Project X and PXIE Design and Beam Physics

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(on behalf of Project X design team)

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Outline

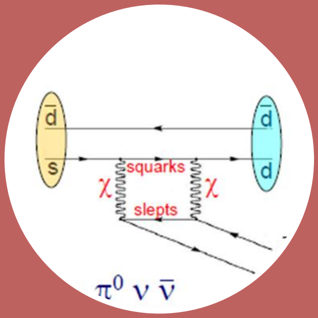
- Introduction: Project X and PXIE
- Optics and Beam dynamics
- R&D on critical components:
  - LEBT
  - RFQ
  - MEBT and Chopper design
  - SC RF: HWR, SSR-325MHz, Eliptical-650 MHz
  - RF
- Conclusion
- Back-up slides: Pulse Linac Design

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

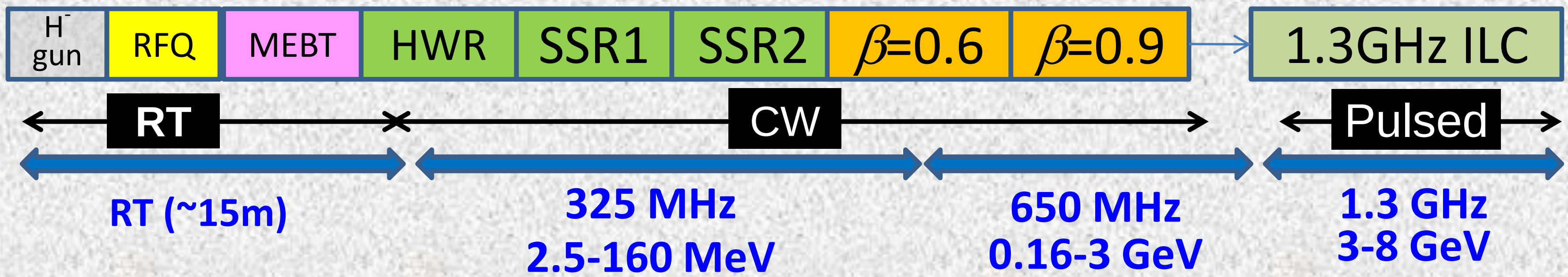
Power Staging for the Research Program

Project X Campaign

Program:	Onset of NOvA operation in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, EDM programs (MI>80 GeV)	Stage-2: Upgrade to 3 GeV CW Linac (MI>80 GeV)	Stage-3: Project X RDR (MI>60GeV)	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power:	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

* Operating point in range depends on MI energy for neutrinos.
** Operating point in range depends on MI injector slow-spill duty factor (df) for kaon program.

Concepts of CW 3GeV and Pulsed Linac



Section	Freq, MHz	Energy(MeV)	Cav/mag/CM	Type
HWR (β_G=0.11)	162.5	2.1-11	8 /8/1	HWR, solenoid, 5.26m
SSR1 (β_G=0.22)	325	11-38	16 /8/ 2	SSR, solenoid, 4.76m
SSR2 (β_G=0.47)	325	38-177	36 /20/ 4	SSR, solenoid, 7.77m
LB 650 (β_G=0.61)	650	177-520	42 /14*/ 7	5-cell ellip, doublet, 7.1m
HB 650 (β_G=0.9)	650	520-3000	152 / 19**/ 19	5-cell ellipt, doubl, 11.2m
ILC 1.3 (β_G=1.0)	1300	3000-8000	224 / 28/ 28	9-cell ellipt., quad, 12.6m

* 7warm and 7 SC doublets. ** All doublets and correctors are warm

+ Lattice design are now is updated. Main focus to improve performance of front –end (PXIE) and 1GeV

Magnetic Focusing

- In the initial part of the low-energy linac, focusing is provided by superconducting solenoids and triplets in MEBT (round beam).
- Starting with the 650 MHz section, a standard FD-doublet lattice is used.
  - *LE650 - half of quads are warm, half –cold*
  - *HE650 – all quads are warm*
- In the ILC section FODO lattice is used. Cold quads in the middle of CM
- All magnets have built-in dipole correctors and BPM for beam steering.
- Cavities and focusing elements are grouped in cryomodules. For the high energy linac, ILC Type-4 cryomodules is possible to use with minor modifications.

Section	HWR	SSR1	SSR2	LE650	HE650	ILC
Focusing	SR	SR^2	SR^2	FDR^3	FDR^8	FR^8DR^8

Elements: S – solenoid, R resonator, FD – doublet (F and D – quads).

Optics in SC cryomodules

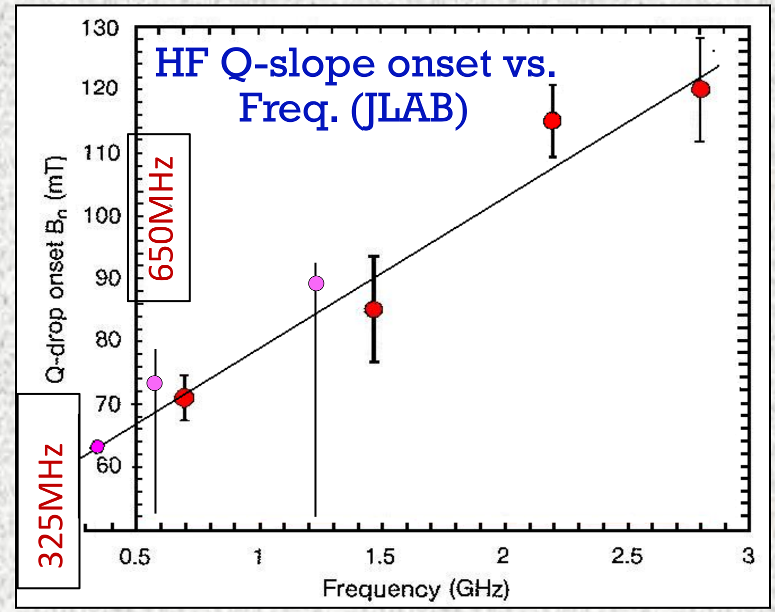
- **Structure of Half-wave cryo-module**
  - *8 cavities, 8 solenoids* **(S C S C S C S C S C S C S C S C)**
  - *Starts with a solenoid to mitigate H_2 influx from MEBT*
- **Structure of SSR1 and SSR2 and 650 MHz Cryo-modules**
  - *8 cavities, 4 solenoids* (**C S C C S C C S C C S C**)
  - LE650 : (**C C C FD C C C**); HE650 - 8 cavities
- **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*
- **Cryomodule interface**
  - *CM-to-CM transition goes through room temperature vacuum chamber*
    - *Good from repair points of view but complicates beam dynamics*
  - *Cryomodules face interface with cavities – improves long. dynamics*
  - *Small space allocated (~20 cm in HWR-SSR1, ~2m at 650 MHz CM's)*
    - *Laser profile monitor, Pumping port*

Choice of cavity gradient

Cavity Gradient Constrains:

- Surface Magnetic field (high field Q-slope onset)

162.5 MHz: B_{pk} < 60mT
325 MHz: B_{pk} < 70 mT
650 MHz: B_{pk} < 70mT
1300 MHz: B_{pk} < 80mT



- Surface Electric Field (Field emission)

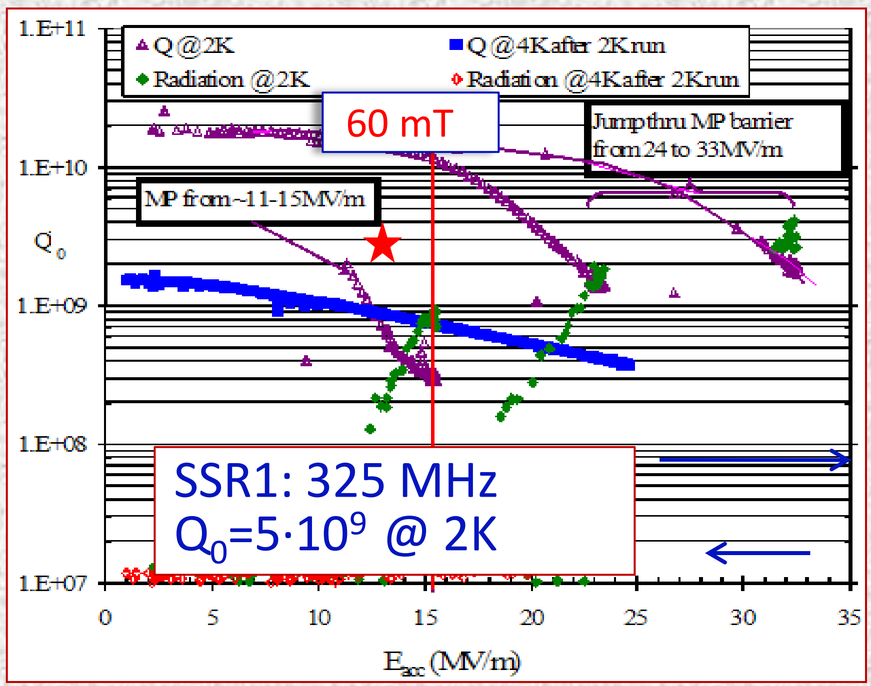
E_{peak} < 40 MV/m

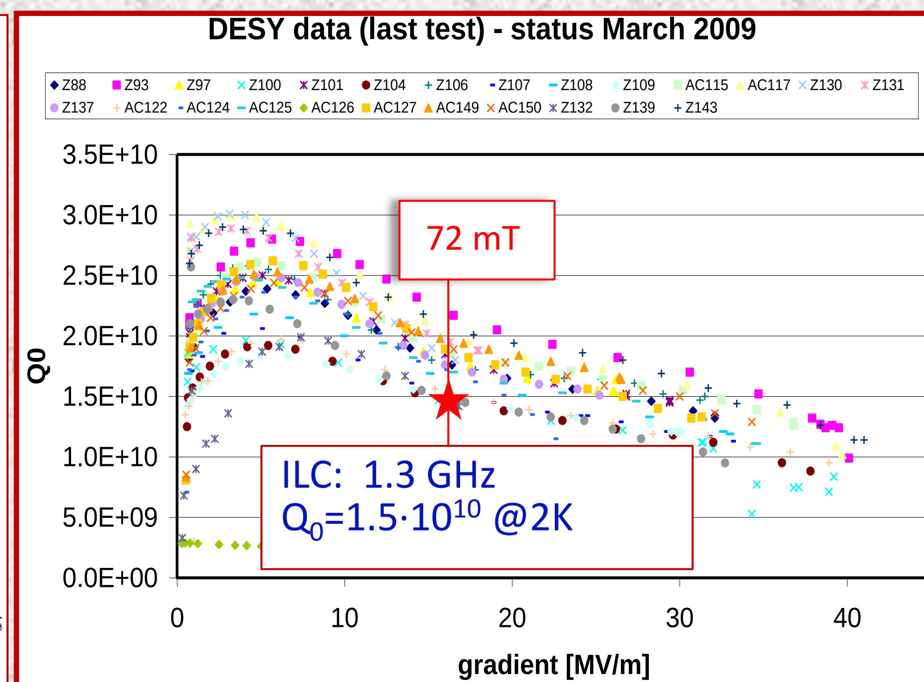
- Limitation of Power dissipation at 2K

250 W per CM total,
- 25 W per cavity (8 cavities/CM)

Cryo-losses: Assumption

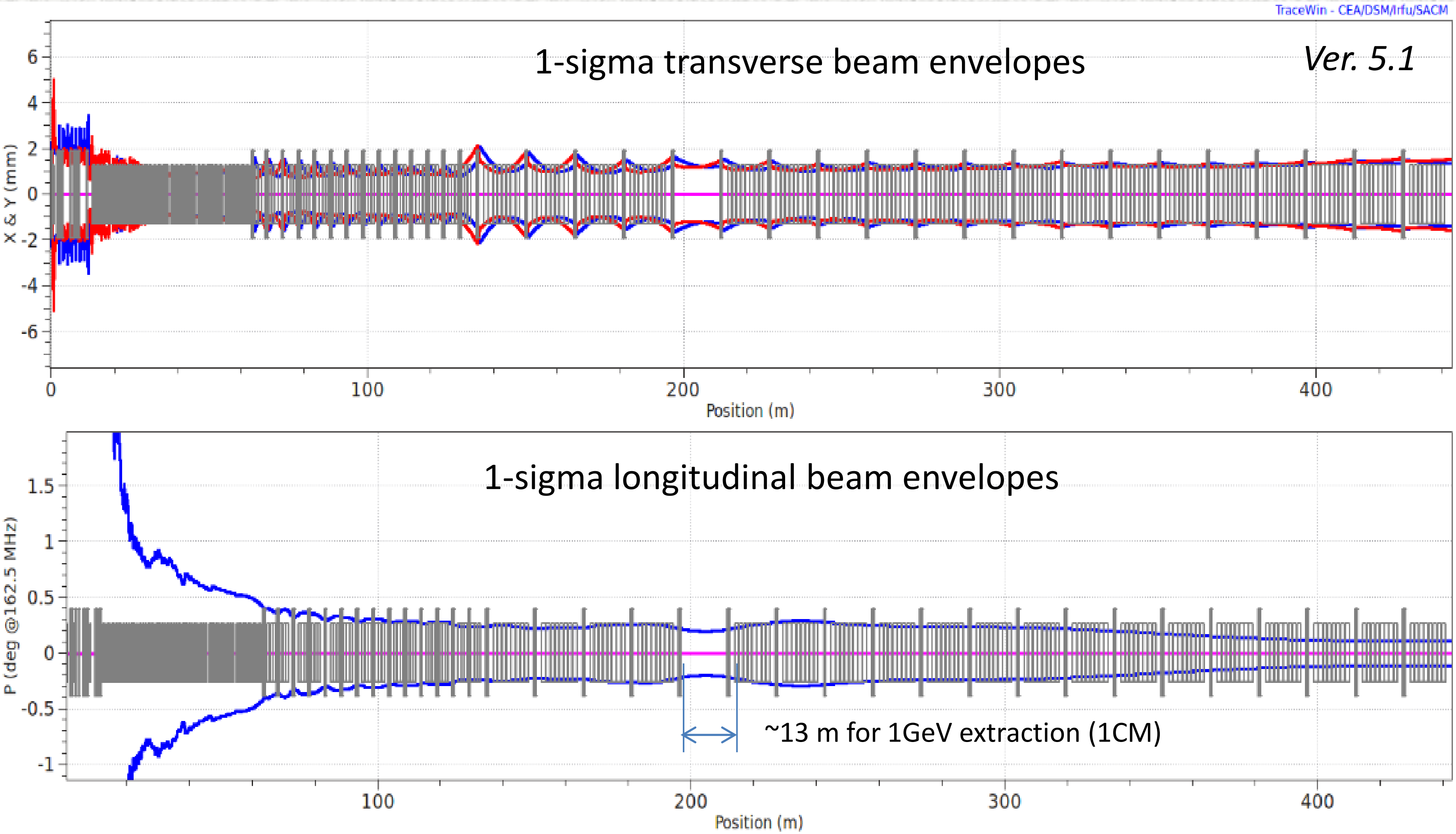
- R_{res} ~ 6 (10) nΩ , frequency independent
- BCS resistance is field dependent (medium field Q-slope). At 2°K we have:
  - *– 325 MHz – resistance is dominated by residual.*
  - *– 650 MHz – BCS and residual gives comparable contribution*
  - *– 1300 MHz – BCS resistance is dominated*
- At ~70 mT medium-field Q-slope gives ~30% of Q-reduction





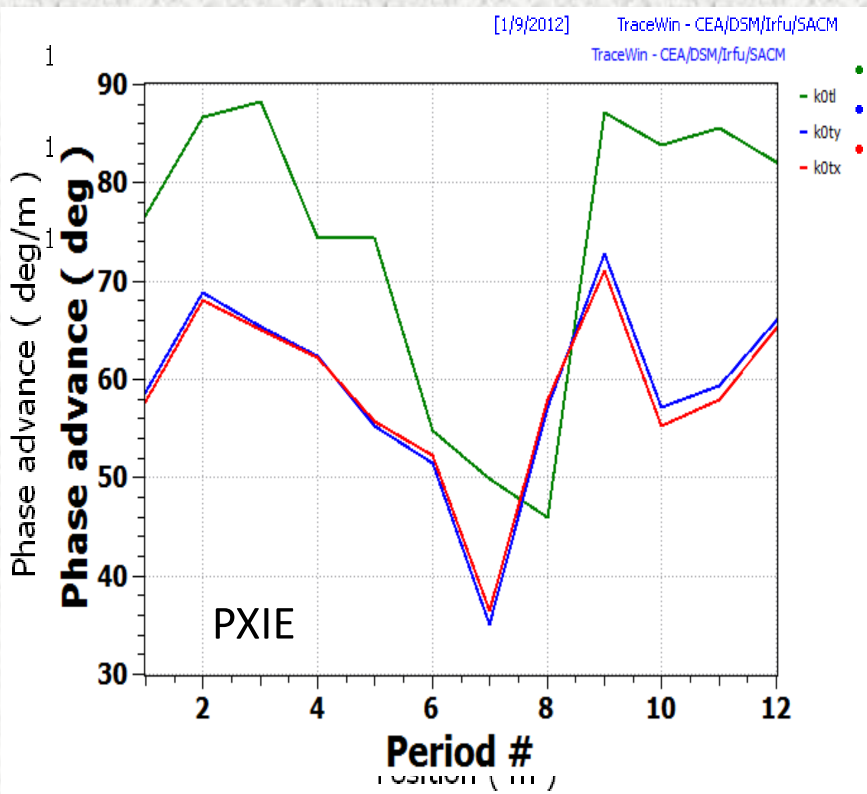
Lattice design and Beam Physics

Lattice of CW 3 GeV Linac

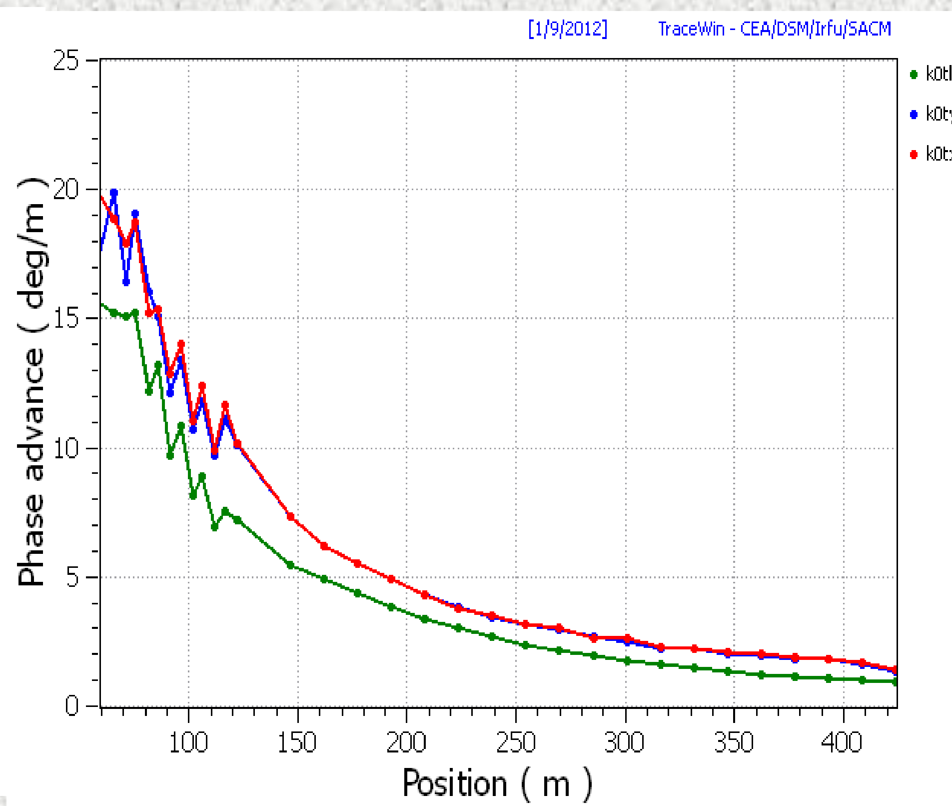


Phase advance

Front End (w/o MEBT)

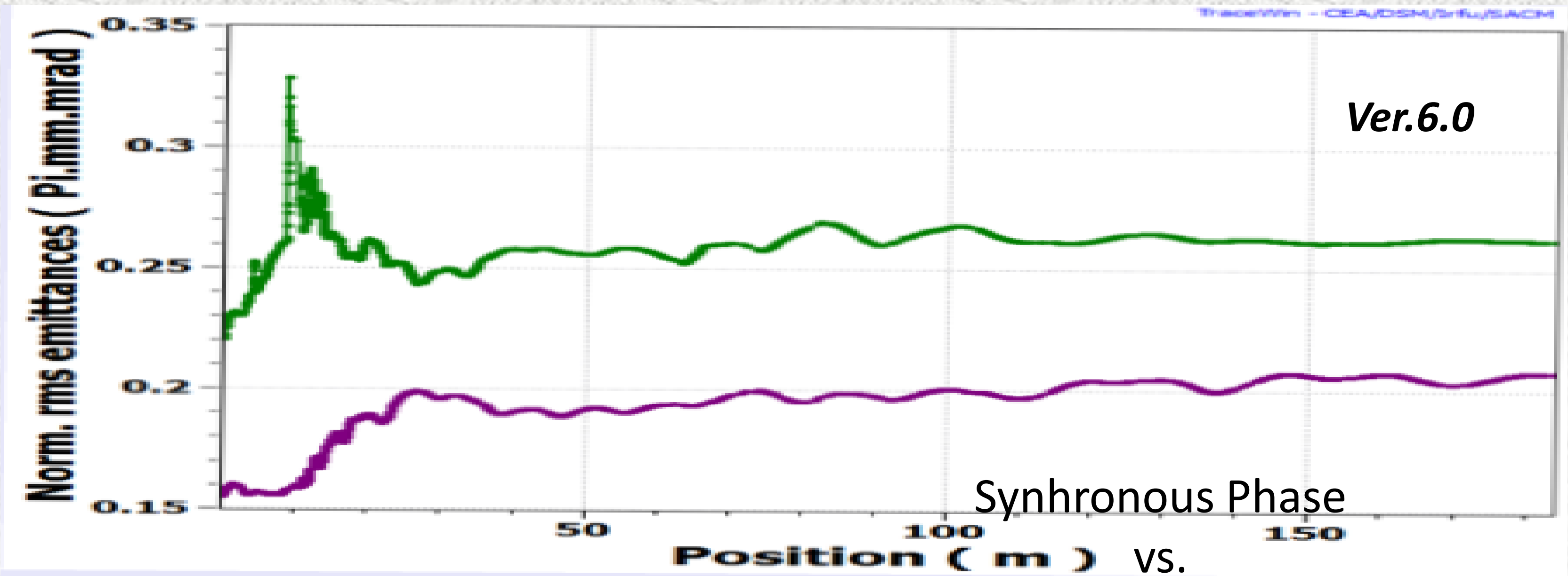


High energy sections

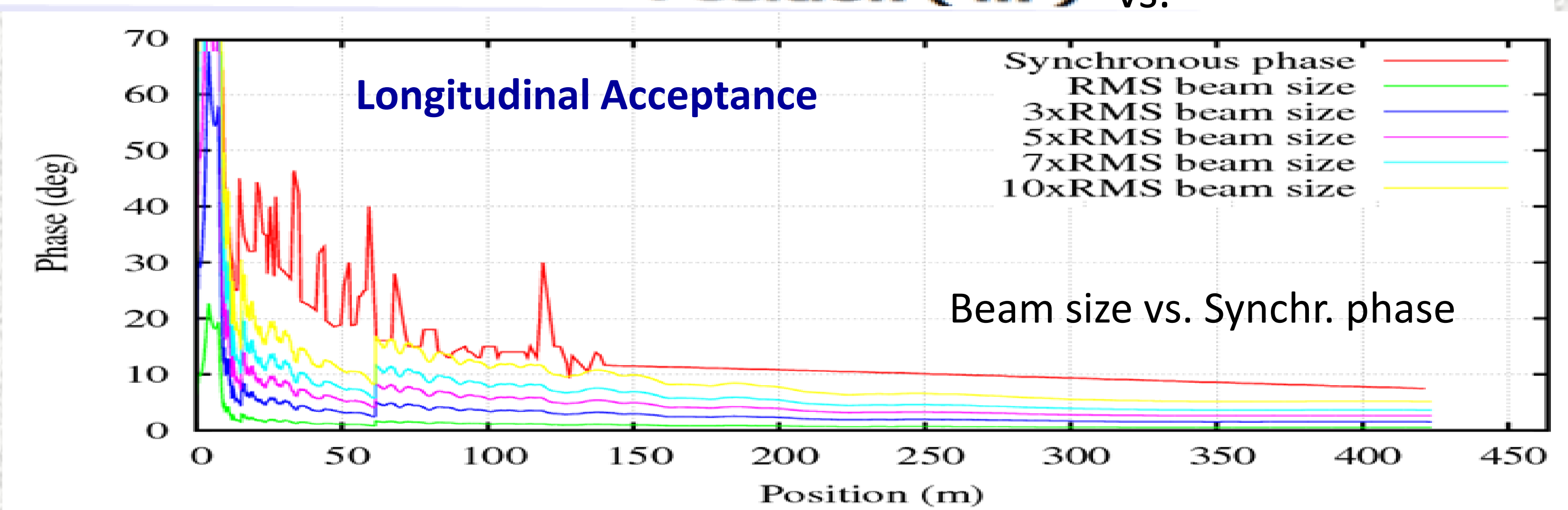


Ver.6.0

Emittances growth

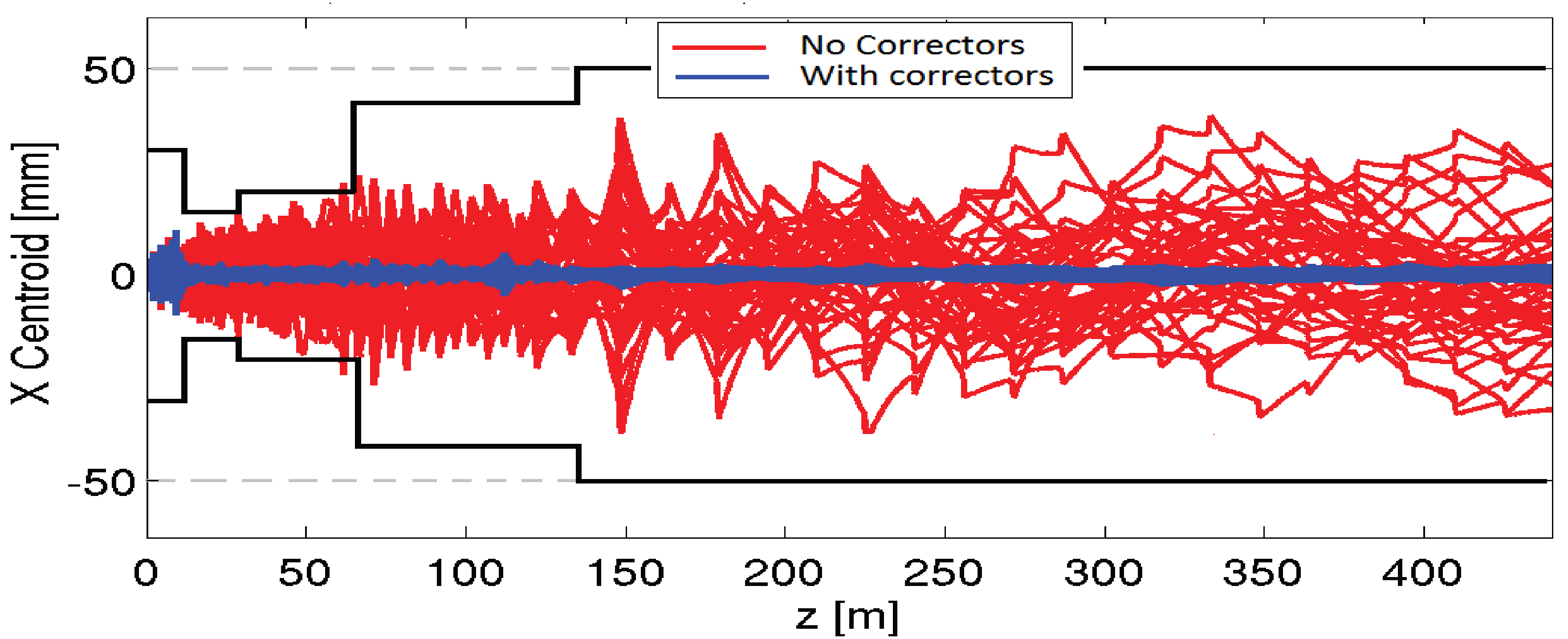


Synhronous Phase vs.



Errors and misalignments

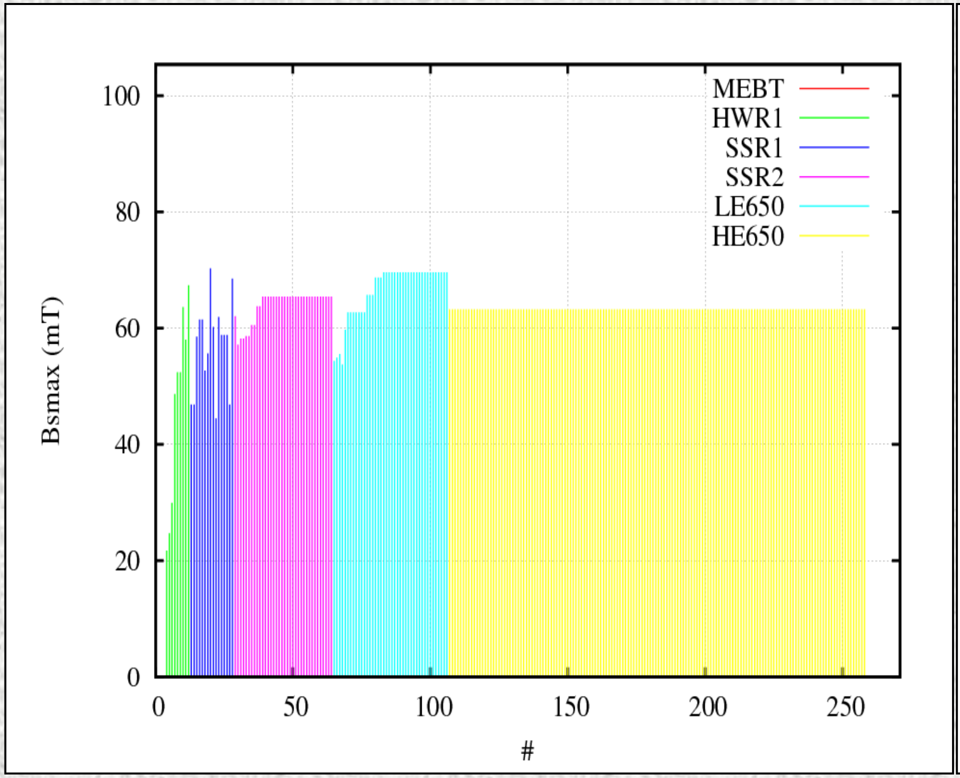
Misalignment of components and RF jitter Studies



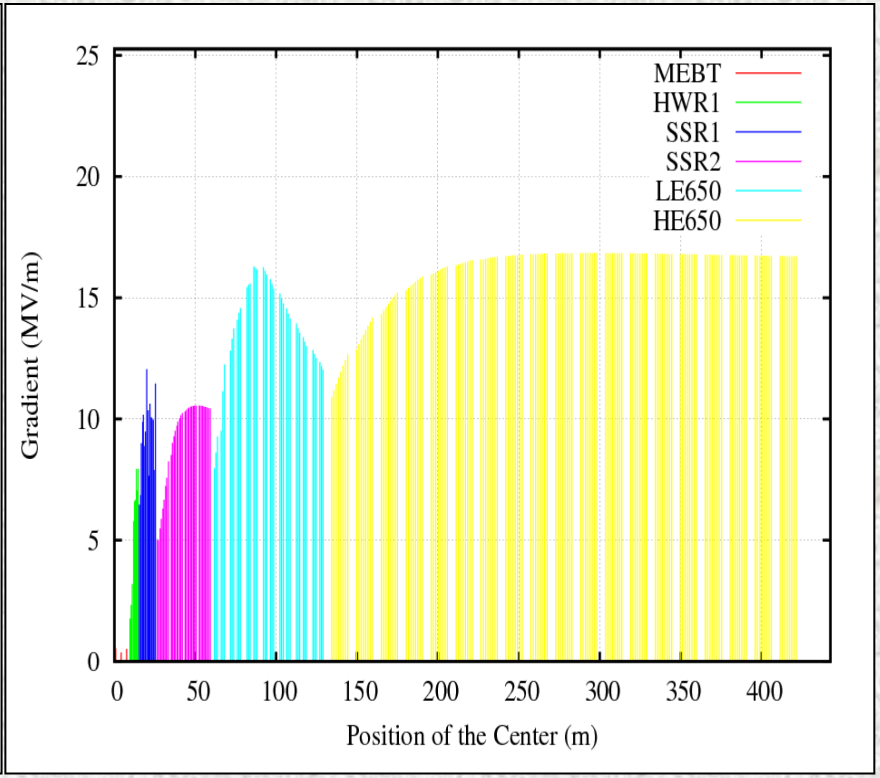
TRACK simulations (400 machines) of corrected/uncorrected beam centroid motion along the linac for the set of errors δ_{xy} =1mm for solenoids & cavities, δ_{xy} =0.5mm for quadrupoles, dynamic RF jitter of 0.5^0 + 0.5% and quad roll of 5 mrad around the z-axis. One corrector and one monitor are used per solenoid and per quadrupole dublet. BPM resolution 30μm.
Big losses (> 1W/m) if no correction ; No losses after alignment correction

Cavities

Surface magnetic field



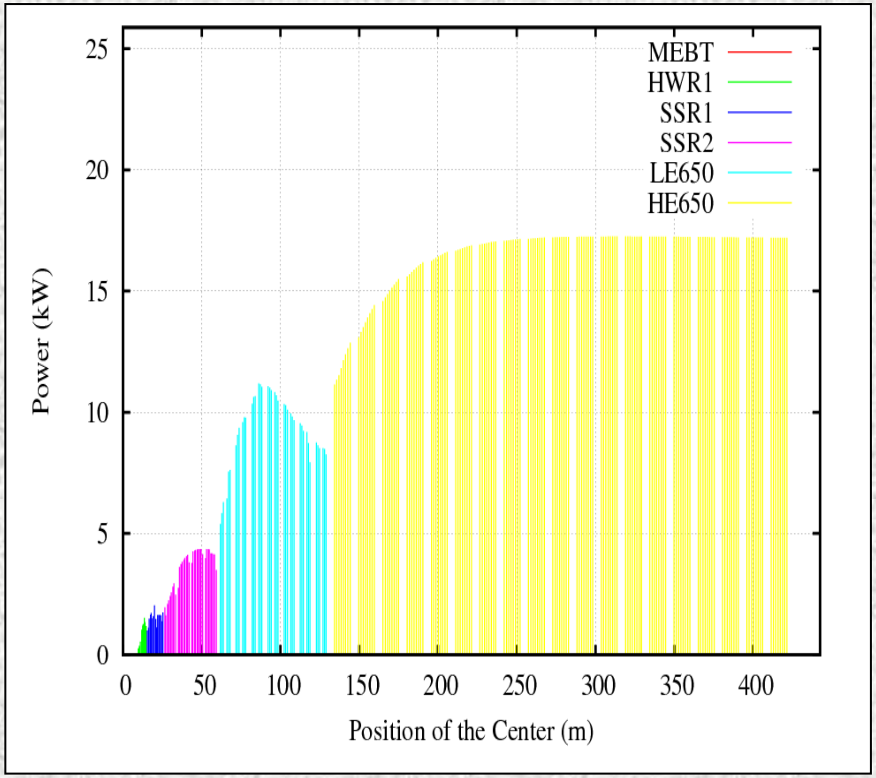
Accelerating Gradient



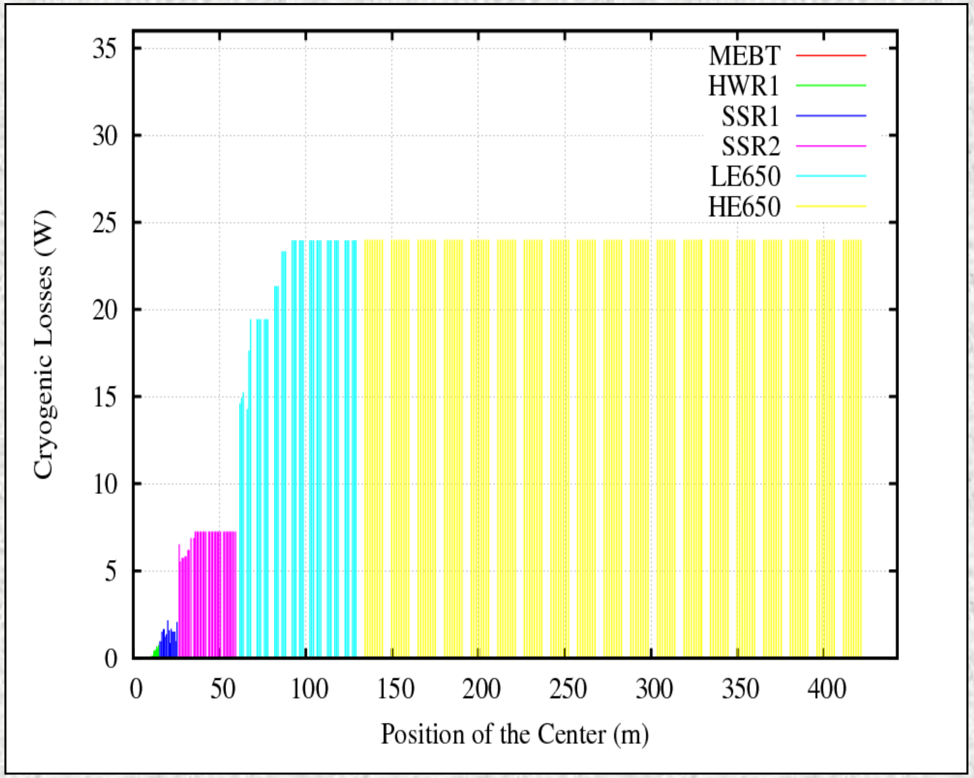
*Recent changes in Front-end design not reflected here

Cavities (2)

Beam Power

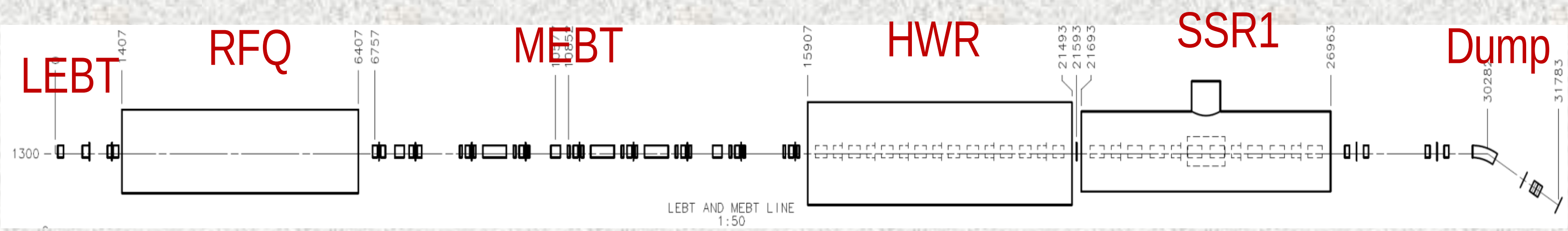


Cryogenic losses



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

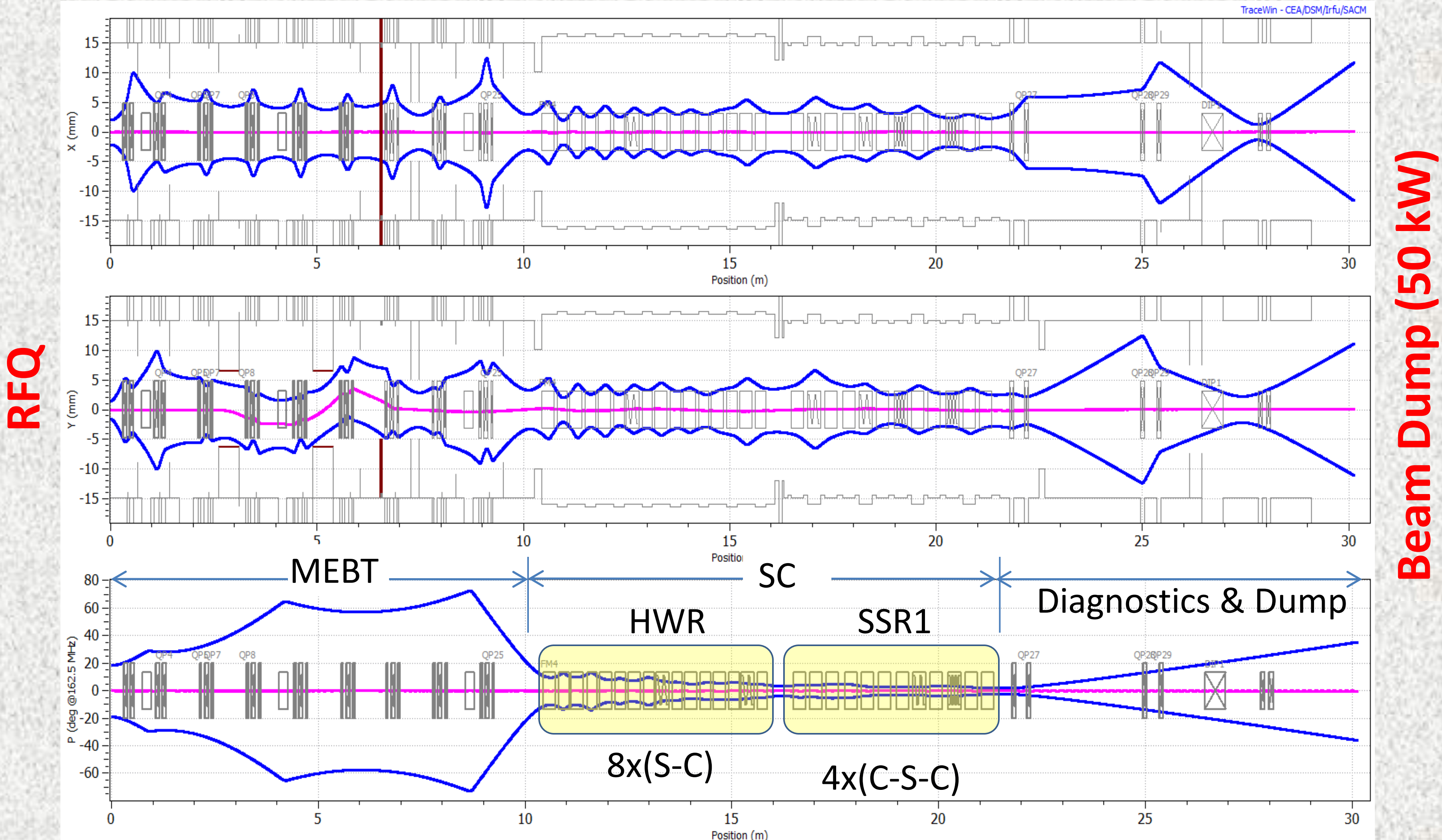
- Specific technical PXIE program goals are to demonstrate (challenges):
  - ***reliable operation of a CW 2.1 MeV RFQ accelerator,***
  - ***a bunch-by-bunch chopper,***
  - ***low-β acceleration in SRF cryomodules***
  - ***sufficiently small emittance growth during initial acceleration and***
  - ***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.

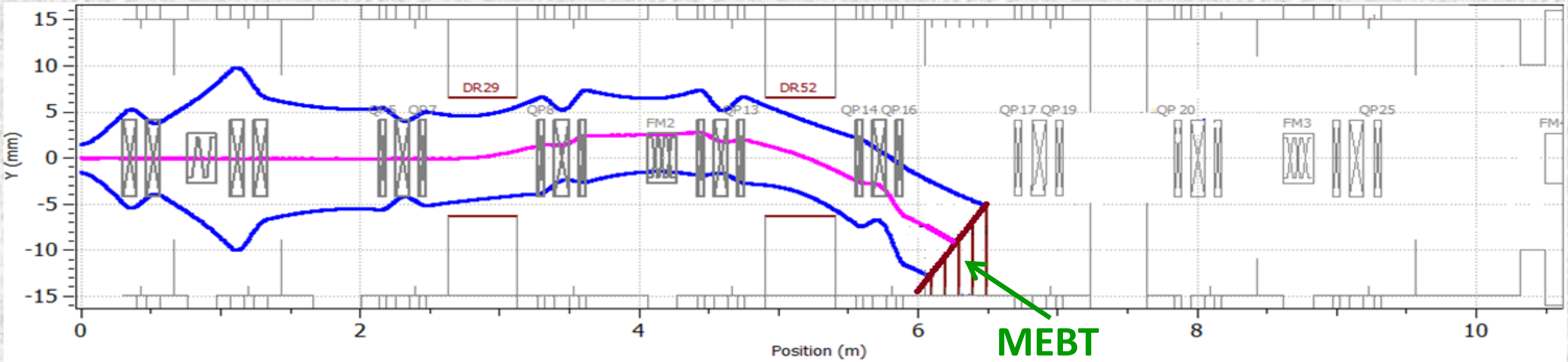
PXIE optics (3-σ envelope)



Kicker polarity in chopper are set for passing beam

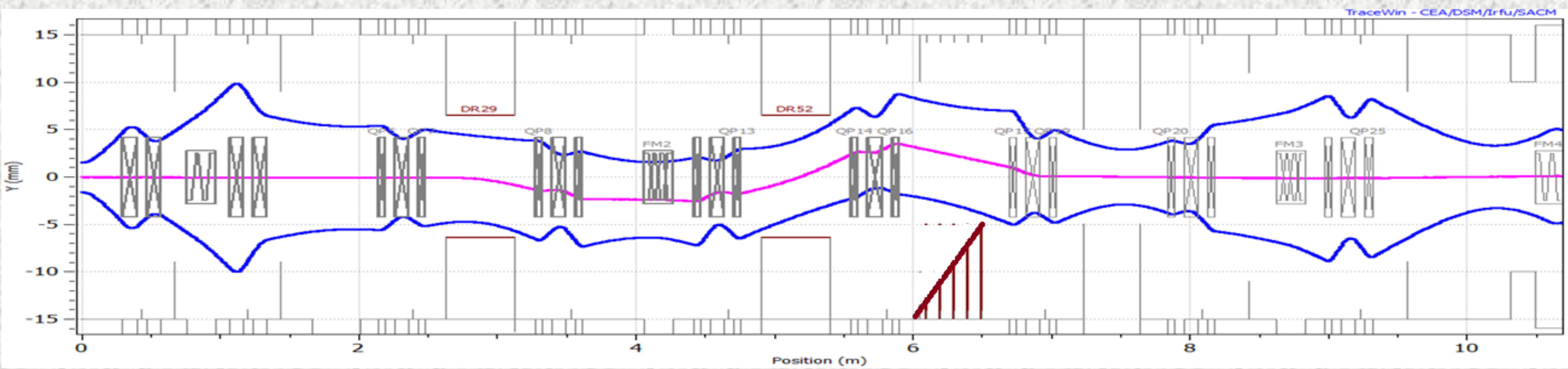
MEBT chopping

Chopped beam



MEBT dump

Passing beam

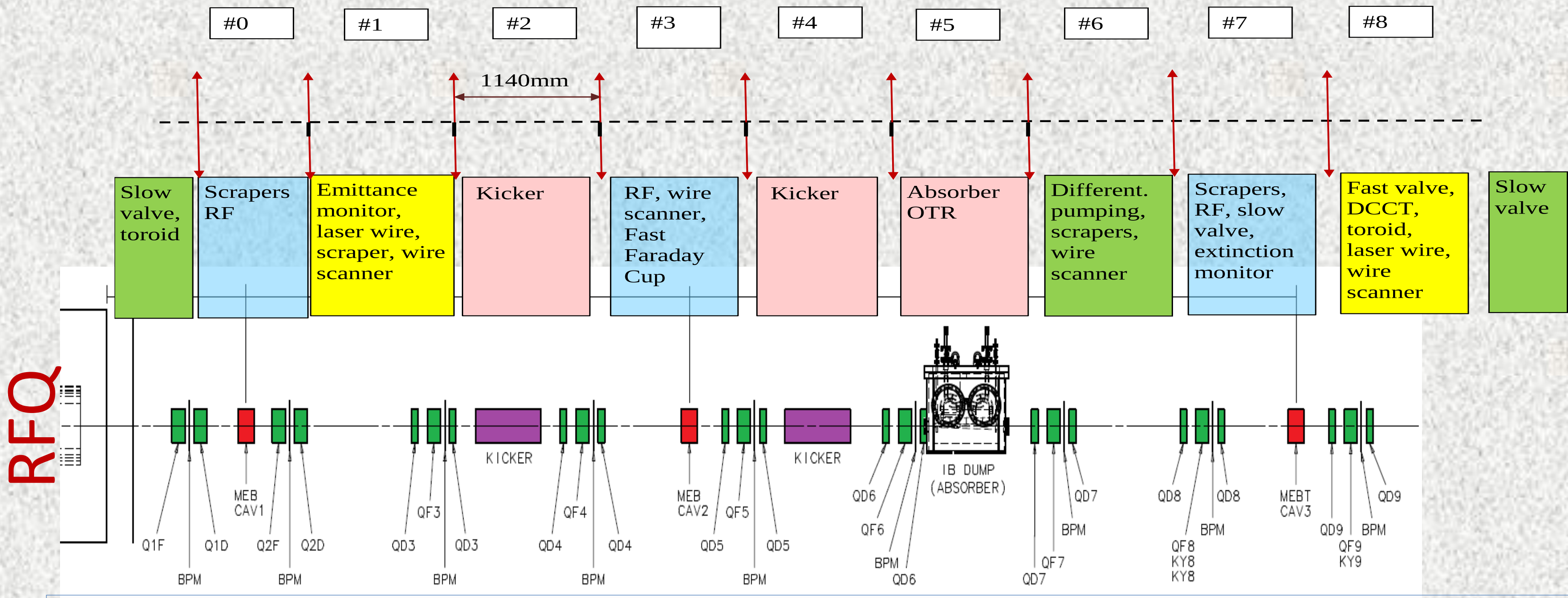


Use of 2 kickers with 180 deg. phase advance reduces kicker voltage

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

DC correctors minimize vertical displacement for passing beam

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).

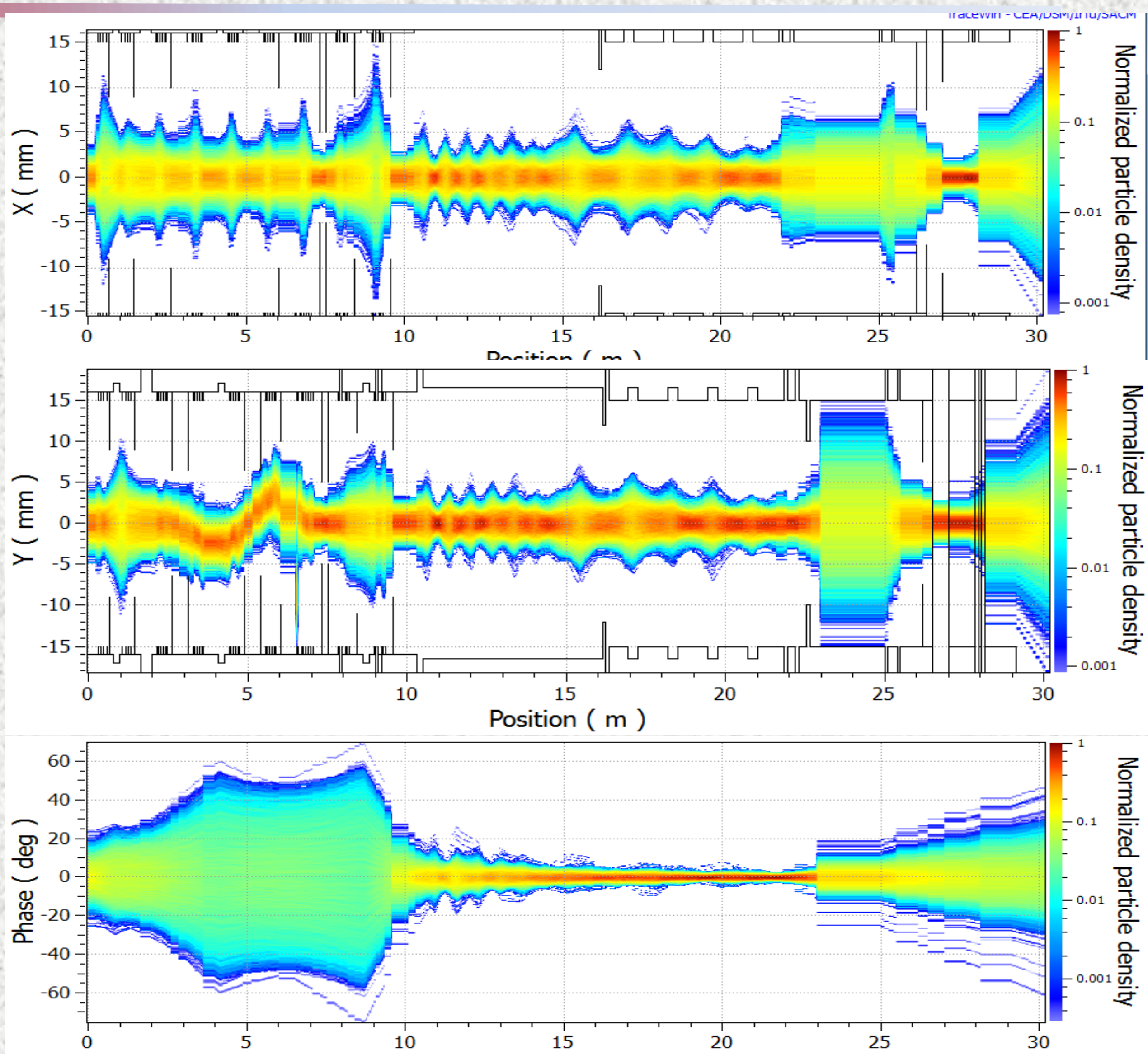
Yellow – **mainly diagnostics** to measure beam coming out of RFQ (#1) and to SRF linac (#8)

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

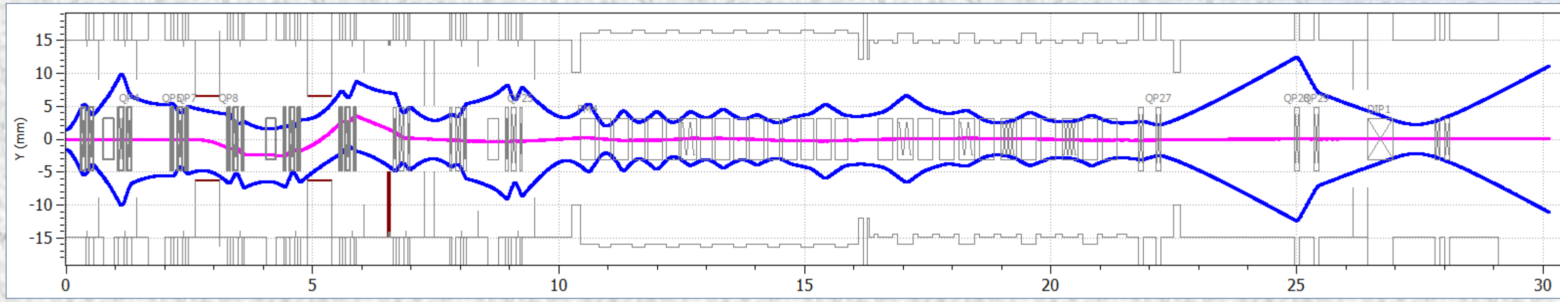
PARTRAN tracking, collimation

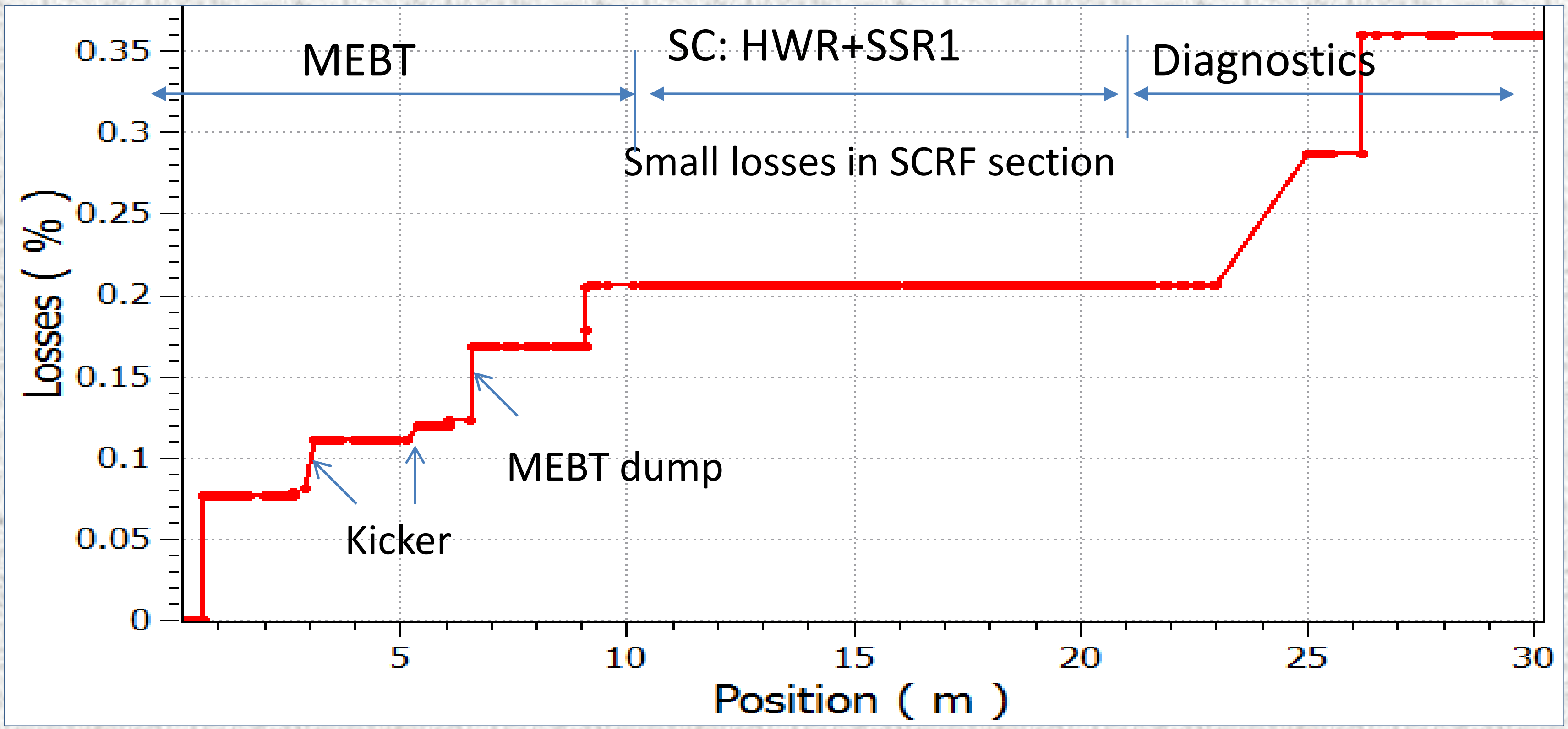


Beam Losses

- 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

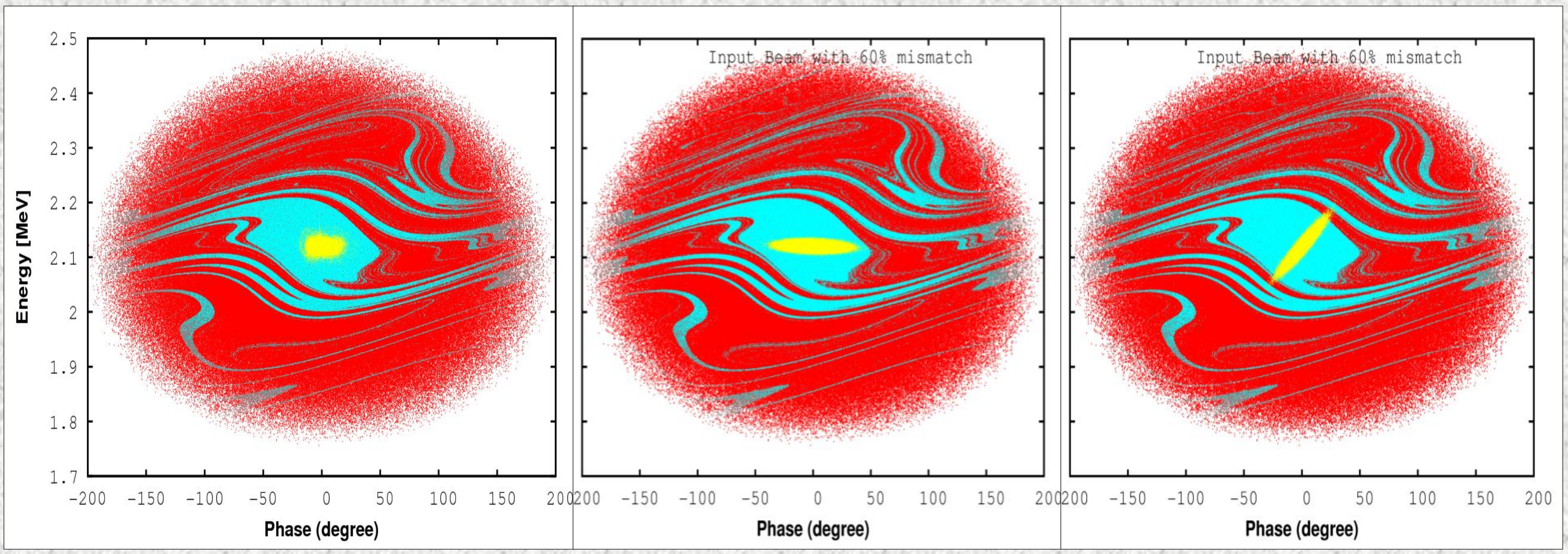




Chopped beam are lost at MEBT dump at level 99.94% (6σ Gaussian)

Longitudinal acceptance @ end of SSR1

- Initial distribution (red)
- Acceptance boundary (cyan)
- 6σ Gaussian (yellow)

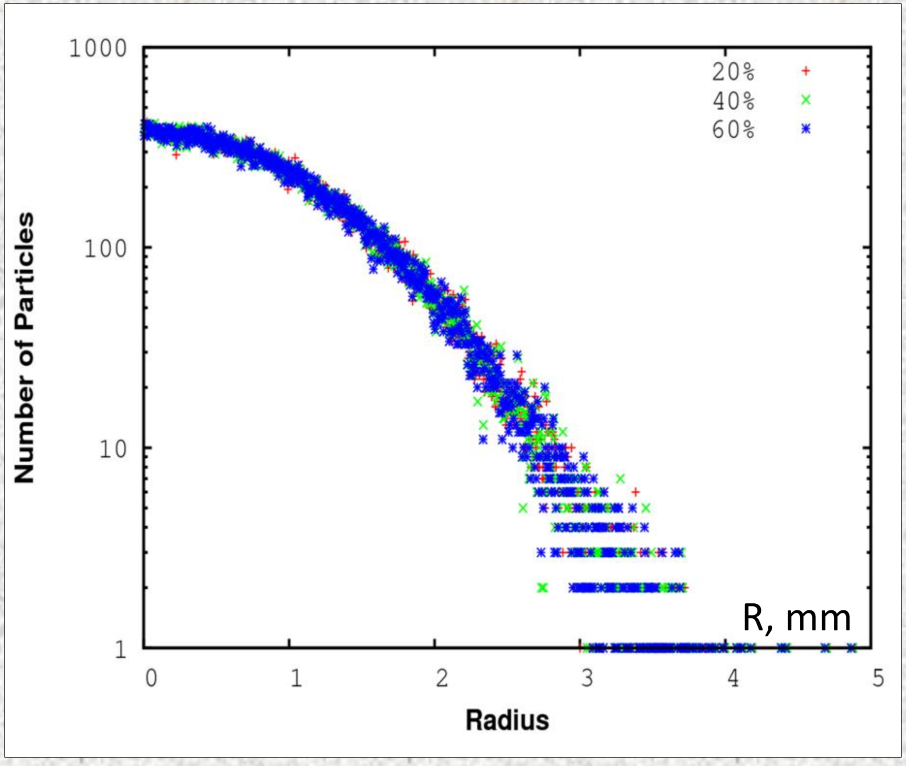


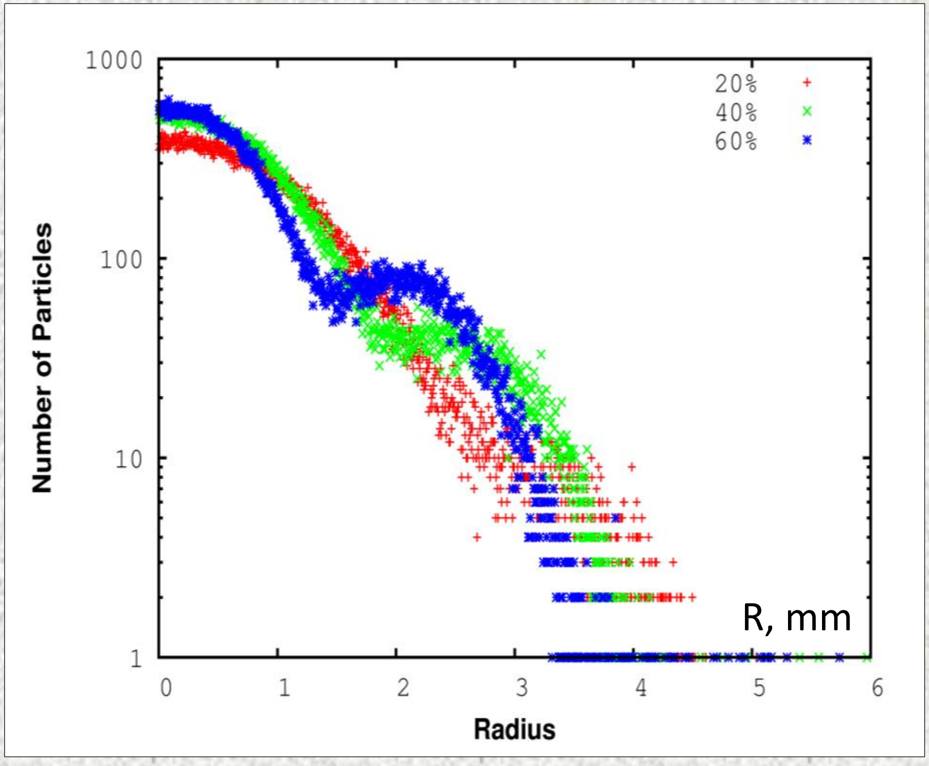
No mismatched

60 % mismatched input beam @ MEBT entrance

60 % mismatched input beam @ HWR entrance

Mismatch effect on Longitudinal profile





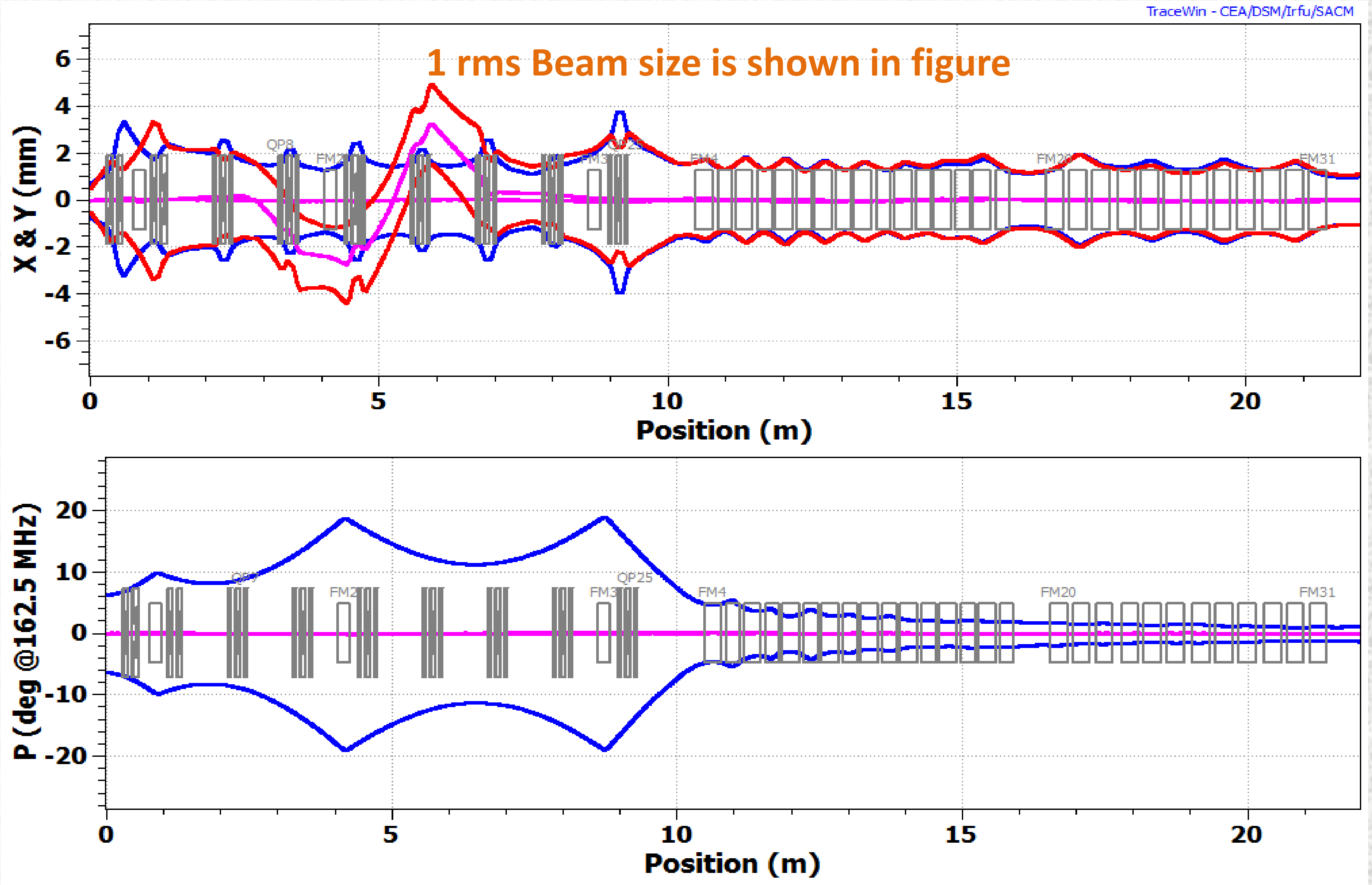
Input beam @ MEBT entrance

Output beam @end of 1 GeV Linac

Small effect on transverse beam profile

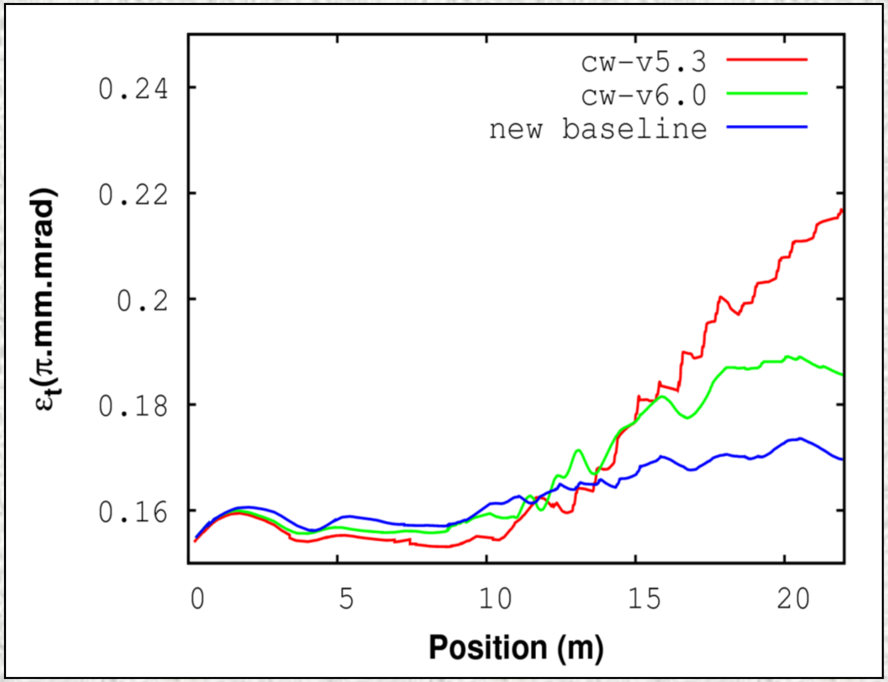
Recent work on optics optimization

Goal: improve longitudinal dynamics, increase acceptance

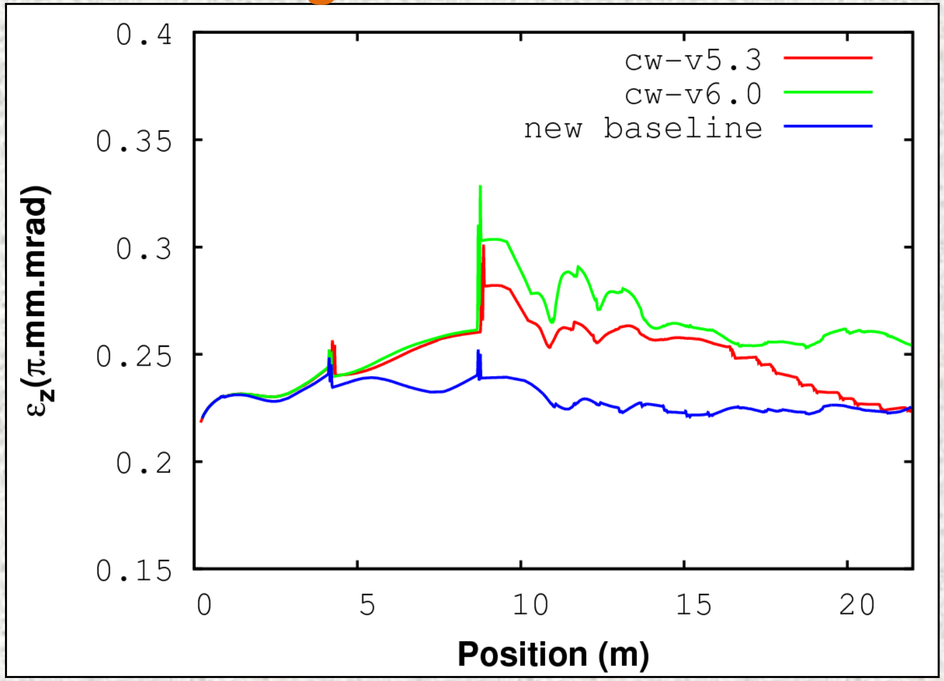


Emittance comparison with earlier version

Transverse emittance



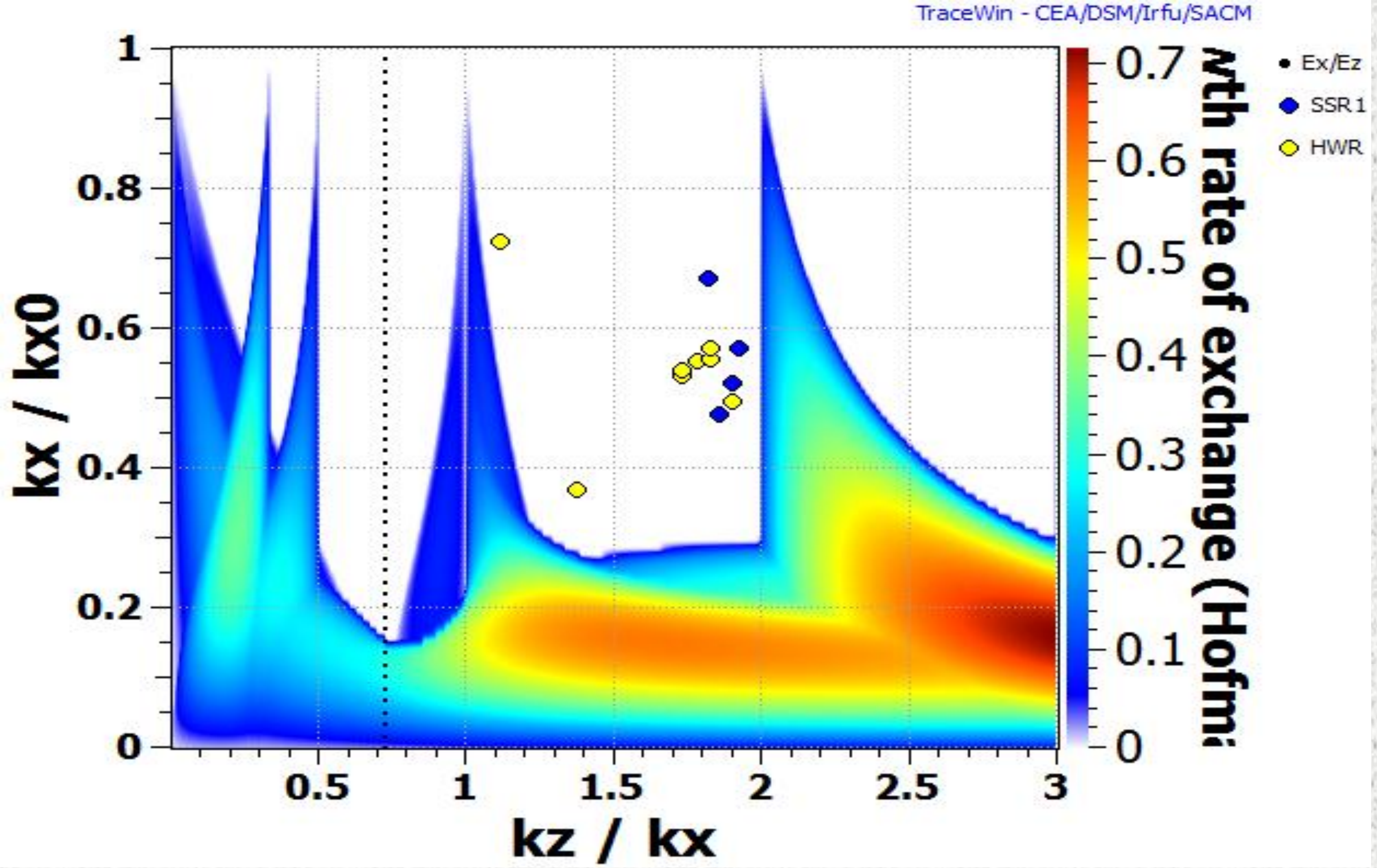
Longitudinal emittance



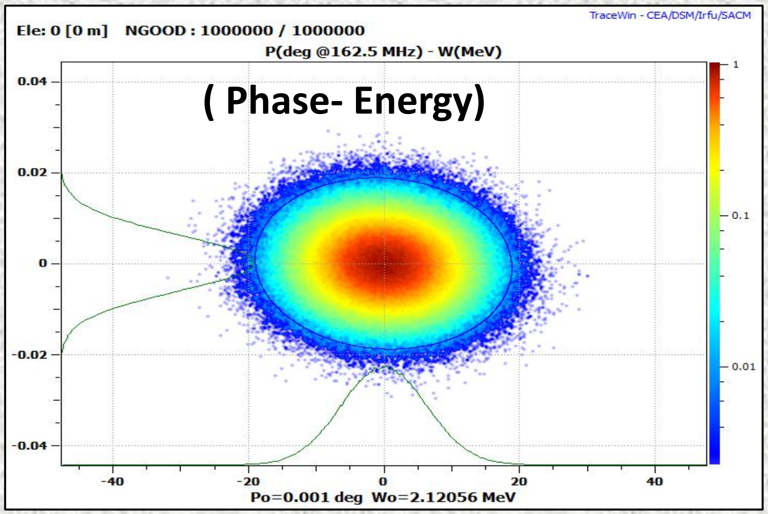
Parameters	CW-v5.3	CW-v6.0	New Lattice
Energy (Mev)	23.72	23.23	18.48
ε_t (pi.mm.mrad)	0.2165	0.186	0.1696
ε_z (pi.mm.mrad)	0.224	0.254	0.225
Lattice length(m)	-	-	21.96 m

A.Saini

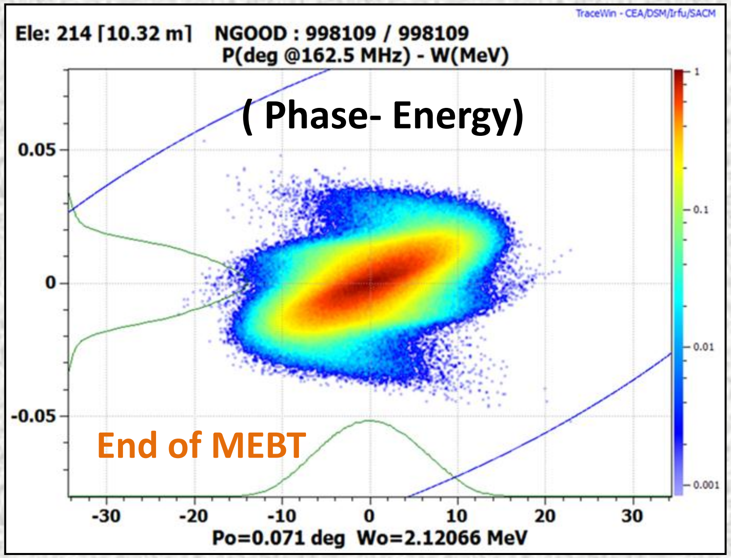
Hoffmann's Stability Diagram

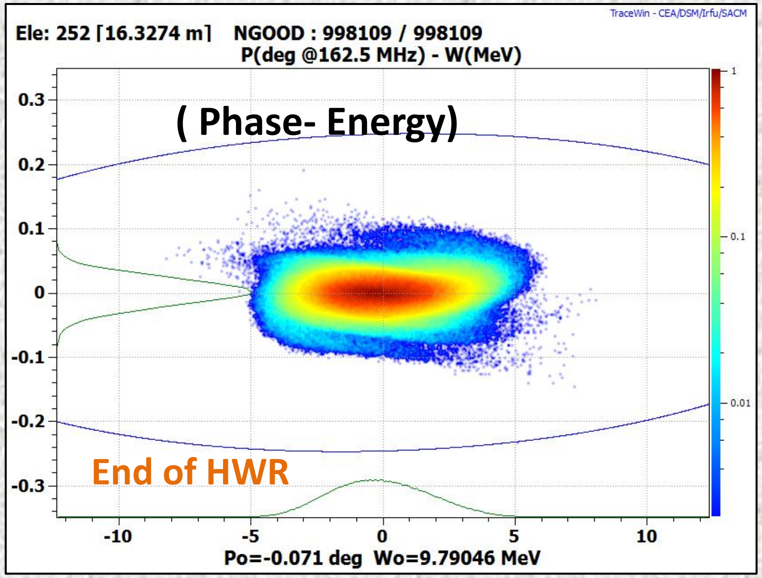


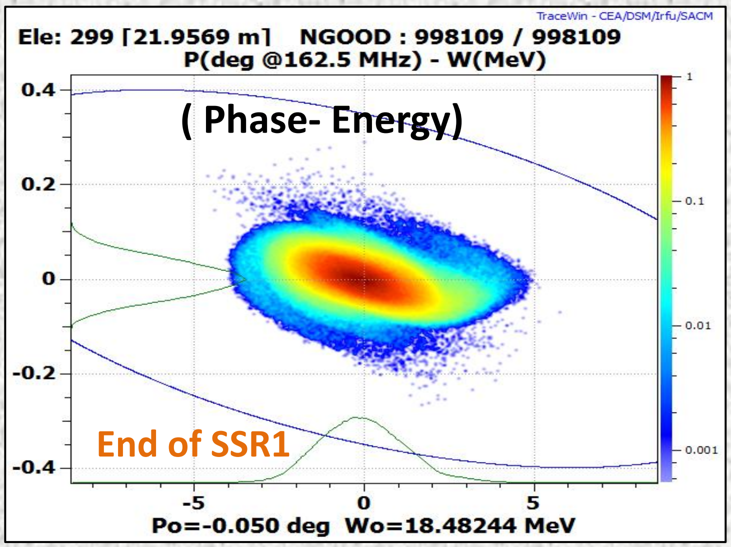
Evolution of Longitudinal phase-space



Input longitudinal beam distribution

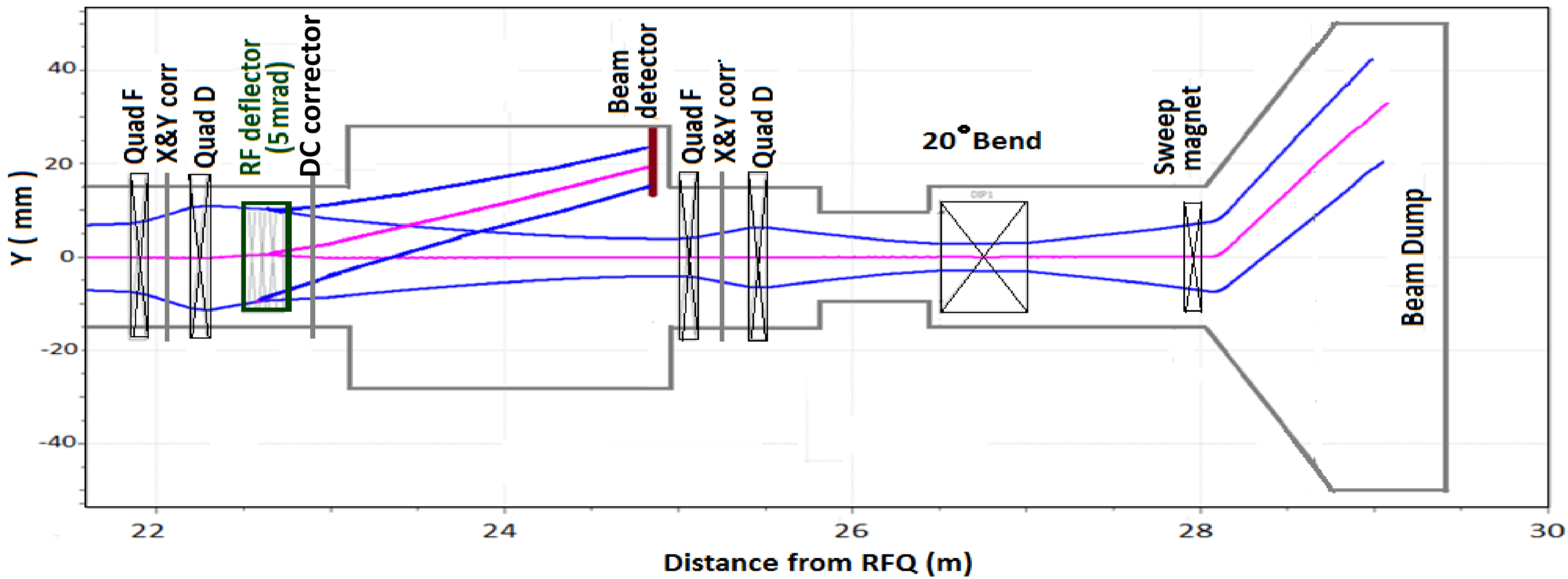






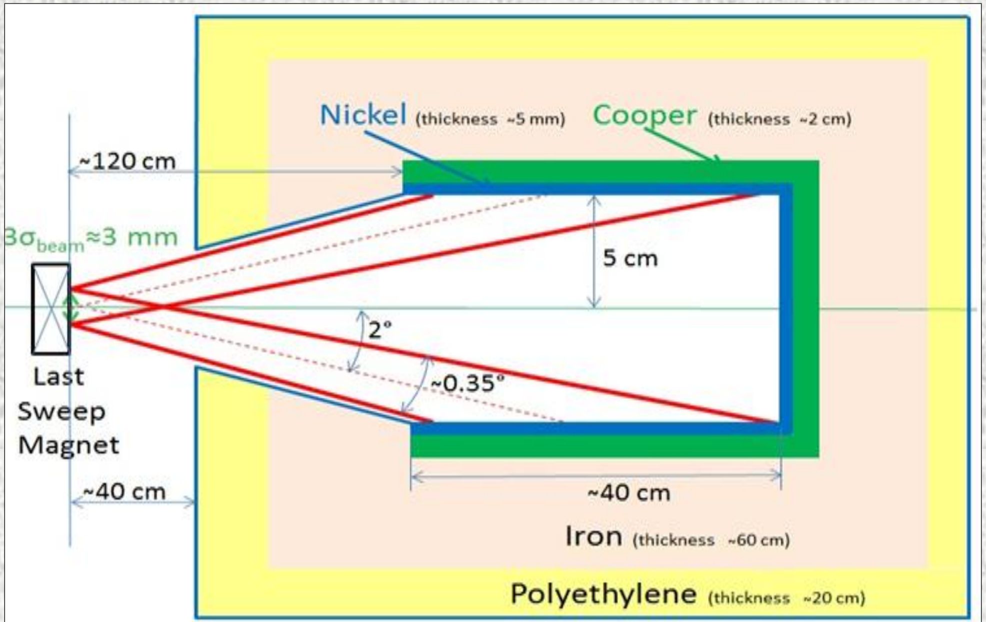
Beam Extinction

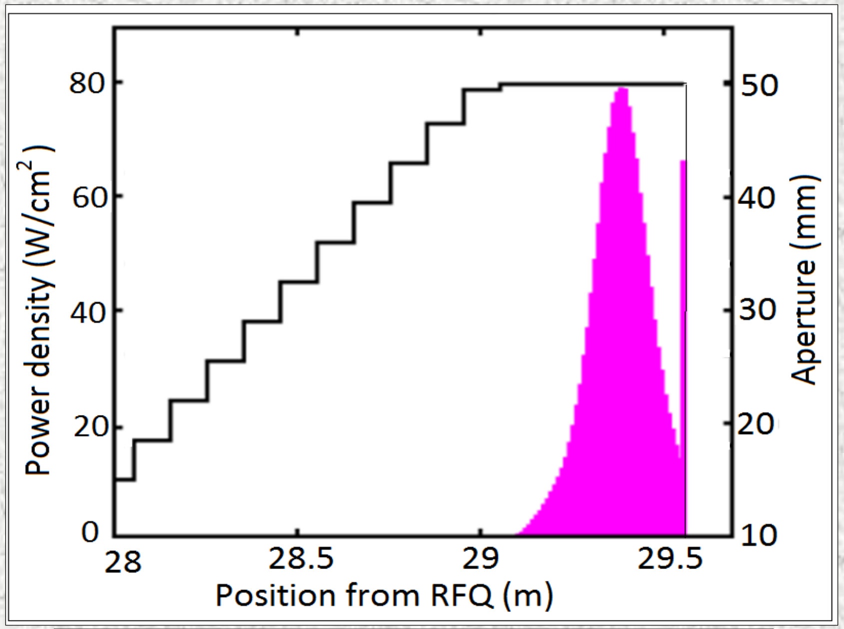
Project X will provide beams for different HEP experiments. Some of them (for example mu2e) have a strict requirement ($<10^{-9}$) for beam extinction for removed bunches. An extinction level better than 10^{-4} is specified for the MEBT. This number is mainly determined by available in MEBT diagnostics.



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

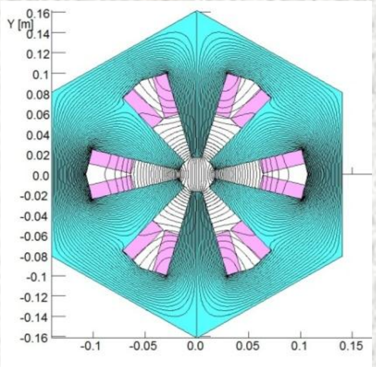
Beam Dump (50 kW)



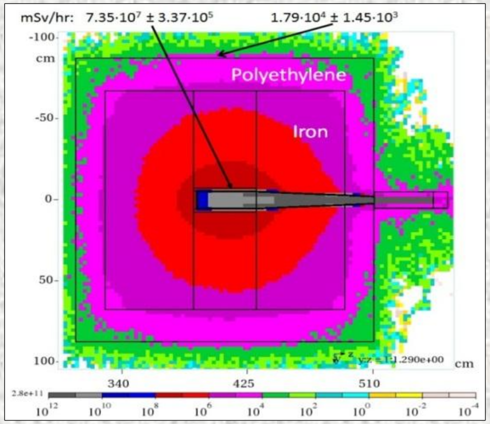


Beam dump, incl. local radiation shielding
Red lines - sweeping beam

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



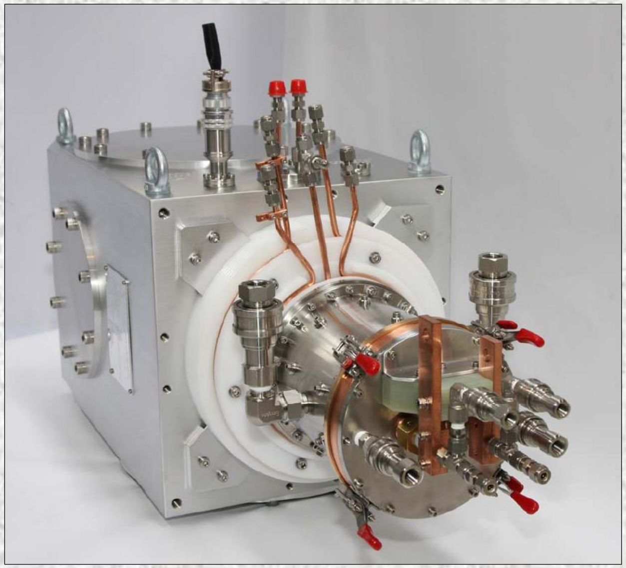
- Local shielding (60 cm iron+20cm polyethylene)
- Attenuation of radiation ~4000 times (~12 W)

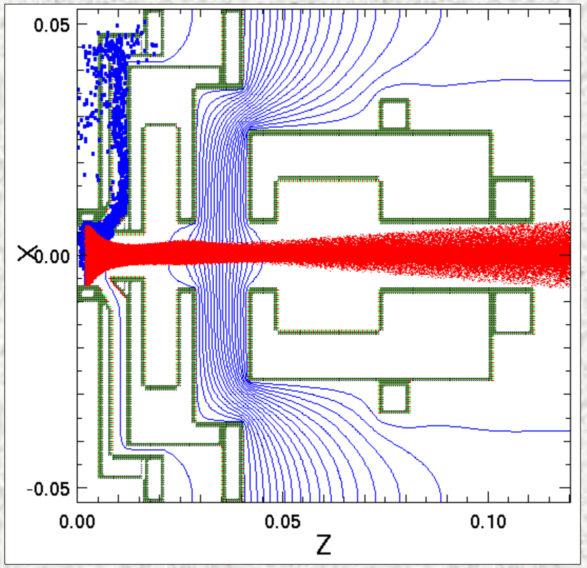
Status of R&D work on critical components for Project X beamline

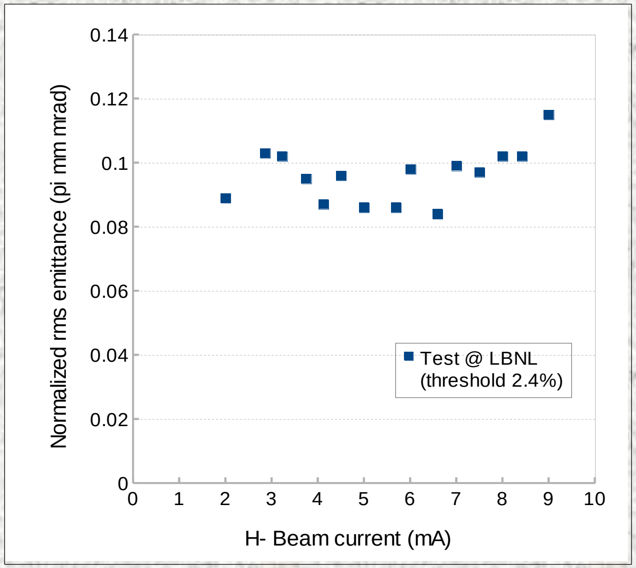
Ion Source

- 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

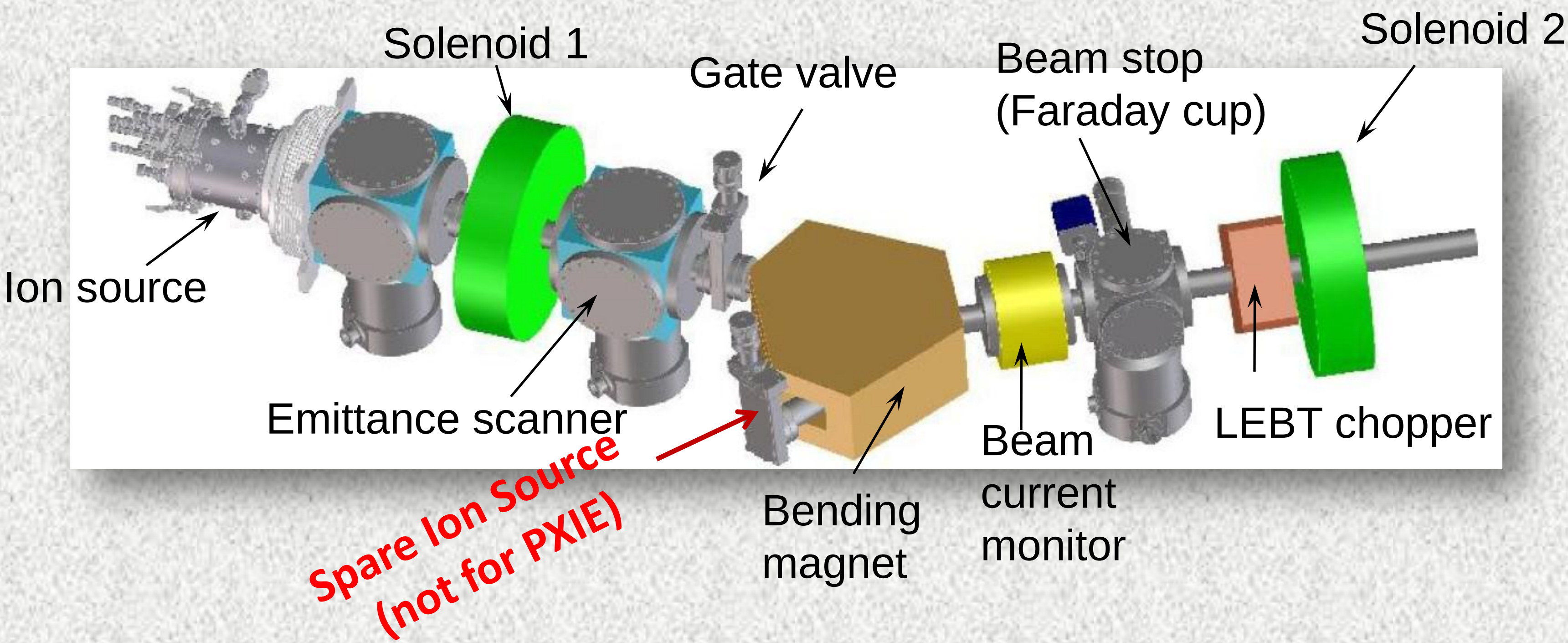
Regardless of the ion source current, the average linac beam current is 1 (2) mA
- this is achieved by a LEBT and MEBT choppers





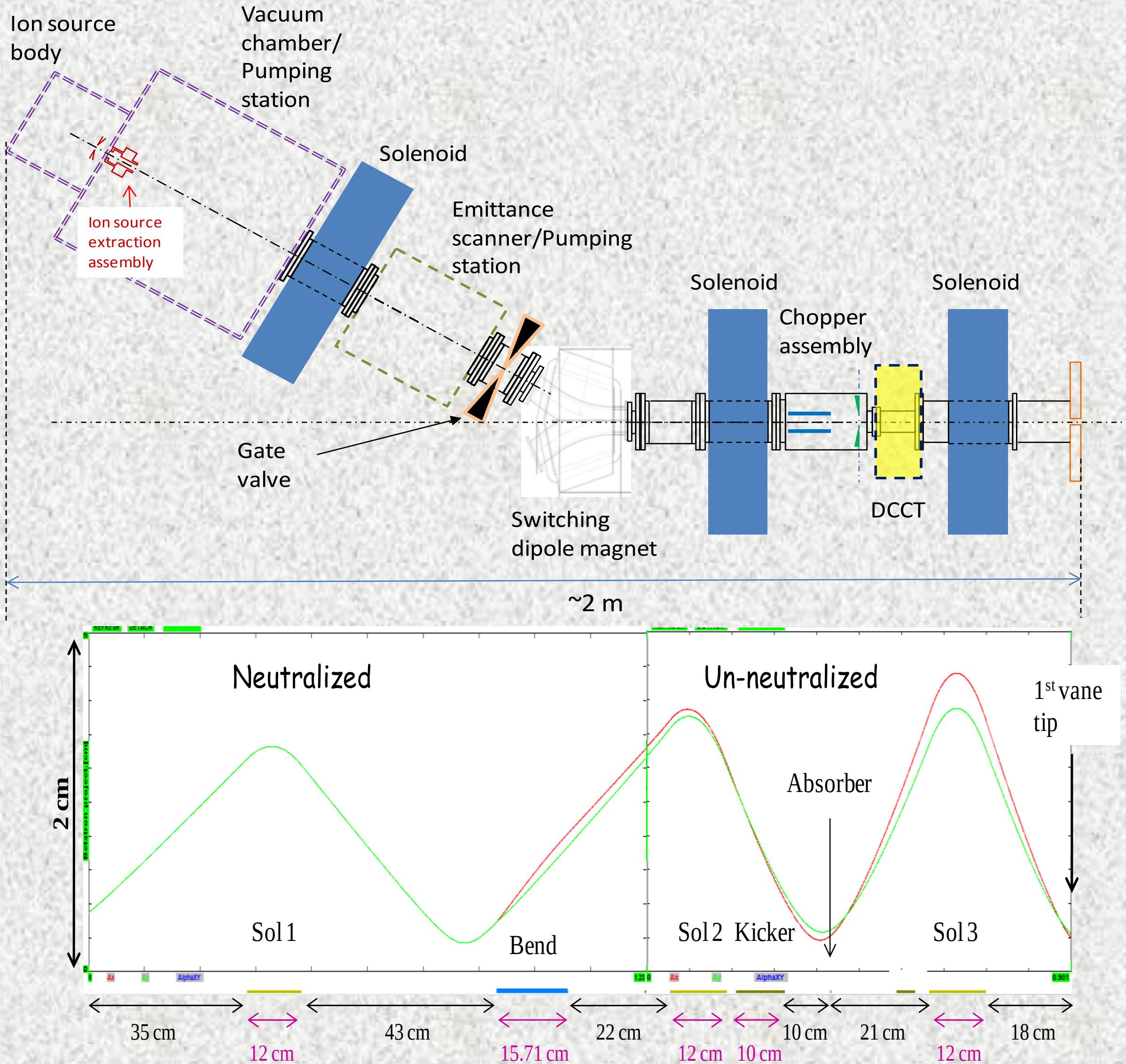


Low Energy Beam Transport



- 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)



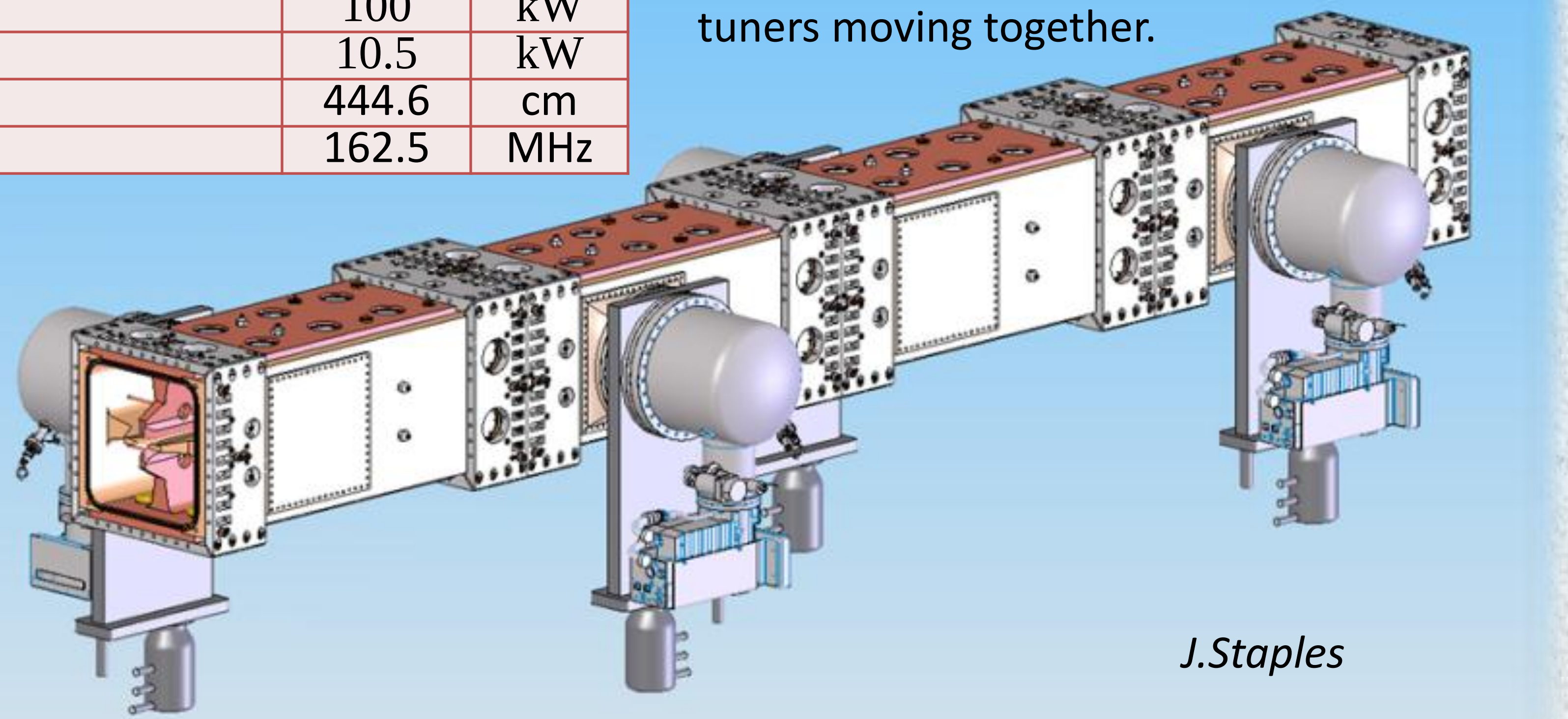
Longer LEBT option (3 solenoids):

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

RFQ design (LBNL)

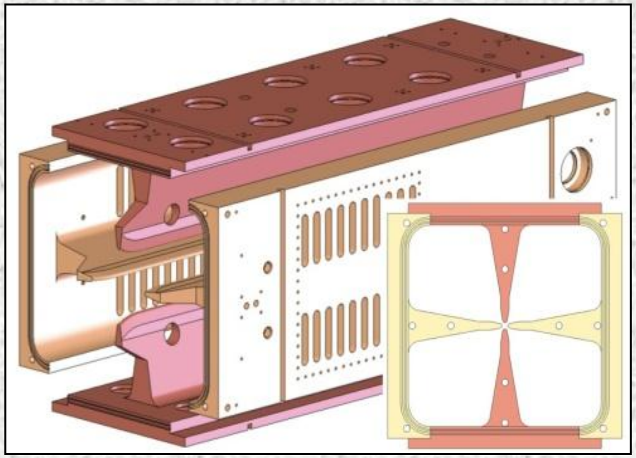
Parameter	Value	Units
Ion type	H-	
Beam current (nom/range)	5 (1-10)	mA
Trans. emitt. (rms, norm)	<0.25	µm
Long. emitt. (rms)	0.8-1.0	keV-ns
Input energy	30	keV
Output energy	2.1	MeV
Vane-vane voltage	60	kV
RF power	100	kW
Beam Power	10.5	kW
Length	444.6	cm
Frequency	162.5	MHz

- **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.

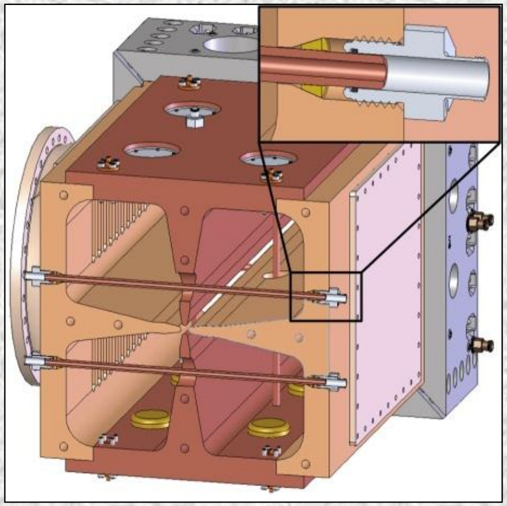


J.Staples

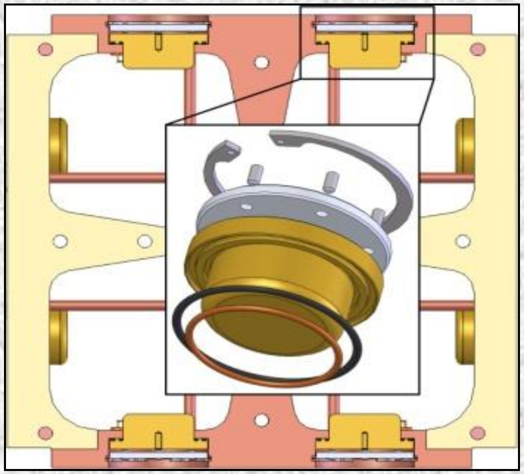
RFQ mechanical design



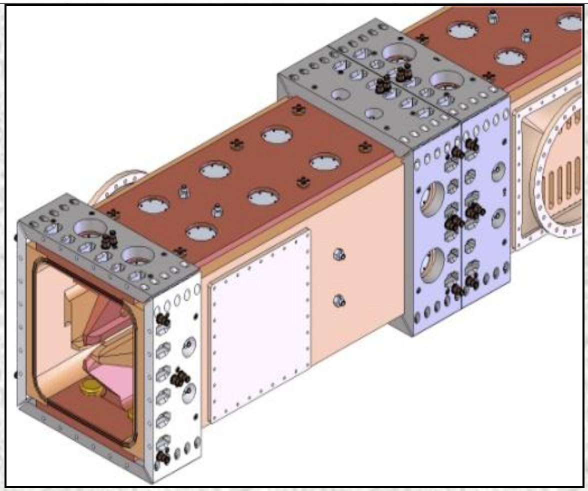
Exploded (1/4) 4-vane module



Pi-mode rod
shifts dipole mode
+17 MHz up

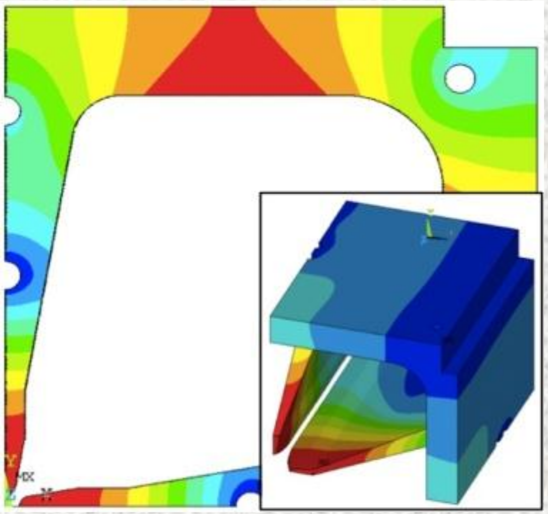


Fixed slug tuner



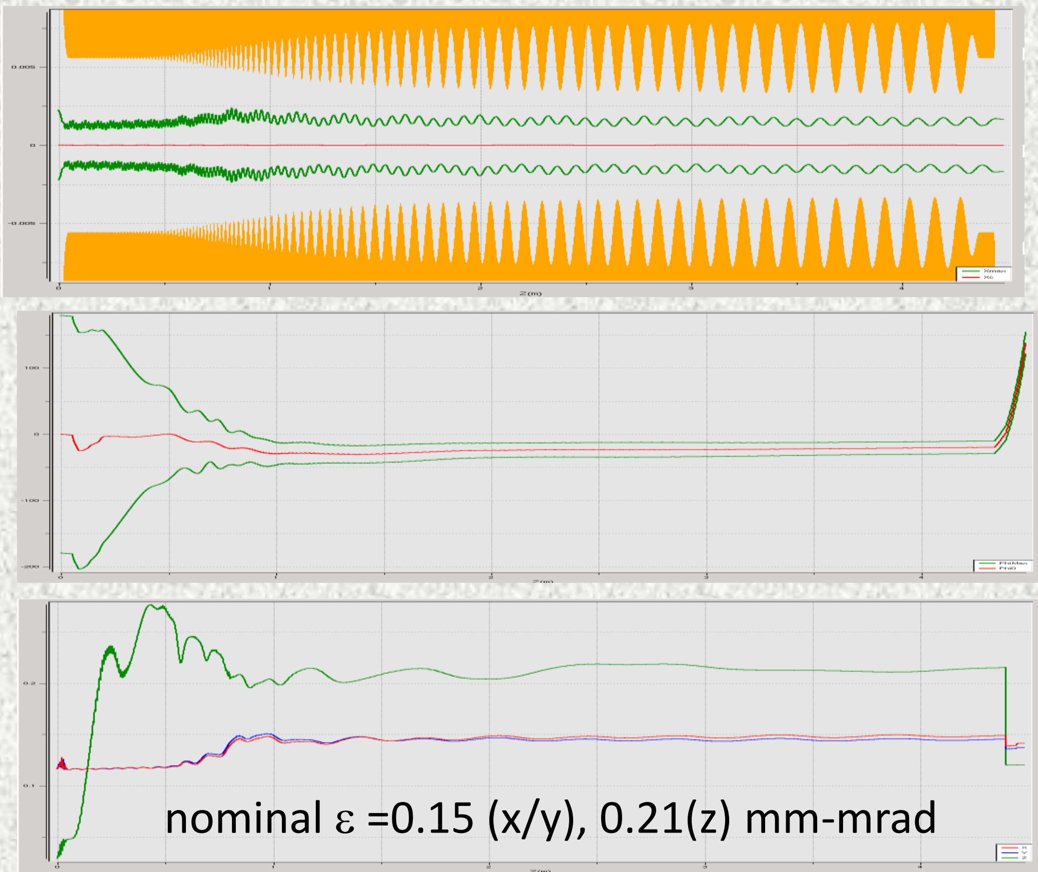
RFQ modules connected by joint plate method

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

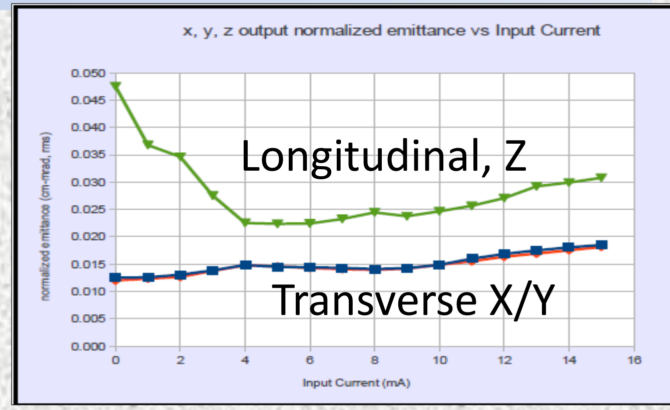


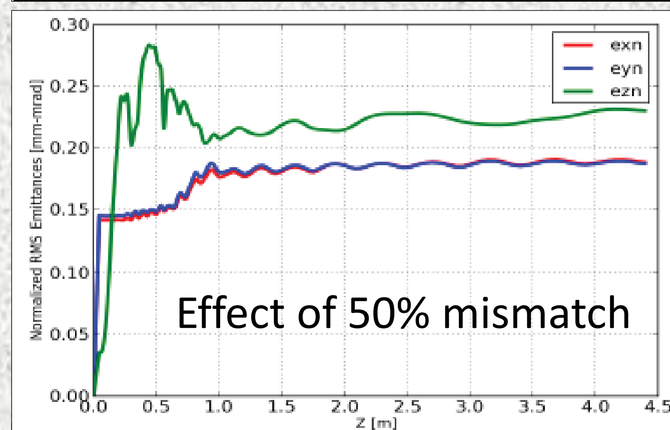
RFQ beam dynamics

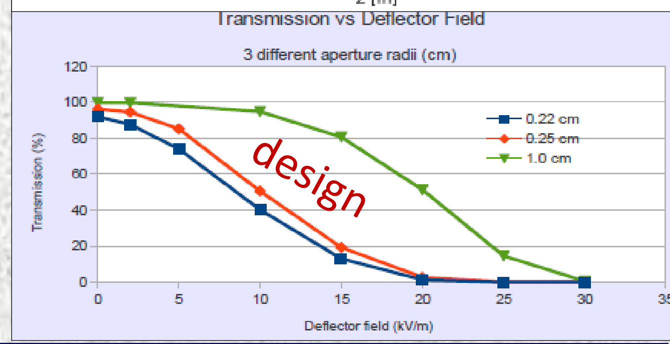
- Design done in PARMTEQ (J.Staples)
- Cross-check: TRACK (3D field-map) and Toutatis
- Errors and mismatch studies (PARMTEQ and Toutatis)



Partially chopped beam







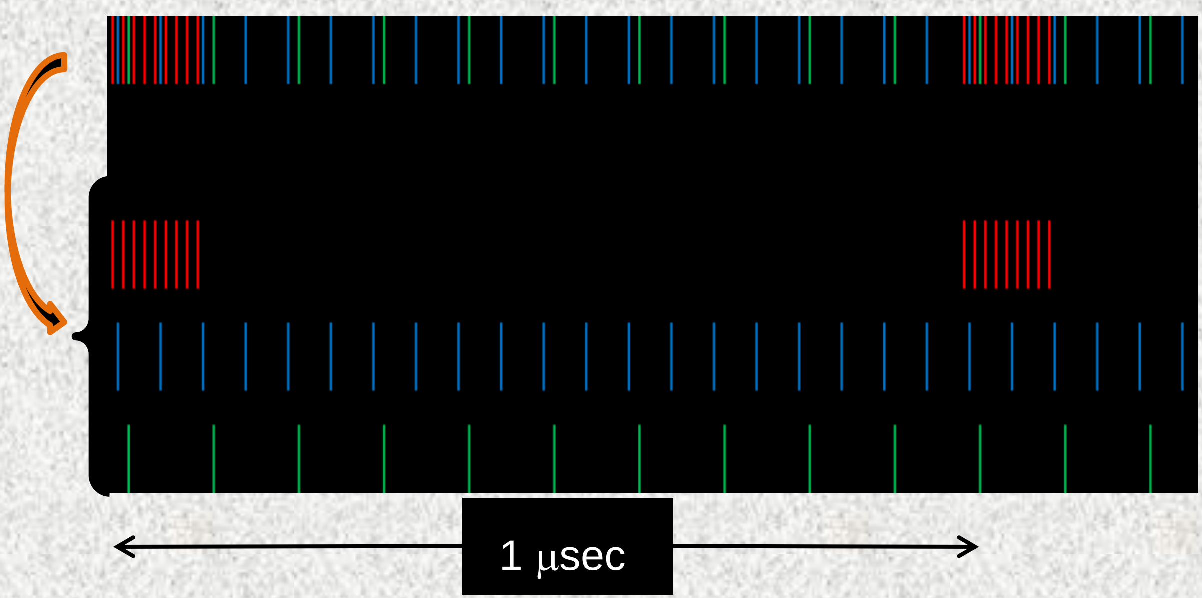
Operating Scenario for 3 GeV CW Linac

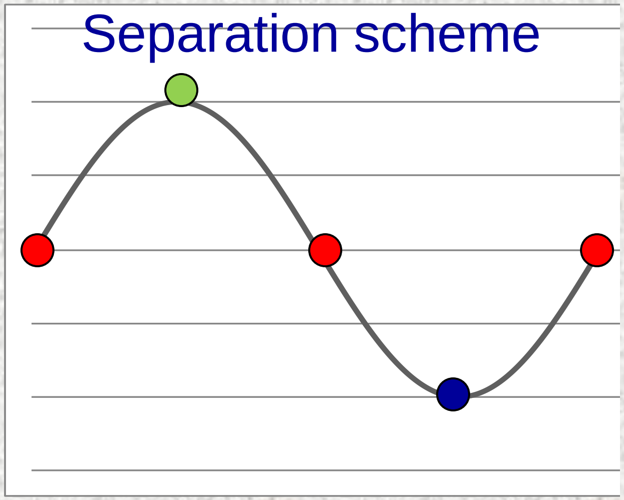
Ion source and RFQ operate at 4.4 mA

77% of bunches are chopped @ 2.1 MeV $\Rightarrow$ maintain 1 mA over 1 μsec

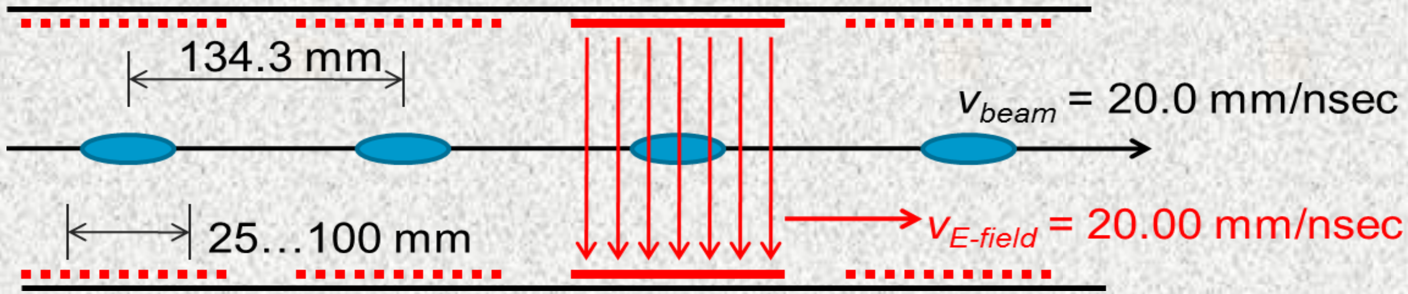
1 μsec period at 3 GeV

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





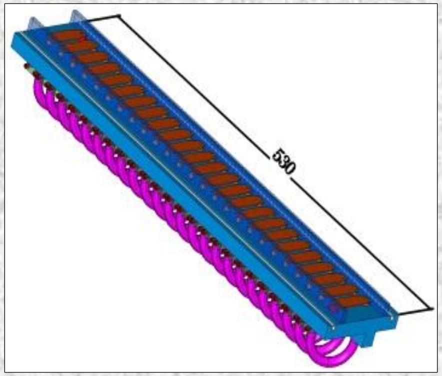
Chopper R&D

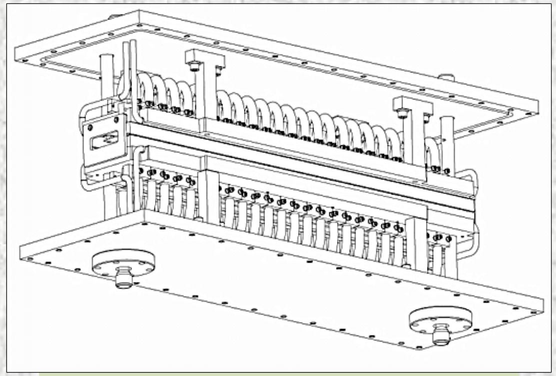


- Kicker
  - Two versions are being pursued: 50 and 200 Ohm
  - Each version must fit into a 65-cm drift: 2 pairs 25-cm long, 16 mm gap
- Kicker driver
  - Broad-band, 500 V, ~2 ns rise/fall time, 30 MHz average pulse rate
  - AC-coupled rf amplifier (50-Ohm) or DC-coupled pulser (200-Ohm)
- Beam absorber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

Wide-band Kicker designs

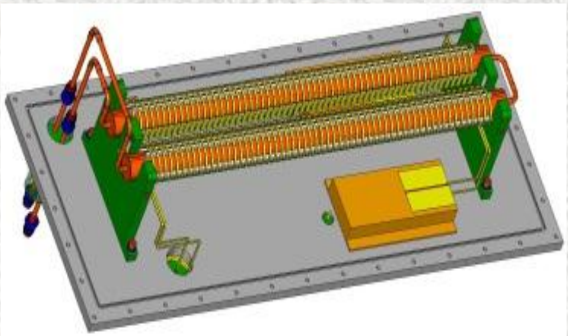
50 Ω planar electrodes, connected in vacuum by coaxial cables with the length providing necessary delays

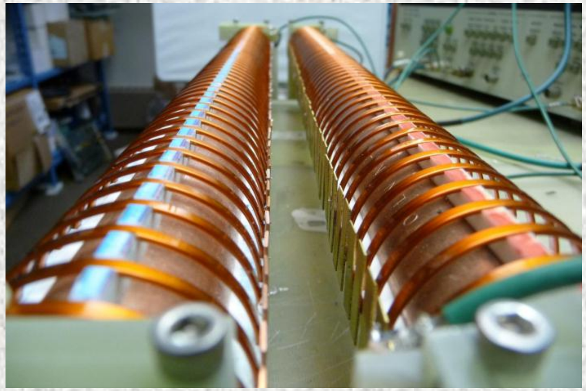




Mechanical schematic of a 50-Ohm kicker

200 Ω helixes





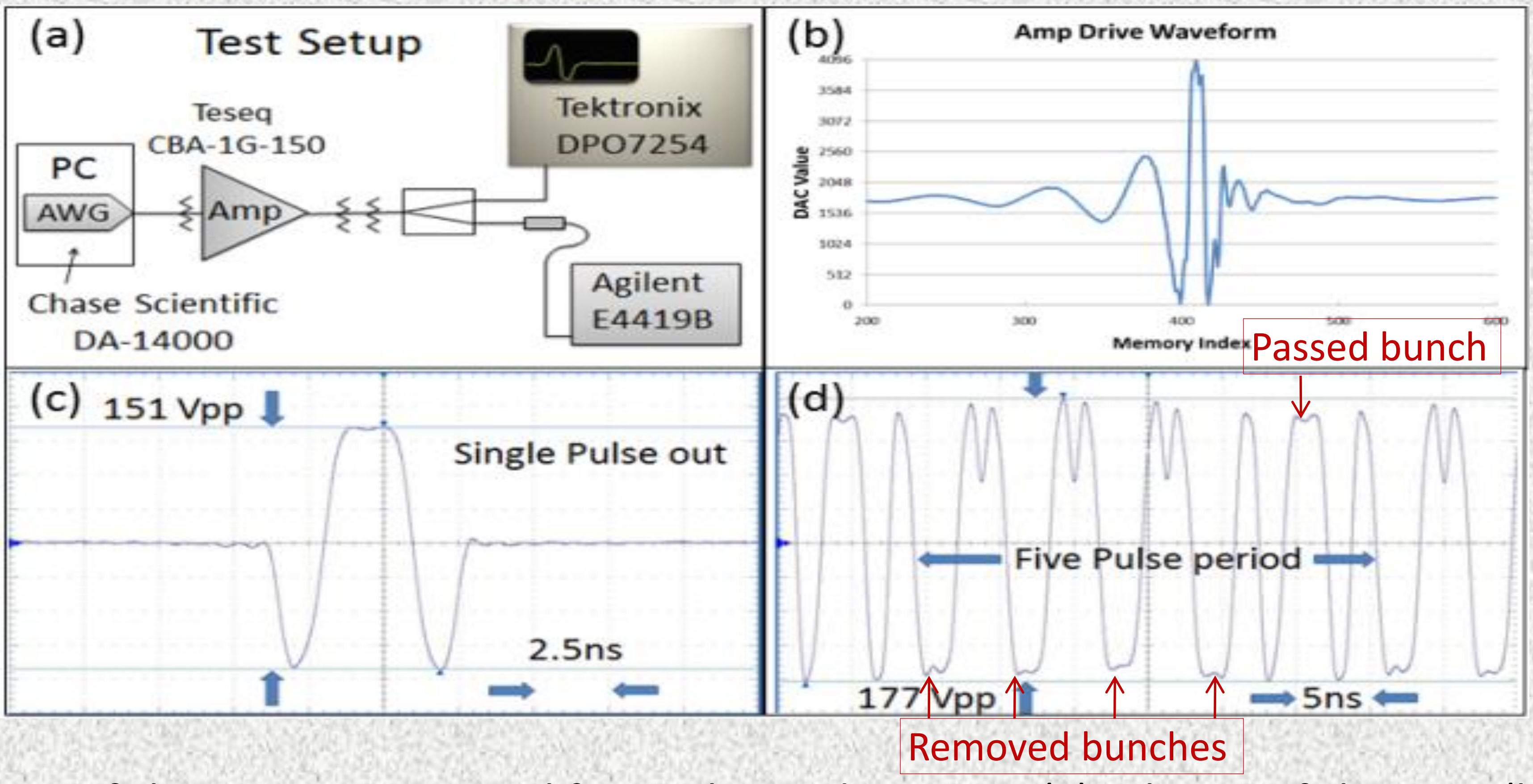
Two helixes

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

Objectives

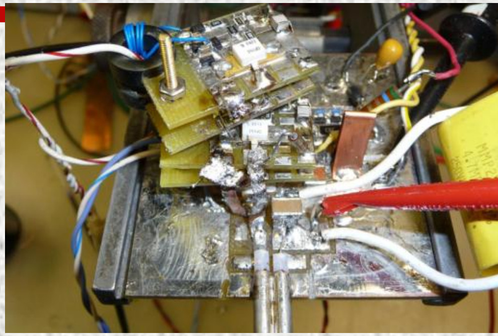
- Two +/- 250 Volts kicker plates
- DC coupled drive to the kicker
- Pulse: ~2 ns rise time, ~1.5 ns wide flattop
- Handle power dissipation for high duty factor (140 W)
- Support variable high duty factor waveforms
- Handle rep. rates, ~30 MHz

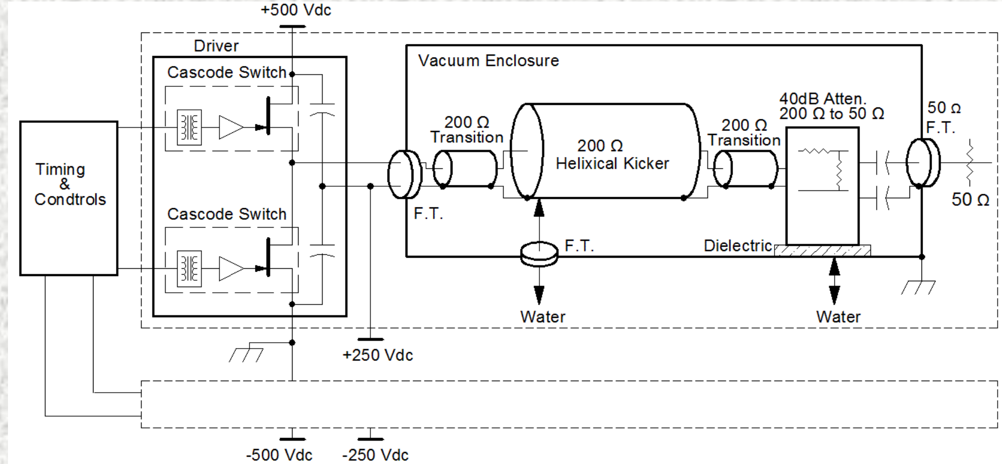
Test at 150 W amplifier

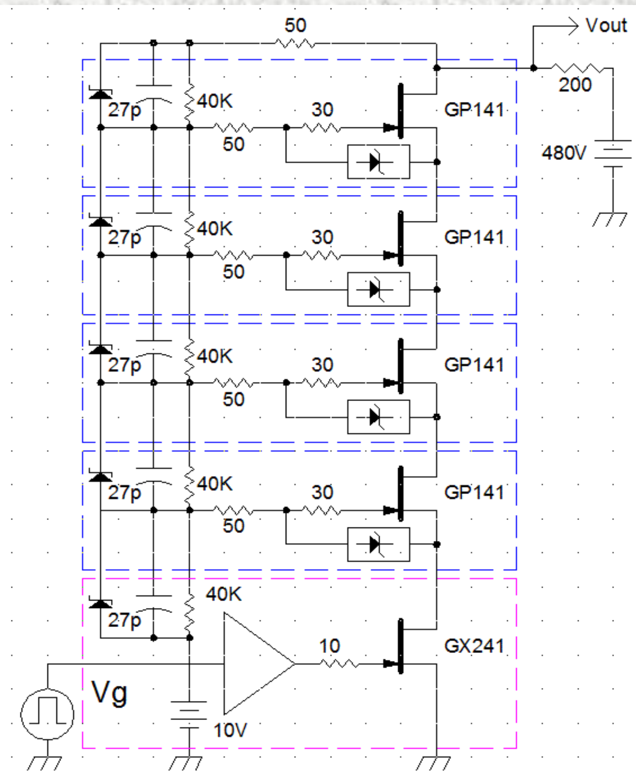


Test of the CBA 1G-150 amplifier with pre-distortion. (a) scheme of the test; (b) pre-distorted input signal and (c) corresponding output signal for a single pulse; (d) output for a CW pattern, corresponding to removal of four consecutive bunches followed by a one-bunch passage. Need 1 kW amplifier

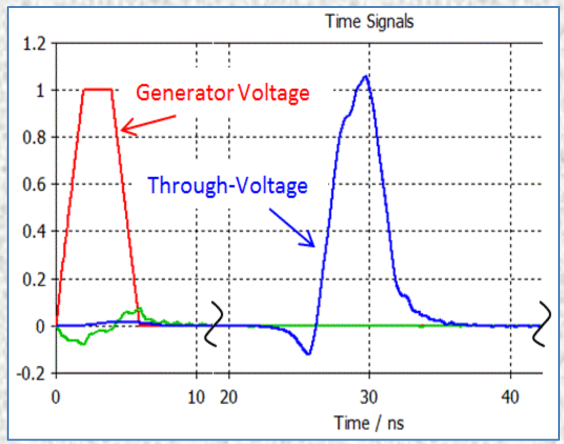
Test of 200 Ω design



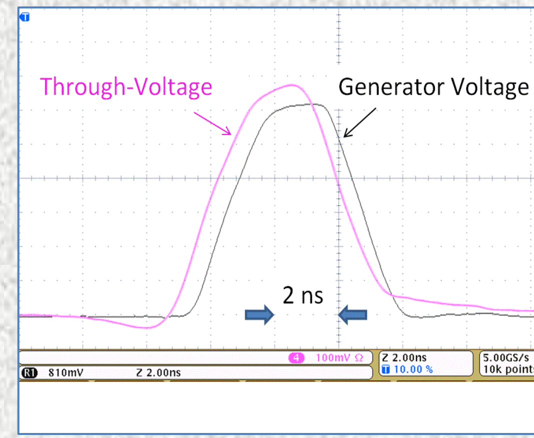




Based on fast GaN FET switches



Simulation results

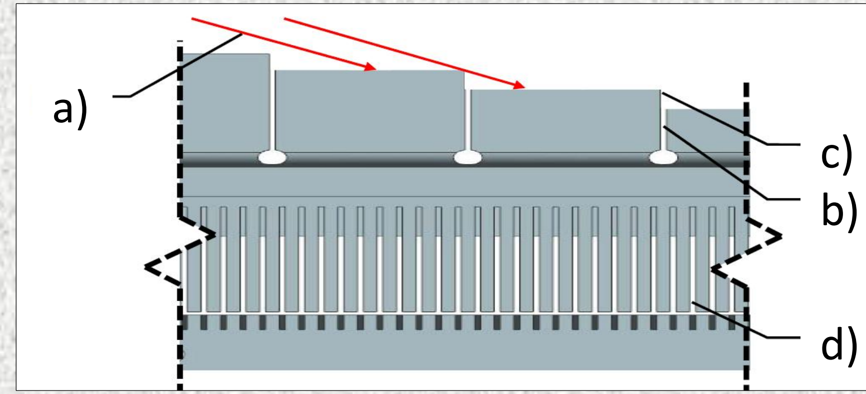


Test results

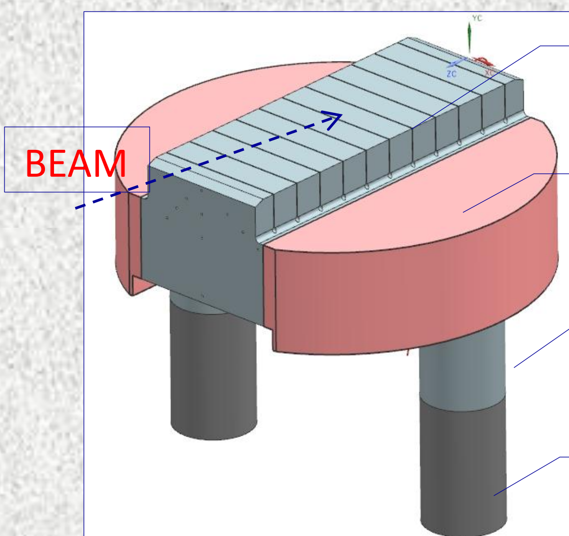
G Saewert et al.,

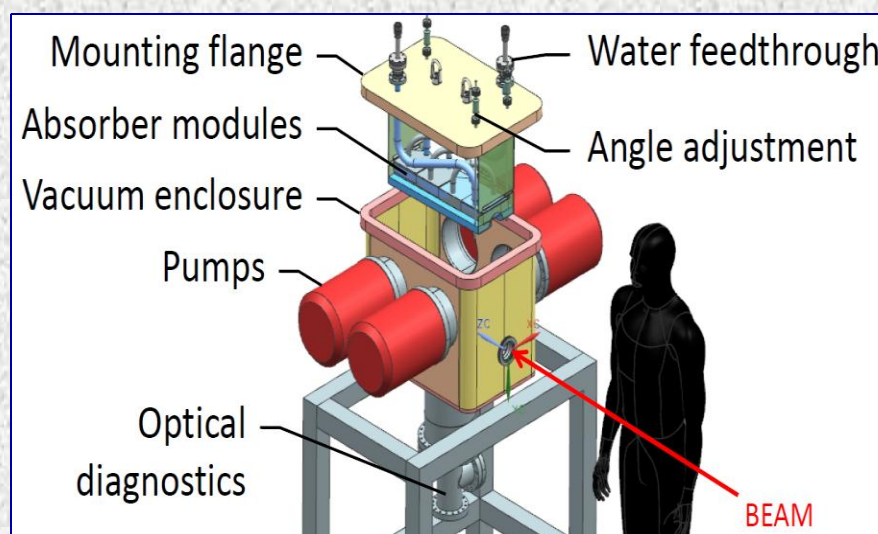
MEBT Absorber

(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.

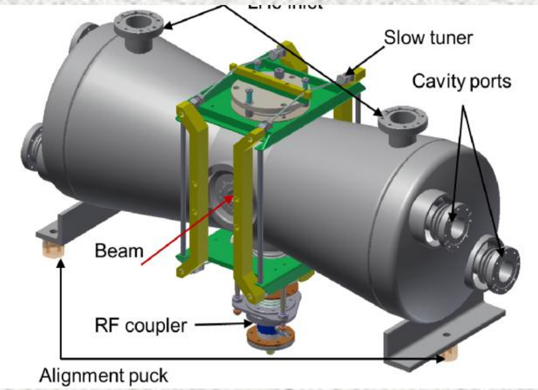


Conceptual design of the MEBT absorber.
Length = 40 cm

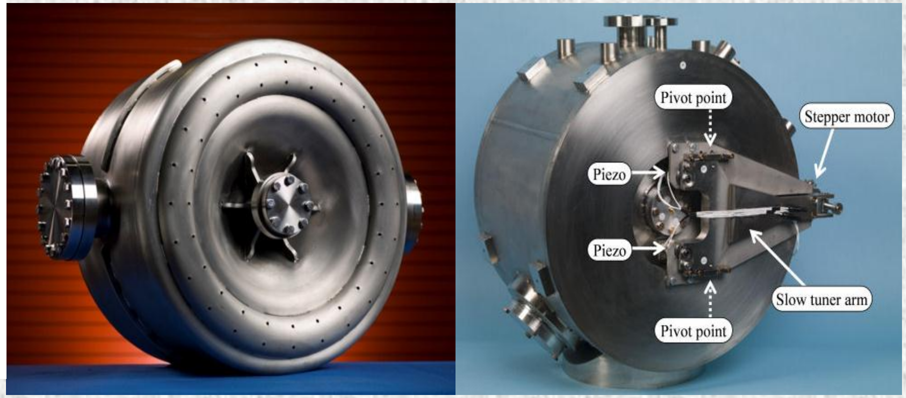




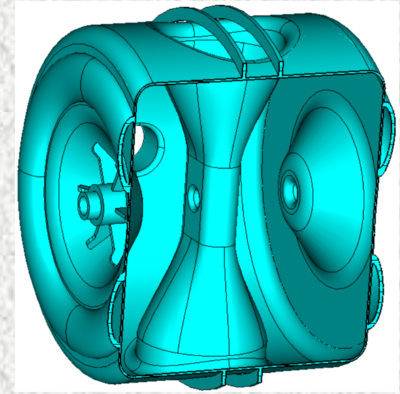
RF Cavities of the Project-X Front-end



HWR model, 162.5 MHz (ANL)



SSR1 prototypes and tests, 325 MHz (FNAL)

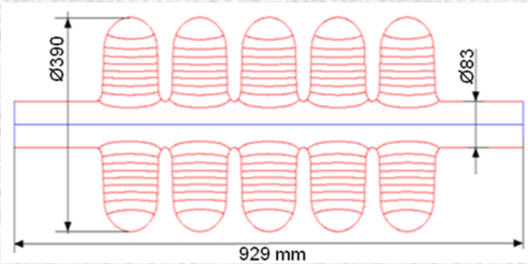


SSR2 model, 325 MHz (FNAL)

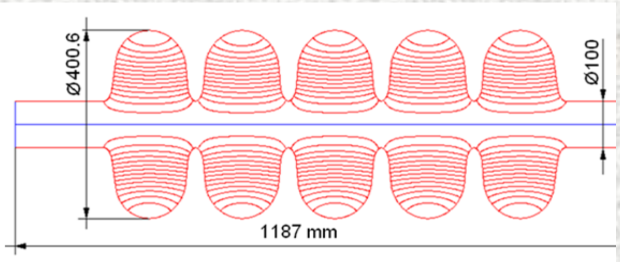
cavity type	β_{geom}	Freq, MHz	Beam pipe ø, mm	E_{acc}, MV/m	$V_{acc,\,max}$ MeV	E_{pk} MV/m	B_{pk} mT	R/Q, Ω	G, Ω	Q_0, $\times 10^{10}$	Power losses W
HWR*	β=0.112	162.5	33	8.2	1.7	38	41	272	47.7	0.5	2.1
SSR1**	β=0.215	325	30	12	2.4	46	70	242	84	0.8	3
SSR2#	β=0.47	325	40	11.4	5	40	70	290	113	1	8.5

- *P.Ostroumovet al., WEPPC039,IPAC12, **T.N. Khabiboulline et.al, WEPPC035, IPAC12; #P.Berrutti, SSR2 report
- Assumption for RF power losses at 2K: $R = R_{res} + R_{BCS} = 10\ n\Omega$

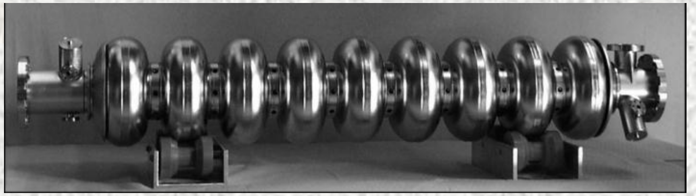
650 MHz and ILC cavities



650 MHz: β=0.61



650 MHz: β=0.9

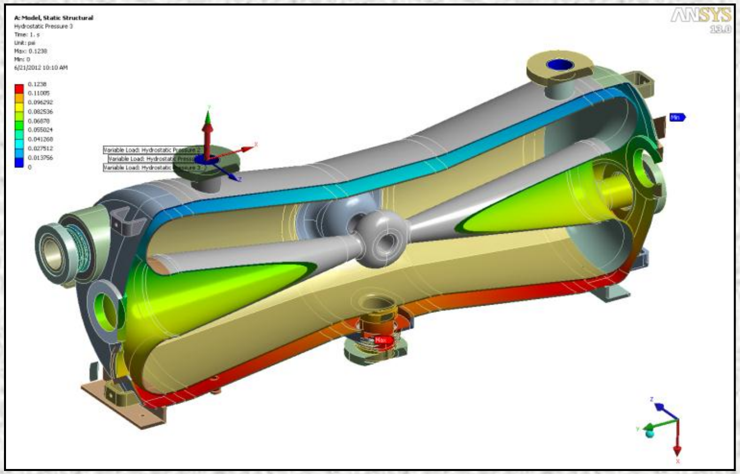


1.3 GHz ILC

Parameter		LE650	HE650	ILC
β_geom		0.61	0.9	1
Cavity Length = $n_{cell} \cdot \beta_{geom} \lambda/2$	mm	703	1038	1038
R/Q	Ohm	378	638	1036
G-factor	Ohm	191	255	270
Max. Gain/cavity (on crest)	MeV	11.7	17.7	17.2
Acc. Gradient	MV/m	16.6	17	16.9
Max surf. electric field	MV/m	37.5	34	34
Max surf. magnetic field,	mT	70	61.5	72
Q_0 @ 2° K	$\times 10^{10}$	1.5	2.0	1.5
P_{2K} max	[W]	24	24	20

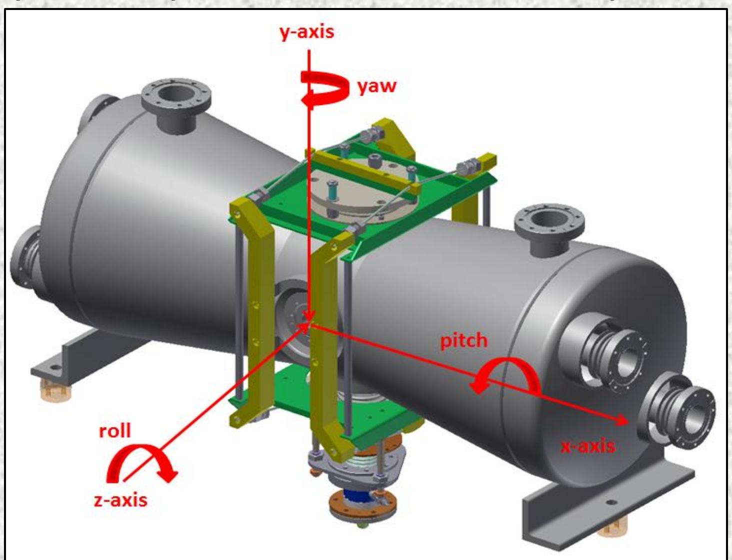
Table 1: HWR main parameters

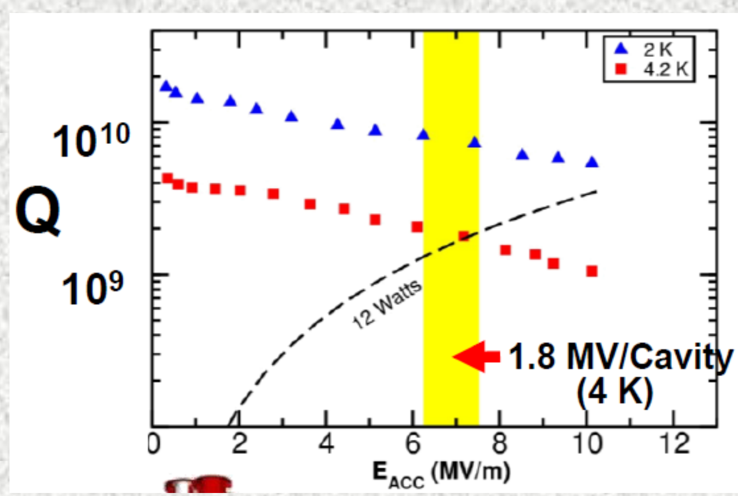
HWR design (ANL)



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
$G = Q_0 R_S$, Ω	48
R/Q_0, Ω	272



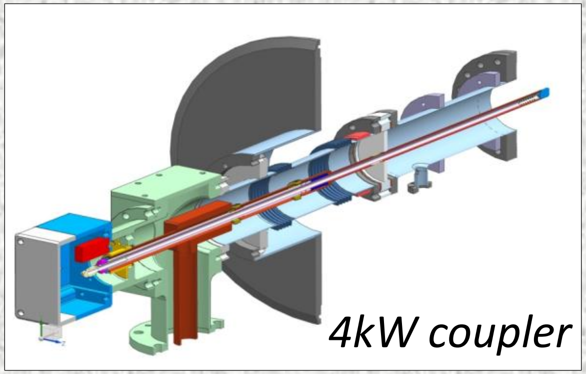


E_{acc}=8.2 MV/m
E_{pk} = 38 MV/m
H_{pk} = 41 mT

Test of 172.5 MHz HWR

SSR1 design and test

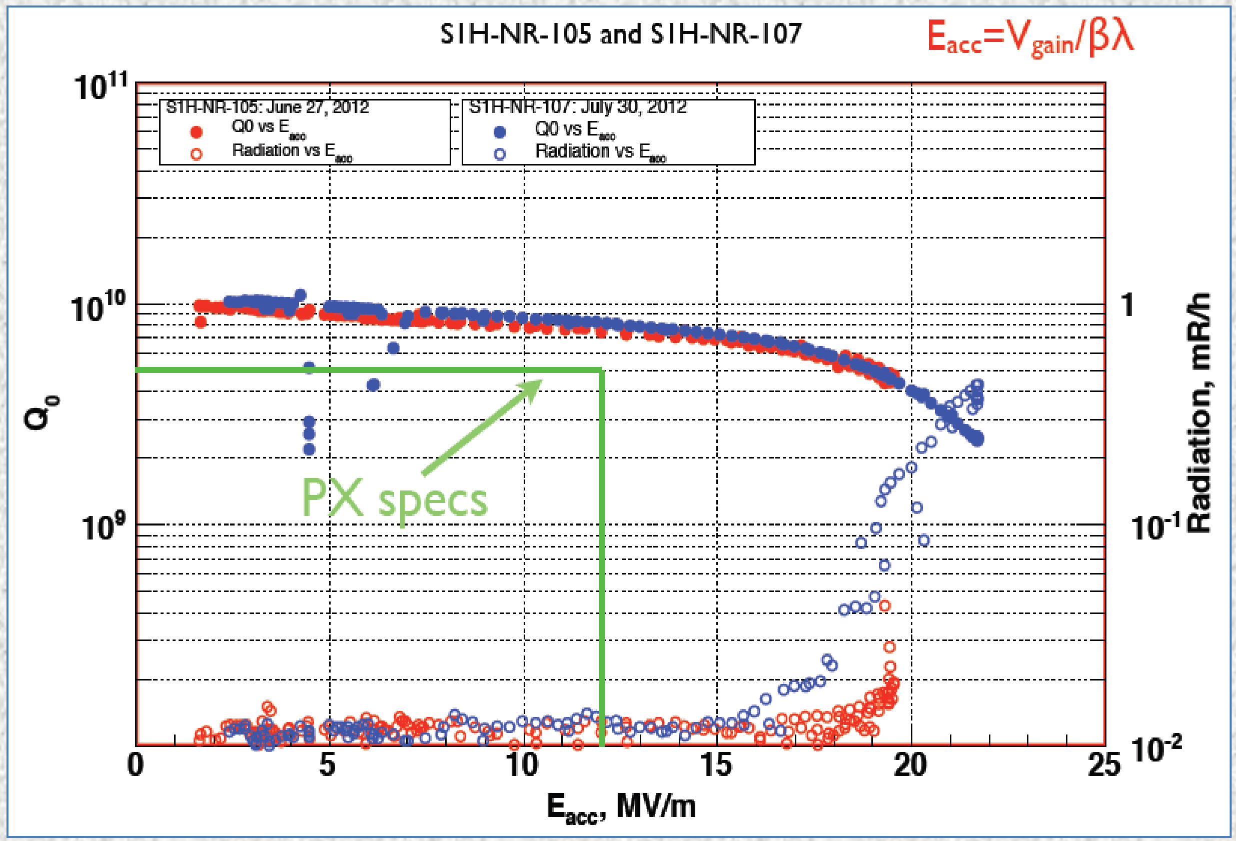
SSR1 cavity



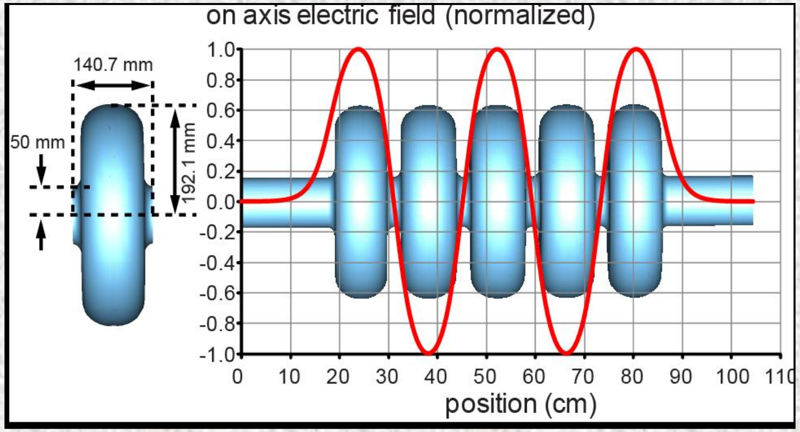
4kW coupler

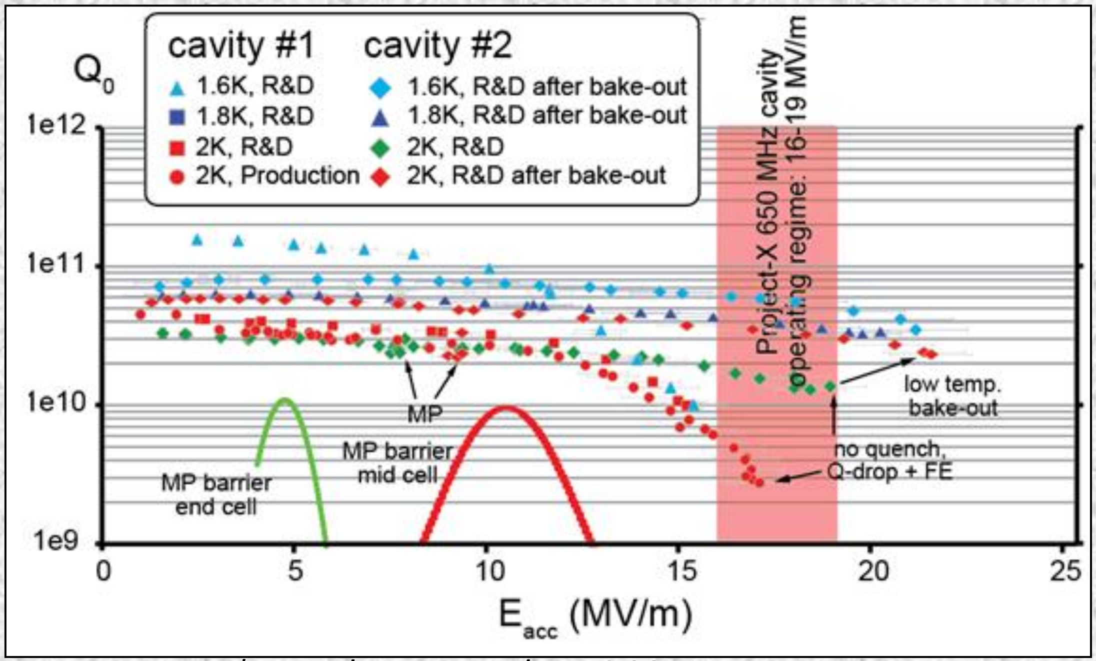
R.Kephart, TH03B03

- **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**



JLAB version of the 650 MHz, beta=0.61 cavity for the Project X





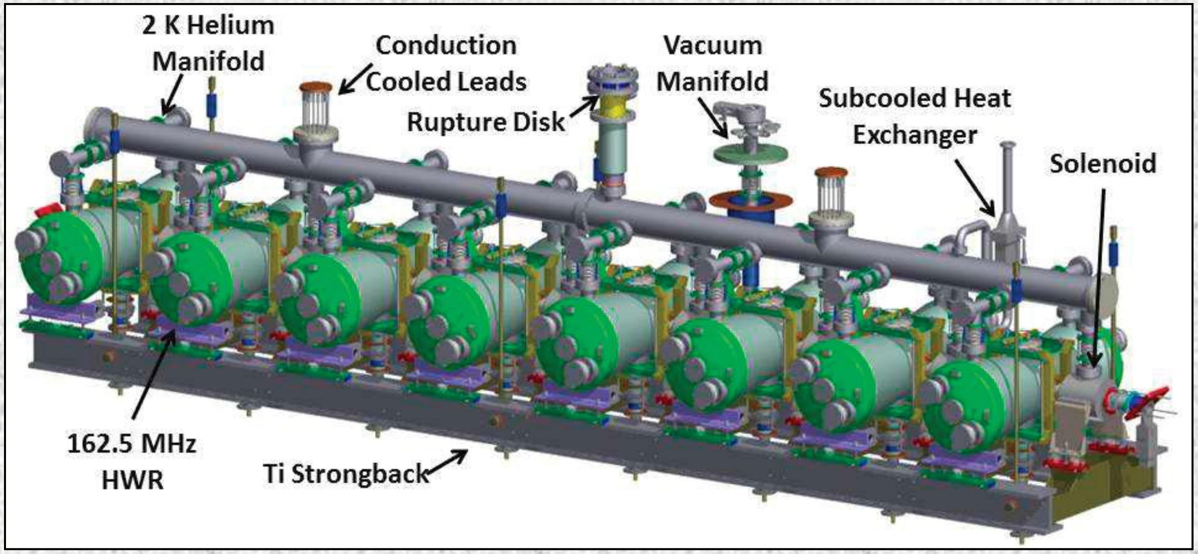
F. Marhauser, et al, IPAC 2011

For single-cell cavity #2:

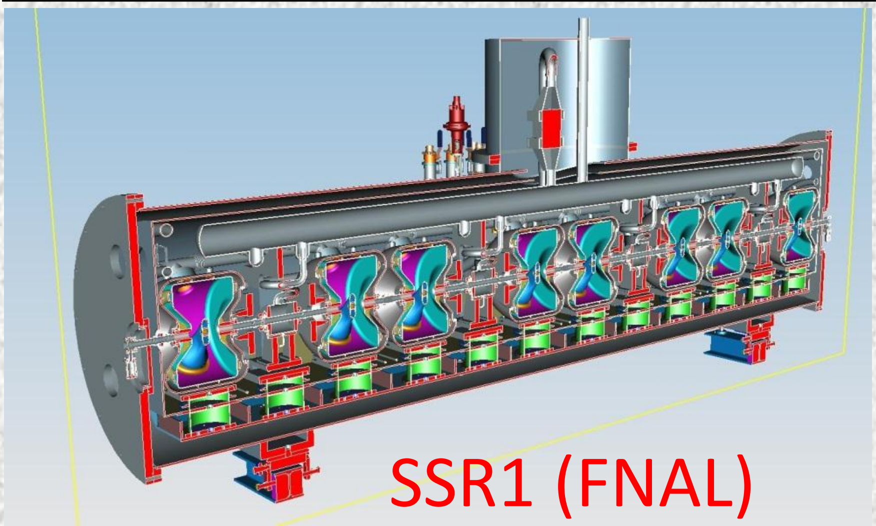
Q_0 >2e10 @17MeV/m

Need more tests and statistics

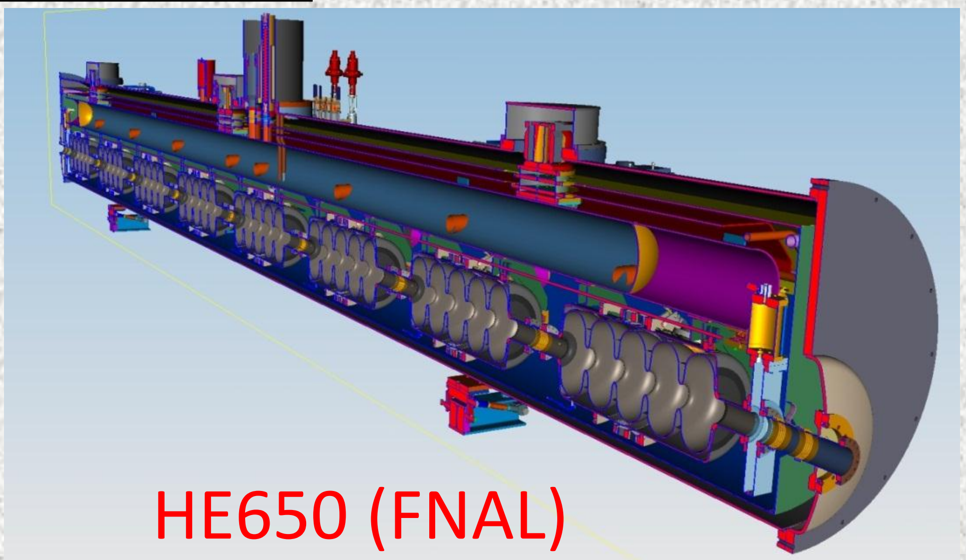
CM designs for Project X CW linac



HWR (ANL)

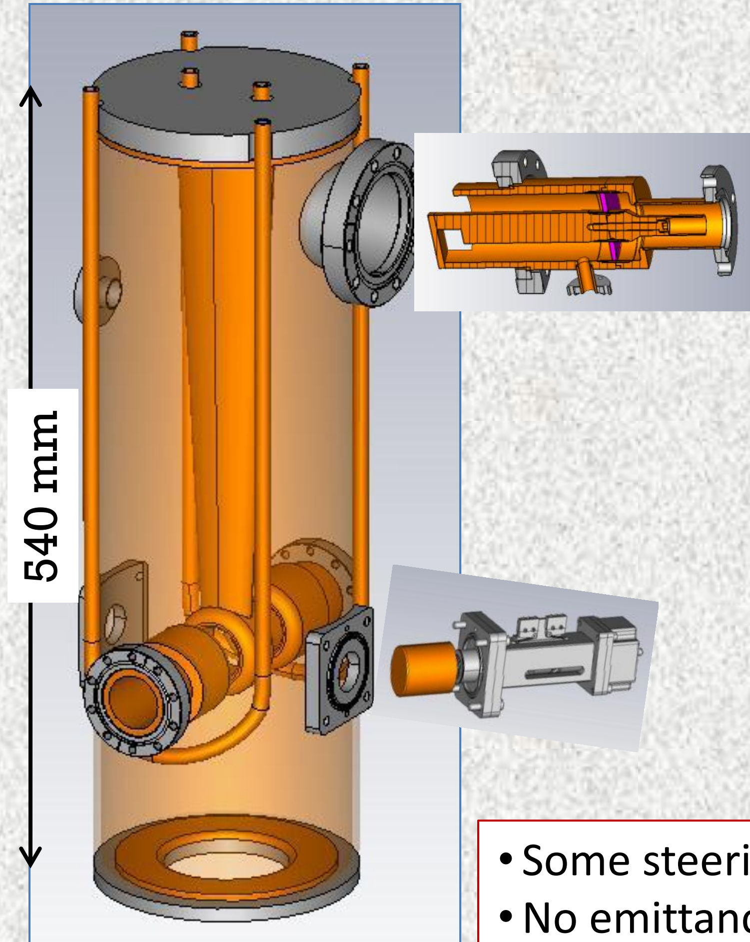


SSR1 (FNAL)
similar design for SSR2



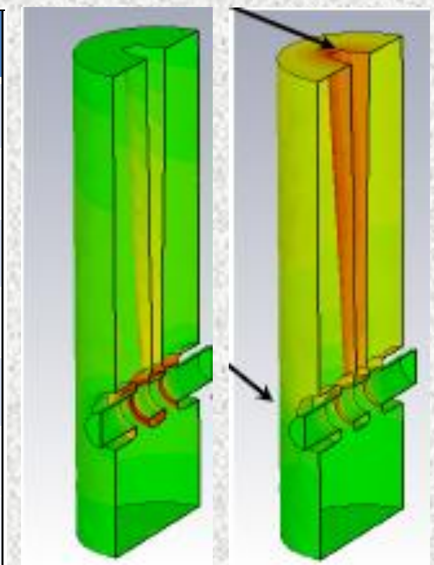
HE650 (FNAL)

QWR Bunching Cavity



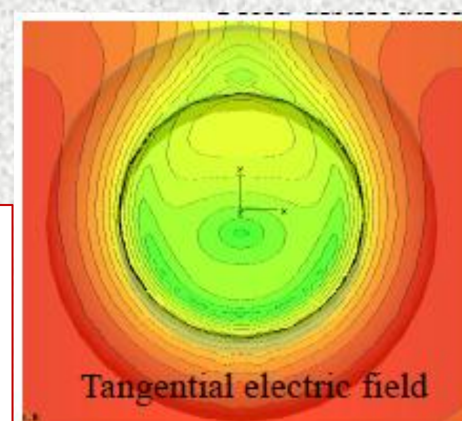
340 mm
(flange-to-flange)

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



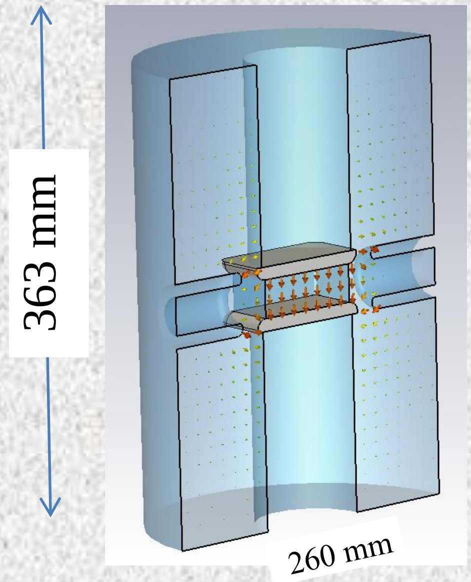
E-field H-field

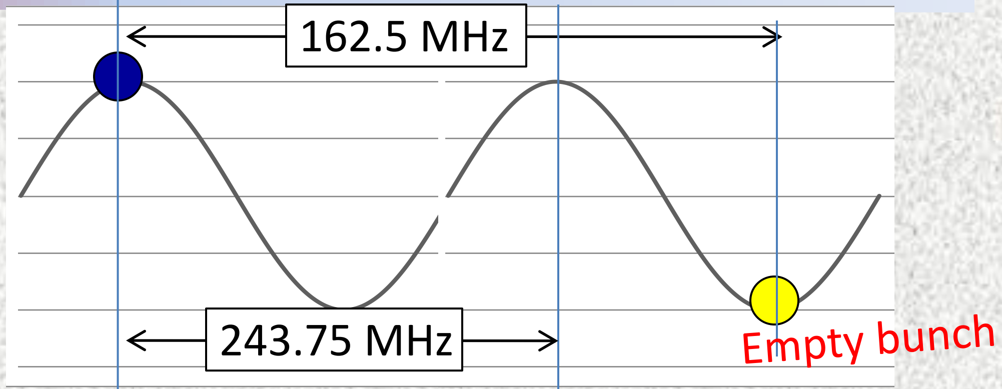
- Some steering effect from field asymmetry.
- No emittance growth is observed.
- Beam deflection is compensated if cavity is shifted down by 0.6mm.



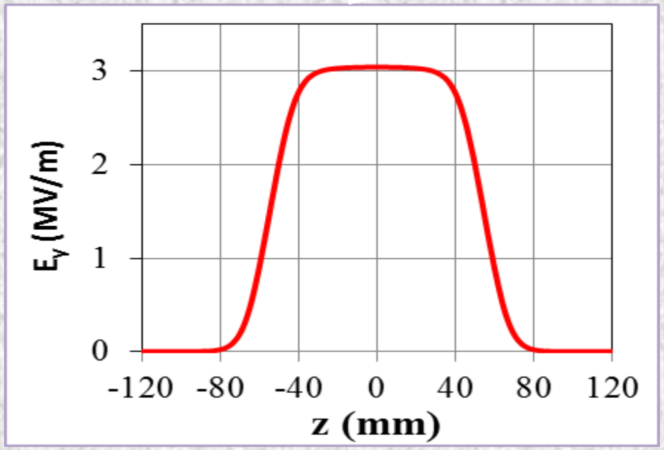
E-field asymmetry

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).

RF Sources for PXIE (CW)

162.5 MHz

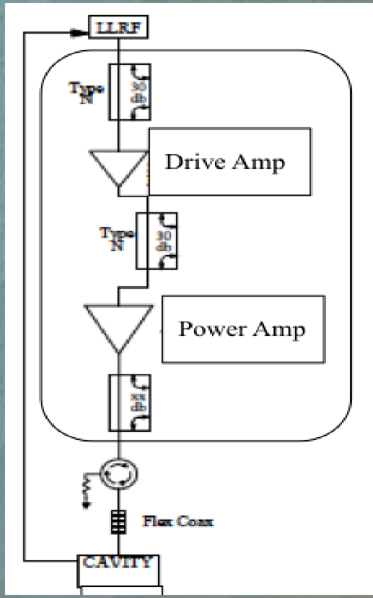
- ***1 RFQ 162.5 MHz – 2 x 75 kW***
- ***3 copper bunchers – 4 kW***
- ***8 SC HWR – 4 kW***

325 MHz

- ***8 SC SSR1 – 4 kW***

243.75 MHz

- ***1 copper RF separator – 7 kW***



Conclusions

- We have good understanding of the Project X lattice and 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.

Thank you for your attention !

Back-up slides

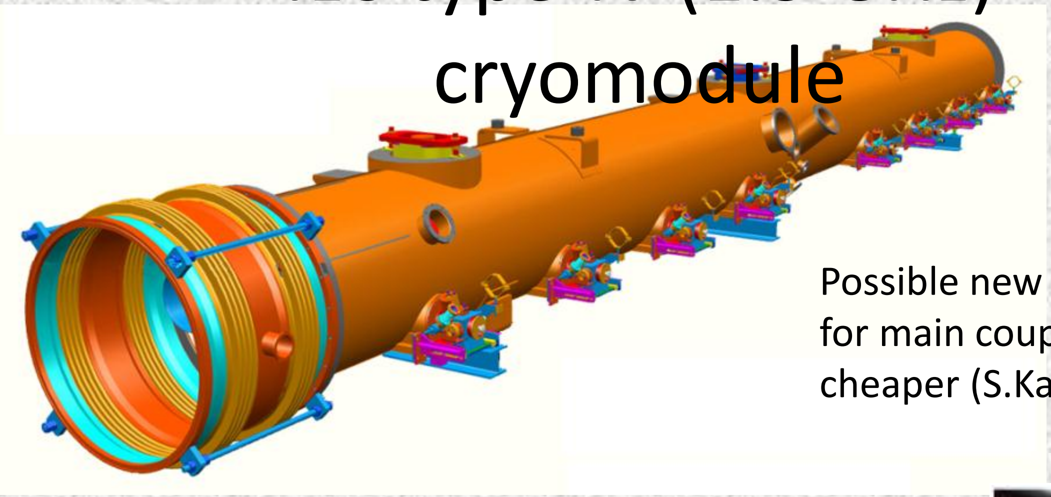
Pulsed Linac

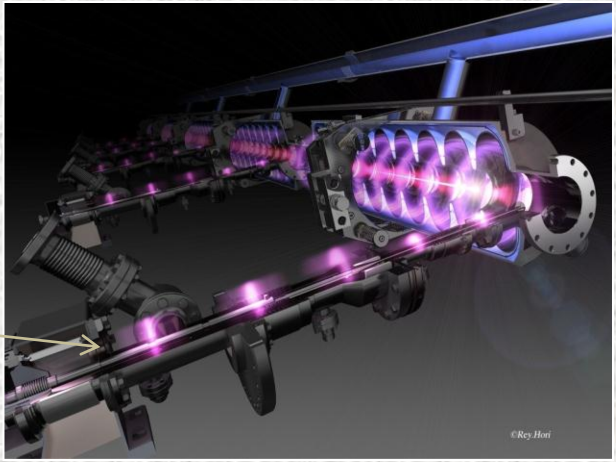
Pulsed 3-8 GeV Linac

Basic Parameters:

- Cryomodule: ILC type with SC quad in center of CM (8cav/CM)
- Focusing : FODO Lattice, each Quad has x/y correctors and BPM
- Cavity:
  - *Average Gradient 25 MV/m; max. spread ±10%*
  - *$Q_0=1\cdot10^{10}$; $Q_{load}=1\cdot10^7$* *(Note: Q_{load} for a matched cavity at 25MV, I_b=1mA is $2.5\cdot10^7$ => $BW_{1/2}$ =26Hz, too small to deal with LFD and microphonics)*
  - *Filling time = 4 ms, flat-top = 4.3 ms*
- RF source:
  - *Pulse length = 8.3 ms; Rep. rate = 10 Hz*
  - *0.4 (0.8) MW klystron per 1(2) CM's (5o kW/cav. with ~60% overhead)*
  - *Other options: Individual pulsed solid state source per cavity ~50 kW*
- H^- beam:
  - *Current = 1 (2) mA; (10 mA peak @ 162.5 MHz)*
  - *Energy 3GeV; emittance~ 0.25 mm*mrad; σ_E/E=0.5MeV(init), < 10 MeV (end)*
  - *Synhronous phase -10°*

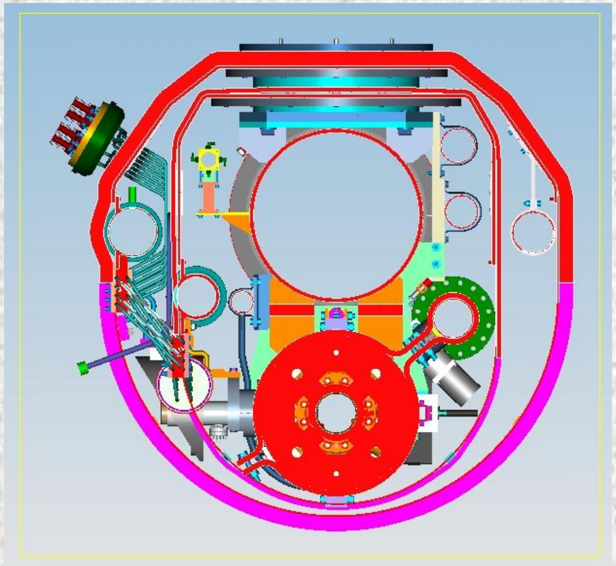
ILC type-IV (1.3 GHz) cryomodule



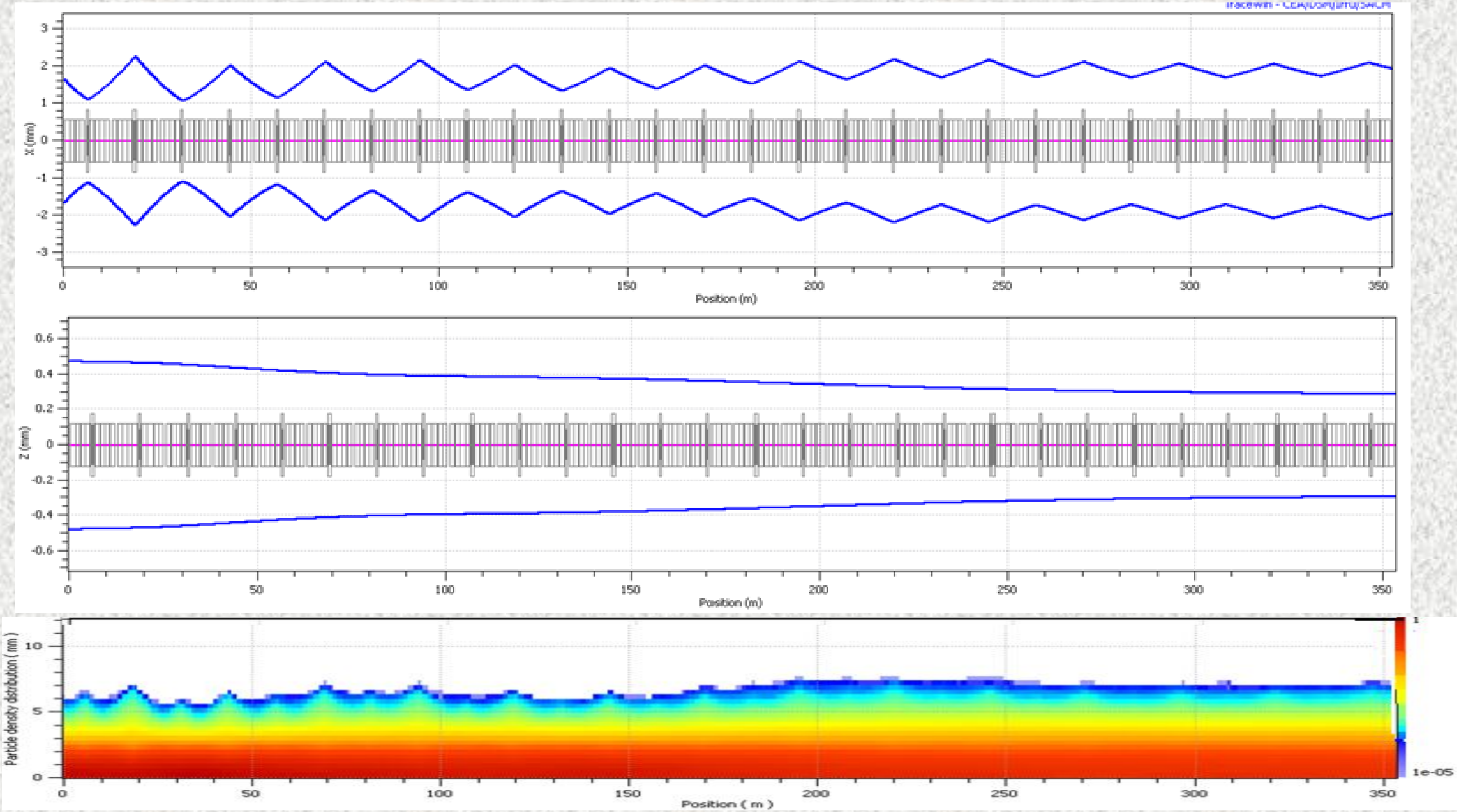


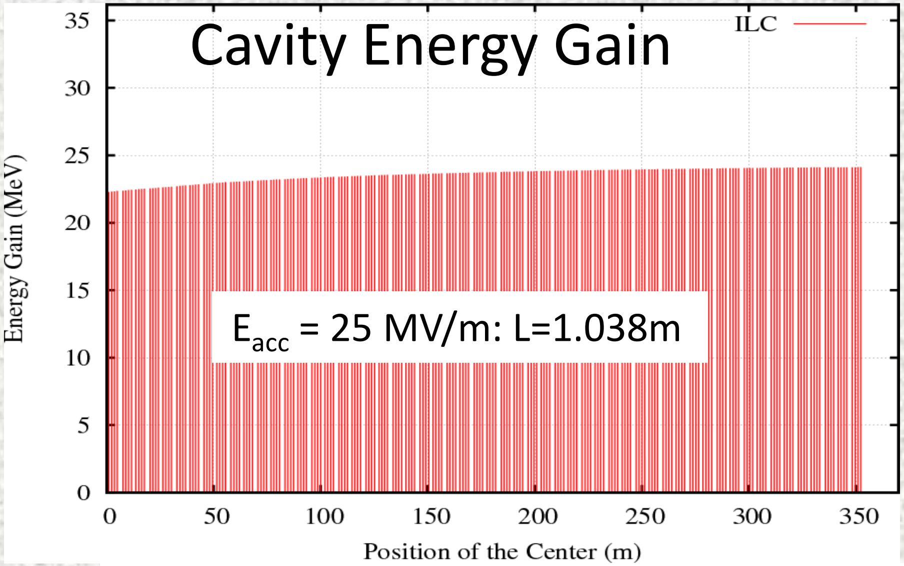
Possible new design for main coupler, cheaper (S.Kazakov)

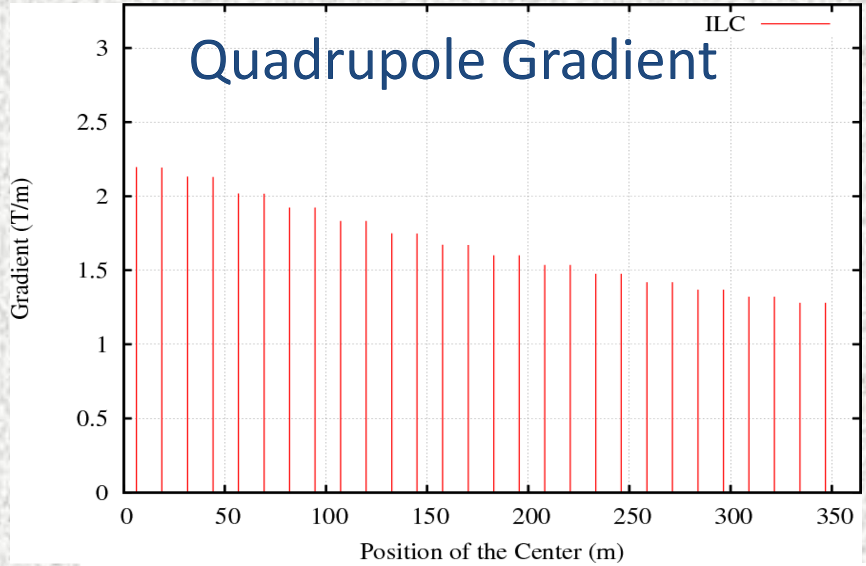
ILC Type-4 cryostat modified (?) for PrX

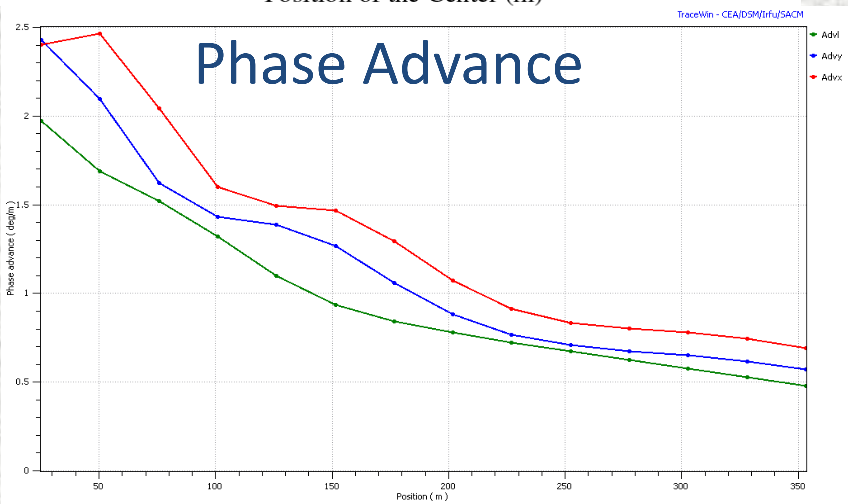


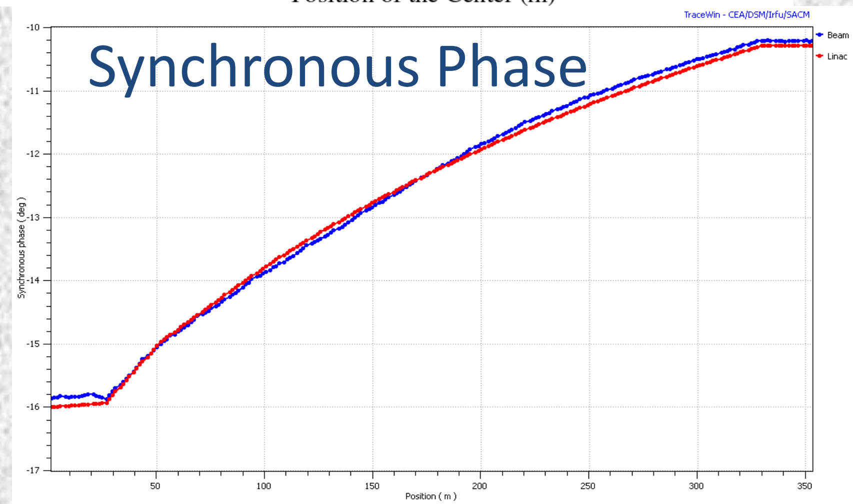
Lattice: Envelopes and Tracking




Cavity Energy Gain
ILC
E_{acc} = 25 MV/m: L=1.038m
Energy Gain (MeV)
Position of the Center (m)
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
350


Quadrupole Gradient
ILC
Gradient (T/m)
Position of the Center (m)
0
0.5
1
1.5
2
2.5
3
0
50
100
150
200
250
300
350


Phase Advance
TraceWin - CEA/DSM/Irfu/SACM
Advl
Advy
Advx
Phase advance (deg/m)
Position (m)
0
0.5
1
1.5
2
2.5
50
100
150
200
250
300
350


Synchronous Phase
TraceWin - CEA/DSM/Irfu/SACM
Beam
Linac
Synchronous phase (deg)
Position (m)
-10
-11
-12
-13
-14
-15
-16
-17
50
100
150
200
250
300
350

1.3 GHz Pulsed Linac RF Parameters

Table of RF Parameters - 1.3GHz Pulsed Linac

	Recycler/MI	Direct Injection into MI
Frequency:	1.3GHz	1.3 GHz
Loaded Q:	1e7	1e7
RF Pulse width:	8.0 mSec	30 mSec
Cavity Gradient:	25 MV/m	25 MV/m
Beam Current:	1 mA	1 mA
Repetition rate:	10 Hz	2 Hz
Cavity RF Power:	32 kW	32 kW
Cavity Power + losses + regulation + EOL:	50 kW	50 kW
Power required per Cryomodule:	400 kW	400 kW

J.Reid

Pulsed Linac: RF Summary

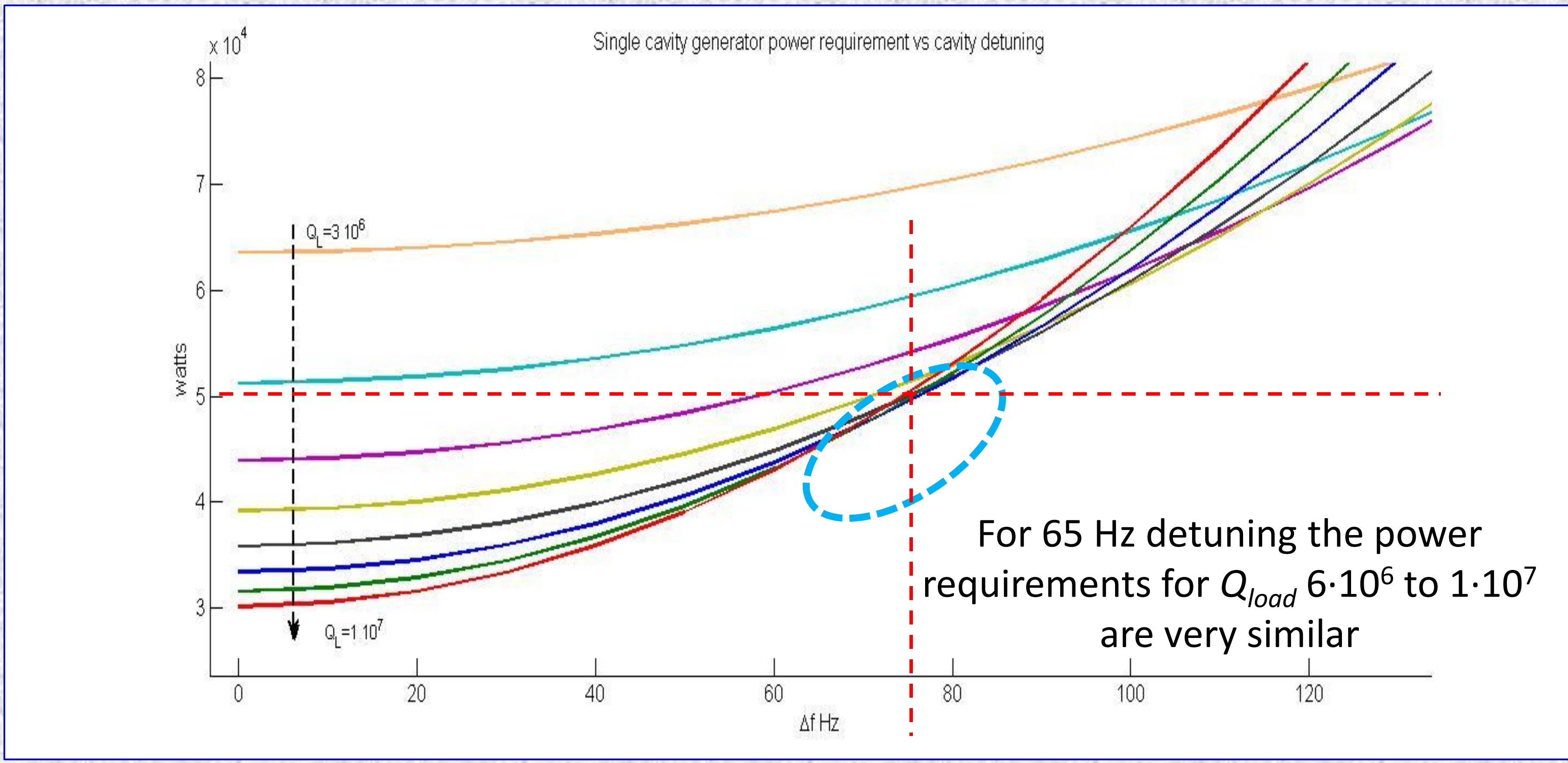
- Determine the required RF power per cryomodule, ~ 400 kW per cryomodule
- Determine the number of cryomodules (1 or 2) per klystron for total of 14 or 28 klystrons
- Possible klystron parameters:

Klystron Type	**SBK**	**MBK**	**SBK**	**MBK**
Klystron Power (kW)	400	400	800	800
Voltage (kV)	54	33	71	44
Current (Amps)	12	20	19	30
Efficiency (%)	60-62	62-64	60-62	62-64
Average Power (kW)	32	32	64	64

- Only 800 kW SBK would require modulator with oil
- Modulator Type (solid state), V&I criteria, No HV pulse transformer and oil
- Power distribution system:
    - Equal power distribution
    - Proportional power distribution

Power vs. LFD and microphonics

$$P_g = \frac{V_{cav}^2}{\left(\frac{r}{Q}\right) Q_L} \frac{1}{4} \left(\left[1 + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \cos\phi_b \right]^2 + \left[\frac{\Delta f}{f_{1/2}} + \frac{\left(\frac{r}{Q}\right) Q_L I_{b0}}{V_{cav}} \sin\phi_b \right]^2 \right)$$

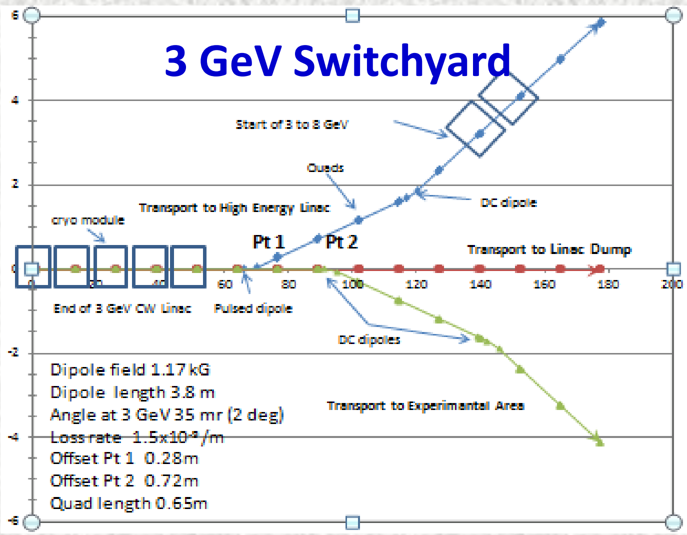


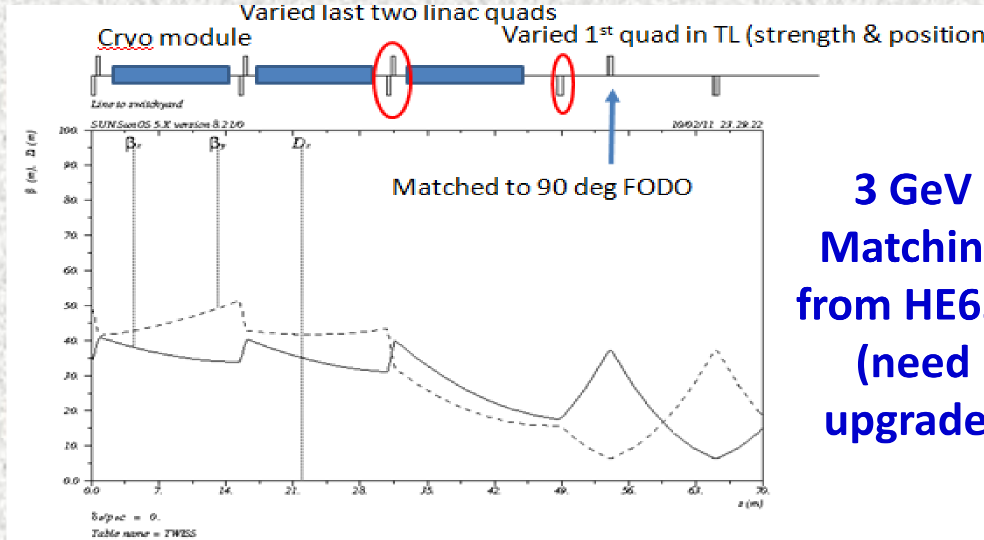
Specs for RF Power overhead ~60% (nominal ~25 kW/cavity, 1 mA)

Transport Lines

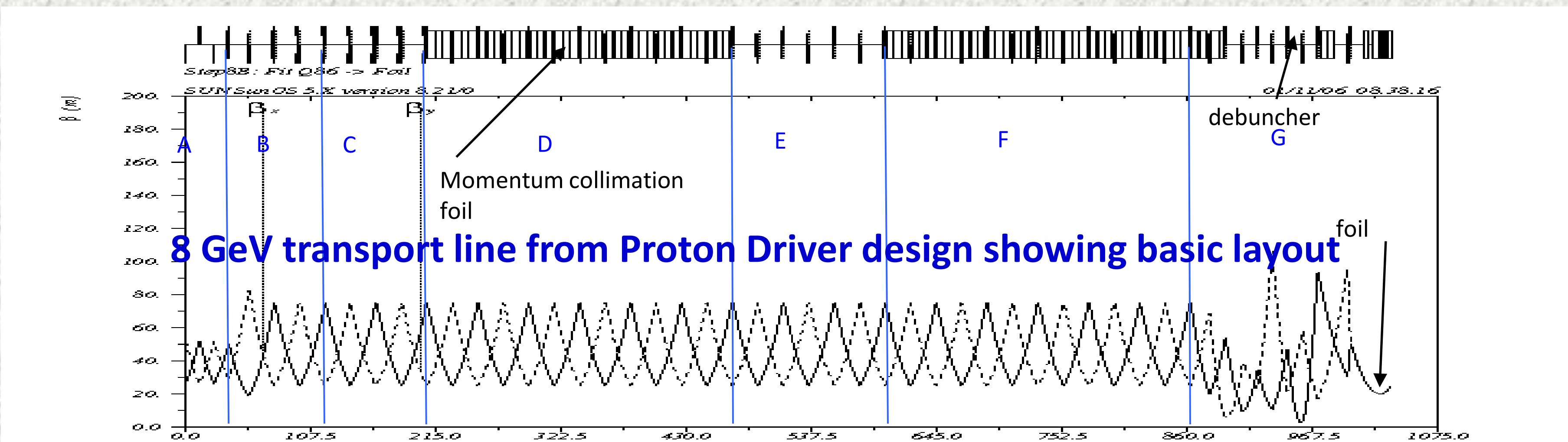
- 1 GeV Extraction (not addressed here)
- 3 GeV Switchyard
  - 3 GeV Linac to 3-8 GeV Linac
  - 3 GeV Dump
  - 3 GeV to Experimental Area
- 8 GeV linac to Recycler

Transport Lines:





3 GeV Matching from HE650 (need upgrade)

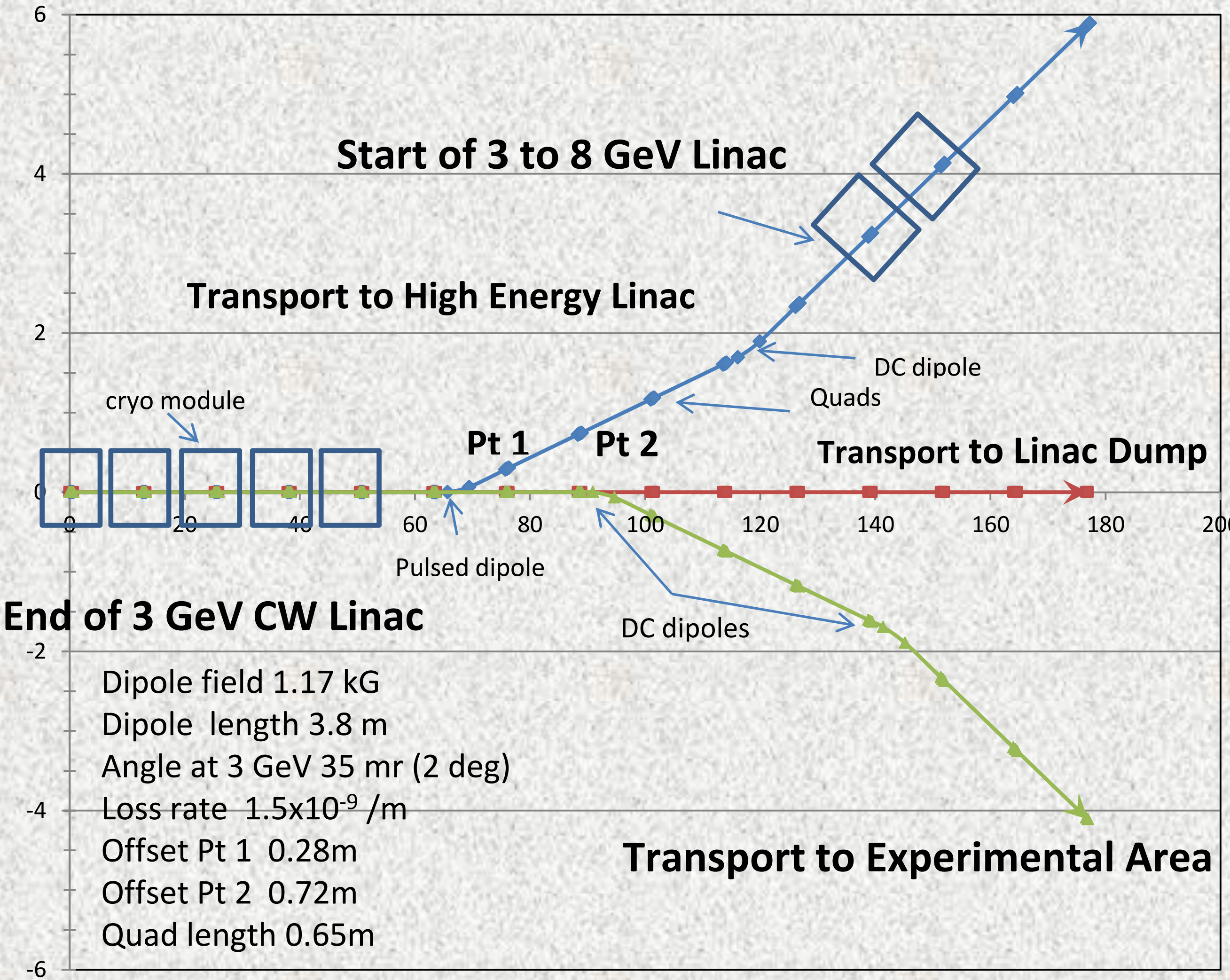


D.Johnson talk at Collaboration meeting, FNAL, Oct.2011

3 GeV Switchyard

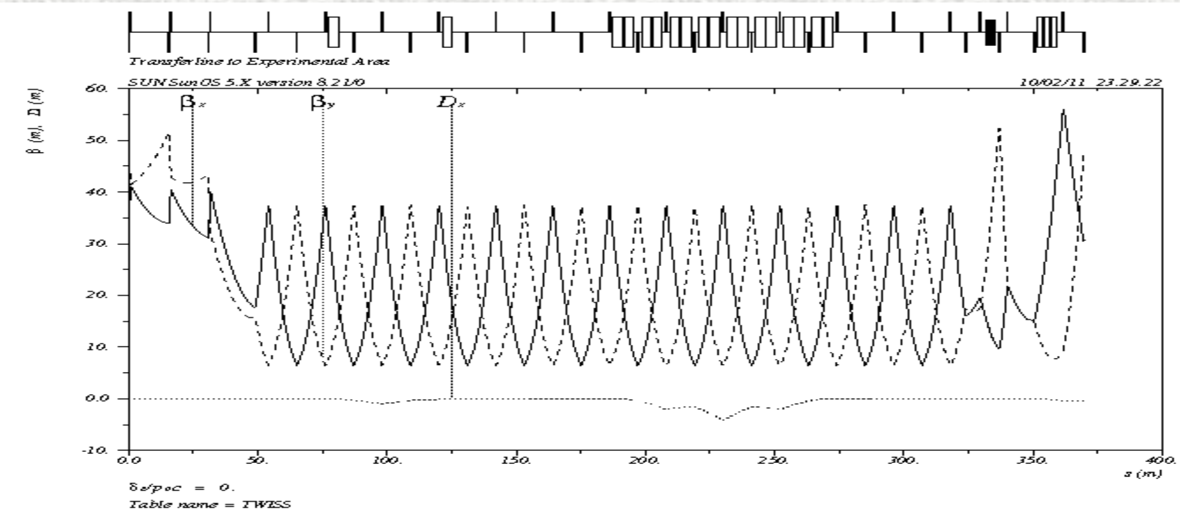
- Initial Layout of 3 GeV Switchyard assumed HE Linac used 1.3 GHz cavities and FODO lattice.
  - The current design of the HE CW linac used 650 MHz cavities and doublet focusing with a period of 14.6m
- All 3 GeV Switchyard lines have a common lattice with 90^o FODO cells with a quad spacing of 10.5m
  - The initial lattice for all matched to 3 GeV FODO and subsequently to 3 GeV doublet. Matching using last 2 quads in linac and 1^{st} quad in T.L. (next slide)
- The 3to8 GeV Linac assumed 1.3 GHz and FODO lattice with uniform quad spacing of ~12m.
  - Match into Linac
- All Bend centers are achromatic with B field chosen to minimize Lorentz stripping

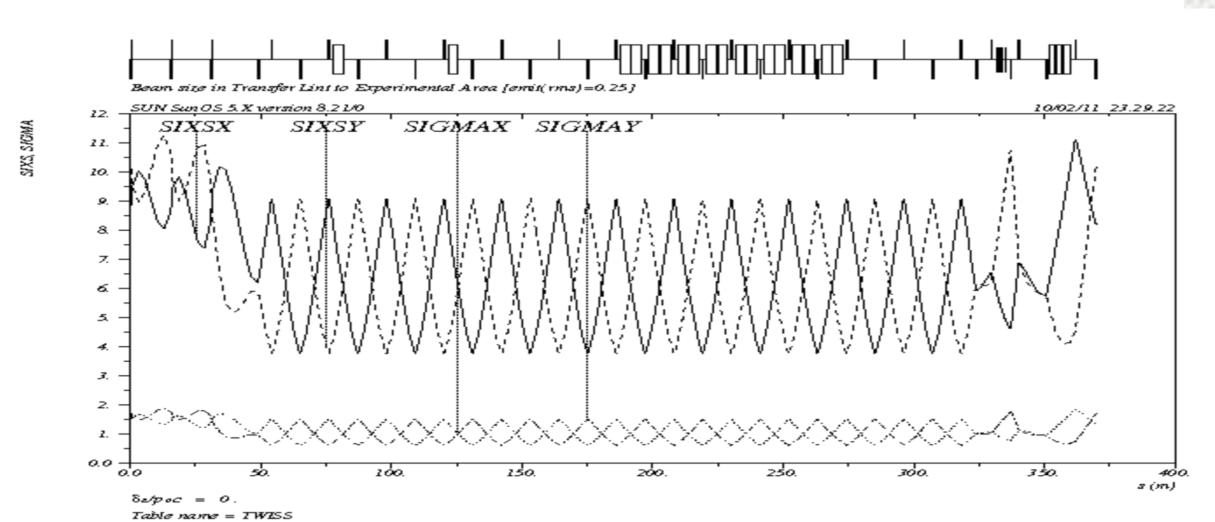
3 GeV Switchyard



Dipole field 1.17 kG
Dipole length 3.8 m
Angle at 3 GeV 35 mr (2 deg)
Loss rate 1.5×10^{-9} /m
Offset Pt 1 0.28m
Offset Pt 2 0.72m
Quad length 0.65m

3 GeV Experimental Area lattice





At 3 MW w/cryo shield BB loss ~ 0.4W/m uniform loss rate.

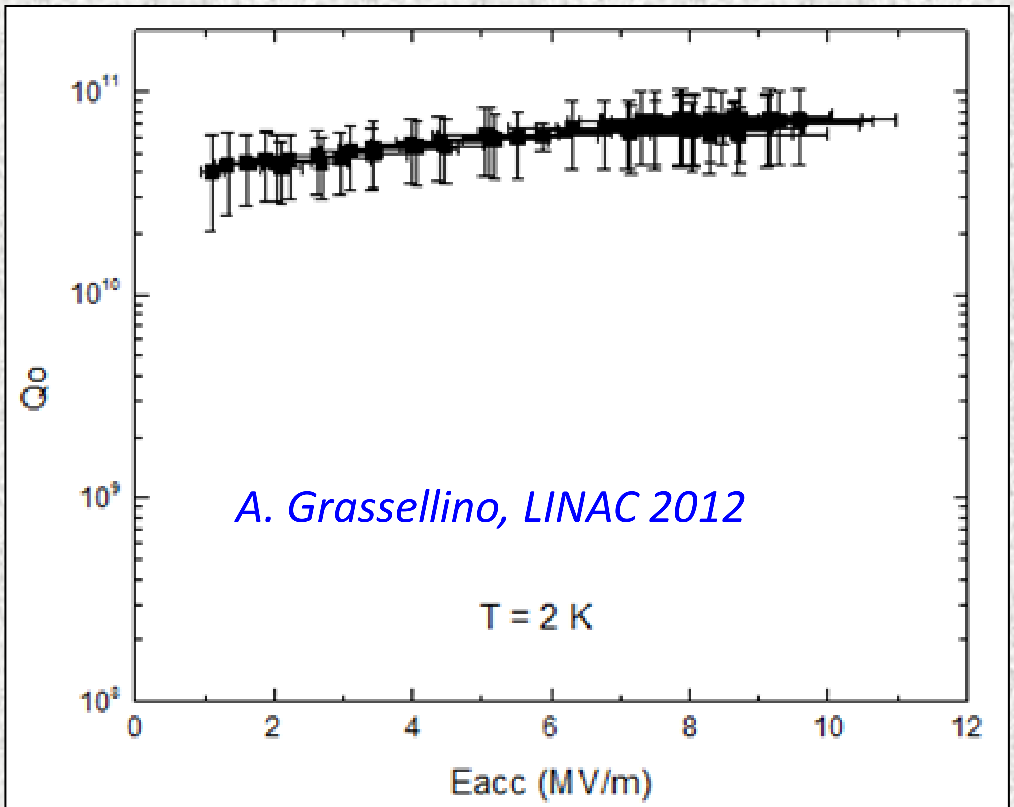
- implies cryo shield in the part of the transport line going to EA.
- potential option to locate a stripping station in conjunction with collimation to convert to protons… ANL CNM collaboration (hopefully)
  - ➢ This removes constraint on cryo shield and max dipole field

8 GeV Linac to Recycler

- Recycler fixed 8 GeV Kinetic Energy
  - Utilize permanent magnets (dipoles and quads) for transport line as we do between Booster and MI with full compliment of powered dipole correctors and matching quads.
  - No need for Cryo-shielding if power <15kW
  - Design presented to Directors Review March ‘09
    - Not expecting any significant changes.

Path to improve Q_0

- NbN: superconductor with higher T_c (~16°K, compared to 9.2°K for Nb);
- Potential for lower surface resistance than Nb;
- Material made via bulk diffusion: simple and inexpensive modification to standard Nb treatments. Large grain Nb is used;



First result at FNAL:

world record **Q_0 ~ 7.5·10^{10}** at 2K and E_{acc} = 10MV/m

for a 1.3GHz single cell

➔residual resistance < 0.5 nΩ!