Fermilab

PIP-II Overview: Goals, Status, Strategy

Steve Holmes

PIP-II Machine Advisory Committee

9-11 March 2015

Since Last Year's Meeting

At the time of last year's meeting we had developed the PIP-II concept, documented the concept in a whitepaper, and presented the concept to P5. Since then…

- P5 process completed
  - Multiple interactions with P5, primarily on funding requirements and schedules
  - P5 report submitted/accepted by HEPAP; strong endorsement of PIP-II:

    Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.
- PIP-II Reference Design Report complete draft released
- Fermilab SRF and PIP-II R&D programs integrated
- Fermilab assumes major responsibilities in LCLS-II
- Annex I to the U.S. DOE-India DAE Implementing Agreement signed

Outline

- Program Goals
- Design Strategy and Concept
- R&D Program
- Project Status and Strategy
- Collaboration
- Recommendations Responses
- Meeting Organization

Motivation

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 @ >1-2 MW
  - SBN @ 10's kW
- Muons
  - Muon g-2 @ 17-25 kW
  - Mu2e @ 8-100 kW
- Longer term opportunities

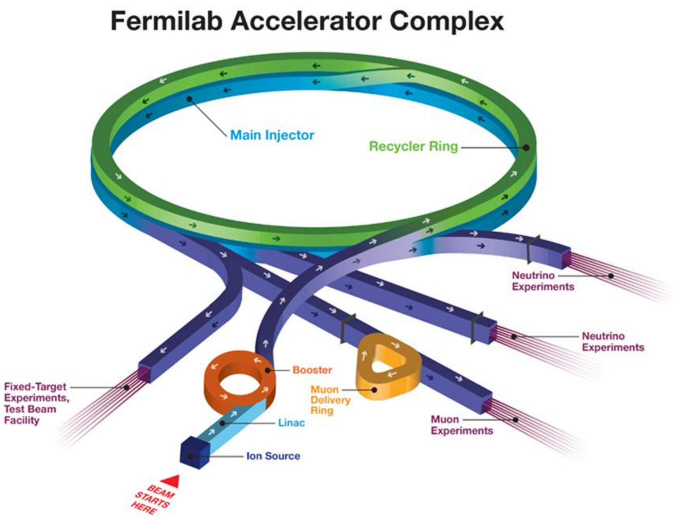
$\Rightarrow$ ***This requires more protons!***

Proton Improvement Plan (PIP) will support initial goals by establishing a base capability of operating the Booster at a 15 Hz beam rate

The Fermilab Accelerator Complex Following PIP

- The Fermilab complex will deliver protons at both 8 and 120 GeV, in support of the neutrino and muon programs:
  - Booster: 4.2×10^{12} protons @ 8 GeV @ 15 Hz = 80 kW
  - MI: 4.9×10^{13} protons @ 120 GeV @ 0.75 Hz = 700 kW

- Limitations
  - Booster pulses per second (15 Hz)
    - Total power available to 8 GeV program limited by the repetition rate
  - Booster protons per pulse
    - Limited by space-charge forces at Booster injection, i.e. the linac energy
  - Reliability
    - Linac/Booster represent a non-negligible operational risk



PIP-II (Proton Improvement Plan–II)

The PIP-II goal is to support long-term physics research goals by providing increased beam power to LBNF, while providing a platform for the future

- Design Criteria (unchanged in last 18 months)
  - Deliver >1 MW of proton beam power from the Main Injector over the energy range 60 – 120 GeV, at the start of LBNF operations
  - Support the current 8 GeV program including Mu2e, g-2, and short-baseline neutrinos
  - 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
- Goal: Initiate operations in newly-configured complex in ~2024

PIP-II Strategy

- Increase Booster/Recycler/Main Injector per pulse intensity by ~50%
  - Requires increasing the Booster injection energy to ~800 MeV
    - 30% reduction in space-charge tune shift w/ 50% increase in beam intensity
- Increase Booster repetition rate to 20 Hz
  - Maintain 1 MW down to 60 GeV or,
  - Provide factor of 2.5 increase in power to 8 GeV program
  - Improve slip-stacking efficiency via larger orbit separation
- Modest modifications to Booster/Recycler/Main Injector
  - Accommodate higher intensities and higher Booster injection energy

$\Rightarrow$ ***Propose: 800 MeV superconducting pulsed linac, extendible to support >2 MW operations to LBNF and upgradable to continuous wave (CW) operations***

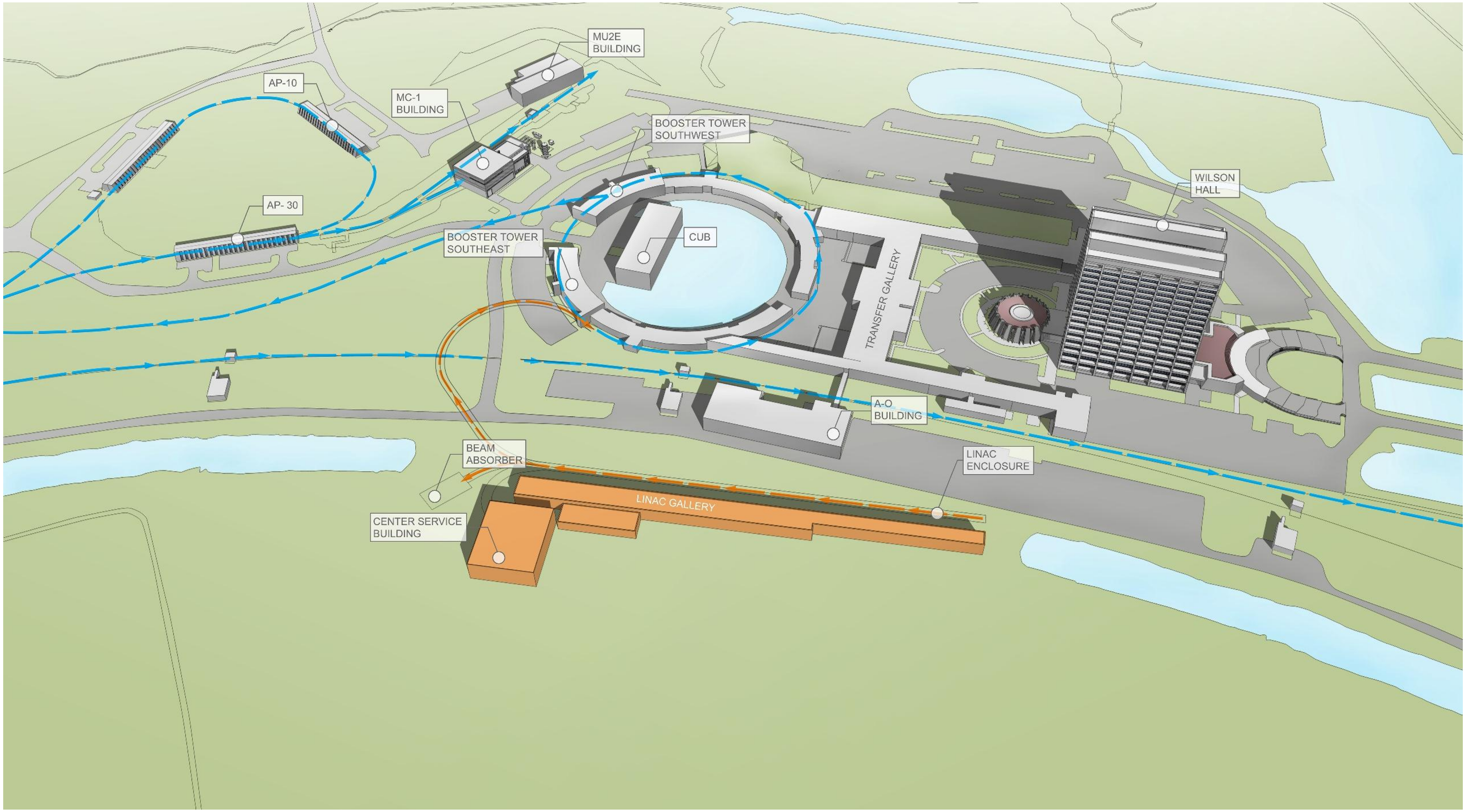
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting RF technologies
  - Eliminates significant operational risks inherent in existing 400 MeV linac
    - Existing linac removed from service upon completion of PIP-II
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector (PIP-III)

PIP/PIP-II Performance Goals

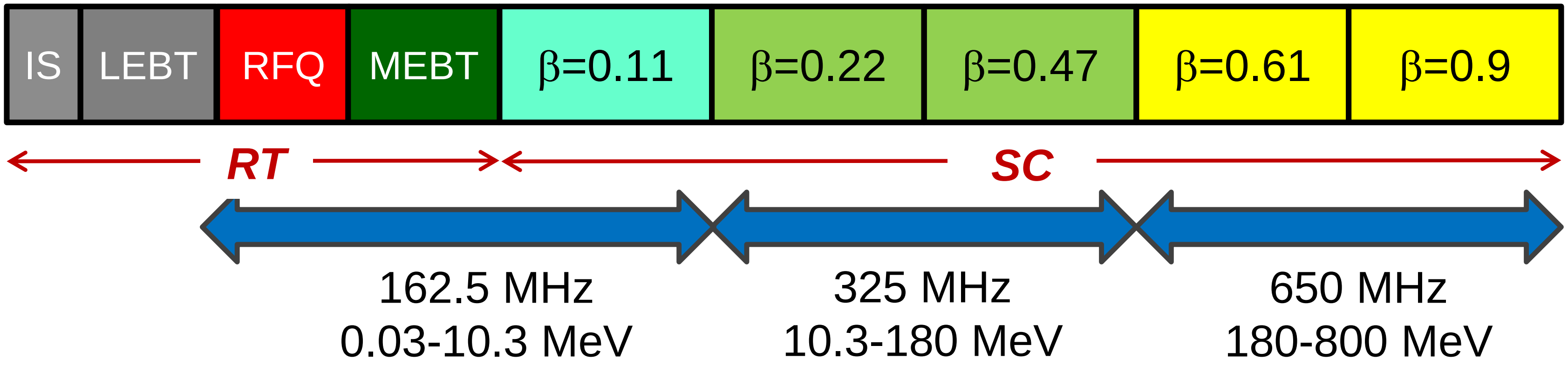
Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Mu2e Upgrade Potential (800 MeV)	NA	>100	kW
Booster Protons per Pulse	4.2×10^{12}	6.5×10^{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}	7.6×10^{13}	
Main Injector Cycle Time @ 60-120 GeV	1.33*	0.7-1.2	sec
LBNF Beam Power @ 60-120 GeV	0.7*	1.0-1.2	MW
LBNF Upgrade Potential @ 60-120 GeV	NA	>2	MW

*NOvA operates exclusively at 120 GeV

PIP-II Site Layout (provisional)



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	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_{opt}=0.65)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_{opt}=0.97)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

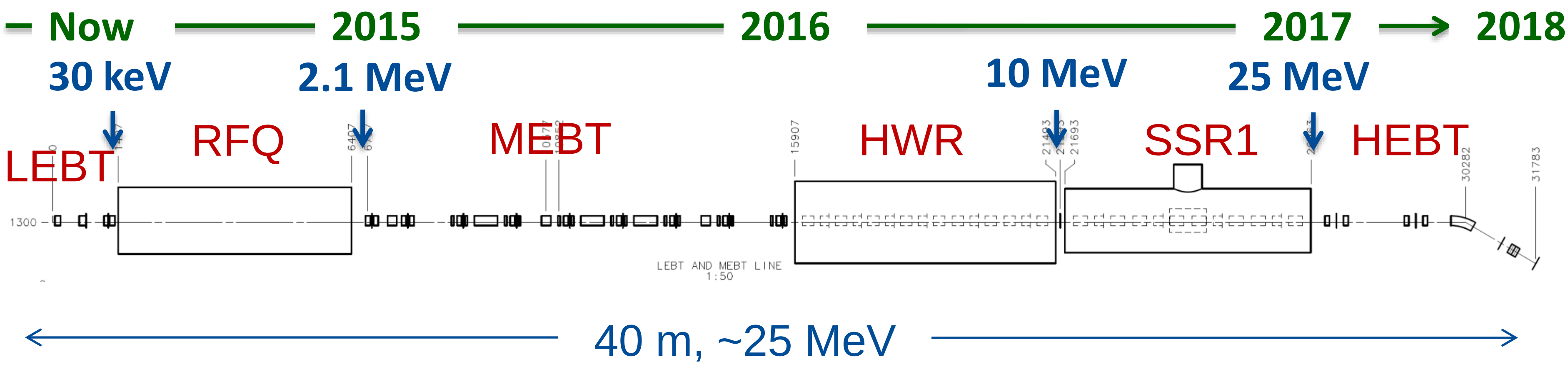
Booster/Recycler/MI Requirements

- Booster
  - New injection region to accept 800 MeV H^- and enable transverse beam painting
  - RF sufficient to support acceleration and transition crossing manipulations (22 cavities total)
  - 20 Hz operations
  - Upgrades to damper and collimator systems
- Recycler
  - RF sufficient for slip-stacking at cycle times as low as 0.7 sec, i.e. 60 GeV
  - New collimators(?)
- Main Injector
  - RF power upgrade
  - Collimator upgrade

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) SC Linac in pulsed mode at low current
    - Primary issue is resonance control in cavities
    - Task force defining options and pursuing development
  - Booster/Recycler/Main Injector beam intensity
    - 50% per pulse increase over current operations
    - Longitudinal emittance from Booster for slip-stacking
    - Beam loss/activation
- Cost Risks
  - Superconducting RF
    - Cavities, cryomodules, RF sources represent 46% of construction costs
- Goal: Be prepared for a construction start in 2019
  - R&D deliverables milestones established

PXIE (PIP-II Injector Experiment)



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 20 kW absorber
- Operation of SSR with beam, including resonance control and LFD compensation in pulsed operations
- Emittance preservation and beam halo formation through the front end

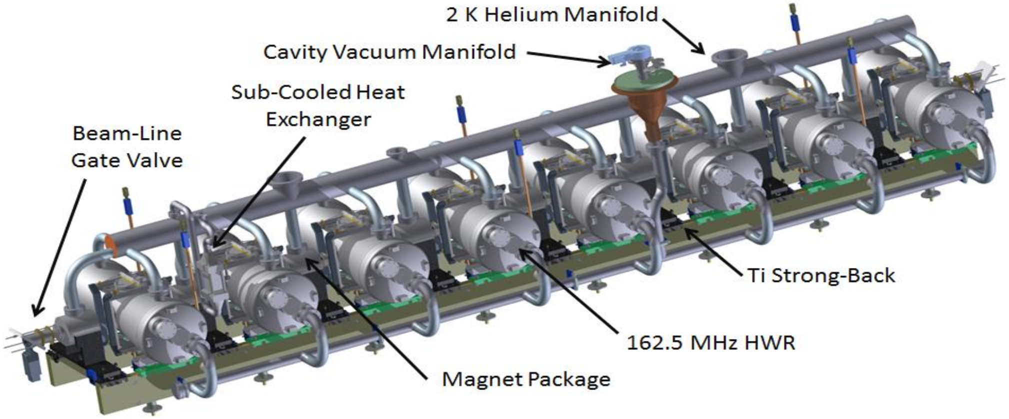
Collaborators

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

SRF Development Status (2-19-15)

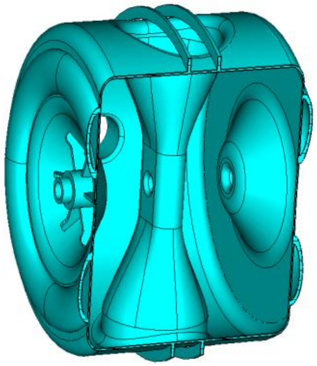
Cavity	Frequency	Cavity Type	Beta	Collaboration?	Cavity EM Design Complete	Cavity Mech Design Complete	Single Cell / Prototype Ordered	Full Cavity Prototype Received	Prototype Tested	Cavities for CM Ordered	Cavities for CM Received	Cavities for CM Tested	Cavities for CM Dressed	CM Cold Mass Design	CM Parts Ordered	# of CM Assembled	Est % complete
Half Wave Resonator (HWR)	162.5 MHz	1-HWR CW	0.11	ANL	yes	yes	yes	yes	yes	9	all parts	2	2	yes	yes	10%	60
Single Spoke Resonator 1 (SSR1)	325 MHz	1-spoke CW	0.22	India	yes	yes	2	2	2	10	10	10	3	80%	70%	not started	75
Single Spoke Resonator 2 (SSR2)	325 MHz	1-spoke CW	0.47	India	yes	yes	not started	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
Low Energy 650 (LE 650)	650 MHz	5-cell CW	0.6	India, JLAB	yes	yes	5	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
High Energy 650 (HE 650)	650 MHz	5-cell CW	0.9	India	yes	yes	5 of 10	4	not started	9	4	not started	not started	5%	not started	not started	20

SRF R&D



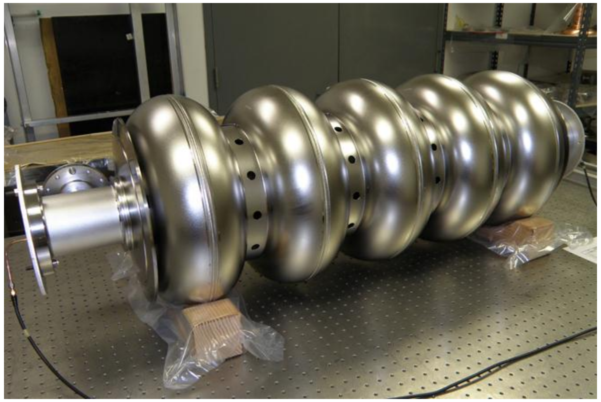
HWR

SSR1



SSR2

LB650



HB650

PIP-II Project Status and Strategy

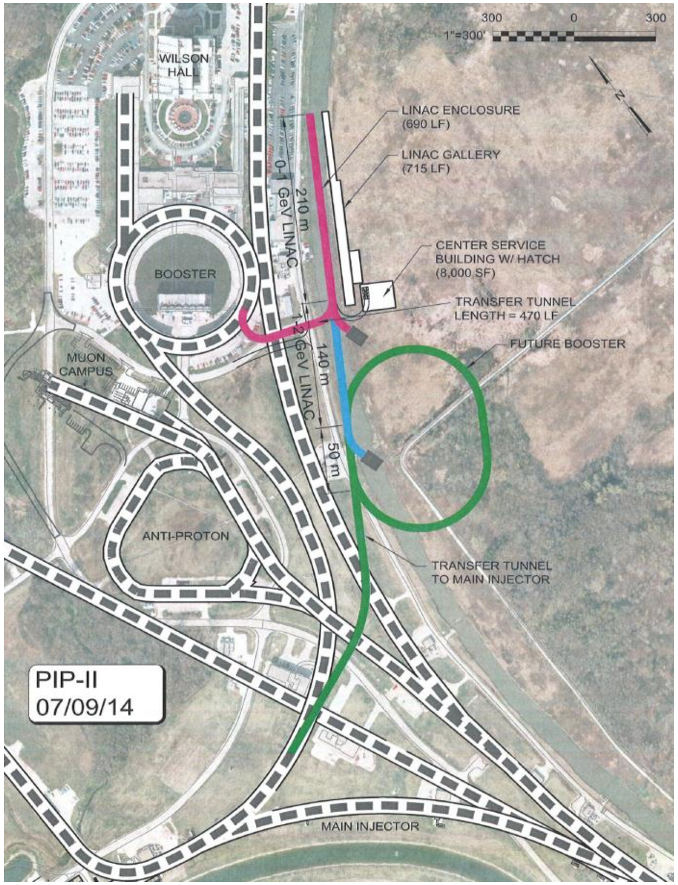
- PIP-II is in the development phase and is not yet recognized as a formal DOE project
  - However, PIP-II has received very strong support from P5, DOE/OHEP, and the Fermilab director
  - Expect formalization of project status (CD-0) in the next ~year, followed by ~8-year development + construction period
- Goals for FY2015
  - 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

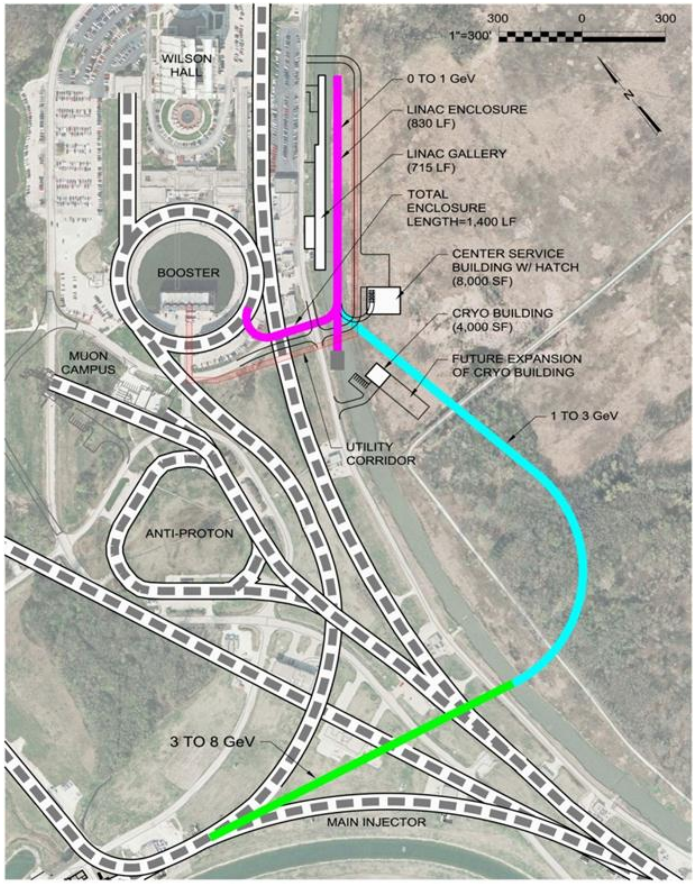
Future Directions

- The configuration and siting of the PIP-II linac are chosen to provide opportunities for future performance enhancements to the Fermilab proton complex
  - >2 MW to LBNF
  - 100's kW for a rare processes program
    - CW capability at 0.8 – 3 GeV
  - Front end for a muon-based facility
- The natural next steps would be upgrading the PIP-II linac to CW operations and replacement of the Booster with higher performance accelerator

Flexible Platform for the Future

- Opportunities for Booster replacement include full energy (8 GeV) linac or RCS





PIP-II Collaboration

- Organized as a "national project with international participation"
  - Fermilab as lead laboratory
- Collaboration MOUs for the development phase (through CD-2) :

<u>National</u>

ANL
BNL
Cornell
Fermilab
LBNL
MSU
NCSU
ORNL/SNS
PNNL
UTenn
TJNAF
SLAC
ILC/ART

<u>IIFC</u>

BARC/Mumbai
IUAC/Delhi
RRCAT/Indore
VECC/Kolkata

- Annex I to the U.S. DOE-India DAE Implementing Agreement signed in January 2015
  - Significant Indian contribution to PIP-II R&D and construction
  - Joint DOE-DAE evaluation of R&D accomplishments in 2018
- Ongoing contacts with CERN (SPL), Orsay, RAL/FETS (UK), ESS (Sweden), China/ADS

Cost Estimate/Proposed Budget Profile

	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	Total
PIP II Funding Profile (Cost to DOE)	23.4	28.5	39.5	44.8	61.9	79.0	80.0	75.0	59.0	491.1
In-kind International Contributions	0.3	1.1	1.9	17.5	37.7	39.5	39.2	23.0		160.2

- Profile based on FY19-23 construction period
  - As presented to P5
  - All amounts are $M then-year
  - Inconsistent with FY15 actual ($20.0M) and FY16 PBR ($19.5M)
- Assumes $160M offset from international in-kind contributions
- PXIE and SRF are major elements of the R&D program
  - Complete set of deliverables established, designed to retire technical risks in advance of the construction start

Response to Last Meeting's Recommendations

- All recommendations have been considered
  - Responses are available on the indico site
- Selected highlights:
  - Integration of PIP and PIP-II.
    - Revised strategy on linac power sources and Booster rf cavities
    - Transition plan under development
  - Development of Recycler/Main Injector strategy
    - R&D plan under development
  - Implications of Total Loss Monitor (TLM) approach
    - ESH&Q Section approval of TLM as an accredited safety system; Accelerator Division working for a final approval during CY15
  - Priorities in face of resource shortages
    - PXIE is highest priority (includes HWR and SSR1 prototypes)
    - HB650 is next highest (includes cavity testing; CM design w/India)

Organization of the Meeting

PIP-II Machine Advisory Committee 3rd Meeting March 9-11, 2015				
Start	Duration	End	Speaker	Topic
Monday, March 9, 2015				
8:00	0:30	8:30	S. Nagaitsev	*Executive Session*
8:30	0:30	9:00	S. Holmes	PIP-II Overview: Goals, Status, and Strategy
PIP-II Design Concept				
9:00	0:30	9:30	V. Lebedev	PIP-II Design Overview
9:30	0:30	10:00	V. Lebedev	800 MeV Linac: Cold Linac
10:00	0:20	10:20		*Discussion*
10:20	0:15	10:35		*Coffee Break*
10:35	0:25	11:00	A. Shemyakin	800 MeV Linac: Warm Front End
11:00	0:25	11:25	B. Pellico	Booster Upgrades: Overview
11:25	0:25	11:50	I. Kourbanis	MI/RR Upgrades: Overview
11:50	0:15	12:05		*Discussion*
12:05	1:00	13:05		*Lunch*
13:05	1:00	14:05	J. Leibfritz, A. Grasselino	*Tour*
14:05	0:15	14:20	J. Hunt	Siting/Conventional Facilities
14:20	0:20	14:40	D. Mitchell	Engineering Activities
14:40	0:15	14:55		*Discussion*
14:55	0:15	15:10		*Coffee Break*
R&D Program				
15:10	0:25	15:35	P. Derwent	R&D Program Overview
15:35	0:20	15:55	J. Leibfritz	CMTF infrastructure
15:55	0:30	16:25	L. Prost	PXIE Warm Status
16:25	0:20	16:45	J. Steimel	RFQ Status and Commissioning Plan
16:45	0:15	17:00	J. Anderson	PXIE Operational Readiness
17:00	0:15	17:15		*Discussion*
17:15	1:15	18:30		*Executive Session*
19:00	1:30	20:30		*Dinner*
Tuesday, March 10				
R&D Program (cont)				
8:30	0:15	8:45	H. Padamsee	Superconducting RF: Development Strategy
8:45	0:20	9:05	P. Ostroumov	Superconducting RF: HWR Status
9:05	0:30	9:35	L. Ristori	Superconducting RF: SSR1, SSR2 Status
9:35	0:20	9:55	A. Grasselino	Superconducting RF: LB650, HB650 Status
9:55	0:20	10:15		*Discussion*
10:15	0:15	10:30		*Coffee Break*
10:30	0:20	10:50	W. Schappert	Superconducting RF: Resonance control
10:50	0:20	11:10	B. Chase	LLRF
11:10	0:15	11:25	R. Pasquinelli	RF Sources
11:25	0:15	11:40	V. Scarpine	Instrumentation
11:40	0:20	12:00	S. Mishra	International Collaborations
12:00	0:15	12:15		*Discussion*
12:15	1:00	13:15		*Lunch*
Executive Session				
13:15	1:00	14:15		Followup questions/discussions as requested by the Co
14:15	3:45	18:00		Executive Session
Wednesday, March 11				
Executive Session and Closeout				
8:00	3:00	11:00		Executive Session
11:00	1:00	12:00		Closeout
12:00				Adjourn

Design Concept

Dinner @ Chez Leon

R&D Program

Executive Session/Closeout

Fermilab

Summary

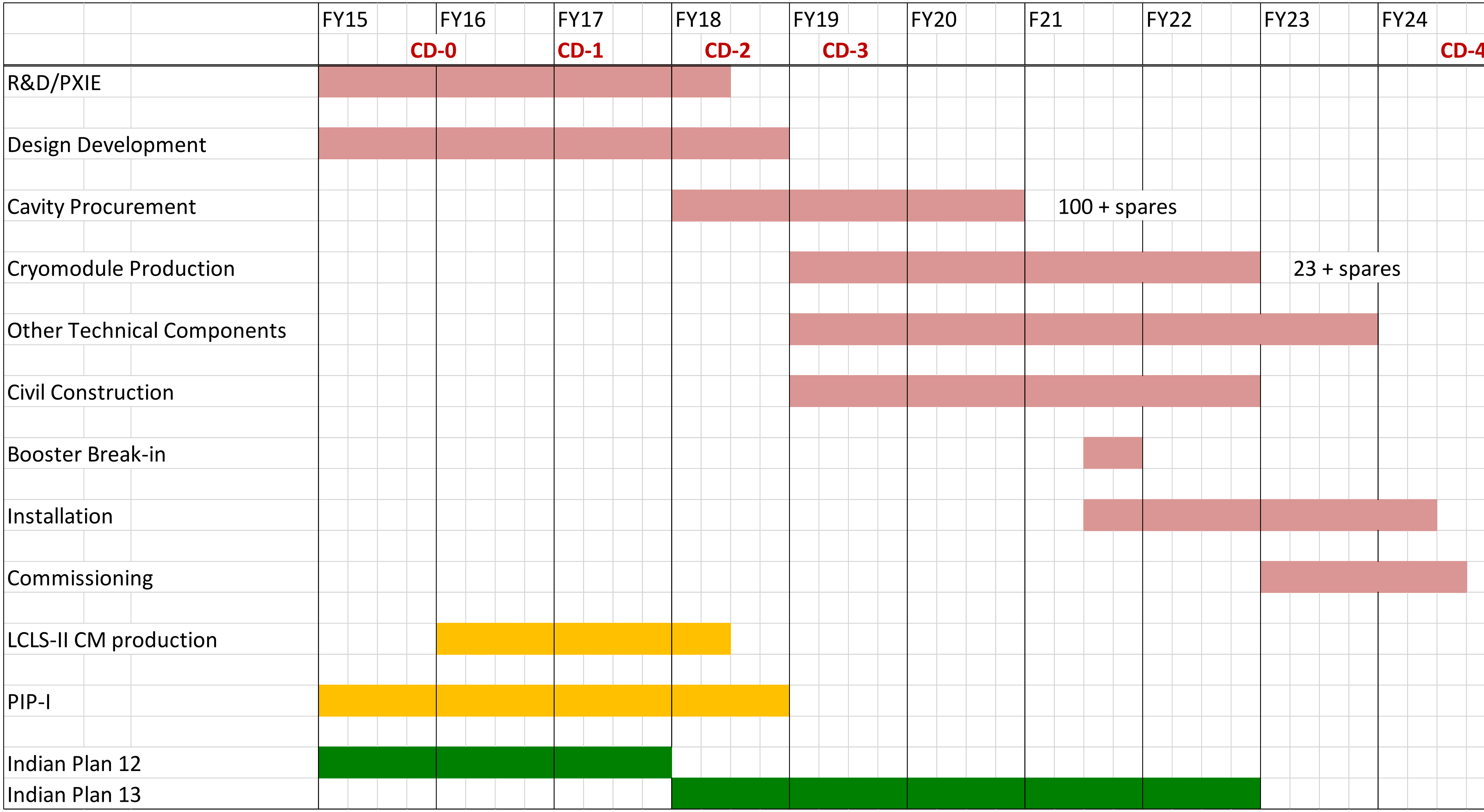
- Fermilab is committed to establishing LBNF as the leading long-baseline program in the world, with >1 MW at startup
- PIP-II is a complete, integrated, cost effective concept, that meets this goal, while
  - Building on the accomplishments of PIP
  - Leveraging U.S. superconducting rf investment,
  - Attracting international partners,
  - Providing a platform for the long-term future
  - Documented in the Reference Design Report
- PIP-II represents a first step in the realization of the full potential of the Fermilab complex
  - LBNF >2 MW
  - Mu2e sensitivity $\times 10$
  - MW-class, high duty factor beams for future experiments
- The PIP-II R&D program targets primary technical and cost risks
  - Organized to support a 2019 construction start
- We are looking for your input, with particular attention to the charge elements

Backups

PIP-II & LCLS-II: The PIP-II Perspective

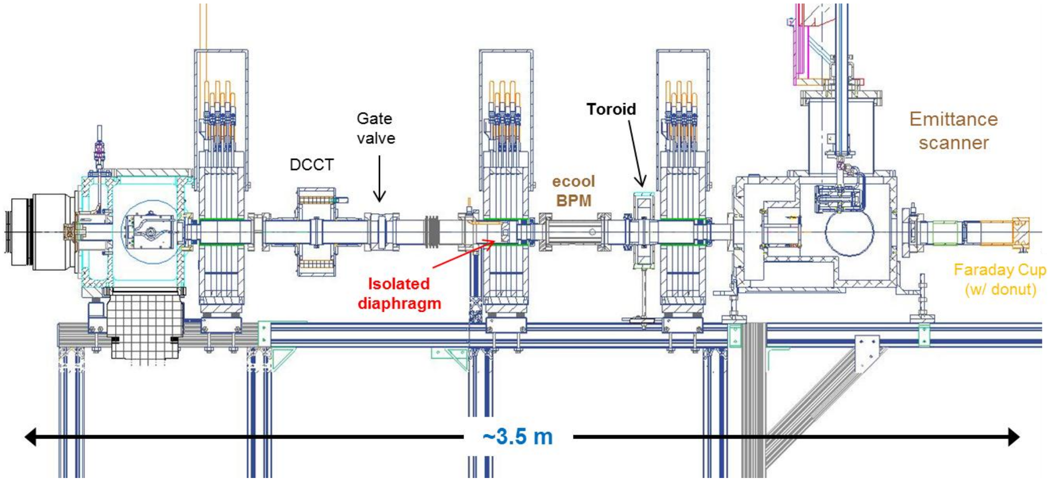
- Pluses
  - **PIP-II will inherit a work force and associated infrastructure capable of producing cryomodules efficiently**
  - LCLS-II production experience will reduce PIP-II risk, and will lend credibility to the PIP-II construction schedule
- But: Need to complete prototype SSR1 + HB650 CMs, and install cryo distribution at PXIE prior to LCLS-II completion
  - Competition for infrastructure during LCLS-II construction phase
    - Plan for assembly of SSR1 CM in Lab 2
    - Utilize space either in Lab2 or ICB-A for HB650 CM
    - In either event we need an additional HPR facility
  - Competition for people during LCLS-II construction phase
    - Peaks in 2016-17
- Minimal impact on HWR (ANL)

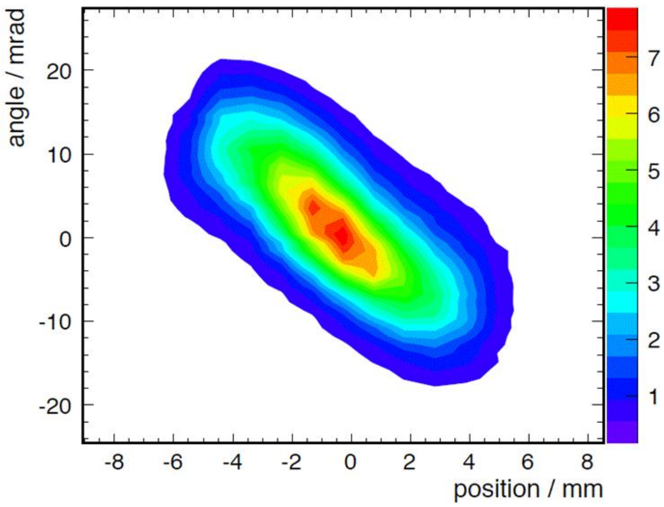
Preliminary Working Schedule



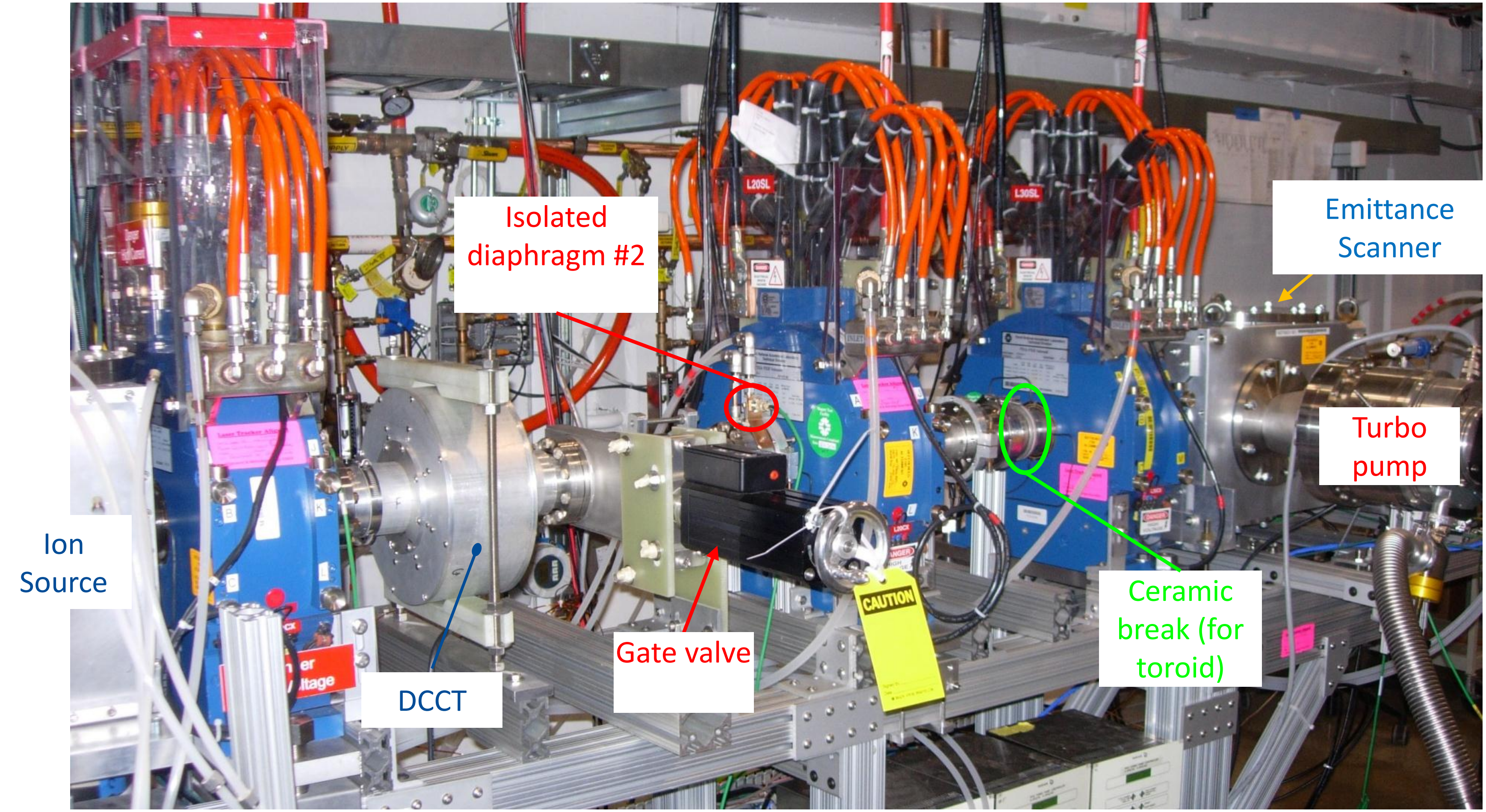
PXIE Current Configuration

- IS and LEBT installed and commissioned with beam
  - Beam characterized at RFQ entrance (emittance scanner)
  - CW/pulsed (400 μsec x 10 Hz) operations @ 5 mA
    - Emittance =0.13/0.12 mm-mrad
    - Consistent with RFQ requirements





PXIE Current Configuration

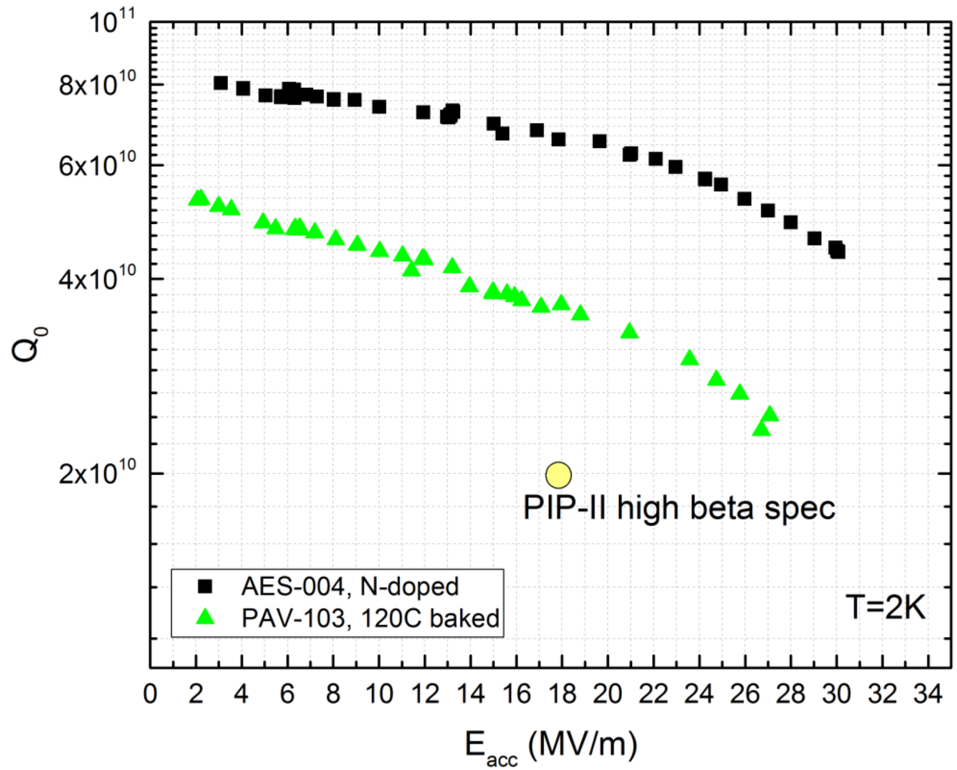


R&D Deliverables (Needs update after agreement)

Deliverable	Date
Reference Design Report	Q1FY15
HB650 Cavity (8, TESLA shape) Vertical Test (US)	Q4FY15
HB650 Dressed Cavity (3) Horizontal Test (US)	Q4FY16
HB650 Dressed Cavity (4) Horizontal Test (India)	Q2FY17
LB650 Dressed Cavity (3) Horizontal Test (US)	Q3FY17
LB650 Dressed Cavity (2) Horizontal Test (India)	Q3FY17
HB650 Cryomodule Design (US, India)	Q2FY16
HB650 Cryomodule Power Test (US)	Q4FY17
650 MHz/30 kW rf Power Test (India)	Q4FY15
SSR1 Dressed Cavity (2) Horizontal Test (India)	Q4FY15
SSR1 Cryomodule Power Test (U.S.)	Q3FY17
SSR2 Dressed Cavity (2) Horizontal Test (India)	Q2FY17
SSR2 Cavity (2) Vertical Test (US)	Q4FY17
SSR2 Dressed Cavity (1) Horizontal Test (US)	Q4FY17
325 MHz/10 kW rf Power Test (India)	Q4FY15
650 MHz Horizontal Test Stand (US & India)	Q3FY16
HWR Cryomodule Test with Beam	Q2FY18
Front End Systems Test (warm components)	Q3FY16

N2 Doping for High Q0

- N_2 gas introduced during vacuum bake:
  - Q_0=7E10 @ 17 MV/m (!)

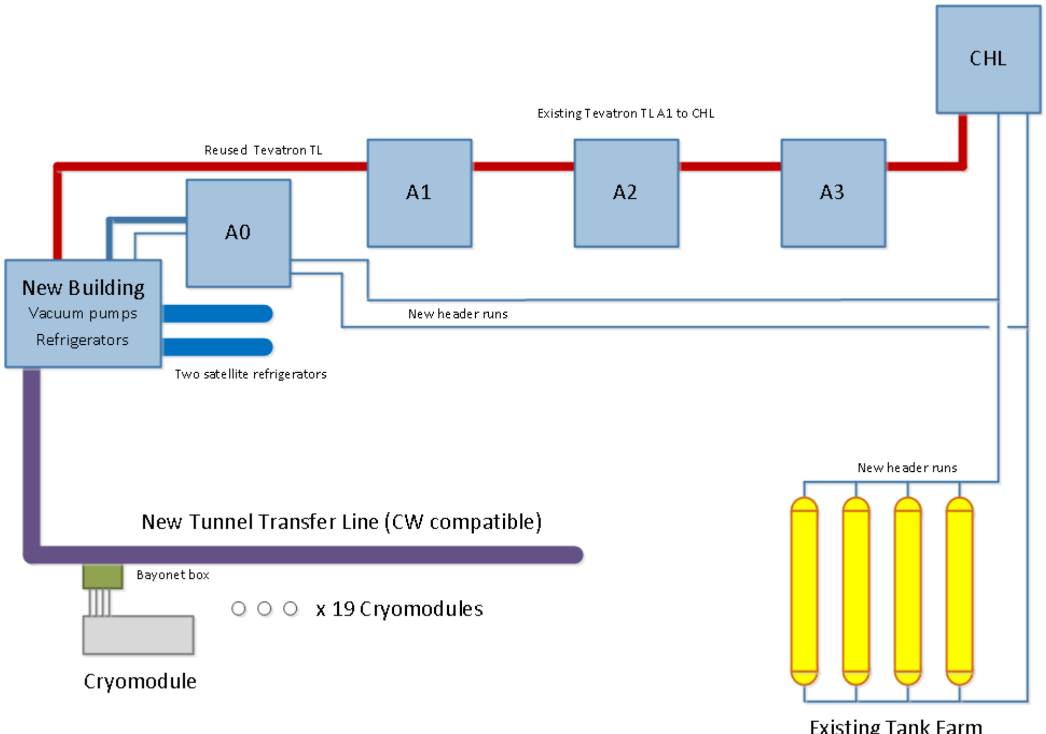


Single-cell HB650 cavity @ 2K

Fermilab

Cryogenic System

- Required to support 5% cryogenic duty factor
  - Configuration capable of 10-15% with more pumping
  - 160 – 240 kW beam power at 800 MeV



PIP-II Options

- Plan A - Superconducting Linac
  - 800 MeV pulsed SC linac
  - Constructed from CW-capable accelerating modules
  - Operated initially at low duty factor
  - Sited in close proximity to Booster and to significant existing infrastructure
- Plan B - Afterburner
  - 400 MeV pulsed linac appended to existing 400 MeV linac
  - 805 MHz accelerating modules
  - Requires physical relocation of existing linac upstream ~50 m
  - ~1 year interruption to operations
  - Less expensive than Plan A

Pluses and Minuses

	Plan A: PIP-II	Plan B
Beam power to LBNE	1.2 MW	1.2 MW
Cost to DOE (FY2020 $M)	~$400	~$250
R&D aligned with efforts to date	**Y**	**N**
Upgradable to 2 MW to LBNE	Y	Y
High Duty Factor Capable	**Y**	**N**
Proton Driver for Muon Facility	Y	N
Upgrade paths utilize 1.3 GHz infrastructure & capabilities	Y	N
Retires significant reliability risks	**Y**	**N**
Interruption to operations	**~2 months**	**>12 months**
International contribution & collaboration	**Significant**	**Minimal**
Reutilization of existing infrastructure	Significant	Modest
Status of technical development/understanding	Advanced conceptual	Pre-conceptual

Future Directions

- The strategy for next step(s) beyond PIP-II will be developed in consideration of the following:
  - Slip-stacking in the Recycler is not possible at intensities beyond PIP-II
  - The Booster cannot be upgraded to support intensities beyond ~7×10^{12} ppp, no matter what the injection energy
  - A new 8-GeV rapid cycling synchrotron (RCS) could meet the needs of the neutrino program
    - Beam power @ 8 GeV ~600kW
    - Injection energy ~2 GeV
  - Construction of an RCS may require long-term utilization of the Recycler for proton accumulation
  - An extension of the PIP-II linac to 6-8 GeV may be required to remove the Recycler from service and/or to achieve the 1-4 MW required to support a muon-based facility
- The strategy will likely be determined on the basis of programmatic choices once PIP-II construction is underway
- In all scenarios it will be necessary to extend the PIP-II linac to at least 2 GeV and to retire the existing Booster
  - Unless realization of “smart RCS” with lower (800 MeV) injection energy

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 $\leq$ 0.6 sec
    $\Rightarrow$>10 Hz rep-rate RCS
  – Or inject a long (linac) pulse containing 1.5×10^{14} protons directly into Main Injector
  – Strategy TBD

2+ MW @ 60-120 GeV

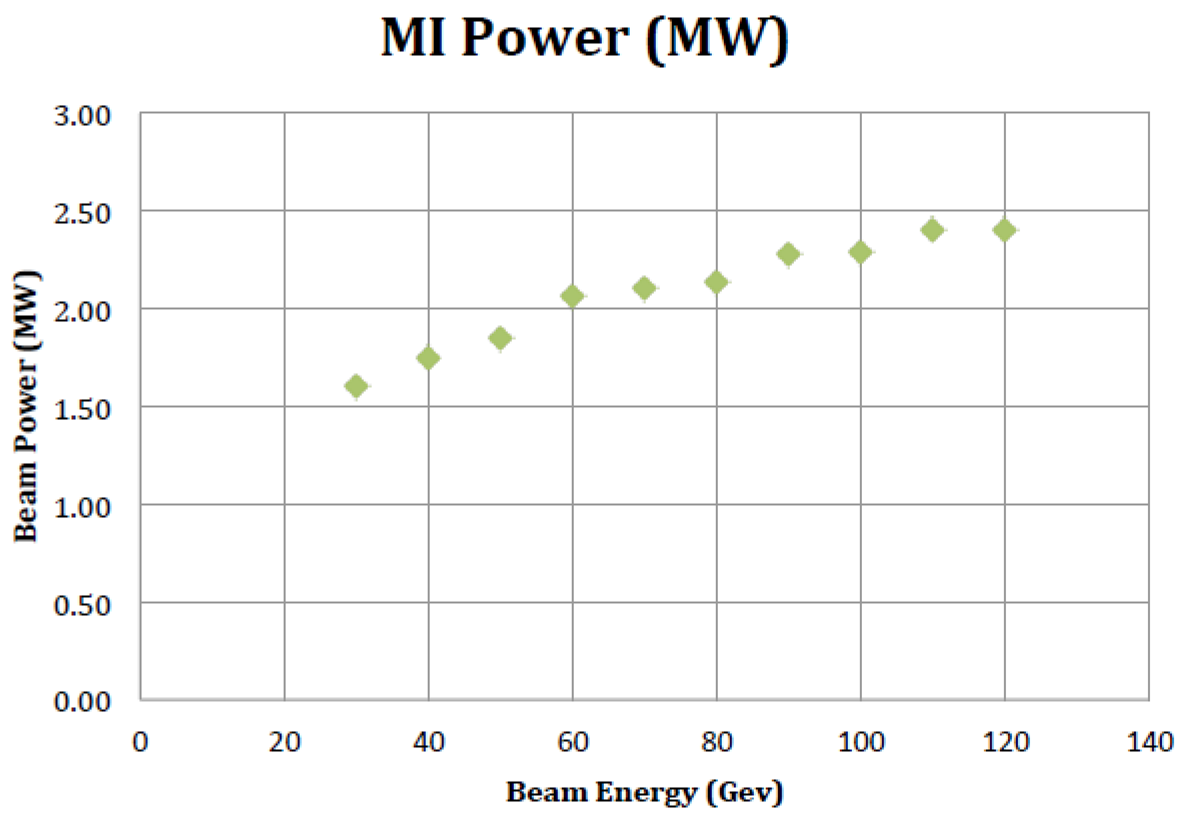
- Booster is not capable of accelerating 2.5×10^{13} no matter what the injection energy, or how it is upgraded:
  - Requires ~0.1% beam loss
  - High impedance
  - Transition crossing
  - Poor magnetic field quality
  - Poor vacuum
  - Inadequate shielding

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

Possible Parameters for post-PIP-II Complex



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

Muon Facility Possible Layout