PXIE at FNAL

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on High-Intensity and High-Brightness
Hadron Beams (HB2012)

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Outline

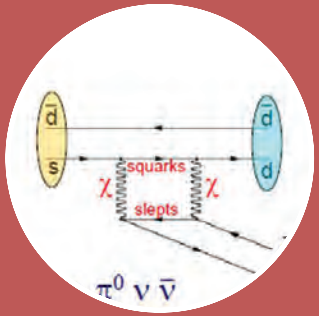
- Introduction: Project X and PXIE, Goals
- Optics and Beam Dynamics
- R&D on critical components:
  - LEBT
  - RFQ
  - MEBT and Chopper design
  - SC RF: HWR and SSR1
  - Beam Diagnostics and Dump
- Conclusion

Project-X Scientific Mission

Project X is a multi-MW proton facility currently under development by Fermilab with national and international partners. The Project X delivery of high power beams to multiple experiments with differing energy and bunch structure requirements (Intensity Frontier).

Long Baseline Neutrino Experiments

2 MW at 60-120 GeV



Kaon, Muon, Nuclei & Neutron precision experiments

3MW at 3 GeV

Platform for evolution to a Neutrino Factory and Muon Collider

Future upgrade to 4MW

Energy Applications: materials irradiation and transmutation

1 MW at 1 GeV

The Project-X Collaboration

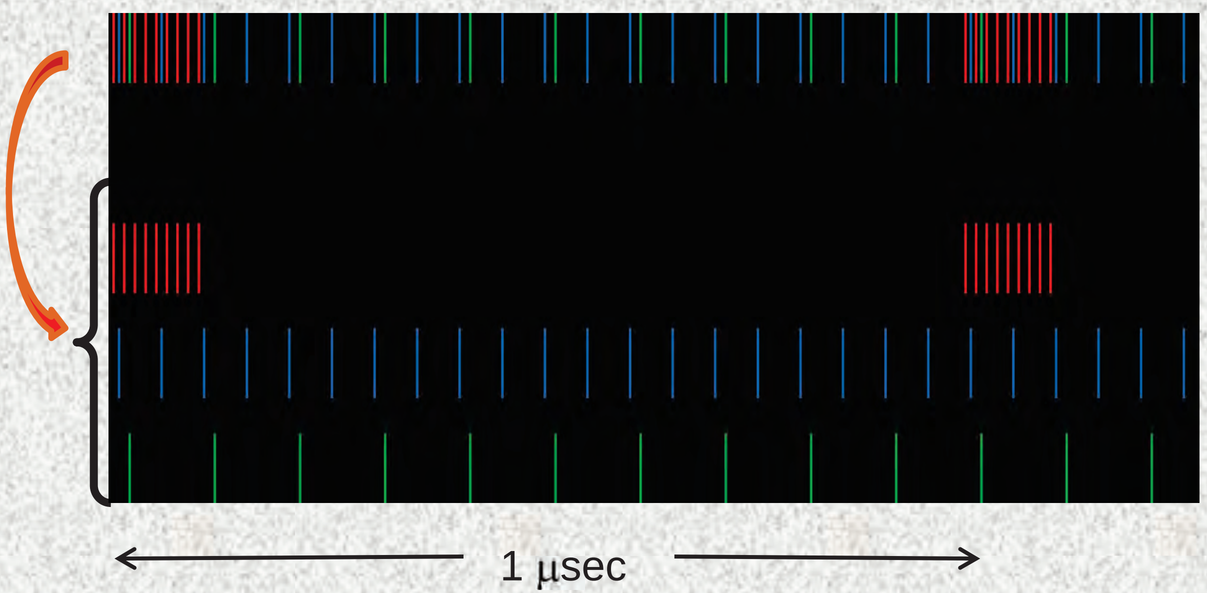
15 formal collaboration members supplemented with several informal collaborative relationships

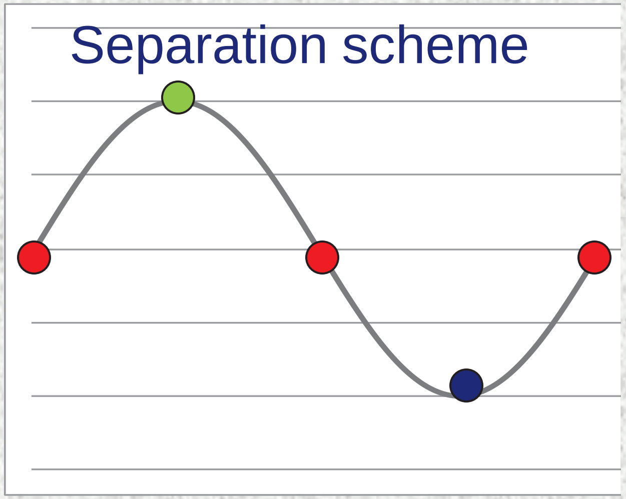
Operating Scenario for 3 GeV CW Linac

Ion source and RFQ operate at 4.4 mA
77% of bunches are chopped @ 2.1 MeV ⇒ maintain 1 mA over 1 μsec

1 μsec period at 3 GeV

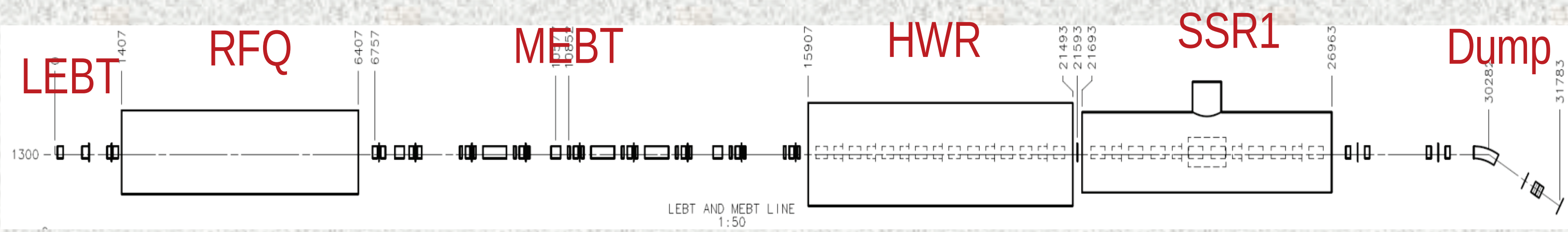
Kaon pulses (17e7) 20 MHz	1540 kW
Nuclear pulses (17e7) 10 MHz	770 kW
Muon pulses (17e7) 80 MHz, 100 nsec burst @ 1 MHz	700 kW





PXIE - Project X Injector Experiment

- PXIE – Front-End of the Project X CW linac
- PXIE should deliver 1 mA CW beam to ~25 MeV energy
  – Arbitrary bunch pattern (5 mA from Ion Source-> 1 mA at the beam dump)
- PXIE includes:
  – *5 mA ion source*
  – *LEBT with pre-chopper*
  – *2.1 MeV 162.5 MHz RFQ*
  – *MEBT with bunch-by-bunch chopper and 11 kW beam dump*
  – *Two SC cryo-modules: HW -162.5 MHz & SSR1 – 325 MHz*
  – *Diagnostics Section and 50 kW beam Dump*



PXIE schematic layout. The total facility length is about 40 m.

PXIE Goals and challenges

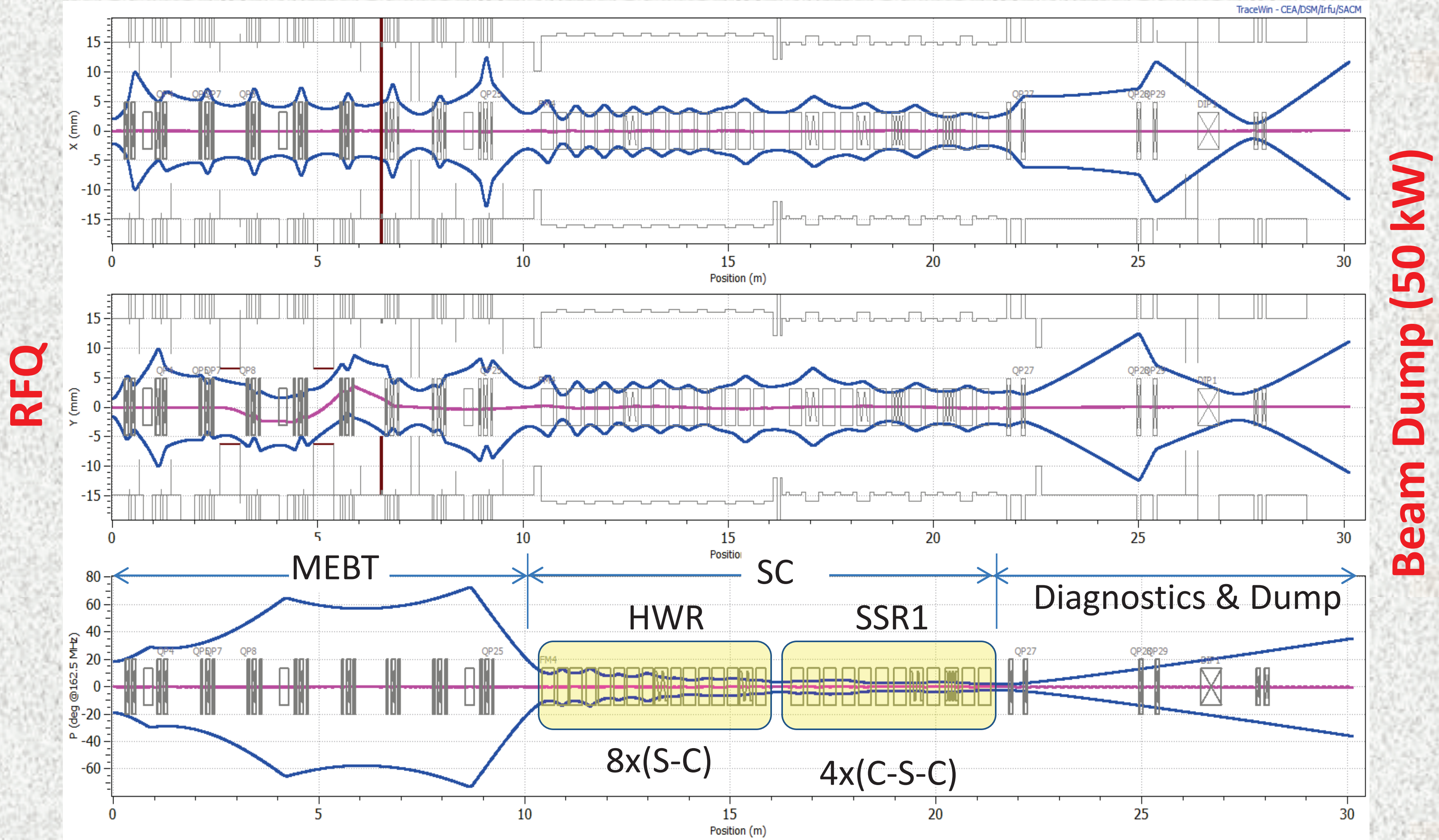
- Specific technical PXIE program goals are to demonstrate (challenges):
  - ***reliable operation of a CW 2.1 MeV RFQ accelerator,***
  - ***a bunch-by-bunch chopper,***
  - ***low-β acceleration in SRF cryomodules***
  - ***sufficiently small emittance growth during initial acceleration and***
  - ***good particle extinction for the removed bunches (10^{-4} – PXIE specs)***

- PXIE has to operate at full Project X design parameters delivering up to 1 mA average current while accommodating up to 100% chopping of 5 mA RFQ beam.

- The beam current upgradability requirement (to 2 mA CW) is determined by possible staging of the Project X and its future upgrades (~20mA peak current at 325 MHz).

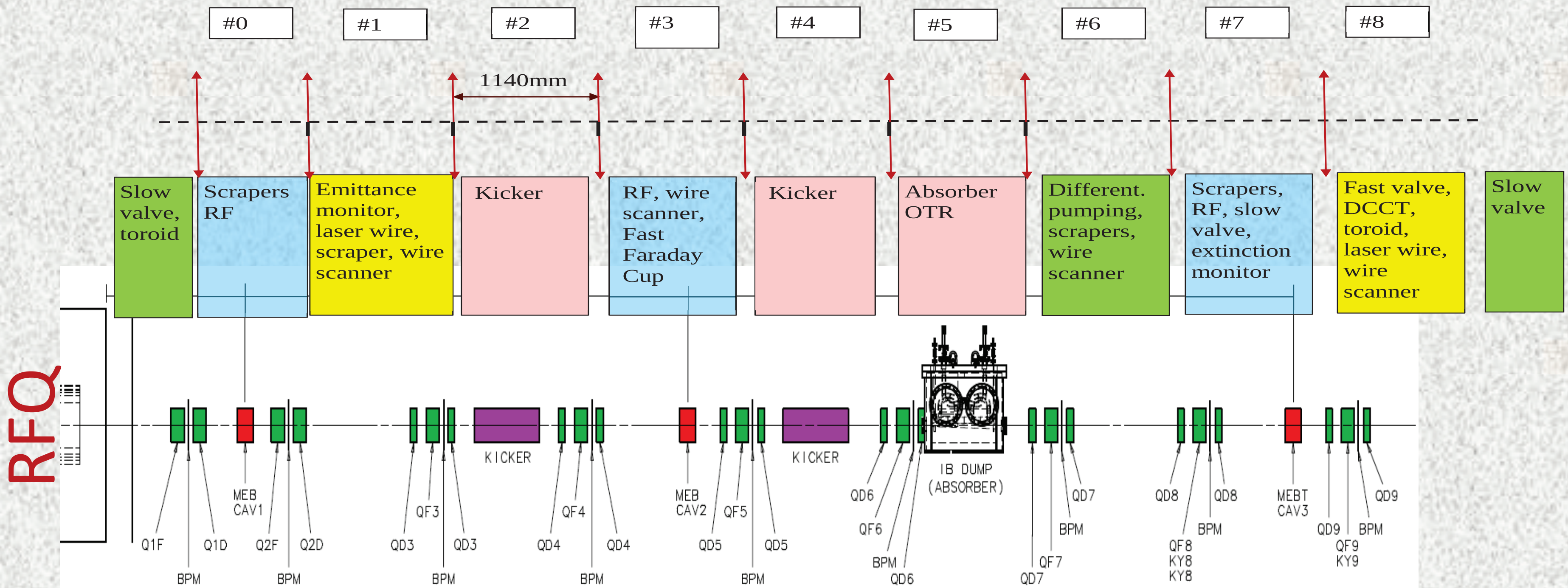
- The PXIE design and construction is being carried out by collaboration between Fermilab, ANL, LBNL, SLAC and Indian institutions. It is planned to have PXIE operational (at least 15 MeV, 1 mA CW, 5 mA peak, arbitrary bunch chopping) by the end of 2016.

PXIE optics (3-σ envelope)



Kiker polarity in chopper are set for passing beam

MEBT diagnostics



Violet - chopping system: 2 kickers (180° tr. phase adv. and absorber (90°from last kicker).

Blue - bunching cavities. + other equipment (scarpers and diagnostics).

Yellow – **mainly diagnostics** to measure beam coming out of RFQ (#1) and to SRF linac (#8)

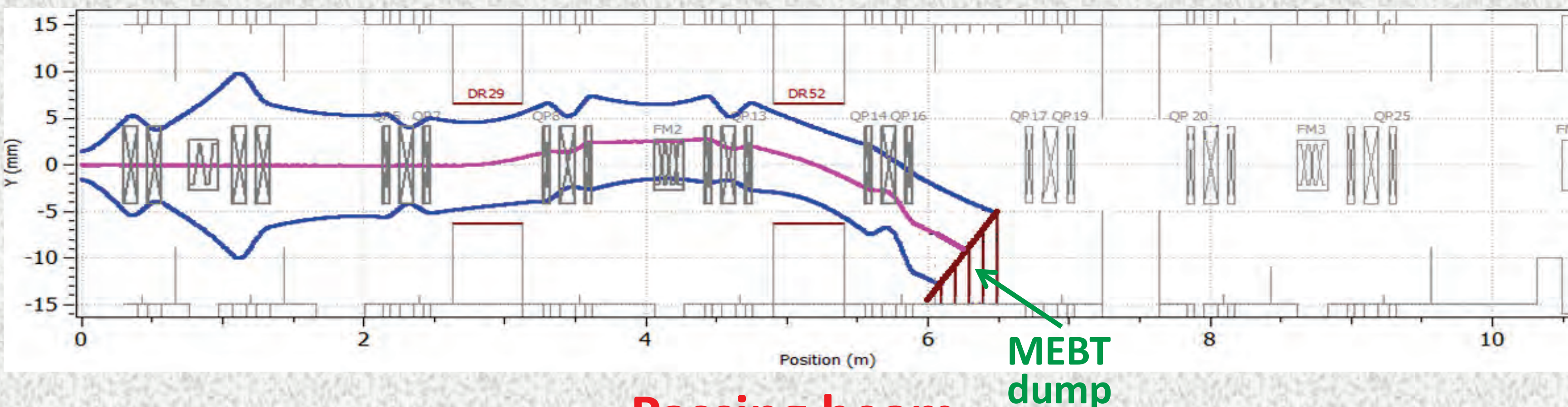
Green - vacuum pumps and **diagnostics**. Start/end– interfaces with the RFQ (left) and HWR

Vacuum:

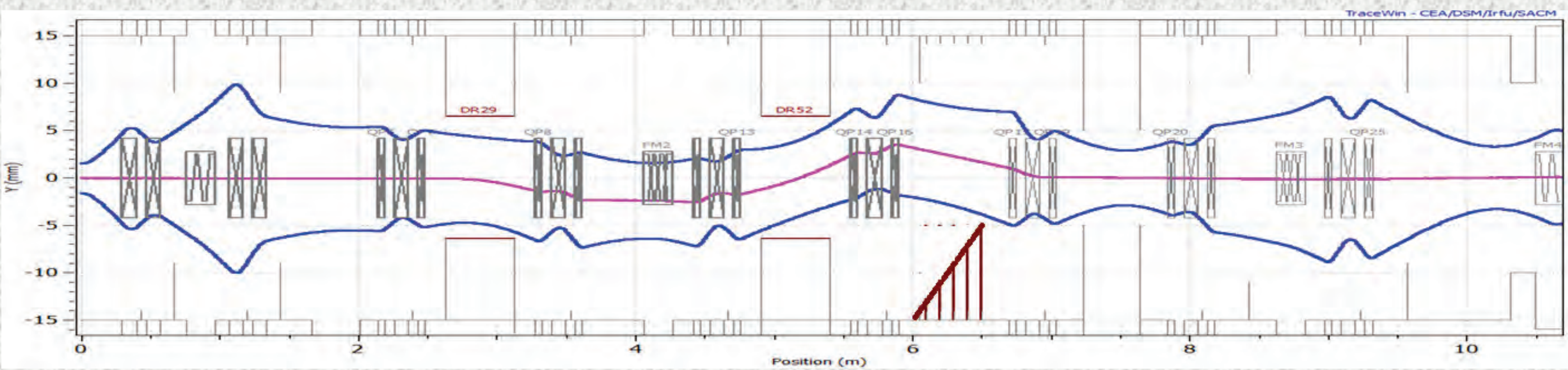
- ~ 10^{-6} Torr in #5 where a large gas flow from the absorber.
- ~10^{-9} Torr in the last sections of MEBT from the absorber section (after #6):
- Vacuum separation insertion ∅10 mm L=200 mm

MEBT chopping

Chopped beam



Passing beam



Use of 2 kickers with 180 deg. phase advance reduces kicker voltage

$\Rightarrow$ *±250 V effective voltage on the kicker, 16 mm gap between plates*

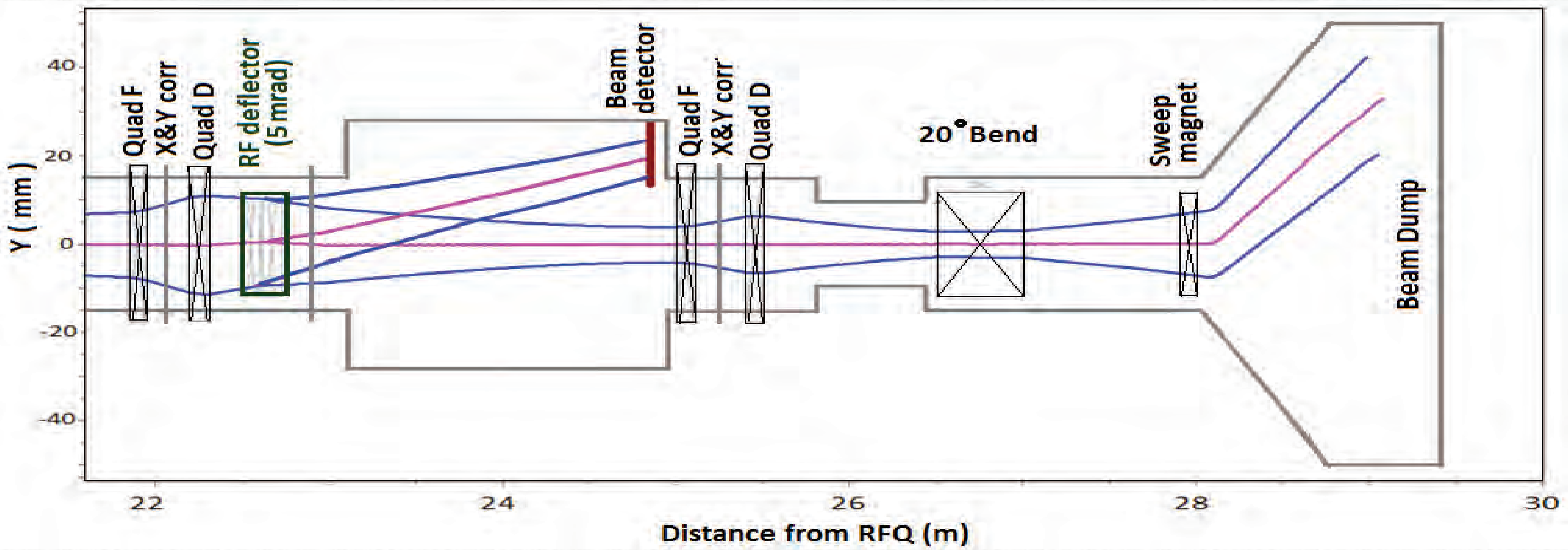
DC correctors minimize vertical displacement for passing beam

Optics in SC cryomodules

- **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**)
- **Both cryomodules have**
  - *X & Y & S BPM near each solenoid*
  - *Transverse (x, y) correctors are located in every solenoid*
  - *Solenoid polarity is changed in each next solenoid (simplifies orbit correction)*
  - *Vacuum valves at each end*
- **HW-to-SSR1 interface**
  - *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 with cavities – improves long. dynamics*
  - *Small space allocated (~20 cm)*
    - *Laser profile monitor, Pumping port*

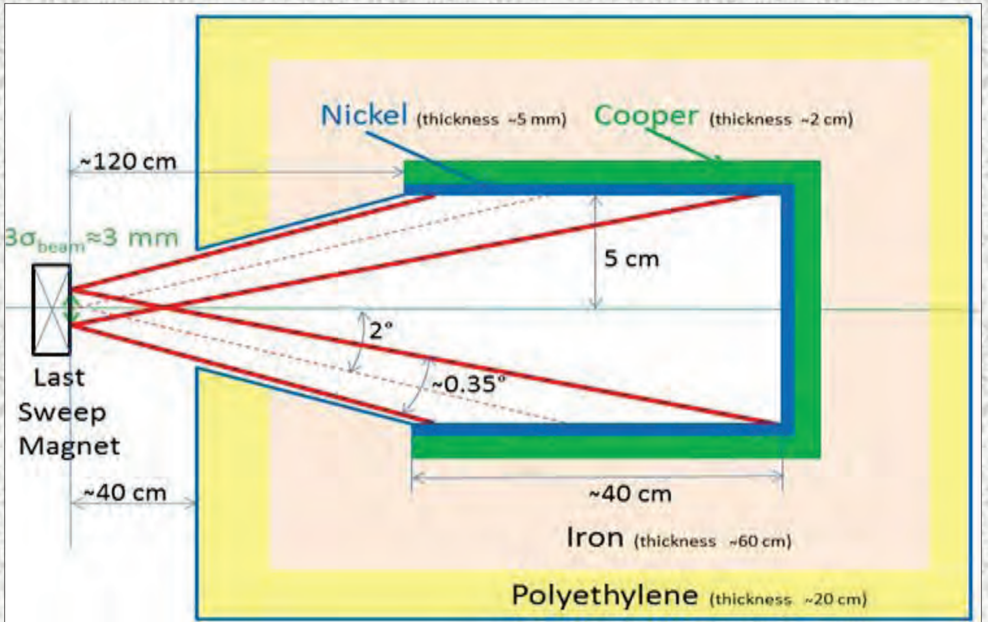
Beam Extinction

Project X will provide beams for different HEP experiments. Some of them (for example mu2e) have a strict requirement ($<10^{-9}$) for beam extinction for removed bunches. An extinction level better than 10^{-4} is specified for the MEBT. This number is mainly determined by available in MEBT diagnostics.

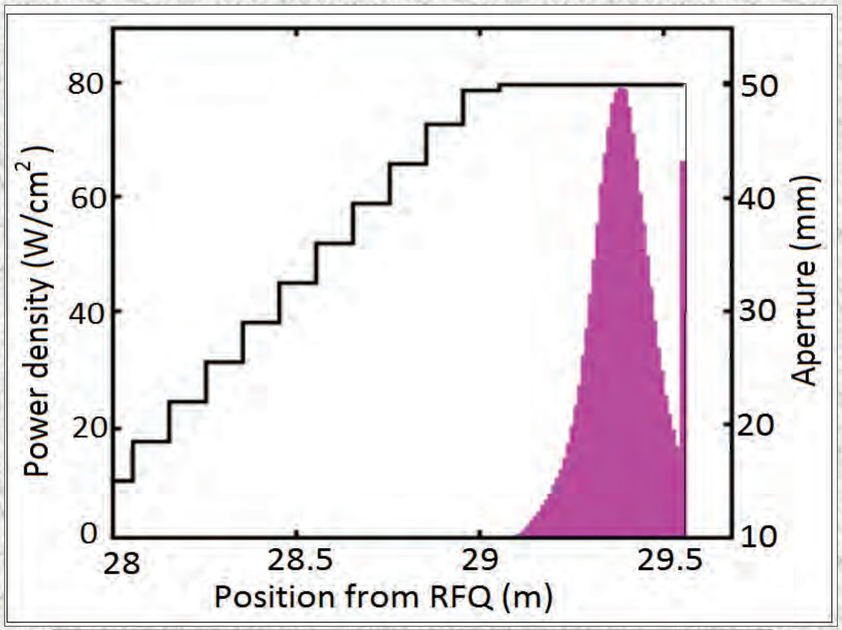


Schematic of extinction measurement experiment, 3-sigma envelope for passing and deflecting beams are shown in blue.

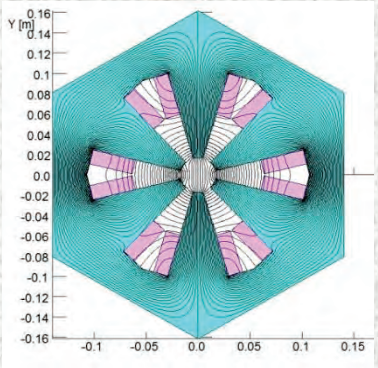
Beam Dump (50 kW)



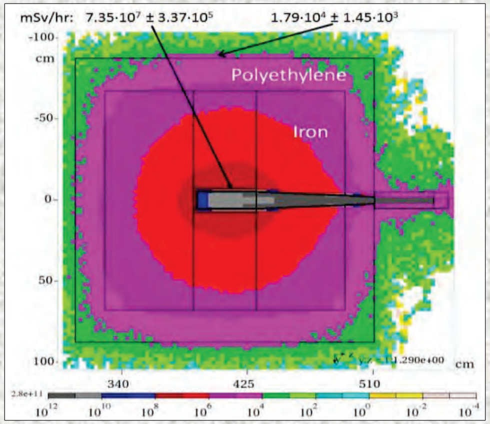
Beam dump, incl. local radiation shielding
Red lines - sweeping beam



Power distribution in absorber

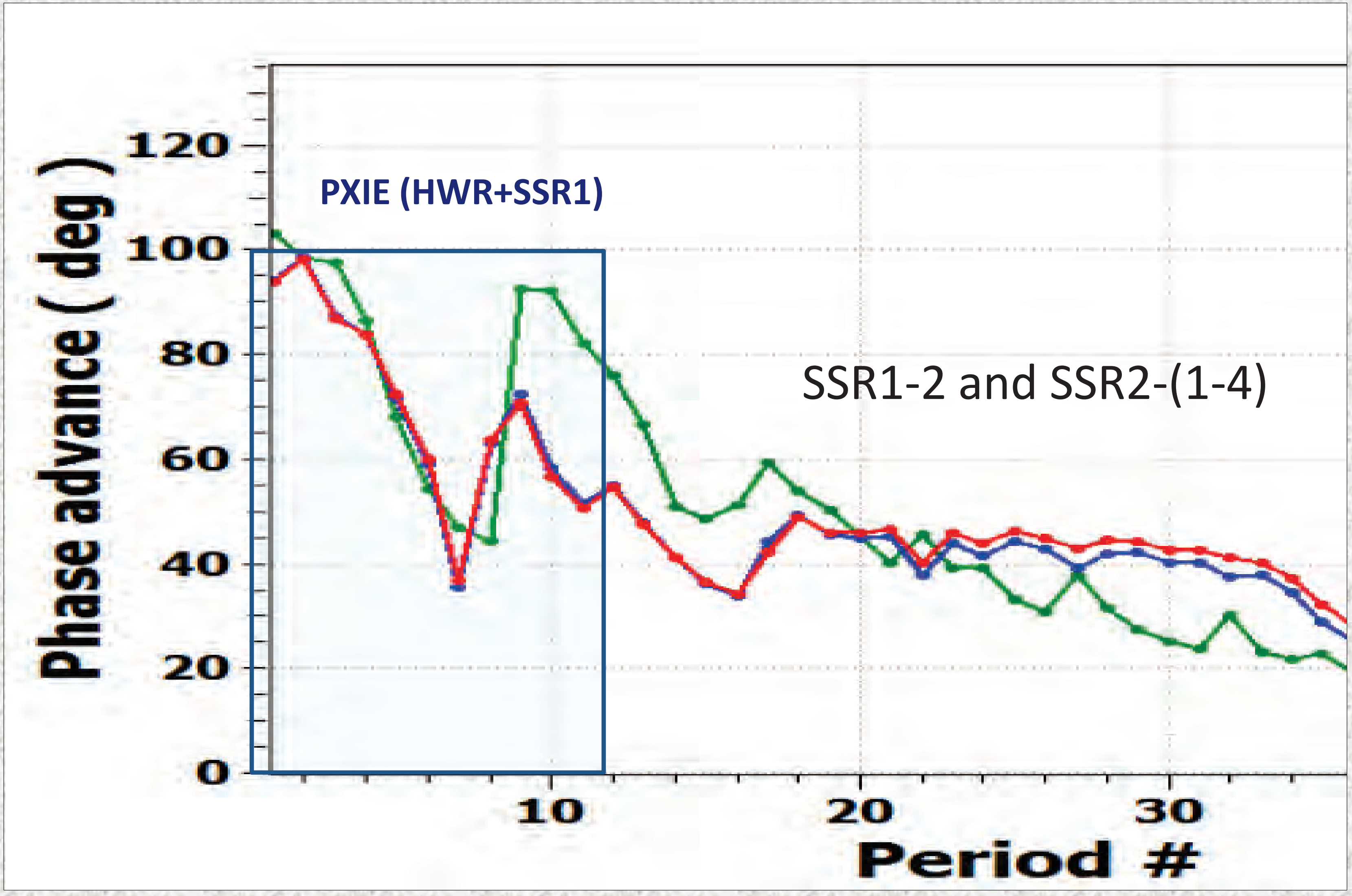


Magnet aperture	**34 mm**
Length	**200 mm**
Dipole field, pk	**0.2 T**
Integ. field	**0.04 T-m**
Current(pk/av)	**250/177 A**
Power	**810 W**

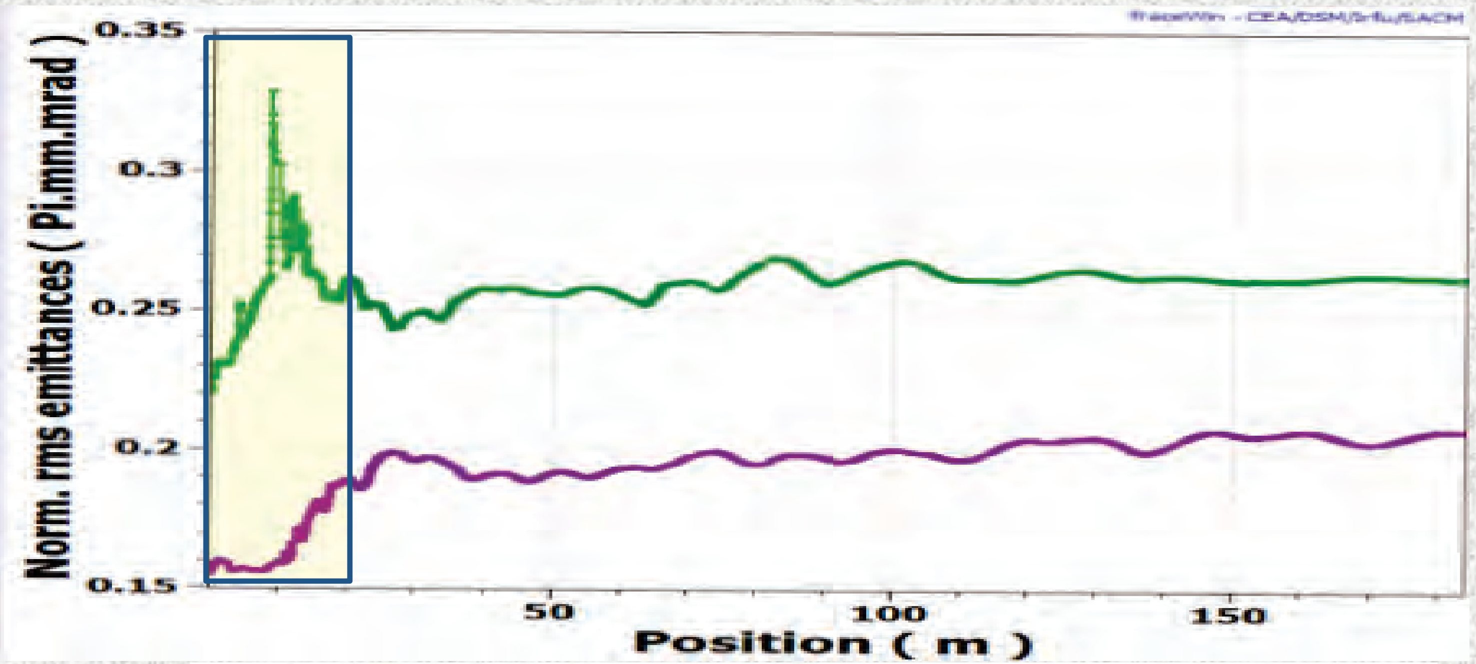


- Local shielding (60 cm iron+20cm polyethylene)
- Attenuation of radiation ~4000 times (~12 W)

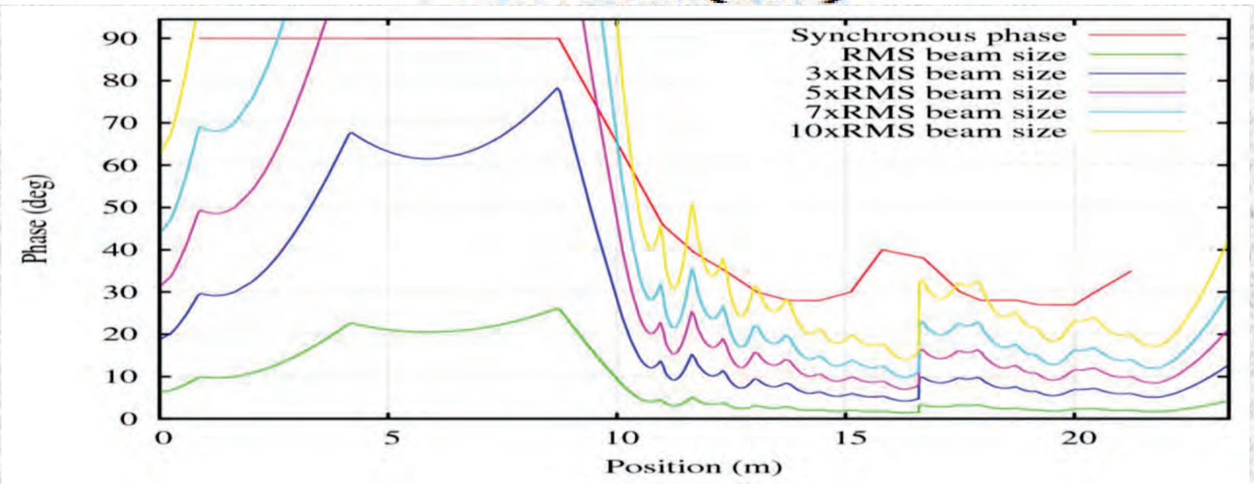
Structural Phase advances



Emittances growth



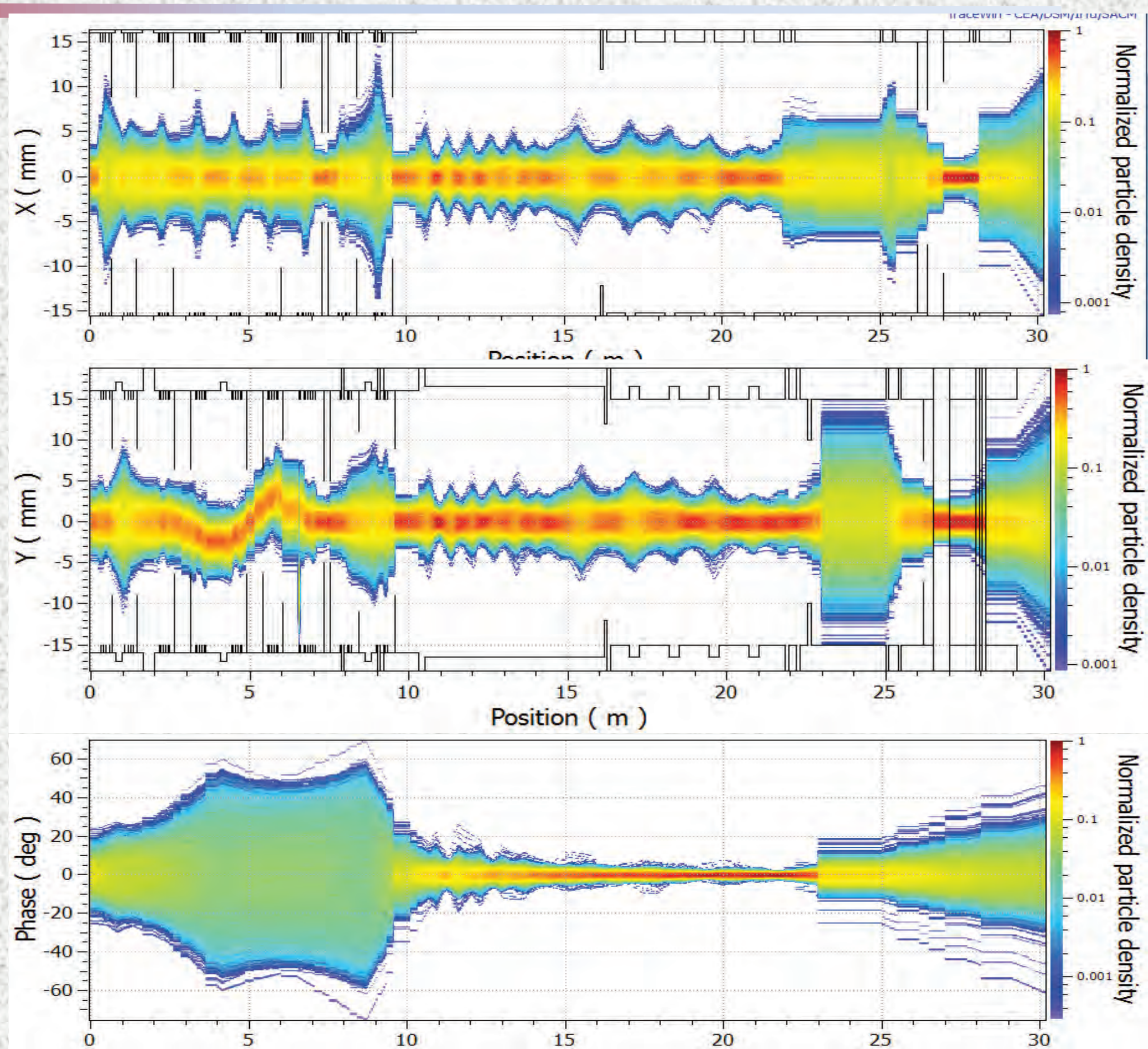
Synhronous Phase
vs.
Bunch length



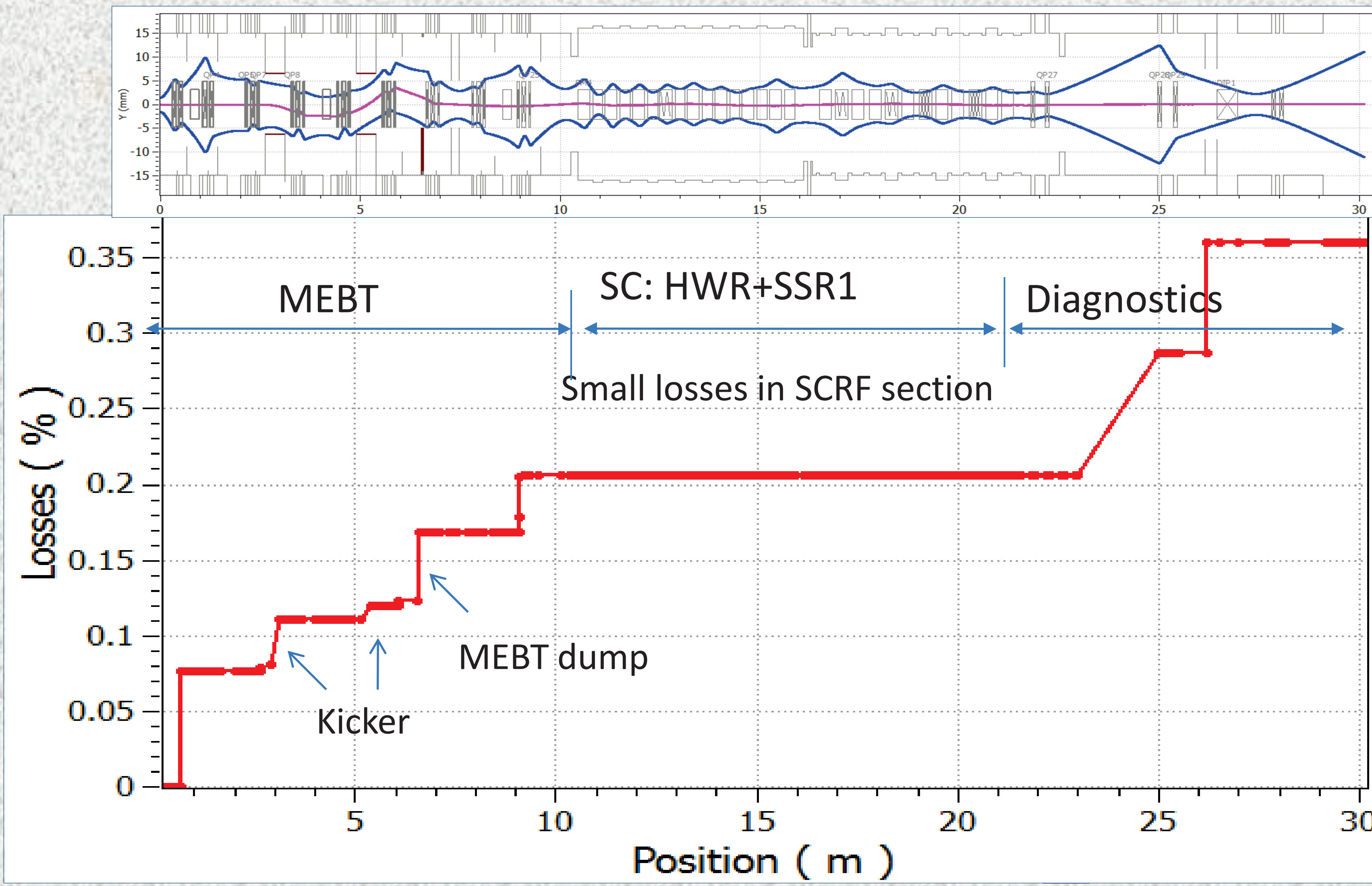
PARTRAN tracking, collimation

Beam Losses

- Intra-beam stripping < 0.5 W
- Non-Gaussian tail of RFQ longitudinal distribution (after RFQ) is the major source of particle loss, $<3\cdot10^{-4}$ (< 10 W) in SCRF section:
  - *Small fraction of total beam loss will be intercepted by warm interface between CM's*
  - *Major fraction will be lost at 2 K*
- It is still small relative to the RF losses in CM (~50 W)

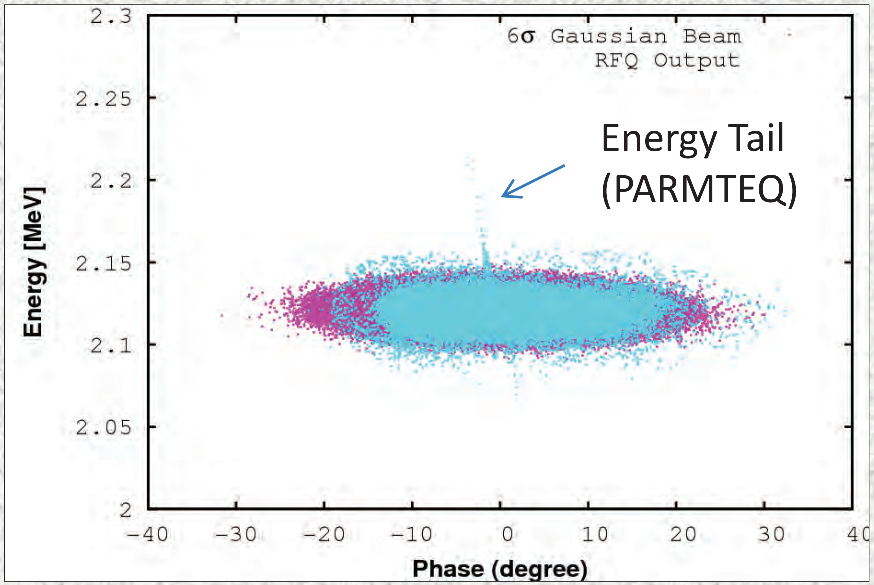


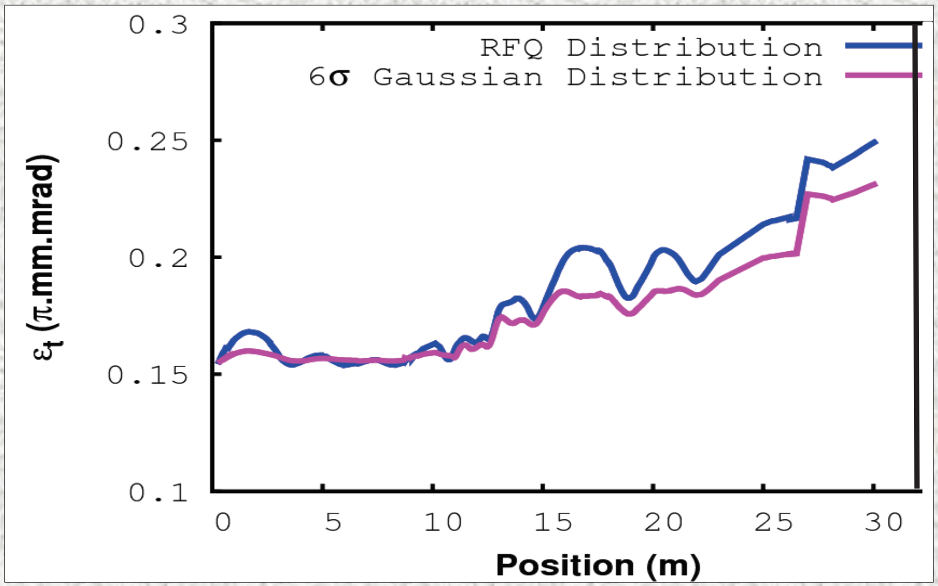
Beam Losses for passing beam

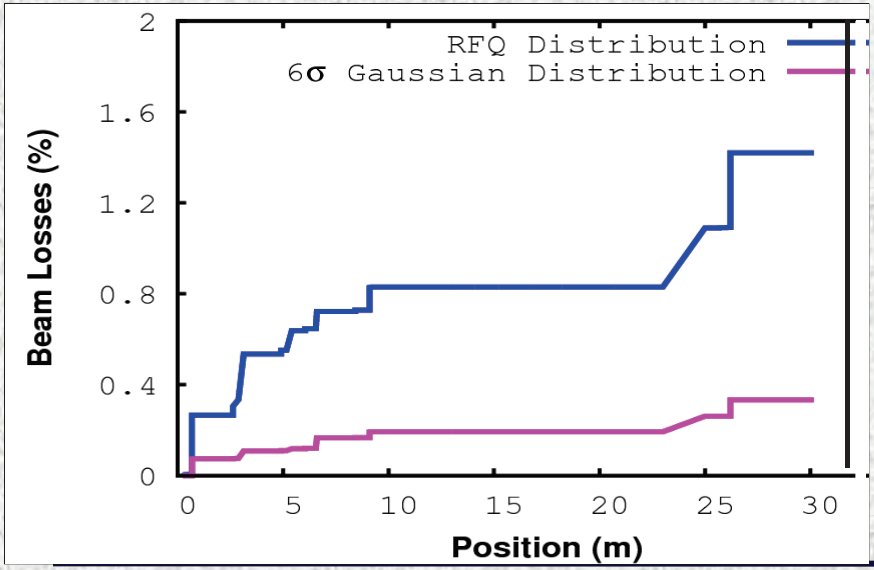


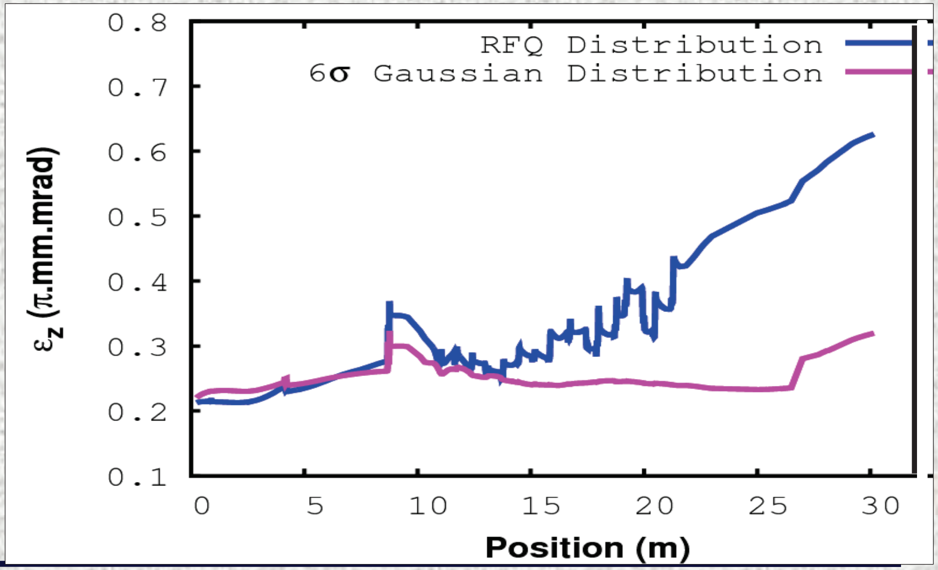
Chopped beam are lost at MEBT dump at level 99.94% (6σ Gaussian)

6σ Gaussian vs. RFQ beam distribution



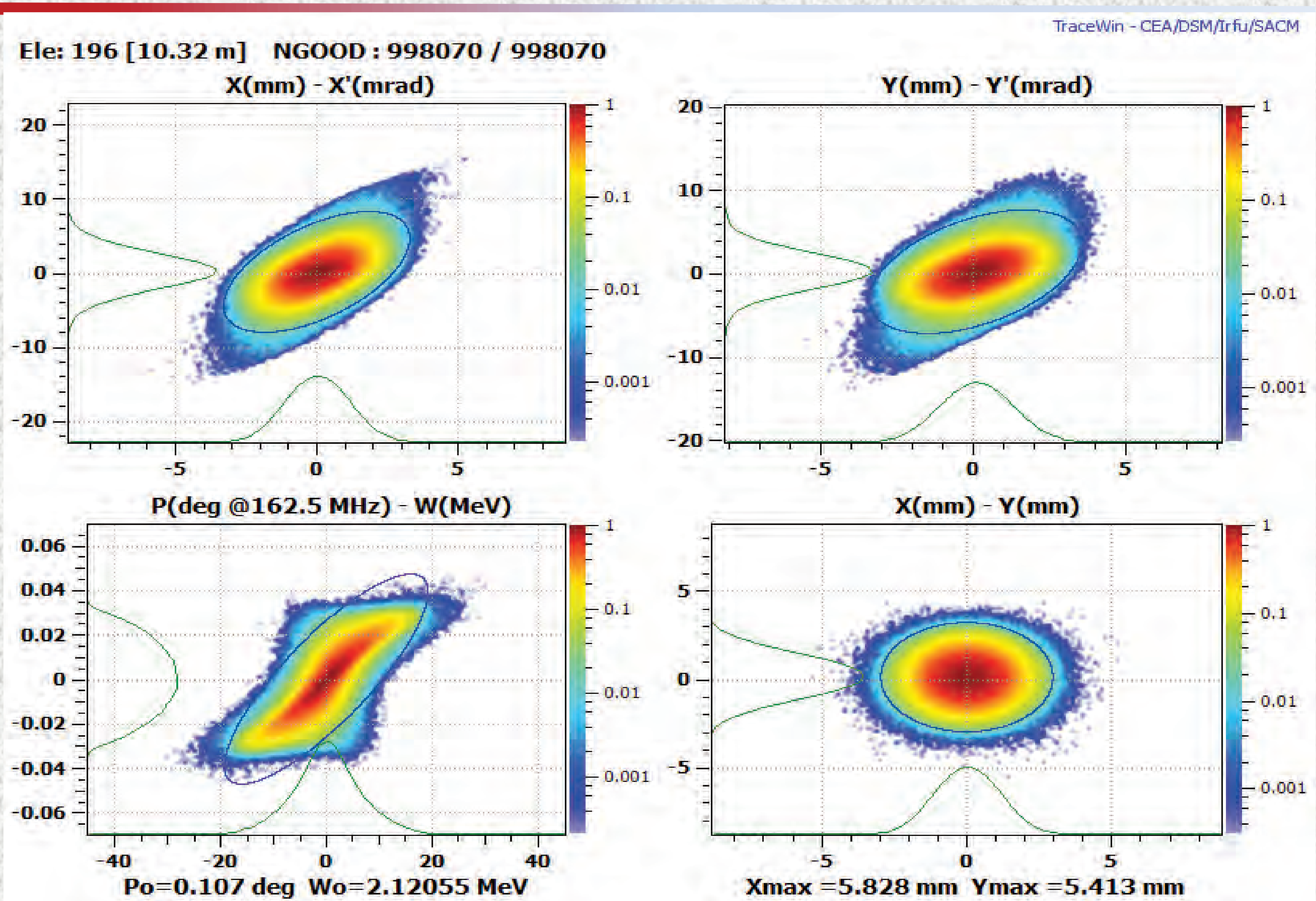




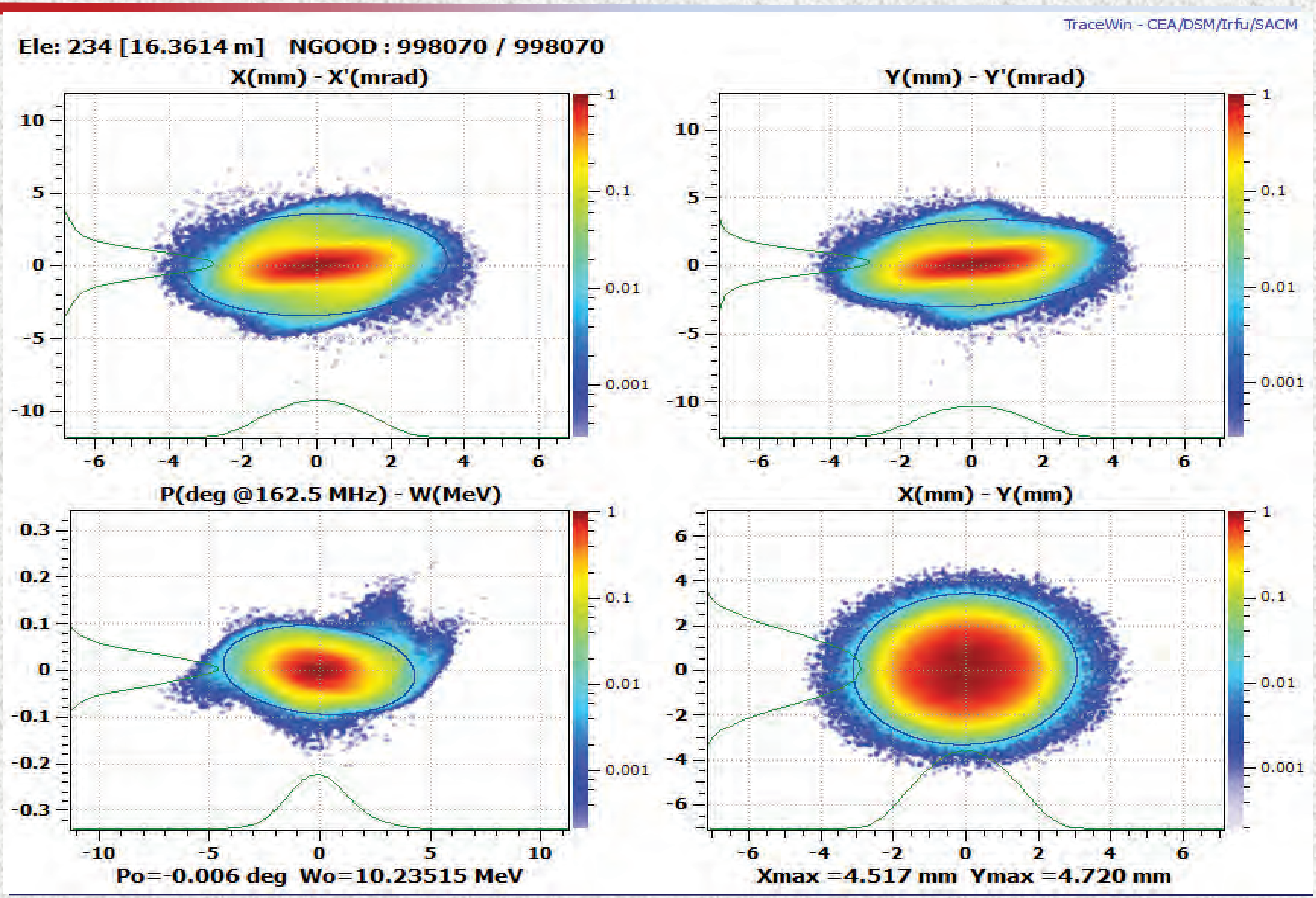


Output Beam @ MEBT End

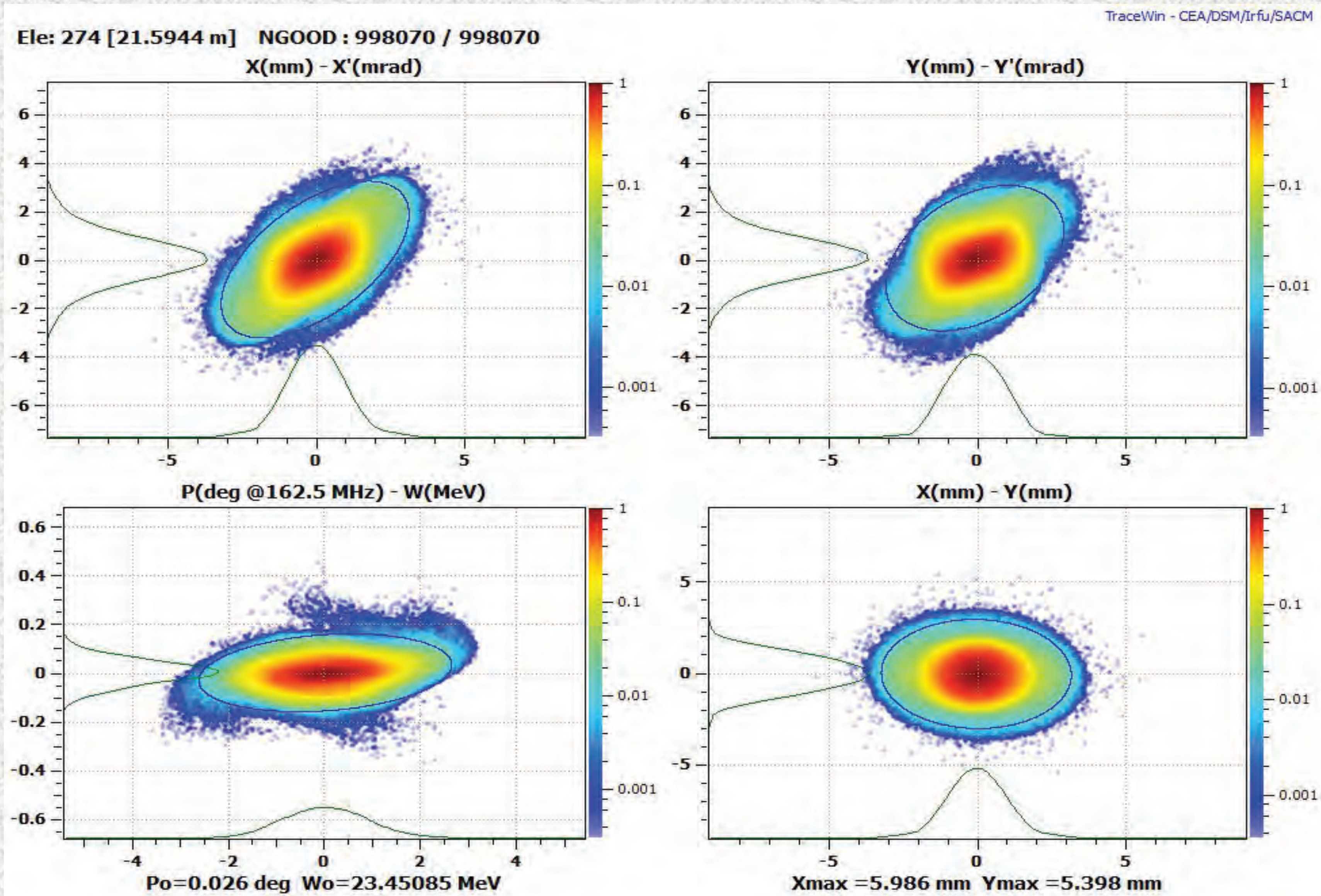
Starts with 6 sigma Gaussian distribution



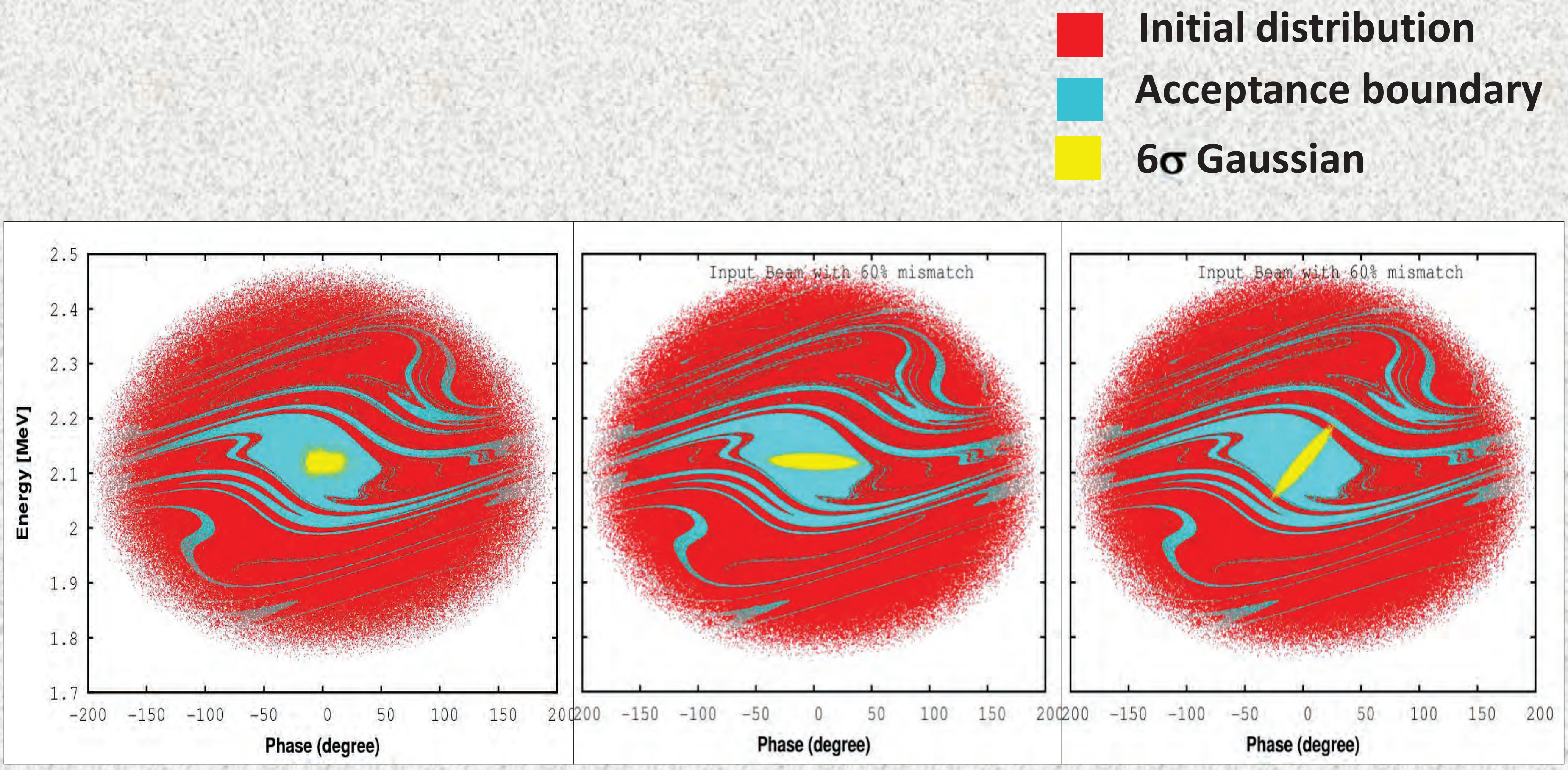
Output Beam @ HWR End



Output Beam @ SSR1 End



Longitudinal acceptance @ end of SSR1

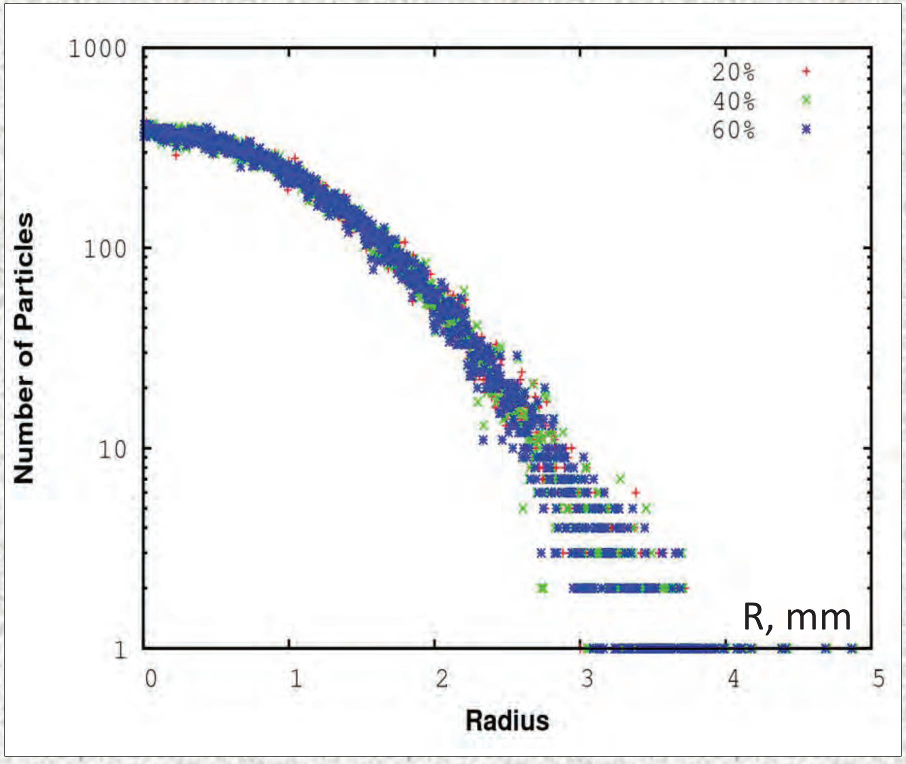


No mismatched

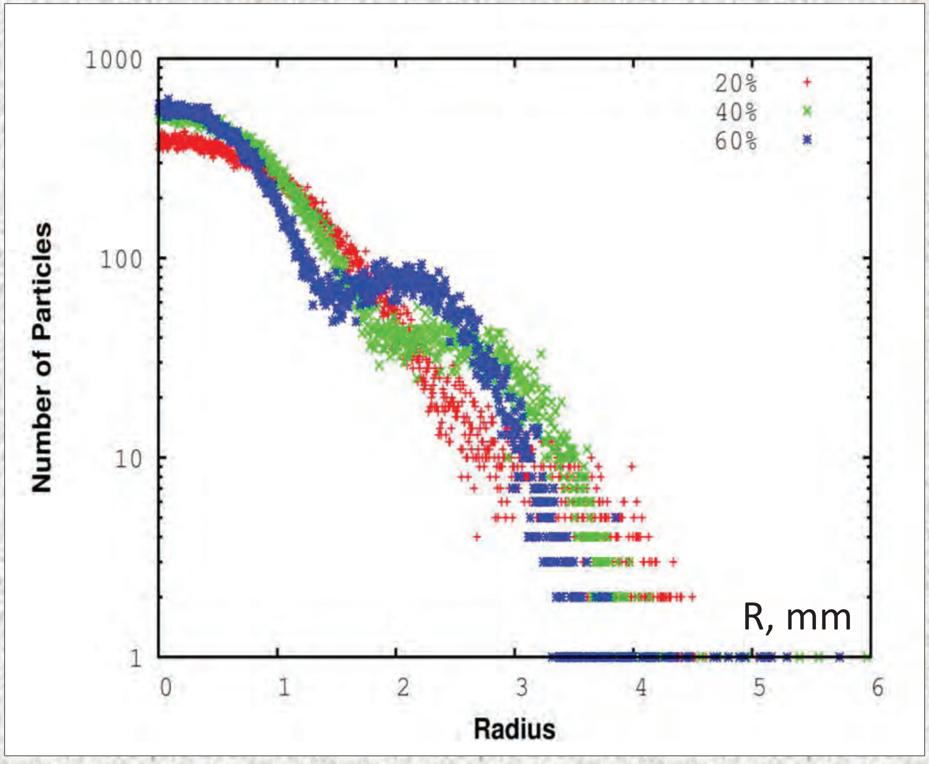
60 % mismatched input beam @ MEBT entrance

60 % mismatched input beam @ HWR entrance

Mismatch effect on Longitudinal profile



Input beam @ MEBT entrance

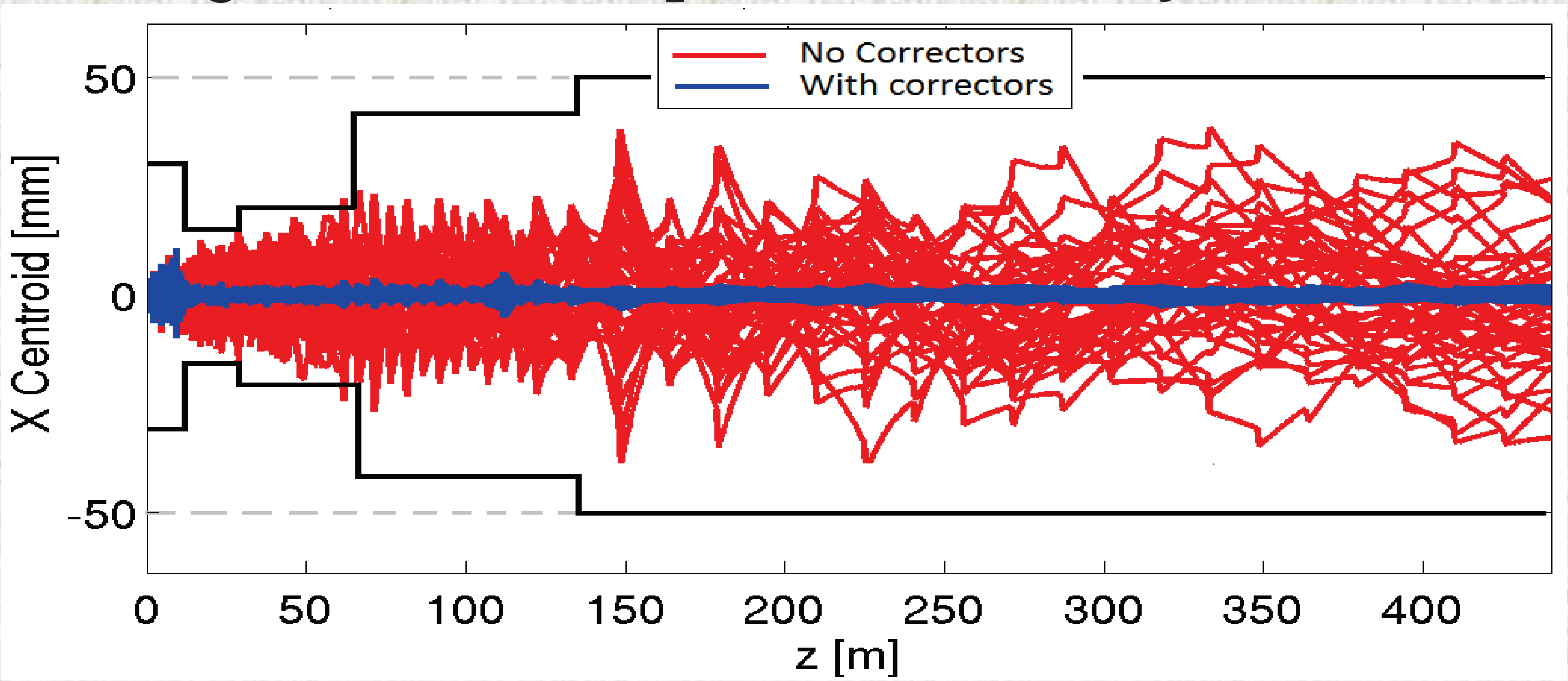


Output beam @end of 1 GeV Linac

Small effect on transverse beam profile

3 GeV Linac

Misalignment of components and RF jitter Studies



TRACK simulations of corrected/uncorrected beam centroid motion along the linac for the set of errors δ_{xy} =1mm for solenoids & cavities, δ_{xy} =0.5mm for quadrupoles, dynamic RF jitter of 0.5^0 + 1.5% and quad roll of 5 mrad around the z-axis. One corrector and one monitor are used per solenoid and per quadrupole dublet. BPM resolution 30µm. No losses.

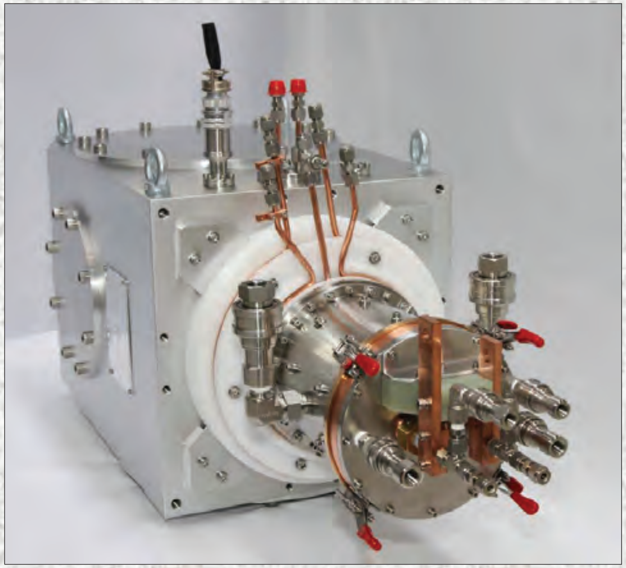
Status of R&D work on critical components for PXIE beamline

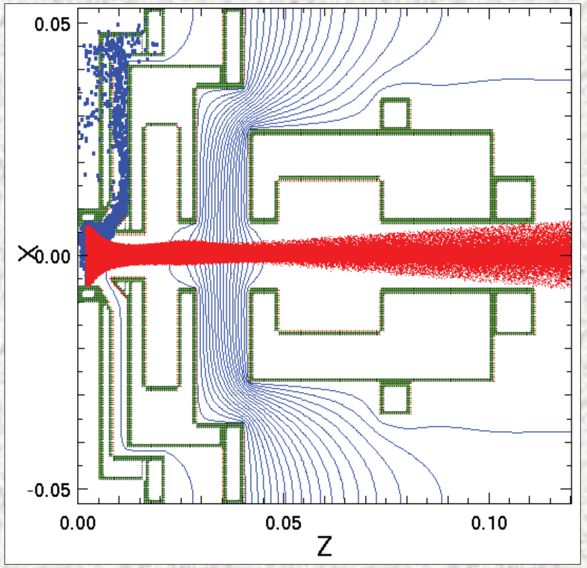
Ion Source

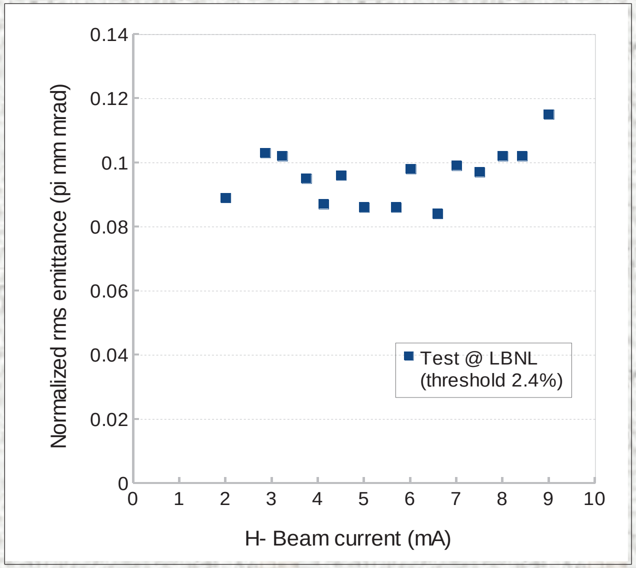
- The Linac beam starts from an H- ion source operating at a constant current, set for a given timeline:
  - The nominal ion source beam current used in Linac design is 5 mA
  - IS is capable of 15 mA; RFQ and MEBT are designed to 10 mA
  - If MI/Recycler is running/NOT running, the min IS current is 1.7 / 1mA

Regardless of the ion source current, the average linac beam current is 1 (2) mA

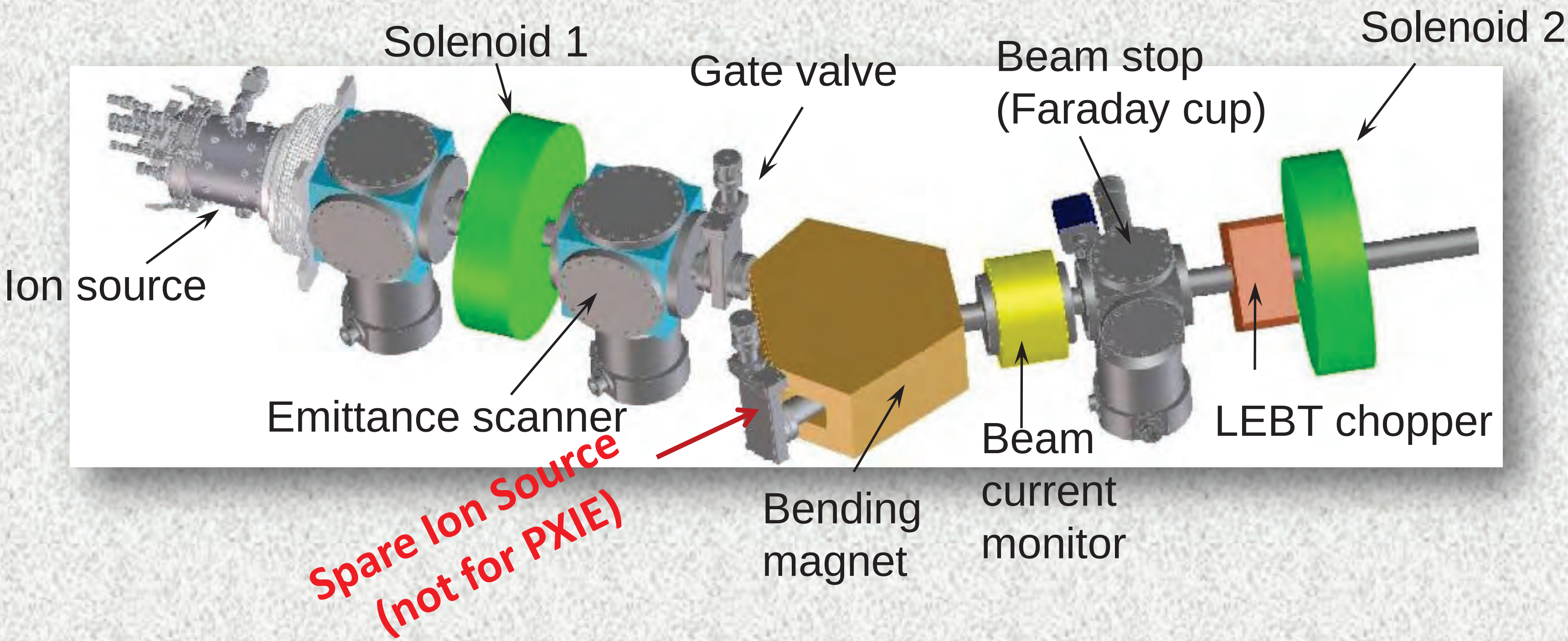
- this is achieved by a LEBT and MEBT choppers





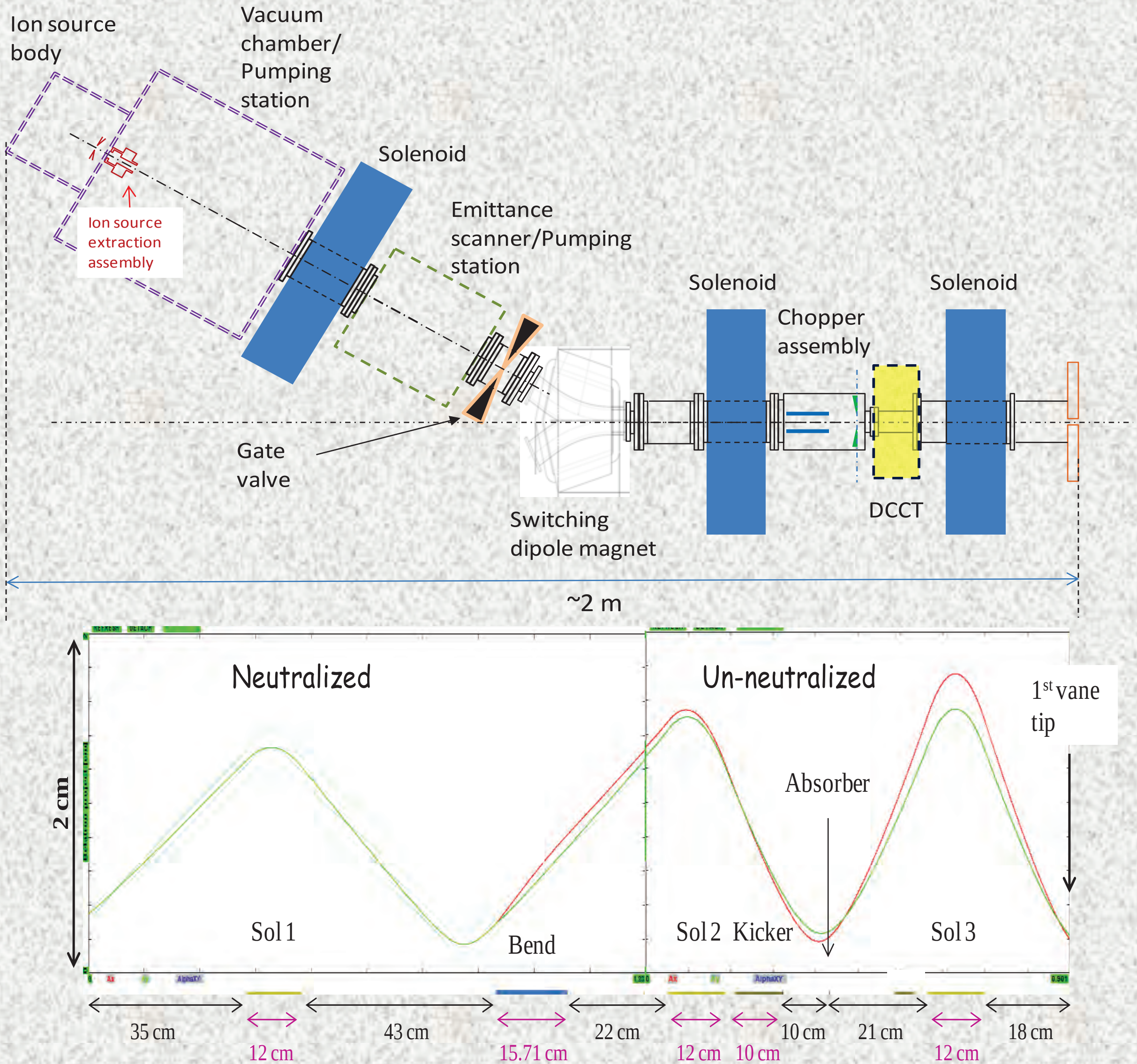


Low Energy Beam Transport



- Provides 30-keV beam transport from the Ion Source to the RFQ
  - two ion sources (not running concurrently); Dipole switch
  - Chopper (pulsed beam operation during commissioning)
  - Diagnostics and machine protection

LEBT (continue)



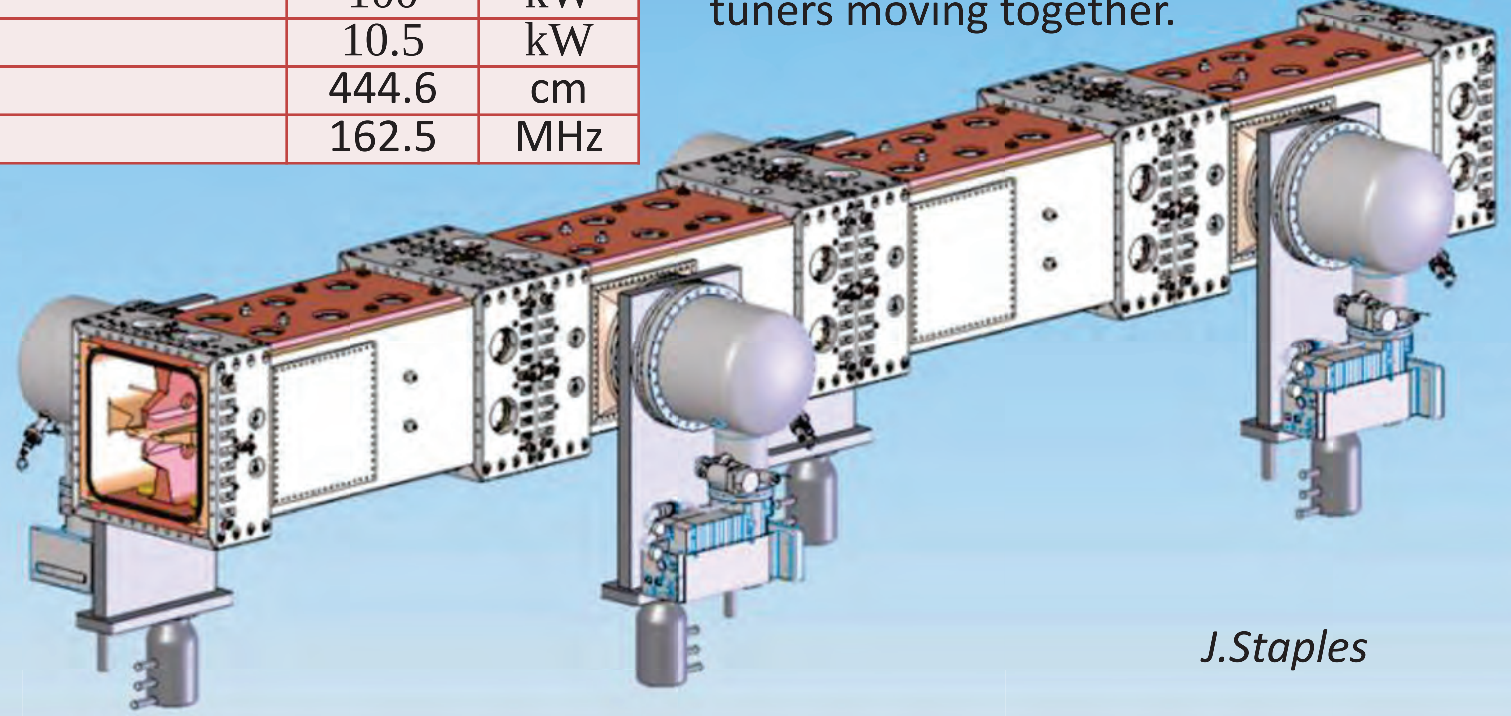
Longer LEBT option (3 solenoids):

- implementation of several diagnostics, in particular after the chopper.
- avoid re-neutralization (and transition effects)
- Beam optics in LEBT.

RFQ design (LBNL)

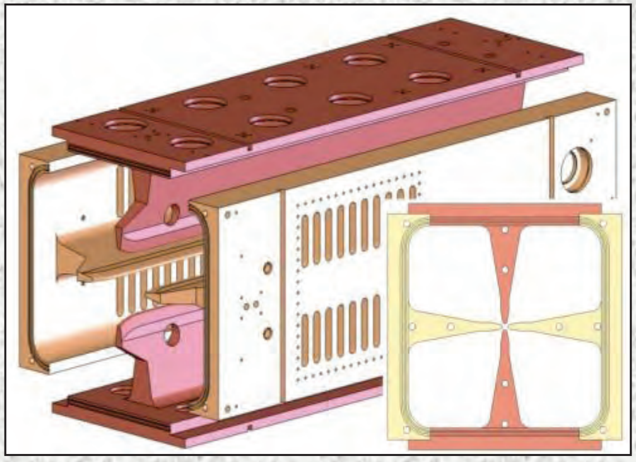
Parameter	Value	Units
Ion type	H-	
Beam current (nom/range)	5 (1-10)	mA
Trans. emitt. (rms, norm)	<0.25	µm
Long. emitt. (rms)	0.8-1.0	keV-ns
Input energy	30	keV
Output energy	2.1	MeV
Vane-vane voltage	60	kV
RF power	100	kW
Beam Power	10.5	kW
Length	444.6	cm
Frequency	162.5	MHz

- **32 pi-mode stabilizers**, 4 pairs in each module separate the dipole frequency to 17 MHz above the 162.5 MHz quadrupole frequency
- **80 tuners**, 20 in each quadrant have a diameter of 6 cm, a nominal insertion of 2 cm, and a tuner sensitivity of 170 kHz/cm, all tuners moving together.

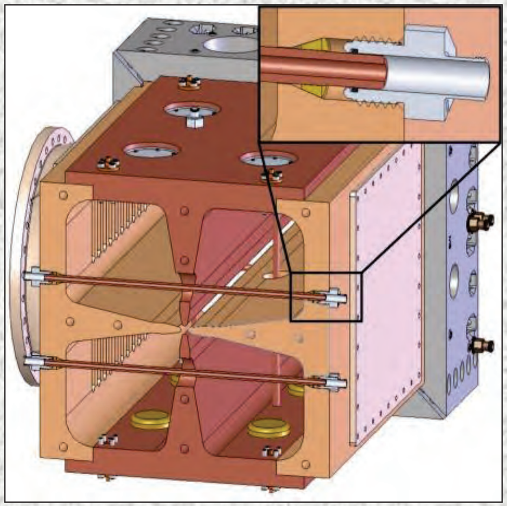


J.Staples

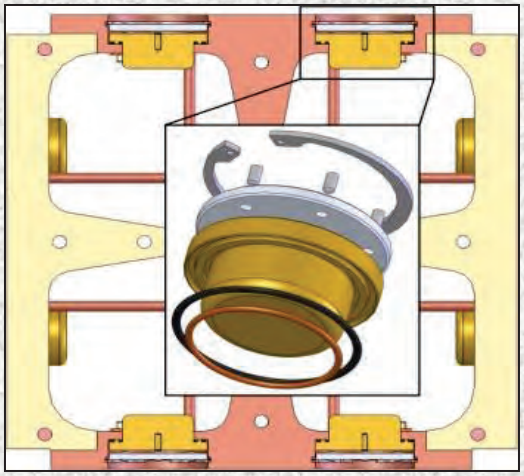
RFQ mechanical design



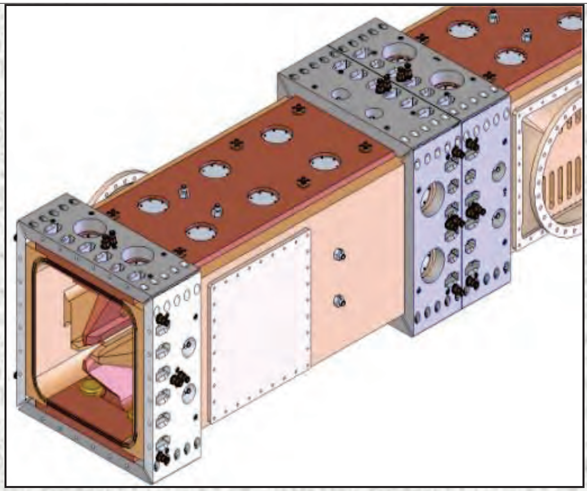
Exploded (1/4) 4-vane module



Pi-mode rod
shifts dipole mode
+17 MHz up

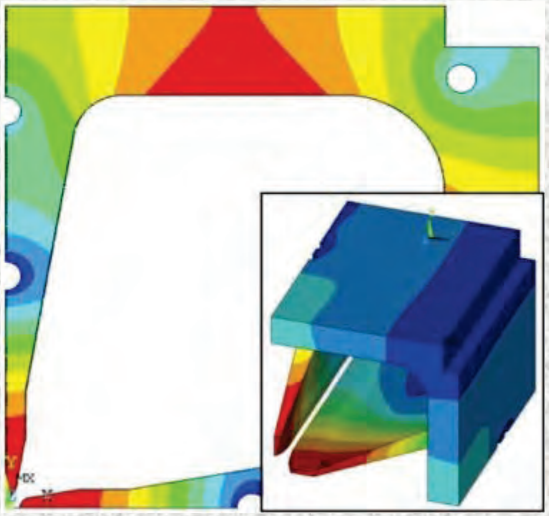


Fixed slug tuner



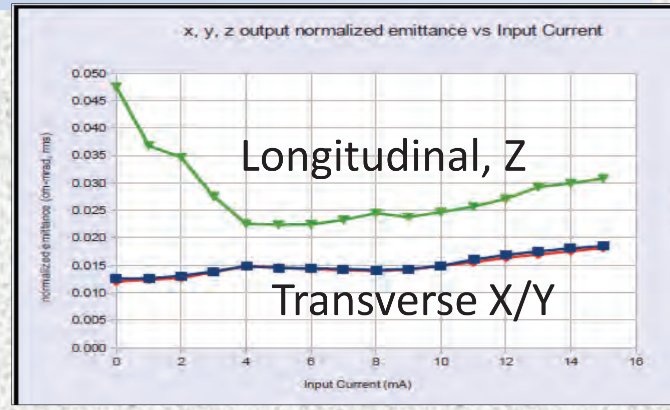
RFQ modules connected by joint plate method

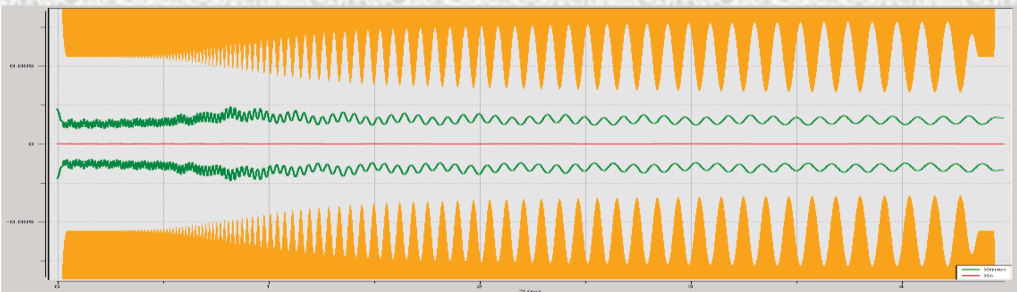
Linear power density =137 W/cm
Peak heat flux = 0.7 W/cm^2.
Tmax = 25°C

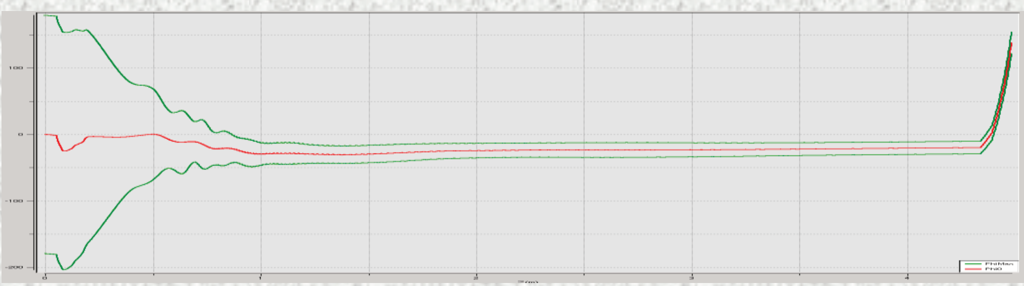


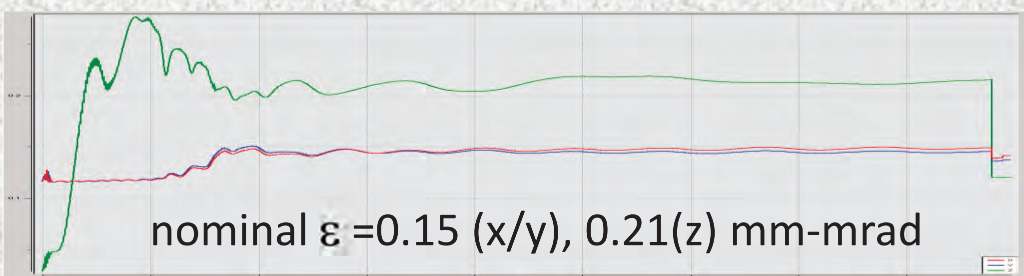
RFQ beam dynamics

- Design done in PARMTEQ (J.Staples)
- Cross-check: TRACK (3D field-map) and Toutatis
- Errors and mismatch studies (PARMTEQ and Toutatis)

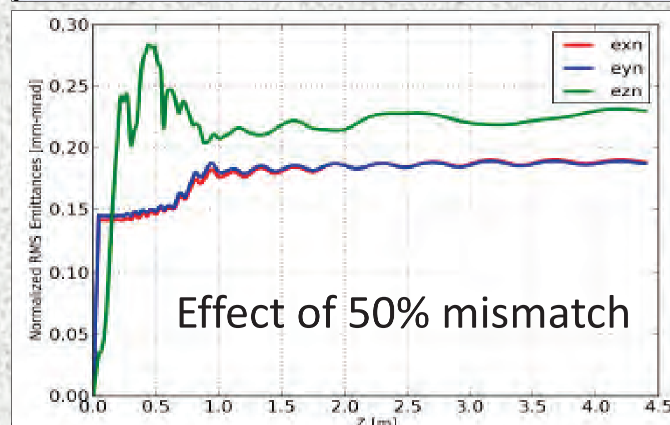


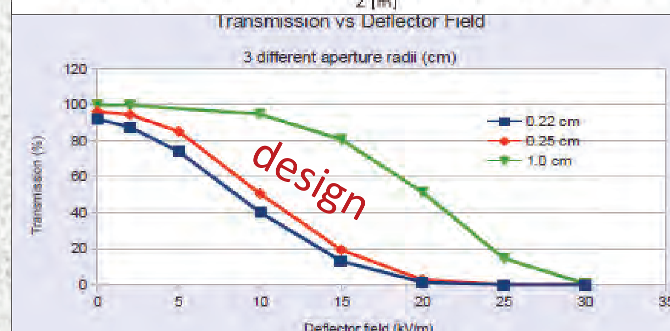




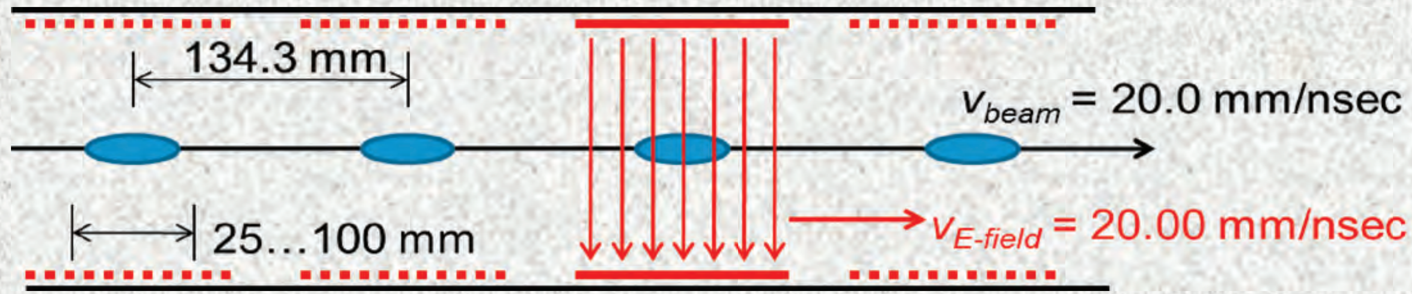


Partially chopped beam





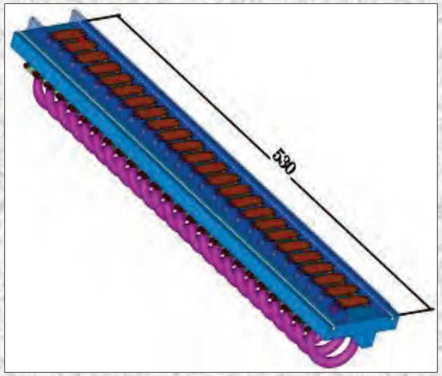
Chopper R&D

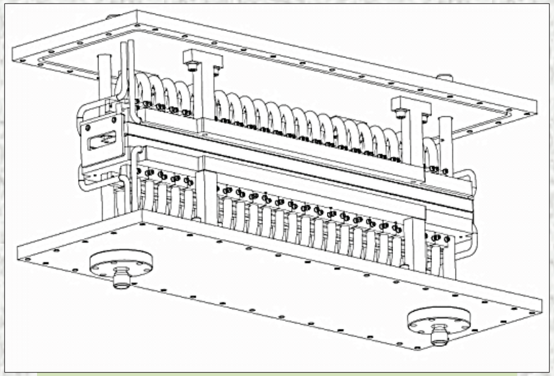


- Kicker
  - Two versions are being pursued: 50 and 200 Ohm
  - Each version must fit into a 65-cm drift: 2 pairs 25-cm long, 16 mm gap
- Kicker driver
  - Broad-band, 500 V, ~2 ns rise/fall time, 30 MHz average pulse rate
  - AC-coupled rf amplifier (50-Ohm) or DC-coupled pulser (200-Ohm)
- Beam absorber
  - 20 kW max. dissipated beam power
  - Issues: high power density, sputtering, high gas load

Wide-band Kicker designs

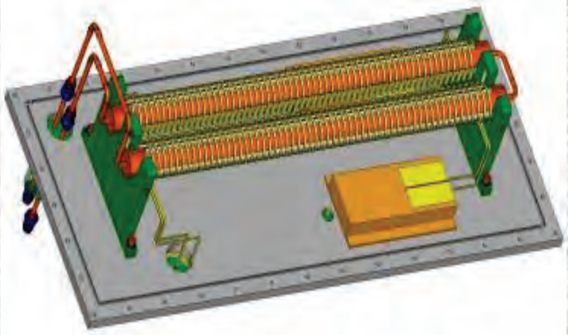
50 Ω planar electrodes, connected in vacuum by coaxial cables with the length providing necessary delays

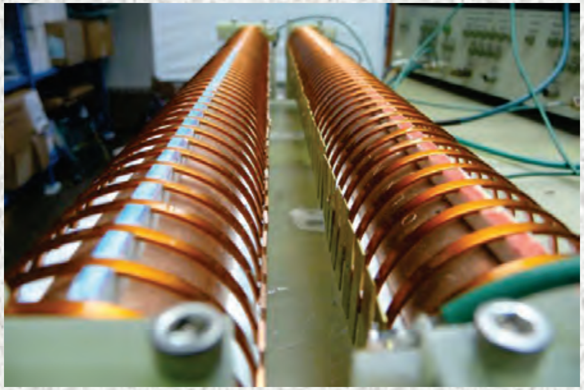




Mechanical schematic of a 50-Ohm kicker

200 Ω helixes





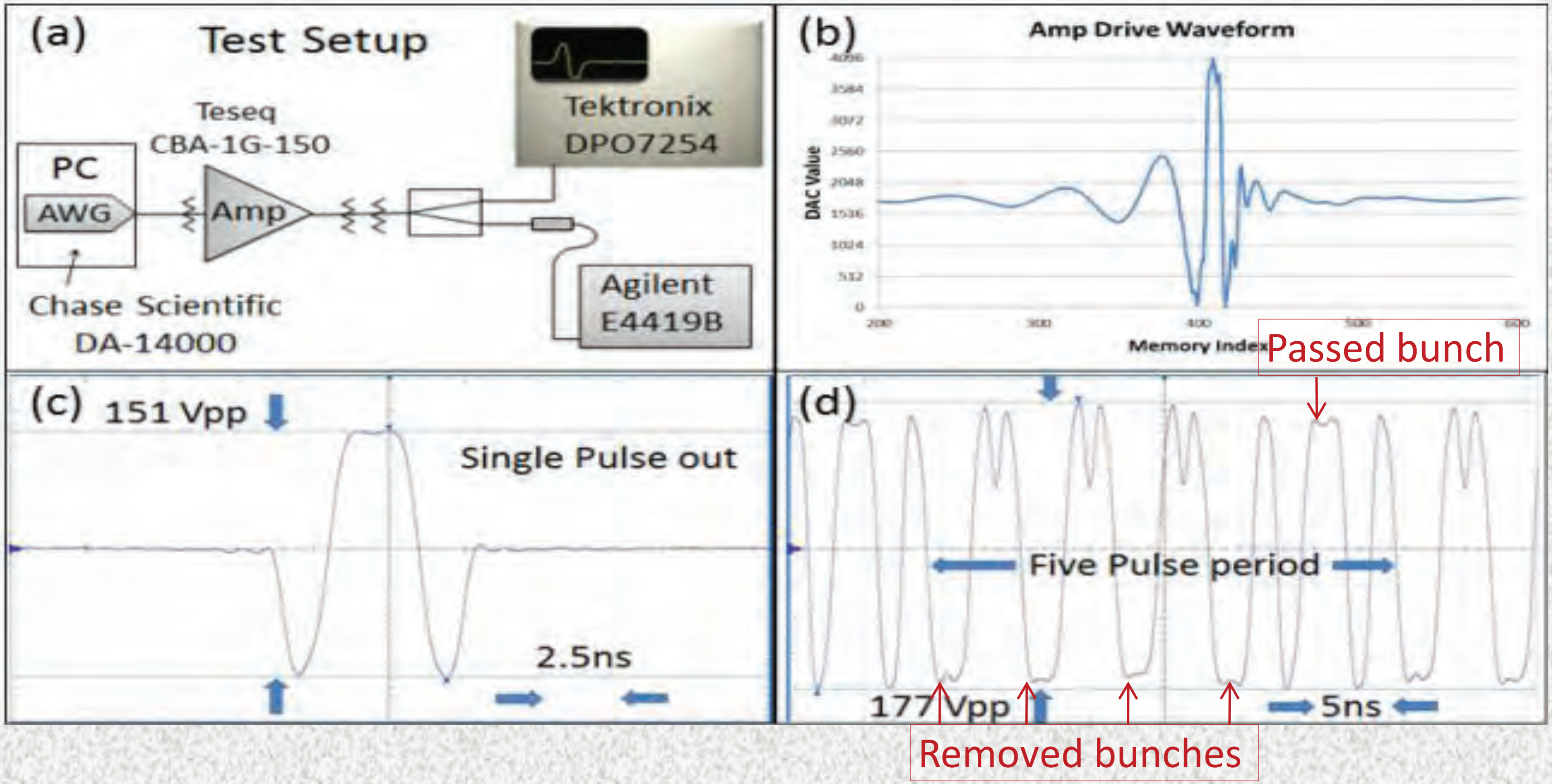
Two helixes

Each helix is a flat wire wound with the 8.5mm helix pitch around a 28.6 mm OD copper grounded tube.

Objectives

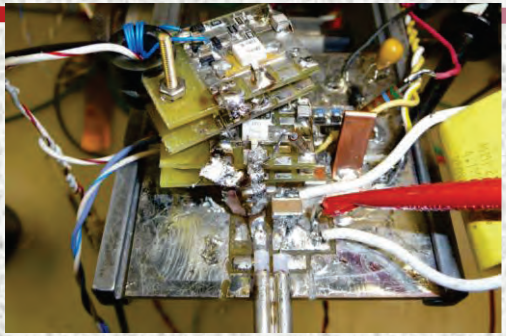
- Two +/- 250 Volts kicker plates
- DC coupled drive to the kicker
- Pulse: ~2 ns rise time, ~1.5 ns wide flattop
- Handle power dissipation for high duty factor (140 W)
- Support variable high duty factor waveforms
- Handle rep. rates, ~30 MHz

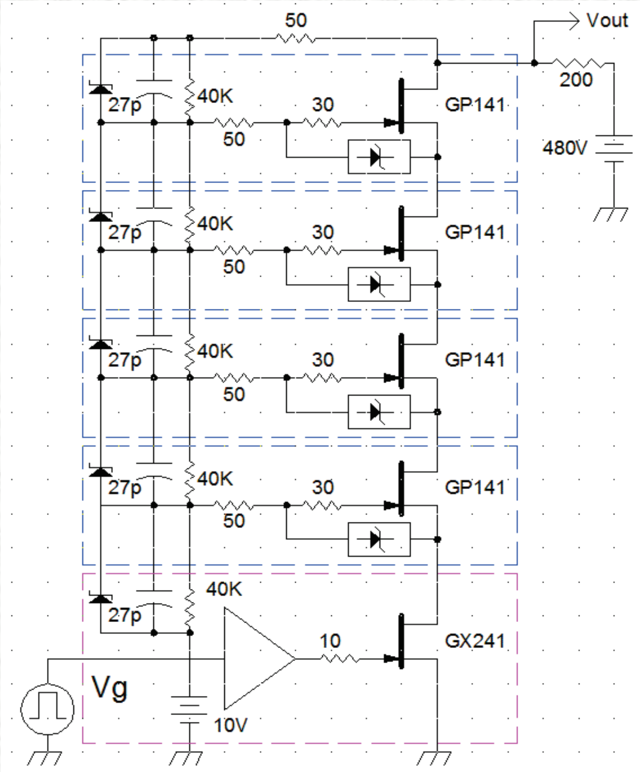
Test at 150 W amplifier

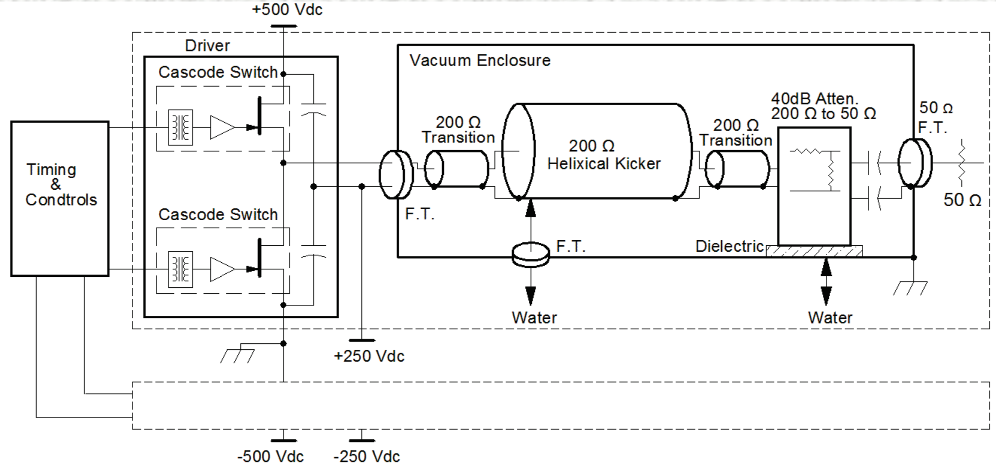


Test of the CBA 1G-150 amplifier with pre-distortion. (a) scheme of the test; (b) pre-distorted input signal and (c) corresponding output signal for a single pulse; (d) output for a CW pattern, corresponding to removal of four consecutive bunches followed by a one-bunch passage. Need 1 kW amplifier

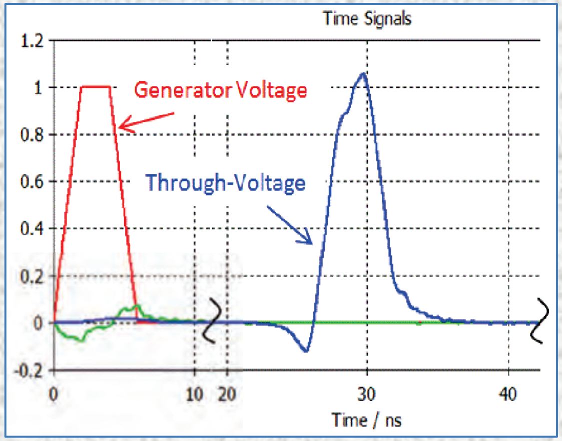
Test of 200 Ω design



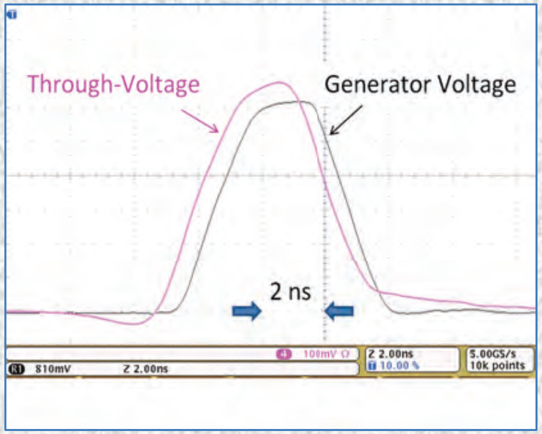




Based on fast GaN FET switches



Simulation results

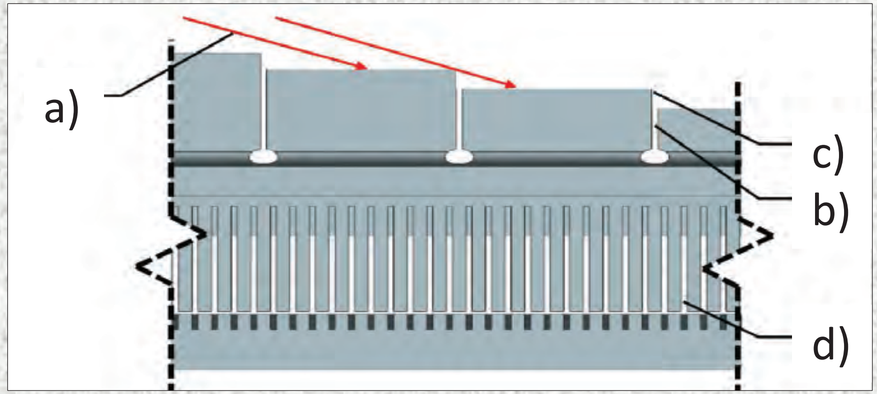


Test results

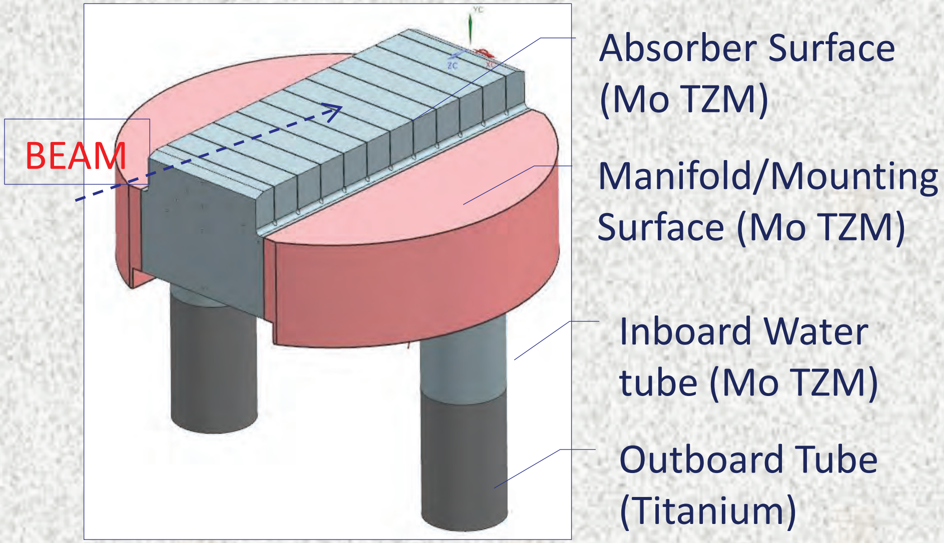
G Saewert et al.,

MEBT Absorber

(a) beam incident on surface 29mrad,
(b) axial stress relief slits,
(c) shadowing step increment (not in scale)
(d) 0.3x1 mm^2 pitch water cooling channels.



Conceptual design of the MEBT absorber.
Length = 40 cm



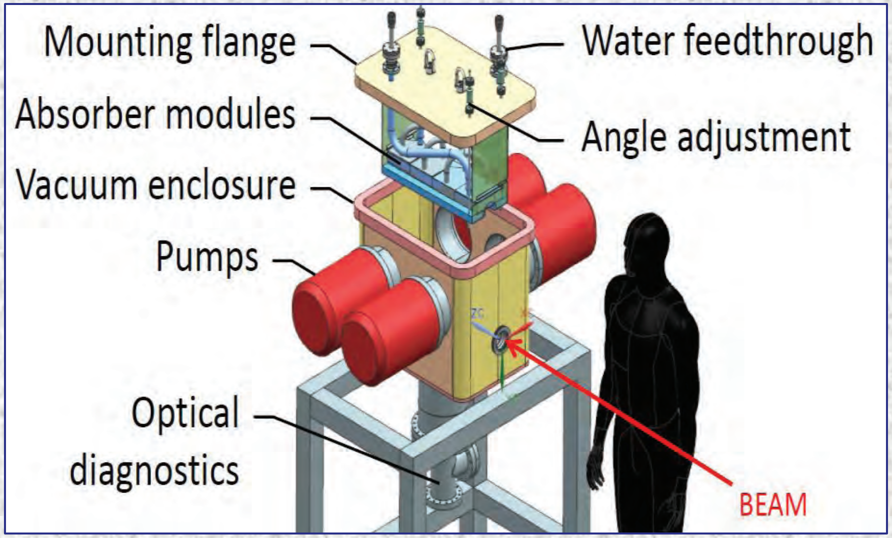
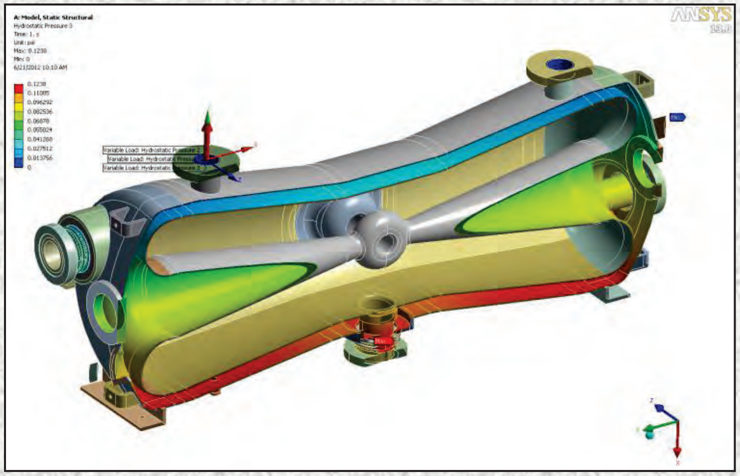
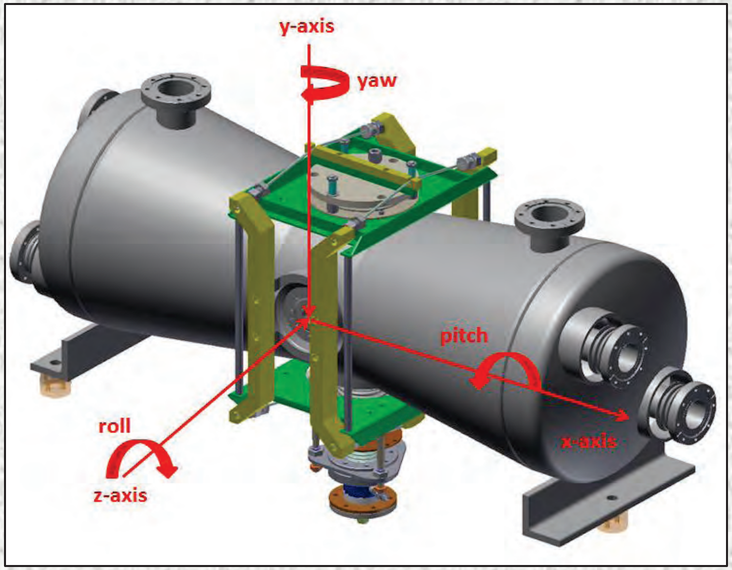


Table 1: HWR main parameters

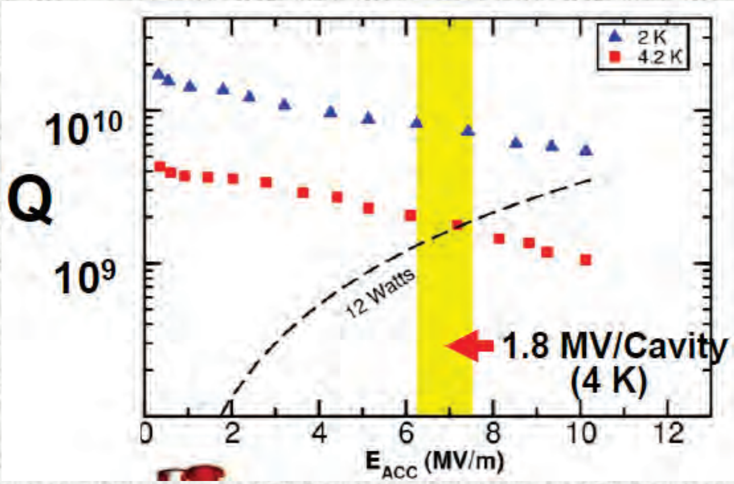
HWR design (ANL)



Donut shape geometry reduce effect of asymmetry in transverse beam dynamics



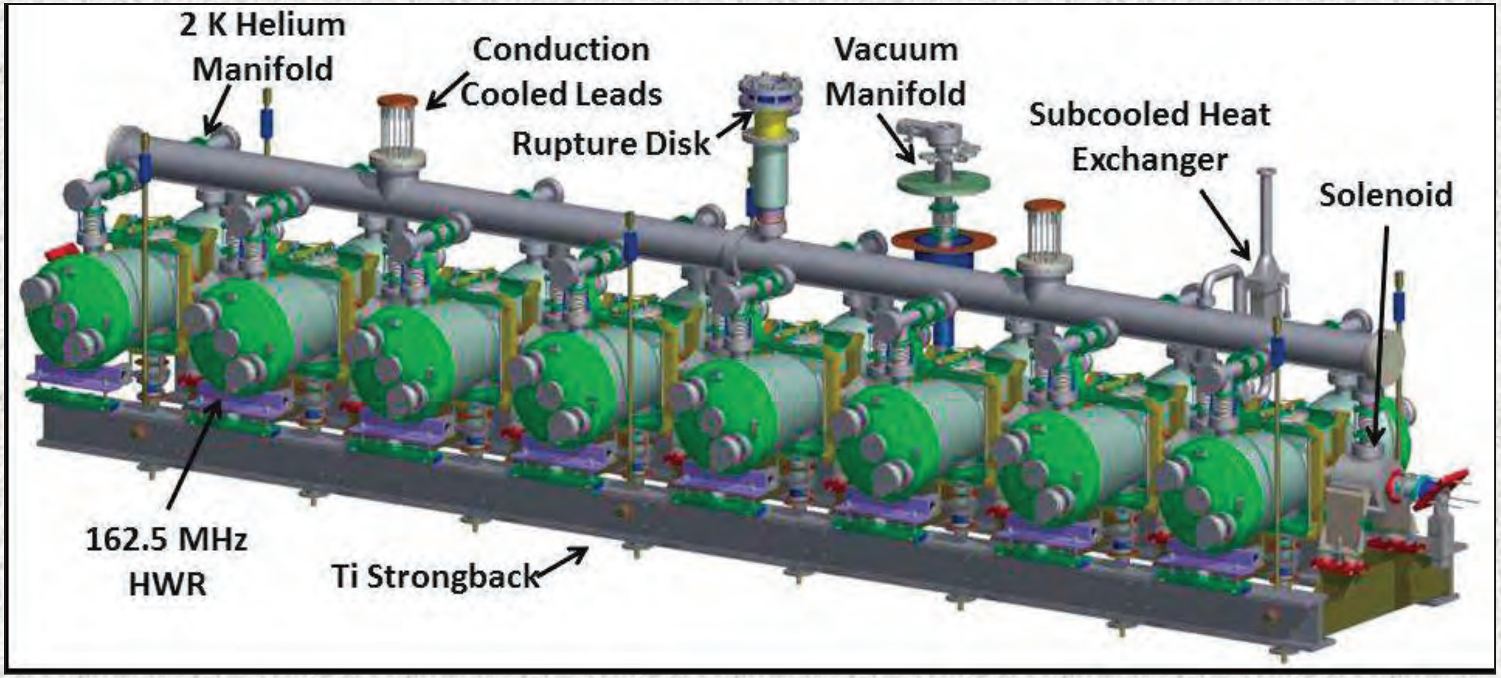
Parameter	PXIE
Frequency, MHz	162.5
Operating temperature, K	2
Optimal beta, β_{OPT}	0.11
$L_{EEF}= \beta_{OPT}\lambda$, cm	20.7
Aperture, mm	33
Accelerating voltage, MV	1.7
E_{PEAK}/E_{ACC}	4.7
B_{PEAK}/E_{ACC}, mT/(MV/m)	5.0
$G = Q_0R_S$, Ω	48
R/Q_0, Ω	272



E_{pk} = 40 MV/m
H_{pk} = 42 mT

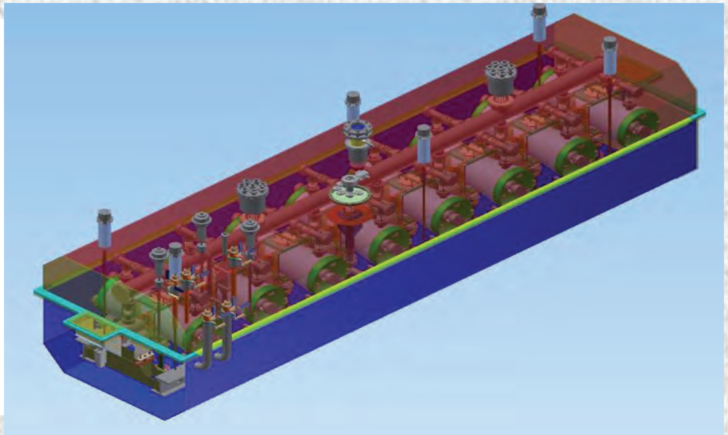
Test of 172.5 MHz HWR

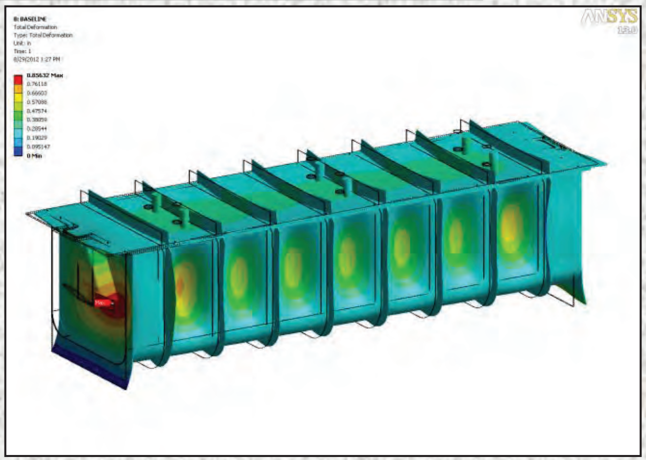
HWR Cryomodule



PROJECT X

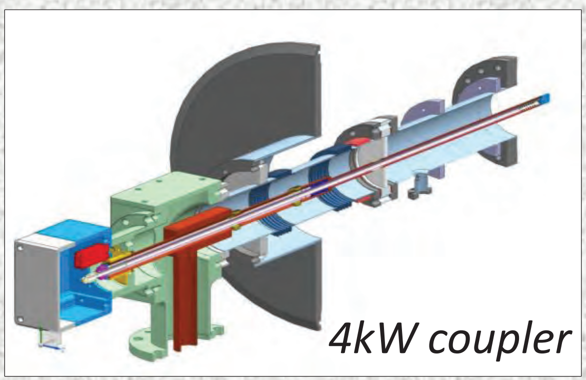
I_{AVE} = 1 mA
I_{PEAK} = 5 mA
W_{IN} = 2.1 MeV
W_{OUT} = 11 MeV





SSR1 design and test

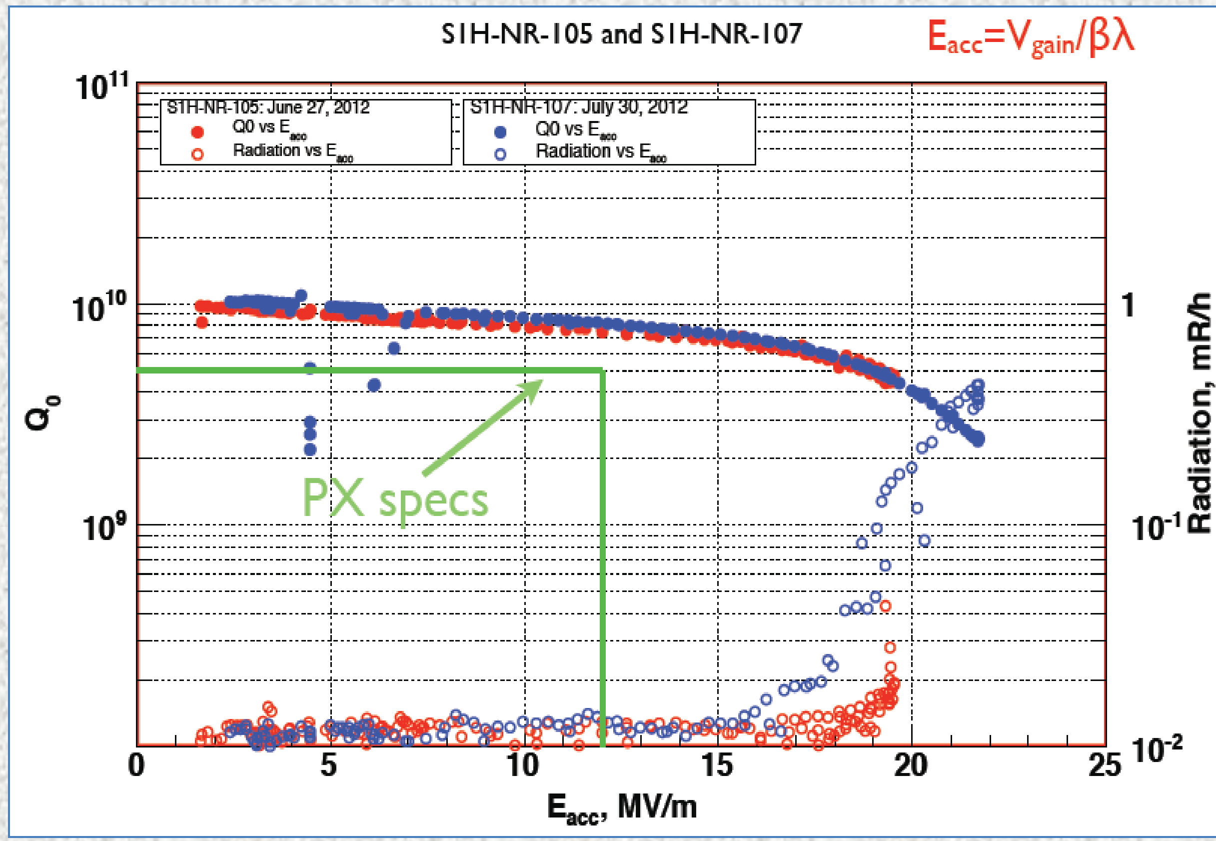
SSR1 cavity



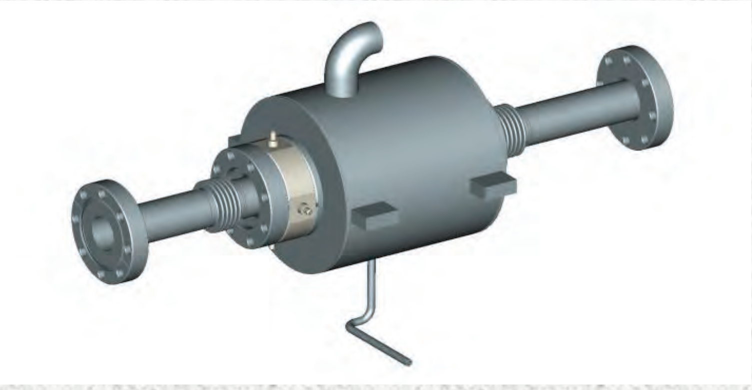
4kW coupler

R.Kephart, TH03B03

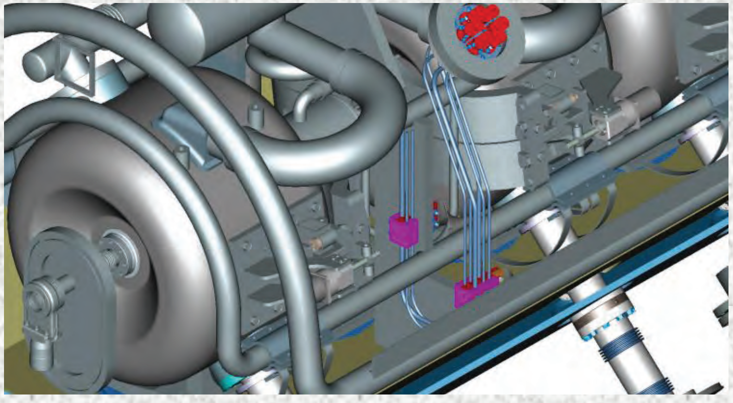
- **10 ordered (Roark), 6 received, 2-tested**
- **Both cavities passed Project X requirements:**
  - **E_{acc} = 12 MV/m; Q_0 > 5e9**
- **Soft multipactor at 2-7 MV/m, gone after processing**



SRR1 cryomodule design



Solenoid and BPM assembly



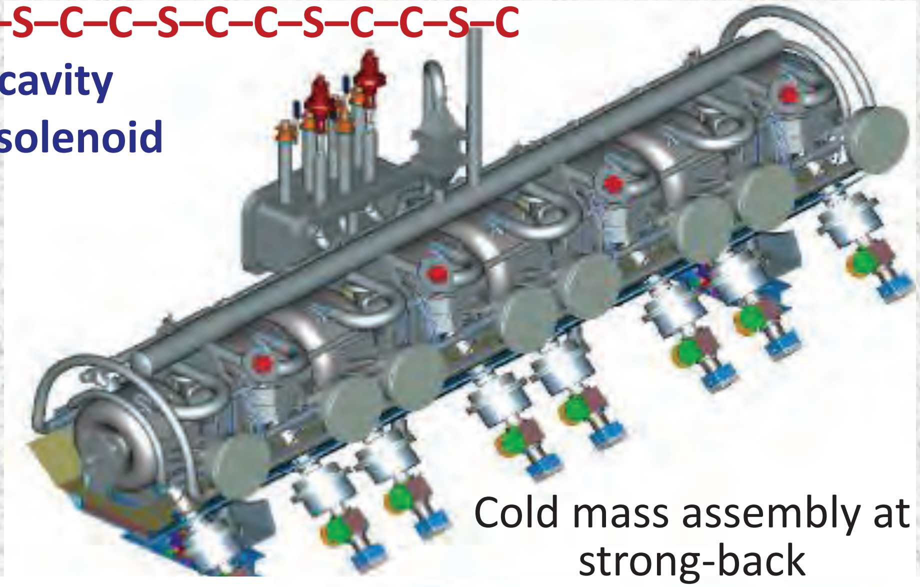
SSR1 cavity assembly

Heat loads:	70 K	5 K	2 K
Total, [W] (Incl. dynamic)	255 0	80 0	27 16

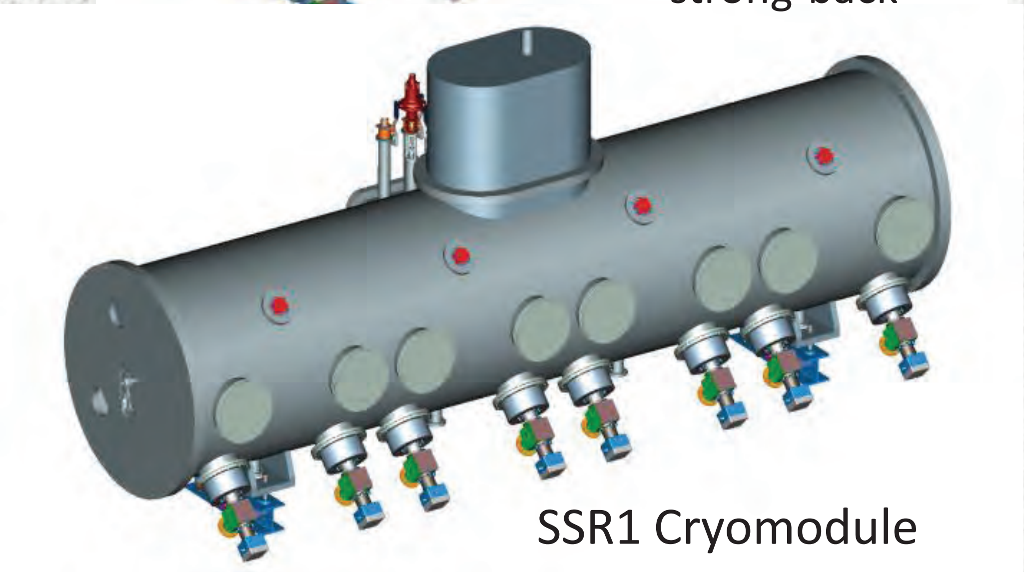
C–S–C–C–S–C–C–S–C–C–S–C

C-cavity

S-solenoid

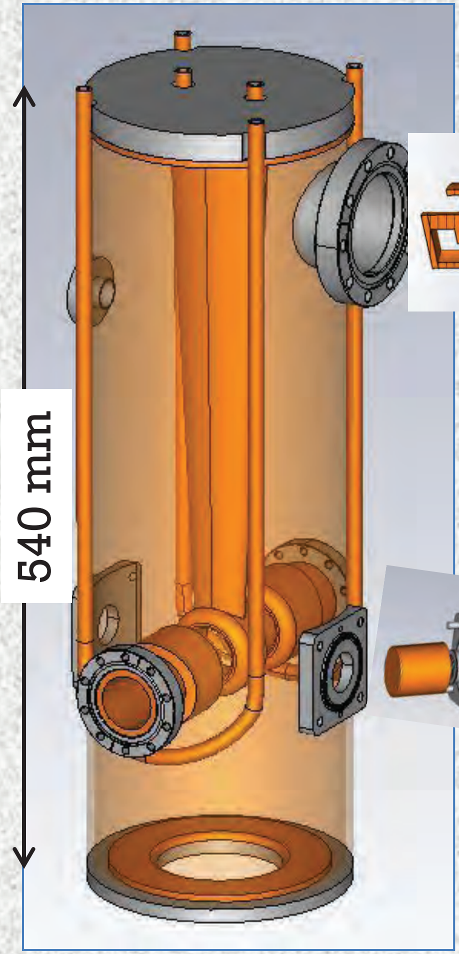


Cold mass assembly at strong-back

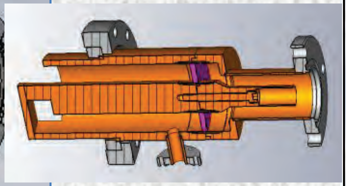


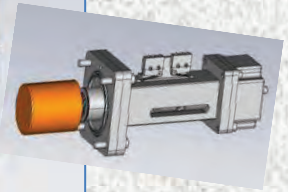
SSR1 Cryomodule

QWR Bunching Cavity

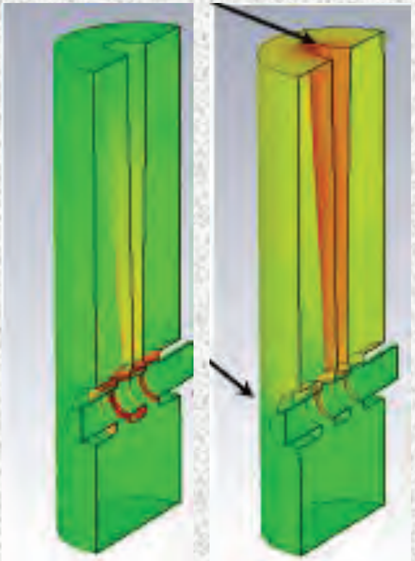


340 mm
(flange-to-flange)



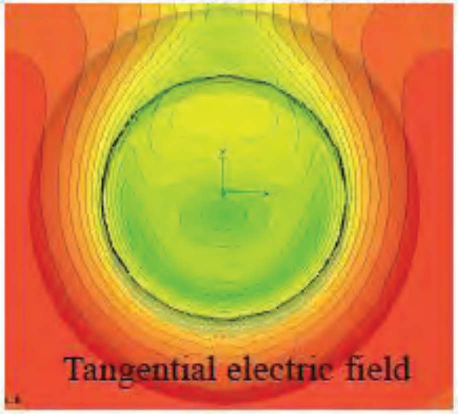


Parameter	Value
Frequency, MHz	162.5
Q factor	10530
Aperture radius, mm	20
Gap, mm	2x23
Particle energy, MeV	2.1
Effect. shunt impedance, Ohm	5.3e6
R_eff/Q	503
Effective voltage, kV	70
Power loss in copper, kW	0.92
Max. elec. surface field, MV/m	4.2



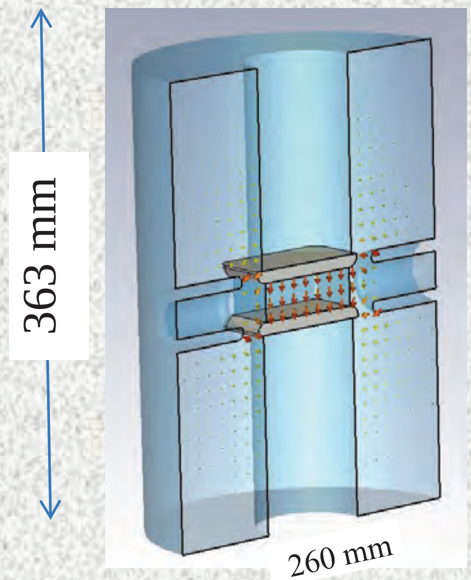
E-field H-field

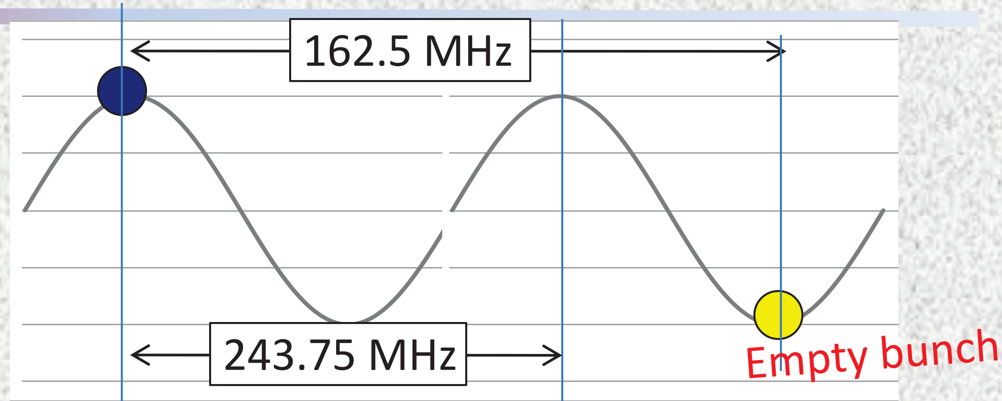
- Some steering effect from field asymmetry.
- No emittance growth is observed.
- Beam deflection is compensated if cavity is shifted down by 0.6mm.



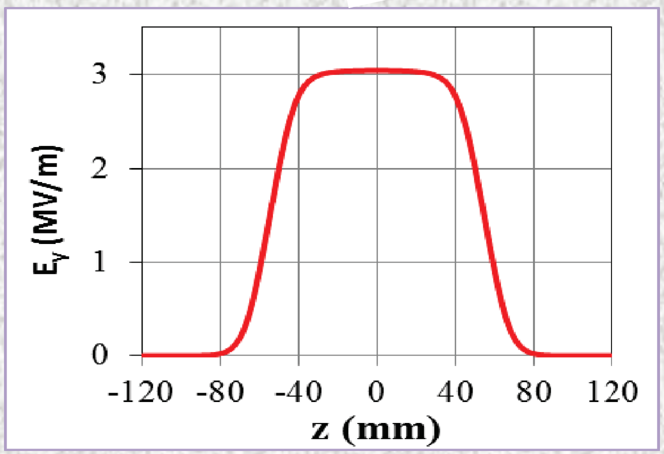
E-field asymmetry

NC RF separator





Parameter	Baseline	20 mm	Low freq
Frequency, MHz	**243.75**	**243.75**	**162.5**
Inner height, mm	363	413	368
Inner diameter, mm	260	260	420
Flange-to-flange, mm	350	350	510
Gap, mm	30	20	30
E_surf_max, MV/m	5.2	4.8	4.56
E_y_max, MV/m	3.04	4.3	2.58
Power losses, kW	**2.9**	**1.44**	**1.94**
Kick voltage, MV	1.07	1.07	1.07
Proton β (23.5 MeV)	0.22	0.22	0.22
Deflecting angle, mrad	5.0	5.0	5.0



deflecting electric field along beam axis

PXIE RF system

- The PXIE RF systems will include all CW amplifiers that are intended for reuse in the Project X front end.
- The complete PXIE RF system consists of three frequencies at power levels ranging from 4 to 150 kW (total of 21 RF systems)
- At PXIE frequencies and power levels, solid-state amplifiers have been chosen for the RF power sources (compact, reliable).

<u>RF Sources for PXIE (CW)</u>

162.5 MHz

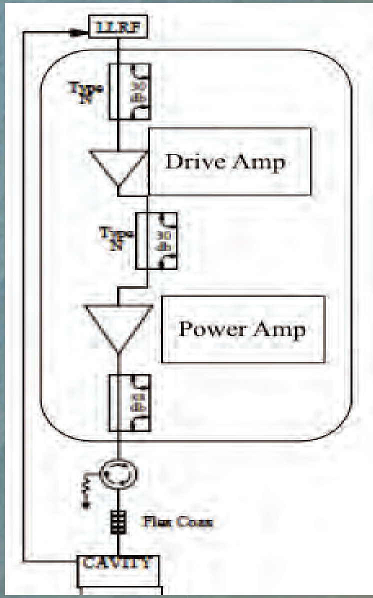
- ***1 RFQ 162.5 MHz – 2 x 75 kW***
- ***3 copper bunchers – 4 kW***
- ***8 SC HWR – 4 kW***

325 MHz

- ***8 SC SSR1 – 4 kW***

243.75 MHz

- ***1 copper RF separator – 7 kW***



Conclusions

- We have good understanding of the PXIE concept.
- Design work on critical components (RFQ, Chopper, HWR and SSR1 cryomodules) is proceeding well.
  - Expect to have conceptual design by the year end
- No obvious showstoppers
- Plan to have PXIE working at design parameters at the end of 2016.

Acknowledgement

- Thanks for providing information for this talk:

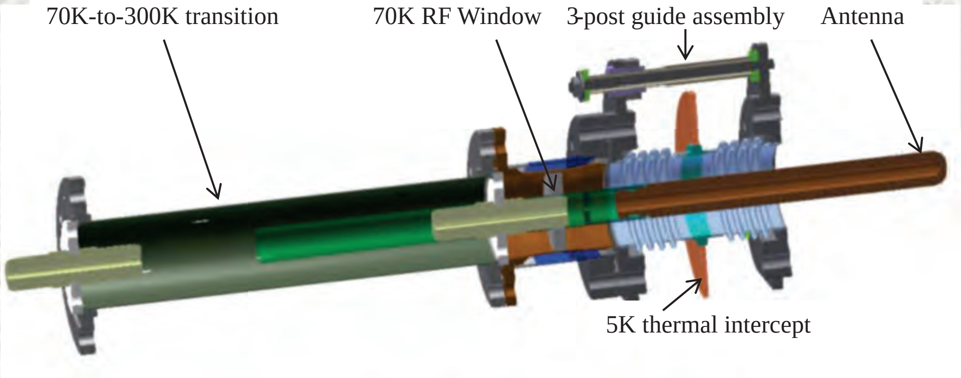
S.Henderson, S.Holmes, R.Kephart, S.Nagaitsev, V.Lebedev, A.Shemyakin, L.Prost, A.Saini, F.Ostiguy, J-P.Carneiro, V.Yakovlev, Y.Eidelman, G.Saewert, J.Staples, P.Ostroumov, L.Ristori, T.Nicol, G.Romanov, I.Gonin, …..

….. (Project X team)……

Thanks for your attention !

Complementary slides

Coupler design (ANL)



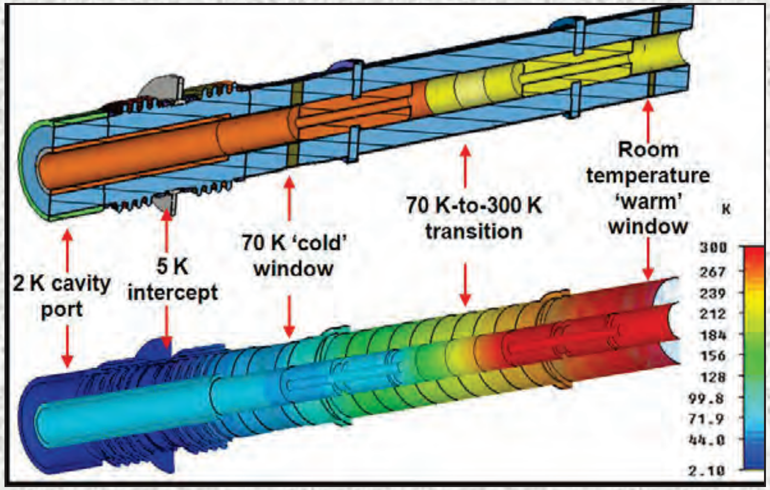
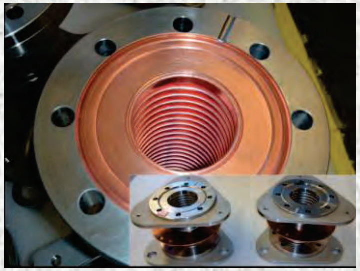


Table 2: Coupler Design Parameters	
Parameter	**Value**
Design RF power, kW	**15**
Outer diameter, mm	50
S11 @ 162.5 MHz, dB	-30
Static load to 2K, W	0.06
Static load to 5K, W	1.6
Static load to 70K, W	2.6

Parts for similar design
72 MHz coupler

50 Ω coaxial capacitive coupler

- Adjustable in the range of $Q=10^5 - 10^7$
- Two ceramic windows (70°K and 300°K)



Two bellows plated by 20 µm of Cu