An 800 MeV Superconducting Linac to Support Megawatt Proton Operations at Fermilab

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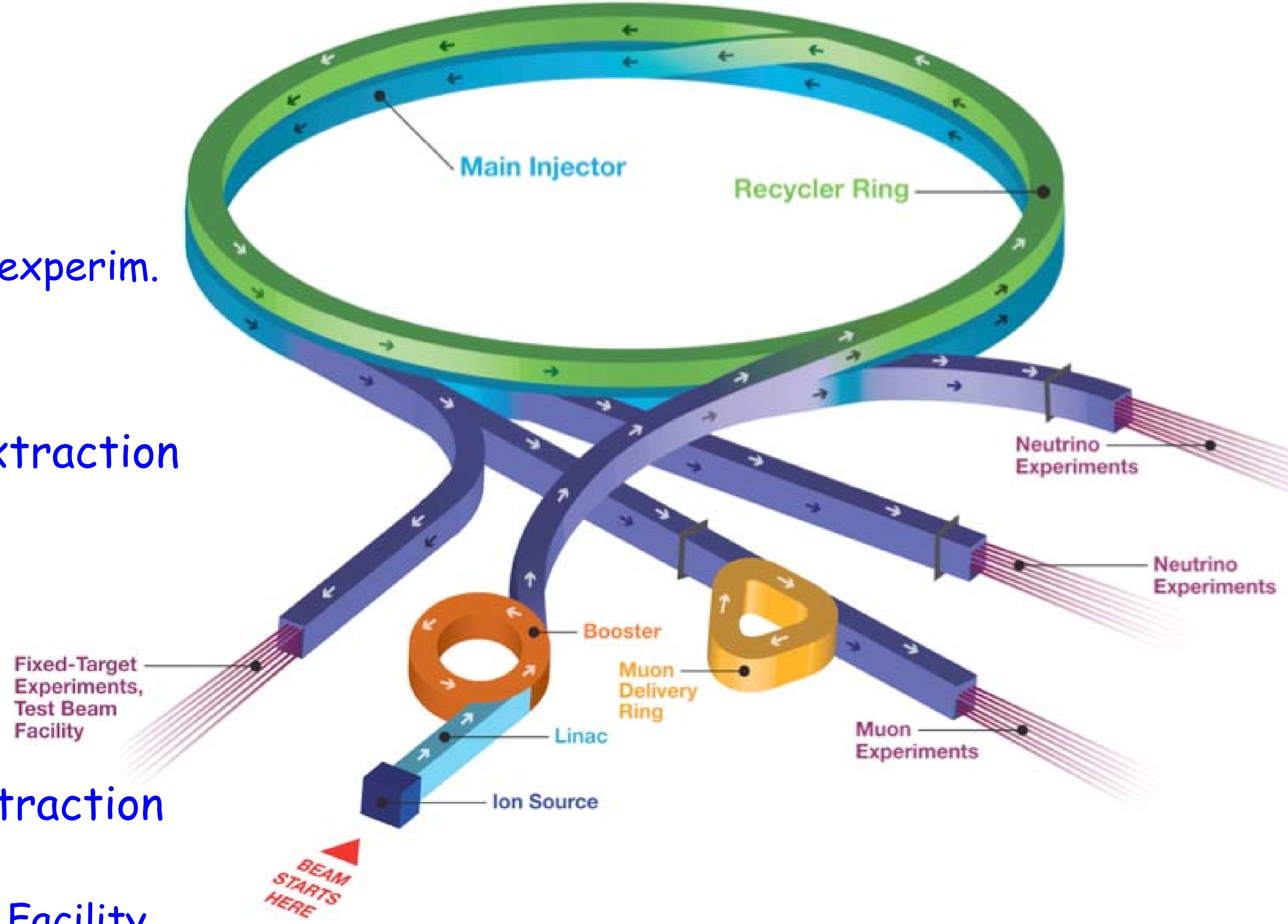
Outline

- Fermilab accelerator complex
- From Project X to PIP-II
- PIP-II goals and parameters
- SC linac, its status and subsystems
  - LEBT and RFQ
  - MEBT
  - SC linac
    - HWR
    - SSR1
    - SSR2
    - LB and HB cryomodules
  - RF power and microphonics
  - Cryogenics
- Summary

Acknowledgement: This presentation uses materials presented in Fermilab PIP-II MAC review (February 25-17, 2014) and PIP-II collaboration meeting (June 3, 2014)

Fermilab Accelerator Complex

- Linac:
  - NTF, MTA
- Booster
  - MicroBooNE
  - 4 short base ν experim. in near future
- Main injector
  - Single turn extraction
    - NuMI:
    - MINOS+,
    - MINERvA,
    - NOvA
  - Slow (resonant) extraction
    - SeaQuest
    - Test Beam Facility



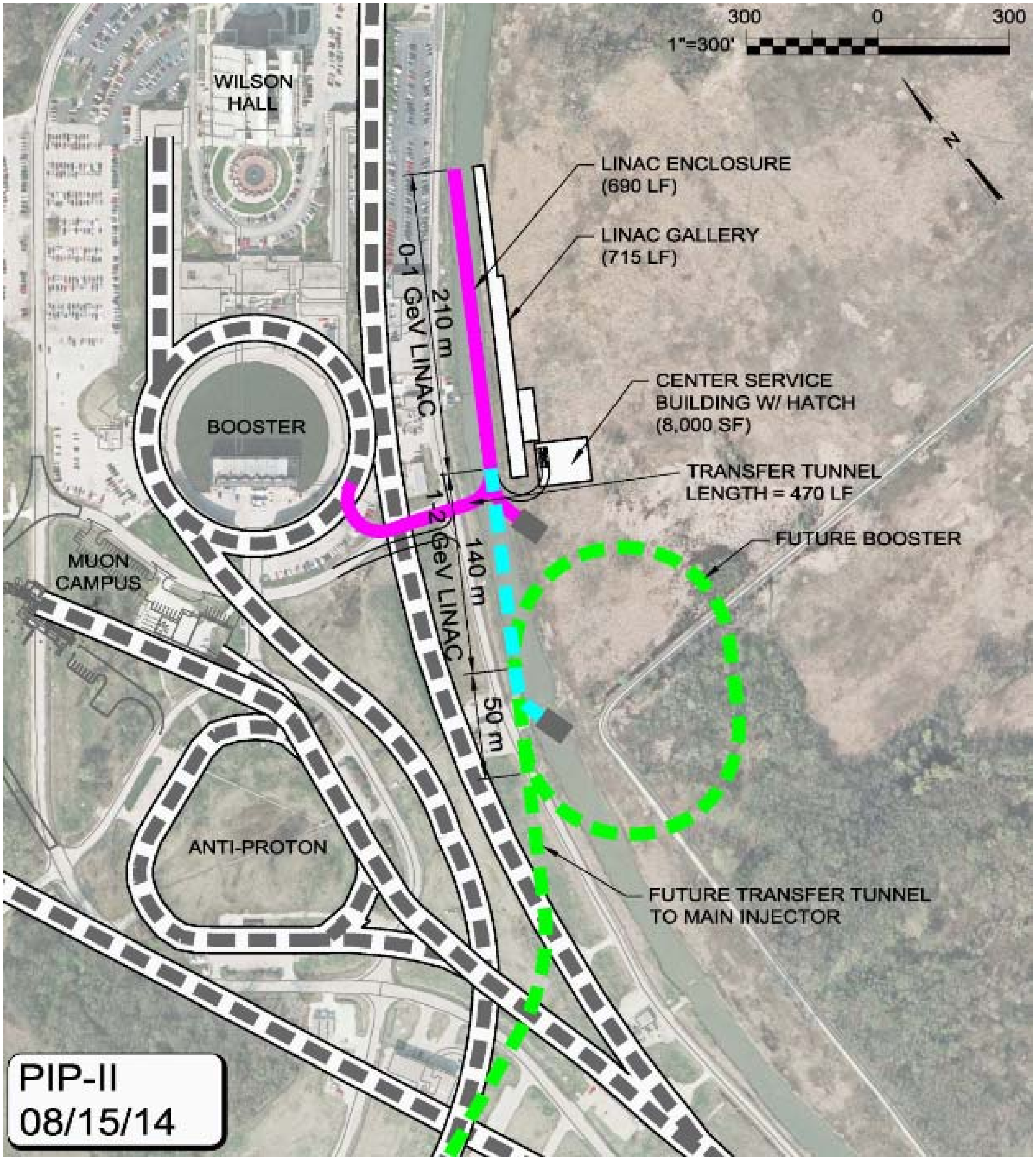
- Near Future: experiments with muons (8 GeV protons from Recycler)
  - g-2
  - Mu2e

From Project X to PIP-II

- A study of neutrinos is the main focus for future experiments
  - ♥Strongly supported by P5 (Particle Physics Project Prioritization Panel)
    - ♦ PIP-I (Booster upgrades to support near future, to ~2022-24)
      - The goal: 0.32 -> 0.7 MW @ 120 GeV (NOvA and Minos+)
    - ♦ PIP-II (New SC linac for to increase E_{inj}, this presentation)
      - The goal – 1.2 MW @ 120 GeV (LBNF)
      - Support of 8 GeV program (SBNE, …)
- Other Project X intensity frontier experiments are postponed
  - ♦ However μ-to-e upgrade is considered to follow as a next step
- Relative to the Project X the scope & cost are reduced
  - ♦ SRF technology map is unchanged
    - Makes future upgrades easier
  - ♦ The scope changes
    - CW linac energy: 2 GeV -> 0.8 GeV
    - Booster is upgraded and used to accelerate to 8 GeV
    - SC linac operation: initially pulsed to avoid construction of new cryo-plant ⇒ significant cost reduction
    - All other systems are CW compatible
      ⇒ creates many possibilities in the future

PIP-II at Glance

- New SC linac
  - 20 Hz, 0.55 ms
  - 2 mA beam current
  - Compatible with CW operation in the future
- Booster upgrade
  - Rep rate: 15 Hz -> 20 Hz
  - ~1.5 times larger N_p $(4.3 \rightarrow 6.5)\cdot 10^{12}$
  - New injection girder
    (1) higher energy:
    400 -> 800 MeV
    (2) longer inj. time:
    12 -> 300 turns
- MI upgrade (12 batch slip-staking, 1.2 s cycle for 120 GeV operation)
  - Higher RF power
  - Beam stability, transition crossing, loss reduction



PIP-II Major Parameters

Performance Parameter	PIP	PIP-II	
Linac Beam Energy	400	800	MeV
Linac Beam Current	25	2	mA
Linac Beam Pulse Length	0.03	0.55	ms
Linac Pulse Repetition Rate	15	20	Hz
Linac Upgrade Potential	N/A	CW	
Booster Protons per Pulse (extracted)	4.2×10^{12}	6.5×10^{12}	
Booster Pulse Repetition Rate	15	20	Hz
Booster Beam Power @ 8 GeV	80	160	kW
8 GeV Beam Power to MI (LBNE)	-	80-120*	kW
Beam Power to 8 GeV Program	-	80-40*	kW
Main Injector Protons per Pulse (12 batches; extr.)	4.9×10^{13}	7.6×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.33	1.2	sec
Main Injector Cycle Time @ 60 GeV	N/A	0.8	sec
Beam Power @ 60 GeV (LBNE)	N/A	0.9	MW
Beam Power @ 120 GeV	0.7	1.2	MW
Upgrade Potential @ 60-120 GeV	-	>2	MW

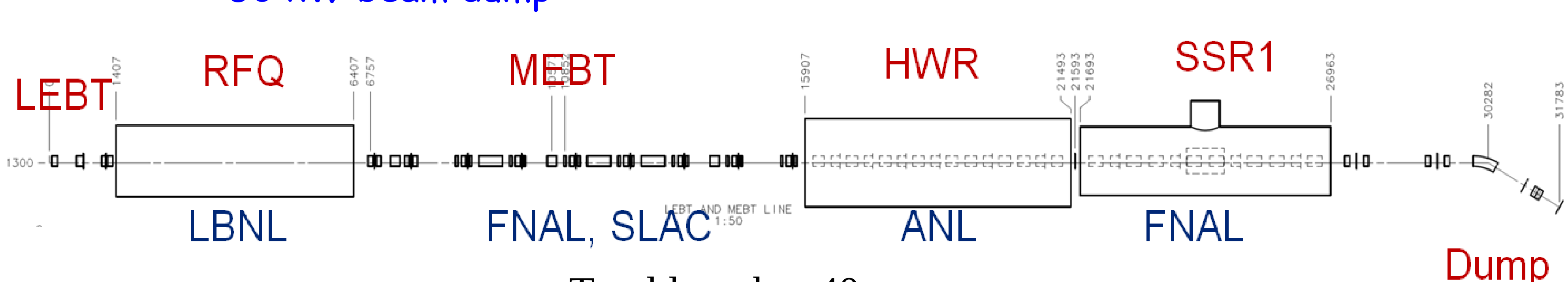
*1st number refers to MI operations @ 120 GeV; 2nd number to 60 GeV.
The PIP-II configuration is capable of maintaining 1.2 MW down to 80 GeV.

Main Requirements to the Machine Conception

- Accelerator physics design is driven by the following requirements
  - Bunch-by-bunch beam chopping in MEBT
    - Minimize required kicker voltage to an acceptable level
    - RFQ frequency
  - Small emittance: to allow low loss painting into Booster phase space in the course of beam injection
  - Small emittance growth and halo generation in the course of beam acceleration
  - Effective acceleration in SC cavities
    - Use maximum voltage available in SC cavities
    - Minimize number of SC cavities
  - Effective diagnostics for measurements of beam parameters
- First 3 cryomodules operate in CW
- Other cryomodules operate in pulsed mode to reduce cryo-load
  - Significant complication for cavity resonance control due to Lorentz Force Detuning (LFD)

PIP-II Frontend

- PXIE represents a complete systems test of the frontend
  - Has to retire major risks
    - (1) CW operation of RFQ, (2) Chopper, (3) MEBT differential pumping, (4) resonance control and (5) low energy acceleration in SC cavities (untested @ HP)
    - Test stand for Lorentz Force Detuning (LFD) to be used for other cavity types
- "Standard" scheme for beam acceleration
  - 30 kV ion source and LEBT (5 mA nominal, 10 mA max)
  - LEBT with beam pre-chopping for machine tuning
  - 2.1 MeV RFQ
  - MEBT (~10 m long, bunch-by-bunch chopping and beam diagnostics)
  - 2 SC cryomodules accelerating beam to ~20-30 MeV
  - Sections which do not belong to PIP-II
    - HEBT
    - 50 kW beam dump



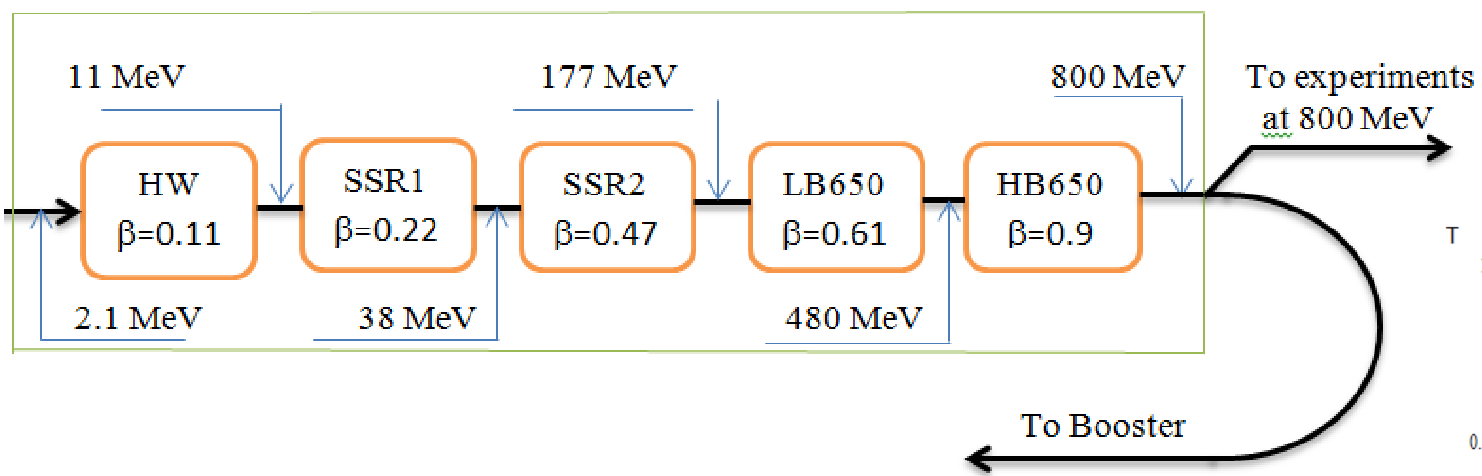
Total length ~ 40 m

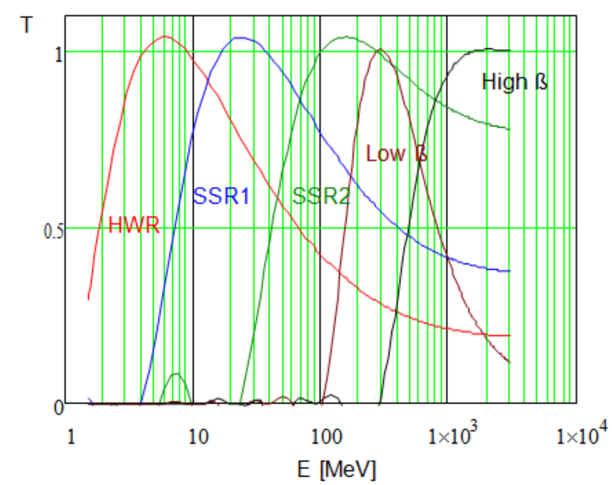
PIP-II SC Linac

- No major changes relative to the Project X linac (smaller energy)

Section	Energy (MeV)	ΔE/cav* (MeV)	R/Q (W)	Cav/CM	CM config.	CM length (m)
HWR	2.1-11	1.7	272	8 / 1	8 x (sc)	5.93
SSR1	11-38	2.05	242	16 / 2	4 x (csc)	5.2
SSR2	38-177	4.98	275	35 / 7	sccsccsc	~6.5
LB650	177-480	11.6	378	30 / 10	(ccc)-(fd)	~3.9
HB650	480-800	17.7	638	24 / 4	(cccccc)-(fd)	~9.5

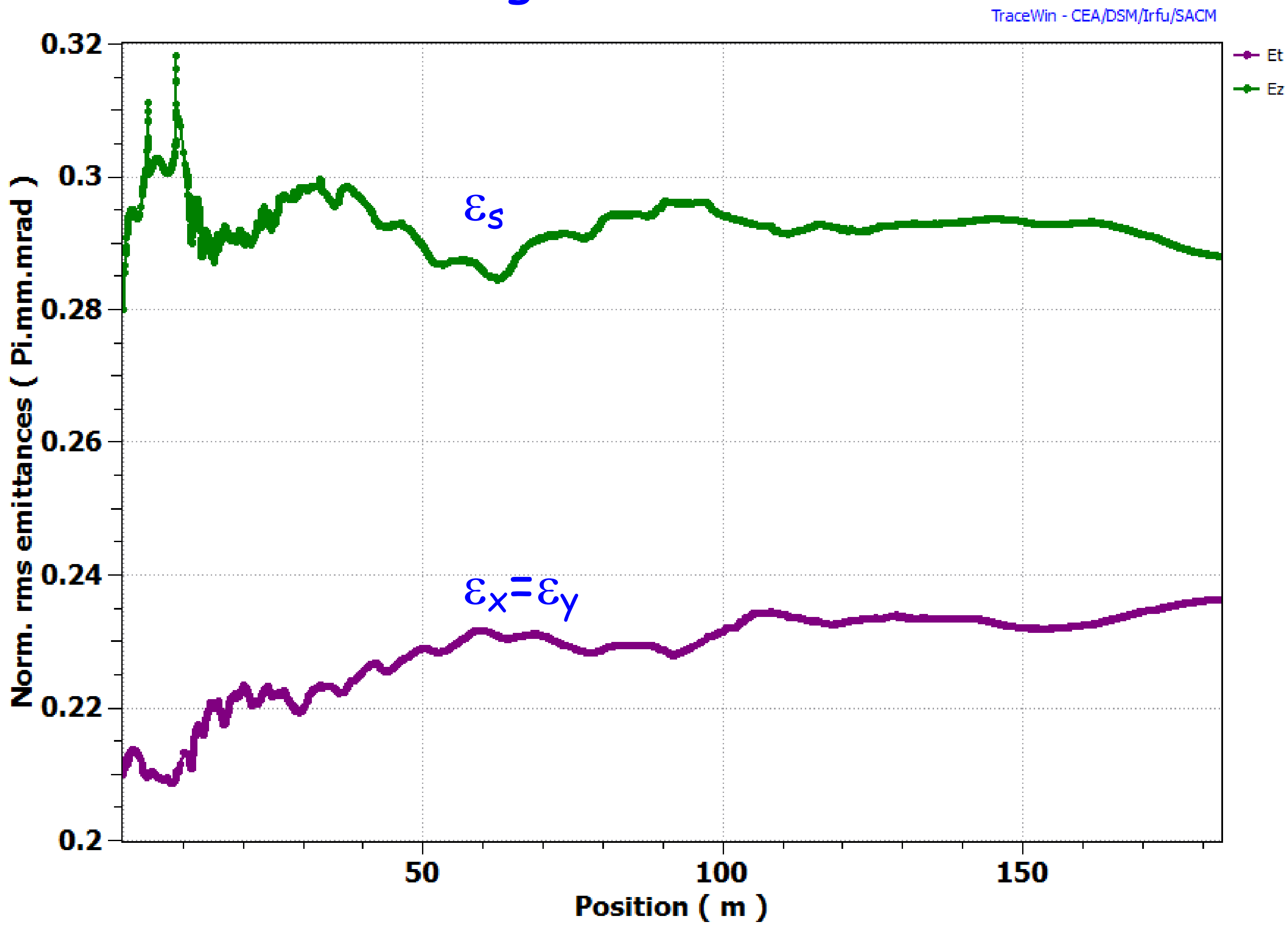
* Actual ΔE is reduced at section-to-section transitions, due to flight factors and off-crest acceleration





Beam Dynamics in SC linac

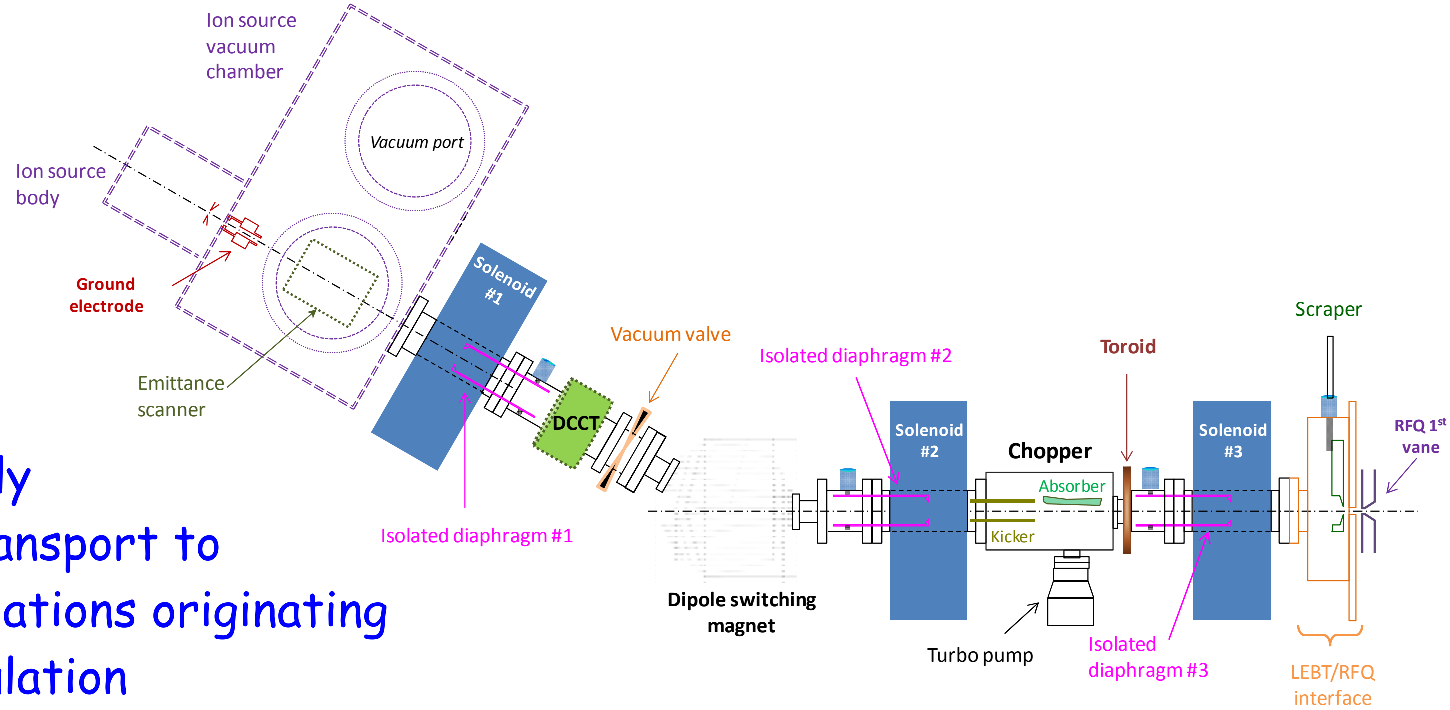
- Compared to the Project X linac there are no changes in the beam dynamics
  - Moderate emittance growth in the course of acceleration

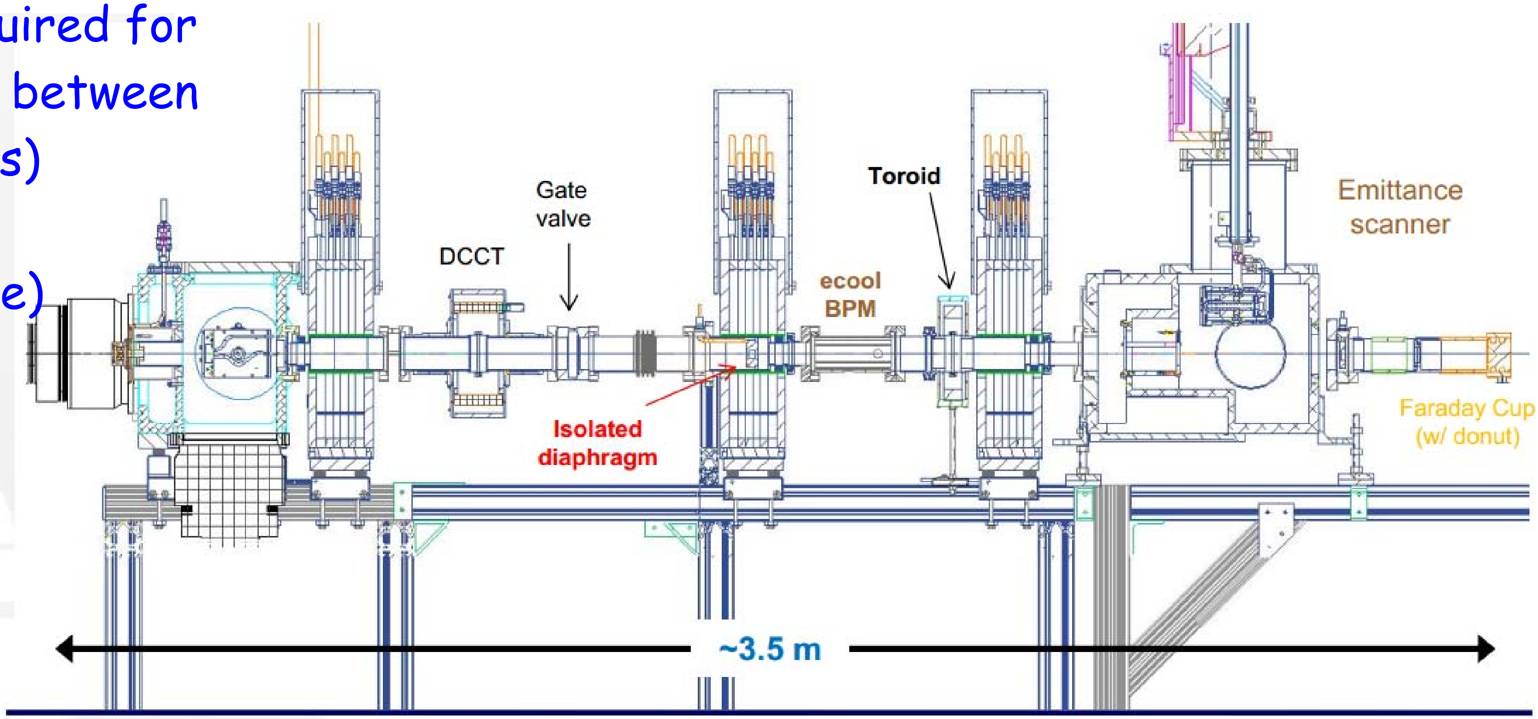


CW Linac : RMS Emittances

LEBT Status*

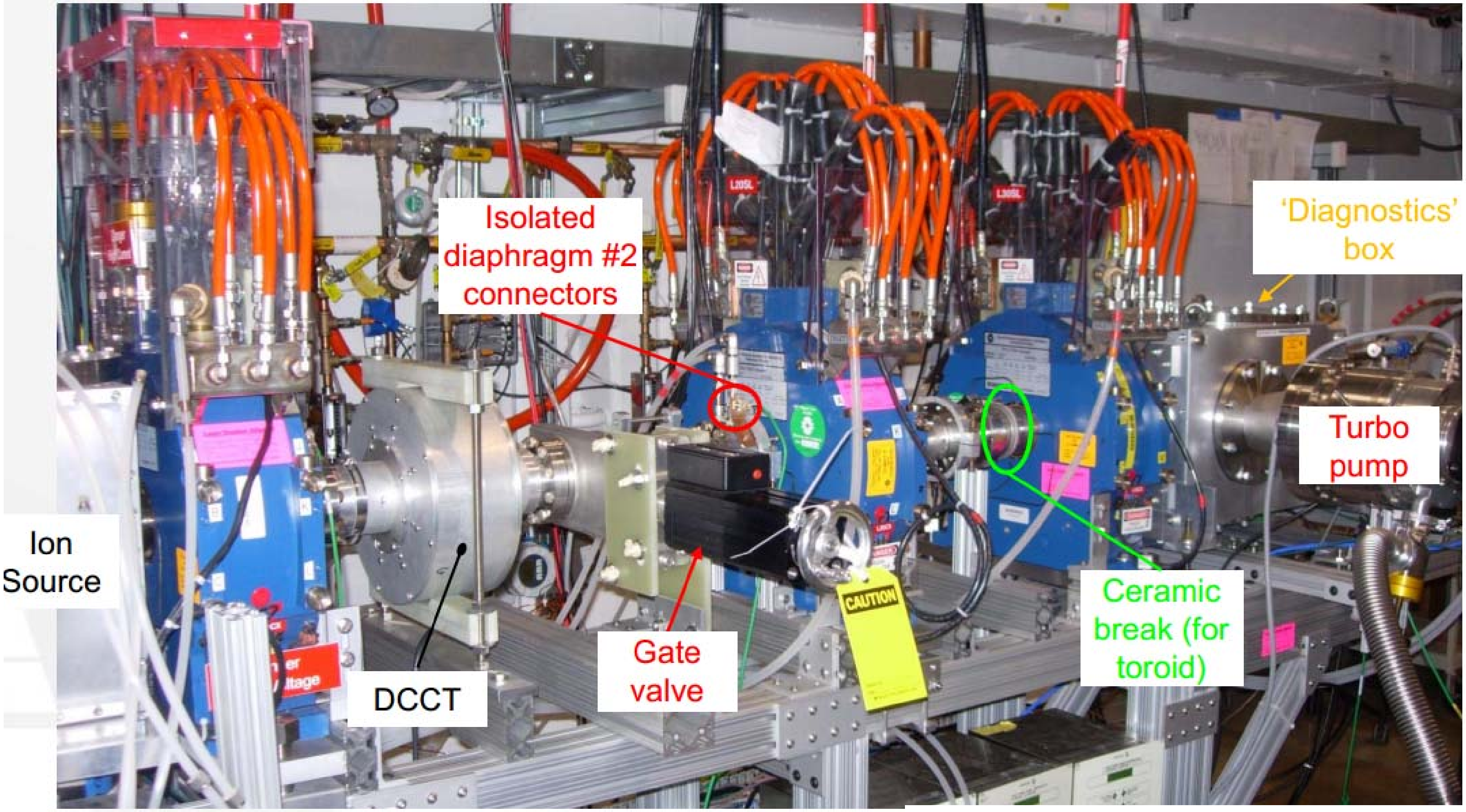
- LEBT is under commissioning
- Features
  - 3 solenoids
  - Partially and fully compensated transport to avoid optics variations originating from ion accumulation
  - No dipole (required for fast switching between two ion sources)
  - LEBT chopper (~1 μs rise time)
  - Good differential pumping between ion source and RFQ



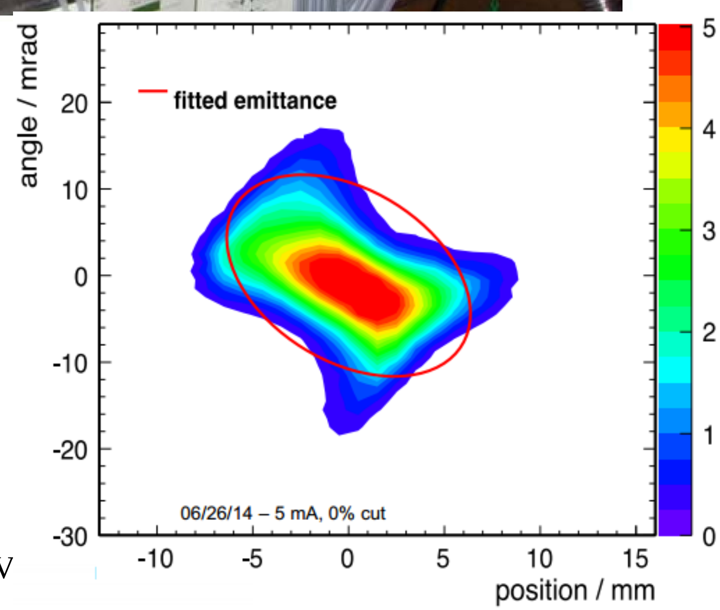


* See details in A. Shemyakin Poster THPP055

LEBT Status (continue)

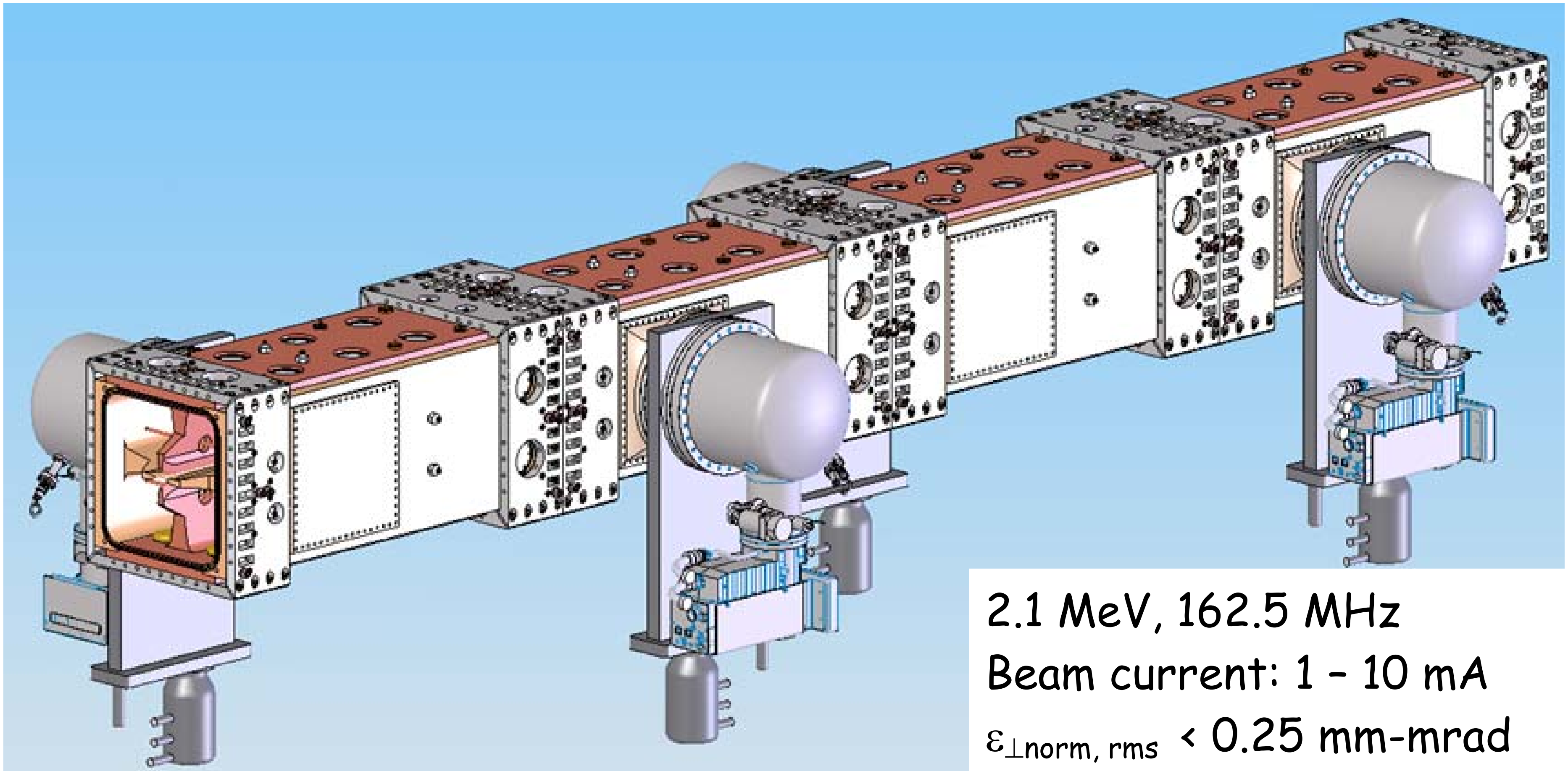


- Measured rms norm. emittances 0.1-0.15 mm mrad (I_b = 0-10 mA)
  - Non-Gaussian (truncated) tails
- LEBT to be ready by spring of 2015 when RFQ will arrive



RFQ Status

- RFQ is constructed in LBNL
  - It is expected to arrive in the spring of 2015
- RF power amplifiers are received and are being prepared for testing



2.1 MeV, 162.5 MHz

Beam current: 1 – 10 mA

$\varepsilon_{\perp norm,\ rms}$ < 0.25 mm-mrad

$\varepsilon_{\parallel norm,\ rms}$ = 0.8 – 1.0 keV-ns

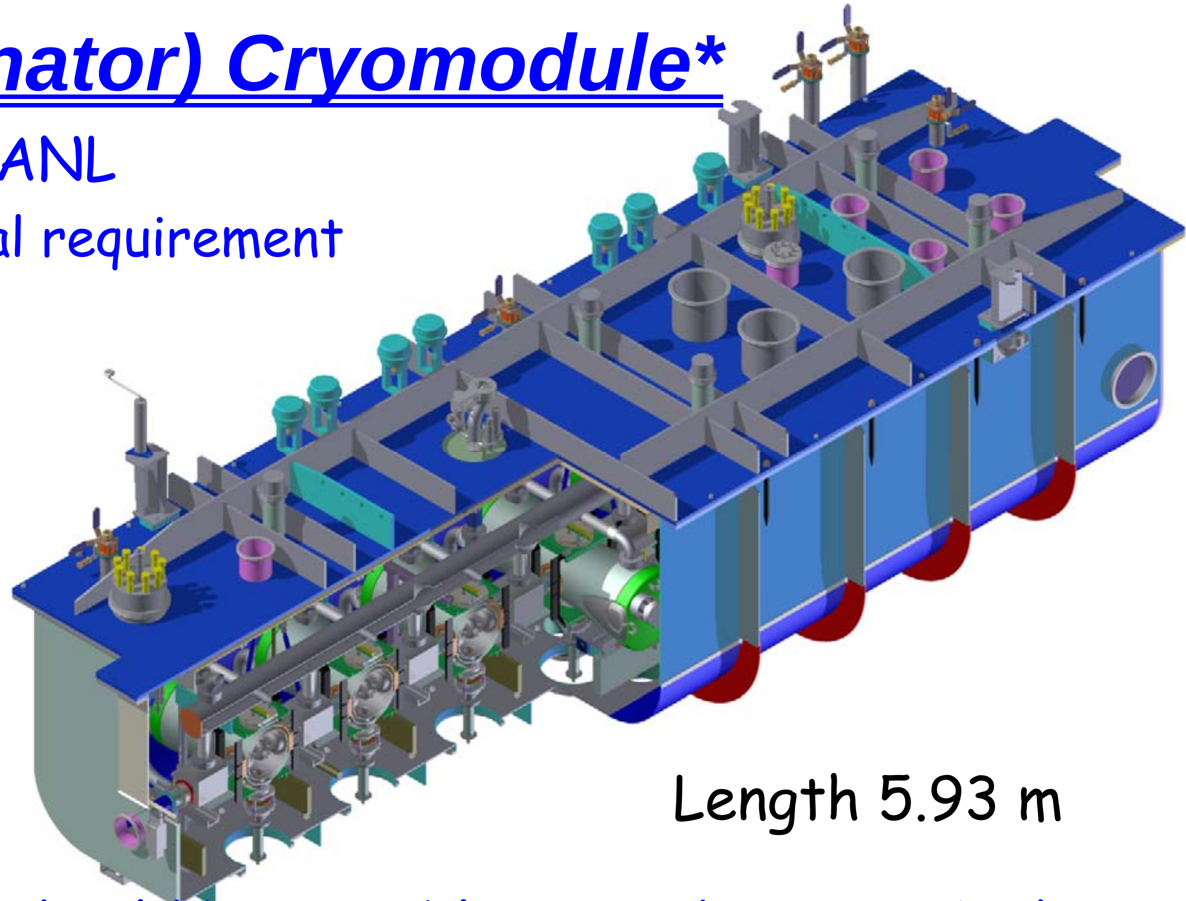
Length: ~4.4 m

MEBT

- Quads will be manufactured by Indian collaborators
  - Prototype is in Fermilab and is being tested
- RF cavities
  - Prototype is in manufacturing at HiTech (will be ready within 1-2 mo.)
- Bunch-by-bunch kicker
  - 50 Ω kicker:
    - built (1 plane of 2),
    - measured and power tested – results are good
    - will be ready for beam test by spring (2nd plane to be assembled)
  - 200 Ω kicker is a backup and is expected to follow shortly
- Shortened MEBT version will be prepared for RFQ tests by spring
  - Also tests for
    - MEBT beam absorber
    - bunch-by-bunch kicker
    - instrumentation
- Full length MEBT to be ready by arrival of SC cryomodules in 2017

HWR (Half-Wave Resonator) Cryomodule*

- Designed and being built by ANL
  - Has to Satisfy all functional requirement specifications (FRS) and Interface Document
  - ANL has considerable experience in building and using low-β cavities (ATLAS)



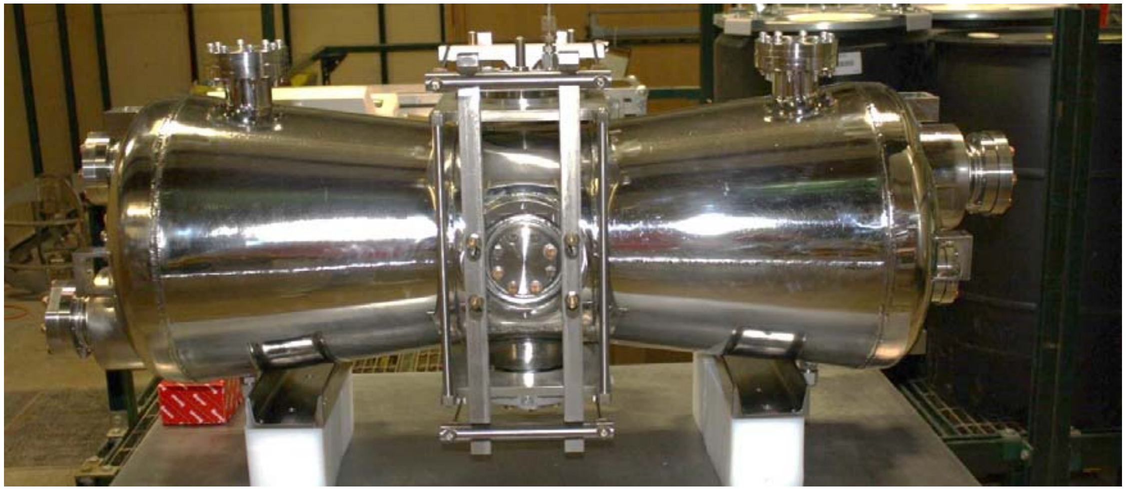
Length 5.93 m

- Compact lattice suitable for acceleration 10 mA beam in CW (higher current should be possible -> roadmap to ADS)
  - 8 SC solenoids, 8 half wave resonators (HWRs) and 8 BPMs
  - Novel design of HWRs: double conical structure
  - Advanced RF surface processing techniques
  - SC solenoid with steering coils in both focusing planes, no magnetic shielding is required
  - “Cold” Beam Position Monitors
  - Pressure controlled tuners

* See details in MOPP001, THPP001 (Z. Conway, *et al.*)

HWR: Recent Progress

- Cavities (β=0.11, ΔE=1.7 MeV, f=162.5 MHz)
  - 2 HWRs are manufactured. The first HWR cavity was tested at 2 K.
  - Key Nb fabrication technologies have been developed
  - First HWR is electropolished
  - 7 production cavities are in advanced stage of fabrication
  - Bare niobium cavities will be completed by the end of calendar year 2014
  - Helium vessels will be installed in all production cavities in one year

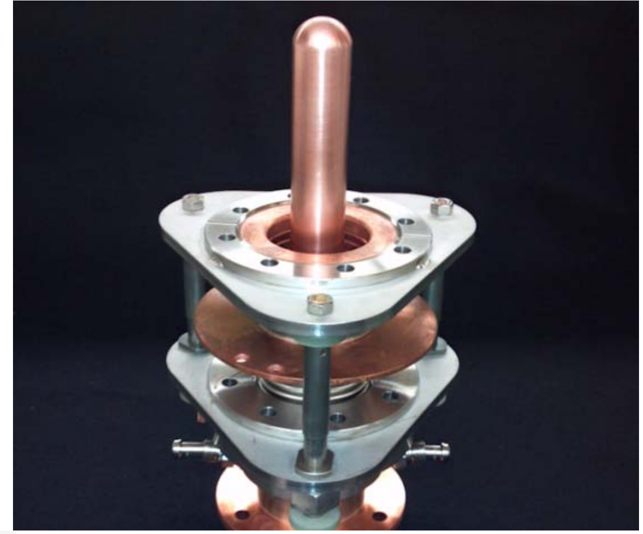


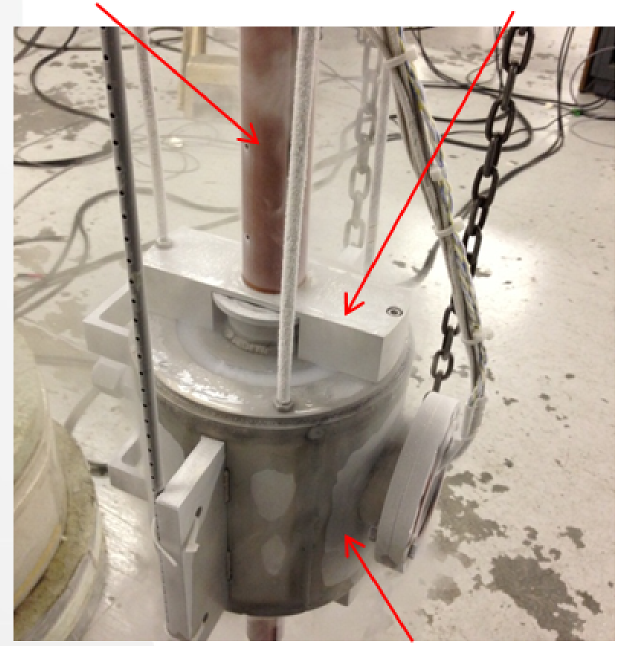
HWR1 with Slow Tuner (Apr.30.2014)

- Cryomodule design is complete
  - Detailed structural analysis has been performed, documented and reviewed by the ANL/FNAL technical and safety reviews
  - Detailed drawings for all components of cold mass are ready for procurement and fabrication
  - The cryostat vacuum vessel is being fabricated at Meyer Tool

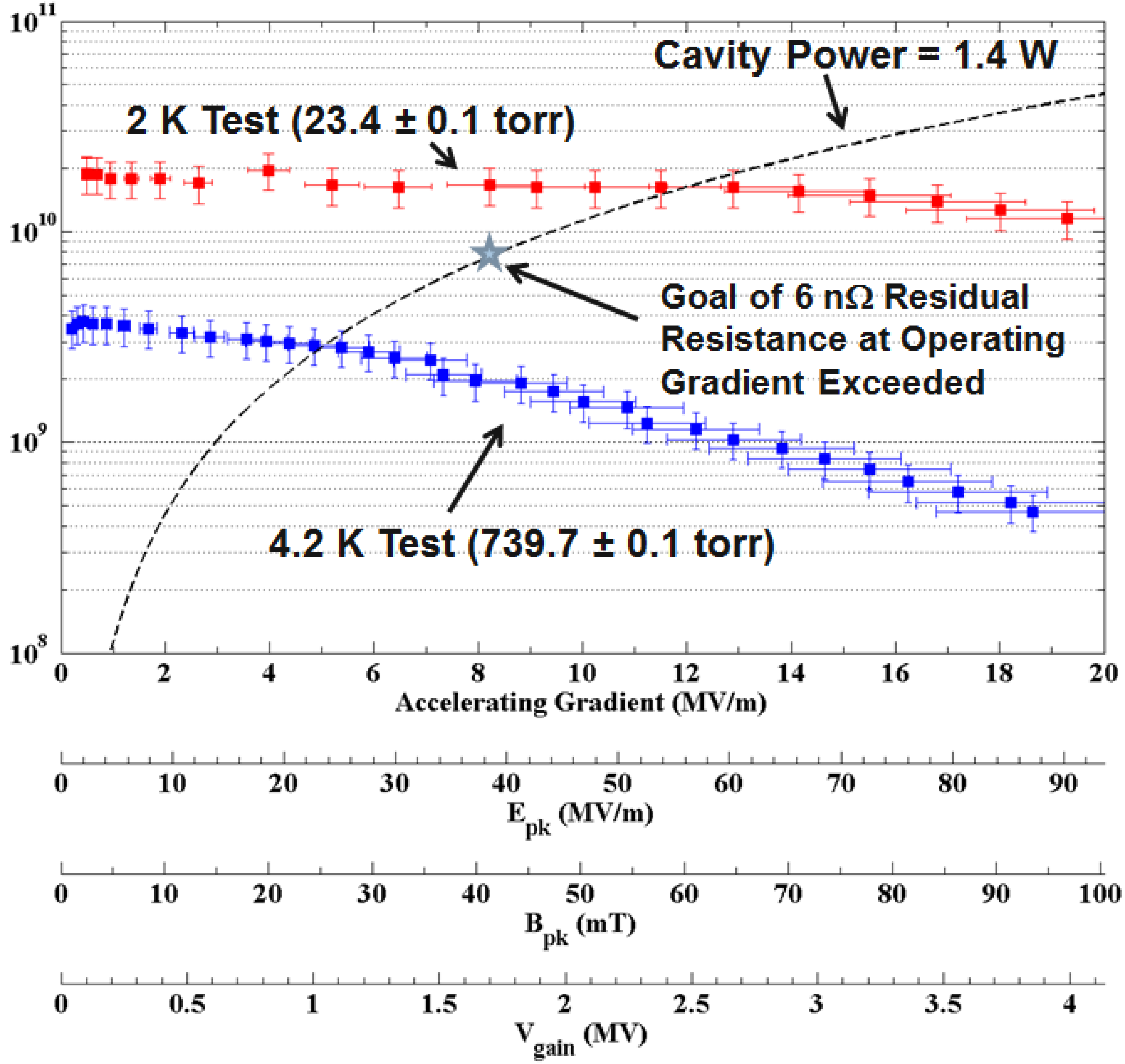
HWR: Recent Progress (1)

- 10-kW RF coupler cold testing up to 9 kW at 162.5 MHz RF power has been performed
  - No multipacting was observed in full reflection regime in the power range of 0 - 9 kW
- Prototype solenoid has been built and tested
- Beam Position Monitor
  - Prototype fabrication complete and RF testing demonstrated the design performance
- Delivery of the cryomodule to FNAL in 2017 is realistic (if funding is provided)





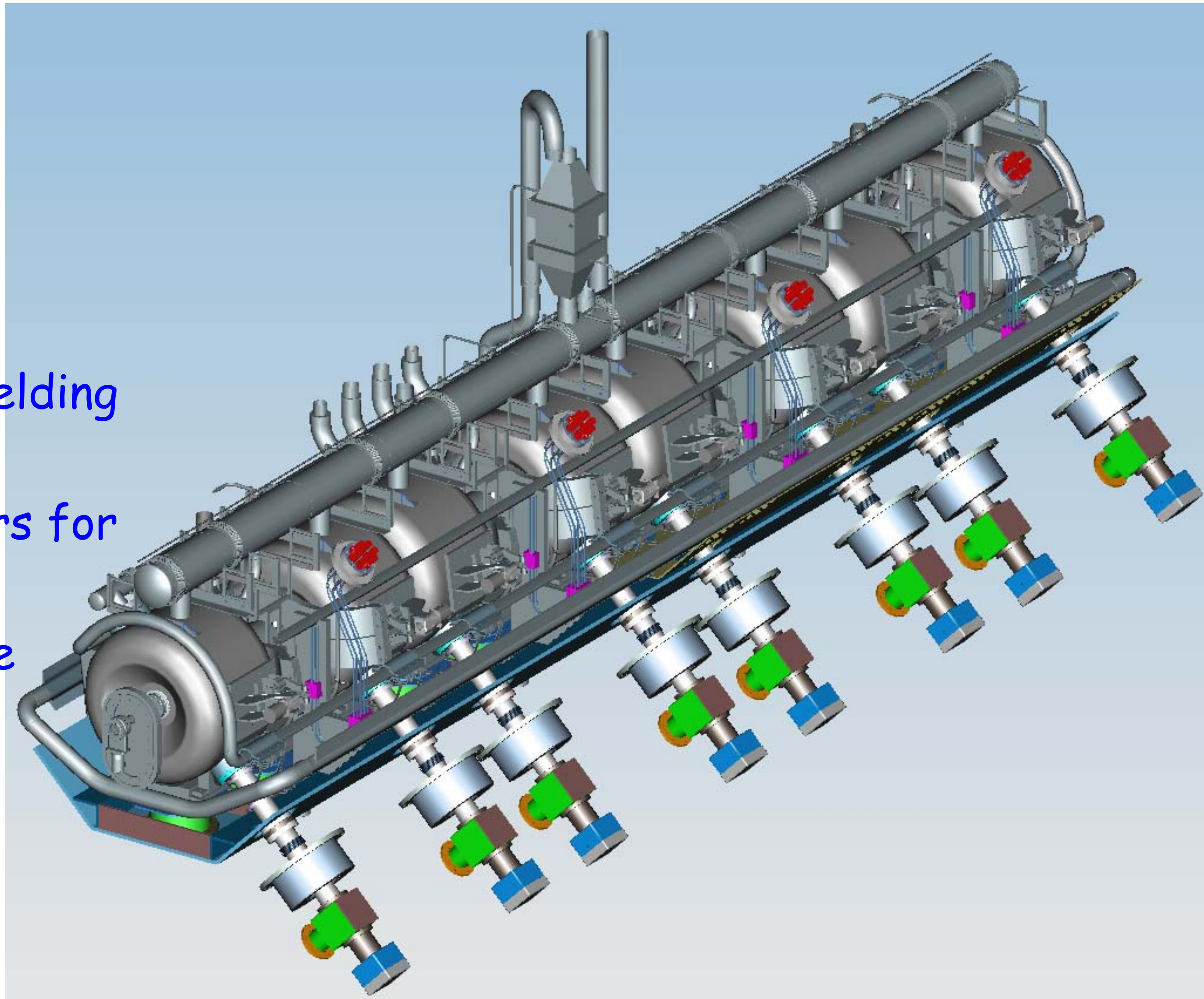
HWR: First Cold Test Result



No X-rays for E_{peak} < 72 MV/m.

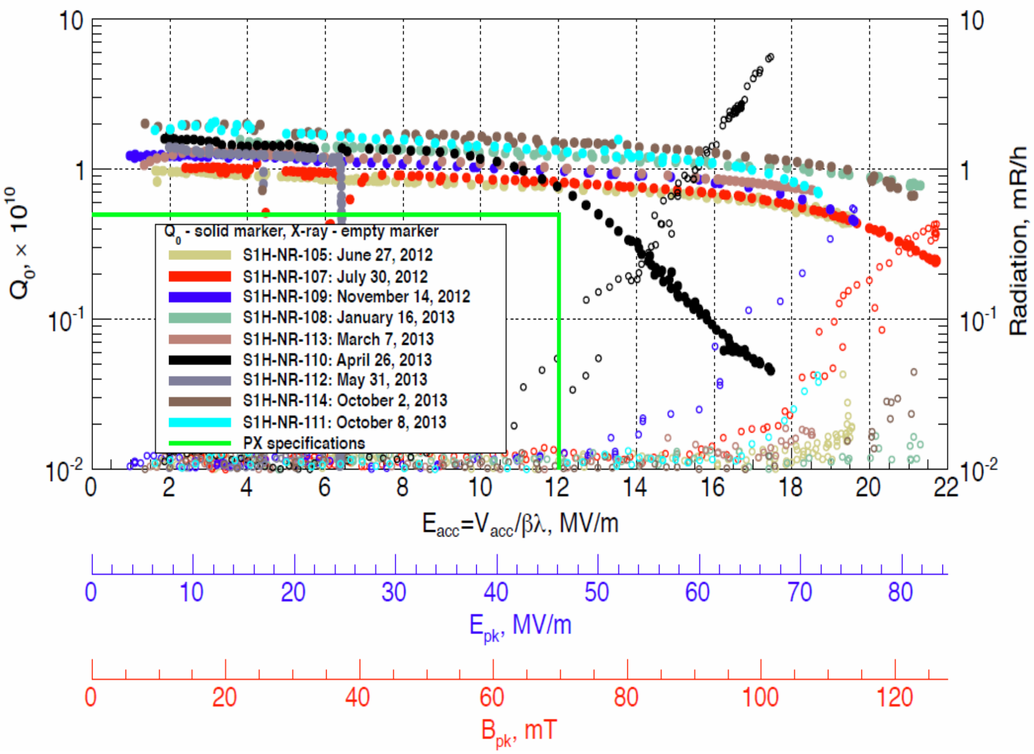
SSR1 Cryomodule

- Designed and being built by Fermilab
- Compact lattice to support acceleration 10 mA peak current (up to 5 mA average)
  Structure: **4 x (csc)**
  - 8 SSR1 cavities
  - 4 SC solenoids,
    - bucking coils: no magnetic shielding
    - steering coils: dipole correctors for both planes & skew-quadrupole
  - 4 BPMs (same as in HWRs)



SSR1: Recent Progress

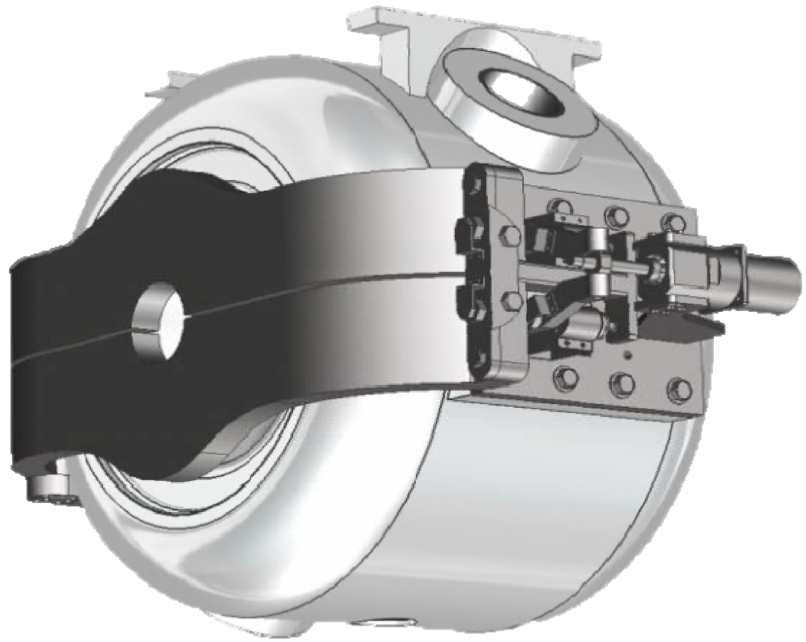
- 10 SSR1 cavities are manufactured (325 MHz)
  - 9 of them are processed, tested and qualified;
  - expect to receive 2 prototype SSR1 cavities from India this year
- New He vessel with reduced df/dP is designed,
  - one SSR1 cavity is dressed.
- RF coupler design is completed, 3 couplers are manufactured, 2 couplers are tested at operational power.
- Tuner design is in progress;
- Solenoid design is completed,
  - 1-st solenoid is manufactured and is tested.
- CM conceptual design is ready
  - main parts (vacuum vessel, strong back and supports) are ordered.



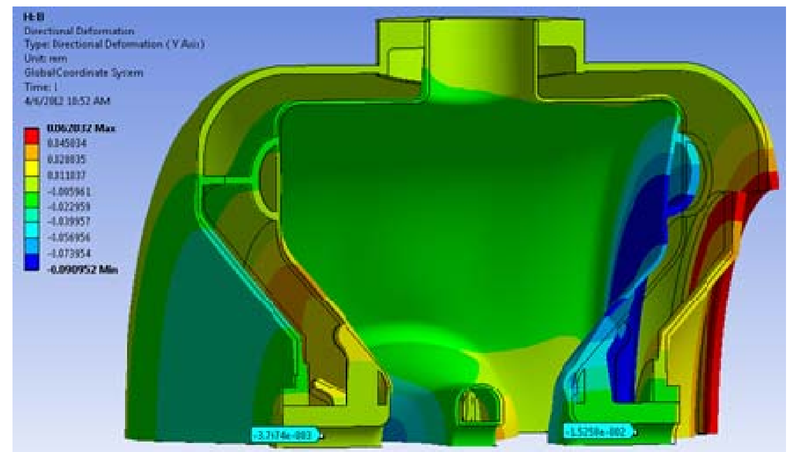
- Performance at 2K° is above PIP-II requirements in both Q_0 & G

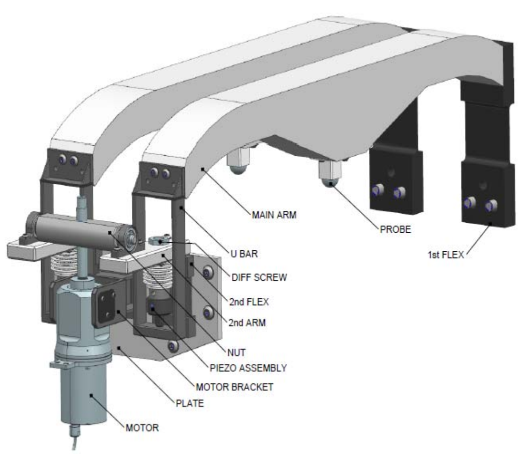
SSR1: Cavity Design

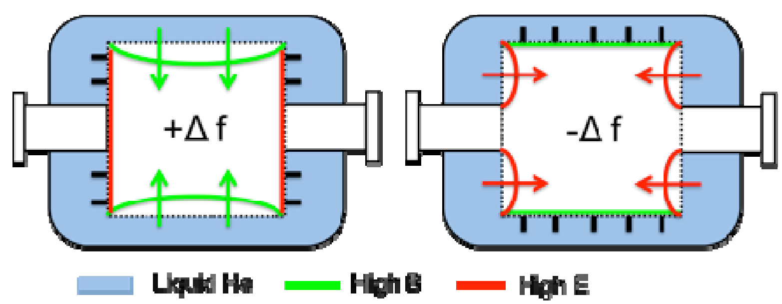
- Cavities (β=0.22, ΔE=2.05 MeV, f=325 MHz, r_{aper}=30 mm)
  - LHe pressure can vary by ± 0.1 Torr
  - For 2 mA current the SSR1 must operate with a small bandwidth of 90 Hz
  - A self-compensating design reduces pressure sensitivity
    - Despite non-negligible deformations (see picture), net shift is very low
      - Bare cavity ~ 600 Hz/Torr,
      - with He vessel < 10 Hz/Torr (meas.)
    - Ease of tuning: 39 N/kHz (bare), 40 N/kHz (with He vessel)
  - Lever tuner
    - Fast piezo (range 1 kHz) and slow (range 135 kHz) tuners are connected serially



Dressed SSR1 with tuner

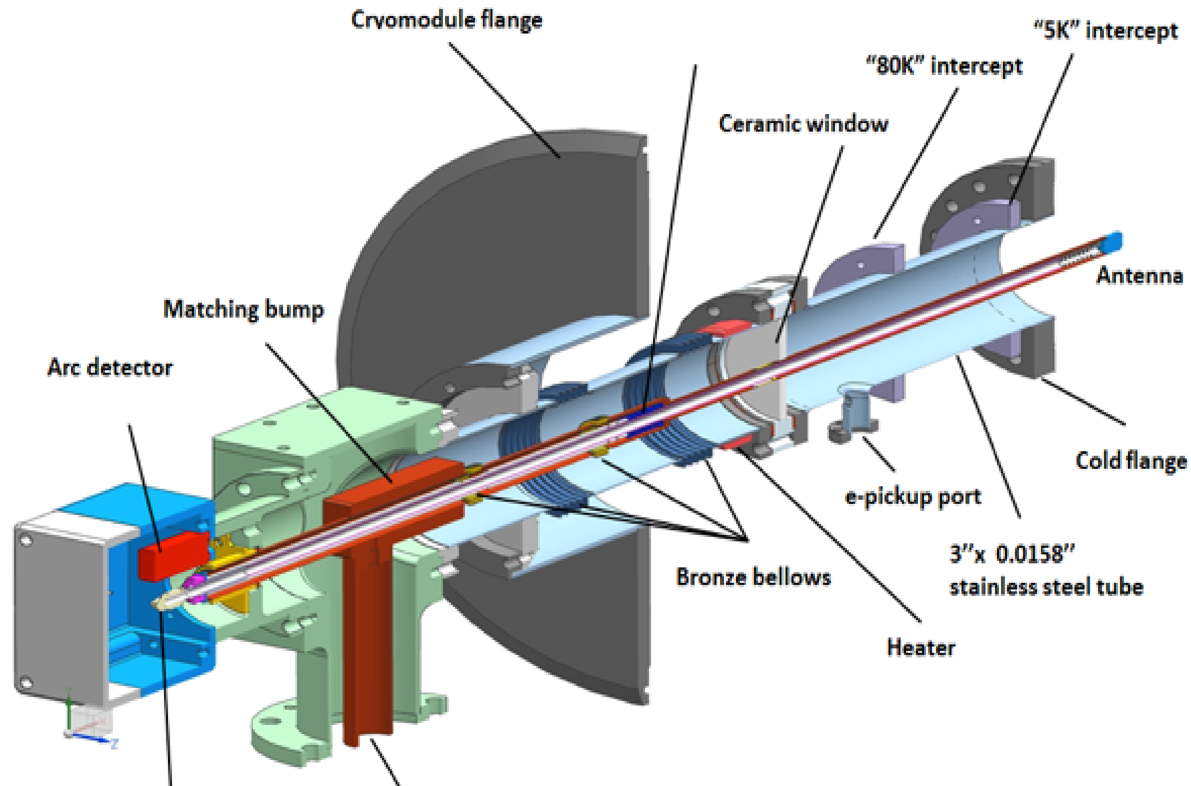


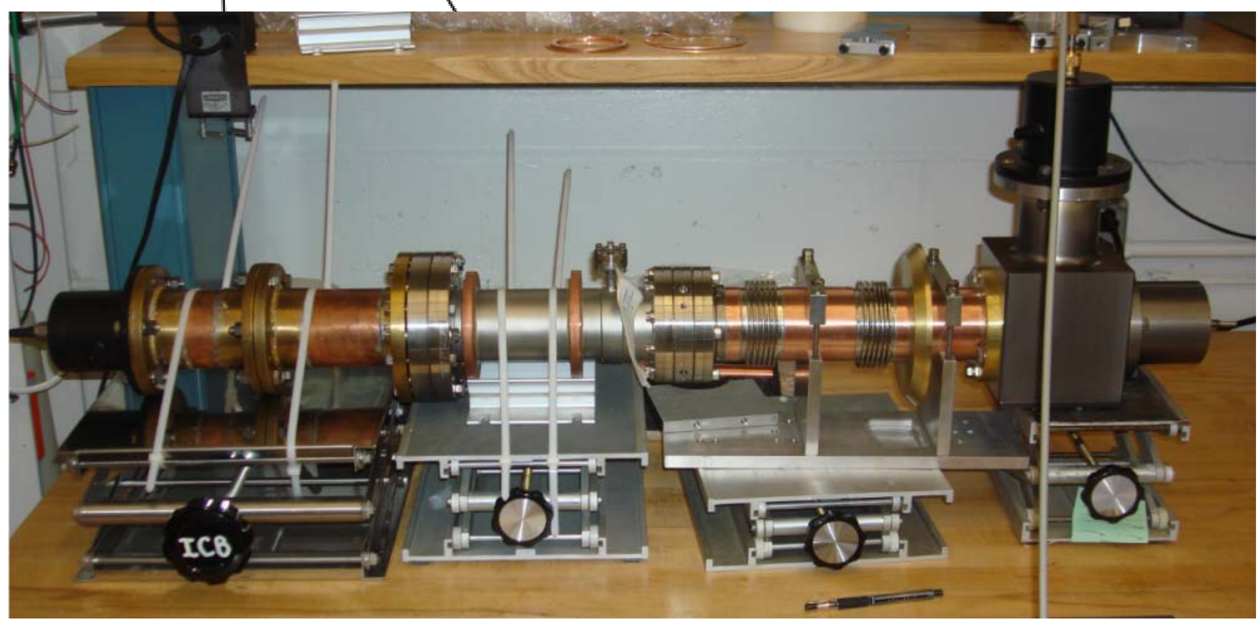




SSR1: Couplers

- The coupler is designed for 30 kW traveling wave at full reflection
- Three couplers are manufactured, measured and tested
  - reflection -22 dB at 325 MHz.
- High power tests started





Elliptic Cryomodules: Low-beta(LB) & High-beta(HB)

- Electro-dynamical cavity design is complete
  - Mechanical design is initiated
    - Reduced sensitivity to helium pressure fluctuations (df/dP) and LFD (Lorentz Force Detuning) are the main challenges
- A number of prototype cavities (1- & 5-cell) were produced & tested
- FRS's for cryomodules and their components are written and have to be signed within month
- Conservative approach for Q_0: HWR & SSR1 - 5×10^9, SSR2- 1.2×10^{10}, LB650 - 1.5×10^{10} HB650 - 2×10^{10}
  - High Q_0 program has delivered extremely promising results*
    - More than two times Q_0 increase in vertical test
    - The goal is to transfer Q_0 increase to operation in a cryomodule
- High-Order Modes
  - HOM damper - vulnerable, expensive and complicated part
  - Analysis of resonance excitation of HOMs, collective effects, cryo-losses and emittance dilution shows that reliable operation can be obtained without HOM dampers for all present and possible future operating scenarios
  - We do not plane use HOM dampers in cavities

* Details in A. Romanenko talk, "Breakthrough technology for very high quality factors in SCRF cavities"

Microphonics in PIP-II Cavities

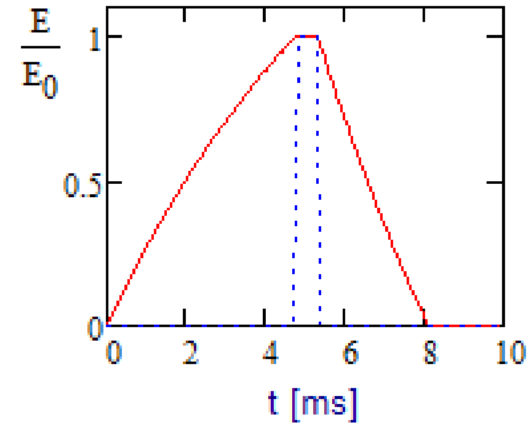
- Low beam loading (2 mA) ⇒ narrow cavity bandwidth ⇒ microphonics issues
- Microphonics Control Strategies
  - Sufficient RF power reserve to compensate for the expected peak detuning levels.
  - Good regulation of the LHe bath pressure to minimize the magnitude of cyclic variations and transients.
  - Reduced sensitivity of resonant frequency to helium pressure
  - Minimizing the acoustic energy transmitted to the cavity by external vibration sources.
  - Active damping of cavity vibrations with fast tuner driven by feedback from measurements of RF voltage and power.
  - LFD is an additional issue for pulsed operation. R&D is in progress

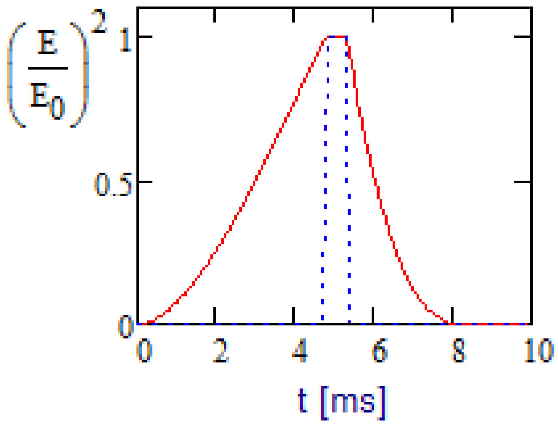
Bandwidth and required power optimized for CW (2 mA)

Section	Freq. f_0 (MHz)	Maximal detune (peak Hz)	Minimal Half Bandwidth, $f_0/2Q$(Hz)	Max Required Power (kW)
HWR	162.5	20	34	4.8
SSR1	325	20	45	5.3
SSR2	325	20	27	17.0
LB650	650	20	29	33.0
HB650	650	20	31	48.5

PIP-II Duty Factors

- The average RF power has 2 contributions:
  - the energy transferred to the beam (~10%)
  - the energy required to fill and discharge the accelerating cavities (90%)
    - It does not depend on the peak RF power
- For a fixed average power the cost of RF increases with peak power
  - therefore its cost achieves minimum with minimum peak power
  - i.e. power equal to the power required for beam acceleration => duty factor for the RF power amplifiers ≈15%
  - In this case the cost savings associated with the pulsed power amplifiers is modest and therefore CW capable RF amplifiers are planned from the beginning





PIP-II Cryogenics

- Cost minimization => reusing existing Tevatron cryogenics
  - including: (1) Central Helium Liquefier, (2) transfer line & (3) compressors
- Cryogenic duty factor is ~6.6%
- The total cryogenic heat load at 2K is dominated by the static load, and is about 17% of the CW load
- Future upgrade to CW operation would require a new 2K cryogenic plant

		Static Load per CM [W]			Dynamic Load per CM [W]	
Type	# of CM	70 K	5 K	2 K	2 K CW	2 K Pulsed, 5%DF
HWR	1	250	60	14	10	10*
SSR1	2	195	70	16	11	11*
SSR2	7	145	50	8.8	43	2.8
LB 650	10	85	25	5	73	4.8
HB 650	4	120	30	6.2	147	9.7
Total		**2985**	**920**	**182**	**1651**	**138**
Cryo-plant		**5720**	**1250**	**490 (margin of 1.5 times)**		

National and International Partnerships

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

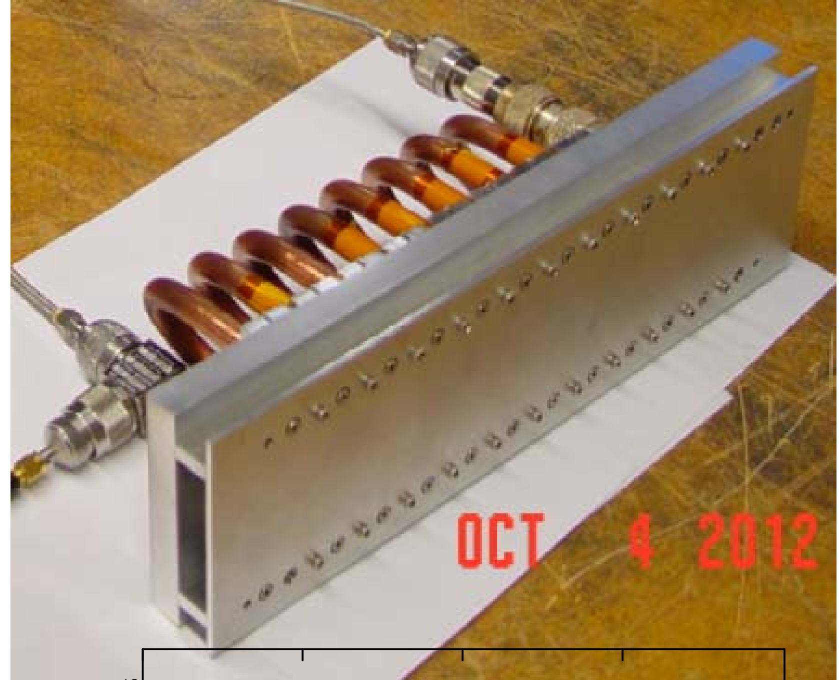
Conclusions

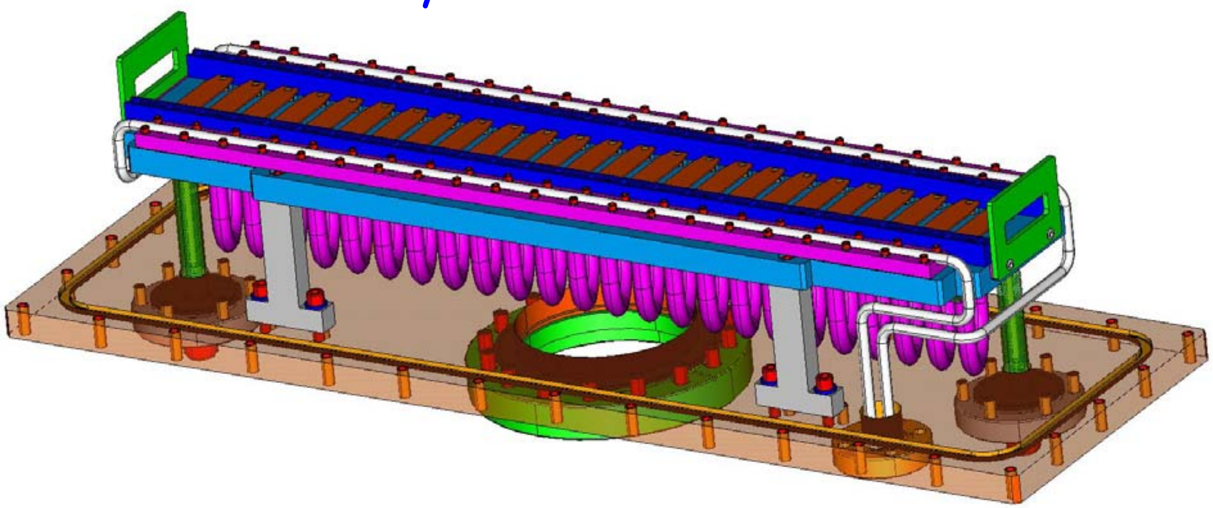
- Strong endorsement of PIP-II in the P5 Report
  - **Recommendation 14:** Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIPII) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.
- Proton Improvement Plan-II supports long term physics research goals by
  - providing increased beam power to LBNE
  - and setting a platform for the future
- PIP-II is in the pre-CD-0 status
  - However, it has strong support from P5, OHEP, and Fermilab director
  - Plan presented to P5 and DOE proposes five year construction period starting in FY2019

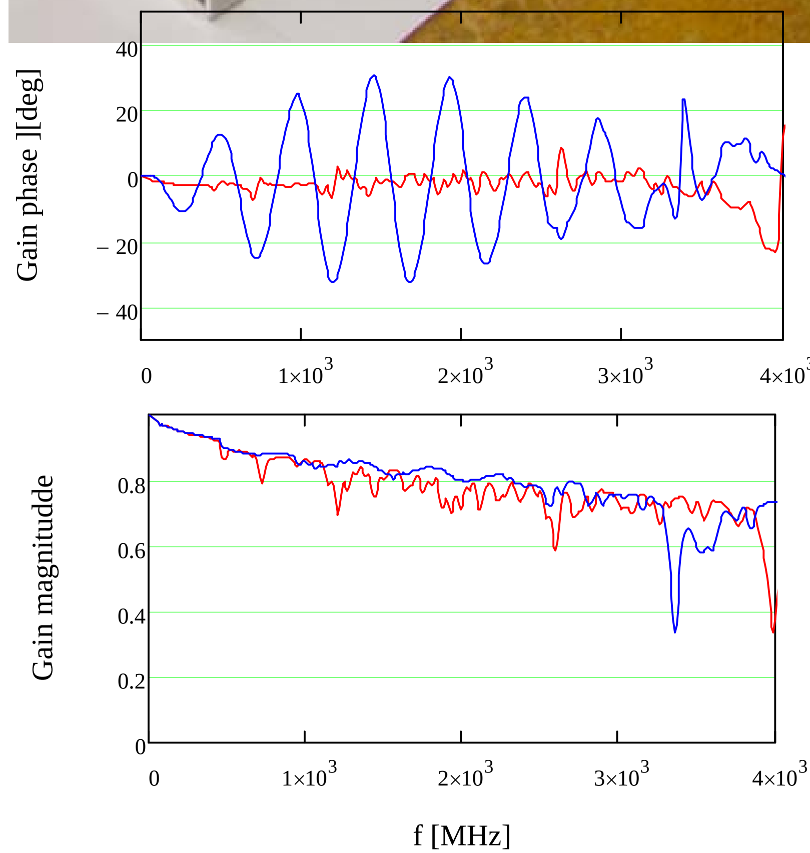
Backup Slides

Bunch-by-Bunch Kicker

- Analysis left only 2 choices
  - Both are based on a helical structure which has a smaller dispersion than a meander based structure
    - 1: Cable connected plates, 50 Ω, bipolar, ±250 V, powered by linear amplifier
    - 2: Helical structure with plates, 200 Ω, 500 V, powered by unipolar fast switch
  - A kicker prototype of the 1-st choice has higher priority and is expected to be ready for tests in the fall



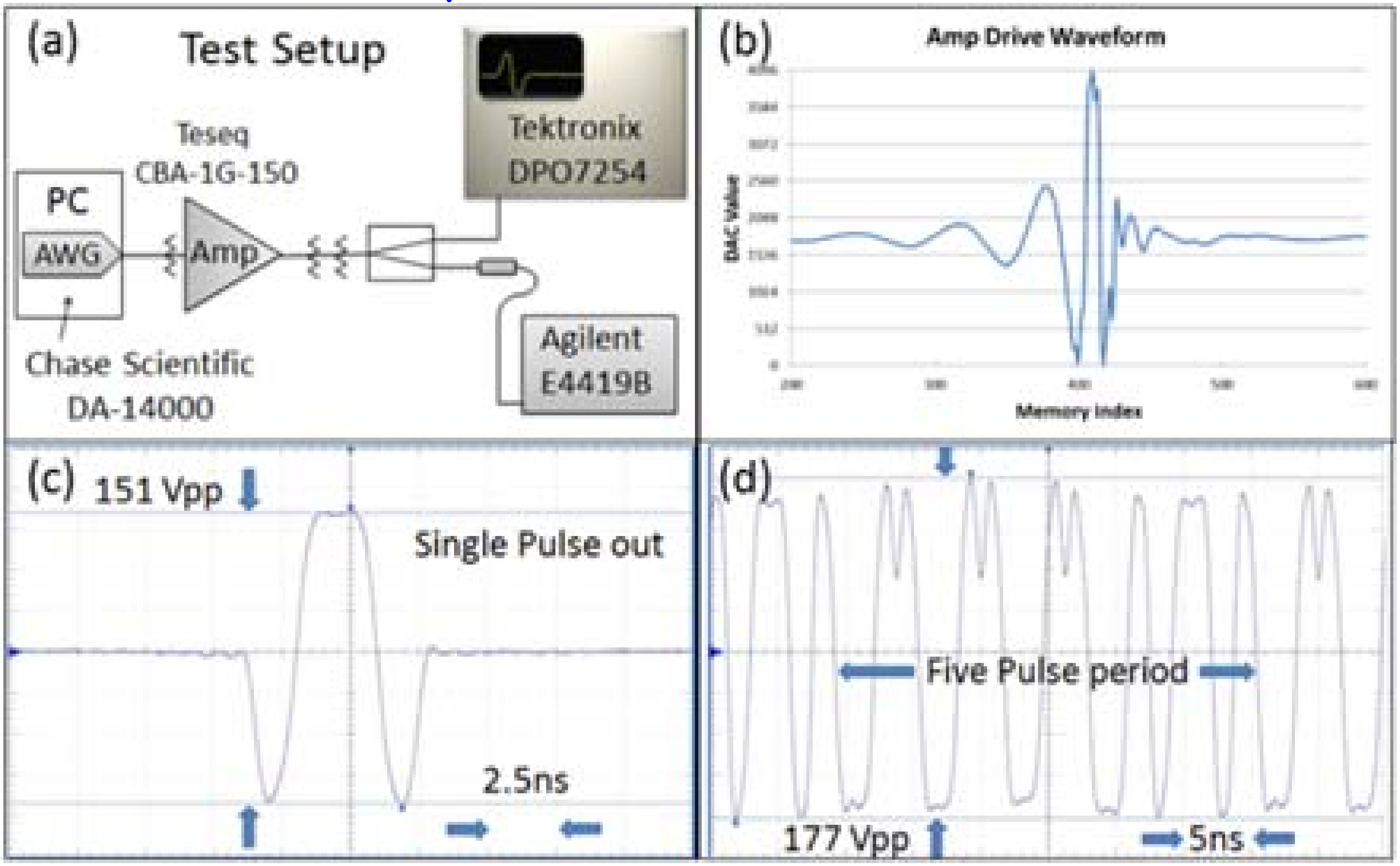




Comparison of meander with helical connections for 6 electrodes

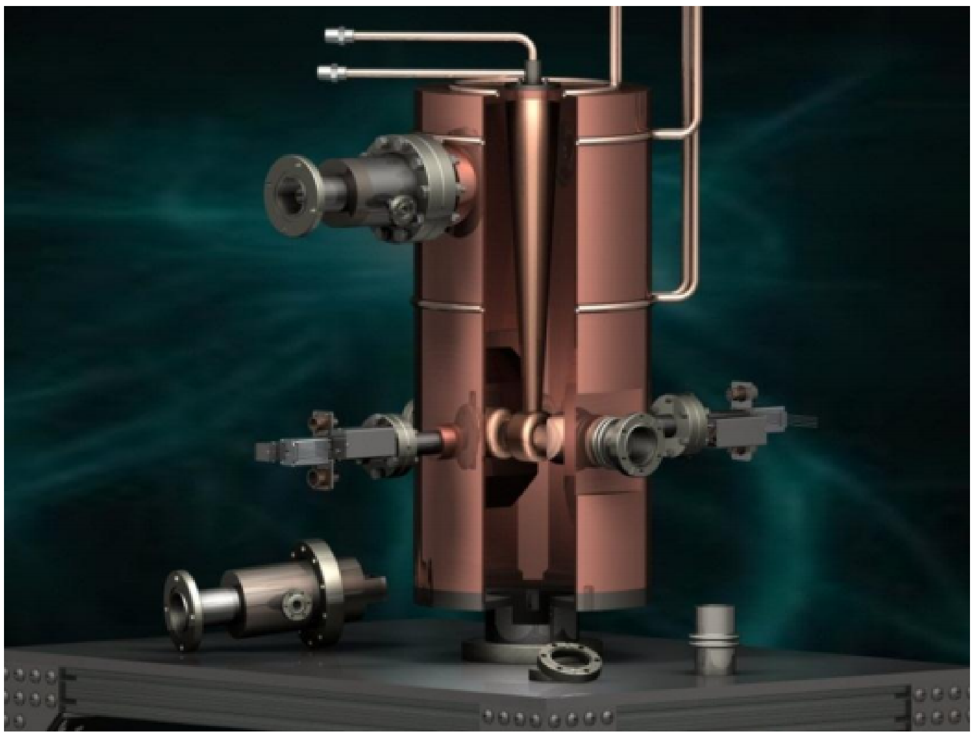
Pulser for 50 Ω Bunch-by-Bunch Kicker

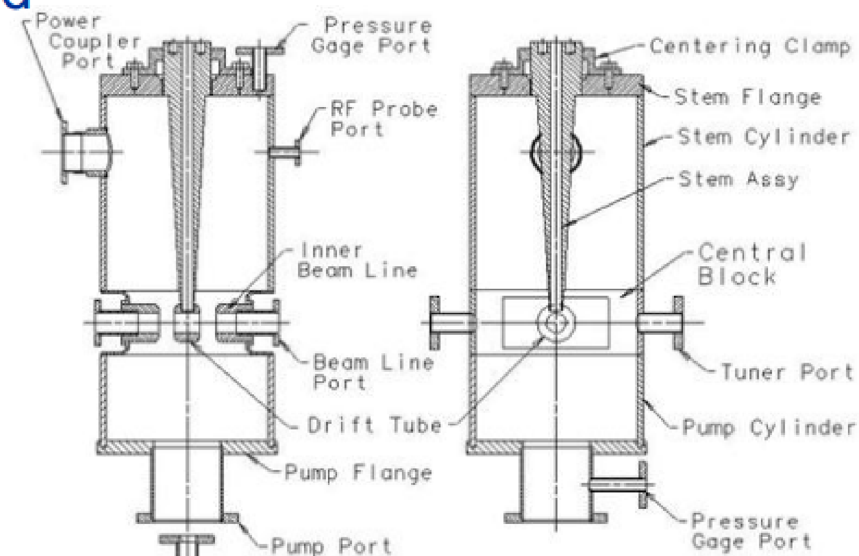
- Pulse predistortion creates "perfect" pulses at amplifier output
- Tests were carried out with Teseq 150 W amplifier
  - Teseq 1 kW amplifier has similar gain dependence on frequency
- Tests of kicker and pulser assured us that the solution is found

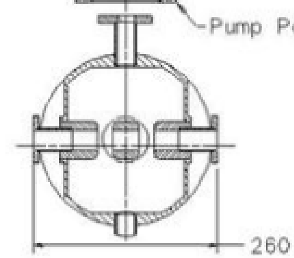


MEBT Bunching Cavities

- 3 normal conducting cavities are required for beam transport through MEBT and longitudinal matching
  - Conceptual design is done
  - Production drawings are being prepared
  - Tests of the prototype cavity are to be completed by Mar-2014







Frequency	162.5 MHz
Max voltage	100 kV
Gap	2x23 mm
Max power loss	1.5 kW

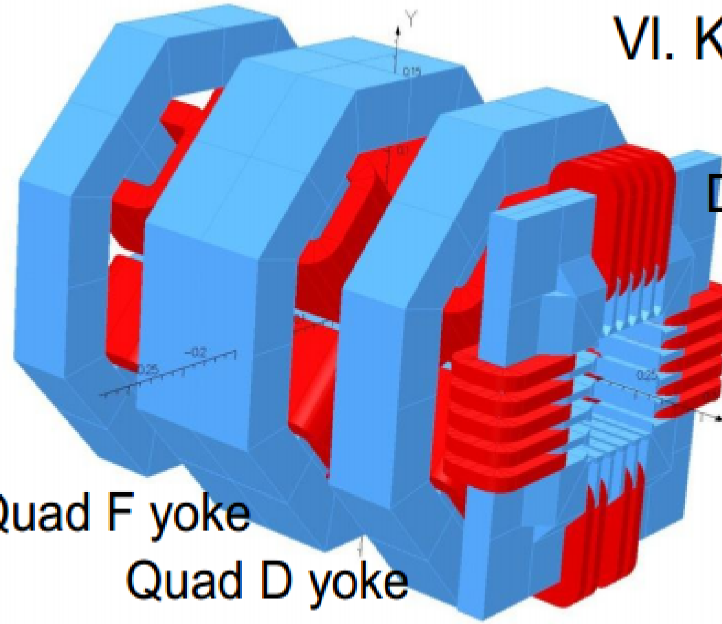
Couplers and tuners from HINS

G. Romanov, I. Gonin, T. Khabiboulline, M. Chen,, J. Coghill, I. Terechkine

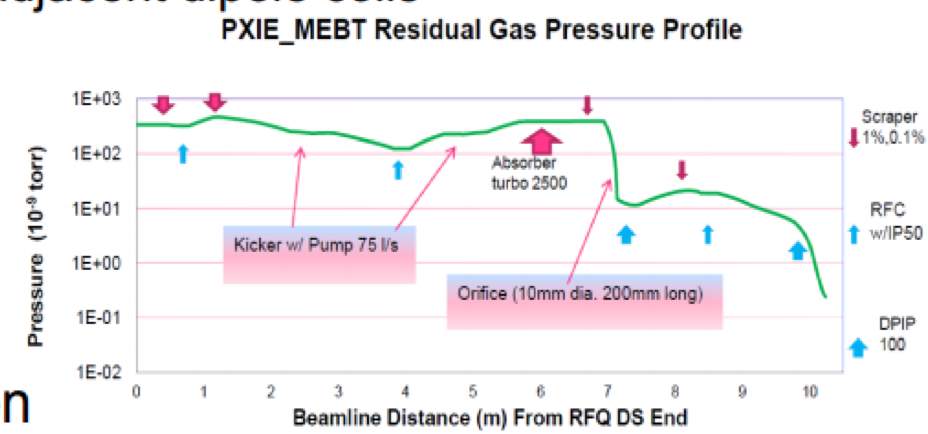
Other MEBT subsystems

- Quadrupoles/ dipole correctors
  - Magnetic design is done
  - Possible collaboration with India for production
  - Prototype quadrupoles and correctors are to be tested by Oct-2013
- Vacuum system – concept
  - Design to be completed by Sep-2015
- Diagnostics, machine protection systems, controls, infrastructure
  - Discussions

Vl. Kashikhin

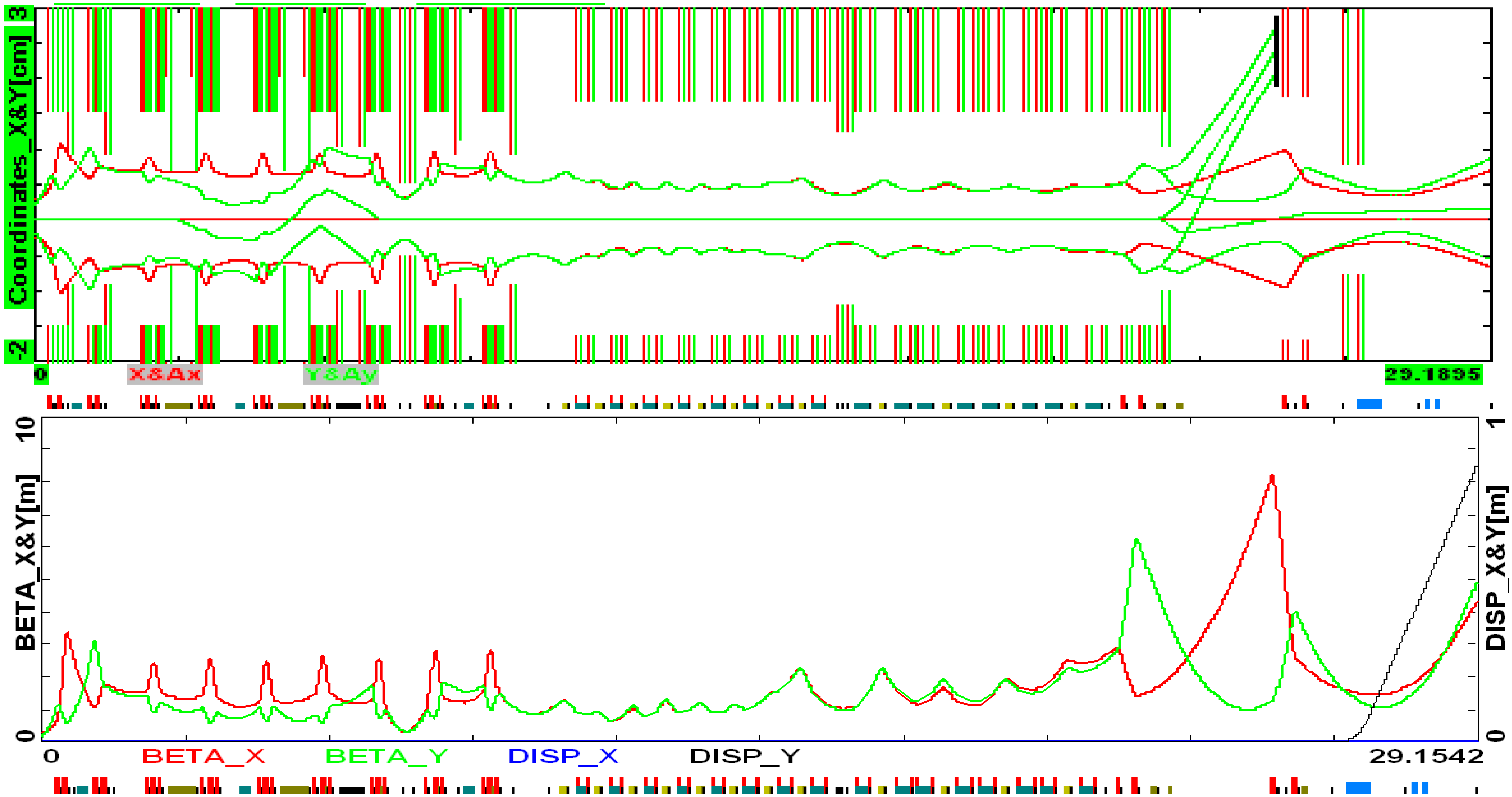


Simulation geometry of the triplet with adjacent dipole coils



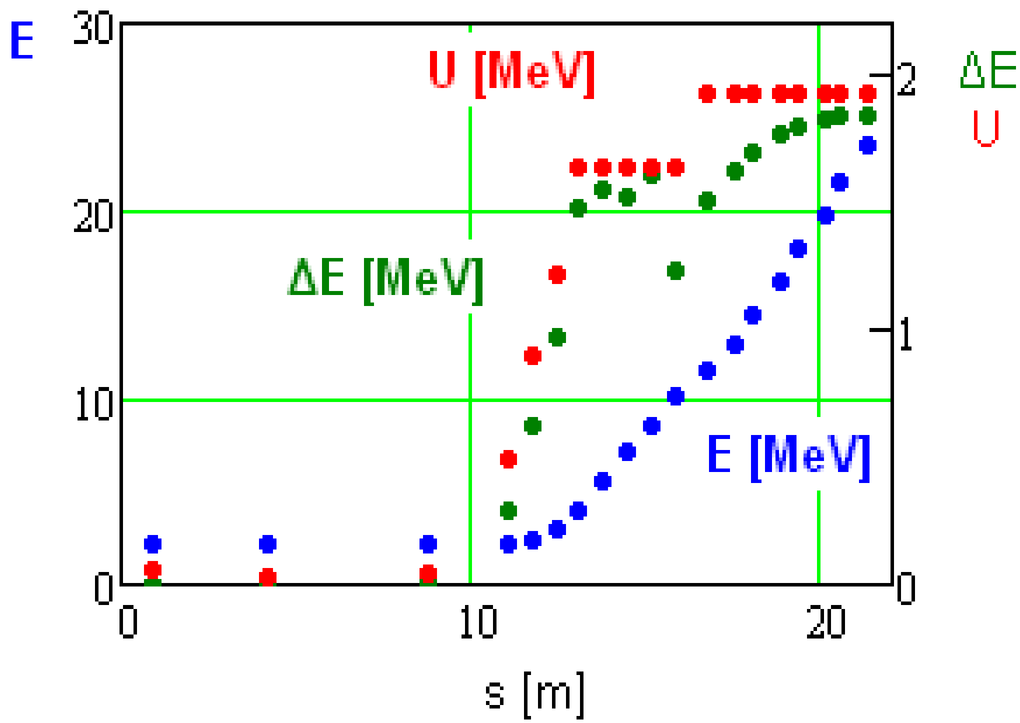
A.Chen

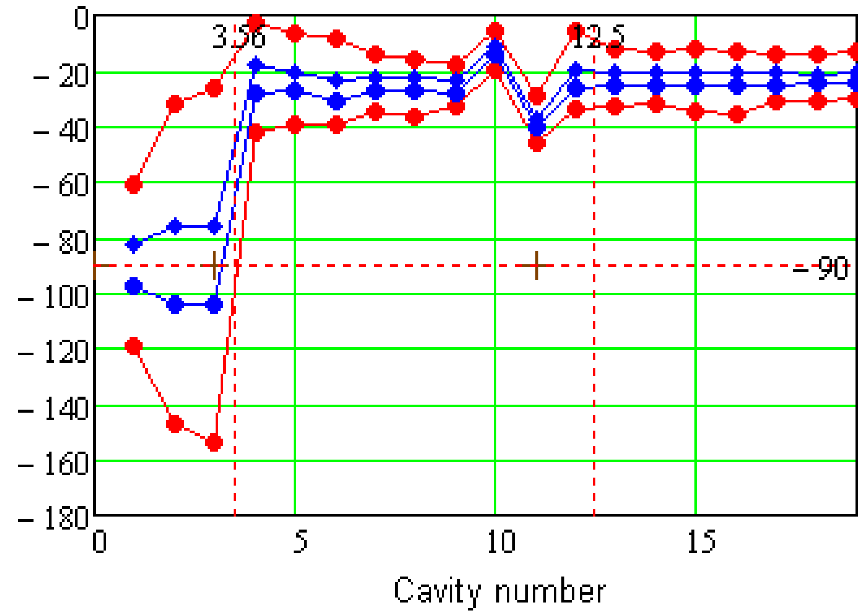
PXIE Optics and HEBT



- HEBT
  - RF separation for beam extinction studies, f=1.5*162.5 = 243.75 MHz
    - Can help in measurements of bunch length and longitudinal tails
  - Magnetic spectrometer (20 deg. bend)
    - 50 KW beam dump can support operation with 2 mA * 25 MeV

Acceleration in SC Cryomodules



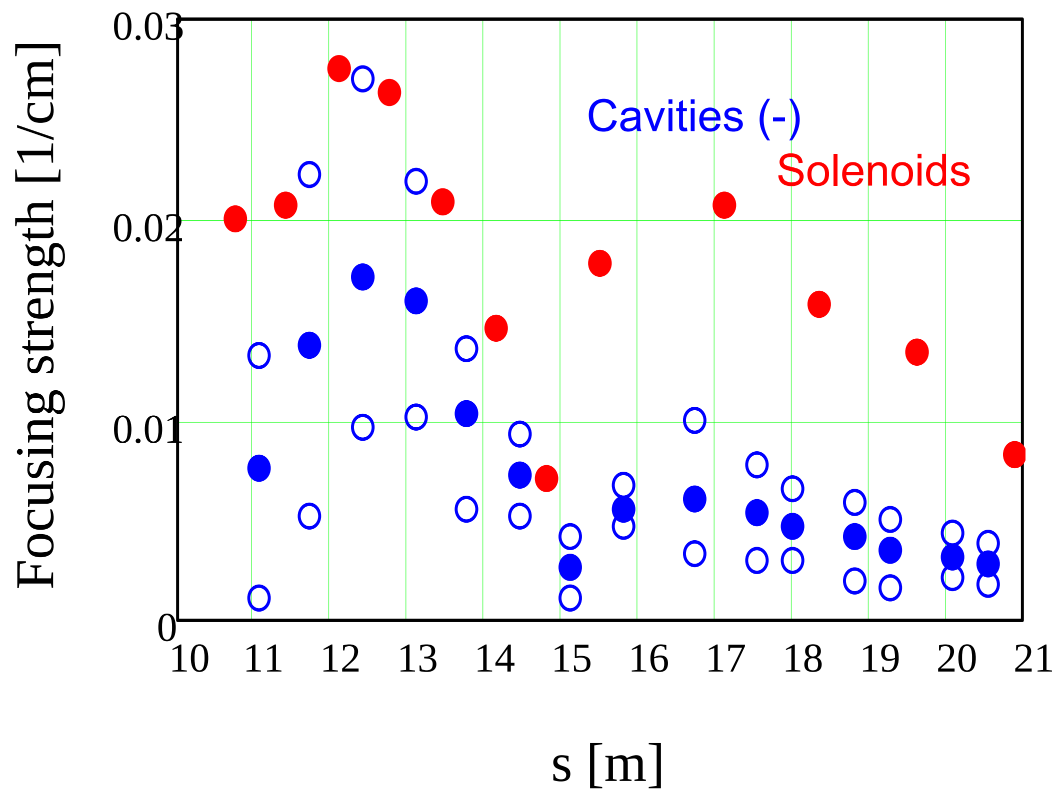


1σ and 4σ bunch ends relative to the accelerating phase [deg]

- Accelerating gradient of the first few SC cavities is reduced due to longitudinal overfocusing
- Design operating gradients
  - HW - 1.7 MV/cavity; SSR1 - 2 MV/cavity
- To support good reproducibility of longitudinal machine optics the accuracies of RF voltage and phase should be within 0.3% and ~0.3 deg. That corresponds to the rms fluctuations of 0.1% and 0.1 deg.

Limitations on Focusing in Cryomodules

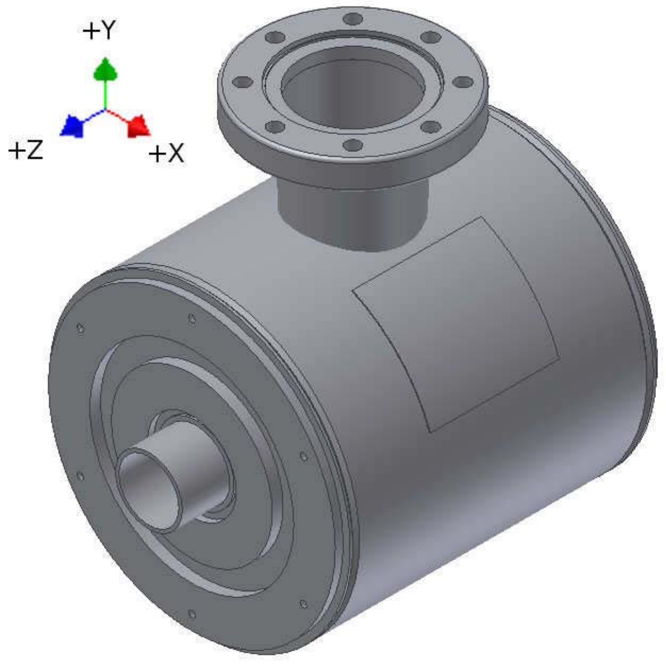
- Strong phase dependent defocusing in SC cavities
  - One cavity per solenoid in HW
- Focusing of solenoids should be large enough to mitigate dependence of focusing on synchrotron phase
- Effect is rapidly reduced with energy
  - Two cavities per solenoid in SSR1

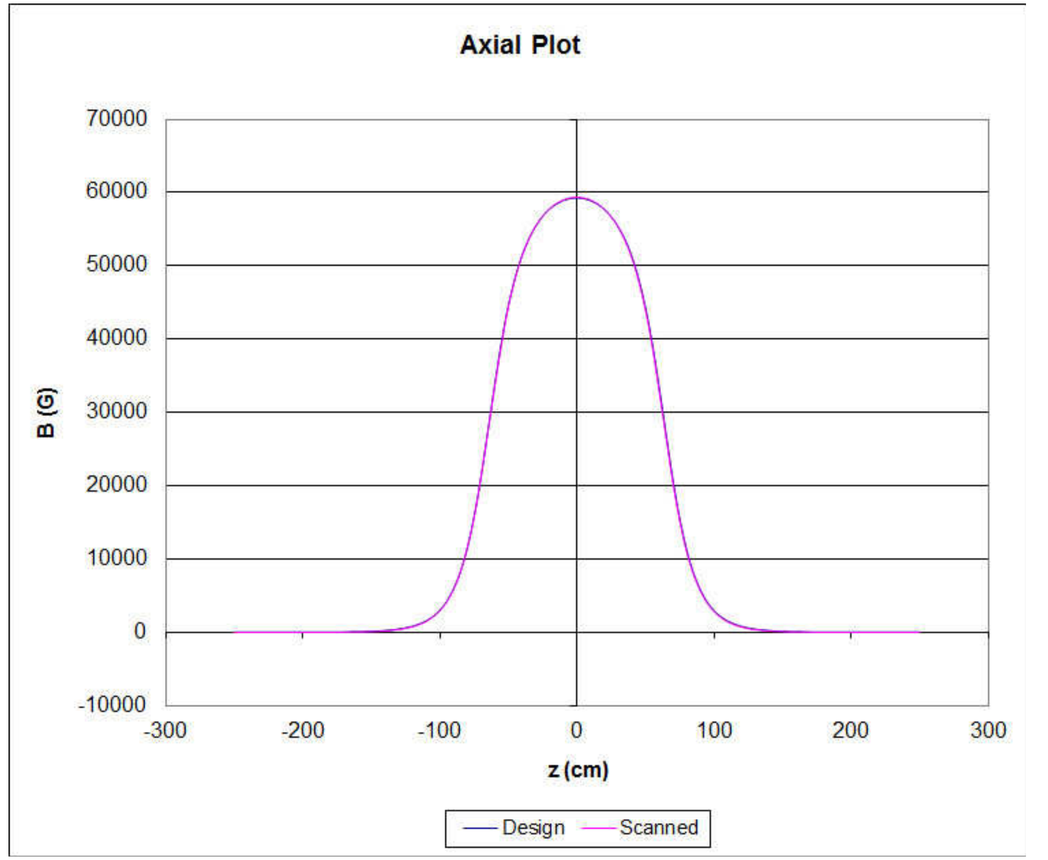


Focusing strength of solenoids (red) and nearby SC cavities for the reference particle (solid blue) and ±4s longitudinal bunch ends. Sign of the *cavity focusing is changed from negative to positive.*

HWR Solenoid

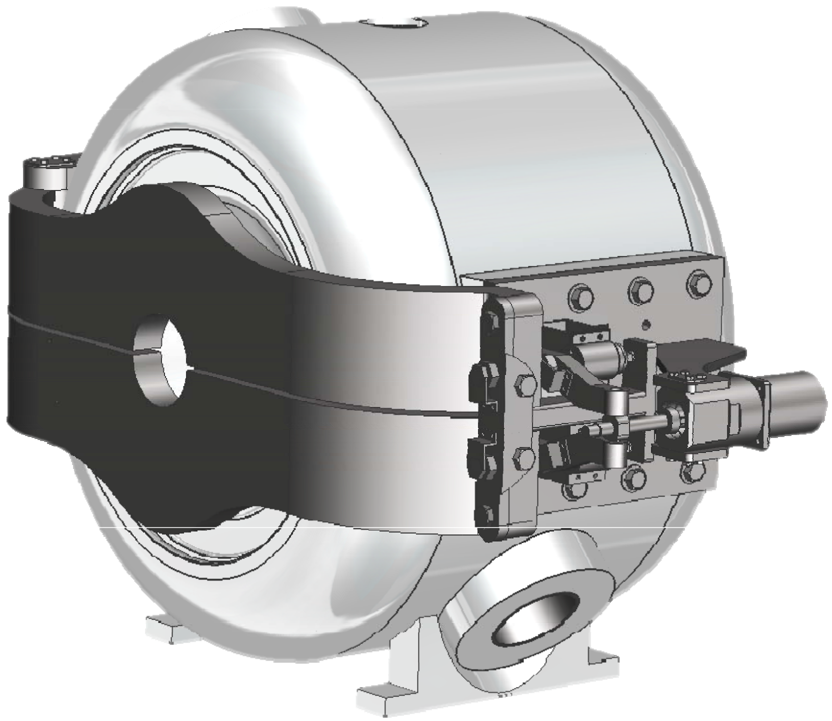
- Designed and manufactured by Cryomagnetic

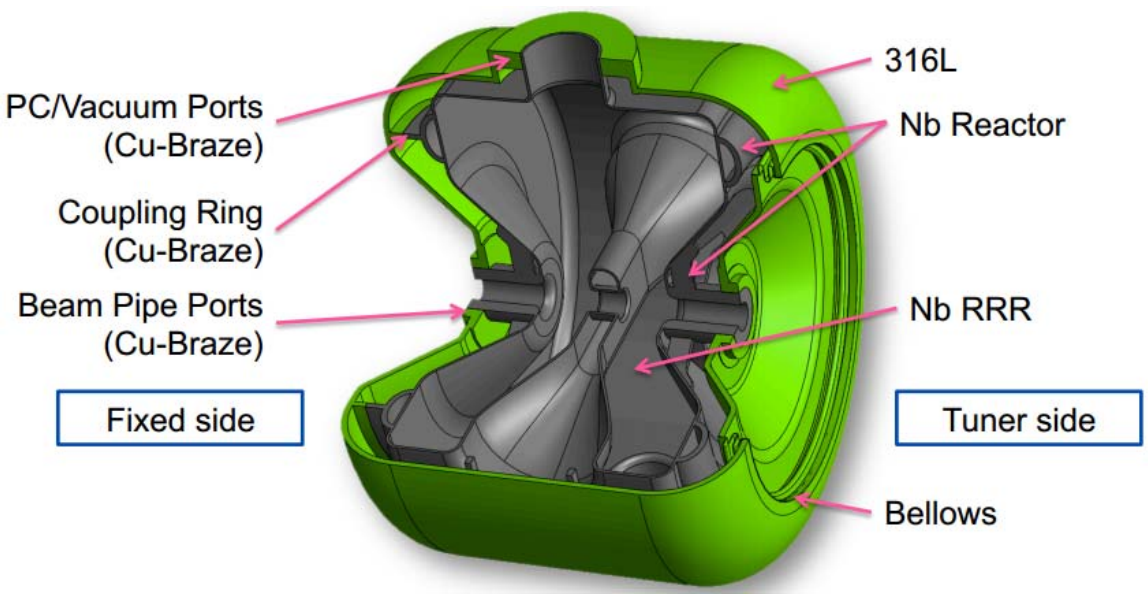


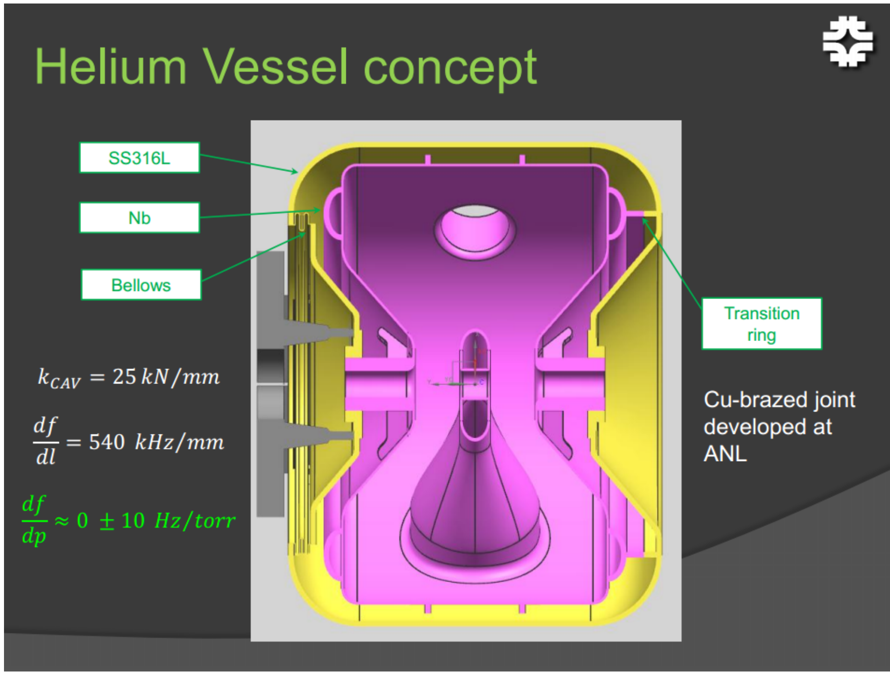


SSR1 Cavity

- Slow (mechanical) and fast (piezo) tuners
- Cryovessel is designed to suppress helium pressure fluctuations (<25 Hz/torr)
- Coarse frequency range
  - 135 kHz (0.25 mm, 7500 N)

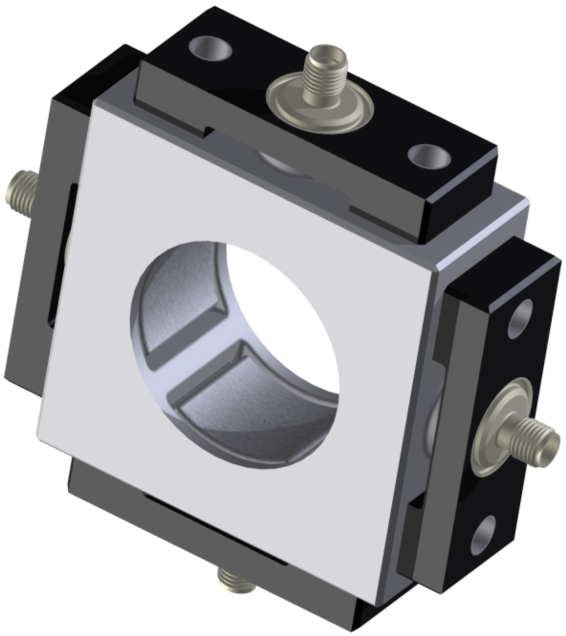






Instrumentation

- BPMs – button type for all cold and warm BPMs
- Design of BPM electronics to be launched in summer



Cold BPM (ANL design)

- Diverse set of instrumentation is planned
  - Emittance monotors (interceptive)
  - Collimators with isolated jaws
  - Laser profile monitors (all 3 planes)
  - Single particle detectors for extinction measurements

PXIE Stages and Time line

- Stage 1 (complete – early FY17)
  - Beam delivered to the end of MEBT with nearly final parameters (2.1 MeV, 1 mA CW, 80% arbitrary chopping)
  - Includes
    - Ion source, LEBT, prototype chopper, RFQ at full power
    - Full MEBT with prototype kickers, (possibly) prototype absorber, temp. dump, bunchers, diagnostics
    - Cryo system
    - SSR1 CM – cold and RF powered, no beam
- Stage 2 (complete – Aug 2017)
  - Includes
    - HWR CM – cold and RF powered, no beam
- Stage 3 (complete – Aug 2018)
  - Includes
    - Full diagnostics line, final MEBT kickers, final 50 kW beam dump, 1-mA CW beam delivered to the dump.