Fermilab

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

R&D Program Overview

Paul Derwent

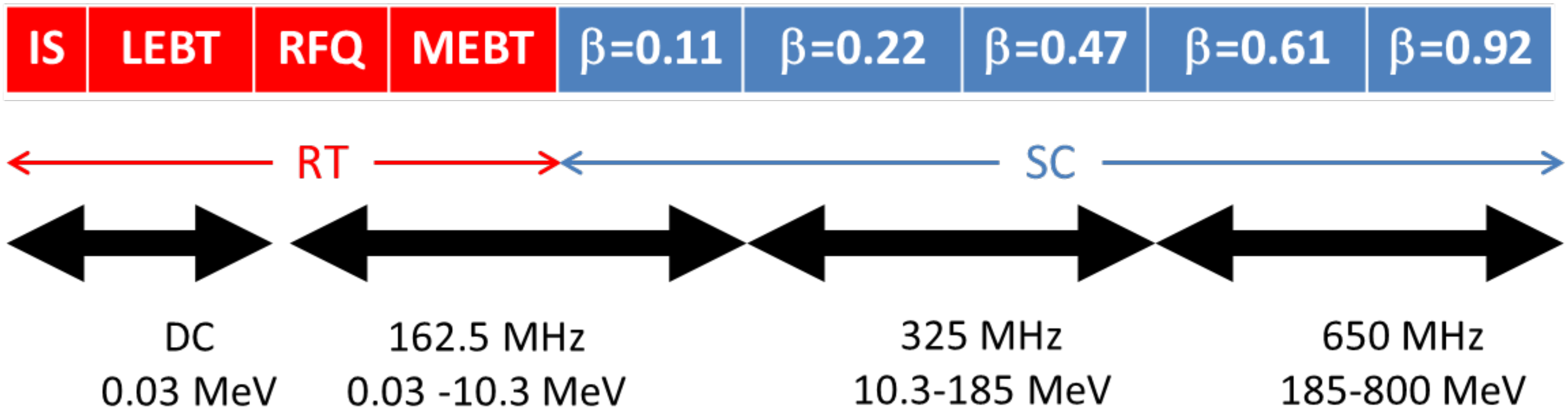
PIP-II Machine Advisory Committee Meeting

15-17 March 2016

PIP-II Proposed Technical Approach

- Construct a modern 800-MeV superconducting linac, of CW-capable components, operated initially in pulsed mode
  - Increase Booster/Recycler/Main Injector per pulse intensity by ~50%
- 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
- This approach is described in the Reference Design Report:
  - 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-II 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_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	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/Main Injector
  - RF:
    - Cavities for Recycler: slip stacking at 0.7 sec cycles
    - Power for Main Injector: Intensity at 240 GeV/sec acceleration
  - Loss Control
    - Transition crossing in MI -> γ_t jump
    - Electron Cloud and instabilities
    - Collimation: losses in designated areas
      - implementing now with future in mind

The PIP-II R&D Program

- The purpose of the R&D program is to mitigate technical and cost risks, by validating the choices made in the PIP-II facility design and by establishing fabrication methods for major sub-systems and components, including the qualification of suppliers
  - Technical risk: impair the ability to meet fundamental performance goals
  - Cost/Schedule risk: compromise the ability to meet currently understood cost or schedule goals
    - CD-2: Approve performance baseline
    - CD-3: Approve start of construction
  - To be ready for CD-3 in 2019

PIP-II Scope

- An 800 MeV superconducting linac (SCL), constructed of CW-capable accelerating structures and cryomodules, intially operating with a peak current of 2 mA and a beam duty factor of 1%;
- Beam transport from the end of the SCL to the new Booster injection point, and to a new 800 MeV dump;
- Upgrades to the Booster to accommodate 800 MeV injection, and acceleration of 6.4×10^{12} protons per pulse;
- Upgrades to the Recycler to accommodate slip-stacking of 7.7×10^{13} protons delivered over twelve Booster batches;
- Upgrades to the Main Injector to accommodate acceleration of 7.5×10^{13} protons per pulse to 120 GeV with a 1.2 second cycle time, and to 60 GeV with a 0.8 second cycle time.

Primary Risks and Required R&D

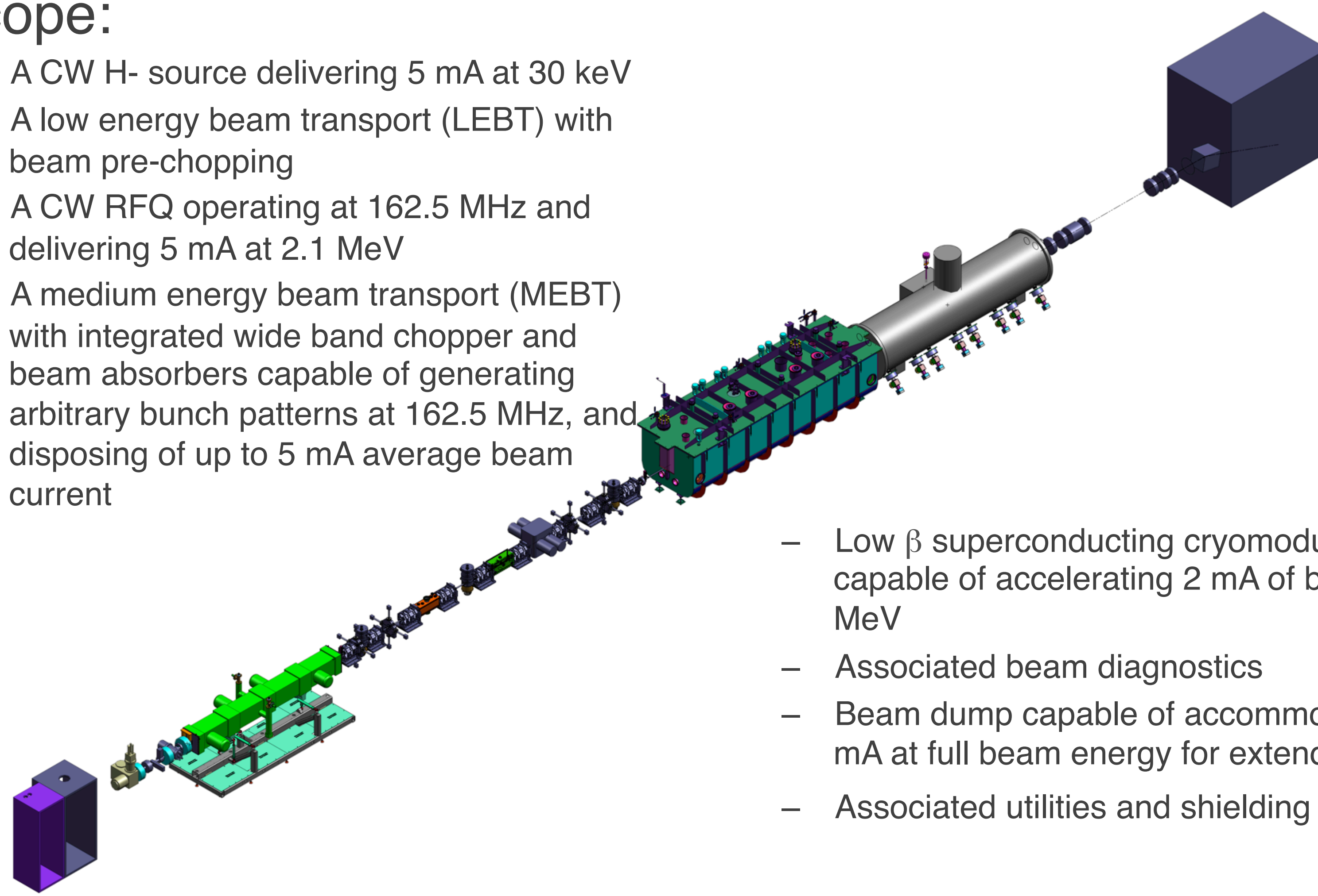
- PXIE should mitigate most risks related to the frontend
  - HWR and SSR1 prototype cryomodules are in fabrication
- Design and testing of SC cryomodules is time consuming process
  - 5 new types of SC cavities: vigorous design work for SSR2, LB650 and HB650 has been initiated
  - Microphonics and LFD detuning suppression
- Major challenge for SC linac – <u>reliable</u> operation in pulsed regime
  - Task force was organized and is working on this problem
- Longitudinal emittance growth at transition crossing in Booster can increase beam loss at slip stacking. It can limit the beam intensity and, consequently, the beam power
  - Detailed simulations of transition crossing are carried out
- Suppression of fast beam instabilities at slip stacking can be challenging enterprise
  - Better understanding of present limitations is required

Primary areas to address technical Risk

1. Development and integrated systems testing of PIP-II Front End components (PXIE)
2. Development and demonstration of cost effective superconducting radio frequency acceleration systems at three different frequencies and with rf duty factors ranging from 10% to 100%
3. Development of requisite capabilities at international partner institutions to successfully contribute to PIP-II construction
4. Development of a Booster injection system design capable of accepting extended beam pulses from the PIP-II linac
5. Development of systems designs capable of supporting a 50% increase in the proton beam intensity accelerated and extracted from the Booster/Recycler/Main Injector complex

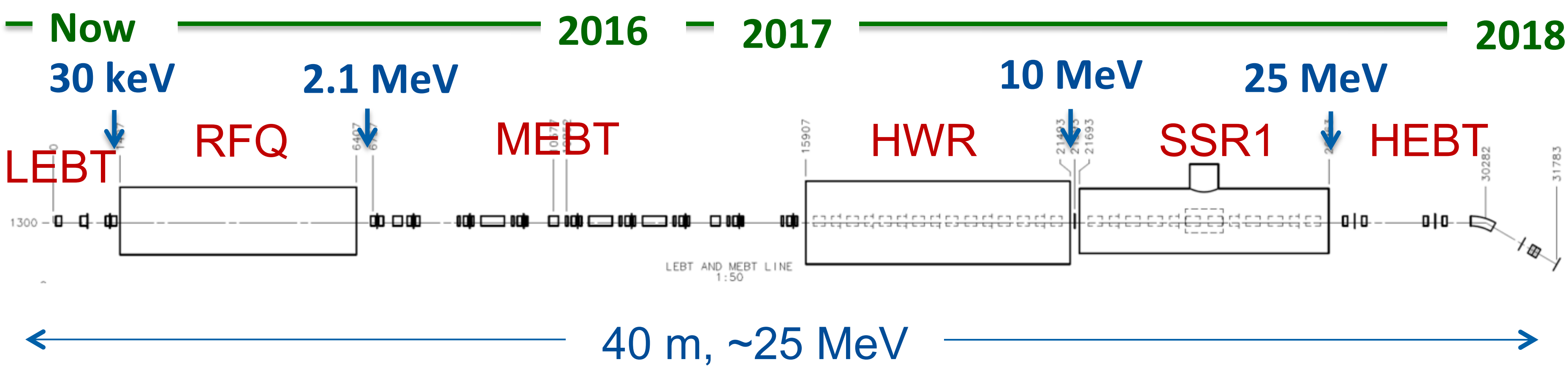
PXIE

- Scope:
  - A CW H- source delivering 5 mA at 30 keV
  - A low energy beam transport (LEBT) with beam pre-chopping
  - A CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
  - A medium energy beam transport (MEBT) with integrated wide band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of up to 5 mA average beam current



  - Low β superconducting cryomodules capable of accelerating 2 mA of beam to 25 MeV
  - Associated beam diagnostics
  - Beam dump capable of accommodating 2 mA at full beam energy for extended periods.
  - Associated utilities and shielding

PXIE (PIP-II Injector Experiment): Deliverables



PXIE will address the address/measure the following:

- LEBT pre-chopping : Demonstrated
- Vacuum management in the LEBT/RFQ region : Demonstrated
- Validation of chopper performance
  - Bunch extinction, effective emittance growth
- MEBT beam absorber
  - Reliability and lifetime
- MEBT vacuum management
- CW Operation of HWR
  - Degradation of cavity performance
  - Optimal distance to 10 kW absorber
- Operation of SSR1 with beam
  - CW and pulsed operation
  - 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, RF
- IUAC: SSR1

Fermilab
PIP-II

Status: PXIE elements

- Ion Source & LEBT: L. Prost
  - has met beam requirements for injection into RFQ
- RFQ: J. Steimel
  - Full field value at 5 msec, 2 Hz operation
- MEBT: A. Shemyakin
  - First stage installed, design going forward
- HWR: Z. Conway
  - delivery in summer 2017
- SSR1: L. Ristori
  - delivery in spring 2018
- LLRF: B. Chase
  - Working for RFQ, ready for MEBT
- RF Power: R. Pasquinelli
  - Working for RFQ (pulsed mode), 162.5 MHz amplifiers for MEBT not settled
- Instrumentation: V. Scarpine
  - Installing and commissioning for MEBT

Schedule: PXIE

- FY16:
  - Characterize beam through the RFQ
  - Pulsed operation, measurements through different stages of the MEBT
- FY17:
  - Characterize chopping and beam parameters at entrance of SRF section
- FY18:
  - Installation of Cyro Distribution, HWR, SSR1, ancillary components

- Critical path to HWR & SSR1 operation
  - cryogenic distribution system
  - 162.5 MHz amplifiers for HWR
  - 325 MHz amplifiers for SSR1

Collaborations Role

- Lawrence Berkeley National Lab:
  - Ion Source: Complete
  - design & build RFQ: delivered!
- Argonne National Lab:
  - design & build Half Wave Resonator CryoModule
- IIFC: PXIE
  - MEBT Magnets
  - 325 MHz RF sources
  - LLRF / RFPI
  - 2 SSR1 cavities
- IIFC: SRF
  - SSR2 Cavity Design
  - LB650 Cavity Design
  - HB650 End Group, He Vessel, Tuner
  - 650 CryoModule Design
  - SSR2, LB650 cavities for power test
  - HB650 cavities for CM test
  - 650 MHz Horizontal Test Stand design, fabrication, commissioning

SRF

- PIP-II includes
  - 5 different SRF cavity types and cryomodules
    - Half Wave Resonator
    - 2 Single Spoke Resonators
    - 2 elliptical cavities
  - 3 different frequencies (162.5 MHz, 325 MHz, 650 MHz)

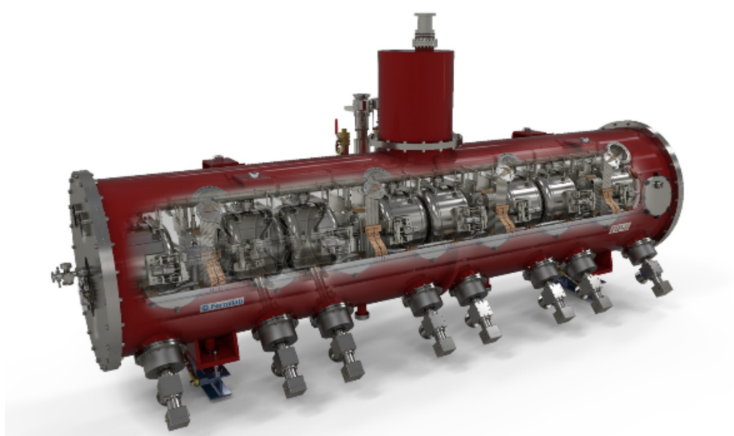
- R&D program:
  - test one complete cryomodule of each frequency to full power
    - HWR & SSR1 @ PXIE with beam
    - HB650 in a test stand
  - test dressed cavities with RF power
    - SSR2 & LB650 in test stands
  - Resonance control of cavities in pulsed mode operation
    - Microphonics
    - Lorentz Force Detuning
    - active frequency control with fast piezo-based tuners

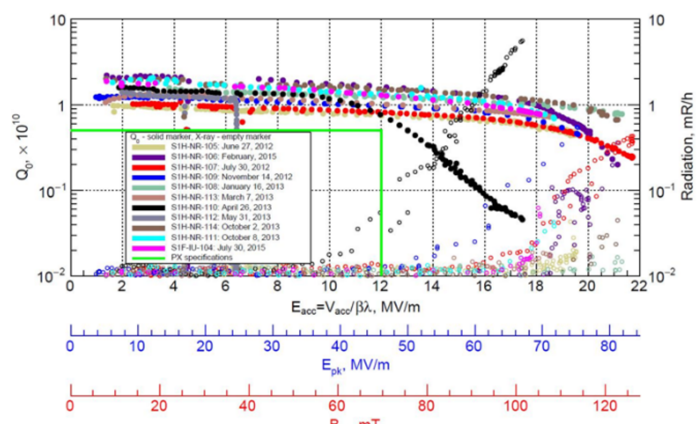
PIP-II R&D: SRF

- R&D deliverables include:
  - Prototype HWR cryomodule (ANL)
  - Prototype SSR1 cryomodule (FNAL, IUAC)
  - Two SSR2 dressed cavities (BARC)
  - Two LB650 dressed cavities (VECC)
  - Prototype HB650 cryomodule (FNAL, RRCAT)

PXIE

- RF sources, LLRF, and RFPI jointly developed by Fermilab and India in support of testing of the above
  - 325 and 650 MHz





SRF: Resonance Control

- Combination of High Q0, pulsed operation
  - Lorentz Force Detuning large compared to cavity bandwidth
  - Active resonance control system
- Passive means: Mechanical design
  - Reduction of sensitivity to He pressure and LFD
  - Engineering aimed at noise reduction in the tunnel

- Developing a peizo-based feed forward and feedback system
  - Testing on individual cavities now at STC
  - Test on SSR1 cryomodule at PXIE

Section	Frequency (MHz)	Maximal detune (peak, Hz)	LFD at operating gradient, Hz	Minimal Half Bandwidth (Hz)	Max Required Power (kW)
HWR	162.5	20	-122	33	6.5
SSR1	325	20	-440	43	6.1
SSR2	325	20	-	28	17.0
LB650	650	20	-192	29	38.0
HB650	650	20	-136	29	64.0

Rings: 50% more intensity, total power loss budget constant

- Booster: a 33% pulse frequency increase
  - Injection
  - 20 Hz operation
  - RF: beam dynamics studies
    - injection : direct injection into bucket (chopping in MEBT)
    - longitudinal emittance preservation, especially through transition
  - Beam quality: beam dynamics studies
    - Emittance and Loss control
    - Collimation

- Recycler: 20 Hz operation & 60 GeV option for LBNF
  - new 53 MHz RF Cavity
    - Cooling: CW at 60 GeV
    - larger separation for slip stacking -> higher peak voltage
  - Beam dynamics and loss control

- Main Injector: Two areas of R&D:
    - RF Power: for 7.5e13 ppp
    - Transition crossing: need a γ_t jump for loss control

Lack of funding has restricted progress in these R&D areas

PXIE and SRF Deliverables:

PIP-II R&D Plan thru FY 2019

Responsible Institution	Deliverable	Due Date	Program
3.1 PIP-II Source, LEBT and MEBT			
IIFC Deliverable	MEBT Dipoles and Quadrupoles	Jul-16	PXIE
3.2 Radio Frequency Quadrupole (RFQ)			
Fermilab/LBNL Deliverable	RFQ	Jan-16	PXIE
3.3 Half Wave Resonator (HWR)			
Fermilab/ANL Deliverable	162.5 MHz, HWR Cryomodule with 8 cavities	Sep-17	PXIE
Fermilab Deliverable	Eight 162.5 MHz, RF system and it distribution system	Jan-18	PXIE
Fermilab Deliverable	Integration and Commissioning	Jun-18	PXIE
3.4 Single Spoke Resonator-1 325 MHz Cryomodule			
Fermilab Deliverable	One SSR1 Cryomodule	Feb-18	PXIE
3.9 System Test of SSR1 CM and RF Power with Beam			
Fermilab Deliverable	SSR1 CM to PXIE	Feb-18	PXIE
Fermilab Deliverable	10 MeV Beam from PXIE	Sep-18	PXIE
DAE Deliverable	Eight, 10 kWatt 325 MHz Solid State RF with Circulator	Jan-18	PXIE
Fermilab Deliverable	Integration and Commissioning	Oct-18	PXIE
3.5 High Beta 650 MHz Cryomodule			
IIFC Deliverable	HB650 CM Design	Dec-16	SRF
Fermilab Deliverable	One HB650 Cryomodule	Sep-18	SRF
3.6 Low Beta 650 MHz Cavity			
IIFC Deliverable	Two LB650 High Power Tested Dressed Cavity	Feb-19	SRF
3.7 Single Spoke Resonator 2 Cavity			
IIFC Deliverable	Two SSR2 Low Power Tested Cavity	Dec-18	SRF
3.8 650 MHz Cavity Horizontal Test Stand			
IIFC Deliverable	HTS-2 Cryostat to Fermilab	Jan-17	SRF
DAE Deliverable	Two 30 kWatt Solid State RF Amplifire with Circulator	Jan-17	SRF
Fermilab Deliverable	Integration and Commissioning	May-17	SRF
Fermilab Deliverable	Test of 1st 650 MHZ Dressed HB650 Cavity	Aug-17	SRF
3.10 System Test of HB650 CM and RF Power			
Fermilab Deliverable	HB650 CM to CMTF	Sep-18	SRF
DAE Deliverable	Six, 30 kWatt 650 MHz Solid State RF with Circulator	Apr-18	SRF
Fermilab Deliverable	Integration and Commissioning	Nov-18	SRF

Booster/MI/RR Deliverables:

PIP-II R&D Plan thru FY 2018

Responsible Institution	Deliverable	Due Date	Program
3.11 Booster			
Fermilab Deliverable	20 Hz Girder Test Complete	Sep-18	Booster
Fermilab Deliverable	Qualification of Existing Collimation System Complete	Sep-18	Booster
Fermilab Deliverable	Initial Gradient Magnet / Absorber Design Complete	Sep-18	Booster
3.12 Main Injector			
Fermilab Deliverable	MI RF Station Modified to operate with 2 PAs	Sep-17	MI
Fermilab Deliverable	MI RF Station High Power Tube Delivered	Sep-17	MI
Fermilab Deliverable	Prototype γt quad tested	Jul-19	MI
3.13 Recycler Ring			
Fermilab Deliverable	Prototype RF Cavity Design Complete	Mar-18	RR
Fermilab Deliverable	Prototype RF Cavity Fabrication Complete	Sep-19	RR

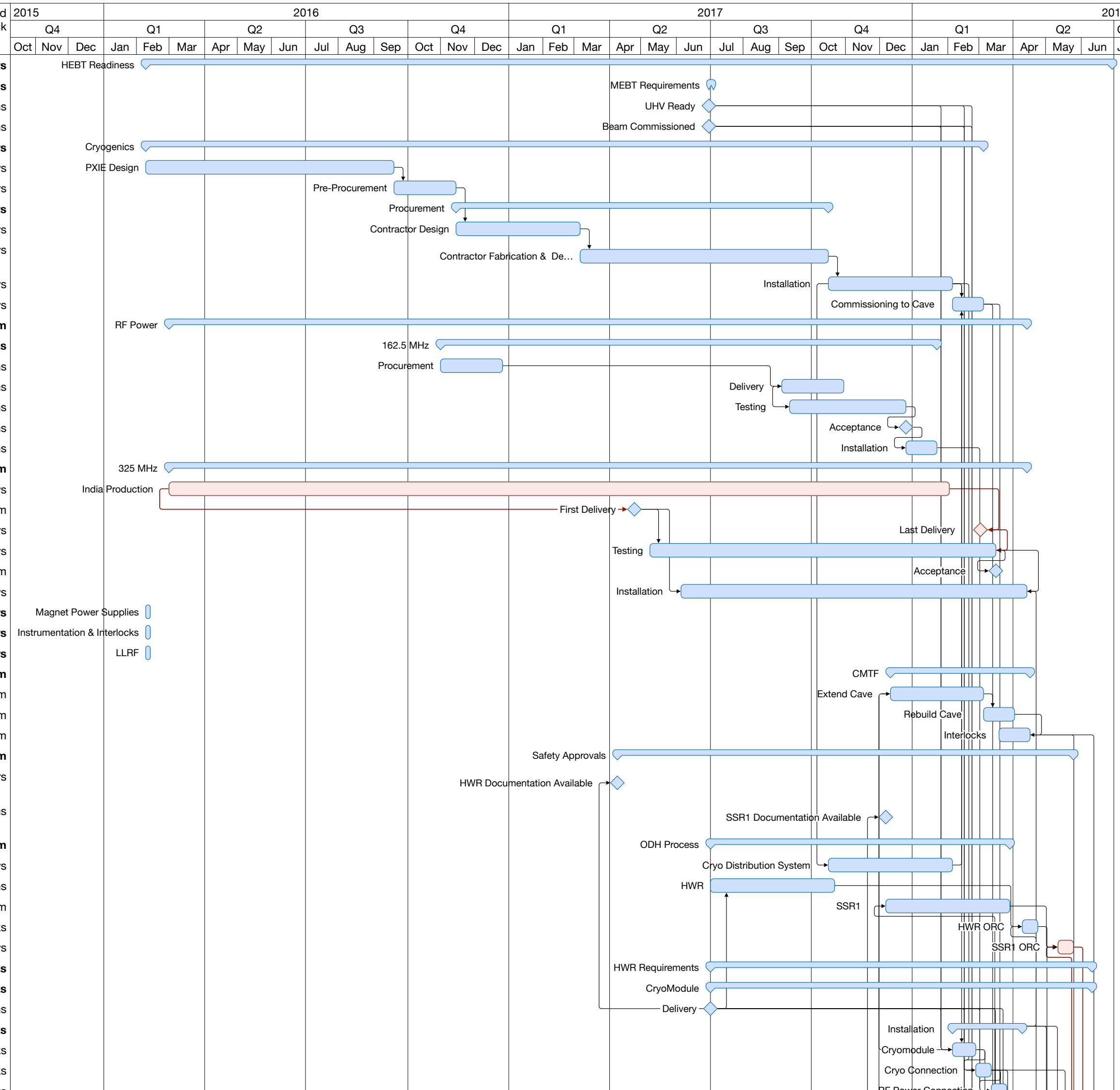
Summary

- Making good progress at PXIE
  - FY16: characterize beam through RFQ
- Have defined R&D deliverables, working towards meeting them
  - Building strong collaborations with Indian Institutions
  - RLS development in FY16 will help us understand schedule and needs to meet the deliverables
- Rings R&D has been delayed because of funding constraints, looking to get going later this year

Backups

PXIE Schedule: to HEBT operation

#	Title	Expected Start	Expected End	Expected Duration	Expected End Slack
0	**HEBT Readiness**	**2/9/16**	**6/28/18**	**2.6 years**	**0 days**
1	**MEBT Requirements**	**6/30/17**	**6/30/17**	**0 days**	**8.5 months**
2	UHV Ready	6/30/17	6/30/17		8.5 months
3	Beam Commissioned	6/30/17	6/30/17		8.5 months
4	**Cryogenics**	**2/9/16**	**Mar 5, 2018**	**2.25 years**	**3 days**
5	PXIE Design	2/9/16	9/19/16	8 months	3 days
6	Pre-Procurement	9/20/16	11/14/16	2 months	3 days
7	**Procurement**	**11/15/16**	**10/16/17**	**1 year**	**3 days**
8	Contractor Design	11/15/16	Mar 6, 2017	4 months	3 days
9	Contractor Fabrication & Delivery	3/7/17	10/16/17	8 months	3 days
10	Installation	10/17/17	Feb 5, 2018	4 months	3 days
11	Commissioning to Cave	2/6/18	Mar 5, 2018	1 month	3 days
12	**RF Power**	**3/1/16**	**4/12/18**	**2.3 years**	**2.8m**
13	**162.5 MHz**	**11/1/16**	**1/22/18**	**1.33 years**	**2.4 months**
14	Procurement	11/1/16	12/26/16	2 months	2.4 months
15	Delivery	9/5/17	10/30/17	2 months	2.4 months
16	Testing	9/12/17	12/25/17	3.8m	2.4 months
17	Acceptance	12/25/17	12/25/17		2.4 months
18	Installation	12/26/17	1/22/18	1 month	2.4 months
19	**325 MHz**	**3/1/16**	**4/12/18**	**2.3 years**	**2.8m**
20	India Production	3/1/16	Feb 1, 2018	2.1 years	0 days
21	First Delivery	4/24/17	4/24/17		11.2m
22	Last Delivery	3/1/18	Mar 1, 2018		0 days
23	Testing	5/8/17	3/15/18	11.2m	0 days
24	Acceptance	3/15/18	3/15/18		3.8m
25	Installation	Jun 5, 2017	4/12/18	11.2m	0 days
26	**Magnet Power Supplies**	**2/9/16**	**Feb 9, 2016**	**1 day**	**2.59 years**
37	**Instrumentation & Interlocks**	**2/9/16**	**Feb 9, 2016**	**1 day**	**2.4 years**
44	**LLRF**	**2/9/16**	**Feb 9, 2016**	**1 day**	**2.59 years**
51	**CMTF**	**12/12/17**	**4/16/18**	**4.5m**	**2.6m**
52	Extend Cave	12/12/17	Mar 5, 2018	3 months	2.6m
53	Rebuild Cave	3/6/18	Apr 2, 2018	1 month	2.6m
54	Interlocks	3/20/18	4/16/18	1 month	2.6m
55	**Safety Approvals**	**4/10/17**	**5/24/18**	**1.22 years**	**1.2m**
56	HWR Documentation Available	4/10/17	4/10/17		1.33 years
57	SSR1 Documentation Available	12/7/17	Dec 7, 2017		7.3 months
58	**ODH Process**	**Jul 3, 2017**	**3/28/18**	**9.6m**	**1.6m**
59	Cryo Distribution System	10/17/17	Feb 5, 2018	4 months	3 days
60	HWR	Jul 3, 2017	10/20/17	4 months	6.7 months
61	SSR1	12/7/17	3/28/18	4 months	1.6m
62	HWR ORC	4/10/18	4/23/18	2 weeks	2.6 weeks
63	SSR1 ORC	5/11/18	5/24/18	2 weeks	0 days
64	**HWR Requirements**	**Jul 1, 2017**	**6/11/18**	**1.02 years**	**2.6 weeks**
65	**CryoModule**	**Jul 1, 2017**	**6/11/18**	**1.02 years**	**2.6 weeks**
66	Delivery	Jul 1, 2017	July 1, 2017		6.7 months
67	**Installation**	**2/6/18**	**Apr 9, 2018**	**2.2m**	**2.6 weeks**
68	Cryomodule	2/6/18	2/26/18	3 weeks	2.6 weeks
69	Cryo Connection	2/27/18	3/12/18	2 weeks	2.6 weeks
70	RF Power Connection	3/13/18	3/26/18	2 weeks	2.6 weeks



PXIE Schedule: to HEBT operation

71	Vacuum Connection	2/27/18	2/28/18	2 days	2m
72	Instrumentation Connections	3/27/18	Apr 2, 2018	1 week	2.6 weeks
73	Magnet Connections	Apr 3, 2018	Apr 9, 2018	1 week	2.6 weeks
74	**Commissioning**	**4/24/18**	**6/11/18**	**1.8m**	**2.6 weeks**
75	Cryo Cooldown	4/24/18	5/21/18	1 month	2.6 weeks
76	Power Conditioning	5/29/18	6/11/18	2 weeks	2.6 weeks
77	Magnet Conditioning	5/29/18	6/11/18	2 weeks	2.6 weeks
78	Interlock Testing	5/22/18	5/28/18	1 week	2.6 weeks
79	BPMs	5/29/18	Jun 4, 2018	1 week	3.6 weeks
80	Ready For Beam	6/11/18	6/11/18		2.6 weeks
81	**SSR1 Requirement**	**3/1/18**	**6/28/18**	**4.3m**	**0 days**
82	**CryoModule**	**3/1/18**	**Mar 1, 2018**	**0 days**	**1.2 weeks**
83	Delivery	3/1/18	Mar 1, 2018		1.2 weeks
84	**Installation**	**3/6/18**	**5/10/18**	**2.4m**	**0 days**
85	Cryomodule	3/6/18	3/26/18	3 weeks	3 days
86	Cryo Connection	3/27/18	Apr 9, 2018	2 weeks	3 days
87	RF Power Connection	4/13/18	4/26/18	2 weeks	0 days
88	Vacuum Connection	3/27/18	3/28/18	2 days	1.6m
89	Instrumentation Connections	4/27/18	May 3, 2018	1 week	0 days
90	Magnet Connections	5/4/18	5/10/18	1 week	0 days
91	**Commissioning**	**5/25/18**	**6/28/18**	**1.2m**	**0 days**
92	Cryo Cooldown	5/25/18	Jun 7, 2018	2 weeks	0 days
93	Power Conditioning	6/15/18	6/28/18	2 weeks	0 days
94	Magnet Conditioning	6/15/18	6/28/18	2 weeks	0 days
95	Interlock Testing	Jun 8, 2018	6/14/18	1 week	0 days
96	BPMs	Jun 8, 2018	6/14/18	1 week	2 weeks
97	Ready For Beam	6/28/18	6/28/18		0 days
98	**10 MeV HEBT**	**2/9/16**	**6/11/18**	**2.54 years**	**2.6 weeks**
103	**25 MeV HEBT**	**2/9/16**	**6/28/18**	**2.6 years**	**0 days**