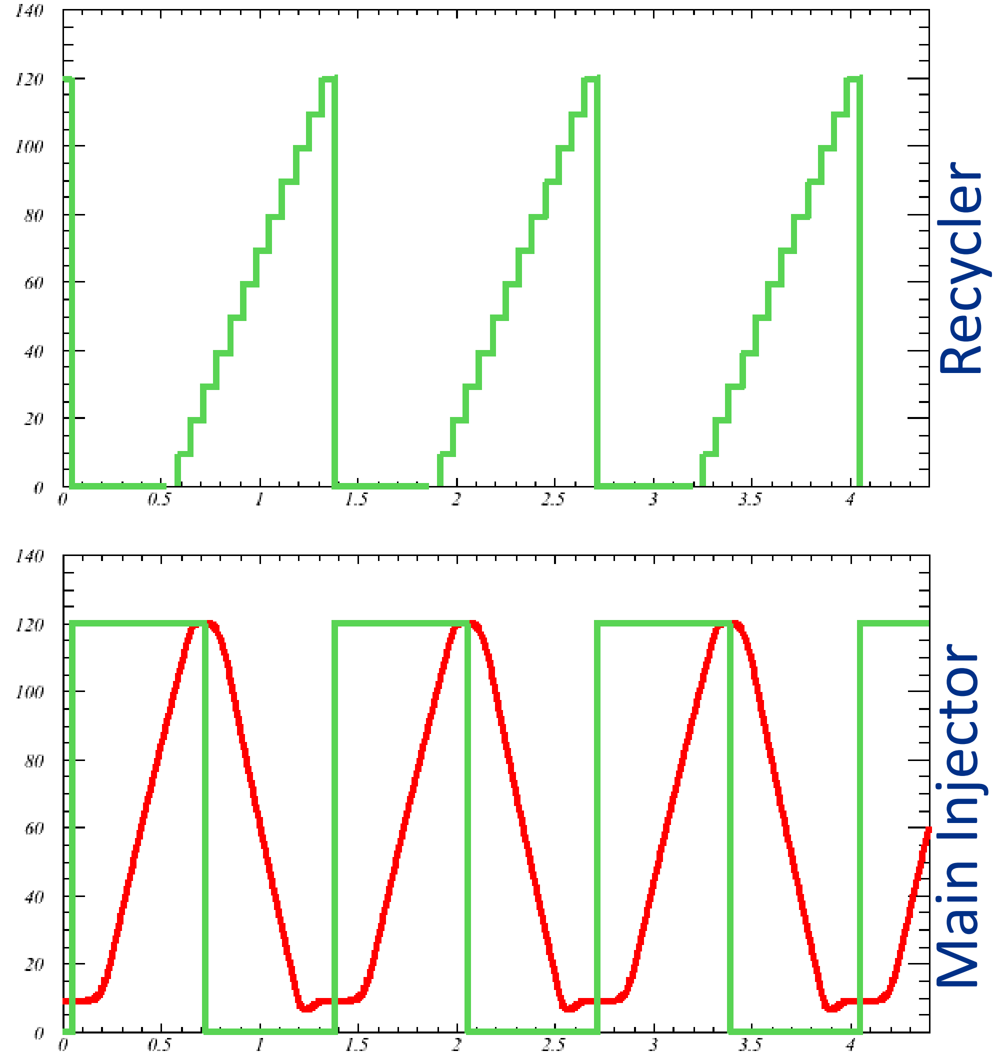
Fermilab Accelerator Complex

- 15 Hz H$^-$ linac
  - -> 400 MeV
- Booster: 15Hz resonant
  - 400 MeV -> 8 GeV
- Recycler
  - 8 GeV fixed
  - Stack beam for MI
- Main Injector
  - 8 -> 120 GeV
- Current status thanks to
  - NOvA project, PIP, ongoing upgrades



NOvA project: Scheme to increase beam power

- Move slip-stacking to Recycler
  - 11 batch -> 12 batch
    - (faster kickers)
- Increase MI ramp rate (204 GeV/s -> 240 GeV/s)
  - 1.33s cycle time
- 380 -> 700 kW with only ~10% increase in per-pulse intensity
  - Don’t expect new beam physics issues
  - ~ double protons through Linac / Booster: need PIP



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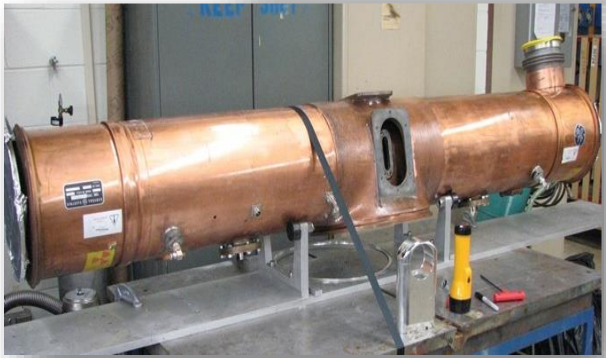
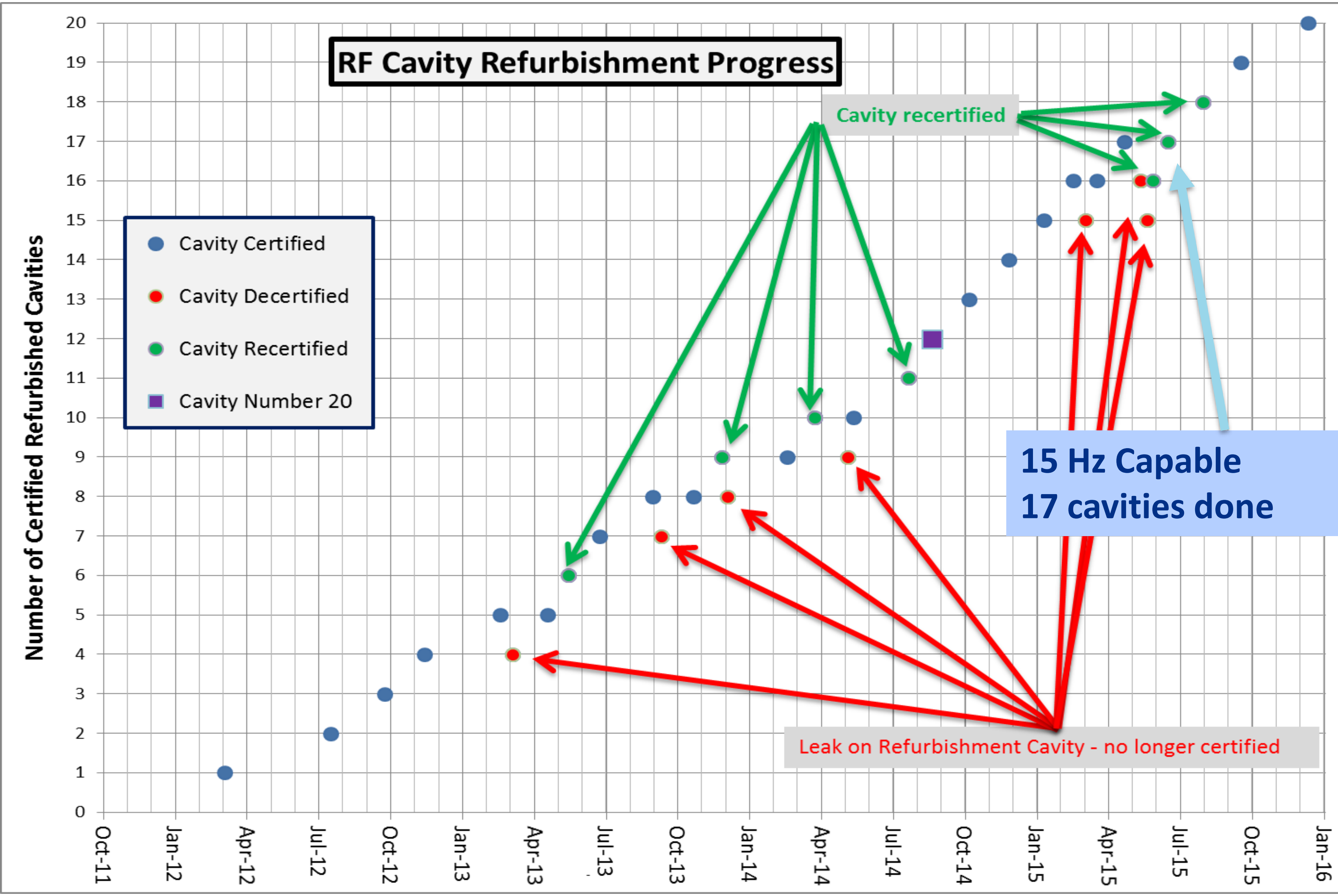
PIP: 15 Hz

- Identify all systems not capable of 15 Hz
  - Booster RF System
    - Anodes: Replace original anodes with modern dry transformer sys
    - **Cavities**: Refurbish all cavities - replacing/repairing/adding cooling
    - Drive Systems (Bias Supplies) – Developed a SS drive and updated Bias supply to handle power
    - Power distribution to tuners (Bus Bar) – improved bus connections
  - Controls/Data acquisitions
    - 15 Hz clock with no gaps – many systems used null in processing
    - Beam diagnostics – collecting BPM data at 15 Hz
  - Booster Kickers
    - Inadequate cooling of loads
    - Inadequate cooling of thyratron

PIP: Booster Cavity Refubishment

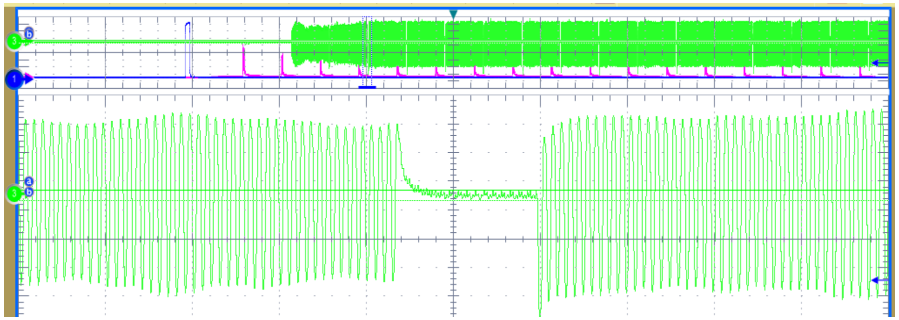
- Booster cavities were new in 1969
- Refurb began Jan 2012
- Booster had 19 cavities
  - Remove two at a time for upgrade
  - 17 is minimum for 4.3E12 ppp
- 17th cavity installed July 2015
  - Begin 15 Hz commissioning
- Now 22 cavities




RF Cavity Refurbishment Progress
Cavity Certified
Cavity Decertified
Cavity Recertified
Cavity Number 20
Number of Certified Refurbished Cavities
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Oct-11
Jan-12
Apr-12
Jul-12
Oct-12
Jan-13
Apr-13
Jul-13
Oct-13
Jan-14
Apr-14
Jul-14
Oct-14
Jan-15
Apr-15
Jul-15
Oct-15
Jan-16
Cavity recertified
15 Hz Capable
17 cavities done
Leak on Refurbishment Cavity - no longer certified

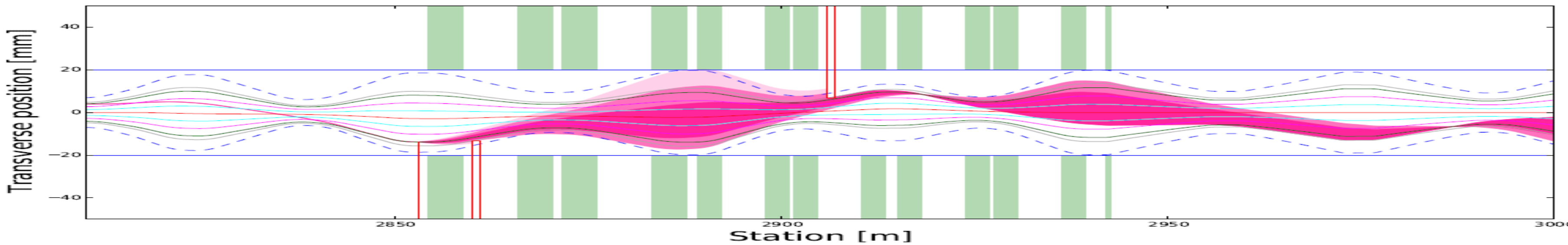
Beam Loss Matters – some highlights

- Linac Laser notch
  - Neutralize H^- with laser at 750 keV to make space for Booster extraction kickers
  - No notching loss in Booster

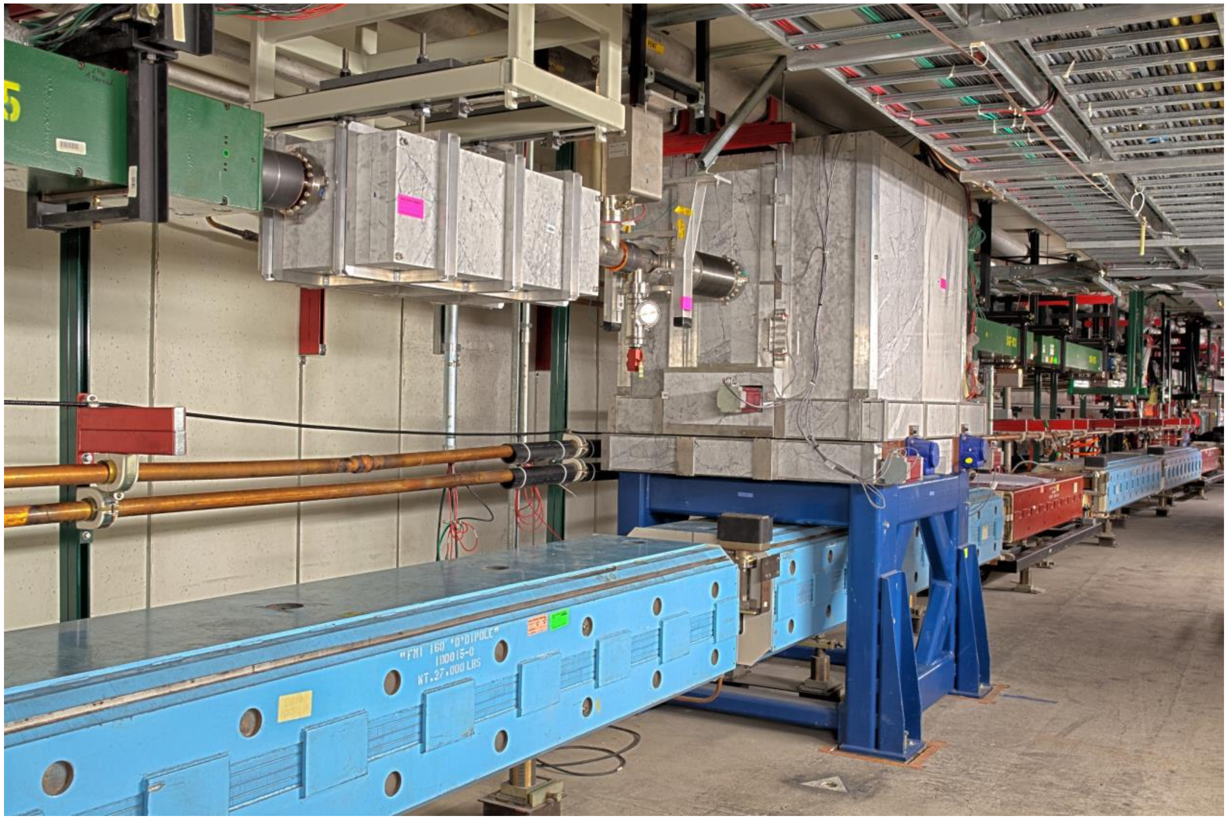


- Booster improvements
  - Lattice correction
  - Aperture improvements – align magnets
  - Magnetic cogging – keep beam in magnet centers (clean fields)
  - Improved transition control & lock to MI/RR
- Main Injector / Recycler
  - New collimators to localize losses
  - Transverse dampers during slip-stacking

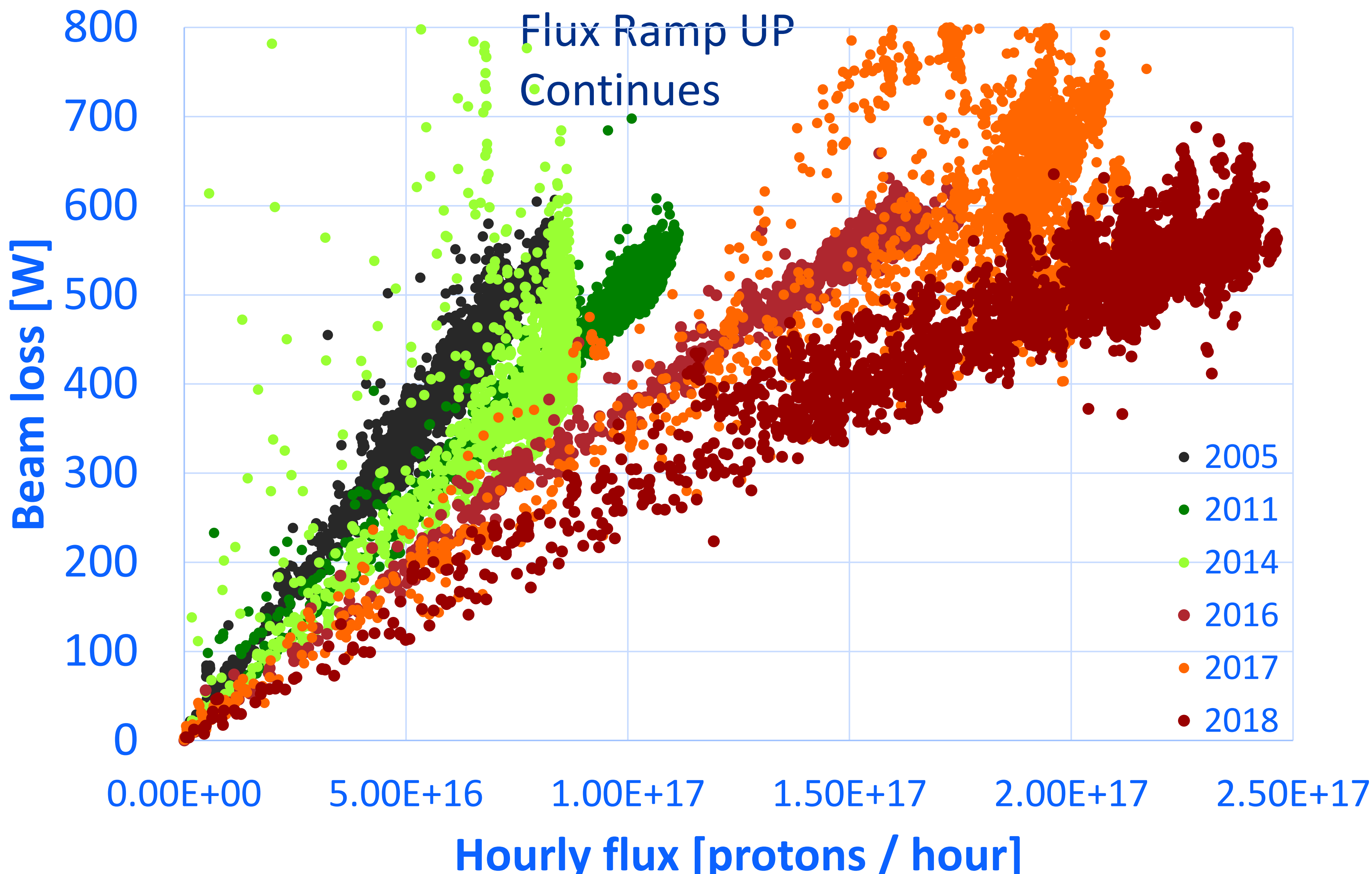
Recycler Collimators



- 2-stage collimation
  - Thin scatterer
  - Two 20 ton steel absorbers
    - Marble clad

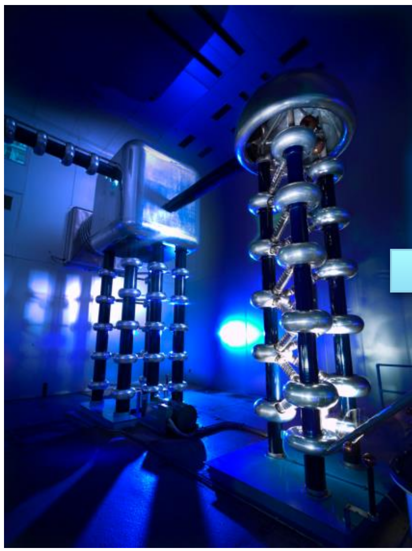


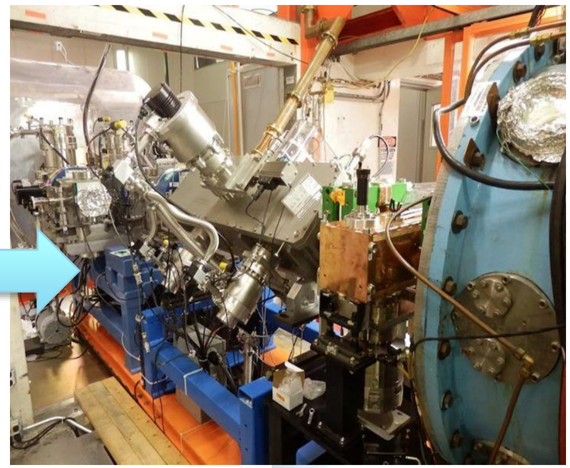
Booster Loss Limit ~PIP goal of 2.4E17 pph



PIP: reliability

- Headline power is nice, but physics needs Protons on Target (= power × uptime)
- Replace old equipment with modern, robust replacement





- Get better beam quality too!

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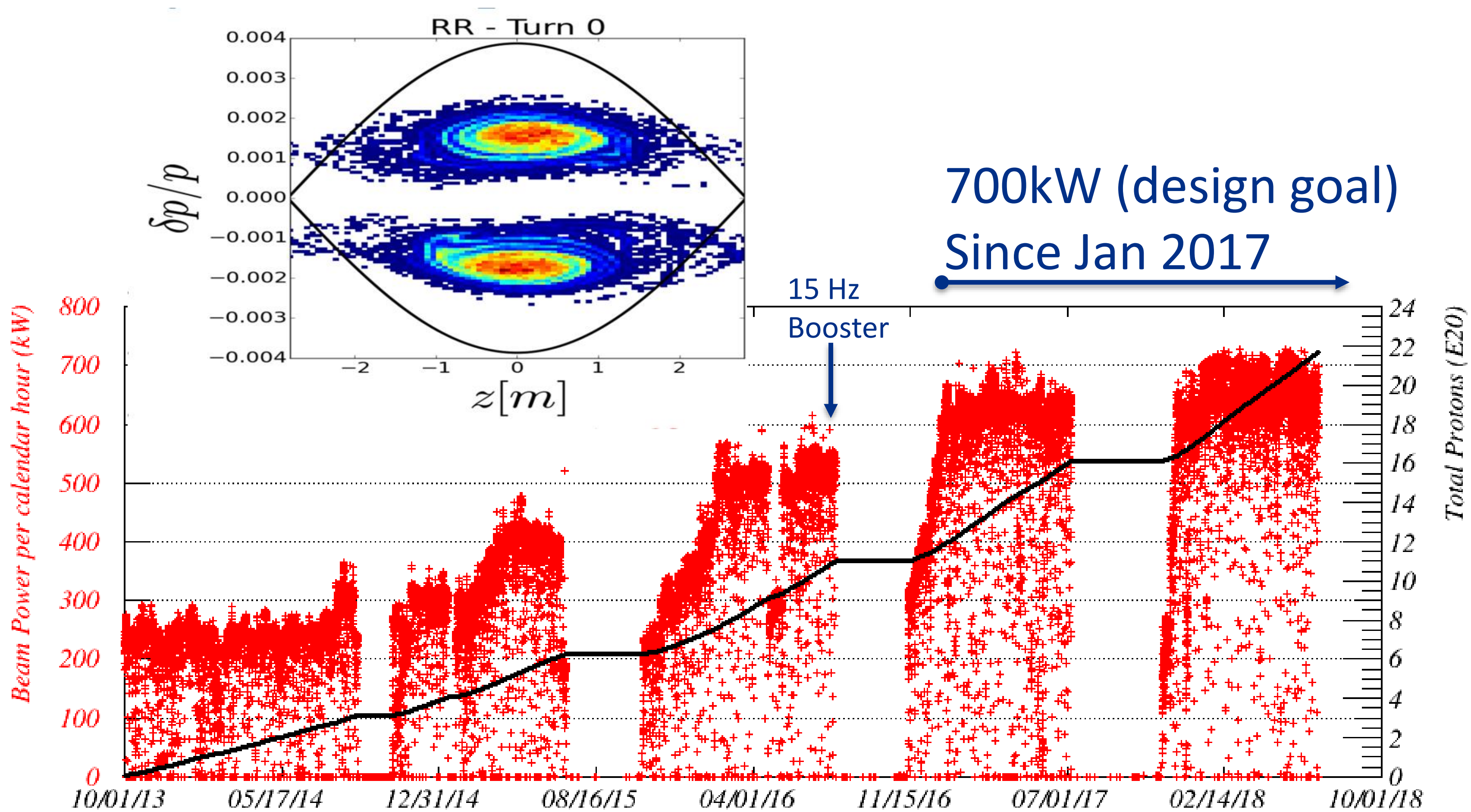
NuMI beam power since start of NOvA



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

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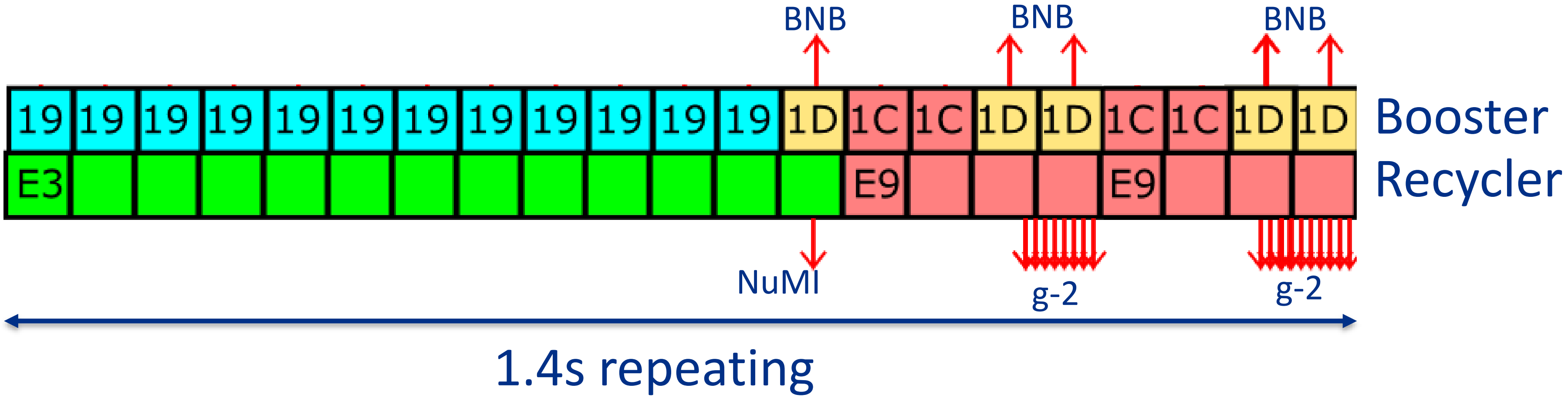
Current Status

- Routinely running 700kW to NuMI
- Routinely running g-2 at design intensity
- Routinely running >5×10^{16} protons per hour to BNB
- ~All 15Hz pulses have beam
- Beam to LBNF in ~2027 (see Heidi's talk next)
  - Current complex not enough -> PIP-II
- Near-term plan to increase NOvA physics yield -> "PIP-I+"



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How could we increase beam power to NOvA?

- Shorten Main Injector (MI) cycle time to 1.2s
  - 11% increase from design (1.33s→1.2s)
  - This capability is close to being available, but…
  - Cuts rate to Muon Campus experiments in half unless also increase repetition rate to 20 Hz
- Increase rep rate from 15 Hz to 20 Hz
  - Requires significant control system changes
  - Requires RF upgrades in Linac, Booster and MI/Recycler
- Increase intensity from Proton Source
  - 28% increase (4.3 E12 → 5.5 E12 protons per pulse)
  - Requires improvements to keep beam quality up and reduce losses even further than achieved by PIP
- All of these require a target station that is robust at 1 MW

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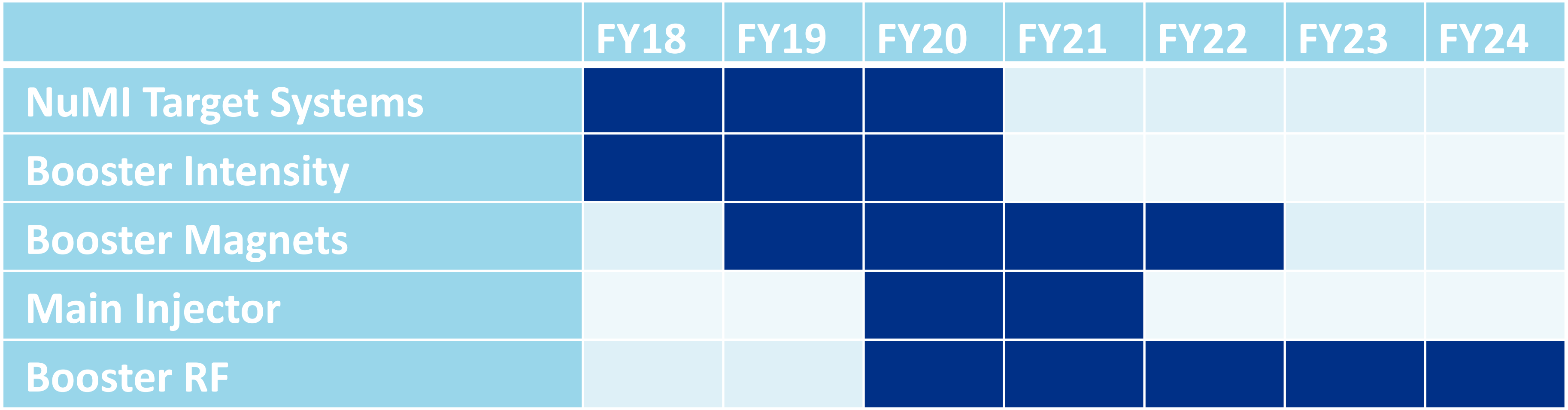
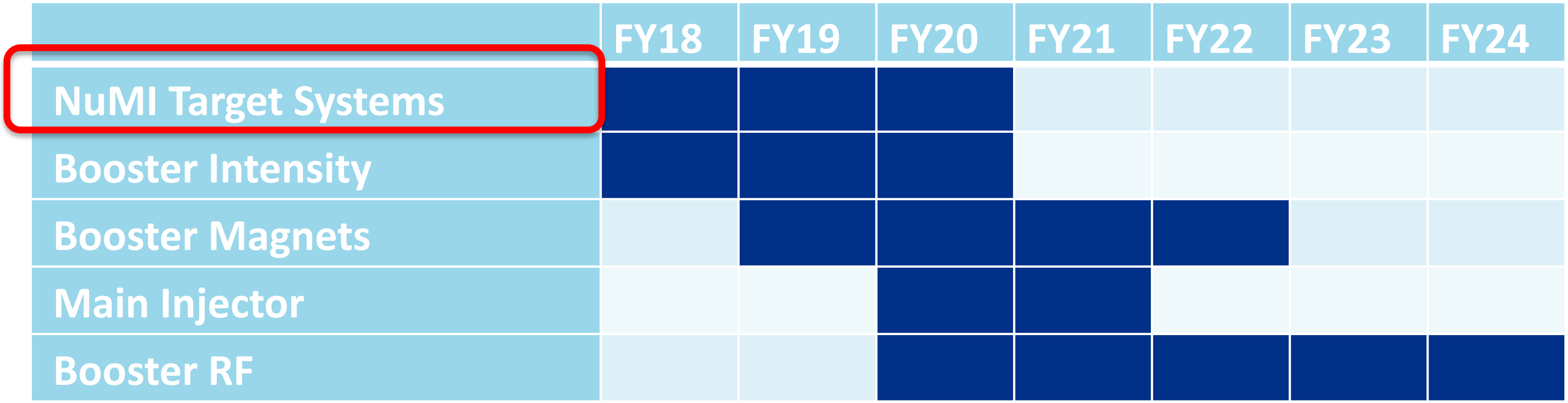
“PIP-1+”: Plan for upgrades for 900kW

- Series of independent Accelerator Improvement Projects



- Includes production and installation of new Booster RF cavities which were prototyped on PIP
  - Larger aperture, 20-Hz capable for PIP-II

“PIP-1+”: Plan for upgrades for 900kW

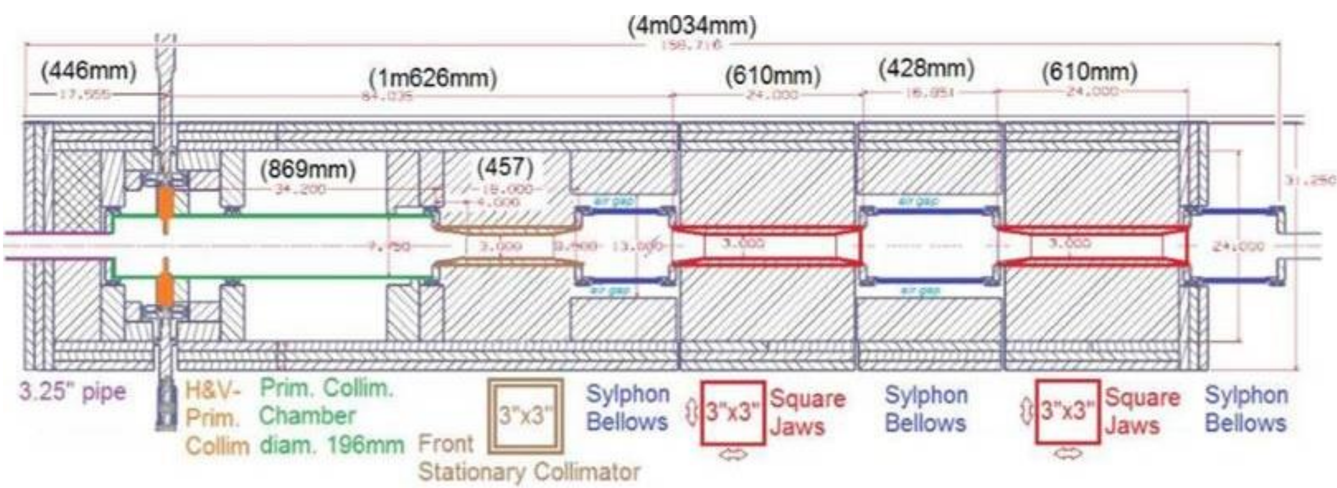


- Thermal issues in target hall components
  - Dynamic stress
  - cooling
- Increased radioactivation
- Aging infrastructure

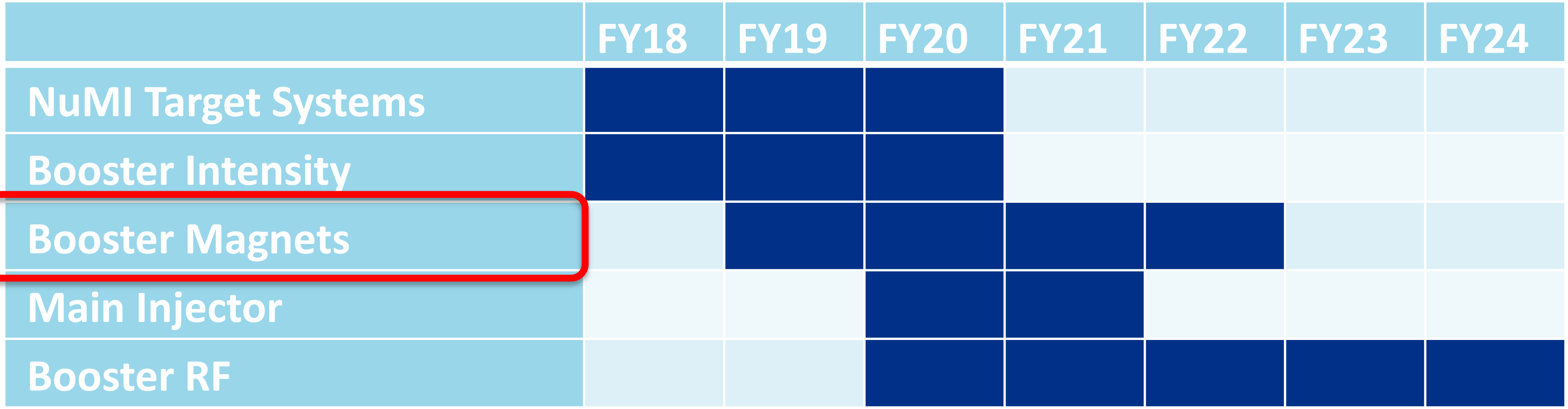
“PIP-1+”: Plan for upgrades for 900kW

	FY18	FY19	FY20	FY21	FY22	FY23	FY24
NuMI Target Systems	■	■	■				
Booster Intensity	■	■	■				
Booster Magnets		■	■	■	■		
Main Injector			■	■			
Booster RF			■	■	■	■	■

- Improved transverse dampers to reduce loss
- New collimators to contain loss

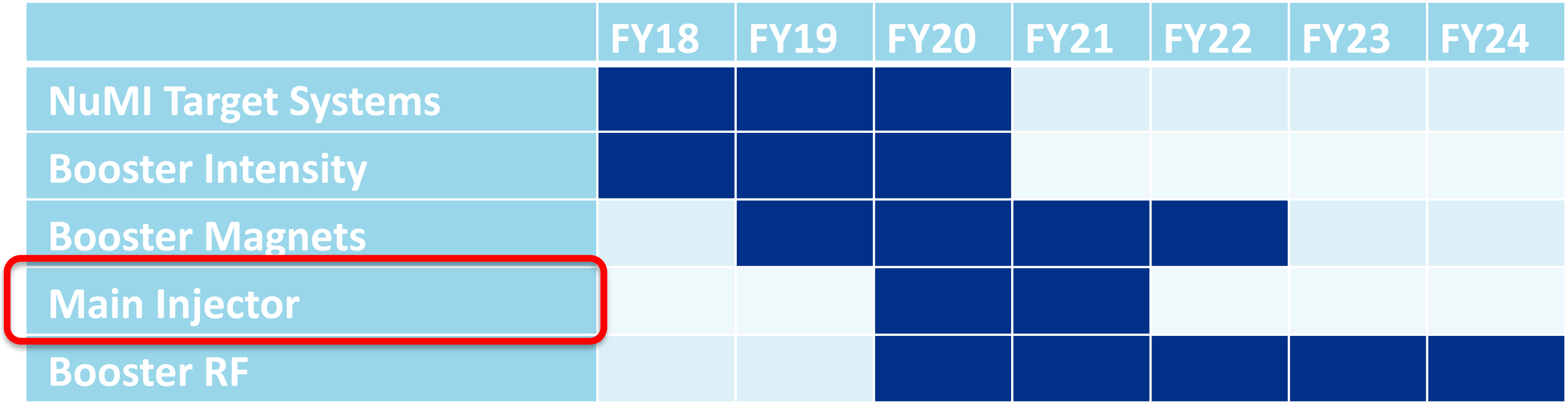


“PIP-1+”: Plan for upgrades for 900kW

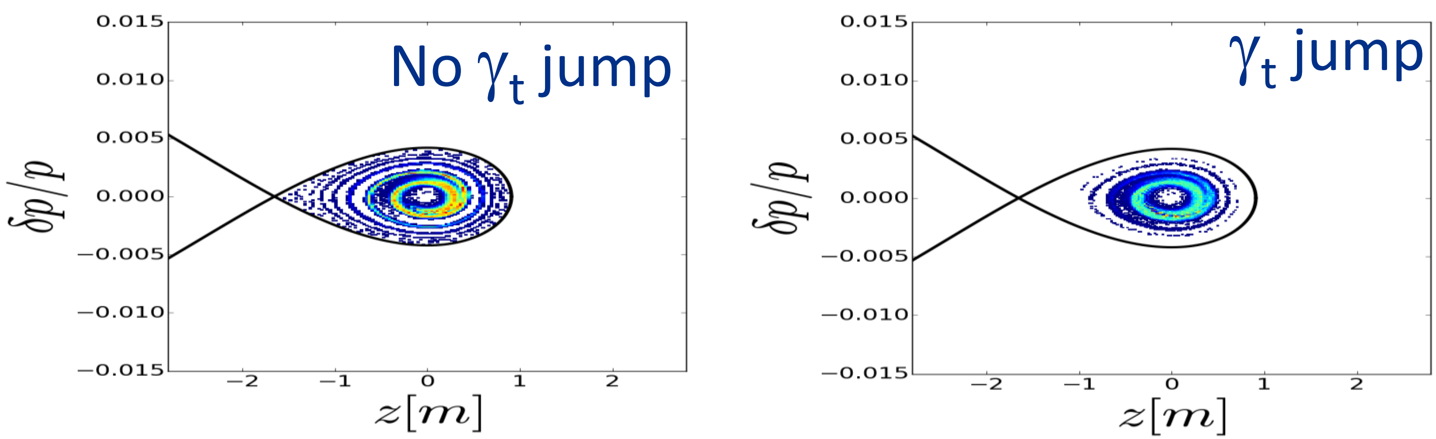


- New defocusing gradient magnet: shorter, with larger aperture

“PIP-1+”: Plan for upgrades for 900kW



- γ_t jump
  - Pulsed quads to cross transition rapidly

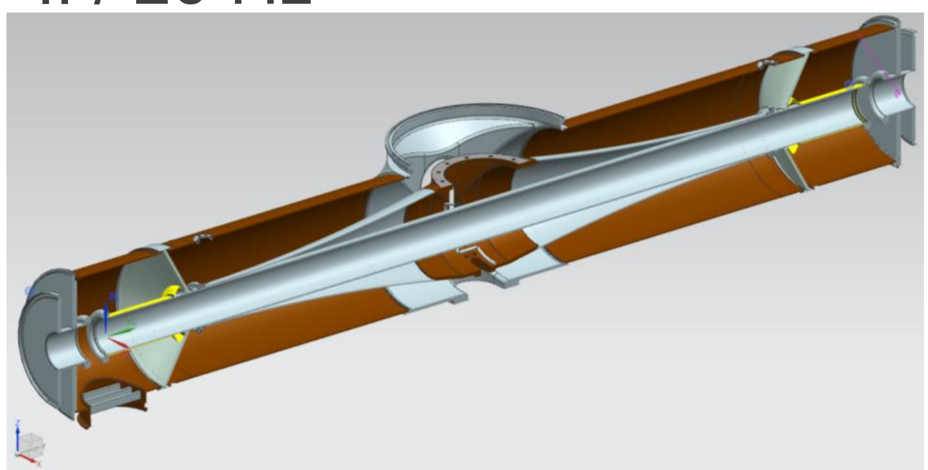


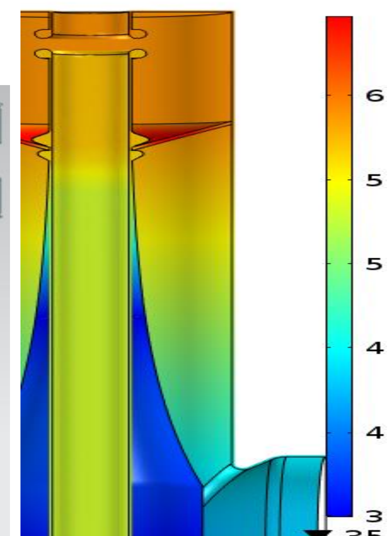
MI at 40 GeV

"PIP-1+": Plan for upgrades for 900kW

	FY18	FY19	FY20	FY21	FY22	FY23	FY24
NuMI Target Systems	■	■	■				
Booster Intensity	■	■	■				
Booster Magnets		■	■	■	■		
Main Injector			■	■			
Booster RF			■	■	■	■	■

- 20 new cavities, 60 kV, also larger aperture
  - Need for PIP-II / 20 Hz
  - Useful early





The PIP-II Project

Mission

PIP-II will deliver the world's most intense beam of neutrinos to the international LBNF/DUNE project, and enable a broad physics research program, powering new discoveries for decades to come.

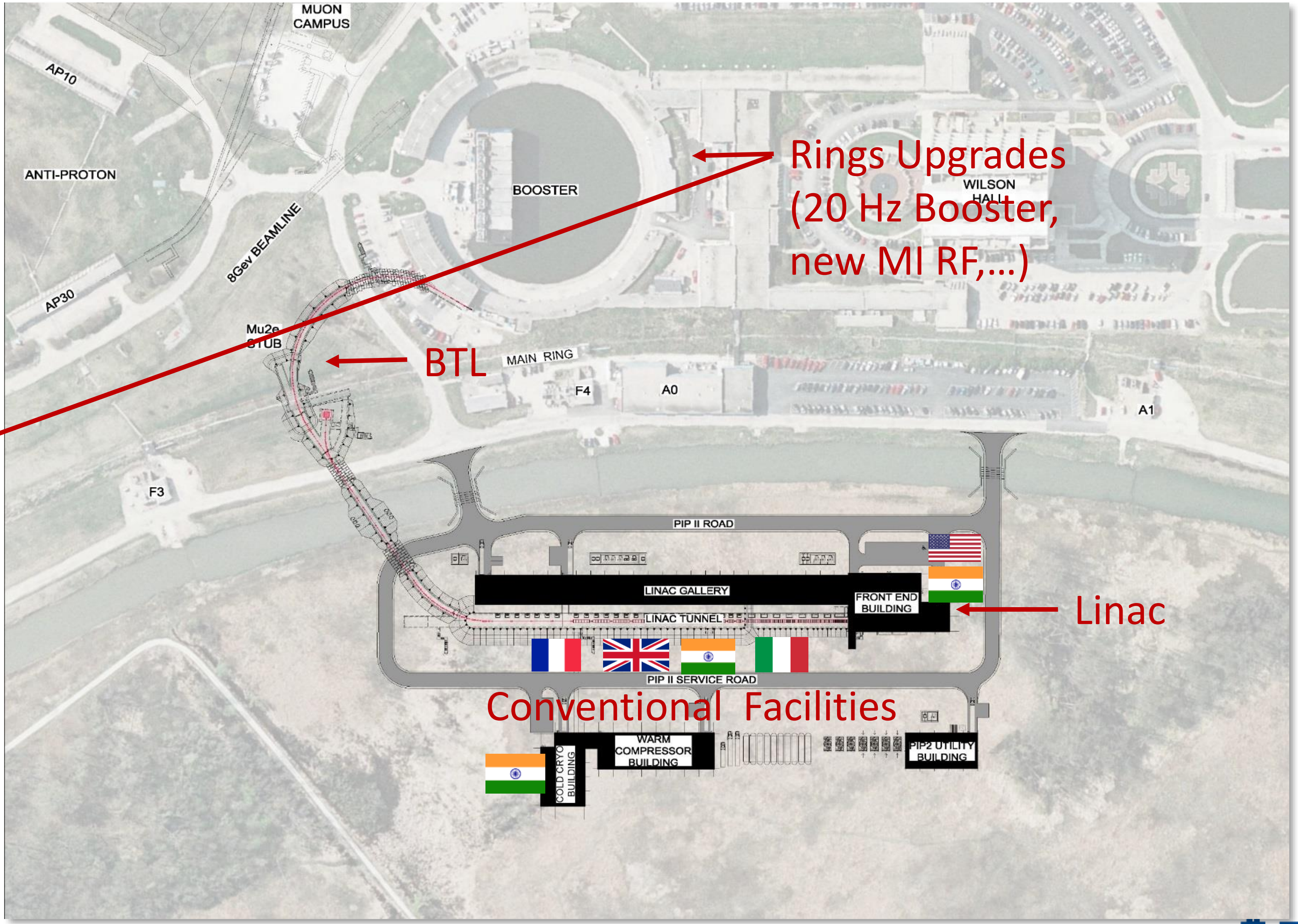
Goals

- Deliver 1.2 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF ops
  - Provide a platform for extension of beam power to LBNF to >2 MW
- Provide a platform for extension of capability to high duty factor/higher beam power and reliable beam operations
  - Support the ongoing 8 GeV program, including an upgrade path for Mu2e

PIP-II Main Features

- A modern SCRF cw-compatible H- linac
  - 1.6 MW at 800 MeV, upgradable energy
    - $\Delta Q_{sc} \sim N_{max}/(\varepsilon \times \beta\gamma^2)$ for Booster injection
  - The H- beam allows stripping injection as well as various laser-based beam manipulations
  - Arbitrary bunch-by-bunch chopping capability
  - Future rf beam splitter would allow multiple users receive beam concurrently
- Main Injector and Booster upgrades allowing for 1.2 MW and multi-MW beam power in the future
- First step towards upgrading Fermilab's aging accelerators

PIP-II: First International Accelerator Project in US



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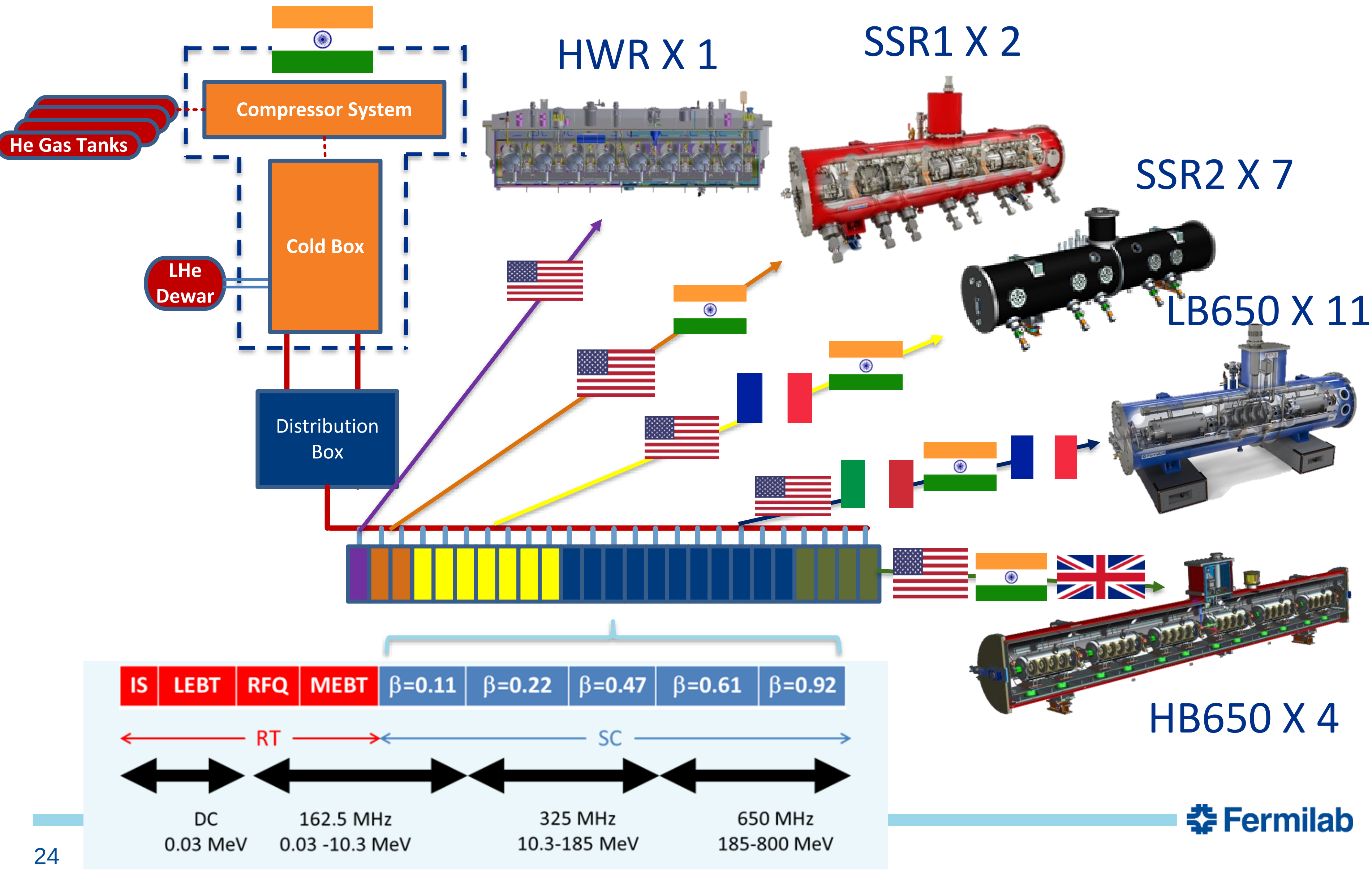
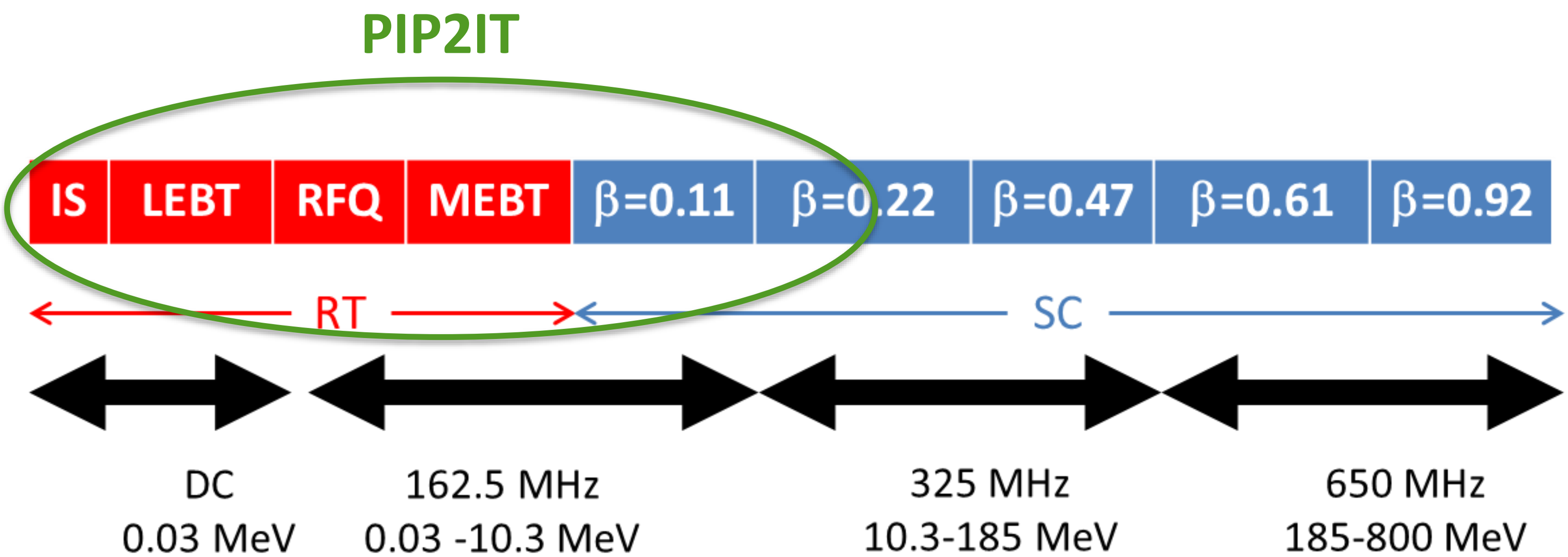
PIP-II Superconducting Linac (cw-capable, 800 MeV, 2 mA)

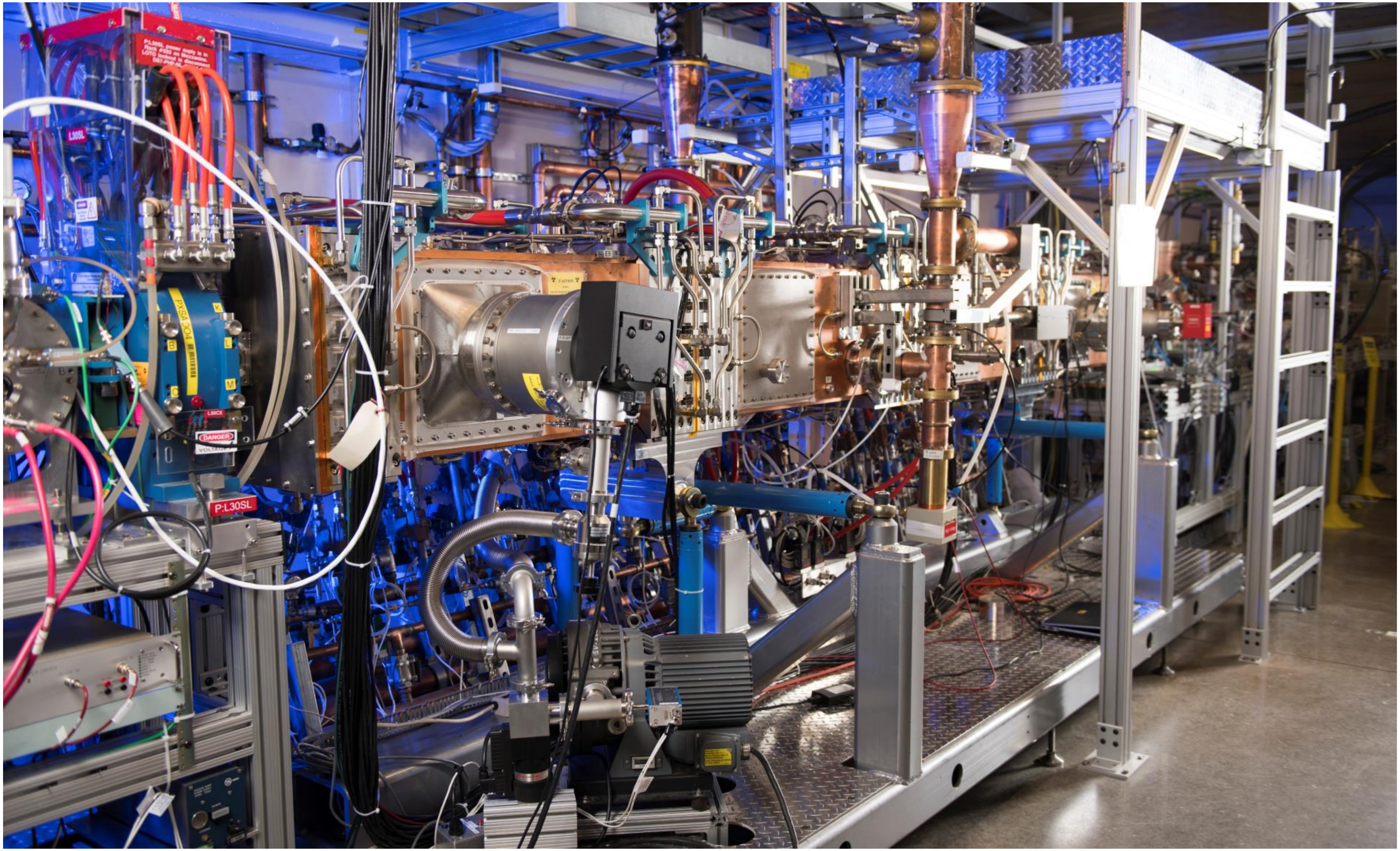


PIP-II has a mature, validated technical design



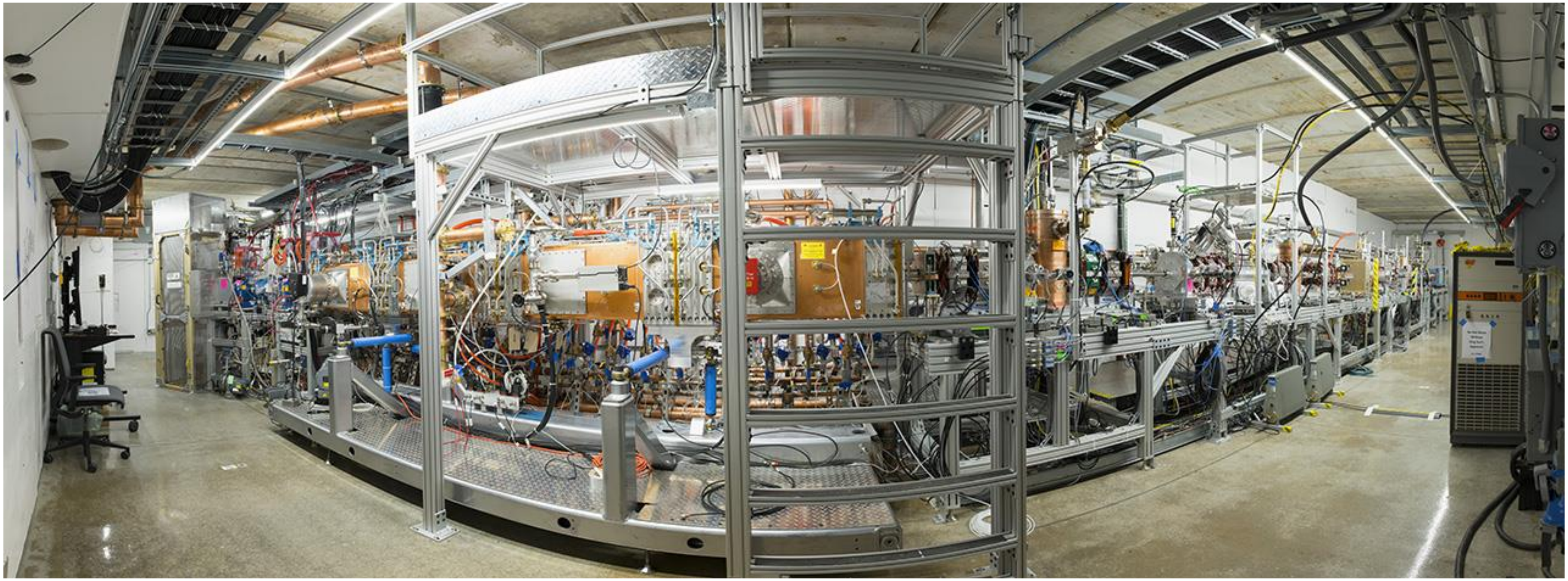
PIP2IT is a complete systems-integration of the PIP-II Front End - coming to completion in FY21

PIP-II: RT front end – a cw 162.5 MHz RFQ



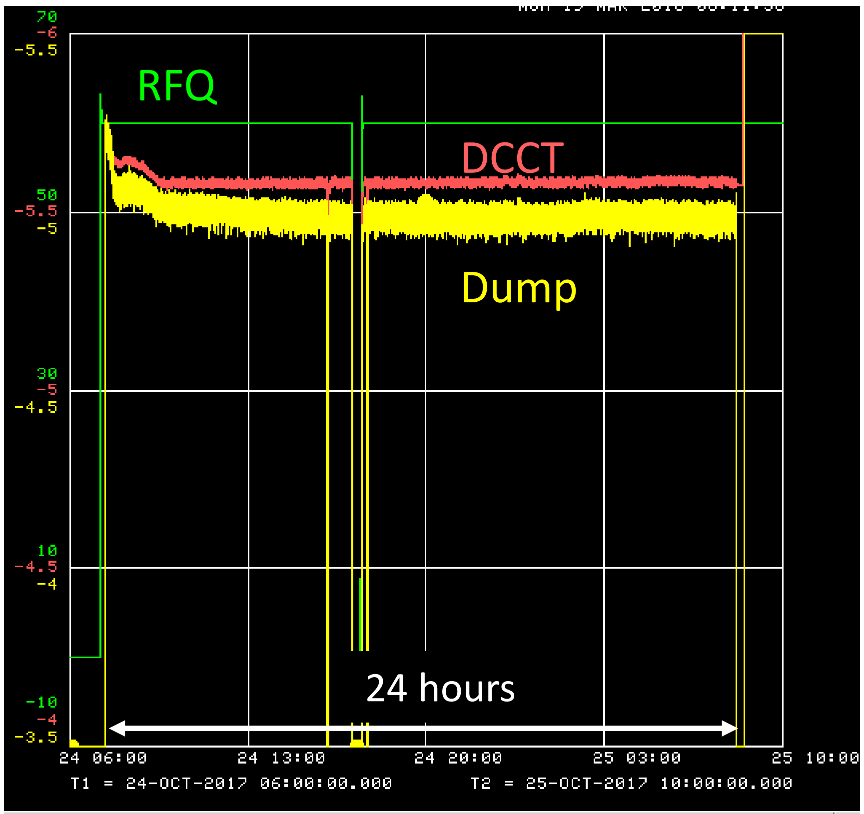
PIP-II Front End (Injector) Test

A collaboration of Fermilab, LBNL, ANL, SNS and Indian partners



Beam through full length MEBT

- Demonstrated transporting the beam at “CDR parameters” through the final-length PIP2IT MEBT for 24 hours
  - 5 mA × 0.55 ms × 20 Hz × 2.1 MeV



0.5 mA/div for currents

Long run demonstration at CDR parameters (24-25 Oct-17)

- Ran by Operators from the Main Control Room
- “Booster injection” chopper waveform
- 2 interruptions (1 hour total)
  - Beam availability ~96%
- Arbitrary bunch structure successfully demonstrated

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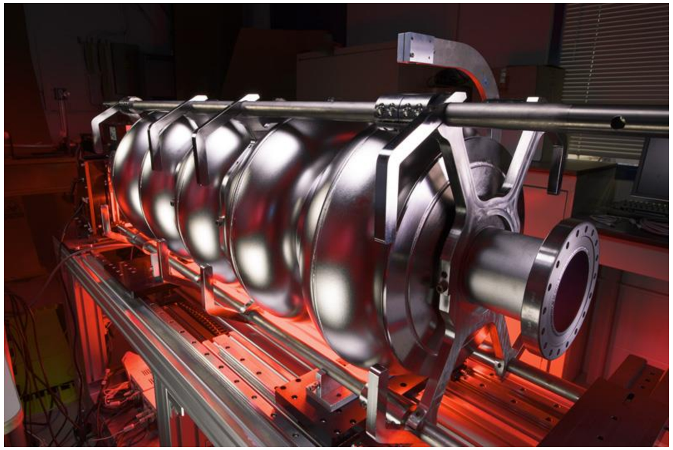
SSR1 Cryomodule being assembled for testing

PIP-II leverages FNAL leadership in SRF technology – pushes state of the art in high gradient, high Qo, CW designs

Single Spoke Cavity Prototype



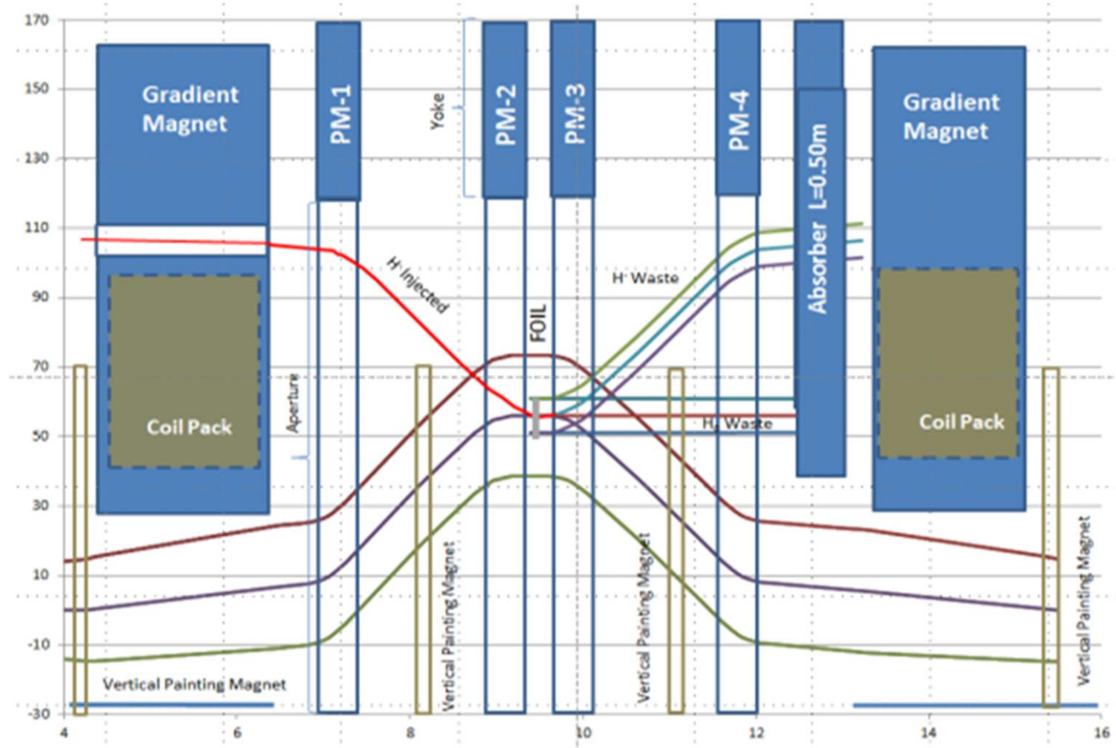
Elliptical Cavity β=0.90 Prototype at FNAL

Elliptical Cavity β=0.90 Prototype at FNAL

- Talk on SCRF R&D by Mattia Checchin
  - 09:00 tomorrow

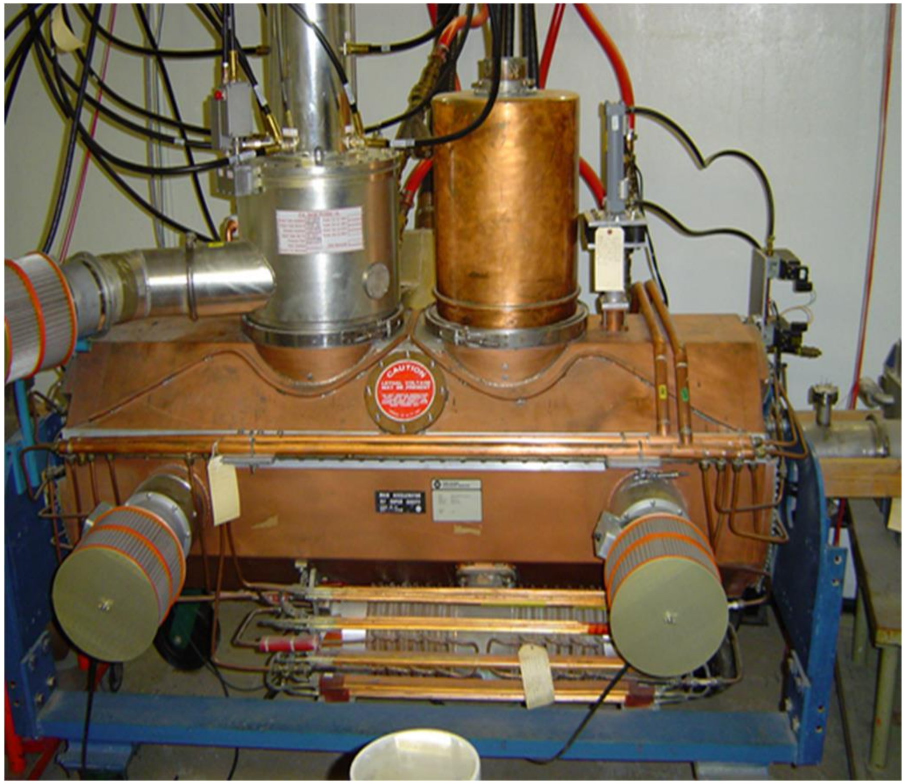
PIP-II: Booster Injection

- Beam painting in X and Y planes
  - Beam stays in same spot on foil
- New, shorter gradient magnets to make space
- Foil – 600 μg/cm2



MI Acceleration

- Need more rf power
  - Current system $< 6.2 \times 10^{13}$ protons (Robinson limit)
  - PIP-II needs 7.5×10^{13} protons per pulse
- Drive existing cavity with two tubes?
- New tube?



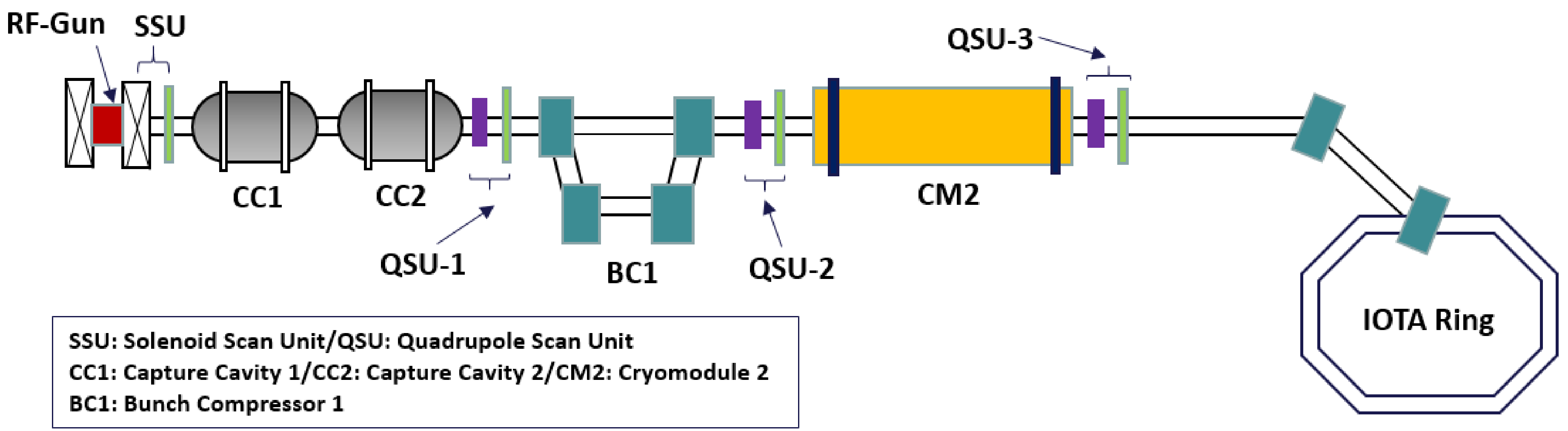
PIP-II

- Project has reached DOE CD-1
  - Plan for CD-2/CD-3a next year
  - Start construction of cryoplant
- PIP-II will provide:
  - 1.2 MW beam power for LBNF (60 – 120 GeV)
  - Beam for existing 8 GeV program
  - Beam at 800 MeV for upgraded mu2e experiment
  - Much more beam available at 800 MeV (CW operation)
- Expect to commission PIP-II and LBNF side-by-side

Beyond PIP-II: PIP-III

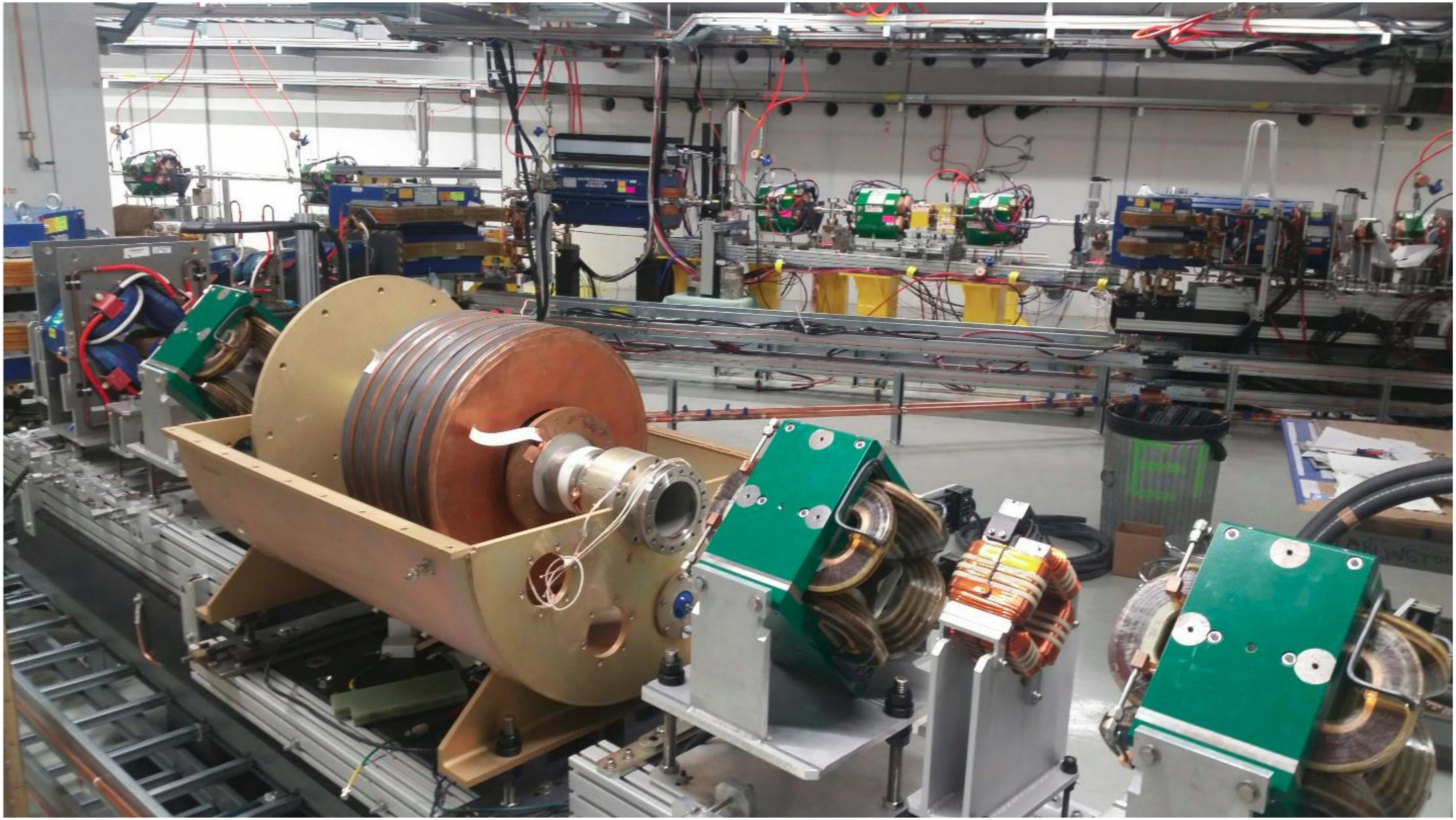
- So let's double the beam power again
  - 1.2 MW -> 2.4 MW +
- Have to replace present Booster
- Have to eliminate lossy slip-stacking (so need 4x PIP-II intensity at 8 GeV)
  - New RCS, or combination of new RCS and more linac, or an 8 GeV linac.
  - H^- stripping at 8 GeV is "very challenging"
  - RCS at 4x PIP-II intensity has lots of space-charge tune shift at 800MeV
    - Can we cope with the space-charge tune shift?

FAST: Fermilab Accelerator Science & Technology facility



- Highly-instrumented & configurable 300 MeV SCRF linac
  - 1.3 GHz ILC-like cryomodule
- IOTA: 150 MeV electron ring
  - Or 2.5 MeV protons
  - Test integrable optics & space charge compensation (octupoles, nonlinear magnets, electron lens, …)
    - First e-beam this year

IOTA Ring : Beam Start-up This Summer



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• IOTA/FAST at IPAC18 (Vancouver)

- Contr Oral: TUXGBF2 Higher-Order-Mode Effects in Tesla-Type SCRF Cavities on Electron Beam Quality (A.Lumpkin et al)
- Contr Oral: THYGBD4 Landau Damping by Electron Lenses: Outperforming Thousands of Octupoles (A.Burov et al)
- Contr Oral: THYGBE2 Results and Discussion of Recent Applications of Neural Network-Based Approaches to the Modeling and Control of Particle Accelerators (A.Morin et al)

– Posters (25):

- TUPAF073 Simulation of Integrable Synchrotron with SC and Chromatic (J.Eldred)
- TUPAL043 e-Column in IOTA (B.Freemire)
- WEPAF040, SUSPL054 Neural Network Virtual Diagnostic & Tuning for FAST LEBL (A.Edelen)
- WEPAG005, SUSPF100 Synchrotron Radiation Beam Diagnostics IOTA (N.Kuklev)
- WEPAL065, SUSPL050 Development of a Gas Sheet Beam Profiler for IOTA (S.Szustkowski)
- THPAF067 Effects of Synchrotron Motion on Nonlinear Integrable Optics (J.Eldred)
- THPAF068 Suppression of Instabilities by an Anti-Damper in IOTA (A.Macridin)
- THPAF071 McMillan Lens in a System with Space Charge (S.Nagaitsev)
- THPAF073 Tomography FAST (A.Romanov)
- THPAF075 SCC with an Electron Lens (E.Stern)
- THPAK082 Perturbative Effects in IOTA (N.Cook)
- THPAK083 An s-Based Symplectic SC (N.Cook)
- THPAK036 Accurate Modeling of Fringe Field Effects on Nonlinear Integrable Optics in IOTA (C.Mitchell)
- THPAK061 Magnetized and Flat Beam Generation at the Fermilab's FAST Facility (A.Halavanau)
- THPAK062 Compression Flat Beams (A.Halavanau)
- THPMF024 Commissioning and Operation of FAST Electron Linac at Fermilab (A.Romanov)
- THPMF025 Emittance Study at FAST (J.Ruan)
- THPMF027 Electron-Beam Characterization in Support of a γ-Ray ICS at the FAST (J.Ruan)
- THPMF028 Coherent Stacking Scheme for ICS at MHz Repetition Rates (J.Ruan)
- THPMF029 Studies of the Novel MCP Based Electron Source (V.Shiltsev)
- THPMK036 Final Focus for a Gamma-Ray Source Based on ICS at FAST (A.Murokh)
- THPML063 Micro-Bunched Beam Production at FAST for Narrow Band THz (J.Hyun)
- THPAK057 Simulation of OSC (M.Andorf)
- THPAK058 Detection and amplification of infrared synchrotron radiation (M.Andorf)
- THPAK035 Modeling Nonlinear Integrable Optics in IOTA with Intense SC Using the Code IMPACT-Z (C.Mitchell)

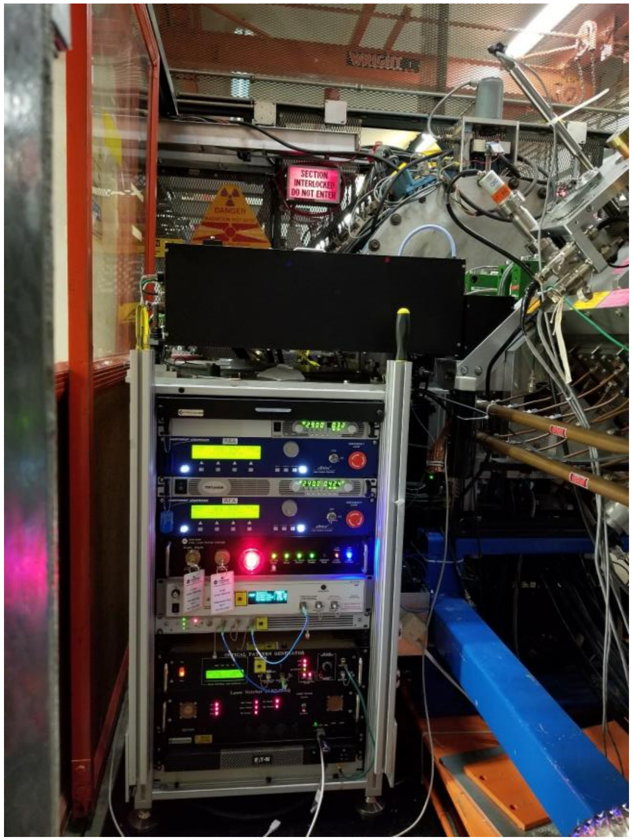
300 MeV from FAST Linac – Nov. 15 , 2017

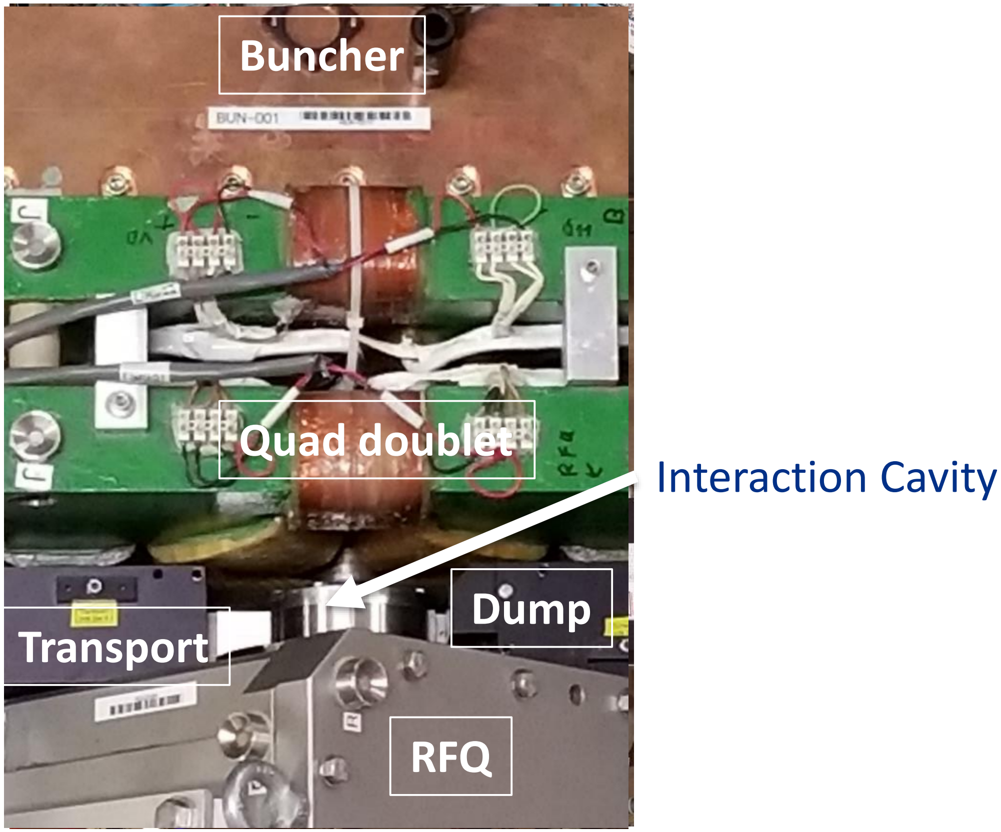
- ILC-type cryomodule acceleration by 255±5 MeV
  - Over 31.5 MV/m
- Total beam energy 300 MeV in the HE beam absorber

Conclusions

- Fermilab's operational accelerator facility: delivering 700kW of proton beam power to NuMI routinely since Jan 2017
- We have a plan for further beam power increases, to 900kW in ~2020
- PIP-II linac and Booster/MI upgrades will allow us to deliver 1.2 MW to LBNF
- Exploring best option for a further doubling to 2.4 MV "PIP-III"
- FAST Accelerator R&D facility off to a great start
  - Powerful & flexible beam diagnostics
  - Results from FAST/IOTA will inform PIP-III planning
  - First electrons in IOTA this year
  - Protons next year

Operational Laser System Installed in Linac





CM-2/FAST Linac Performance vs ILC specs

Parameter	FAST Nov. 2017	ILC specs 2007 RDR/2013TDR	Comments
Total beam energy gain per CM	255 MeV* 31.8 MV/m 8 cavities	252 MeV 31.5 MV/m in each 8/9 cavities	above the spec!
Q_0	0.8 e10	1 e10	Two cavities have >1e10
Pulse length (beam)	0.1 ms	1.0 ms	had 1 ms in other studies
Pulse rep rate	1 Hz	5 Hz	had 5Hz in other studies
# bunches per pulse	10	2625 / 1312	had 1000 bunches in other studies
Bunch intensity	0.2 nC	3.2 nC	1.5nC per bunch in other studies

* compare with European XFEL: there are several CMs in operating at 200+ MeV. The highest gain/CM is 237 MeV.

RR Milestones: more slip-stacking