Beam Loss and Collimation in the ESS Linac

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HB2012

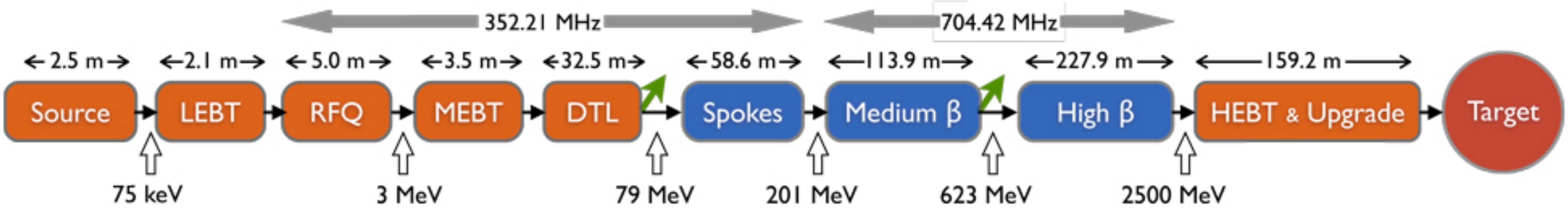
Introduction to ESS

ESS status and schedule

European Spallation Source (ESS) is a spallation neutron source based on a 5 MW proton linac, build in Lund, Sweden.

- 2009-2012: Accelerator Design Upgrade Project
- 2012 (Sept): Technical Design Report (with schedule, costing)
- 2012 (Q4): Review
- 2013 (Q1?): Ground breaking
- 2018 (?): first proton beam
- 2019 (?): first neutron
- 202?: 5 MW operation
- ~2070: decommissioning

ESS linac



One of the biggest challenges for a high power proton linac is to control slow beam losses and this requires comprehensive efforts of

- Identify the loss limit allowing hands-on maintenance
- Simulate/understand beam/machine conditions vs. beam loss patterns
- Establish collimation scheme
- Prepare diagnostics and tuning scheme
- …

ESS high level parameters

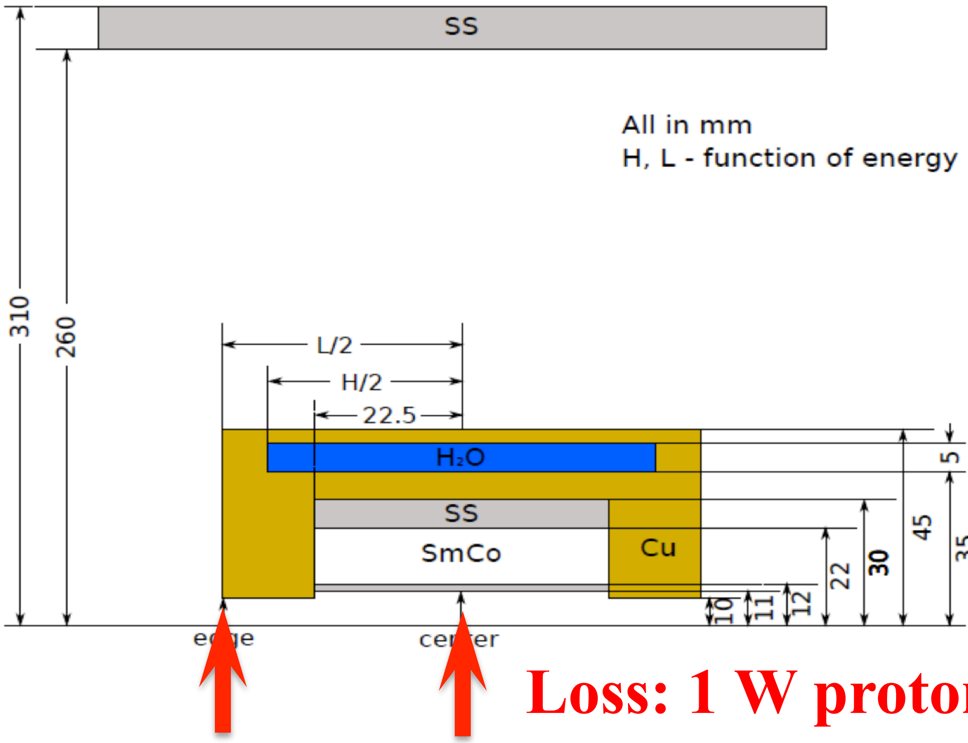
Energy [GeV]	**2.5**
Beam power [MW]	**5**
Repetition rate [Hz]	**14**
Beam current [mA]	**50**
Beam pulse [ms]	**2.86**
Duty cycle [%]	**4**

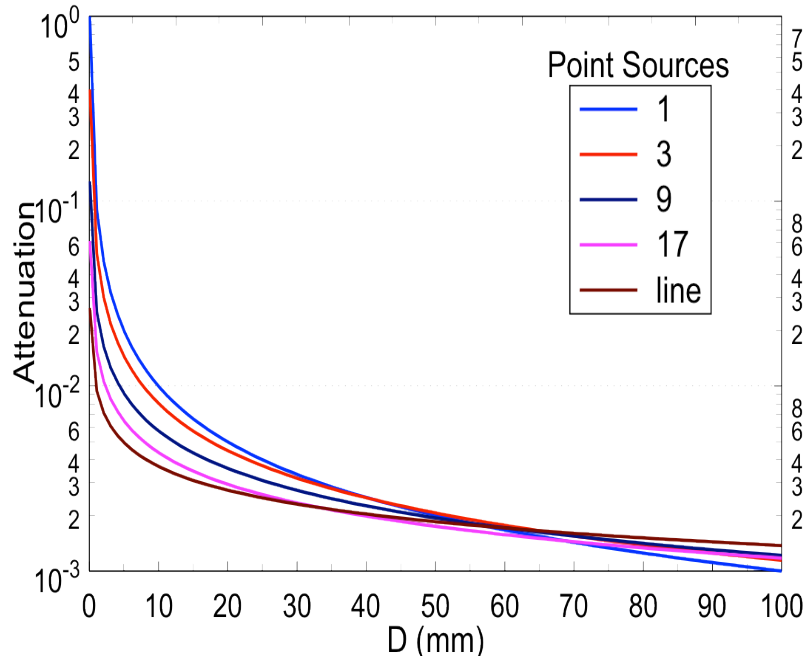
Outline

- Beam Loss Limit in the RFQ and DTL
- Error Studies with a Tracking Simulation
- MEBT Collimation
- HEBT Collimation

Beam Loss Limit in the RFQ and DTL

Dose rate simulation for RFQ/DTL with MARS

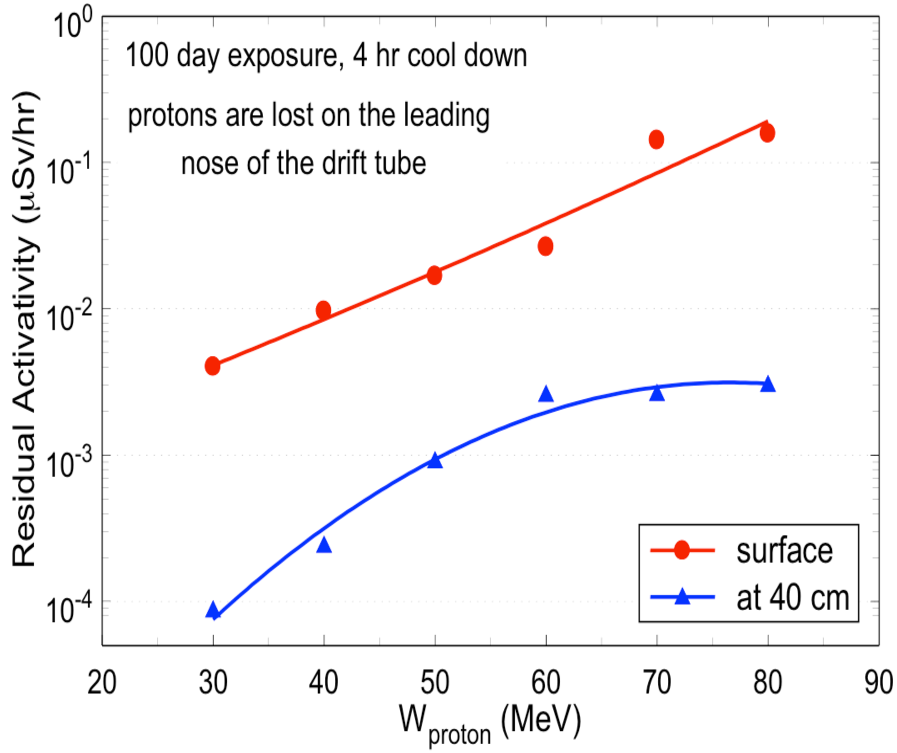


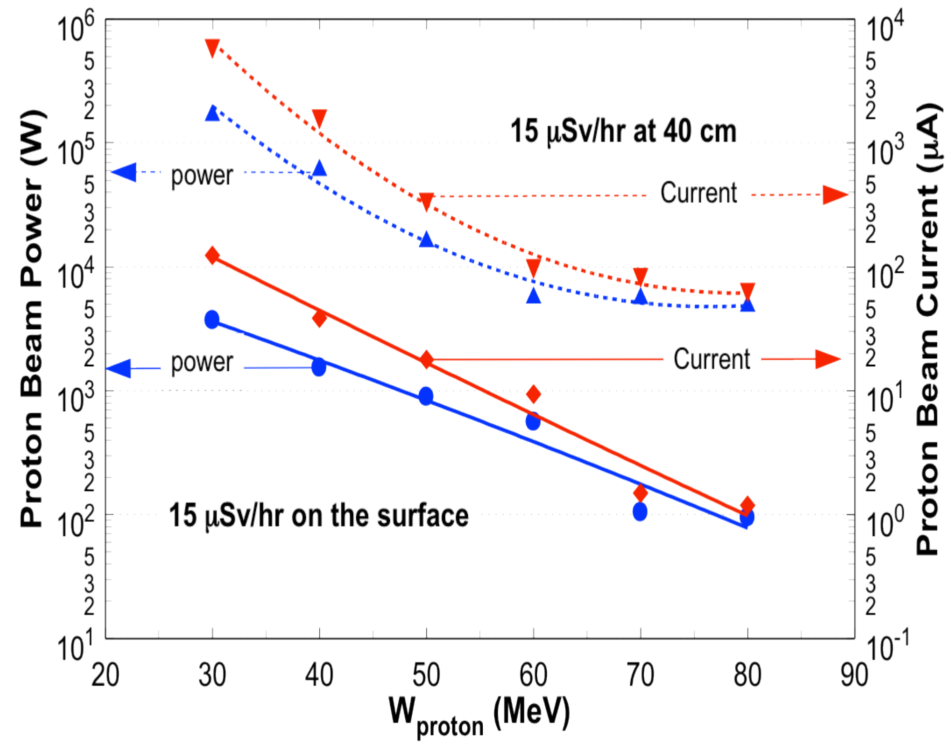


Loss: 1 W proton beam

- **1 W/m also applies to the RFQ and DTL?**
- Use "15 μSv/hr at 40 cm" (CERN's supervised temporally work places) as our criterion.
- Calculate radiation activity for the RFQ and DTL with MARS.

1 W/m doesn't apply to RFQ/DTL (from the point of view of activation)





- Large margin wrt 15 μSv/hr.
- Activation very low below 30 MeV.
- Similar studies planned for superconducting sections.

Error Studies with a Tracking Simulation

SCL error study with TraceWin

- **1 W loss from a 5 MW beam ➔ 20 particles loss in a 100M macro particle simulation.**
- **Possible to simulate loss patterns vs. machine/beam conditions?**
- Quad and cavity static error study for the SCL (see TUOB02):
  - Individual error (identifying the boundary)
  - All the errors combined (100k particles × 1k linacs)

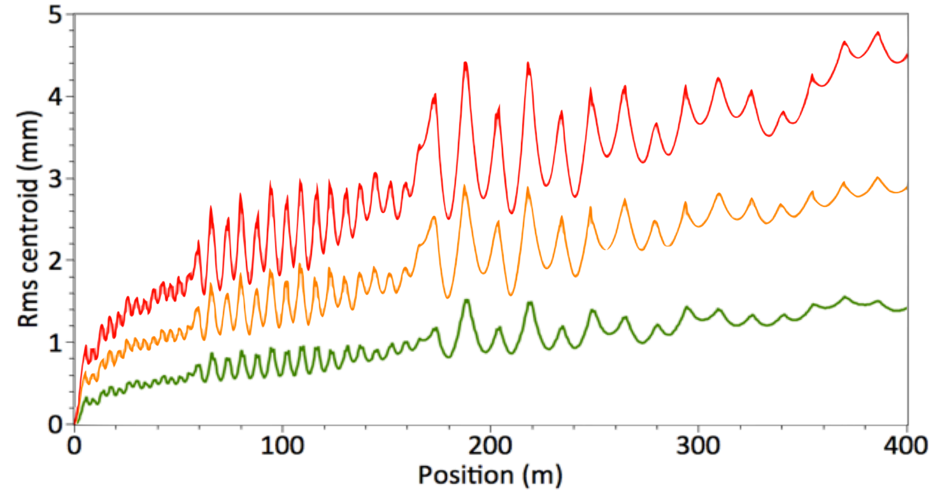
Quadrupole	
Alignment in x and y [mm]	0.3
Rotation around z axis [mrad]	1
Gradient [%]	0.75
Cavity	
Alignment in x and y [mm]	3
Rotation around x and y axes [mrad]	3
Accelerating field strength [%]	1.5
Accelerating field phase [deg]	1.5

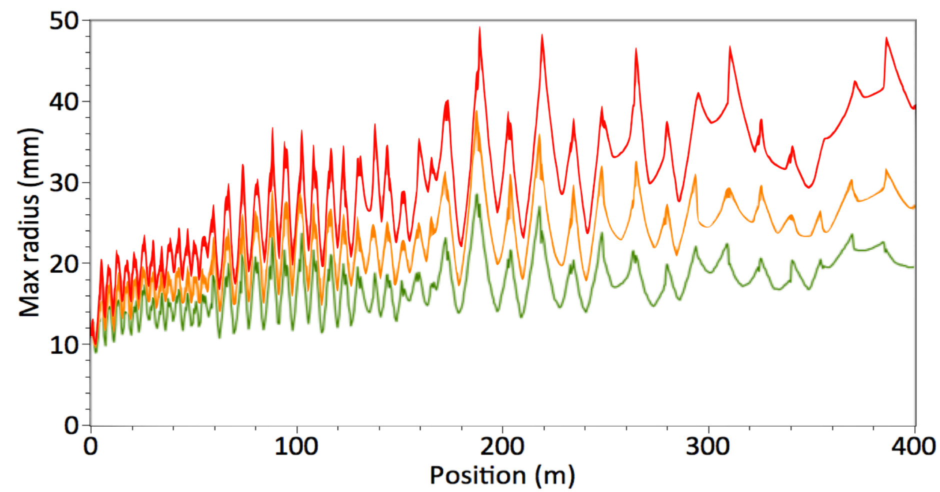
- Values for the worst case considered
- Errors distributed uniformly

Error study result

Table 2: Results of the error study reported as *Average*$\pm\sigma$

Parameter	$^1/_3$	$^2/_3$	$^3/_3$
$\Delta\epsilon_x^*[\%]$	6.50±3.37	23.31±9.71	47.02±21.99
$\Delta\epsilon_y[\%]$	7.33±3.61	25.80±11.33	50.51±23.69
$\Delta\epsilon_z[\%]$	17.47±7.73	56.77±17.50	94.47±34.66
Halo_x	1.97 ±0.12	1.91±0.32	1.94±0.42
Halo_y	1.96±0.13	1.88±0.34	1.91±0.45
Halo_z	2.06±0.26	1.67±0.41	1.46±0.53
$x_\sigma'^{\ddagger}$ [mrad]	0.078	0.149	0.235
y_σ' [mrad]	0.082	0.173	0.250
α_{xy_σ}	0.024	0.058	0.081
$\alpha_{x'y'_\sigma}$	0.012	0.028	0.045

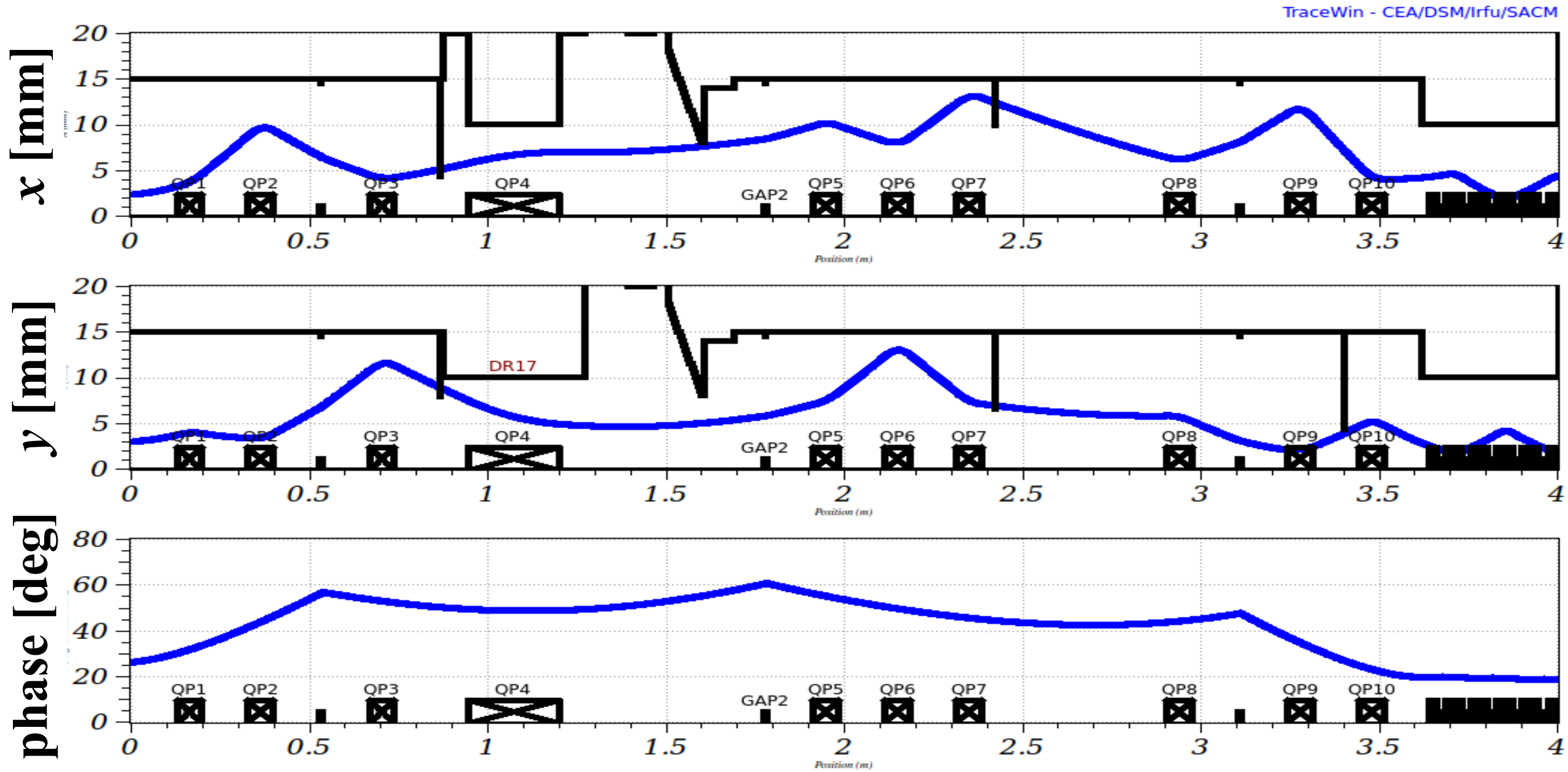




- Emittance grows but no loss. (At least proving robustness of the lattice.)
- More detailed studies planned including dynamic errors, upstream sections…. (Anything else?)

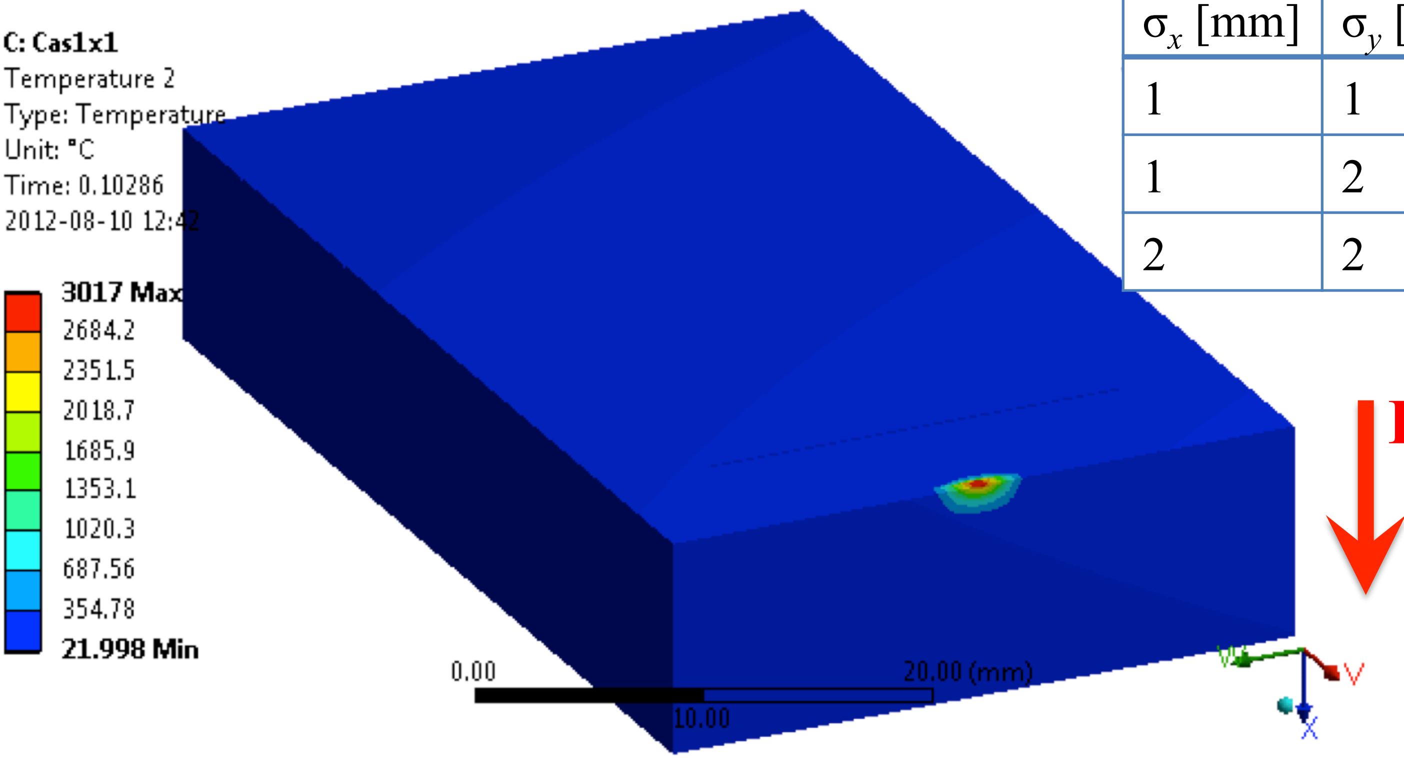
MEBT Collimation

Current MEBT layout and full beam envelope



- MEBT: 1) matching from the RFQ to DTL, 2) a fast chopper, 3) diagnostic devices, 4) collimation.
- MEBT lattice: 3 bunchers and 9+1 quads.
- Changes from the May design (an extra buncher + quad re-adjustment) improved the dynamics.
- **Optimum collimation scheme? Could effect the downstream sections?**

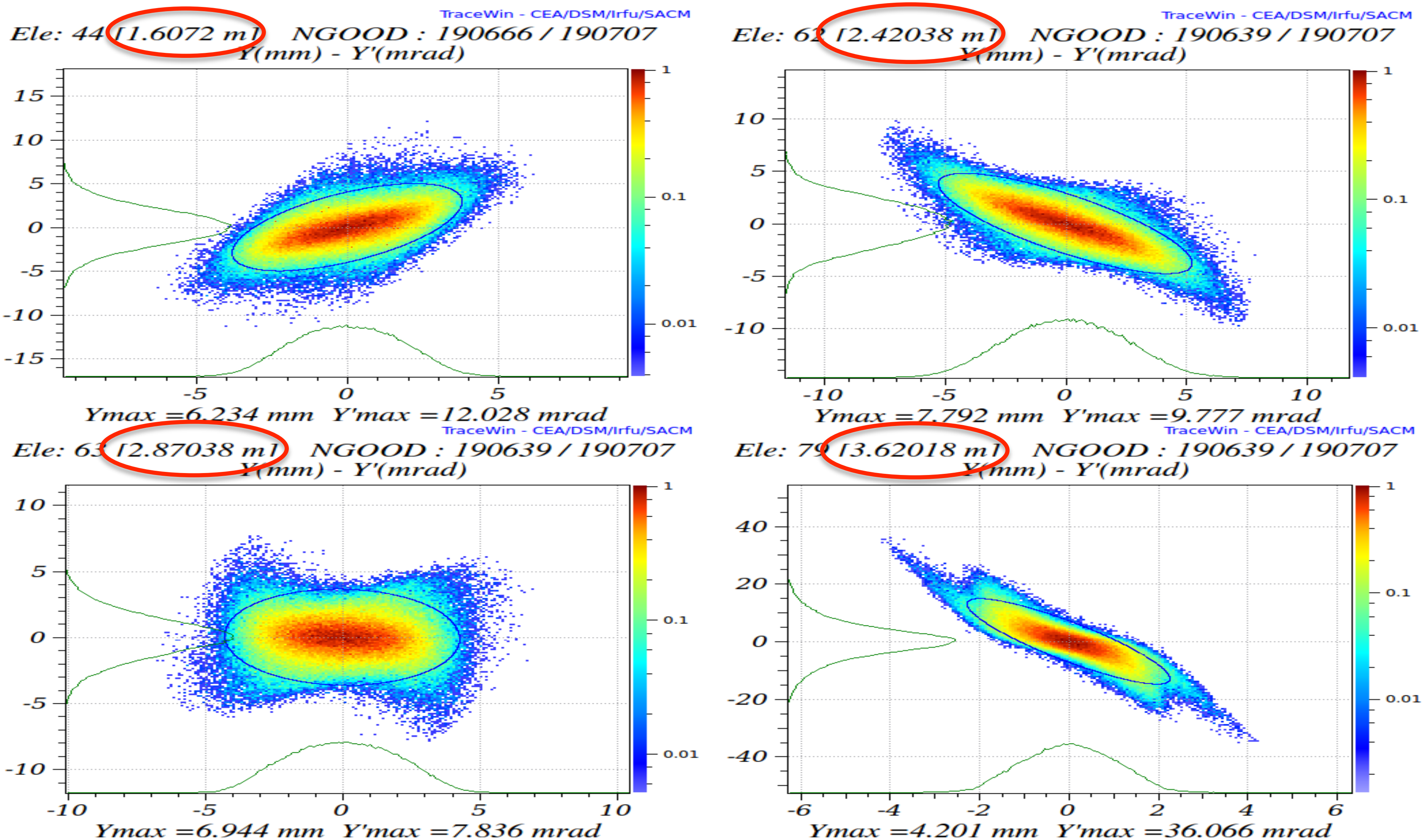
Loss limit of a MEBT collimator?



σ_x [mm]	σ_y [mm]	Temp [C°]
1	1	3017
1	2	1430
2	2	1178

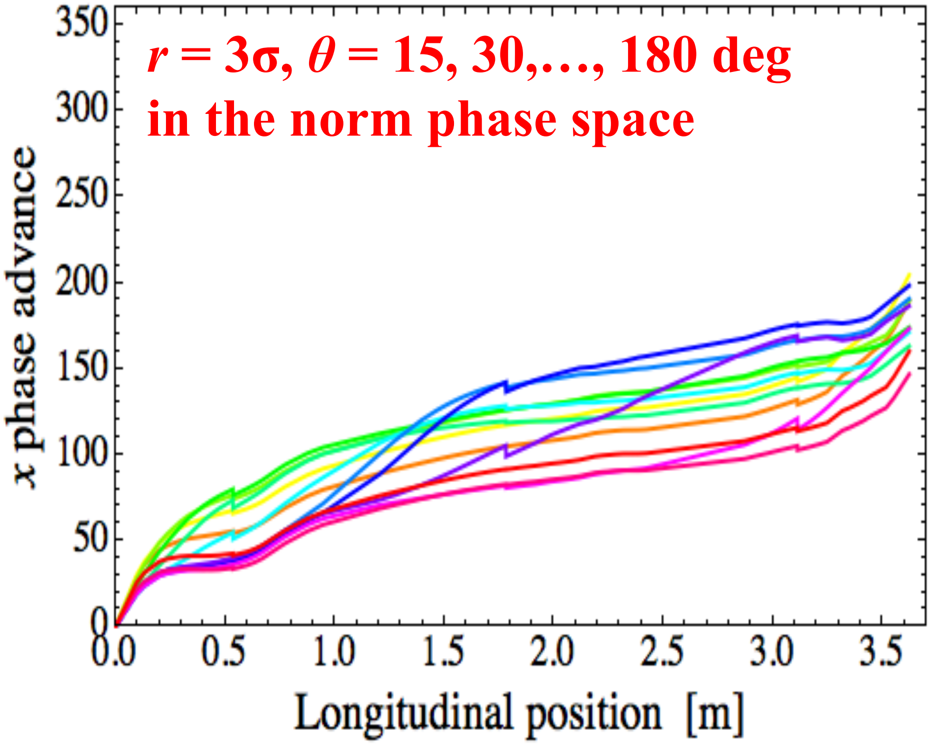
- Assumptions: graphite jaw, Gaussian beam, remove beyond 3σ (~0.25%, ~15 W)
- Graphite may suffer mechanical damages beyond ~1500 C°.
- **In the simulation, stick to ~15 W and avoid where $\sigma_x \sim \sigma_y \sim 1$ mm.**
- Better to know the beam size vs. loss limit in detail.
- Other materials planned to be studied.

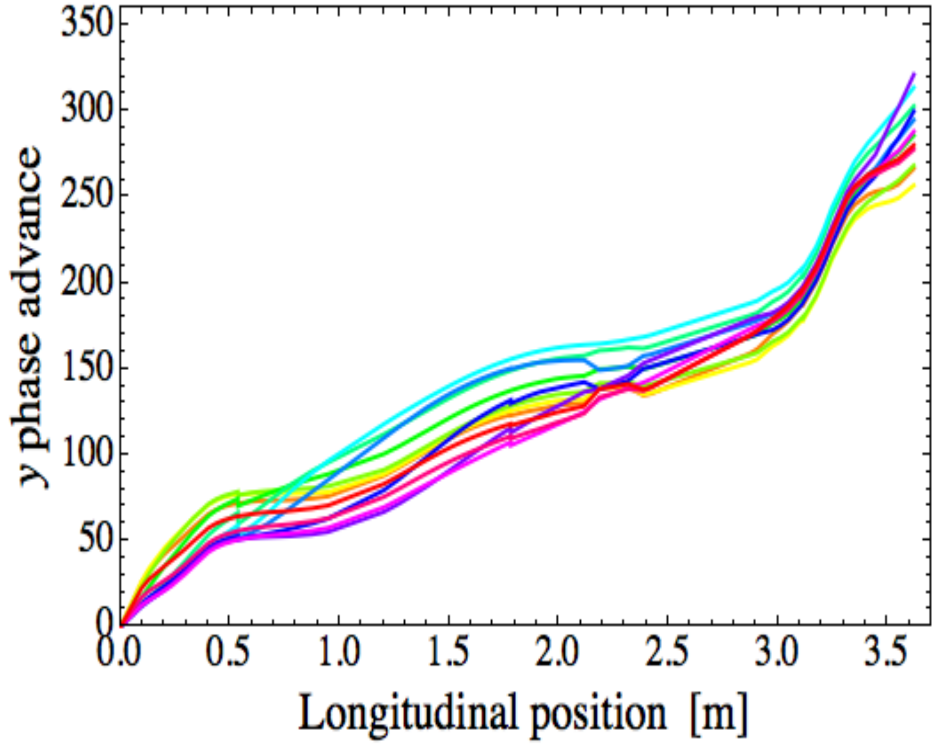
Halo growth occurs in the last half of the MEBT (sometimes in the final 10-20 cm)



Collimation effective in the later part.

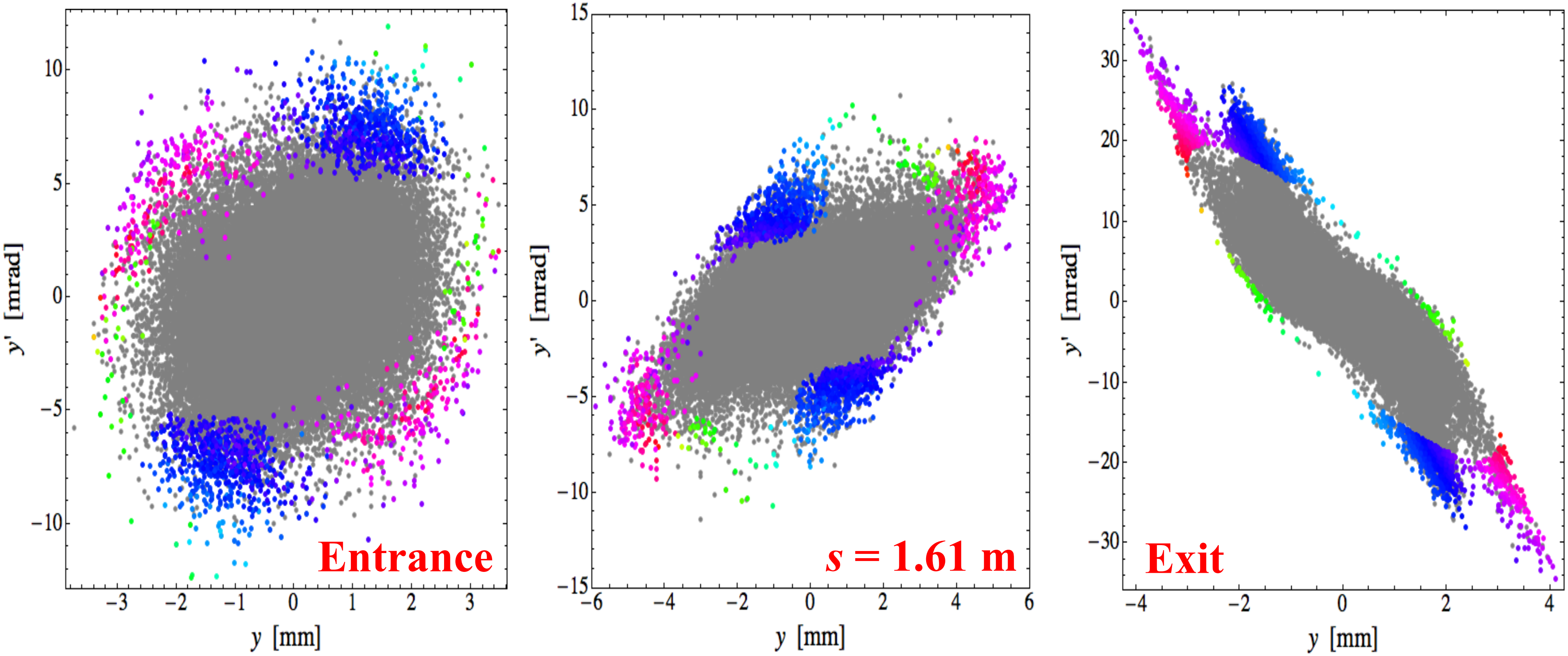
Phase advance under strong space charge





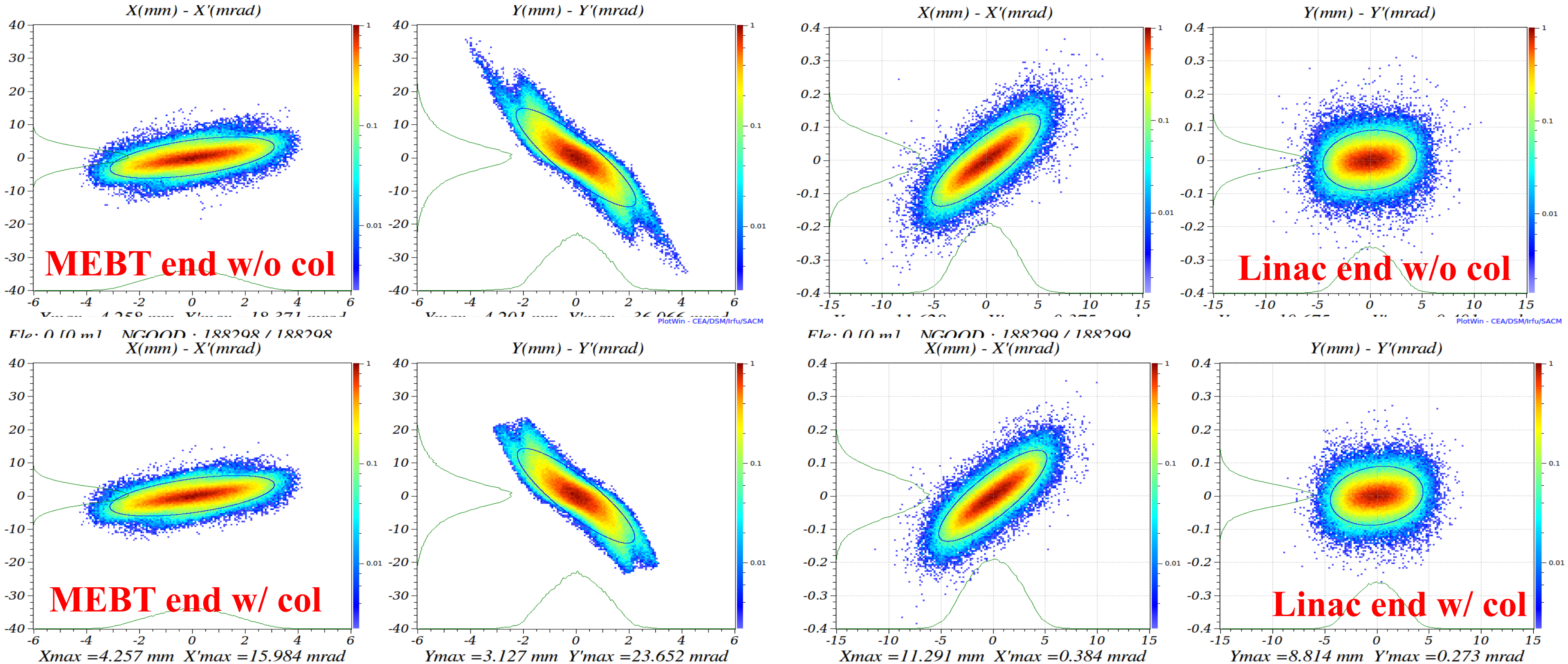
- The standard scheme of two collimators separated by 90 deg and etc is not optimum for the ESS MEBT. (Doesn't apply to HEBT.)
- Phase advance of an individual particle (angle in the normalized phase space) depends on its initial position due to strong space charge.
- Angular distribution of halo particles is not uniform.

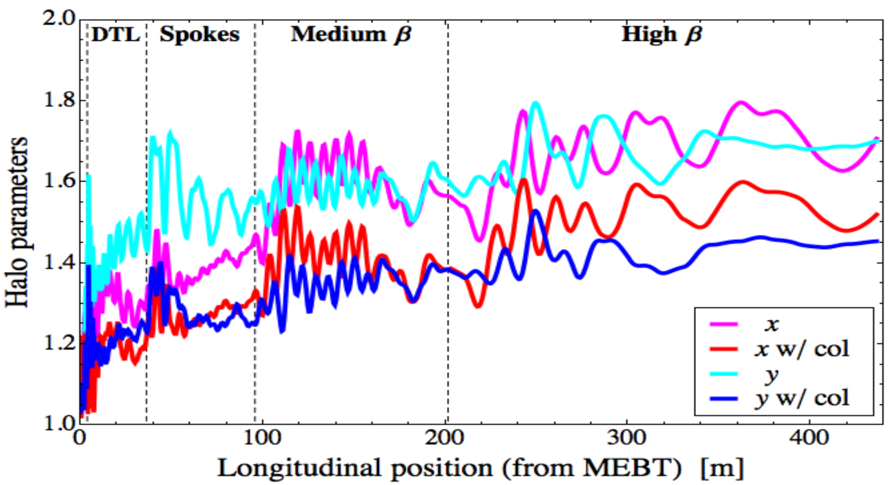
(Primitive) way to determine collimator locations



- Mechanical constraints ➔ a collimator placed only between quads.
- Identify halo particles at the end of the MEBT.
- Trace back the distribution of the halo particles at possible collimator locations and identify the optimum set of locations.
- Stick to ~15 W and avoid where the beam is smaller than $\sigma_x \sim \sigma_y \sim 1$ mm.
- Chaotic behavior? Also indicate collimation effective in the later part.

Improvement with collimators



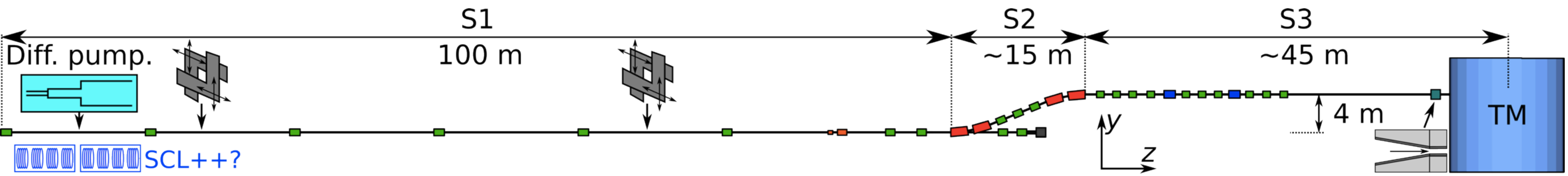


- The distribution and halo improved at the end of MEBT **and also the end of linac**.
- The current MEBT output is already good. **Consider worse input distributions and combine with the error study.**

HEBT Collimation

Dipoles, Quadrupoles Octupoles

The HEBT (2012 May 28)



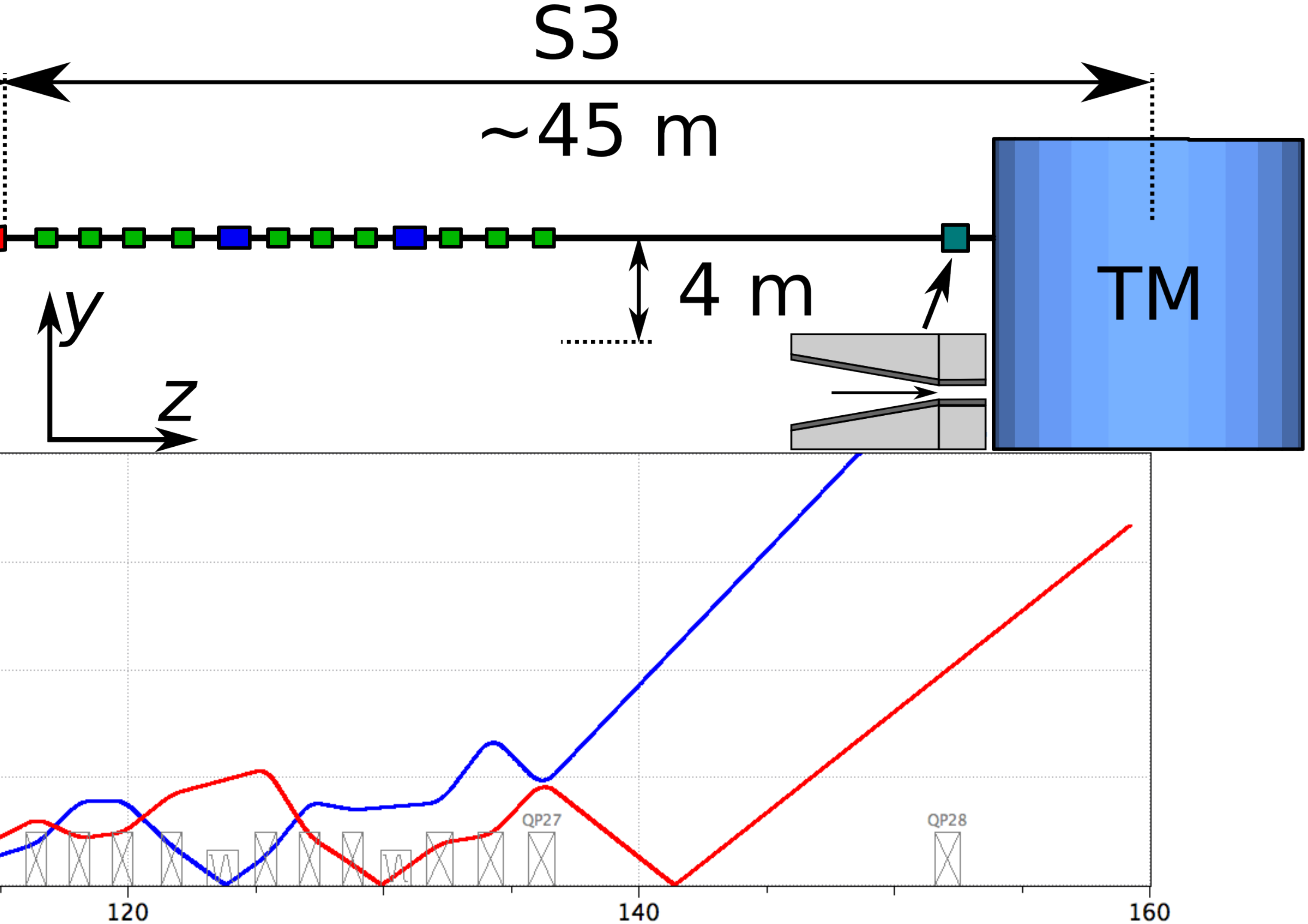
› S1: Energy upgrade + movable collimators.

› S2: Achromatic elevation. Tune-up lines below.

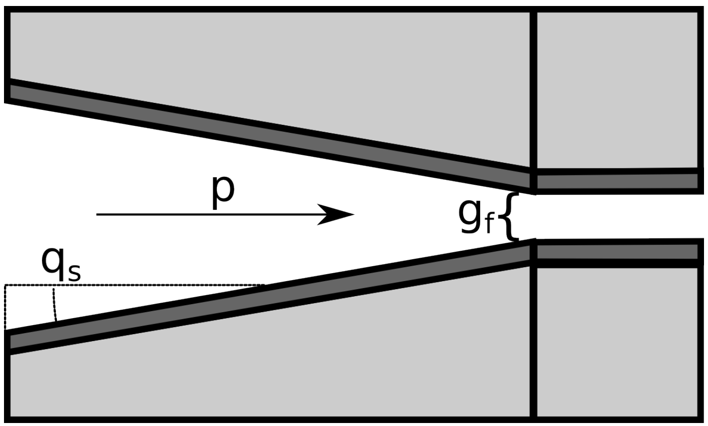
› S3: Linear + non-linear (octupole) expansion of beam + fixed collimator.

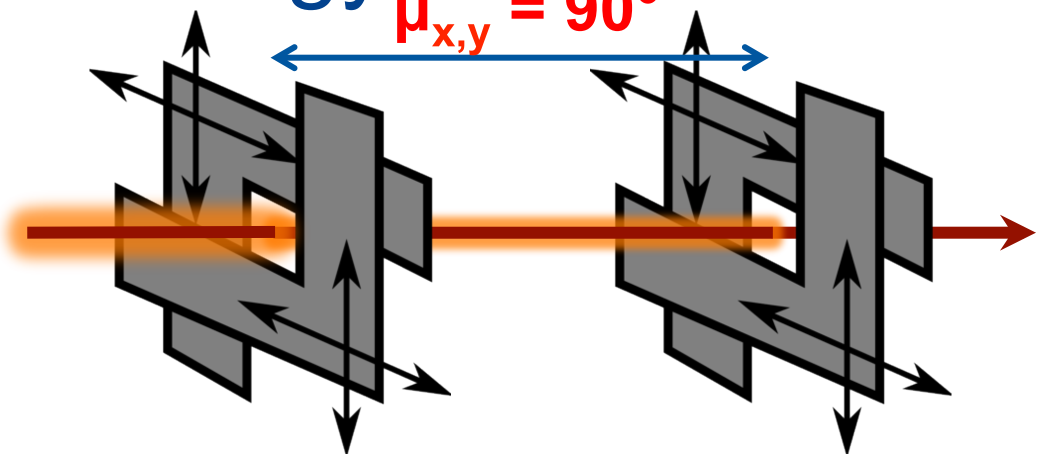
The HEBT (2012 May 28)

Dipoles,
Quadrupoles
Octupoles



HEBT Collimation Strategy





Fixed Target Collimator:

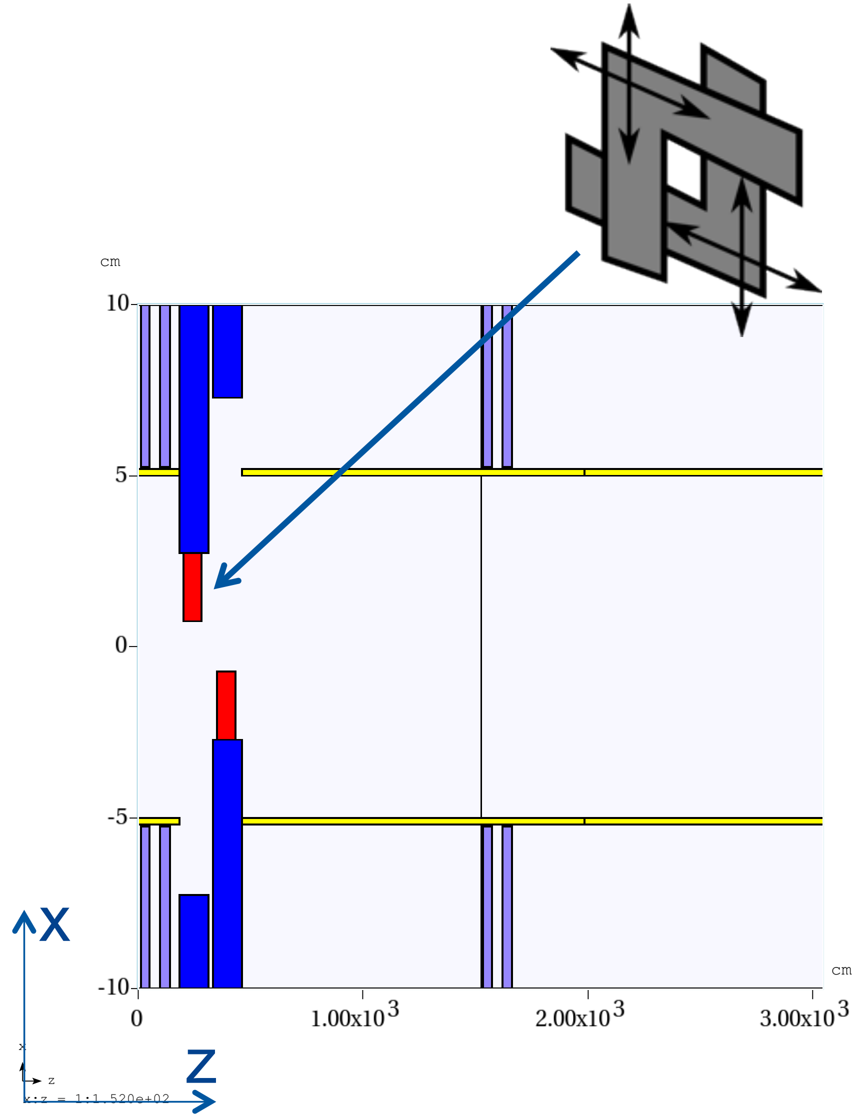
- Upstream of PBW, target, etc.
- Halo & over-focused particles, **25 kW**
- To be designed by NCBJ, Świerk, Poland

Movable Collimators:

- Uncontrollable losses in HEBT, **24 kW / 8 jaws**
- Relieve fixed collimator
- Protect downstream aperture restrictions
- Handle and measure unforeseen halo?

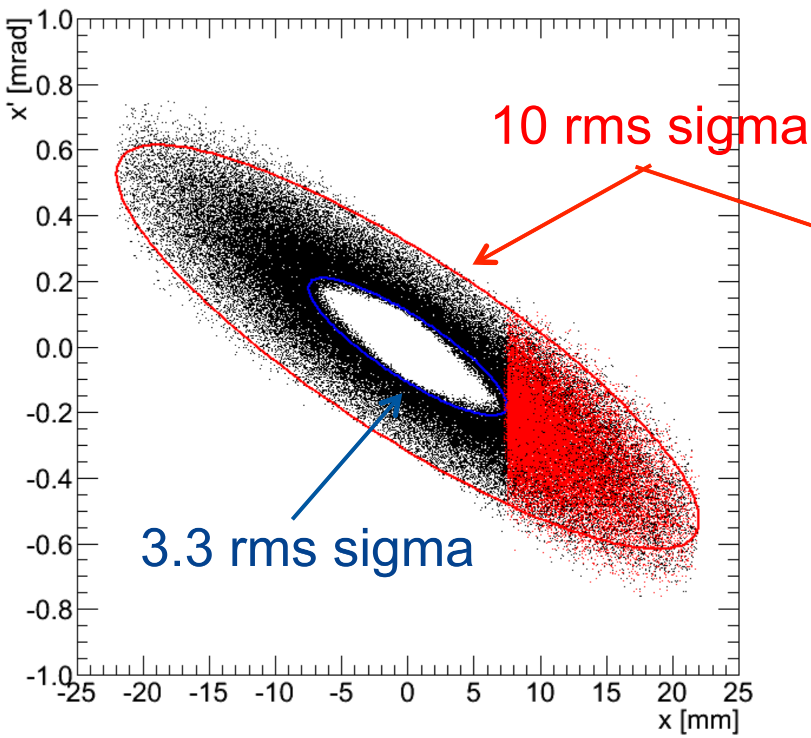
A MARS15 Model

- Jaws:
  20 x 50 x 800 mm^3 SS316
- Collimator radiation shield:
  H x W x 1.3 m SS316
- Beam pipe: ID Ø100 mm
- Magnet poles
- *Extreme beam* on jaws:
  - Exp. Halo: 3.3 σ < x < 10 σ:
  - ~7 mm half-gap (3.4 σ)
  - Fractional beam ~ 3.1E-3
  - Power ~ 15 kW in H-plane!

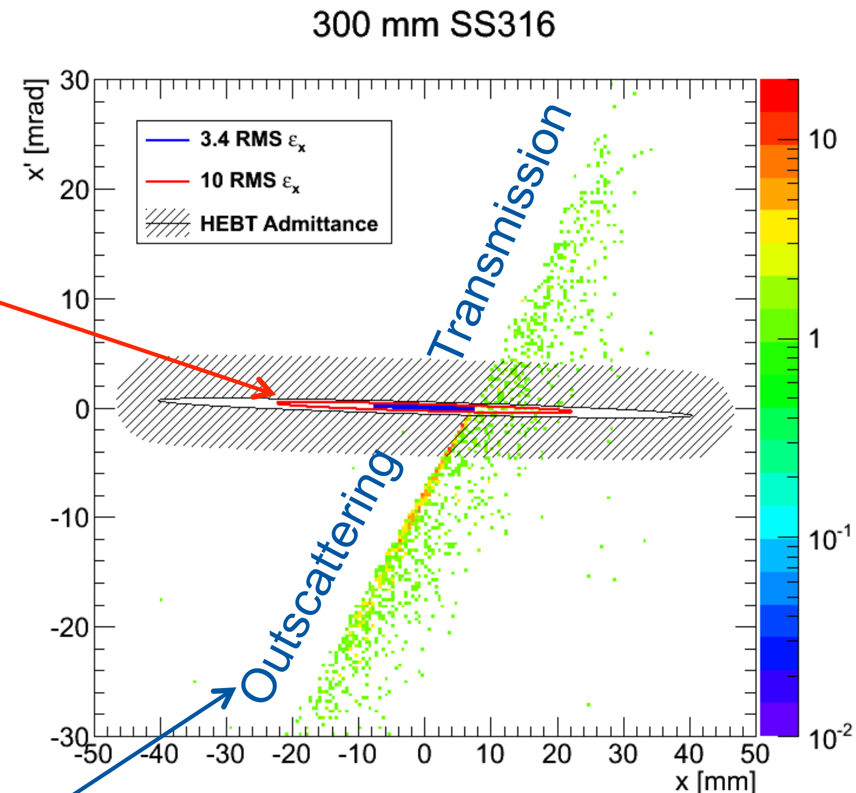


1st Jaw

H Phase space before 1st Jaw



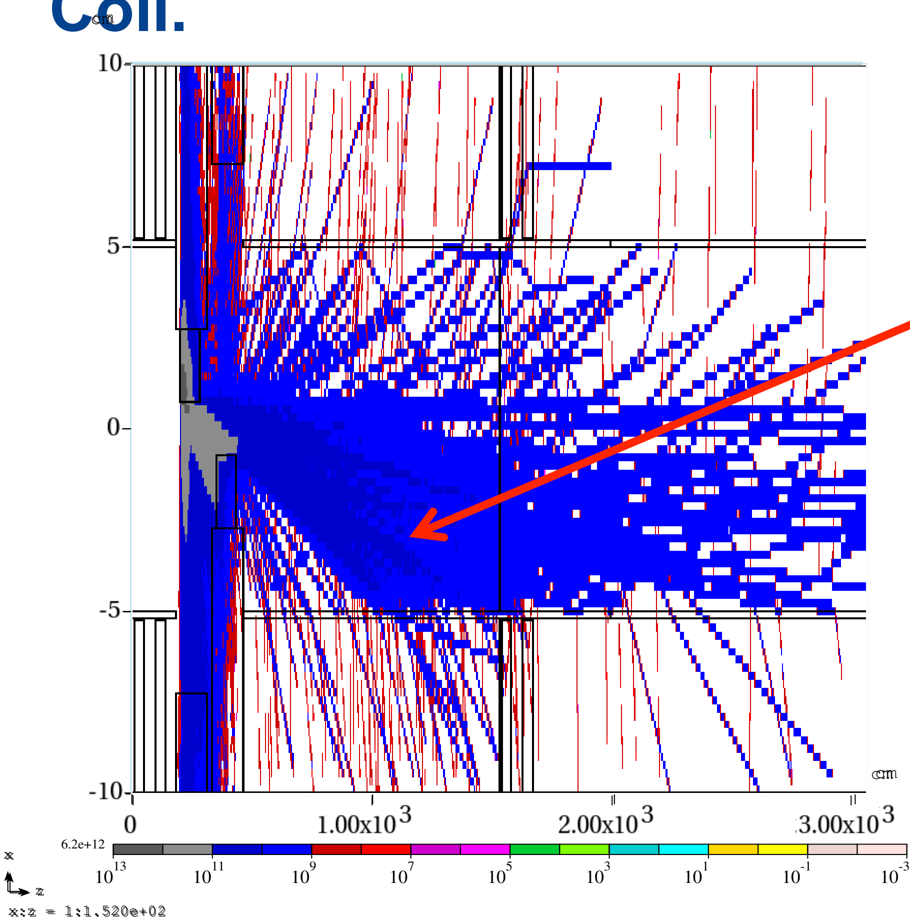
H Phase space density after 1st Jaw



(~6% @ 800 mm) ➔ masks & absorbers

Particles on Collimator

Proton Fluence @ 3.4 σ Coll.



Further Work

- Finalize materials and dim.
- Masks? Activation?
- Repeat optimized col. system after $\mu_{x,y}$ = 90°
- Effects of beam offsets for
  - Collimators
  - Beam on target.

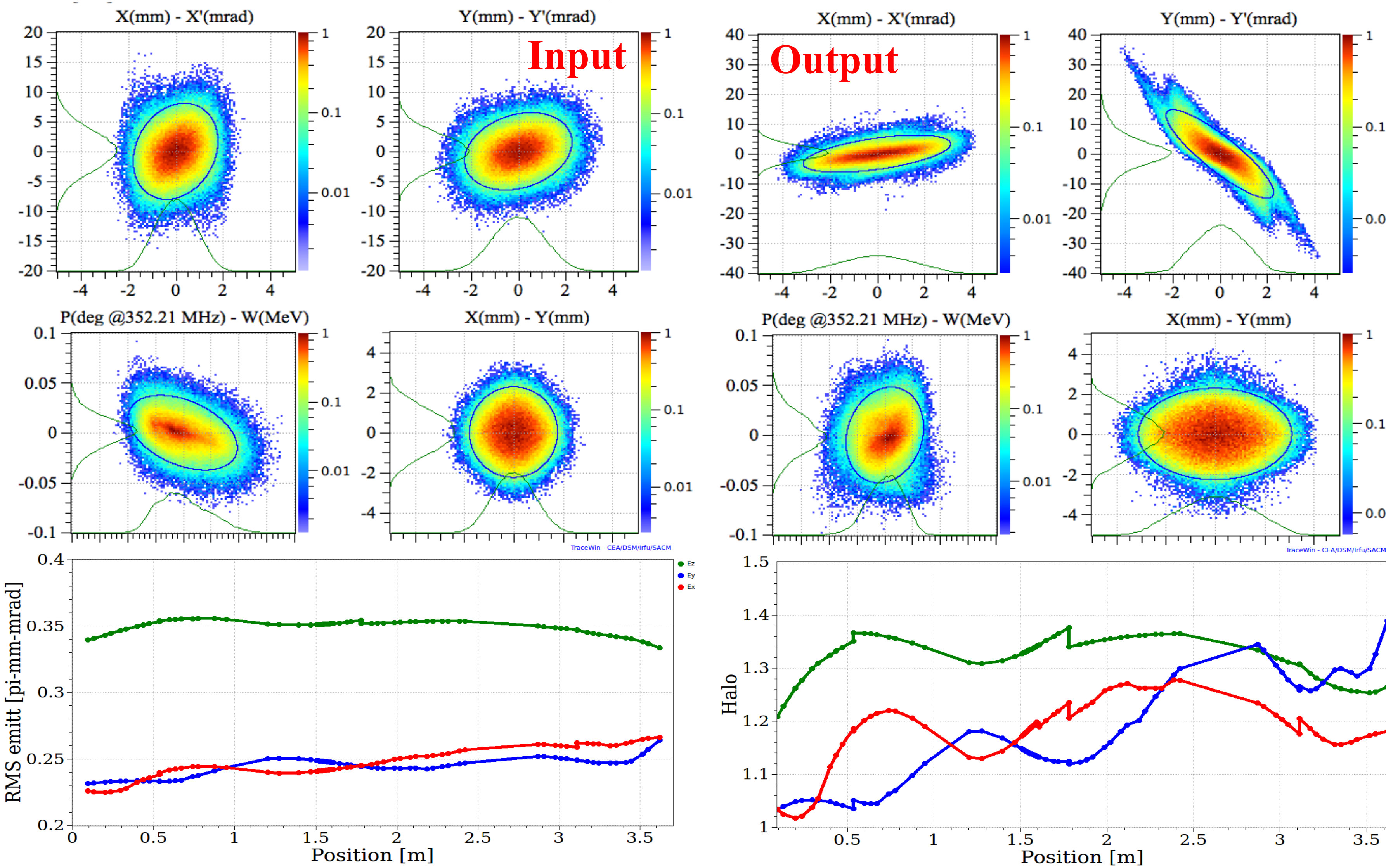
Conclusions

- ESS will be a spallation neutron source based on 5 MW proton linac, based at Lund, Sweden. It is planed that the commissioning starts by the end this decade and 5 MW operation starts in early 2020s.
- Control of slow beam losses is one of the biggest challenge for the ESS linac.
- Dose rate simulations indicate that we may be able to loose the 1 W/m criterion for the RFQ and DTL.
- Error study has been initiated for the SCL but no loss has been observed in the simulation, demonstrating robustness of the present lattice design.
- MEBT and HEBT collimation schemes are studied.
- Comprehensive study of the beam loss will be continued and improved. Suggestions and comments are very welcome!

Thanks for your attention!

Backup Slides

MEBT beam dynamics improvement



- Changes from the May design (an extra buncher + quad re-adjustment) improved the dynamics.

Halo definition (Wangler's)

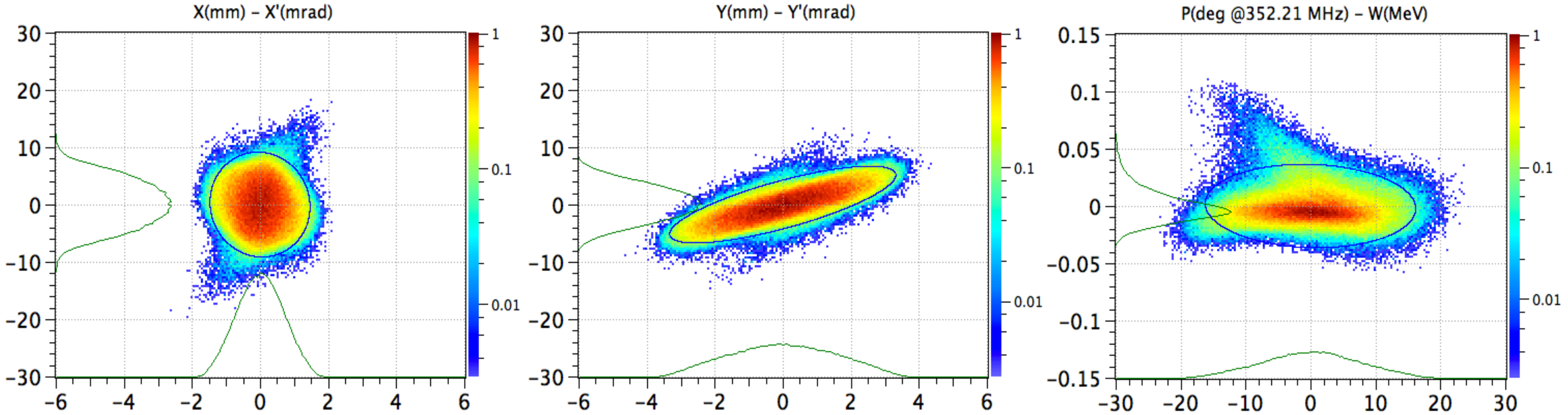
- The *spatial profile parameter* (Kurtosis):

$$h = \frac{< x^4 >}{< x^2 >^2} - 2$$

- The *halo intensity parameter* (extension to 2D)

$$H = \frac{\sqrt{3}}{2}\frac{\sqrt{< x^4 >< x'^4 > + 3 < x^2 x'^2 >^2 - 4 < x^3 x' >< x x'^3 >}}{< x^2 >< x'^2 > - < x x' >^2} - 2$$

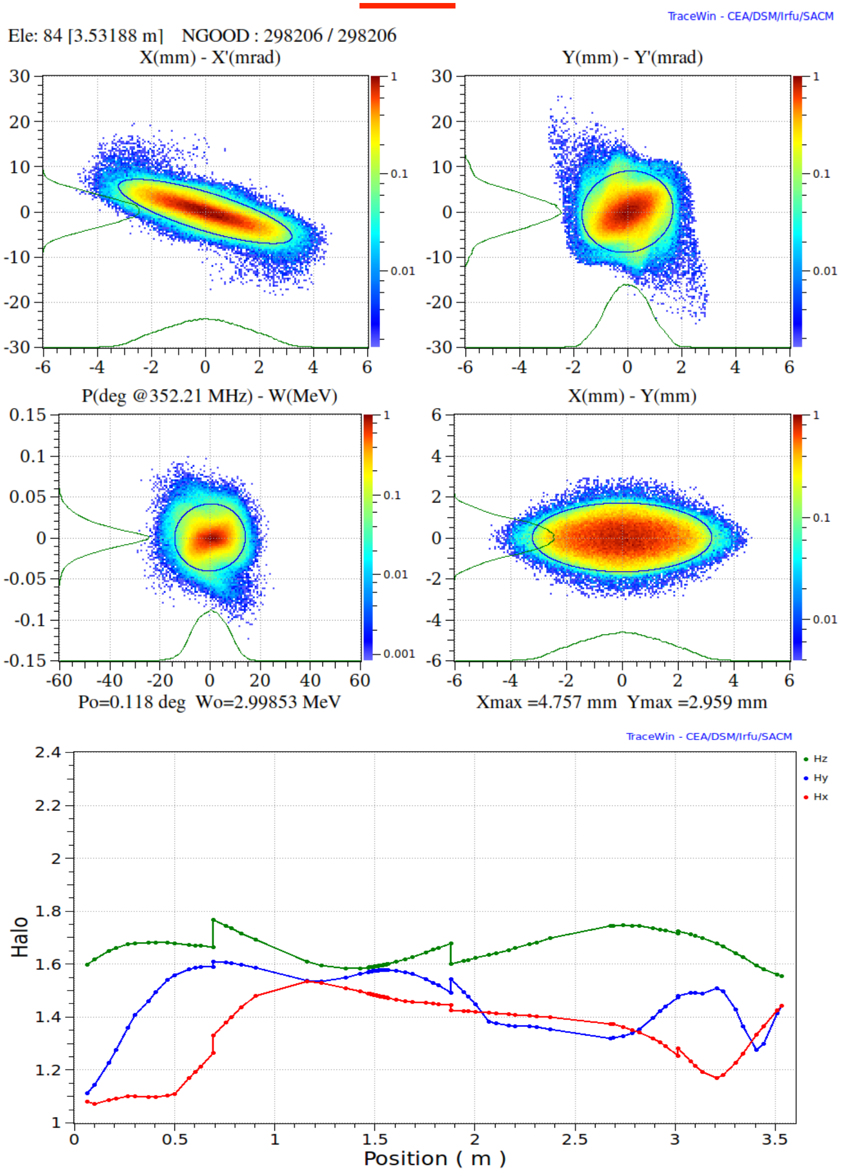
- The normalization "2" to make the "KV" = 0 and "Gaussian" = 1.



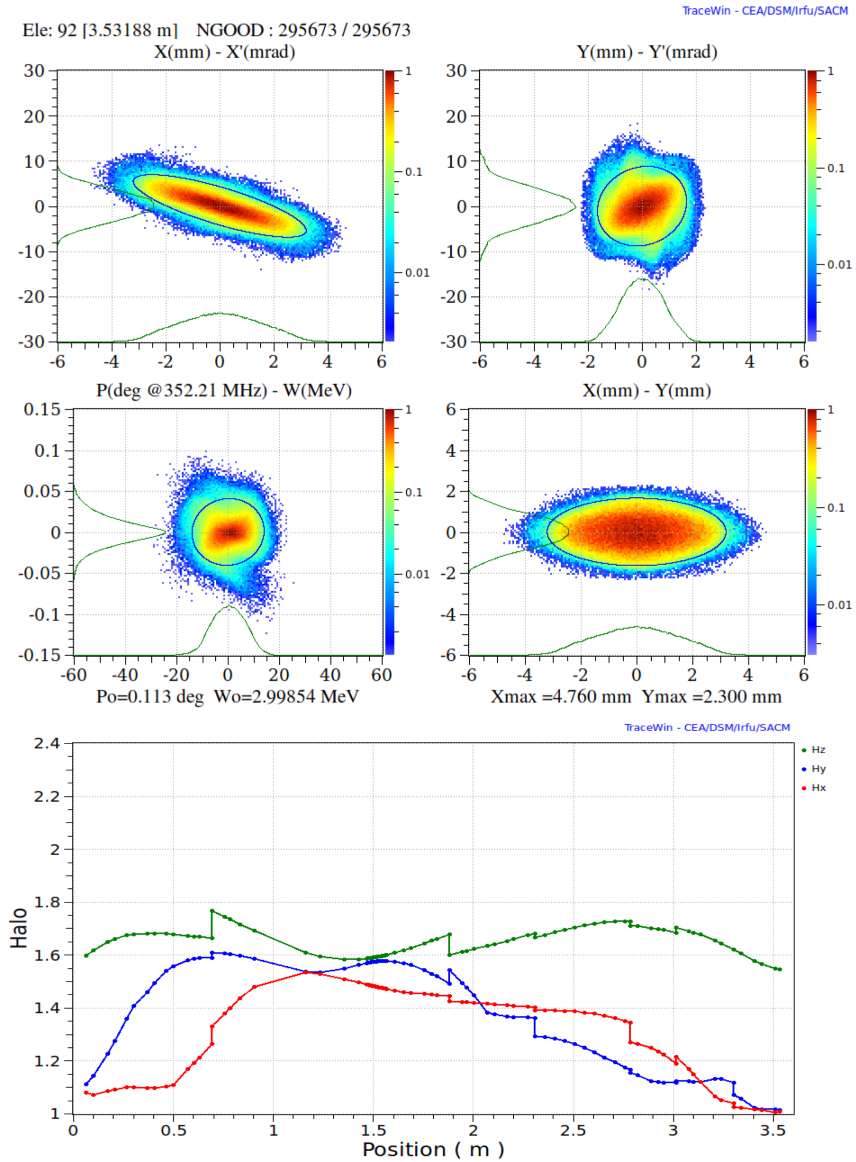
Distribution into the DTL (from a simulation of the RFQ by A. Ponton)

Output distribution and halos w/ and w/o collimators

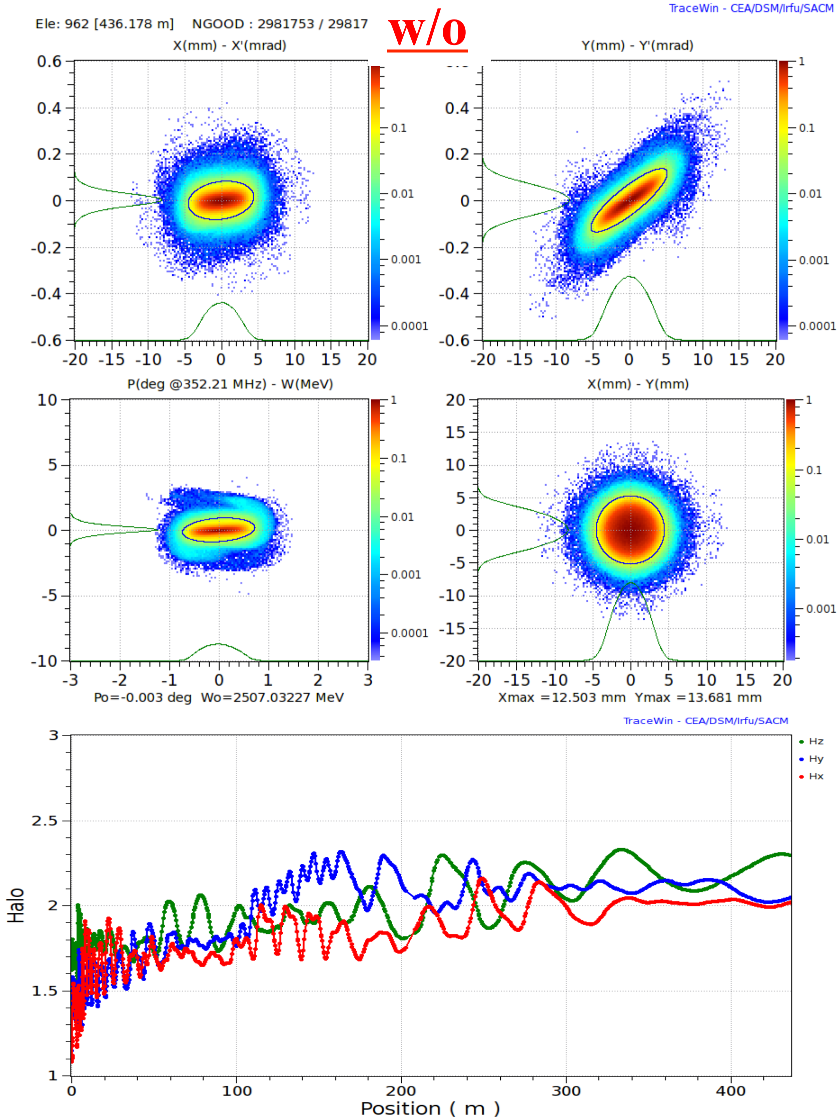
w/o

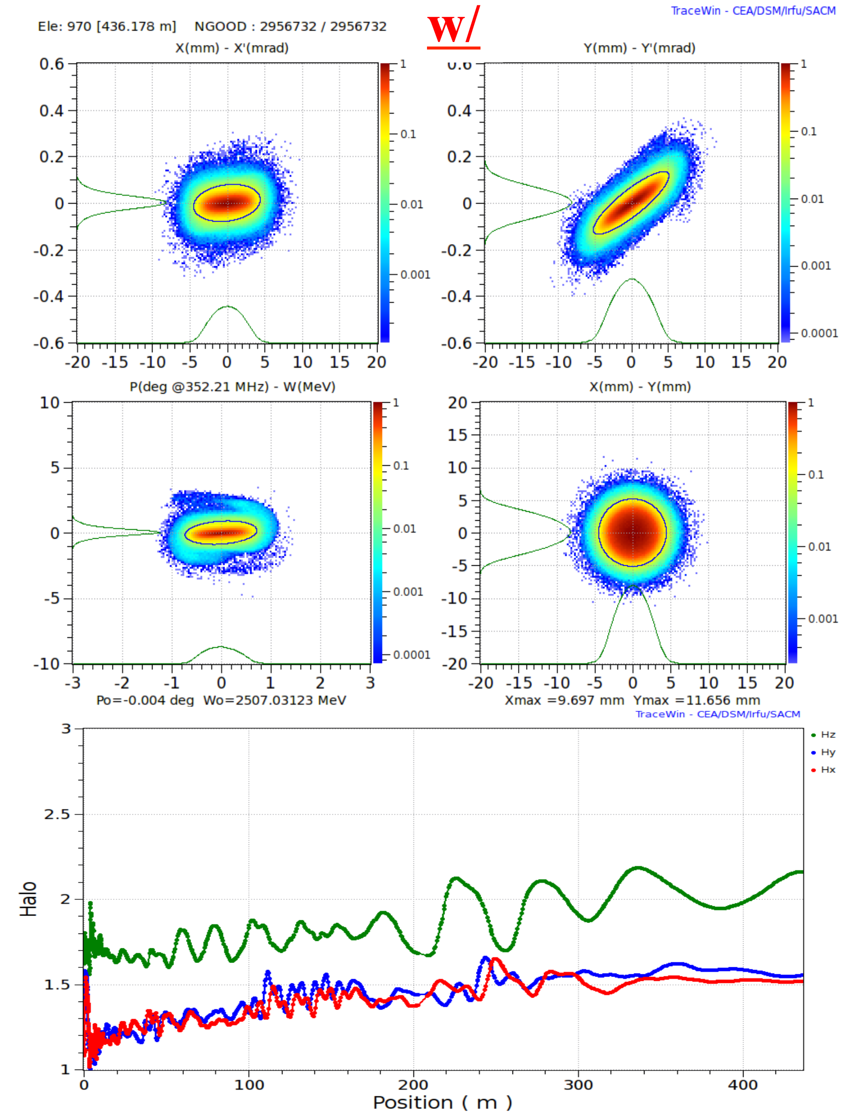


w/



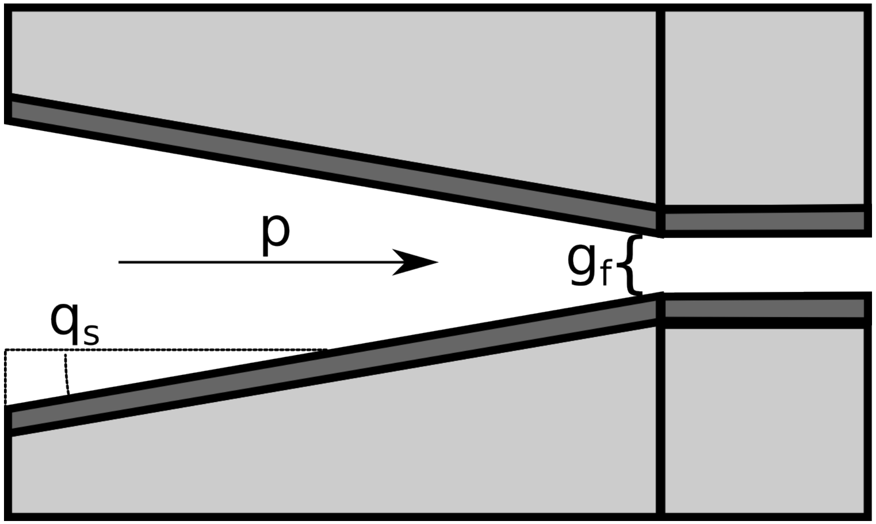
Distribution out of the linac and halos w/ and w/o collimators





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

Collimator Before Target Region



SS316 + concrete?

- Fixed collimator
- Partly masks PBW and target
- To handle halo & over-focussed particles (octupoles).
- Could be 5-25 kW (avg.)
- Built to handle a full pulse (360 kJ)?
  - MPS: beam off in <0.4% pulse!

Sketch:

To be designed by NCBJ, Świerk, Poland