PXIE and Project X

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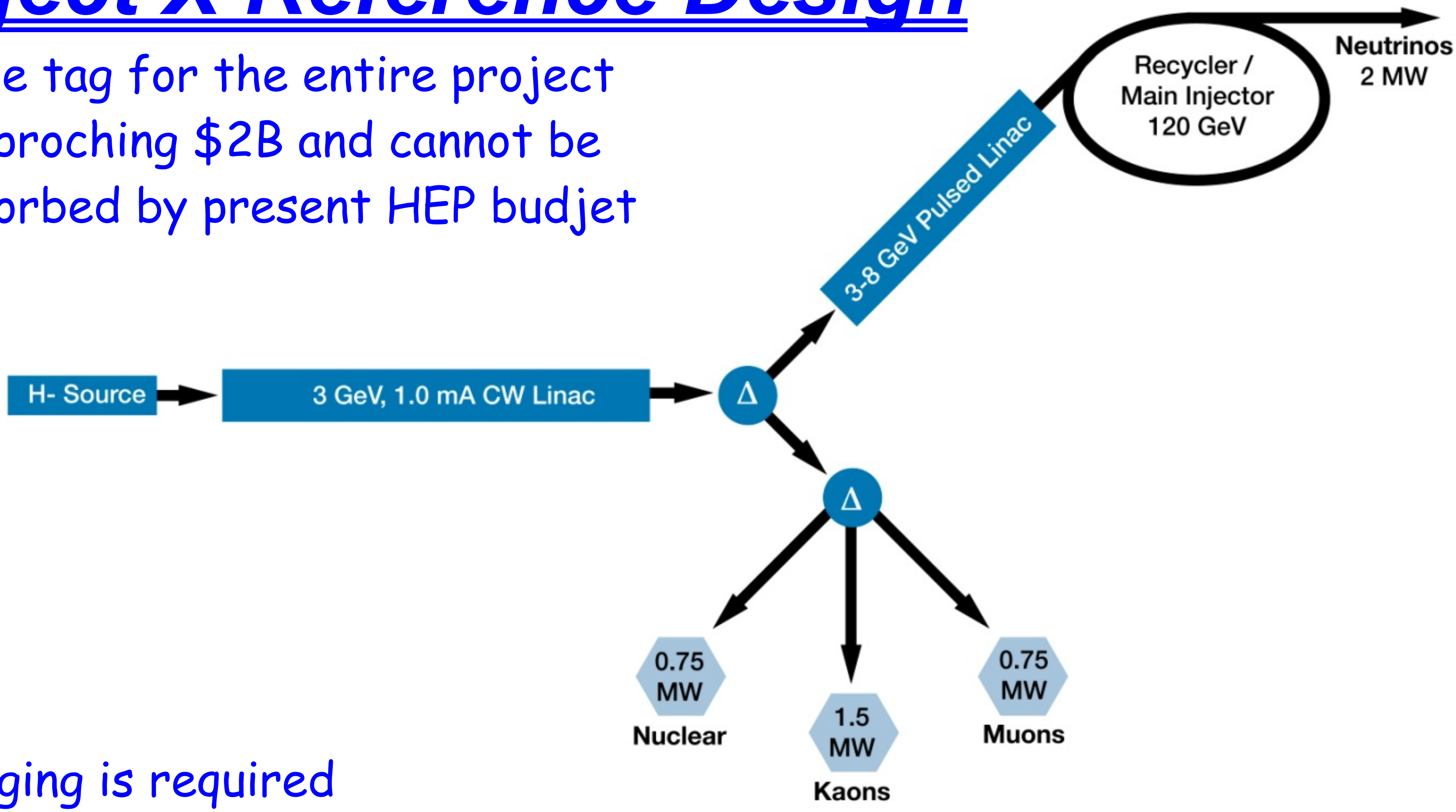
Contents

SLHiPP-2
Catania, Sicily
May 3-4, 2012

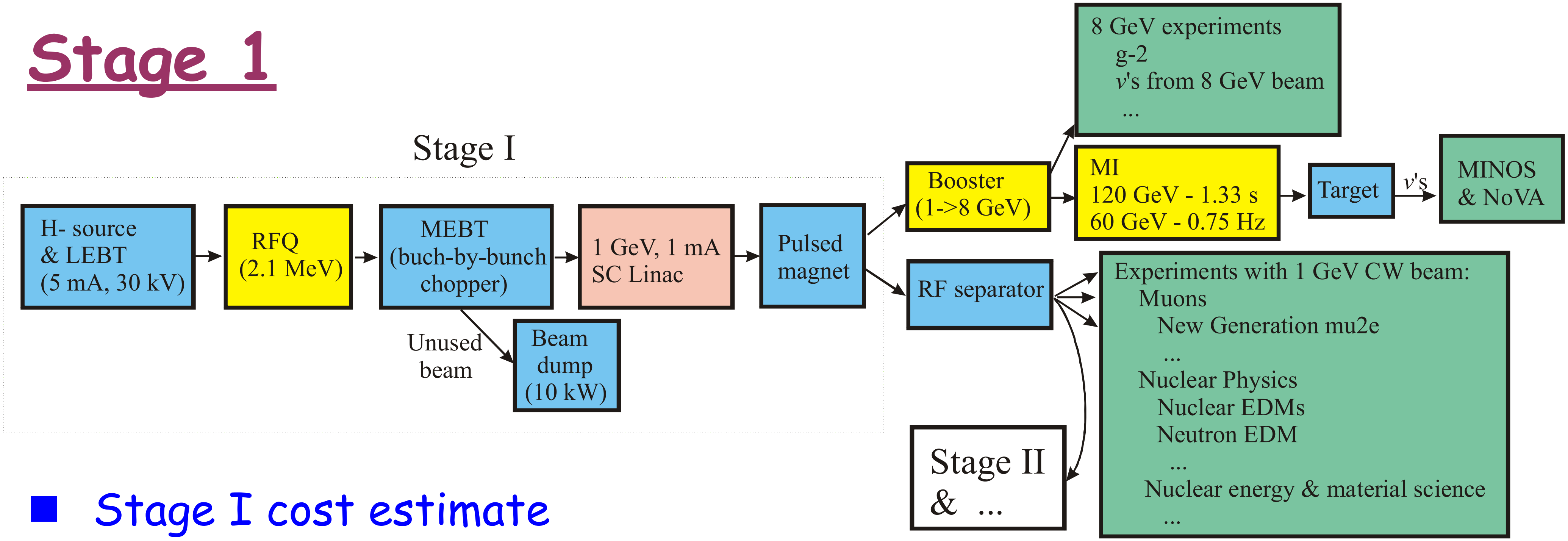
Project X Reference Design

- Price tag for the entire project is aproching $2B and cannot be absorbed by present HEP budjet

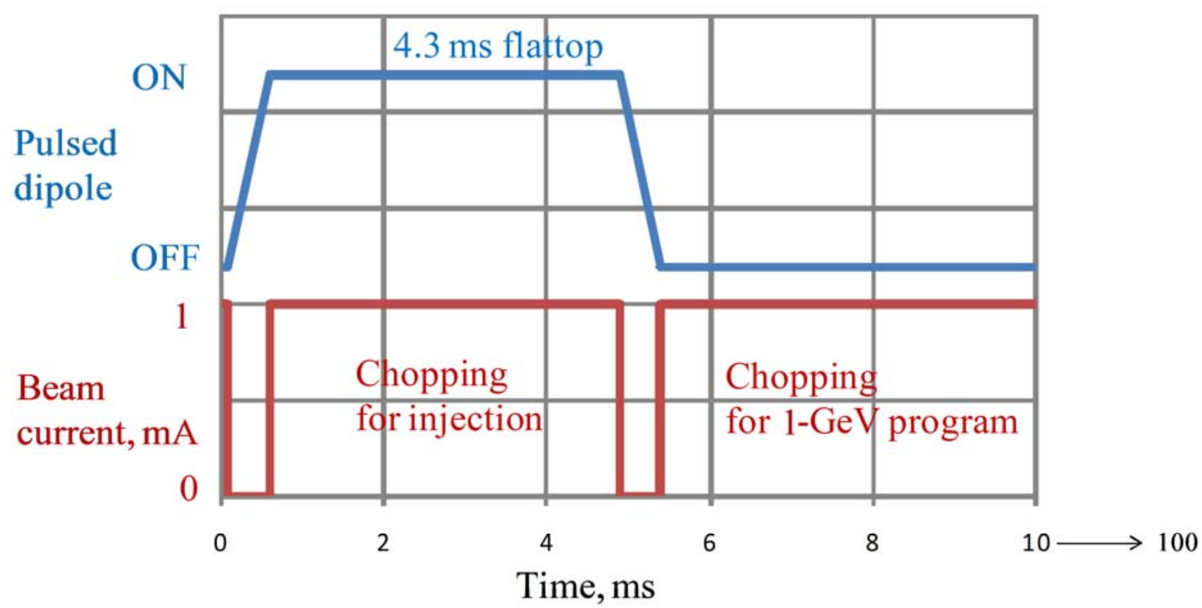


- Staging is required
- Stage I – 1 GeV CW linac with beam injection to existing Booster
  - It can support
    - all CW experiments except kaons
    - can more than double proton flux for MI neutrino program (NoVA, LBNE?) with moderate increase of beam power

Stage 1

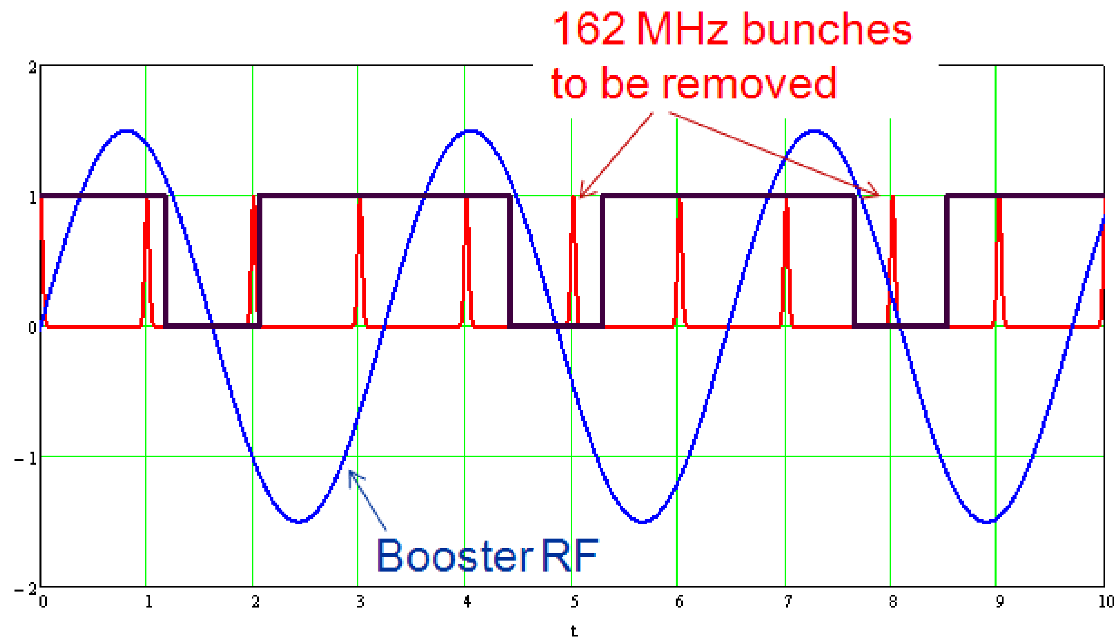


- Stage I cost estimate
  - well under $1B
- Active discussion of Project X physics program is going
- 2 mA in SC linac can significantly strengthen the program
  - ~$30M price increase



Stage 1: Injection to Existing Booster

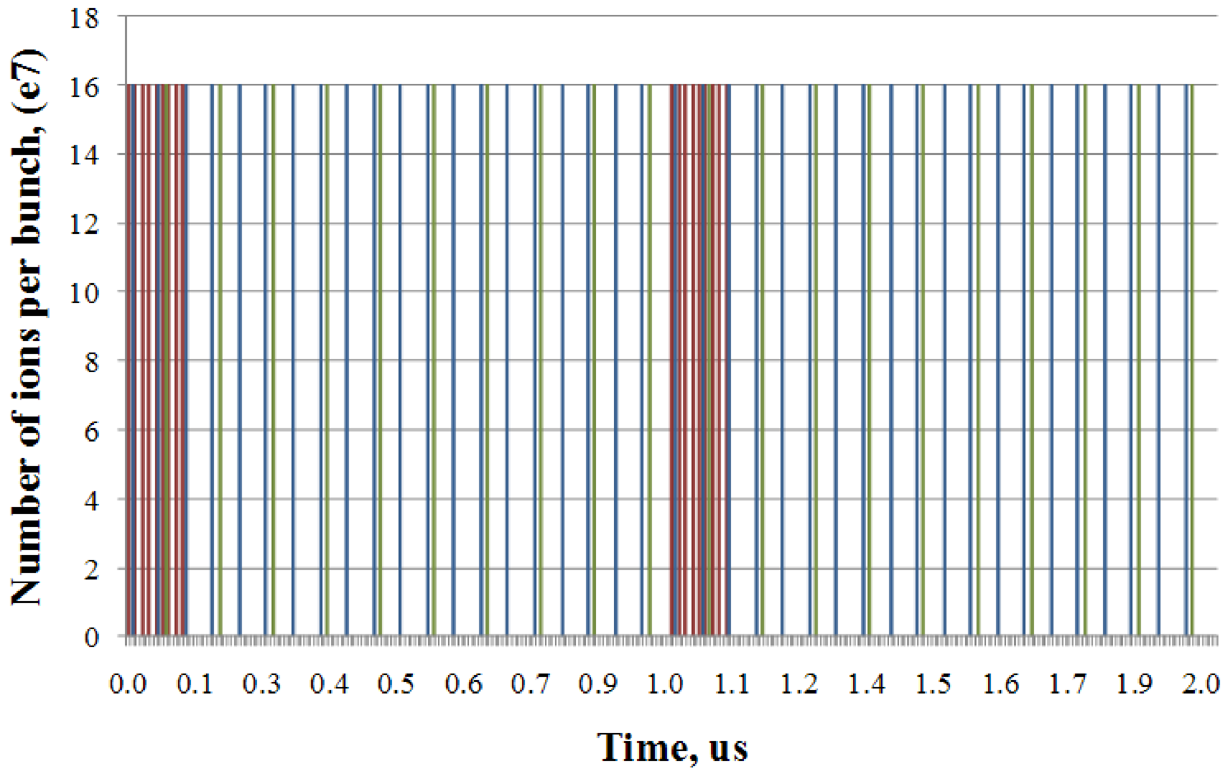
- Injection energy increase: 0.4→1 GeV
  ⇒ Space charge tune shift is decreased ~2.5 times ($\propto \beta\gamma^2$)
  - But other limitations
    - transition crossing
    - instabilities in Booster and MI
  - We expect ~1.5 times intensity increase

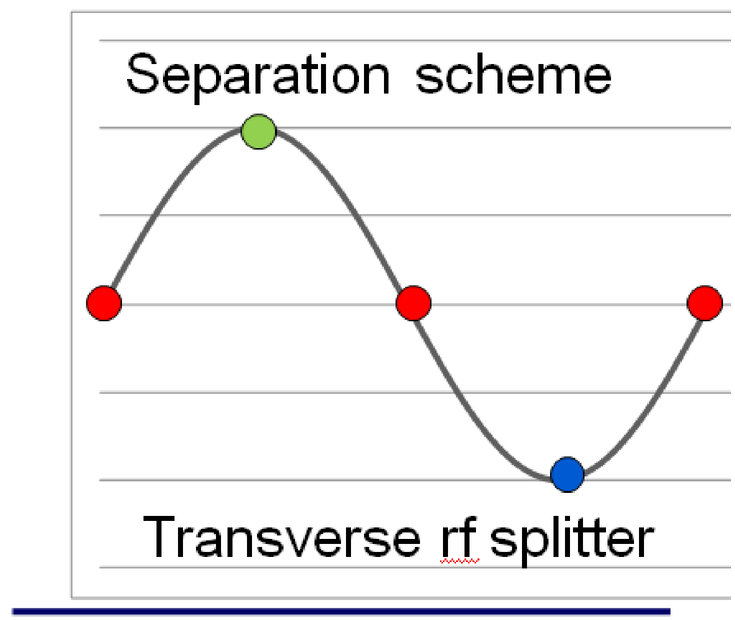


- 1 mA, ~1.1 ms at 15 Hz; gives $6.7\cdot10^{12}$ protons per cycle (50% increase versus present $4.5\cdot10^{12}$)
  - 20 Hz booster operation is discussed to make an additional increase of Booster power to support LBNE goals (MI: E_{kin} =120→60 GeV, P=700 kW)
- Chopping for injection at 1 GeV is similar to the RDR
  - RF frequency at injection into the Booster : ~46.5 MHz
- Chopper needs to provide a kicker gap (~100 ns per 1.8 μs) and needs to remove bunches that fall into "wrong" phase of ring RF voltage.

Stage 1: Chopping and Splitting

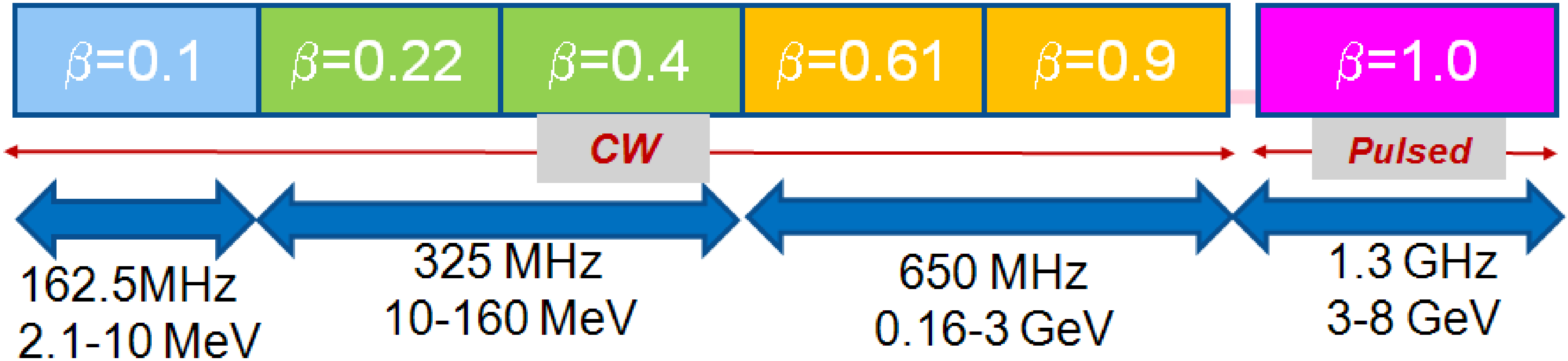
- Bunch sequence for each experiment is controlled by bunch-by-bunch chopper
  - Ubdesired bunches are removed from uniform RFQ bunch stream
    - Up to ~10 kW beam power goes to the MEBT beam dump





SRF Linac Technology Map

- 5 types of SC cavities are required for Stage I



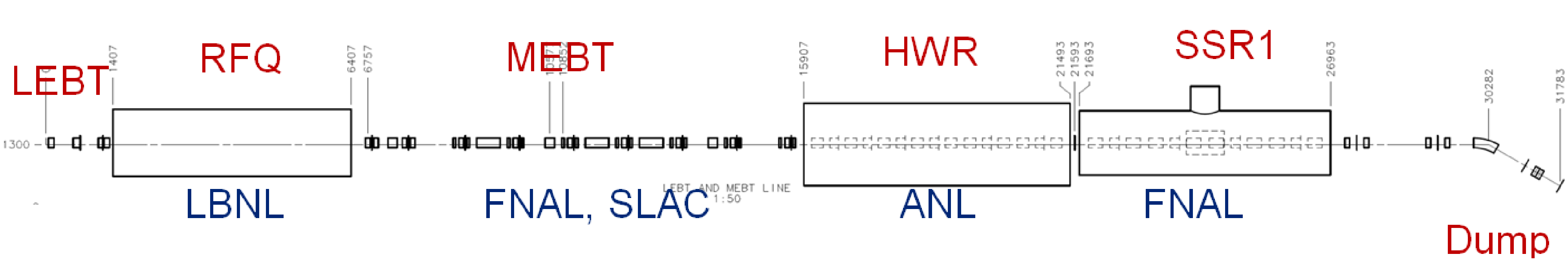
Section	Freq	Energy (MeV)	Cav/mag/CM	Type
HWR (β_G=0.1)	162.5	2.1-10	8 /8/1	HWR, solenoid
SSR1 (β_G=0.22)	325	10-42	16/8/ 2	SSR, solenoid
SSR2 (β_G=0.47)	325	42-160	36/20/4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-460	42 /14/7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	460-3000	152/19/19	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 /28 /28	9-cell elliptical, quad

PXIE – Project X Injector Experiment

- Key Project X R&D areas
  - Beam chopping
  - RFQ tails and Low-beta SCRF acceleration
  - Stripping injection

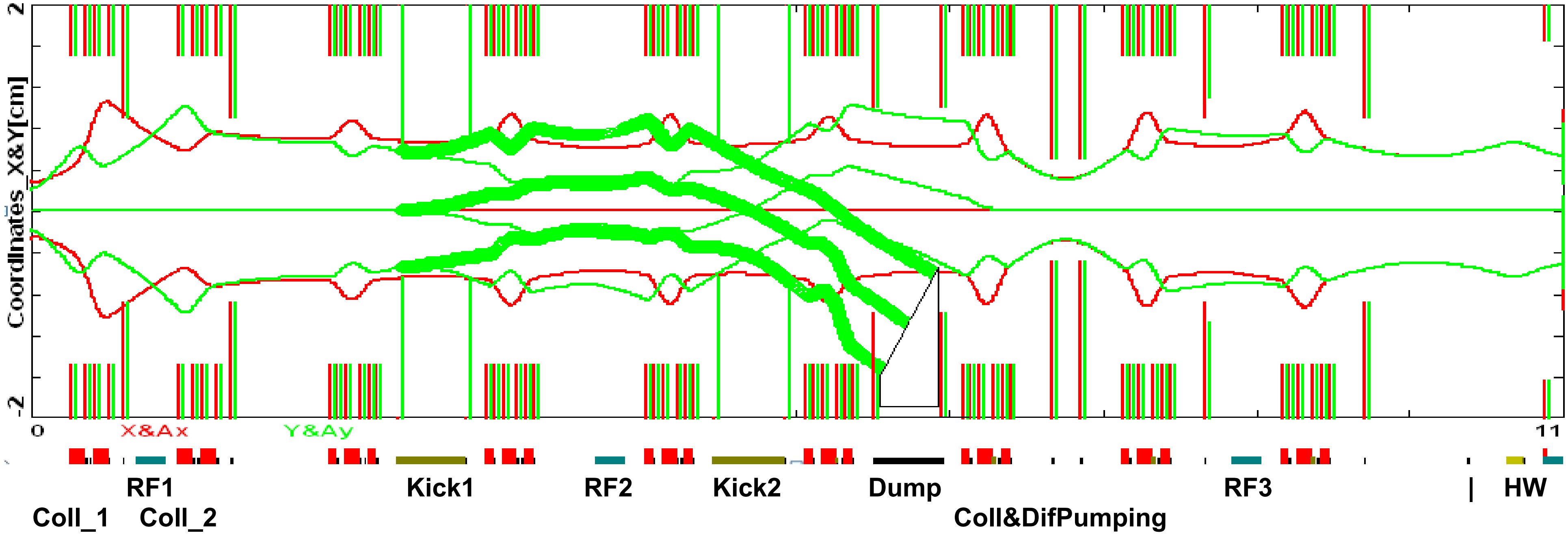
  (Beam chopping; RFQ tails and Low-beta SCRF acceleration: Addressed by PXIE program)
- PXIE is an integrated systems test of the Project X first ~25 MeV
  - Validate the concept for the Project X front end, thereby minimizing the primary technical risk elements within the Reference Design.
    - Demonstrate wideband chopper; low-β acceleration
    - Operate at full design parameters
- Goals (to be achieved by 2016)
  - 2 mA average current with 60-80% chopping of ion source beam
    - 5 mA peak, arbitrary bunch chopping
  - Beam acceleration to ~25 MeV with nearly final parameters
  - Demonstrate high extinction for removed bunches
    - Minimum goal $<10^{-4}$
    - Optimistic goal (as desired by μ-to-e experiment) $\ll 10^{-9}$
- Collaboration between Fermilab, ANL, LBNL, SLAC, India

Main PXIE Parameters



- CW H^- source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping (needed for machine tuning)
- CW RFQ operating at 162.5 MHz and delivering 5 mA at 2.1 MeV
- MEBT
  - Beam diagnostics
  - Wide-band chopper and beam absorbers capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing up to 5 mA average beam current
- Low beta superconducting cryomodules: 2 mA; 2.1-11 & 11-25 MeV
- Diagnostics line with beam dump
  - Beam dump: CW beam, 30 MeV, 50 kW beam
  - Beam diagnostics to measure distribution tails and beam extinction
  - Utilities and shielding

Major PXIE Features

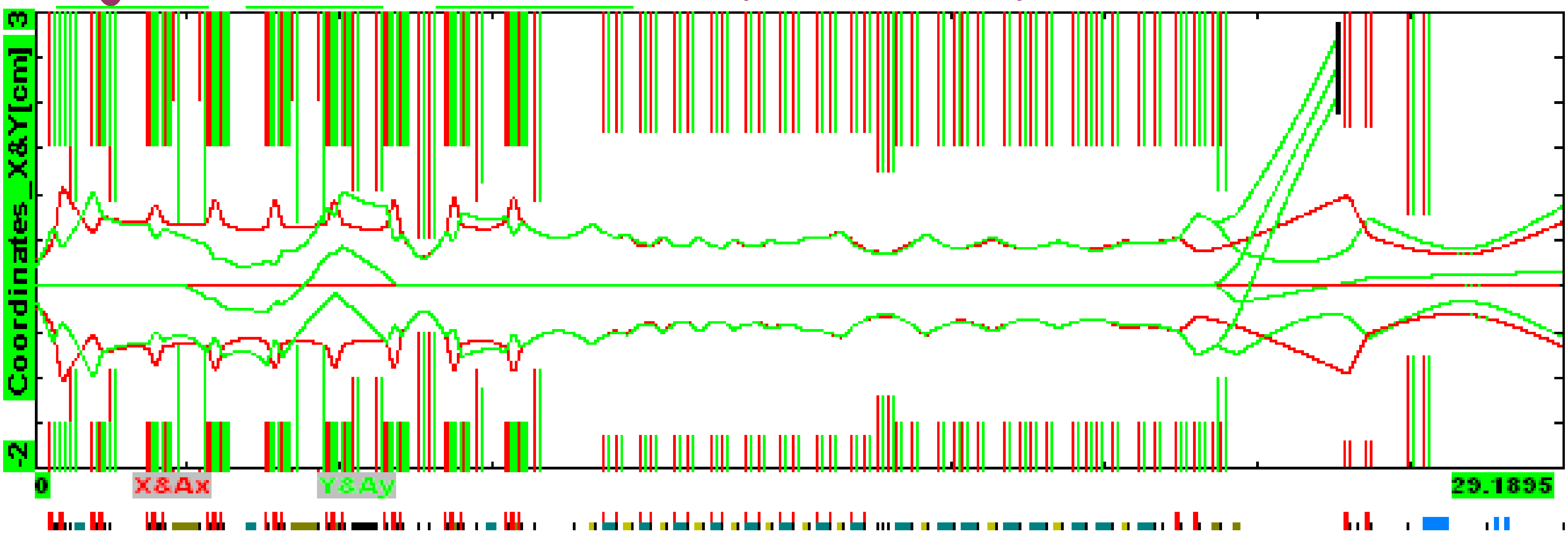


*3σ beam envelopes (ε_{rms_n}=0.25 mm mrad); v. kick is excited by kickers (U=±200 V, 13 mm gap, 2*0.5 m)*

- "Adiabatic optics"
  - small β-function variation
  - Mitigation of space charge
- LEBT
  - LEBT chopper
    - Supports machine tuning in pulsed mode: $\Delta t \sim 1\ \mu s - 1$ ms, f_{rep}= 60 Hz

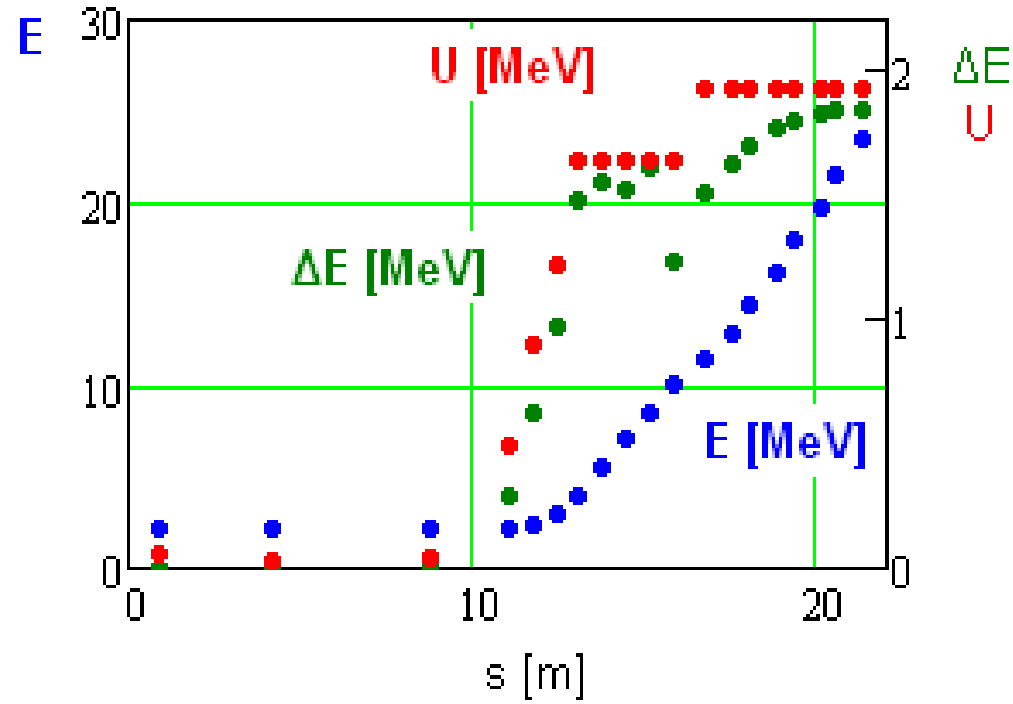
- 162.5 MHz RFQ
  - lower RF power
  - freq. low enough for bunch-by-bunch chopping: $T \approx 6.2$ ns
- MEBT
  - "Two-kickers chopping" makes chopping possible with present technology
  - 11 kW beam dump

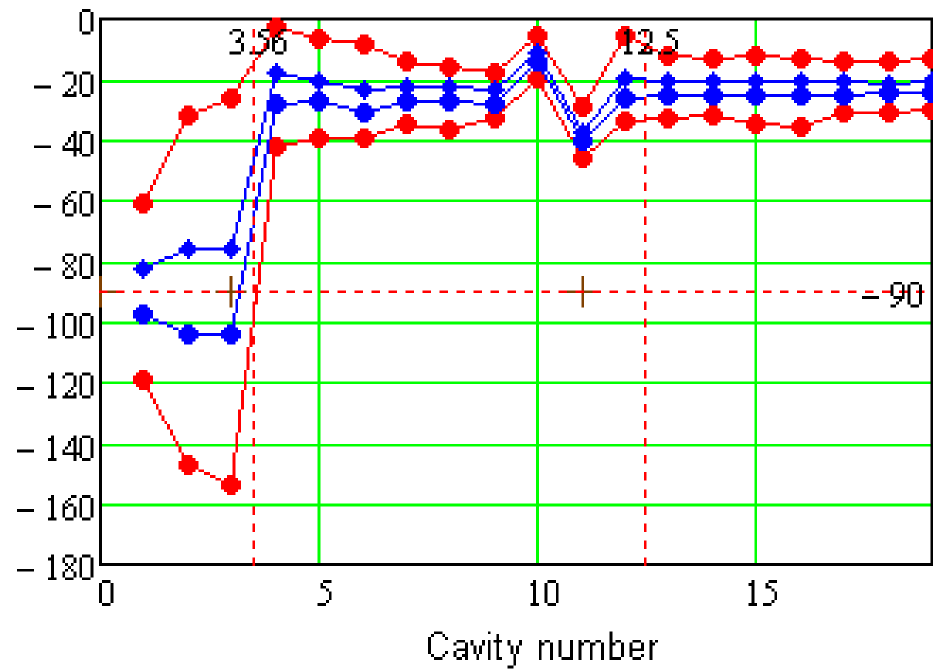
Major PXIE Features (continue)



- SC cryomodules operating at 2 K
  - Solenoidal focusing
  - Warm gap between cryomodules
  - Fast vacuum valves at both sides of the cryomodules
- Diagnostics line
  - RF separation for beam extinction studies, f=1.5*162.5 MHz
    - Can help in measurements of bunch length and longitudinal tails
  - Spectrometer
  - 50 KW beam dump can support operation up to 2 mA beam current

Acceleration in SC Cryomodules



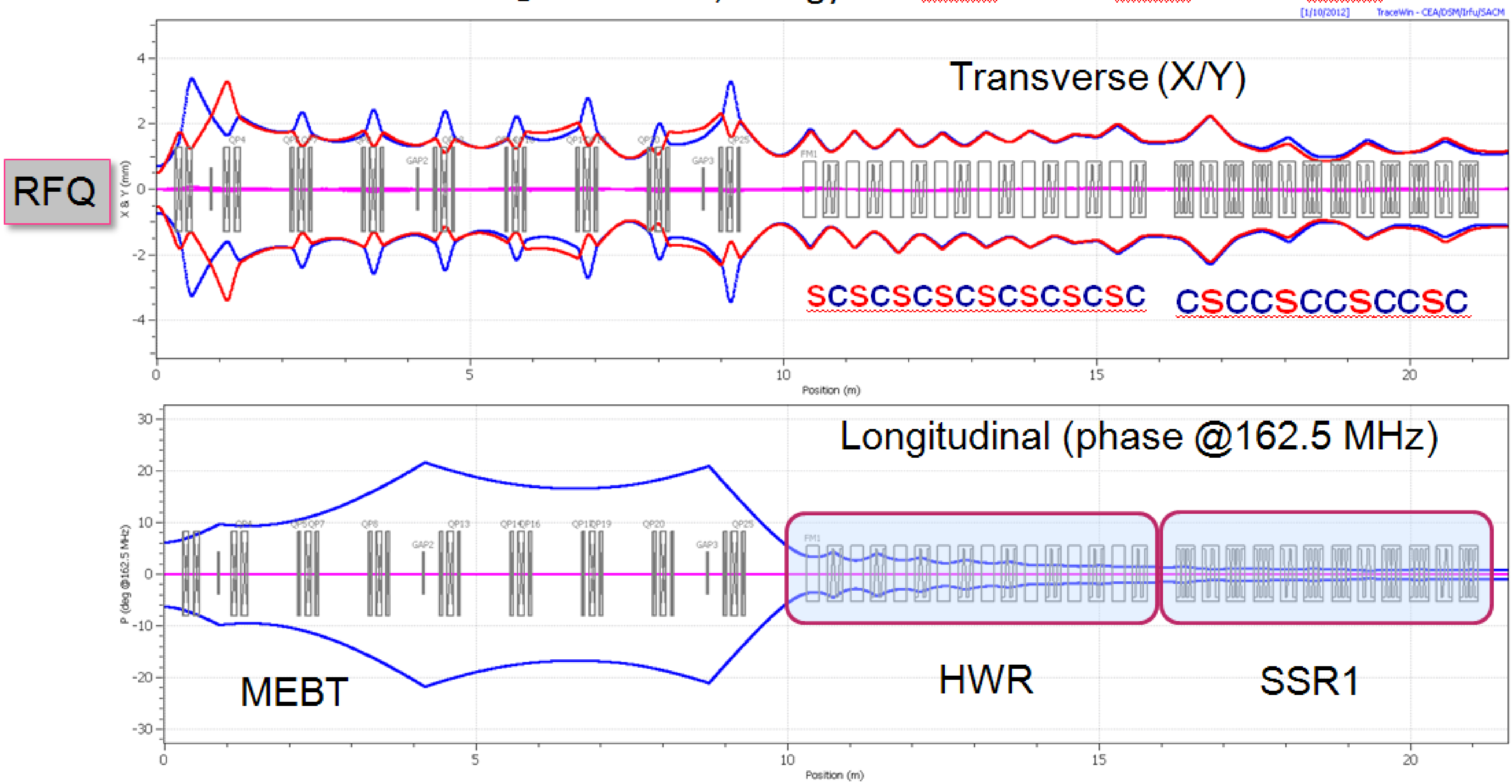


1σ and 4σ bunch ends relative to the accelerating phase [deg]

- Accelerating gradient of the first 3 SC cavities is reduced due to longitudinal overfocusing
- Design intent for operating voltages are: 1.7 MV – HW & 2 MV SSR1
- To support reliable operation the accuracies of RF voltage and phase should be better than 1% and ~0.5 deg

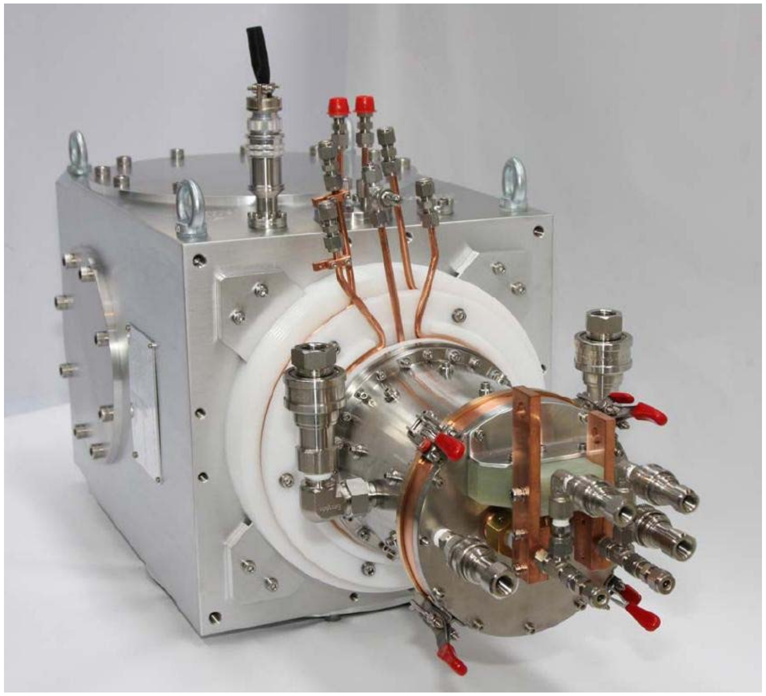
Beam Transport Simulations with Space Charge

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

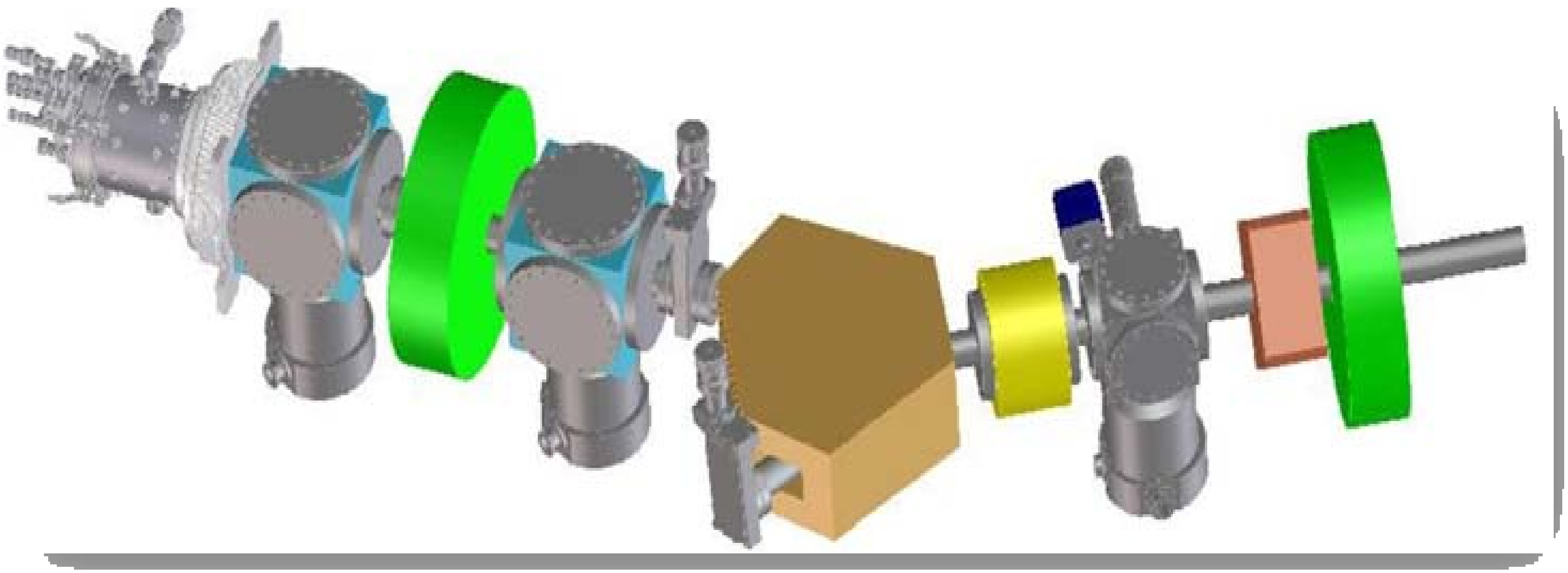


- SC – CS transition between cryomodules
- Moderate emittance growth – 40% - transverse; 60% - longitudinal

Ion Source and LEBT



- The ion source is capable of 15 mA
  - Beam energy -30 kV
- LEBT RFQ and MEBT are designed to 10 mA
- LEBT with 3 solenoids are discussed
  - Better differential pumping
  - More reliable chopping
  - It is longer ⇒ larger emittance growth due to absence of compensation in the second half of the beam transport



RFQ

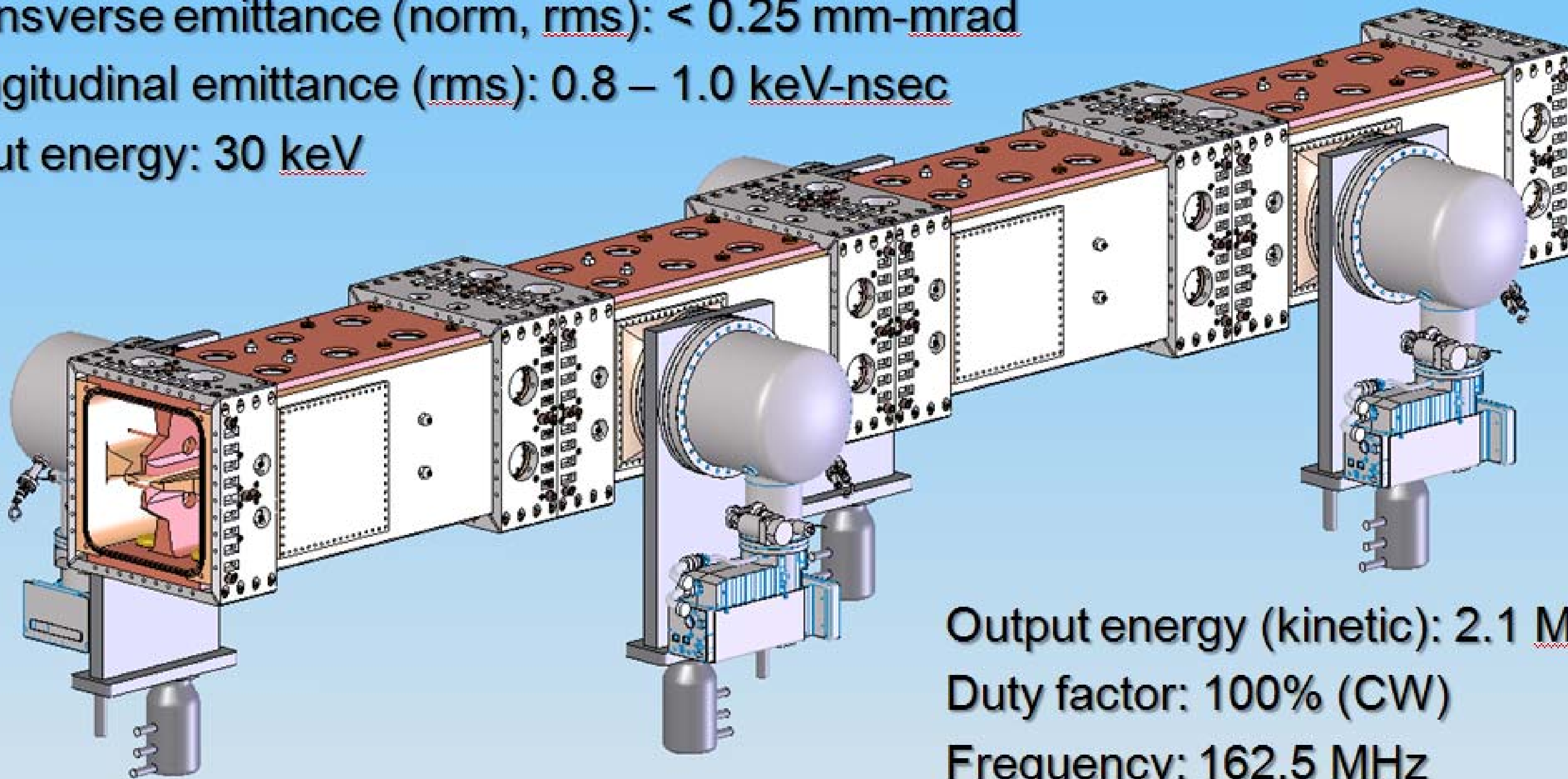
Ion type: H-

Beam current: 5 mA (nominal); 1 – 10 mA

Transverse emittance (norm, rms): < 0.25 mm-mrad

Longitudinal emittance (rms): 0.8 – 1.0 keV-nsec

Input energy: 30 keV



Output energy (kinetic): 2.1 MeV

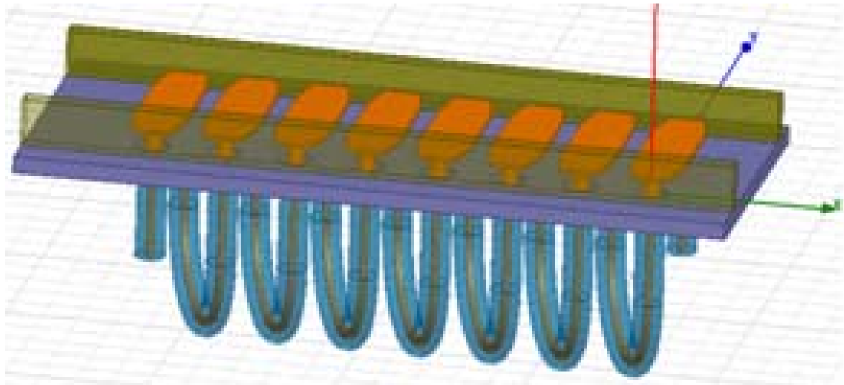
Duty factor: 100% (CW)

Frequency: 162.5 MHz

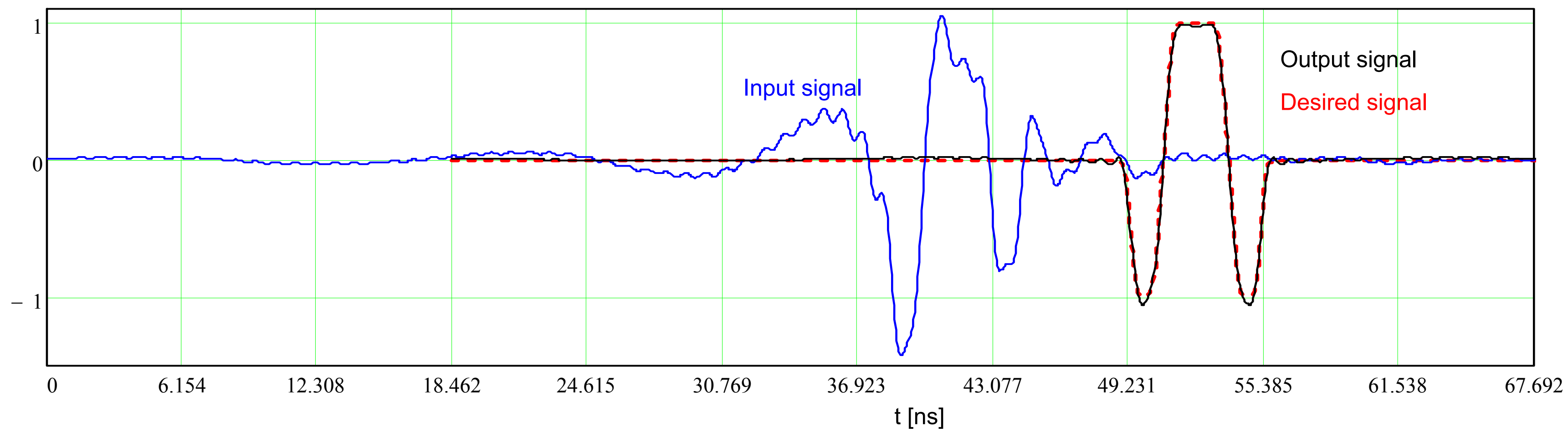
Length: ~4.4 m

- Power source – 2 RF amplifiers, 75 kW each

Bunch-by-Bunch Chopper

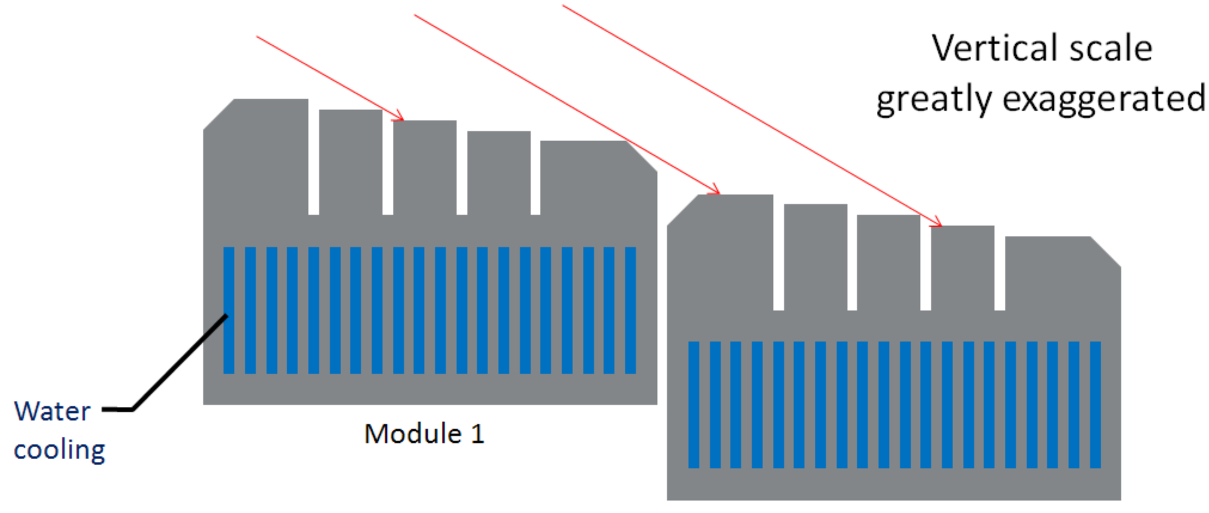


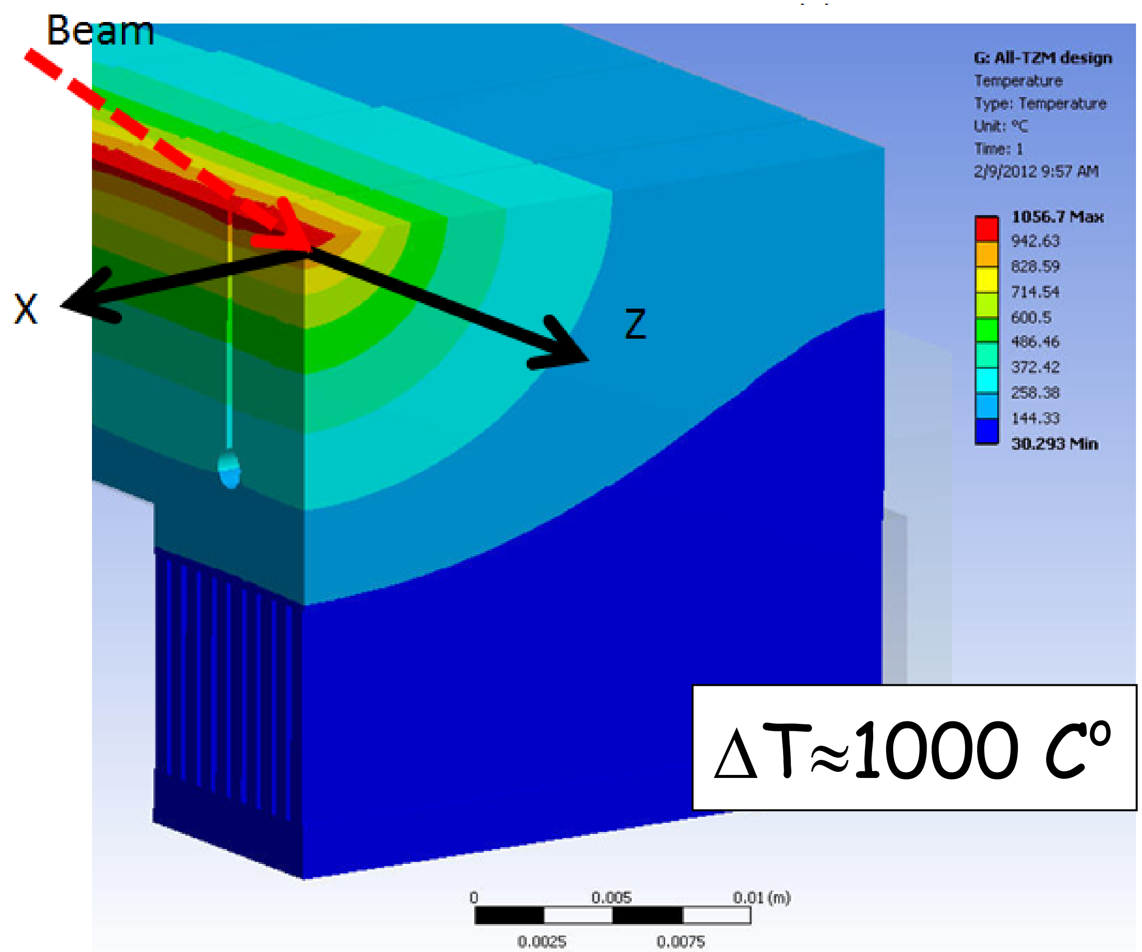
- 2 designs are investigated
  - 50 Ω – plates connected by cables; powering from wide band amplifier
    - Looks like no show-stoppers left
  - 200 Ω – helical coil with plates attached; powering is based on a transistor switch
    - proceeds well
- Pulse pre-distortion allows forming nearly perfect pulses with commercial amplifier (1 kW, 50 – 1000 MHz, ~±300 V)



MEBT Beam Dump

- 21 kW in $\sigma_x \approx \sigma_y \approx 2$ mm
- High power density in the beam, ~80 kW/cm^2
  - 29 mrad grazing angle $\Rightarrow$ 2.2 kW/cm^2
  - micro-channel cooling
  - 650 mm available length
- Spattering and blistering
  - ~0.2 mm/year
  - TZM alloy has high endurance to blistering and good relationship between thermal expansion, Young's modules and yield stress
- ~25% beam power is reflected due to multiple scattering, σ_θ~100 mrad

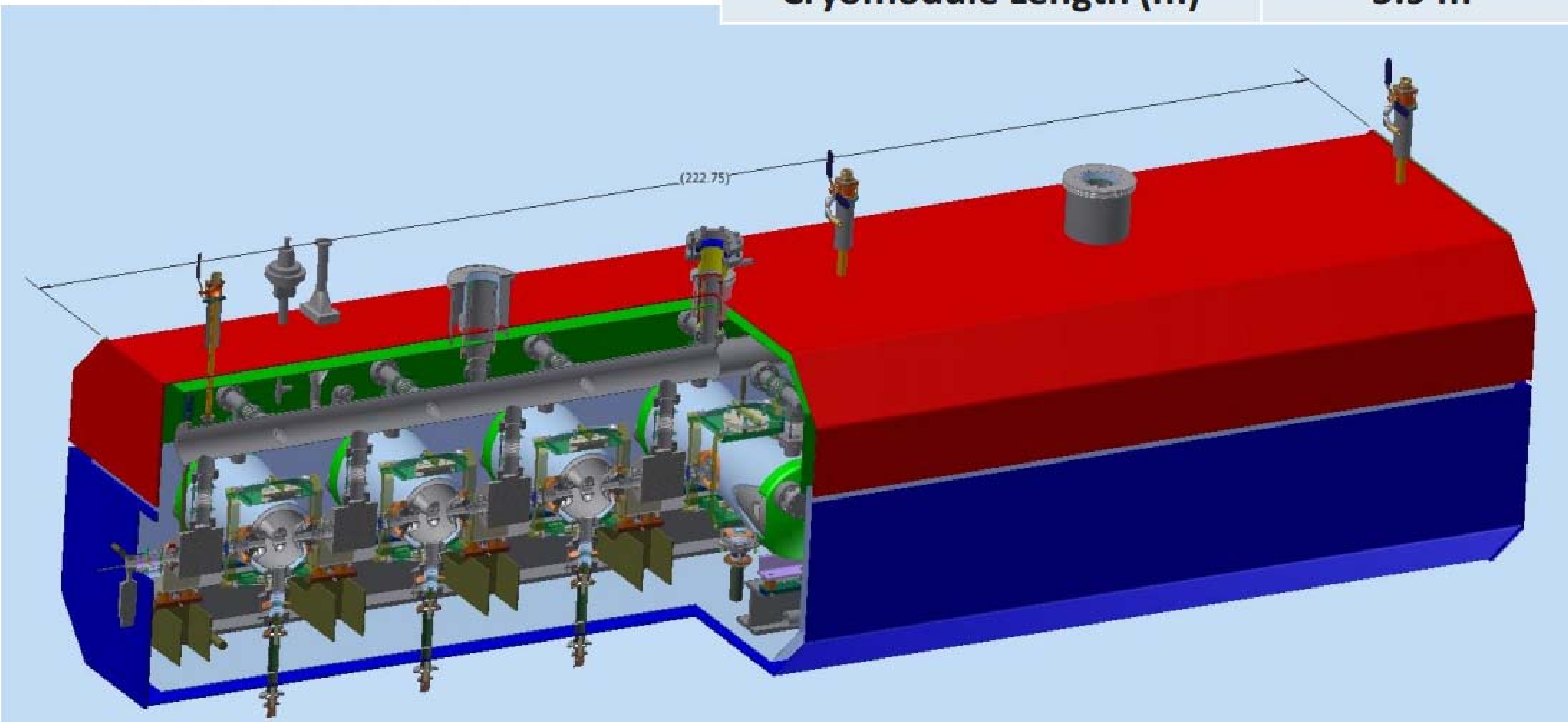




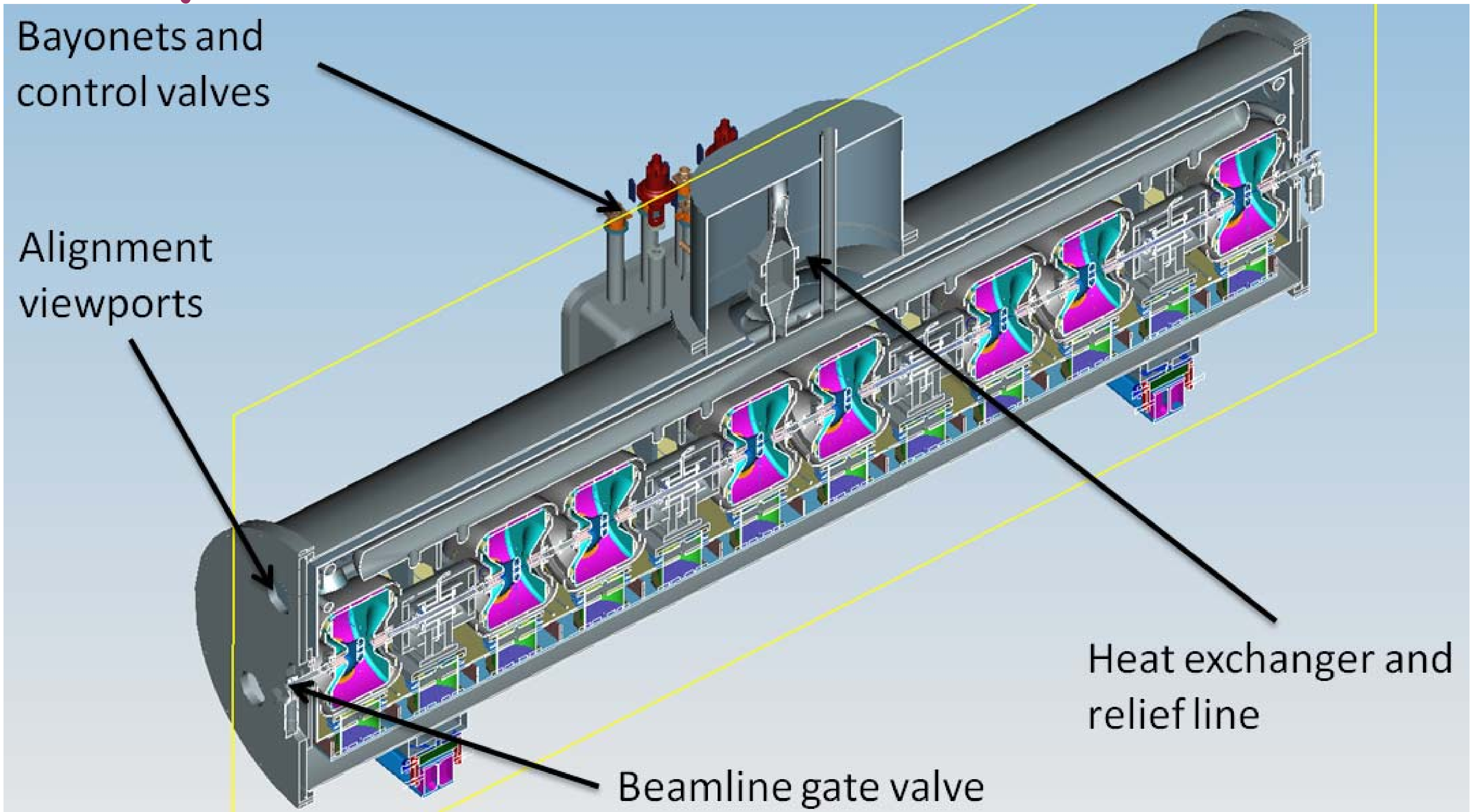
HW Cryomodule (ANL)

- Remaining detailed design work
  - He distribution system
  - Vacuum vessel with thermal and magnetic shielding

Parameter	Dimension
Cryomodule Width (m)	1.6 m
Cryomodule Height (m)	1.8 m
Cryomodule Length (m)	5.9 m



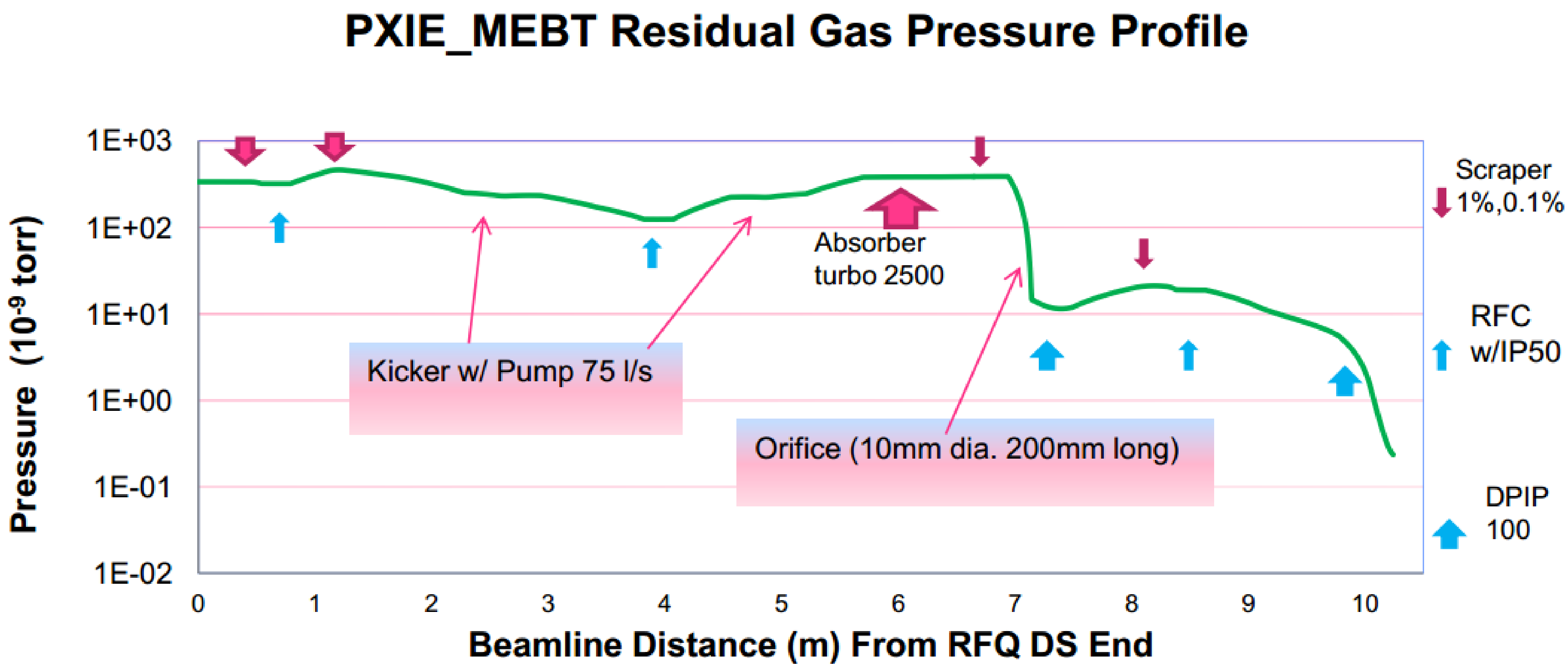
SSR1 Cryomodule (Fermilab)



- Good progress with design work
  - Coupler is designed and its test should proceed soon
  - Cryo-vessel design suppresses df/dP
    - Mechanical tuner with piezo-tuner for microphonics control
  - Solenoid with active shielding
    - button BPM is bolted to solenoid

Vacuum

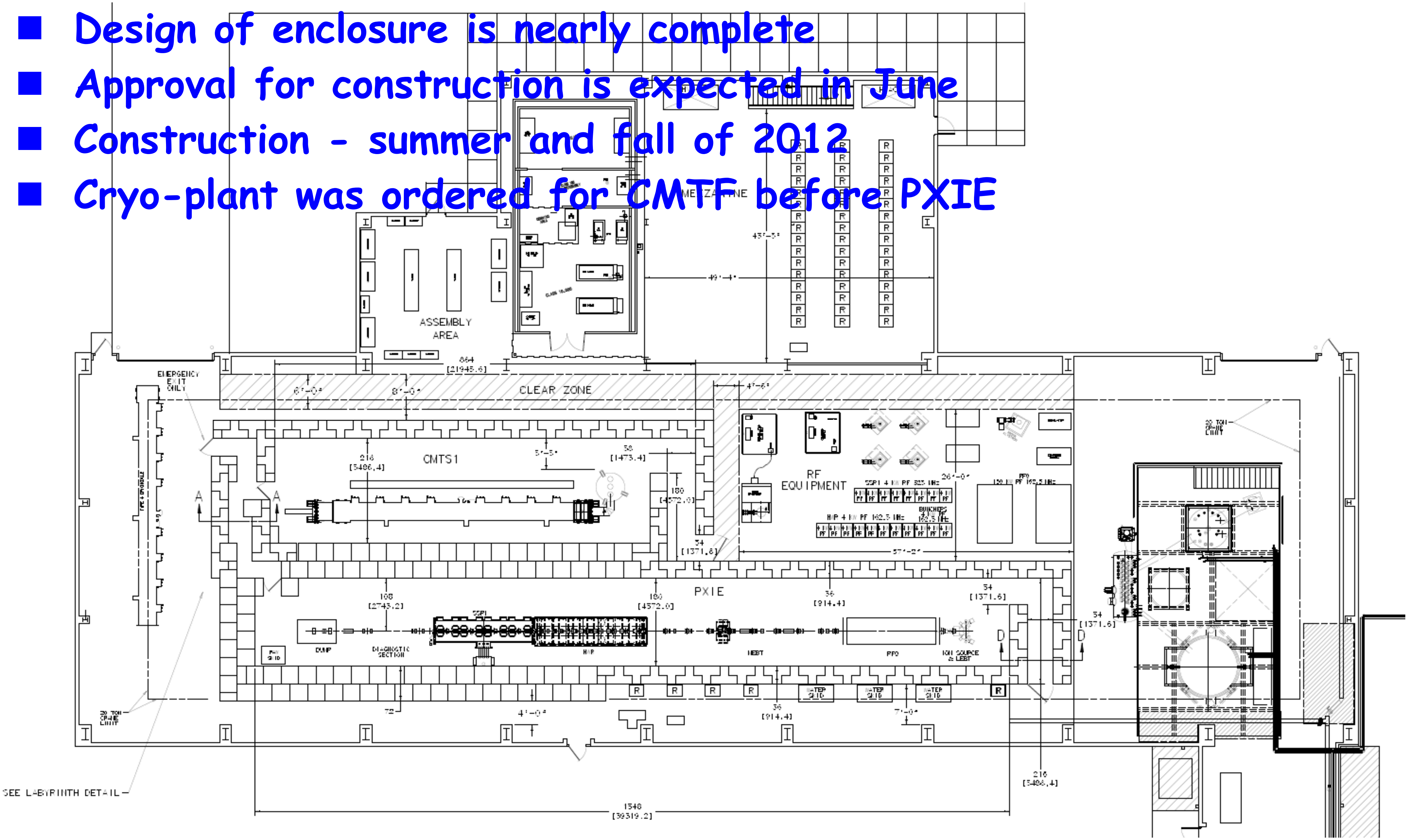
- Large pumping speed and differential pumping
  - to support good vacuum in RFQ
  - to reduce H^- stripping on the residual gas in warm sections
  - to minimize degradation of Q-values in SC cryomodules due to contamination by hydrogen and other species
- Incoming H^- beam brings large volume of H_2 : 5 mA = $4.4 \cdot 10^{-4}$ $l \cdot torr/s$



beam tube has 1.37" id.

PXIE Layout

- PXIE will be located in the existing CMTF building (near NML)
  - It takes place of the second cryomodule test stand
- Design of enclosure is nearly complete
- Approval for construction is expected in June
- Construction - summer and fall of 2012
- Cryo-plant was ordered for CMTF before PXIE



PXIE Timeline

- Jan 2012 - Complete PXIE design layout and preliminary cost/schedule estimates
- Nov 2012 - Complete RFQ design and begin fabrication
- Early FY13 - Ion source and LEBT installation begins at Fermilab
- Apr 2014 - Start RFQ high-power testing without beam
- Nov 2015
  - Beam delivered to the end of MEBT with nearly final parameters (2.1 MeV, 2 mA CW, up to 100% arbitrary chopping)
  - Begin installation of β=0.1 and β=0.2 CMs
- Oct 2016 - Beam to 25 MeV with nearly final parameters (2 mA CW, 5 mA peak, arbitrary bunch chopping)

Summary

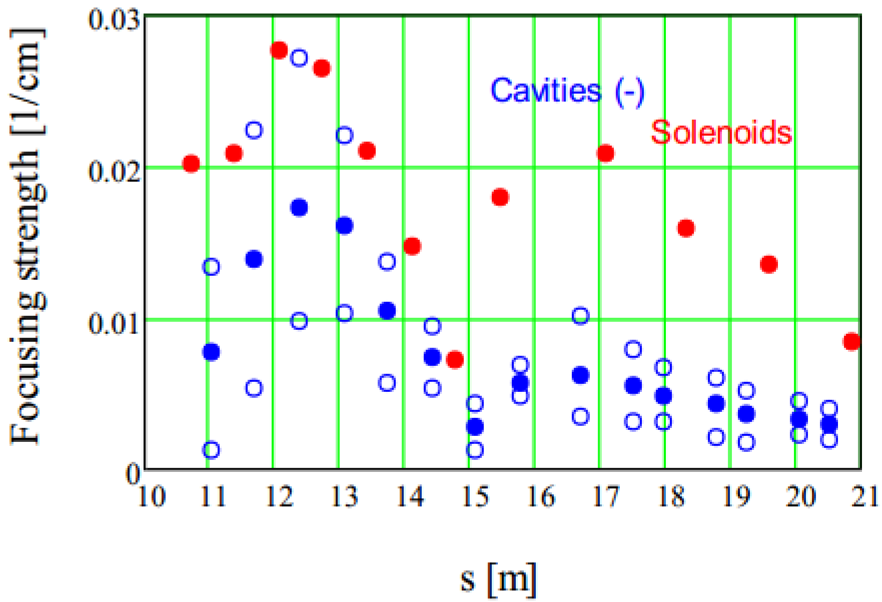
- Project X R&D program is underway with very significant investment in SRF technology
  - PXIE has been identified as a centerpiece of the program – planning, design and technology tests are underway
    - Will address main technical uncertainties with
      (1) chopper kicker
      (2) chopper driver
      (3) beam absorber
      (4) beam extinction for the removed bunches
      Integration test of LEBT, RFQ, MEBT, HWR, SSR1
- More details can be found in presentations of recent Project X collaboration meeting - https://indico.fnal.gov/conferenceDisplay.py?confId=5300

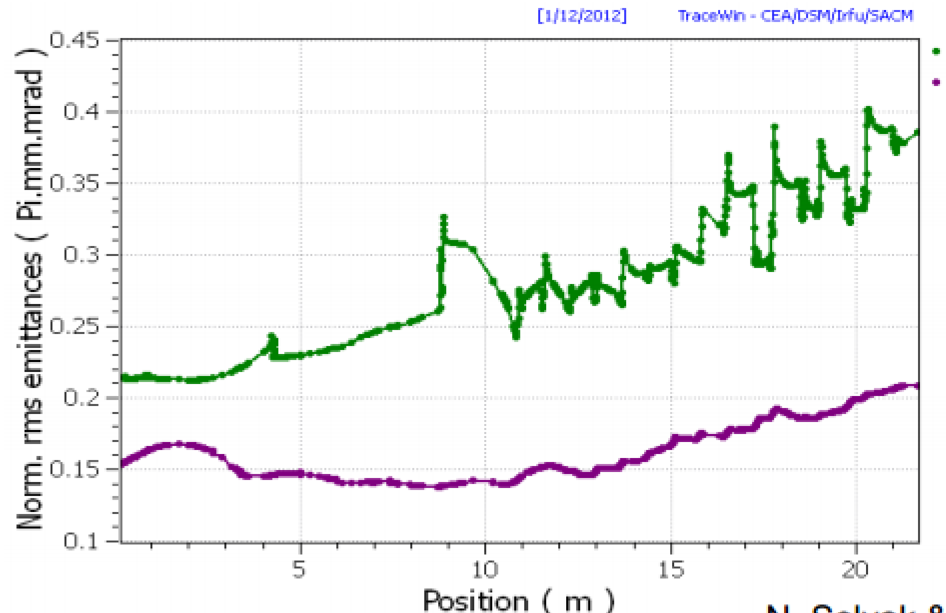
Backup slides

Physics and Engineering Questions for PXIE studies

- LEBT: neutralization, chopper, stability, emittance growth, differential pumping
- RFQ: longitudinal halo formation, high average power, reliability
- MEBT: beam dynamics, chopper driver, chopper kicker, absorber, diagnostics, extinction, differential pumping and vacuum near SCRF cavities.
- HWR: losses, acceleration, effect of magnetic field of solenoids on SCRF cavities, microphonics
- SSR1: losses, acceleration, effect of magnetic field of solenoids on SCRF cavities, microphonics and its control with piezo-tuners, untested cavity design, cavity Q-values and load on a cryogenic system
- Beam line: beam properties, extinction, low losses, measurements of particle distribution tails

Project X
Focusing and Beam Transport in SC Cryomodules

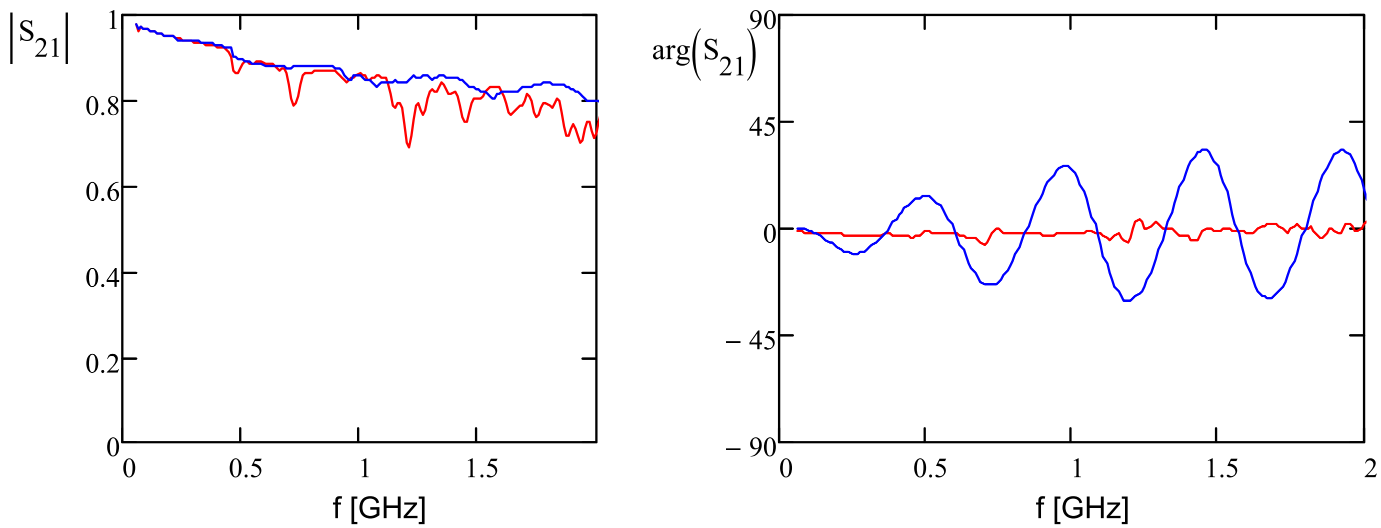




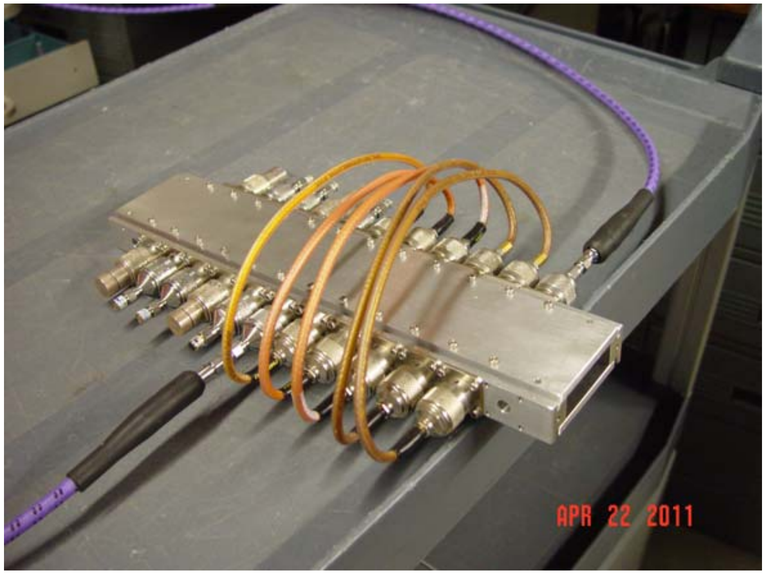
N. Solyak &
B. Shteynas

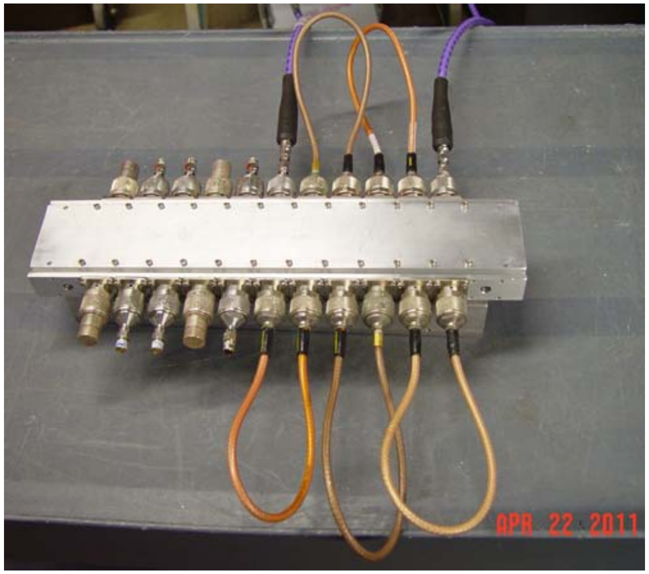
- Defocusing in SC cavities is RF phase dependent
  - That sets minimum focusing strength of the SC solenoids
- Transverse and longitudinal focusing are adjusted to compensate space charge effects.
  - Space charge does not produce harmful effects and does not produce noticeable beam loss
  - However growth of longitudinal emittance is not negligible

Kicker Prototype (continue)



S21 for "helical" (red) and "meander" (blue) connections of 6 electrodes

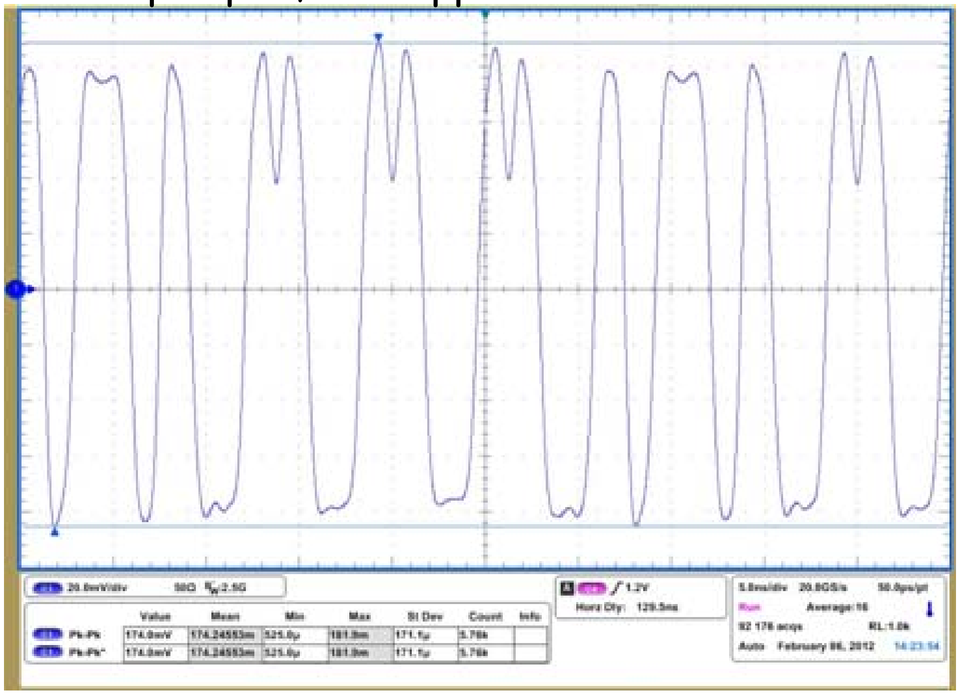




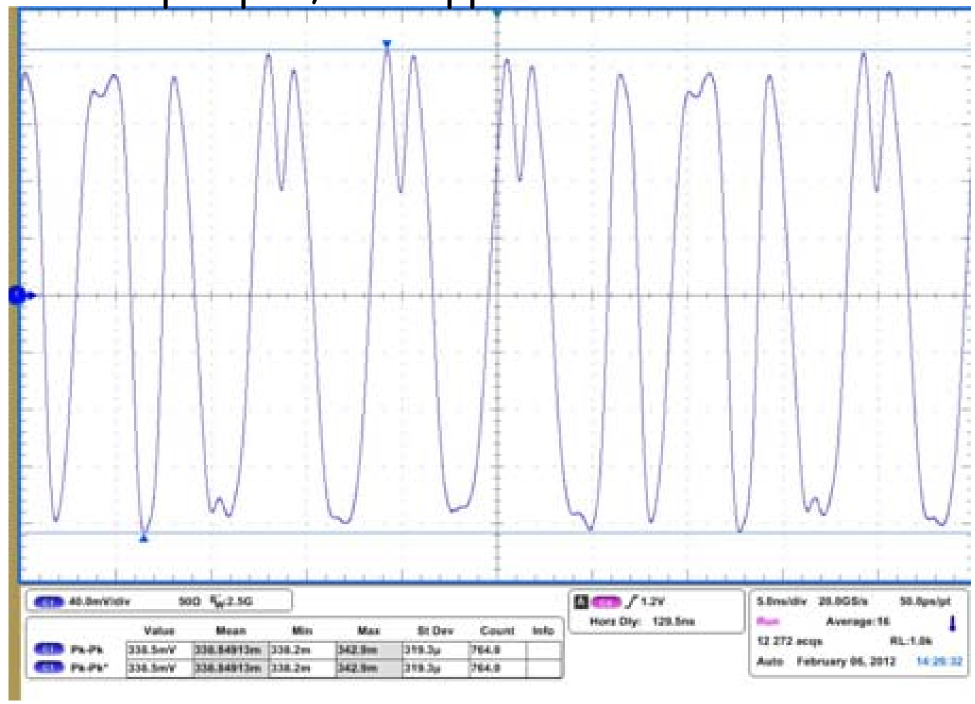
- Obtained results proved the concept validity
  - Practical issues to be addressed (vacuum, high power, beam heating)

Five pulses test

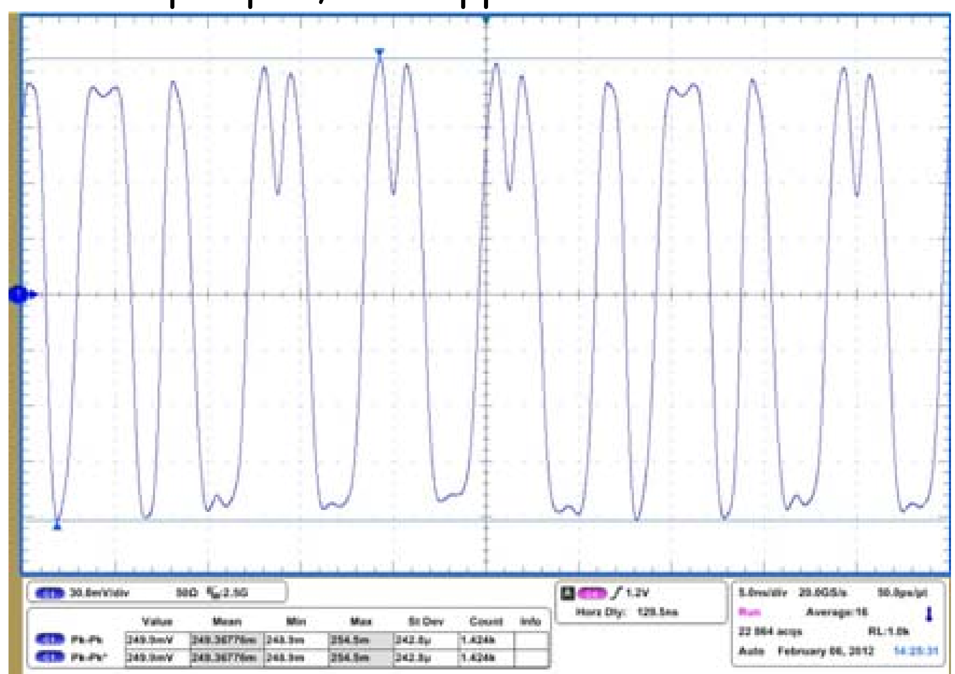
6 dB input pad, 123 Vpp out



3 dB input pad, 177 Vpp out



0 dB input pad, 240 Vpp out



- 150 W amplifier makes almost half of the required voltage
- 1 kW amplifier should deliver±310 V
  - i.e. it has 25% margin, most of which will be absorbed by loss of kicker efficiency and the wave damping along the kicker

Power Amplifier

- Required power – 0.5 – 1 kW
  - Limited choice of amplifiers with ~1 GHz bandwidth
  - All designs are based on combination of outputs of many small power amplifiers
  - Gain is far from being good enough
  - After testing/checking a few brands we stopped at the SBA series (Teseq AG, Switzerland)
    - CBA 1G 150 was tested
    - CBA 1G 1000 is considered as an amplifier which satisfies all our requirements

      Price ~$200K for 1 kW,

      4 amplifiers are required

CBA 1G 150

- Class A linear and low distortion design
- High reliability gallium arsenide technology
- Mismatch tolerant and unconditionally stable
- Wide instantaneous bandwidth
- Typical 2 dB compression data (as described in IEC 61000-4-3) provided
- Three year parts and labour warranty

CBA 1G 1000