Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

PIP-II and the Future of Protons at Fermilab

Paul Derwent

Accelerator R&D Subpanel

27 August 2014

Fermilab Program Goals

Fermilab's goal is to construct & operate the foremost facility in the world for particle physics research utilizing intense beams.

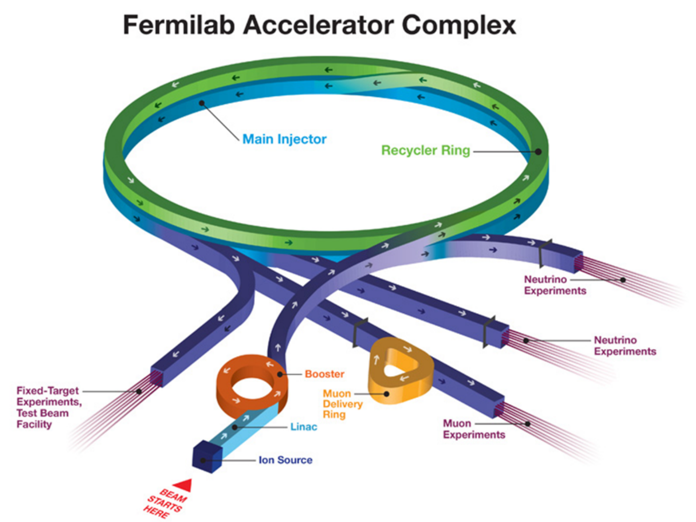
- Neutrinos
  - MINOS+, NOvA @700 kW
  - LBNF @ multi-MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

⇒ ***This requires more protons!***
(and this statement tends to be time invariant)

The Fermilab Accelerator Complex Today

- The Fermilab complex delivers protons for neutrino production at both 8 and 120 GeV, with a present capability*:
  - Booster: 4.2×10^{12} protons @ 8 GeV @ 7.5 Hz = 40 kW
  - MI: 3.5×10^{13} protons @ 120 GeV @ 0.75 Hz = 500 kW

- Present limitations
  - Booster pulses per second
    - The Booster magnet/power supply system operates at 15 Hz
    - However the RF system is only capable of operating at ~7.5 Hz
  - Booster protons per pulse
    - Limited by space-charge forces at Booster injection, i.e. the linac energy
  - Target systems capacity
    - Limited to ~700 kW by a large number of factors



* As currently configured

Strategy for the next ~10 years
Proton Improvement Plan (PIP)

The near-term goal is to double the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

- Required for simultaneous operations of NOvA, g-2, Mu2e, SBN
- 700 kW to NOvA

- Design Criteria
  - 15 Hz beam operations at 4.2×10^{12} protons per pulse (80 kW)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life for the Linac through 2023 and the Booster through 2030
- Scope
  - RF upgrades/refurbish
  - Replace components posing high availability risk
    - DTL rf $\Rightarrow$200 MHz klystrons/modulators
    - Additional Booster rf cavities
  - RFQ, dampers, collimators/absorbers
    - To maintain activation at current levels
- Execute over the years 2011 – 2018

Strategy for the next ~10 years
Proton Improvement Plan-II (PIP-II)

The longer-term goal is to increase the beam power delivered from the Main Injector by an additional 50% and to provide increased beam power to the 8 GeV program, while providing a platform for the future

- Strategy
  - Increase the Booster per pulse intensity by 50%
    - Requires increase in injection energy to ~800 MeV
  - Modest modifications to Booster/Recycler/MI
- Design Criteria
  - Deliver 1.2 MW of beam power at 120 GeV, approaching 1 MW down to 60 GeV, at the start of LBNF operations
  - Support the current 8 GeV program, including Mu2e, g-2, and the suite of short-baseline neutrino experiments
  - Provide an upgrade path for Mu2e
  - 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 operations
  - At an affordable cost to DOE
- Execute over 2015 – 2023

PIP-II

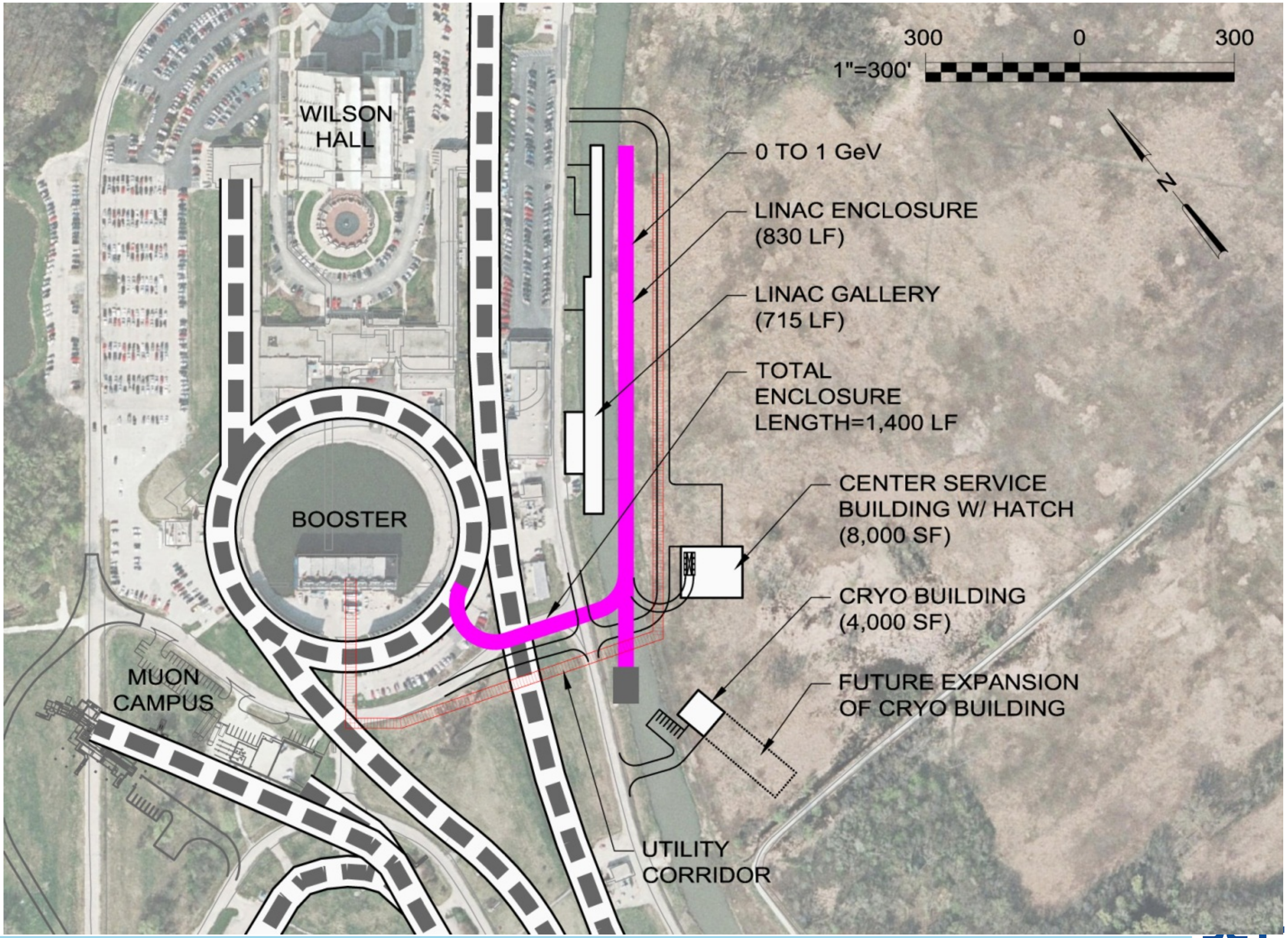
- *"The central element is a new 800 MeV superconducting linac operated at low duty factor but constructed to be capable of continuous operation" P5 report, p. 47*

- PIP-II plans to build an 800 MeV superconducting pulsed linac, extendible to support multi-MW operations to LBNF and constructed of continuous wave (CW) capable components
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting rf technologies
  - Eliminates significant operational risks inherent in existing linac
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector
- Whitepaper available at

  projectx-docdb.fnal.gov/cgi-bin/ShowDocument?docid=1232

At completion of PIP-II the existing 400 MeV linac will be removed from service

PIP-II Site Layout (provisional)

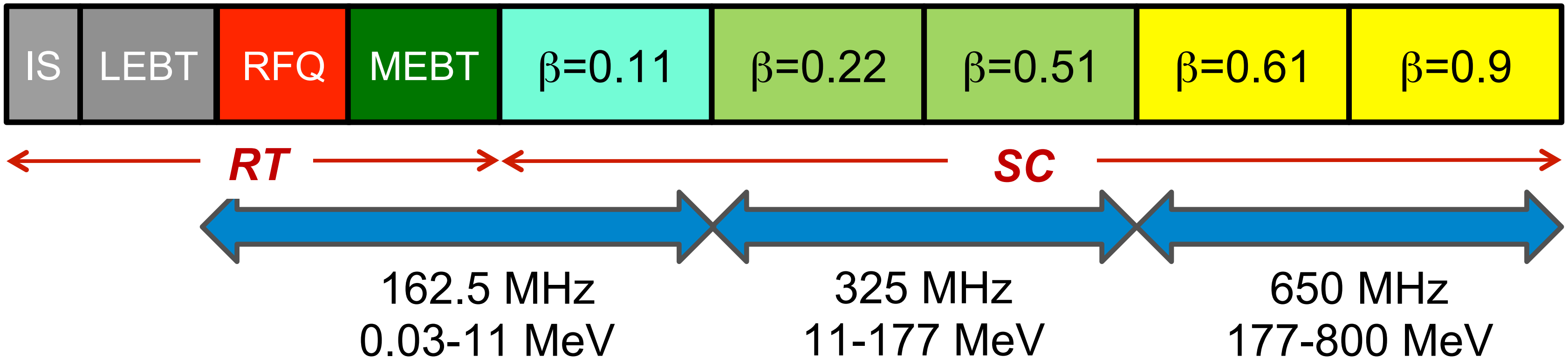


Performance Goals

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	13	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Beam Power	8	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
Beam Power to 8 GeV Program (max)	32	80	kW
Main Injector Protons per Pulse	4.9×10^{13}	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
LBNF Beam Power @ 120 GeV	0.7	1.2*	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*LBNF beam power can be maintained down to ~60 GeV, then scales down with beam energy

PIP-II Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

All components CW-capable ***First HWR cavity recently tested at ANL***

Future Directions

- The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements to the Fermilab proton complex
  - multi-MW to LBNF
  - 100's kW for a rare processes program
    - CW capability at 0.8 – 3 GeV
    - Muons
    - Kaons
    - Neutrons
  - Front end for a muon-based facility

Future Directions beyond 1 MW PIP-II program

- The strategy for next step(s) beyond PIP-II will be developed in consideration of the following:
  - Slip-stacking in the Recycler may not be possible at intensities beyond PIP-II
  - The Booster cannot be upgraded to support intensities beyond $\sim 7\times10^{12}$ ppp, no matter what the injection energy
  - A new 8 GeV source is necessary
  - Models:
    - 1.5-2 GeV linac + conventional Rapid Cycling Synchrotron
    - ‘supersmart RCS’ that mitigates beam losses (R&D into space charge effects)
    - ‘brute force’ but cost effective 6-8 GeV linac (R&D into performance and cost)
- The strategy will be determined on the basis of R&D progress and physics programmatic choices

Example: 2+ MW @ 60-120 GeV

- 2.4 MW requires 1.5×10^{14} protons from Main Injector every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Accumulation requires either:
  - Box-car stack (in Recycler) six batches of 2.5×10^{13} protons in ≤ 0.6 sec
    - ⇒>10 Hz rep-rate RCS
  - Or inject a long (linac) pulse containing 1.5×10^{14} protons directly into Main Injector
  - Strategy TBD

Possible Parameters for post-PIP-II Complex

Proton Source	RCS	Linac	
Particle Type	p	H-	GeV
Beam Kinetic Energy	8.0	8.0	GeV
Protons per Pulse	2.6×10^{13}	1.5×10^{14}	
Beam Pulse Length	0.0016	10	msec
Pulse Repetition Rate	20	20	Hz
Pulses to Recycler	6	NA	
Pulses to Main Injector	NA	1	
Beam Power at 8 GeV (Total)	660	3960	kW
Beam Power to Main Injector*	160/280	160/280	kW
Beam Power Available for 8 GeV Program*	500/380	3800/3680	kW
Main Injector			
Beam Kinetic Energy*	120/60	120/60	GeV
Main Injector Protons per Pulse	1.5×10^{14}	1.5×10^{14}	
Main Injector Cycle Time*	1.2/0.7	1.2/0.7	sec
LBNF Beam Power*	2.4/2.1	2.4/2.1	MW

*First number refers to 120 GeV MI operations; second to 60 GeV

Supporting Technologies: R&D opportunities

"Power upgrades beyond those envisioned for PIP-II will require R&D for high average power proton linacs and target systems." P5 report, page 47

- Superconducting RF (H. Padamsee)
  - High energy/high duty factor linacs require SRF
  - Q_0 is the most important performance parameter as it impacts directly cryogenics systems capital and operating costs
    - Note: Q_0 refers to performance in a cryomodule(!)
  - Opportunities to reduce construction costs through exploration of (alternative) fabrication/processing procedures

  "It is appropriate for the PIP-II effort to be supported partially by temporary redirection of GARD funding of SCRF R&D and facilities at Fermilab" P5 report, page 47
- Mitigation of beam loss (A. Valishev, P. Spentzouris, R. Zwaska)
  - Any facility one can imagine has a ring somewhere: either RCS or an accumulator
    - Instabilities, radiation control and loss mitigation
  - Performance is often dictated by space-charge in the first ring the beam sees
    - This drives cost via injection energy and aperture
  - Opportunities for mitigation of beam loss due to space-charge in high intensity beams could be a game-changer

Supporting Technologies: R&D Opportunities

- High Power Targets (P. Hurh)
  - This is now an enabling technology for particle physics research
  - It is in many ways easier to develop credible concepts for multi-MW beams than for the targets that they strike
    - High radiation environments
    - High thermal 'shock'
    - High temperatures
  - There is a critical need to establish expertise and development programs in high power targets, comparable to what we are doing in SC magnets and SRF

Summary

- Proton Improvement Plan-II has been developed as a first step in establishing a world-leading facility for particle physics research based on intense beams, at Fermilab
  - LBNF >1 MW at startup
  - 8 GeV program >40 kW coincident with LBNF
- PIP-II retains flexibility to eventually realize the full potential of the Fermilab complex
  - multi-MW to LBNF
  - multi-MW to SBN program
  - High power/high duty factor operations at 0.8-3 GeV
    - Muons, kaons, neutrons
- Capitalizing on these longer term opportunities will require advances in SRF, space-charge and beam loss mitigation, and high power targets

Backups

2+ MW @ 60-120 GeV

- Booster is not capable of accelerating 2.5×10^{13} no matter what the injection energy, or how it is upgraded:
  - Requires ~0.1% beam loss
  - High impedance
  - Transition crossing
  - Poor magnetic field quality
  - Poor vacuum
  - Inadequate shielding

$\Rightarrow$ ***Achieving 2+ MW from Main Injector will require replacement of the Booster with either a 6-8 GeV pulsed linac or a rapid cycling synchroton (RCS) fed by a $\geq$2 GeV linac***

Proton Economics and Power Scaling

- Every proton that strikes a production target is supplied by the Booster. Conservation of energy:

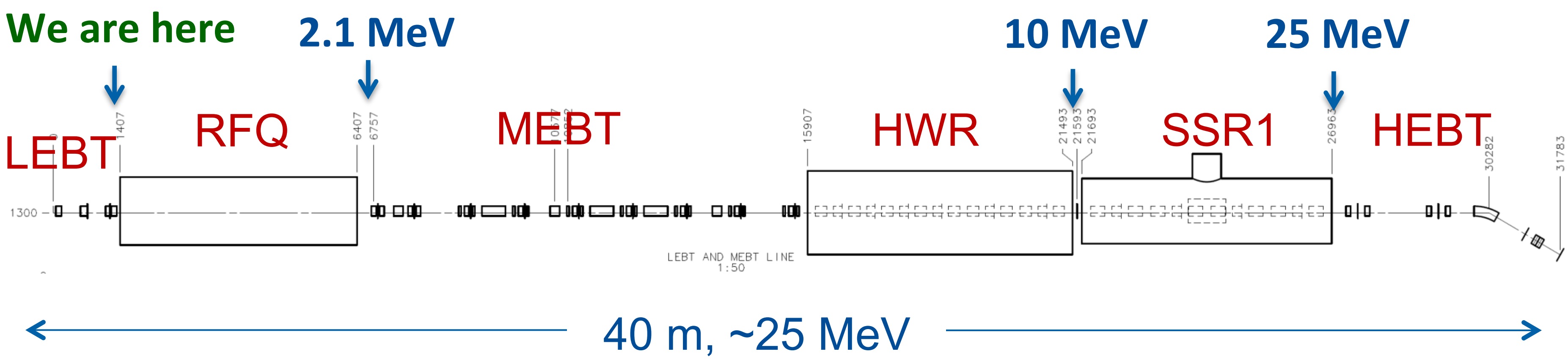
$$P_{Booster} = P_{8\,GeV} + P_{E_{MI}} \left(8\,GeV / E_{MI}\right)$$

  - (Secondary constraints related to the Main Injector loading scheme and cycle times)
- In the PIP-II configuration the most straightforward means to raise the Booster beam power further is to increase the repetition rate
  - Believe 20 Hz is achievable and currently developing concepts
  - Booster beam power from 120 $\rightarrow$ 160 kW
  - Doubles power to 8 GeV program for MI operations at 120 GeV

PIP-II R&D Strategy

- Goal is to mitigate risk: Technical/cost/schedule
- Technical Risks
  - Front End (PXIE)
    - Complete systems test: Ion Source through SSR1 (25 MeV)
  - Operations of (high Q_0) superconducting linac in pulsed mode
    - Primary issue is resonance control in cavities
    - Generally applicable to next generation SC linacs
    - Task force defining options
    - Options evaluated at PXIE
- Cost Risks
  - Superconducting RF
    - Cavities, cryomodules, RF sources represent 46% of construction costs
- Goal: Be prepared for a construction start in 2018-19

PXIE



PXIE will address the address/measure the following:

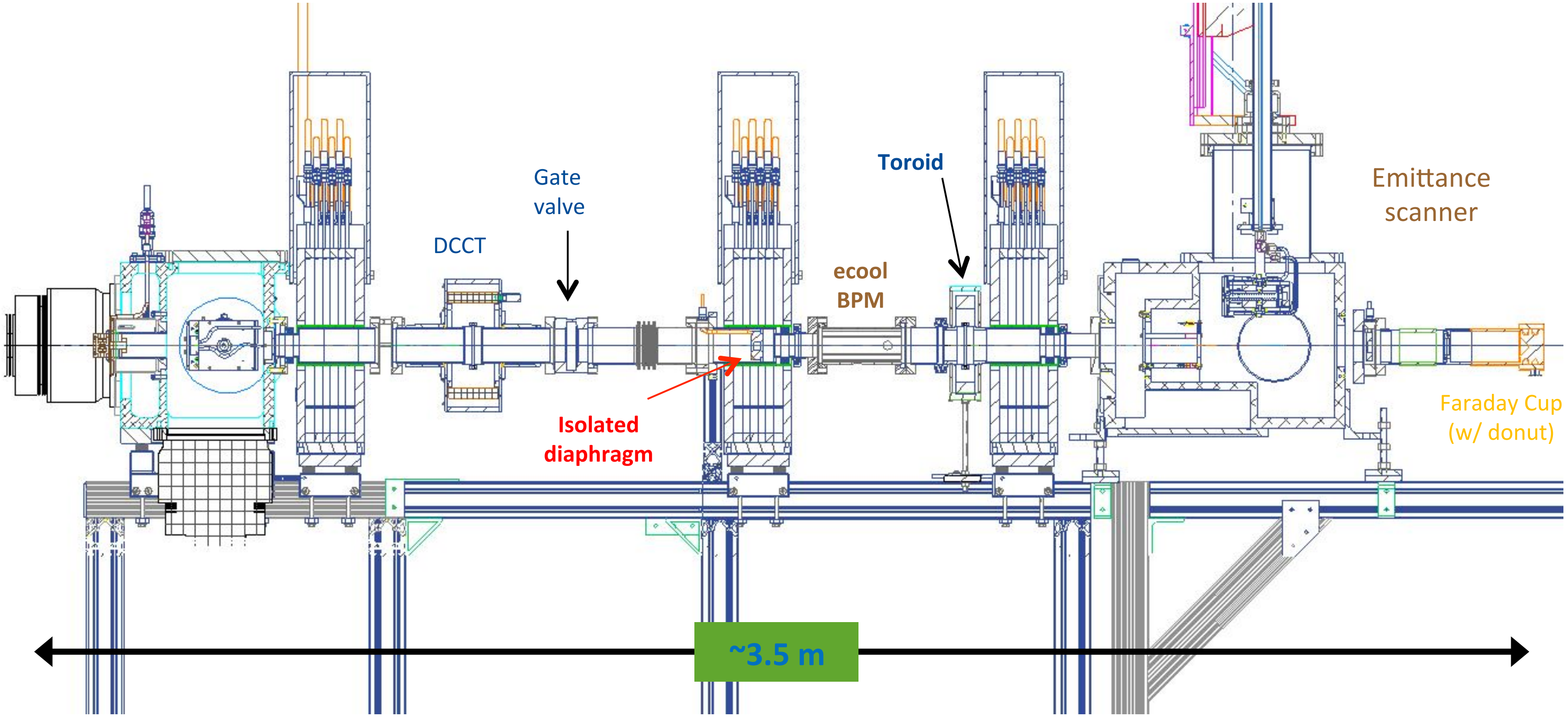
- LEBT pre-chopping
- Vacuum management in the LEBT/RFQ region
- Validation of chopper performance
- Bunch extinction
- MEBT beam absorber
- MEBT vacuum management
- Operation of HWR in close proximity to 10 kW absorber
- Operation of SSR with beam, including resonance control
- Emittance preservation and beam halo formation through the front end

Collaborators

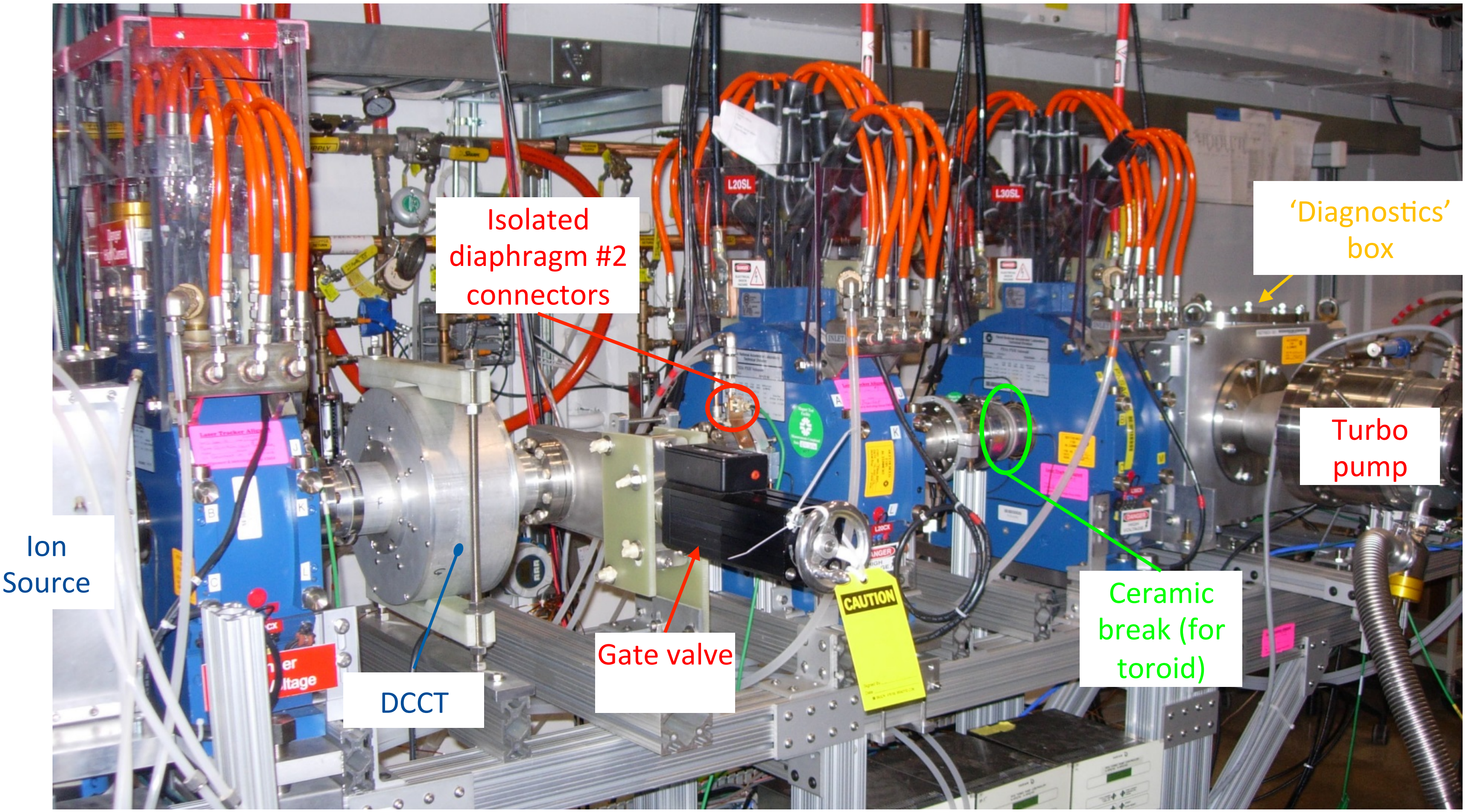
- ANL: HWR
- LBNL:LEBT, RFQ
- SNS: LEBT
- BARC: MEBT, SSR1

Current Configuration (August 2014)

- All solenoids installed
  - + ecool BPM as ‘clearing’ electrode until chopper is ready
  - Emittance scanner at ~location of RFQ entrance

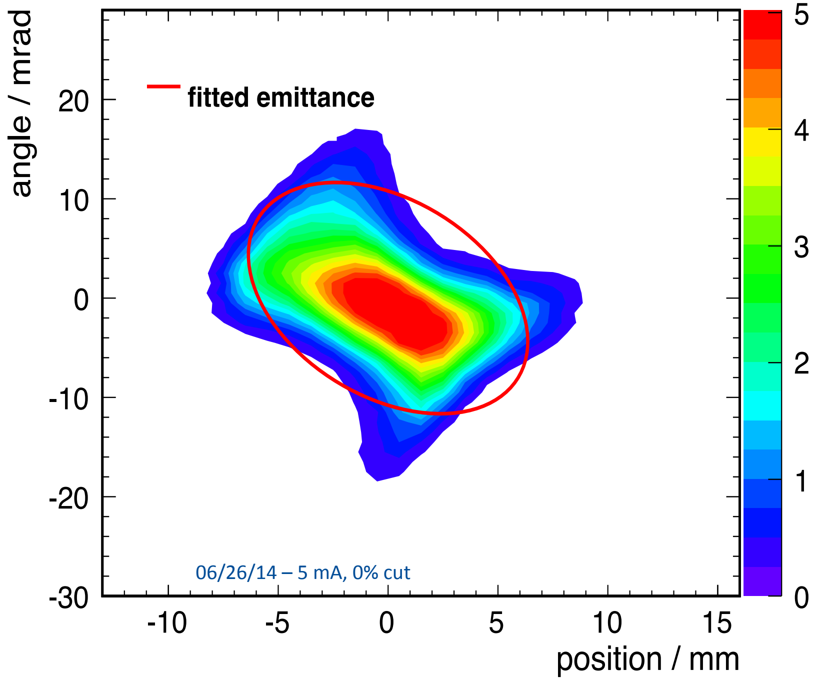


Current Configuration (August 2014)

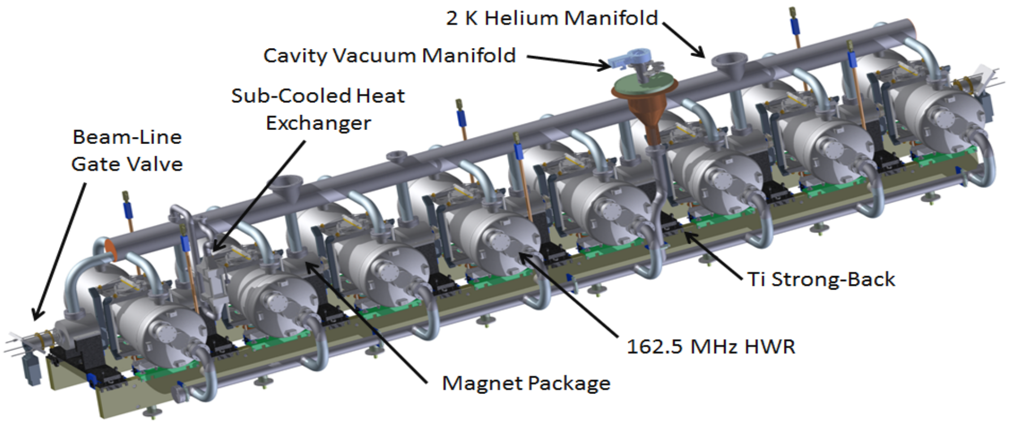


Emittance measurements

- Carried out emittance scans for various conditions
  - Analyses underway
  - Preliminary calculations of the emittance for beam settings similar to those from 6/6/14 (i.e. donut data set) are ~30% higher
  - core shape vs tail contribution

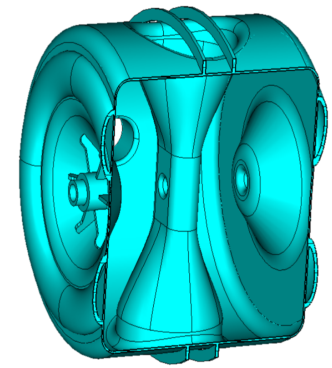


SRF R&D



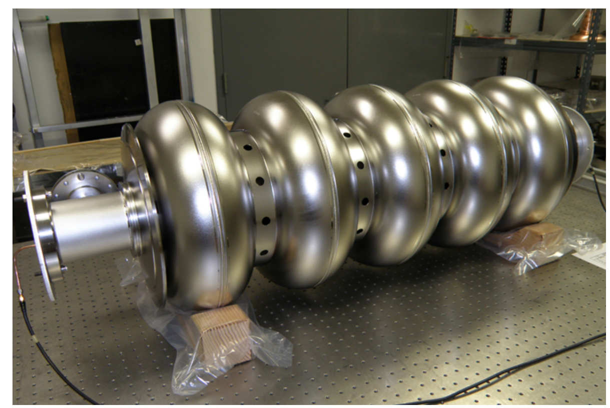
HWR

SSR1



SSR2

LB650



HB650

PIP-II Status and Strategy

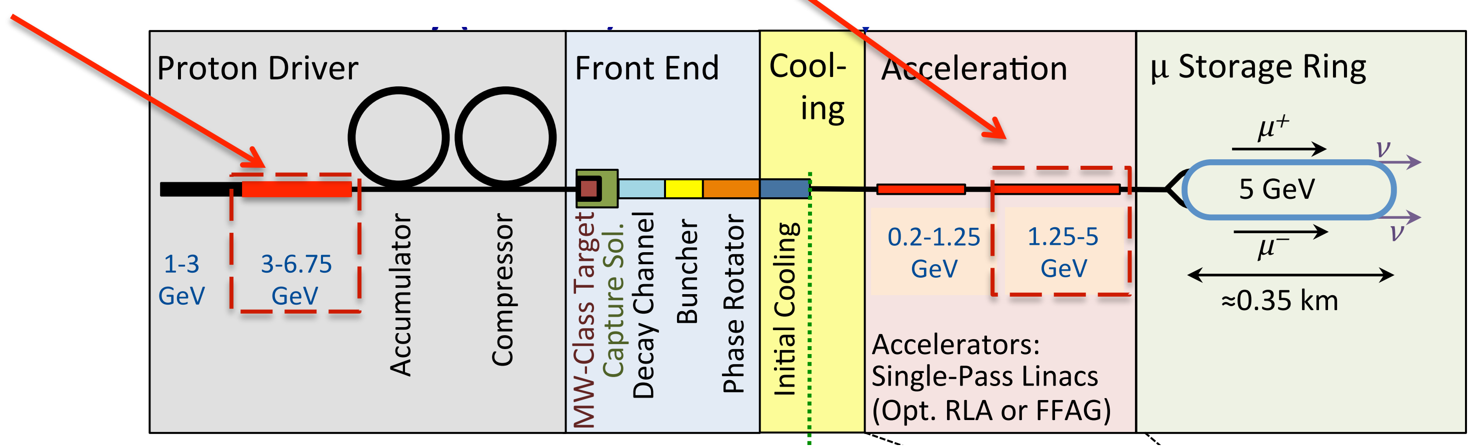
- PIP-II is in the development phase and is not yet recognized as a formal DOE project
  - However, PIP-II has received very strong support from P5, DOE/OHEP, and the Fermilab director
  - Expect formalization of project status (CD-0) in the next year, with a ~5-year construction period, starting in the current decade
- Goals for FY2105
  - Release PIP-II Reference Design Report
  - Update current cost estimate as necessary
  - Start developing a resource loaded schedule
  - Receive RFQ (from LBNL) and initiate commissioning at PXIE
  - Keep HWR and SSR1 fabrication on schedule
  - Develop deliverables strategy with India (and Europe)
  - Support DOE/OHEP in development of Mission Needs Statement
  - Establish PIP-II Office

Proton Driver for Muon-based Facilties

- Previous work based on Project X
  - 8 GeV H- linac delivering 4 MW
  - Accumulation Ring to convert H- to protons and reformat beam into a few (~4)intense bunches
  - Compressor Ring bunch to shorten bunches
  - Delivery beam lines to deliver multiple bunches to target
- Strategy built upon PIP-II is incorporated within MASS
  - 6.75 GeV H- linac delivering 1 MW
    - 5 mA × 50% chopping × 4 ms × 15 Hz × 6.75 GeV = 1 MW
    - 3-6.75 GeV dual use: proton and muon acceleration
  - Basic Accumulator/Compressor/multi-bunch targeting scheme retained

Dual Use Linac

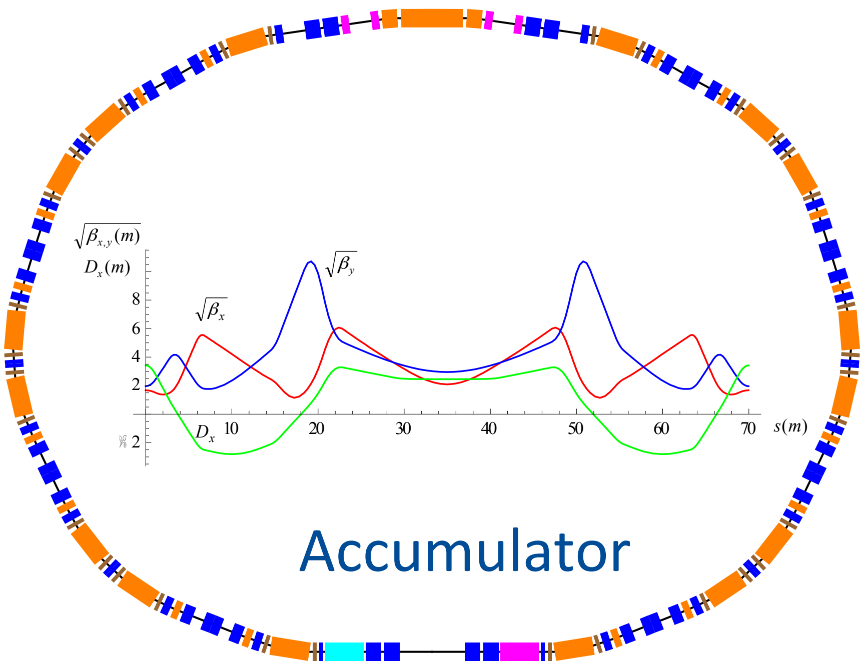
- MASS: MAP linac for muon acceleration can be used for H- acceleration
  - muon beam 1.25 to 5 GeV
  - H- beam 3 to 6.75 GeV

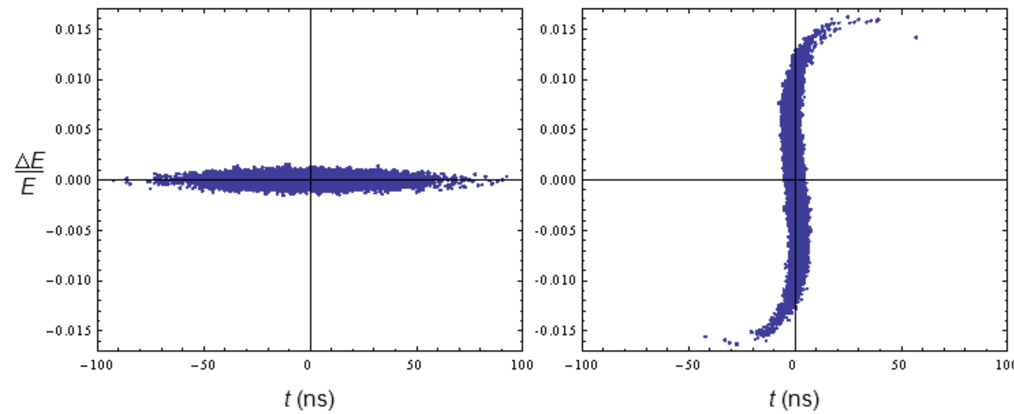


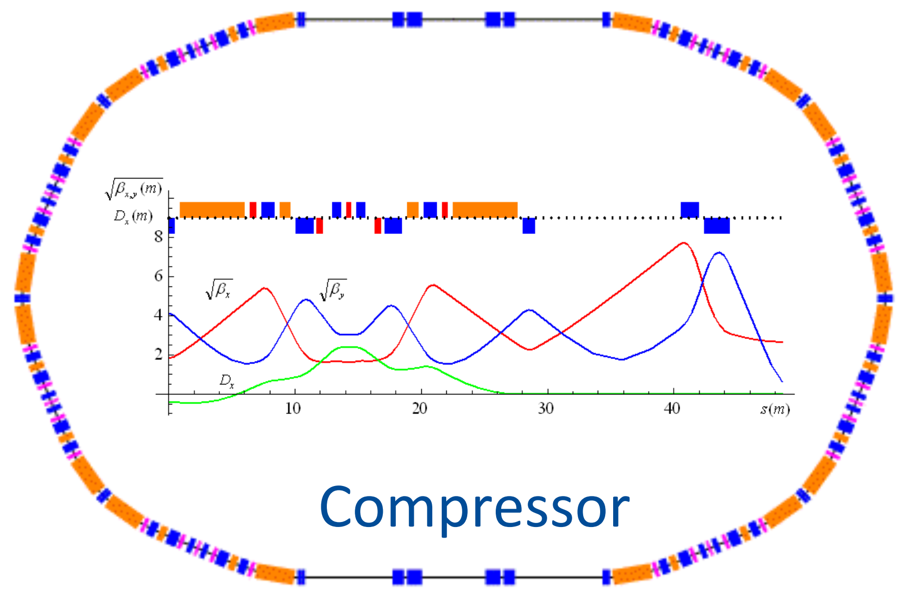
  - muon requirements are more stringent
    - Studies to see H- beam performance to be done

Expanded Previous Rings' Studies

- Compatible with 6.75 GeV and MASS staging

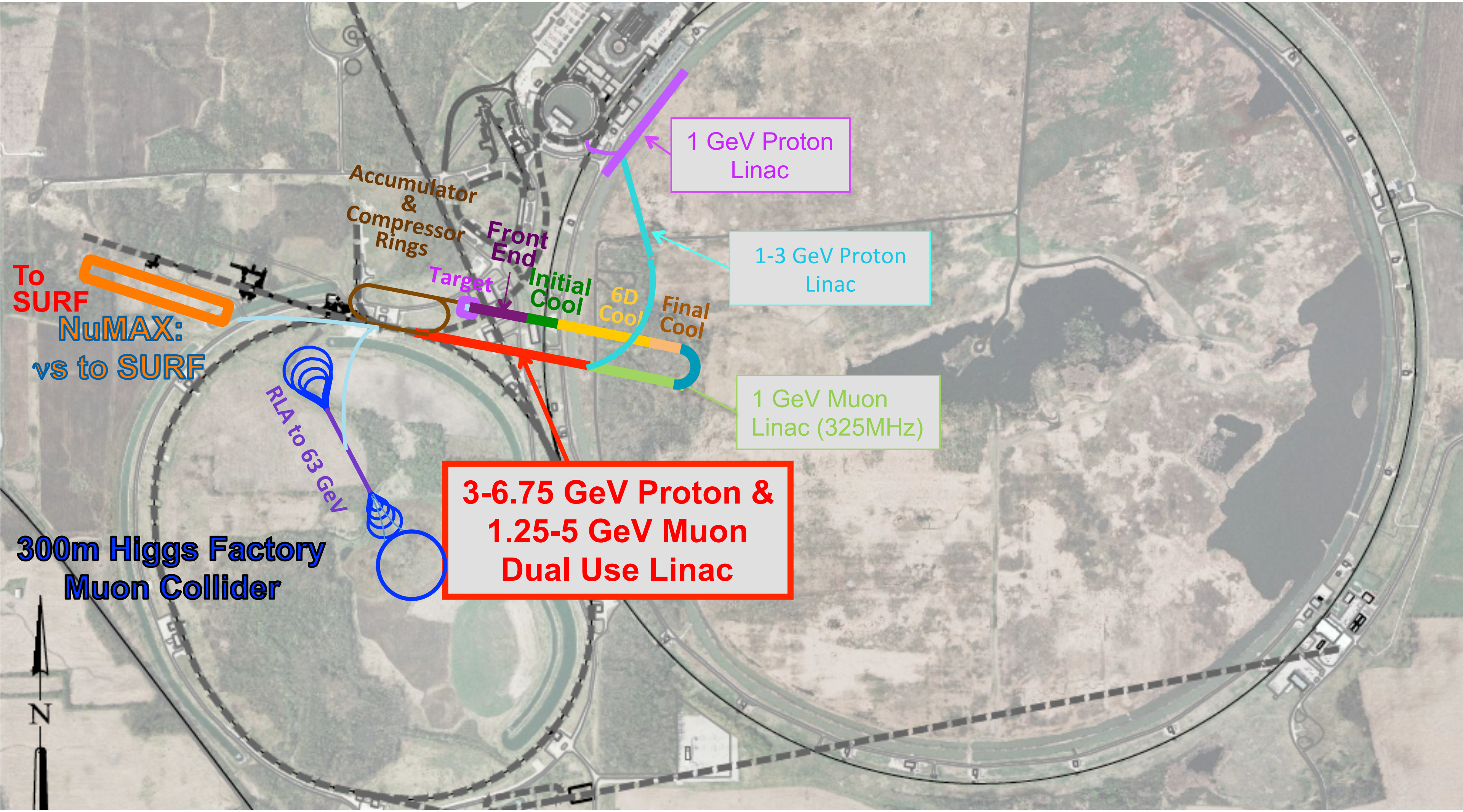




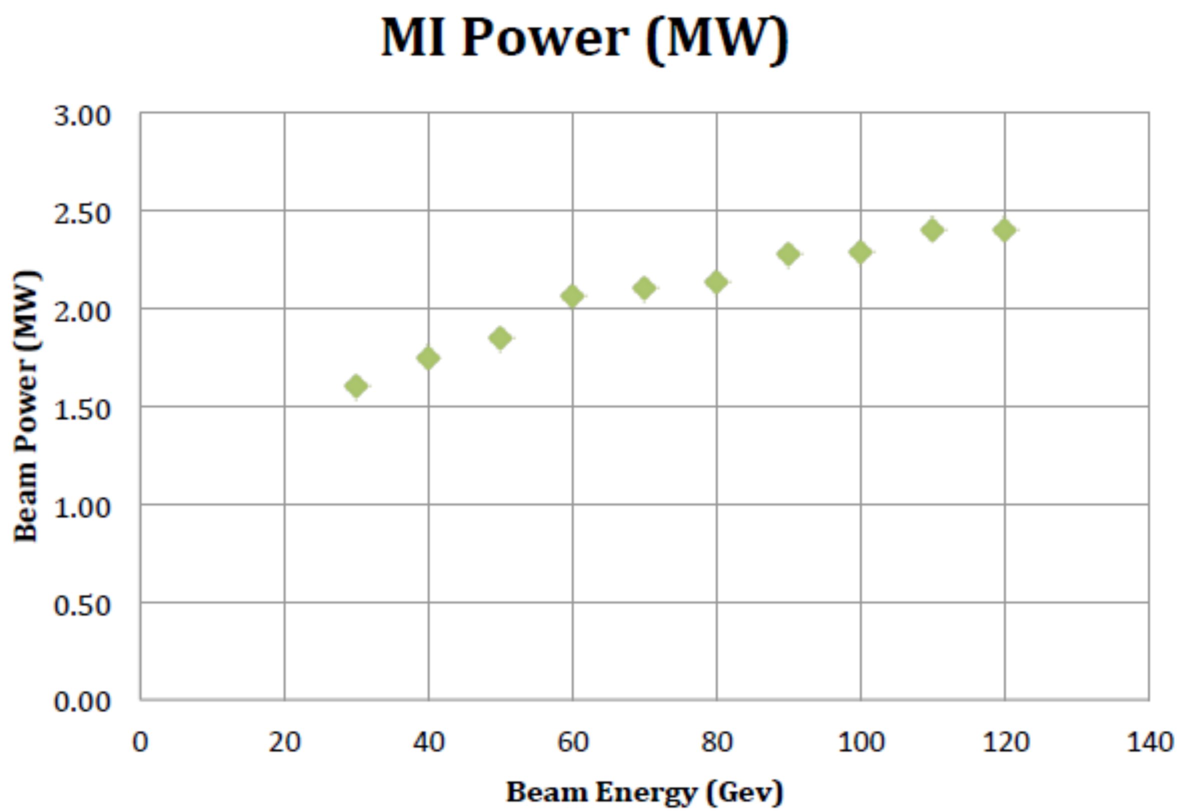


- To be done
  - More detailed simulation studies of the rings' lattices with space charge
  - Full design and study of injection and stripping (initial work next slide)

Possible Layout



Possible Parameters for post-PIP-II Complex



PIP-II Collaboration

- Collaboration MOUs for the RD&D phase (through CD-2) :

National		IIFC
ANL	ORNL/SNS	BARC/Mumbai
BNL	PNNL	IUAC/Delhi
Cornell	UTenn	RRCAT/Indore
Fermilab	TJNAF	VECC/Kolkata
LBNL	SLAC	
MSU	ILC/ART	
NCSU		

- Ongoing contacts with CERN (SPL), RAL/FETS (UK), ESS (Sweden), RISP (Korea), China/ADS
- Annual Collaboration Meeting (June 3-4 at Fermilab)

  https://indico.fnal.gov/conferenceDisplay.py?confId=8365