# PXIE Optics and Beam Physics

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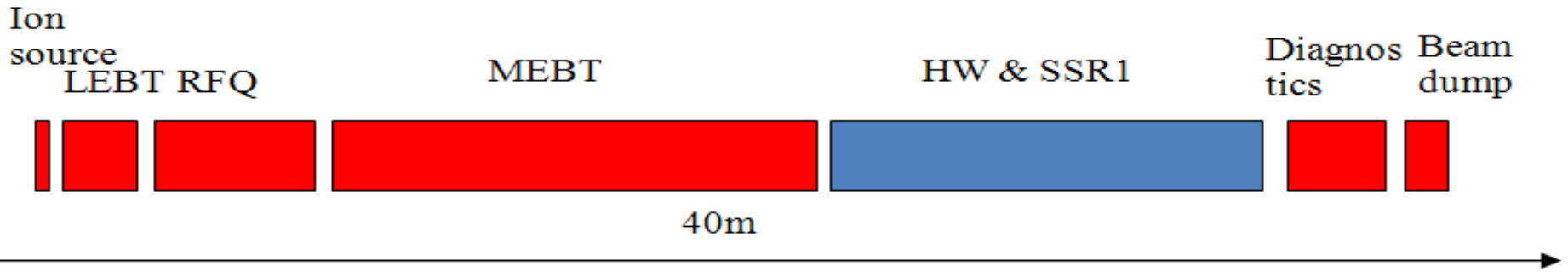
# Project X Injector Experiment - PXIE

- 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
  - Obtain experience in design and operation of SC proton linac
  - Study limitations on the beam extinction
    - Official goal ~$10^{-4}$
    - Is $10^{-9}$ – $10^{-11}$ achievable?
- It does not imply that the development of other high risk Project X items should be slowed down (SSR2, 2 types of elliptic cavities, …)
- PXIE should deliver 1 mA CW beam to ~30 MeV energy
- PXIE includes

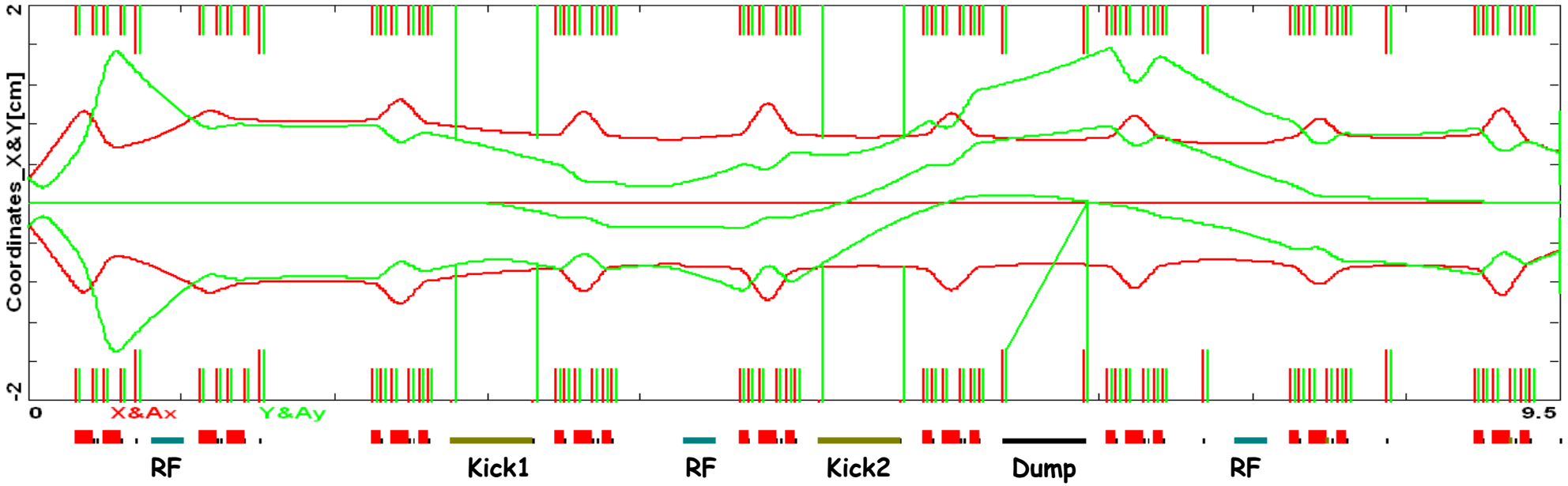


# LEBT, Ion Source and RFQ

- Ion source: H-, 5 mA - DC, 30 kV (10 mA max cost)
- LEBT
  - goals
    - Optics match of ion source to RFQ
    - Differential pumping
  - Features
    - LEBT chopper to reduce power at the beam dump of MEBT chopper
    - Space charge compensation
      - Should not be affected by LEBT chopper operation
        - $\Rightarrow$ trapping & clearing electrodes
    - Instrumentation : emittance and beam current measurements
- RFQ
  - 2.1 MeV, 5 mA (10 mA compatible)
    - 10 kW @ 5 mA at the MEBT beam dump (tough if L~40 cm)
  - 162.5 MHz
    - to make possible bunch-by-bunch chopping, 6.1 ns
- Bunch parameters @ RFQ exit
  - Norm. rms emittances < 0.25 mm for all planes ($\varepsilon_L$<0.78 eV·μs)
  - Bunch population $1.9 \cdot 10^8$ @ 5 mA

# MEBT

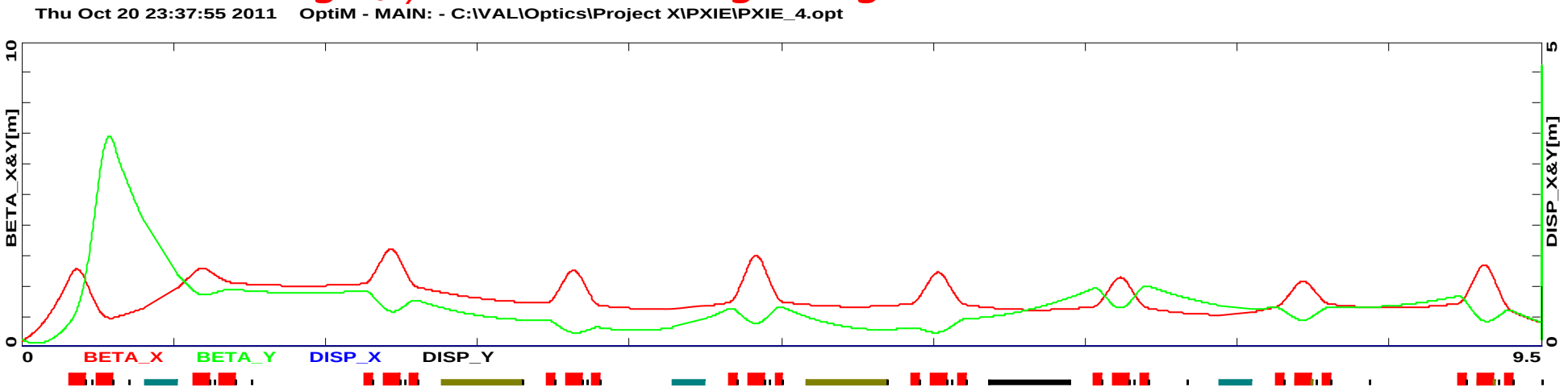
- PXIE goal is to test all critical technologies, i.e. it's not a copy of Project X frontend
  - Number of kickers for chopper is reduced from 4 to 2
    - Bunch by-bunch current regulation is not required
      ⇒ Reduced MEBT length
      - Bunch current regulation with scraping still can be tested (for all bunches)
  - Additional space for diagnostics (may be not required in Project X)
  - Project X MEBT
    - 2 additional kickers
      ⇒ 2 or 3 additional periods (2.3 – 3.45m)
- Triplet focusing & 180° phase advance between kickers minimize kicker aperture




*3σ beam envelopes ($\varepsilon_{rms\_n}$ = 0.25 mm mrad); kicker strength (E = 310 V/cm, 2*0.5 m)*

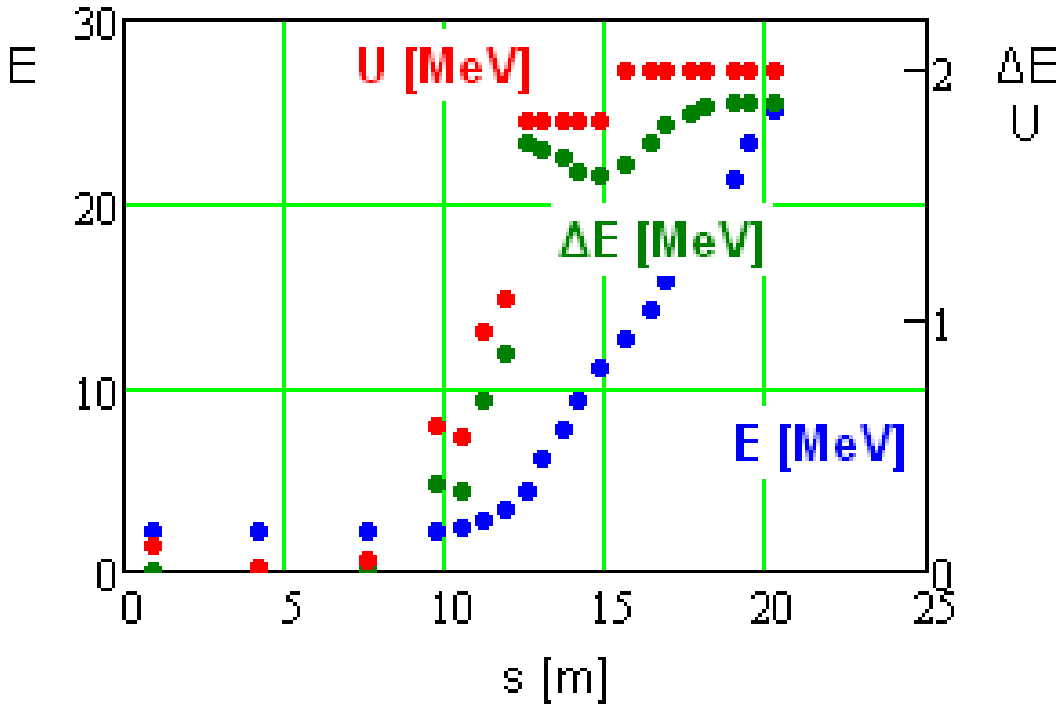
- Beam dump takes "entire period" (80 cm)
  - Prevents spattered material from reaching kicker and cavity
  - Differential pumping to get good vacuum in RF cavities
- Three 162.5 MHz RF cavities
  - Voltages are up to ~100 kV (95, 10, 50)
  - 4$\sigma$ beam envelopes are within ~ ±70 deg
  - Distance to HW cavities should not be too large
    - presently, L = 2.2 m (center-to-center)
- Cavities introduce significant defocusing for transverse motion

  $\Rightarrow$ Small transverse beta-functions in the cavities
- It is desirable to reduce $\alpha$-functions at RFQ end to $|\alpha_{x,y}| < 0.6$
  - Too large $\beta_y$ at the line beginning



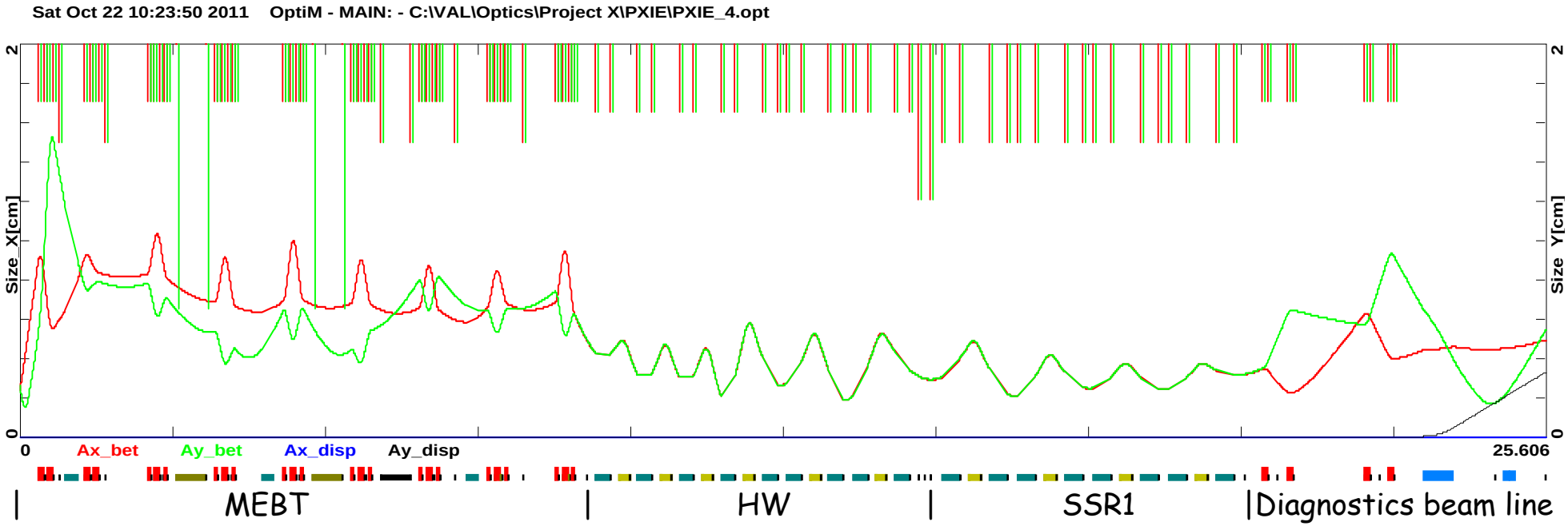

*Beta-functions in MEBT*

# Acceleration in PXIE

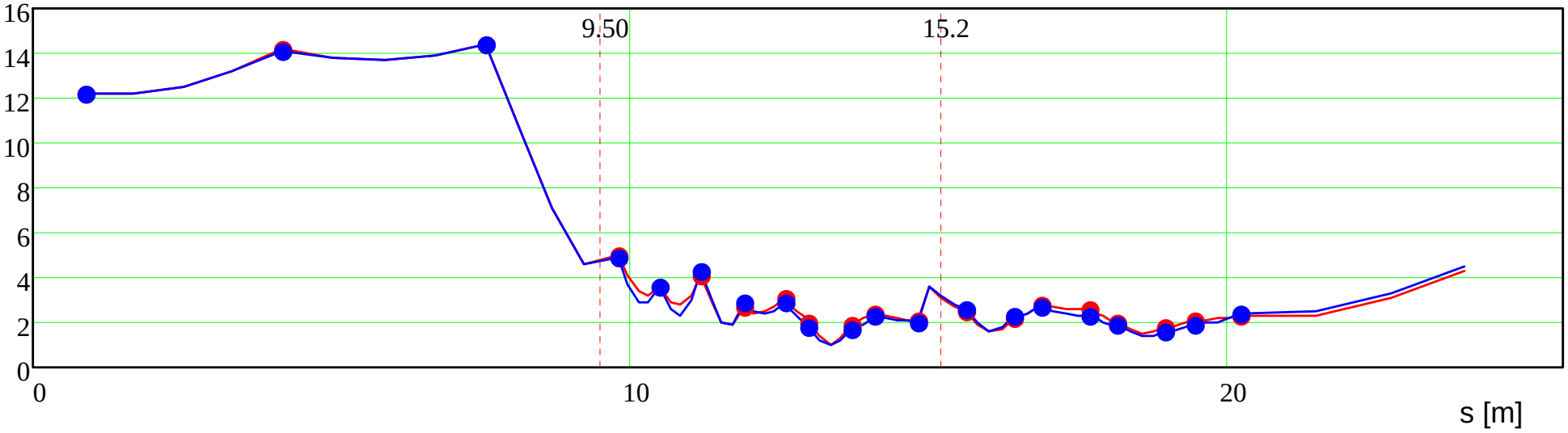



- SC cavities parameters
  - HW: 1.8 MV, ~60 mT, aperture 40 mm, 9 cavities
  - SSR1: 2 MV, ~60 mT, aperture 30 mm, 8 cavities
- That yields: MEBT – 2.1 MeV, HW – 11 MeV,
- SSR1 – 27 MeV
- Accelerating gradients in SSR1 are ~35% higher than in the RDR
  - Experiment should point out which gradients have to be used for reliable operation
- HW (half-wave) cavities have twice higher energy gain per cavity than SSR0
  - Improved beam physics performance
    - Reduced beam defocusing due to lower frequency
  - Smaller length, price and number of cavities
  - Would not be possible without ANL help

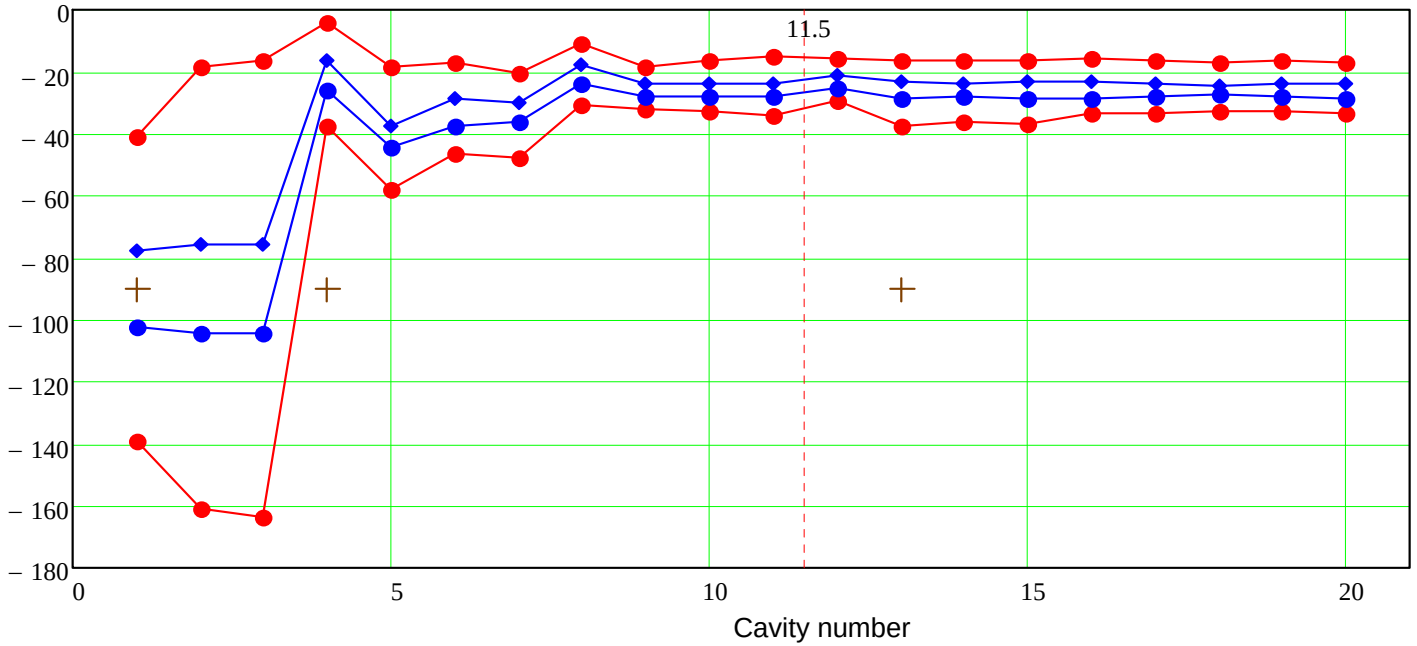
# Beam Envelopes in PXIE




*3σ transverse beam envelopes (zero beam current)*

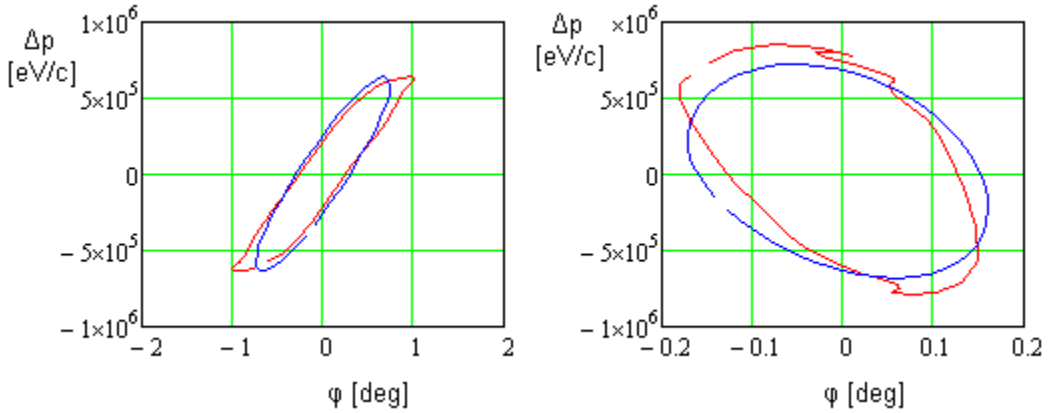



*1σ bunch length in deg. of nearby RF cavities (zero beam current)*



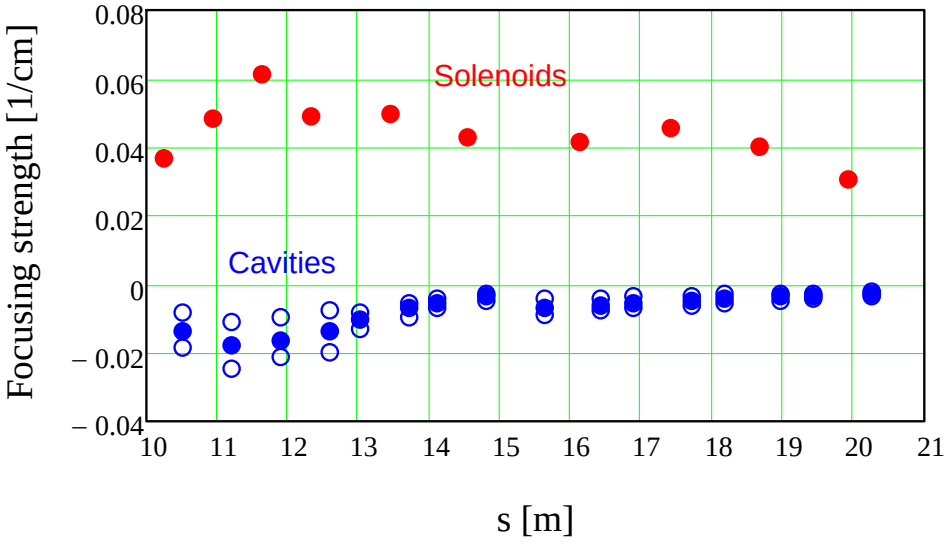

*Bunch end phases (relative to the on-crest acceleration) for 1σ and 4σ ($I_{beam}$ = 0)*

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

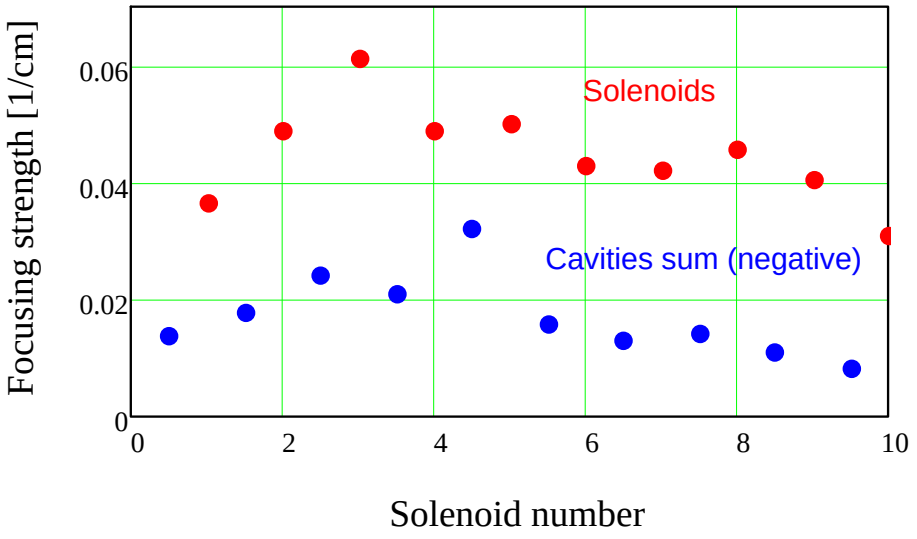



*Longitudinal phase space for 1σ (blue) and 4σ (red, reduced in 4 times) ellipses: left – after MEBT, right - after SSR1 cryo-module.*

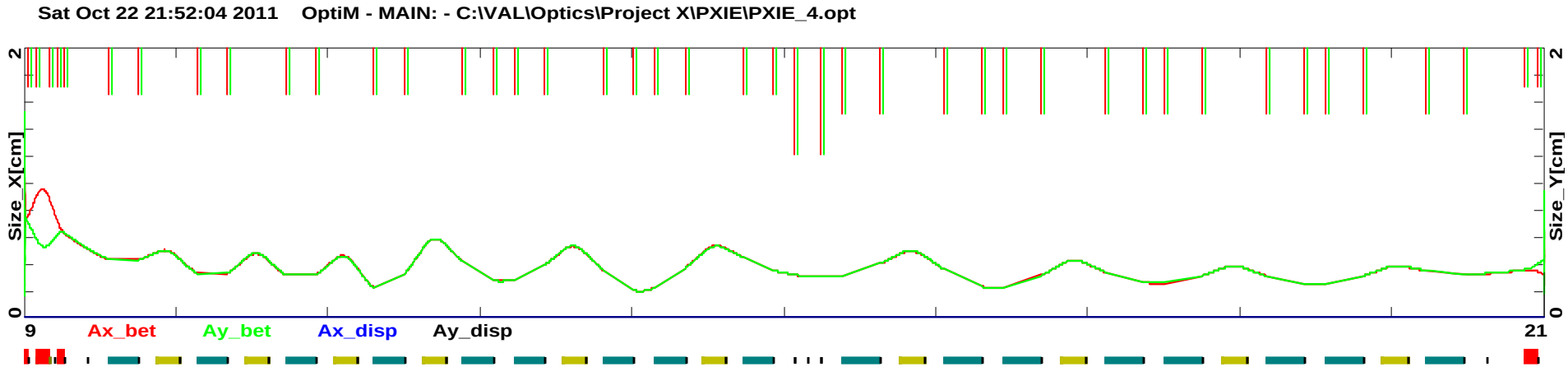
- Cavities introduce strong transverse defocusing
  - Mitigation: first 4 cavities go as single cavities; then double cavities follow
- Focusing depends on particle longitudinal position




*Focusing of solenoids and cavities (@ bunch center & ±4σ)*



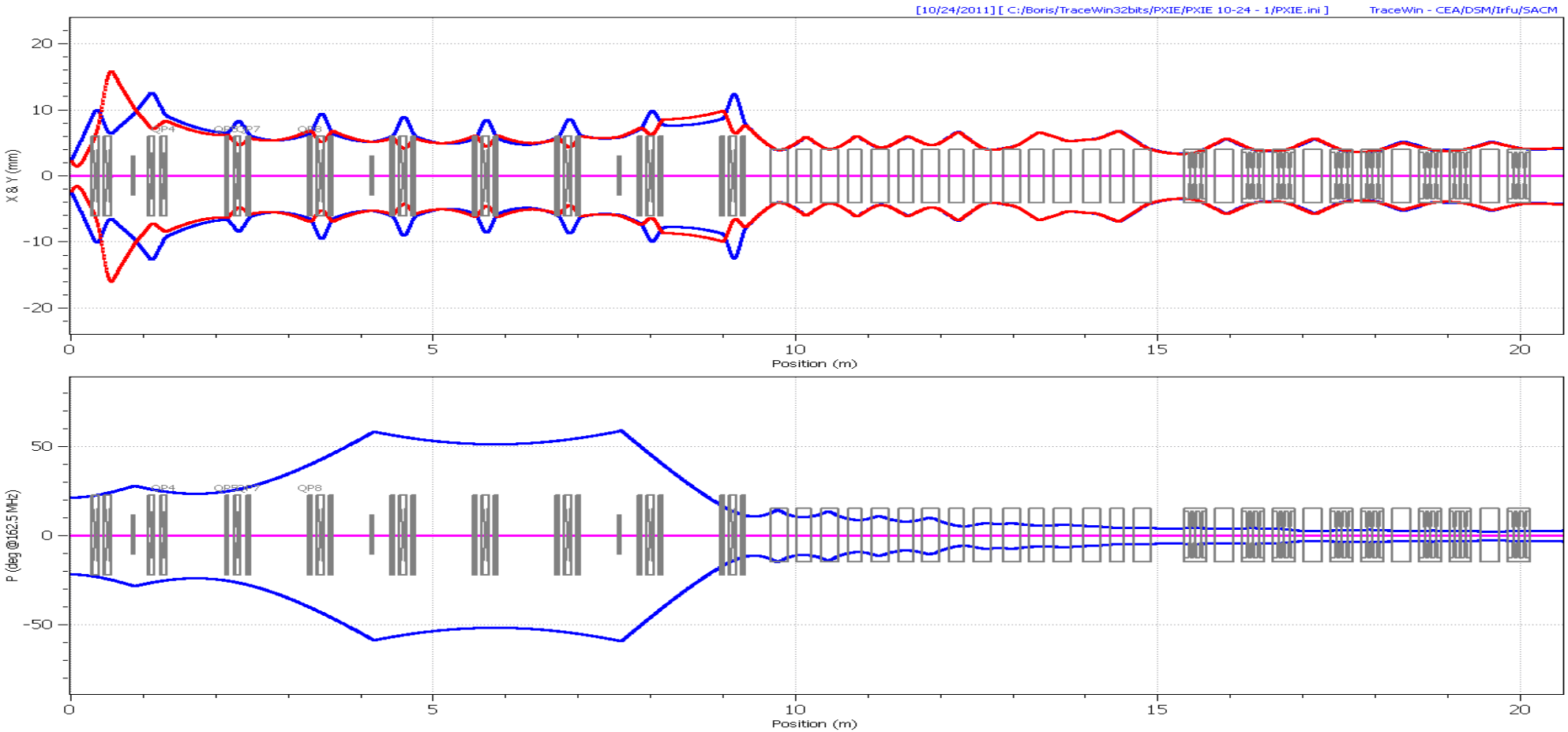

*Comparing of focusing for solenoids and cavities between them*



# Structure of Half-wave and SSR 1 cryo-modules

- X & Y & S BPM near each solenoid
- Each plane corrector is located in every second
- Solenoid polarity is changed in each next solenoid
- Each cryo-module starts and ends with cavity
  - HW:9 cavities, 6 solenoids ( C S C S C S C S C C S C C S C )
  - SSR1: 8 cavities, 4 solenoids ( C S C C S C C S C C S C )
- HW-to-SSR1 interface
  - HW-to-SSR1 transition goes through room temp. vacuum chamber
    - Good from engendering and repair points of view
      - complications of beam dynamics are manageable
    - Small space is left for instrumentation (~5 cm)
      - Laser profile monitor
- Functional requirements specifications are close to be completed

# Simulation results with the space charge† (TracewWin)




*3σ envelopes*

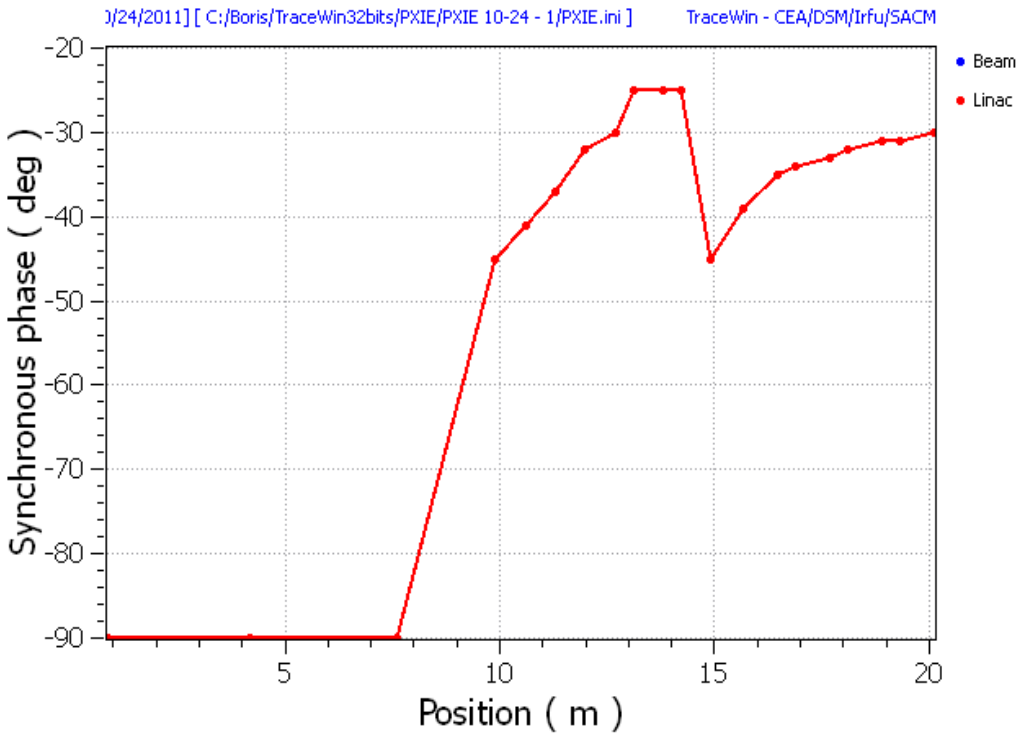
*Energies: 2.1 MeV – 10.8 MeV – 24.4 MeV*

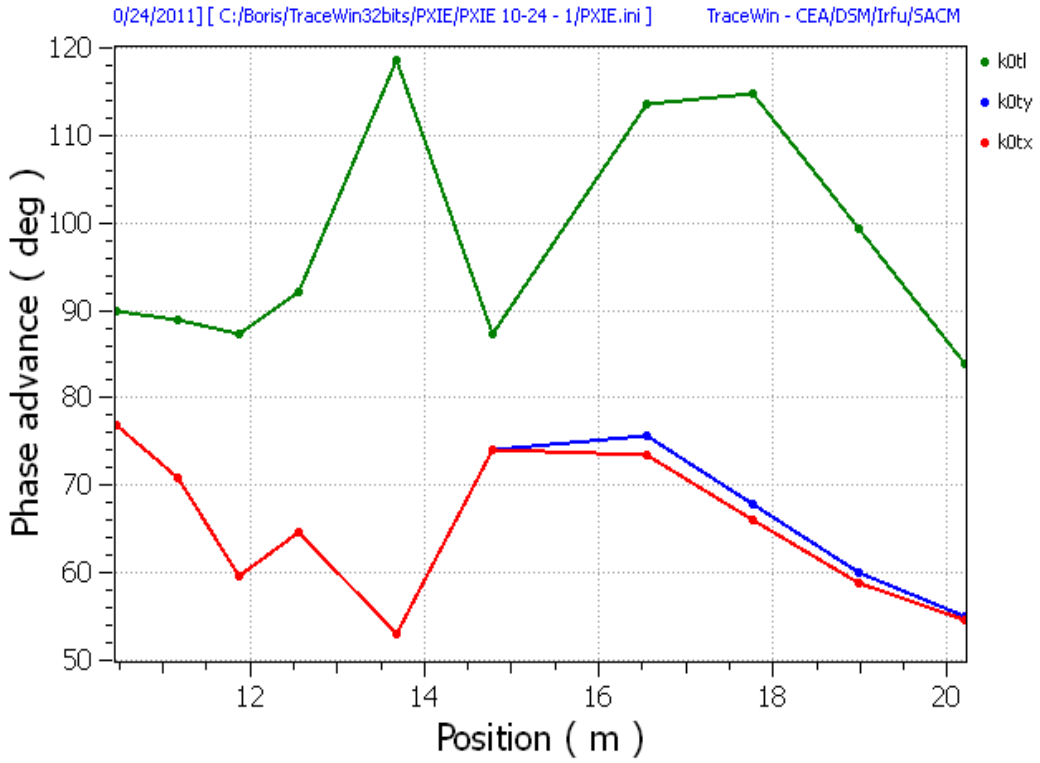
*Rms norm. emittances: 0.25, 0.25, 0.25 mm*mrad*

*5 mA @162.5 MHz*

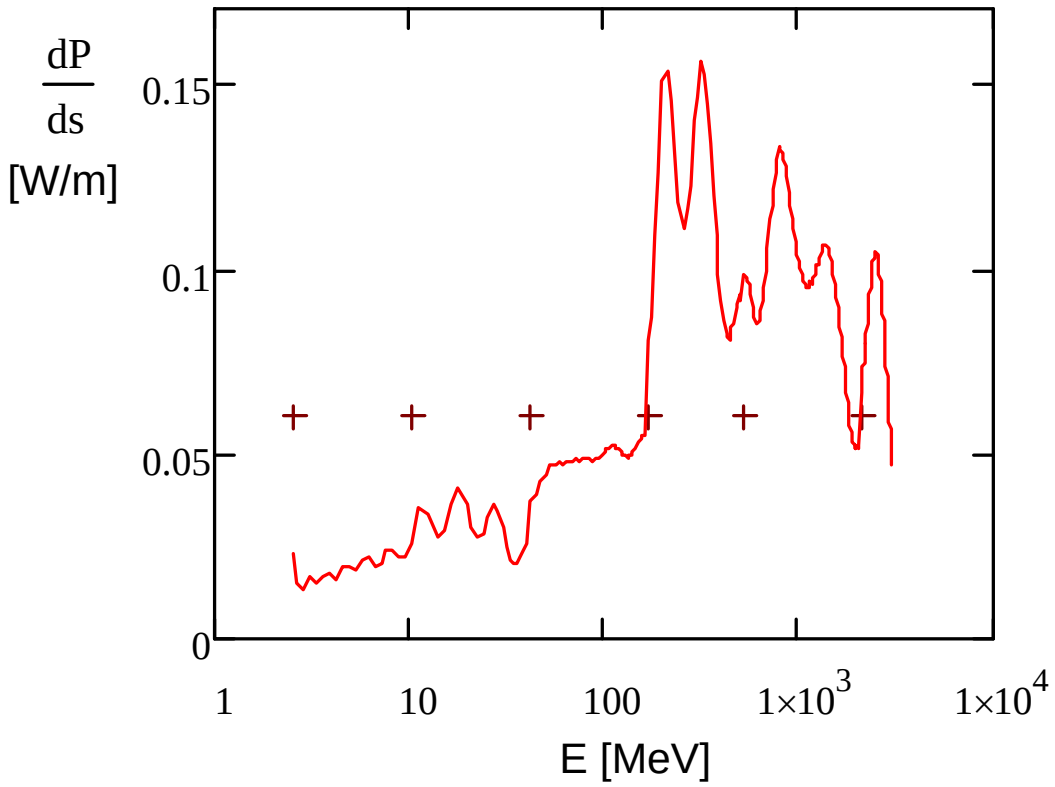
† B. Stheynas

# Synchronous Phase and Phase Advances



# Beam Collimation in SC Cavities

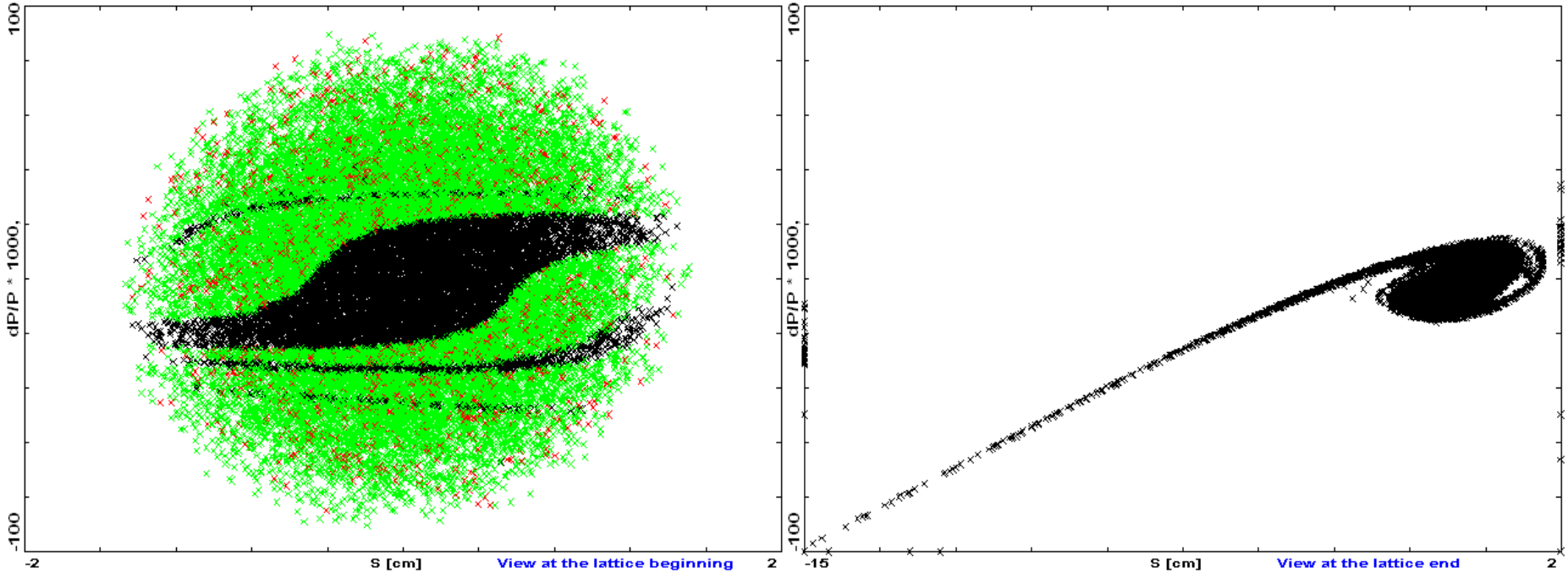



*Intrabeam stripping estimate for Project X*

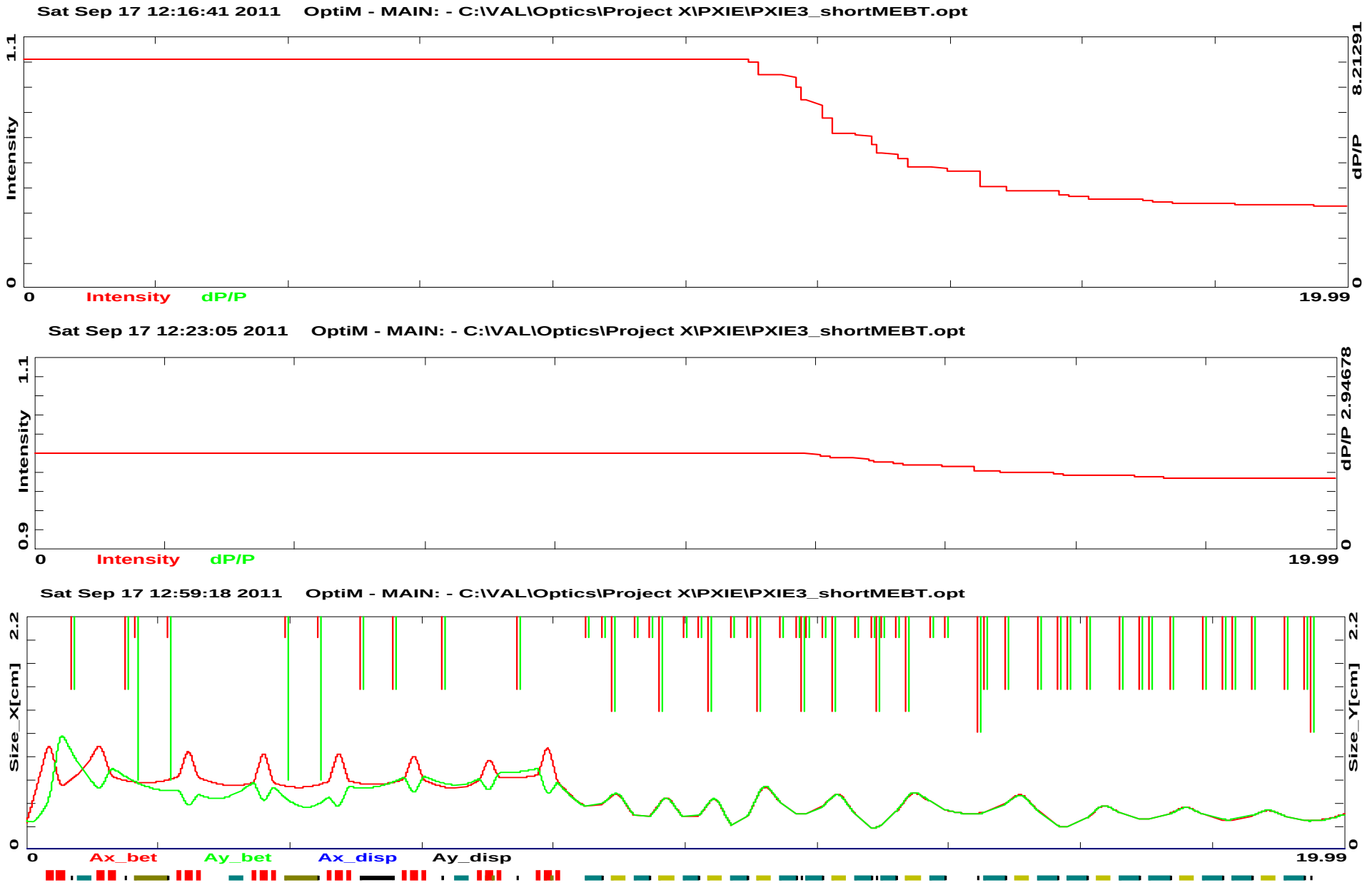
- Particle loss due to IB stripping is expected to be less than 0.05W/m
- Angular divergence is determined by $\beta_{min}$~40 cm
- Interception of 90% loss particles requires beam collimation with "two solenoids" period
- Taking into account overall small loss we can accept particle loss at 2 K

# Beam Collimation in SC Cavities (continue)

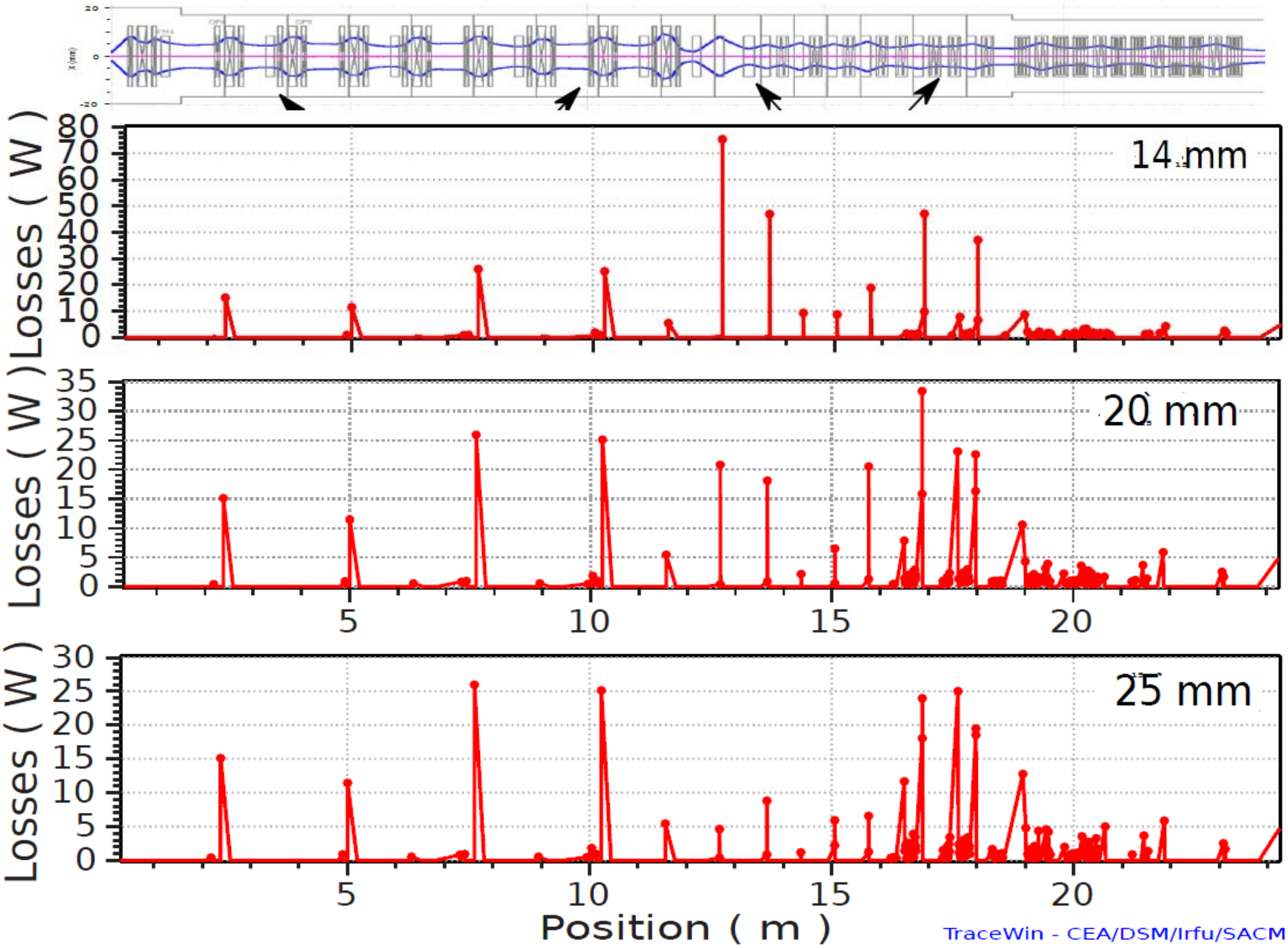
- RFQ tails can present larger loss than the IB stripping at the acc. beginning
- Most losses happen in the second part of HW cryo-module
  - However energy lost in the SSR1 cryo-module is about the same
- Beam loss is happening so fast that a "reasonable" collimation cannot intercept its major part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




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



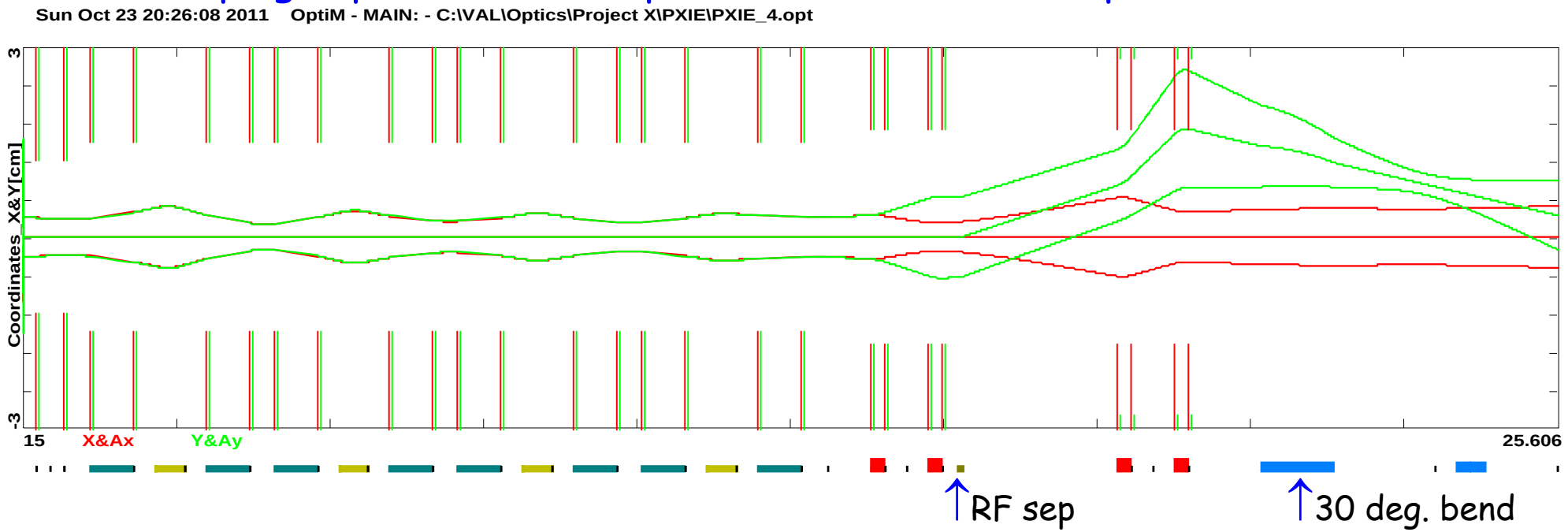

*Beam intensity reduction due to particle loss for beam consisting of tails only. Tails are presented by uniform distribution truncated at 20σ (top) and 5σ (middle); reference rms norm. long. emittance - 0.25 mm mrad. There is no particle loss if truncation is below 4.5σ. Bottom plot presents 3σ transverse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




*Simulations with tail in momentum spreading to ~50% down*

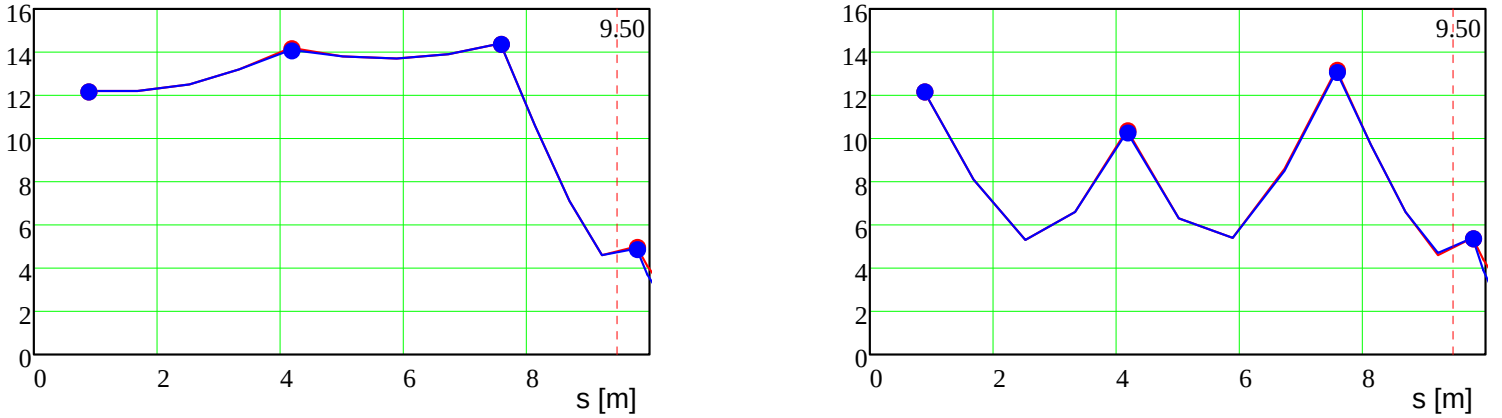
# Diagnostic Section and Beam Dump

- We did not discuss it yet
- Very preliminary thoughts and goals
  - RF separator
    - (81.25+325n) MHz, ~400 kV, warm, half-wave cavity, ~4 kW
  - Laser profile monitor to measure bunch distribution in all three planes
  - Spectrometer based on 30 deg. bend
    - Accurate measurements of longitudinal tails
  - 30 kW 30 MeV beam dump
  - Swiping-dipole to reduce power on the beam dump face



# Beam Extinction

- Serious discussion did not start yet
- PXIE official goal is ~$10^{-4}$
- It is highly desirable to achieve $10^{-9}$ - $10^{-12}$
  - Means of achievement
    - Scraping optimization
    - Wide band chopping (wider than it is presently considered, ~1 GHz)
    - RFQ tuning
    - Cavity phasing
      - In particular, increased L phase advance between chopper kickers




*Long. phase advance between 2 kickers ~90 deg allows scraping in both Δp/p & s.*

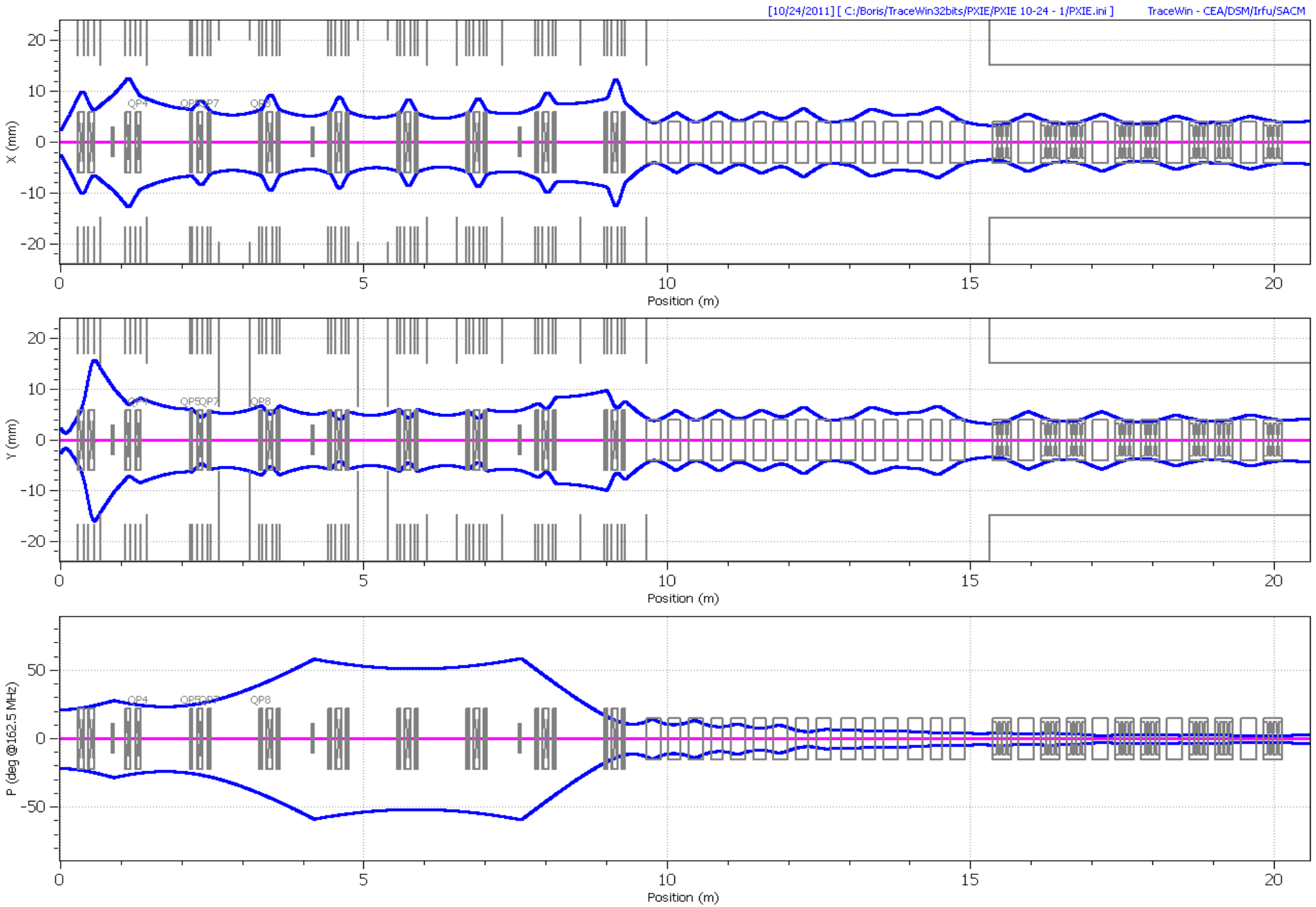
*It requires $V_{max}$ = 95 → 130 keV*

- Control
  - RF separation & Single particle detection

# Conclusions

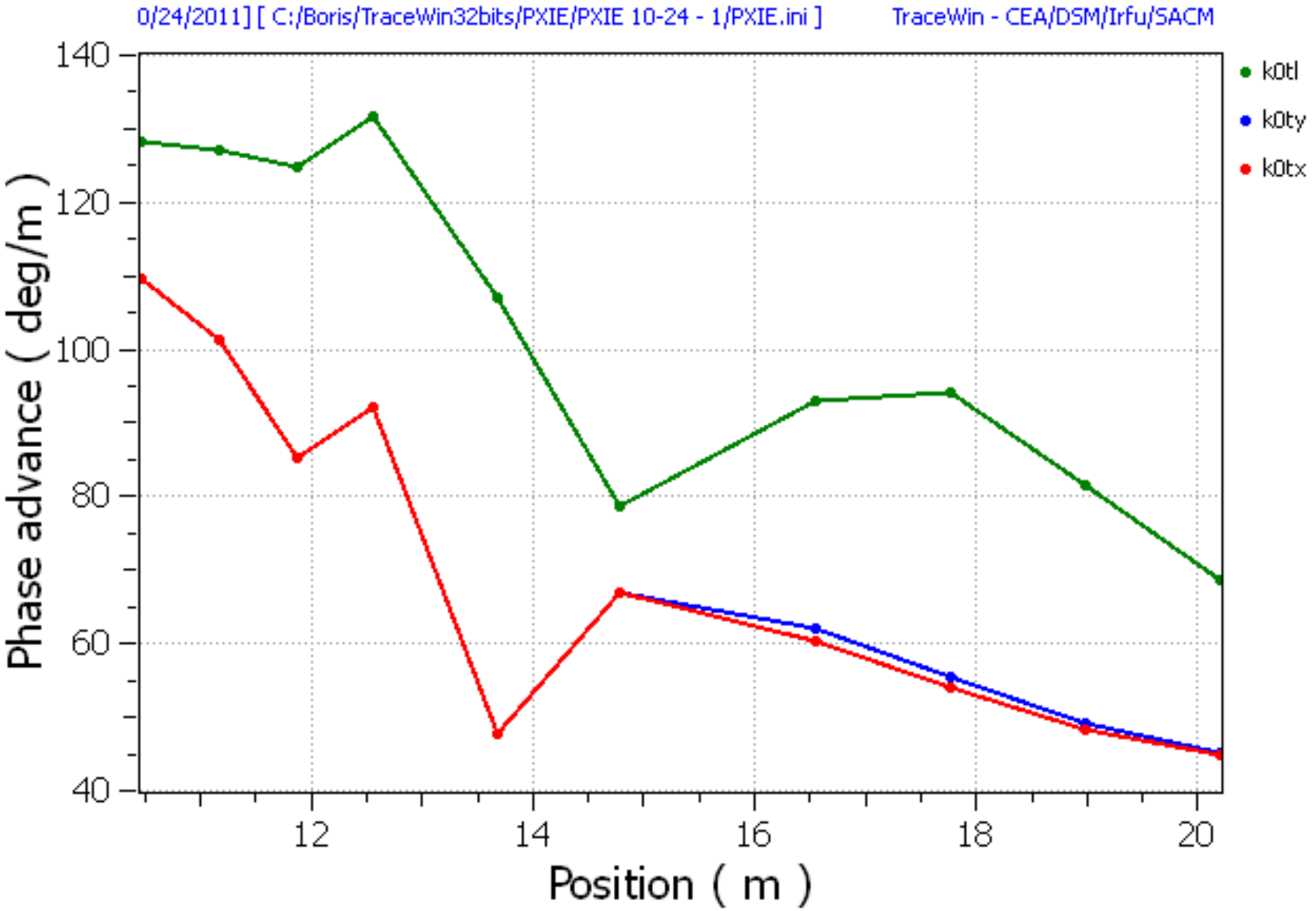
- Construction and successful commissioning of PXIE will eliminate major Project X vulnerabilities for 3 GeV operation
- It should deliver clear answer on the achievable extinction rate
- We are at the very beginning
  - We have good understanding of goals and means to achieve them
  - We are in the process of writing functional requirement documents for major systems
  - PXIE operation by the end of 2016 looks realistic
    - Support of the laboratory will be crucial to achieve this goal

# Backup Slides

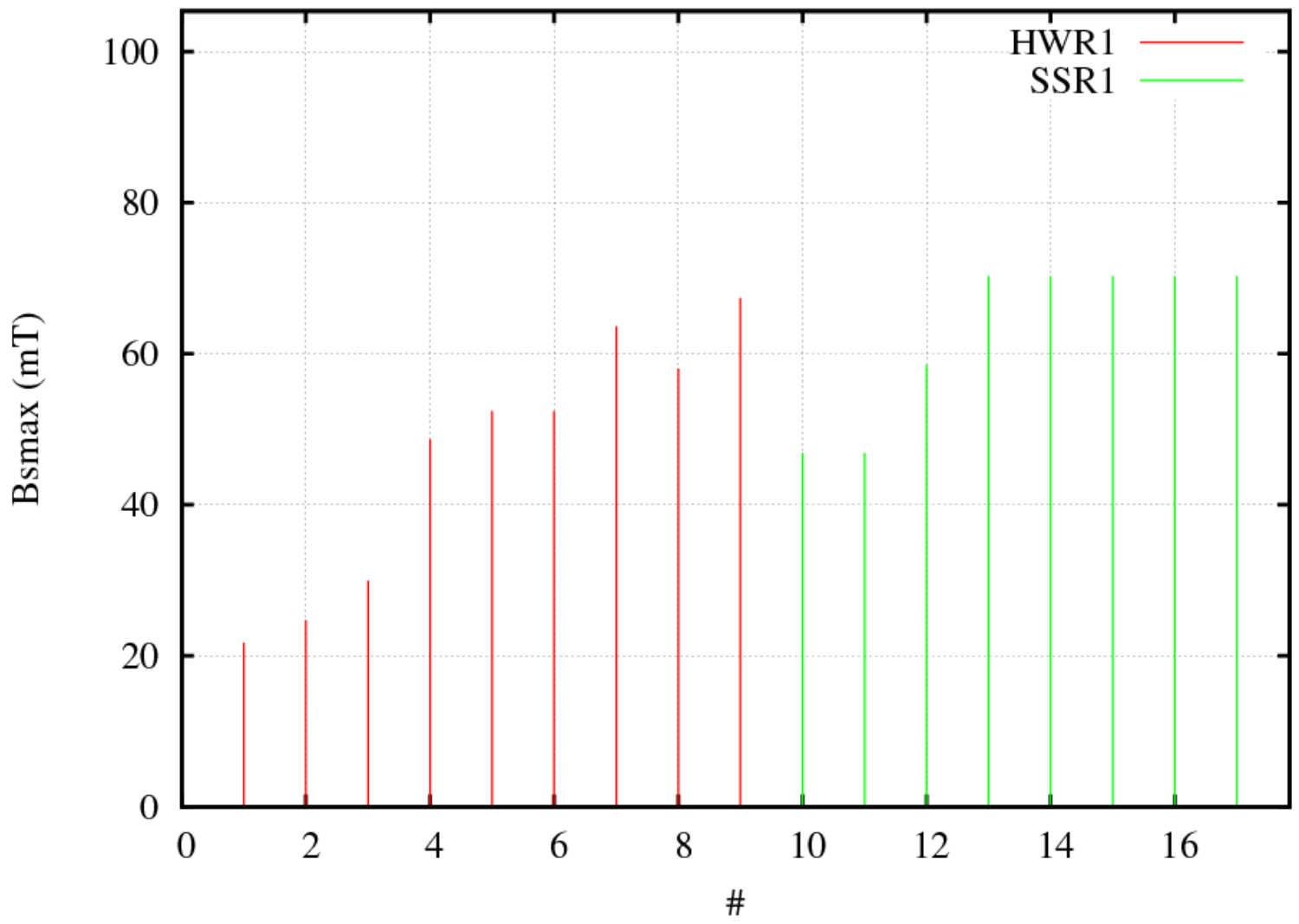



***3-sigma envelopes with apertures;***

*Energy 2.1 MeV – 10.8 MeV – 24.4 MeV; Emittances: 0.25, 0.25, 0.25 pi*mm*mrad*




*Phase advance per meter*




*Surface magnetic field*