Beam Dynamics Challenges in the ESS Linac

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57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams

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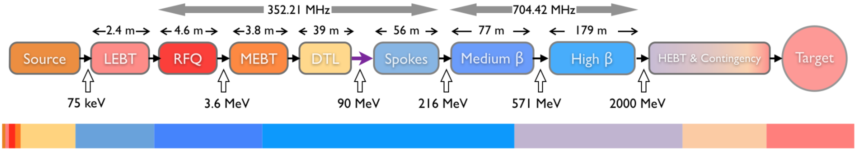
Content

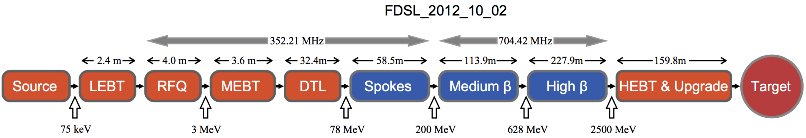
- Overview of accelerator - changes since TDR
- Beam dynamics in the different sectors
- Study of losses in integrated study

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	2.4
RFQ	3.65	1	1	-	$\sim$ 300	4.6
MEBT	3.65	-	3	-	$\sim$ 300	3.8
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

Changes Since the TDR



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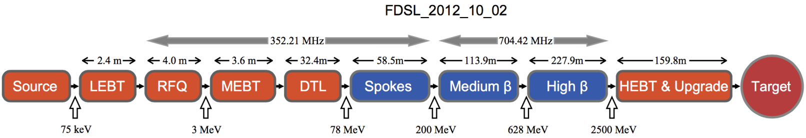

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- Longer RFQ (3 -> 3.6 MeV)
- Longer DTL (78 -> 90 MeV)

Changes Since the TDR

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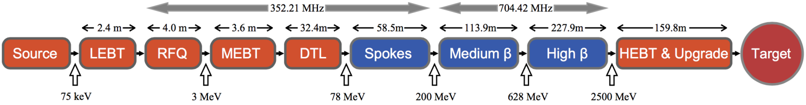

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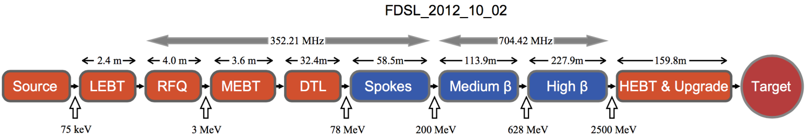

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- Increased SRF gradients by ∼ 11%

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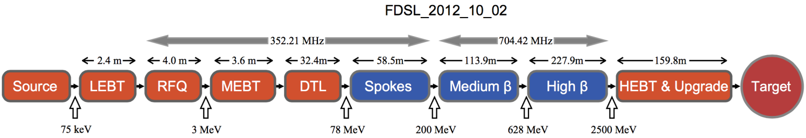

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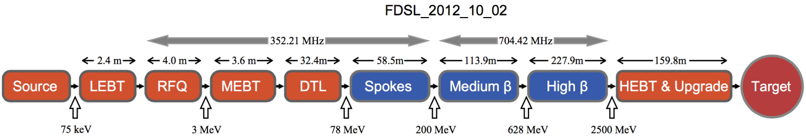

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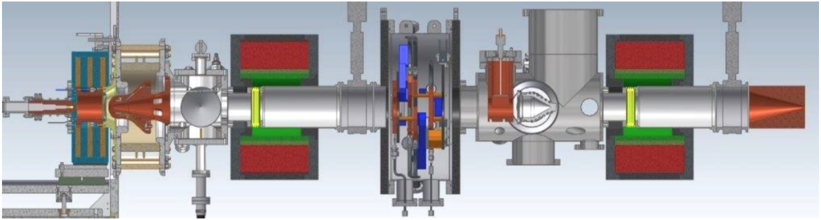
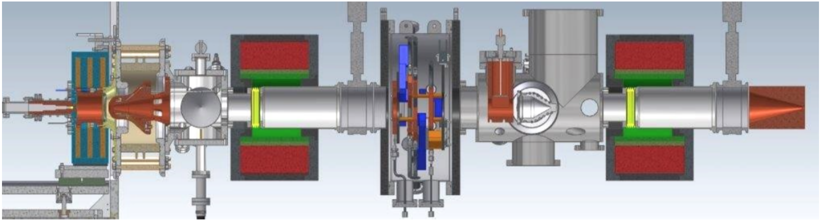
- Longer contingency space maintains same upgrade possibilities



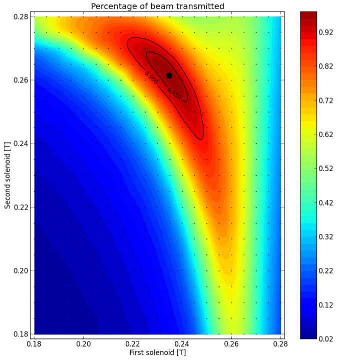
- IS and LEBT built by our IC partners in INFN Catania
- Microwave Discharge Ion Source
- High reliability and long mean time between failure (MTBF)
- Up to 3 ms long pulse at flat top
- 75 keV energy

Sections: IS+LEBT

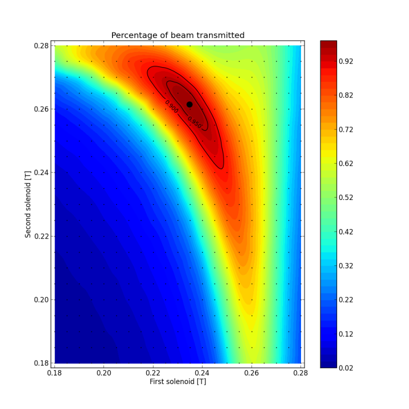


- IS and LEBT built by our IC partners in INFN Catania
- LEBT 2.4 m long
- Two solenoids of 330 mm length
- Iris to clean transversal tails/halo
- Chopper removes low quality head and tail of beam
- Diagnostics to characterise and monitor beam
- Expected space-charge compensation of 95 % or better

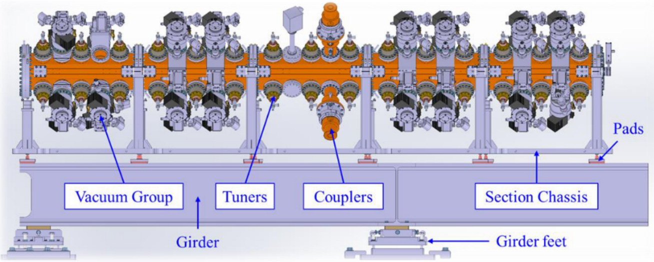
Example - Solenoid Transmission Scan



Example - Solenoid Transmission Scan

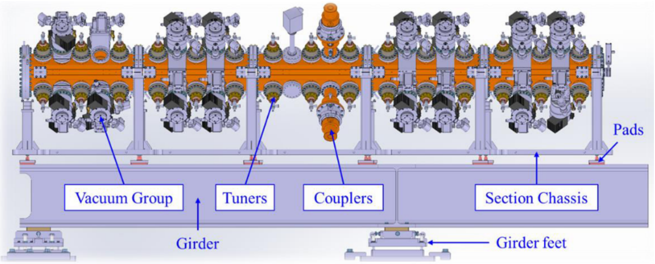


Also discussed in R. Miyamoto talk on beam commissioning in ESS later today.



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

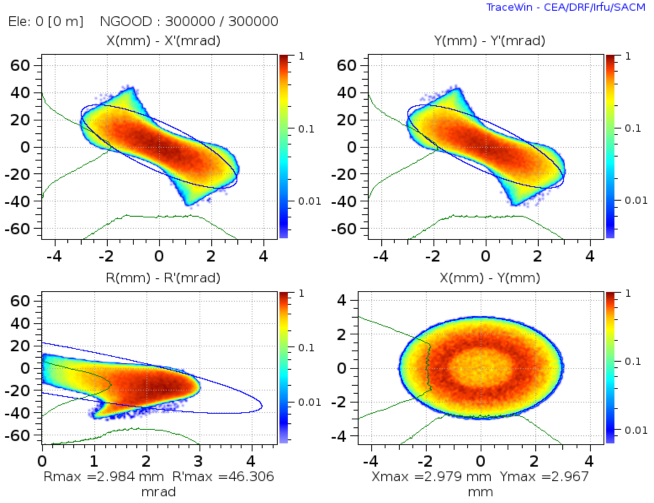
- RFQ built by our IC partners in CEA Saclay
- 4-vane structure, 4.55 m long, accelerates to 3.62 MeV
- 60 tuners, 4 coupler ports, 36 vacuum ports, 28 pick-up ports, 80 cooling connectors
- Design choices similar to that of Linac4



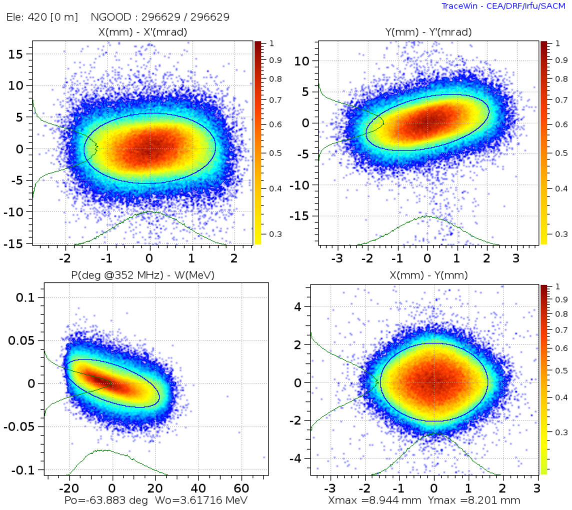
From Chirpaz-Cerbat et al., IPAC'16 proceedings

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

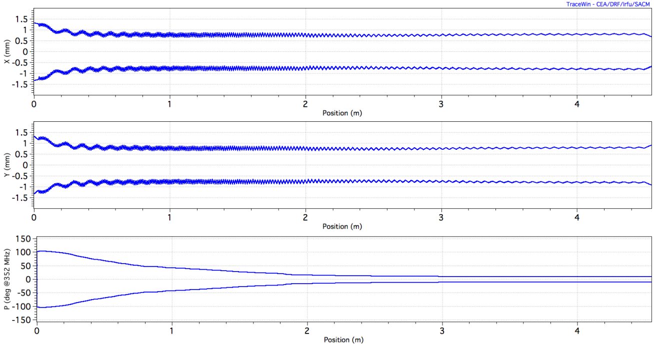
Input Beam Distribution



Output Beam Distribution



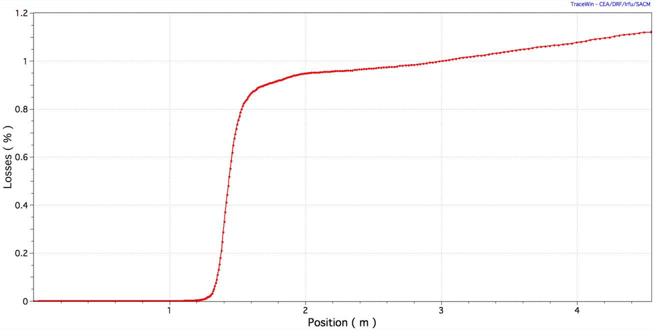
Beam Envelopes



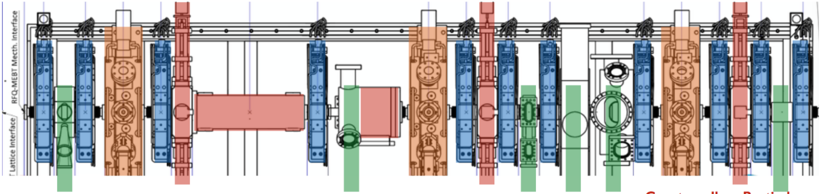
Matching for tail (transmission) so core is not perfectly matched

Sections: RFQ

Beam Losses in the RFQ

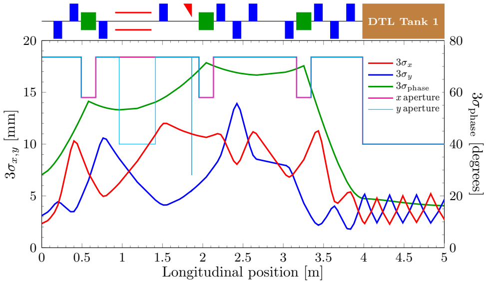


Sections: MEBT

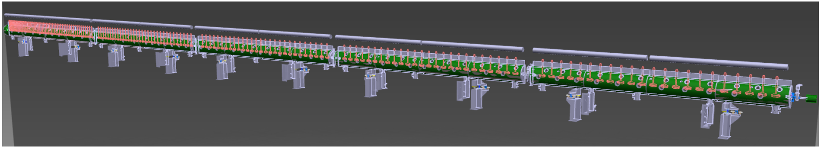


- MEBT built by our IC partners at ESS-Bilbao
- Match and rebunch beam into DTL, characterize beam
- 3.8 m long
- 11 quadrupoles, 3 buncher cavities
- Fast stripline chopper to clean mismatched head of pulse

Sections: MEBT

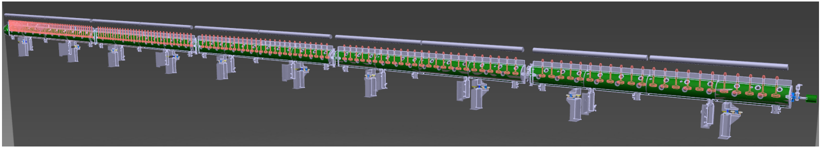


- No periodic structure -> time consuming to match
- Cannot focus as strongly as RFQ or DTL -> emittance growth unavoidable

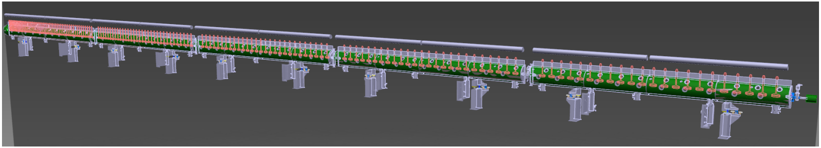


- DTL built by our IC partners at INFN-LNL
- 5 tanks of 8 m
- Energy 3.62 MeV -> 90 MeV
- 2.8 MW klystron for each tank, 2.2 MW needed for acceleration field assuming 50 % ohmic losses

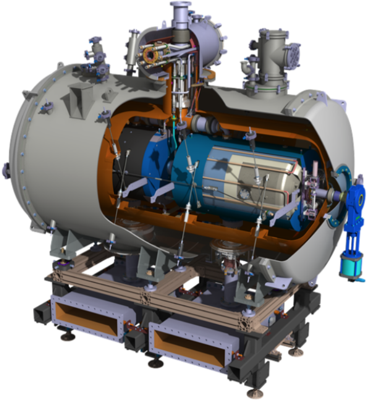
Sections: DTL



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



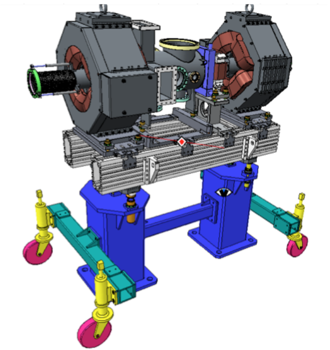
- Beam phase & amplitude commissioning of 1st tank particularly challenging
- 15 BPM's planned, 3 per tank
- Ongoing work to optimise the positions of BPM's (see talk by R. Miyamoto later this afternoon)



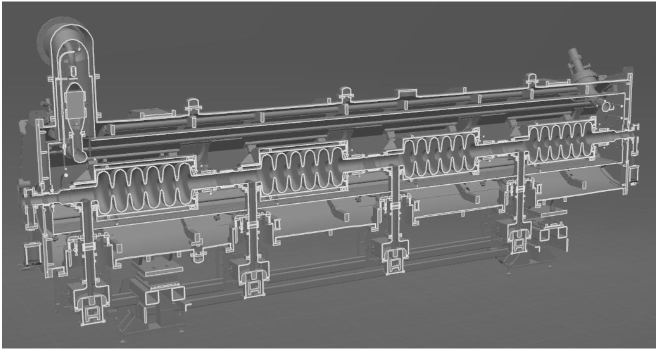
- Spoke cavities built by our IC partners at IPN Orsay
- DTL-Spoke transition to superconducting (LEDP)
- 2 spokes per cryostat, 13 cryostats
- Max gradient 9 MV/m
- Larger aperture compared to NC structures

Courtesy S. Bousson

Linac Warm Units (LWU)



- All quadrupoles and corrector magnets after DTL built by our IC 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



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

- The frequency jump is an unstable 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.

Sections: Elliptical Cavities

- The frequency jump is an unstable point for beam dynamics
- Require soft longitudinal transition between Spoke - Med. β
- We see losses originating from this region in end-to-end studies

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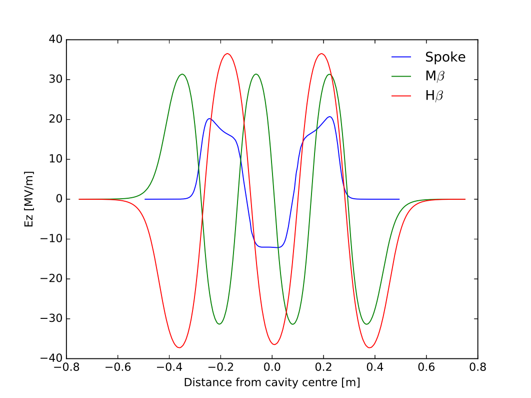
Field Map Comparison

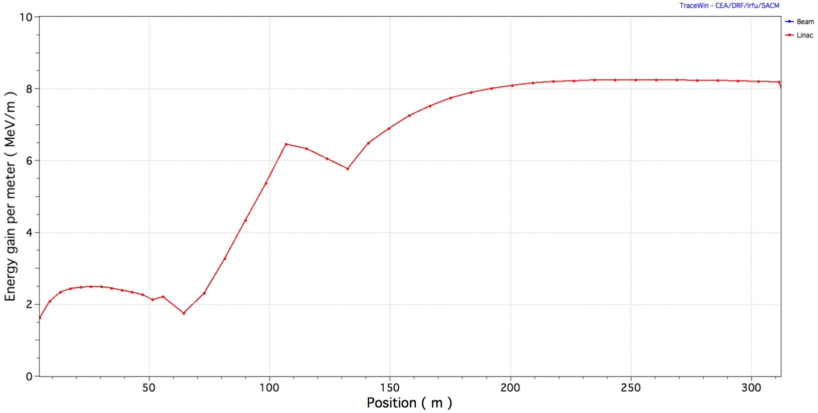
Accelerating field



Beam Dynamics Design Main Considerata

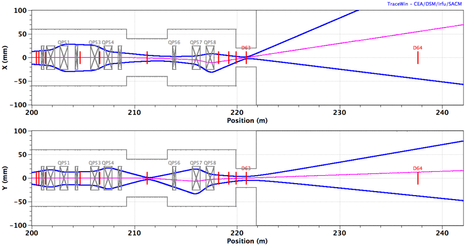
- The zero current phase advance per period in all the planes must be less than 90 deg
- The phase advance per meter (average phase advance) variation should be smooth and continuous
- At ESS on top of this the average phase advance changes monotonically
- The tune depression, k_{sc}/k_0 , must stay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

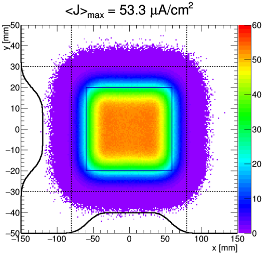
Energy Gain in SC Linac



- HEBT beam physics design by our IC 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 40 kHz vertical and 29 kHz horizontal paint the beam onto the rectangular target area

Sections: Contingency, Dumpline, A2T





Courtesy H.Thomsen

Error Studies

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

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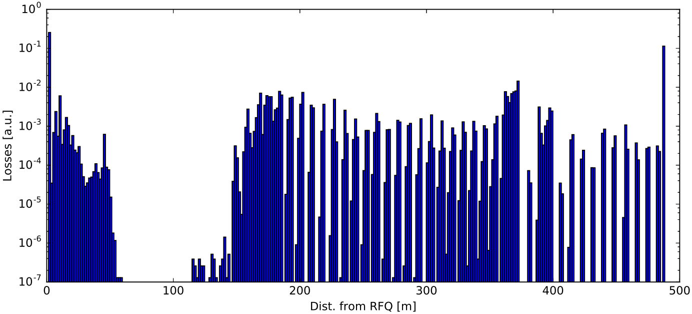
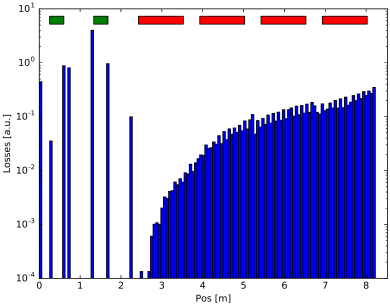
- Add dynamic errors for RF field and amplitude (ie uncorrected)
- Simulate multiple machines in TraceWin.
- Here presenting some results from a study of 20 000 machines tracking from RFQ exit to target, a total of about 10^{10} particles tracked.

Loss Distribution

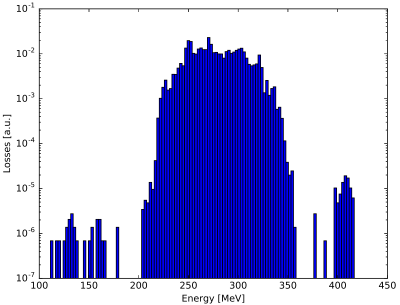


Loss Distribution along the Med.-β sections



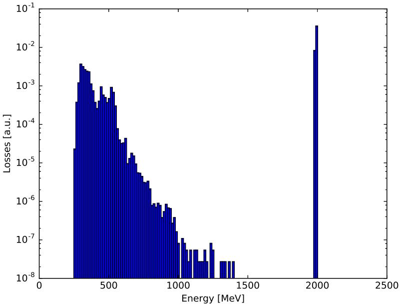
- Quads in green, cavities in red
- Note logarithmic scale!
- Aperture in cavity set to constant 60 mm in this simulation (conservative)

Energy distribution of losses



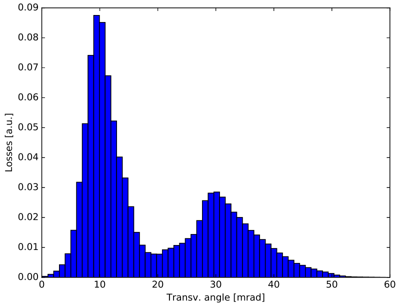
- Losses in Med.-β and beginning of High-β
- Clear cut at Med.-β input energy (216 MeV)
- Frequency jump challenging

Energy distribution of losses - dogleg



- All 2 GeV losses here, first and only dispersive region
- Again see losses from the frequency jump

Transversal distribution of losses



- Only losses in High-β region shown here
- Above $\sim$ 20 mrad are losses on LWU, lower angles are mixed
- Losses in cryostat are predominantly horizontal losses

Summary

- 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
- Discussed simulated losses originating in start of Mβ, believed to be related to frequency jump