Fermilab

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PIP-II Injector Test: Challenges and Status

Paul Derwent : representing many who have contributed
Fermi National Accelerator Laboratory
LINAC 2016

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

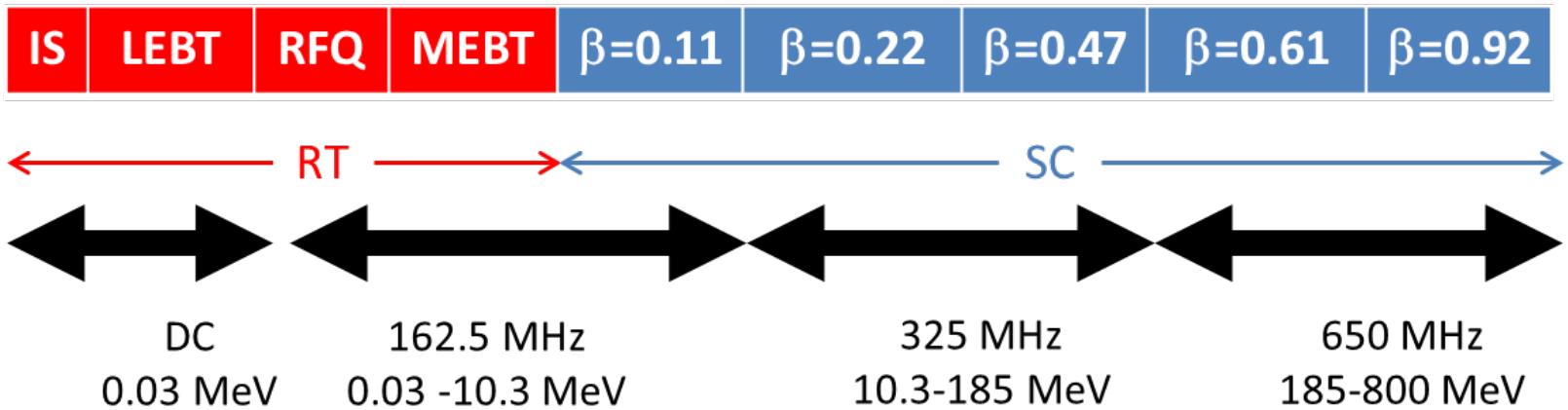
⇒ ***This requires more protons!***

(and this statement tends to be time invariant)

"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 the first operation of the new long-baseline neutrino facility" – Recommendation 14, P5 report

PIP-II : Mission Need (Critical Decision 0) November 2015

PIP-II Technology Map



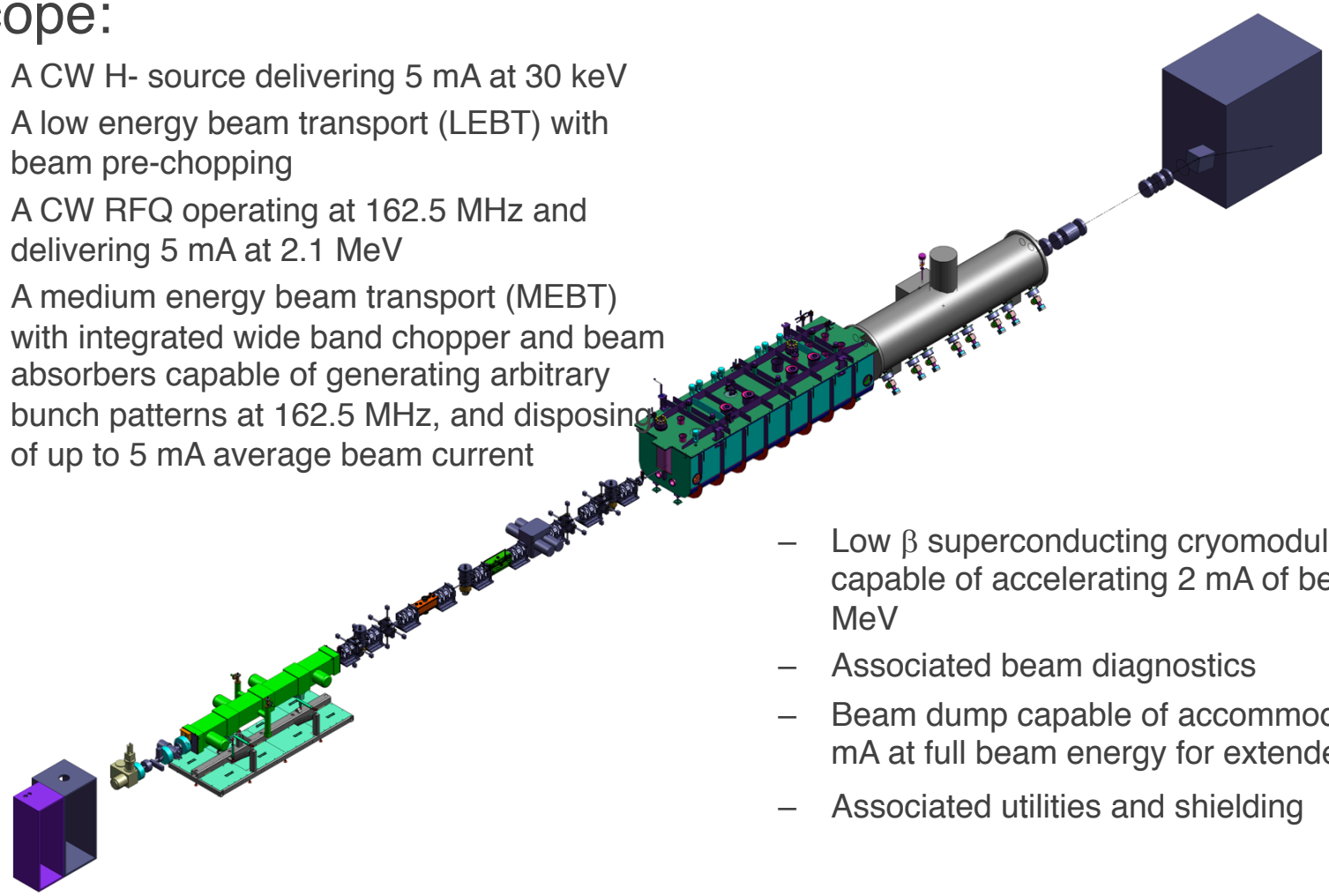
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-10.3	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	10.3-35	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.47)	325	35-185	35/21/7	SSR, solenoid
LB 650 (β_g=0.61)	650	185-500	33/22/11	5-cell elliptical, doublet*
HB 650 (β_g=0.92)	650	500-800	24/8/4	5-cell elliptical, doublet*

*Warm doublets external to cryomodules

All components CW-capable

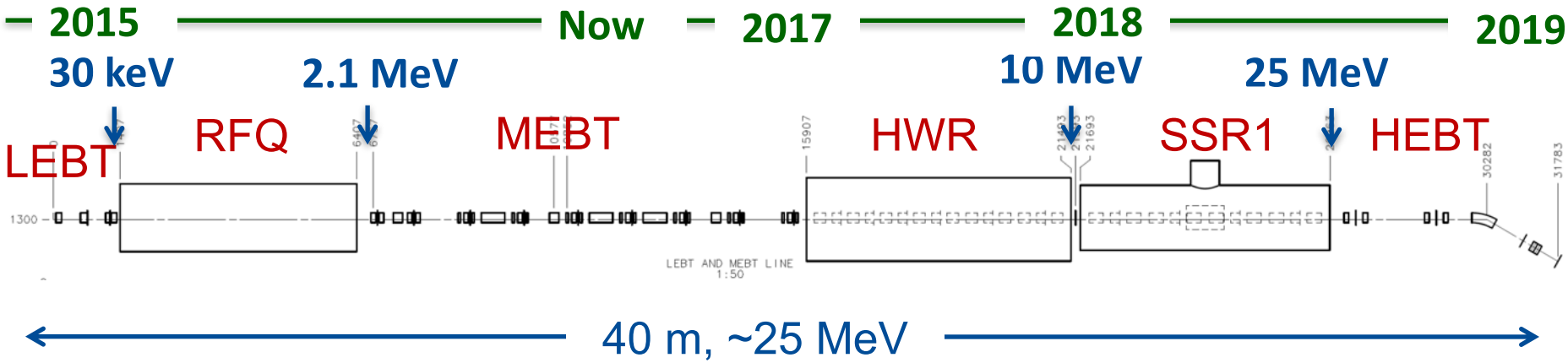
PIP-II Injector Test:

- 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

PI-Test (PIP-II Injector Test): 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

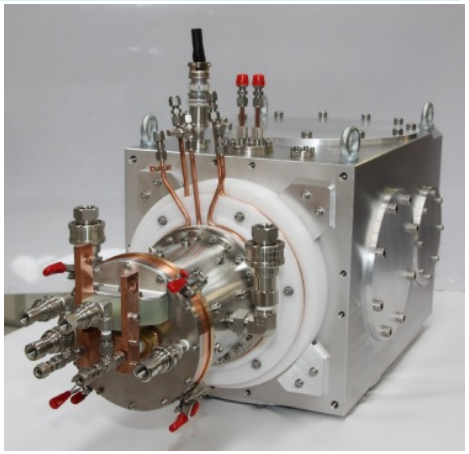
SNS: LEBT

BARC: MEBT, RF

IUAC: SSR1

Ion source and LEBT layout

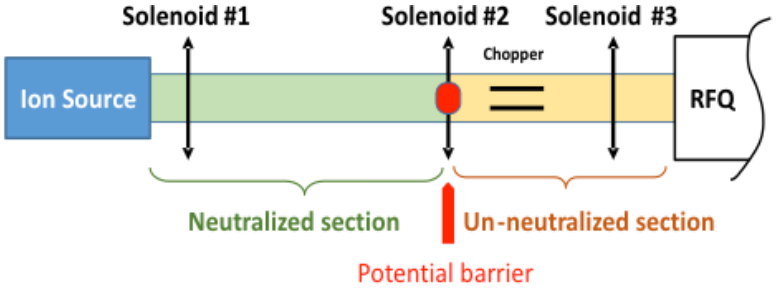
- Non-cesiated, filament-driven ("TRIUMF-type"), 15-mA DC, 30 keV, H^- volume-cusp ion source from D-Pace, Inc.
  - Added a modulator to the extraction electrode ⇨ 5 μs -16 ms pulses
  - Water-cooled Allison scanner mounted on the IS vacuum chamber
    - Modified version of previous designs from LBNL/SNS



D-Pace ion source with vacuum chamber

- Atypical transport scheme motivated in part by the goal of maintaining good vacuum in the RFQ
  - Full neutralization upstream of Solenoid #2
    Un-neutralized downstream

Parameter	Value	Unit
Kinetic energy	30	keV
Nominal/Maximum beam current, DC	5/10	mA
Output transverse emittance over 2-5 mA current range	< 0.18	μm
Typical pressure	$\sim 10^{-6}$	Torr
Chopping frequency, max	60	Hz
Pulse length	1-16600	μs



Transport scheme pictorial

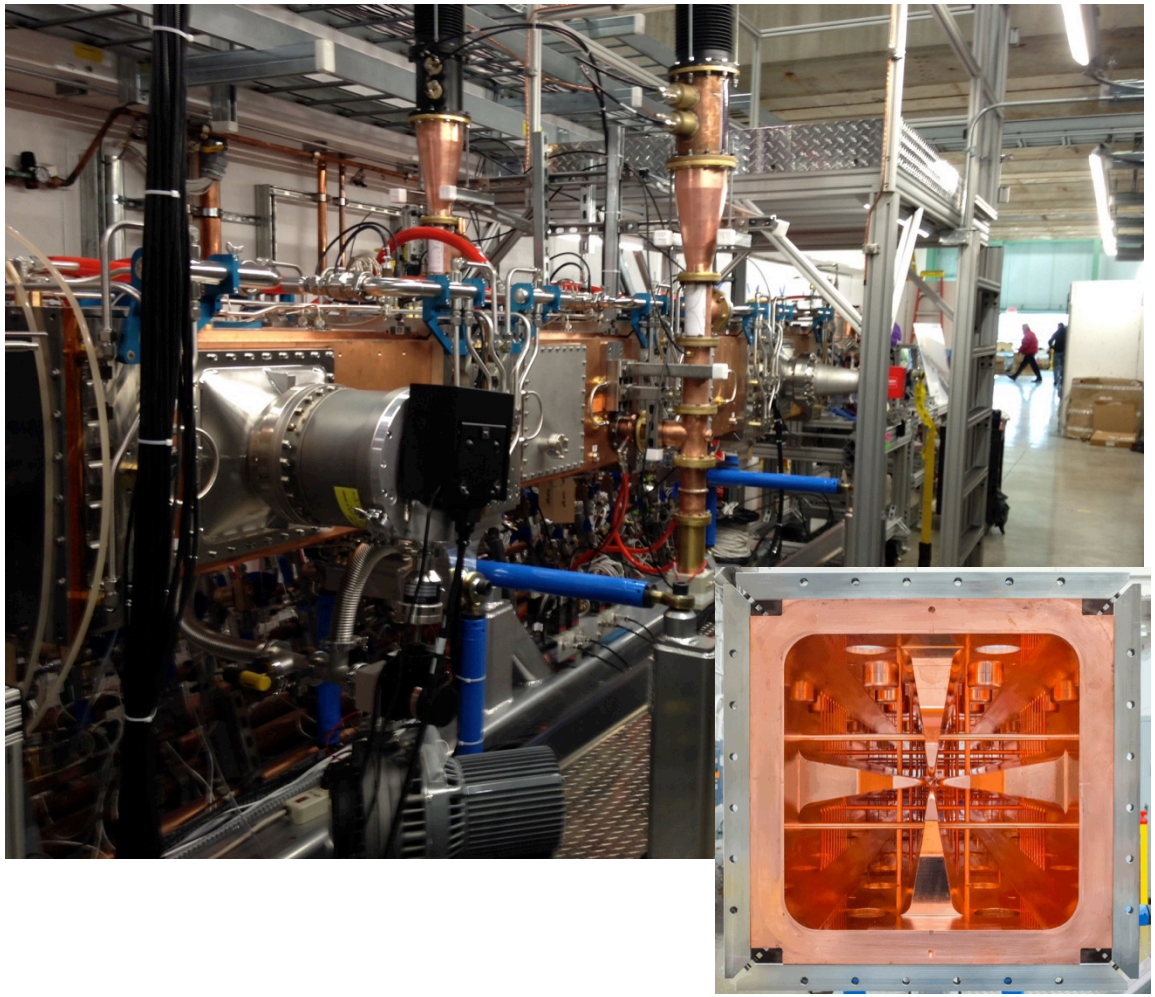
Commissioning results (LEBT straight configuration)

- Up to 10 mA (DC and pulsed) to the end of the LEBT
- Ion source and LEBT settings optimized for injection into the RFQ at 5 mA
  - Input emittance is 0.13 mm (rms, normalized)
  - Scheme with partial neutralization was realized
- >20% of beam is scraped off in Solenoid #1 and upstream
- Vacuum near the RFQ entrance is $< 3 \times 10^{-7}$ Torr in all modes of operation
  - ~0.5% of the beam is converted into fast protons travelling through the entire LEBT (in its straight configuration)
- Observed drifts of the beam Twiss parameters
  - Day-to-day and over long runs
  - Stabilization loops (software) have been implemented

RFQ Status

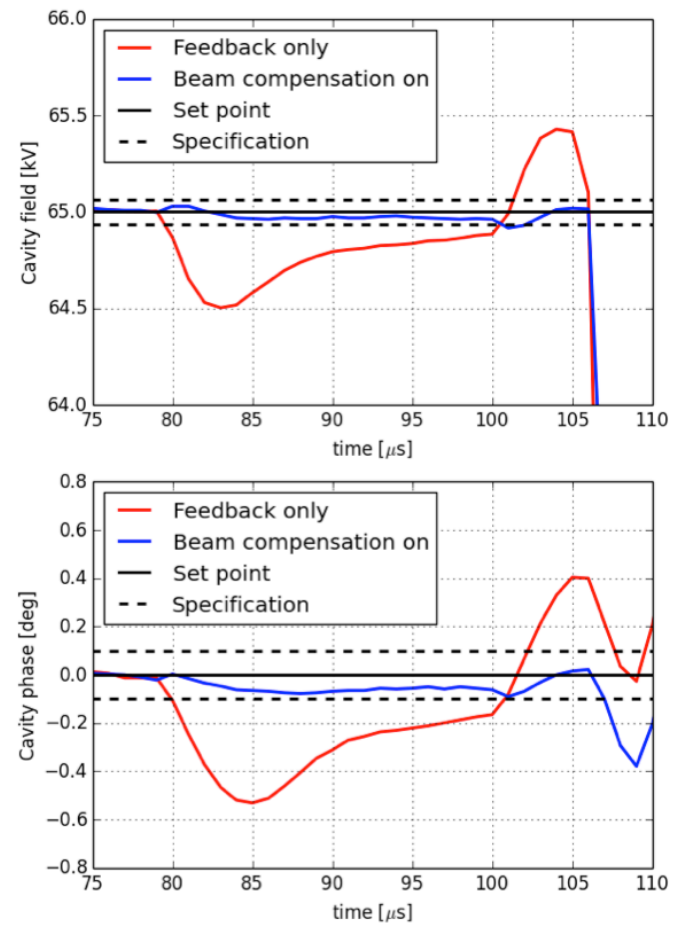
- RFQ Installation is complete.
- RFQ successfully conditioned with 120kW input power initially at 5% duty cycle,
  - Taking into account measured Q0 and beta, estimate vane potential at 66kV (10% above specified).
- 95 kW in CW operation
  - 62 kV vane potential
- J. Steimel, THPLR065
- S. Kazakov, TUPLR056

RFQ in Enclosure



LLRF Update

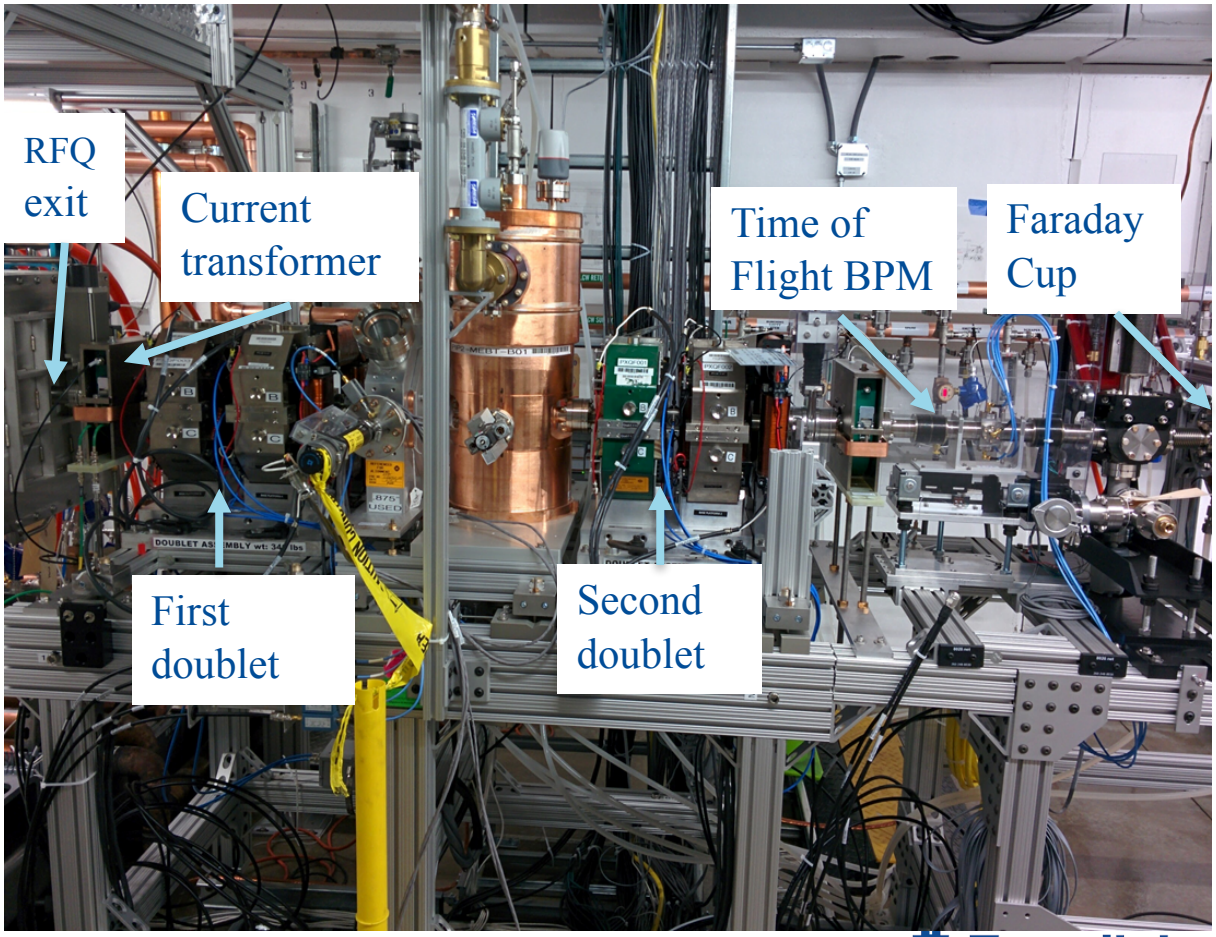
- Provides a wide verity of pulse widths from 100-microsecond to 5-miliseconds
- Optimized the RF pulse for fast turn-on
- Demonstrated CW operation
- Demonstrated regulation to the 10^{-3} level during a 20-μsecond beam pulse
- Provided calibration of amplifier gain and phase to ensure proper match into the RFQ
- Improved control over the RF system in the presence of temperature drifts with slow phase-feedback



Beam from RFQ

- We received permission to run the beam through RFQ on March 23, and saw an accelerated beam within an hour

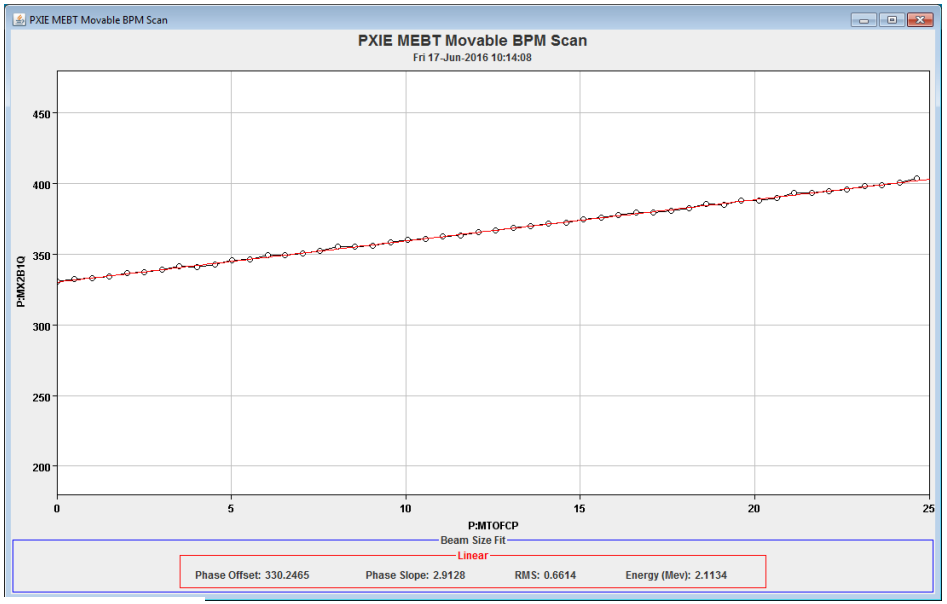
- Since March:
  - 98% ± 3% transmission efficiency
  - 1 - 10 mA pulsed beam
  - Energy measurements
  - Emittance measurements

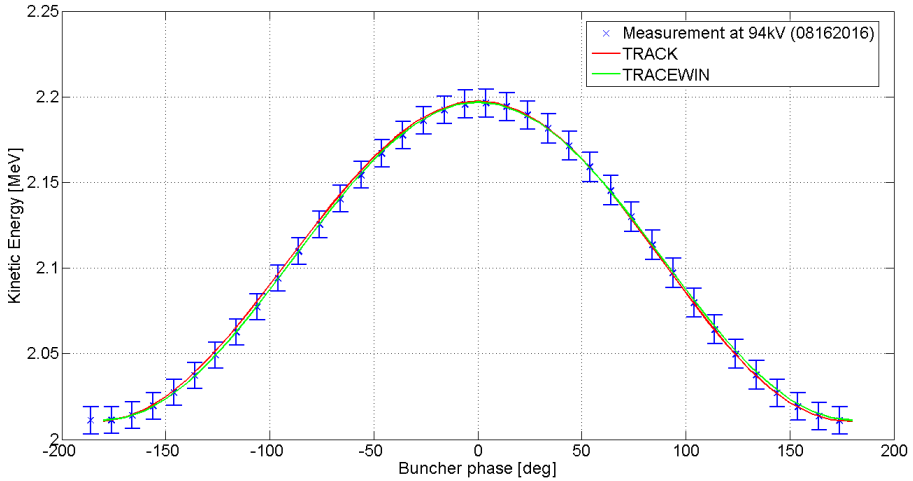


Beam Characterization

- Energy Measurement:
  - Time of Flight BPM
  - 2.11 MeV ± 0.5%

Preliminary : working to
understand calibrations
understand optics
understand uncertainties

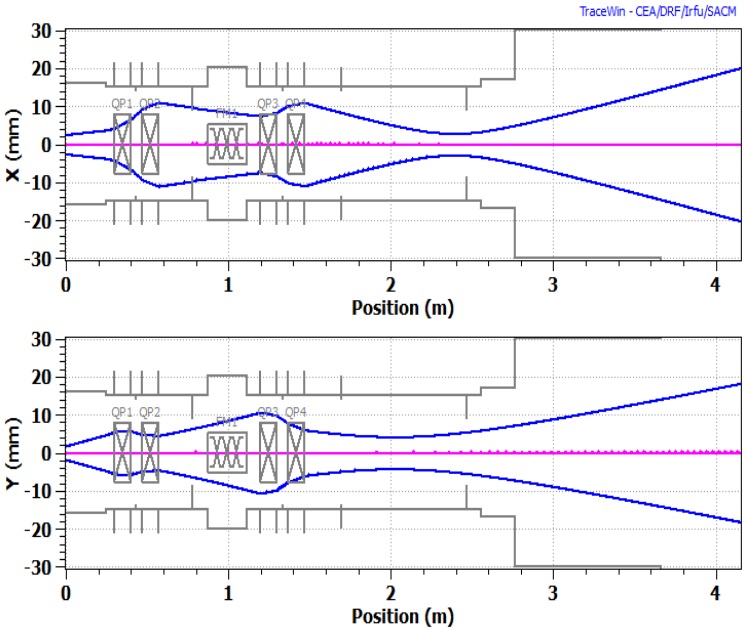




- Energy Measurement:
  - Phase difference between 2 BPMs
  - vary buncher cavity phase and compare to simulations
  - 90° is nominal vaue

Beam Envelope: Simulation

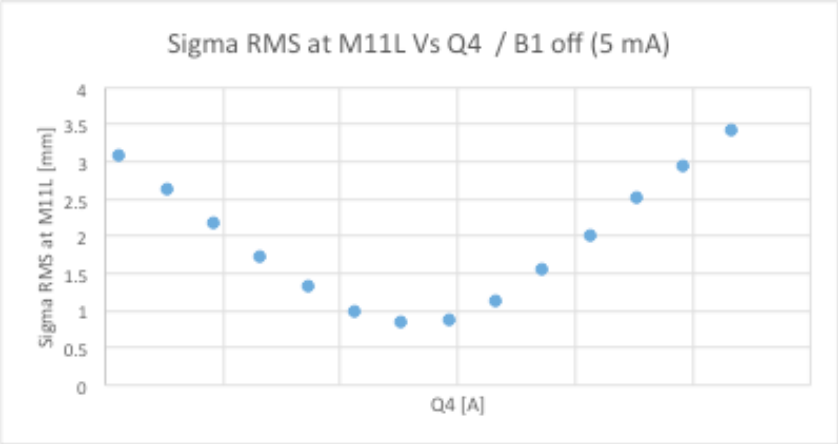
3 RMS Beam Envelope



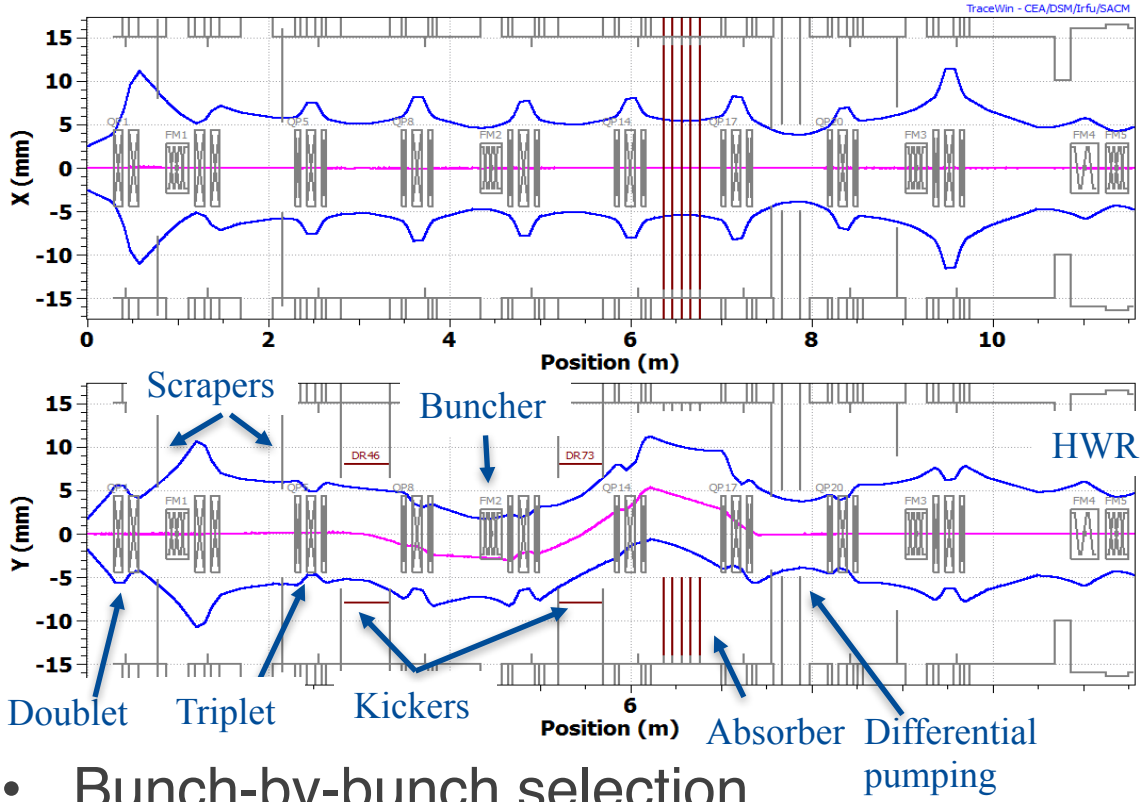
- Quadrupole current scans at these locations
  - reconstruct beam size using scrapers
  - fit to give transverse emittances
  - working to verify quadrupole and scraper calibrations
  - do not have emittance values to present today

Initial Settings

- Beam Energy is 2.1 MeV
  - Measurement settings for Quads:
  - M00QD = 11.07 T/m
  - M00QF = 9.14 T/m
  - M10QD = 7.91 T/m
  - M00QF = 7.12 T/m
- Quadrupole length: 0.1 m
- Doublet length: 0.27 m
- 4 position scraping system to remove transverse tails
  - A. Saini THPRC026



MEBT configuration and main features



3σ envelopes of passing bunches. 2.1 MeV, 5 mA. TraceWin.

- Focusing
  - 2 doublets and 7 triplets
  - 3 bunching cavities
- Chopper
  - 2 kickers
  - absorber

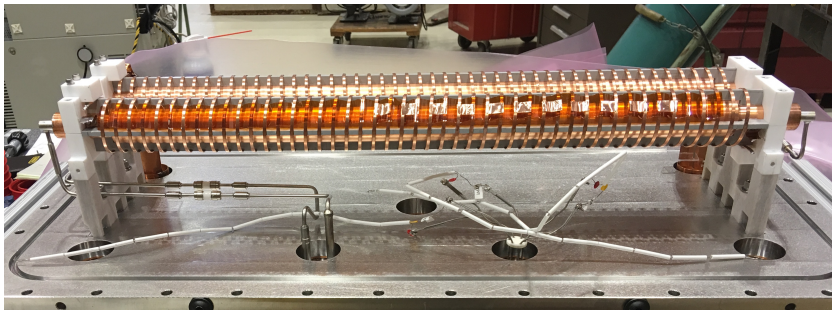
- Bunch-by-bunch selection
  - Any bunch from initial CW train can be removed or passed
  - Programmed into LLRF
- Transition from sub-10^{-6} Torr to UHV, particle-free near SRF
- Scraping system (see A. Saini THPRC026 Poster)

Components

- All magnets have been manufactured by BARC, India and are being measured there

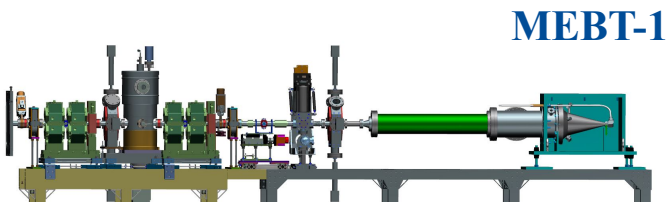
Doublet 1 Doublet 2 Triplet 1 Triplet 2 Triplet 3 Triplet 4 Triplet 5 Triplet 6 Triplet 7

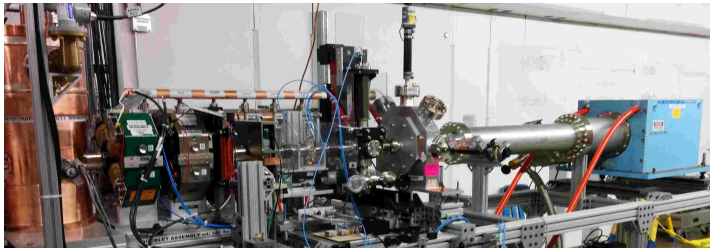
- Bunching cavities are in final stage of manufacturing
  - RF amplifiers go through post-manufacturing adjustments
- Most of girders and vacuum chambers are on hand; an absorber prototype is being tested; diagnostics and scrapers are partially ready
- Kicker prototypes are ready for installation

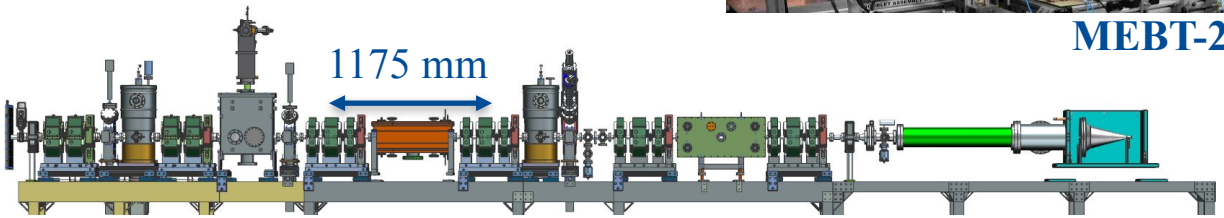


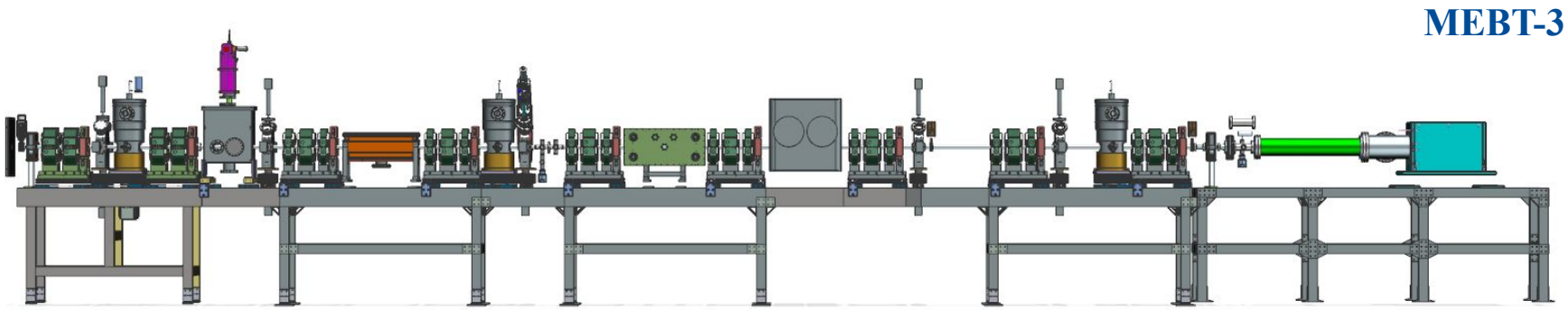
MEBT stages

- MEBT is being installed in 3 main stages, different in the number of focusing elements
  - Full-length MEBT is expected to be installed in 2017



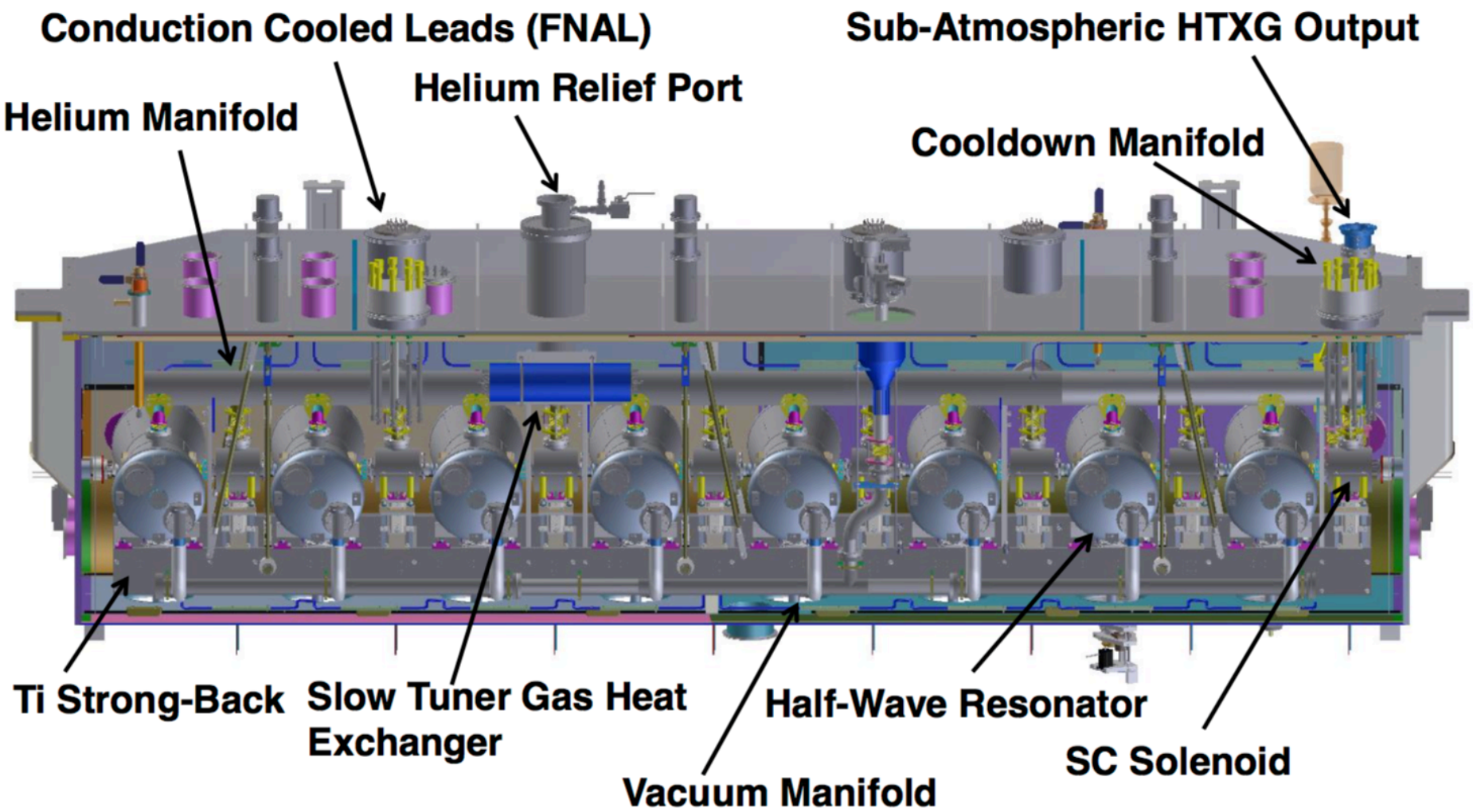






Half-Wave Resonator Cryomodule

Argonne National Lab



2.2 m X 2.2 m X 6.2 m

Z. Conway Poster THPLR027

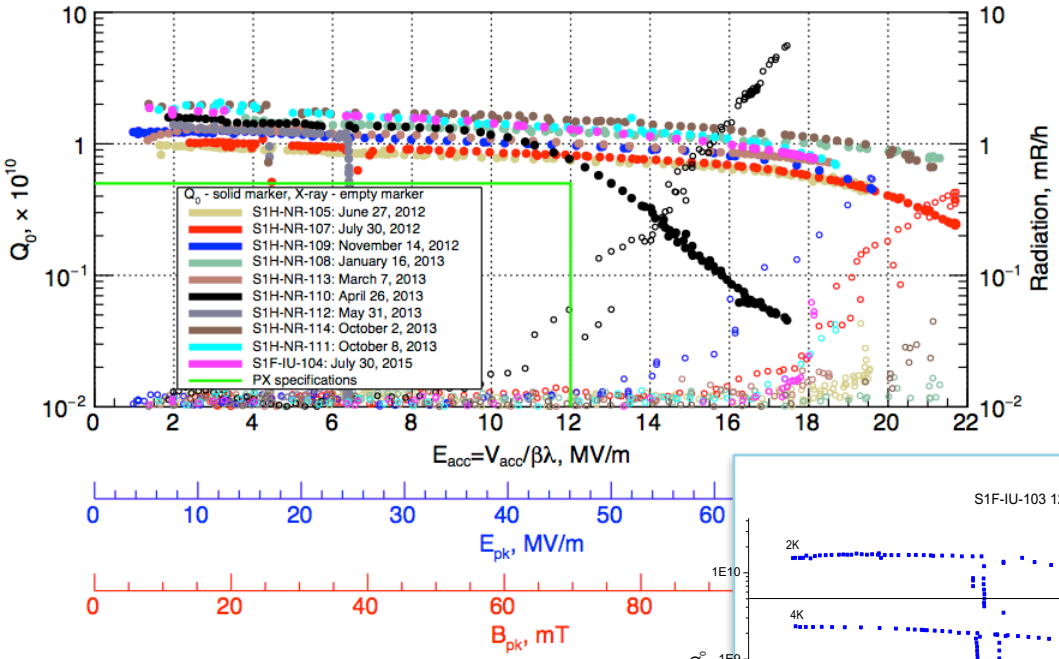
Technical Developments

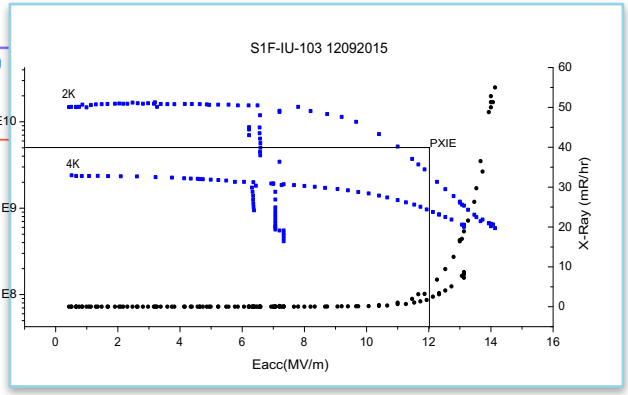
- Novel design of half-wave resonators: double conical structure to reduce peak fields and cryogenic load while providing a high shunt impedance.
- Integrate into the superconducting solenoid a return coil and x-y steering coils without additional magnetic shielding.
- Cold, low-particulate clean, beam position monitors.
- Compact lattice suitable for the acceleration of several mAs of H^- or proton beams.
- When finished the half-wave cryomodule will be the first superfluid helium cooled TEM-class cryomodule.

Single Spoke Resonator : Cavities

Two SSR1 cavities were received from IUAC, chemically processed and cold-tested at Fermilab. S104 yielded excellent results, S103 presented some issues with UHV flange connections, fixable

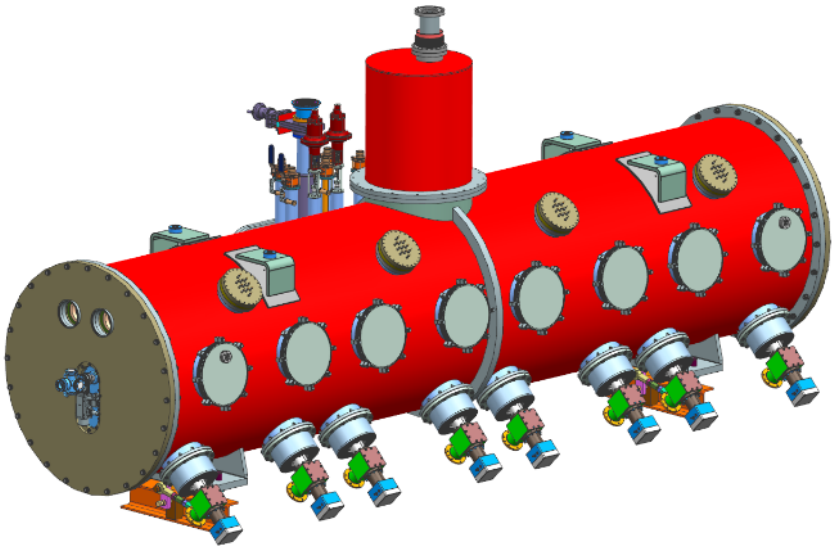
Jacketing will happen at BARC. Delivery to FNAL by **Dec 2016** for integration in SSR1 CM.



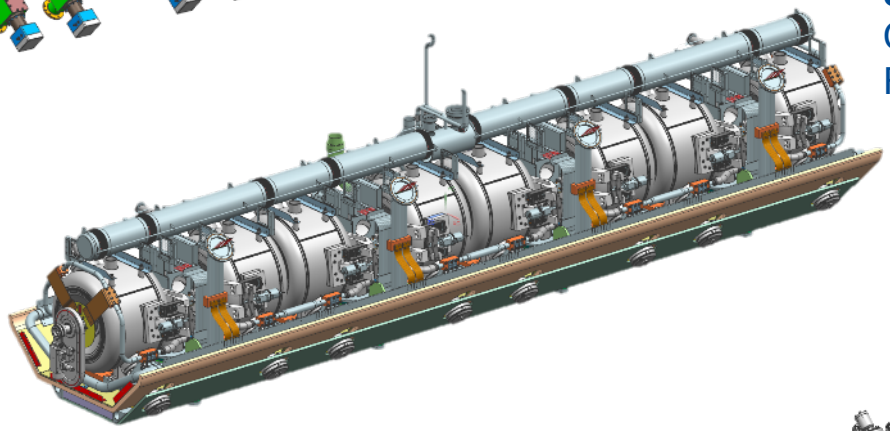


Cold Tests of SSR1 Resonators Manufactured by IUAC for the Fermilab PIP-II Project, L. Ristori et. al, SRF15 Conference

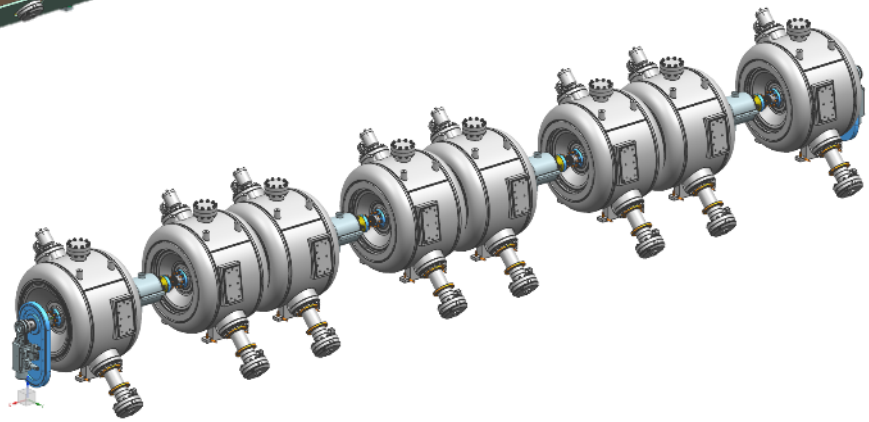
Status of SSR1 Cryomodule



SSR1 cryomodule – Top assembly
Conceptual design: completed
Final design: ~80% completed



SSR1 coldmass
Conceptual design: completed
Final design: ~80% completed



SSR1 string assembly
Final design: 100% completed
Procurement: 100% completed

Challenge: Detuning in the PIP-II Cavities

- PIP-II design calls for narrow bandwidth (f1/2 ≅30 Hz) cavities operating in pulsed mode
  - Narrow bandwidth makes cavities susceptible to vibration induced detuning
  - Pulsed mode LFD can excite vibrations
- PEAK detuning of PIP-II cavities must be limited to 20 Hz or less
  - PIP-II cavities will require active detuning compensation of both LFD and microphonics during routine operation
    - Will require combination of
      - best LFD compensation achieved to date
      - AND best active microphonics compensation achieved to date
      - AND 24/7 operation over hundreds of cavities for several tens of years
- No examples of large machines that require active detuning control during routine operation currently exist
- W. Schappert, Presentation TU2A03 and Poster MOPLR028

	N	f	Q_0	r/Q	E	$L_{Effective}$	Voltage	Current	Control	Losses	P_{Beam}
		MHz	10^9	Ω	MV/m	m	MV	mA	%	%	kW
HWR	8	162.5	5.0	275	9.7	0.21	2.01	2	20	10	4.02
SSR1	16	325	6.0	242	10.0	0.21	2.05	2	20	10	4.10
SSR2	35	325	8.0	296	11.4	0.44	4.99	2	20	10	9.99
LB650	33	650	15.0	375	15.9	0.75	11.86	2	20	10	23.72
HB650	24	650	20.0	609	17.8	1.12	19.92	2	20	10	39.84

Schedule: PI-Test

- FY16:
  - Characterize beam through the RFQ
    - Pulsed operation: Energy, Transmission, Emittance
- FY17:
  - Pulsed & CW operation, measurements through different stages of the MEBT
  - 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

Summary and Conclusion

- PIP-II Injector Test: integral part of the PIP-II Project R&D
- Successfully accelerated 10 mA through RFQ
  - Energy 2.11 MeV ± 0.5%
  - >97% transmission
- MEBT installation and chopper test planned in FY17
- Half Wave Resonator and Single Spoke Resonator cryomodules scheduled for installation in FY18
- On schedule to support CD3 in FY19/20 time frame