Project-X Injector Experiment (PXIE)

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Project X team**
**AP&T seminar, FNAL
March 5, 2013**

Outline

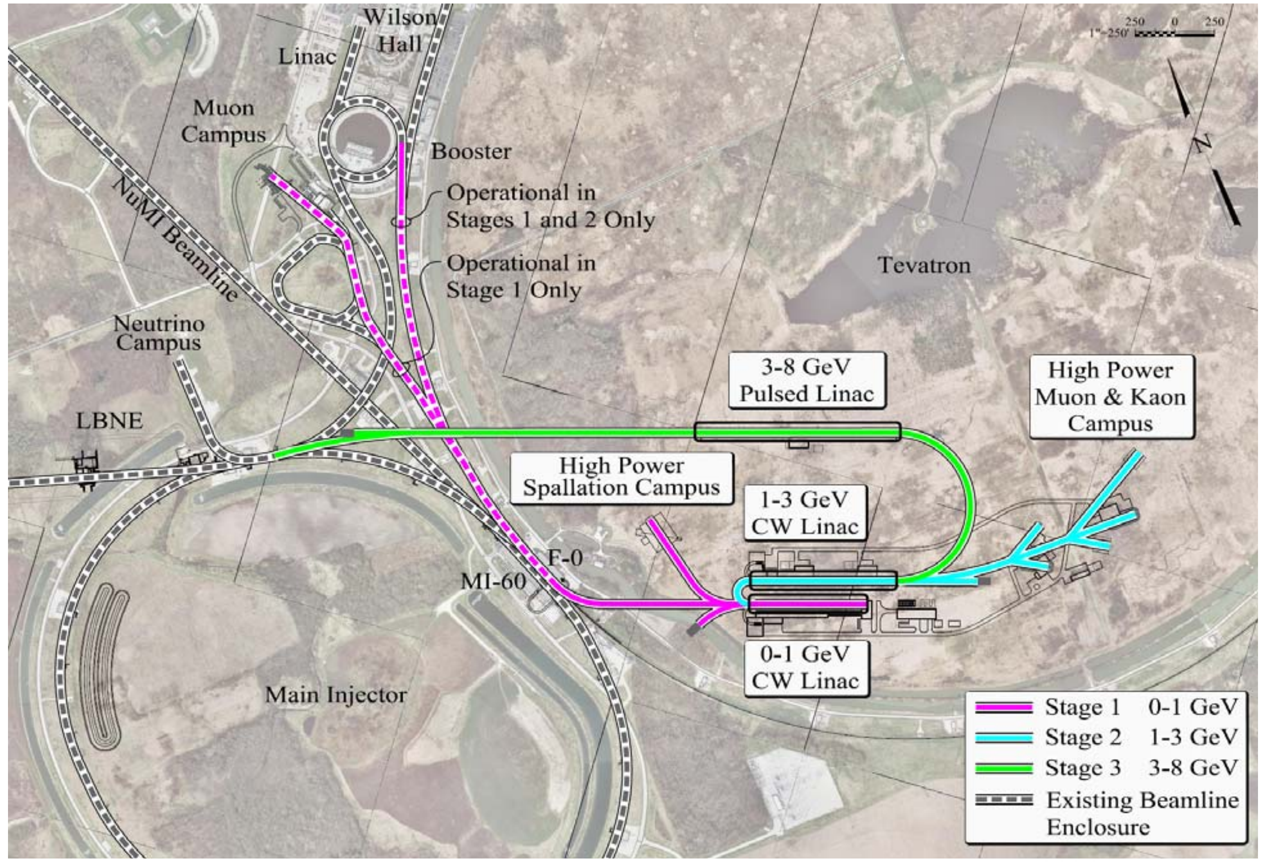
- Introduction to Project X
- PXIE structure and goals
- Main requirements to machine conception
- Subsystems
  - Ion source to HEBT
- PXIE optics and optics simulations
- Particle extinction and its measurements
- Summary

Project X

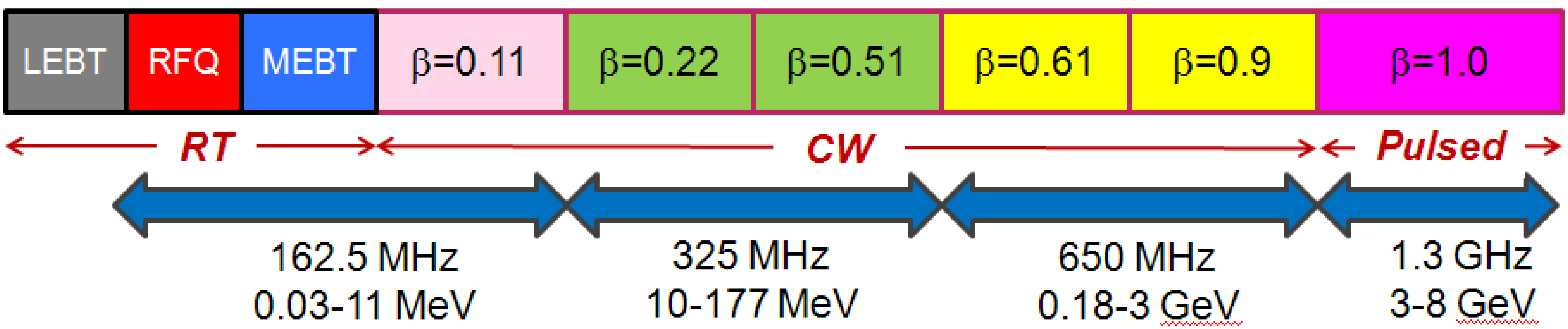
- 1 MW @ 1 GeV
- 3 MW @ 3 GeV
- 0.2 MW @ 8 GeV
- >2 MW @ 60-120 GeV
- 6 MW TOTAL

PXIE

- LEBT to the middle of β=0.22 section

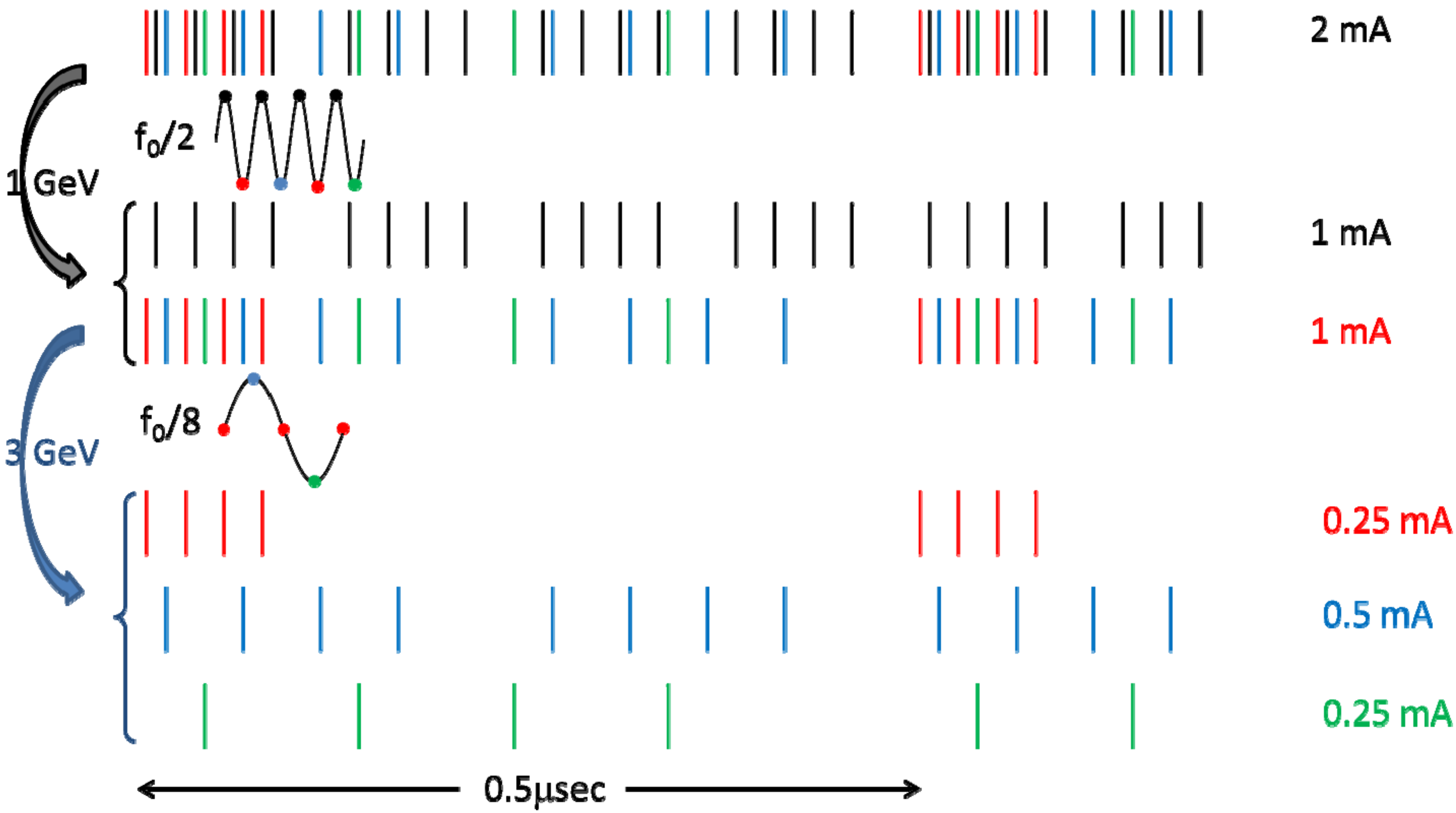


Project X Linac Technology Map

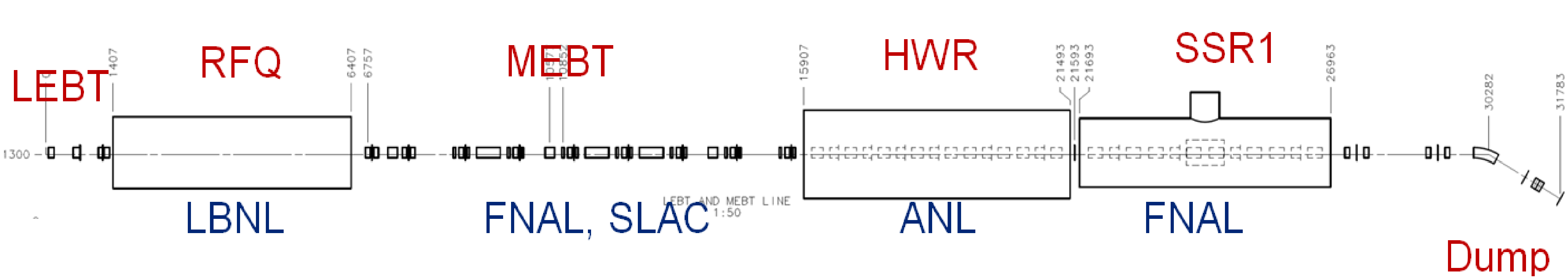


RF Separation & Bunch-by-bunch Chopping

- RF Separation & bunch-by-bunch chopping are two corner stones of the project
  - Each experiment can receive desired bunch structure



PXIE Structure



- "Standard" scheme for beam acceleration is used
  - 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, chopping and beam diagnostics)
  - 2 SC cryomodules accelerating beam to 20-30 MeV
  - HEBT
  - 50 kW beam dump
- Total length < 40 m

PXIE Goals

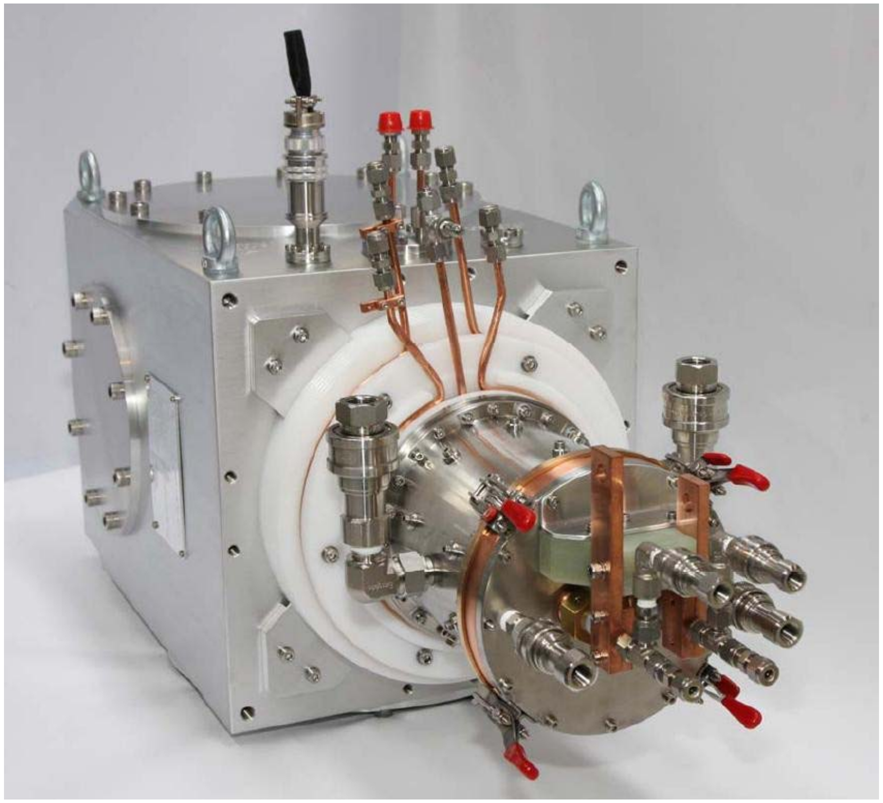
- Validate the Project X concept and eliminate technical risks (Most risks are related to the frontend)
  - CW RFQ (reliability, …)
  - Bunch-by-bunch chopper (kicker and absorber)
  - MEBT/HWR interface (vacuum, differential pumping, micro-particle migration to HWR through/from MEBT)
  - High-current beam acceleration in HWR and SSR1
    - Loss of RFQ longitudinal tails
    - Halo generation by beam space charge
  - Extinction for the removed bunches
    - $<10^{-9}$ – as desired by μ-to-e experiment (no formal specification)
- Obtain experience in design and operation of SC cryo-modules
  - SSR1 cryomodule will be designed and built by Fermilab

Main Requirements to the Machine Conception

- Accelerator physics design is driven by the following requirements
  - Bunch-by-bunch beam chopping
    - Minimize required kicker voltage to an acceptable level
  - 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
    - Measurements of extinction for removed bunches well below 10^{-9}

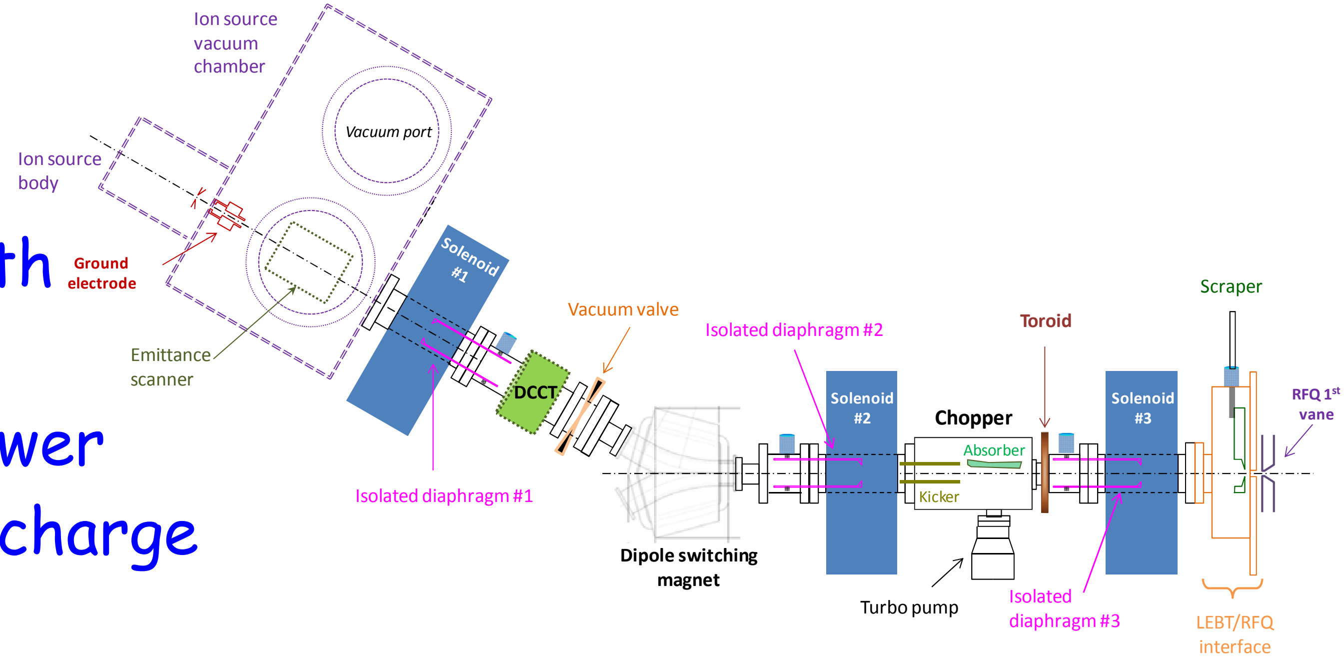
Ion Source

- Small transverse emittance is required to have effective multi-turn injection into Project X circular machines
  - It also allows comparatively small apertures in accelerating structures
- Commercial H- source:
  - 5 - 15 mA DC current
    - Baseline scenario implies operation at 5 mA
    - Maximum beam current through RFQ – 10 mA
    - ~300 hours lifetime at maximum current
  - Measured emittances are well within our specifications
    - $\varepsilon_{rmsN\_x} \approx \varepsilon_{rmsN\_x} \approx$[0.09 - 0.12] mm mrad for I = [2 - 10] mA



LEBT

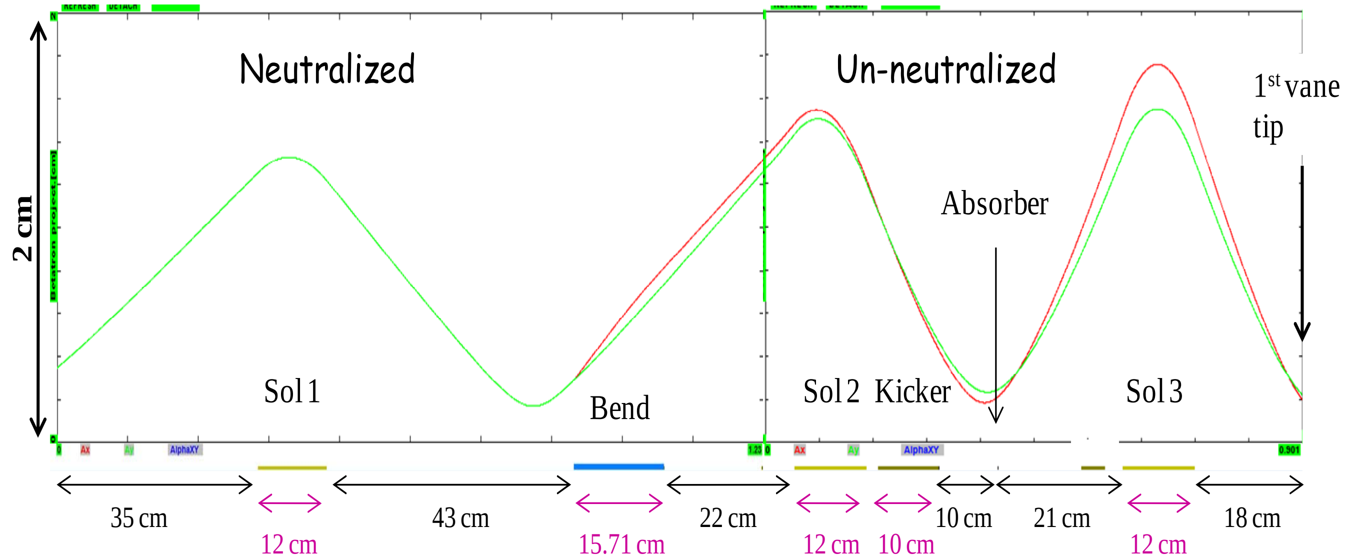
- Low (30 kV) LEBT energy reduces length of RFQ adiabatic buncher and RFQ power but increases space charge effects in the LEBT

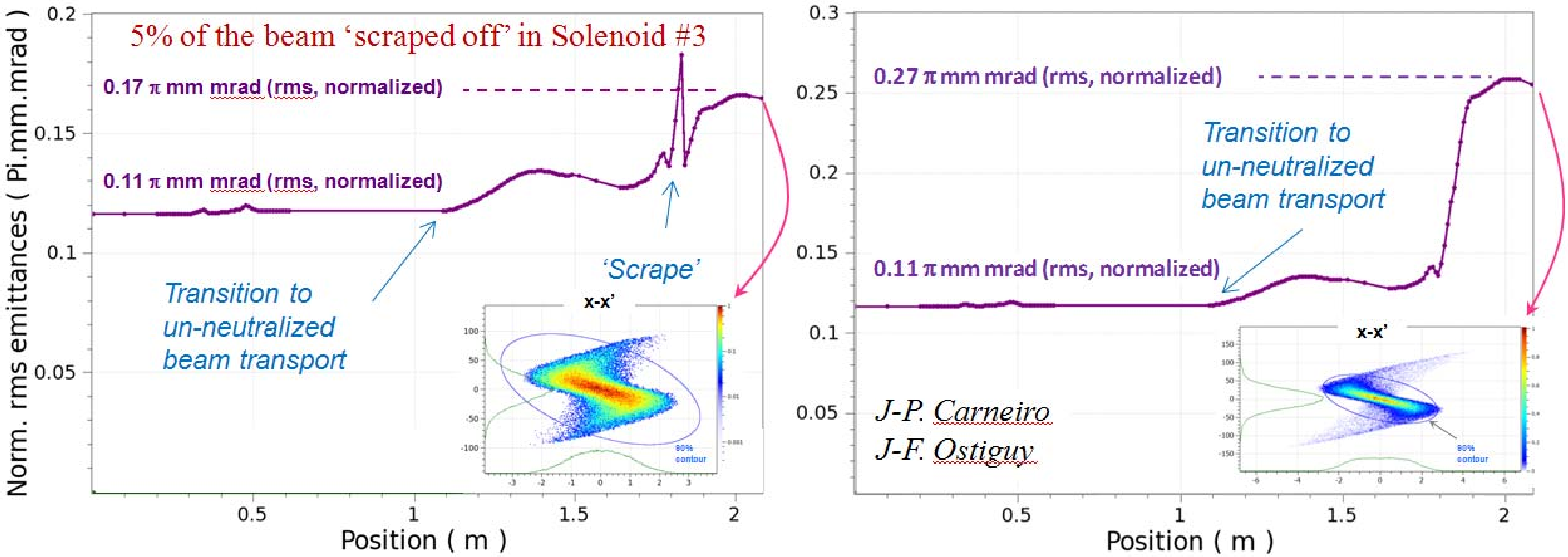


- Solenoidal focusing is chosen in the LEBT
  - 2 solenoids are required to match beam envelopes to the RFQ
  - 3 solenoids and partially compensated transport are suggested to minimize difference between short pulse and CW operation
    - Operation with fully compensated transport is possible too
  - Long LEBT improves differ. pumping between ion source and RFQ
- Dipole magnet do switch between two ion sources
  - Edge focusing is adjusted to minimize focusing asymmetry
  - Only one source to be used in PXIE
- LEBT chopper creates pulses (1 μs - DC) for commissioning

LEBT (2)

- Emittance growth with un-neutralized transport is mostly associated with small beam size needed at the absorber – It may be improved with some scraping of the beam
  - Low energy + ion source current overhead makes scraping possible

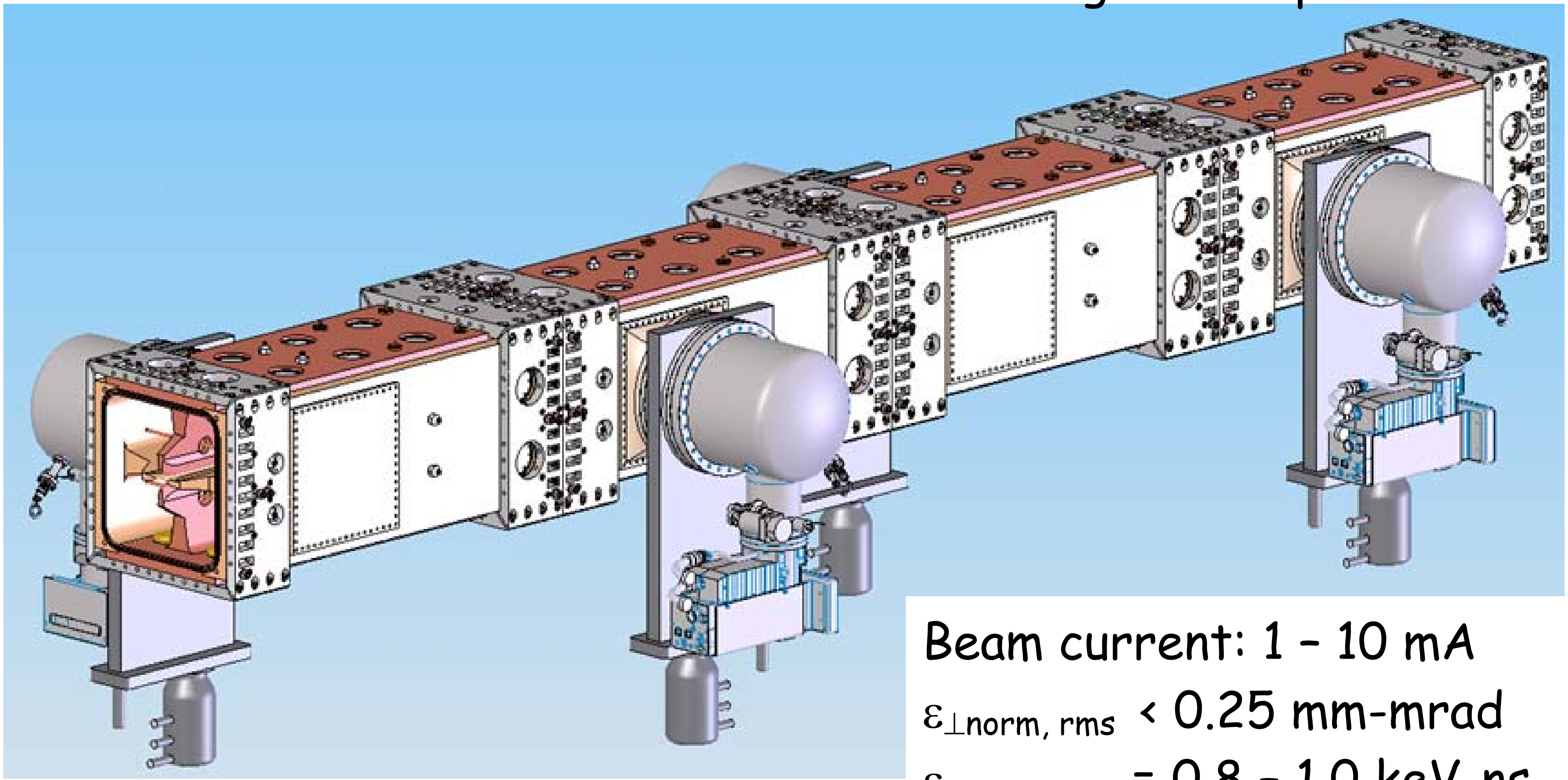




Emittance evolution along the LEBT with (left) and witout (right) beam scraping – Tracewin simulations with 5 mA and Gaussian beam distribution

RFQ

- Choice of parameters
  - 162.5 MHz frequency to make bunch-by-bunch chopping possible
  - 2.1 MeV energy to exclude residual radiation in the MEBT
    - The energy is large enough to avoid space charge problems in the MEBT for both transverse and longitudinal planes



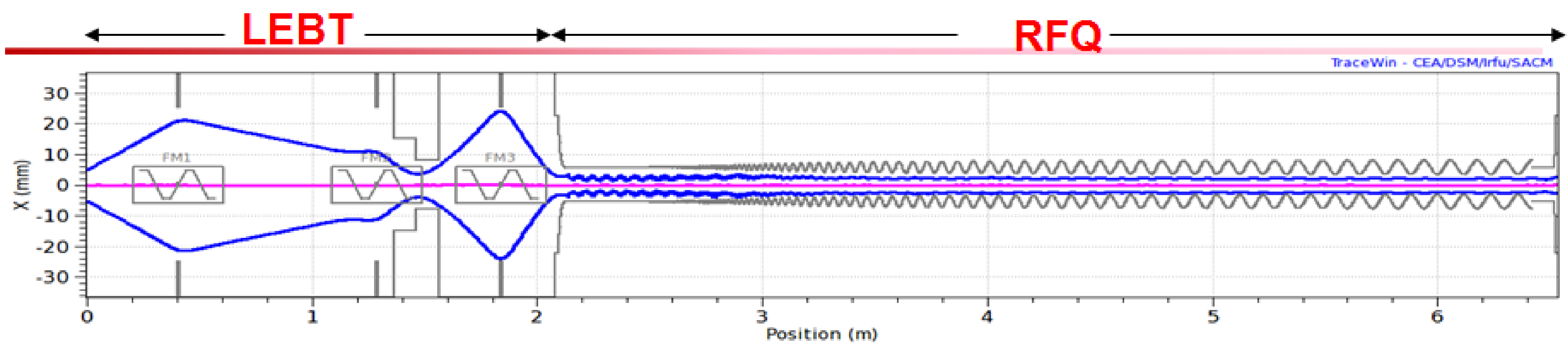
Beam current: 1 – 10 mA

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

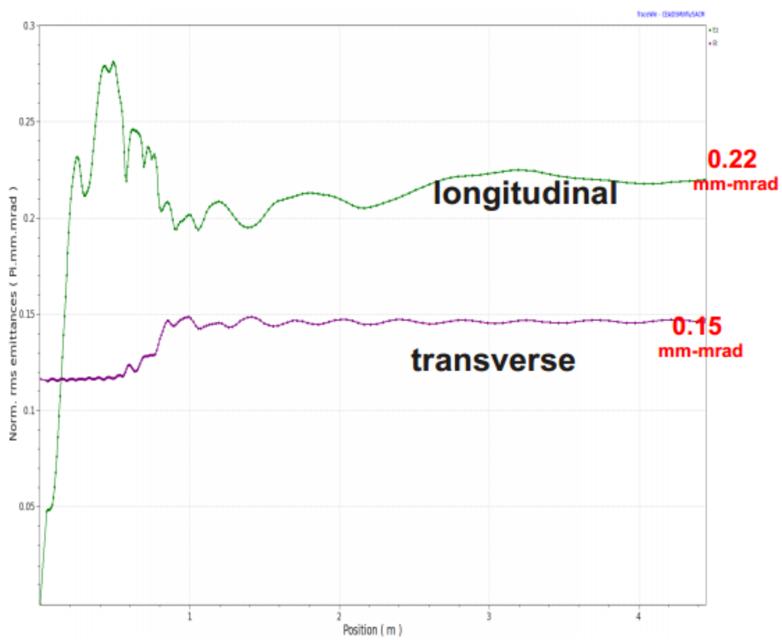
$\varepsilon_{|| norm, rms}$ = 0.8 – 1.0 keV-ns

Length: ~4.4 m

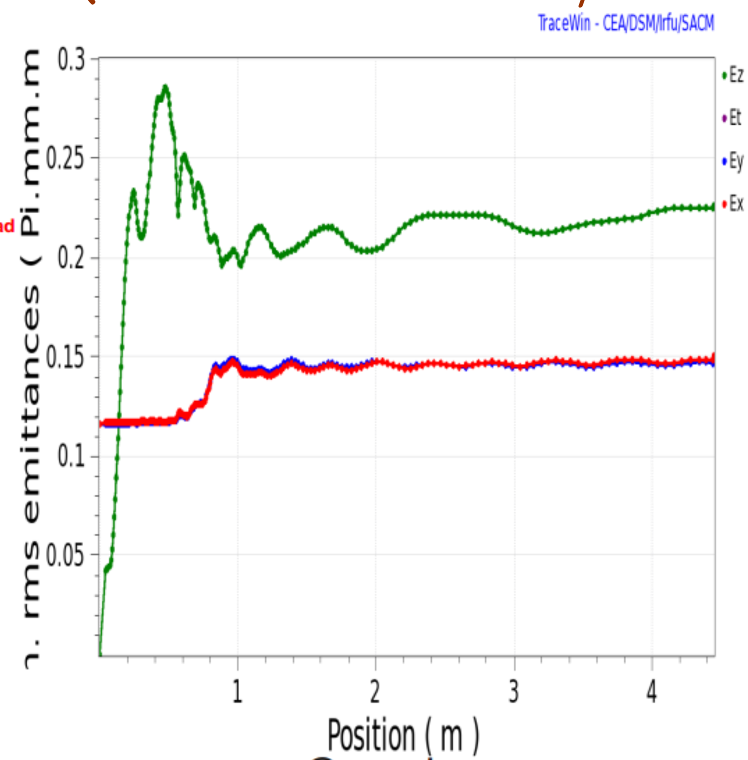
RFQ Simulations



3σ beam envelope (x) in LEBT and RFQ for Gaussian Beam at input



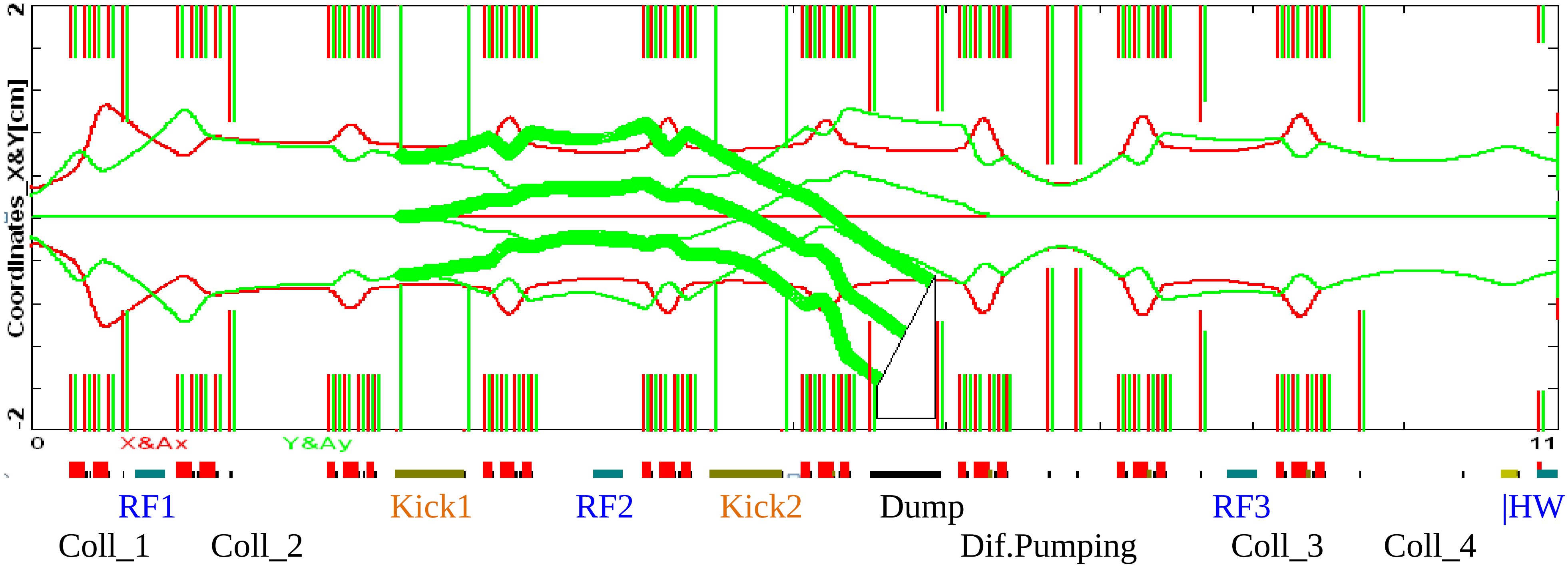
Nominal (Staples)



Gaussian

Emittance evolution for "measured" (left) and ideal Gaussian (right) RFQ input distribution; I=5 mA (courtesy of F.Ostiguy)

Major Features of MEBT Optics

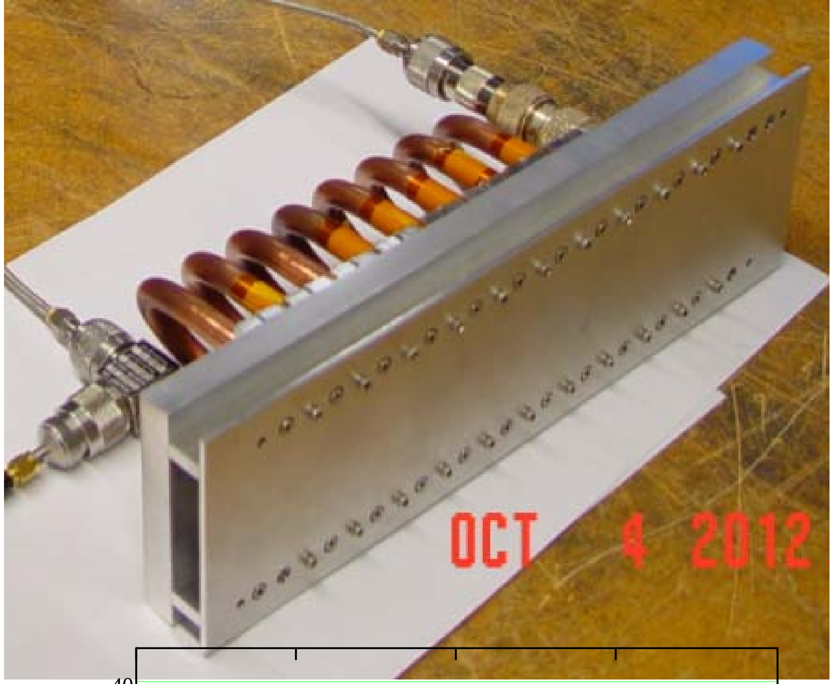


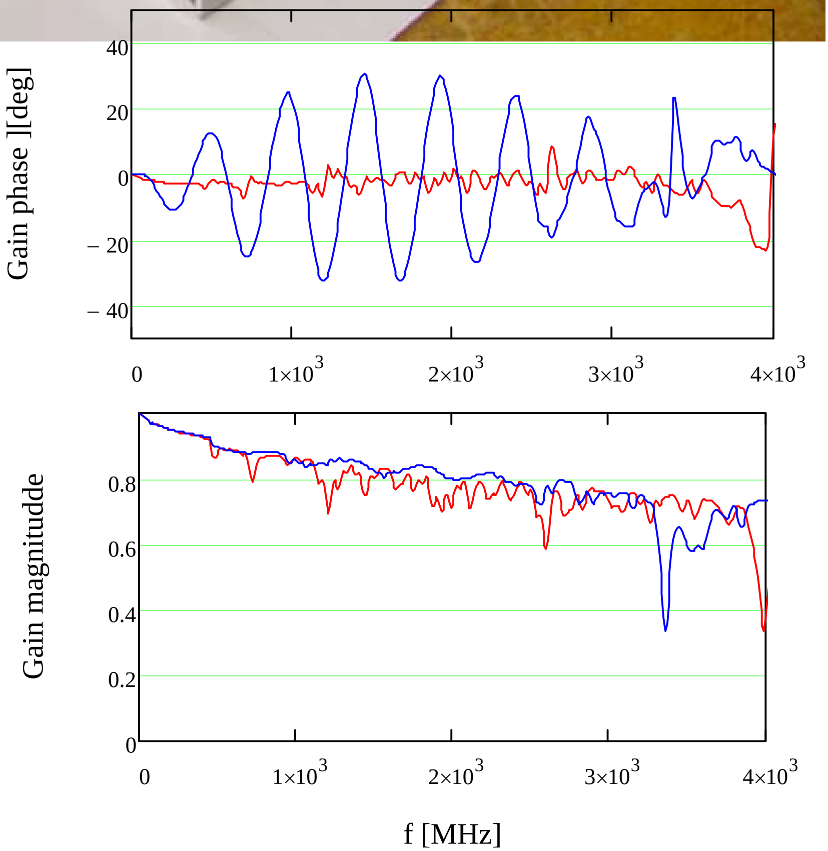
*3σ ⊥ beam size (ε_{rmsn}=0.25 mm mrad); v. kick is excited by kickers (U=±200 V, 13 mm gap, 2*0.5 m)*

- "Adiabatic optics"
  - Small β-function variation
  - Mitigation of space charge
- "Two-kicker chopping" makes it possible with present technology
  - 180 deg. between kickers
  - 22 kW beam dump (I_{beam}=10 mA) with differential pumping section before CM
- 3 RF cavities for longitudinal focusing and matching

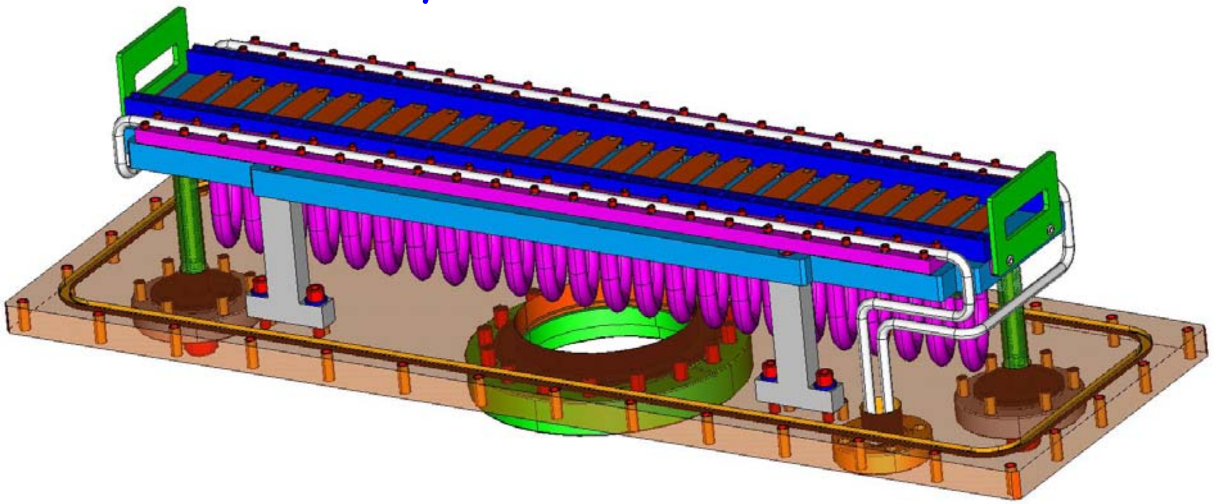
Bunch-by-Bunch Kicker

- 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



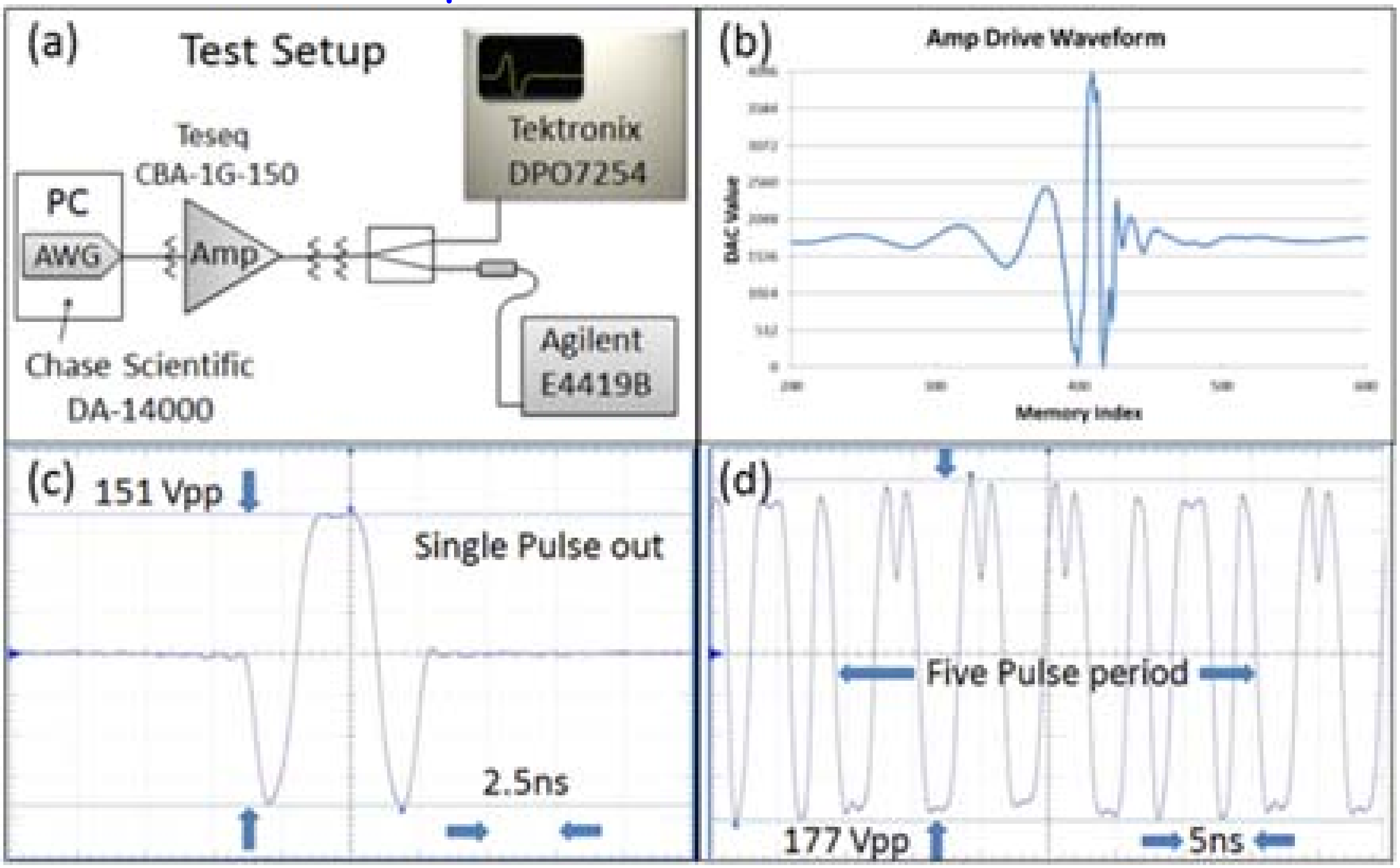


Comparison of meander with helical connections for 6 electrodes



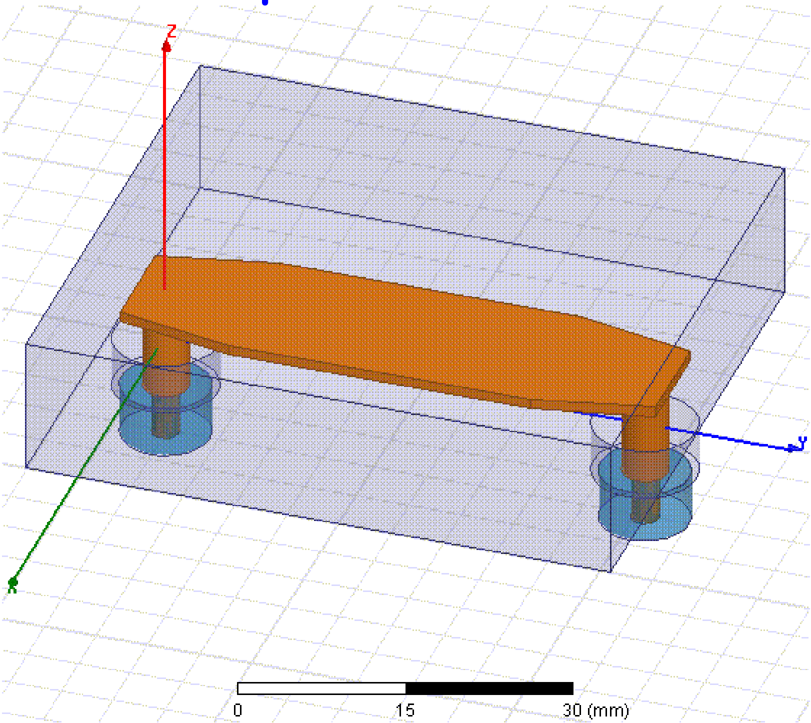
Pulser for 50 Ω Bunch-by-Bunch Kicker

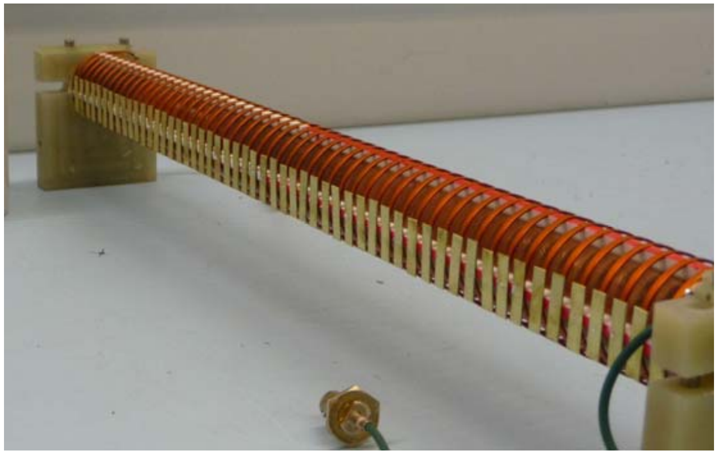
- Pulse predistortion creates "perfect" pulses at amplifier output
- Tests were carried out with Teseq 150 W amplifier
  - Teseq 1 kW amplifier has similar gain dependence on frequency
- Tests of kicker and pulser assured us that the solution is found



50 and 200 Ω bunch-by-bunch kickers

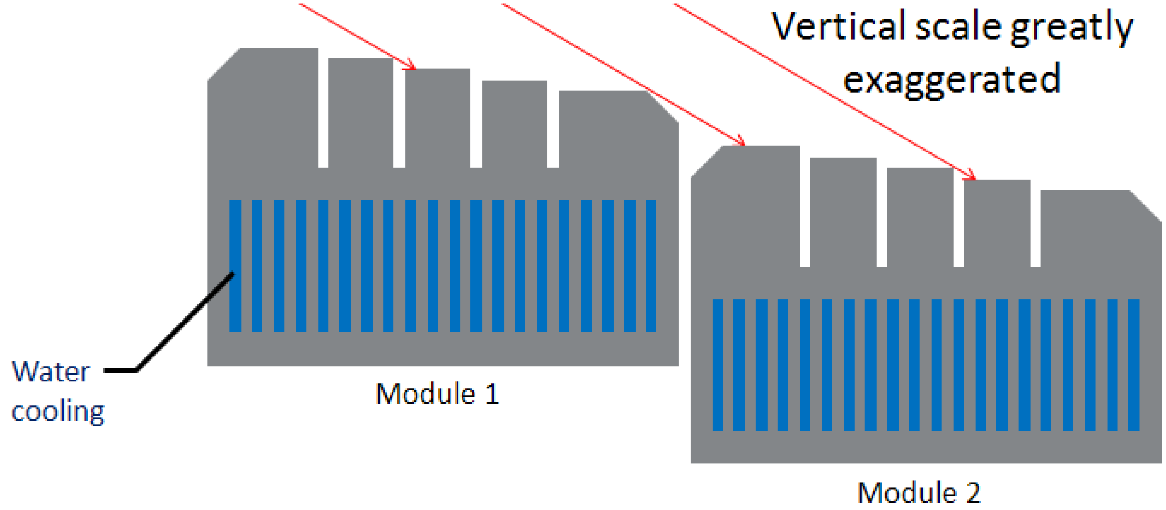
- 200 W kicker is a backup choice
  - Has larger dispersion but much smaller power
  - Pulser needs to be demostrated but is expected to be less expensive than 50 Ω 1 kW amplifiers (~$1M)

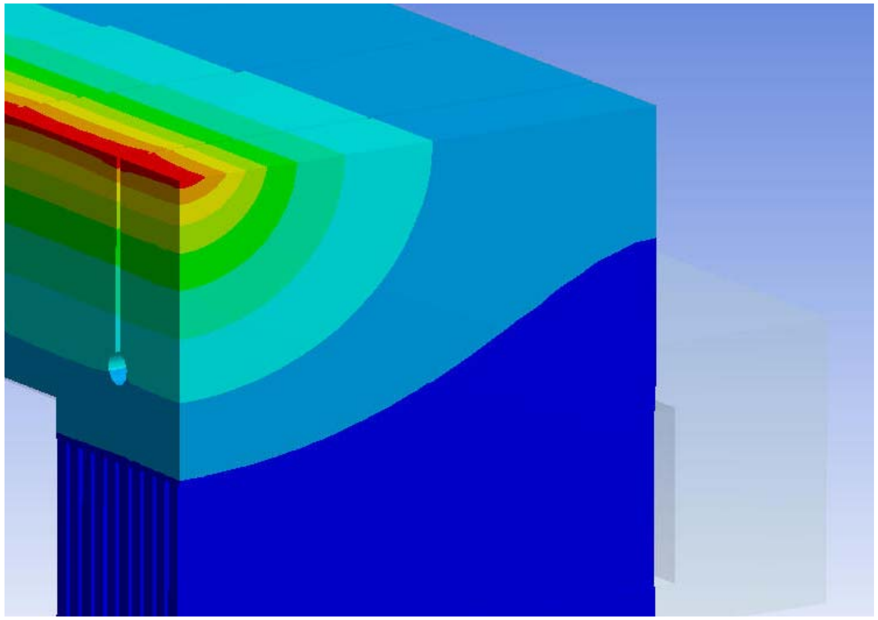




MEBT Beam Absorber

- The absorber should withstand 10 mA @ 2.1 MeV
  - i.e. 21 kW focused into a spot with σ = 2 mm
- Difficulties
  - Thermal load & mechanical stress
  - Outgassing (flux of incoming H^-)
  - Blistering & sputtering
- Design features
  - Small grazing angle (29 mrad) reduces temp. & thermal stresses
    - ~40% of particles are reflected
  - Molybdenum alloy (TZM)
    - TZM has good ratio between mechani-cal properties and thermal expansion
    - High melting temperature
    - Reduced susceptibility to blistering
  - Stress relieve slits & Microchannel cooling

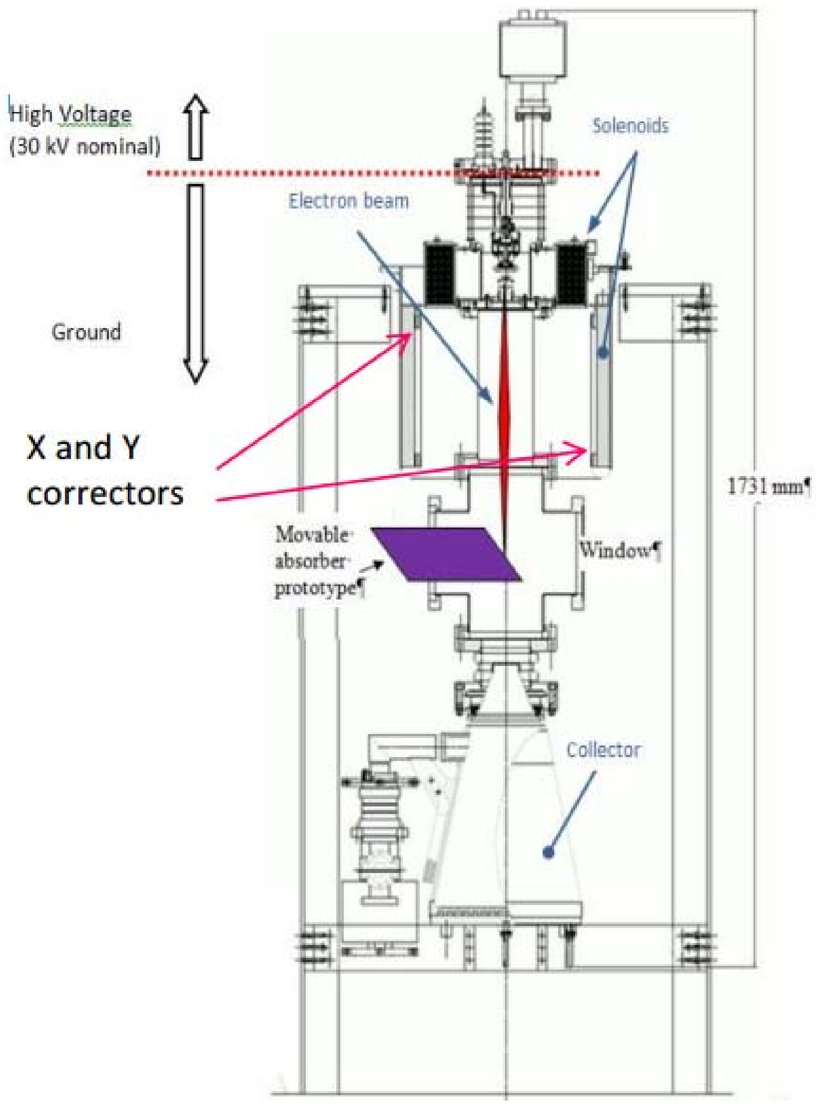


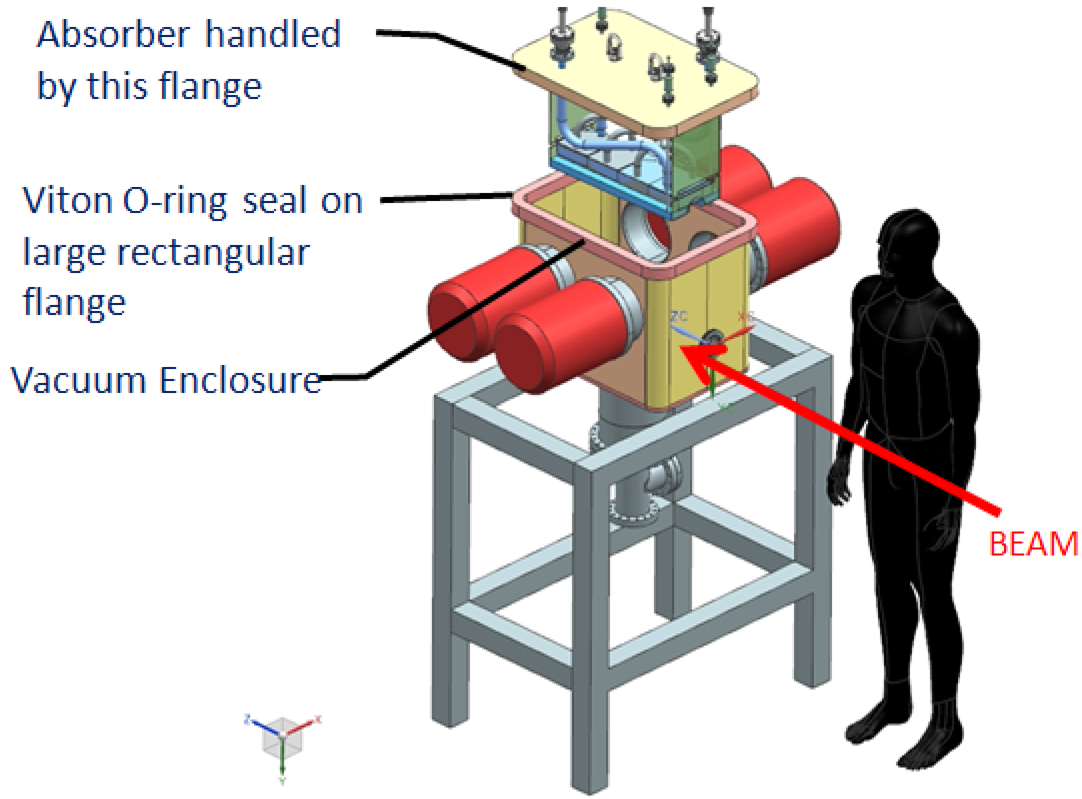


Absorber has 4 modules
T_{max} = 1050°C on beam absorbing surface

MEBT Beam Absorber (2)

- Detailed analysis
  - thermal and stress, water channel optimization, particle reflection, residual radiation

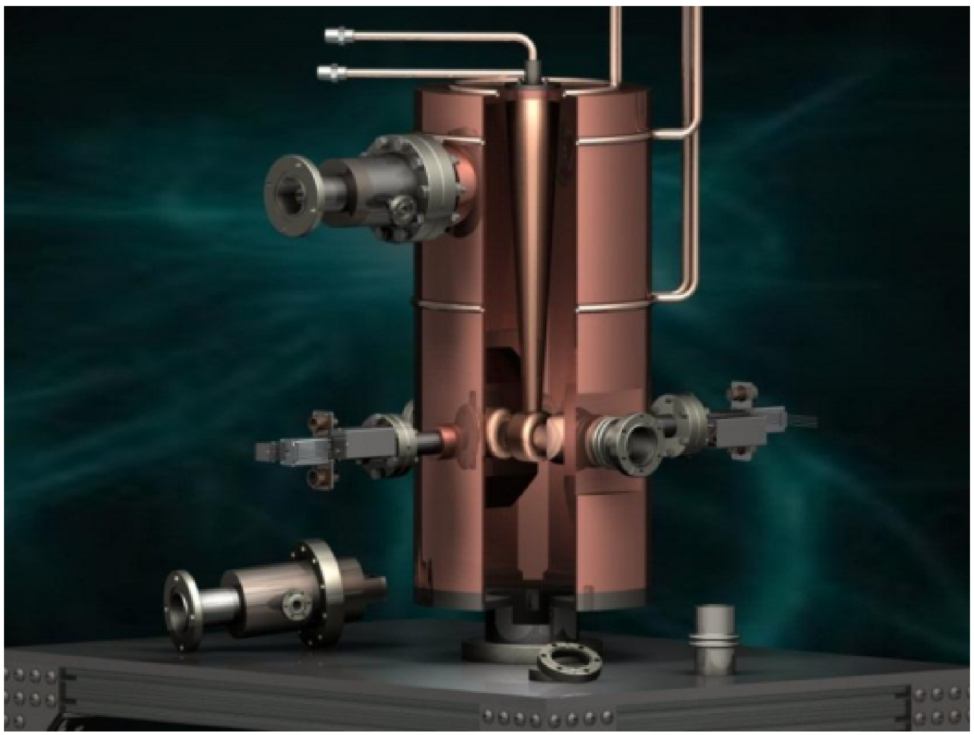


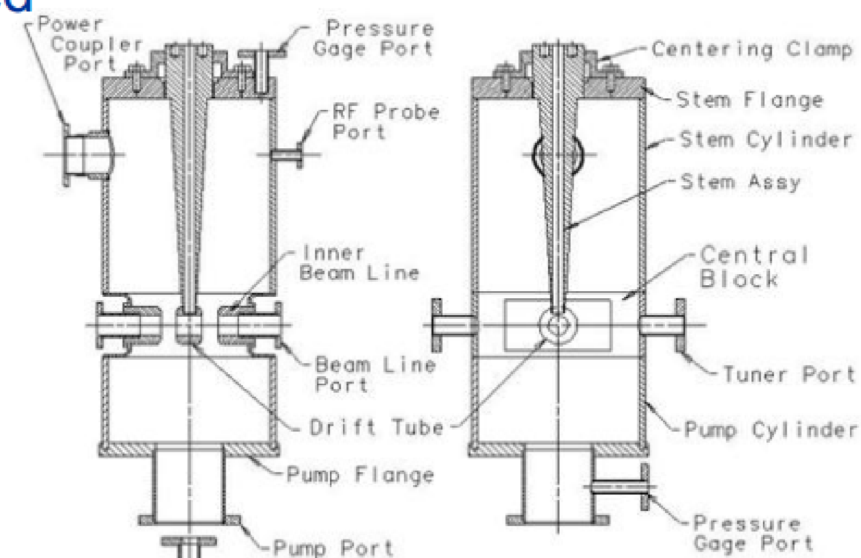


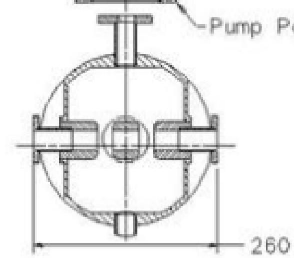
- The final absorber is to be completed by Aug-2015
  - A 1/4 - size prototype will be tested with an electron beam
    - It has been designed and is being manufactured
  - Spattering and blistering can be only tested with full power RFQ

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

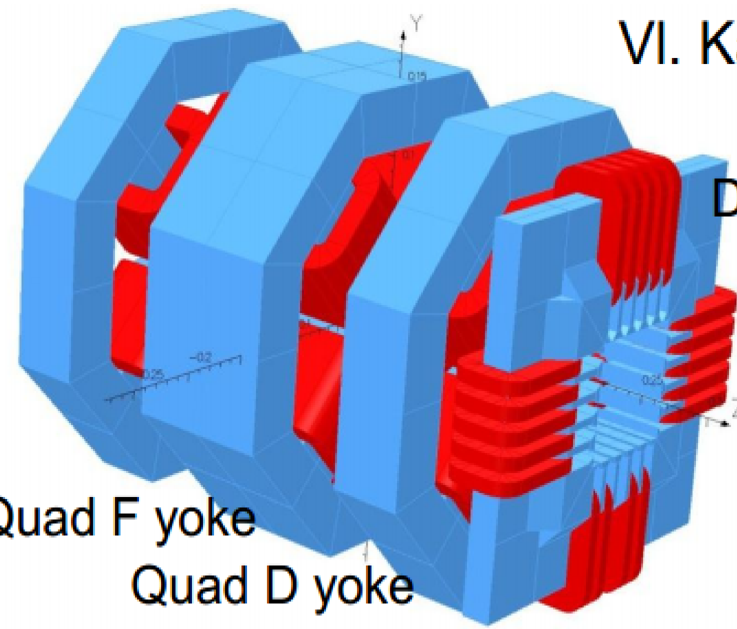
Couplers and tuners from HINS

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

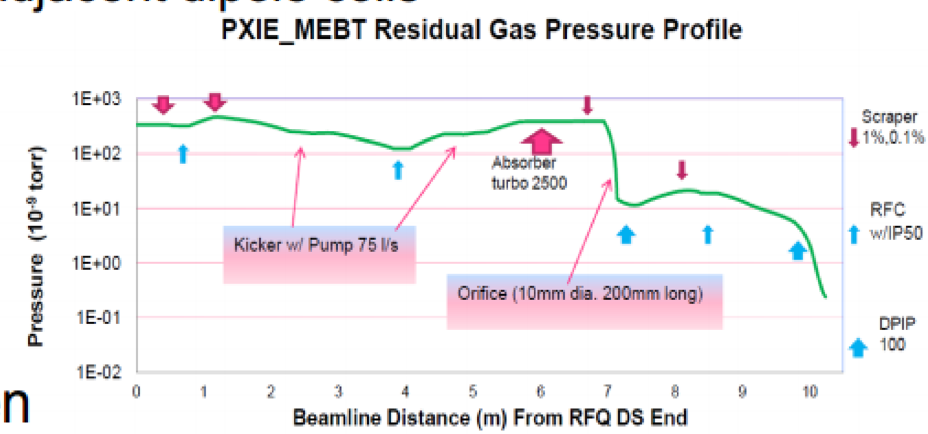
Other MEBT subsystems

- 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

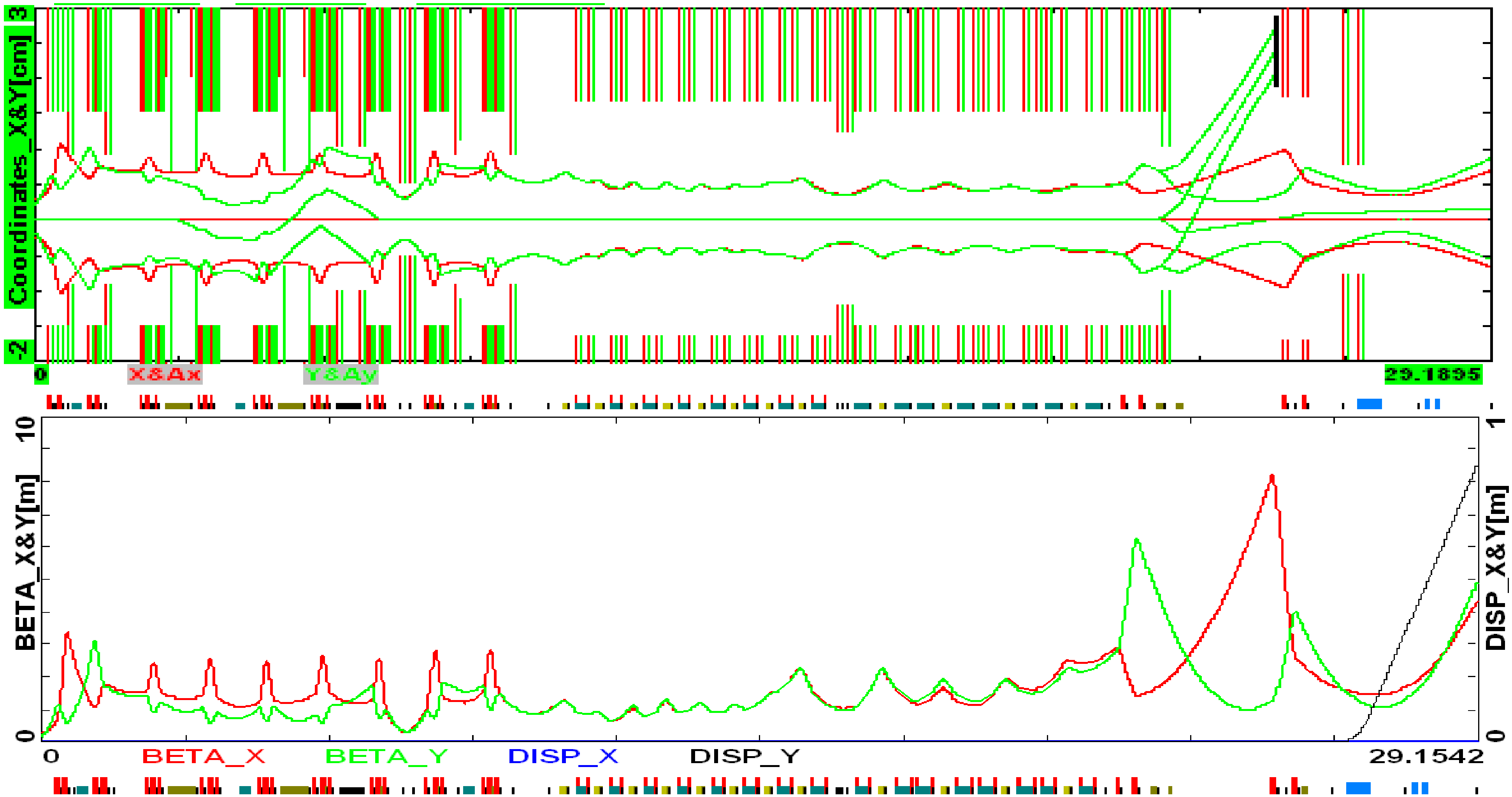


A.Chen

SC Cryomodules

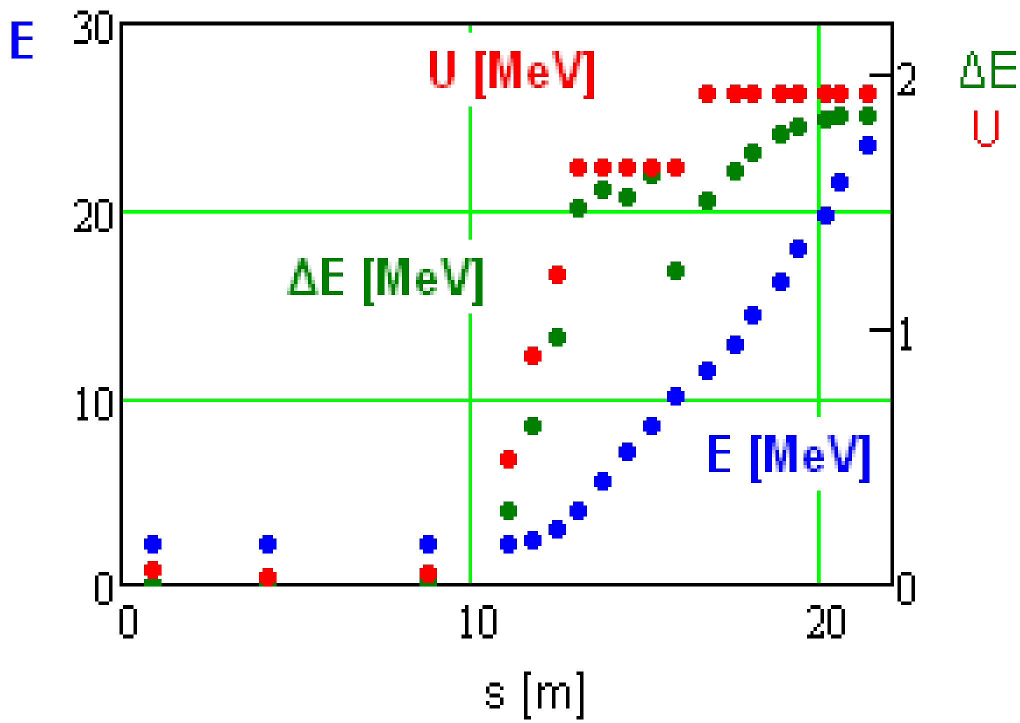
- PXIE will have two SC cryomodules operating at 2 K
  - Solenoidal focusing
  - Warm gap between cryomodules
  - Fast vacuum valves at both sides of the cryomodules
- Both cryomodules have
  - A BPM attached to each solenoid (measures X & Y & S)
  - Transverse (x, y) correctors are built-in to every solenoid
  - Vacuum valves at each end
- Structure of Half-wave cryo-module
  - 8 cavities, 8 solenoids (S C S C S C S C S C S C S C S C)
  - Starts with a solenoid to mitigate H_2 influx from MEBT
- Structure of SSR1 cryo-module
  - 8 cavities, 4 solenoids (C S C C S C C S C C S C)
  - Separated coils of dipole correctors allow creation of skew-quad
- Solenoid polarity can be changed
  - Simplifies orbit correction and helps with compensation of SSR1 cavities quad-field

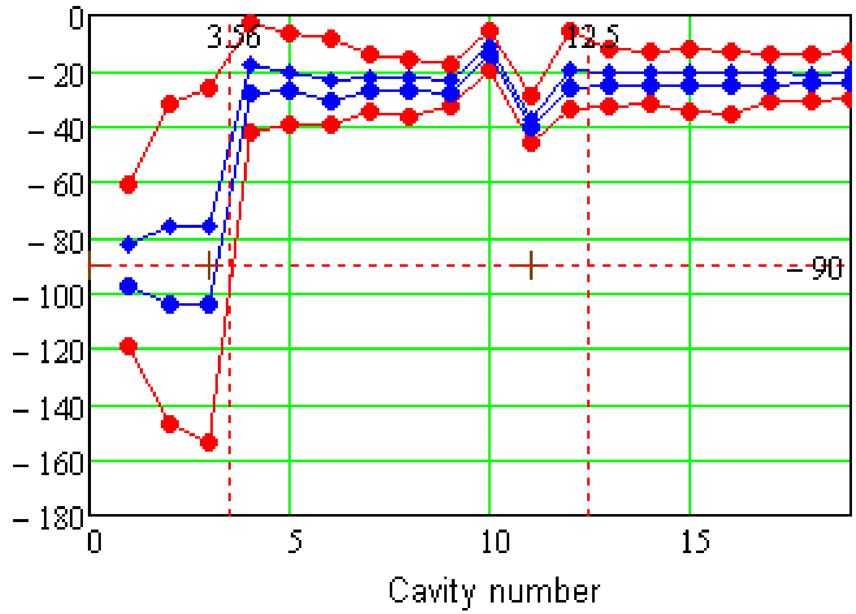
PXIE Optics and HEBT



- 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



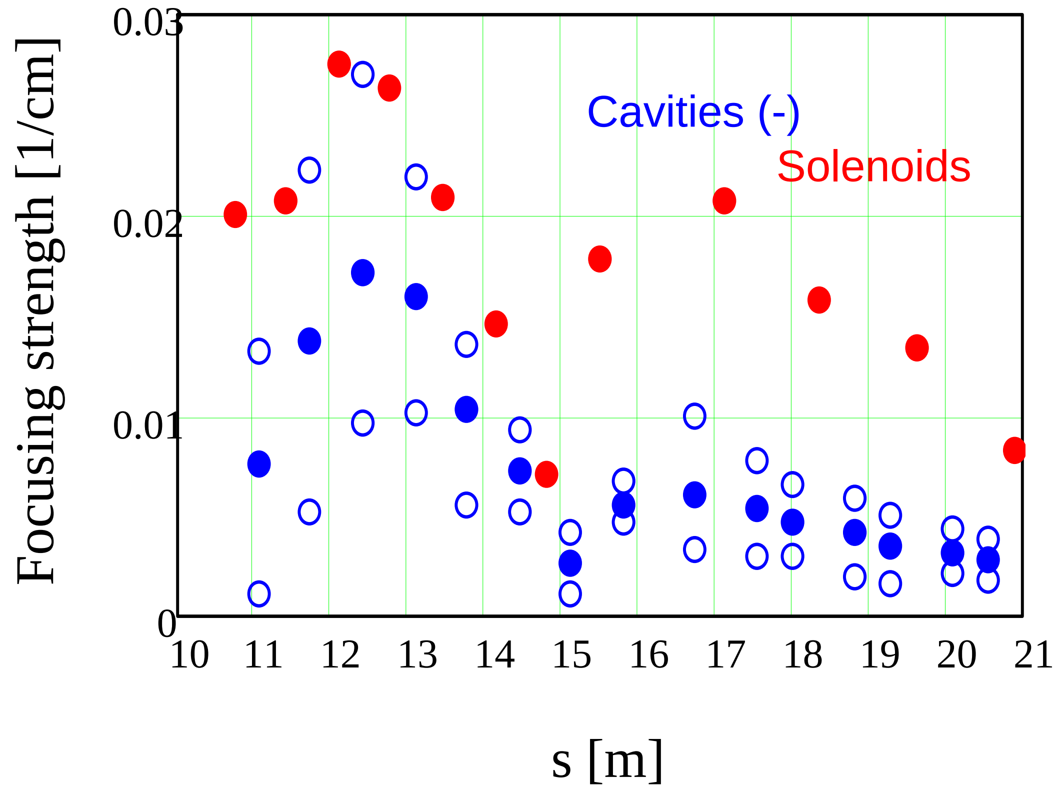


1σ and 4σ bunch ends relative to the accelerating phase [deg]

- 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.

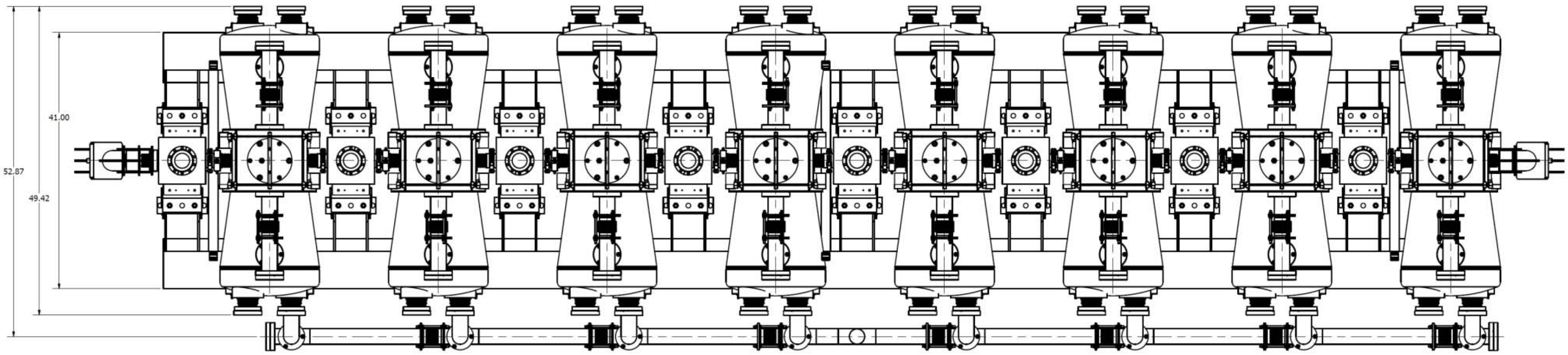
Limitations on Focusing in Cryomodules

- 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

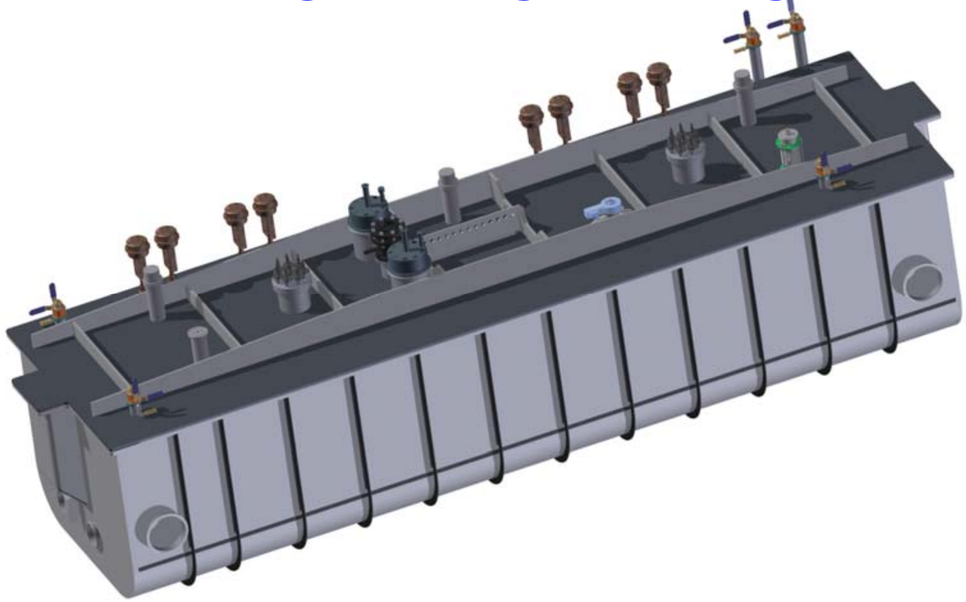


Focusing strength of solenoids (red) and nearby SC cavities for the reference particle (solid blue) and ±4s longitudinal bunch ends. Sign of the cavity focusing is changed from negative to positive.

HWR Cryomodule (β_G=0.11)

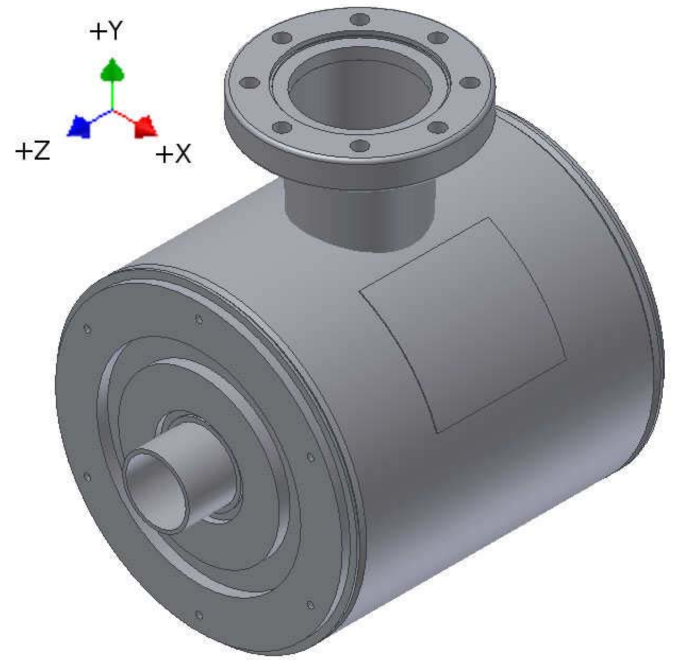


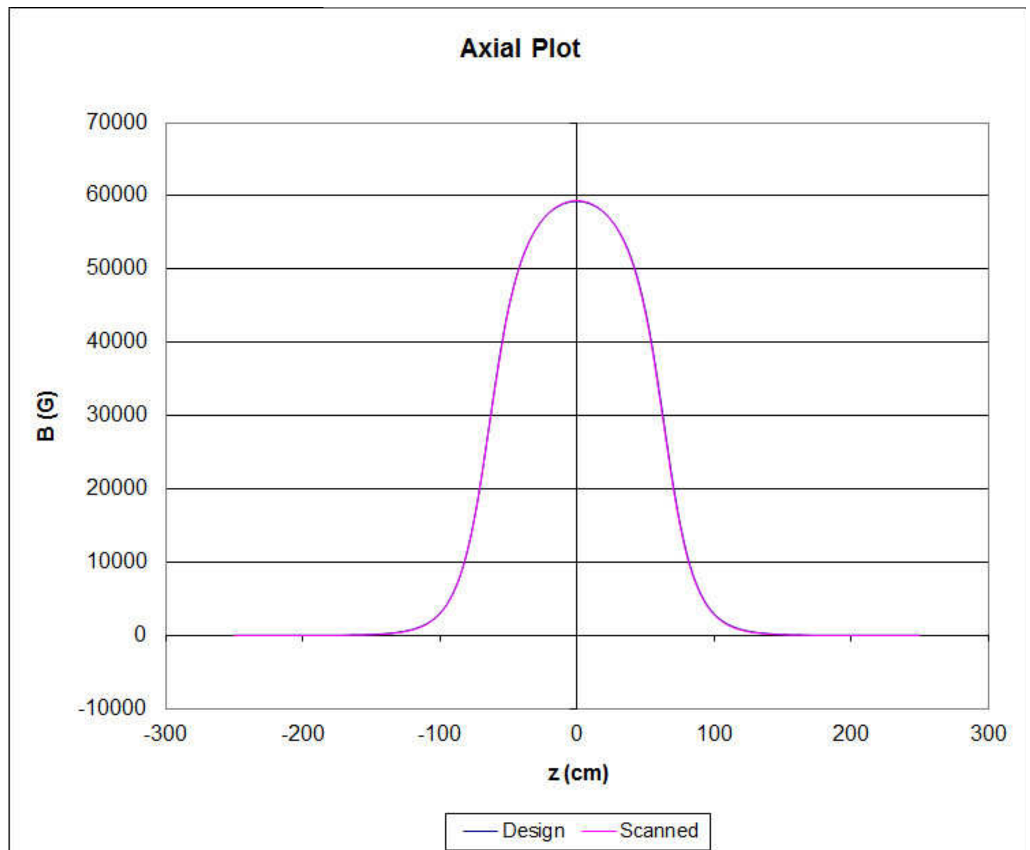
- 8 cavities, 8 SC solenoids (x,y correctors) and 8 BPMs
- Beam energy: 2.1 - 11 MeV
- The first upstream element is a SC solenoid to mitigate vacuum transition
- CM Length (flange-to-flange) ~ 5.9 m



HWR Cryomodule Status

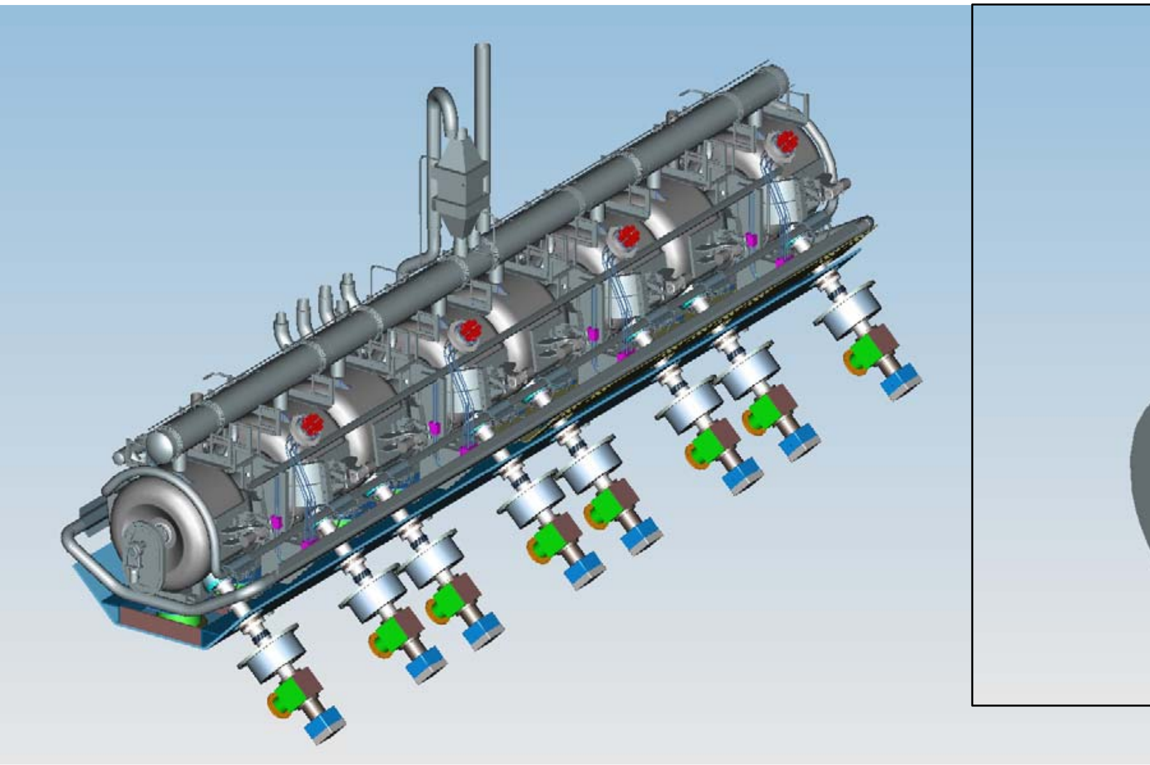
- Fabrication of prototype 10-kW RF coupler, SC solenoid and BPM is complete
  - Tests are carried out
- Fabrication of two prototype SC cavities is in progress
- ANL is focused on the next three milestones:
  1) Review of the cryomodule design;
  2) Forming of niobium parts for production cavities;
  3) Cold testing of two fully dressed SC cavities
- HWR cryomodule can be delivered to FNAL in the beginning of FY17 if the funding profile is maintained.

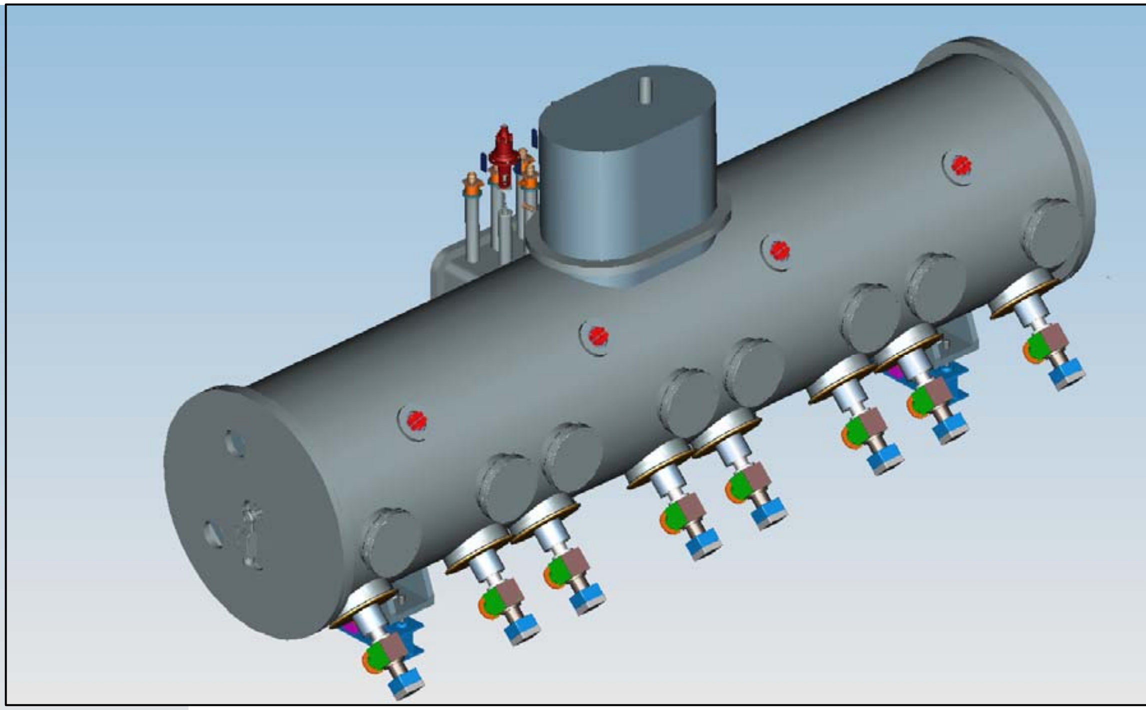




SSR1 Cryomodule (β_G=0.22)

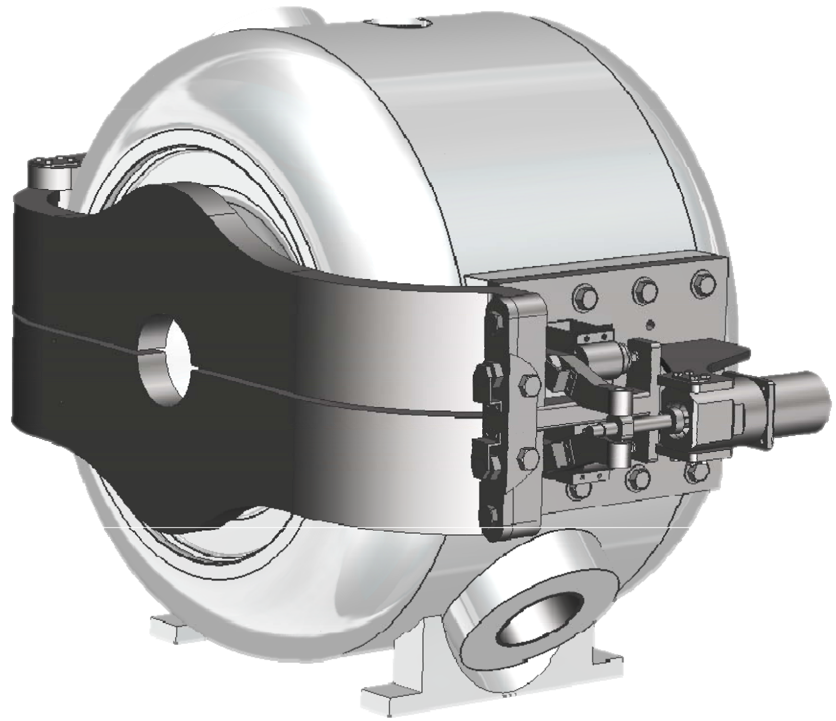
- 8 cavities, 4 SC solenoids (x,y correctors) and 4 BPMs
- Beam energy: 11 - 25 MeV
- The first upstream element is a cavity to mitigate longitudinal dynamics
- CM Length (flange-to-flange) ~ 5.4 m
- SC solenoids do not have magnetic materials (same as for HWR)
  - Additional coil is used for return flux and reduction of outside field
  - Correctors are located between coils of solenoid (+skew-quad)

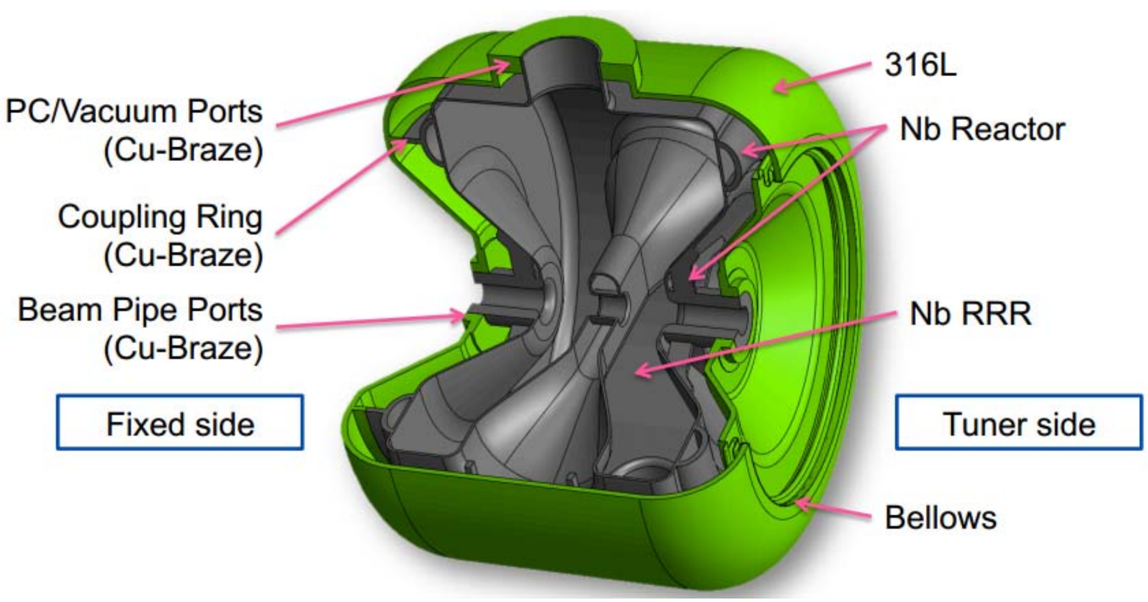


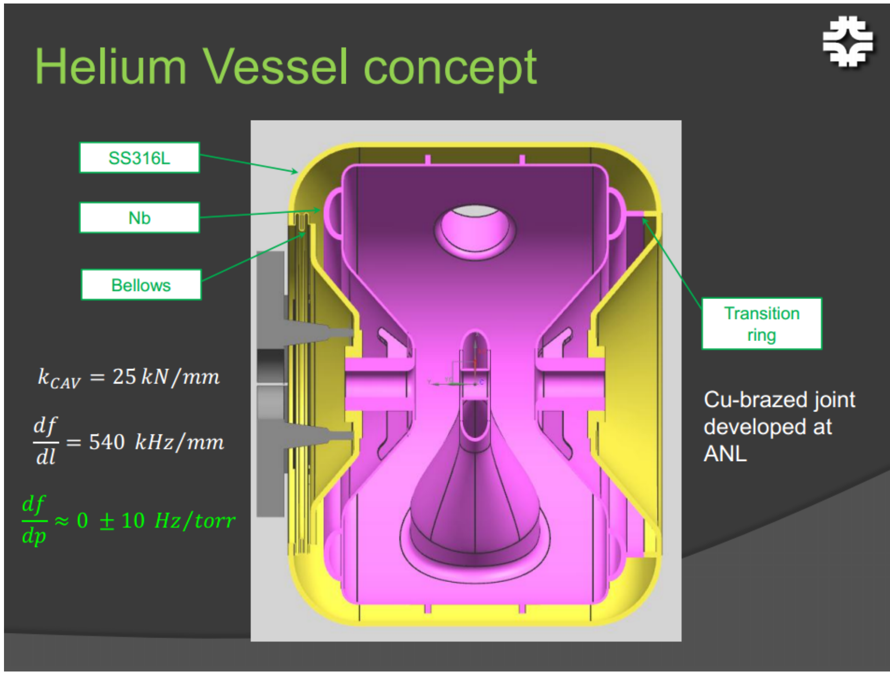


SSR1 Cryomodule (2)

- 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)



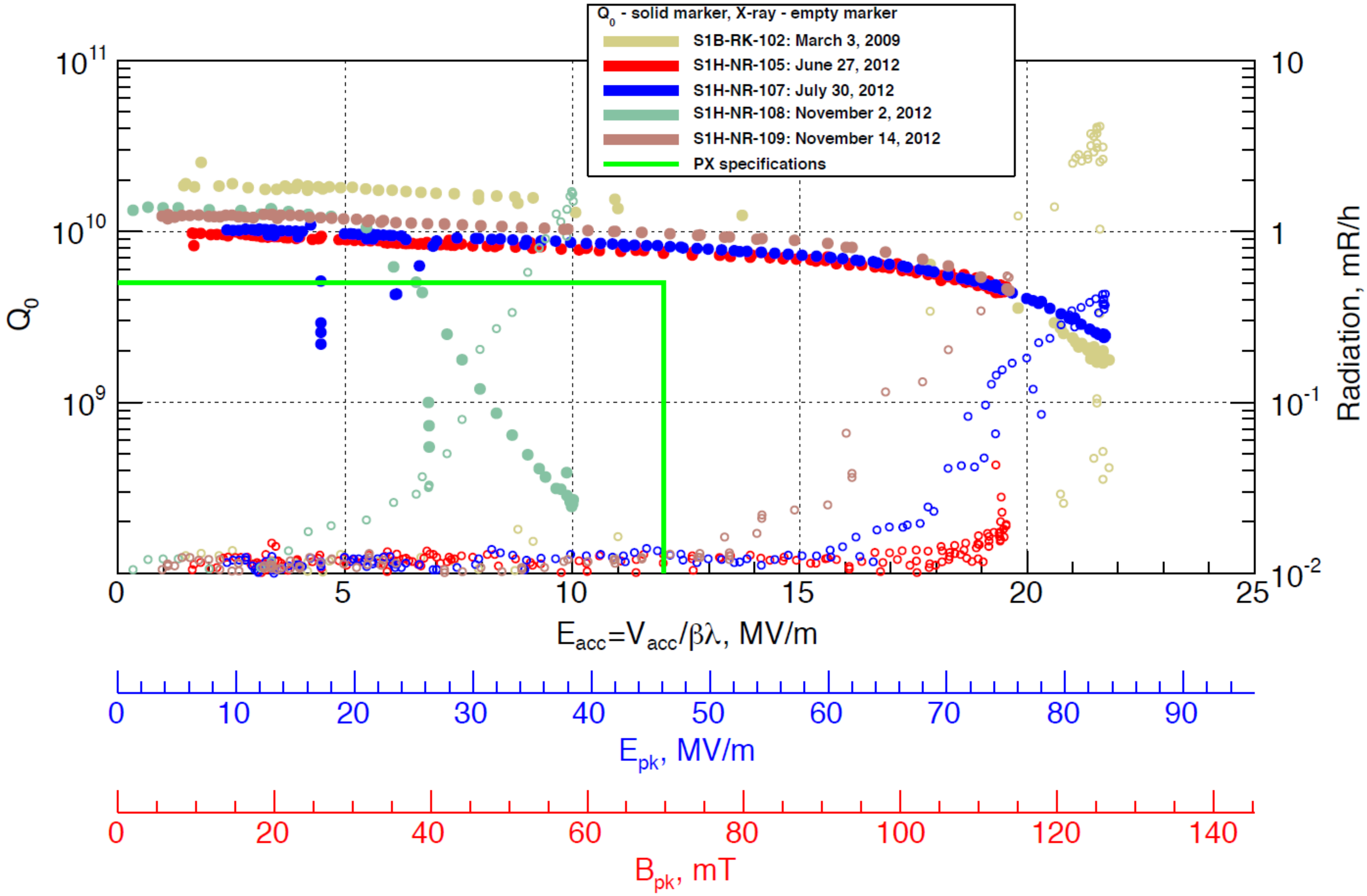




SSR1 Cryomodule Status

- Design – to be complete in the fall
  - Good progress is being made on each of the main sub-components.
    - Support system.
    - Cavities, helium vessels and tuners.
    - Solenoids and current leads.
    - RF couplers.
  - Integration of them all into the overall cryomodule design is going well. Preliminary model has been turned over to design/drafting.
  - We've answered many of big questions posed when first starting.
    - Solenoid strength, operating temperature, type of cooling, etc.
    - One or two coupler windows.
    - Tuner access ports.
    - Alignment verification technique.
- Production
  - First production batch of 10 cavities is complete.
    - Tests proceed well
  - Prototype helium vessel and solenoid are moving to production
  - Input coupler and test stand have been reviewed, procurement of prototypes is in-process, test plans are in-process.

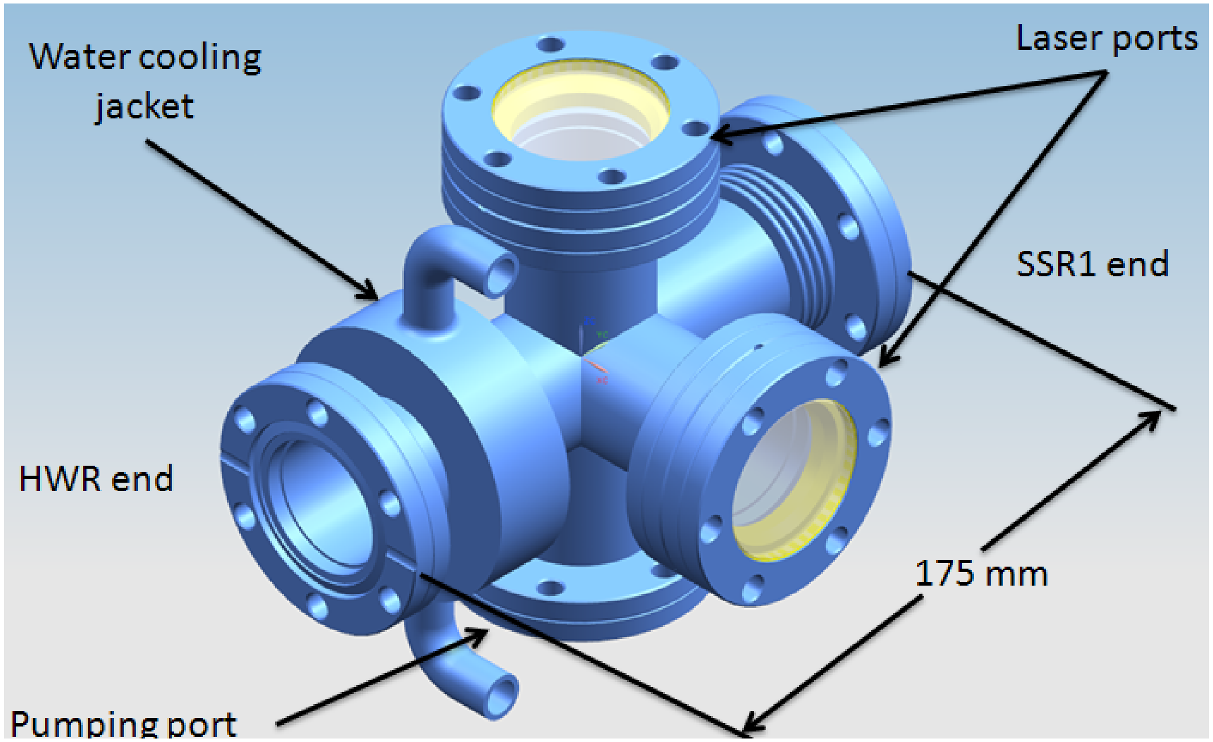
SSR1 VTS Test Summary as of Dec 2012



- 5 more bare cavities (S110-S114) will be tested in VTS between now and June 2013
- Jacketing operations of first cavity (S107) will occur in Spring 2013.

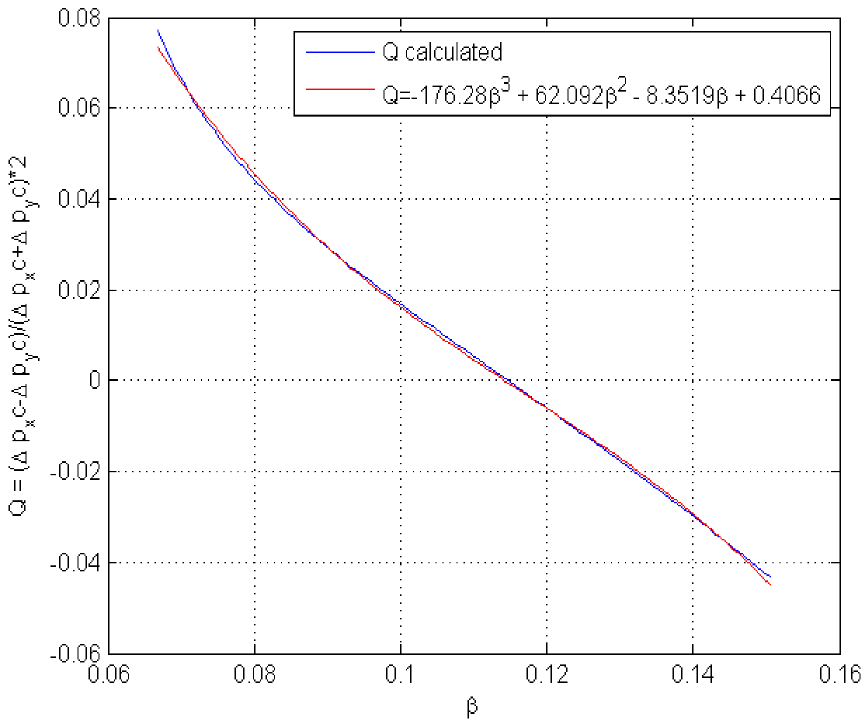
HW-to-SSR1 Interface Box

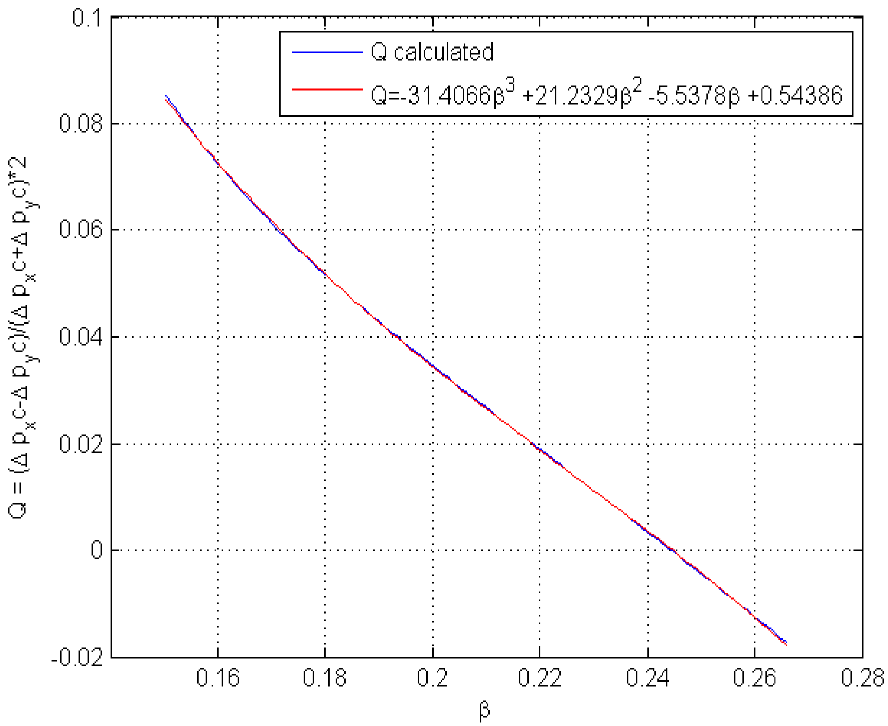
- HW-to-SSR1 transition goes through room temperature vacuum chamber
  - Good from engendering and repair points of view but complicates beam dynamics
  - Both cryomodules face interface box with cavities – improves long. dynamics
  - Small space allocated (~20 cm)
  - It will include
    - Laser profile monitors
    - Pumping port
    - Beam collimator



Quadrupole Fields in HW and SSR1 Cavities

- Asymmetry in cavity geometry adds quadrupole component to defocusing field (tilted by 45 deg. for SSR1)
  - Elliptical aperture and donut geometry of central electrode hole were investigated.
  - Donut geometry was found to be more effective in reduction of quadrupole field

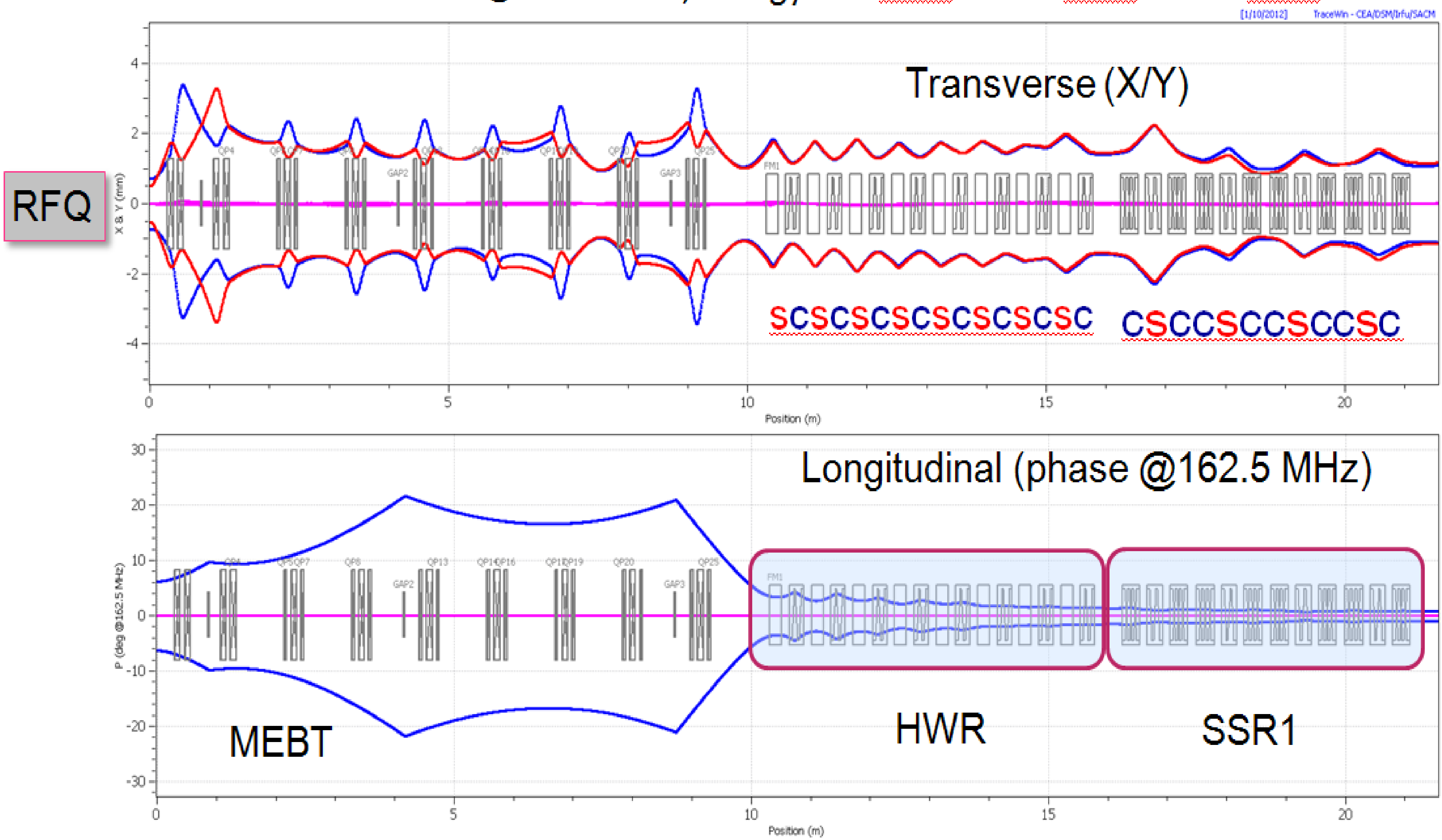




Quadrupole effect in the HWR (left) and SSR1 (right) cavities versus the particle velocity β; red and blue lines show simulation and approximation

Beam Transport Simulations with Space Charge

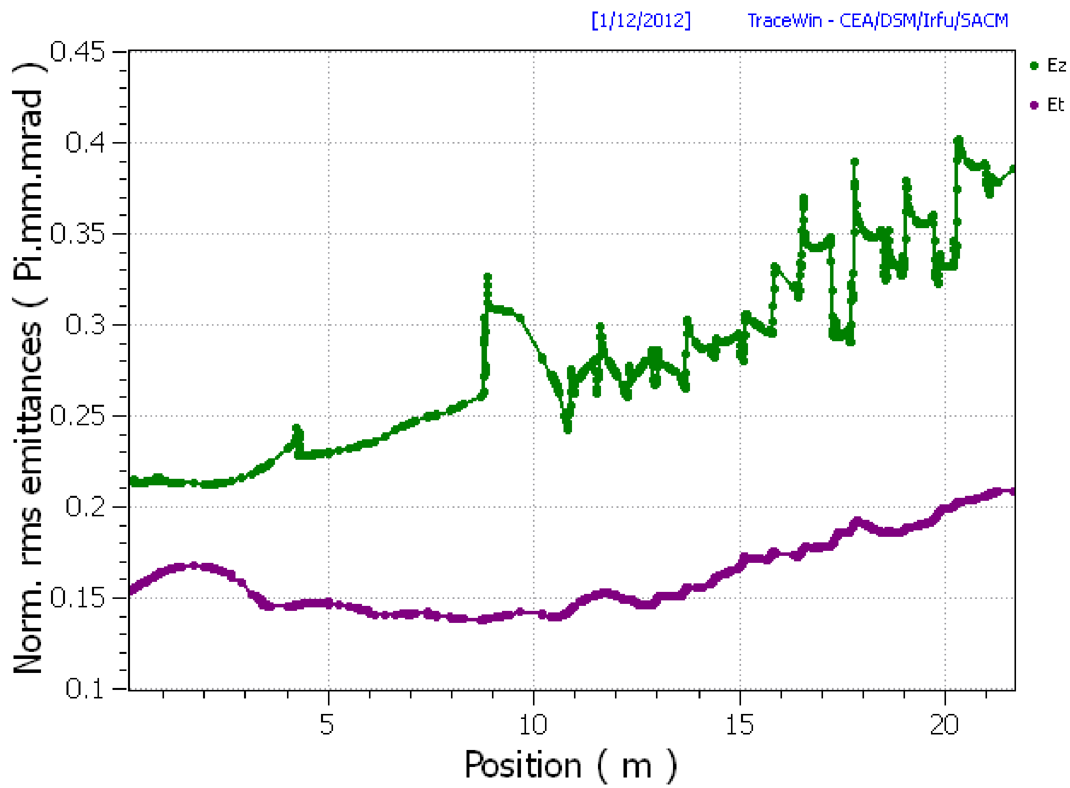
Current 5 mA@162.5 MHz; Energy: 2.1 MeV – 10.8 MeV – 22.1 MeV



Transverse (top) and longitudinal (bottom) rms beam envelopes (TraceWin)

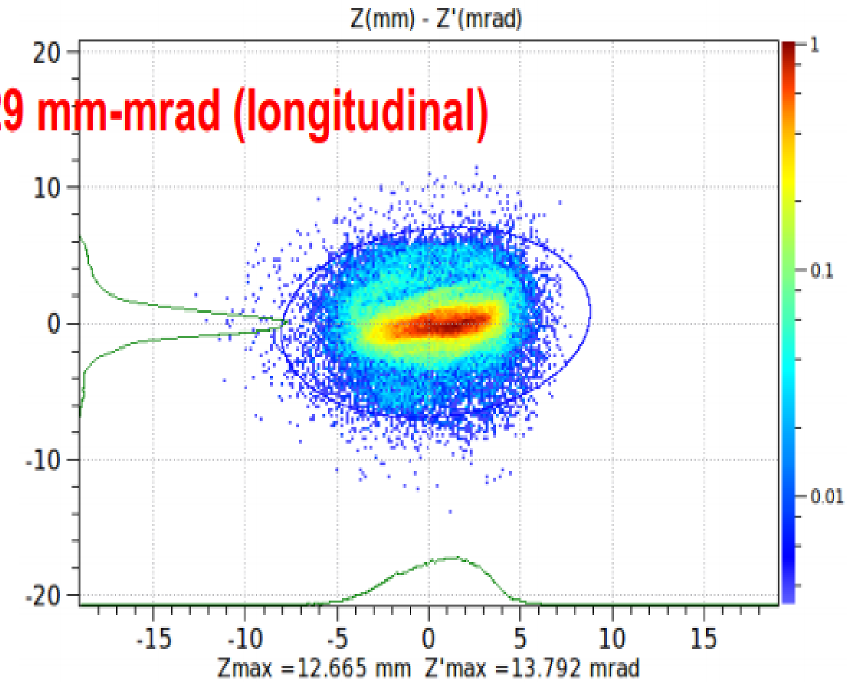
Beam Transport Simulations with Space Charge (2)

- Transverse and longitudinal focusing are adjusted to compensate space charge effects.
- Space charge does not produce harmful effects and does not produce noticeable beam loss
- However the growth of longitudinal emittance is not negligible
  - Long. emittance growth would be smaller for initial Gaussian distribution



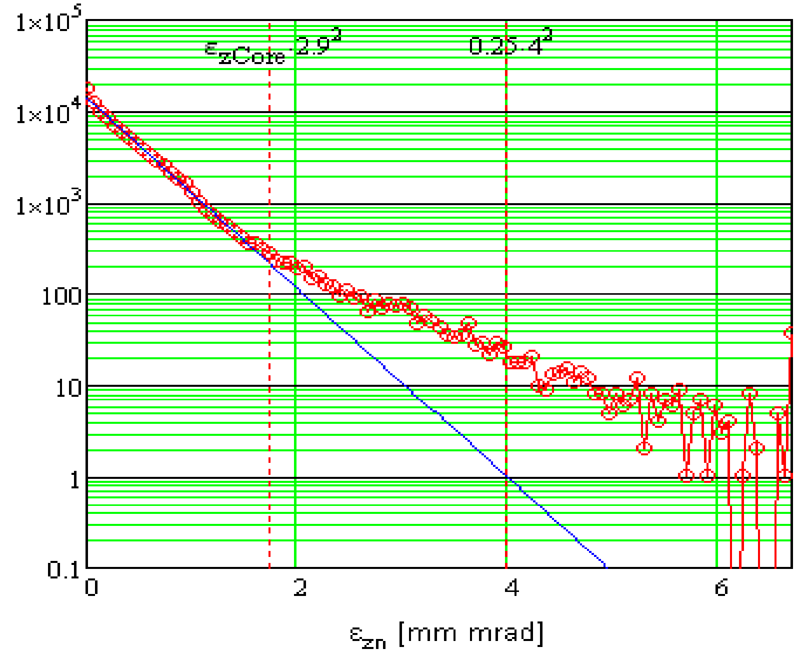
Dependence of longitudinal (green) and transverse (red and blue) rms emittances on longitudinal coordinate from the RFQ exit to the SSR1 end for 5 mA beam current (peak). RFQ exit distribution is used as initial particle distribution.

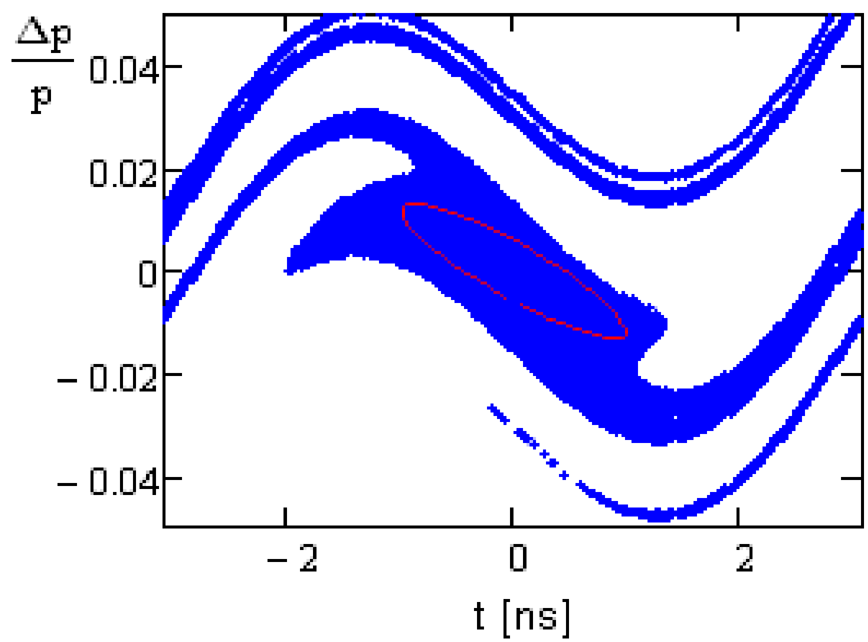
RFQ Tails & Particle Extinction



Long. distribution at RFQ output for ideal Gaussian beam at LEBT input; total bucket length is 123 mm

- RFQ tails will result in additional loss in further acceleration in Project X linac
- Characterization of tails and ways of mitigation of tails related problems are important part of PXIE program
- RFQ tails can be a mechanism limiting particle extinction for removed bunches

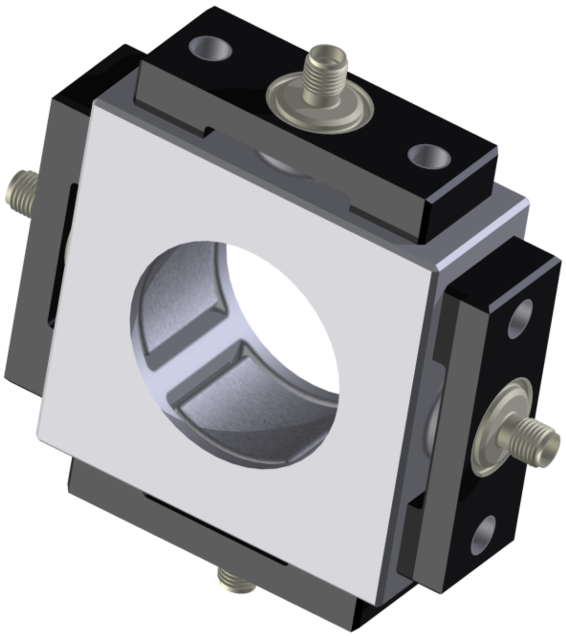




Long. phase space at beam chopper location for particles accepted for further acceleration (blue dots). Red line shows 4σ bunch boundary. Particles within ~9σ cannot be accepted to other buckets

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.

Summary

- Stable proposal: No change in PXIE design for > 1 year
  - PXIE design and optics represent our present understanding of the Project X frontend design and optics
    - Can serve as Project X frontend
  - Major part of beam physics design for PXIE is complete
  - Impressive progress with technical design
    - Bunch-by-bunch kicker and MEBT absorber
    - SC cryomodules
      - both HW and SSR1 cryomodules are at final stage of design
      - Tests of SSR1 cavities are in progress
- Stable optics: loss of SC cavity or solenoid only marginally effects machine operation
- Organization is in place and functioning
  - Published the PXIE design handbook
  - Developed RLS & adjusted the schedule to align with projected budgets
    - Funding significantly slows down the PXIE R&D
- Our studies show that PXIE has enough "freedom" and "leverage" to achieve the beam parameters required for the Project X