EUROPEAN SPALLATION SOURCE

INFN

BEAM DYNAMICS DESIGN OF ESS WARM LINAC

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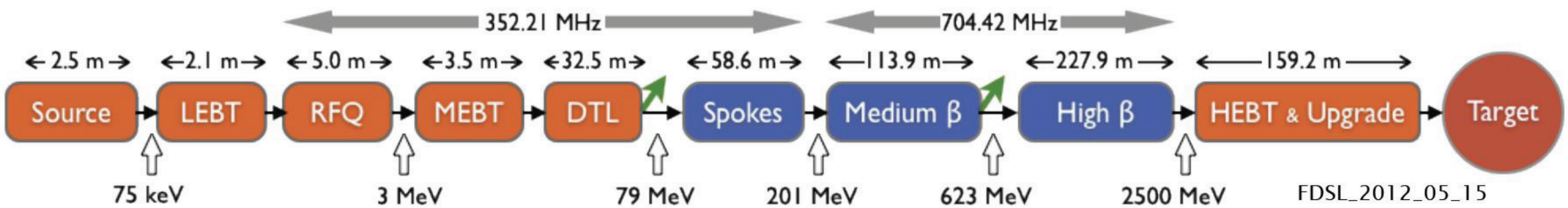
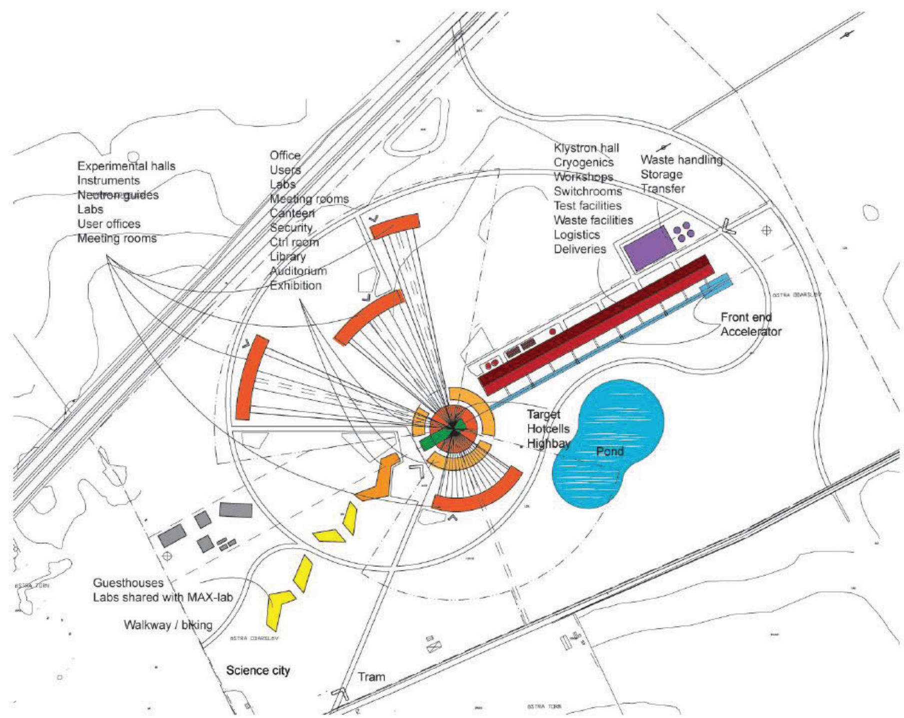
Outline

- ESS Parameters
- SOURCE
- LEBT
- RFQ
- MEBT
- DTL

ESS parameters



Particle species	p
Energy	2.5 GeV
Current	50 mA
Average power	5 MW
Peak power	125 MW
Pulse length	2.86 ms
Rep rate	14 Hz
Max cavity surface field	40 MV/m
Operating time	5200 h/year
Reliability (all facility)	95%



SOURCE

Proton Source Requirements

Proton Energy 75 keV

Large currents (60-**80** mA)

Pulsed operation (**2.86 ms - 14 Hz**)

Low emittance (**0.2** to 0,3 π mm mrad)

Short pulse rise time (100 ns)

Long lifetime (>> 1 month)

Robust extraction system

High reliability (> 99%)

LEBT optimization

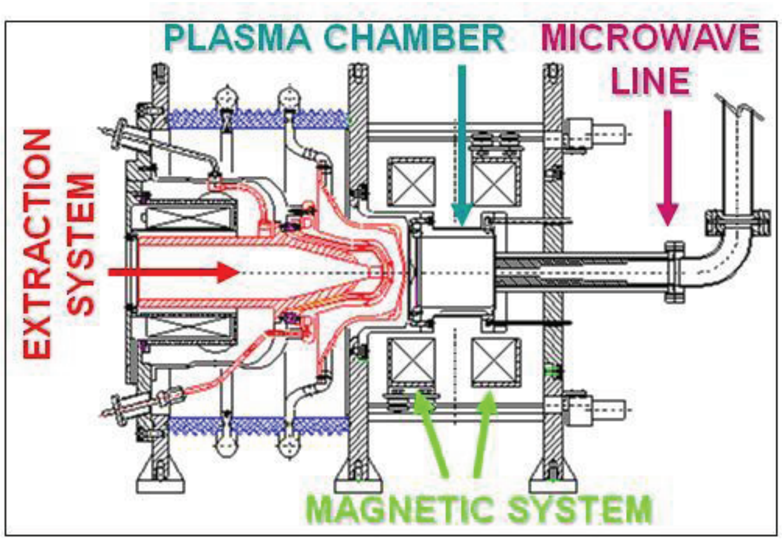
Issues: experimental investigations planned to validate calculations

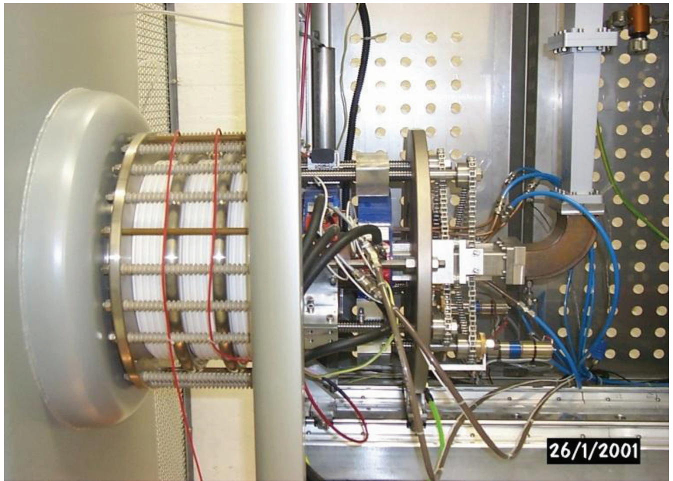
Proton source

Based on knowledge acquired with TRIPS, SILHI and VIS high intensity proton sources

	Status
Beam energy	80 keV
Proton current	55 mA
Proton fraction	≈80%
RF power, Frequency	Up to 1 kW @ 2.45 GHz
Axial magnetic field	875-1000 G
Duty factor	100% (dc)
Extraction aperture	6 mm
Reliability	99.8% @ 35mA (over 142 h)
Beam emittance at RFQ entrance	0.07πmmmrad @ 32 mA

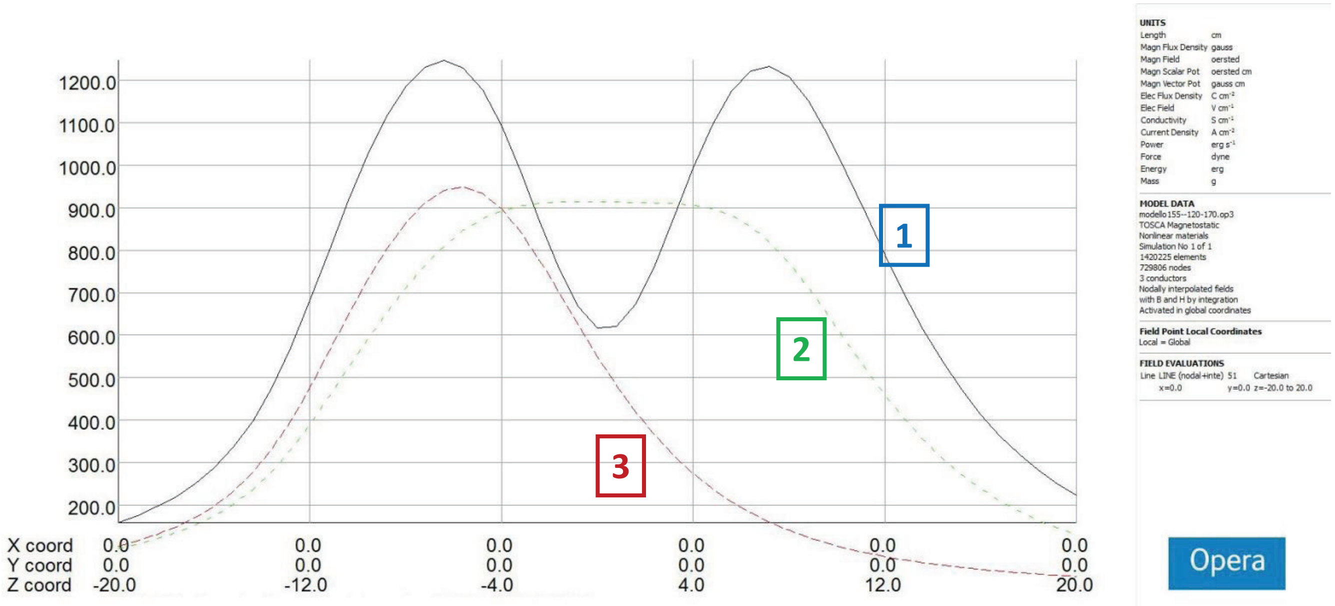
TRIPS



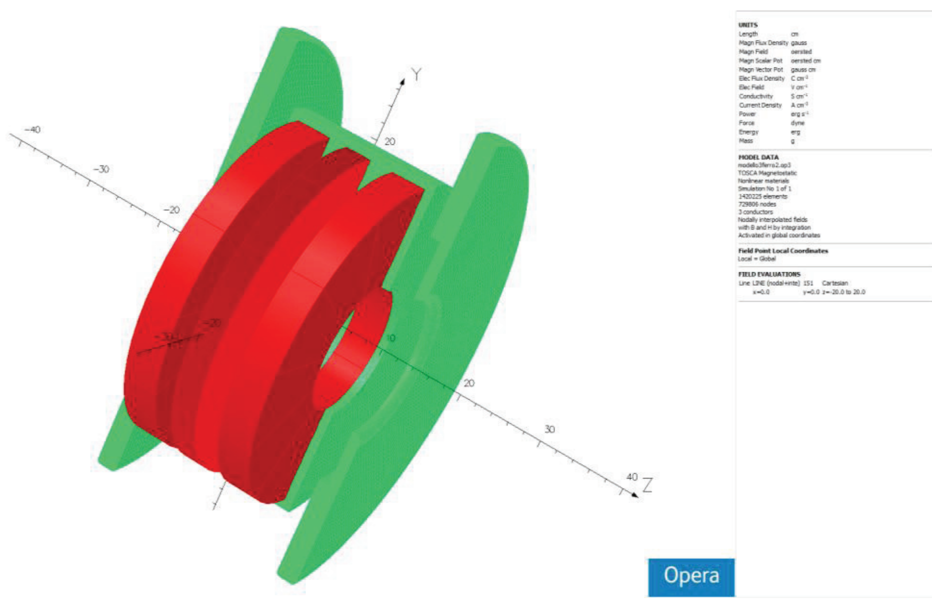


- **Movable magnetic system composed by two solenoids**
- **Five electrodes extraction system**

Flexible Magnetic field

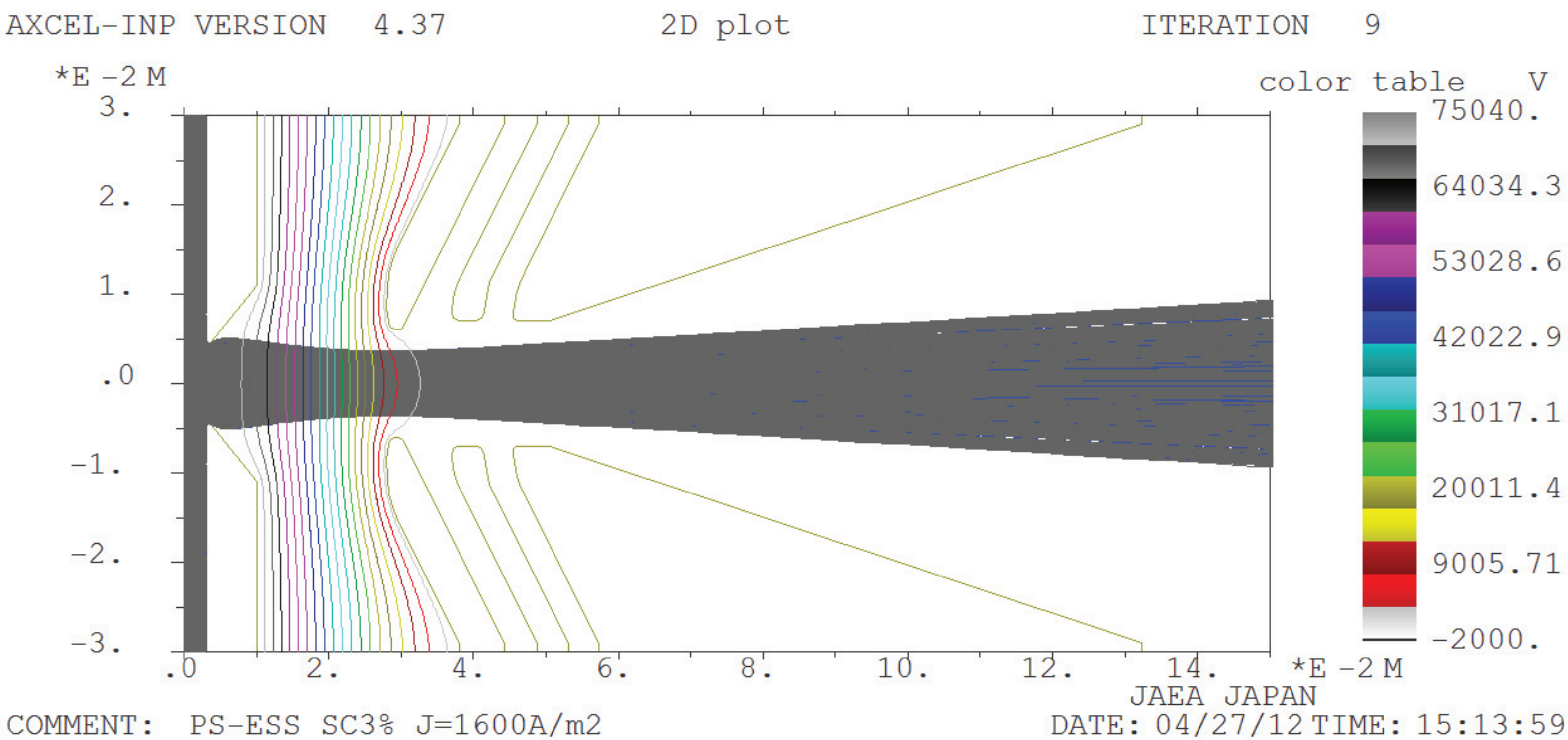


1. "Simple Mirror"
2. "Off-Resonance "
3. "Magnetic Beach"



current [A]	Inj	Med	Ext
Simple Mirror	400	-300	400
Off-Resonance	155	120	170
Megnetic Beach	260	0	0

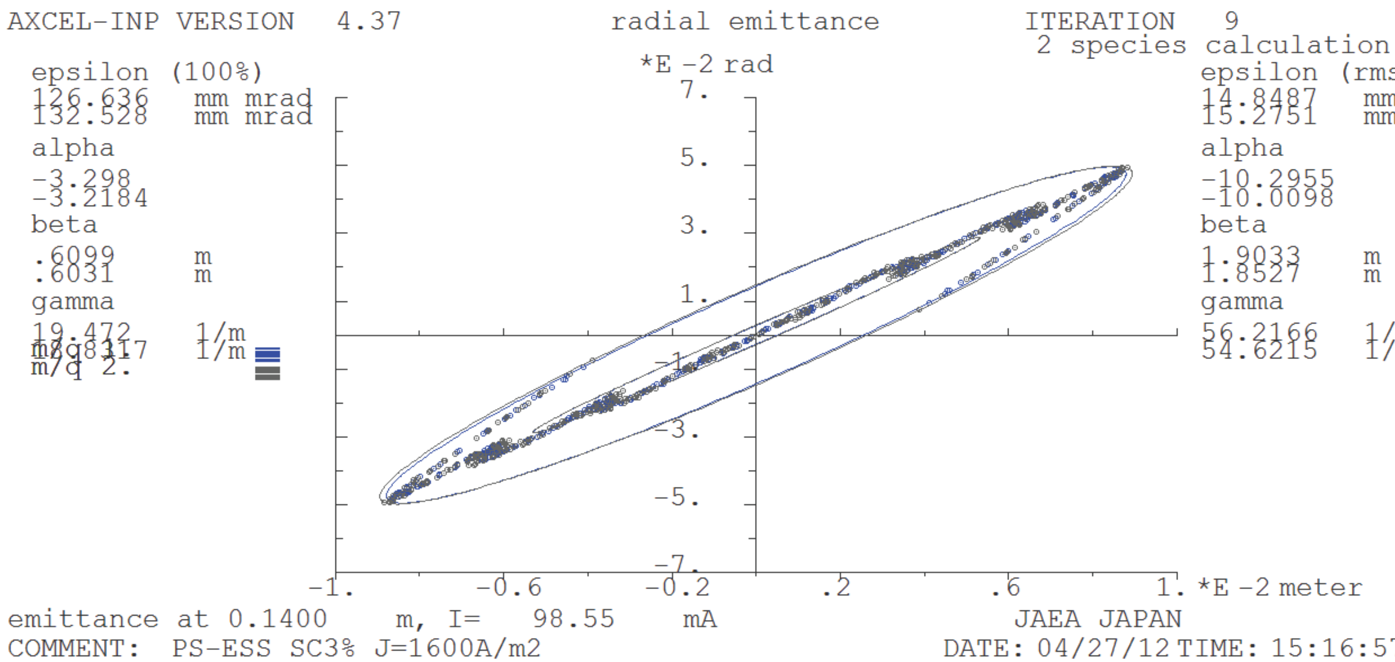
PS-ESS beam extraction



Itot= 98.55 mA

(H^+=90%; H_2^+=10%)

PS-ESS beam extraction



Alpha =-10.2955
Beta = 1.9033

Proton beam emittance rms norm. @ 0.14 m = 0.126 pi mm mrad

AXCEL Beam output @ 0.14 m has been used as input for TRACEWIN simulations.

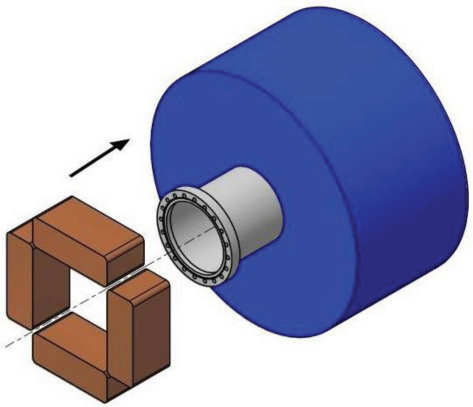
SOURCE status

- The required for the ESS facility can be satisfied by means of conventional Microwave Discharge Ion Source (MDIS) based on the plasma direct absorption of the pumping electromagnetic waves through the Electron Cyclotron Resonance mechanism.
- In PS-ESS design we merged the best solutions already tested in previous sources with a flexible magnetic system able to produce both standard and new magnetic profiles that will allow us to increase the current, increase the proton fraction, reduce the emittance and take under control the beam formation.

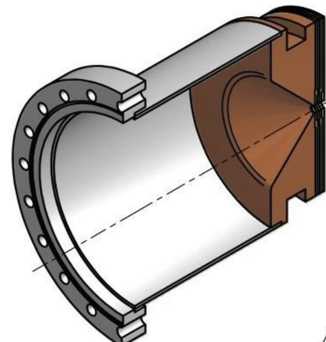
LEBT

LEBT design

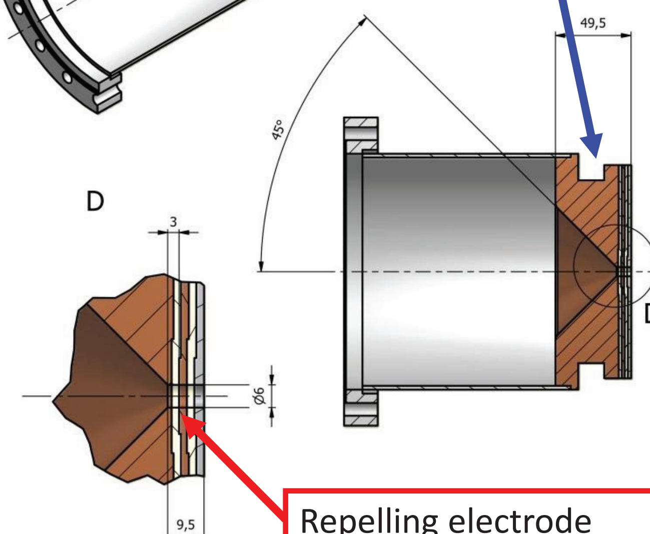
Solenoid assembled with steerer



RFQ collimator used to dump the chopped beam

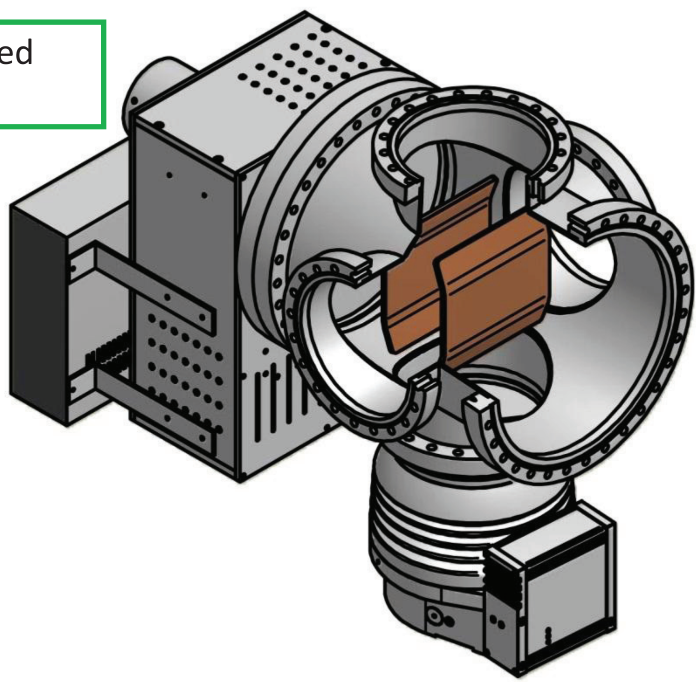


Cooling system will be sized for full beam power (300W)

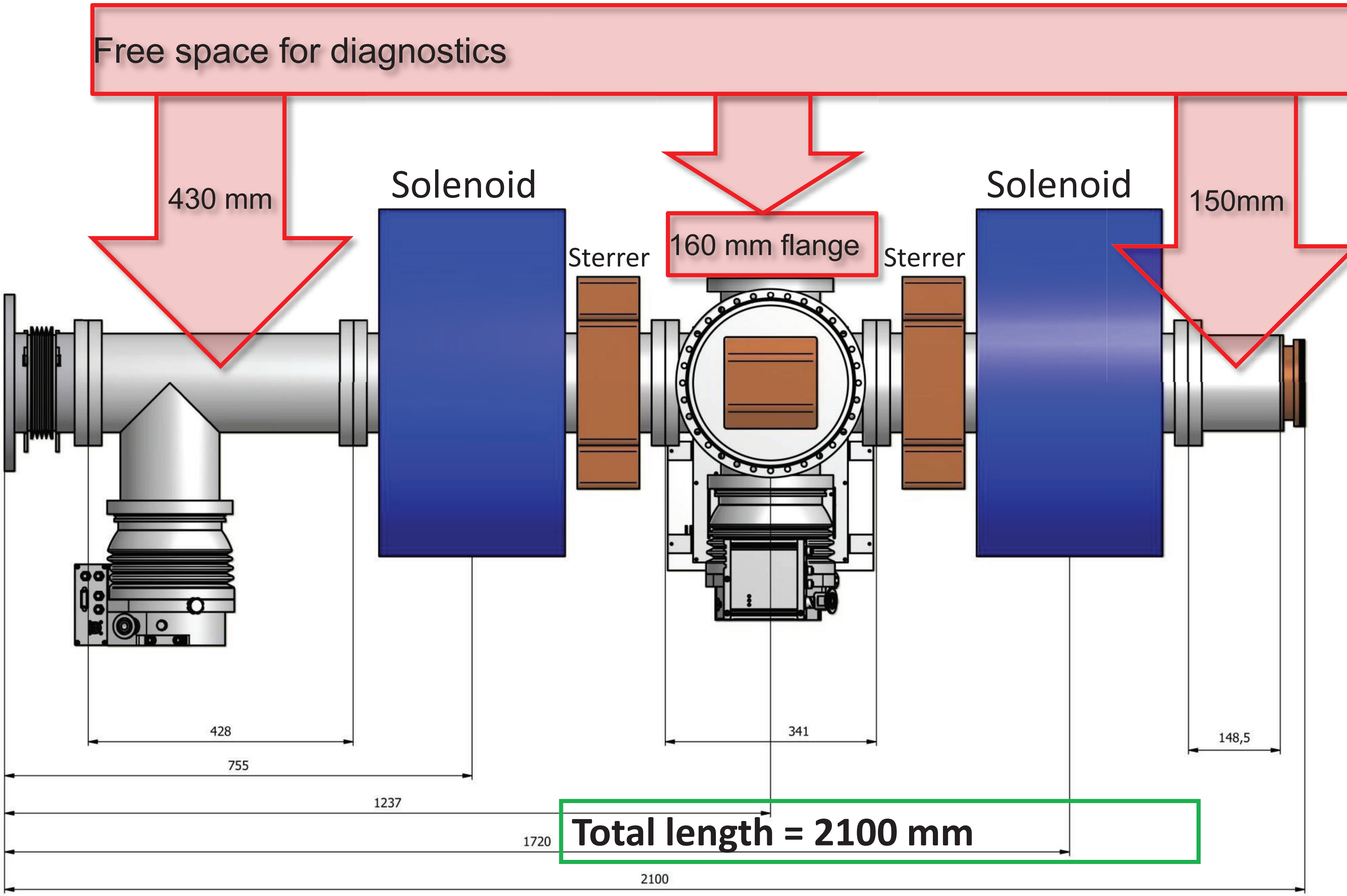


Repelling electrode

Chopper assembled with TMP

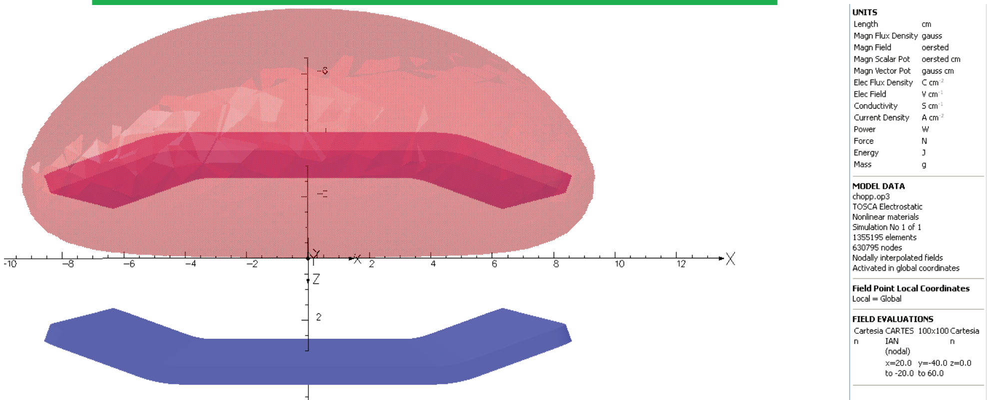


LEBT configuration

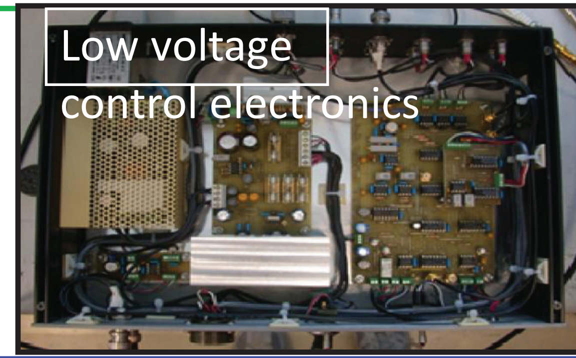


Chopper

Chopper plates was bent of 20°
to flat transversal electric field



Electronics developed by INFN-LNS for
SPIRAL 2 project
already tested at CEA-IRFU



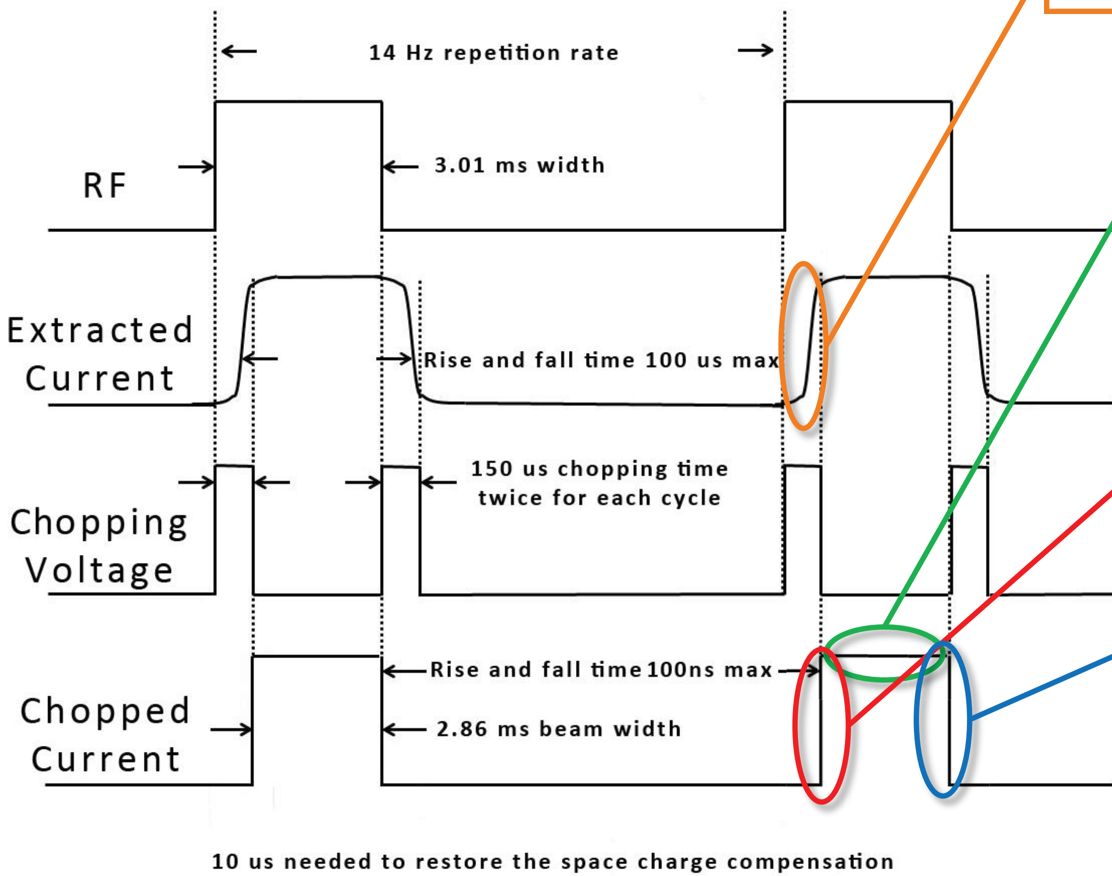
Measured performance @ 10kV:
- ✓ Rise and fall time of 13-15 ns (A,B)
- ✓ Up to 1.3 KHz of repetition rate (C)

ESS requirements:
- ✓ Beam rise and fall time of 100 ns
- ✓ 14 Hz repetition rate

Yellow = HV signal Blue = TTL driver Purple = pick-up signal

Pulse beam formation

ESS requirements:
- 14 Hz repetition rate
- 2.86 ms beam width
- Emittance < 0.2 π.mm.mrad
- 100 ns rise and fall time



Highly divergent beam during source startup must be stopped

Low emittance growth and Twiss parameters coupled to RFQ acceptance are required

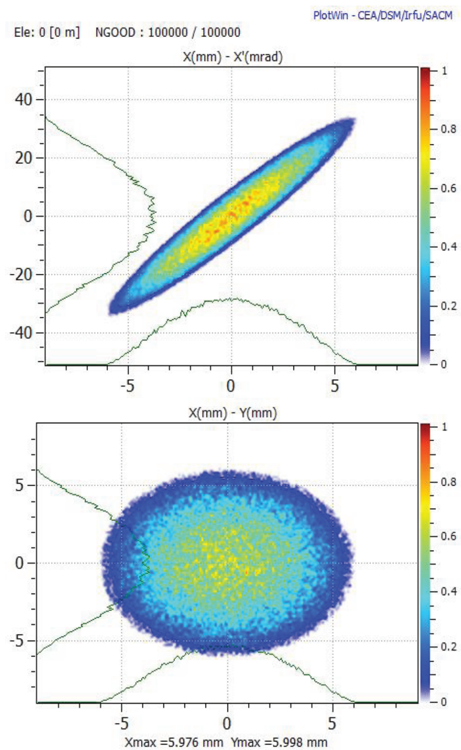
- Estimate and reduce the rise time
- Estimate the charge that must be cut by MEBT-Chopper

Estimate the fall time

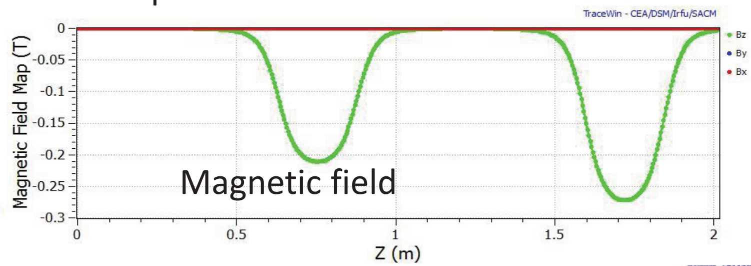
Steady state

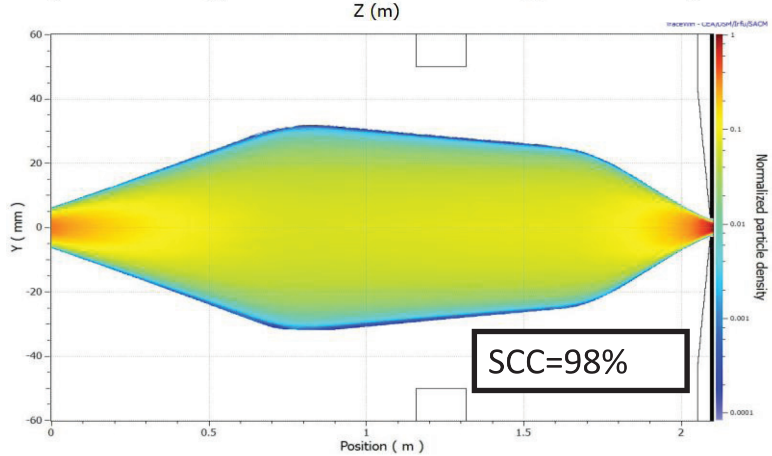
Output of Axcel extraction system simulation

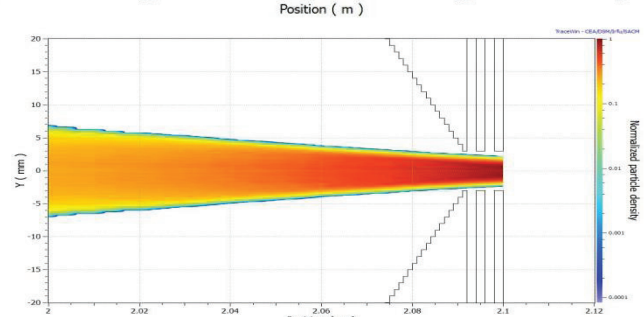
X-X'
Emit [rms] = 0.1260 Pi.mm.mrad [Norm.]
Emit [97%] = 0.6300 Pi.mm.mrad [Norm.]
Beta = 0.6099 mm/Pi.mrad
Alpha = -3.2980



Optimum magnetic configuration have been found with TraceWin beam transport simulation…

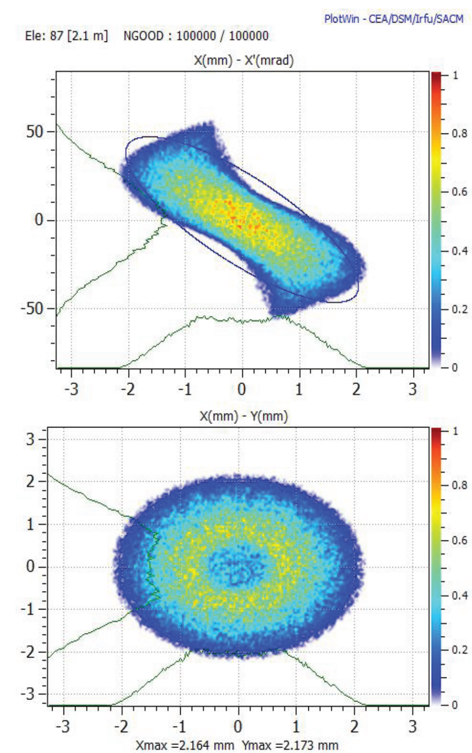






…to match RFQ twiss parameters

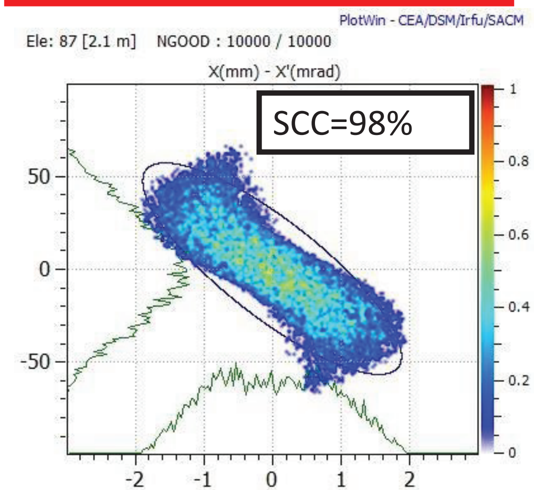
X-X'
Emit [rms] = 0.1525 Pi.mm.mrad [Norm.]
Emit [93%] = 0.7623 Pi.mm.mrad [Norm.]
Beta = 0.0587 mm/Pi.mrad
Alpha = 1.4715

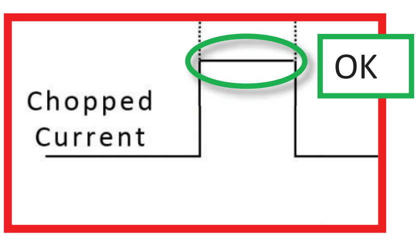


Necessity of high SCC value

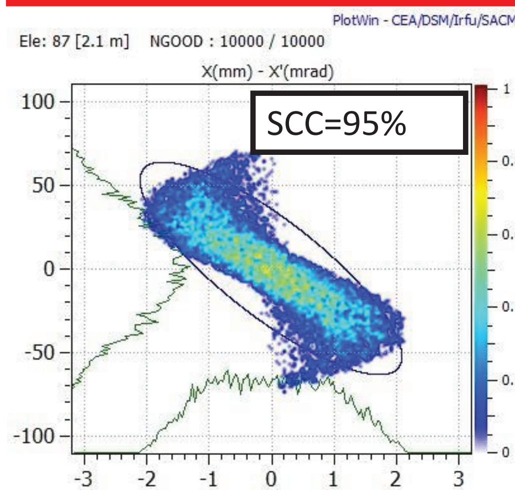
ESS requirement : Emittance < 0.2 π.mm.mrad

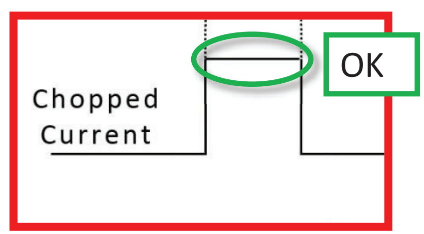
X-X'
Emit [rms] = 0.1525 Pi.mm.mrad [Norm.]
Emit [93%] = 0.7623 Pi.mm.mrad [Norm.]
Beta = 0.0587 mm/Pi.mrad
Alpha = 1.4715



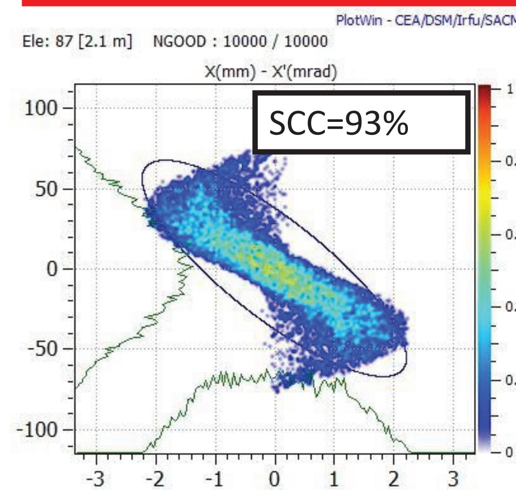


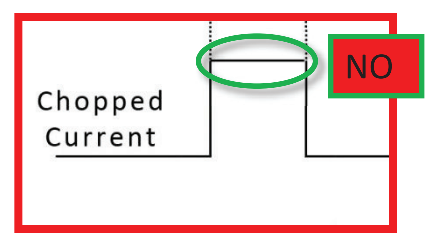
X-X'
Emit [rms] = 0.1896 Pi.mm.mrad [Norm.]
Emit [93%] = 0.9479 Pi.mm.mrad [Norm.]
Beta = 0.0588 mm/Pi.mrad
Alpha = 1.4751





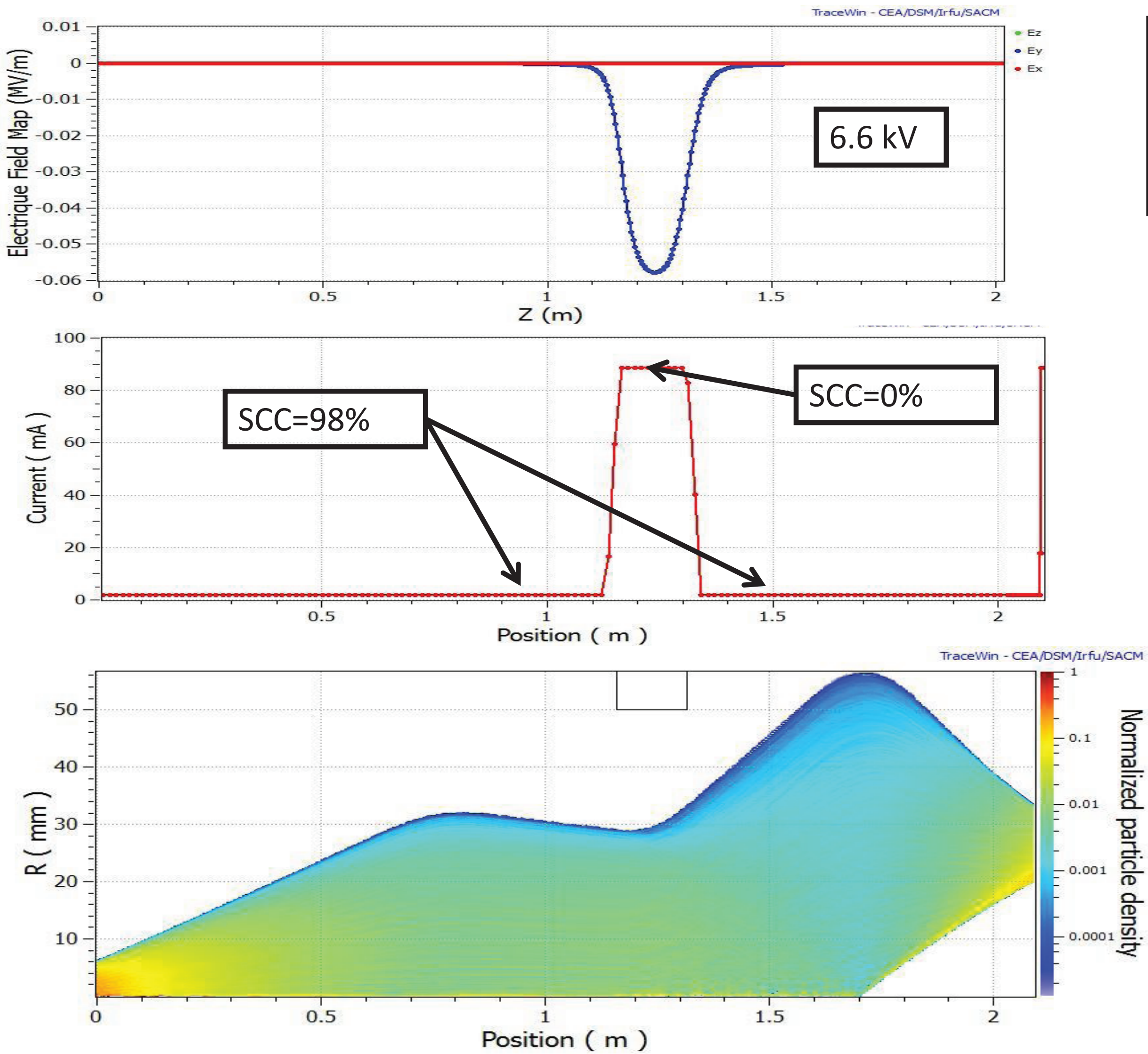
X-X'
Emit [rms] = 0.2118 Pi.mm.mrad [Norm.]
Emit [93%] = 1.0590 Pi.mm.mrad [Norm.]
Beta = 0.0588 mm/Pi.mrad
Alpha = 1.4765

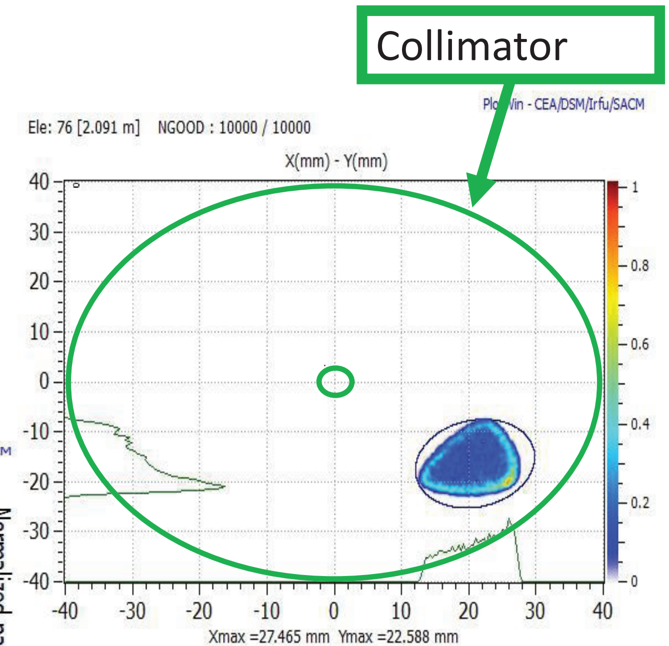




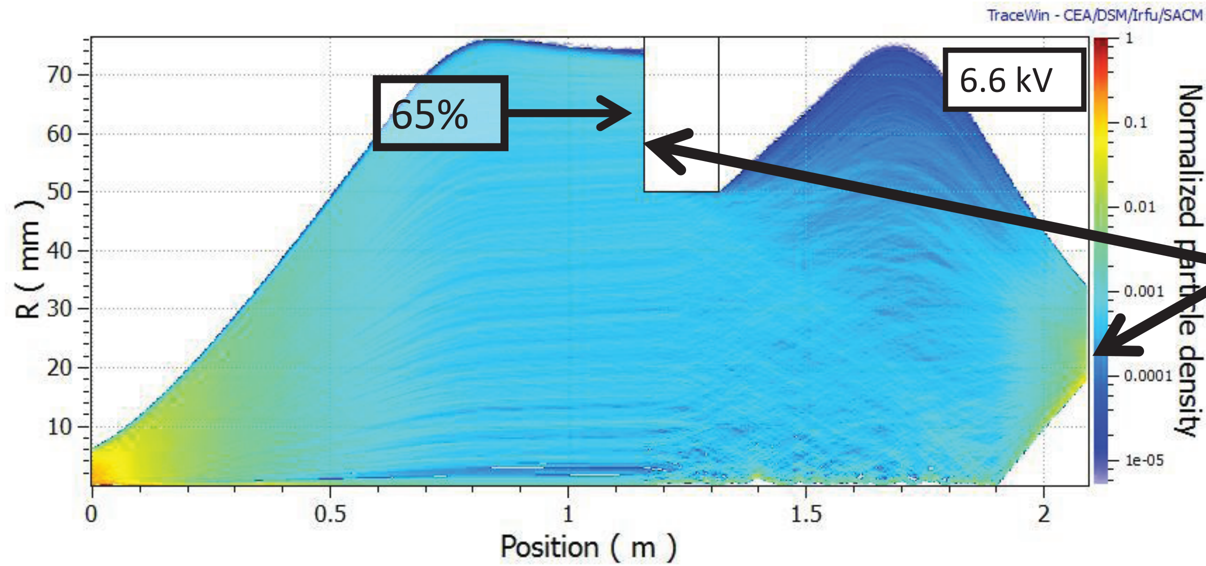
Chopped beam

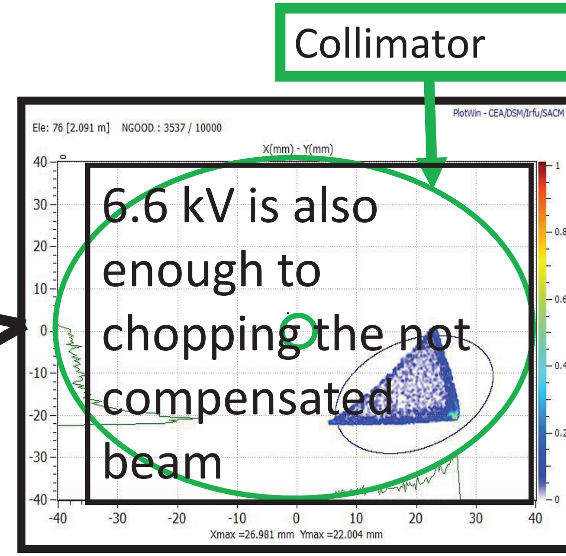
6.6 kV is enough to chopping the beam into the collimator

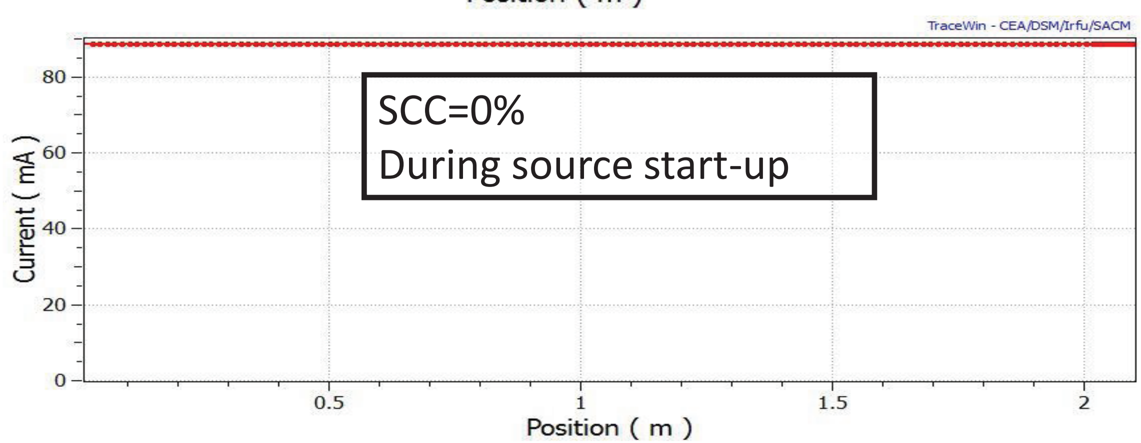


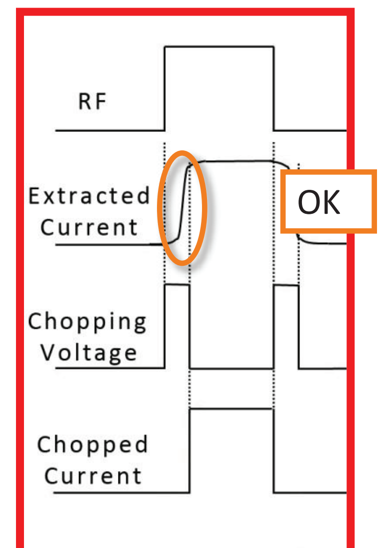


Chopping of not compensated beam









LEBT status

- To fulfill 100ns beam rise time requirement a MEBT CHOPPER is mandatory.
- It is necessary an high Space Charge Compensation, more than 95%, to avoid emittance growth and compensate LEBT Chopper effects.
- The SCC can be speed-up by injecting Argon.

RFQ

RFQ DESIGN EVOLUTION

Motivations for a shorter RFQ

Performance requirements

Previous design

- Initial operation at a peak beam current of 50 mA but upgradable at 75 mA
- Beam loss above 2 MeV limited to 1 W/m to limit activation
- Transverse and longitudinal emittances minimized to reduce potential for subsequent halo development
- No longitudinal tails as they are known to translate into transverse halo

Current design

- Peak operational beam current will not exceed 50 mA
- No limit to allowable beam loss below 3 MeV
- Halo development and beam loss in the high energy linac section traceable to the RFQ are minimized
- No longitudinal tails as they are known to translate into transverse halo
- Phase advances matched to adjacent sections

Benefits

- **Fabrication and operational risk**: less tuners, vacuum and RF seals, pumps, ...
- **Cost in machining and brazing**
- **Alignment**

Results

RFQ with 5 one-meter sections:

- High performance stand-alone structure
- Very long bunching section
- Slow rate of acceleration
- Fulfills all requirements

RFQ with 4 one-meter sections:

- Fully integrated in the linac
- Higher losses at high energy
- But very similar performances
- Fulfills all requirements

RFQ parameters

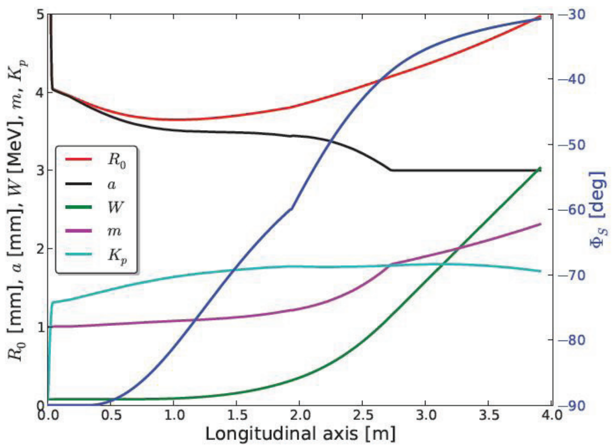


Figure 1: Main geometry parameters.

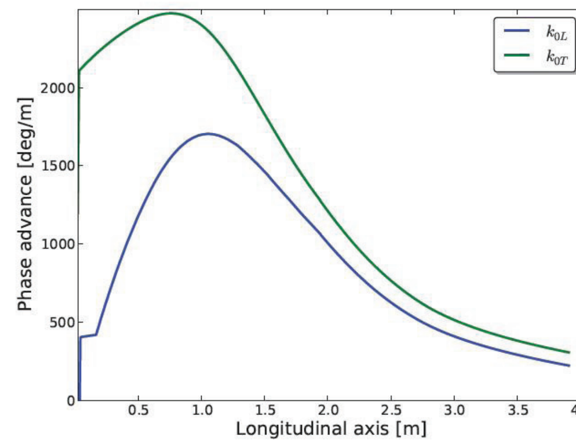


Figure 3: Phase advances.

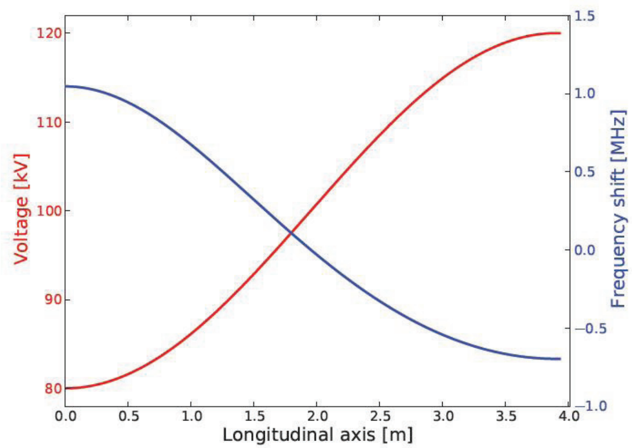


Figure 2: Voltage and 2 D frequency shift.

Emit rms=0.13 MeVdeg

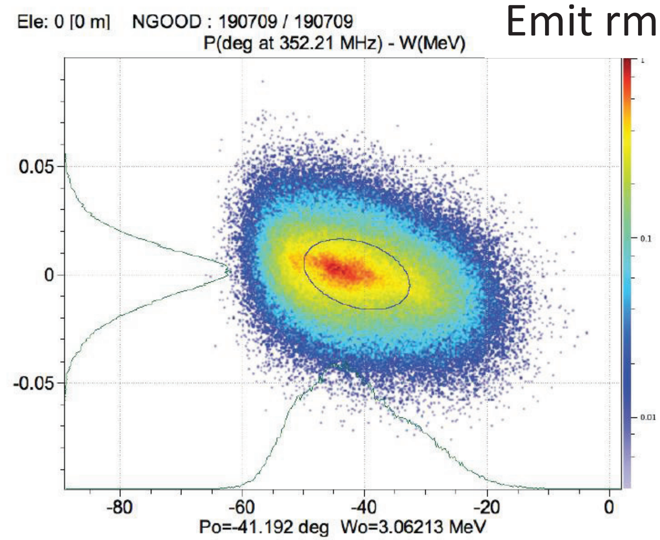


Figure 4: Beam portrait in longitudinal phase space.

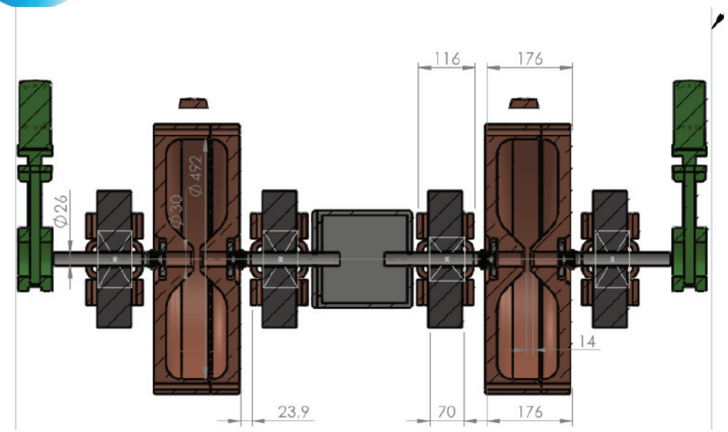
RFQ status

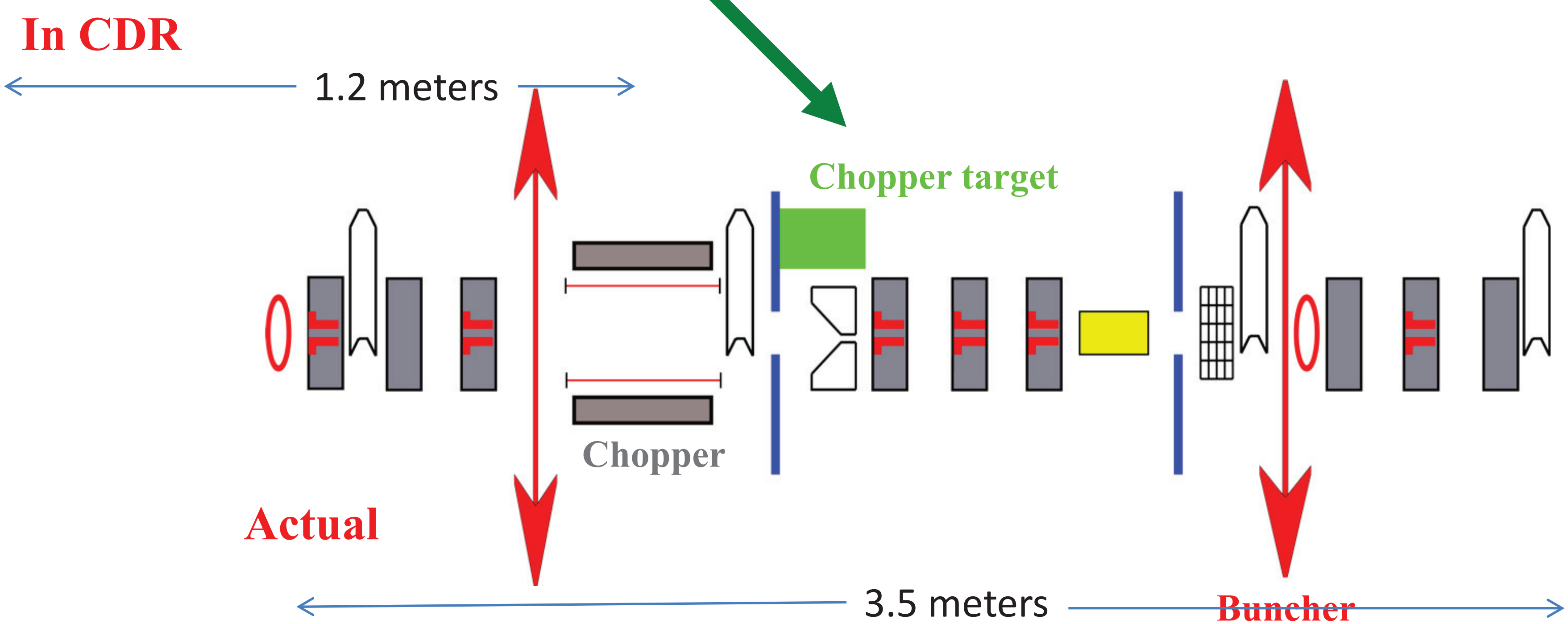
- The transmission is very high and the longitudinal distribution is tailless.
- Significant improvements in the integration of the RFQ design have also been achieved in parallel with the consolidation of the ESS linac physical design.
- The new RFQ design is fulfilling all the updated performance requirements and the fabrication and operational risks as well as the cost have also been lowered substantially.

MEBT

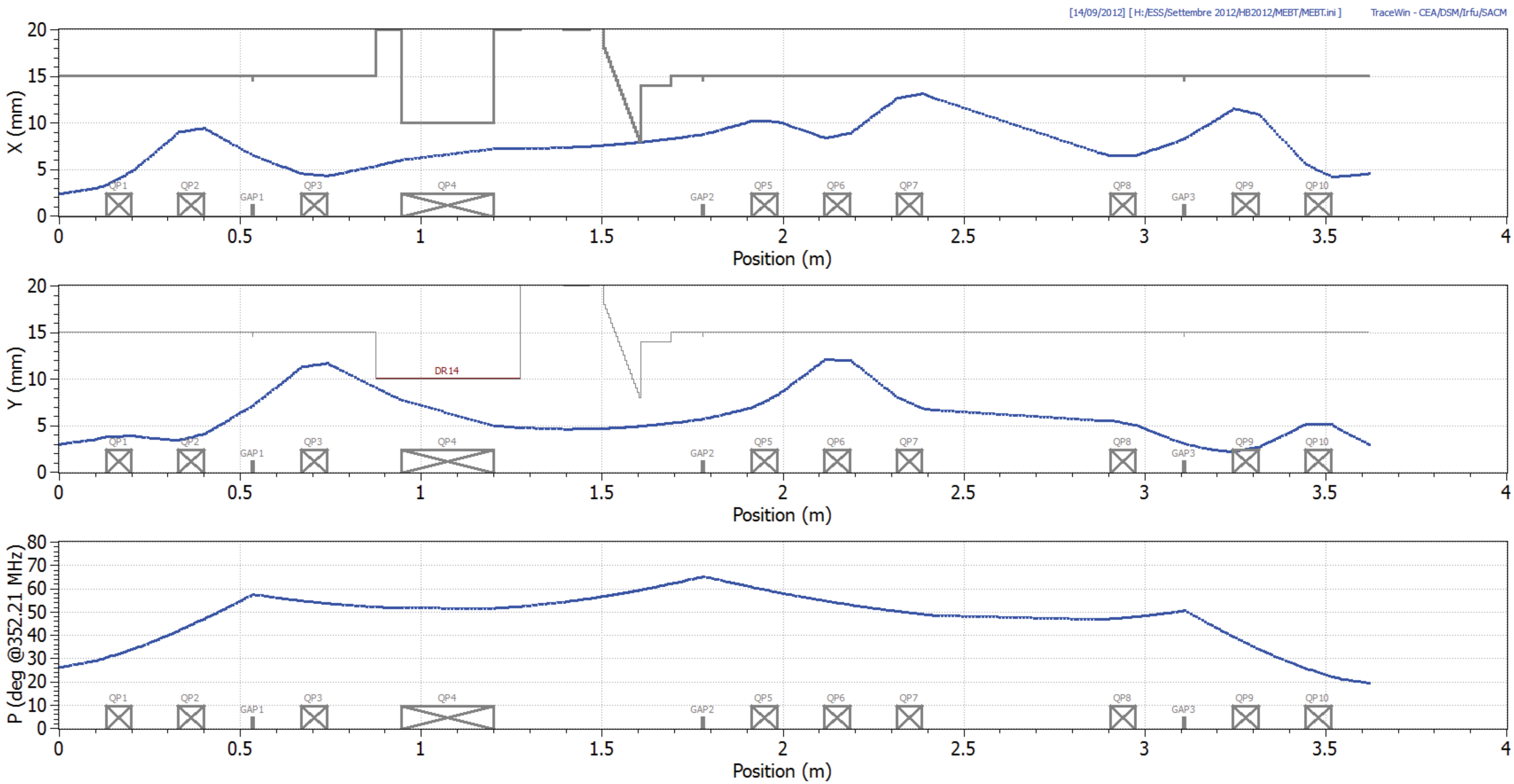
From a short to long MEBT

From the May 2012 baseline, the MEBT was extended to include
- Fast chopper
- Beam instrumentation
- Collimation

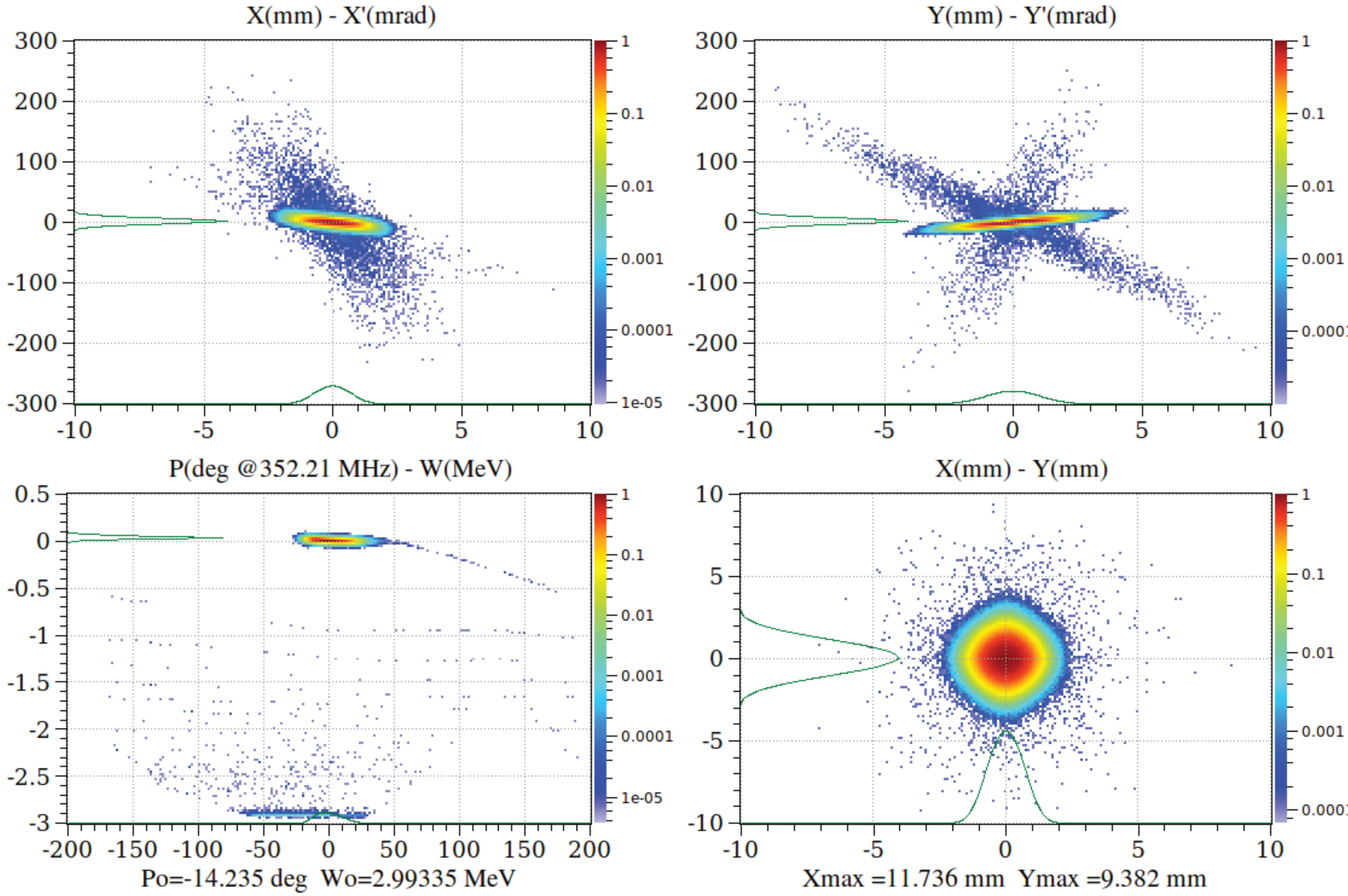




MEBT envelopes

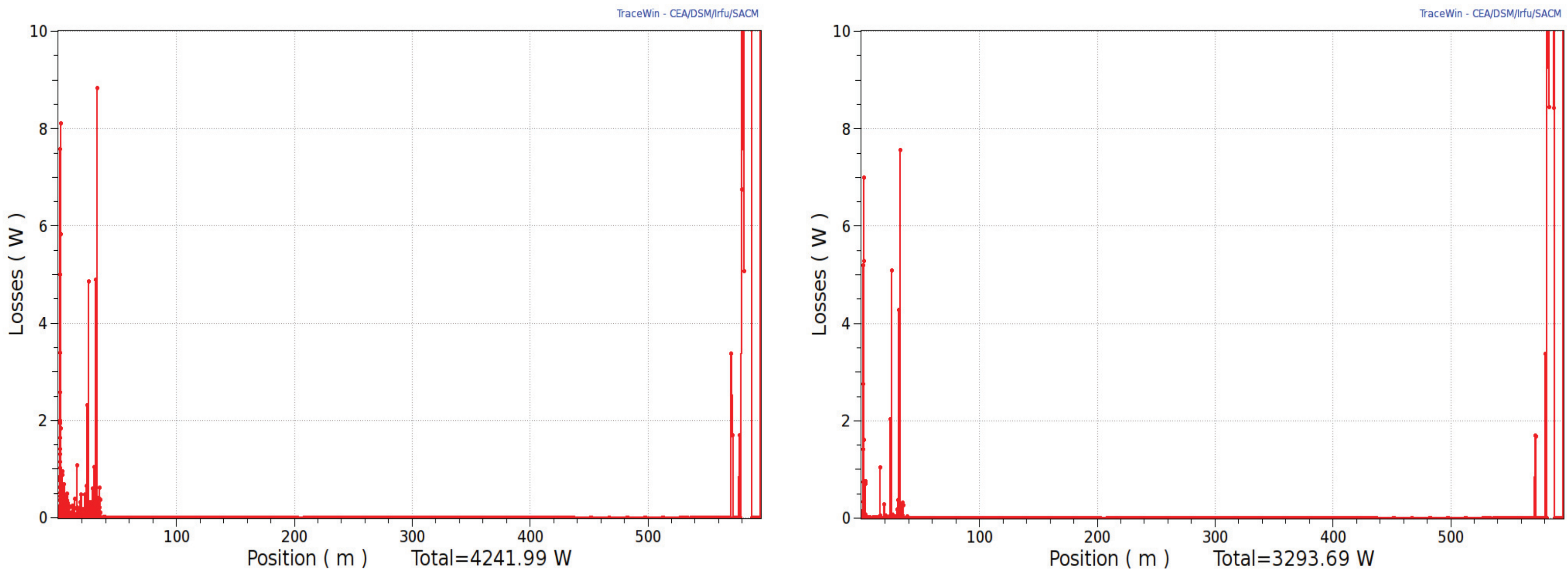


The RFQ un-captured particles



The RFQ simulation actually includes the un-captured particles.

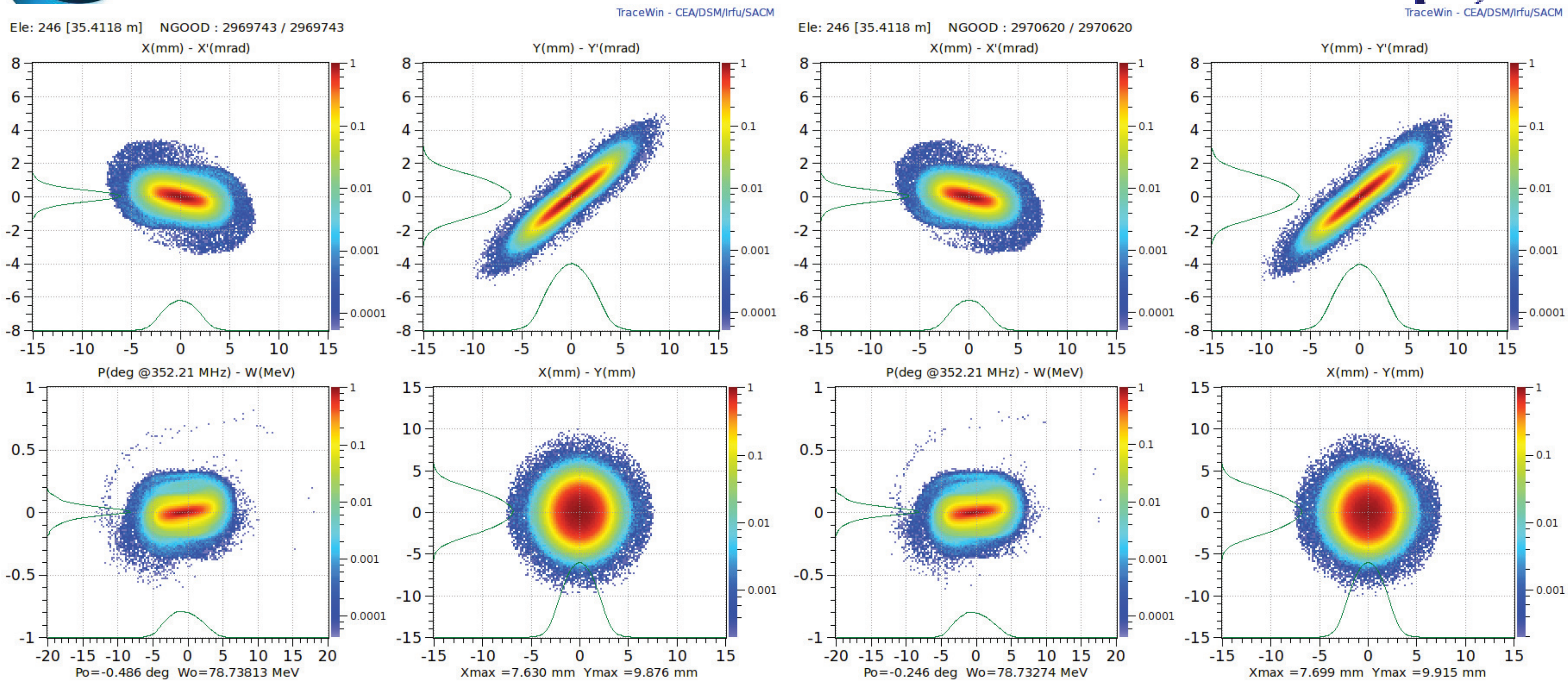
Loss w/ and w/o the cut



w/o cut **w/ cut**

Most of the un-captured particles seem lost by the end of the DTL. No loss in the SC part for both case but some difference in the HEBT.

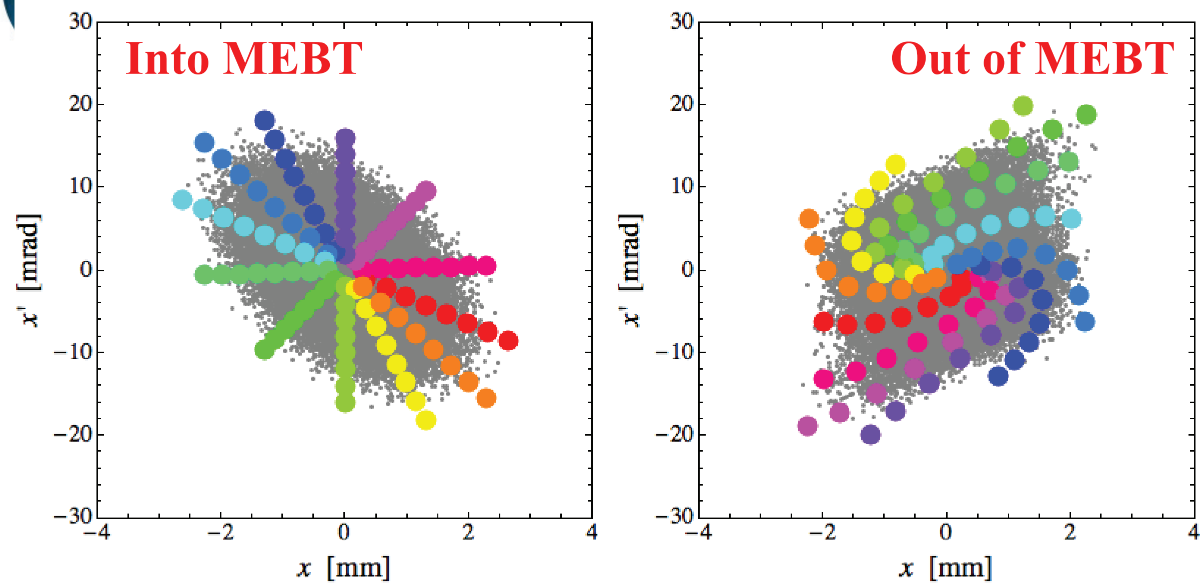
Distributions out of the DTL w/ and w/o the cut



w/o cut **w/ cut**

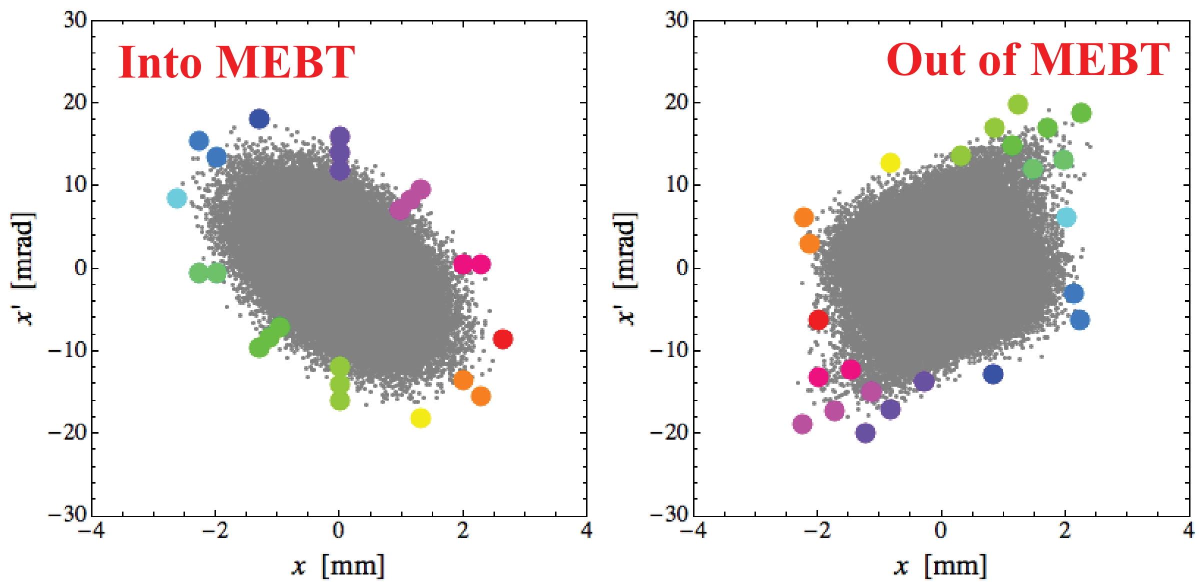
- Distributions become quite similar by the end of the DTL.
- The computation accurate for the un-captured particles?

How to decide collimator locations

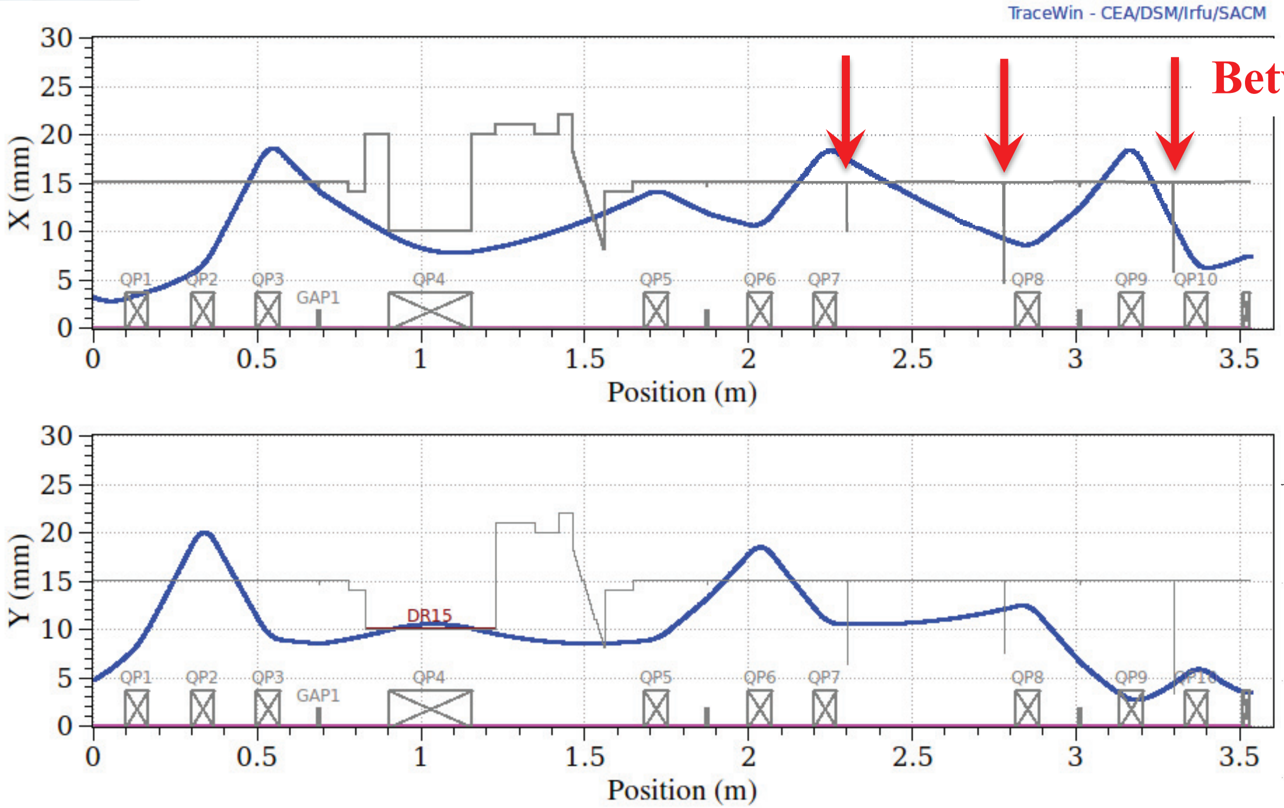


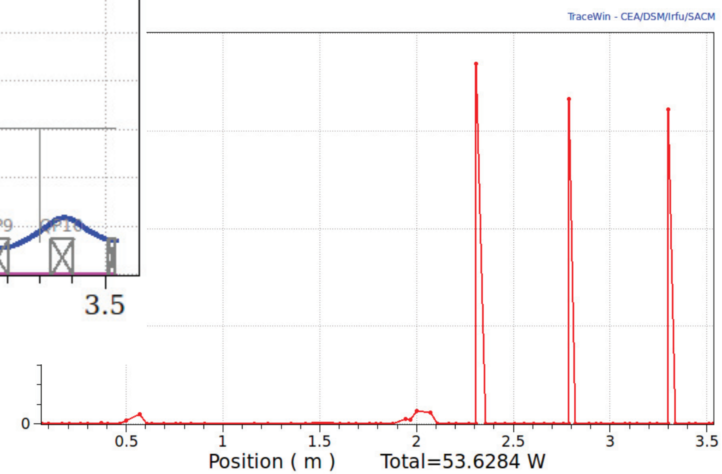
- Sample particles in the normalized phase space:
  - 0.5σ, 1.0σ, …, 4.0σ
  - 30°, 60°, …, 360°
- Space charge deforms the distribution

- Samples particles of 3σ and above at the end of the MEBT are left.
- Not all samples above 3σ at the entrance ends at above 3σ at the end.
- An effective collimation requires weights on specific angles even for a Gaussian distribution.



possible collimator locations for the MEBT

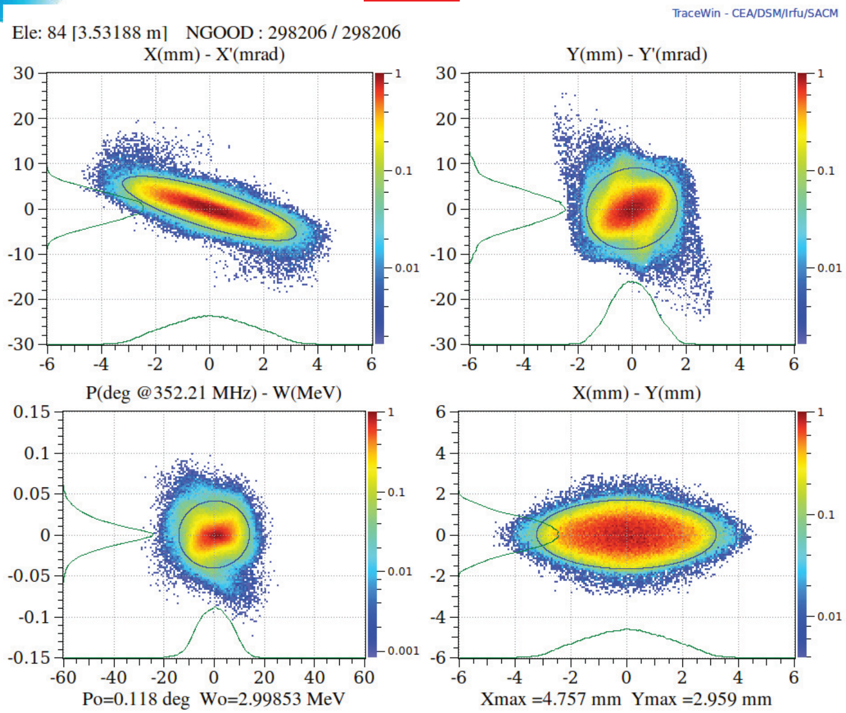


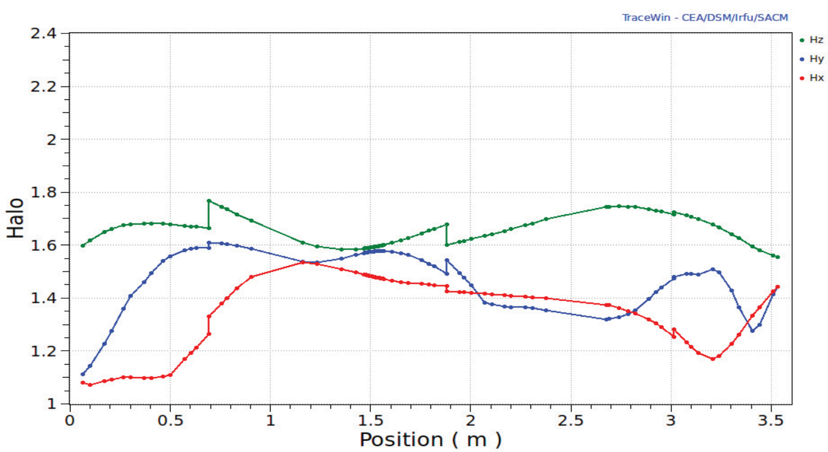


- Good locations found in the second space for BI.
- 6kW × 0.25% (~3σ) = 15 W. (Feasible ??)
- The influence hardly seen on the halo if placed as far as ~4σ.

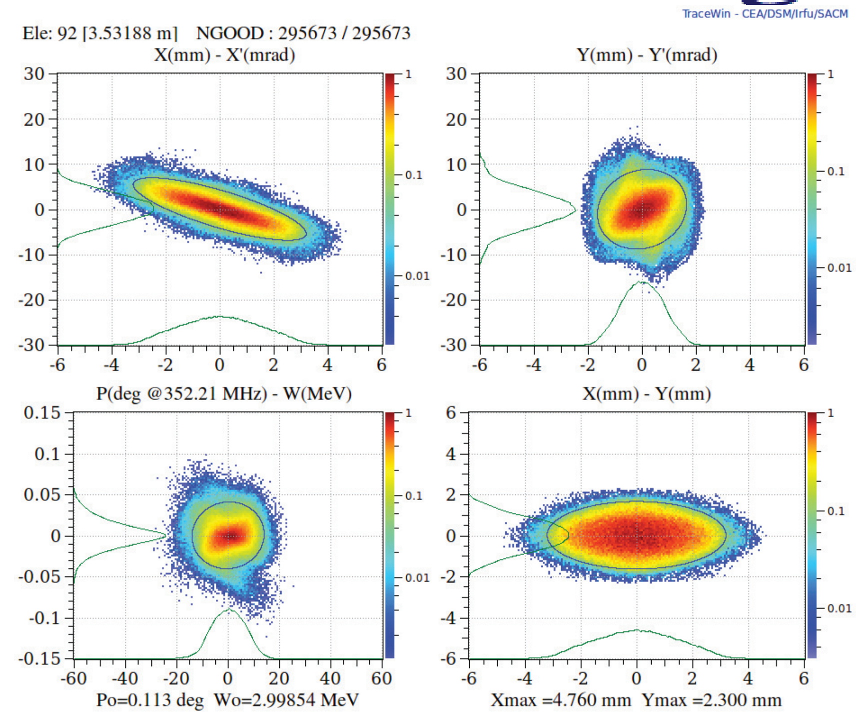
Output distribution and halos w/ and w/o collimators

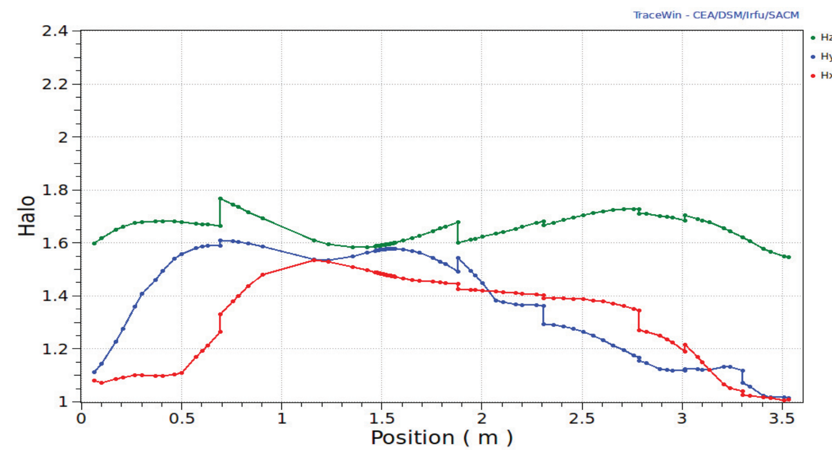
w/o



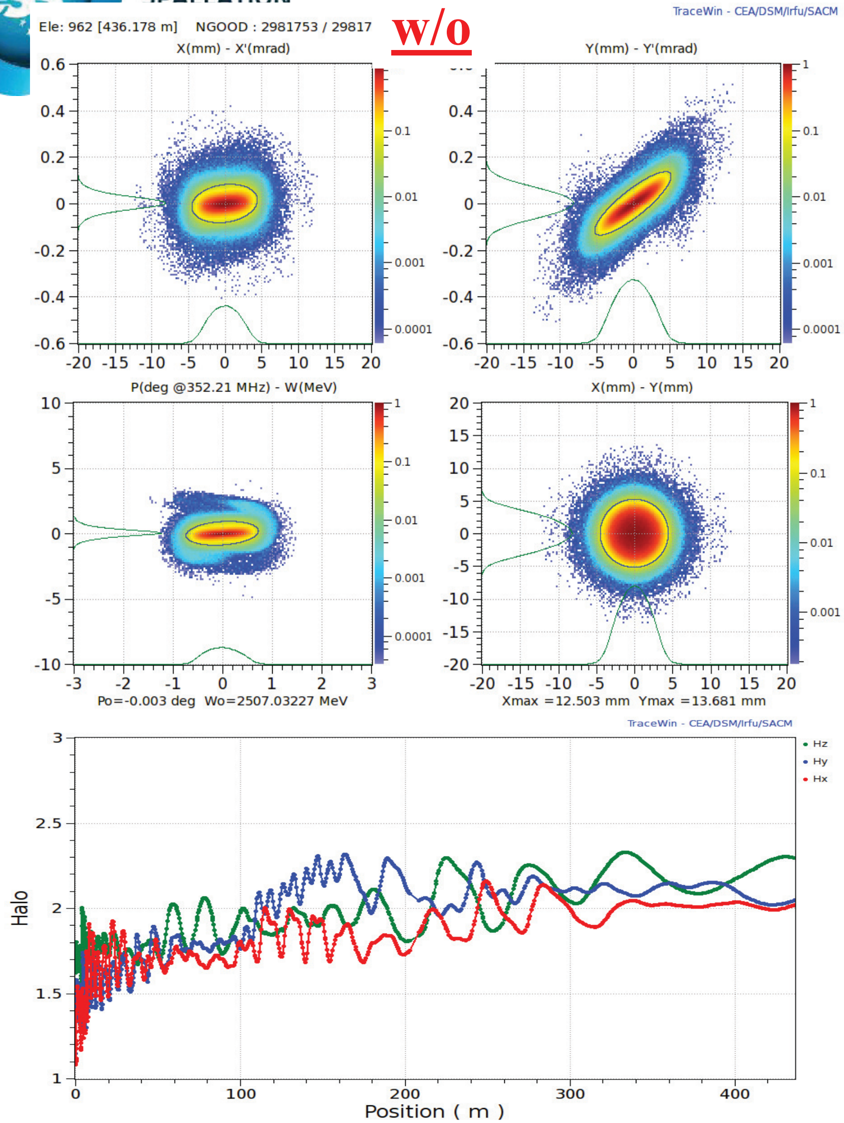


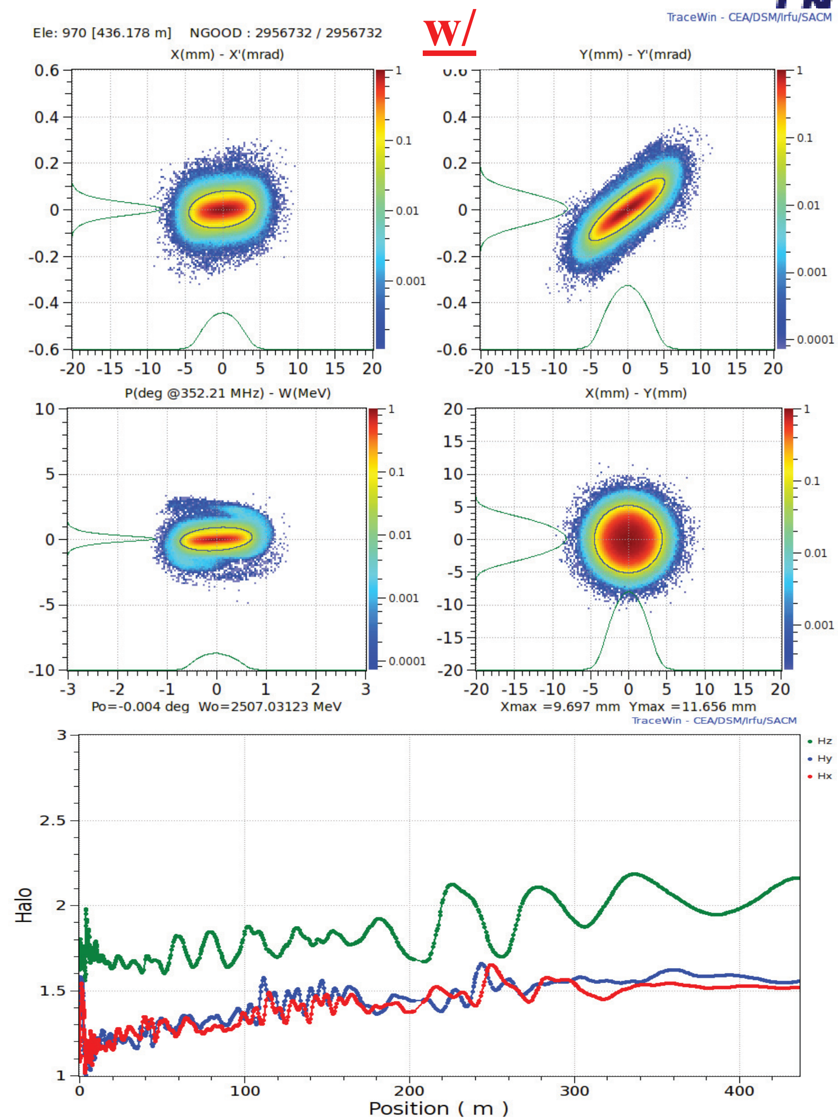
w/





Distribution out of the linac and halos w/ and w/o collimators





- Transverse emittances are slightly improved as well.
- **The influence on the loss in the SC sections haven't been studied yet.**

MEBT status

- In the May 2012 baseline, the MEBT was extended from ~1.2 m to ~3.5 m to include the fast chopper, diagnostic devices, and collimators.
- Due to concern with the shape of the output distribution, the MEBT has been modified and one configuration with better beam dynamics property was found. It was seen that the modified MEBT improves the beam dynamics throughout the linac.
- Following the SNS experience, the MEBT collimation scheme has been studied. It is observed that the collimators could reduce the halo throughout the linac but their influence on the loss in the SC section haven’t been clarified yet.

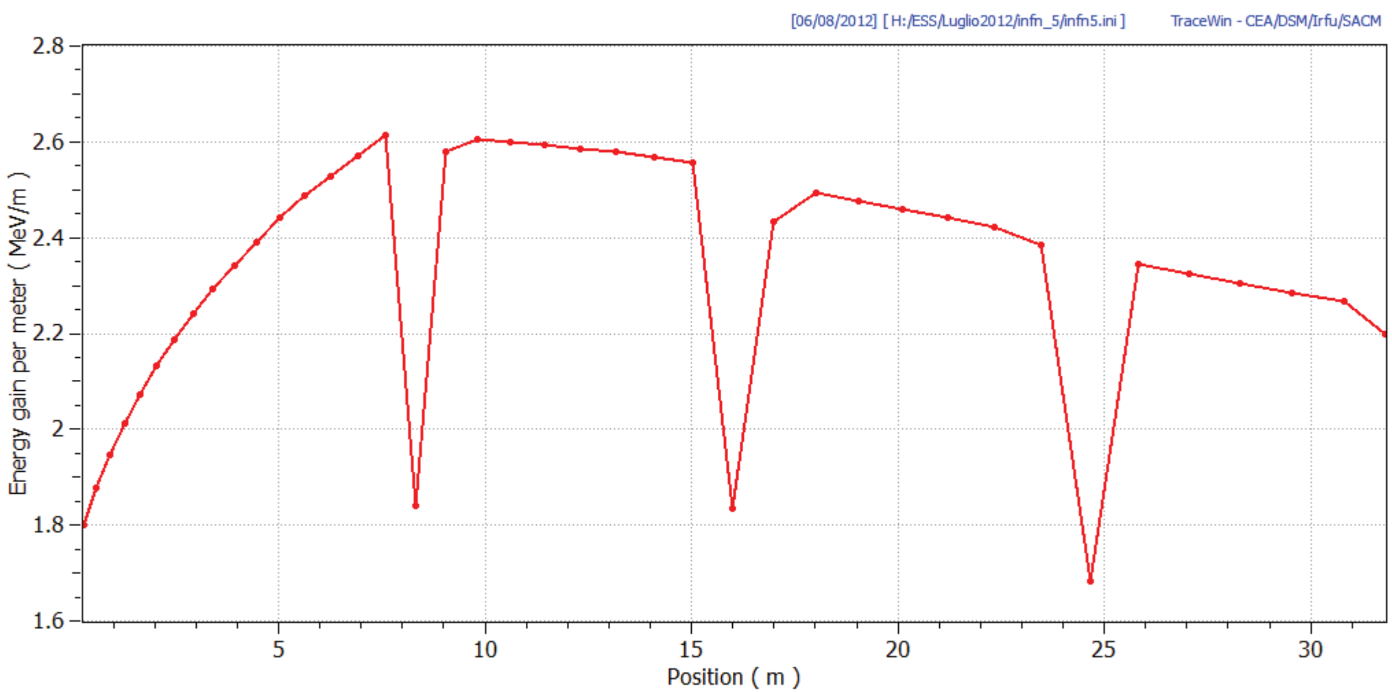
DTL

DTL Design

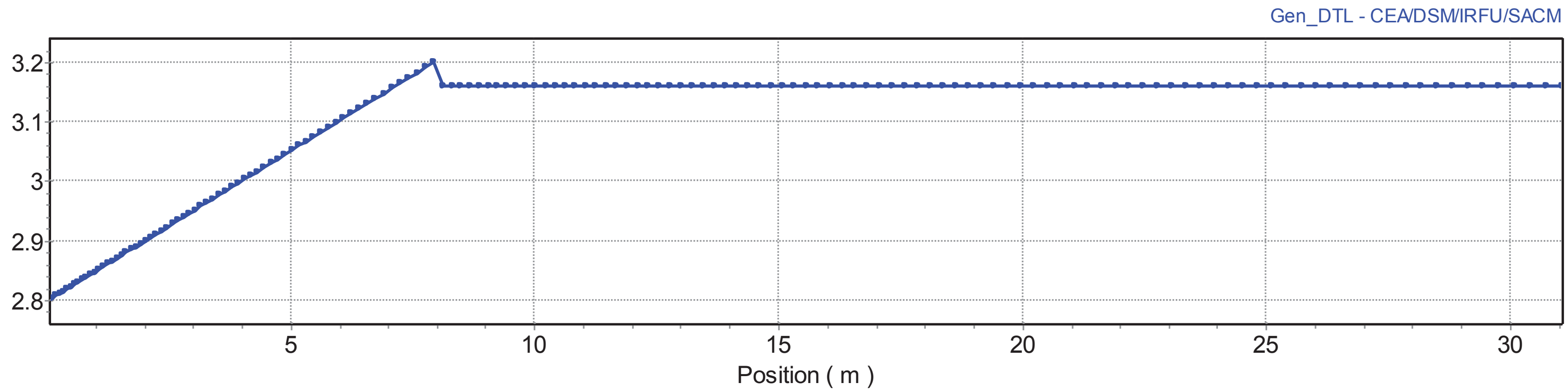
- Input energy of 3 MeV.
- Maximum integrated field of 3.8T for PMQ.
- Currents: 50 mA.
- FODO PMQ Lattice.
- PMQ law almost equipartitioned.
- Input RMS emittance Tr. / Long. 0.22/0.28 mmmrad

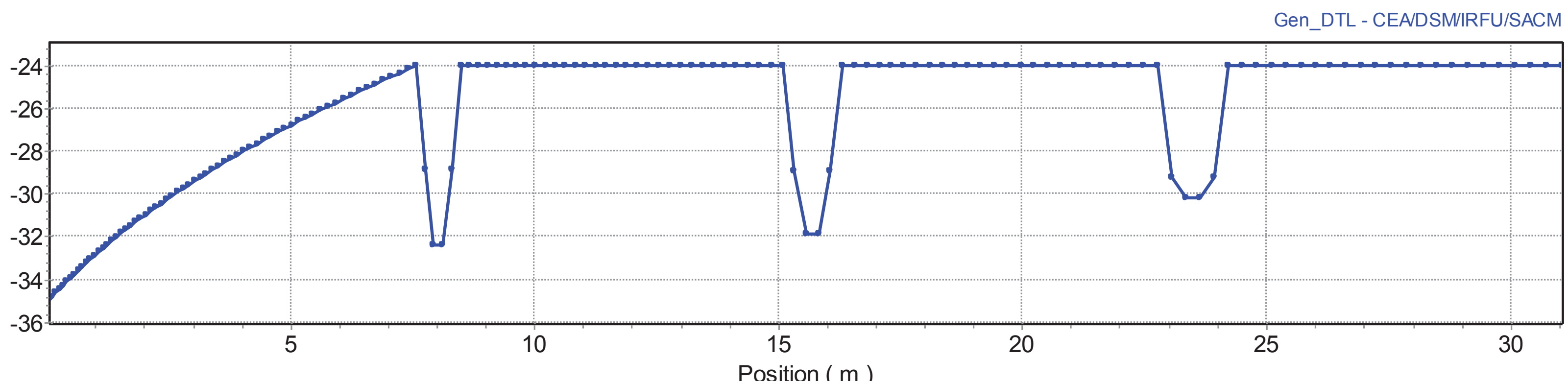
DTL Layout

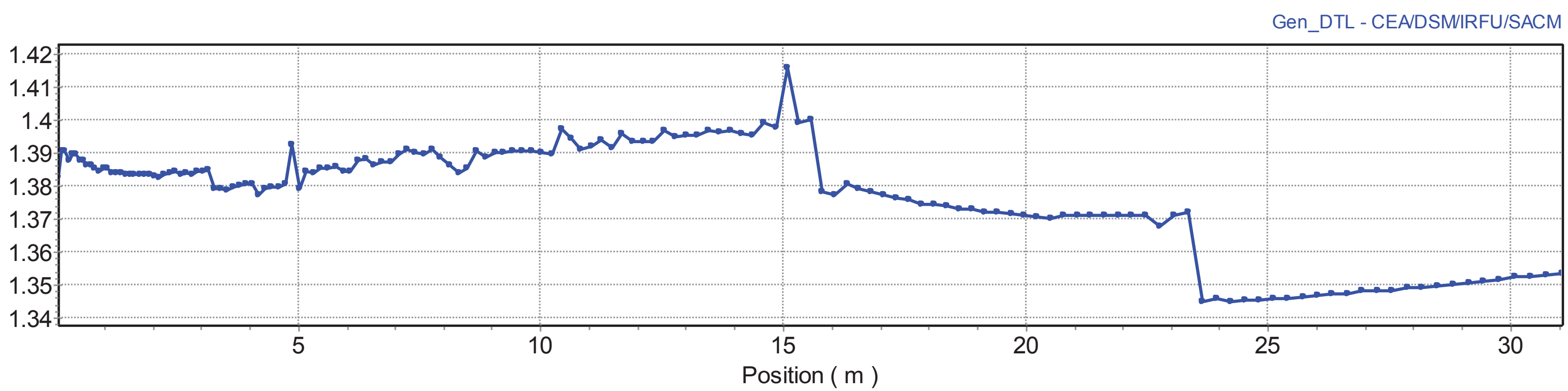
Tank	Length [m]	Cells	Total Power [kW]	Max Kp	Final Energy [MeV]	E0 [MV/m]	R bore [mm]	Flat length [mm]	Phase [deg]
1	7.953	66	2061	1.42	21.5	2.8 ÷ 3.2	10	0.7	-35 ÷ -24
2	7.628	36	2117	1.43	41.1	3.16	10	0.5	-24
3	7.762	29	2099	1.40	60.0	3.16	11	0.5	-24
4	7.724	25	2076	1.36	77.7	3.16	12	0.4	-24



Design Laws on E0 phase and surface field

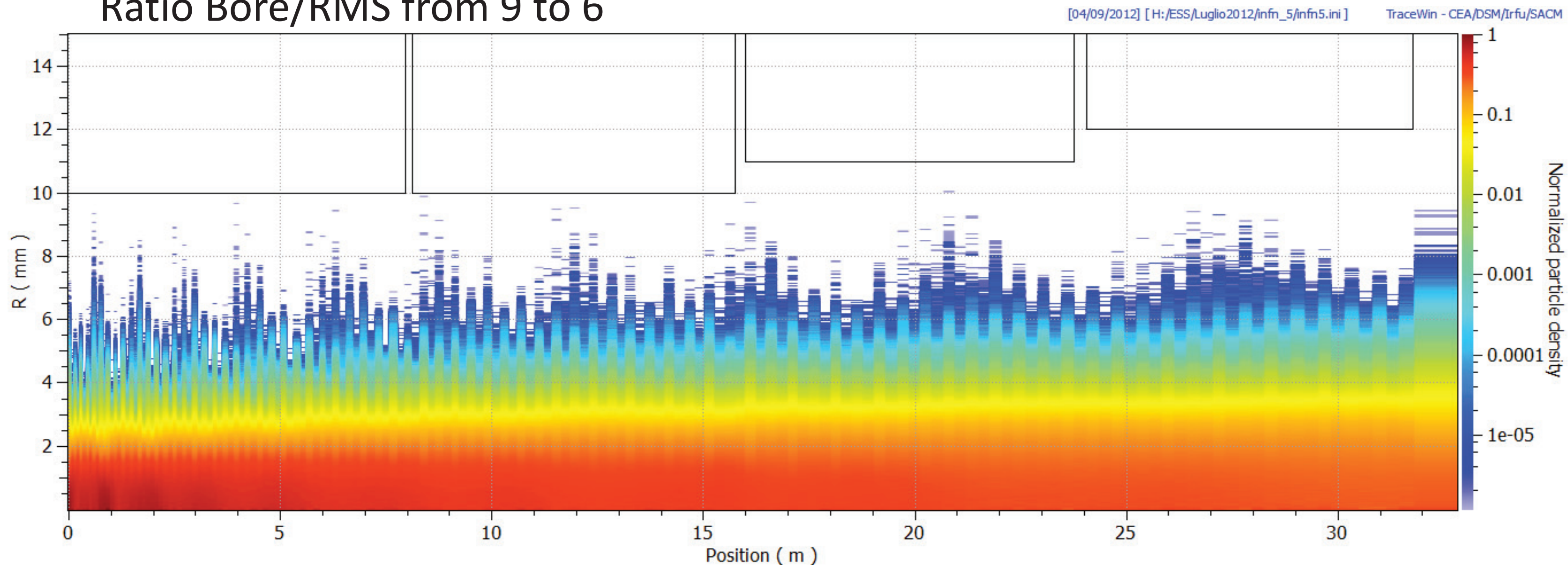


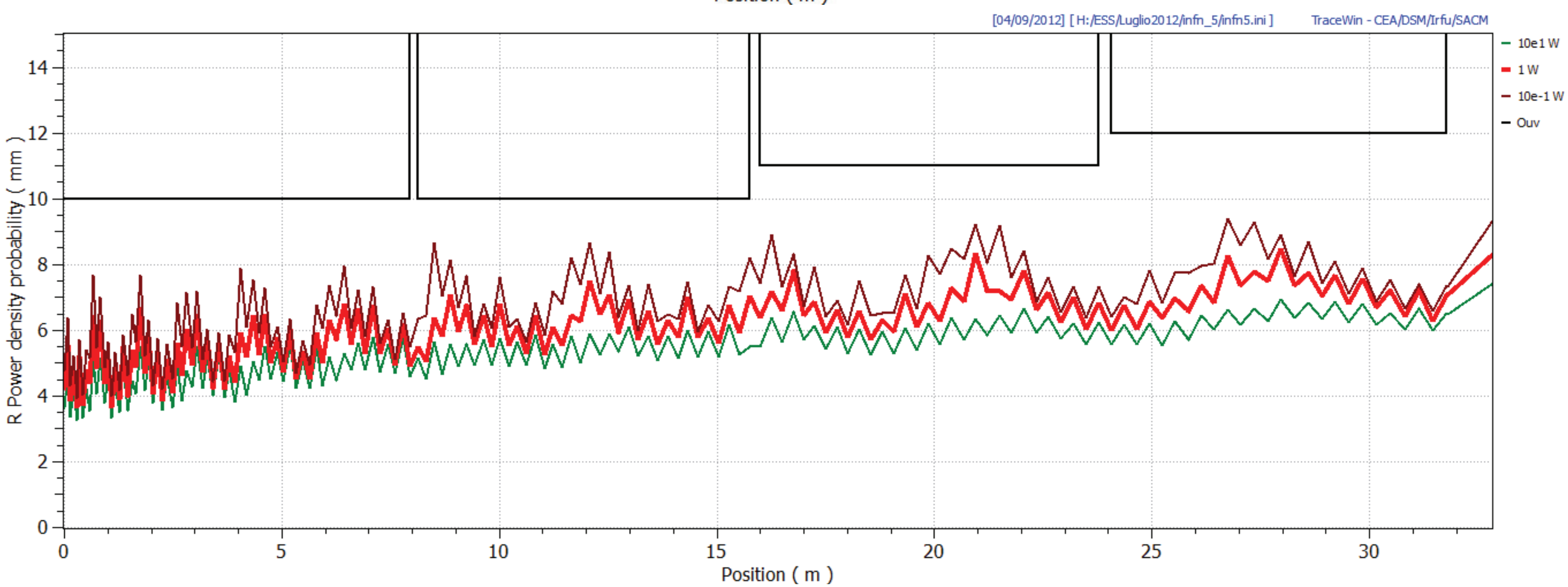




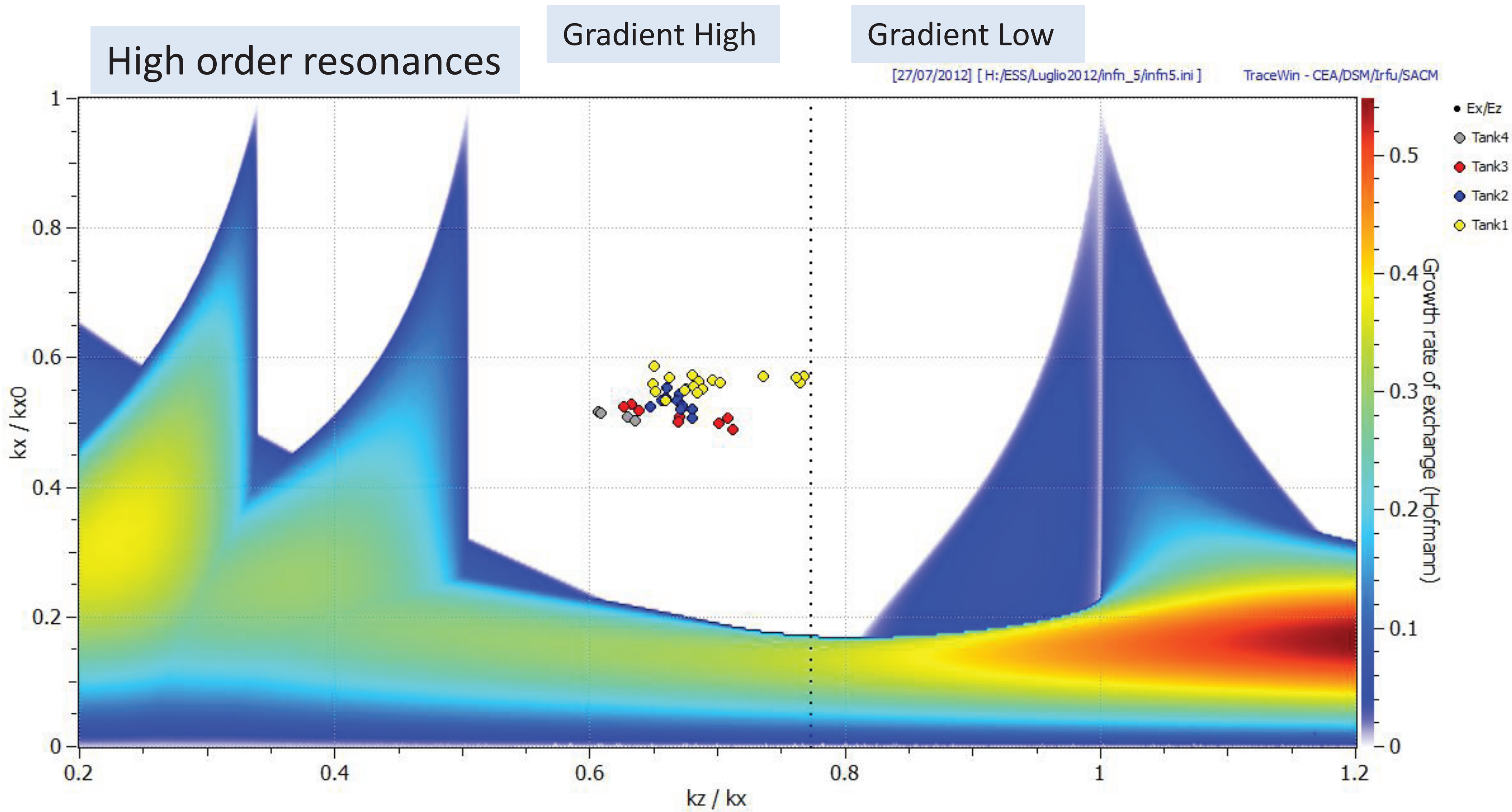
Beam Density with Input distribution Gaussian 6σ

Ratio Bore/RMS from 9 to 6

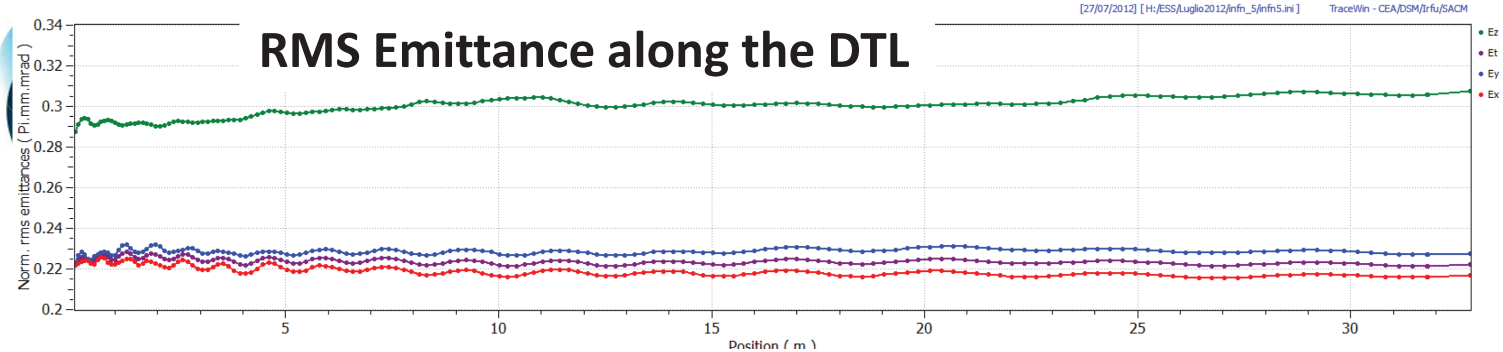




Equipartitioning all along the DTL

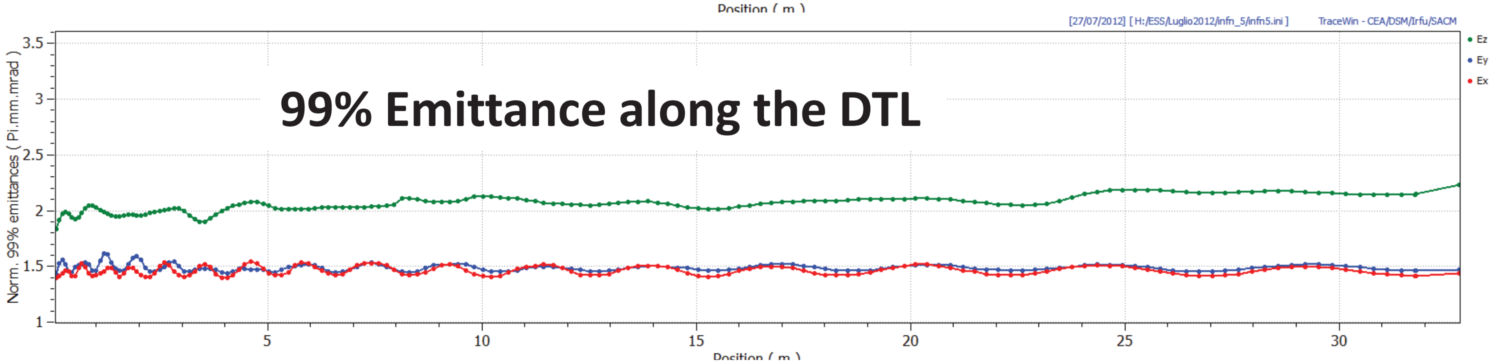


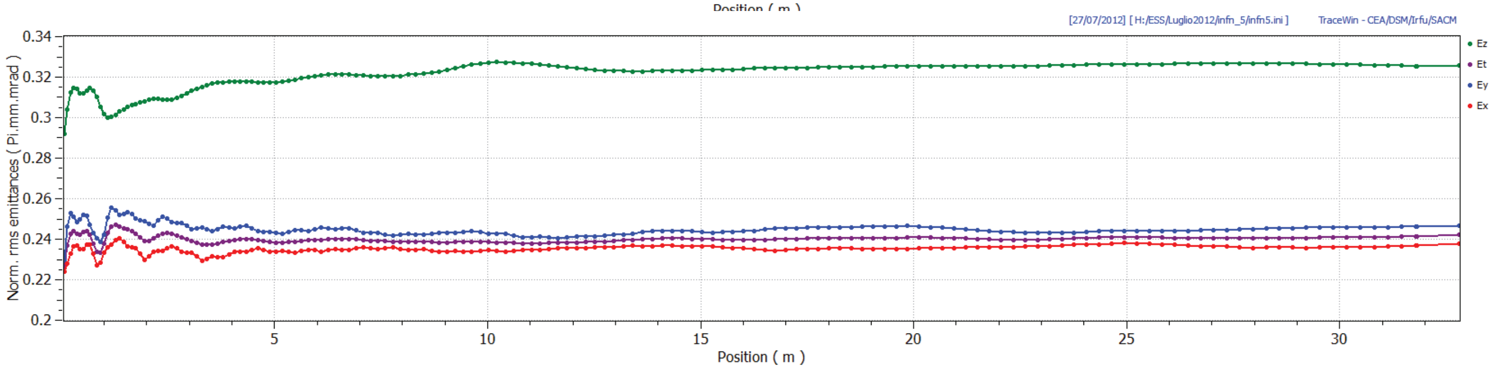
RMS Emittance along the DTL



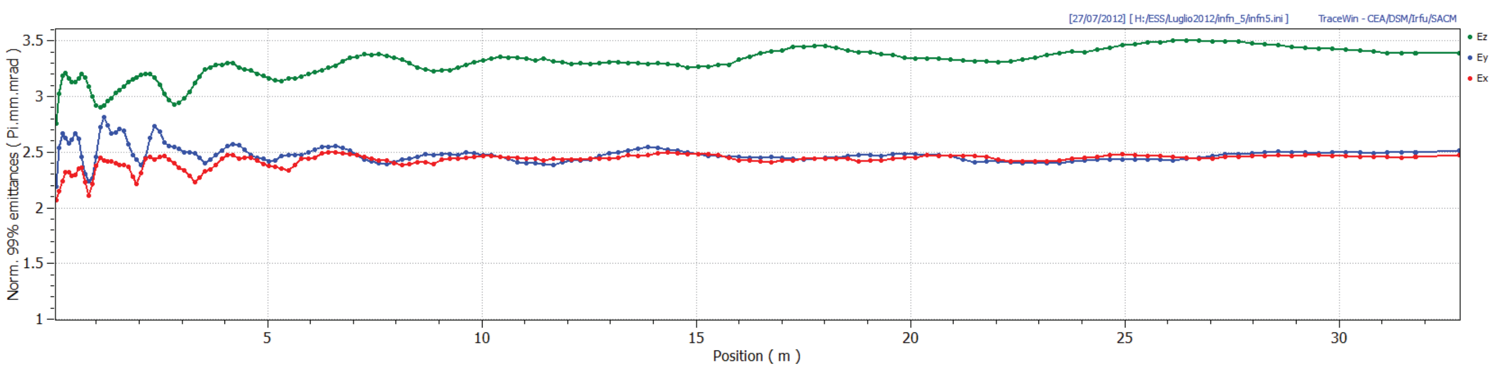
Uniform:
ET/E0T=1.05
EL/E0L=1.09

99% Emittance along the DTL

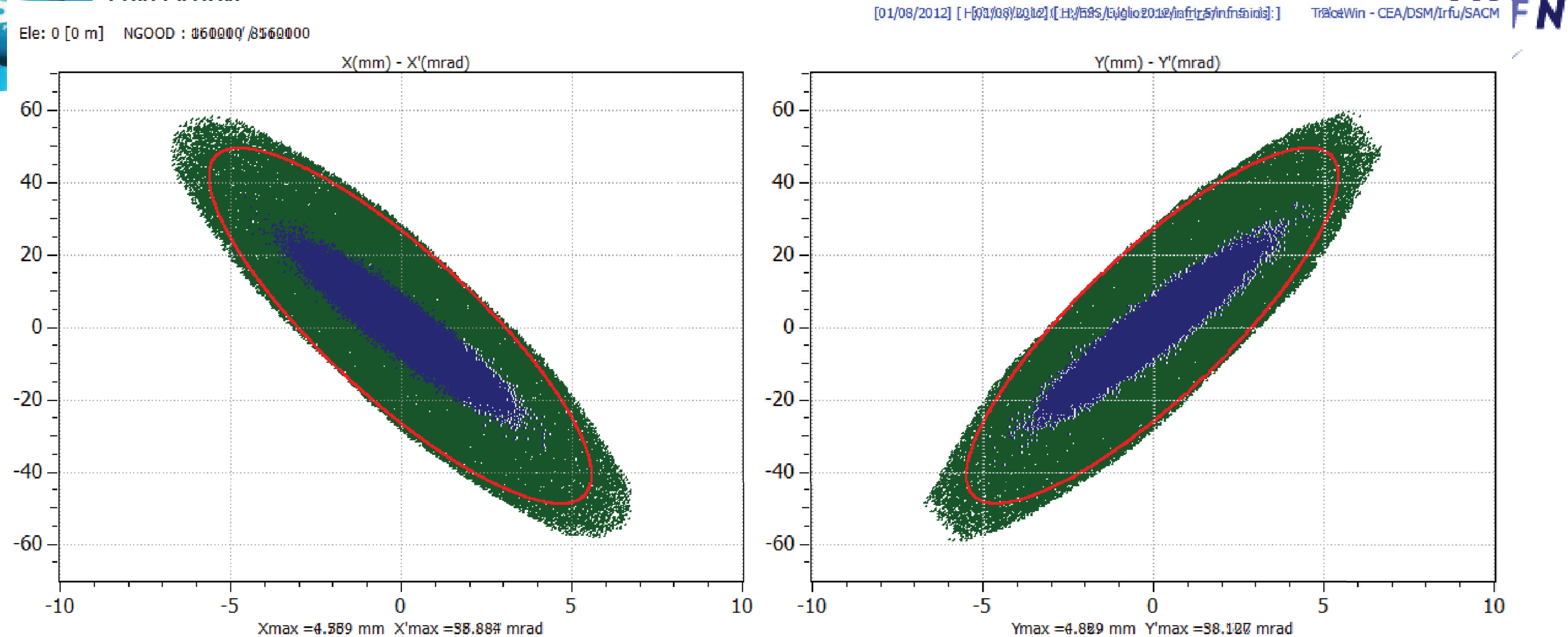




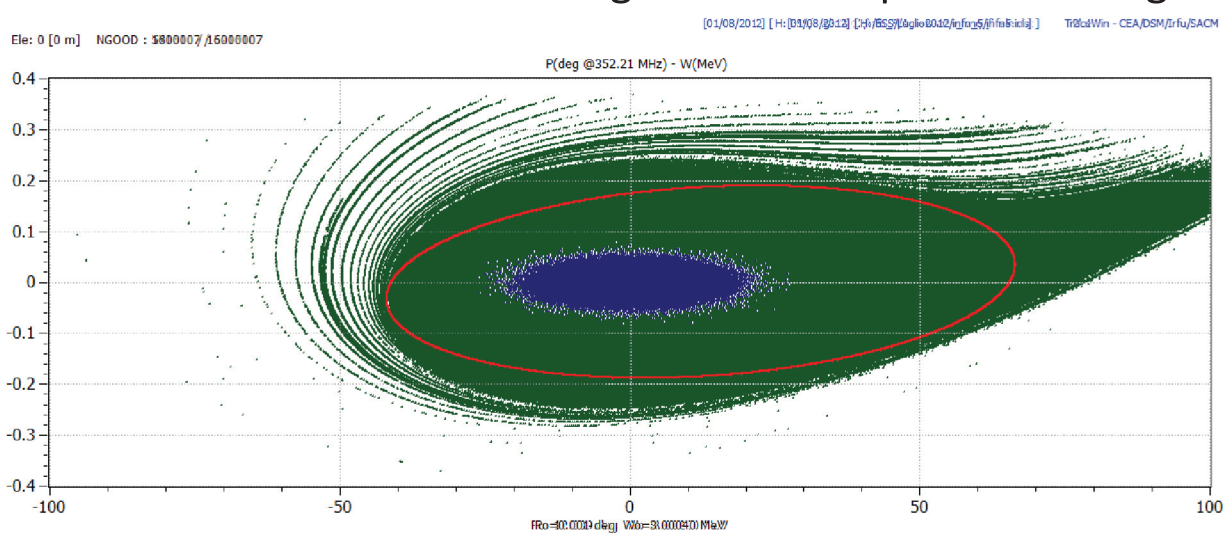
Gaussian:
ET/E0T=1.14
EL/E0L=1.18



Max transverse acceptance=11.6 mmmrad norm.



Max Longitudinal acceptance=10 degMeV



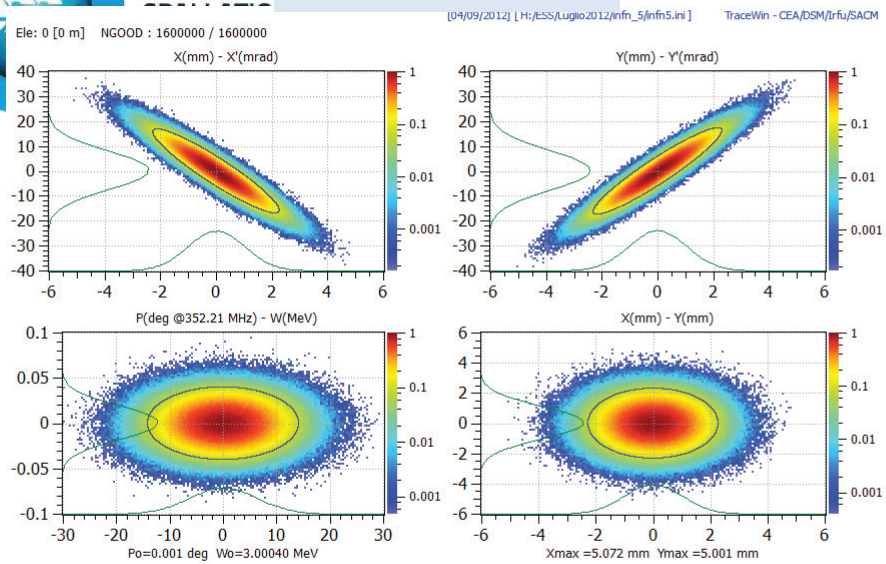
Acc/RMS Ratio:
Transverse=53
Longitudinal=91

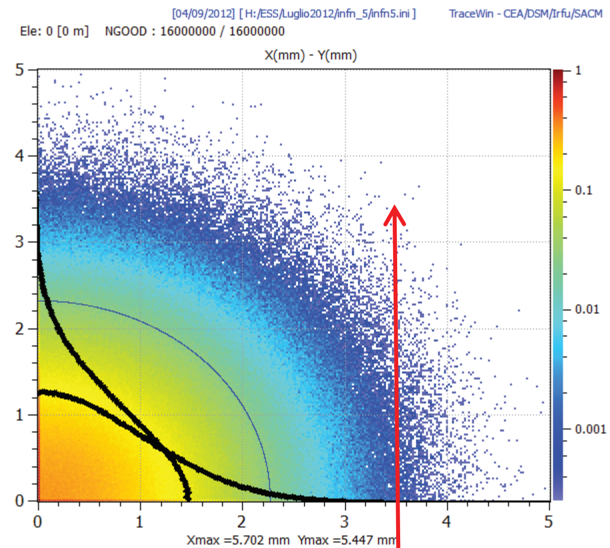
Error study on the DTL

- All errors apply together with a Uniform input beam distribution
- with added a “halo” distribution with 3times the emittance
- and 3σ as gaussian size distribution, 0.625% of the beam as halo,
- i.e. 1kW.
- 100 random DTL generated.
- 1.6*10^5 particles i.e. 1 W for particle at 50 mA, 80 MeV.
- Separate X,Y Steerer used with max force of 1.6 mT*m.
- 4 Steerers and 2 BPM for each tank.
- Diagnostics BPM with 0.05 mm accuracy.

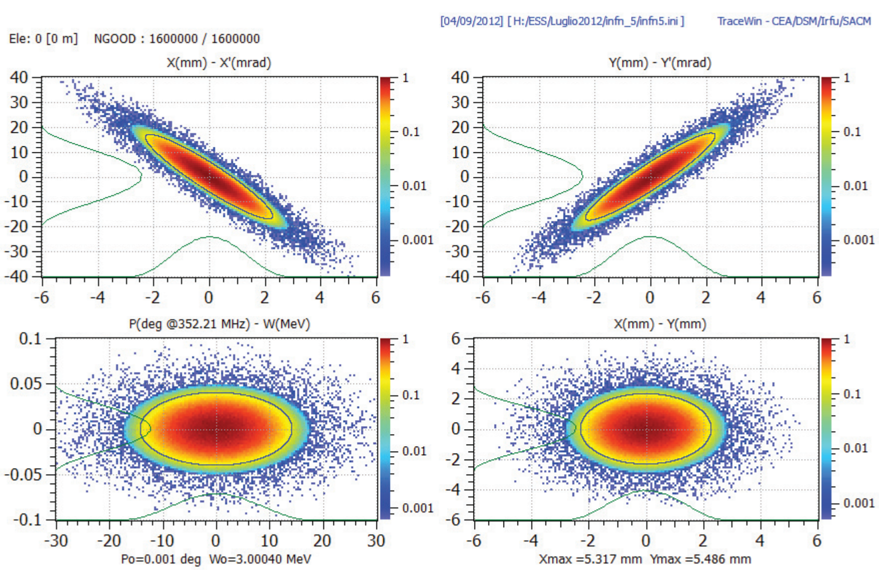

SNS Steerer, max 1.9 mT*m

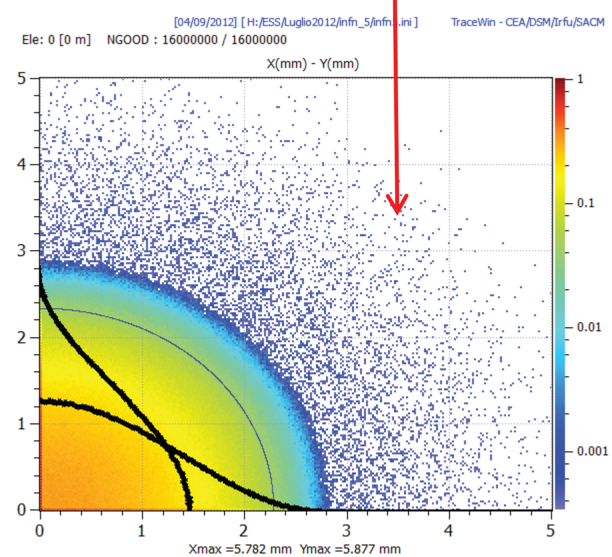
Gaussian 6σ





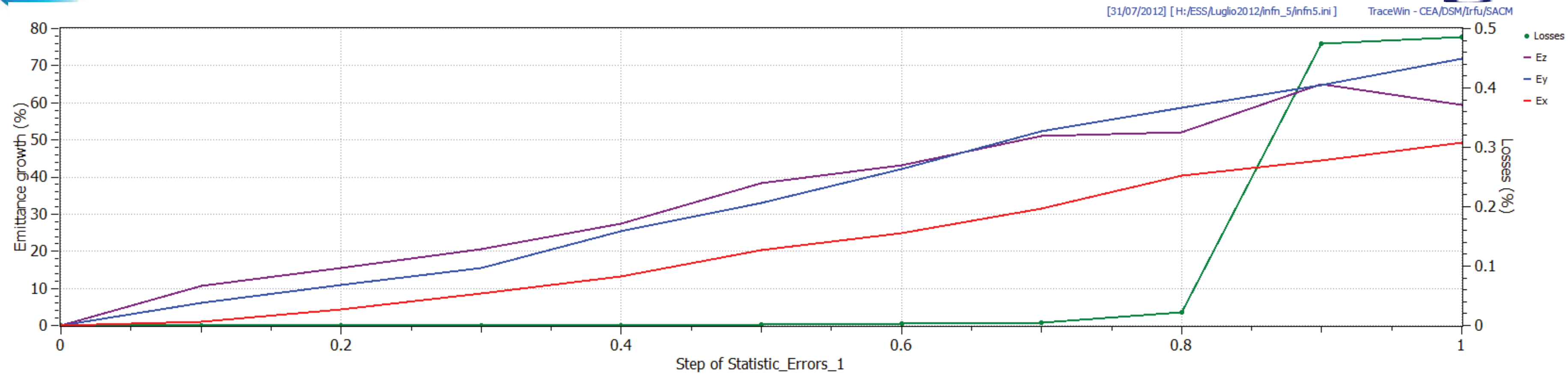
Uniform+Halo



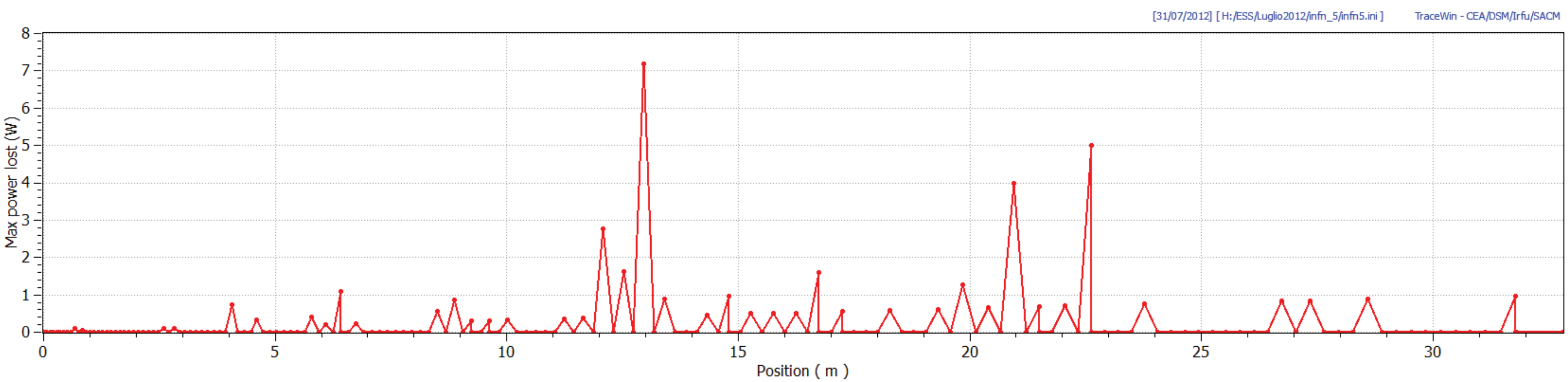


With Uniform+Halo is increased the number of particles at large amplitude

Errors results on quad without correction Steerers



Step 1 ≡ Maximum Quad shake of X,Y ±0.2 mm; ±1°; ±1%

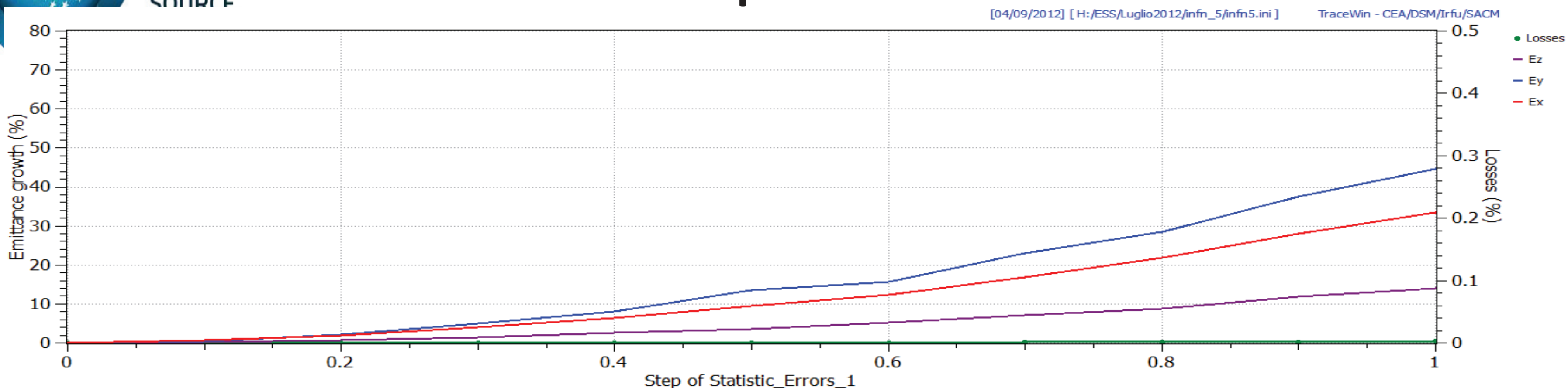


Quad shake of X,Y ±0.1 mm; ±0.5°; ±0.5%

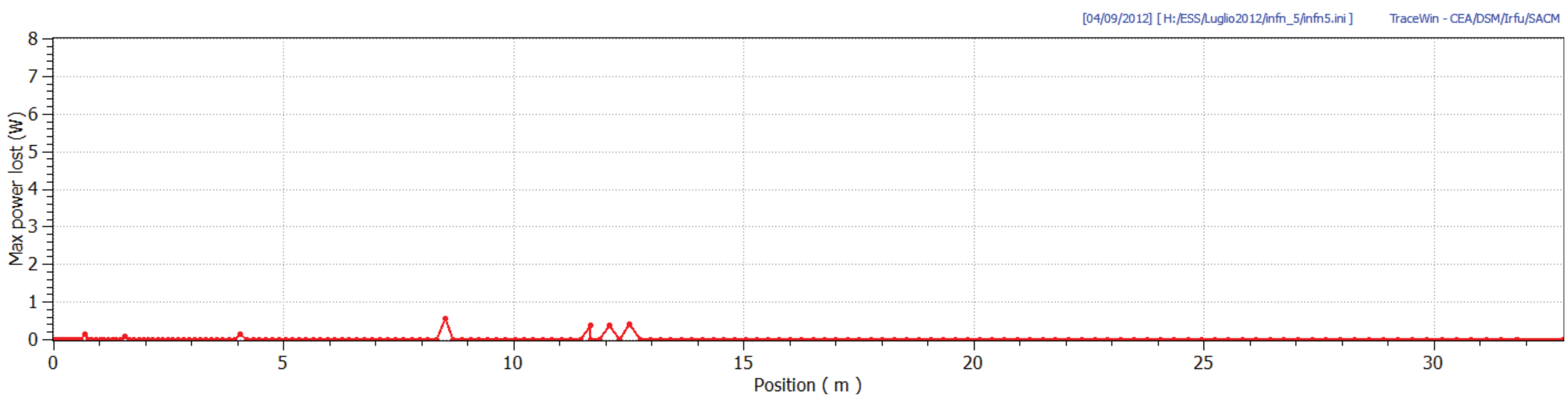
Total loss=42 Watts

Max emittance growth=40%

Errors results on quad with correction Steerers



Step 1 ≡ Maximum Quad shake of X,Y ±0.2 mm; ±1°; ±1%



Quad shake of X,Y ±0.1 mm; ±0.5°; ±0.5%

Total loss=2 Watts

Max emittance growth=20%

DTL status

- Complete definition of DTL parameters.
- Solution with 4 Tanks.
- With the steerers the losses are reduced by a factor 10 and the emittance growth by a factor 2.

Conclusion

The general rules used are:

- Smooth variation of the phase advance between sections.
- Equipartitioning law in the DTL, to avoid emittance exchange phenomena.
- Check the Halo formation and development from the RFQ up to the target.
- Use of collimators in the MEBT.
- Avoid tune depression below 0.4.

By using these laws, the design is more robust and less sensitive to any source of errors.

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