Beam Dynamics of the ESS Linac

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High-Brightness Hadron Beams

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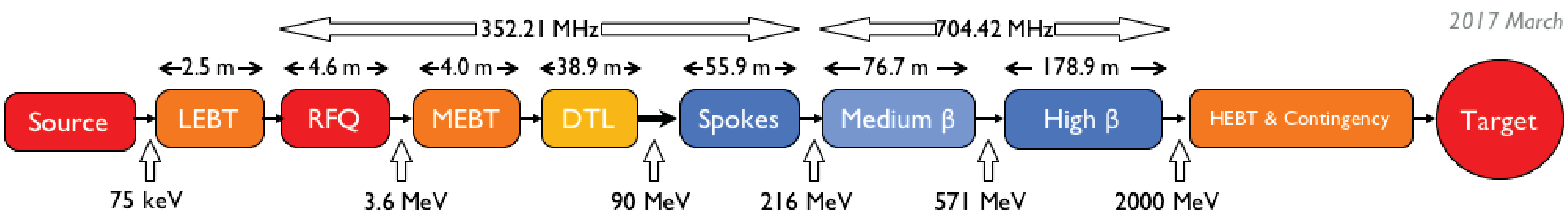
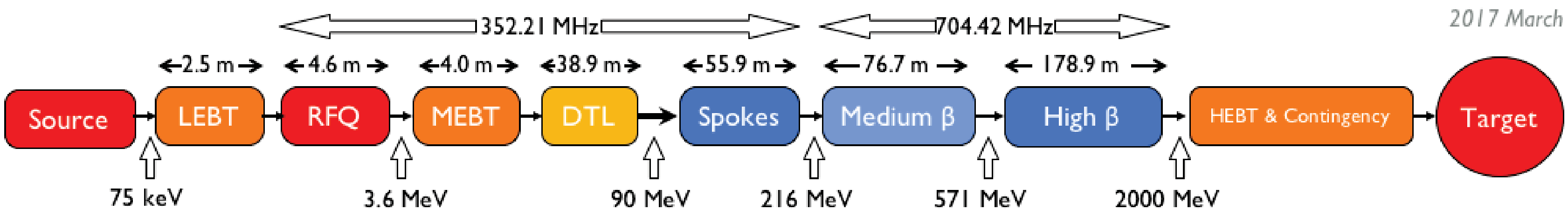
- Overview of accelerator
- ESS linac changes since TDR (2012)
- Beam Dynamics considerations
- Beam Dynamics Studies
- Outlook

The ESS Linac



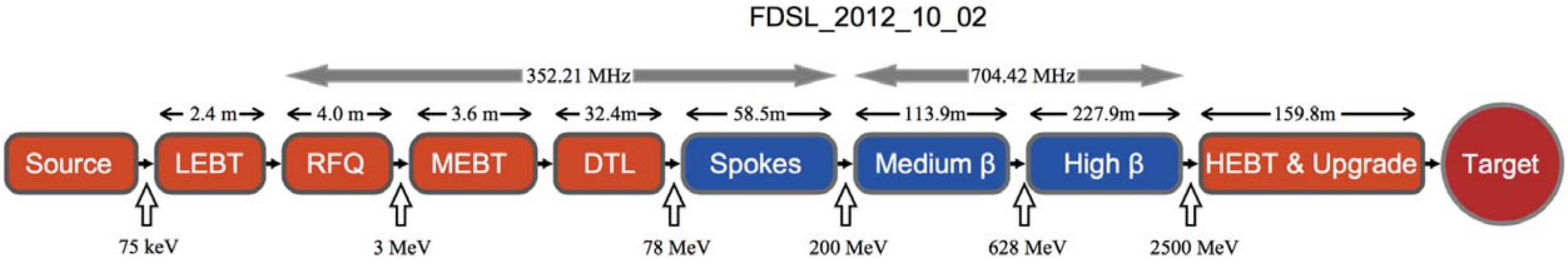
Parameter	Value	Unit
Average Power	5	MW
Final Energy	2	GeV
Peak Current	62.5	mA
Pulse Length	2.86	ms
Repetition Rate	14	Hz
Duty Cycle	4%	-

The ESS Linac



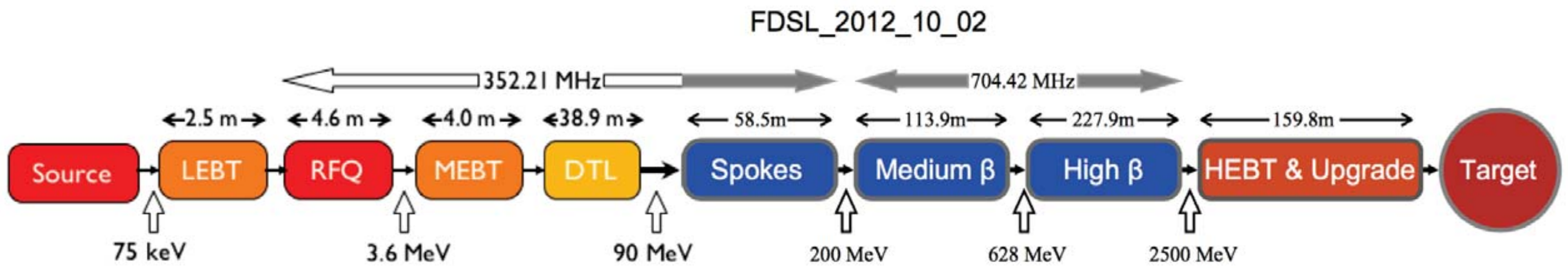
	Energy [MeV]	# modules	cav./mod.	$\beta\gamma$	Temp. [K]	Length [m]
Source	0.075	-	0	-	~ 300	-
LEBT	0.075	-	0	-	~ 300	2.5
RFQ	3.62	1	1	-	~ 300	4.6
MEBT	3.62	-	3	-	~ 300	4.0
DTL	90.0	5	-	-	~ 300	38.9
Spokes	216	13	2	-	~ 2	55.9
Med.-β	571	9	4(6C)	0.67	~ 2	76.7
High-β	2000	21	4(5C)	0.86	~ 2	178.9
HEBT	2000	-	-	-	~ 300	239.5

Changes Since the TDR



What has changed?

Changes Since the TDR



What has changed?

- Longer RFQ (3 $\rightarrow$ 3.6 MeV)
- Longer DTL (78 $\rightarrow$ 90 MeV)

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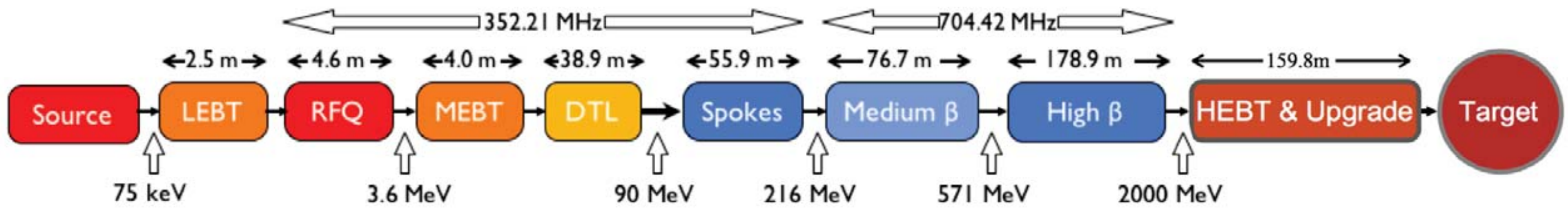

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- Shorter elliptical cavity sections (medium/high β)

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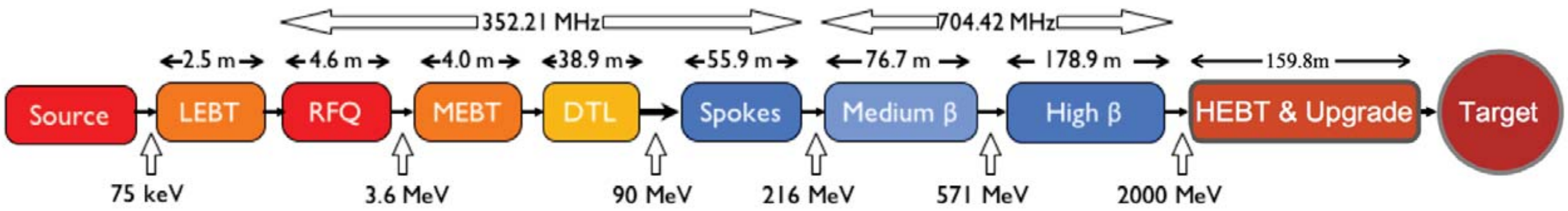

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- Increased SRF gradients by $\sim$ 11%

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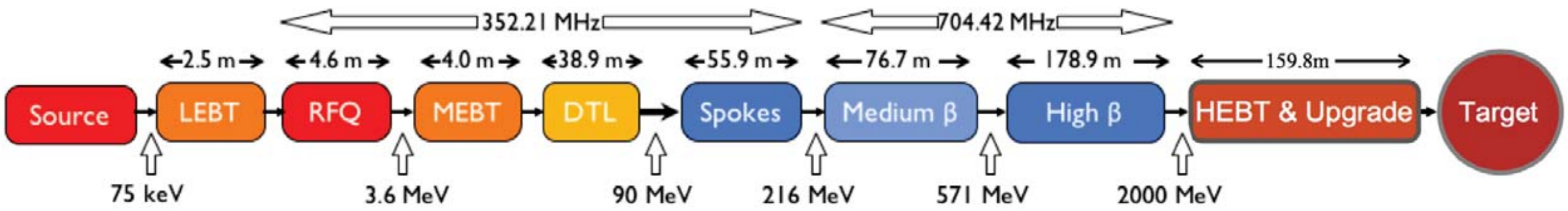

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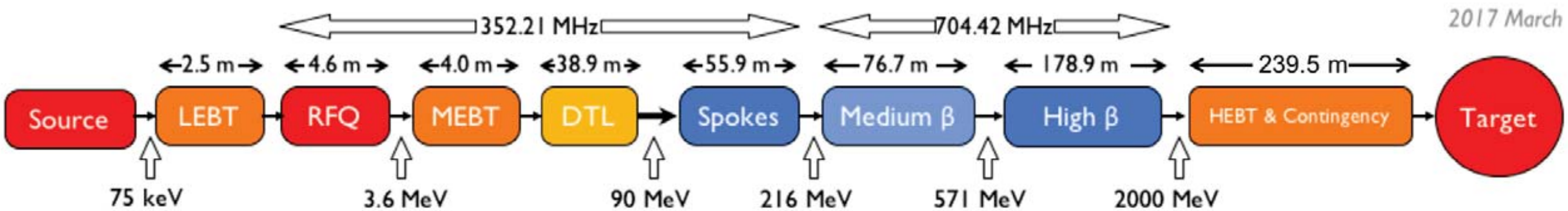

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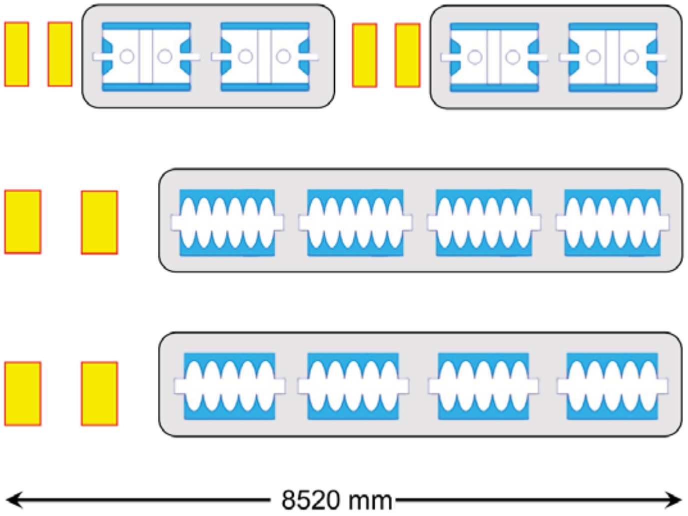
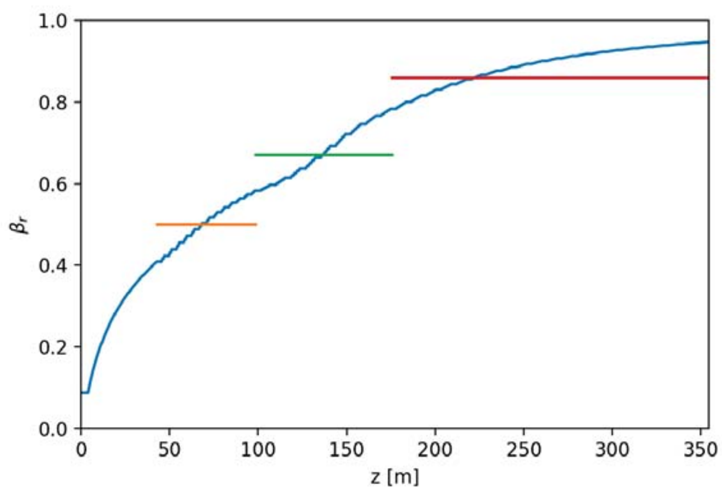
- Increased SRF gradients by $\sim$ 11%
- Increased beam intensity
- Contingency space maintains same upgrade possibilities

Modular cryomodules+LWUs in the Cold Linac





Boundary conditions

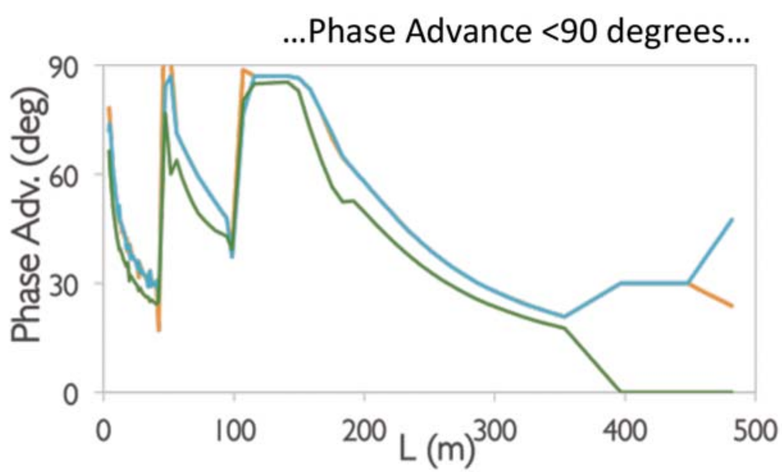
- Unprecedented loss control $\rightarrow$ 1 W/m loss limit
- Main cause of losses is connected to halo creation
  - mismatches
  - high space charge and tune depression
  - non-linear fields
  - escape of particles from the accelerating bucket
  - errors (misalignment, machining, construction, ...)

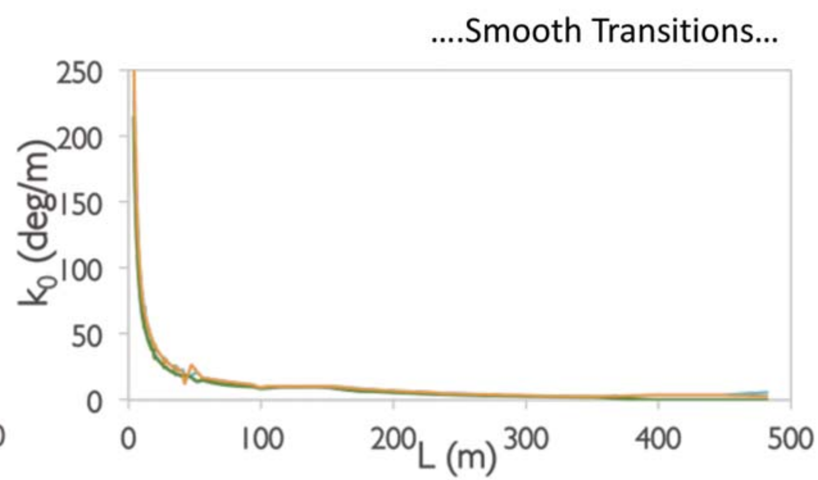
Design Main Choices

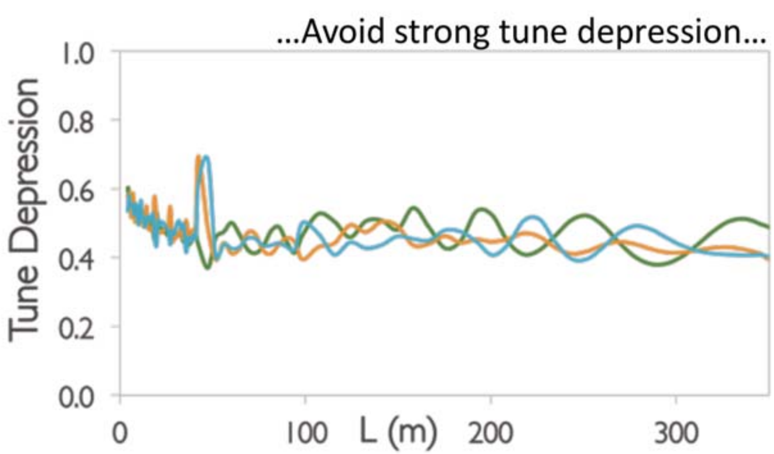
- The zero current phase advance per period in all the planes must be less than 90 deg
- The phase advance per meter (average phase advance) variation should be smooth and continuous
- At ESS on top of this the average phase advance changes monotonically
- The tune depression, k_{sc}/k_0 , must stay above 0.4 in all the planes during acceleration

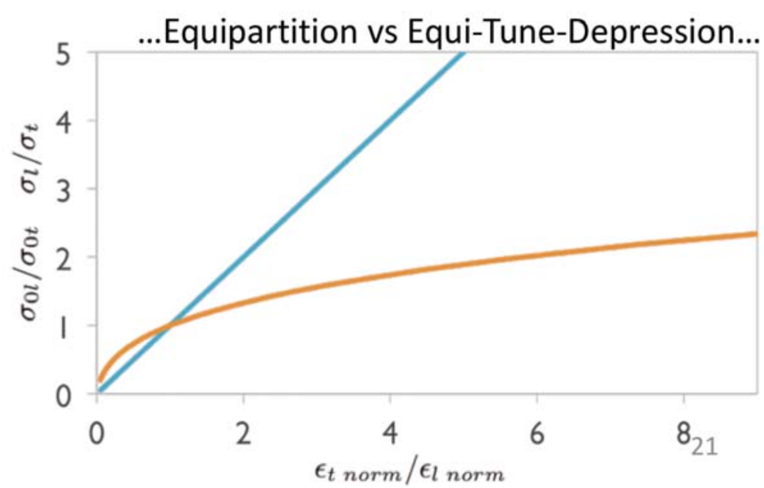
Beam Dynamics Considerations

Tune Depression

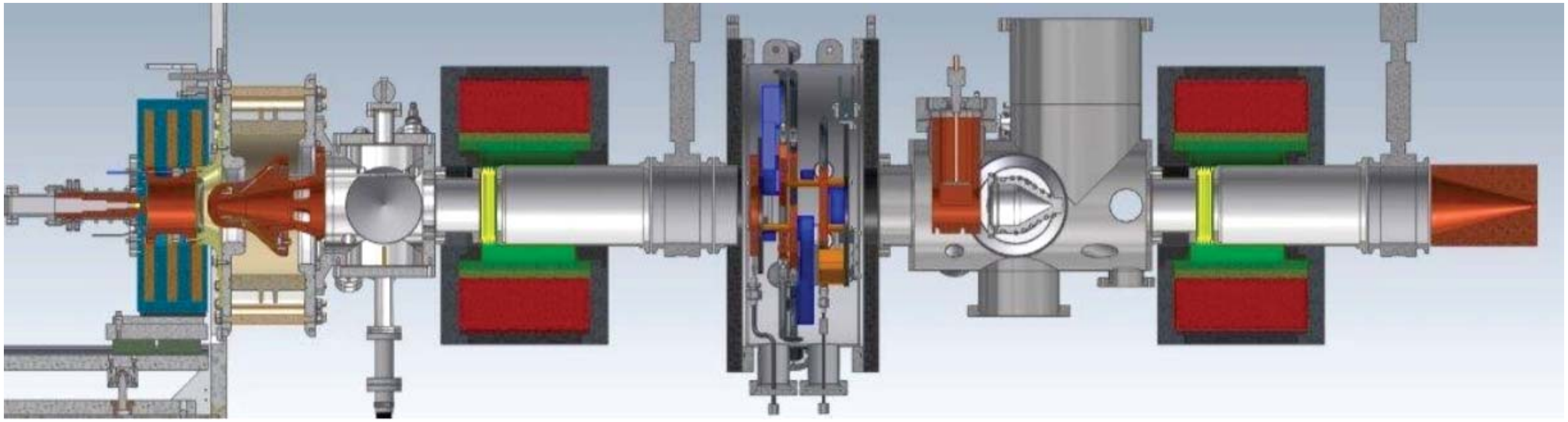






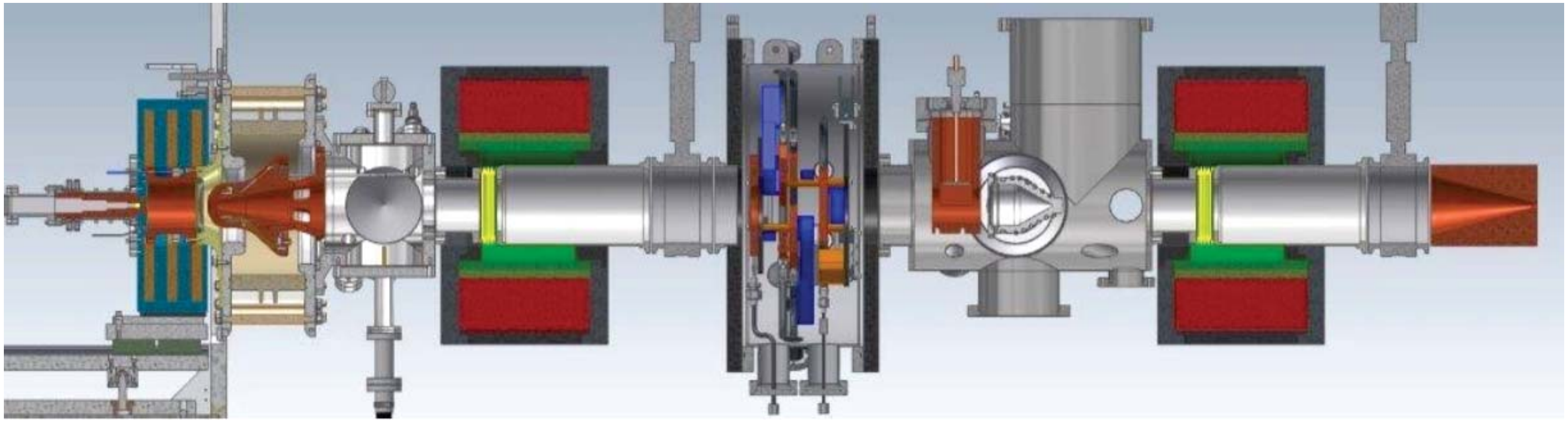


Sections: IS+LEBT



- IS and LEBT built by our in-kind partners in INFN Catania
- Microwave Discharge Ion Source
- High reliability and long mean time between failure (MTBF)
- Up to 3 ms long pulse at flat top
- 75 keV energy

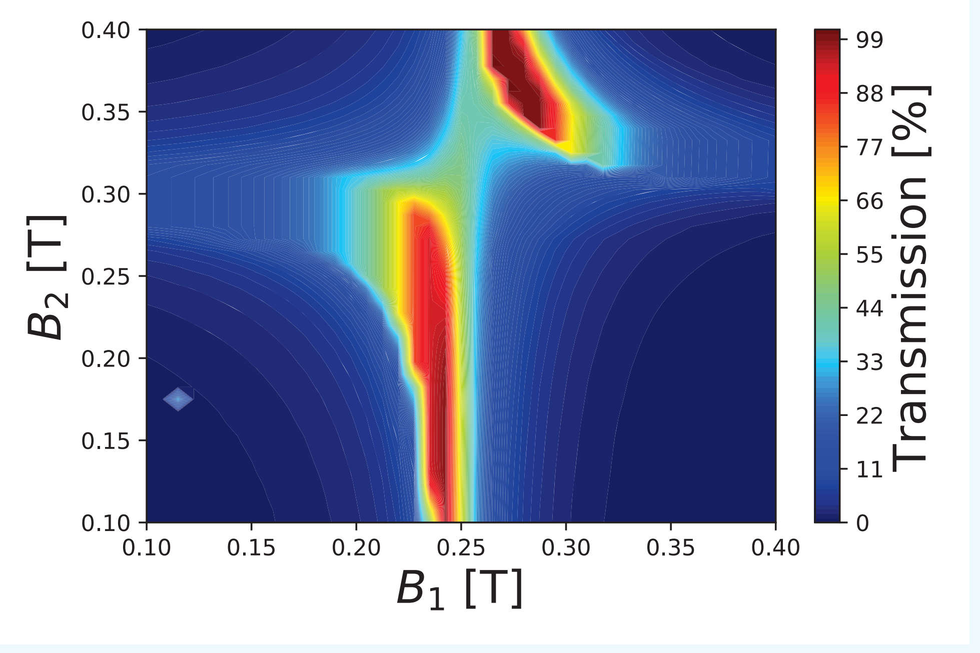
Sections: IS+LEBT



- IS and LEBT built by our in-kind partners in INFN Catania
- LEBT 2.5 m long with two solenoids
- Iris to adjust the current
- Chopper removes low quality head and tail of beam
- Diagnostics to characterise and monitor the beam
- Design space-charge compensation (SCC) of 95 %
- Capability to inject H_2 and N_2 to enhance SCC

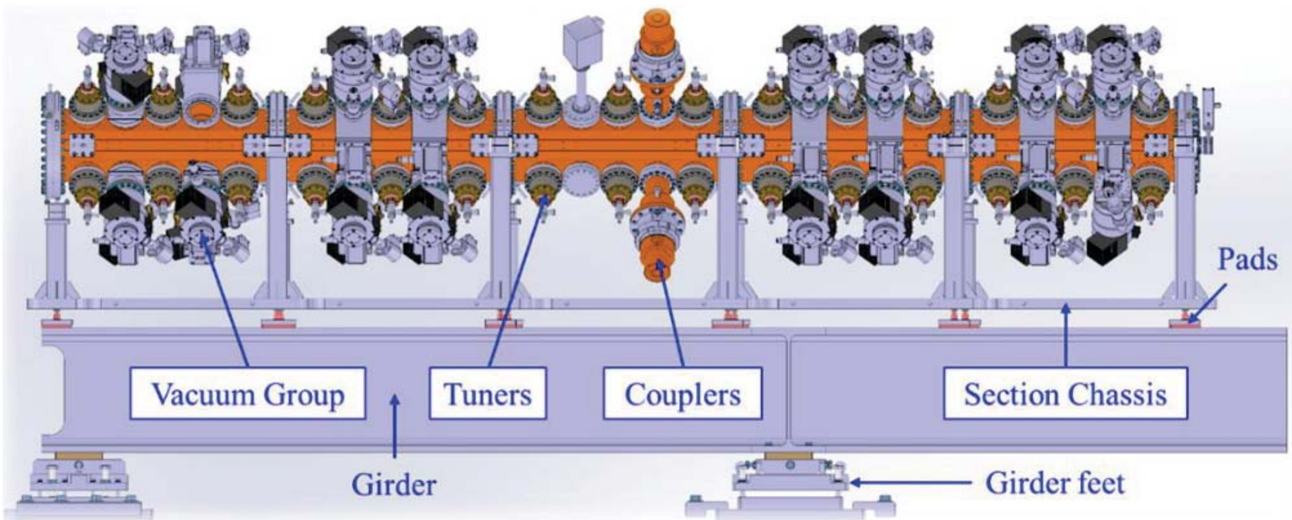
Sections: IS+LEBT

Example - Solenoid Transmission Scan



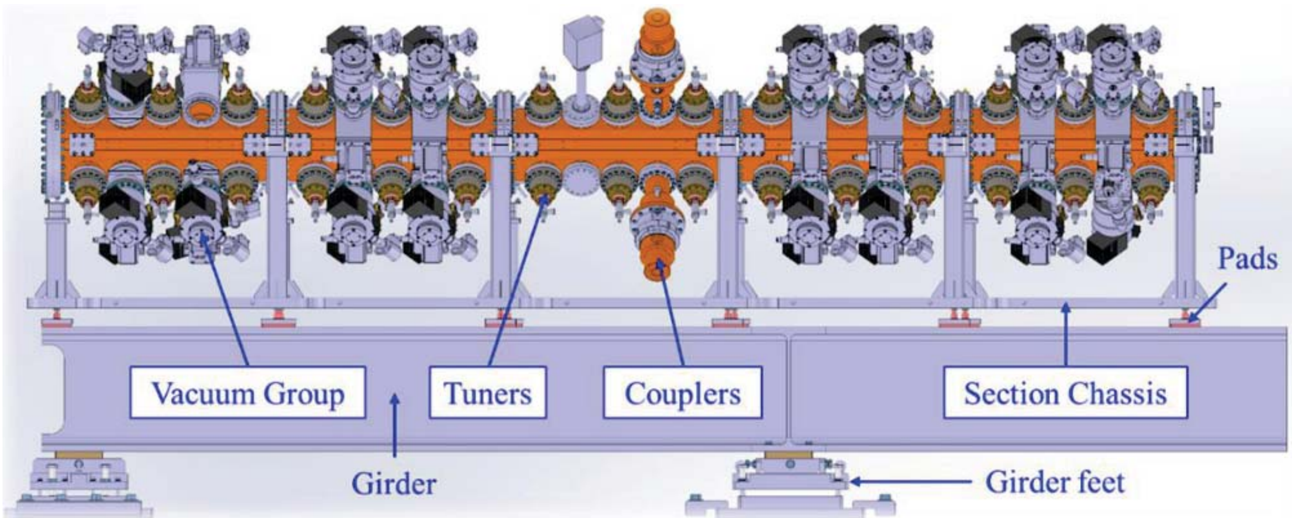
Courtesy A. Ponton

Sections: RFQ



From Chirpaz-Cerbat et al., IPAC'16 proceedings

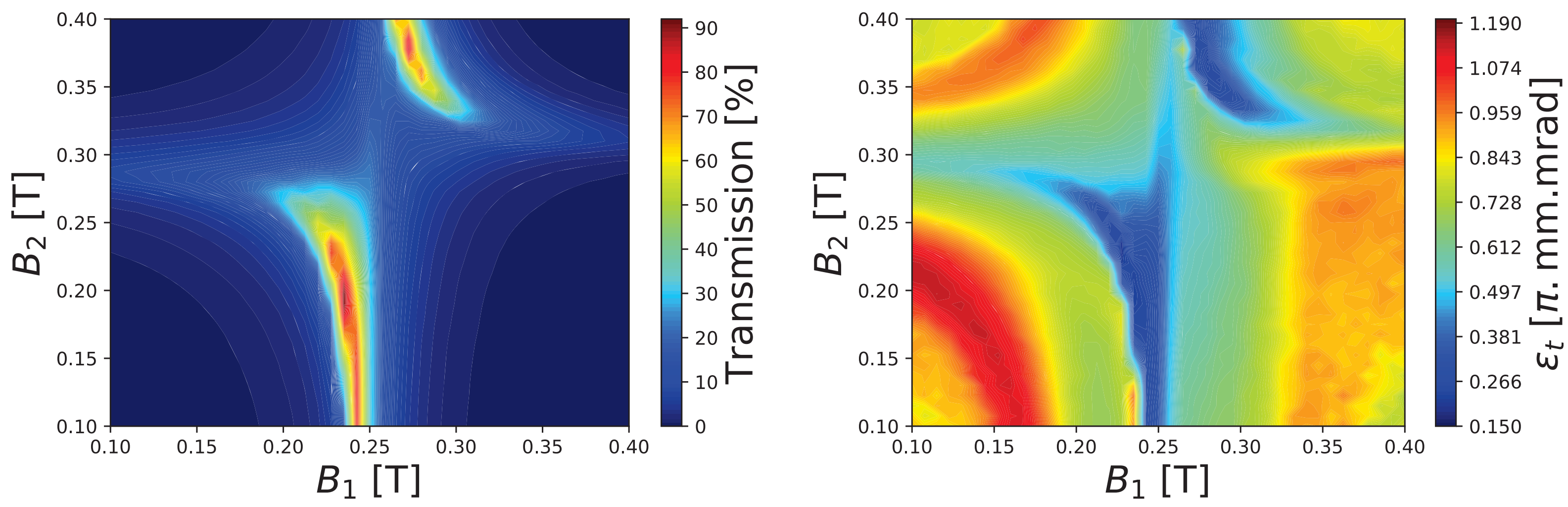
- RFQ built by our in-kind partners in CEA Saclay
- 4-vane structure, 4.55 m long, accelerates to 3.62 MeV
- 60 tuners, 4 coupler ports, 36 vacuum ports, 28 pick-up ports, 80 cooling connectors



From Chirpaz-Cerbat et al., IPAC'16 proceedings

- Designed to minimize RF power losses, and ease machining
- Aperture profile at entrance optimized for minimal convergence of input beam
- Final focal section section at end provide slight divergence to optimise matching into MEBT

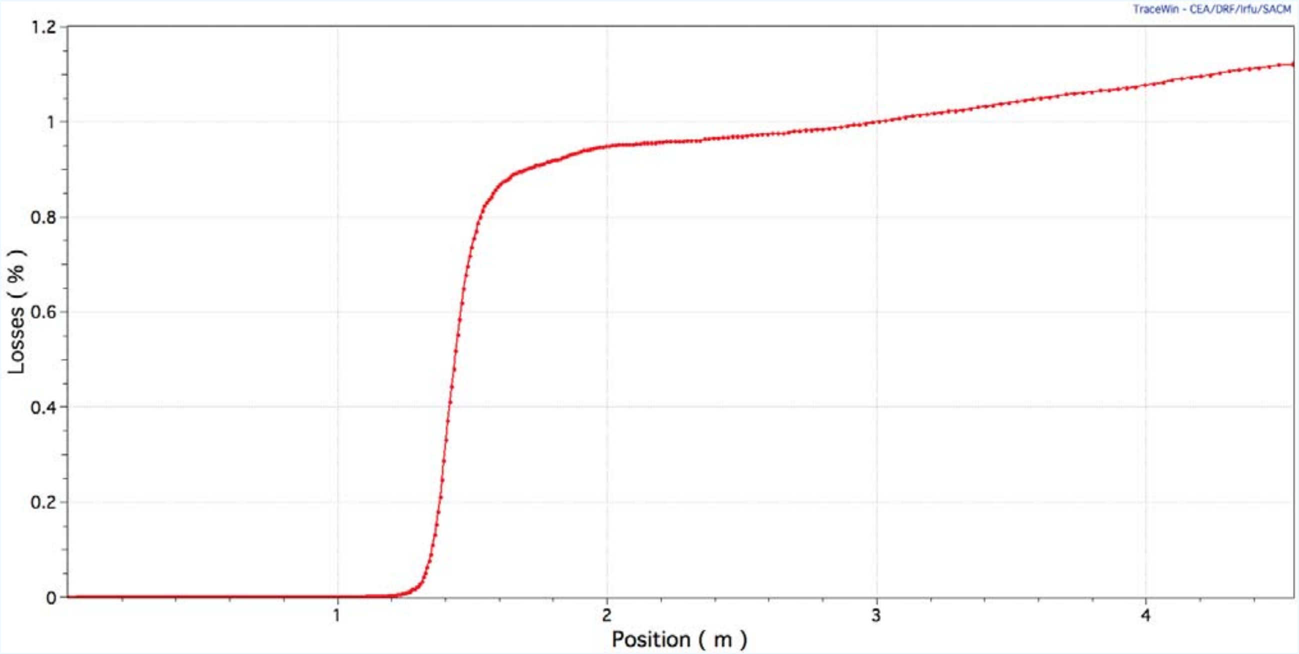
Solenoid Transmission Scans: LEBT+RFQ



Courtesy A. Ponton

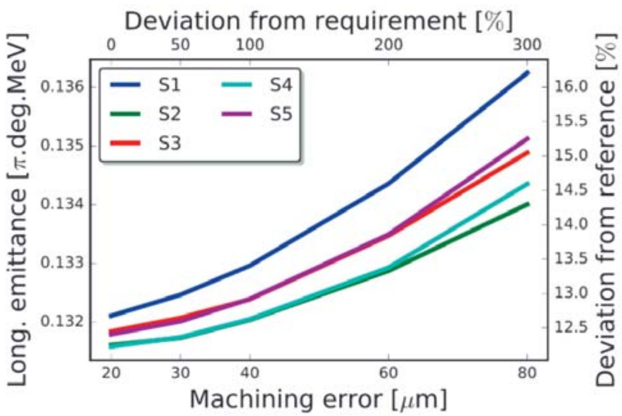
- Best transmission is 92% for (B1,B2) = (0.235, 0.1975)
- Simulations taking into account aperture limitations.

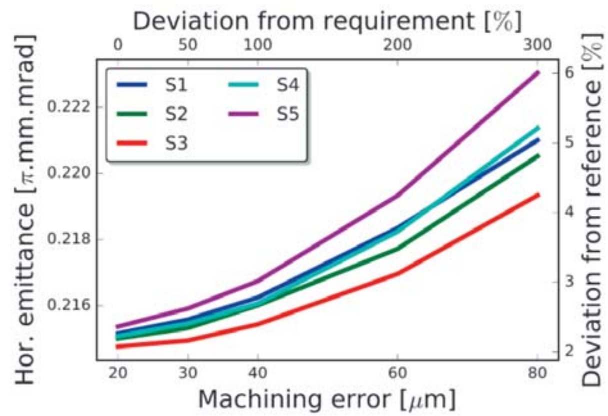
Beam Losses in the RFQ

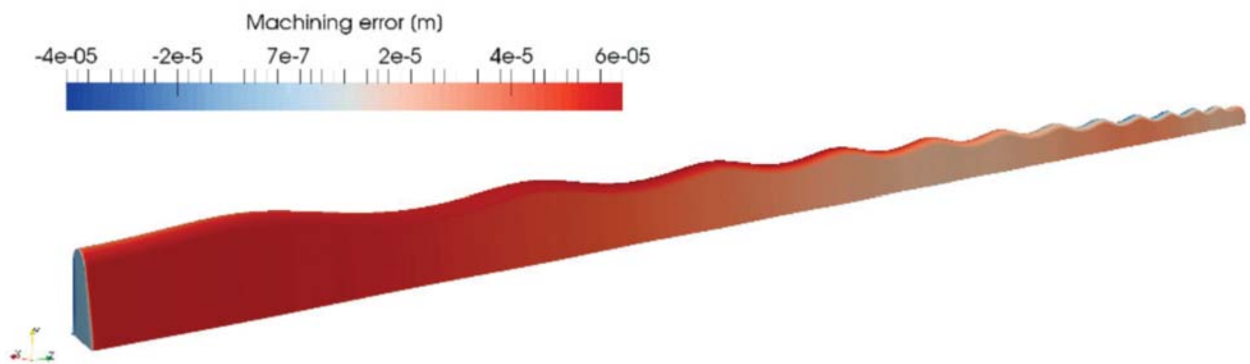


Very good transmission, majority of losses in the beginning of acceleration phase

Study on RFQ errors and non-conformity

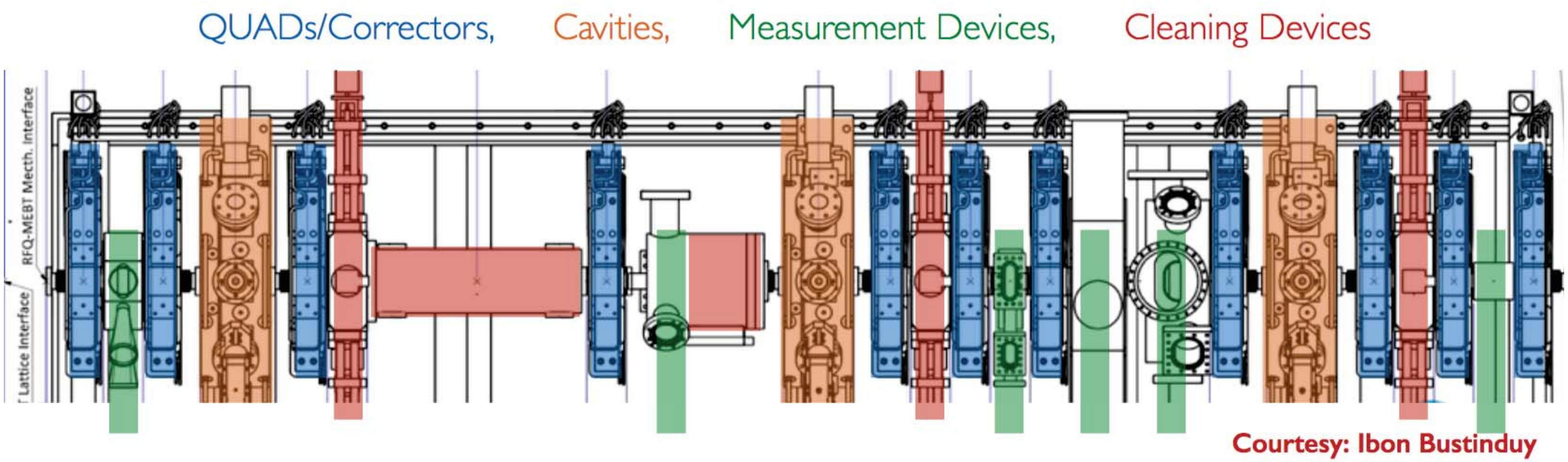






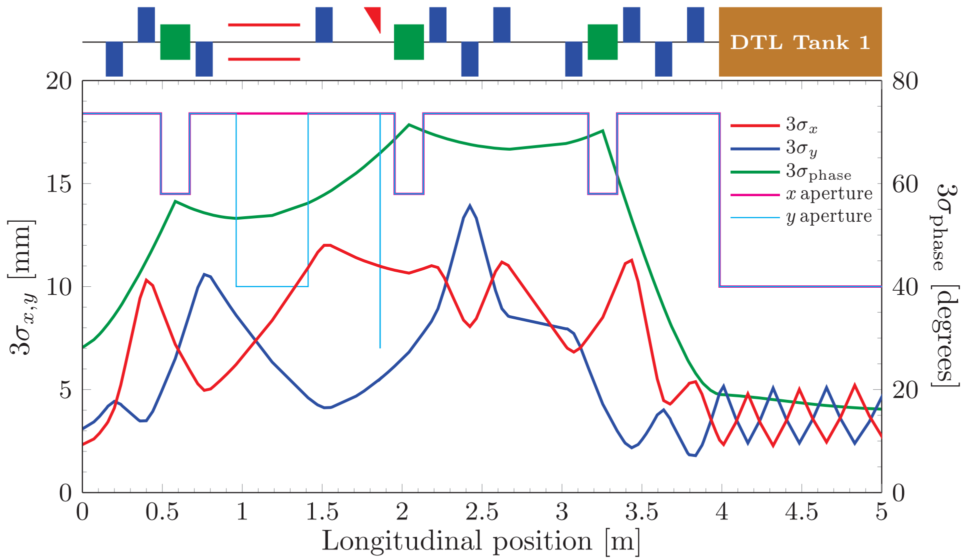
From A. Ponton, TUPAF067 IPAC'18

Sections: MEBT



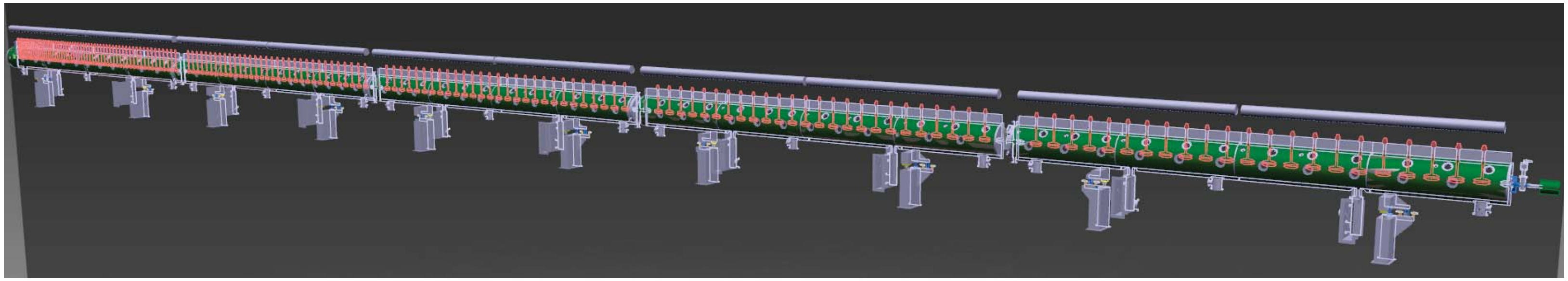
- MEBT built by our in-kind partners at ESS-Bilbao
- Match and transport the beam into DTL, characterise the beam from the RFQ
- 4.0 m long (check)
- 11 quadrupoles, 3 buncher cavities
- Fast chopper to clean mismatched head of the pulse

Sections: MEBT



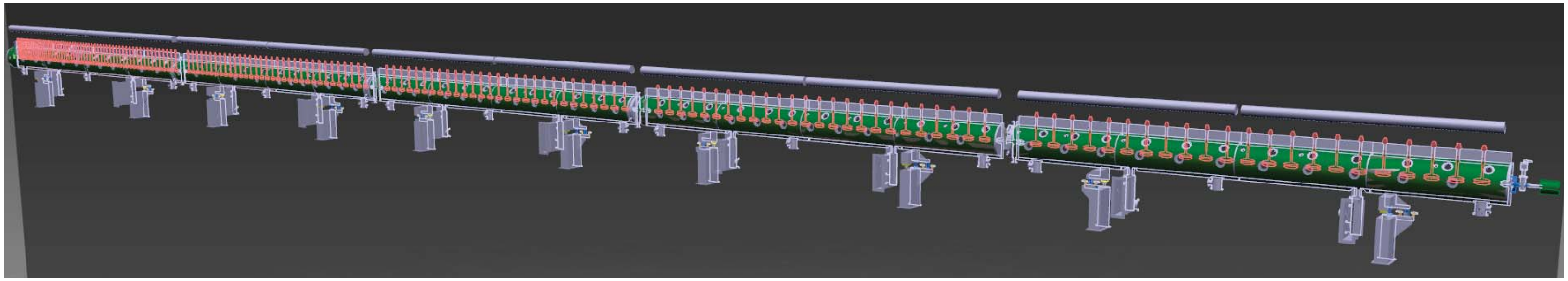
- No periodic structure → non-trivial to match
- Cannot focus as strongly as RFQ or DTL → emittance growth unavoidable

Sections: DTL



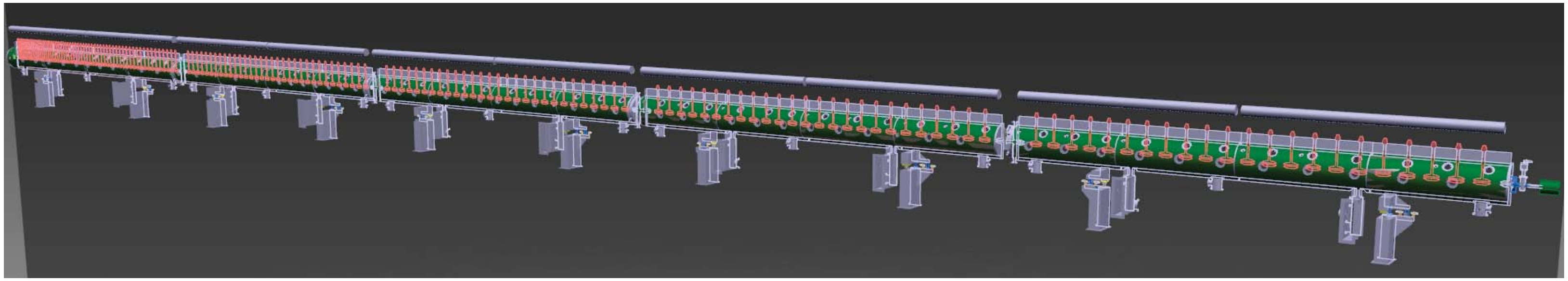
- DTL built by our in-kind partners at INFN-LNL
- 5 tanks of around 8 m length
- Energy 3.6 MeV $\rightarrow$ 90 MeV
- 2.8 MW klystron for each tank, 2.2 MW needed for acceleration field assuming 50 % ohmic losses

Sections: DTL



- Increased input energy simplifies first drift tubes
- Transverse focusing by permanent magnets in every 2nd DT
- RF phase & amplitude corrected tank-by-tank

Sections: DTL



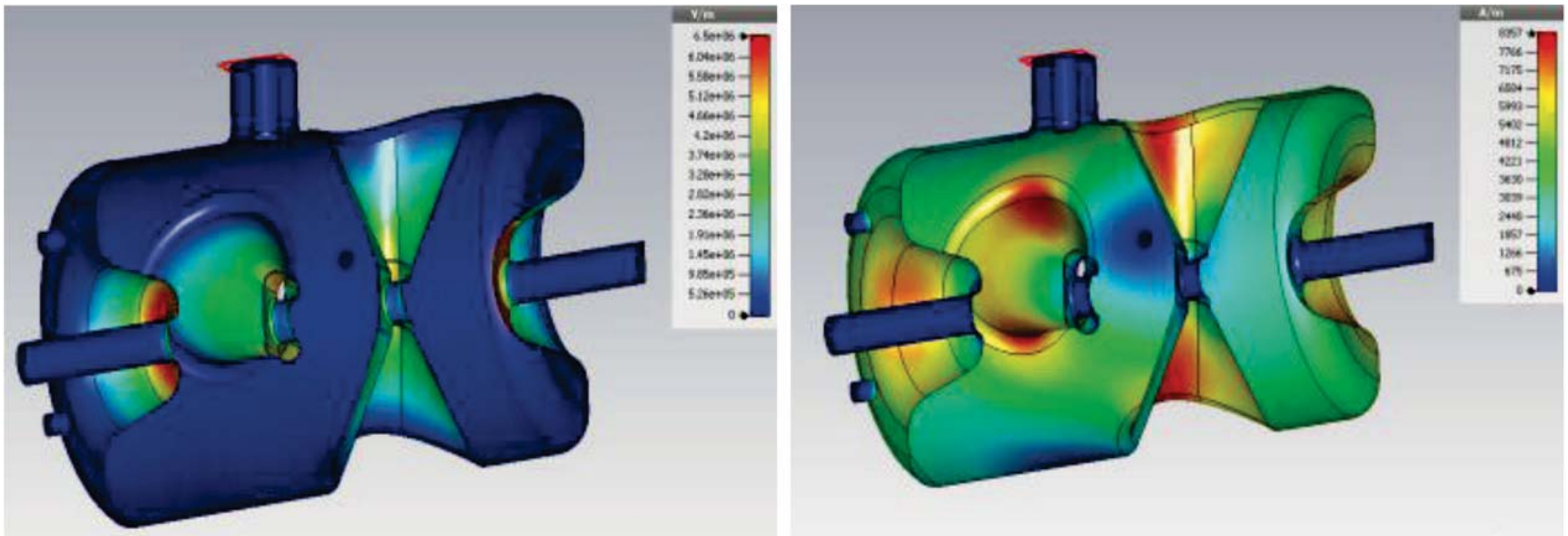
- Commissioning of 1st tank particularly challenging
- 15 BPM's planned, at least 2 per tank (tank distribution is 6, 3, 2, 2, 2)
- The positions of BPM's and steerers are optimised for trajectory correction

Sections: Spokes

Courtesy S. Bousson

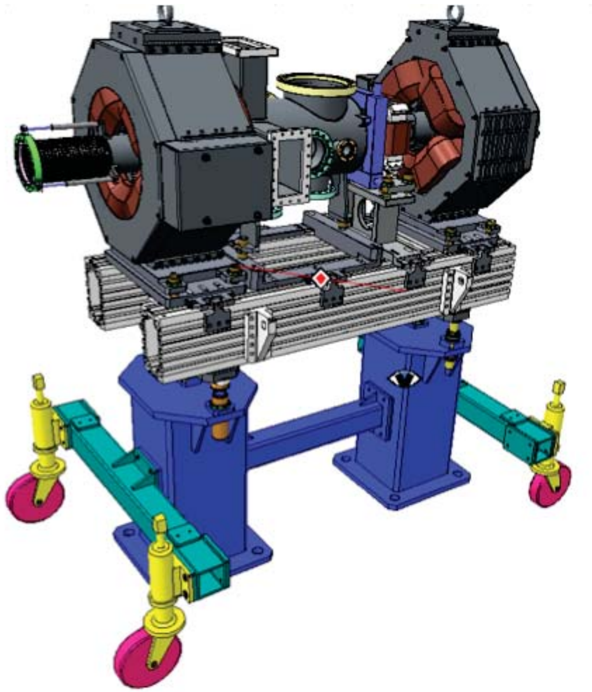
- Spoke cavities built by our in-kind partners at IPN Orsay
- DTL-Spoke transition to superconducting (LEDP)
- 2 spokes per cryostat, 13 cryostats
- Max gradient 9 MV/m
- Larger aperture compared to NC structures

Sections: Spokes



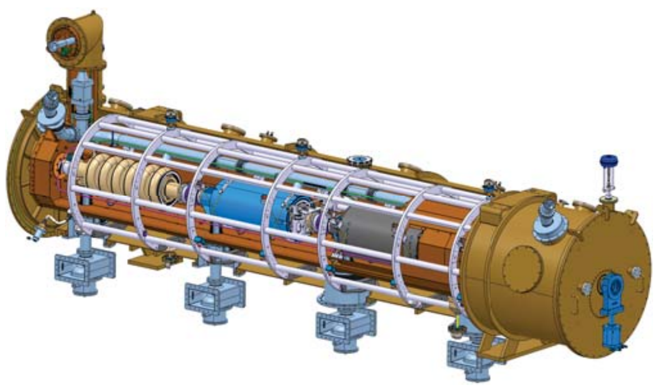
The electric (left) and magnetic (right) field maps of the spoke cavity

Linac Warm Units (LWU)



- All quadrupoles and corrector magnets after DTL built by our in-kind partners at Elettra
- Between each cryomodule there is one Linac Warm Unit (LWU)
- 2 quadrupoles, 1 BPM, 1 dual-plane corrector, central slot for diagnostics

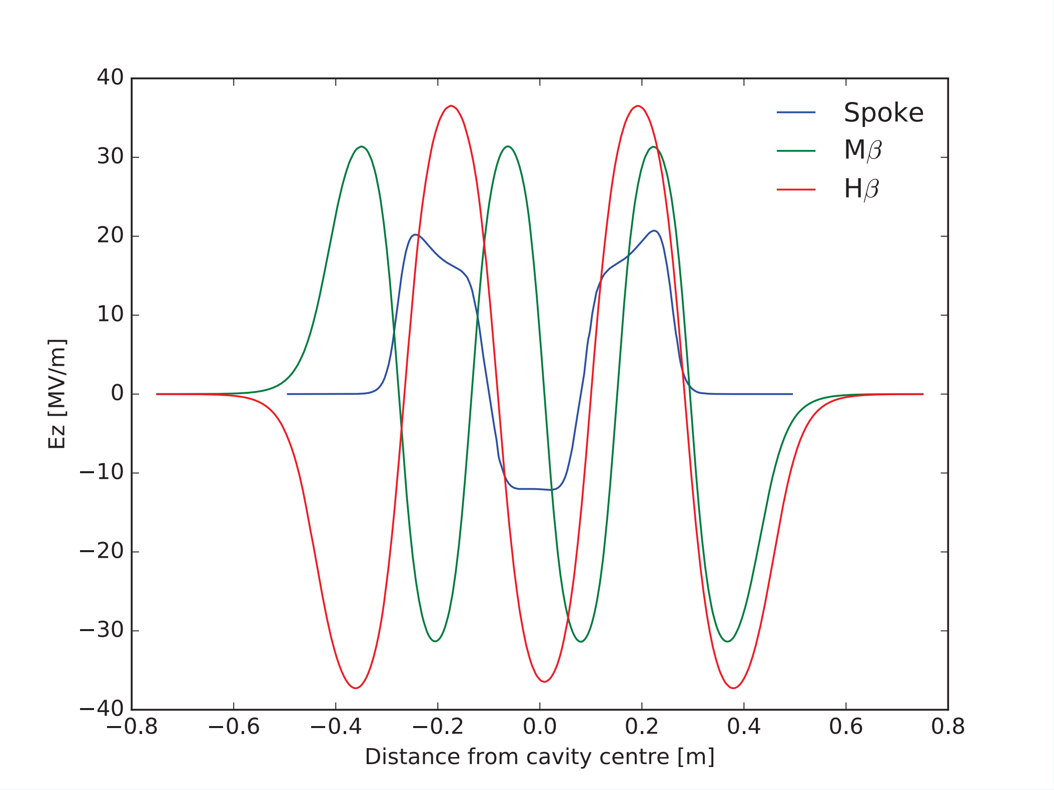
Sections: Elliptical Cavities



- 6-cells Mβ almost same length as 5 cells Hβ
- 4 cavities per cryostat, cryostat 5.6 m long
- 9 Mβ and 21 Hβ cryostats

Field Map Comparison

Accelerating field



Frequency Jump

- The frequency jump is a challenging point for beam dynamics
- Require soft longitudinal transition between Spoke - Med. β

352 MHz vs. 704 MHz

Lower frequencies are favoured due to looser tolerances in manufacturing cavity components. Lower frequencies also have the advantage of reducing RF losses in superconducting cavities, decreasing beam losses through larger apertures, and ameliorating higher order mode (HOM) effects from the high-current beams. Higher frequencies are encouraged by the desire to keep the size of the superconducting cavities small, making them easier to handle and reducing manufacturing costs. The cryogenic envelope and power consumption are also reduced at higher frequencies.

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- Require soft longitudinal transition between Spoke - Med. β
- We see losses originating from this region in end-to-end studies

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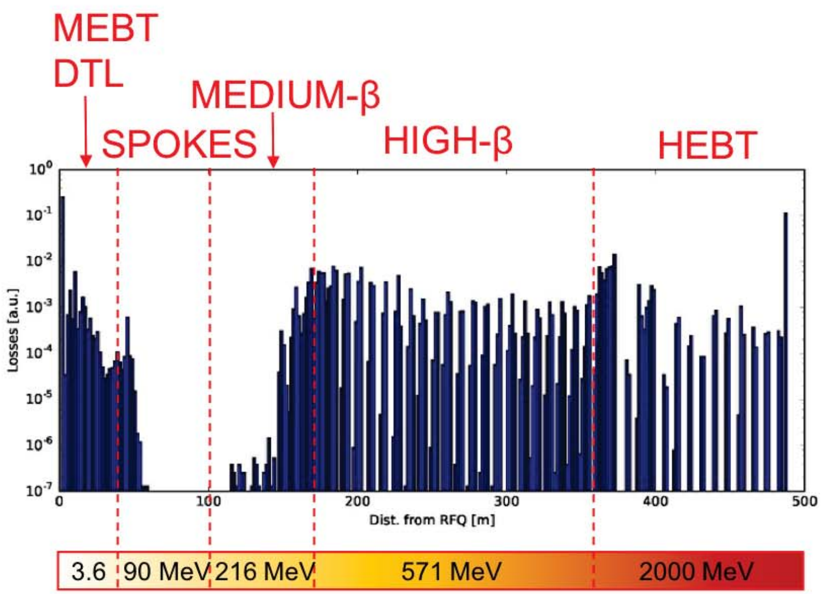
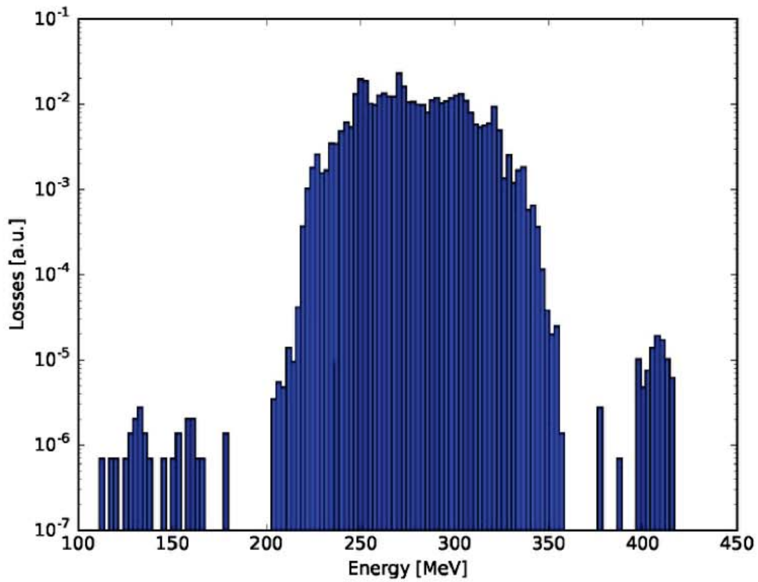
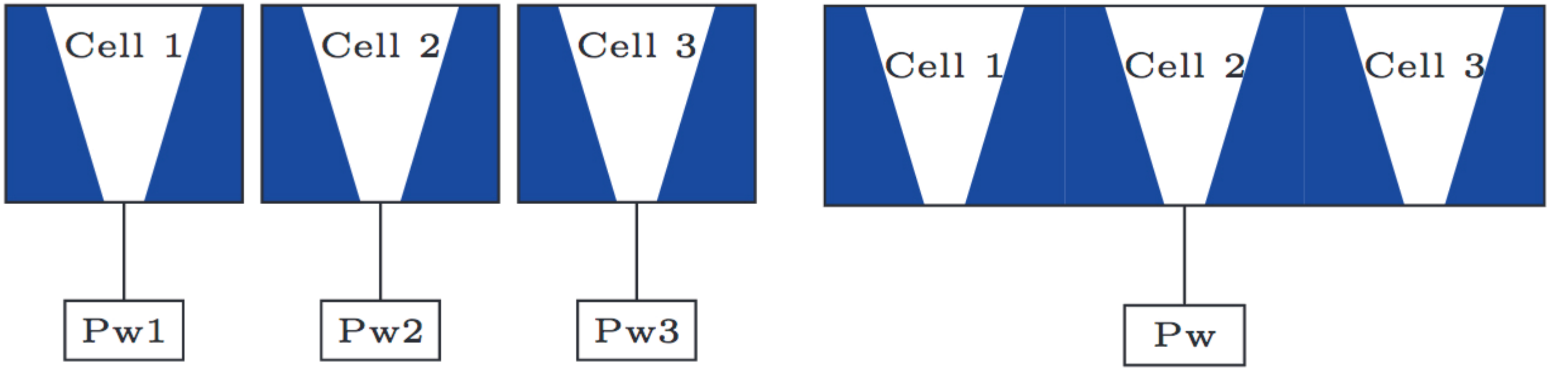
Frequency Jump: Losses





- Distribution of losses along the ESS linac
- The energy distribution of the particles lost from the start of the medium-β and a few periods into the high-β section. Almost no losses from the upstream linac are seen.

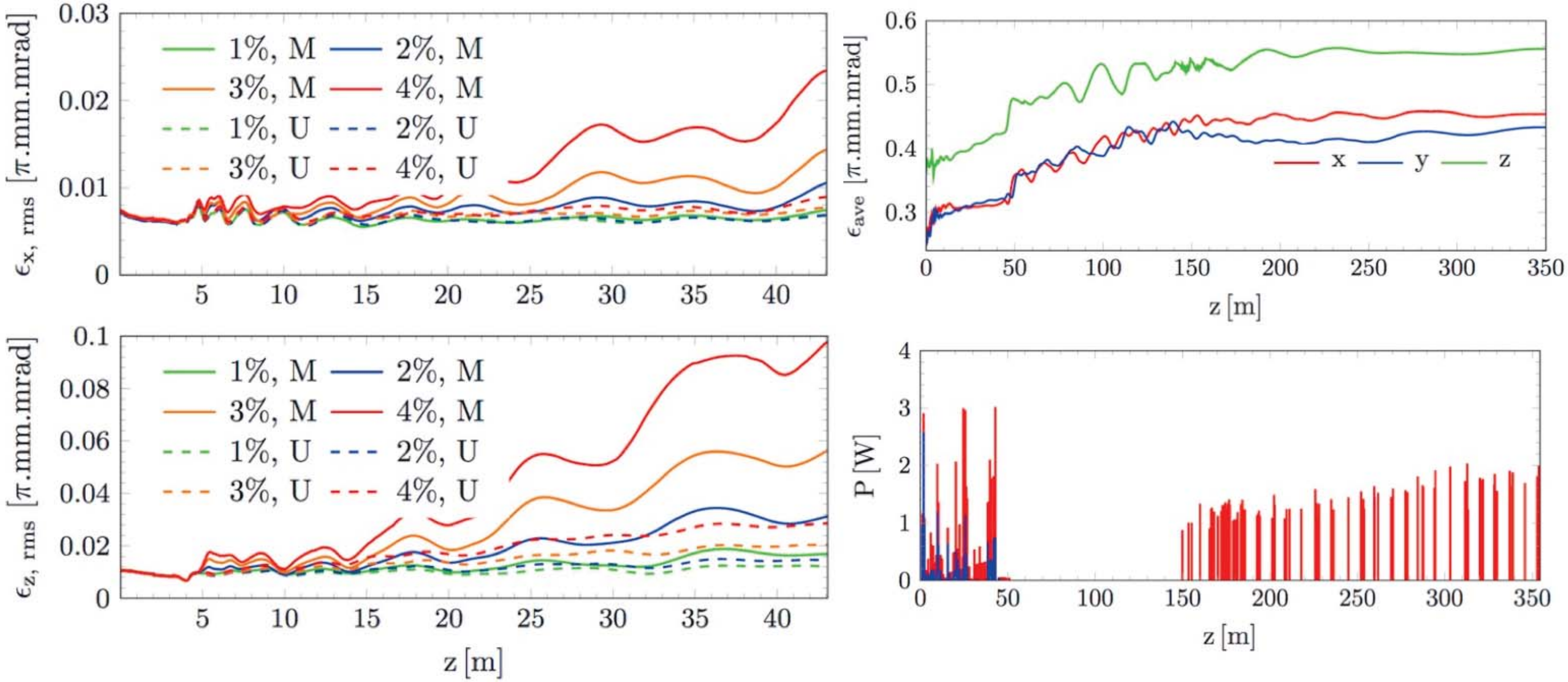
Losses and error studies on the ESS accelerating structures



From R. de Prisco, TUPAF063 IPAC'18

- Considering the cells of the same cavity as independent gaps is an unrealistic approach
- Mechanical error in a cell influences the accelerating field in all the cavity and not only in that cell.

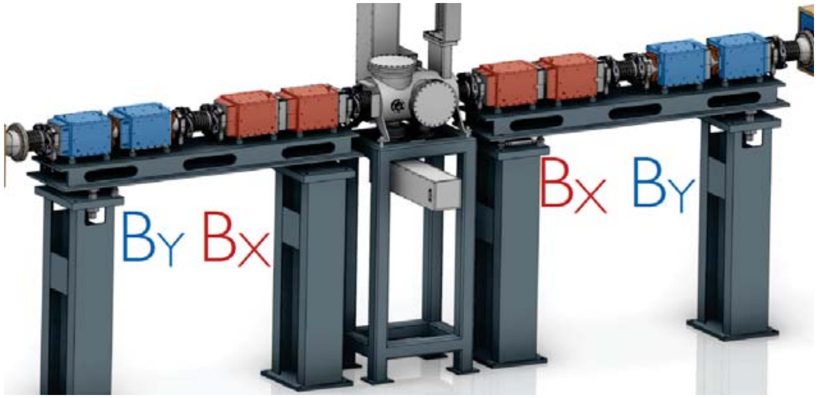
Losses and error studies on the ESS accelerating structures



From R. de Prisco, TUPAF063 IPAC'18

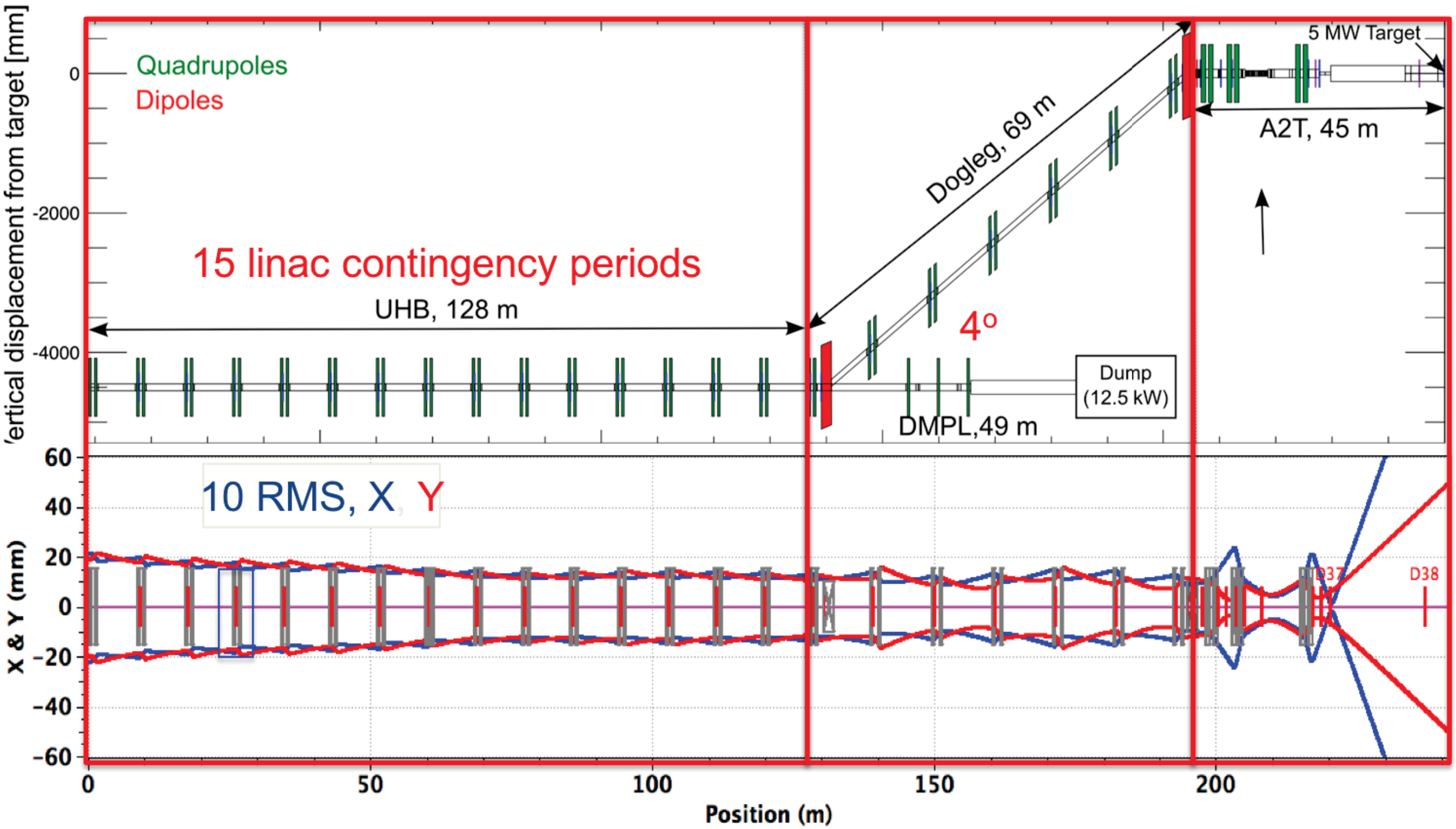
- Averages of the normalised RMS emittances and power loss at 100% (red) and 99% (blue) confidence levels.

Sections: Contingency, Dumpline, A2T



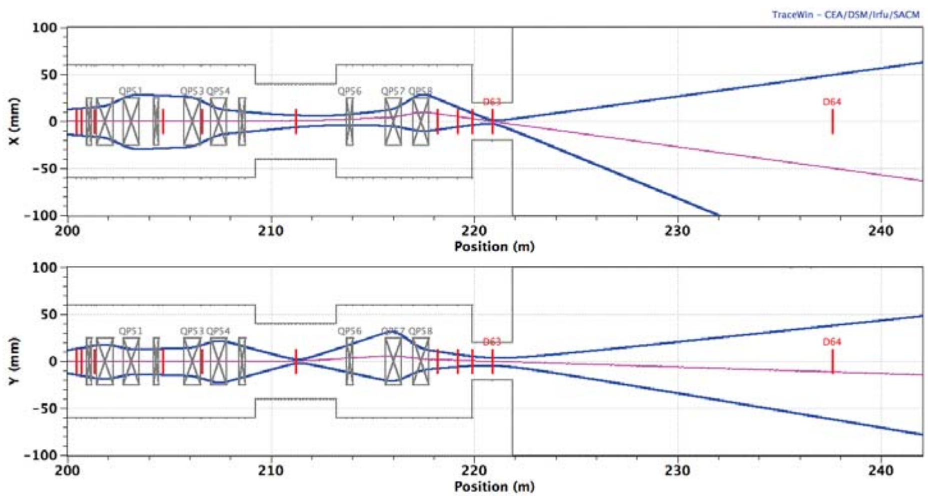
- HEBT beam physics design by our in-kind partners at Aarhus University
- Contingency of 130 m, for future upgrades, 15 lattice periods
- Dipole brings beam up to target level at a 4°angle
- Achromatic dogleg
- Dipole off → beam to dump
- H+V rastering at up to 40 kHz vertical and 29 kHz horizontal paint the beam onto the rectangular target area
- Phase advance between raster centre and the cross over point is set to 180 deg.

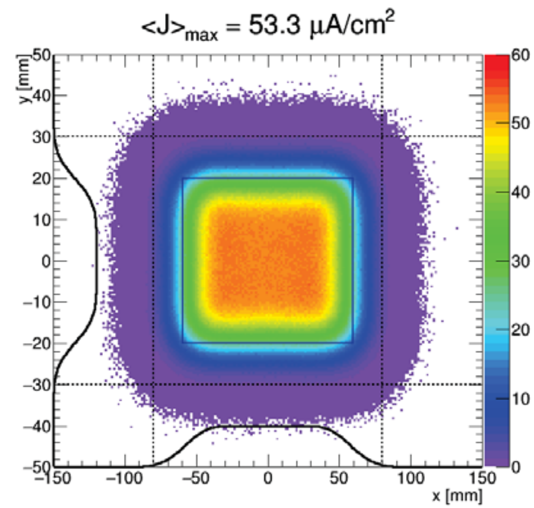
Sections: Contingency, Dumpline, A2T



Courtesy H.Thomsen

Target Painting





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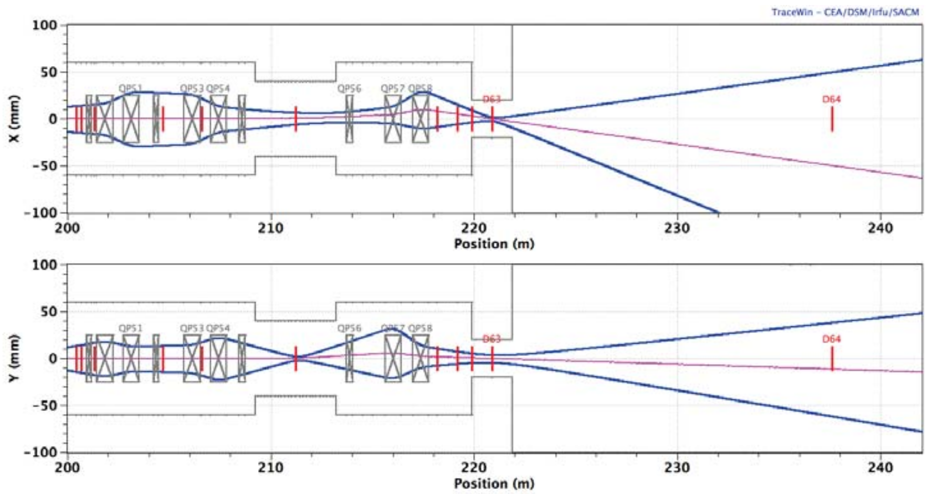

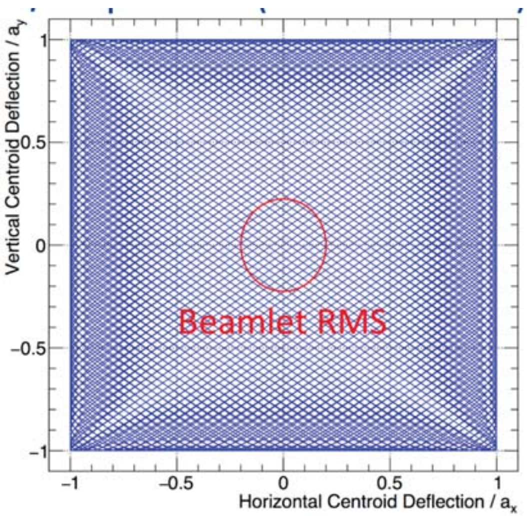

Courtesy H.Thomsen

Outlook

- The beam dynamics design of the ESS linac has advanced since the TDR
- The strict requirement on losses and halo control together with reliability and cost drives the design optimisations

Thank you!