Loss control and reliability issues in high intensity linacs

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46th ICFA Advanced Beam Dynamics Workshop on
High-Intensity and High-Brightness Hadron Beams

Outline

- Beam Loss control by Beam Dynamics Design
  - Emittance growth control
  - Halo formation control
- Reliability issues by redundancy and high efficiency components
- IFMIF example (the RFQ design)
- Future Spallation Neutron Source example (challenges for DTL design)

Emittance Growth

- Transverse Emittance:
  - Source and Extraction system (Busch Theorem, Source electrodes, LEBT Neutralizations and magnets aberrations).
  - MEBT Transport (Phase advance matching between RFQ and DTL/SC cavity).
  - Non linear effects in RF components (Bessel behaviors of E.M. Fields).
  - Non linear effects in Magnetics components.
  - Space Charge Effects (Redistribution, Mismatch, Equipartitioning).
  - Structure resonances (phase advance choice, tune depression).

- Longitudinal emittance:
  - Emittance formation in the RFQ (shaper length, phase advance rotations).
  - Non linear effects in RF components (Bessel behaviors of E.M. Fields).
  - Frequency Jump (Phase advance matching).
  - Space Charge Effects (Redistribution, Mismatch, Equipartitioning).
  - Structure resonances (phase advance choice, tune depression).

Halo formation

- Definition of Halo?
- Emittance growth induces beam halo formation.
- Beam mismatch induces halo formation.
- Is halo formation possible without emittance growth?

Beam halo definitions based upon moments of the particle distribution

$$I^i{}_2 = \langle q^2{}_i \rangle \langle p^2{}_i \rangle - \langle q_i p_i \rangle^2$$

$$I^i{}_4 = \langle q^4{}_i \rangle \langle p^4{}_i \rangle + 3 \langle q^2{}_i p^2{}_i \rangle^2 - 4 \langle q_i p^3{}_i \rangle \langle q^3{}_i p_i \rangle$$

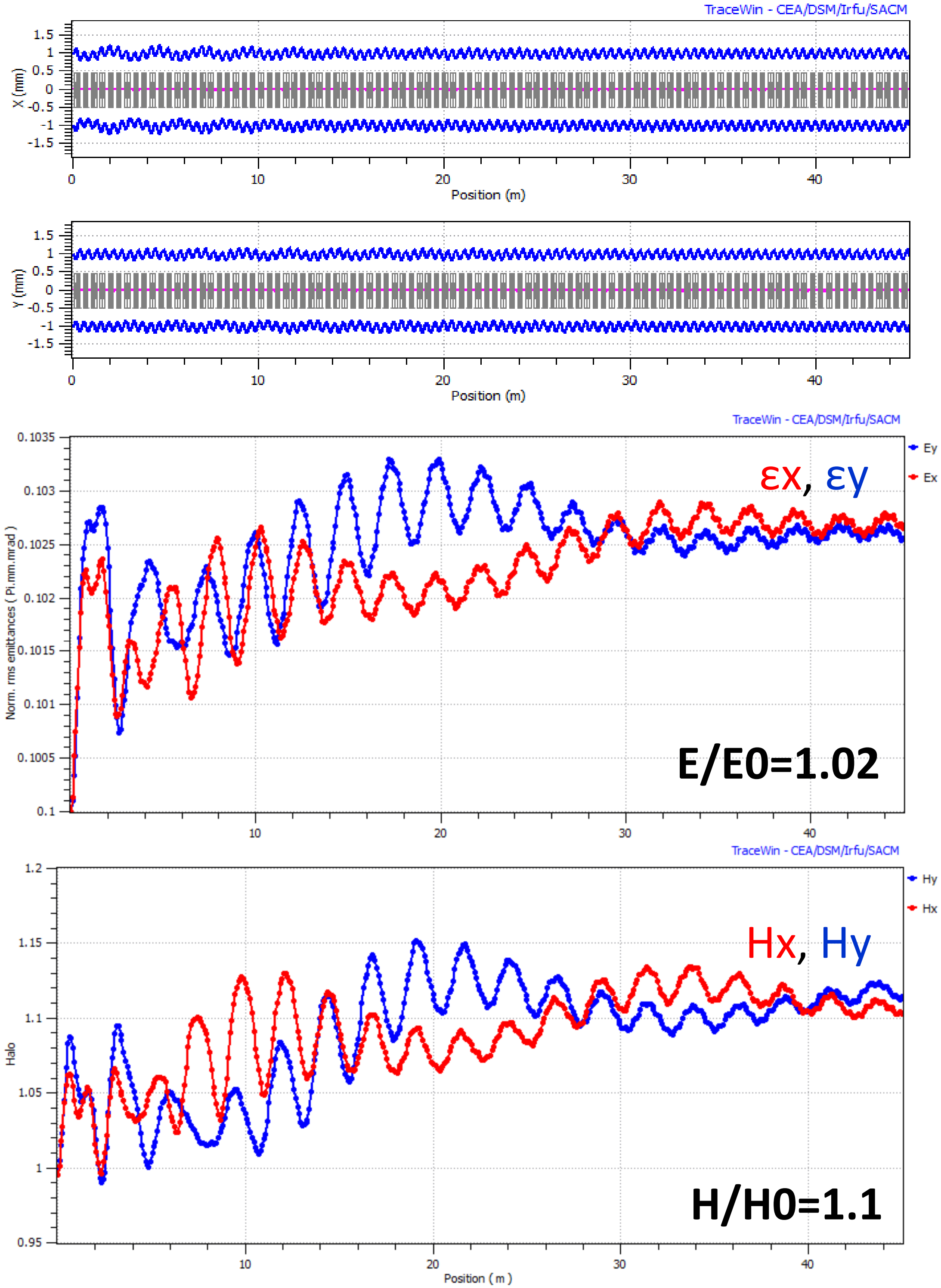
$$H_i = \frac{\sqrt{3 I^i{}_4}}{2 I^i{}_2} - 2 \quad \textit{Continuous Beam}$$

$$H_i = \frac{\sqrt{3 I^i{}_4}}{2 I^i{}_2} - \frac{15}{7} \quad \textit{Bunched Beam}$$

Distribution	Continuous Beam	Bunched Beam
Uniform	0	0
Parabolic	1/4	4/21
Gaussian	1	6/7
Hallow	1/4	75/112

C. K. Allen and T. P. Wangler PRST - AB,VOLUME 5, 124202 (2002)

Beam halo formation



Example of FODO Channel

σ_0=40°

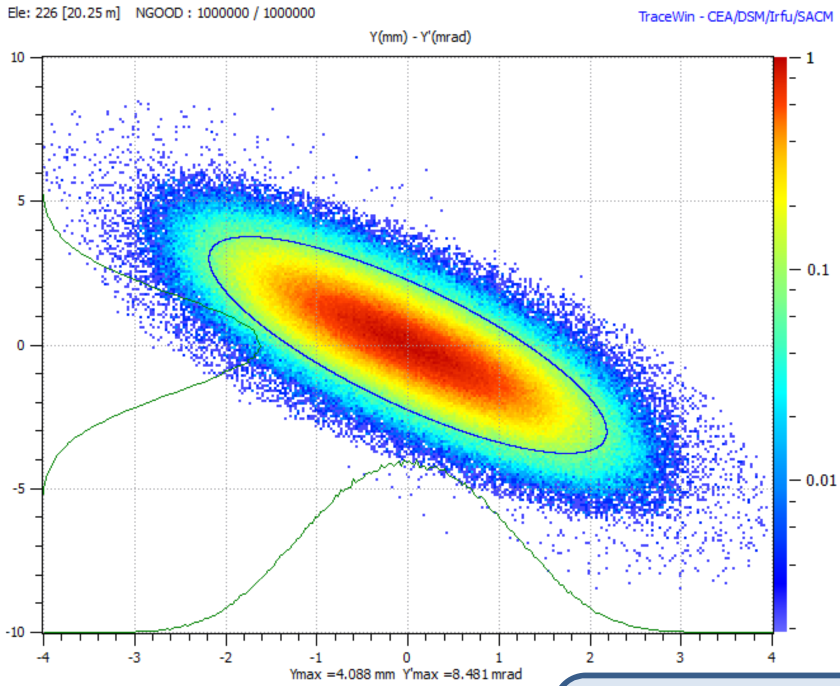
σ/σ_0=0.65

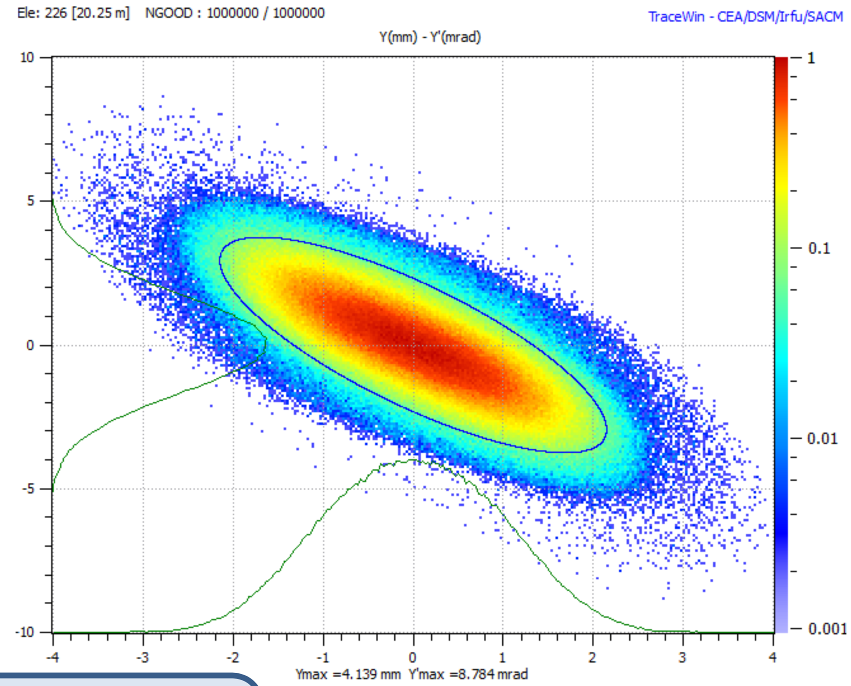
16% MISMATCH

GAUSSIAN DIST.

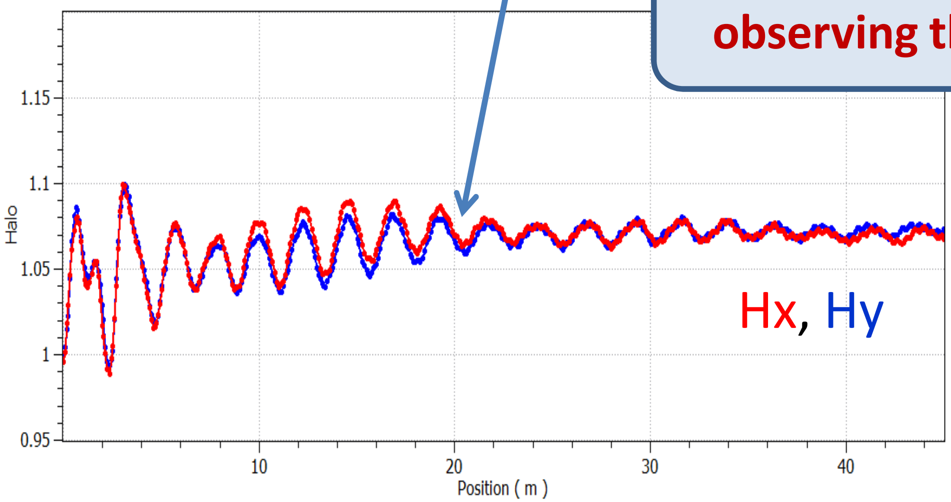
The Halo H parameter is more sensitive than the RMS emittance

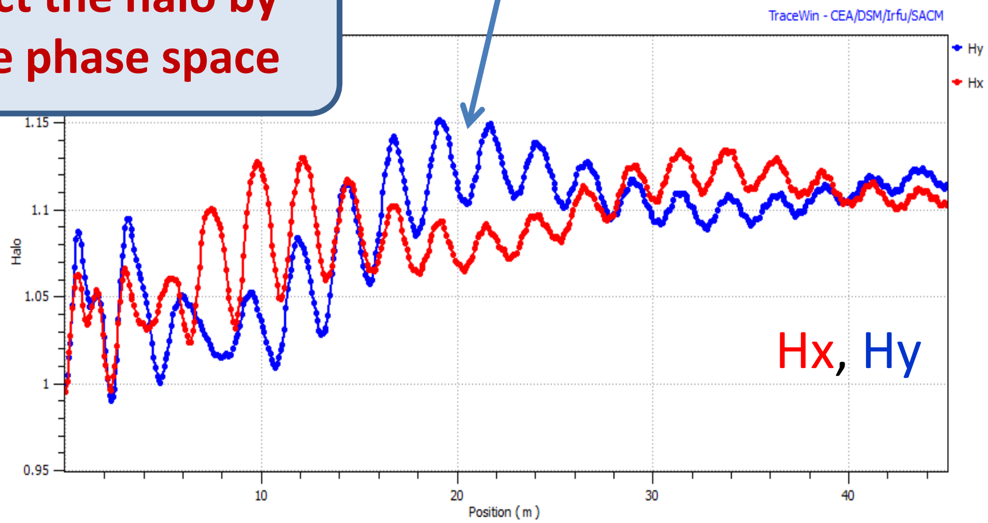
Beam Halo Formation





Hard to detect the halo by observing the phase space





Beam Losses allowed

- **High Energy Linac** (Losses < 1W/m)
  - Above 1 GeV the 1 W/m limit corresponds to approximately 2 10^11 n/s produced by Spallation on a metallic (W) target orthogonal to the beam.
  - For 1MW beams the losses must be below 10^{-6}
- **Low Energy Linac** (Losses > 1W/m)
  - At low energy the neutron production is much less abundant and allowed losses must be scaled with the lower neutron production.
  - IFMIF case: more than 100 W/m from the RFQ, with neutron production on copper approximately below 10^10 n/s @ 5 MeV.

Beam Losses Allowed

- **High Energy Linac:**
  - Avoid the halo formation and emittance growth in the low energy part that can induce losses at high energy.
  - Short and regular focusing lattice (at example DTL for spallation source Linac).
- **Low Energy Linac:**
  - Avoid beam losses, no needed of low emittance.
  - Large cavity bore.
  - We can use long focusing lattice (at example IFMIF Linac).

Beam Loss Control by general design criteria

- Phase advance design
- Cavity Bore / RMS beam size >10
- Avoid emittance growth

Phase Advance Design

$$\sigma_u = \int_s^{s+L} \frac{\varepsilon_u}{\langle u^2 \rangle} ds \quad u \equiv x, y, z$$

$$\frac{\sigma}{\sigma_0} > 0.4$$

Avoid profound depression tune

$$\sigma_0 < 90°$$

Envelope instability and resonances

$$k_{s1}[°/m] = k_{s2}[°/m]$$

Continuity of phase advance per meter and smooth variation between accelerator sections

$$Frequency\ \ jump \begin{cases} \dfrac{\phi_s}{f_{RF}} = cst \\ E_0 T \cdot f_{RF} \cdot \sin\phi_s = cst \end{cases}$$

Continuity of longitudinal acceptance

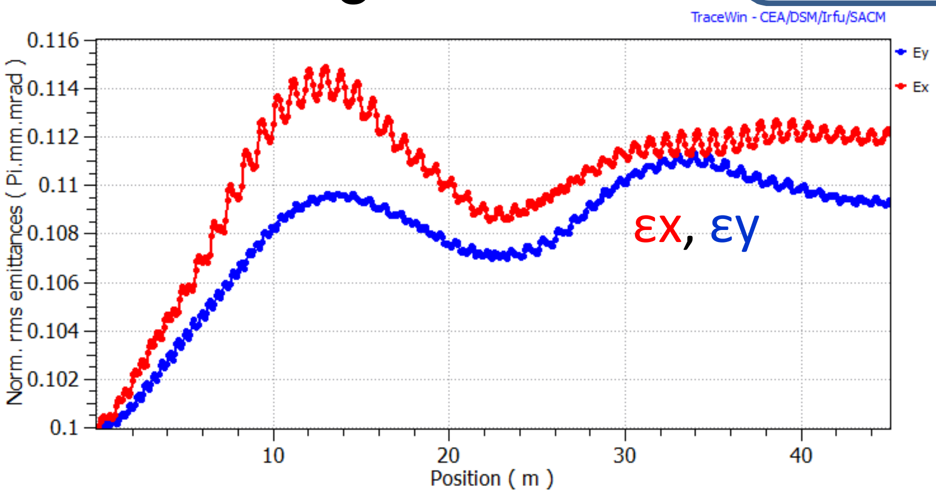
$$k_x \cdot \varepsilon_x = k_y \cdot \varepsilon_y = k_z \cdot \varepsilon_z$$

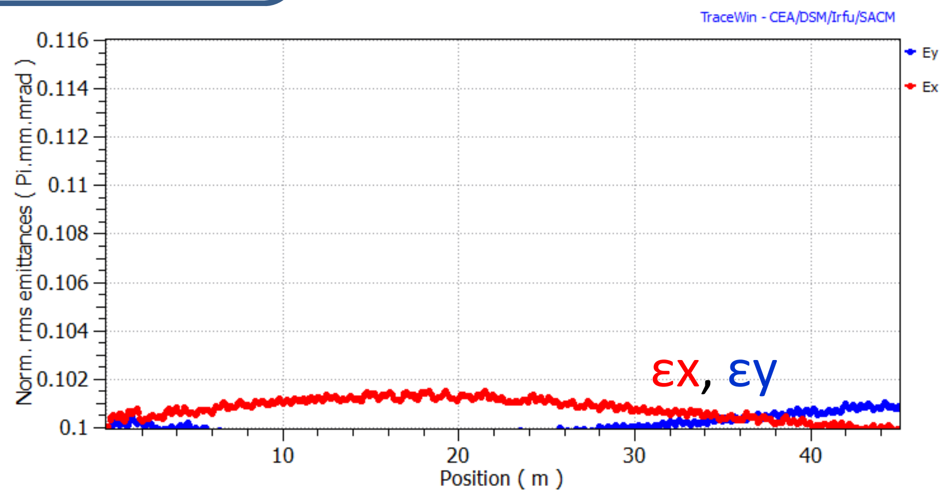
Equipartitioning

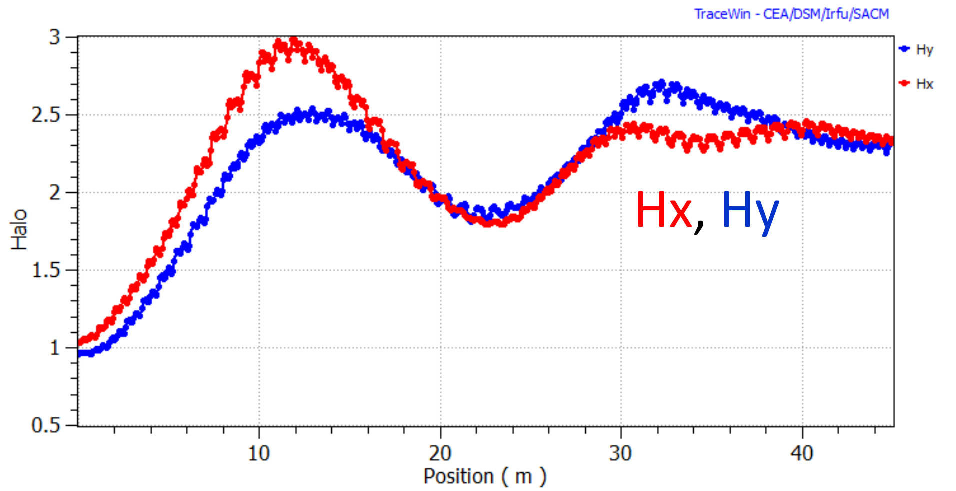
σ_0=95°

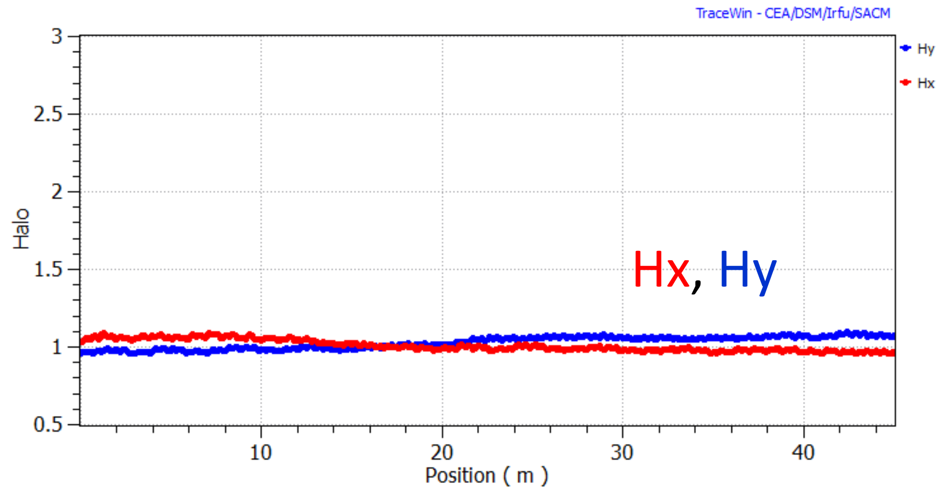
σ0 < 90° to avoid emittance growth

σ_0=85°







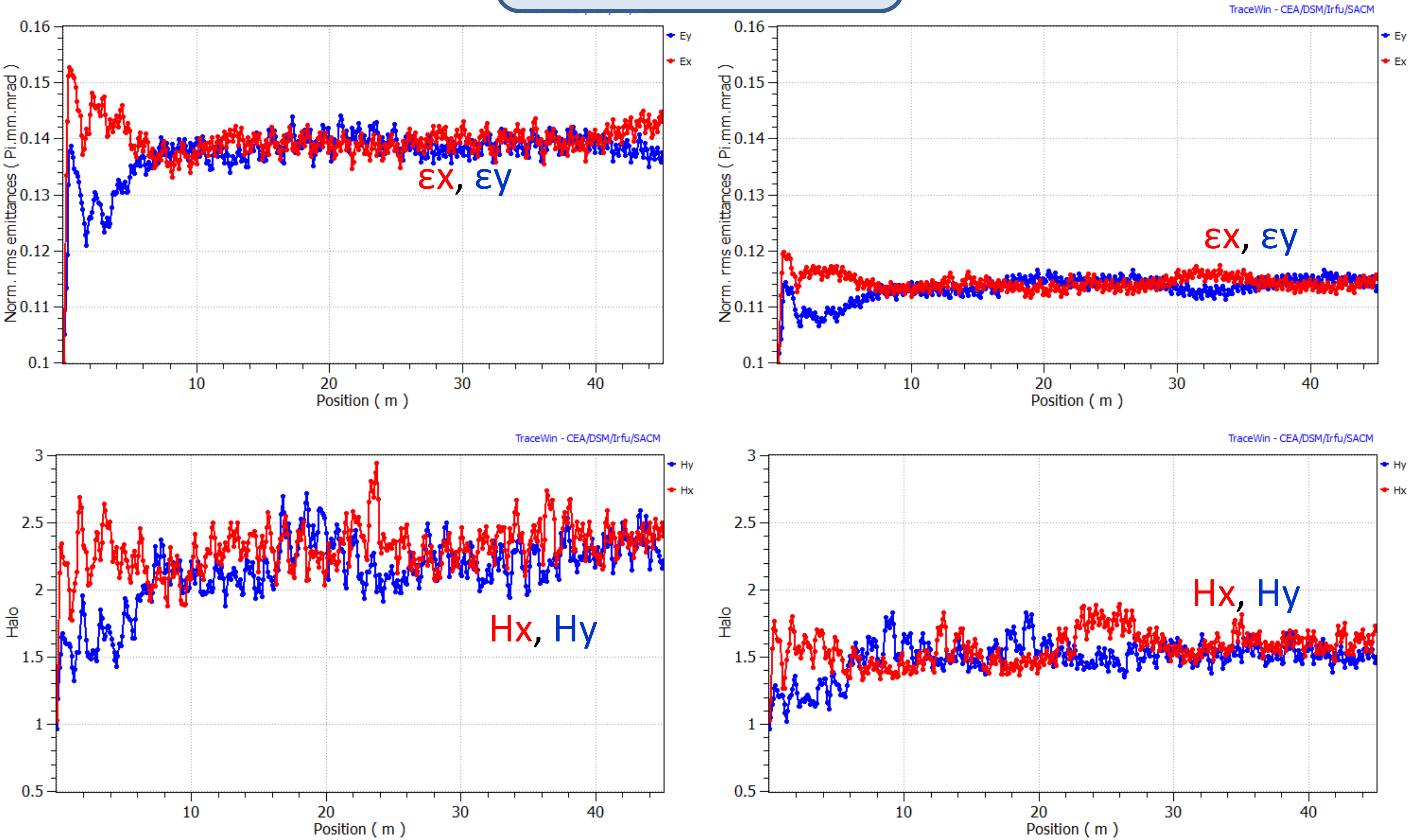


Example of FODO Channel σ/σ_0=0.85 GAUSSIAN DIST.

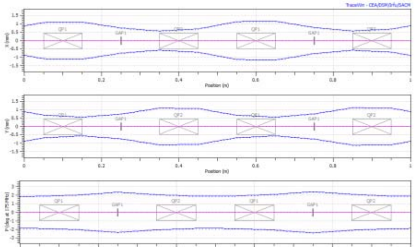
σ/σ_0=0.35

σ/σ0 > 0.4 to avoid emittance growth

σ/σ_0=0.45

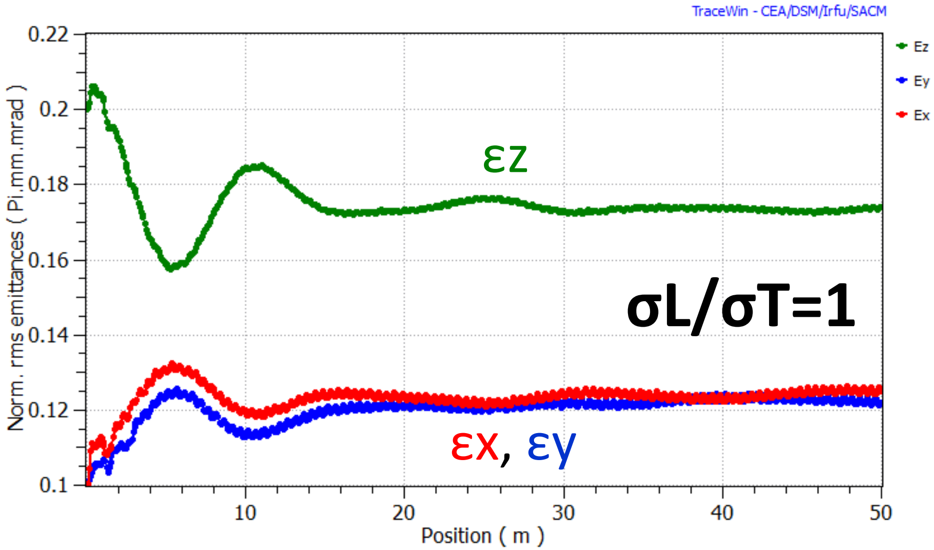


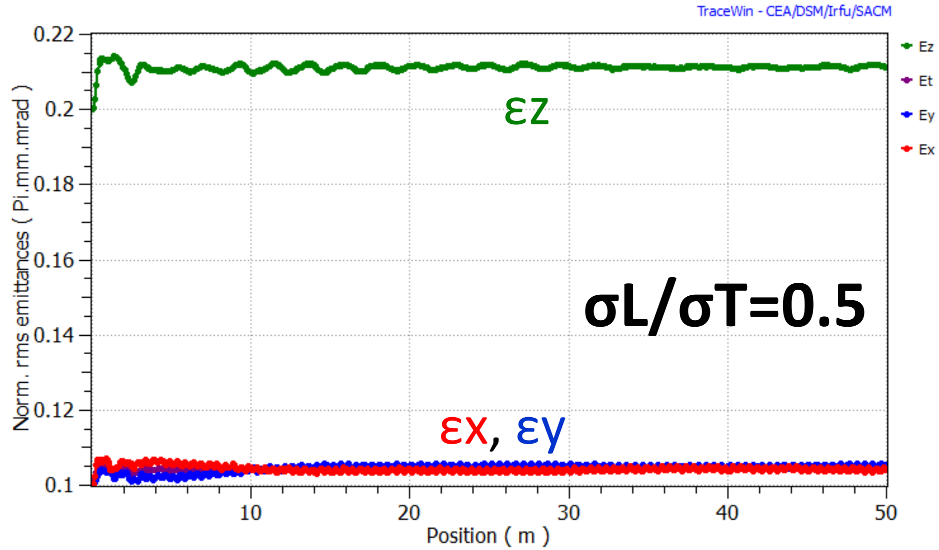
Example of FODO Channel σ_0=85° GAUSSIAN DIST.

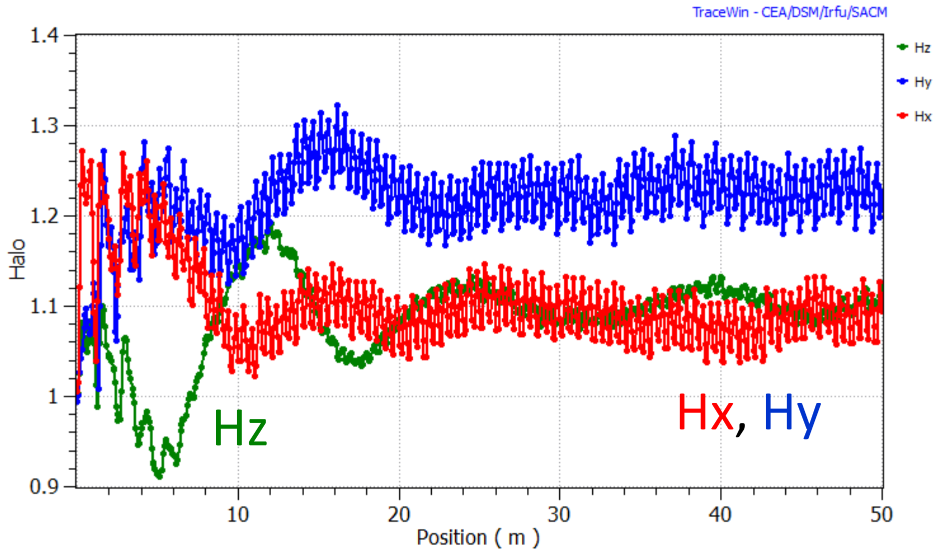


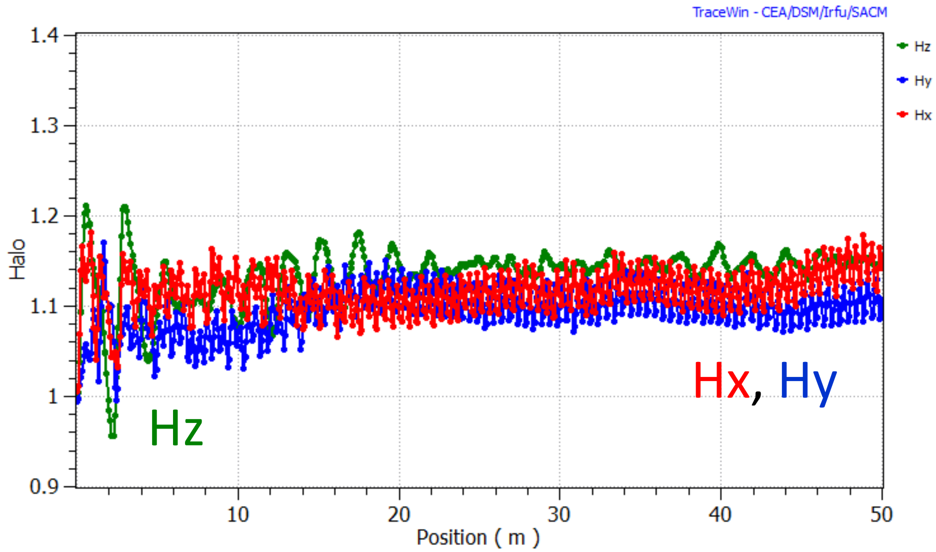
Equipartitioning to avoid emittance exchange

Equipartitioning









FGD Lattice σ0=85° σL/σT=1 $\sigma T/\sigma T_0$=0.62 **εz/εx=2** Gaussian Dist.

FGD Lattice σ0=85° σL/σT=0.5 $\sigma T/\sigma T_0$=0.7 **εz/εx=2** Gaussian Dist.

Beam Reliability

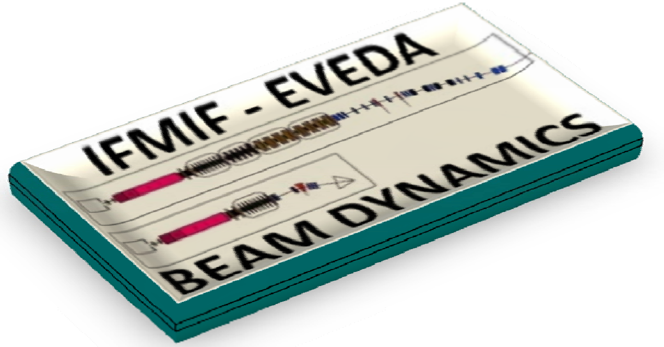
- Reliable and redundant hardware.
  - reliable RF system, possibly redundant or with graceful fault (multistage solid state).
  - Derating (oversize the system).
- Good ion Source (Beam on > 99% of the time)
  - Reduced consumption of components (gas use, cathode).
  - Low spark rate.
- Possibility of two ion sources?
- Flexible Lattice with additional optics transport solutions.
  - beam dynamics design contribute with a stretchy lattice and steering that allows beam transport with faulty elements.
- Large longitudinal acceptance could even handle the instantaneous failure of one cavity (scenario studied for ADS)

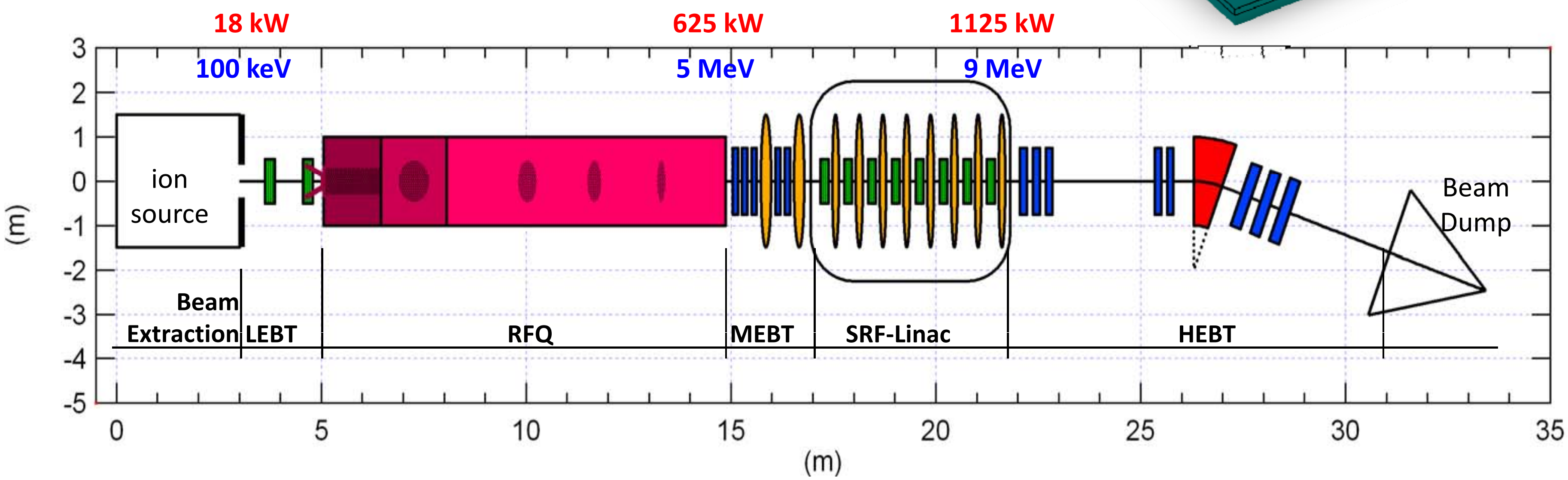
Example of IFMIF-EVEDA

- High Intensity CW Linac
- RFQ CW with current of 125 mA of D^+

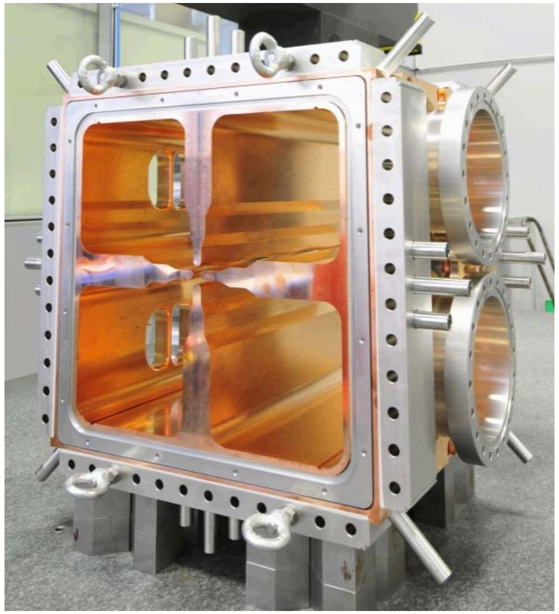
The IFMIF-EVEDA project is characterized by very challenging specifications,
with 125 mA of deuteron CW accelerated up to 5 MeV.
The objectives of EVEDA (Engineering Validation Engineering Design Activities)
are to produce the detailed design of the entire IFMIF facility,
as well as to build and test a number of prototypes,
including the high-intensity CW deuteron RFQ that will be design and build in Italy by
INFN and then assembled and operated at Rokkasho in Japan.

IFMIF-EVEDA Accelerator

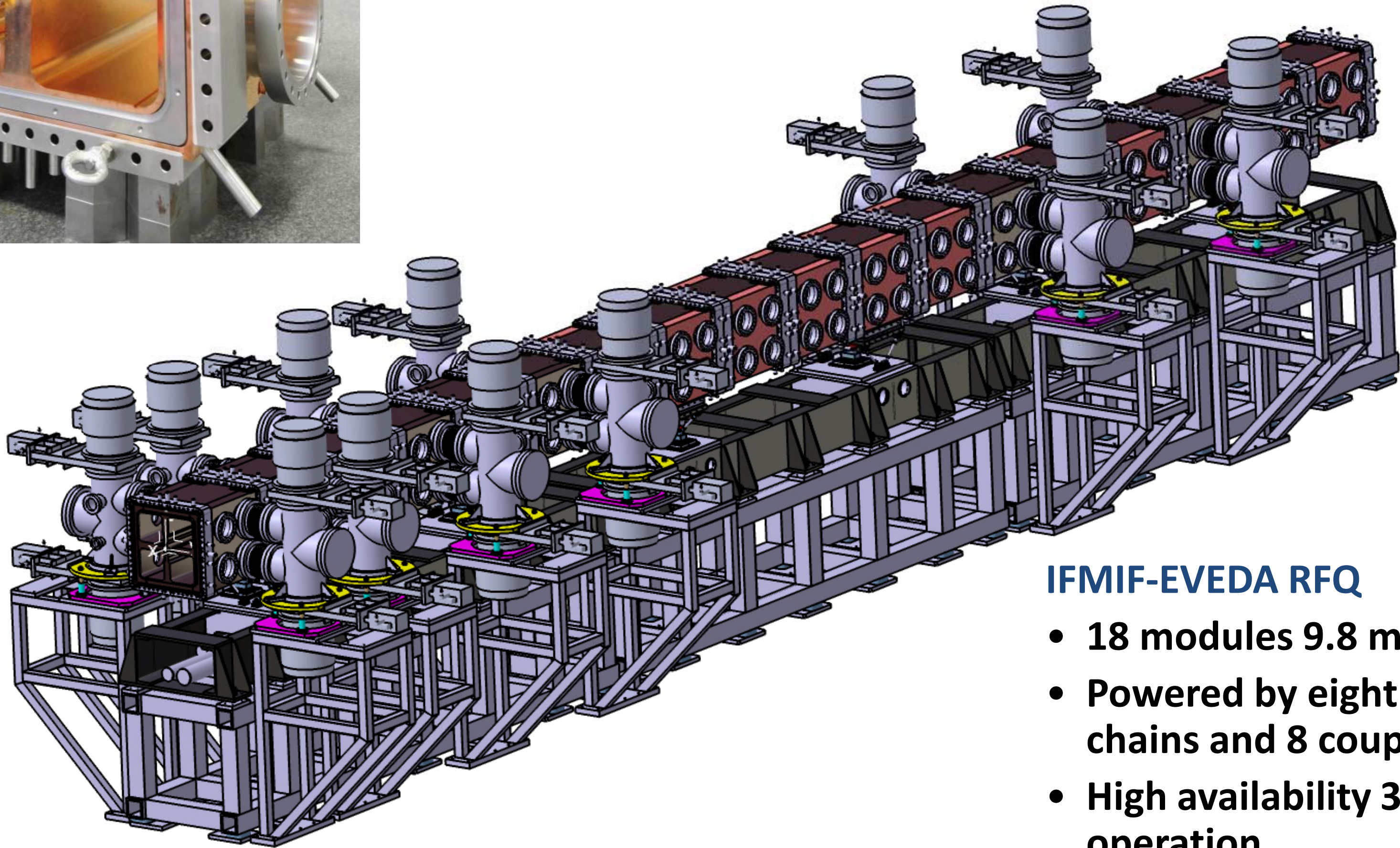




- **CW** Deuteron Beam up to 1.1 MW.
- Current 125 mA, final Energy of 9 MeV
- Will be install in Japan (Rokkasho).



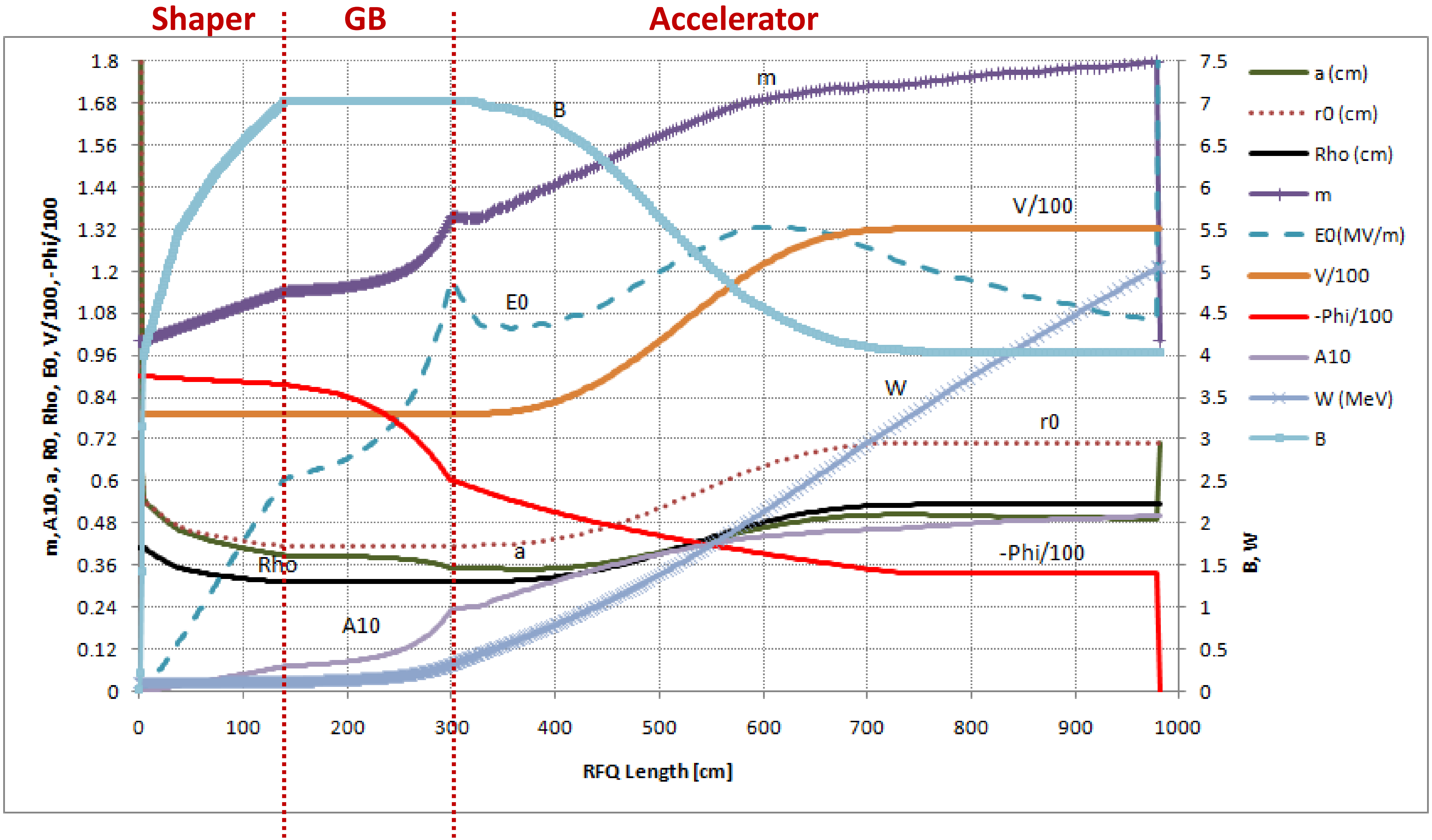
IFMIF RFQ



IFMIF-EVEDA RFQ

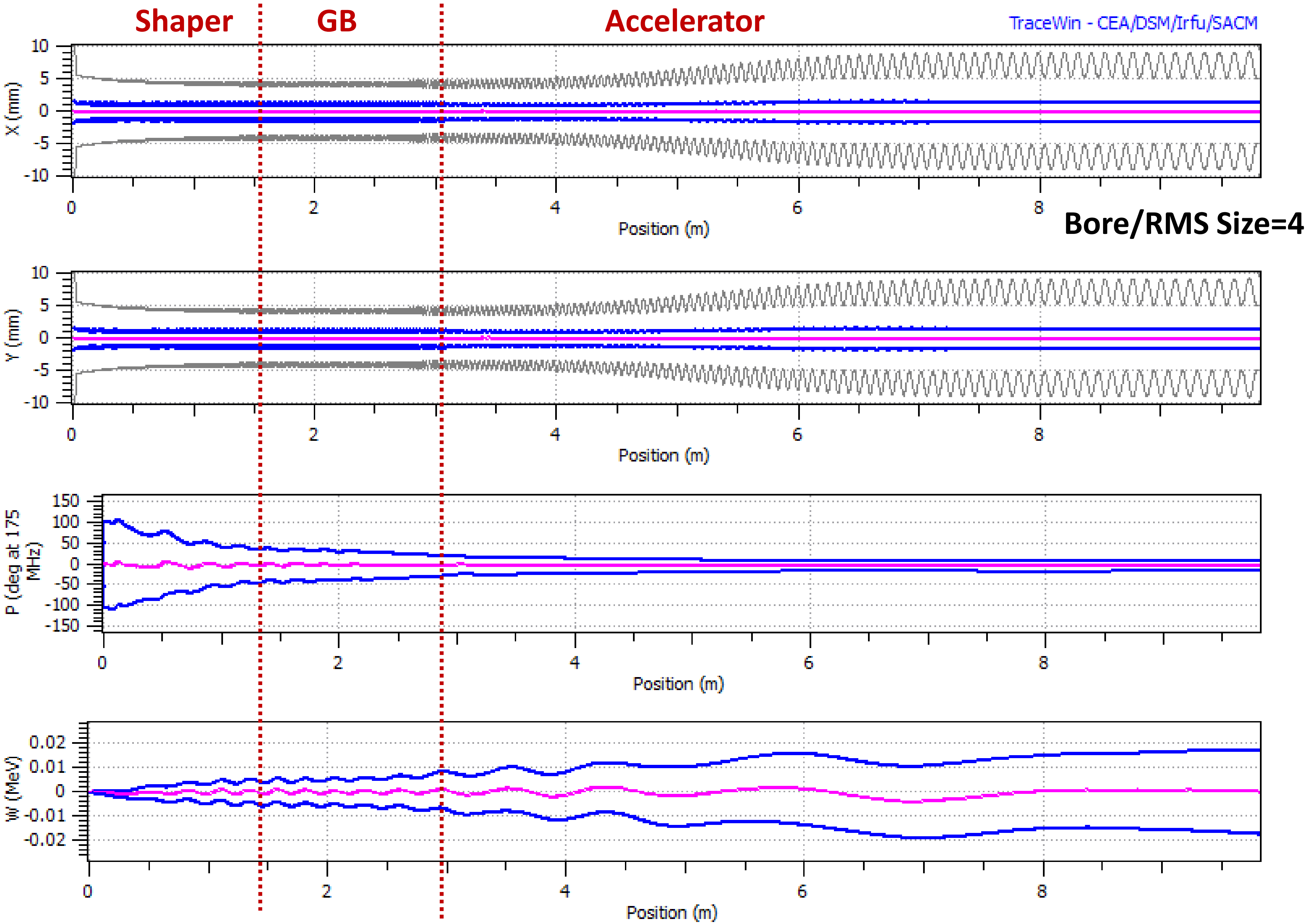
- **18 modules 9.8 m**
- **Powered by eight 220 kW rf chains and 8 couplers**
- **High availability 30 years operation.**
- **Hands on maintenance**
- **First complete installation in Japan**

Main IFMIF RFQ Parameters

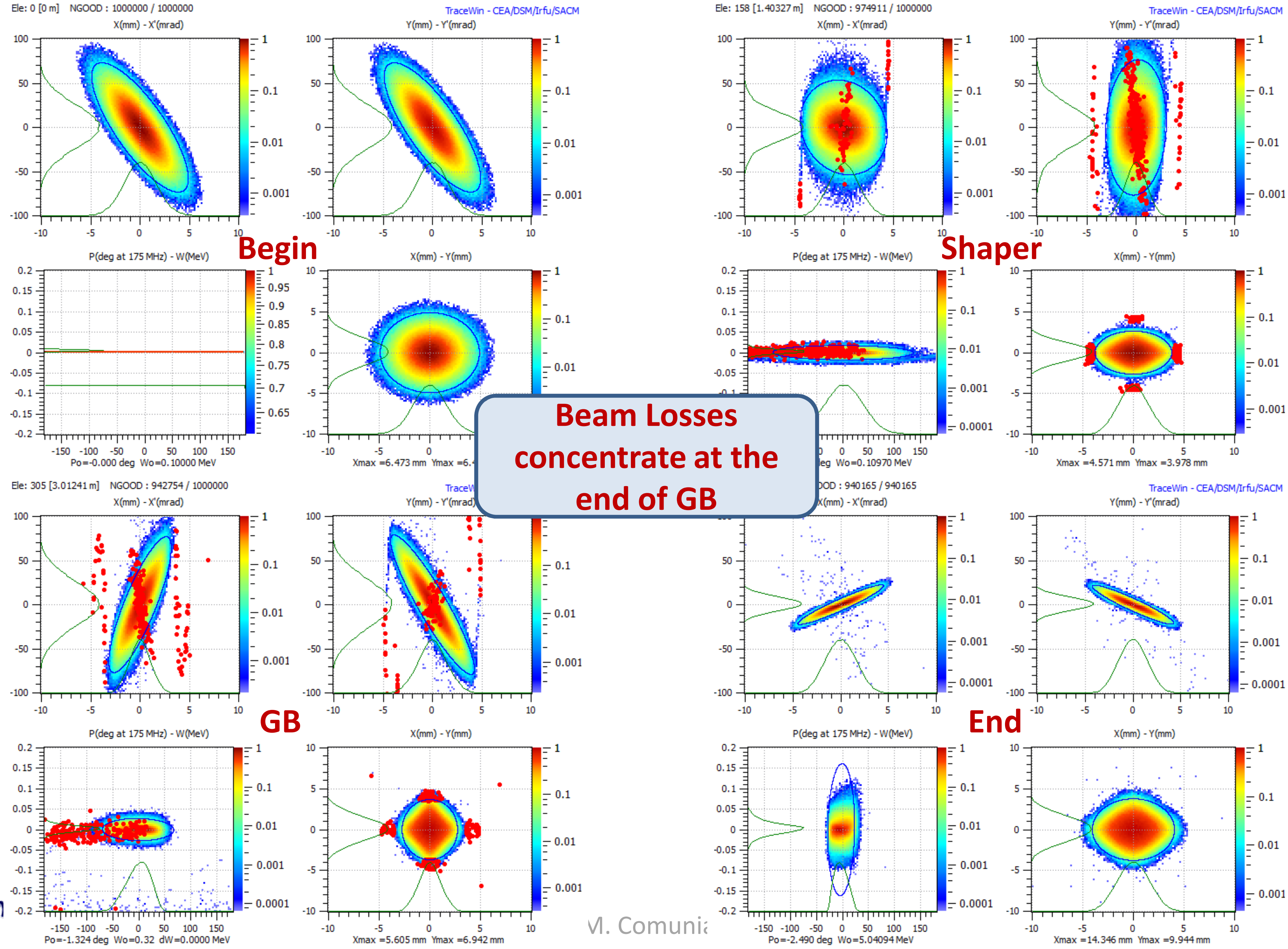


Deuteron Beam, Frequency=175 MHz, Current=130 mA, **CW**, energy from 0.1 MeV to 5 MeV

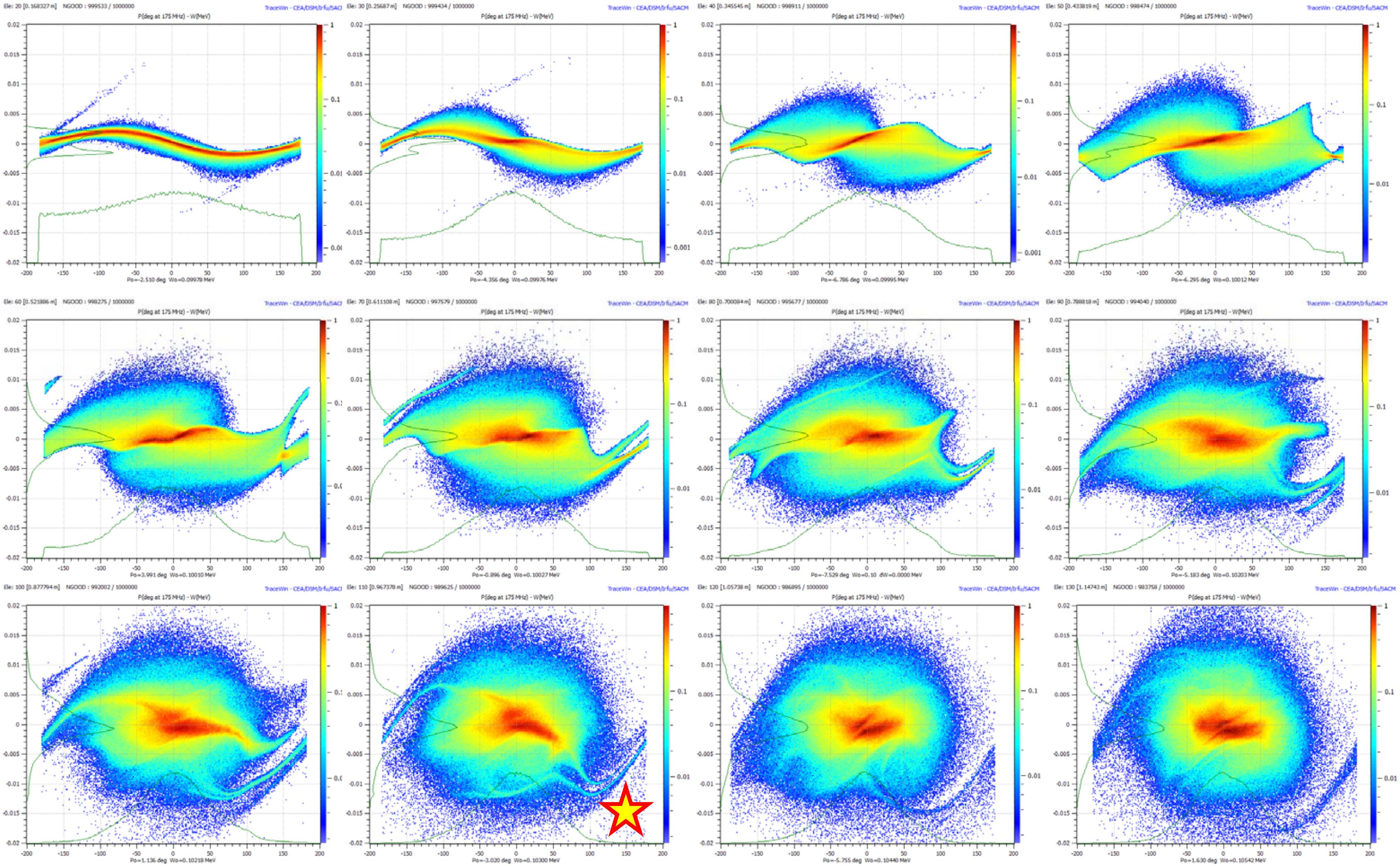
IFMIF RFQ Beam Envelopes RMS size



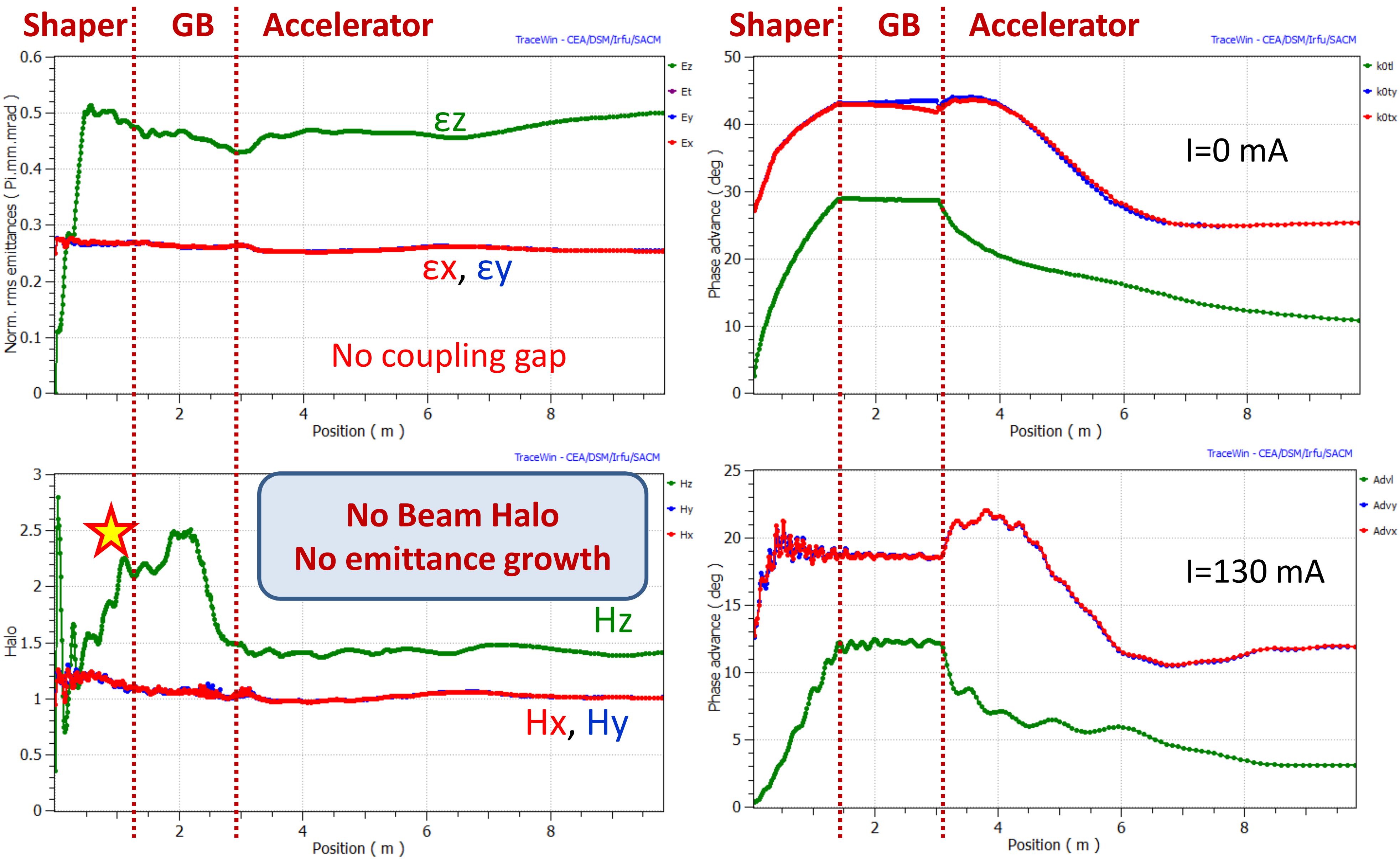
Phase Space in the IFMIF RFQ



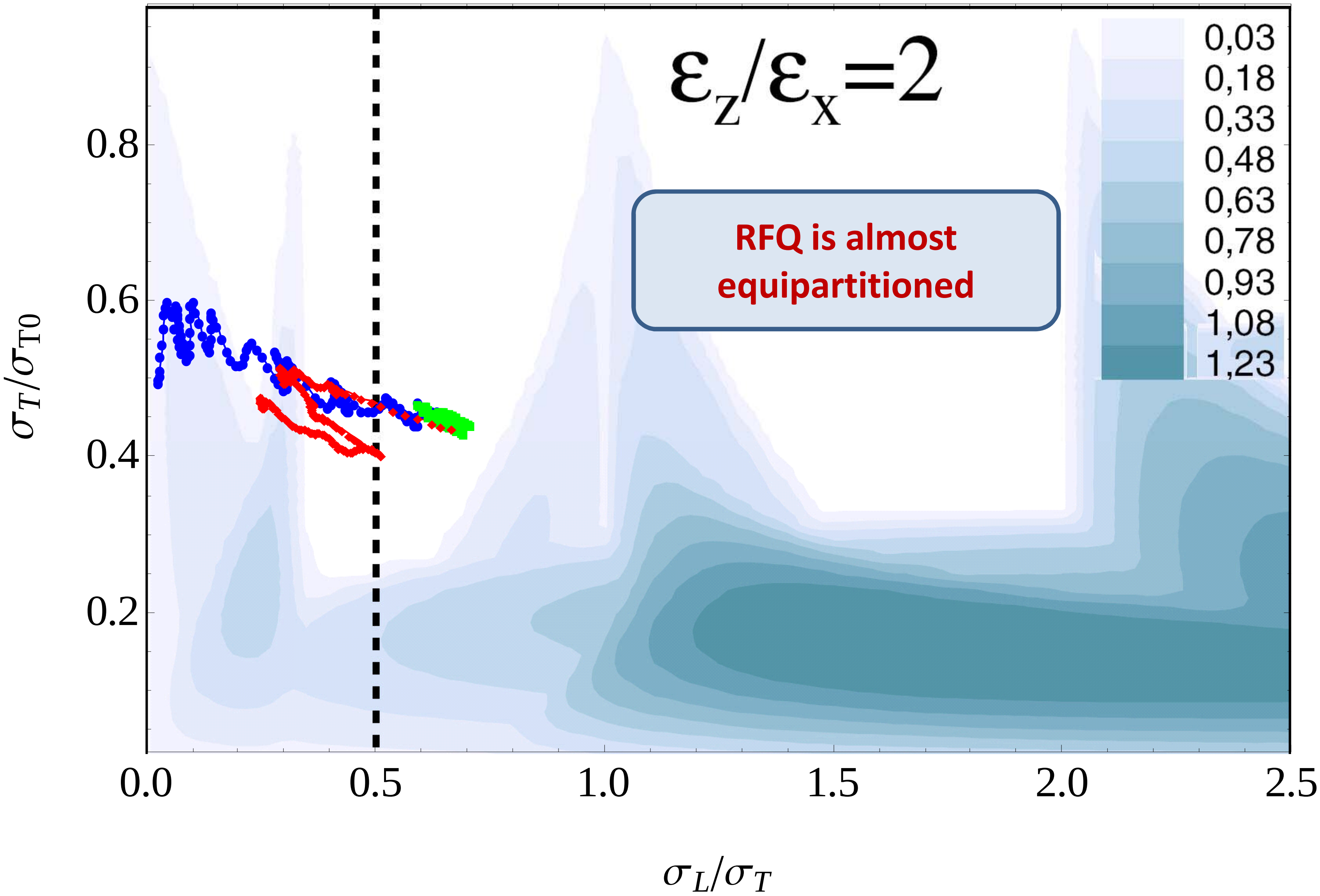
Longitudinal Emittance Formation in the IFMIF RFQ
(every 10 cells step to end of Shaper)



Emittance, Halo and phase advance along the IFMIF RFQ

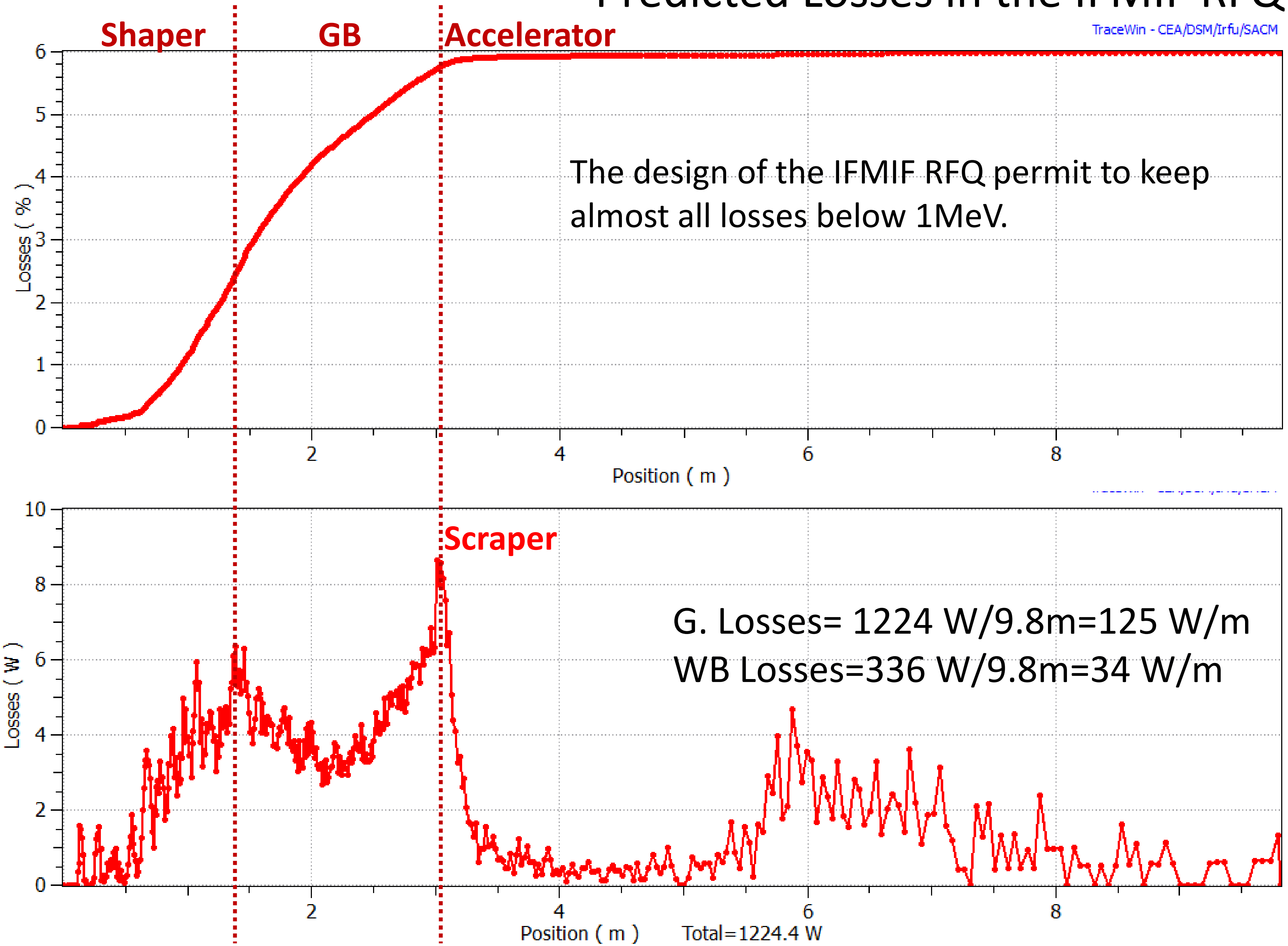


Equipartitioning for IFMIF RFQ

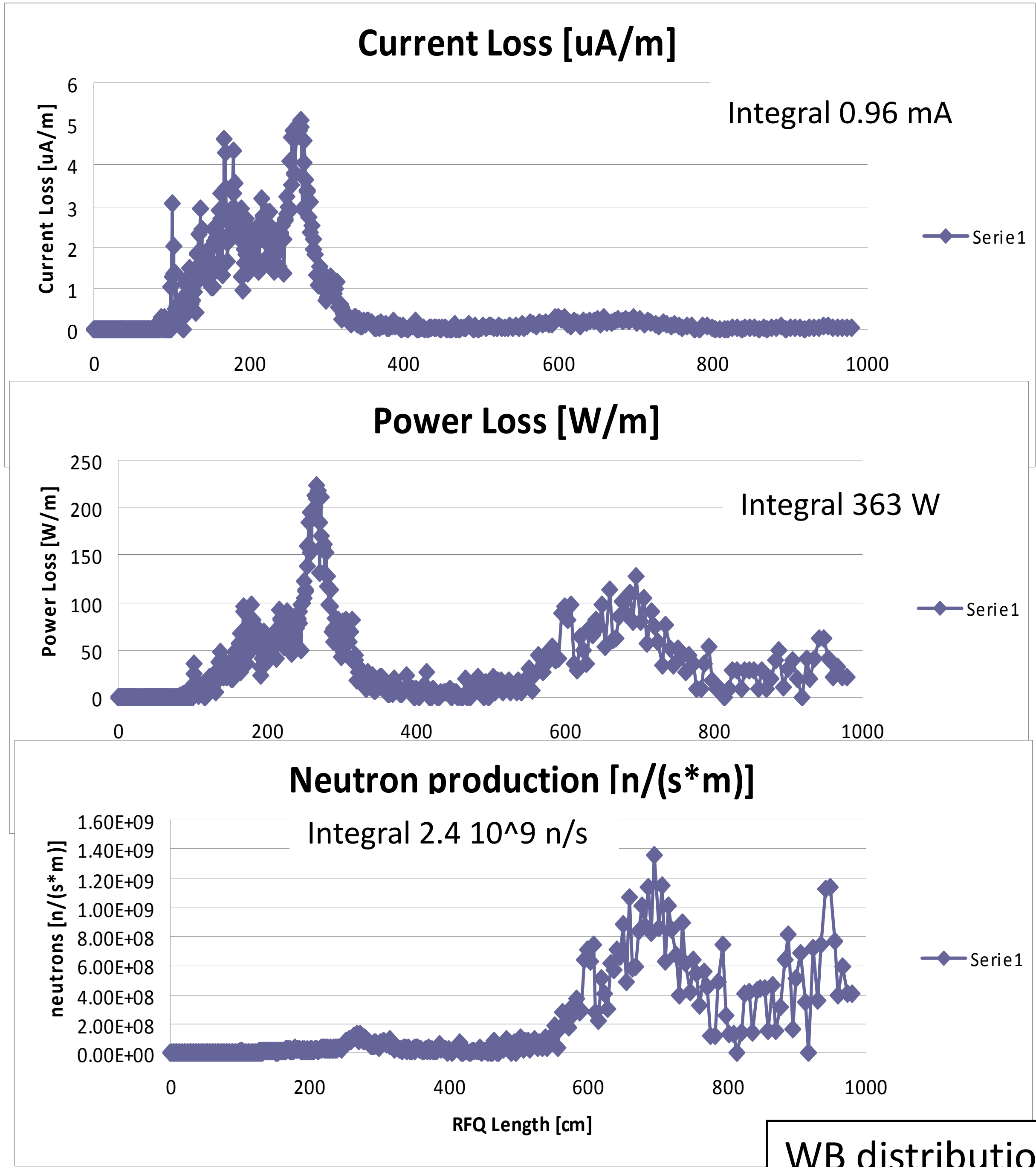


Stability chart, with overlapped the phase advance ratio for **Shaper, G. Buncher,** and **Accelerator**

Predicted Losses in the IFMIF RFQ



Current 130 mA, Erms=0.25 mmmrad, **Gaussian Dist.**, matched solution



Beam losses in IFMIF RFQ

To achieve Beam losses concentrated in the low energy part is very important since neutron production is proportional to Energy^2

$$n = 5.15 * 10^{-7} N w^{2.1}$$

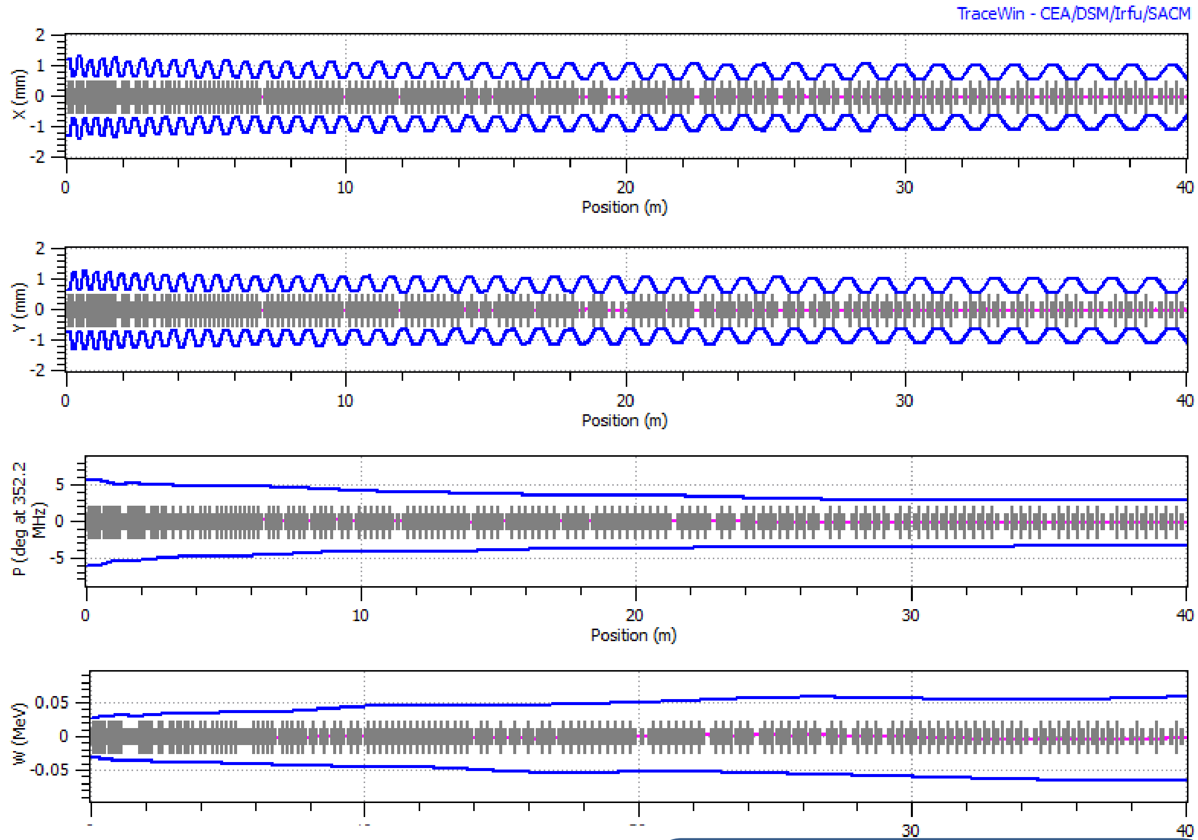
WB distribution 0.25 mm mrad rms norm I=130 mA

Example of SPES DTL

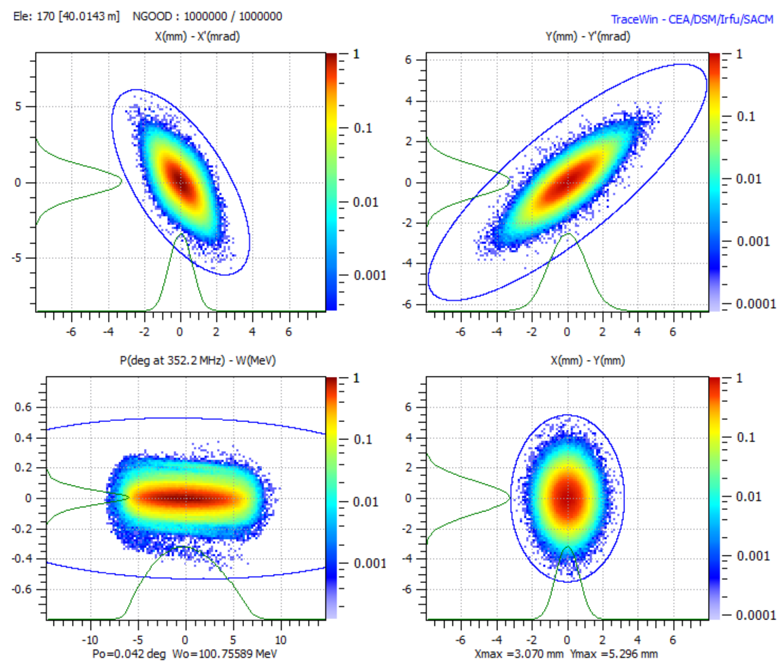
- Similar in the design of Linac4 DTL
- Can be a starting point for the ESS-DTL

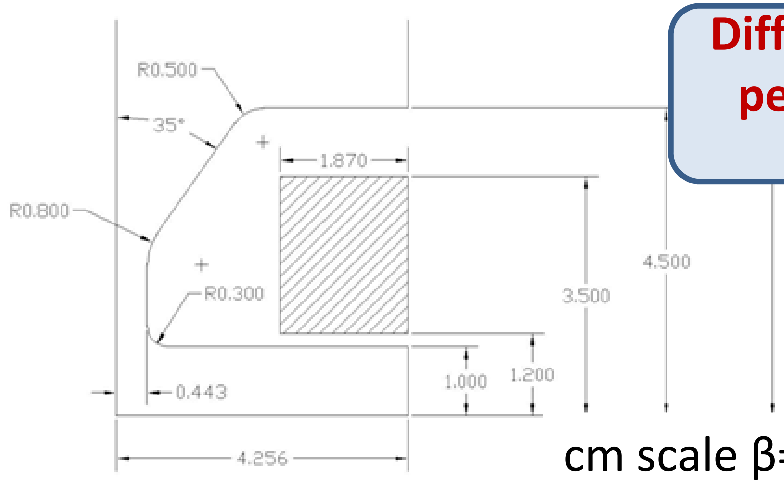
A 2008 proposed SPES driver, is composed by a four vanes RFQ and an Alvarez DTL, generates a high intensity beam, for an average current of 1.5 mA and an energy of 43 MeV, upgradable to 95 MeV. The high rep rate (50 Hz) is necessary for the correct mechanical behavior of the target.
The accelerator is composed by the source **TRIPS, built at LNS** and now in operation at LNL, by **the RFQ of TRASCO** research program (5 MeV 30 mA), finish in the construction, and by a normal conducting Drift Tube Linac (DTL). This last accelerating structure is the same proposed for **DTL of LINAC4** at CERN. A prototype of this structure, has been constructed in Italy with the joint effort of CERN and LNL.

SPES DTL



Proton beam @ 352 MHz
Energy from **5** to 100 MeV
FFDD Lattice
Current of 50 mA
Gradient from 50 to 45 T/m
Phase sync. from -35° to -20°
RMS N. Input emittance 0.2 mmmrad
DTL bore radius=10 mm
RF Fields by SuperFish cell by cell
Bore /RMS beam size=10

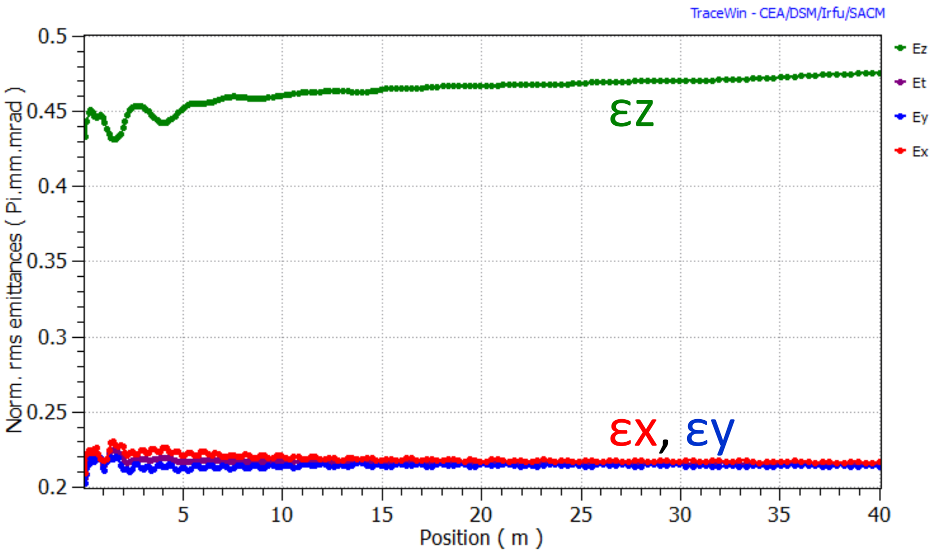


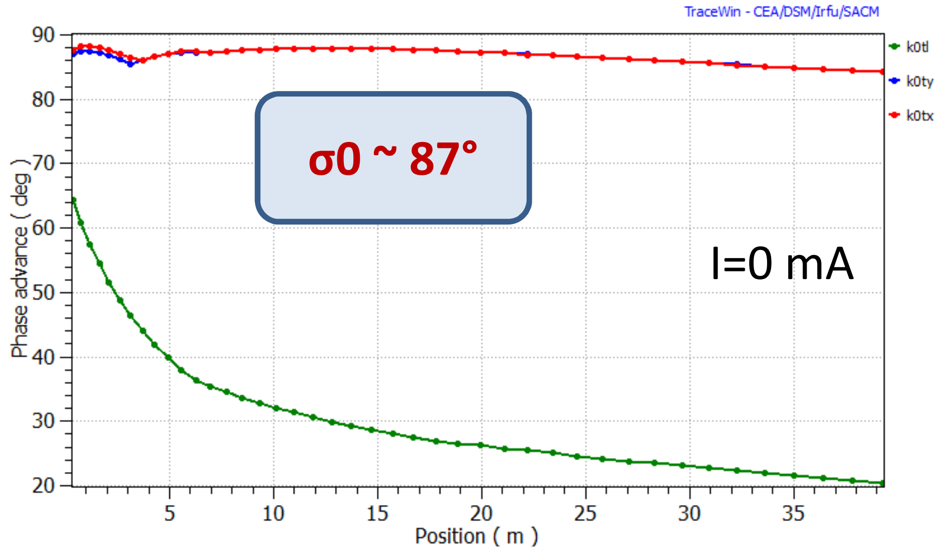


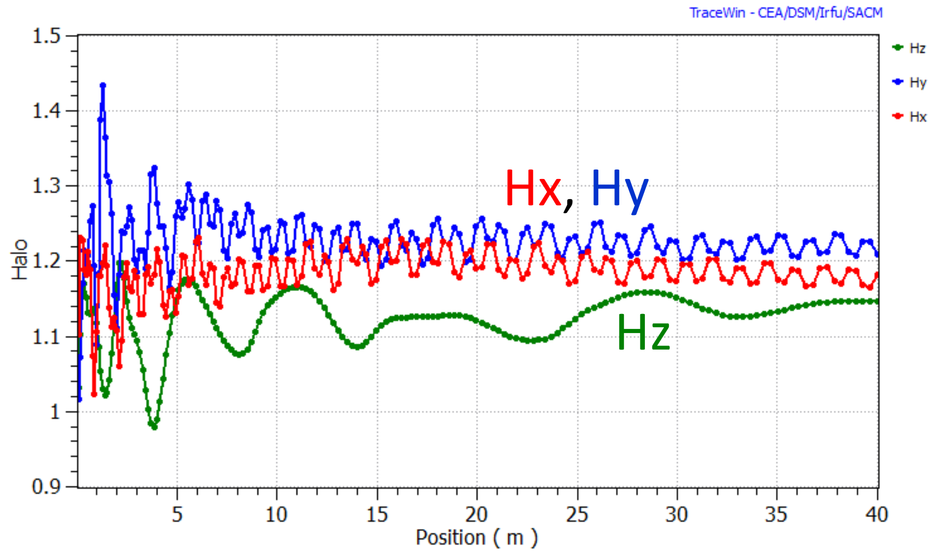
Difficult to allocate the permanent quads at low energy

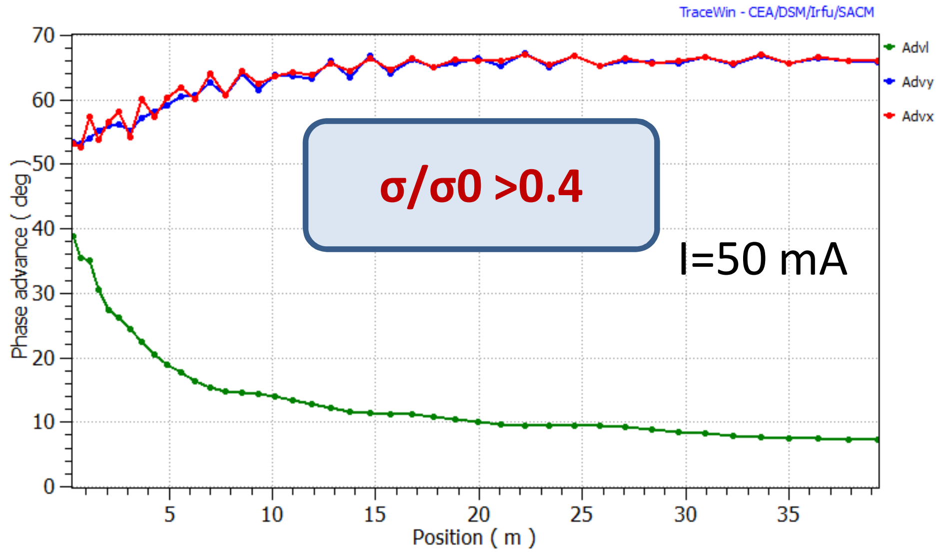
cm scale β=0.11 DTL nose

Phase advance, Emittance and Halo in SPES DTL

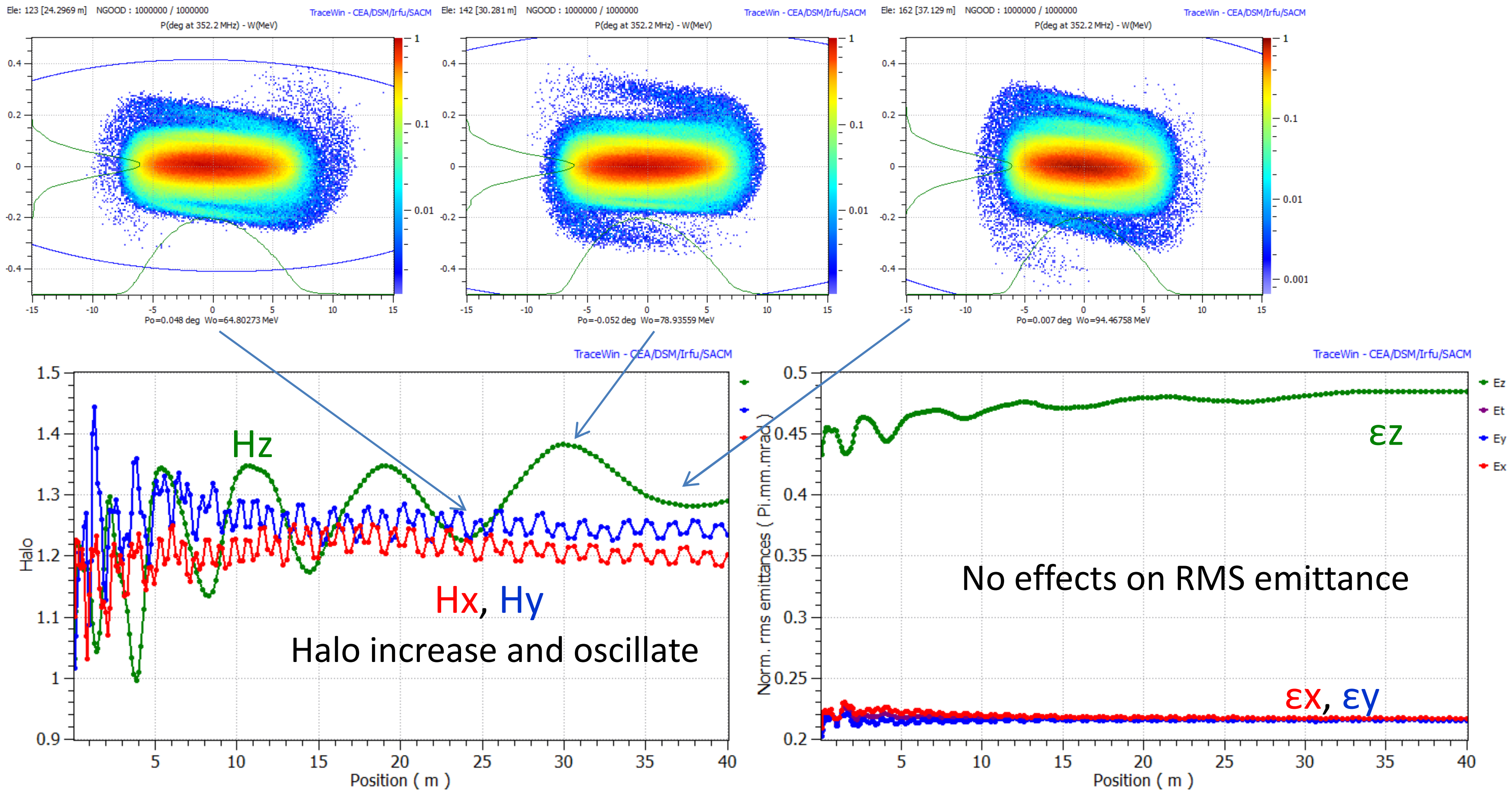




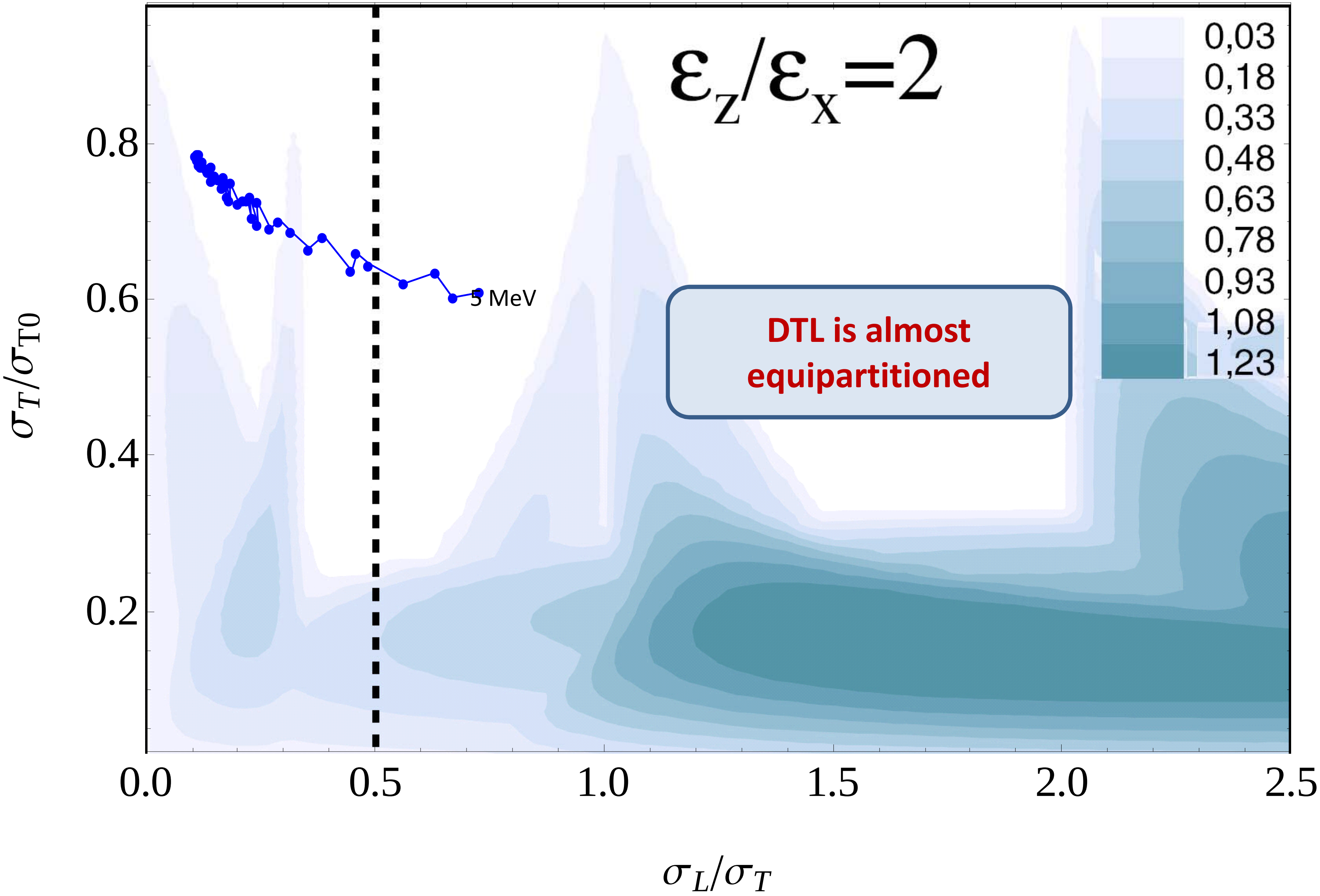




Effects of Longitudinal Mismatch on SPES DTL



Equipartitioning for SPES DTL



Conclusion

- Beam loss control and reliability only by “good” design.

- Beam Reliability issues:
  - Redundancies Hardware.
  - Flexible lattice.
  - Large Longitudinal acceptance.

- High Energy Linac:
  - For avoid beam losses is very important to mitigate beam halo formation at low energy (RFQ and DTL).
  - Look at Equipartioning in the RFQ and DTL and at the Longitudinal emittance formation.

- Low Energy Linac:
  - No problem by the emittance growth.
  - Use large cavity bore: Bore/rms>10.
  - MEBT matching between NC section and SC section.