RFQ Simulations

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Acknowledgments

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- N. Solyak, L. Prost, V Lebedev

- J. Staples, D. Li
(for sharing design files and data)

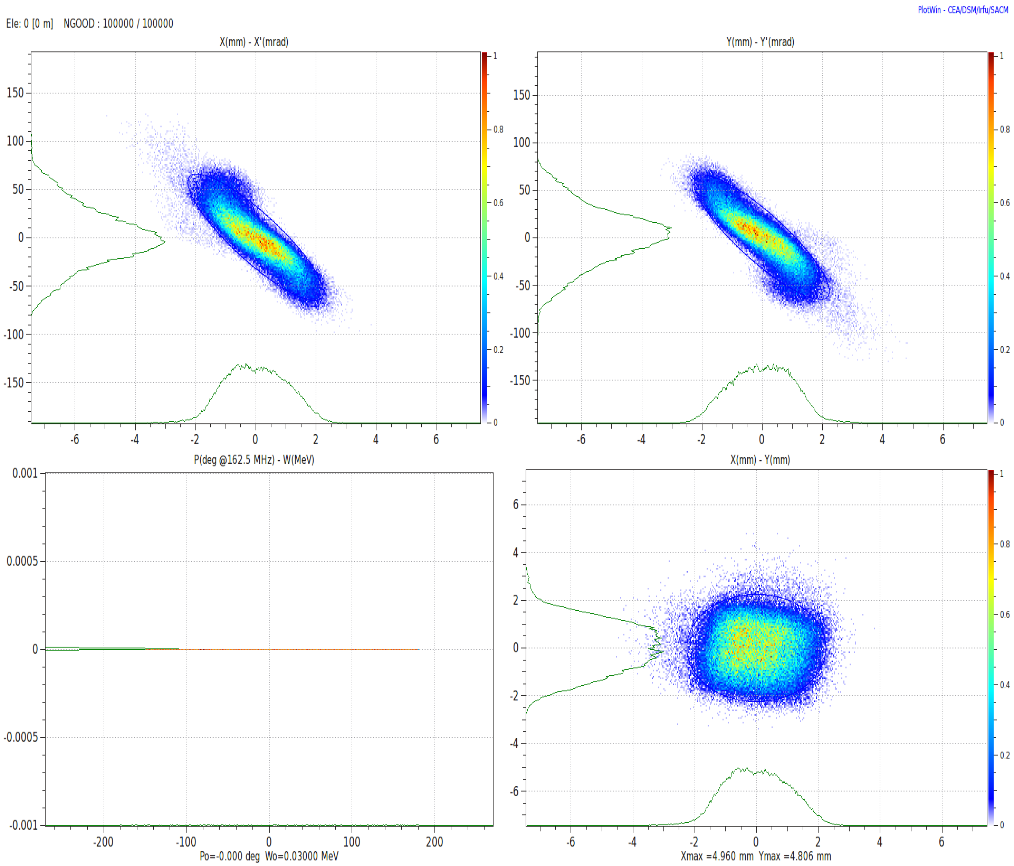
Notes on Codes

- The PXIE RFQ has been designed by LBNL using PARMTEQM. LBNL is also using its own tools to perform tracking through the LEBT from the ion source.
- For a few yrs now, we have been using with good success TraceWin from CEA/Saclay to perform linac design and simulation work.
- Toutatis, the RFQ code from CEA/Saclay is available not only as a stand-alone code, but also as a module within TraceWin. This is very convenient for end-to-end studies.
- Strictly for RFQ design, Toutatis does not offer overwhelming advantages over PARMTEQM. In principle, it is more accurate because it solves Laplace's equation for the entire RFQ geometry. It also has a MG space charge solver.
- In contrast with PARMTEQM, the max no of particles is not hard-coded, allowing for high statistics runs.
- For the PXIE RFQ, benchmarking tests show that agreement between PARMTEQM and Toutatis is excellent.
- Toutatis, just like PARTMTEQM has many flags, options and features that are not always as well-documented and/or debugged as they should be. Understanding how to use the code correctly and verifying that the results produced are correct is an important and on-going task. CEA-Saclay is generally responsive to our requests for information. Bug reports have been handled a timely manner.
- There are a number of know limitations in Toutatis that need to be circumvented and/or addressed in order to do reliable end-to-end tracking with statistical errors.
- Our objectives are
  - get a good understanding of the RFQ design and how performance might be affected by construction/tuning errors
  - Simulate the accelerator (PXIE and PX) as a complete system starting from the ion source, with high statistics
  - Understand and devise strategies to minimize losses along the entire linac and especially, in the low energy cryomodules.

SPACE CHARGE

- The losses/emittances predicted by an RFQ code depend, among other things, on the no of particles tracked and the type of SC solver used.
- For expediency, all results shown here were produced by tracking 100k particles and using an r-z solver. The predicted emittances may be off by a few % or so from those obtained with higher precision runs and/or a full 3d solver.

“Nominal” RFQ Input Distribution (J. Staples)



$$\alpha_t = 1.75$$
$$\beta_t = 0.07 \quad \text{mm/mrad}$$
$$\epsilon_t = 0.12 \quad \text{mm mrad}$$
$$\epsilon_\ell = 0$$

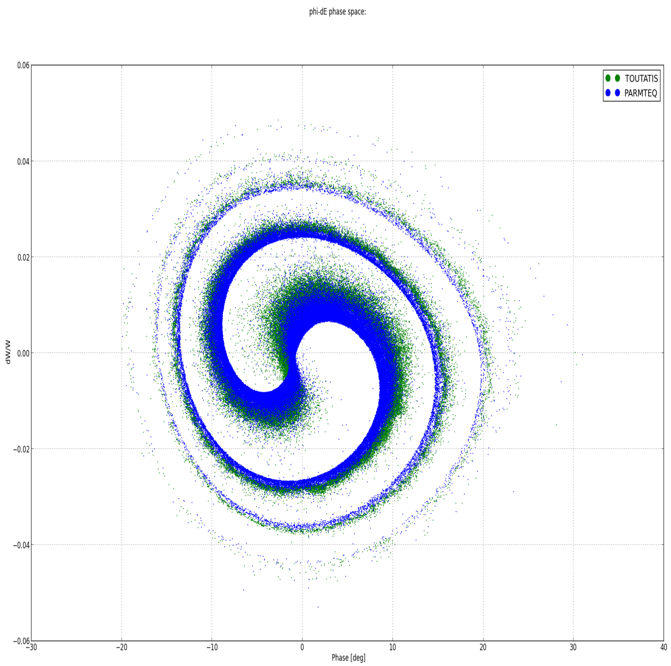
RFQ matched beam parameters

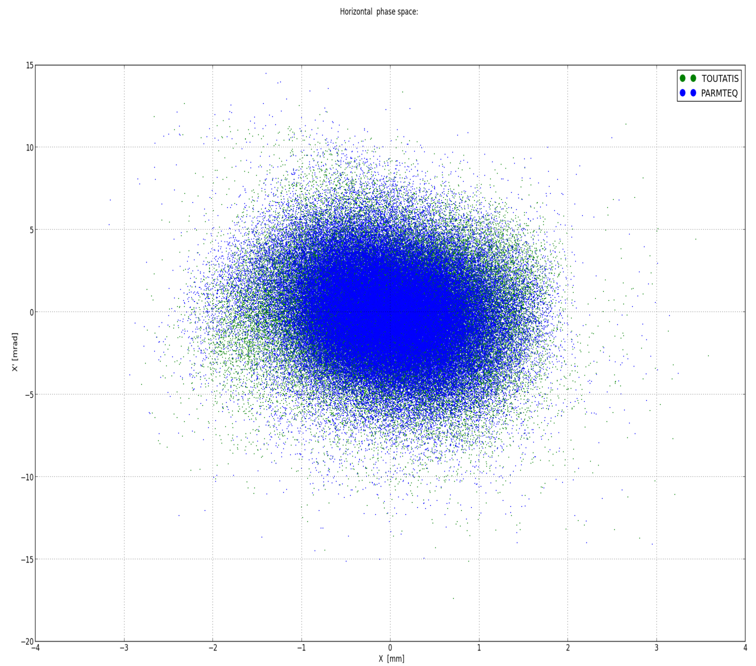
Nominal RFQ input distribution
Obtained from measured H- source distribution tracked trough a two- solenoid, fully neutralized LEBT (using LBNL Genrays code).

Project X

Validation:
Toutatis vs PARMTEQM

Project X Longitudinal Distribution I_b=0 mA



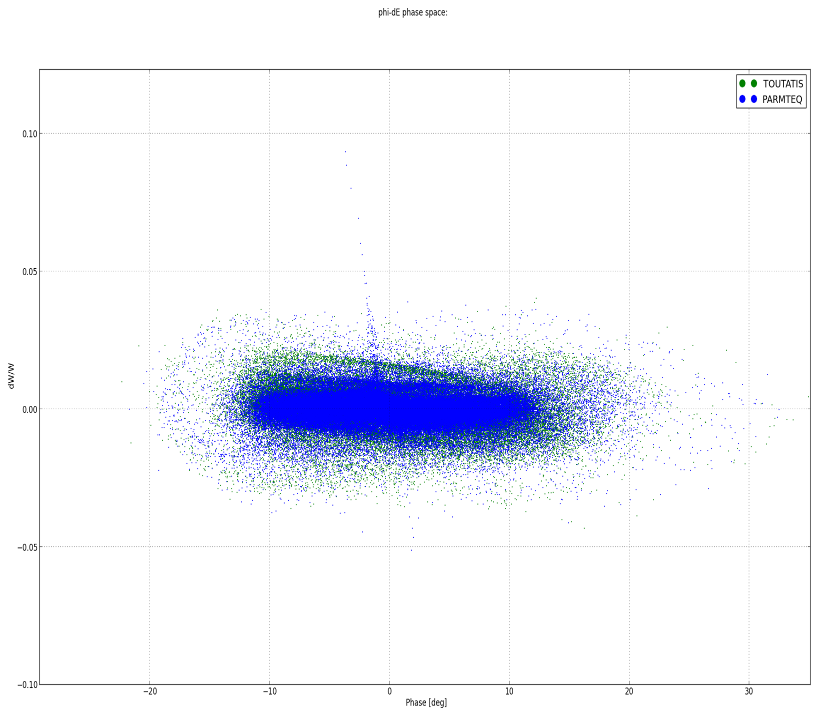


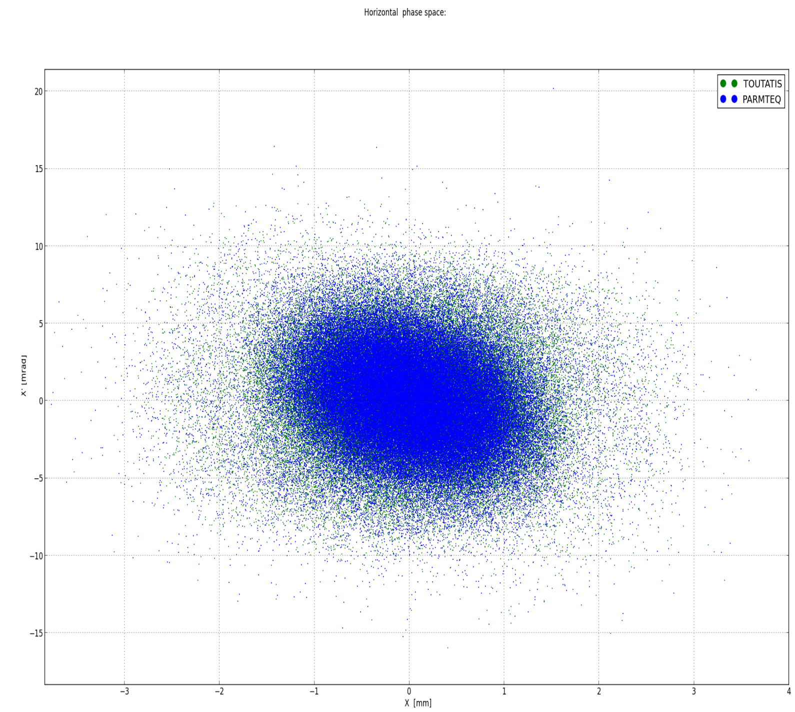
Toutatis (Green) vs PARMTEQM (Blue)
Longitudinal Phase Space at RFQ output

Toutatis (Green) vs PARMTEQM (Blue)
Horizontal Phase Space at RFQ output

TOUTATIS vs PARMTEQ RFQ Output Distributions

I_b=5 mA, Input = Staples

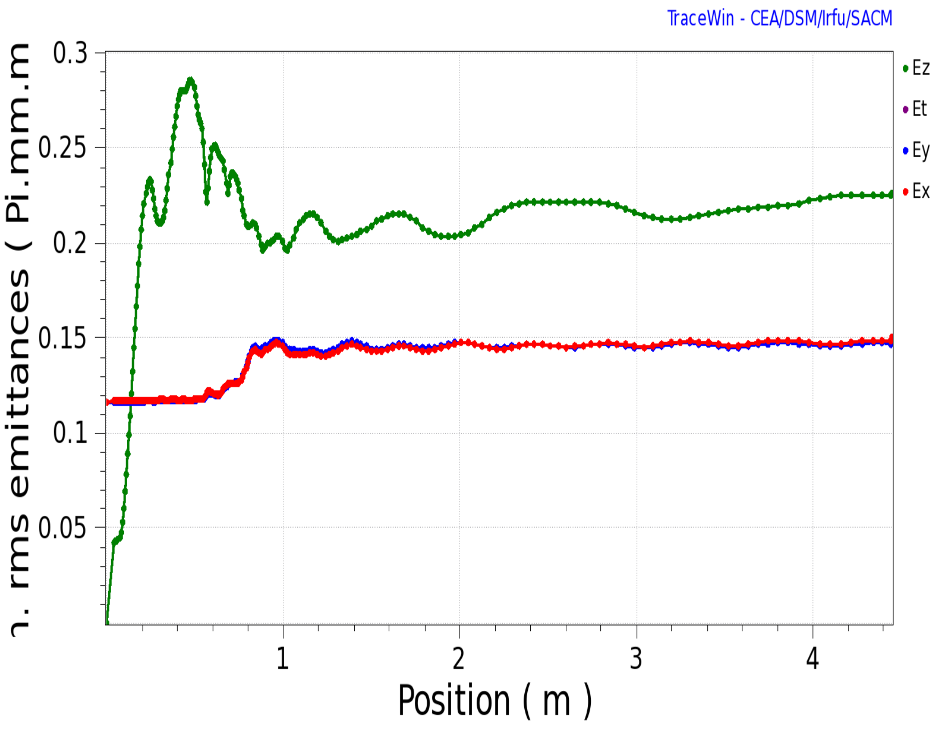




Toutatis (Green) vs PARMTEQM (Blue) Longitudinal Phase Space at RFQ output

Toutatis (Green) vs PARMTEQM (Blue) Horizontal Phase Space at RFQ output

RFQ Emittance Evolution
RFQ Input = Matched Input Beam (Gaussian)



Matched RFQ Input parameters

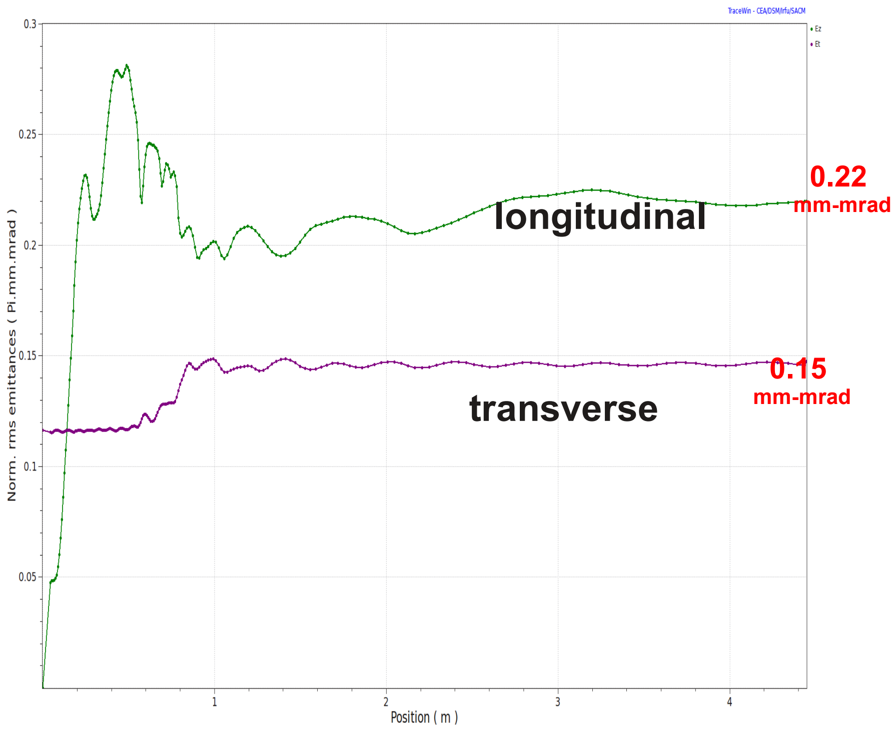
Plane	Emittance mm-mrad	alpha	Beta (mm/mrad)
x	0.11	1.6	0.07
y	0.11	1.6	0.07
z	0.0	-	-

Ideal Gaussian Distribution at RFQ input produces identical emittance growth through the RFQ as the nominal Design Distribution

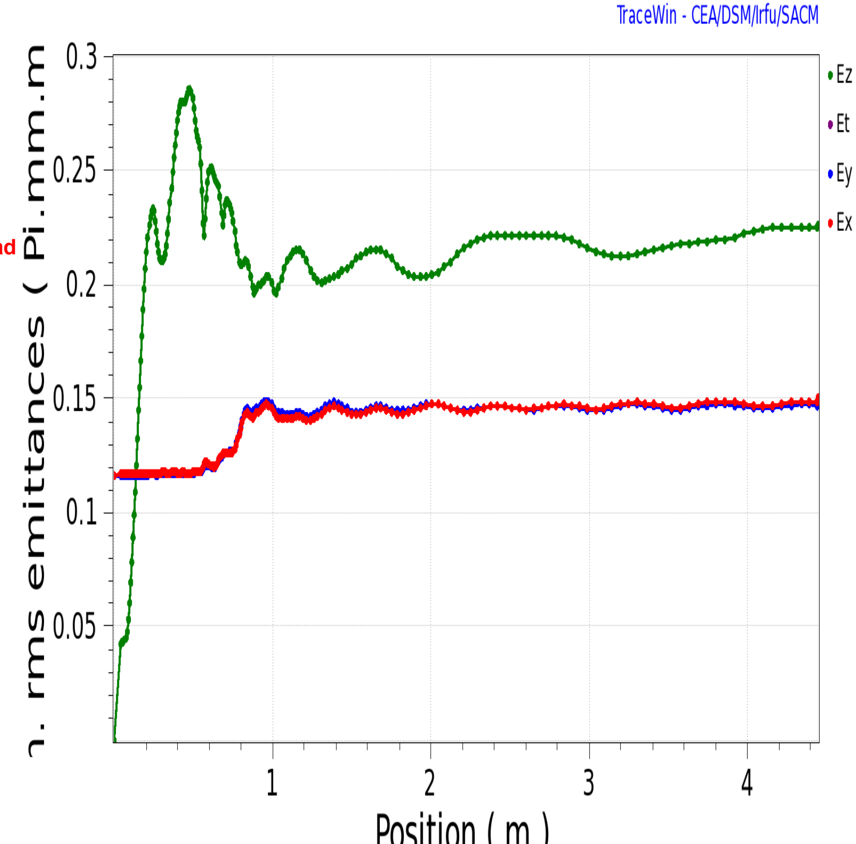
Project X

Nominal vs Ideal Gaussian RFQ Input Distribution Emittance Evolution

I=5 mA

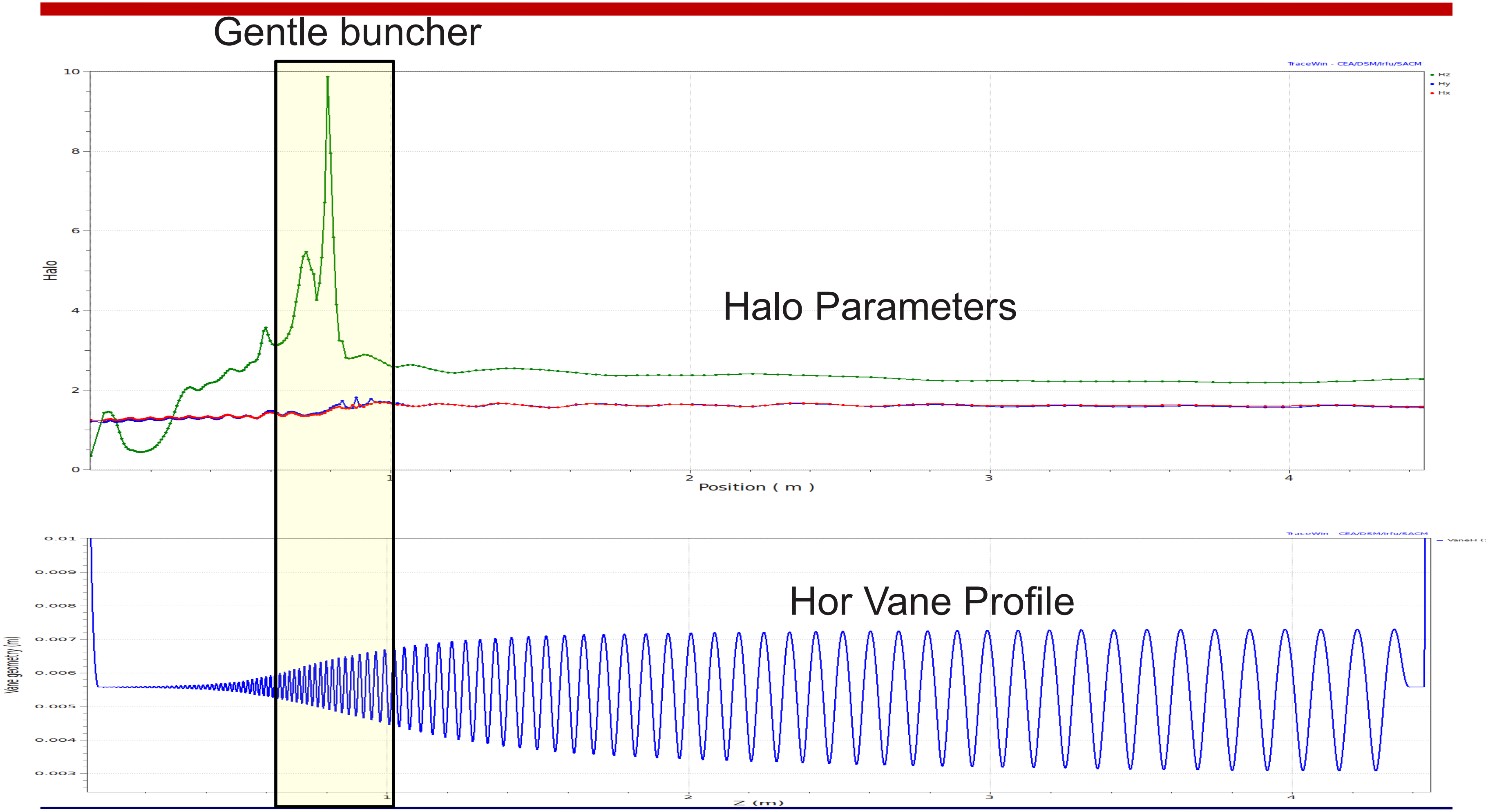


Nominal (Staples)

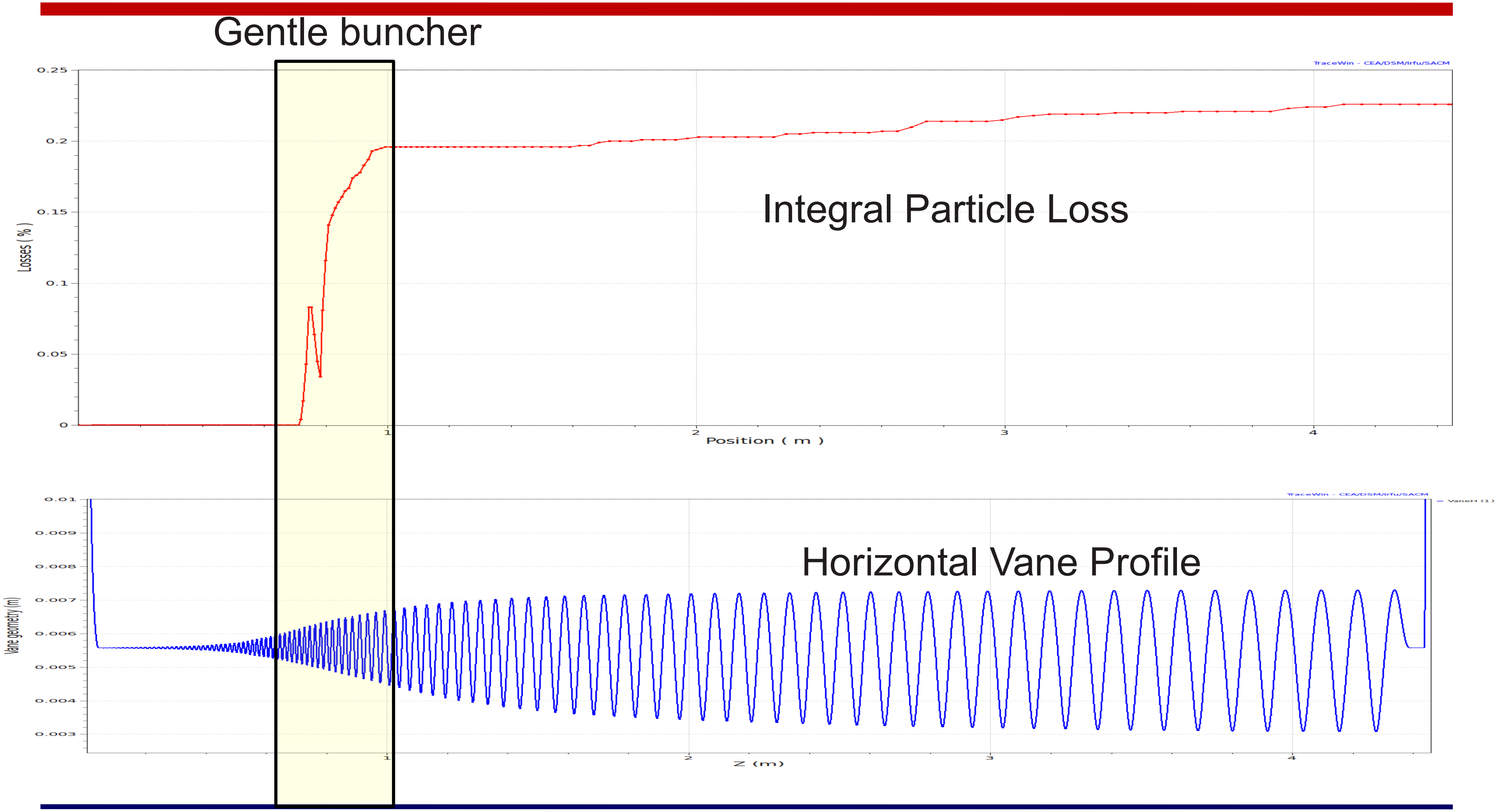


Gaussian

TOUTATIS
Nominal RFQ – Halo Parameters
I=5 mA, Input = Staples



TOUTATIS
Nominal RFQ – Losses
I=5 mA, Input = Staples



RFQ Performance 1 – 10 mA

	Current (mA)	ϵ_L mm-mrad (deg-MeV)	ϵ_T mm-mrad	Lost Particles (N=100k)
	1	0.39 (0.0703)	0.12	116
	2.5	0.30 (0.0565)	0.13	112
Nominal	5	0.22 (0.0397)	0.15	186
	7.5	0.22 (0.0397)	0.14	222
	10	0.24 (0.0434)	0.15	517

LEBT with Un-neutralized Section

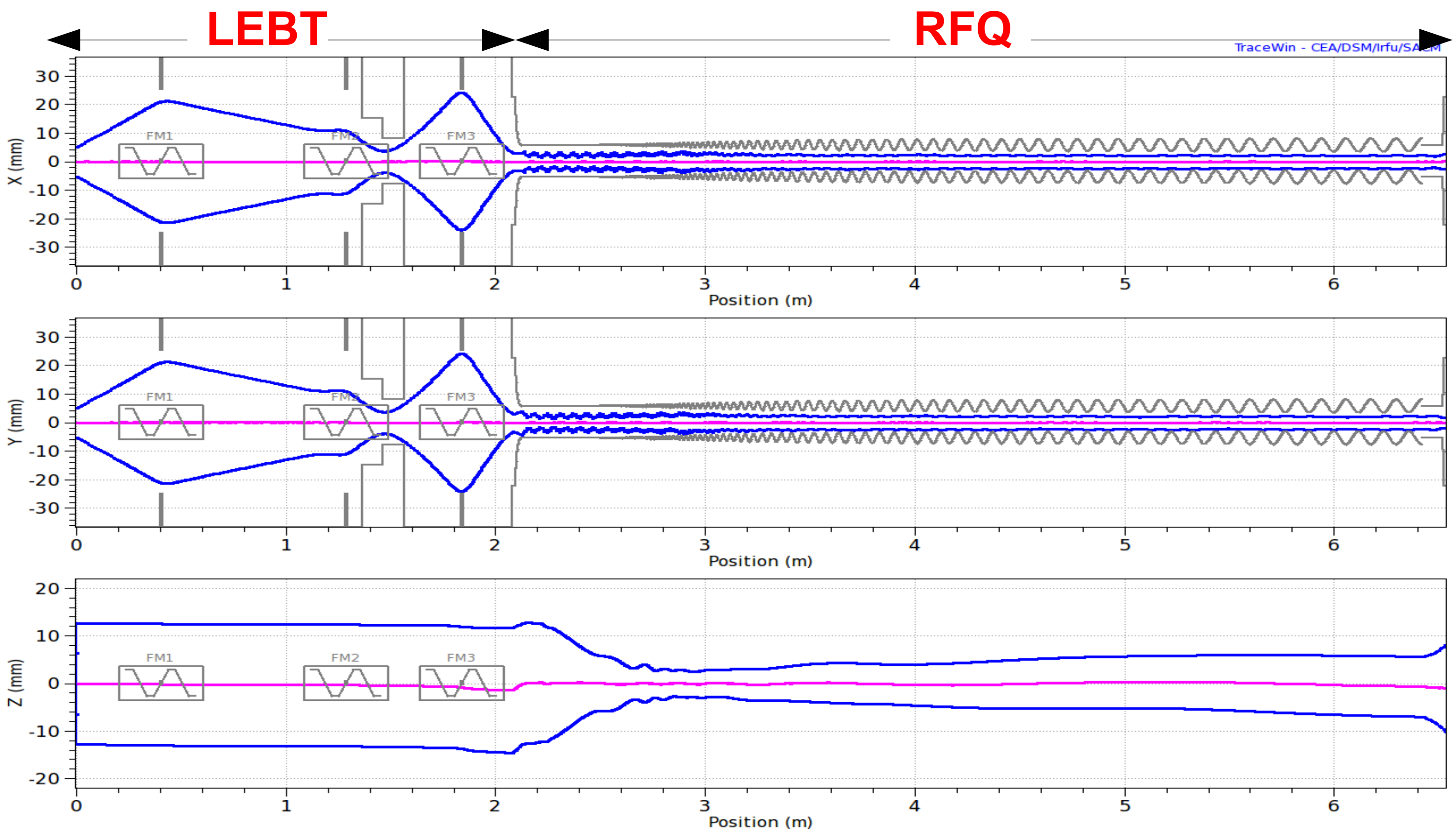
- The LEBT includes a chopper which has for function to reduce the average beam power for commisioning
- Chopping a fully neutralized beam implies a transient change in the state of neutralization and therefore some uncertainty about the quality and stability of the match into the downstream RFQ
- A LEBT with a fully non-neutralized section is a way to circumvent this uncertainty. However:
  - Measurements have shown that the transverse distribution downstream of the ion source is Gaussian-like
  - A low energy (30 keV) un-neutralized Gaussian beam has significant “free energy” that can get converted into emittance growth. Growth tends to occur more rapidly if the beam envelope size is subjected to rapid variations.
  - The LEBT optics is constrained by various factors: need to match into RFQ, aperture limitation of the chopper/absorber etc …

LEBT + RFQ

LEBT Input = Ideal Transverse Gaussian

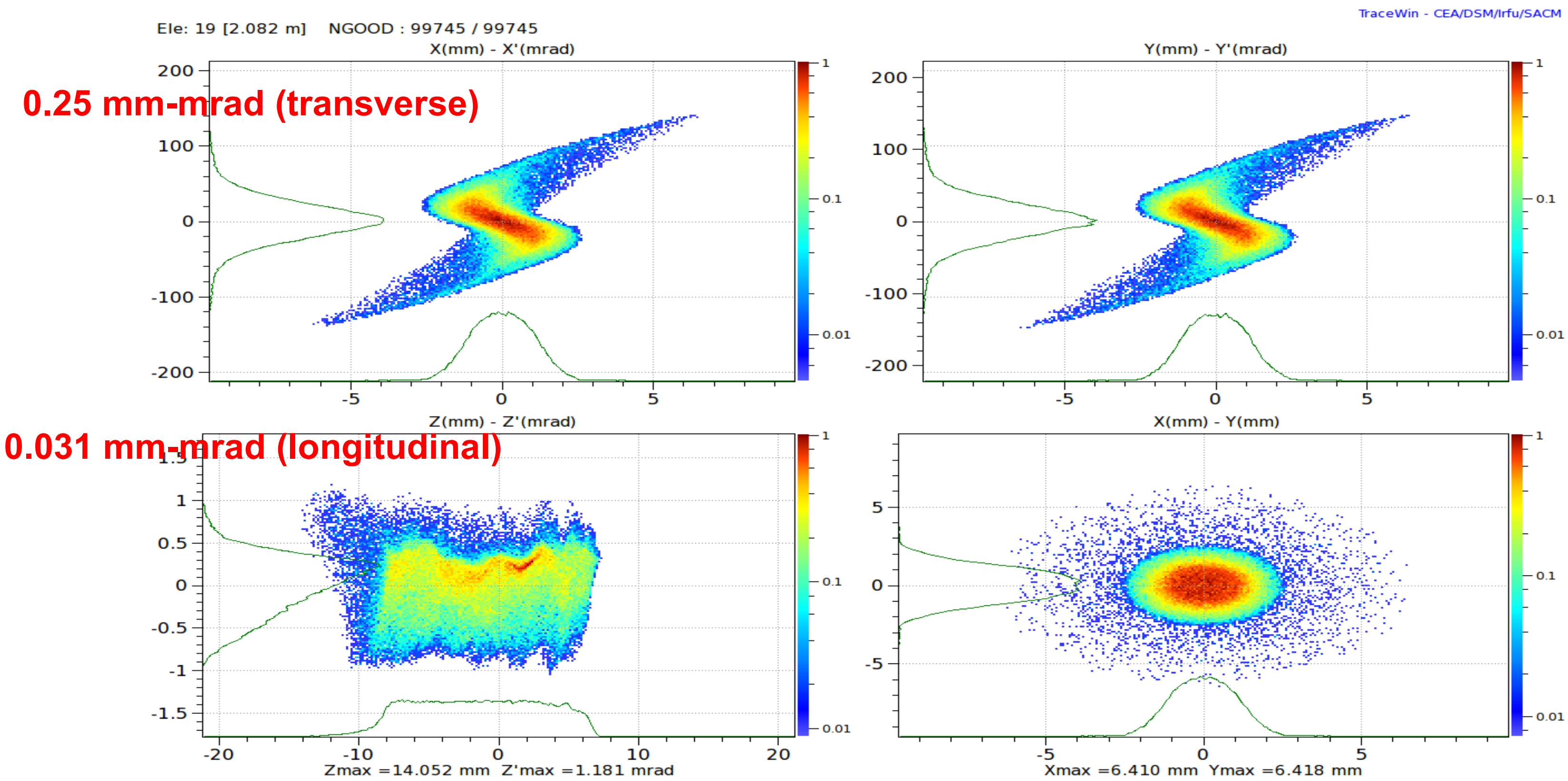
LEBT output beam tuned to match RFQ

LEBT + RFQ
Input = Gaussian Beam
Envelopes (3-sigma)



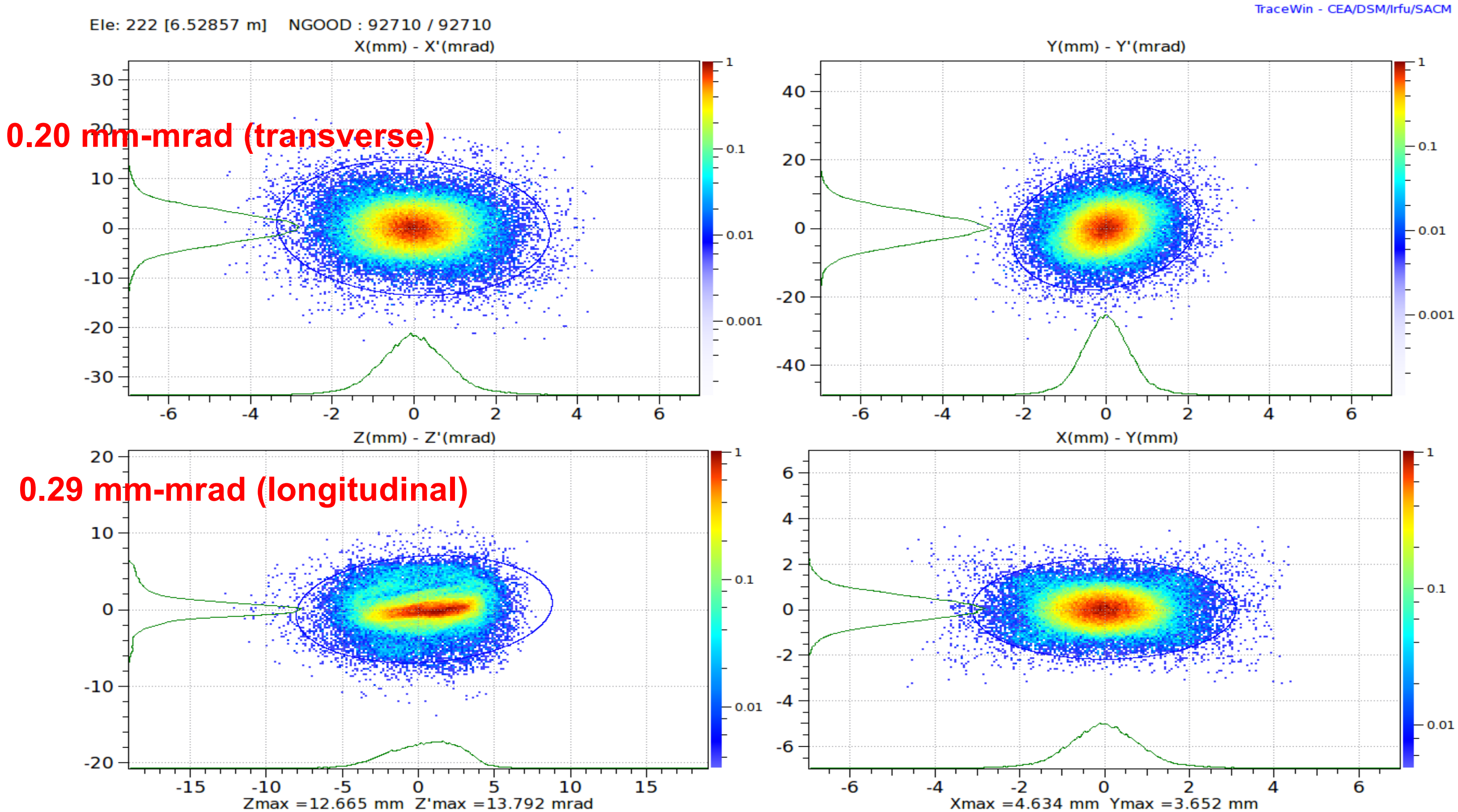
Neutralized **un-neutralized**

LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Distributions at RFQ Input

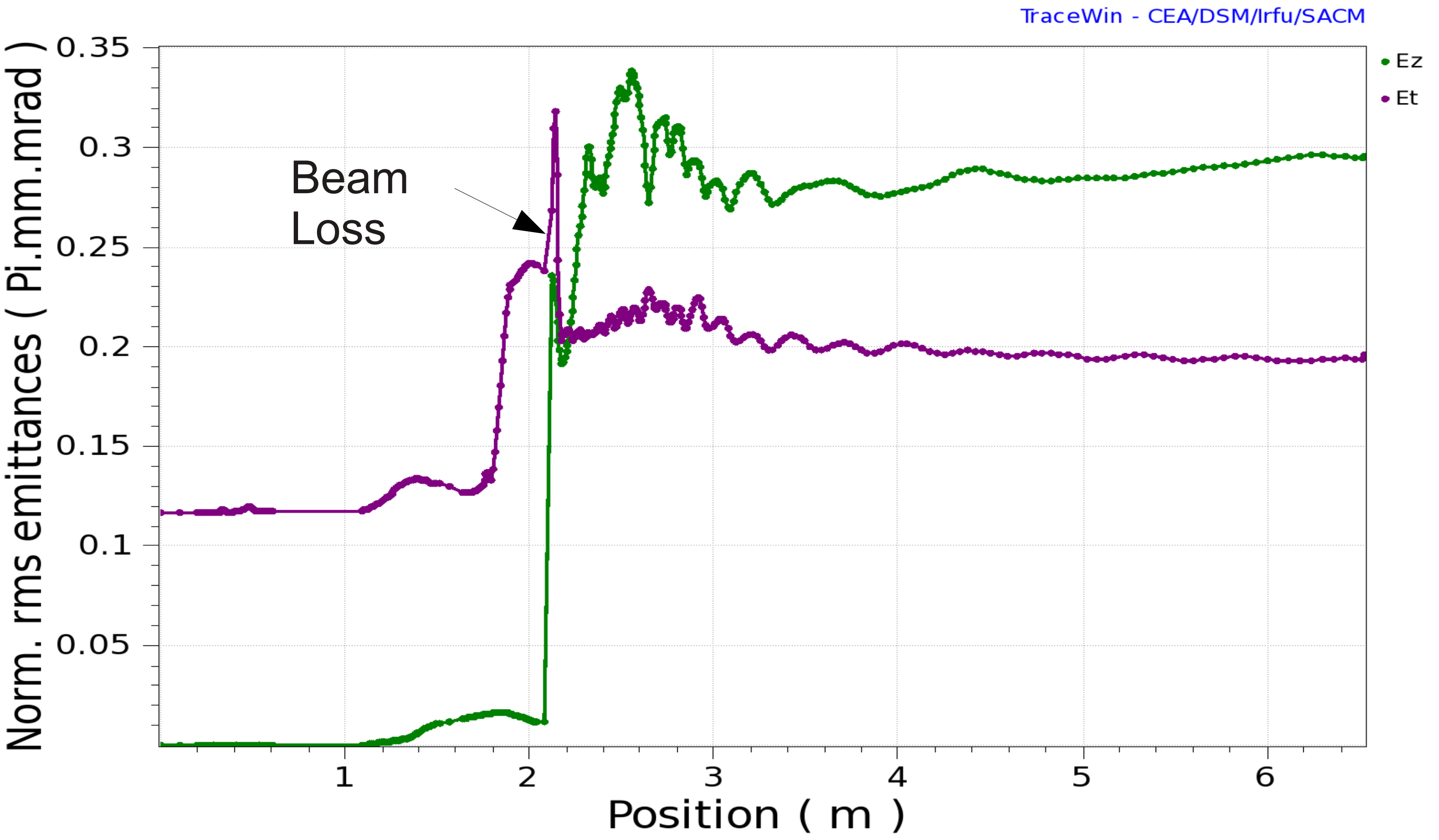


LEBT tuned for matched (envelope) beam parameters at RFQ input

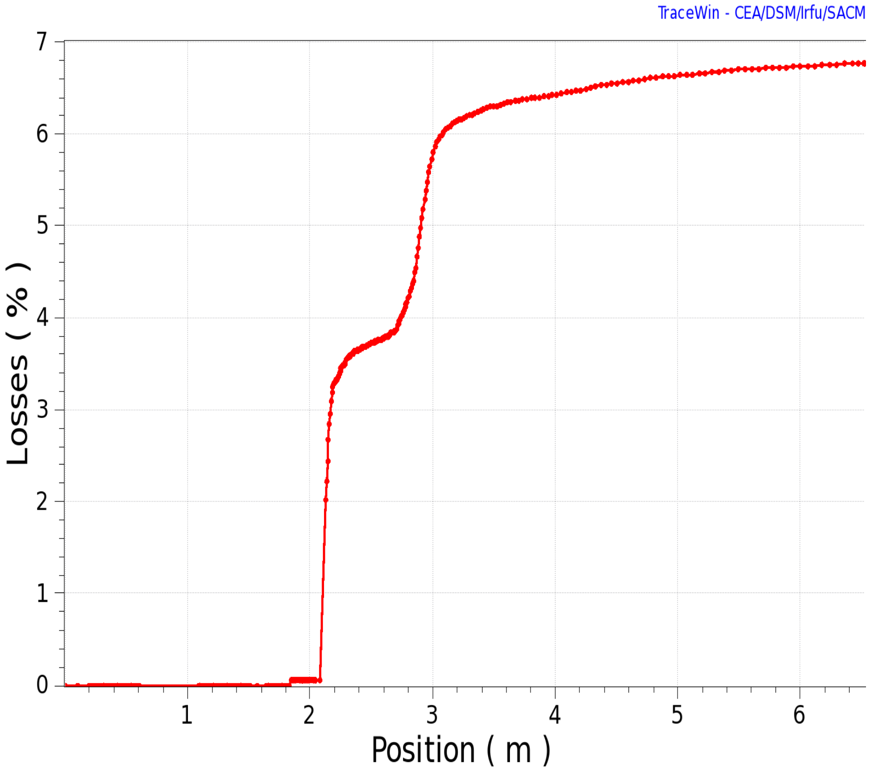
LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Distributions at RFQ Output

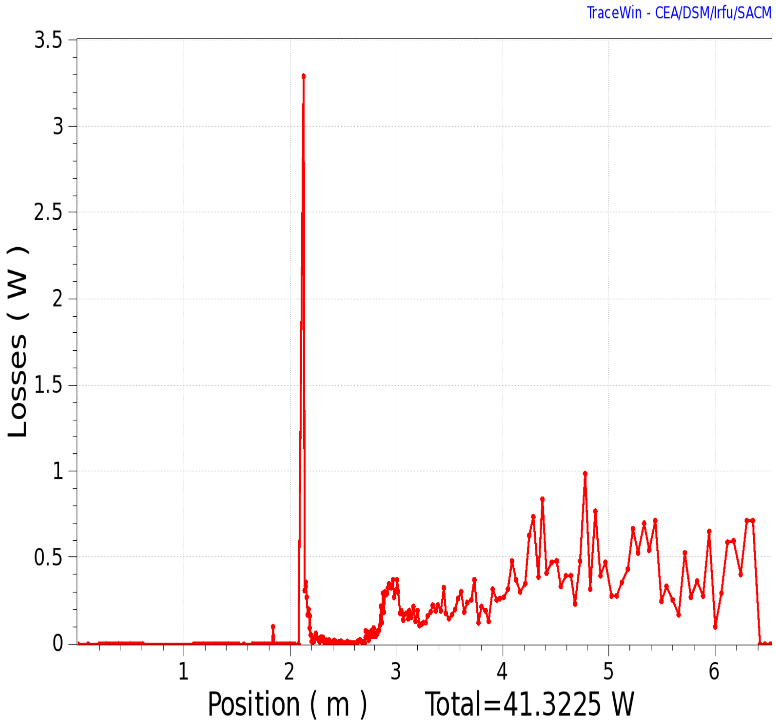


LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Emittance Evolution

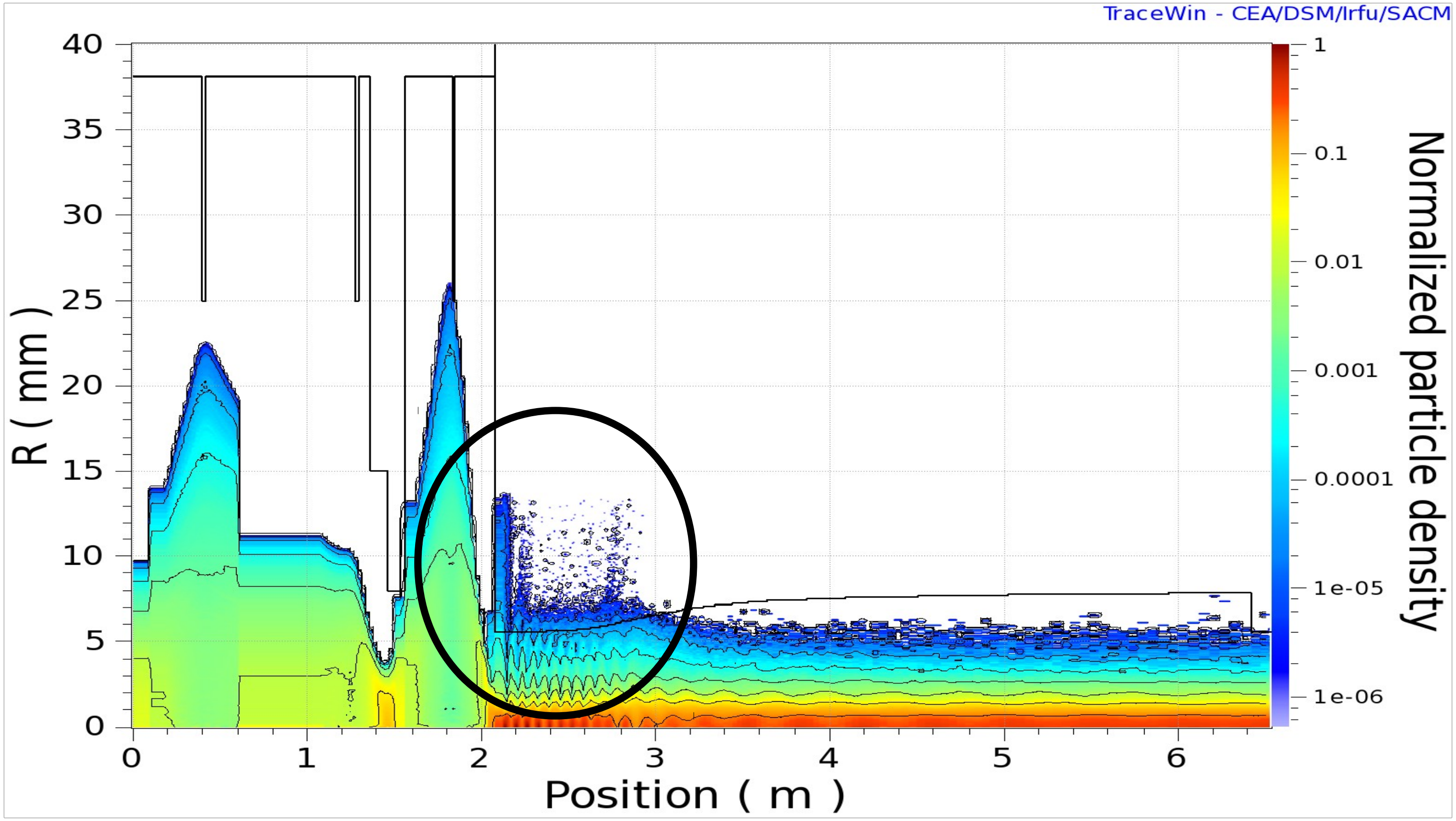


LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Particle and Power Losses





LEBT + RFQ
Input = Gaussian Beam
Radial Particle Density

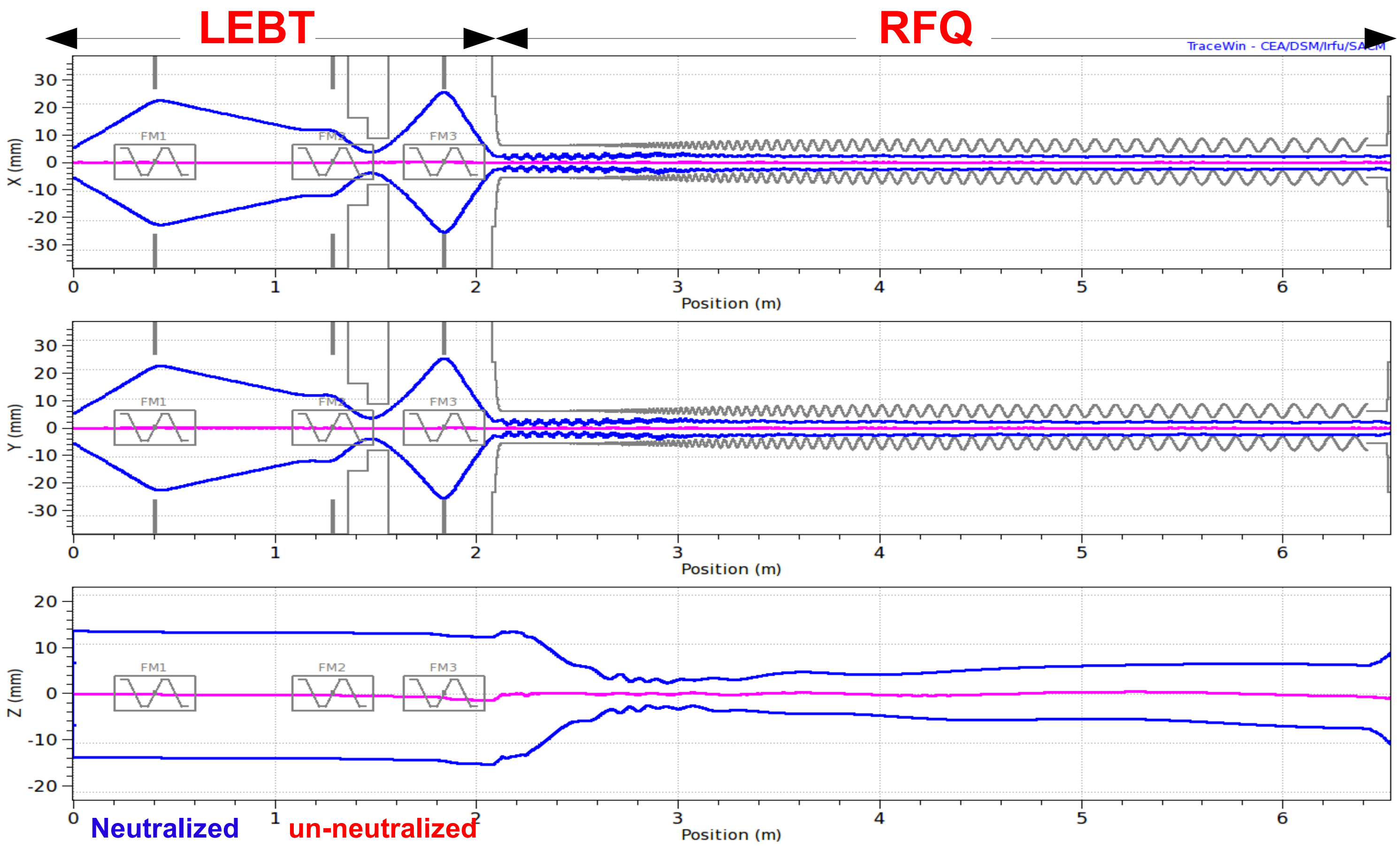


LEBT + RFQ

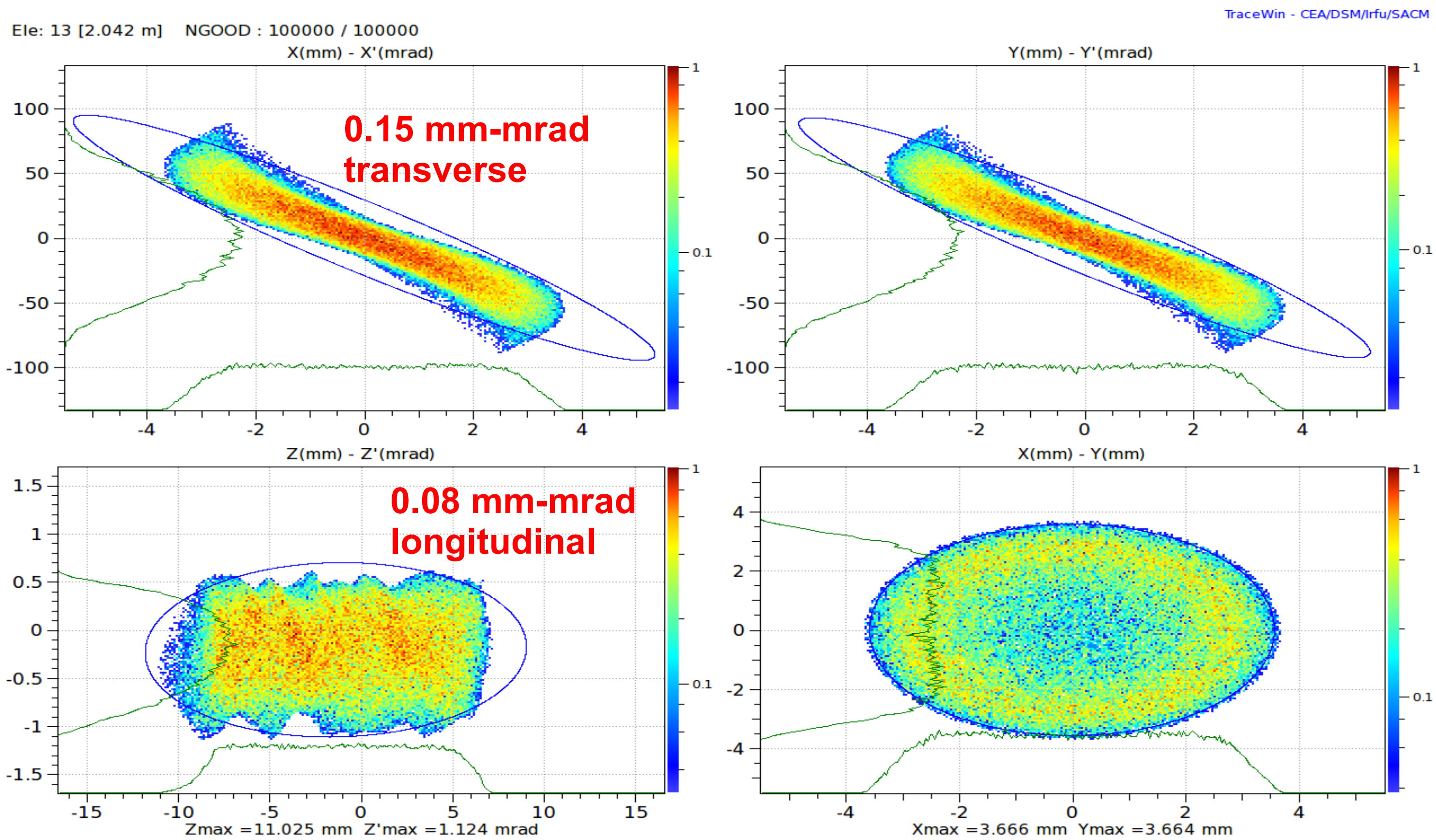
LEBT Input = Transverse Uniform Distribution

LEBT tuned to match RFQ

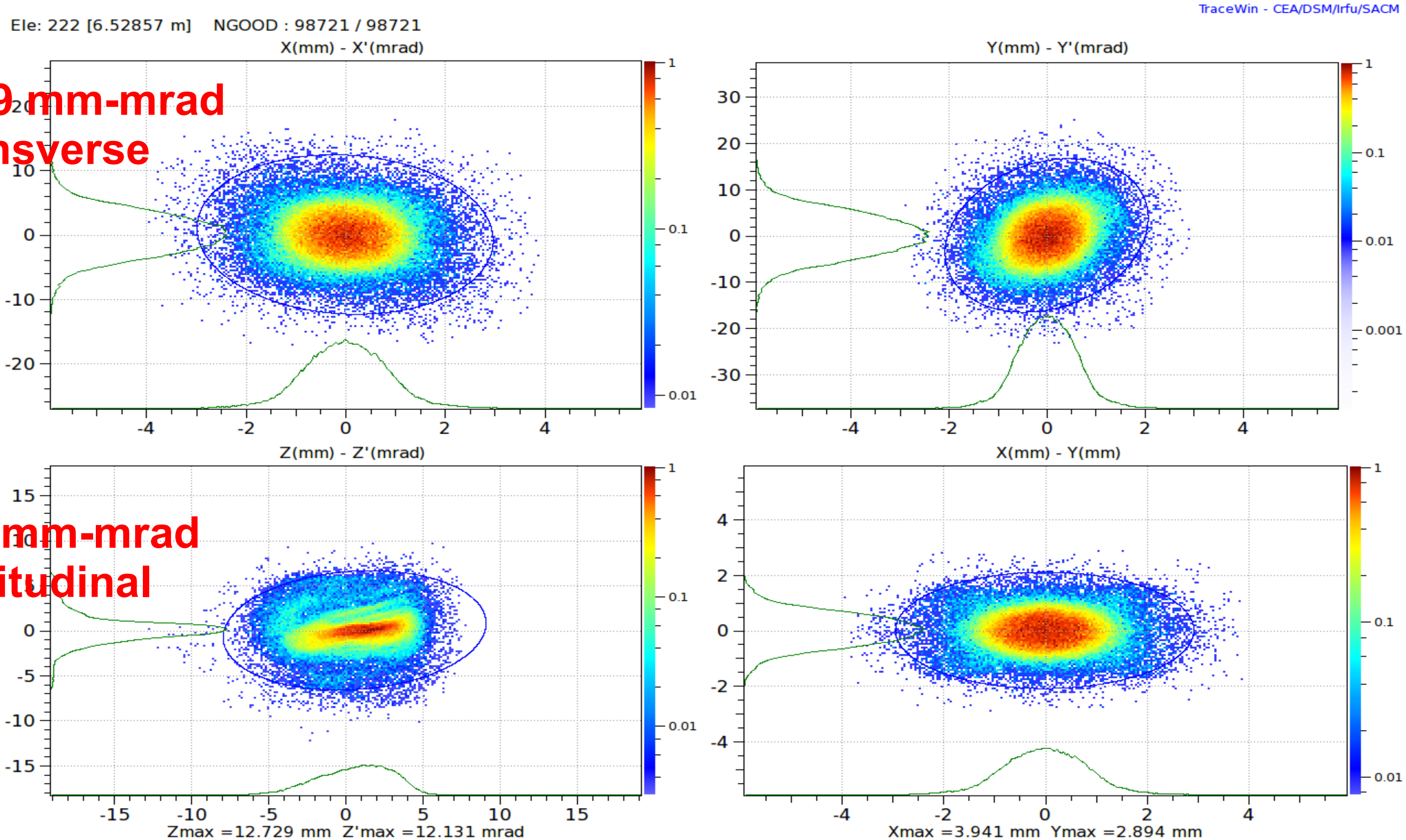
LEBT + RFQ
Input = Uniform Beam
Envelopes (3 sigma)



LEBT + RFQ
LEBT Input = Ideal Uniform Beam
RFQ Input Distributions



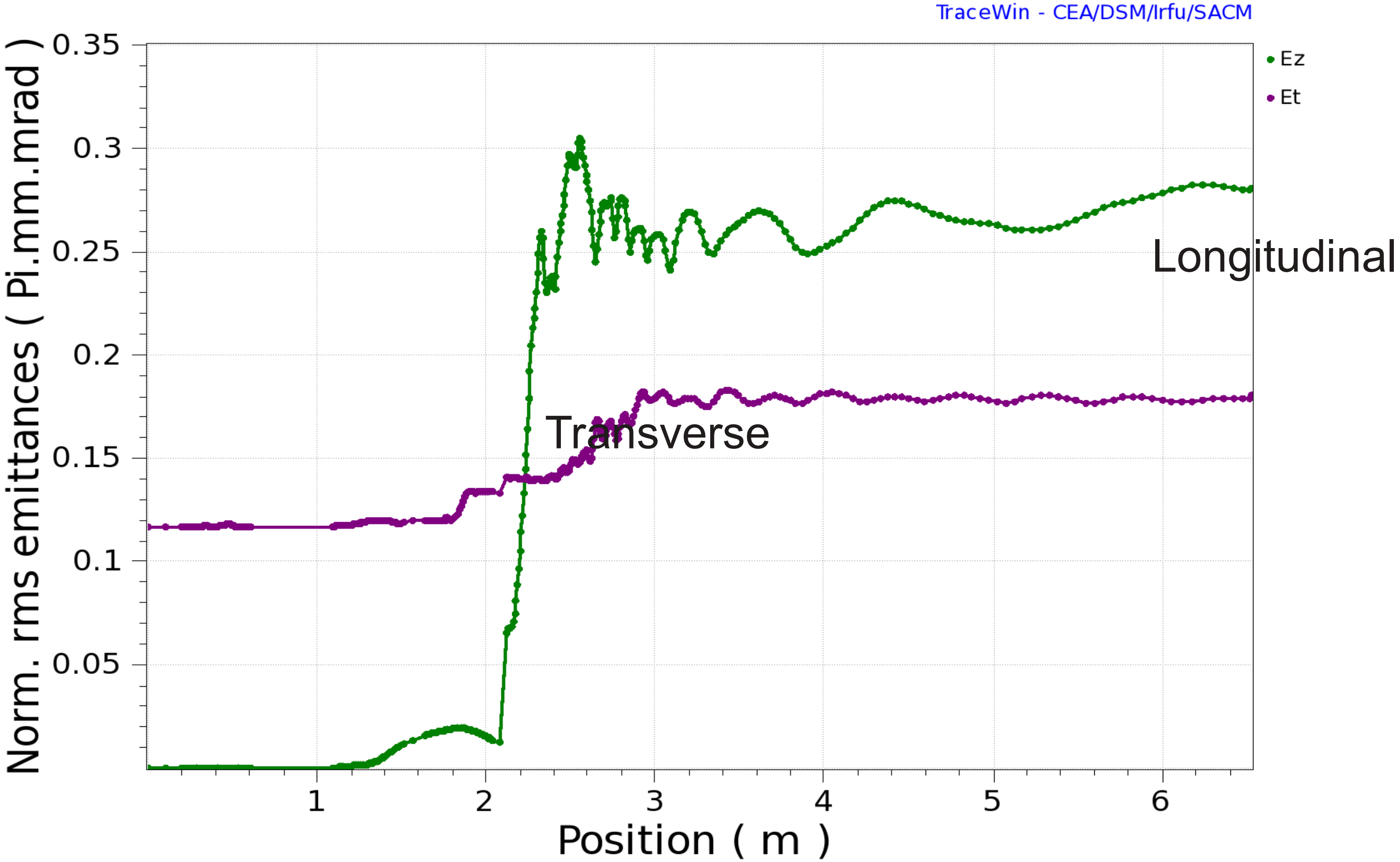
LEBT + RFQ
LEBT Input = Ideal Uniform Beam
RFQ Output Distributions



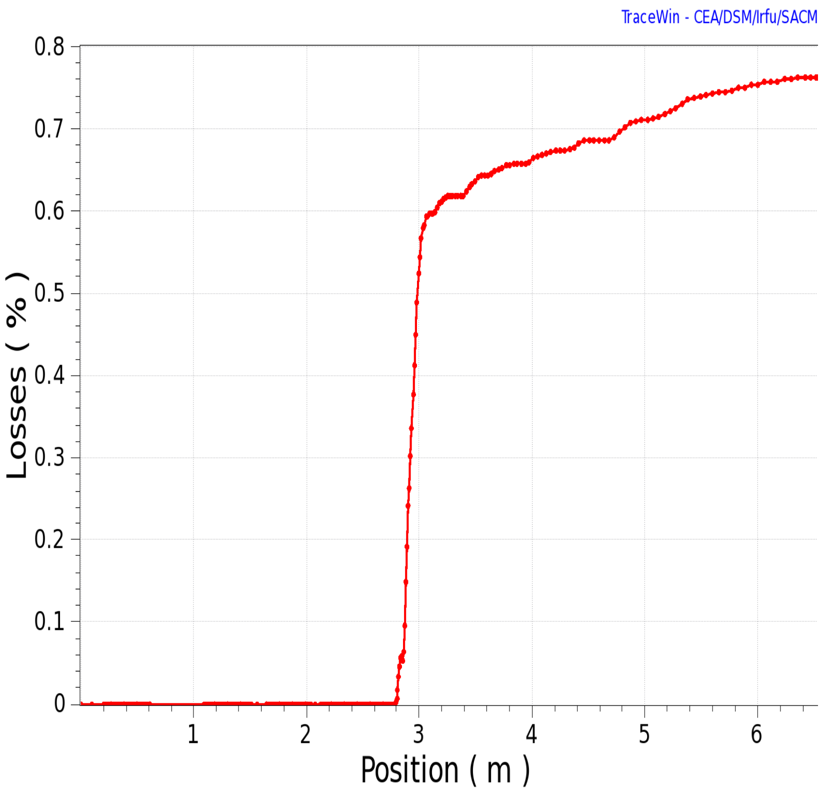
0.19 mm-mrad transverse

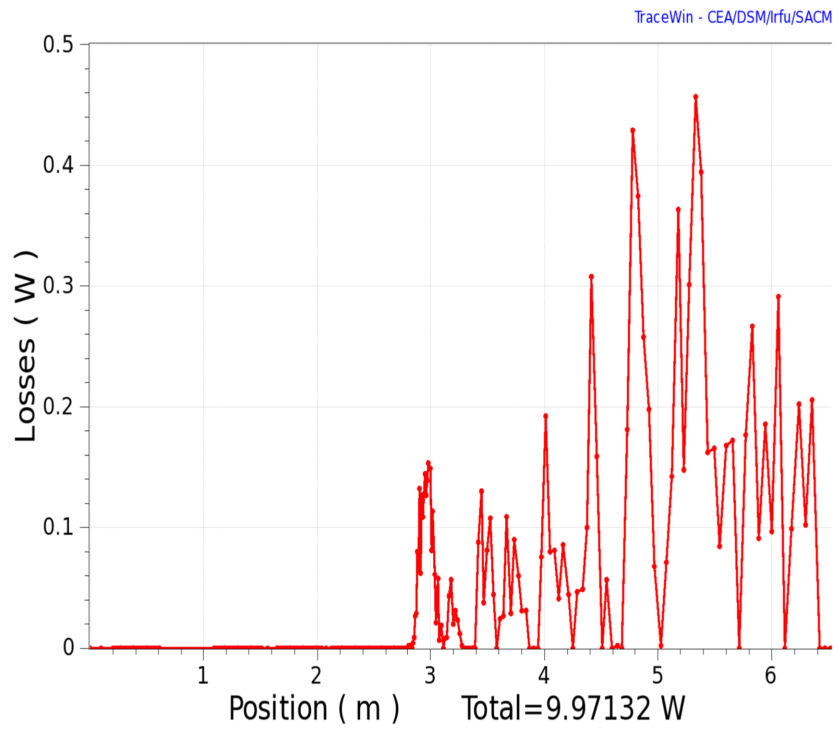
0.28 mm-mrad longitudinal

LEBT + RFQ
LEBT Input = Ideal Uniform Beam
Emittance Evolution

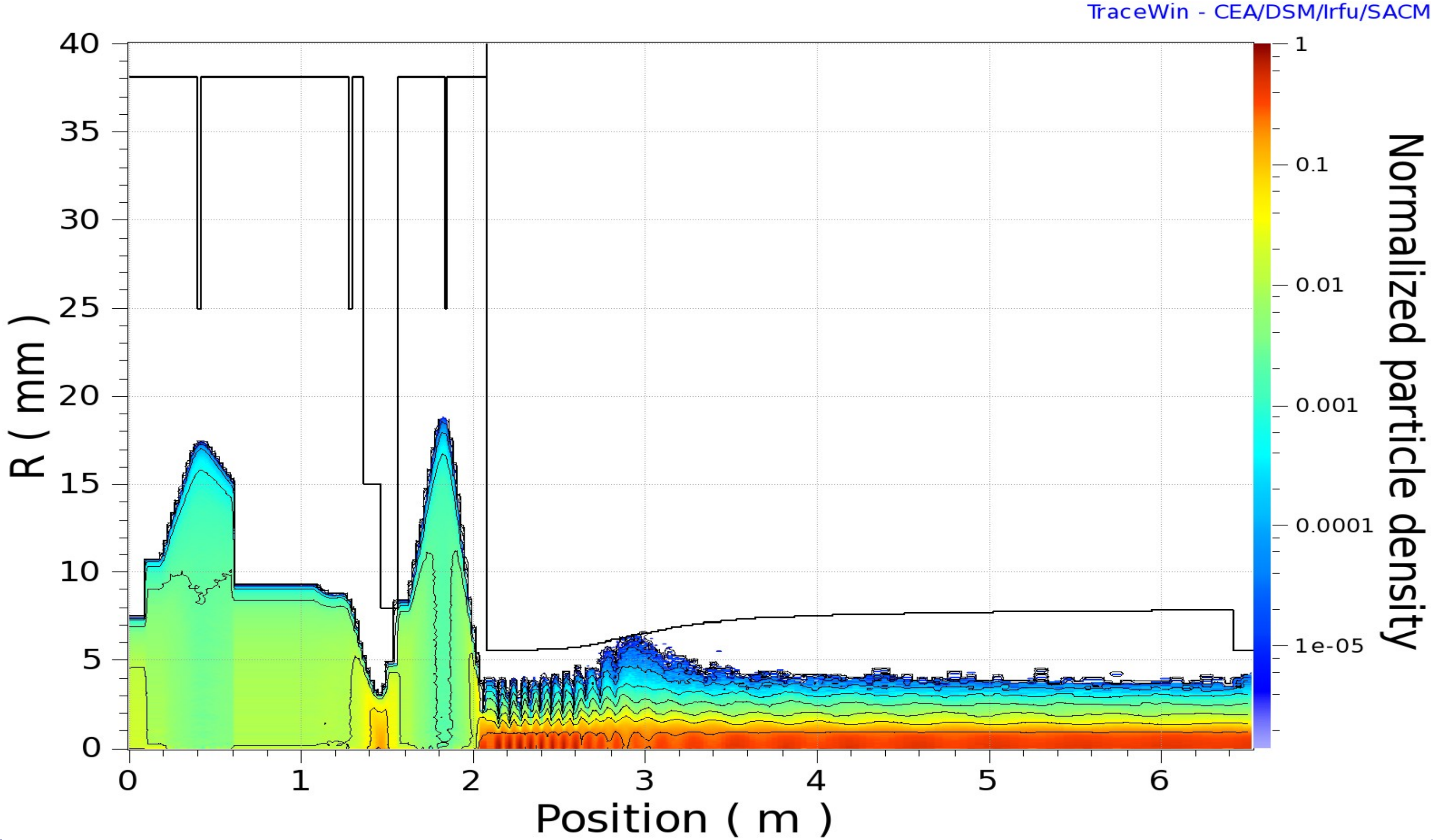


LEBT + RFQ
LEBT Input = Uniform Beam
Particle and Power Losses

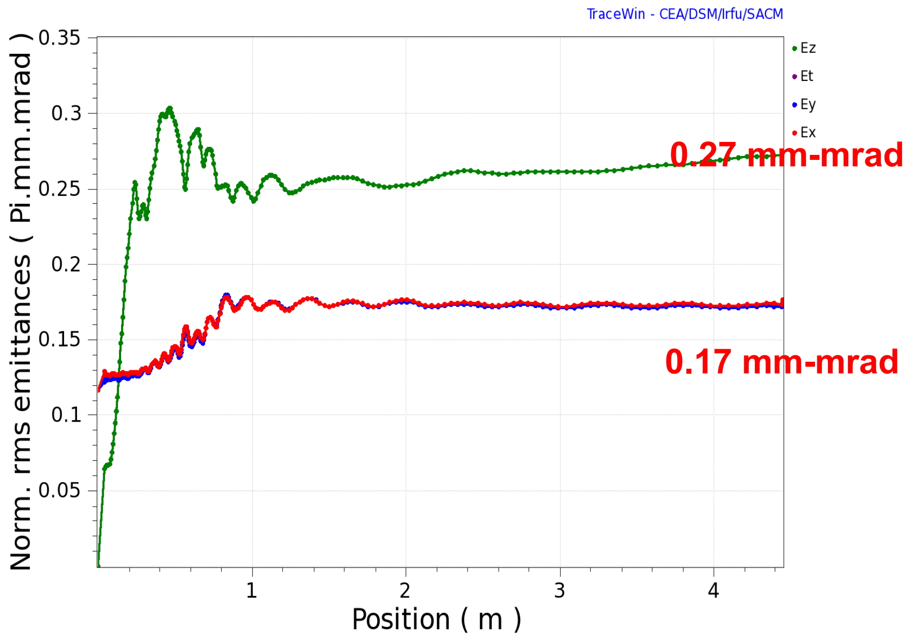




LEBT + RFQ
LEBT Input = Uniform Beam
Radial Particle Density



RFQ Emittance Evolution with RFQ input = Ideal Gaussian Beam with reduced convergence



Input beam parameters

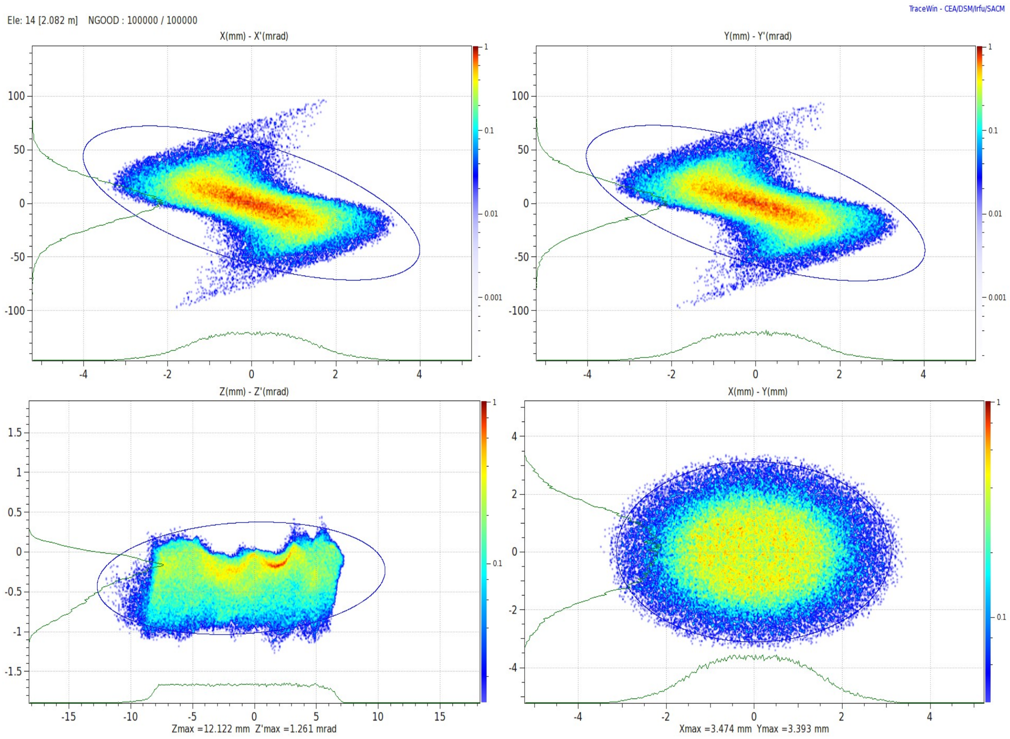
Plane	Emittance mm-mrad	alpha	Beta (mm/mrad)
x	0.11	**0.8**	0.07
y	0.11	**0.8**	0.07
z	0.0	-	-

Mismatch
("relaxed" convergence)

We investigate a reduction in the beam convergence w/r to the matched value at the RFQ input.
To estimate the **minimal impact** of such a mismatch, we use an ideal Gaussian beam at the RFQ input

LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Mismatched Beam at RFQ input

Distributions at RFQ Input



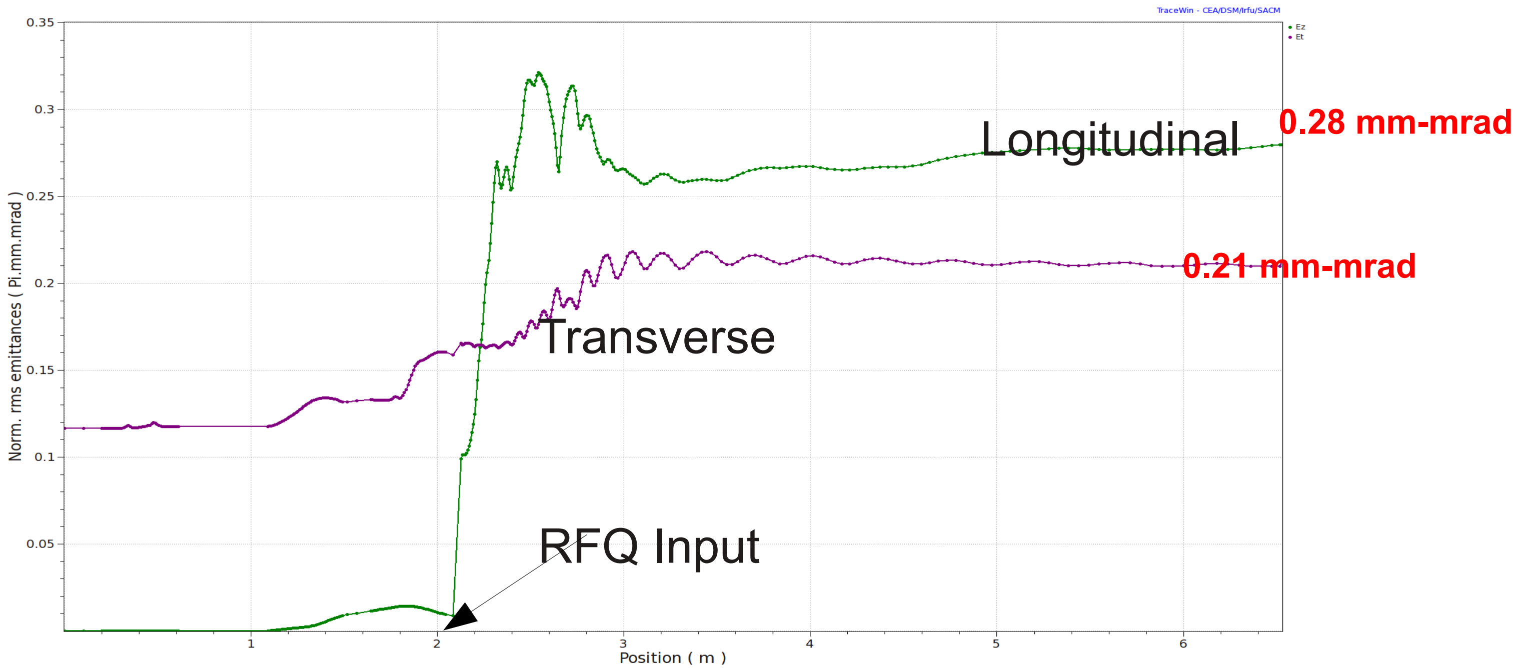
Input beam parameters
(computed from distribution)

Mismatched to RFQ

Plane	Emittance mm-mrad	alpha	Beta (mm/mrad)
x	**0.16**	**0.76**	0.07
y	**0.16**	**0.76**	0.07
z	**0.01**	-	-

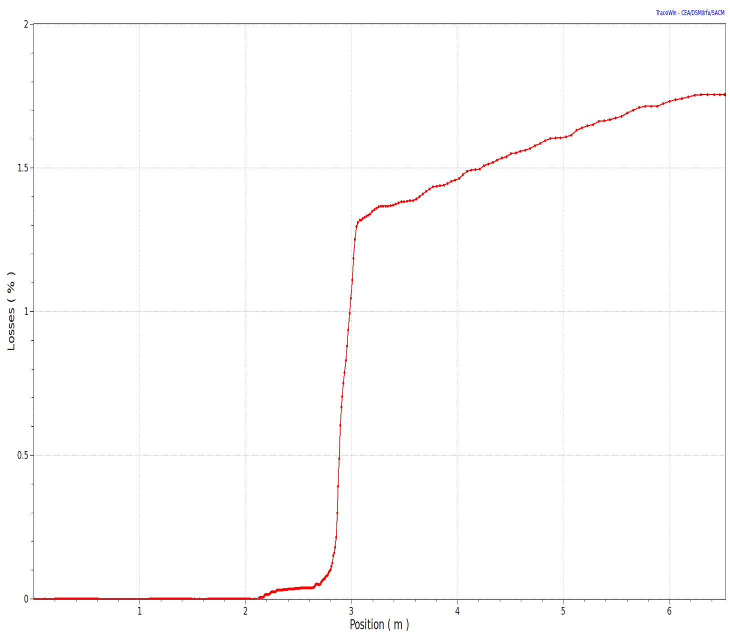
LEBT tuned to achieve desired reduced convergence at RFQ input.

Emittance Evolution
LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Mismatched Beam at RFQ Input

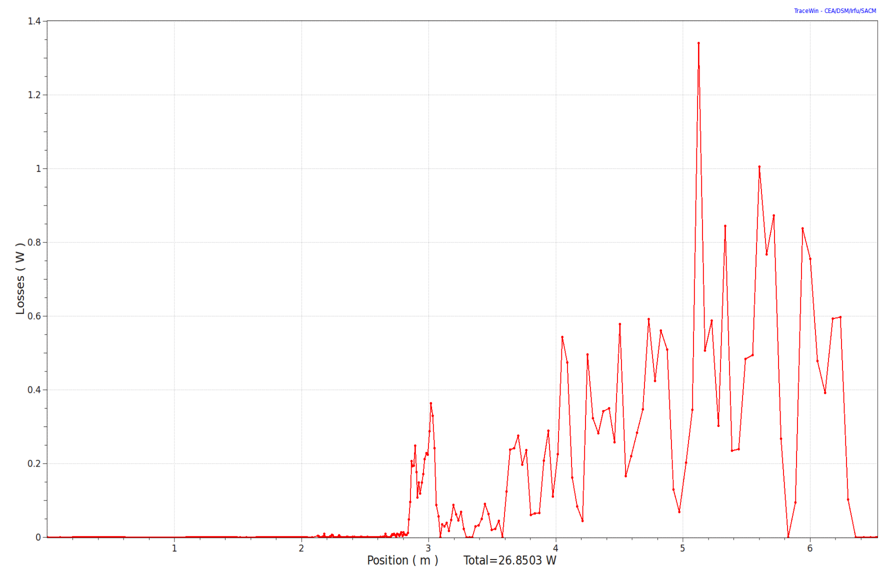


Not surprisingly, distorted transverse phase space at the RFQ input results in more elevated final emittance than with a pure Gaussian.

Particle & PWR Losses
LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Mismatched (reduced convergence) at RFQ Input

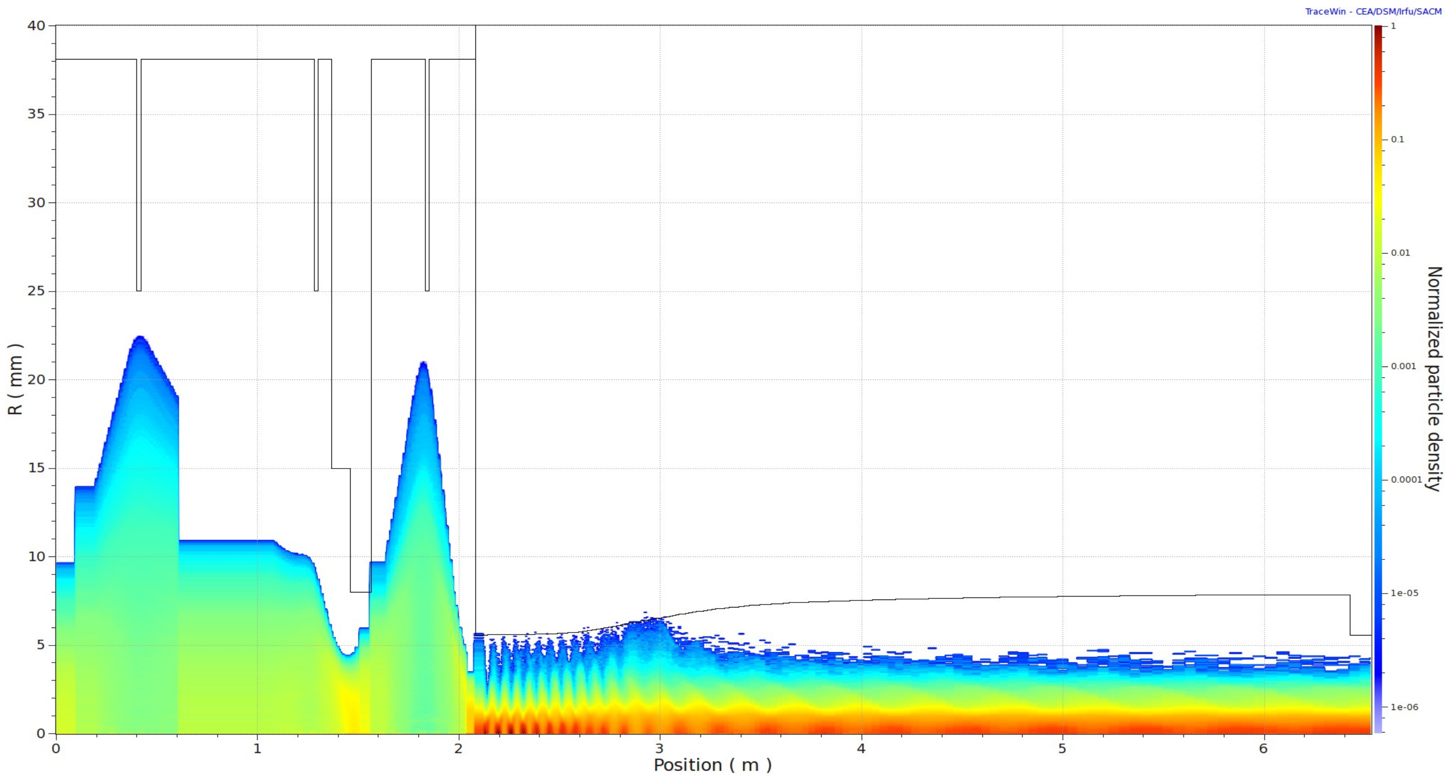


1.77% loss



Total Pwr Loss = 27 W

Radial Particle Density
LEBT + RFQ
LEBT Input = Ideal Gaussian Beam
Mismatched (reduced convergence) at RFQ Input



Summary

LEBT in	ϵ_T in mm-mrad	ϵ_L in mm-mrad	ϵ_T out mm-mrad	ϵ_L out mm-mrad	Losses	Pwr Losses Watt
Nominal	0.11	0	0.15	0.22	< 1.0e-3	0
Gaussian Matched LEBT	0.11	0	0.20	0.30	6.5%	40
Gaussian 50% Alpha mismatch	0.11	0	0.21	0.28	2%	30
Gaussian 5.5% scraping in S3, Matched	0.11	0	0.19	0.28	8 %	40
Uniform, Matched LEBT	0.11	0	0.18	0.28	1%	10

Conclusions

- Toutatis and PARMTEQM are generally in very good agreement
- In general, our benchmarks confirm the results of LBNL for various type of construction/field errors. In particular, the RFQ is not very sensitive to input mismatch.
- To successfully operate a LEBT with a non-neutralized section with the proposed configuration, we may be forced to tolerate a nominal input mismatch into the RFQ in order to reduce emittance growth in the LEBT.
- The transverse aperture margin in the linac is comfortable, so a slighthly higher than nominal transverse emittance at the linac input is probably tolerable.
- An increase in the expected longitudinal emittance may require a readjustments in the linac front-end optics.
- Next steps:
  - Investigate improving the optics of the LEBT
  - High statistics end-to-end simulations of PXIE and PX with various errors
  - Investigate ways to either improve or side-step Toutatis limitations.