FNAL Accelerator Complex Upgrade Possibilities

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NAPAC16

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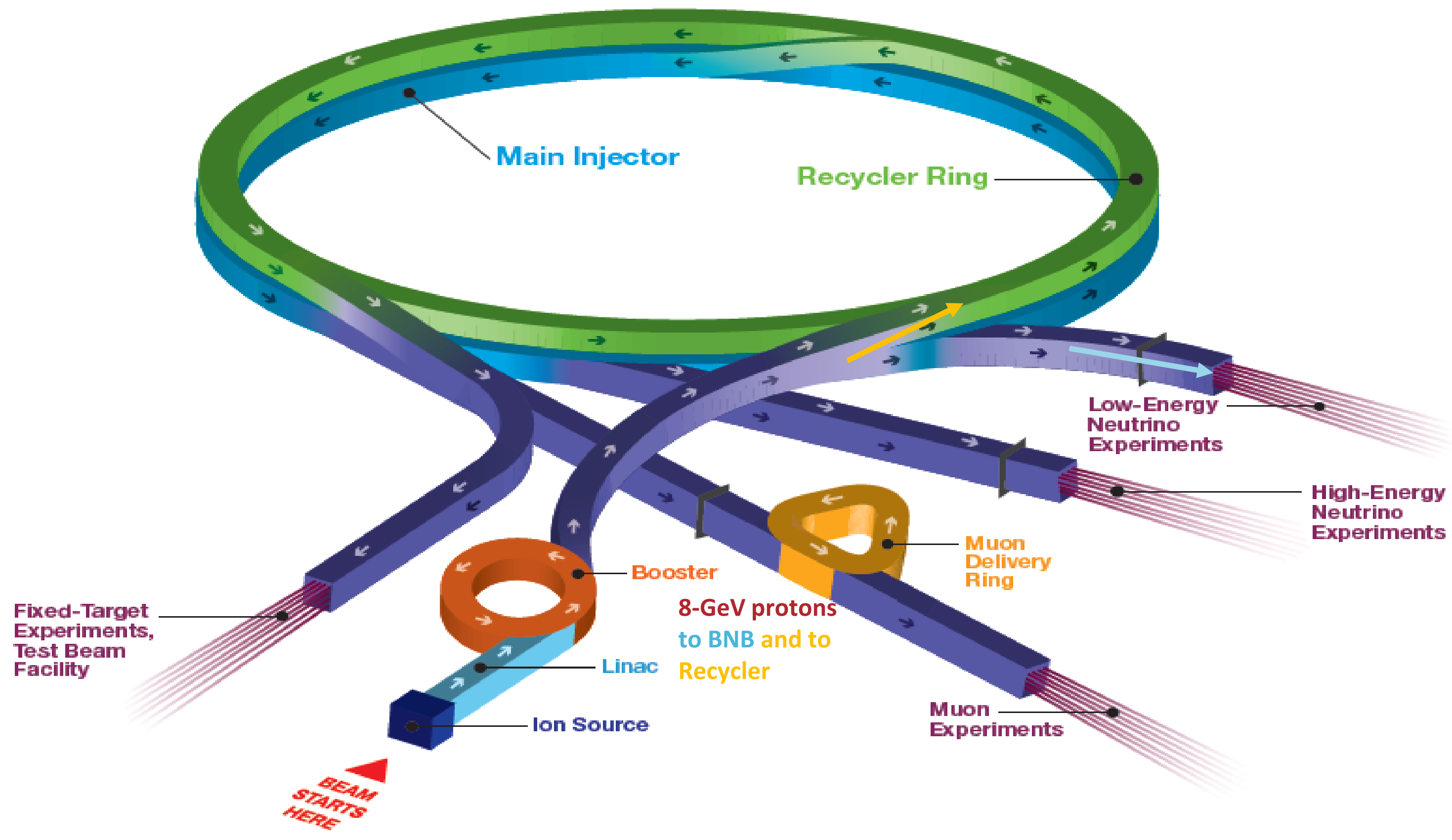
Outline

- Fermilab Accelerator Complex
  - Linac
  - Booster
  - Main Injector
  - Recycler
- 700KW.
- 1.2 MW (PIPII).
- 2.5 MW (PIPIII).
- Beyond 2.5 MW.
- Summary

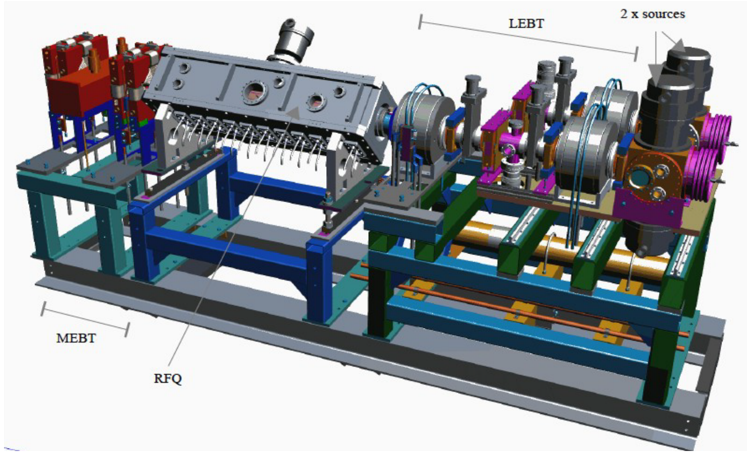
Fermilab Accelerator Complex

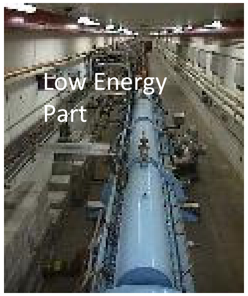


- **Fermilab's Accelerator Complex has been re-configured for high power operations**

Linac

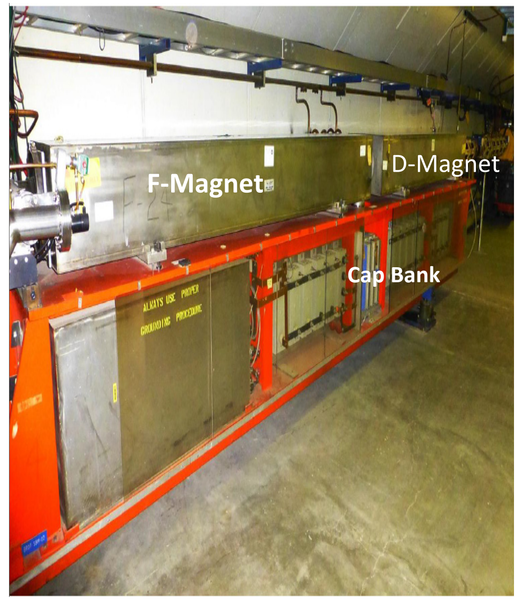
- Upgraded to 400 MeV
- Replaced the Cockcroft-Walton with an RFQ in 2012.
- Old part of the Linac (up to 116 MeV) uses Drift tubes powered by the RCA 7835 Triodes (single vendor).

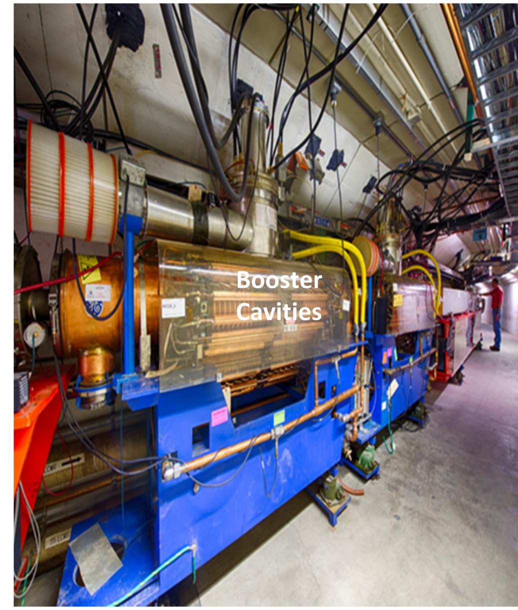


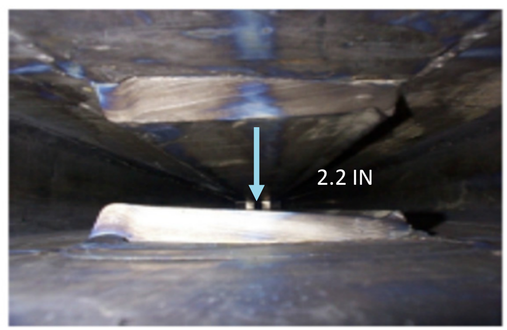


Booster

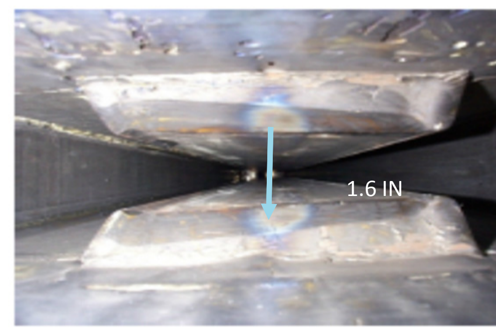
- Booster uses combined function magnets with exposed laminations.
- Crosses transition without a gamma-t jump.
- The original RF cavities were recently refurbished to allow 15 Hz beam operations.
- The RF system was upgraded with SS Drivers and new Anode Supplies.
- Three new RF cavities were installed to increase reliability.







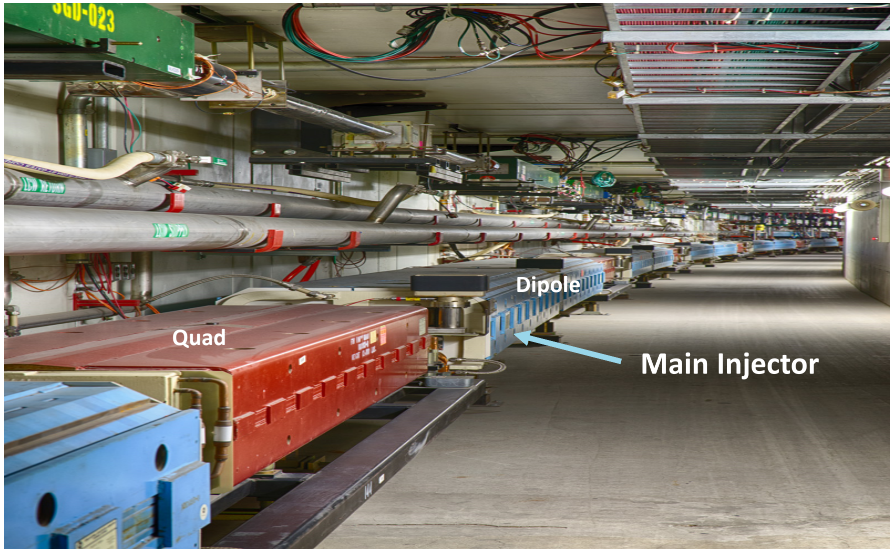
focusing



defocusing

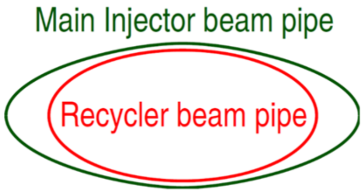
Main Injector (MI)

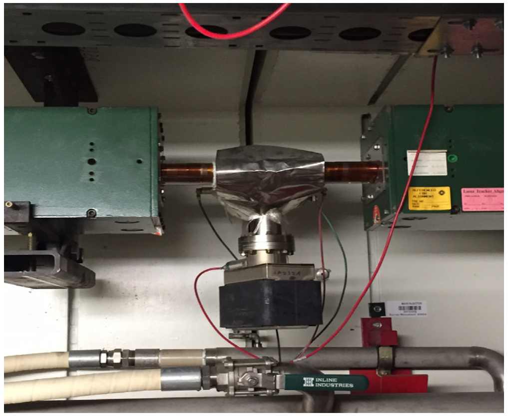
- Commissioned in 1999.
- Seven times the Booster circumference.
- All new dipole magnets with sagitta.
- Most of the quad magnets are recycled from the old Main Ring.
- Uses the old Main Ring cavities upgraded with SS Drivers.
- Large admittance.
- Crosses transition with no gamma-t jump.
- Accelerates from 8-120 GeV with 240 GeV/sec



Recycler (RR)

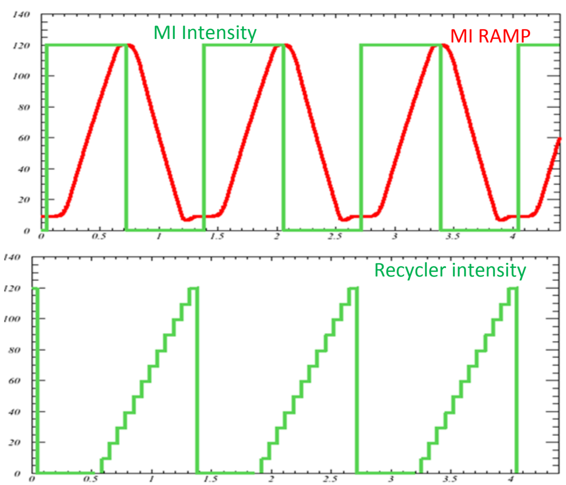
- Fixed energy storage Ring located in the MI tunnel.
- Same size and same lattice with MI.
- 344 combined function magnets and 86 quad made out of permanent magnets.
- Two phase trombones for tune corrections.
- Was designed to store and cool antiprotons.

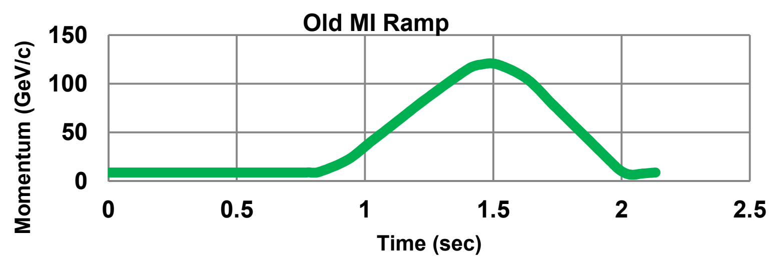


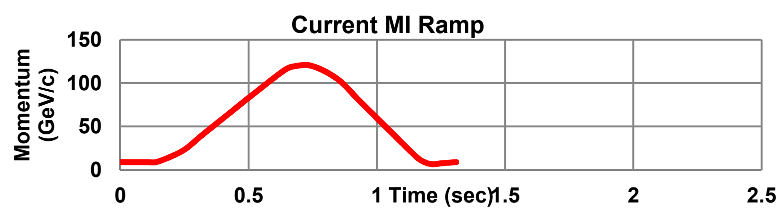


Achieving 700 KW

- Reduce the MI Cycle Time!
  - Transform the Recycler into a proton stacker and slip stack 12 Booster batches while MI is ramping.
  - Increase the beam power by a factor of 1.8 with only a 10% increase in the beam intensity (12 Booster batches instead of 11).
  - The power losses increase by the same factor also.
  - Need 9 Hz Booster operation

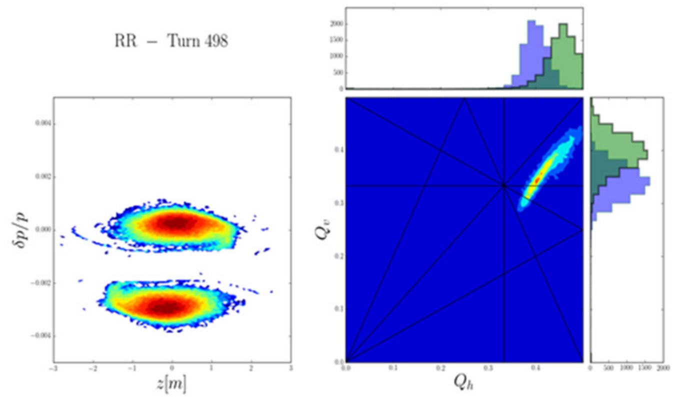




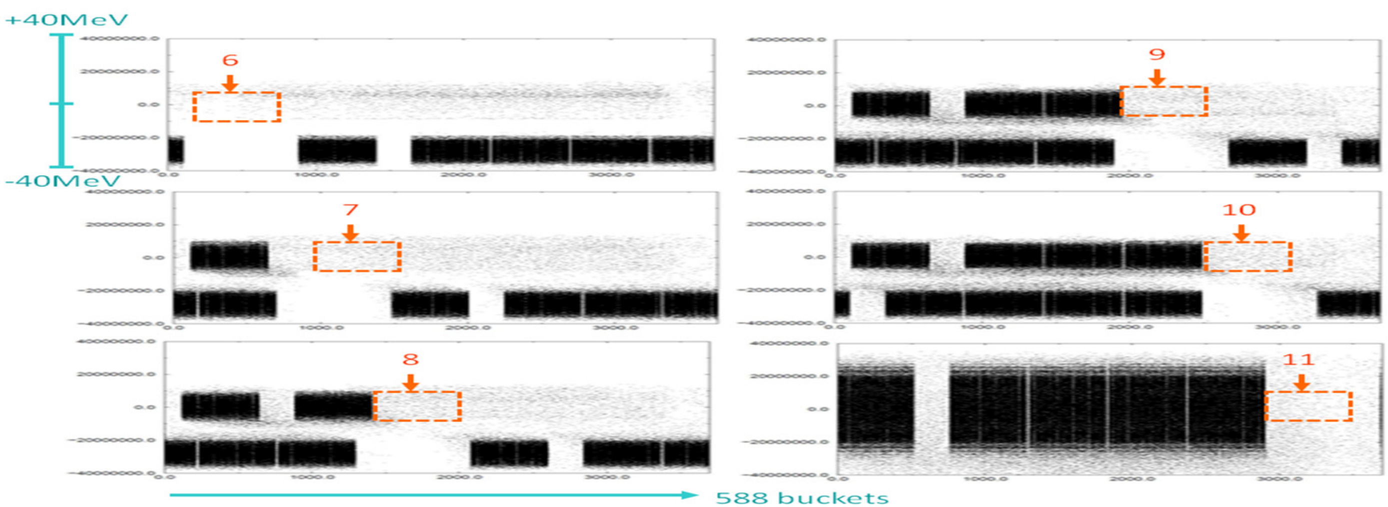


Slip stacking

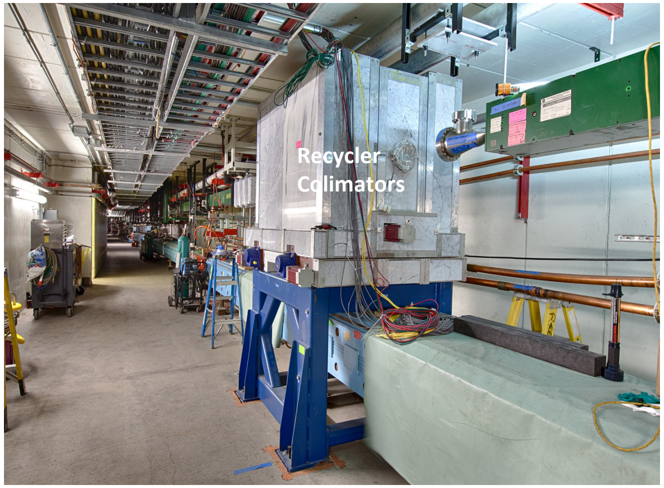
- Beam separation depends on the Injector rep rate.
- Figure of merit Δf/fs
- Process ~95% efficient.
- Losses have to be controlled.



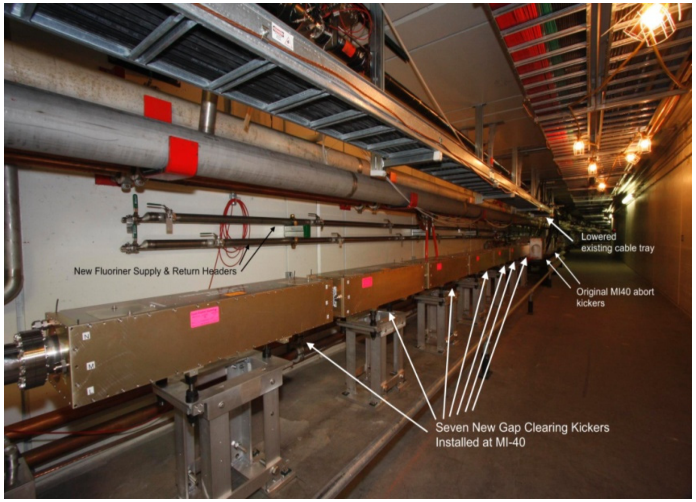
Slip Stacking simulations



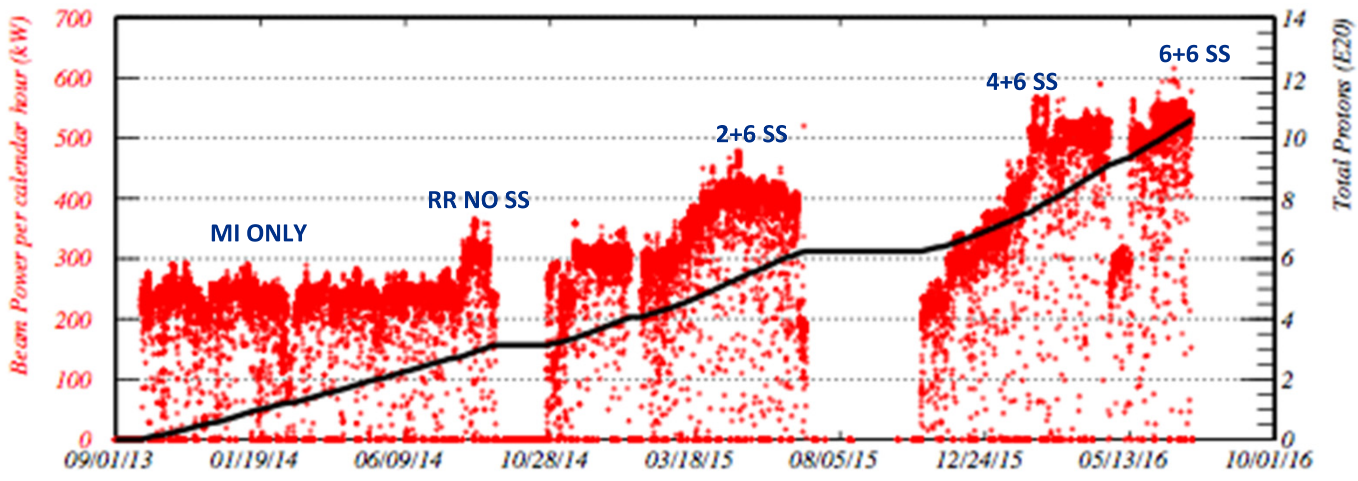
Loss Control



- MI Collimators for un-captured beam.
- Recycler collimators for beam lifetime losses.
- Gap Clearing Kickers for beam in the injection gap.



Beam Power and Integrated beam since 2013



- Beam power gradually increased by slip stacking more Booster batches.
- We have been running with average power of 550 KW to NuMI. target before the summer shutdown with SY120 (10% of timeline).
- Expect to ramp to 700 KW after the shutdown.

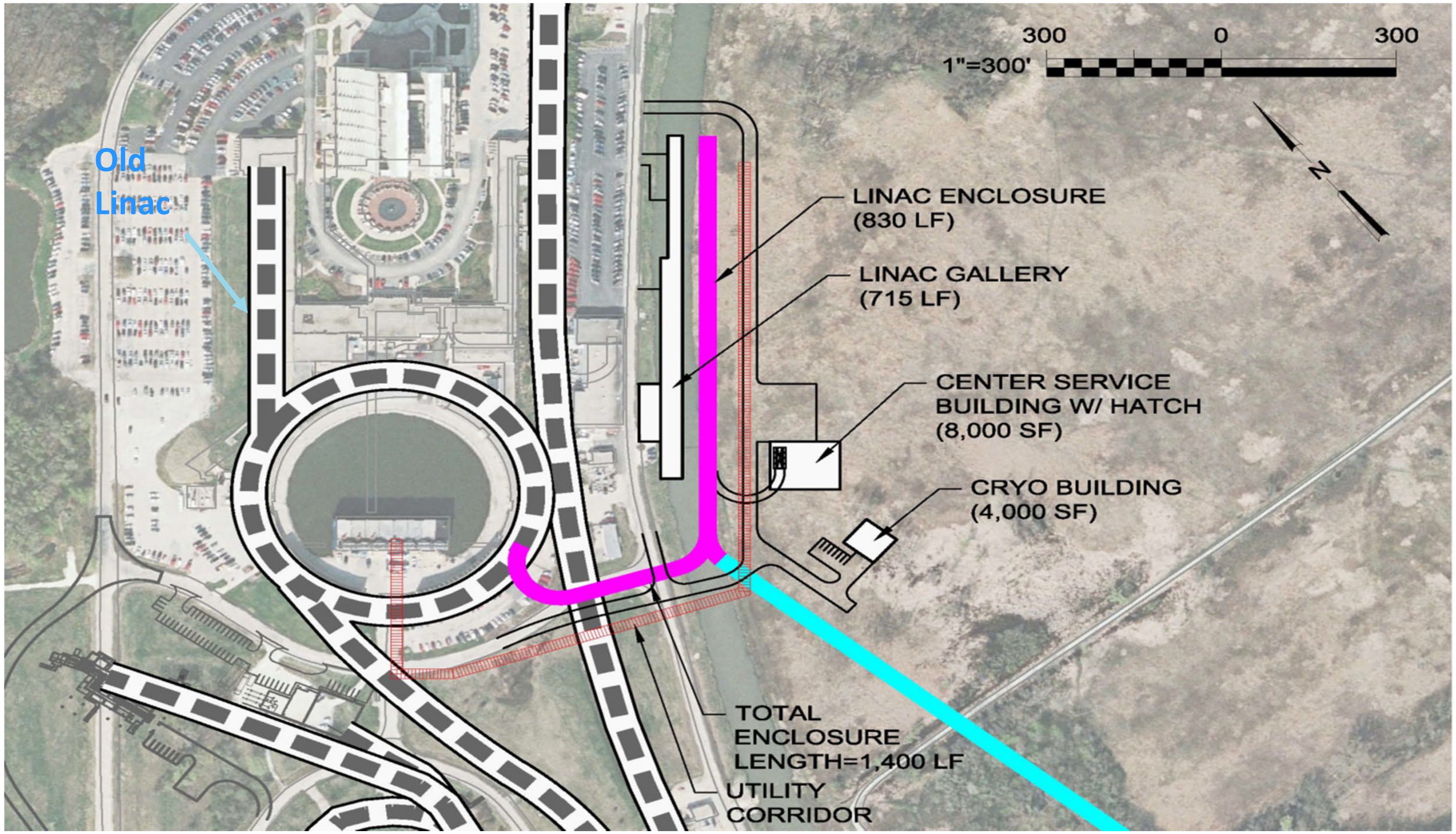
PIP II (1.2 MW)

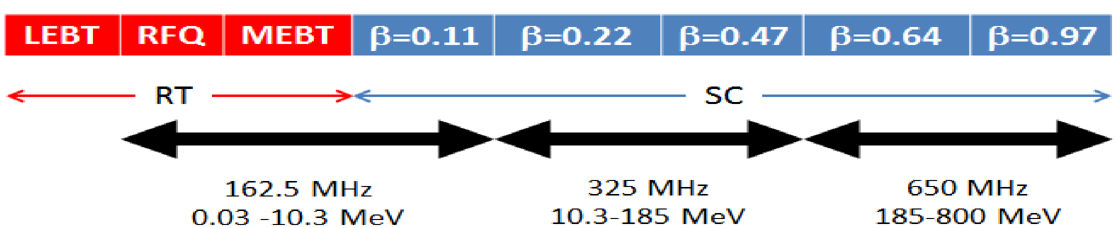
- Replace the current proton source and Linac with a new 800 MeV superconducting Linac with CW capability.
- Increase the current Booster rep rate to 20 Hz and the intensity per pulse by 50%.
  - Rep rate increase reduces slip stacking losses and increases the Booster 8 GeV Beam power.
- Slip stack and accelerate 50% more beam intensity in Recycler and MI.
- Decrease the MI cycle time to 1.2 sec from 1.33 sec.
- Deliver 1.2 MW beam power to the proton target.

Upgrades in current Accelerators required for PIPII.

- Booster has to accommodate beam stripping from the new Linac and accelerate 50% more beam.
  - New injection girder with a new stripping system and absorber.
  - New RF cavities (better cooling, larger aperture).
  - Damper and collimator upgrades.
  - 20 Hz modifications.
- Recycles has to slip stack 50% more beam at 1680 Hz separation
  - New 53 MHz cavities for slip stacking (Higher voltage; CW capability).
- MI has to accelerate 50% more beam.
  - RF Power.
  - Gamma-t jump.

PIPII Linac





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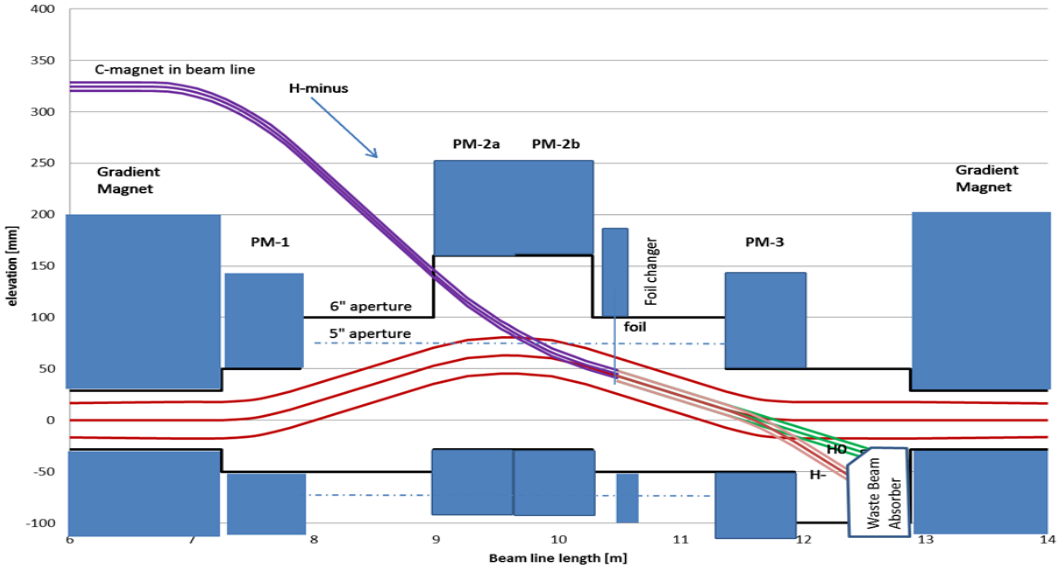
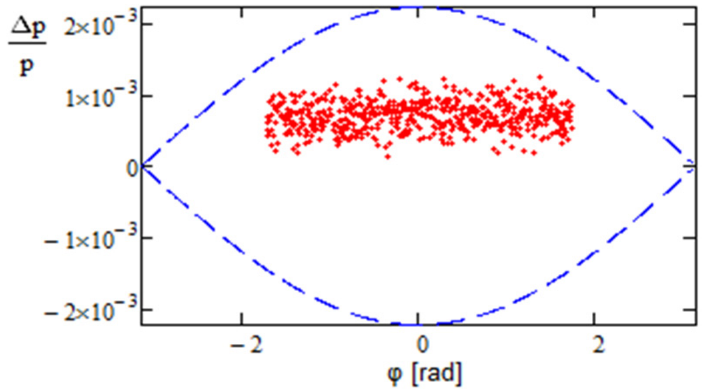
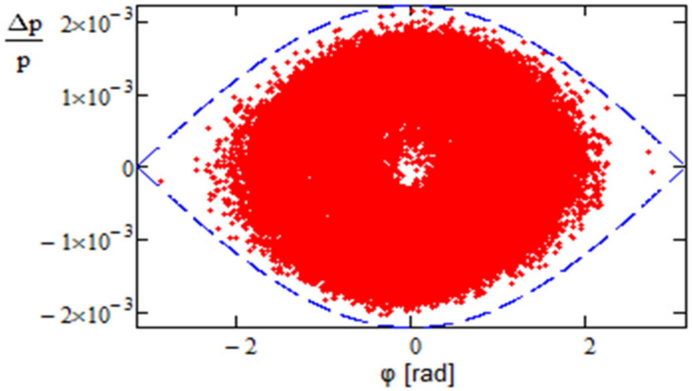
Booster Injection in PIPII



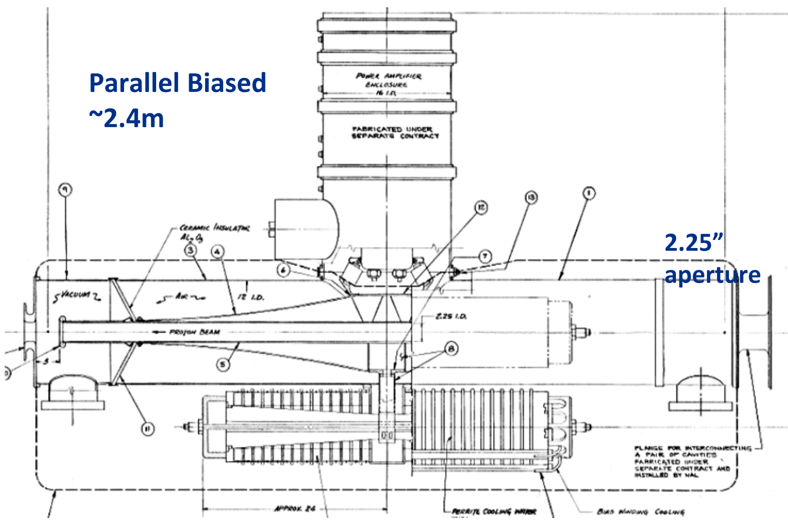
- **Conceptual design of 800 MeV Injection in the current Booster**

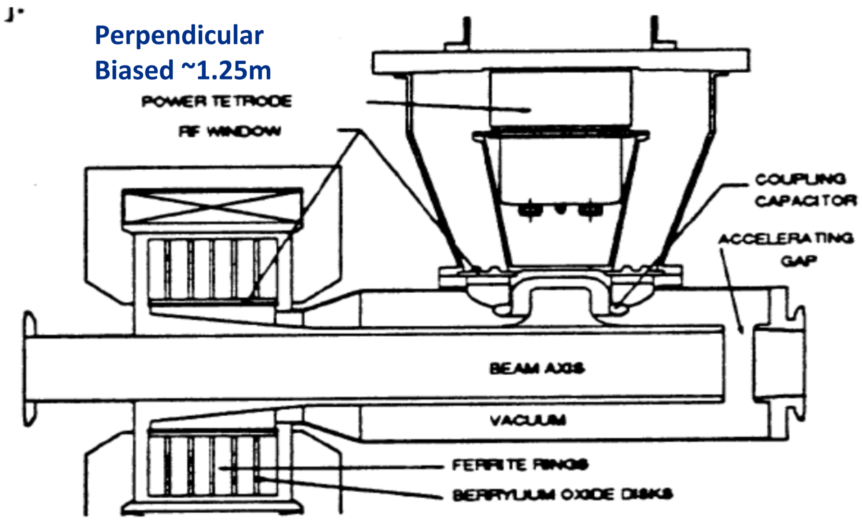




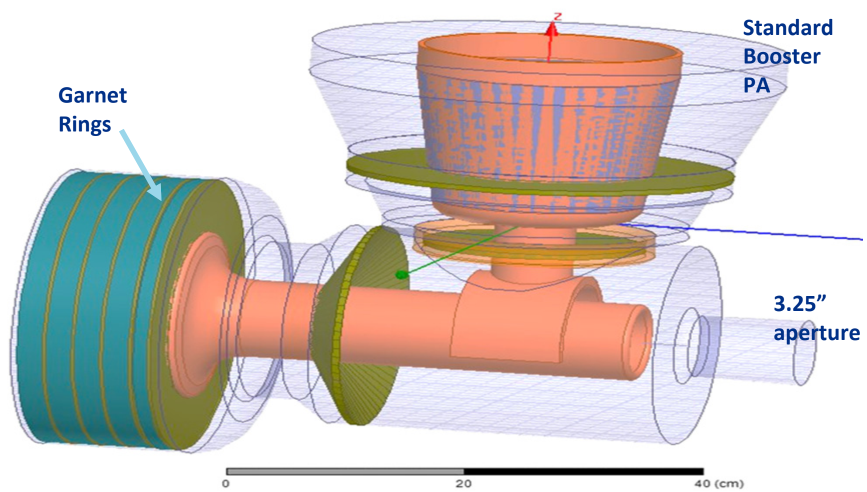
- **Longitudinal phase space painting during the 300 turns injection**

New RF Cavities for Booster

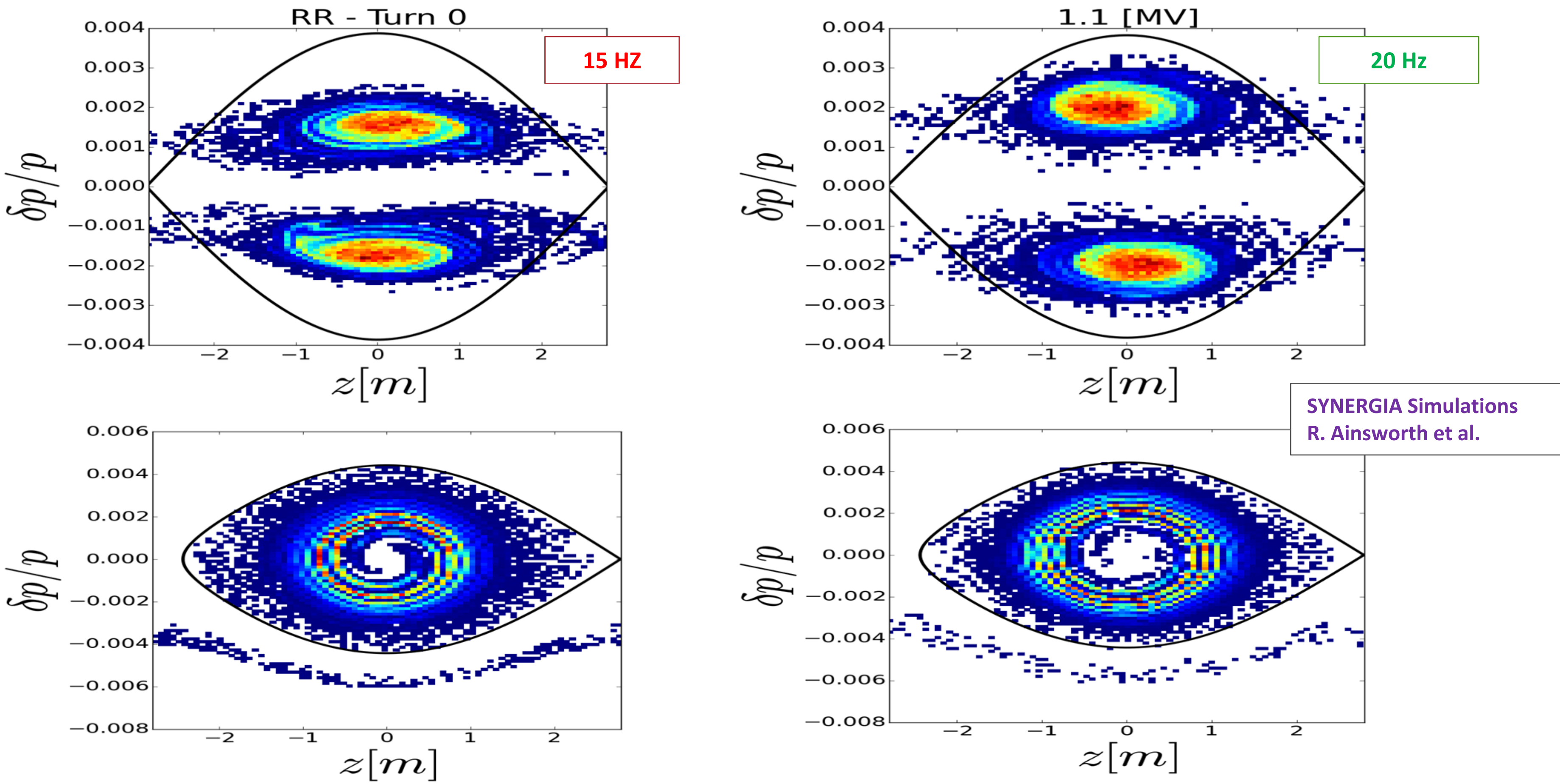




- Plans under way to build a perpendicular biased second harmonic cavity for Booster(G. Romanov et al.)
- The cavity will be used at injection and around transition.



Slip stacking with 1260 Hz (15 Hz Booster) vs 1680 Hz (20 Hz Booster)



- Slip stacking with larger separation results in better efficiency but larger emittance.

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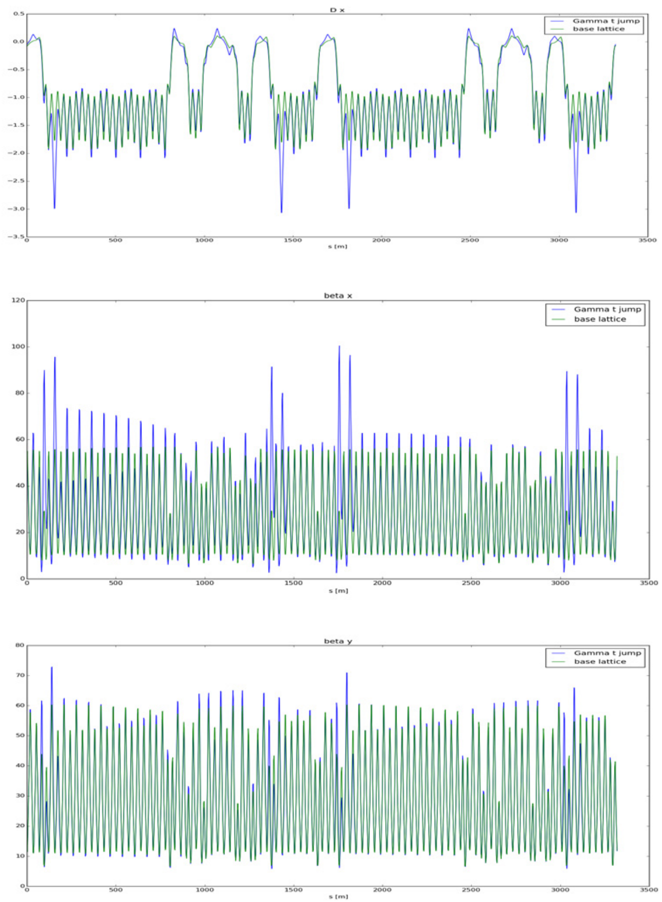
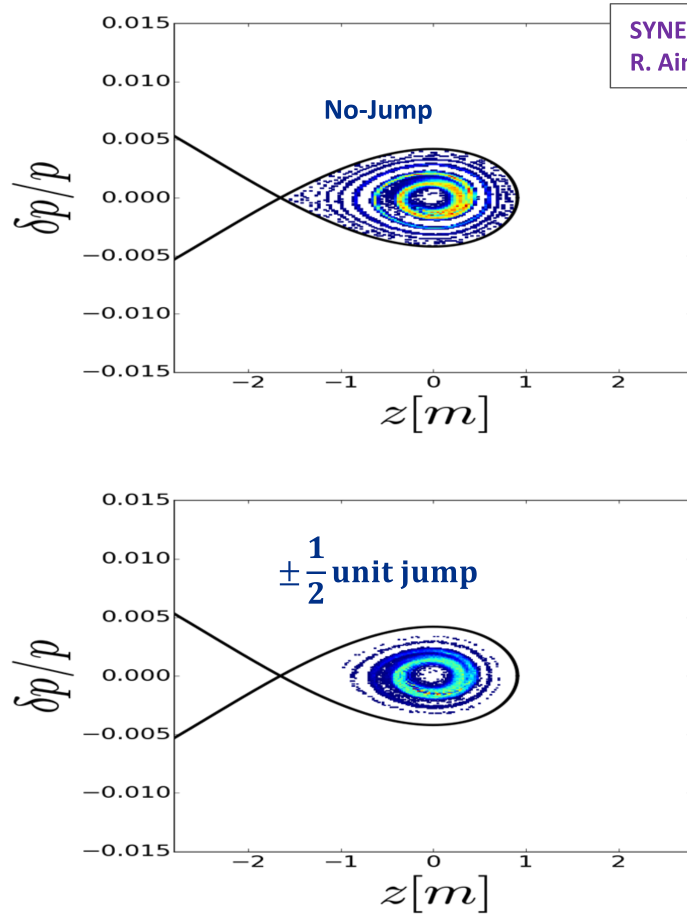
MI Transition crossing simulations with a gamma-t jump

Lattice Functions

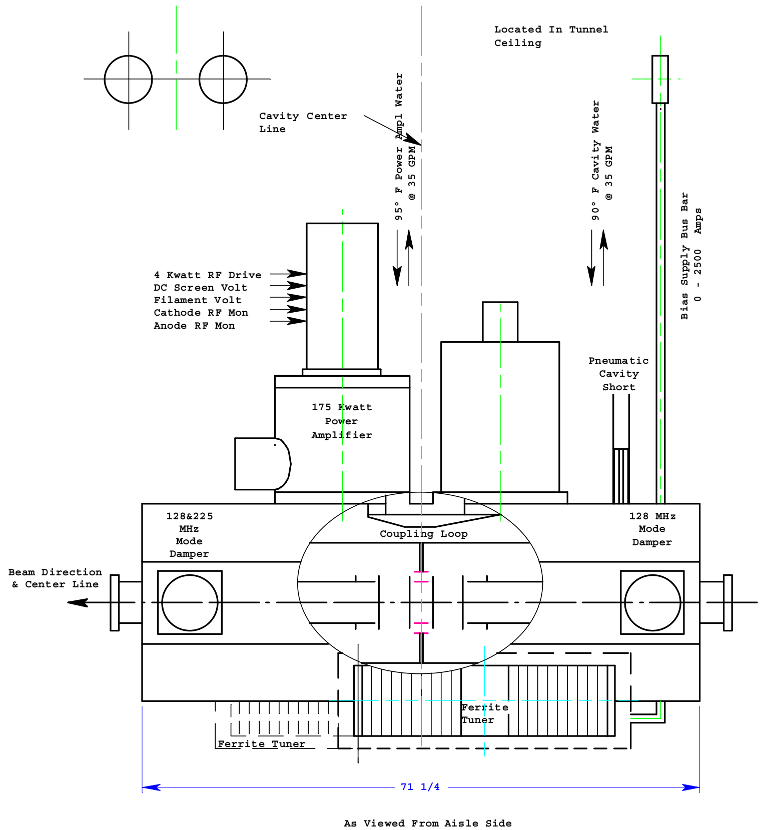


Longitudinal Distributions at 40 GeV

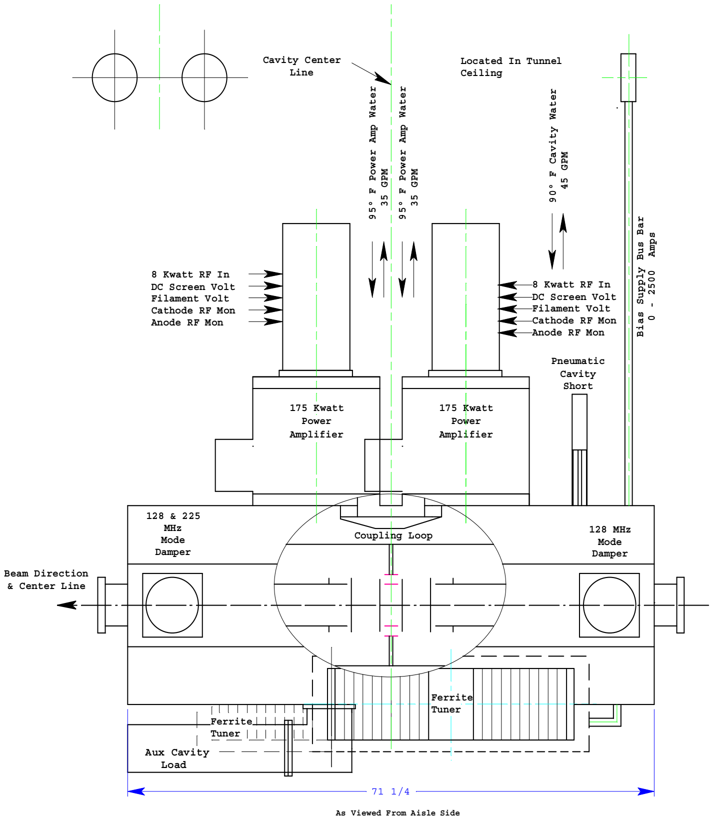
SYNERGIA Simulations
R. Ainsworth et al.



MI RF Power Upgrade



Present Main Injector Cavity



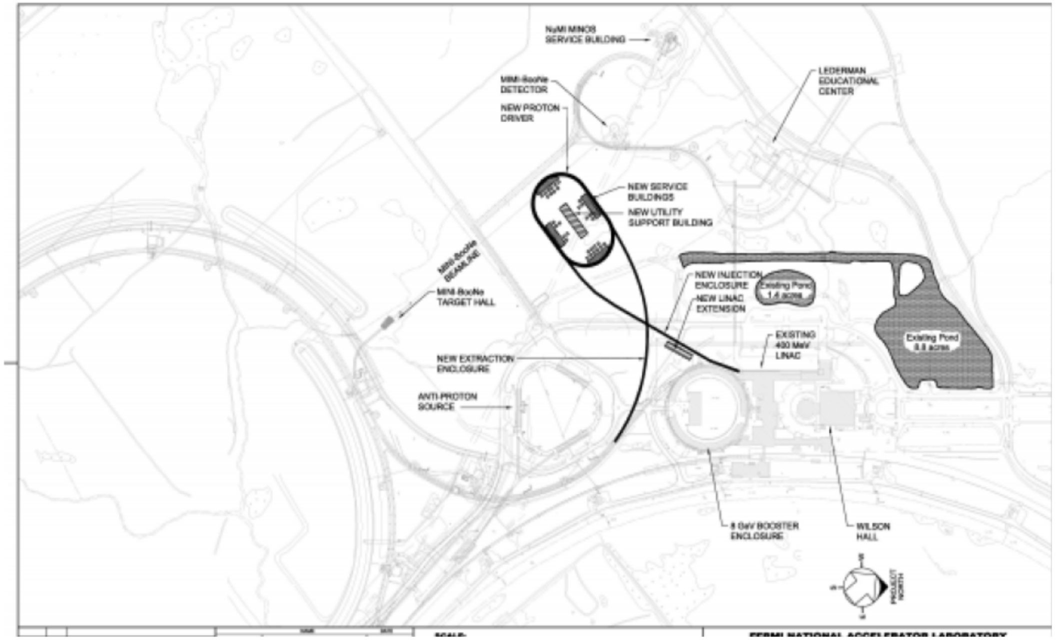
Modified Main Injector Cavity for Two Power Amplifiers

- Adding another PA to each of the MI cavities will allow us to accelerate up to 1.1E14 with 240 GeV/sec.

Reaching 2.5 MW (PIPIII)

- Replace the Booster with a new RCS capable of delivering the required protons per bunch.
  - No slip stacking.
- Eliminate Recycler (except the section from 10-30)
  - Small aperture.
  - Decaying field in magnets.
  - Limits the MI options (two machines in same tunnel).
- A new Linac is also an option but serious issues need to be addressed.
  - Where and how we do the 8 GeV stripping.
  - A new Ring for stripping will be required
- A new MI RF system will be required.

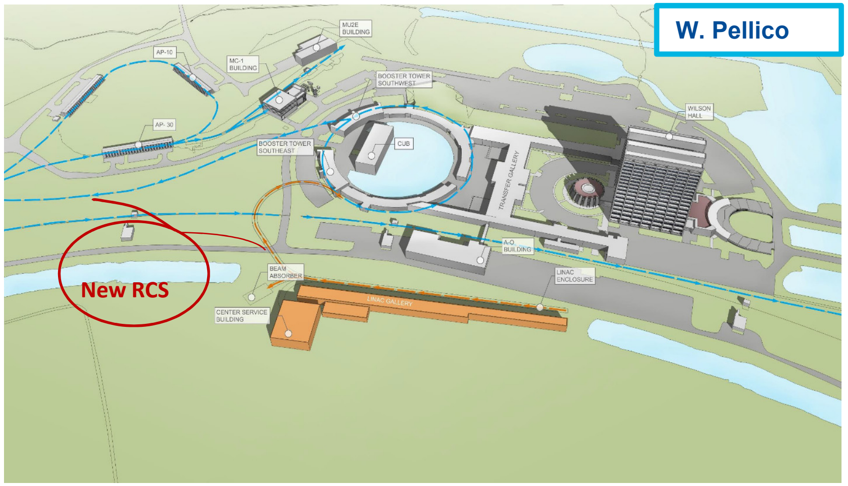
New RCS



- **An new RCS designs exists since 2002. (Proton Driver studies 1,2).**
- **Latest design had a race track design with no transition crossing.**

Parameters	PD1	PD2
Ring circumference (m)	711.3	474.2
Linac energy (MeV)	400	600
Synchrotron peak energy (GeV)	16	8
Protons per cycle	3×10^{13}	2.5×10^{13}
Protons per bunch	2.4×10^{11}	3×10^{11}
Repetition rate (Hz)	15	15
RF frequency (MHz)	53	53
Normalized transverse emittance (mm-mrad)	60π	40π
Beam power (MW)	1.2	0.5

New RCS Location

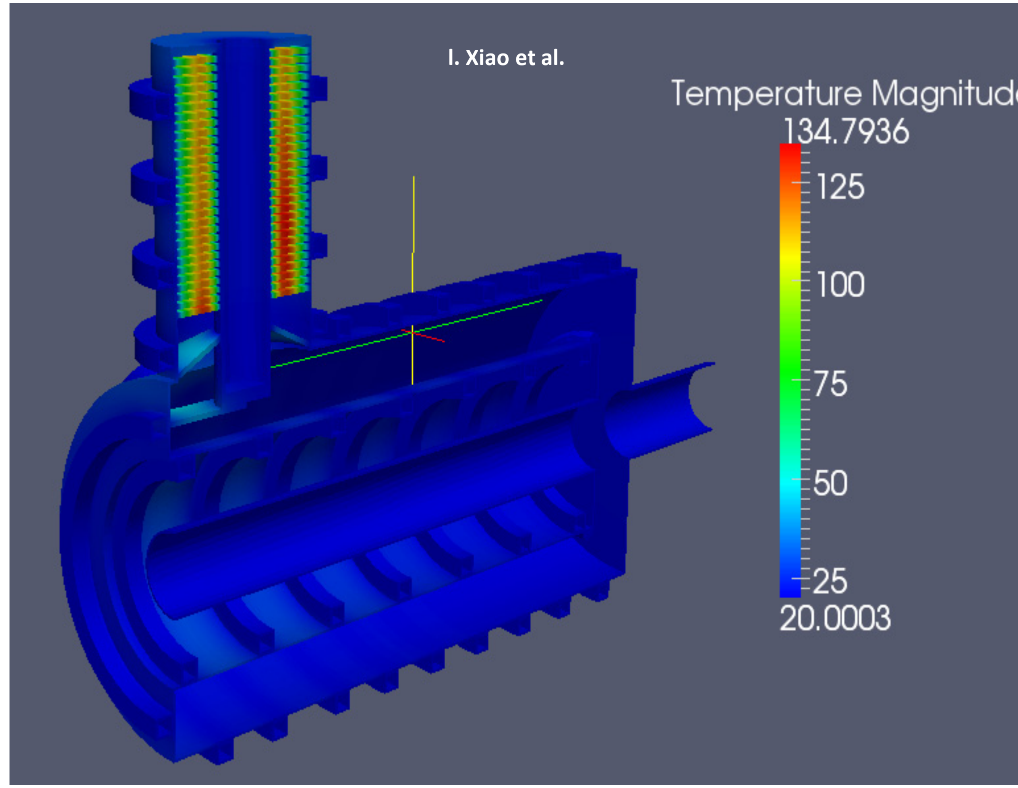


W. Pellico

	PIP-III (RCS)
MI	
Beam Energy[GeV]	120
Cycle Time[s]	1.45
Protons per pulse[1e12]	190
Power[MW]	2.5
Proton Source	
Injection Energy[GeV]	0.8-2.0
Extraction Energy[GeV]	8
Protons per Pulse[1e12]	32
Beam Power to Recycler/MI[kW]	168
Maximum Beam Power to 8 GeV[kW]	645

New MI RF

Parameter	Value	Units
Frequency	52.617-53.104	MHz
Max Acc. Rate	240	GeV/sec
Frequency Slew Rate	1.6	MHz/sec
Acceleration Voltage	2.7	MV
Peak Beam Power	6.2	MW
Average Beam Power	3	MW
Peak Voltage	4.7	MV
Average Beam Current	2.3	A
Fundamental RF Current	3.7-4.1	A



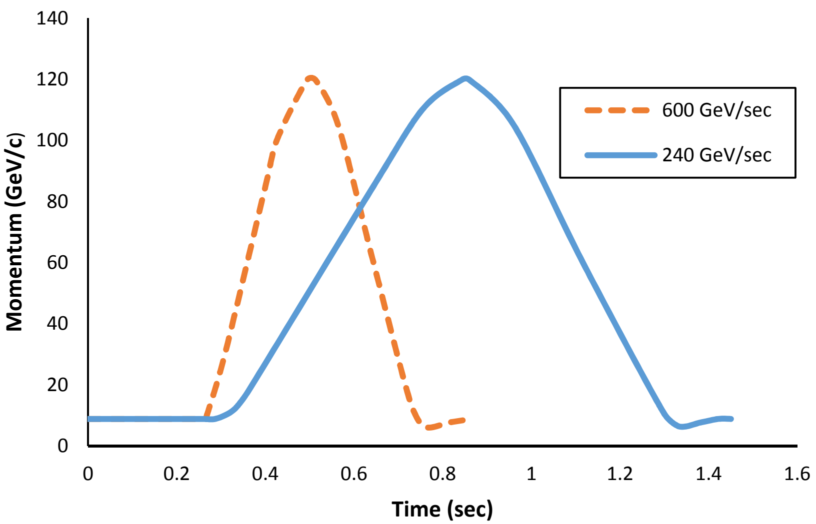
- **Use Eimac 8973 Power Tetrode as power source**
- **Output power ~1MW**
- **Plate dissipation ~1MW**

Running above 2.5 MW

- It will be difficult at this stage to increase the beam intensity so we need to consider reducing the MI cycle time.
- It is possible to consider doubling the MI acceleration rate to 600GeV/sec from 240 GeV/sec.
- We will need to add 2 Bend Supplies and 1 Quad PS to every MI service bulding.
  - This will require civil construction of Service buildings.
  - Double the numbers of feeders
  - 2 additional transformers and harmonic filters.
- We will have enough power in the new RF system to accelerate faster but we will need more volts (more stations).
  - A minimum of 31 RF stations will be needed.

MI Ramp with 600 GeV/sec

Seq.	Type	Delta t	Time	Momentum	Pdot	Pddot
THE RAMP:						
1	INITI	0.25000	0.25000	8.884	0.00	0.00
2	VPARAB	0.01382	0.26382	8.96	11.00	796.05
3	VPARAB	0.00276	0.26658	9.5	380.00	133591.67
4	VPARAB	0.04184	0.30842	30	600.00	5258.54
5	VPARAB	0.09167	0.40008	85	600.00	0.00
6	VPARAB	0.02542	0.42551	100	580.00	-786.67
7	VPARAB	0.06793	0.49344	119.7	0.00	-8538.07
8	CAPDEP	0.02000	0.51344	119.7	0.00	0.00
9	VPARAB	0.05069	0.56413	105	-580.00	-11442.18
10	VPARAB	0.07965	0.64377	60	-550.00	376.67
11	VPARAB	0.08182	0.72559	15	-550.00	0.00
12	VPARAB	0.03127	0.75687	6.4	0.00	17587.21
13	VPARAB	0.06063	0.81750	7.7945	46.00	758.69
14	VPARAB	0.04737	0.86487	8.884	0.00	-971.09
15	CAPDEP	0.00100	0.86587	8.884	0.00	0.00



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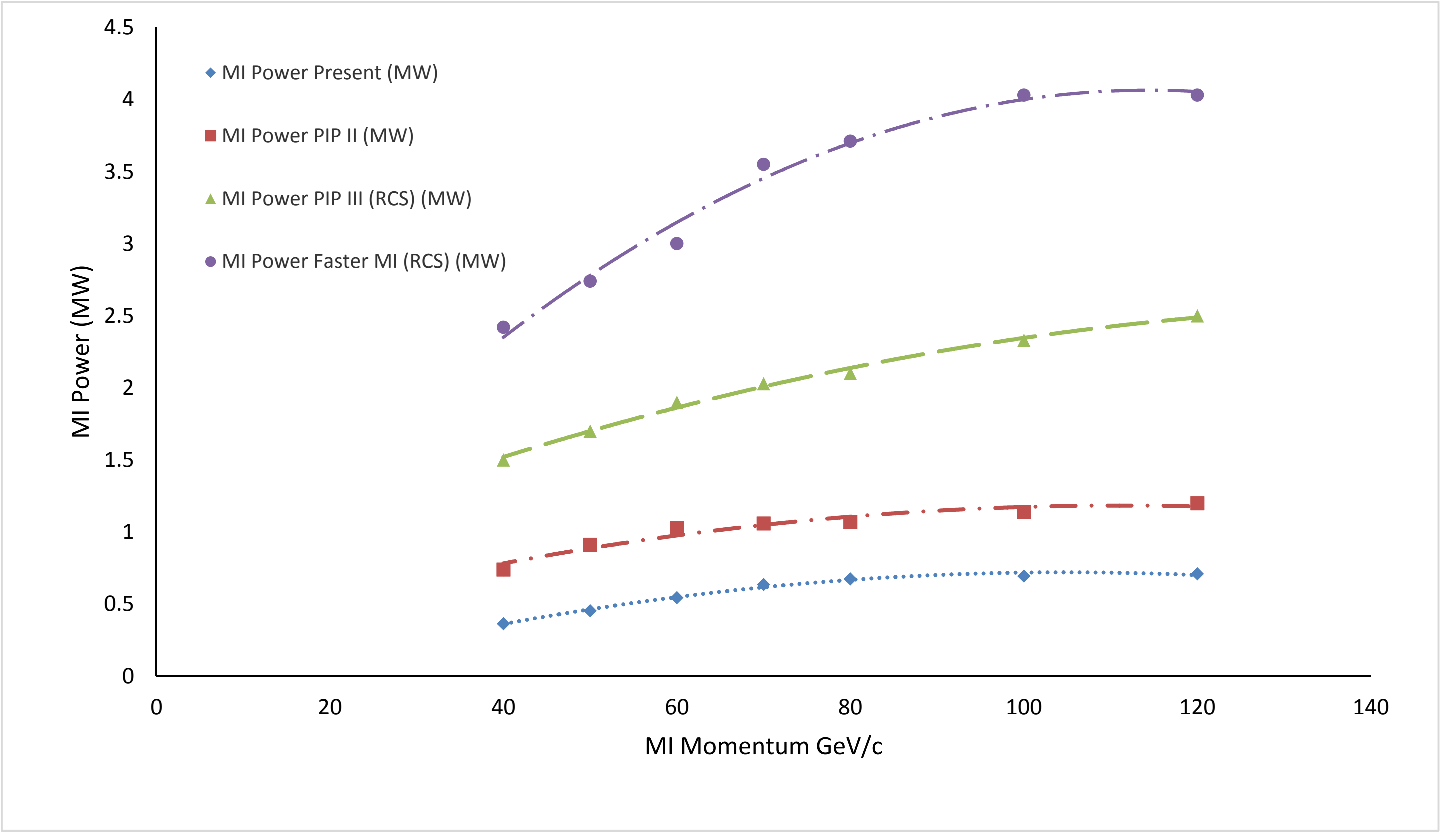
MI and Proton Source Parameters for the Different Scenarios

	Present	PIP-II	PIP-III (RCS)	Faster Main Injector (RCS)
MI				
Beam Energy[GeV]	120	120	120	120
Cycle Time[s]	1.33	1.2	1.45	0.9
Protons per pulse[1e12]	49	75	190	190
Power[MW]	0.7	1.2	2.5	4.0
Proton Source				
Injection Energy[GeV]	0.4	0.8	0.8-2.0	0.8-2.0
Extraction Energy[GeV]	8	8	8	8
Protons per Pulse[1e12]	4.3	6.4	32	32
Beam Power to Recycler/MI[kW]	38	82	168	271
Maximum Beam Power to 8 GeV[kW]	25	82	645	401

MI Beam Power vs momentum



Summary

- Fermilab Accelerator complex will be running at 700 KW beam power after the current shutdown.
- Planned upgrades (PIPII) will increase the beam power to 1.2MW.
- By replacing the Current Booster and taking advantage of the fast ramping capabilities of Main Injector we can increase the beam power to ~4MW.