Major Requirements to PXIE Optics and Design

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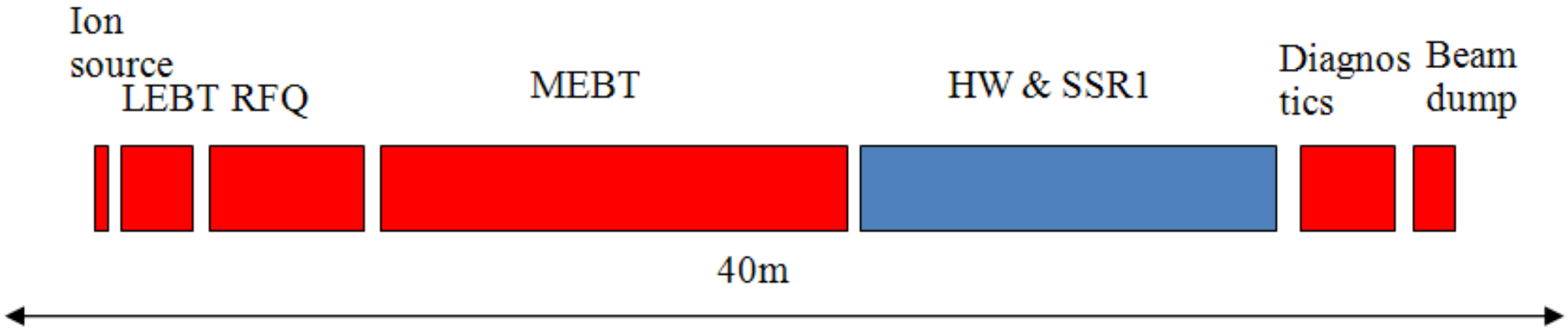
Project X Injector Experiment - PXIE

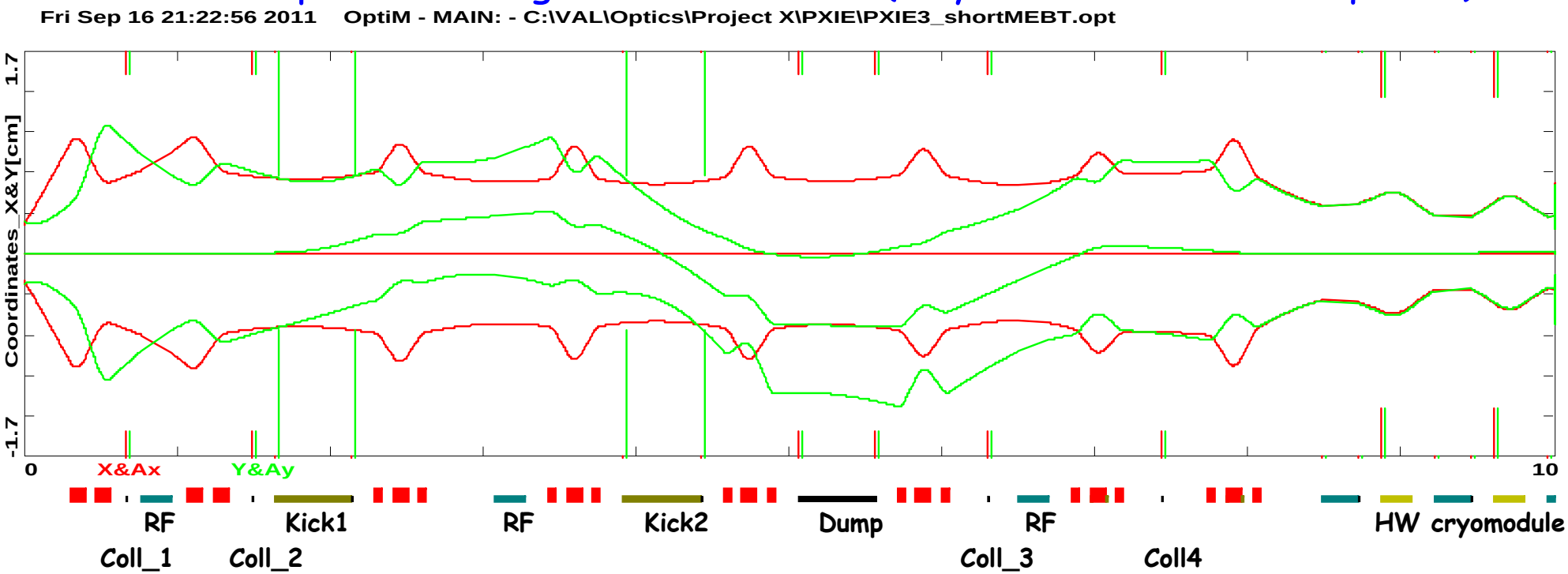
- PXIE should deliver 1 mA CW beam to ~30 MeV energy
- PXIE includes



- Goals
  - Validate the Project X concept and eliminate technical risks
    - 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
    - CW RFQ
  - Obtain experience in design and operation of SC proton linac
- Can be financed from existing budgets (Project X, SRF, GAD)
- Does not imply that the development of other high risk Project X items should be slowed down (SSR2, 2 types of elliptic cavities, …)

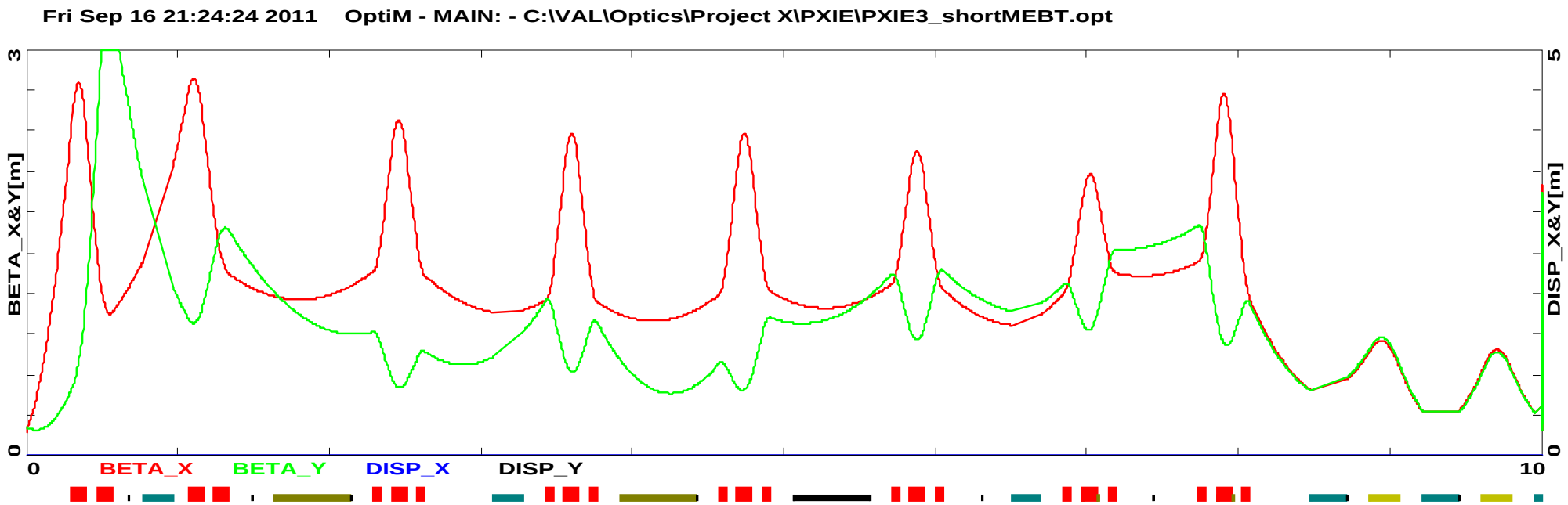
MEBT and its Limitations

- Number of kickers for chopper is reduced from 4 to 2
  - Bunch by-bunch current regulation is not required ⇒ Reduced MEBT length
- Additional space for diagnostics is added (may be more will be required)



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

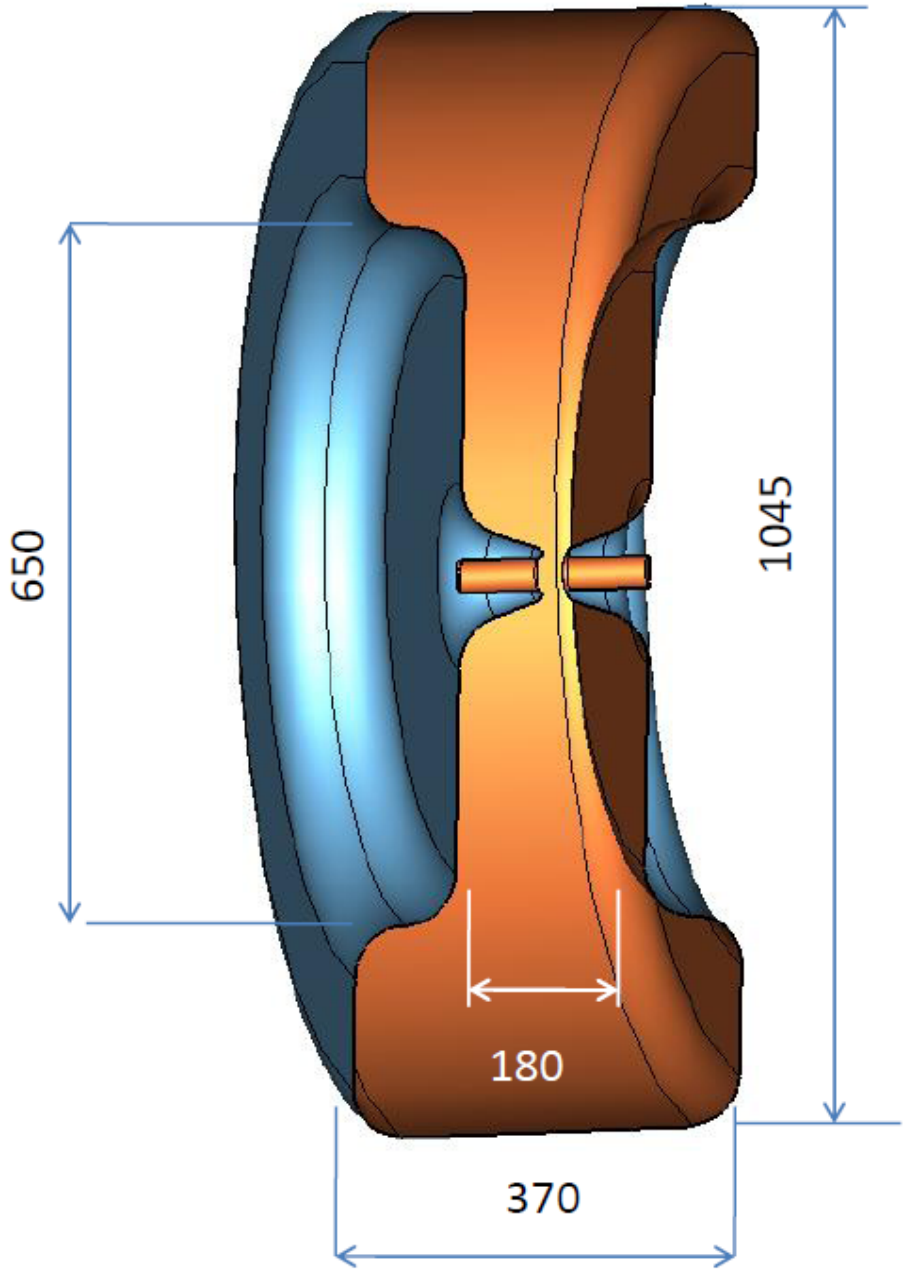
- Distance between cavities is increased ⇒ 162.5 MHz RF
  - Voltages are up to ~100 kV (95, 10, 50)
  - 4σ beam envelopes are within ~ ±70 deg
  - Distance to HW cavities should not be large; presently L = 2 m (center-to-center)
- Use of 325 MHz is questionable if space between cavities is not reduced



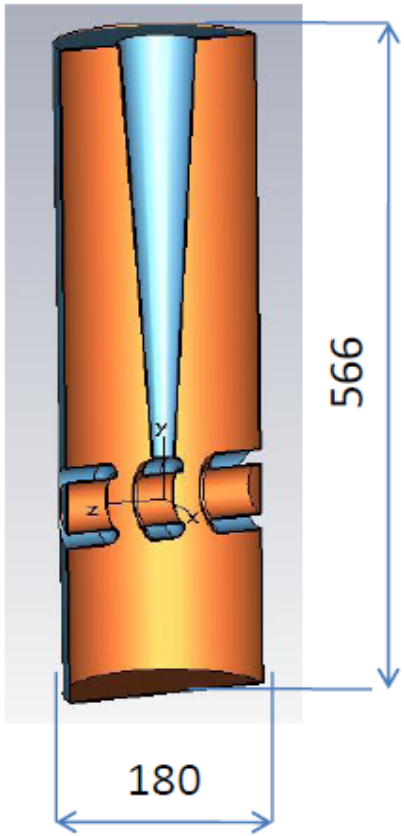
Beta-functions in MEBT

- Cavities introduce significant defocusing for transverse motion
  $\Rightarrow$ Small transverse beta-functions in the cavities
- Final layout is expected to be ready by mid October

MEBT RF



Pillbox vs QWR, 162.5 MHz



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MEBT RF (continue)

Re-buncher cavity parameters

Cavity	Pillbox	QWR
Frequency, MHz	162.52	162.5
Q factor	27250	8668
Aperture radius, mm	15	15
Gap, mm	25	2x25
Particle energy, MeV	2.5	2.1
Effect. shunt impedance, Ohm	2.5e6	3.48e6
Max. energy gain, kV	100	100
Power , kW	3.9	2.88
Max. electric surface field, MV/m	6.9	3.28

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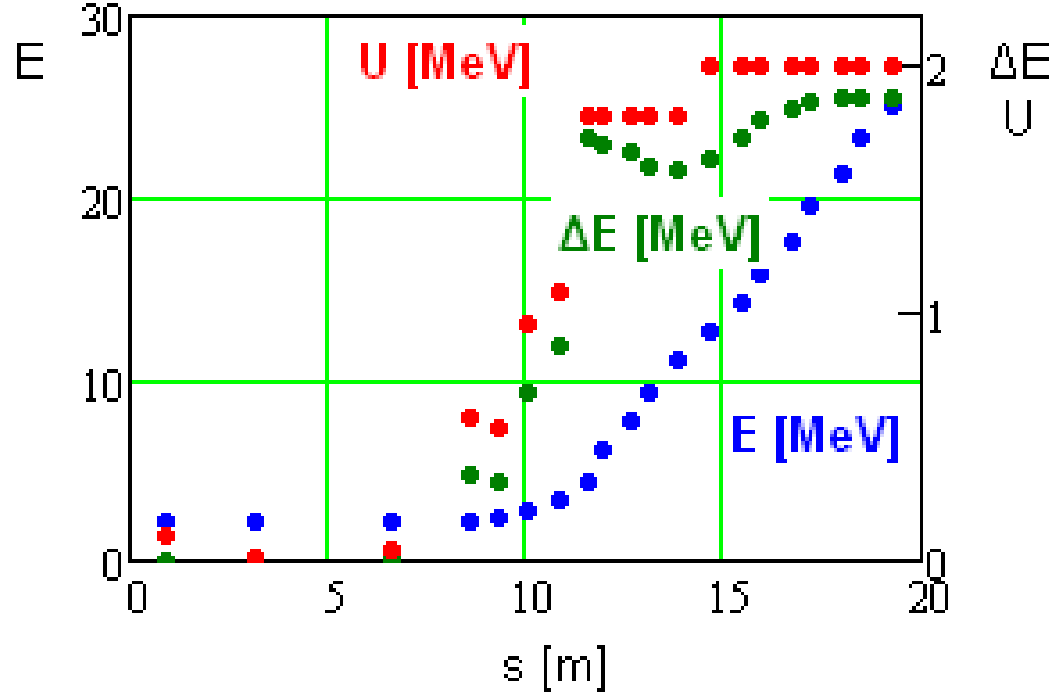
- QWR is preferred
  - Smaller sizes, smaller power
  - ~3 kW power looks OK

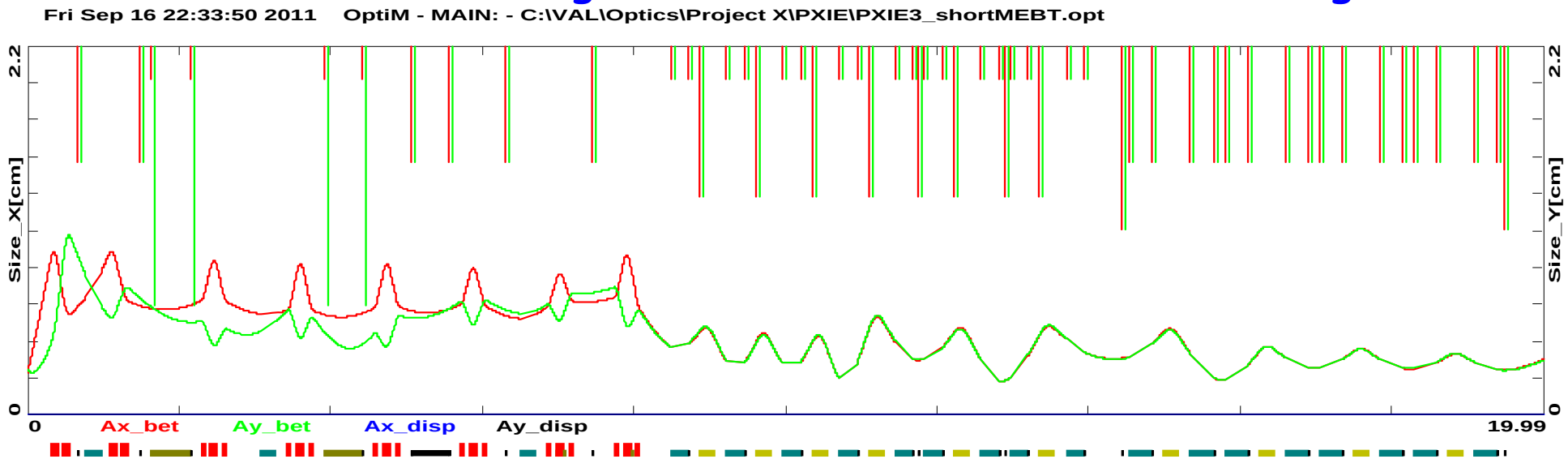
Acceleration in PXIE



- SC cavities parameters
  - HW: 1.8 MV, ~60 mT, aperture 40 mm, 9 cavities
  - SSR1: 2 MV, ~60 mT, aperture 30 mm, 8 cavities
- That yields: MEBT – 2.1 MeV, HW – 11 MeV,
- SSR1 – 27 MeV
- Accelerating gradients in SSR1 are ~35% higher than in the RDR
  - Experiment should point out which gradients have to be used for reliable operation
- HW (half-wave) cavities have larger aperture and twice higher energy gain per cavity
  - Improved beam physics performance
    - Potentially, smaller beam loss at 2 K due to larger aperture
  - Smaller length, price and number of cavities
  - Would not be possible without ANL help

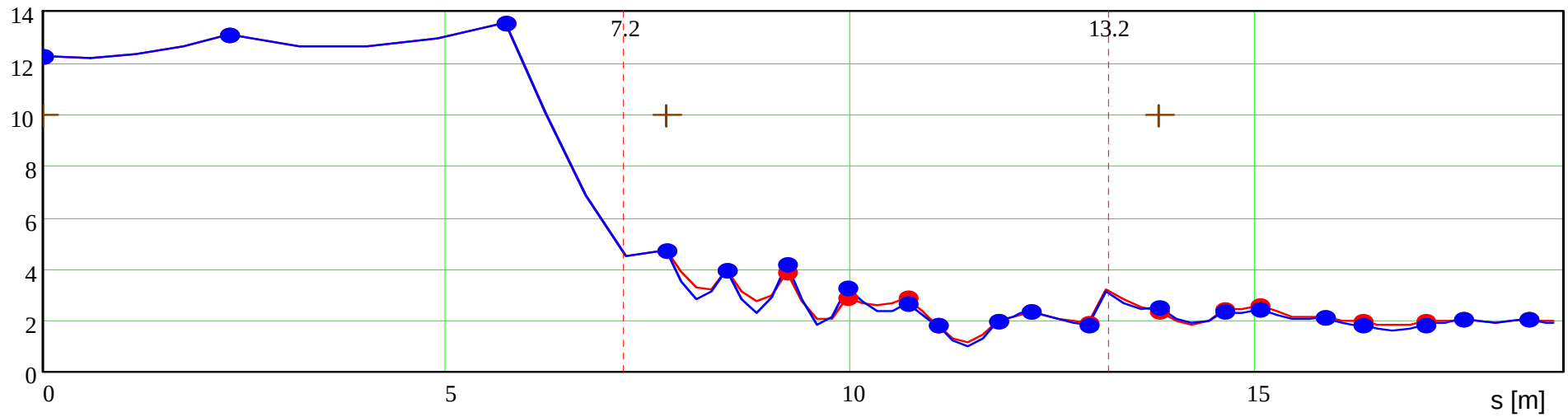
Beam Envelopes through PXIE

- Cavities introduce strong correction to transverse focusing

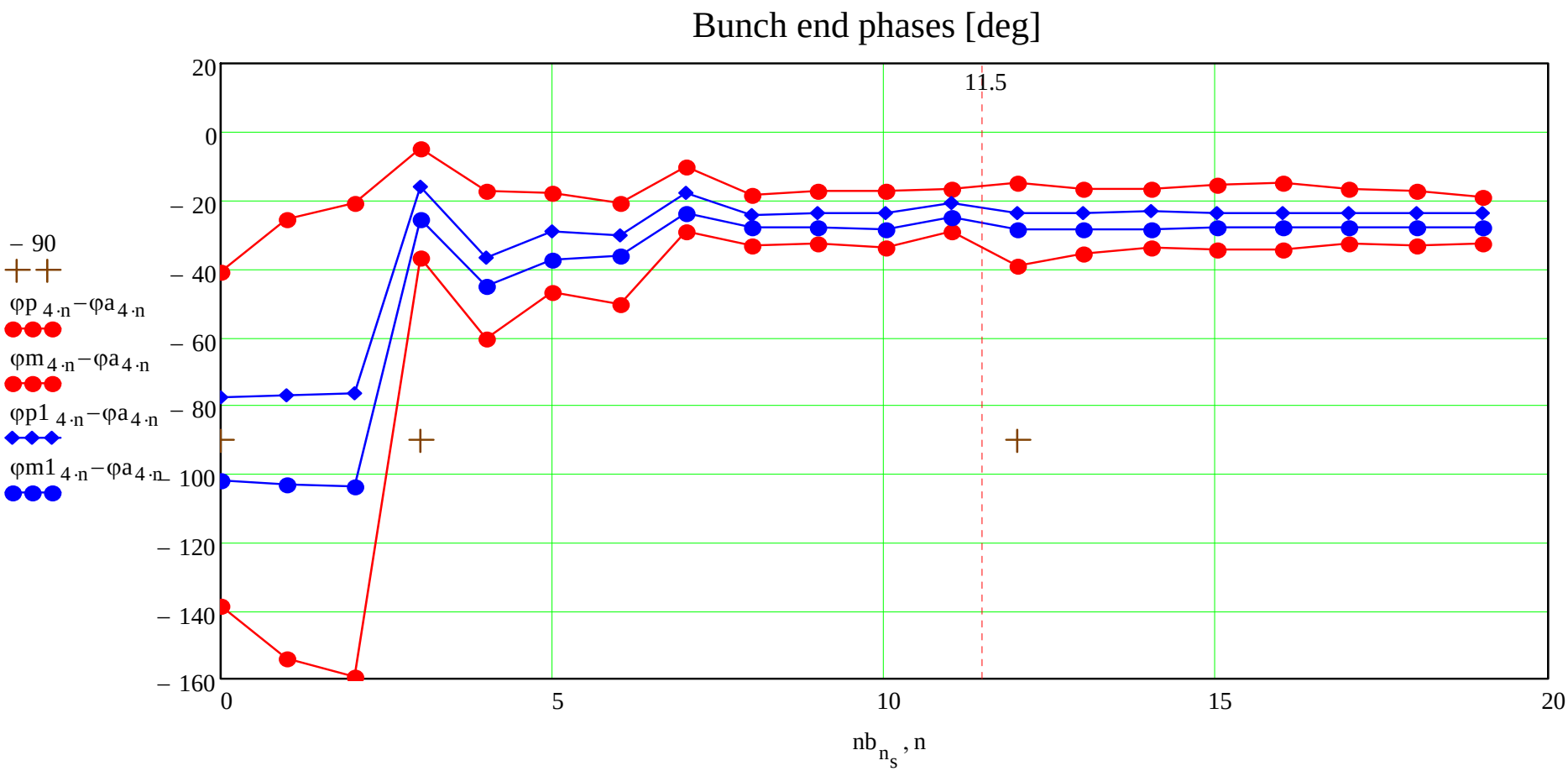


3σ transverse beam envelopes (zero beam current)

Bunch end phases [deg] for 1 sigma initial ellipse

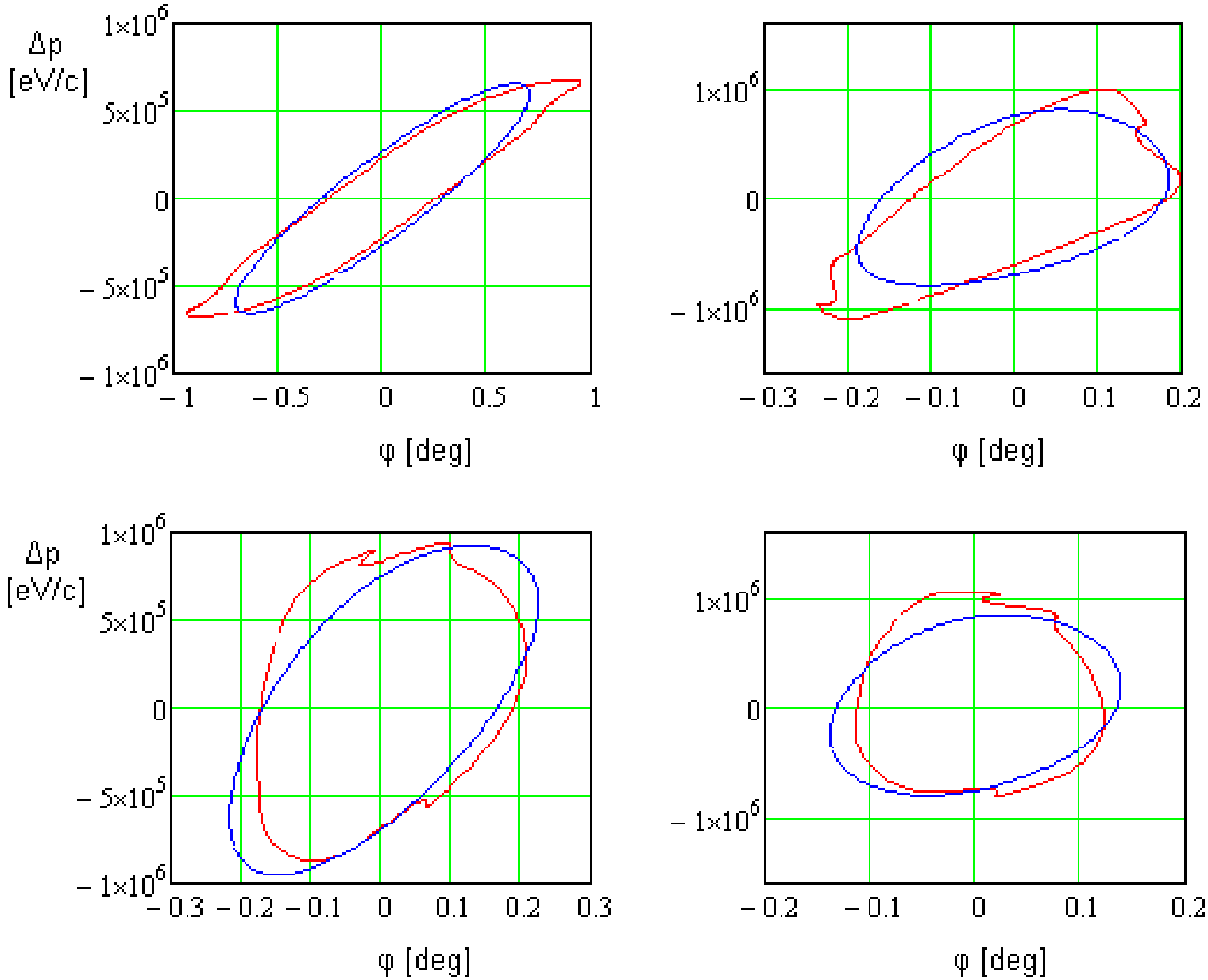


1σ bunch length (zero beam current)

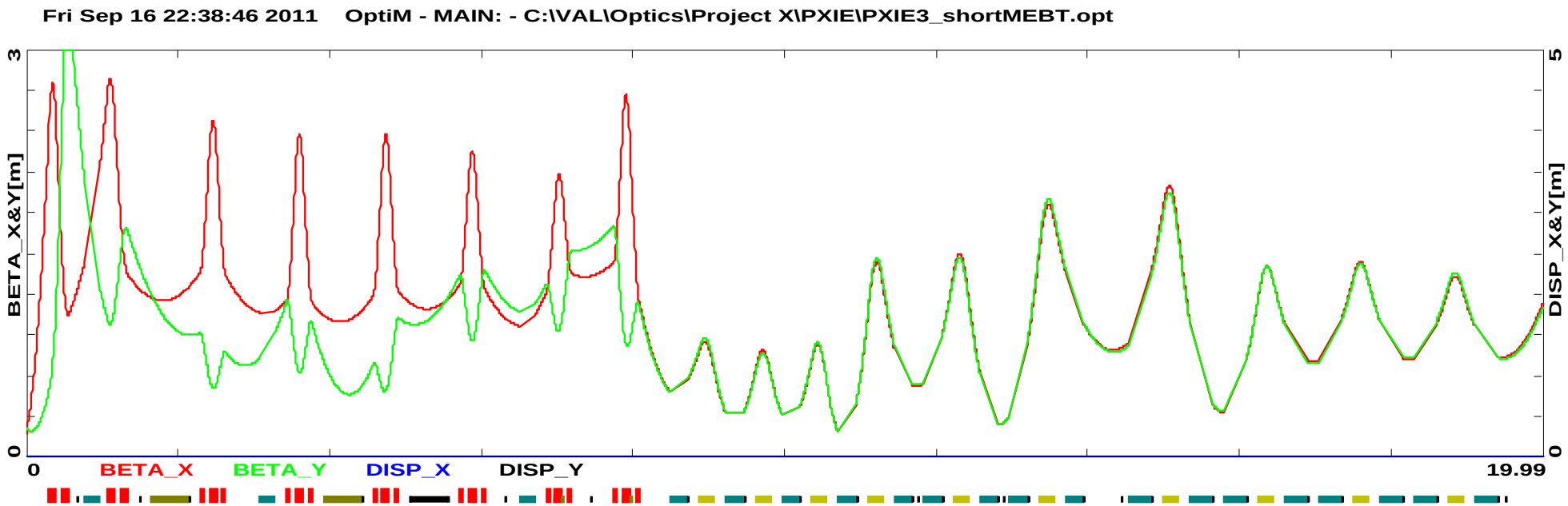


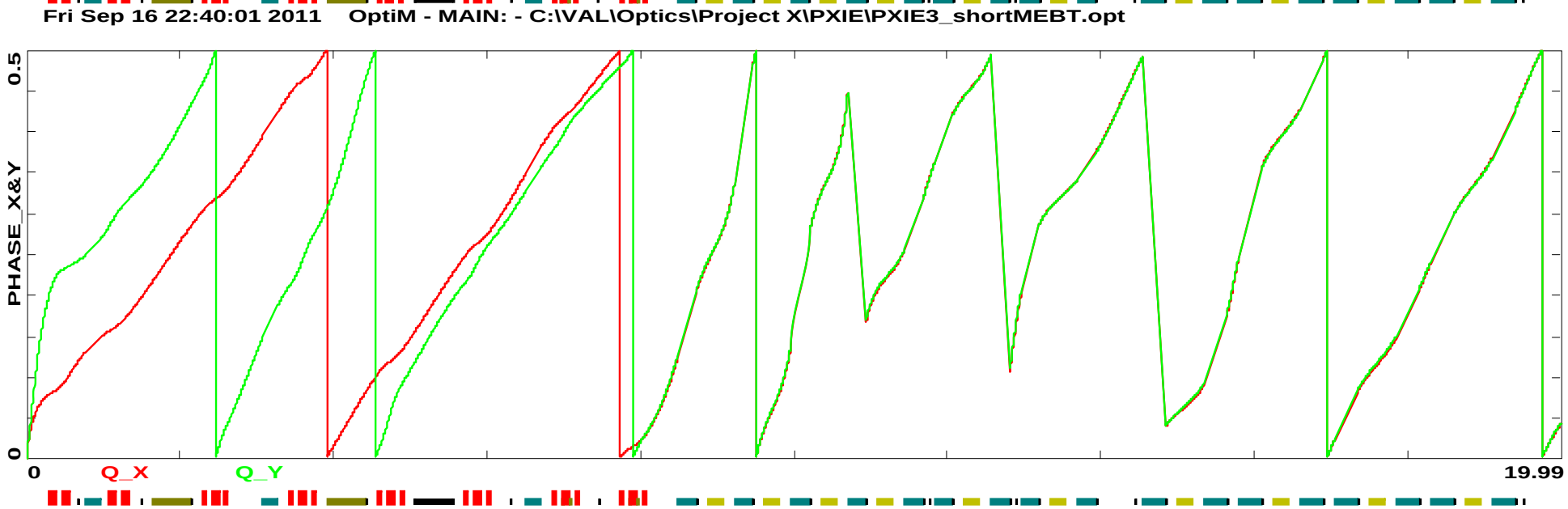
Bunch end phases (relative to the on-crest acceleration) for 1σ and 4σ (I_{beam} = 0)

- Careful adjustment of cavity phases and amplitudes minimizes non-linear distortions of the longitudinal phase space



Longitudinal phase space transformation for 1σ (blue) and 4σ (red) ellipses starting at the RFQ exit. 4σ ellipse is reduced by factor 4: top-left – after MEBT, top-right – after cavity 4 in HW cryo-module, bottom-left - after HW cryo-module, bottom-right - after SSR1 cryo-module.





Beta-functions and betatron phase advances along PXIE

Structure of Half-wave cryo-module

- Final details should be settled by Collaboration meeting (Oct. end)
- Present vision
  - 9 cavities, 6 solenoids (C S C S C S C S C C S C C S C)
  - X & Y & S BPM near each solenoid
  - Each plane corrector is located every second solenoid (x y x y ..)
  - Solenoid polarity is changed in each next solenoid (orbit correct.)

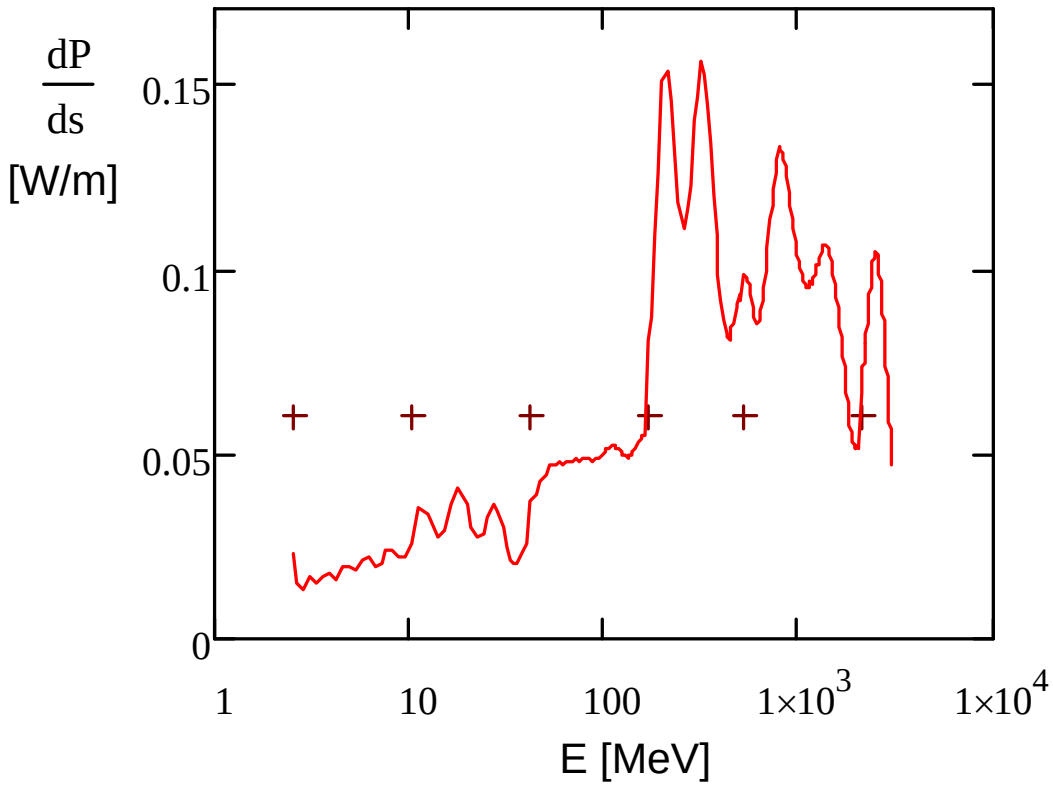
Structure of SSR1 cryo-module

- Final details is a subject of our work
- Present vision
  - 8 cavities, 4 solenoids (C S C C S C C S C C S C)
  - X & Y & S BPM near each solenoid
  - Each plane corrector is located every second solenoid (x y x y ..)
  - Solenoid polarity is changed in each next solenoid

HW-to-SSR1 interface

- HW-to-SSR1 transition goes through room temp. vacuum chamber
  - Good from engendering and repair points of view but complicates beam dynamics
  - Small space can be left for instrumentation

Beam Collimation in SC Cavities

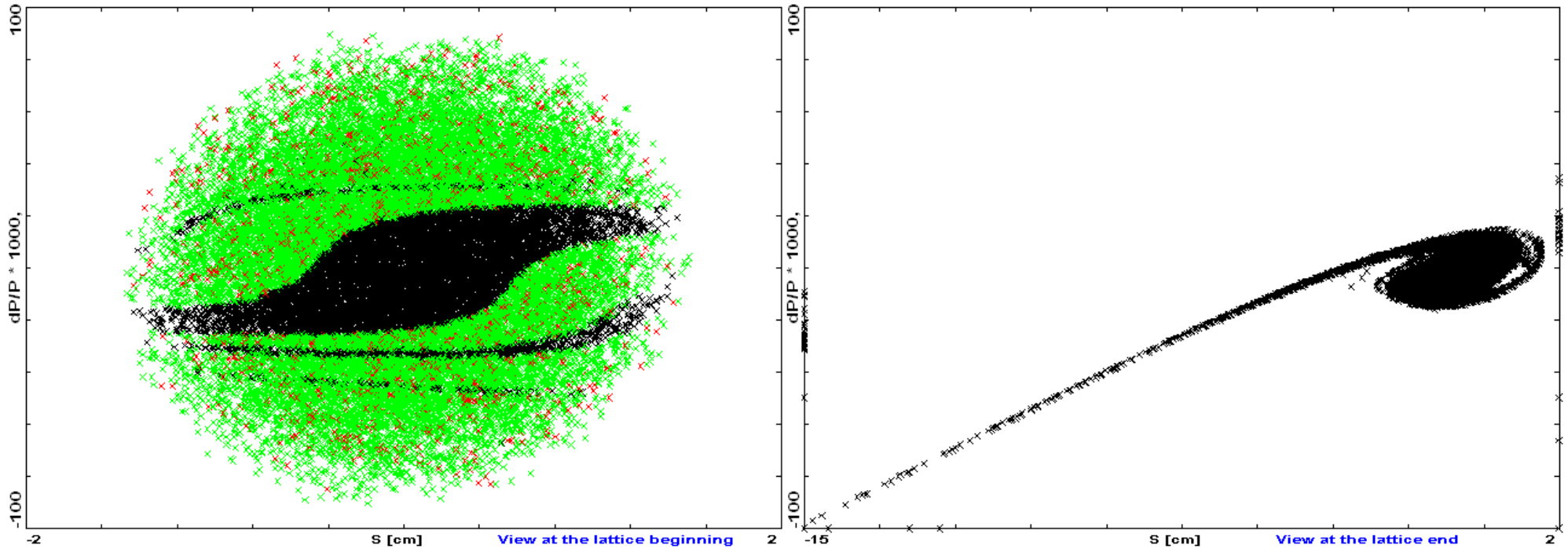


Intrabeam stripping estimate for Project X

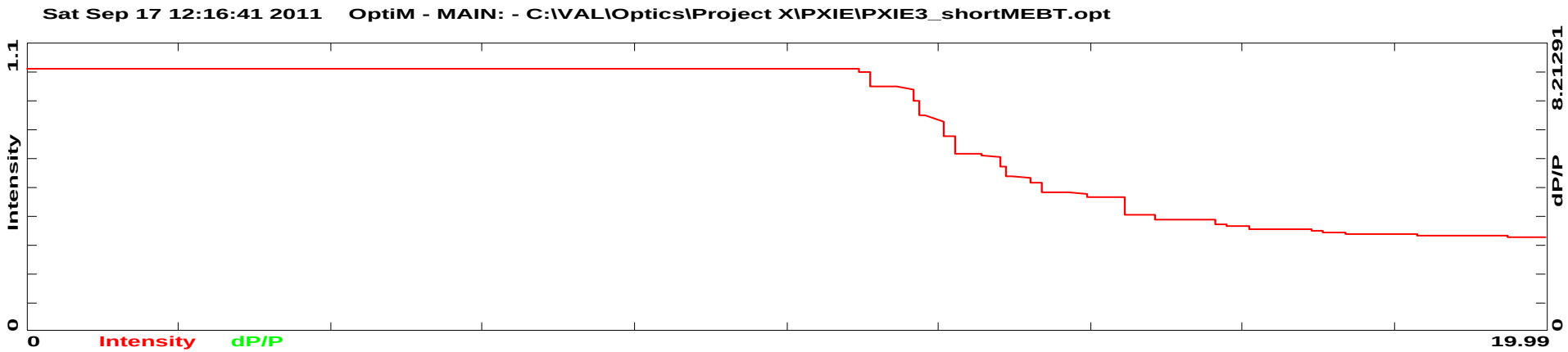
- Particle loss due to IB stripping is expected to be less than 0.05W/m
- Angular divergence is determined by β_{min}~40 cm
- Interception of 90% loss particles requires beam collimation with "two solenoids" period
- Taking into account overall small loss we can accept particle loss at 2 K

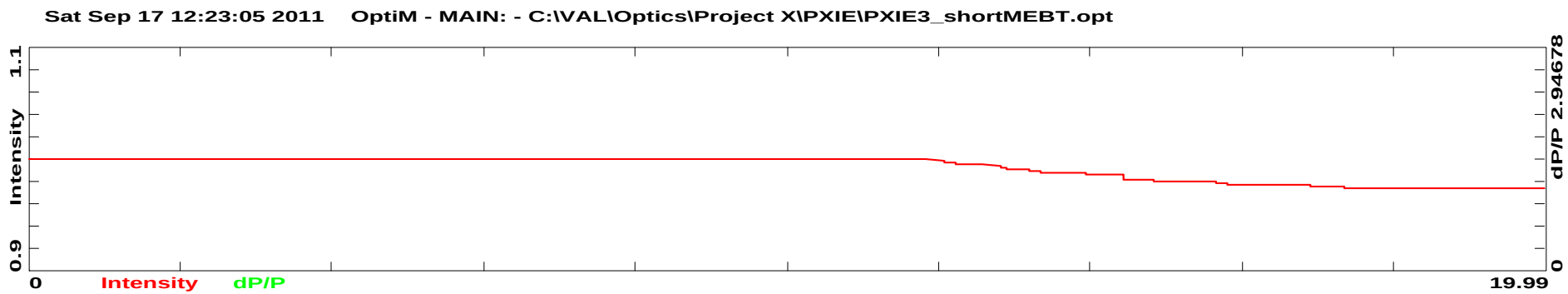
Beam Collimation in SC Cavities (continue)

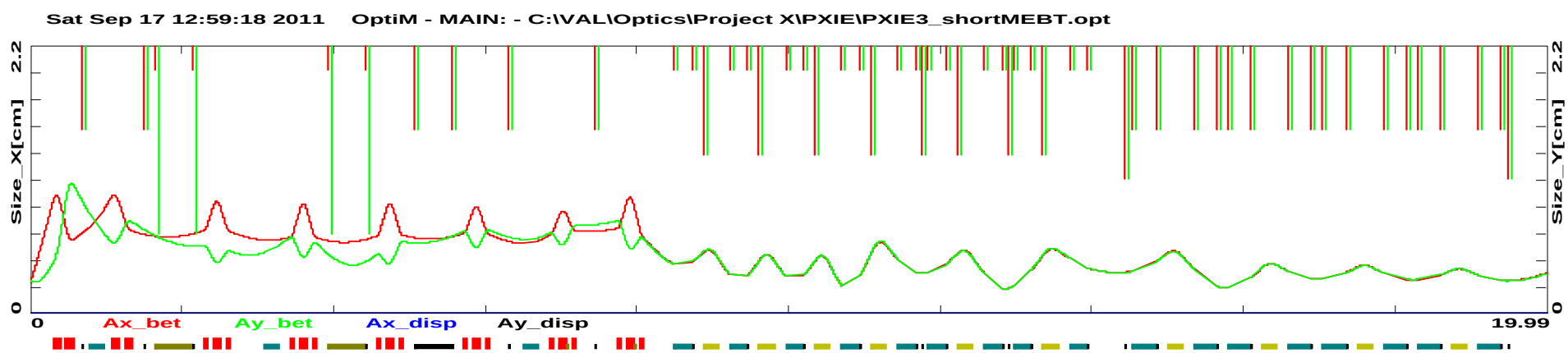
- RFQ tails can present larger loss than the IB stripping at the acc. beginning
- Most of losses happen in the second part of HW cryo-module
  - However energy lost in the SSR1 cryo-module is about the same
- Beam loss is happening so fast that a "reasonable" collimation cannot intercept its major part
- Looks like that instead of collimation in the SC cryomodules strict requirements to the RFQ tails look more practical



Longitudinal phase space: left – initial with 20σ boundary, right – final. Red and green crosses present particles to be lost in the course of acceleration.







Beam intensity reduction due to particle loss for beam consisting of tails only. Tails are presented by uniform distribution truncated at 20σ (top) and 5σ (middle); reference rms norm. long. emittance - 0.25 mm mrad. There is no particle loss if truncation is below 4.5σ. Bottom plot presents 3σ transverse beam envelopes for nominal long. emittance.

Adjustments to the PXIE optics

- Optics will be adjusted to satisfy all important engineering requirements
  - Interfaces for cryomodules
    - MEBT to HW
      - ⇒ required space?
    - HW to SSR1
      - ⇒ cold-warm-cold versus cold-cold
      - ⇒ required space between cryomodules
  - Space requirements for all elements (cavities, tuners, solenoids, correctors, BPMs, etc.)
- There is enough room and flexibility to compensate for complications related to the actual machine design

The plan

- To have PXIE operating by October 2016
- Location – attached to the CMTF building (Cryomodule Test Facility)
- Major FY'12 goals (not finalized yet)
  - Warm part
    - Test chopper kicker prototype
    - Finish RFQ design
    - Warm part design is half done
  - Half-wave resonators
    - Finish the design of prototype HW cryo-module.
    - All details of the interface to the MEBT and SSR1 are settled
  - SSR1
    - Design of one period of the cryomodule is complete
      - Cryomodule design should be finished by June 2013.
    - SSR1 lens design is complete (including all required exp. tests)
      - Decision on possible use of build solenoids is made
    - Prototype cavity (designed for CW operation) is ordered.
      - Decision on possible use of ordered cavities is made.
    - 325 MHz test coupler design is complete and the coupler is ordered