Fermilab

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PIP-II 800 MeV Linac

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PIP-II Machine Advisory Committee Meeting

15-17 March 2016

Outline

- Introduction
- Highlights of progress since last review - March/2015
- Alternative Analysis Strategy
- Summary

PIP/PIP-II Performance Parameter

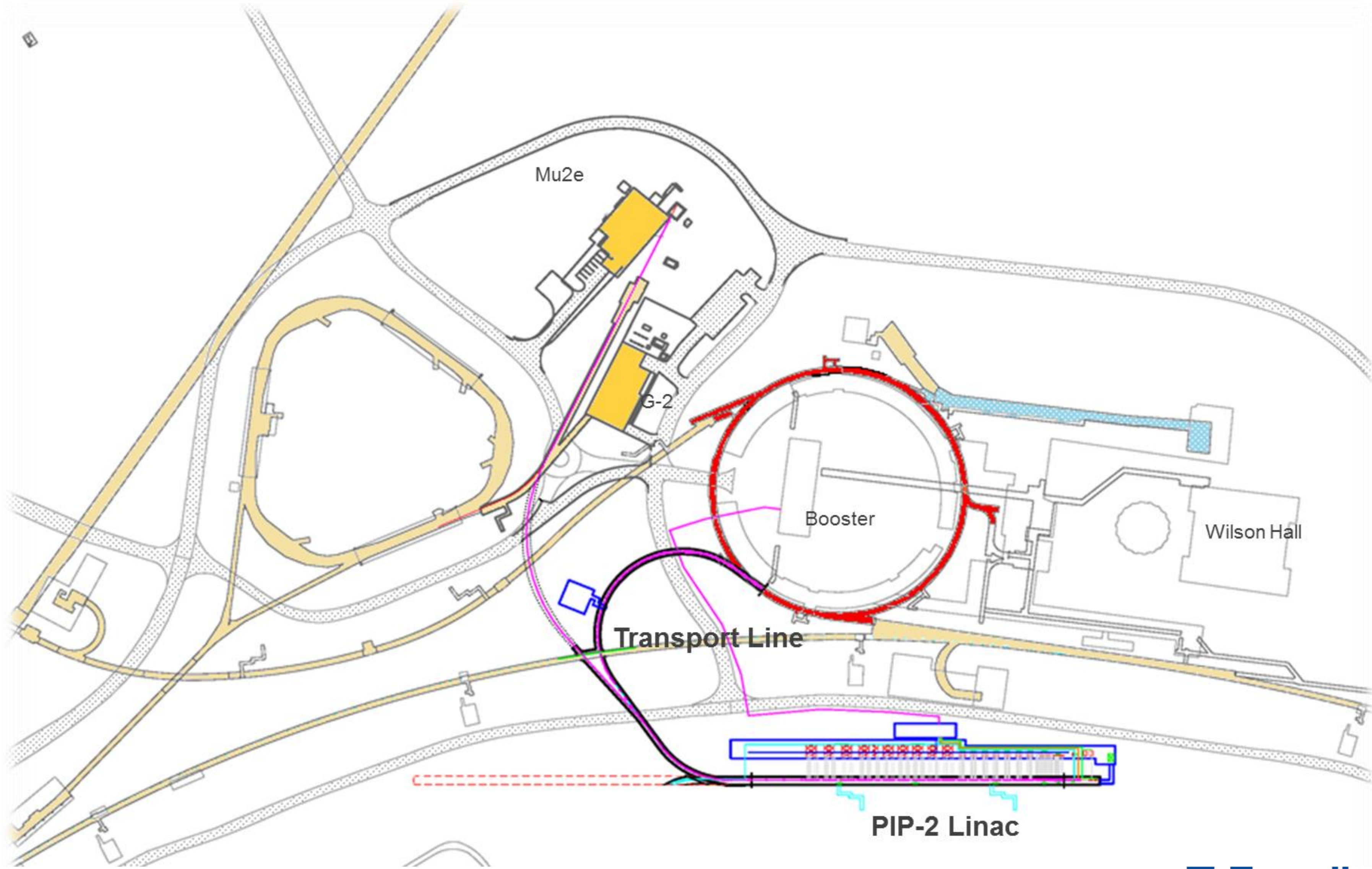
Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Linac Pulse Repetition Rate	15	20	Hz
Linac Beam Power to Booster	4	18	kW
Linac Beam Power Capability (@>10% Duty Factor)	4	~200	kW
Power to be delivered to Mu2e upgrade	NA	>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

PIP-II 800 MeV Linac Basic Design

- Initially PIP-II Linac is foreseen to operate in
  - pulse mode at 20 Hz, 0.55 msec, 2mA

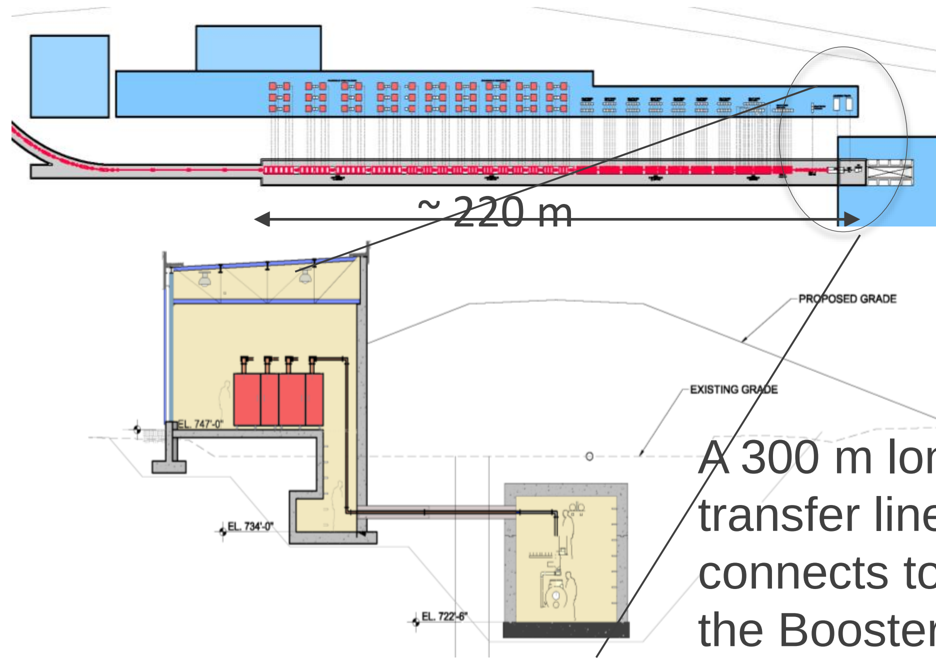
- Main features on the design
  - Components are CW compatible
  - Accelerating structures, RF power, infrastructure are dimensioned for high duty operation
  - Beam instrumentation and focusing elements are located inside the low energy cryomodules (HWR, SSR1&2)
    - reduce the space charge effects and to achieve more efficient acceleration
  - Space provided at the end of the linac for expandability

PIP-II: Future connection to Booster and Muon campus



PIP-II: 800 MeV linac surface building cross section

- The PIP-II linac will be located in a 210 m long tunnel ~ 7 m underground
- It will use superconducting RF accelerating cavities at three different frequencies (162.5, 325, 650 MHz)
  - Surface building will house radio frequency amplifier and other equipment
- Beam focusing is provided by quadrupoles (NC) and solenoids (SC)



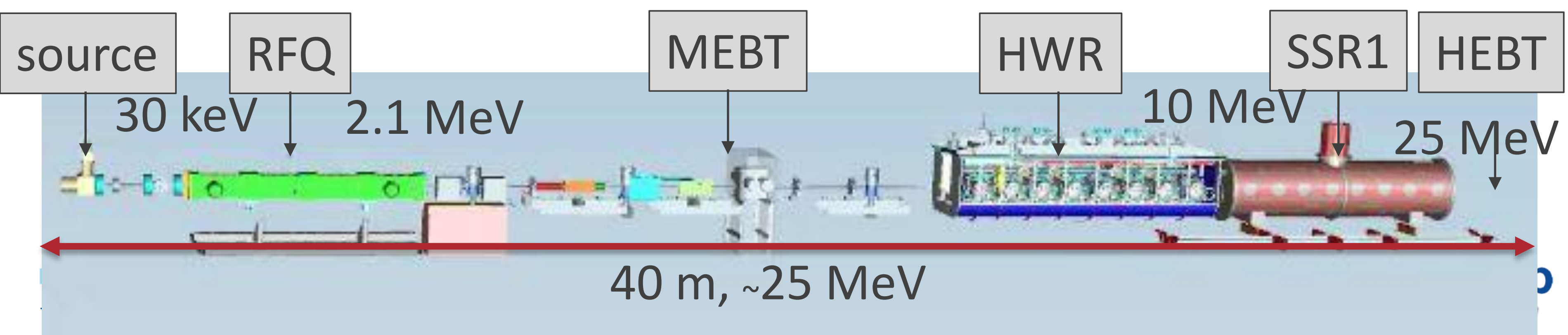
A 300 m long transfer line connects to the Booster

- Access building on both ends connect the two levels and provides access to the underground installations

	RFQ	HRW	SSR1	SSR2	LB650	HB650	Units
Output Energy	2.1	10.3	35	185	500	800	MeV
Frequency	162.5	162.5	325	325	650	650	MHz
Nº Cavities/CM	1	8/1	16/2	35/7	33/11	24/4	
RF Amp. Power/cavity	75	5	7	20	40	70	kW
Length of CM		6.2	5.2	6.5	3.9	9.5	m

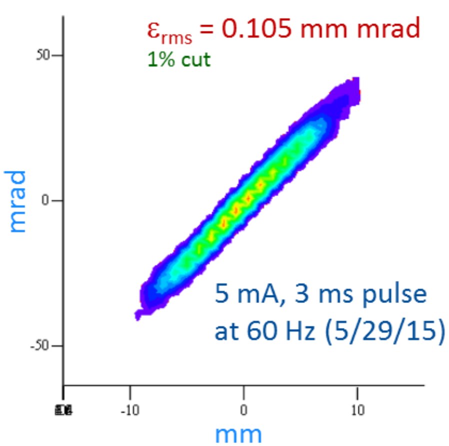
PIP-II Front End - PXIE

- PXIE will demonstrate the front end of the PIP-II linac by accelerating H- ions up to 25 MeV in about 40 m length
  - H- ion source: 30 kV, 10 mA
  - LEBT - pre-chopping
  - RFQ - 2.1 MeV, CW mode
  - MEBT – bunch-by-bunch chopper with beam absorber, vacuum management
  - Operation of HWR in close proximity to 20 kW absorber
  - Operation of SSR1 with beam
    - CW and pulsed
    - Resonance control and LFD compensation in pulse mode

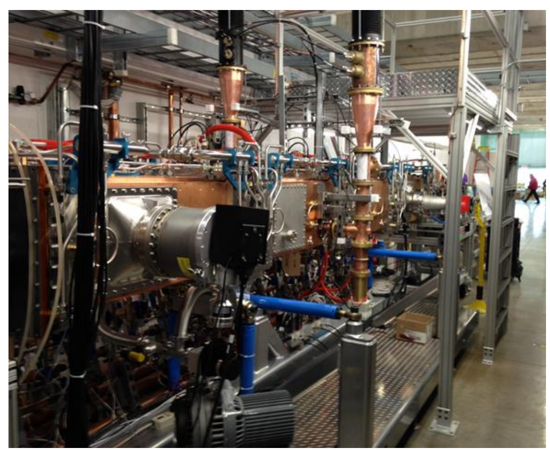


PIP-II - PXIE Front End

- IS/LEBT
  - 30 kV, 15 mA H- commercial ion source
  - fully commissioned on both pulsed and DC
    - beam up to 10 mA
    - ready to support RFQ beam commissioning
- RFQ
  - 2.1 MeV, LBNL design
  - delivered to FNAL Sept/15
  - fully installed and RF conditioned complete at full power low duty cycle
- MEBT
  - vacuum management near the SRF linac
  - beam chopping – arbitrary bunch formation



see Prost's talk



see Steimel's talk

2 doublets and bunching cavity

see Shemyakin's talk

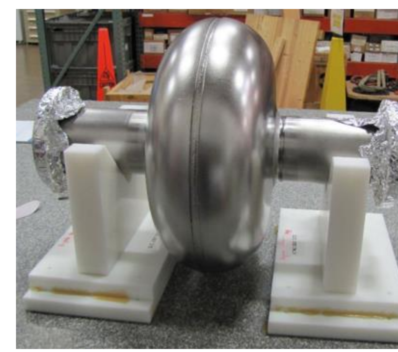
PIP-II SRF Section

- The PIP-II superconducting section portion will occupy ~150 m of the enclosure and it will be equipped with
  - 8 cavities (1-CM) HWR, 162.5 MHz
  - 51 cavities (9-CM) SSR1& SSR2 325 MHz,
  - 57 cavities (15-CM) LB & HB 650 MHz

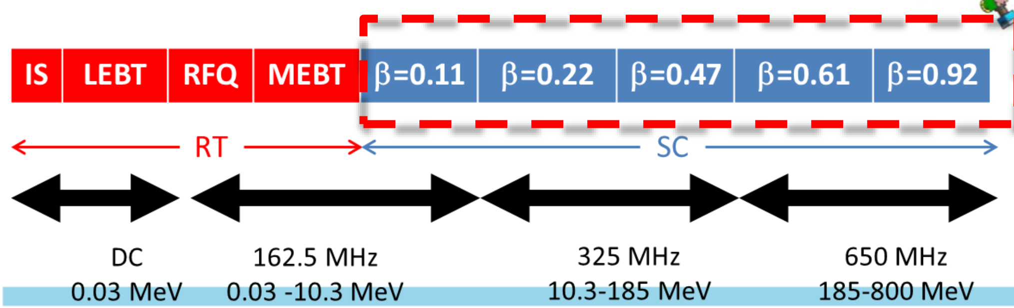
HWR 162.5 MHz - ANL

Jacketed SSR1 cavities

SSR1-2 cryomodule



650 MHz β=0.9 RRCAT



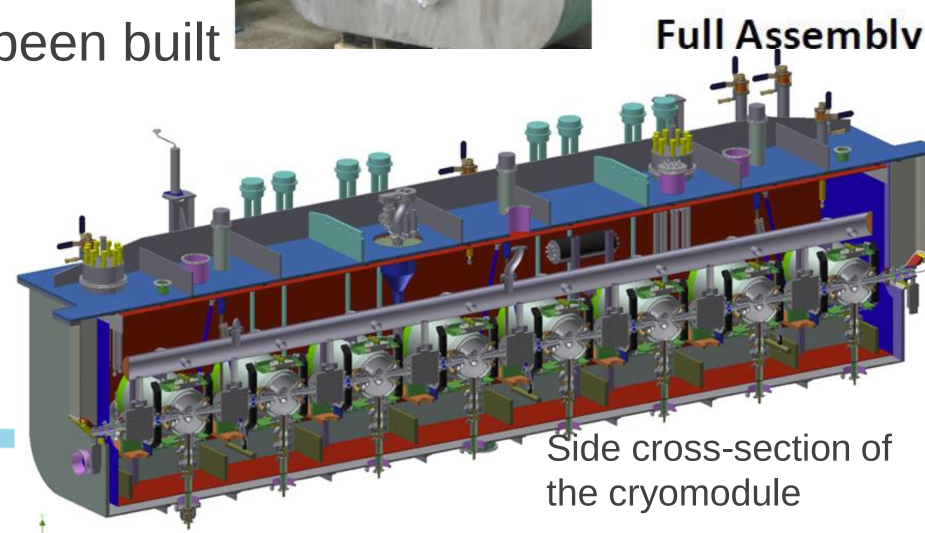
PIP-II Cold Section
Half-Wave Resonator (HWR), 162.5 MHz

see Zach's presentation

HWR Cryomodule:
- 8 162.5 MHz β=0.11 Half Wave cavities
- 8 SC focusing solenoids, BPM
- 2.1 MeV -> 10.3 MeV
- 6.2 m , 5kW RF
- Institution: ANL

Status

Design complete, under fabrication at ANL
- Testing components schedule for 2016
  - HWR, RF couplers, slow tuners
- 8 of 8 magnet assemblies have been built
- Vacuum vessel leak tight



Side cross-section of the cryomodule

PIP-II Cold Section
Single-Spoke Resonator (SSR1/SSR2), 325.0 MHz

SSR1/SSR2 cryomodule:
16/35 325 MHz β=0.22 (0.47) Single Spoke cav.
8/21 SC focusing solenoids, BPM
2/7 CM, 5.2/6.2 m long
10.3/35 MeV -> 35/185 MeV
7/20 kW RF power per cav.
Institution: FNAL/IIFC - BARC

SSR1 dressed cavity

Status (SSR1)

- Cavity design complete, optimized to CW mode
  - 12 cavities fabricated – 10 FNAL/2 IIFC
- Cryomodule design mature and near completion
- Tuner
  - Prototype built and tested, final design modified based on test experience
- Coupler
  - 3 couplers and DC blockers fabricated
  - 10 couplers and DC blocker under fabrication
- Expect to start fabrication/assembly 2017

Design approach for SSR2

- SSR2 design should derive from SSR1
  - Similar tuner
  - Same coupler
  - CMs should contain as many identical parts as possible

see Ristori's presentation

PIP-II Cold Section
Elliptical Cavities (LB/HB), 650.0 MHz

LB/HB Cryomodule:
- 33/24 650 MHz β=0.61/0.9(0.92) elliptical cavities
- 22/8 warm focusing solenoids, BPMs
- 11/4 CM, 3.9 m/9.5 m long
- 185/500 MeV -> 500/800 MeV
- 40/70 kW RF power amplifier
- Institution: FNAL/IIFC - VECC & RRCAT

see Nicol's presentation

Status

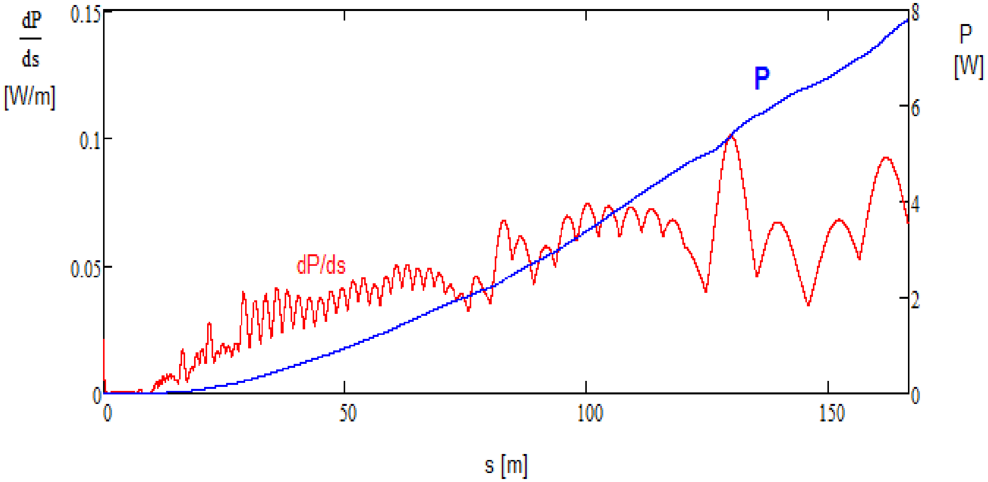
Lots of progress on many fronts

- Cavities
  - LB RF and end group design complete
  - HB 4 cavities received and processed
- Cryomodule
  - LB to be derived from the HB design
  - HB design complete
- Tuner/Coupler
  - Prototype design near completion
  - LB design similar to HB design

PIP-II Linac Beam Loss Control

- Main source of beam loss in the superconducting linac is due to intrabeam stripping
  - Intrabeam losses estimate for PIP-II are below < 0.1W/m for CW operation
  - Losses related with intra beam are well within the requirements for PIP-II
- Fixed aperture collimators are part of the design to minimize beam losses at the cryogenic parts

Courtesy V. Lebedev

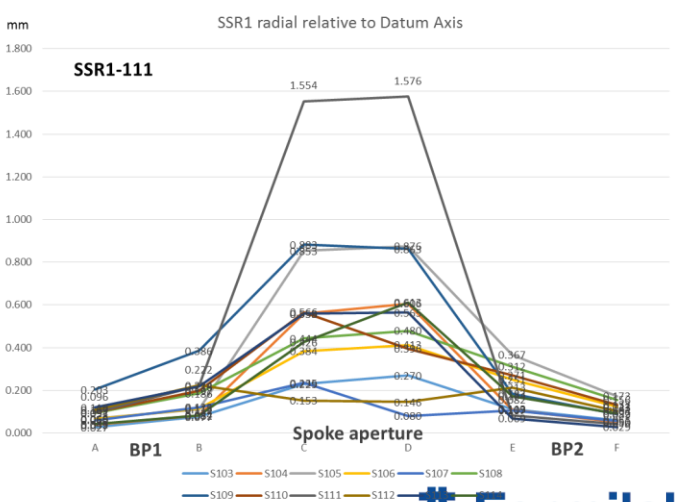


PIP-II Linac Alignment Requirements

Major factors which can limit an accelerator performance is the alignment of cavities/focusing elements

- Solenoids
  - Solenoid alignment requirement inside the CMs of an order
    - 500 μm (offset)
    - 1.0-0.5mrad (angular)
  - The alignment error influence can be compensated by correcting dipoles
    - Critical for maintaining low beam loss and suppression of halo formation
- SSR1 cavity misalignment
  - Offset between electrical and geometrical axis has been found to be not negligible
  - Transverse kicks (max ~ 0.8 mrad) have been found to be well within the dipole corrector range

Courtesy P. Berrutti



Fermilab PIP-II

Alternative Analysis

PIP-II Alternative Analysis

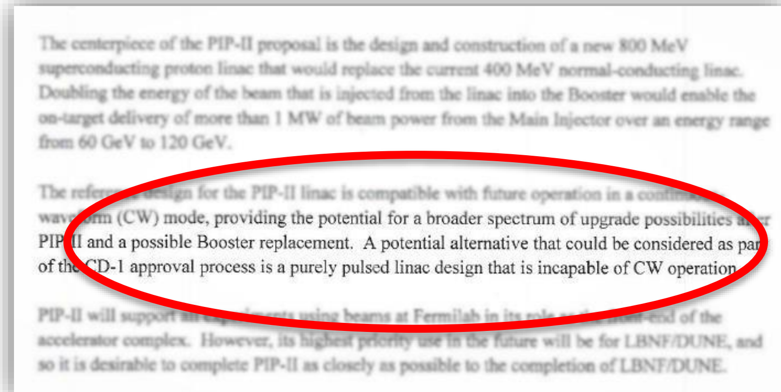
- Requirements for the Alternative Analysis are defined by the Mission Need Statement (MNS)
  - Our goal is to meet these requirements in the most efficient manner possible

- Alternative selection
  - Four technical alternative analysis will be carried out
    - CW vs Pulsed vs SC expansion of the existing facility vs NC expansion of the existing facility

- Build up a trade-off table
  - Systematically capture data related with each alternative
  - Based on alternative study plan
    - Analysis and commentary on how the options perform under the evaluation criteria established by DOE (SH)

PIP-II Alternative Analysis cont.

- PIP-II Design Criteria
  - **<u>Deliver >1 MW of proton beam power</u>** from the Main Injector, over the energy range 60 – 120 GeV, at the start of operations of the Long Baseline Neutrino Facility/Deep Underground Neutrino Experiment (LBNF/DUNE) program;
  - Sustain **<u>high reliability operations</u>** of the Fermilab accelerator complex through the initial phase of LBNF/DUNE operations;
  - **<u>Support the currently operating and envisioned 8-GeV</u>** program at Fermilab including the Mu2e, g-2, and the suite of short-baseline neutrino experiments;
  - Provide a **<u>platform for eventual extension</u>** of beam power to LBNF/DUNE to >2 MW;
  - Provide a **<u>flexible platform for long-range development of the Fermilab complex</u>**; in particular provide an upgrade path for a factor of ~10 increase in beam power to the Mu2e experiment, and for extension of accelerator capabilities to include high duty factor/higher beam power operations.



The centerpiece of the PIP-II proposal is the design and construction of a new 800 MeV superconducting proton linac that would replace the current 400 MeV normal-conducting linac. Doubling the energy of the beam that is injected from the linac into the Booster would enable the on-target delivery of more than 1 MW of beam power from the Main Injector over an energy range from 60 GeV to 120 GeV.

The refer[illegible] design for the PIP-II linac is compatible with future operation in a contin[illegible] wave[illegible]rm (CW) mode, providing the potential for a broader spectrum of upgrade possibilities [illegible] PIP[illegible]II and a possible Booster replacement. A potential alternative that could be considered as par[illegible] of the CD-1 approval process is a purely pulsed linac design that is incapable of CW operation.

PIP-II will support [illegible] using beams at Fermilab in its role [illegible]end of the accelerator complex. However, its highest priority use in the future will be for LBNF/DUNE, and so it is desirable to complete PIP-II as closely as possible to the completion of LBNF/DUNE.

Fermilab PIP-II

PIP-II Alternative Analysis cont.

SC Linac pulsed -- CW compatible	* 800 MeV SRF linac constructed of CW-capable components, operated initially in pulsed mode * Average beam current ~2 mA * Civil construction and Linac commissioning parasitically to operations * Located on the Tevatron infield -- close proximity to Booster and existing infrastructure * Accompanied by necessary modifications to the Booster/Recycler/Main Injector accelerators
SC Linac pulsed	* 800 MeV SRF linac, low-duty factor pulsed operations * Average beam current ~5-25 mA * Civil construction and Linac commissioning parasitically to operations * Located on the Tevatron infield -- close proximity to Booster and existing infrastructure * Accompanied by necessary modifications to the Booster/Recycler/Main Injector accelerators
SC - Afterburner	* 800 MeV linac constructed by appending a 400 MeV SRF linac to existing linac -- optimized for low-duty factor pulsed operations * Average beam current ~25 mA * Added to the existing but relocated 400-MeV linac upstream * ~1 year interruption to the program * Accompanied by necessary modifications to the Booster/Recycler/Main Injector accelerators
NC linac	* 800 MeV linac constructed by appending a 400 MeV NC linac to the existing linac, low-duty factor pulsed operations * Average beam current ~25 mA * ~1 year interruption to the program * Accompanied by necessary modifications to the Booster/Recycler/Main Injector accelerators

PIP-II Alternative Analysis cont.

Different ramifications to the overall schedule, level of risk, cost, …

- Suggest evaluation criteria to DOE/OHEP
  - Cost to DOE
  - Beam power from the Main Injector
  - Reliability of operations of the Fermilab accelerator complex
  - Beam power for the 8-GeV neutrino program
  - Suitability as a platform for upgrading the accelerator complex to 2 MW to LBNE
  - Suitability as a platform for a second generation Mu2e experiment at 100 kW
  - Suitability as a platform for upgrading to high beam-power, high-duty factor operations
  - Extent of interruption to ongoing accelerator operations during construction
  - Technical risk
  - Potential for international contributions

Evaluation status

Process is underway

Expected first draft by summer 2016

PIP-II AoA Pluses and Minus of these Options

	SC pulsed linac –CW compatible	SC pulsed linac	SC linac - Afterburner	NC linac
Beam power > 1 MW	Yes	Yes	Yes	Yes
High duty factor capable	Yes	No	No	No
Upgradable	Yes	Yes	No	No
High reliability operations	Yes	Yes	No	No
Interruption to operations	~ 3 months	~ 3 months	> 12 months	> 12 months
International contributions & collaborations	Yes	?	No	No
R&D aligned with efforts to date	Yes	Yes	No	No

Few thoughts about installation and integration

PIP-II Strategy for Installation and Integration

- One of the most appealing characteristic of the current design is that most of the PIP-II civil engineering work, infrastructure installation and installation of machine components can coexist with ongoing scientific program
- Foreseen up to 6 months dedicated shutdown to tie into Booster
  - In conjunction with LBNF shutdown for MI tie in

POSSIBLE SCENARIO

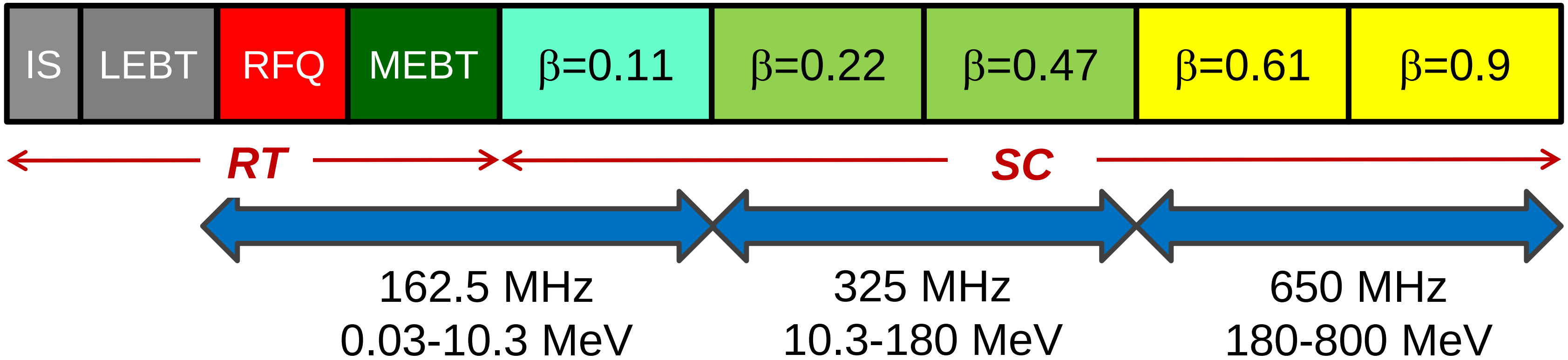
Year	Event
2019	Site prep and long-lead procurements
2020	Cryomodule production starts
2021	
2022	Infrastructure installation
2023	Installation of machine components
2024	Shutdown – tie-in new transfer line to Booster
2025	PIP-II commissioning
2026	PIP-II operational

Summary

- PIP-II project is progressing well
- 800 MeV SC linac design is unchanged for sometime
  - Basic design retains flexibility to high duty factor
  - Sitting consistent with future plans for expandability
  - Eliminate significant operational risks inherit with existing linac
- R&D activities are making good progress on many fronts
- Strategy for the Alternative Analysis is in place
  - Expect to have the first draft by early summer'16

STOP

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_{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

PIP-II Resonance Control (pulsed mode)

- Controlling detuning in the PIP-II cavities requires careful attention
  - High gradient and small beam current
    - PIP-II cavities have a small cavity bandwidth
    - high sensitivity to microphonics and LFD
  - Requires a combination of passive and active approaches
    - Passive
      - Reduction of sensitivity to He pressure and LFD
      - Close attention to eliminate mechanical vibrations due to external sources
    - Active
      - Piezo tuners

PIP-II Beam Current

- PIP-II Conceptual design
  - 800 MeV SC Linac, compatible with CW operations
    - initially operation mode 20 Hz, 2mA
    - Injection scheme is multi-turn strip-injection
      - Low beam current => order of magnitude smaller than current op.
      - Suitable for longitudinal and transverse painting (correlated painting) due to
        - large # of turns ~ 290 (~ 550 μsec)
        - small emittances
      - Expect to suppress beam SC effects and improve longitudinal beam stability
      - 50% more beam intensity and double injection energy -> reduce ΔQ_{SC} ~30%