PXIE Accelerator Physics

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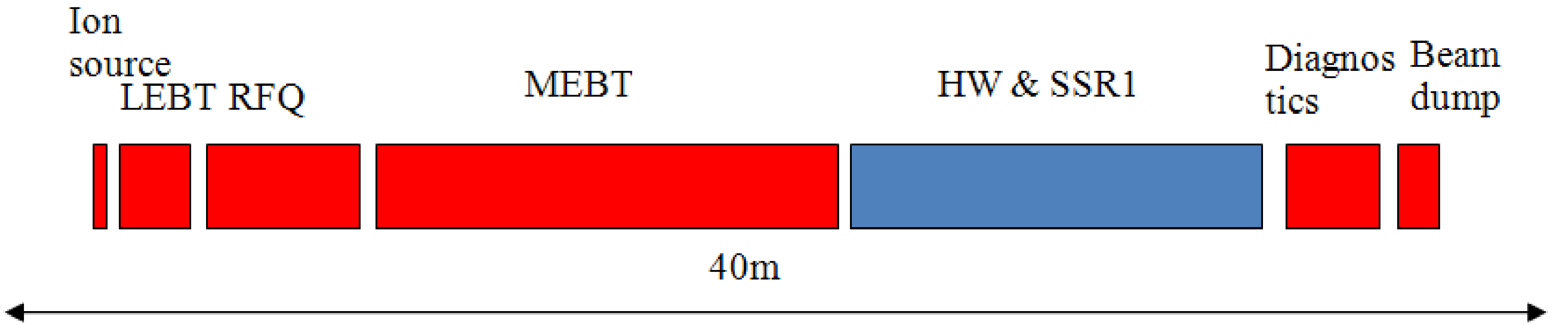
Outline

- Goals
- PXIE Optics
  – Concept
  – Major limitations
  – Failure analysis
- Non-standard hardware
- Non-standard instrumentation
- Conclusion

PXIE - Project X Injector Experiment

- 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
  - 2.1 MeV 162.5 MHz RFQ
  - MEBT with bunch-by-bunch chopper and 11 kW beam dump
  - Two SC cryo-modules: HWR -162.5 MHz & SSR1 – 325 MHz
  - Beam diagnostics, spectrometer and 50 kW beam dump



PXIE Goals

- Validate the Project X concept and eliminate technical risks
  - CW RFQ
  - Bunch-by-bunch chopper
  - Initial stage of acceleration in SC linac – never tested in experiment
    - Complications can be due to beam loss of RFQ tails in SC linac
  - Extinction for the removed bunches better than
    - 10^{-4} – specified by the PXIE FRS and determined by multi-experiment operation
    - $<10^{-9}$ – as desired by μ-to-e experiment
- Obtain experience in design and operation of SC proton linac
  - HWR cryomodule and cavities will be designed and build by ANL
  - SSR1 cryomodule will be designed and build by Fermilab

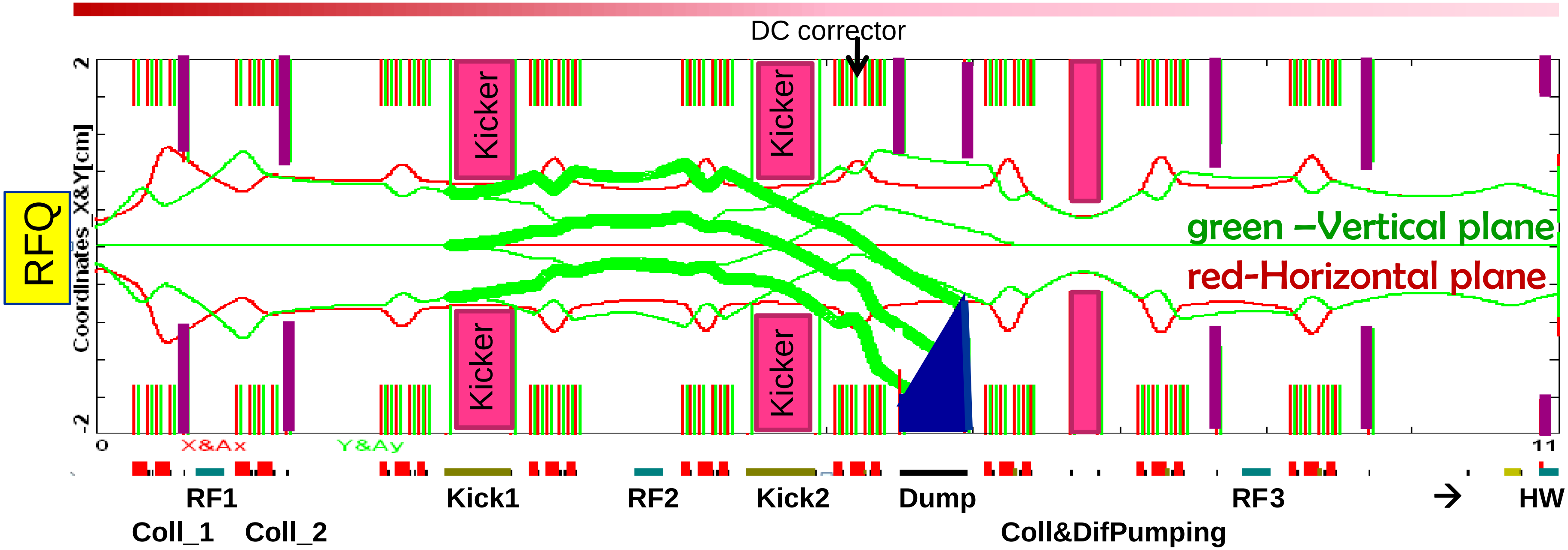
Major PXIE Features

- "Adiabatic optics" – small beta-function variation (smoothness)
  - Mitigation of space charge
- LEBT
  - LEBT chopper
    - Supports machine tuning in pulsed mode: $\Delta t \sim 1 - 10\ \mu s$, f_{rep}=60 Hz
- RFQ
  - 162.5 MHz RFQ
    - Reducing frequency reduces RF power,
    - but the major reason is a possibility of bunch-by-bunch chopping, $T \approx 6.2$ ns, bandwidth of ~ 1 GHz
- MEBT
  - "Two-kickers chopping" makes chopping possible with present technology
  - 11 kW beam dump for chopped-out beam
    - Large pumping speed to achieve sufficiently good reducing H^- stripping on the residual gas
  - Differential pumping to minimize H_2 leakage to the SC cryomodules and RFQ

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
- RF separation at the top energy for beam extinction studies, f=1.5*162.5 MHz
  - Can help in measurements of bunch length and longitudinal tails
- Instrumentation (not a complete list)
  - Single bunch beam position and beam current measurements averaged over micro cycle (~1 μs); it is not required for all BPMs
  - Built-in synchronous detection:
    - optics measurements in the course of operation
    - suppression of dispersion and reflections in MEBT chopper
    - loss detection
    - required for laser profile monitors with detection of H^- beam current variations
- Spectrometer at the end of the machine
- 50 KW beam dump
  - can support operation up to 2 mA beam current

Optics in MEBT



*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)*

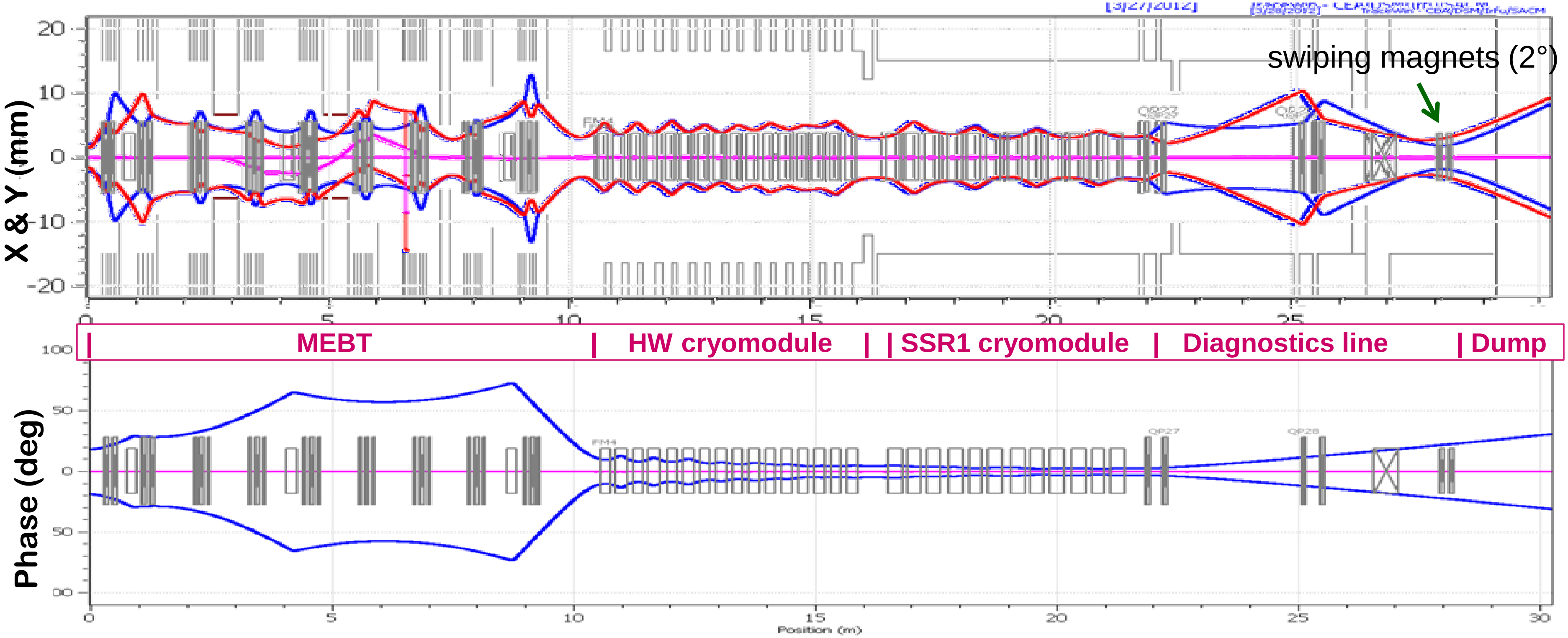
- Use of 2 kickers with 180 deg. phase advance reduces kicker voltage
  - ***Bunch by-bunch current regulation is anticipated in Project X*** ***$\Rightarrow$ 2 additional kickers, increased MEBT length***
- Sufficient space for diagnostics and differential pumping
- 16 mm gap between kicker plates protects them from the direct beam hit $\Rightarrow$ ***±250 V effective voltage on the kicker***
- DC correctors to 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) for
    - ***Laser profile monitor, Pumping port***

Optics in PXIE (passing beam)

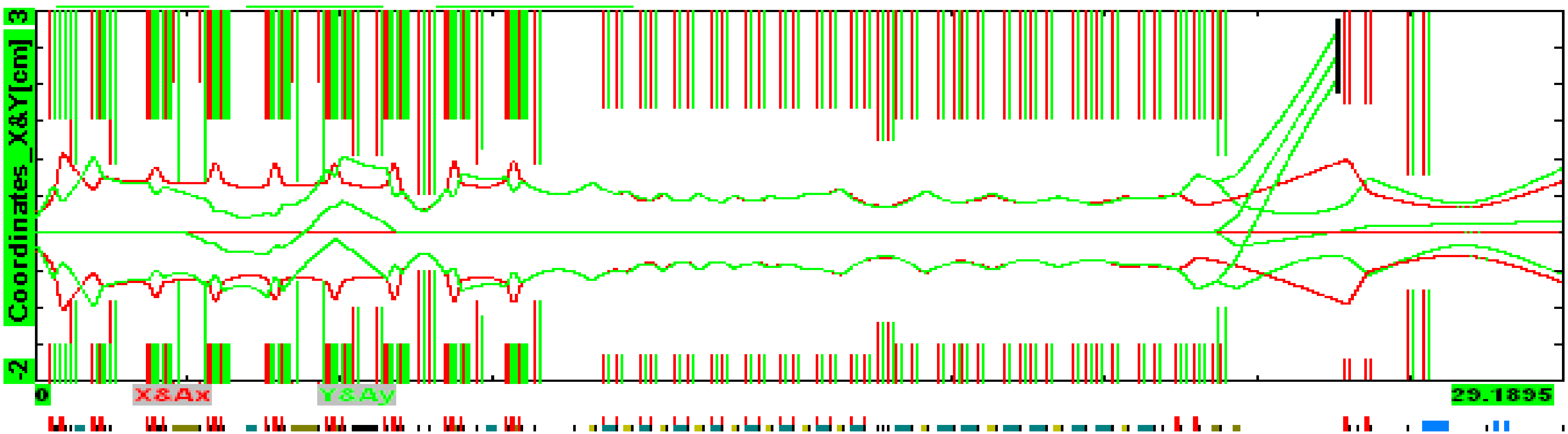
(kickers: ±185 V; Asymmetric dump aperture: 5 mm)



- Doublet/Triplet focusing in MEBT, Solenoidal focusing in HW and SSR1 cryomodules
- …S-C – C-S… focusing at CM transition reduces nonlinearities of Long. motion
- Bending magnet in diagnostics line for momentum spread measurements
- Beam dump with X&Y swiping magnets (angle ~2°)

PXIE Optics (continue)

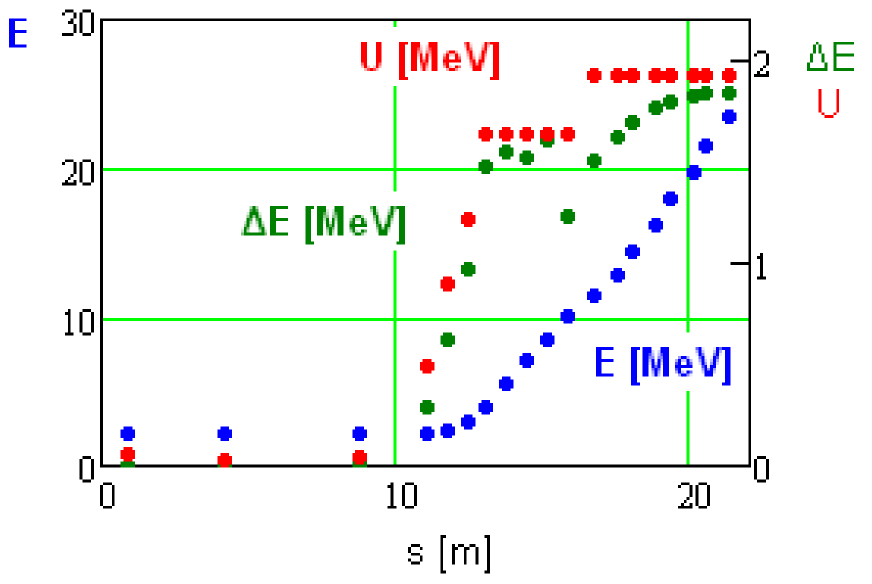
3σ beam envelopes (ε_{rms_n}= 0.25 mm mrad)

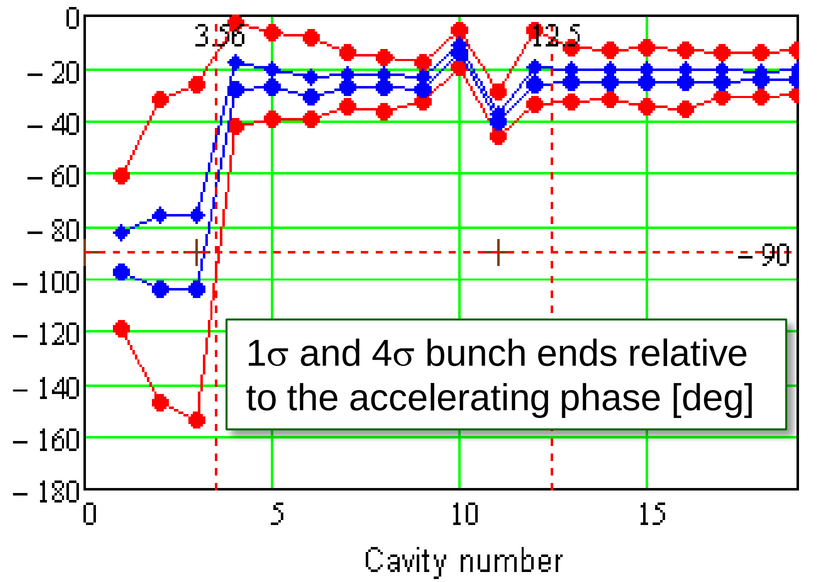


Apertures:

- **MEBT – 30 mm (13 mm - kickers, 10 mm - dif. pumping with L=200 mm)**
- **HWR – 33 mm**
- **Interface box between cryomodules – 25 mm**
- **SSR1 – 30 mm**
- **Diagnostic section – 30 mm (20mm – RF kicker, 15 mm – diff. pumping with Length=300 mm)**

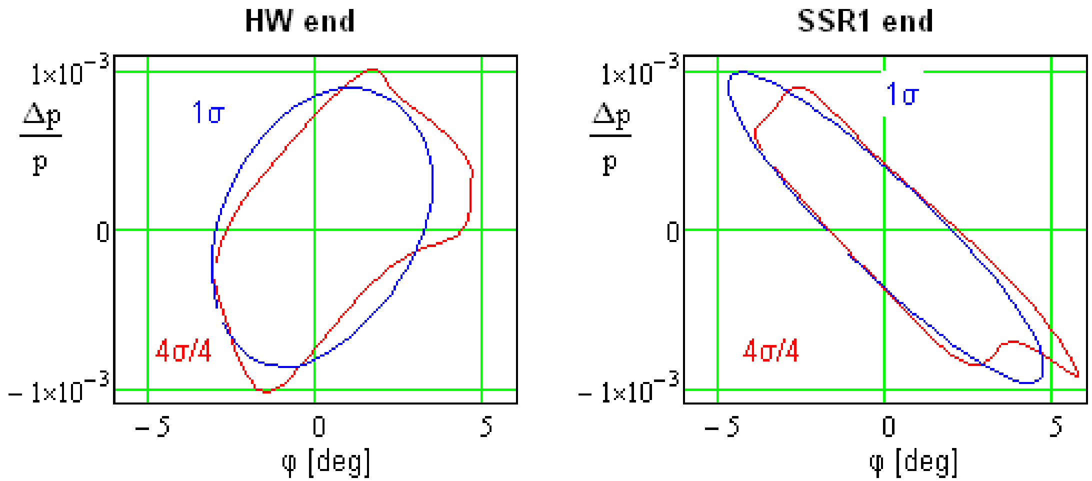
Acceleration in SC Cryomodules



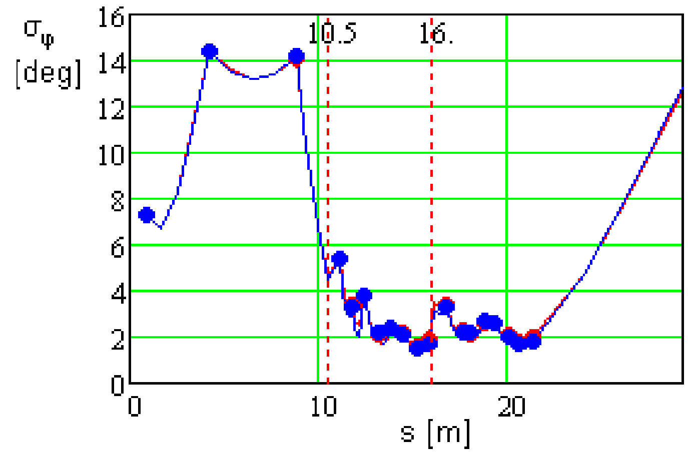


- Accelerating gradient of the first 3 SC cavities is reduced due to longitudinal over-focusing.
- Design intent for operating voltages are: 1.7 MV – HWR & 2 MV - SSR1
- To support reliable operation the accuracies of RF voltage and phase should be better than 1% and ~0.5 deg (misalignment and RF errors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

Optics for Longitudinal Degree of Freedom



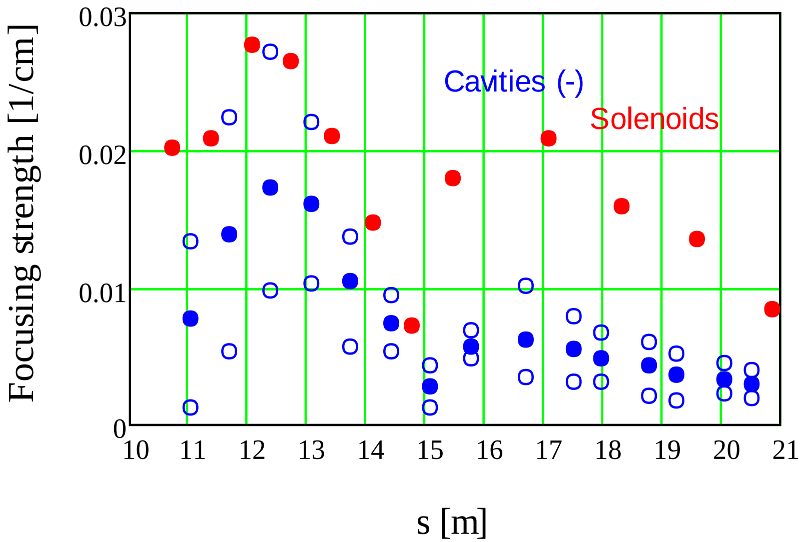
Transformation of 1s and 4s envelopes to the end of HW (left) and SSR1 (right) CM; $\varepsilon_{L\_rms\ n}$*=0.25 mm mrad or 0.782 eV μs*

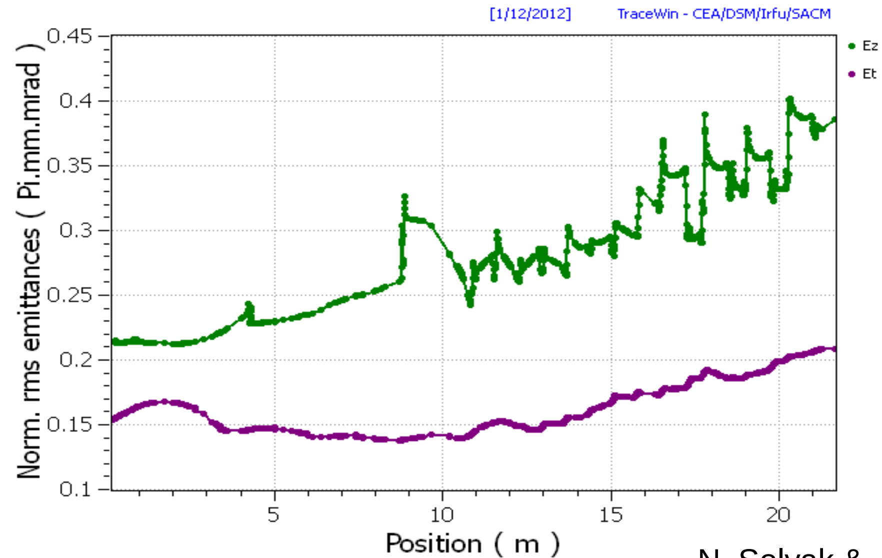


Bunch length (deg) for 1σ initial ellipse from RFQ to the beam dump

- Three NC cavities in MEBT provide longitudinal focusing and match RFQ to SC linac
  - Present voltages are 65, 30 and 45 kV
  - 100 kV is specified as maximum voltage. It results in sufficient freedom for longitudinal optics
- Amplitude motion in MEBT is sufficiently linear
  - 4σ beam envelopes are within ~ ±70 deg
- Focusing nonlinearity of different cavities is compensated by appropriate phase advance
- In SC sections RF synchronous phase is chosen to have acceptance > 5 σ_φ to reduce nonlinearity

Focusing and Beam Transport in SC Cryomodules

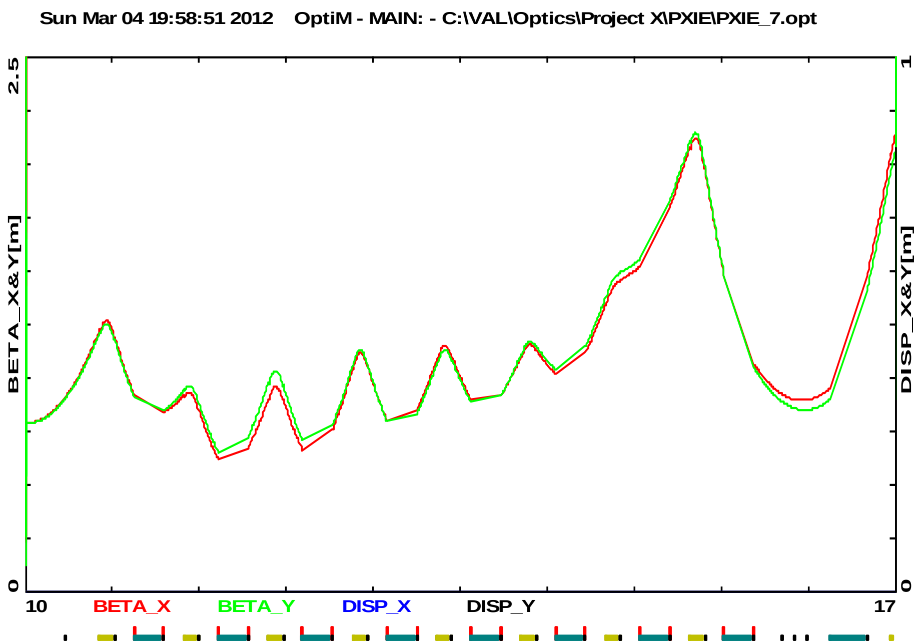


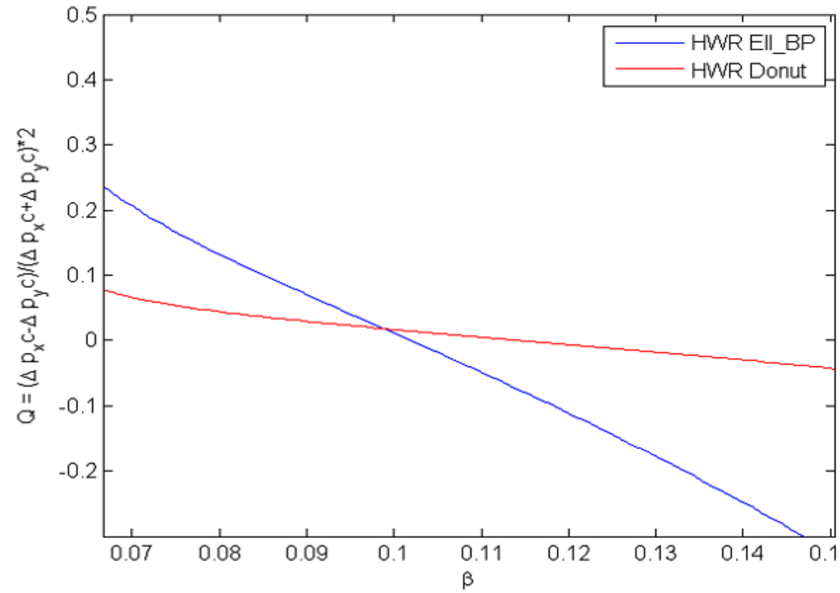


N. Solyak & B. Shteynas

- 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

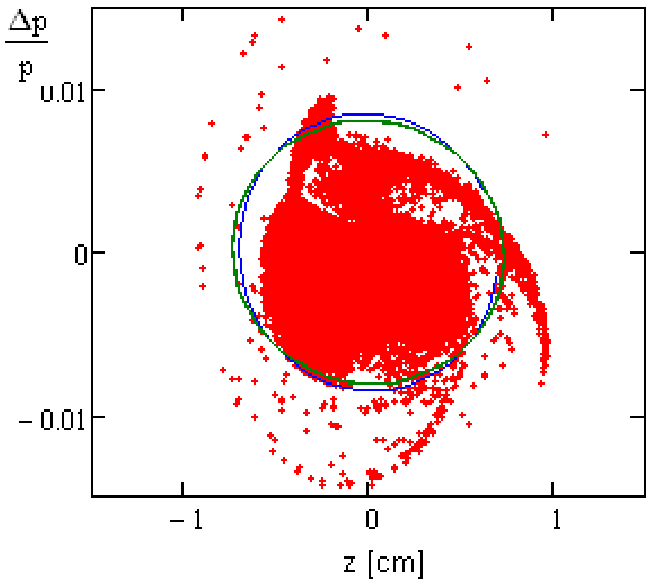
Quadrupole fields in HW Cavities



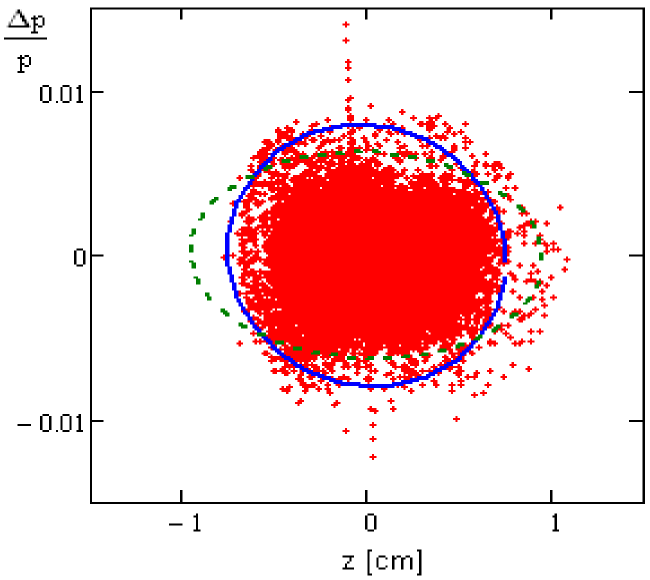


- Asymmetry in cavity geometry produce quadrupole components in defocusing field
- Ways to reduce asymmetry: elliptical beam pipe or donut geometry in beam pipe region.
- Donut geometry is more effective in reduction of quadrupole field to an acceptable level

RFQ produced tails



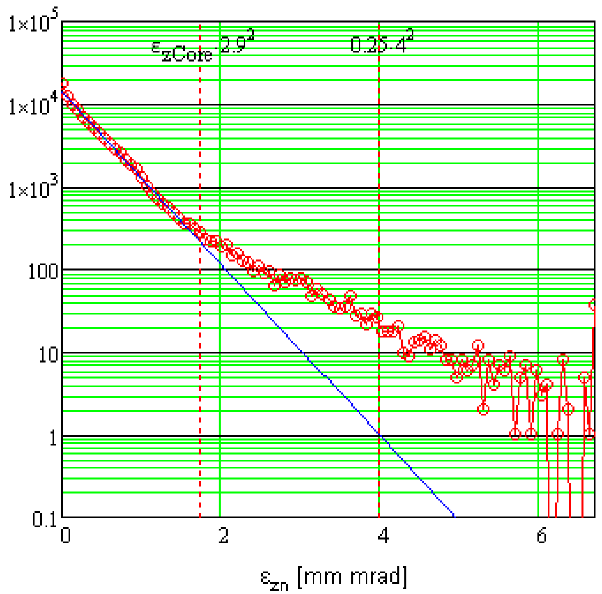
G. Romanov (Track-3D, MWS field map, water-bag initial transv. distr)



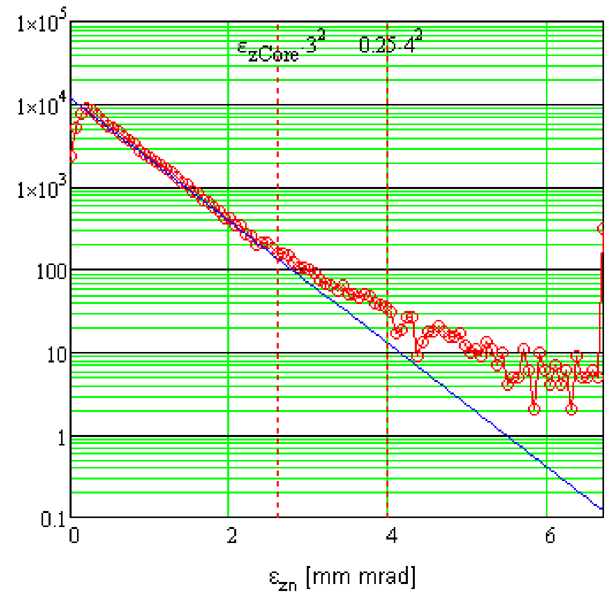
J. Staples (Parmteq, Gaussian-like initial transverse distribution)

- Two different simulations produce not-negligible difference of the tails behavior
- We launched additional studies to understand this difference and possible ways for reduction of the loss

RFQ tails (continue)



G. Romanov (water bag tr. Distr.)

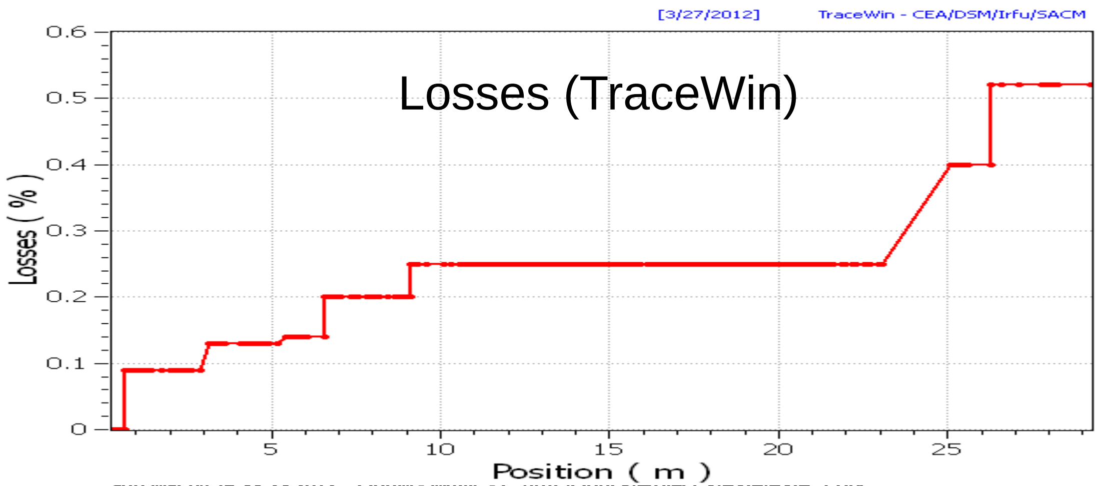


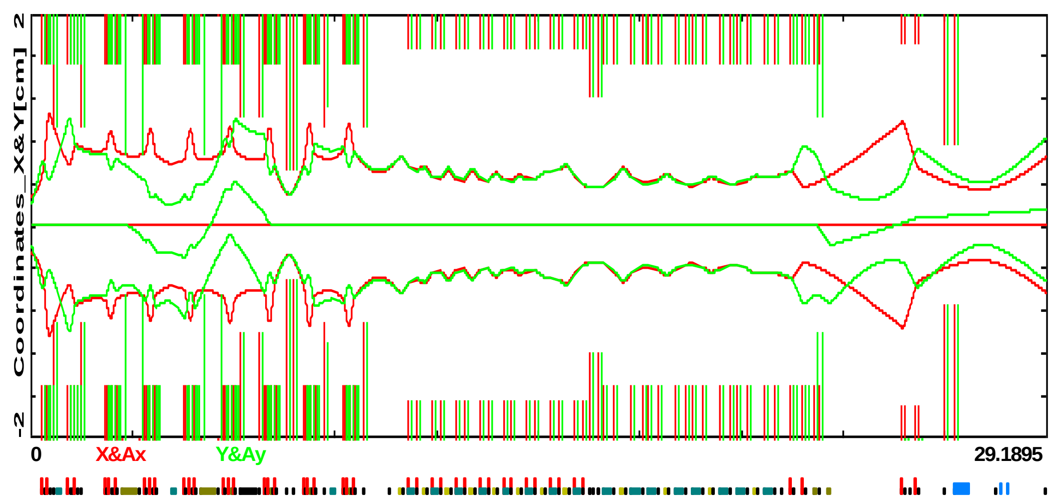
J. Staples (Gaussian tr. distr.)

- **Although z-p_z distributions look different the particle distributions over action look very similar**
- **RFQ tails will result in additional loss in further acceleration in PrX linac.**
- **Characterization of tails in PXIE and ways of possible mitigation tails related problems are important part of PXIE program**

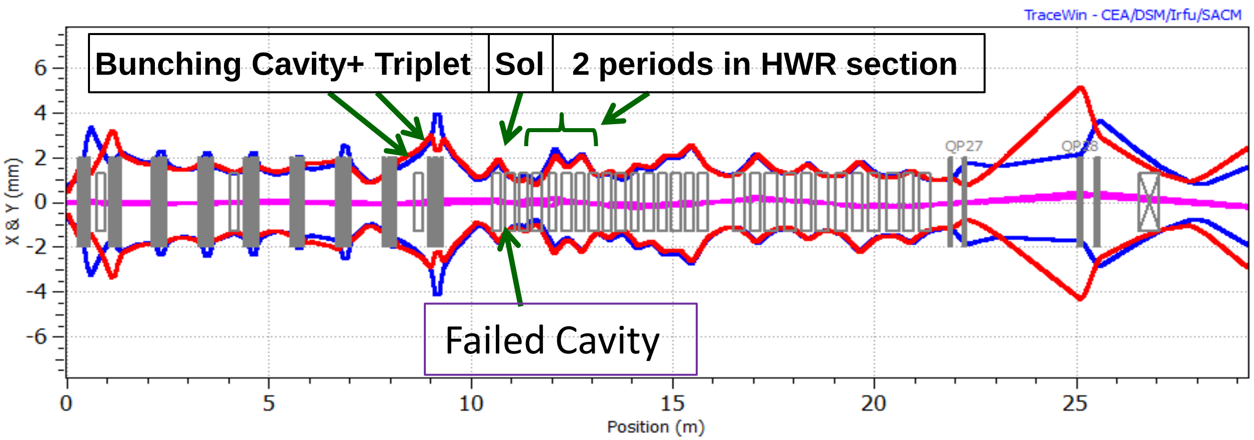
Beam loss in SC Cryomodules

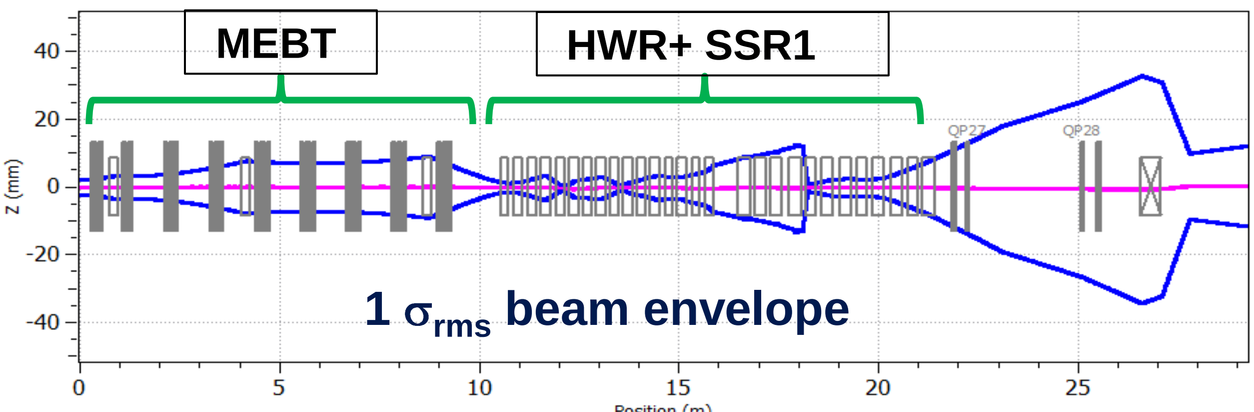
- Loss due to intra-beam stripping is expected to be < 0.5 W
- Non-Gaussian tail of RFQ longitudinal distribution is the major source of particle loss, $<3 \cdot 10^{-4}$ (<10 W).
- Loss interception with good efficiency is impossible
  - Too large relative energy change in a single SC cavity
    => loss in one lattice period
- Collimators in NC sections will mostly intercept the lost beam
- Small fraction of total beam loss will be intercepted by warm interface between cryomodules
- Some fraction will be lost at 2 K
  - < 10 W total particle loss
  - It is still small relative to the loss due to e.-m. fields (~50 W)





Failure Analysis for the PXIE (failed 1st cavity or solenoid in HWR)





A.Saini

Initial Parameters		
$E_{initial}$	2.12	MeV
ε_z	0.211	$\pi \cdot$ mm mrad
ε_y	0.153	$\pi \cdot$ mm mrad
ε_x	0.152	$\pi \cdot$ mm mrad

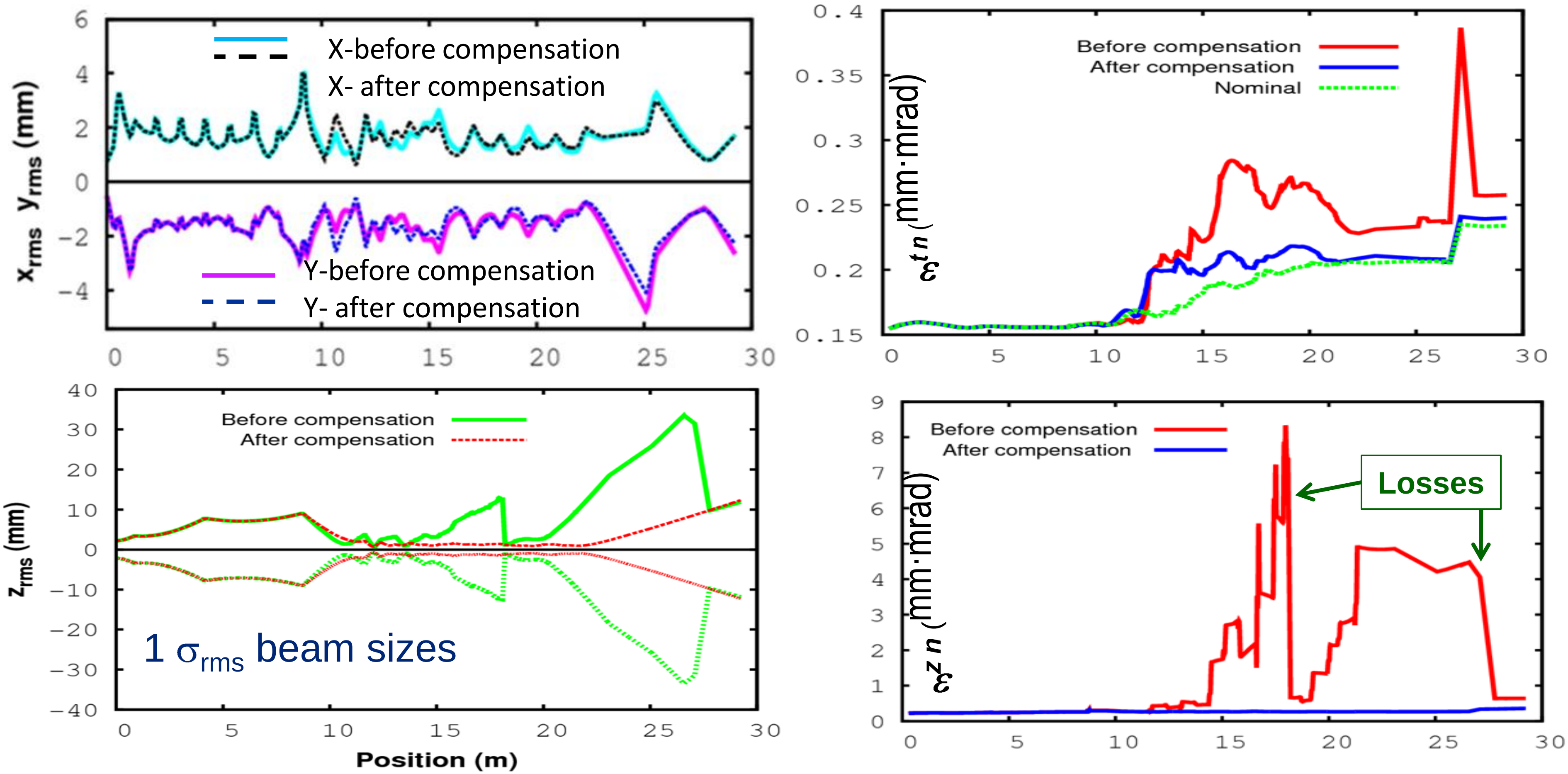
- 6σ Gaussian beam distribution is used.
- 10 K macro particles are used for study

Neighboring elements in the vicinity of failed cavity / solenoid are retuned in order to achieve

- designed beam energy
- smooth L. and T. envelopes
- 100 % transmission i.e. no beam losses after applying local compensation.

- Both Choppers are switched off.
- PXIE_7 (03-22-12) lattice is used for study

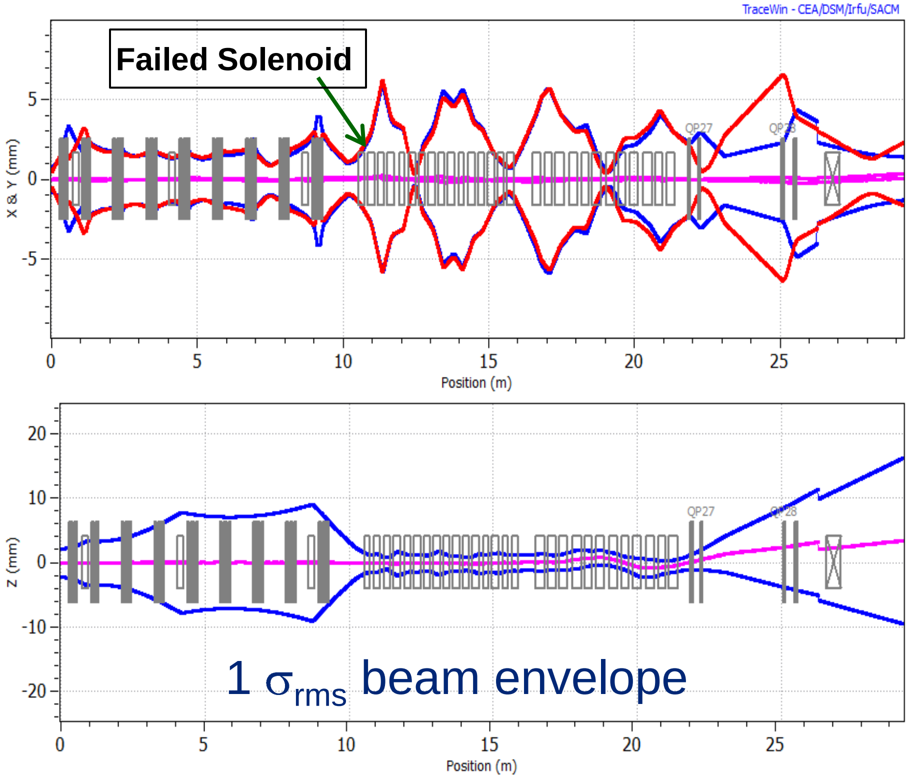
Compensation of the failed 1st cavity: Transverse & Longitudinal Beam Dynamics



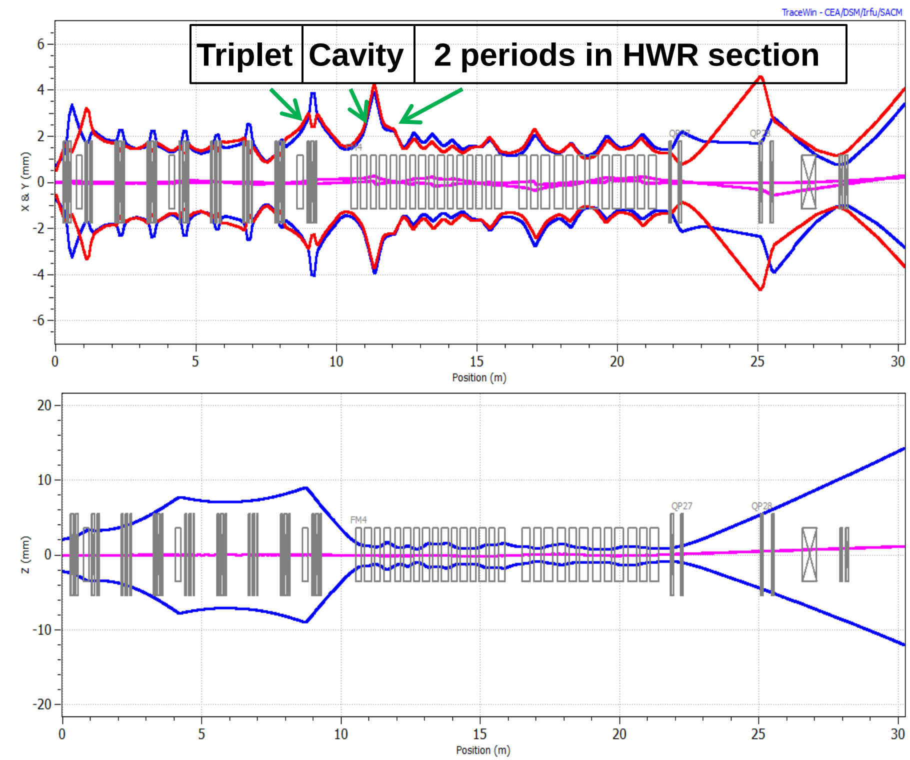
- **Failed cavity dramatically changes L. dynamics; small disturbance in T. dimensions**

Failure of 1st solenoid in HWR section

Before compensation



After local compensation

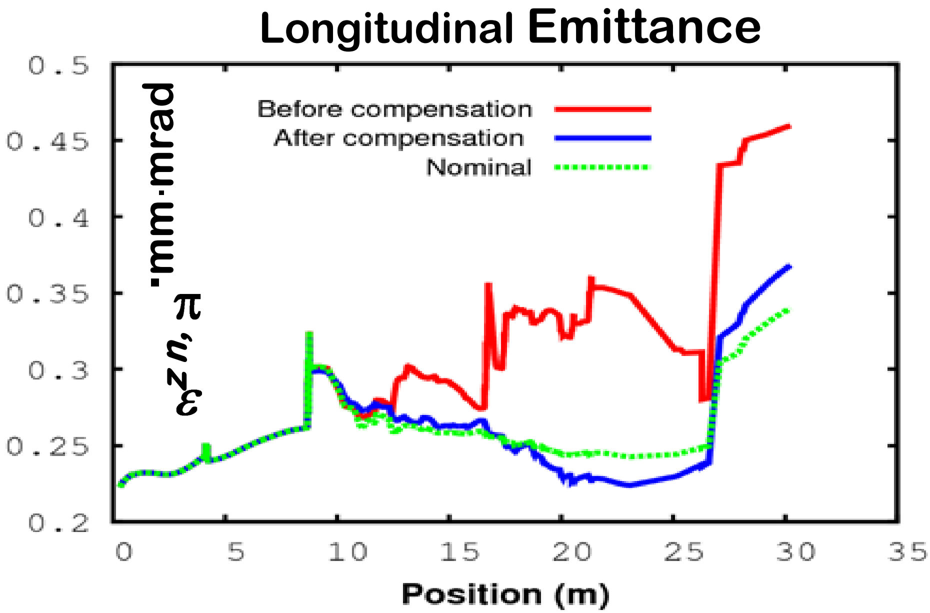


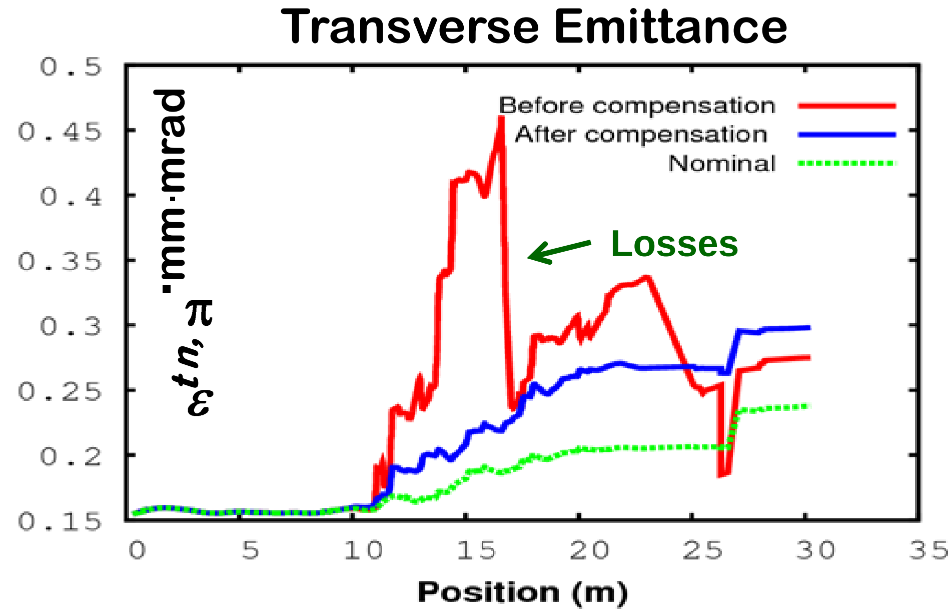
- 40% of the beam is lost (incl.15% between CM's)

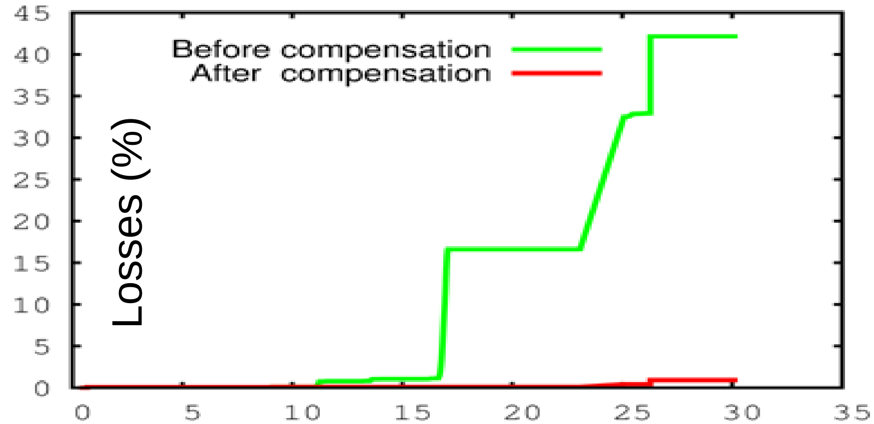
- ~0.5% additional losses(vs.nominal lattice) mostly at the end of beam-line, no losses in SC sections

Failure of 1st solenoid (continue): Beam Emittances and Losses

Project X







- Without compensation failure of 1st solenoid causes huge mismatch and ~40% beam losses
- Local compensation scheme allow to re-tune linac and reduce losses to a < 1% level.

Summary of failure analysis

Failed 1st HW cavity

(*Parameters at the end of PXIE Lattice)

	Baseline	After Failure	After local compensation
Energy (MeV)	23.52	23.24	23.25
ε_z ($\pi\cdot$ mm mrad)	0.326	0.639*	0.359
ε_t ($\pi\cdot$ mm mrad)	0.234	0.258*	0.240

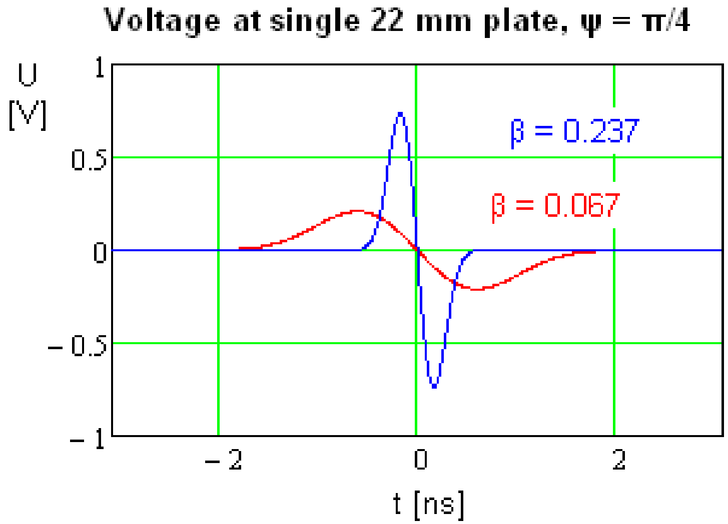
- *Failure of 1st cavity in HWR section is locally compensated.*
- *No additional losses are obtained after compensation.*

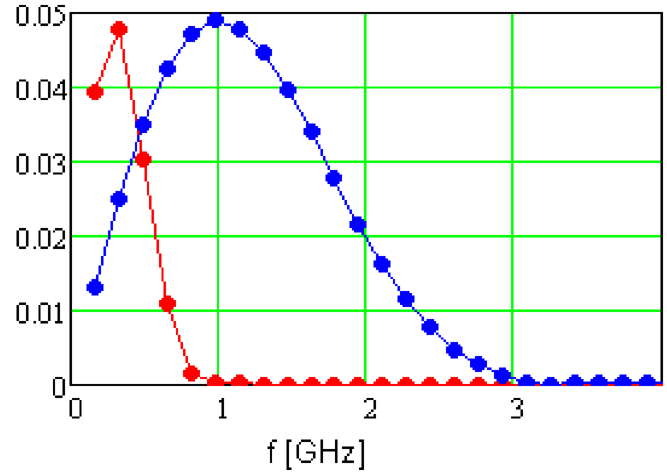
Failed 1st solenoid

	Baseline	After Failure	After local compensation
Energy (MeV)	23.52	23.52	23.61
ε_z ($\pi\cdot$ mm mrad)	0.340	0.459*	0.368
ε_t ($\pi\cdot$ mm mrad)	0.238	0.275*	0.298

- *Failure of 1st solenoid in HWR section is locally compensated.*
- *There are some additional beam losses (0.5 %) even after local compensation*

BPMs

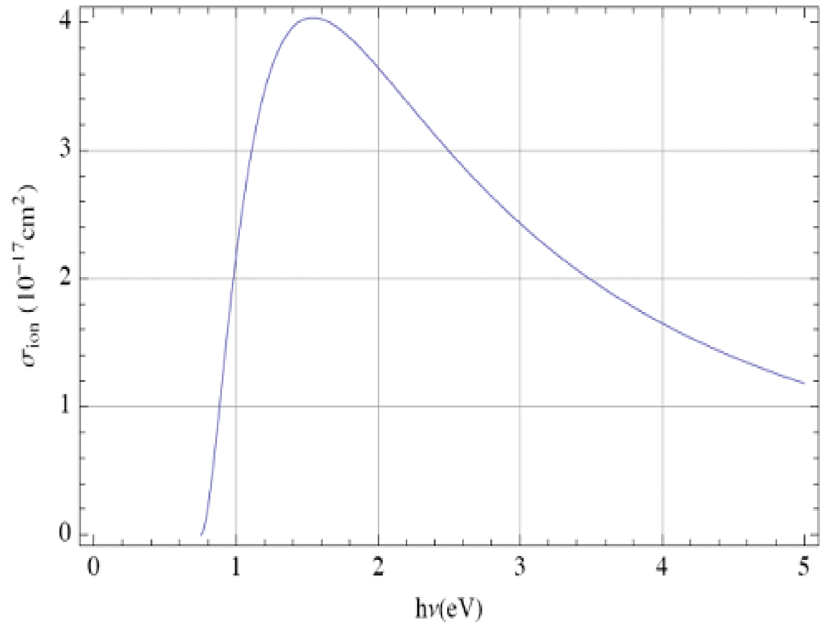




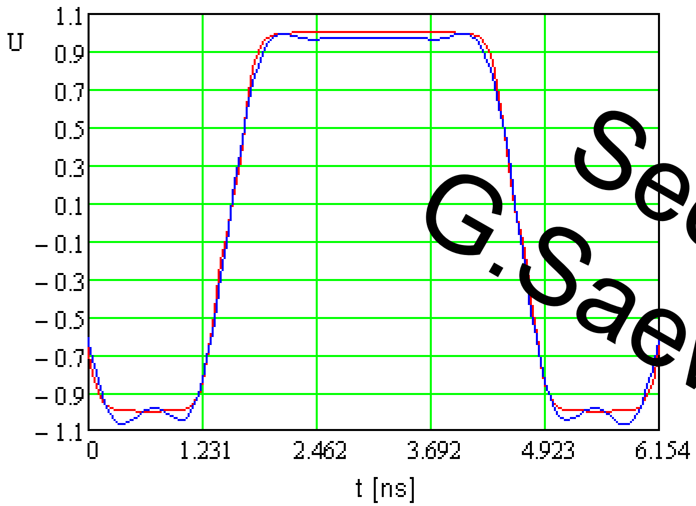
- Button type BPMs: four electrodes, three coordinates (x, y, s)
  - Better sensitivity and smaller size than strip-line BPMs
- Used for: beam position measurements & optics measurements with differential orbits
- Duration of the signal is determined by BPM radius and particle velocity
  - Bunch duration is shorter and can be neglected
- Bunch-by-bunch measurements are very attractive
  - Looks tough but doable
- Sensitivity will be determined by preamplifier noise. Shot noise is smaller.
- Averaging over micro-cycle (~1 μs) should deliver a few μm-scale sensitivity

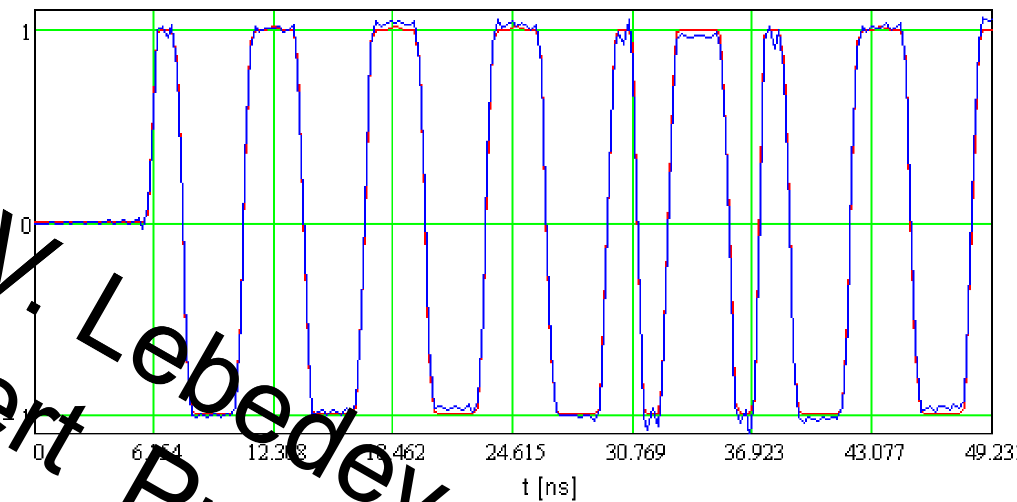
Laser Profile Monitor

- Plans to have 3 Laser Profile monitors
  - MEBT; Transition HWR-SSR1, Diagnostic section at the end.
- Measurements of all 3 beam profiles is possible
- At least 1 MEBT profile monitor will have an electron detection.
- 1 W laser strips ~3.5e-6 relative charge. Signal is large enough to measure change in current of H^- beam
  - Synchronous detection of resistive wall monitor signal or sum BPM signal
  - Measurement time ~ 10 s per degree of freedom in CW regime



Bunch-by-bunch Chopper Kicker



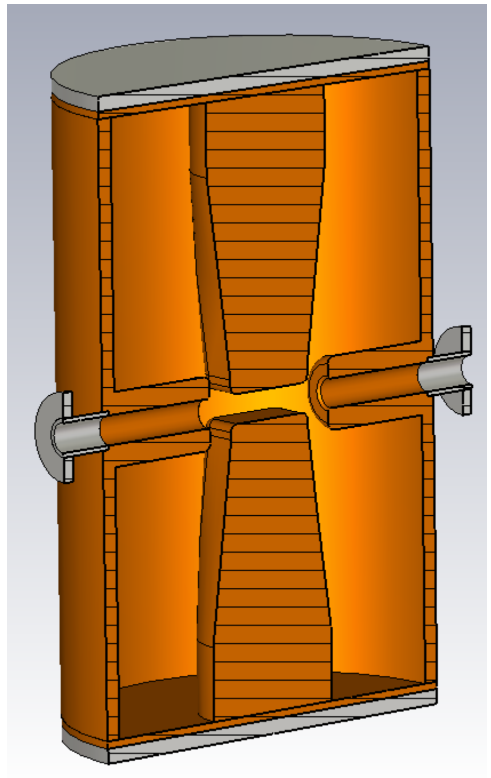


See V. Lebedev and G.Saewert Presentation

- Two variants of chopper kicker are being developed: 50 & 200 Ω wave impedance
  - Each includes kicker and high voltage/power pulser/amplifier
- Experience accumulated over last 2 years assures that a full scale demonstration for 50 Ω kicker is realistic by the FY end
  - Satisfies FRS
    - Amplifier 1 kW, ±300 V, 50 – 1000 MHz band – available at the market
    - 2 W beam power can be lost at single plate (50 W at the kicker)
  - Success is based on pulse pre-distortion (will allow compensation of reflections and dispersion in kicker)
- 200 Ω kicker
  - Work on a 500 V pulser proceeds

RF Splitter

- Required effective kick voltage is 250 kV
- Deflection – 5.1 mrad
- Power – 6 kW



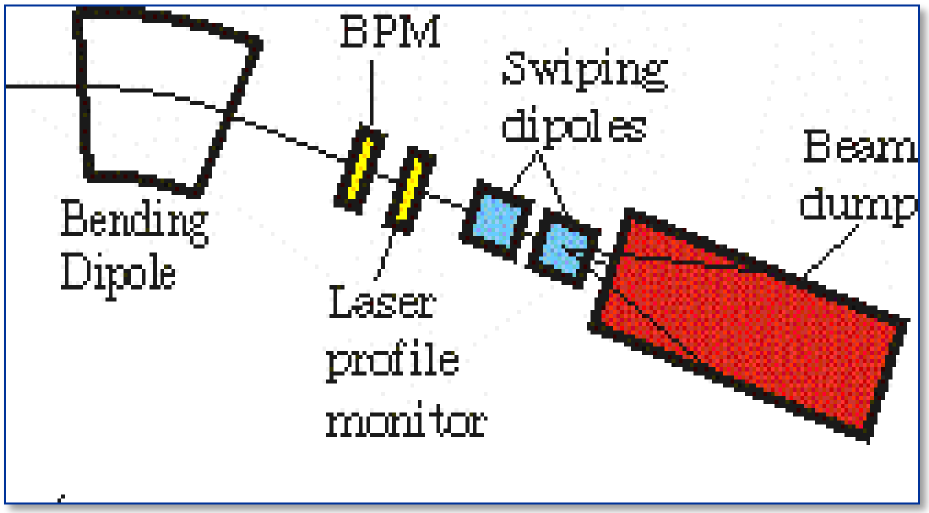
Preliminary design (G.Romanov)

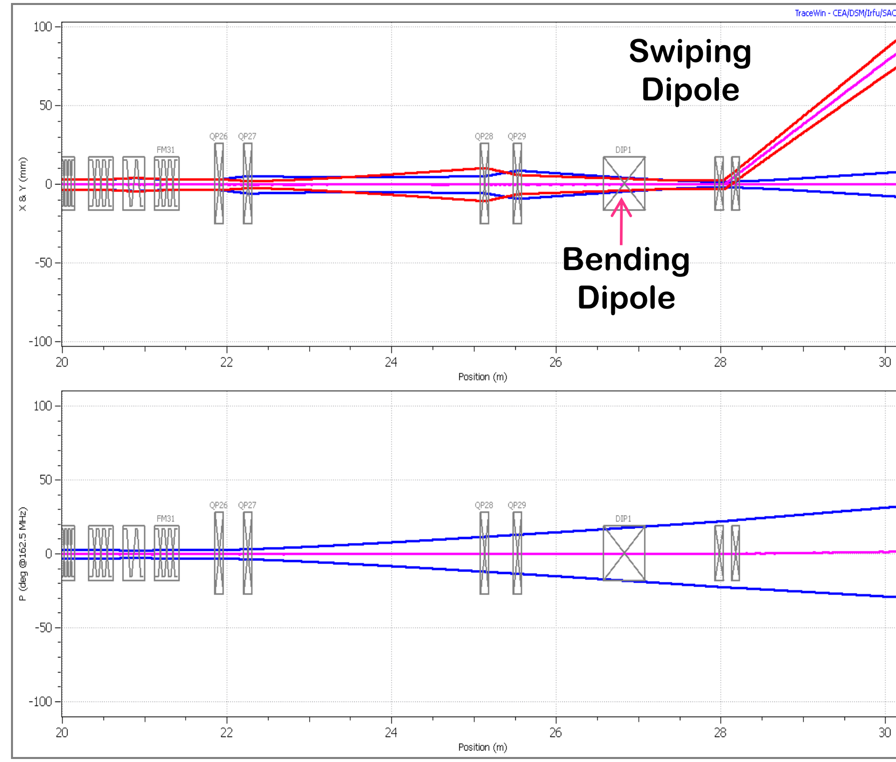
- Inner radius 130 mm
- Gap 20 mm
- Plate side 65 mm
- Drift tube to drift tube 100 mm
- Radius of stem base 50 mm

Cavity parameters

Half wave coaxial cavity	
Frequency, MHz	243.75
E_surf_max, MV/m	13.75
Power losses (average), kW	6.0
Q	13420
Kick voltage,	250 kV
Proton β	0.22

Beam Diagnostics and Dump

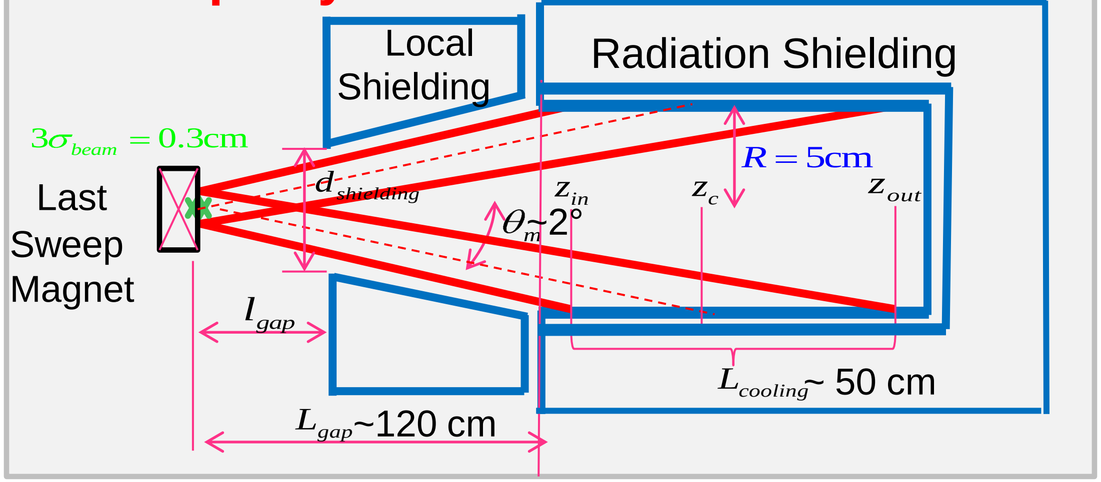




- Power rating – 50 kW at beam energy 25 MeV
- Local radiation shielding of the beam dump and the bending dipole
- Start conceptual design

Beam Dump: Sketches of the Dump + Radiation Shielding

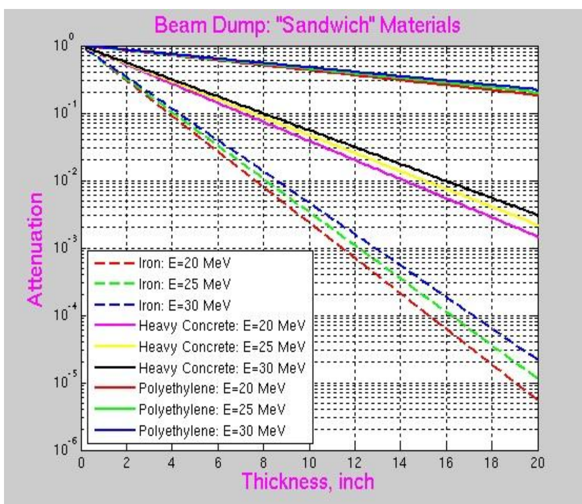
Dump Layout



Attenuation as a function of thickness *d* of material and energy *E (GeV)* of the beam:

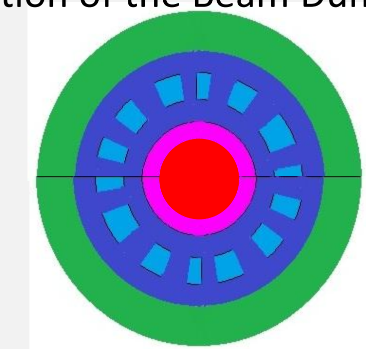
$$A(d,E) = 10^{-\frac{d}{\lambda}\frac{1}{1-0.8\exp(-5E)}};$$

Material:	ρ, $\frac{g}{cm^3}$	λ, cm
Iron	7.84	35
Heavy concrete	3.6	65
Concrete	2.35	100
Polyethylene	0.95	250
Polyethylene filler	0.8	290

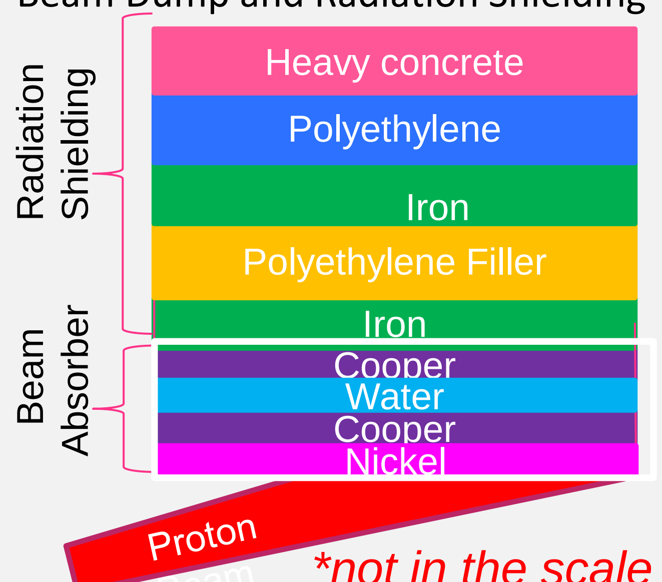


Cross Section of the Beam Dump

Y.Eidelman



Front Section of the Beam Dump and Radiation Shielding



Conclusions

- We have good understanding of the PXIE concept
- Optics was designed and studied (first order approximation)
  - Ongoing program for LEBT and RFQ beam physics studies
- Design work of HWR and SSR1 cryomodules is proceeding well
  - Expect to have conceptual design by the end of this year
    - ANL - HWR
    - FNAL – SSR1
- No obvious showstoppers