Beam Dynamics Error Studies of the ESS Linac

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on behalf of the ESS Beam Physics Section

ESS - J-Parc Workshop

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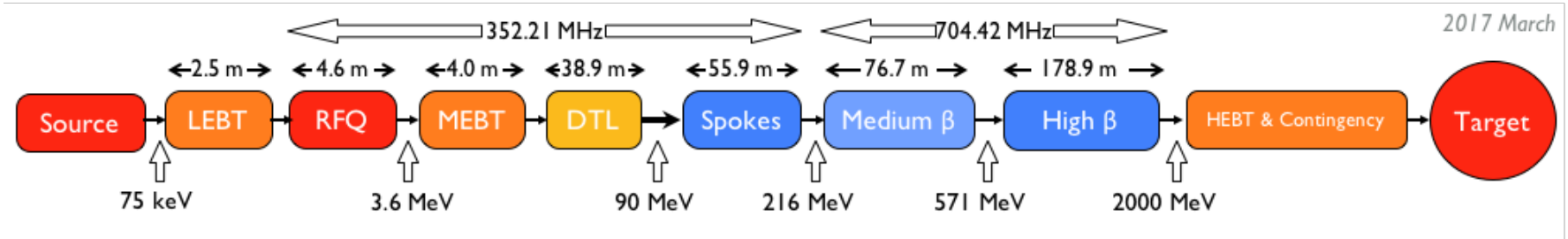
Content

The ESS Linac

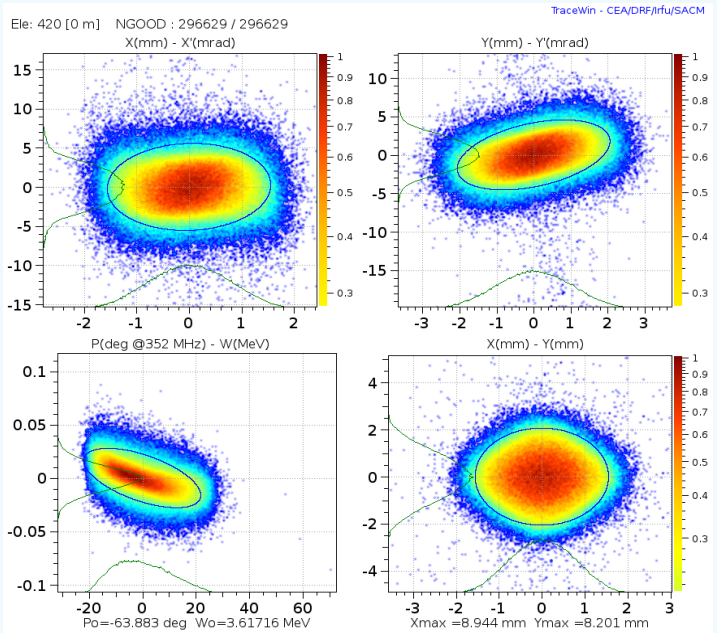


	Energy [MeV]	# modules	cav./mod.	$\beta\gamma$	Temp. [K]	Length [m]
Source	0.075	-	0	-	$\sim$ 300	-
LEBT	0.075	-	0	-	$\sim$ 300	2.5
RFQ	3.65	1	1	-	$\sim$ 300	4.6
MEBT	3.65	-	3	-	$\sim$ 300	4.0
DTL	90.0	5	-	-	$\sim$ 300	39
Spokes	216	13	2	-	$\sim$ 2	56
Med.-β	571	9	4(6C)	0.67	$\sim$ 2	77
High-β	2000	21	4(5C)	0.86	$\sim$ 2	179
HEBT	2000	-	-	-	$\sim$ 300	241

Beam Parameters

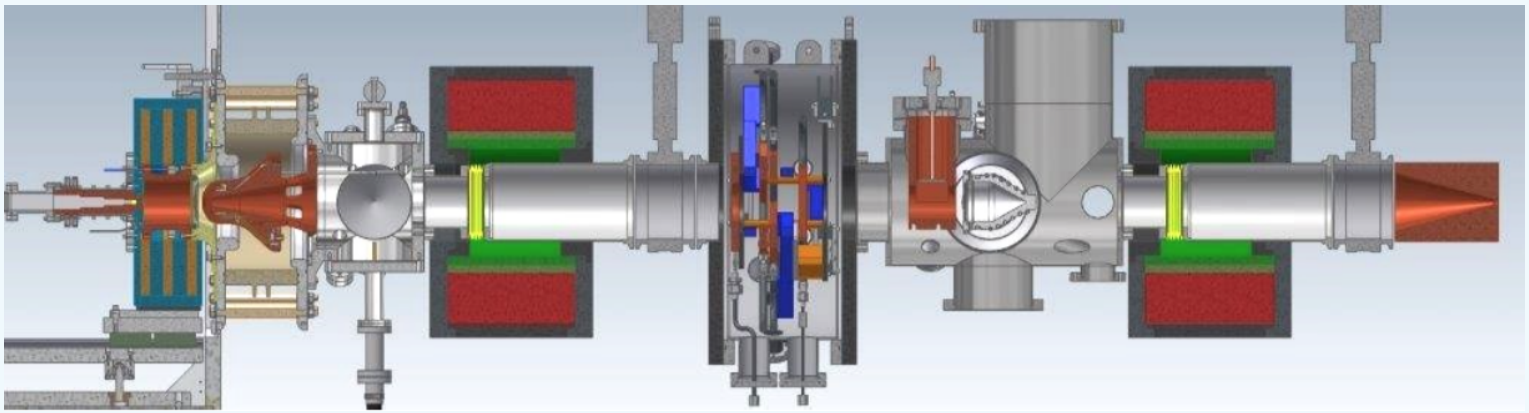
Beam current	62.5 mA
Pulse length	2.86 ms
Repetition rate	14 Hz
Duty cycle	4 %
ϵ_{transv} (source)	0.12 µm rad
Beam energy	2.0 GeV
Peak beam power	125.0 MW
Avg. beam power	5.0 MW

Beam at RFQ exit

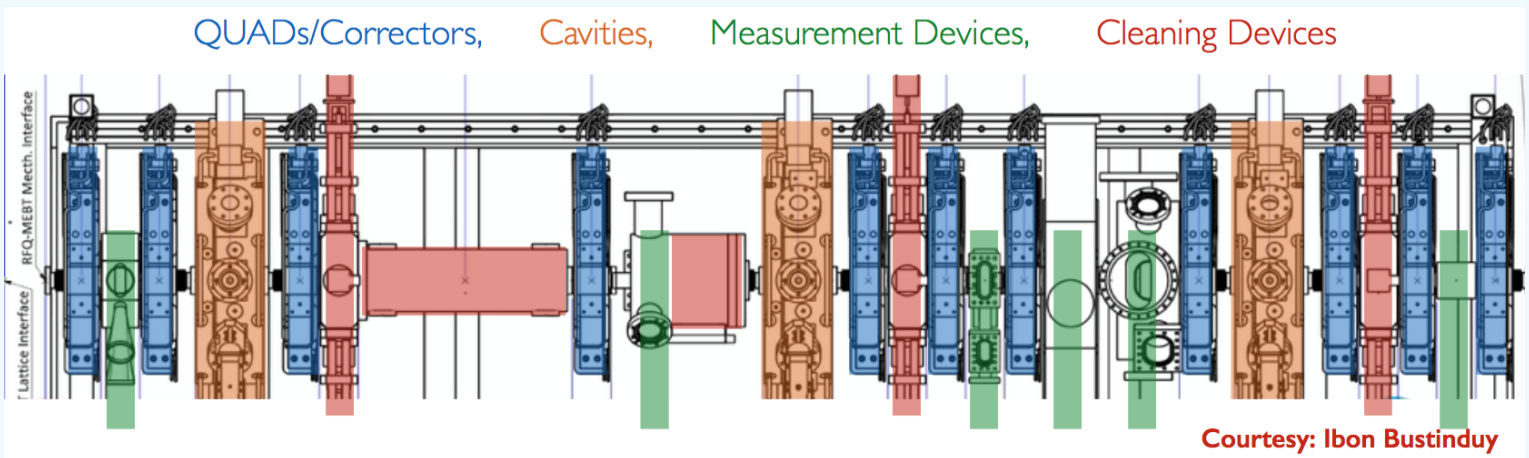


Introduction

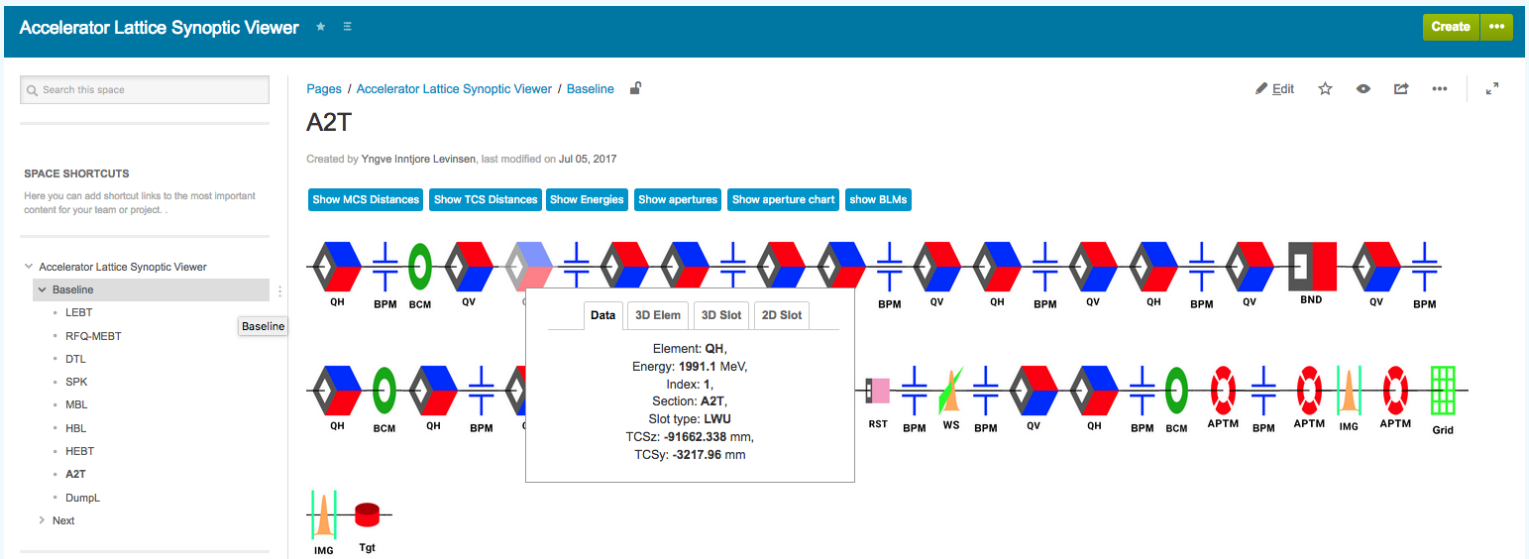
LEBT



MEBT



Synptic Viewer



Error Studies

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- Realistic end-to-end error studies of the entire linac is needed to verify the beam dynamics tolerances

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- Simulate multiple machines (seeds) in TraceWin.

What are static errors?

Static errors are originating primarily from installation and manufacturing, but can also arise from long term drifts, during upgrades and consolidation of problems in the tunnel etc.

- Static errors stay constant for a long period of time, which means we can measure them precisely (multiple shots).
- For beam dynamics, we do not care what the origin of the error is, we care only about how it modulates the electromagnetic field.
- Example: transversal movement of a dipole is not relevant, as long as the beam stays within the good field region. (GFR).

What are dynamic errors?

Dynamic errors are changes which happen faster than the time between corrections/setup.

- Dynamic errors will typically vary randomly, e.g. electrical noise, vibrations, jitter...
- Drifts (e.g. sinking ground floor) are not considered.
- Generally dynamic errors are smaller than static errors.
- Fast dynamic errors (seconds and less) limit our measurement precision of static errors.

Beam Dynamics Design and Simulation Strategy

- Beam exit RFQ with static errors: 0.3 mm offset, 1 mrad rotation, 5 % size, 1 % current. Dynamic 10 % of those values
- Quadrupole errors always uniform, static. 0.2 mm offset, 0.06 deg z-rotation, 0.5 % gradient error

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- Cavity alignment NC: 0.5 mm offset, 0.115 deg rotation
- Cavity alignment SC: 1.5 mm offset, 0.129 deg rotation
- Static RF phase/amplitude NC: 1.0 deg/% (0.5 deg DTL tube-tube)
- Dynamic RF phase/amplitude NC: 0.2 deg/% (0 for DTL tube-tube)
- Dynamic RF phase/amplitude SC: 0.1 deg/%

Evaluating simulations

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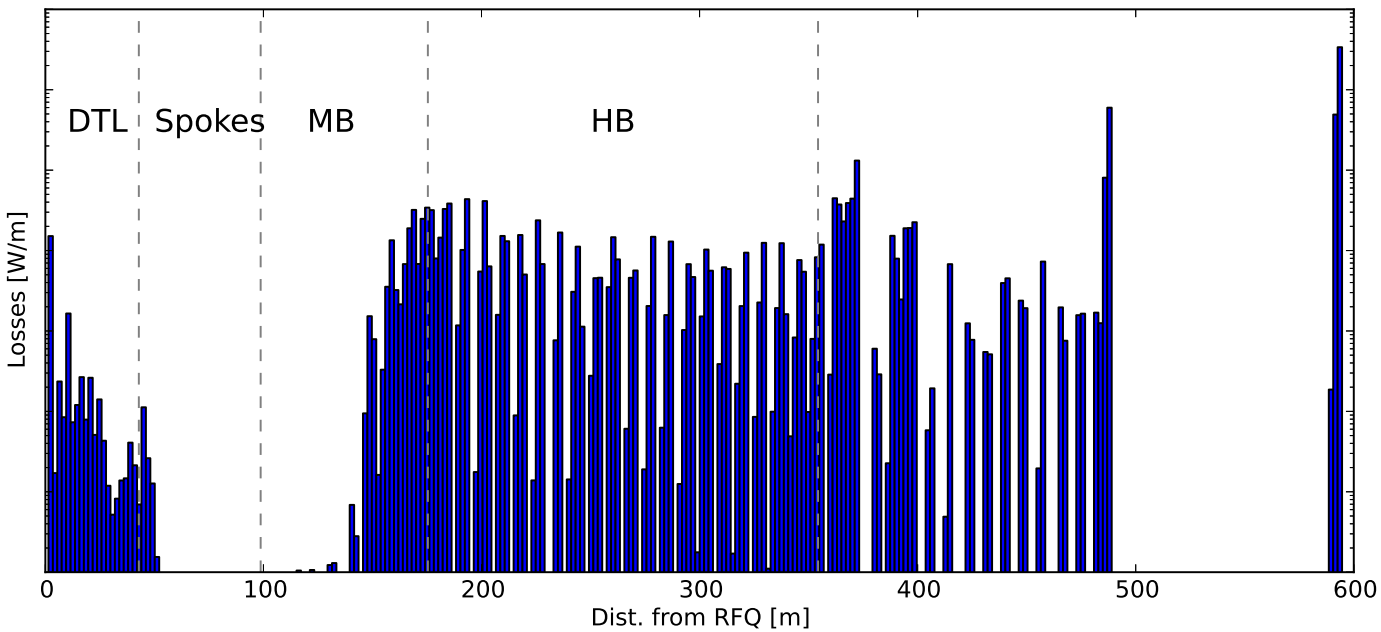
DIRECT: With errors, a certain increase in particle losses are observed.

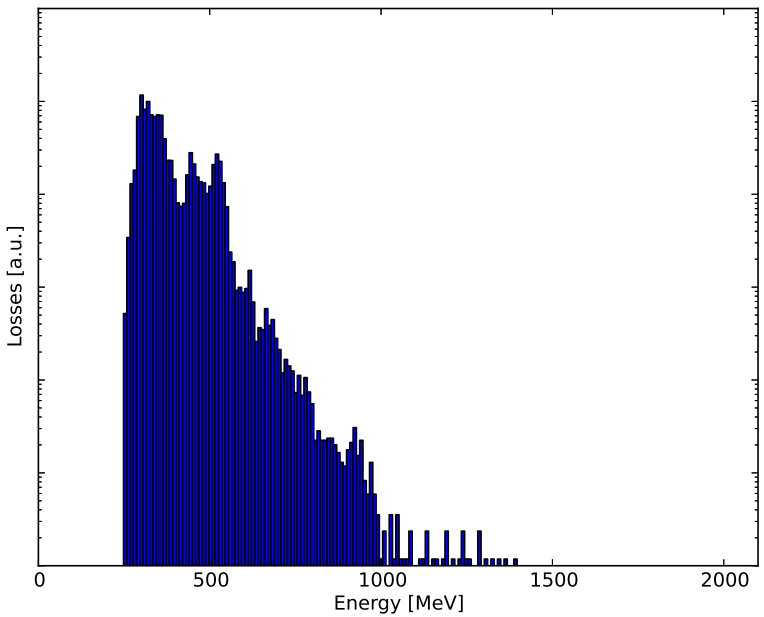
INDIRECT: Errors introduce additional growth of beam size (emittance), which in reality translate to increased losses.

Requirement: Losses should not exceed 1 W/m, emittance growth approx 10 % per sector or less.

Loss Distribution



Energy distribution of losses - dogleg



- Most failures and error studies show significant losses in the dogleg.
- The frequency jump between SPK-Mβ is a clear source of particle losses in our studies.

Dynamic RF Errors

Varying longitudinal dynamic errors

	NC ampl %	NC ph deg	SC ampl %	SC ph deg
1	0.0	0.0	0.0	0.0
2	0.2	0.2	0.1	0.1
3	0.4	0.4	0.2	0.2
4	0.6	0.6	0.3	0.3
5	0.8	0.8	0.4	0.4

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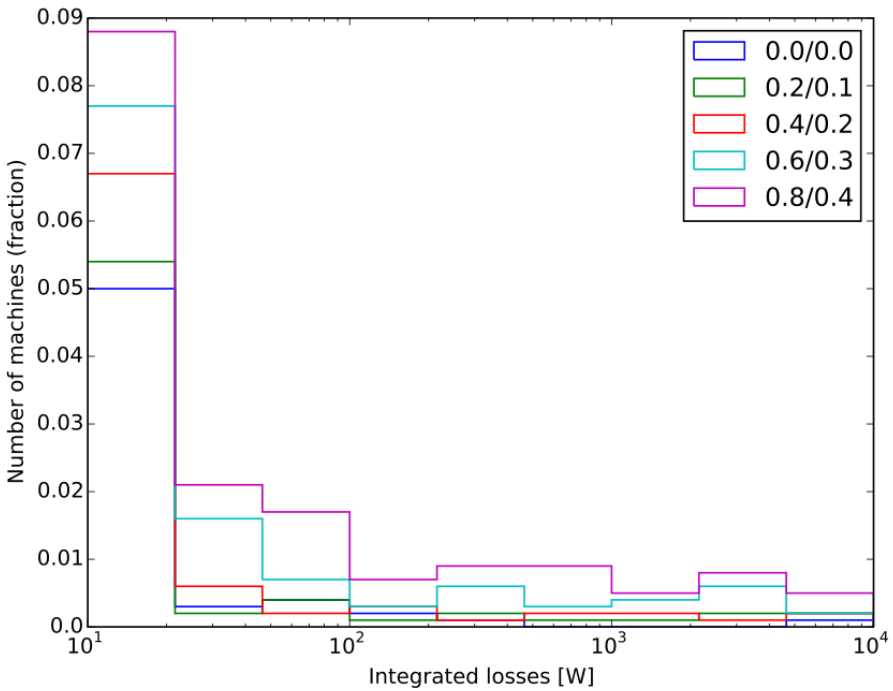
2	**0.2**	**0.2**	**0.1**	**0.1**
3	0.4	0.4	0.2	0.2
4	0.6	0.6	0.3	0.3
5	0.8	0.8	0.4	0.4

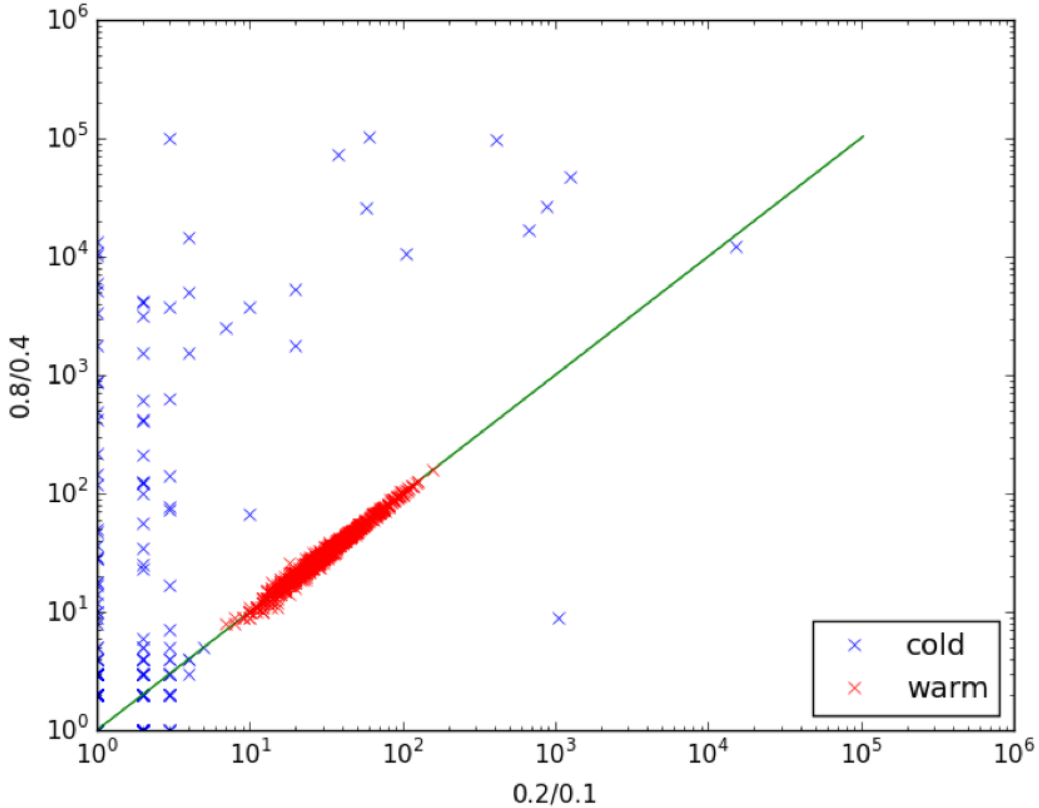
Our baseline requirement

Dynamic RF Errors



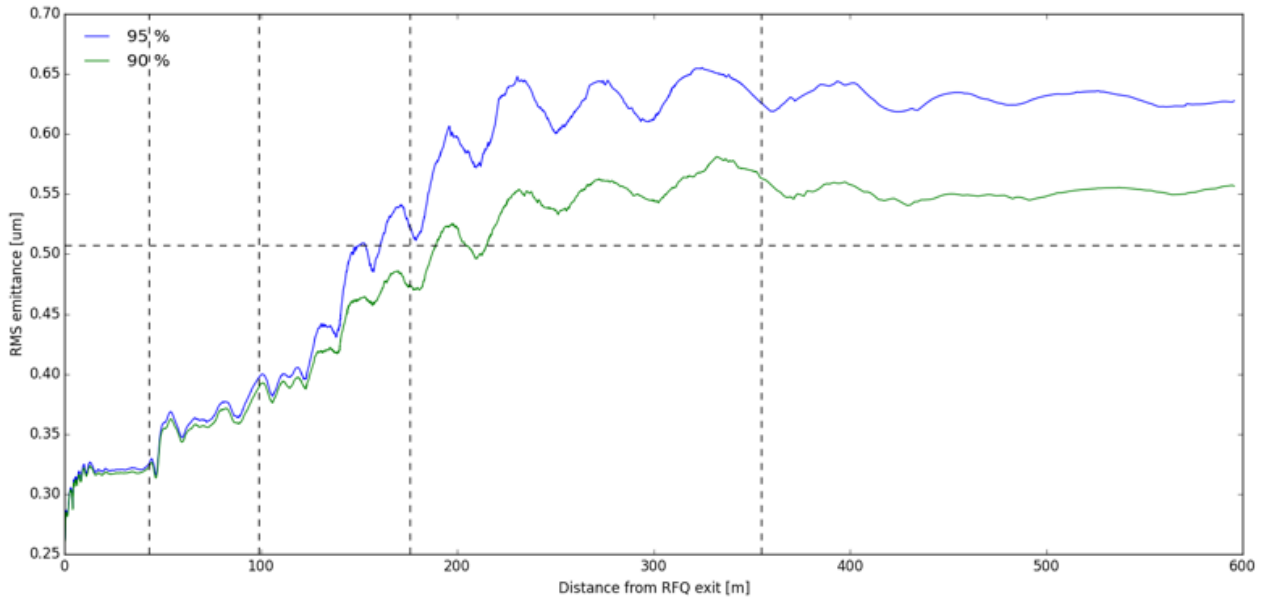
The integrated losses in watt for the machines depending on dynamic error tolerances (NC/SC).

Dynamic RF Errors



Integrated losses along the machines (arbitrary units), comparing nominal dynamic errors on the horizontal axis vs 4x nominal errors on the vertical axis, split in losses in warm linac (red) and cold (blue).

Dynamic RF Errors

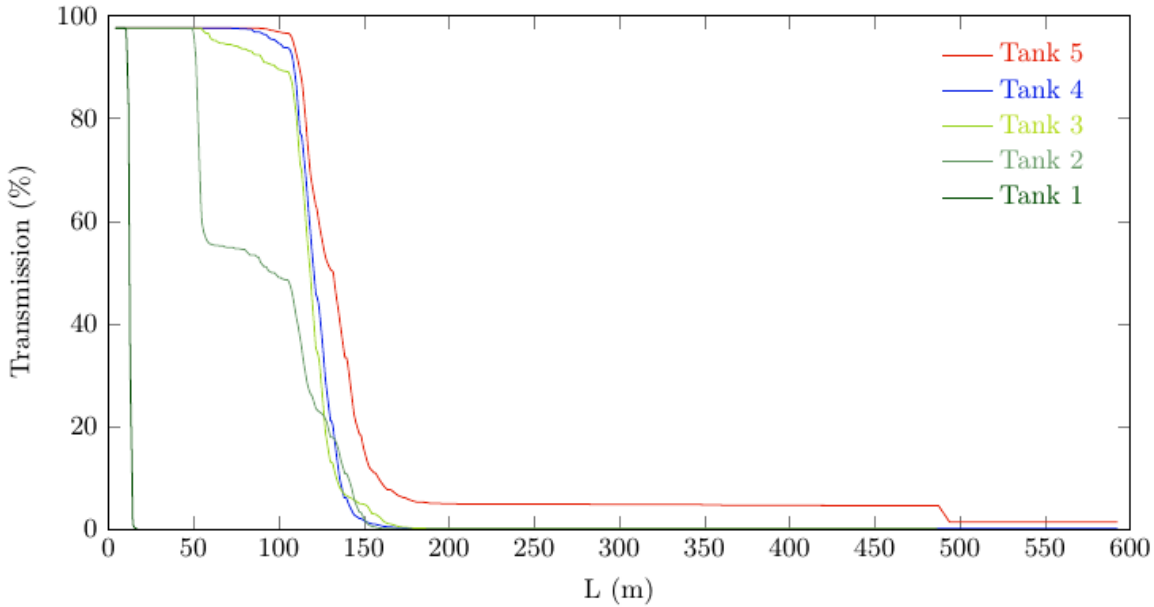


If we look at the emittance growth with nominal tolerances, we see that we are already close to the limit we defined (horizontal dashed line)

Single Failure Modes

We made a catalogue of losses from complete failure of single elements (quadrupole/cavity), not taking into account transients or feedback -> worst case scenarios.

MEBT and DTL failures



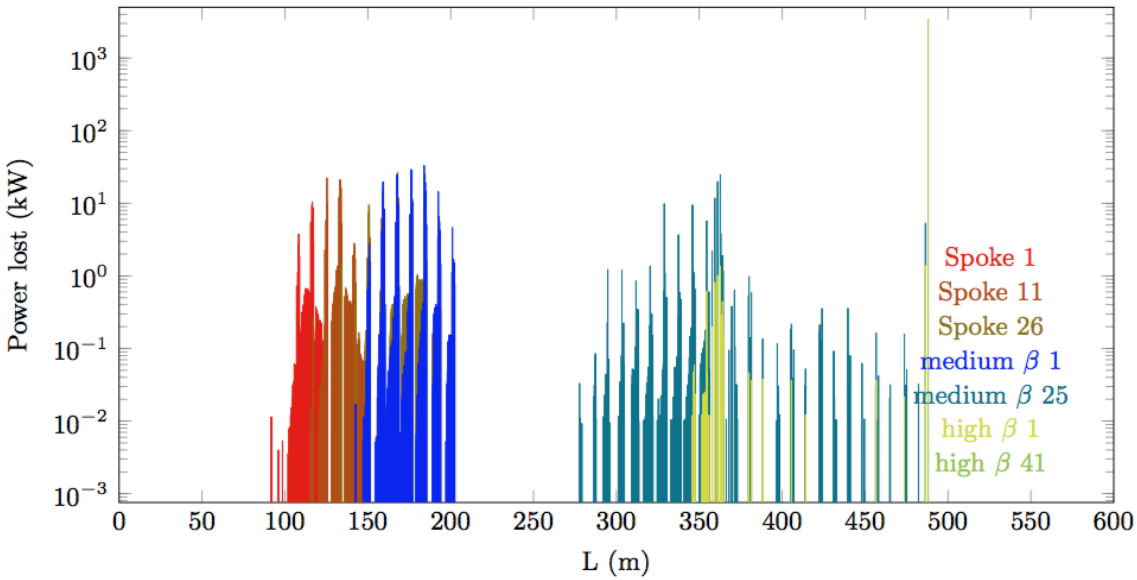
MEBT Buncher Cavity

Complete failure cause losses on the 100 W level downstream. Scrapers not helpful as this is a longitudinal blowup.

DTL Tanks

No power in one DTL tank cause losses on the 1000 W level downstream. Tank 1 -> all lost in DTL, tank 3-5 -> losses in SC only.

SC Cavity failures



Spoke, MB, HB Cavities

Complete failure of a SC cavity cause losses on the 10 kW level downstream, with peak in dogleg of up to 1 MW. From approx. middle of Mβ, some transmission to target.

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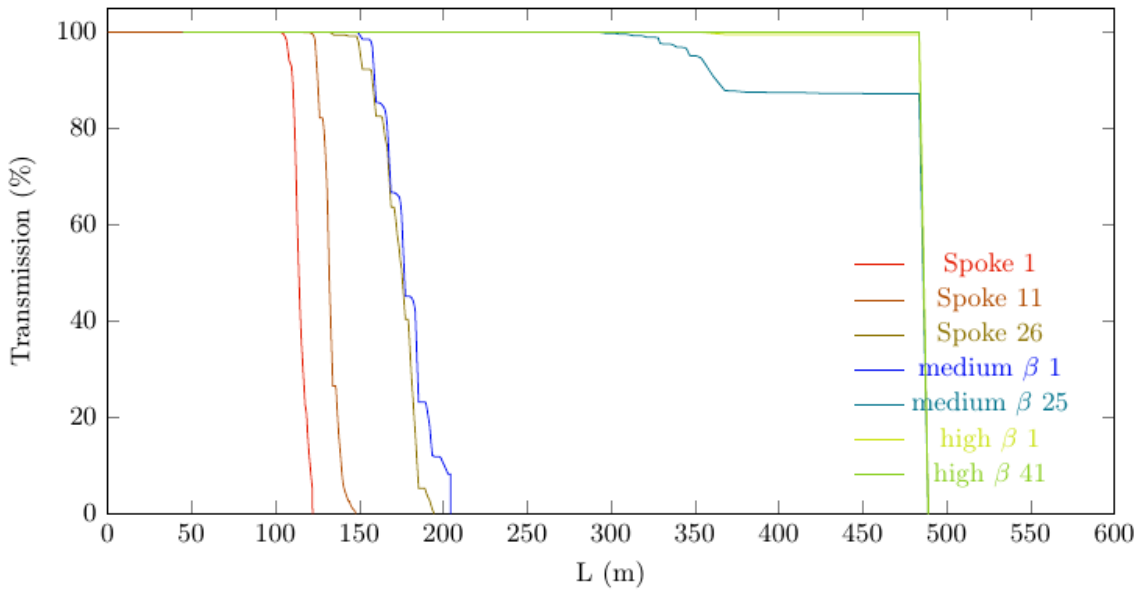

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Summary

- The beam dynamics design of the ESS linac is mature, many studies have been done.
- There is a large collection of various error and failure studies for the ESS beam dynamics.
- The studies were primarily done using TraceWin.
- Significant portion of losses end up in the dogleg for most type of errors/failures
- The dynamic errors from RF is expected to be a main source of beam losses -> realisation of LLRF and phase reference line very important.

References

- M. Eshraqi et al, TAC'09
- M. Eshraqi et al, ESS-0031413
- M. Eshraqi et al, IPAC'14: *"Statistical Error Studies in the ESS Linac"*
- Y. Levinsen et al, IPAC'15