Comparison of longitudinal emittance of various RFQs

- RFQs selection and comparison method
- Main parameters and formulas
- Comparison results and analysis
- Example of TRASCO RFQ re-design
- Conclusion
- References
- Acknowledgments

M. Comunian

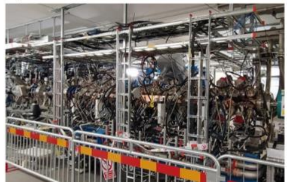
Why the RFQ comparison ?

- The longitudinal emittance formation process is not fully understood.
- The design choices are fundamentally different.
- Is possible to considered a RFQ design evolution ?
- How is it possible to design a small longitudinal emittance RFQ to be compliant with a small longitudinal LINAC acceptance.

RFQs selected

RFQ	IFMIF	ESS	SPES	SPIRAL2	TRASCO
Beam (Q/A)	Deuteron (1/2)	Proton (1)	Ions (1/7)	Ions (1/3)	Proton (1)
Current [mA]	130	62.5	0.1	1	30
Final Energy [MeV/u]	2.5	3.6	0.727	0.75	5
Input Tr. rms Emittance [N.mmmrad]	0.25	0.25	0.1	0.4	0.2
Length [m] (L/λ)	9.8 (5.7)	4.6 (5.4)	6.95 (1.9)	5.077 (1.5)	7.13 (8.3)
Frequency [MHz]	175	352.21	80	88.05	352.21
Measured Transmission [%]	90 - 92	95 - 96	-	99 - 100	-
Duty Cycle	CW	4%	CW	CW	CW
Reference	[2]	[5]	[3]	[4]	[1]

- 4-Vanes
- Already built
- High d.c.


Comparison method

- Toutatis code (https://www.dacm-logiciels.fr/)
- Matched input conditions, with Gaussian 3σ as input distribution.
- Longitudinal cut to eliminate the not accelerated particles (0.2 MeV)
- 20 steps per period
- 100 000 macroparticles
- Nominal RFQ, without any mechanical or voltage error considered.
- Plots obtained directly from the input/output files

RFQ main formulas

$$\sigma_L{}^2 = -\frac{\pi^2}{2}\frac{qA_{10}V}{W_s}\sin(\phi_s)$$

$$\sigma_T{}^2 = \frac{B^2}{8\pi^2} - \frac{1}{2}\sigma_L{}^2$$

$$B = \frac{q}{M}\frac{V}{R_0{}^2}\frac{1}{f^2}$$

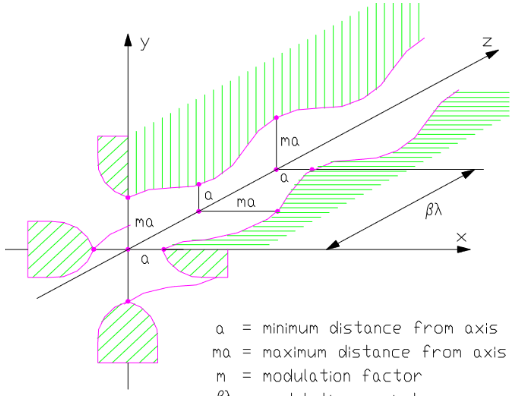
$$A_{10} = \frac{m^2-1}{m^2 I_0(ka) + I_0(mka)}$$

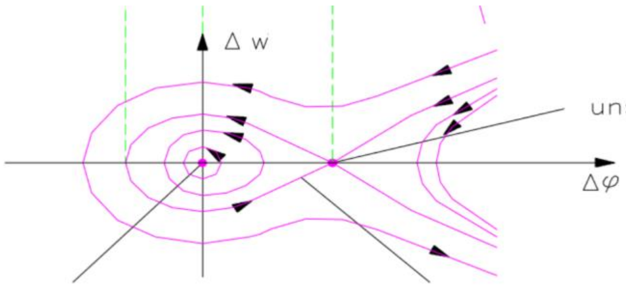
$$k = \frac{2\pi}{\beta\lambda} = \frac{\pi}{L_c}$$

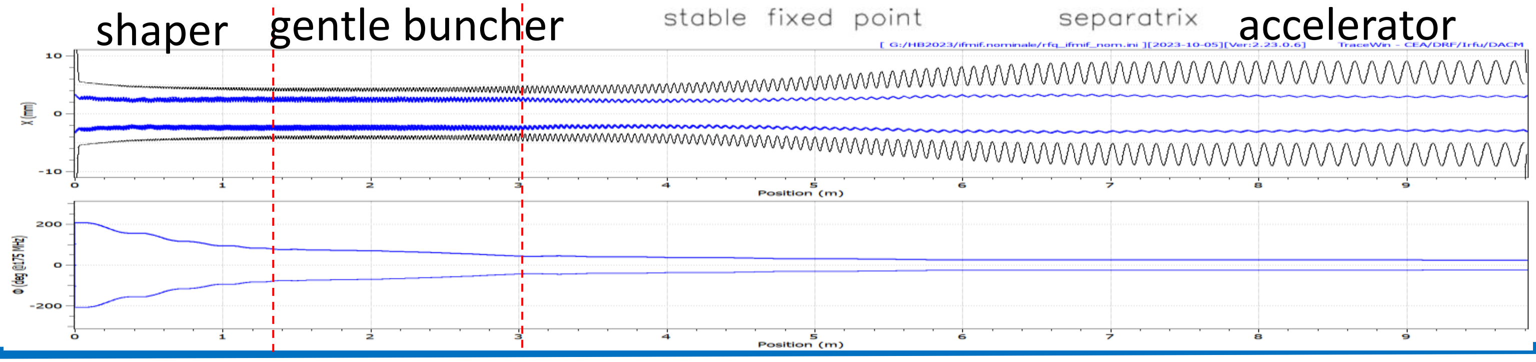
$$S = W_s\frac{\sigma_L}{2}\Psi(\phi_s)\sqrt{1-\frac{\phi_s}{\tan(\phi_s)}}$$

$$\tan(\phi_s) = \frac{\sin(\Psi(\phi_s)) - \Psi(\phi_s)}{1-\cos(\Psi(\phi_s))}$$

$$\Psi(\phi_s) \approx -3\phi_s + 0.27\phi_s{}^3 - 0.252347\phi_s{}^5$$







$\phi_s \rightarrow$ Synchronous Phase

$V \rightarrow$ Voltage

$W_s \rightarrow$ Synchronous Energy

q $\rightarrow$ Charge

$f \rightarrow$ Frequency

$L_c \rightarrow$ Cell Length

$\lambda \rightarrow$ Wavelength

$m \rightarrow$ modulation

$a \rightarrow$ minimal aperture

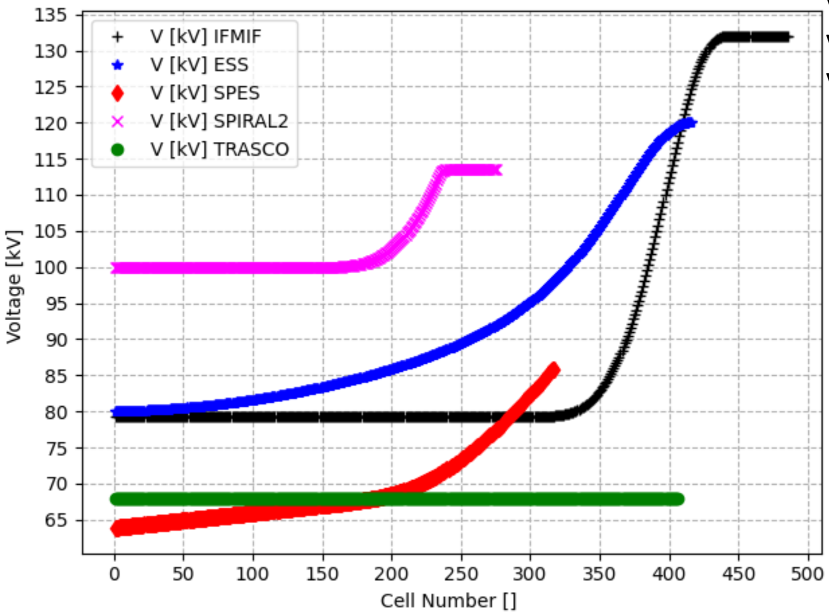
$R_0 \rightarrow$ Average aperture

$S \rightarrow$ Separatrix area

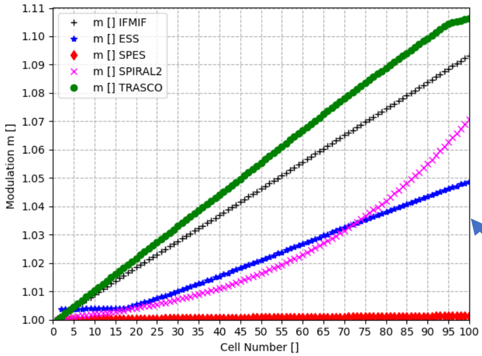
$A_N \rightarrow$ Transverse acceptance

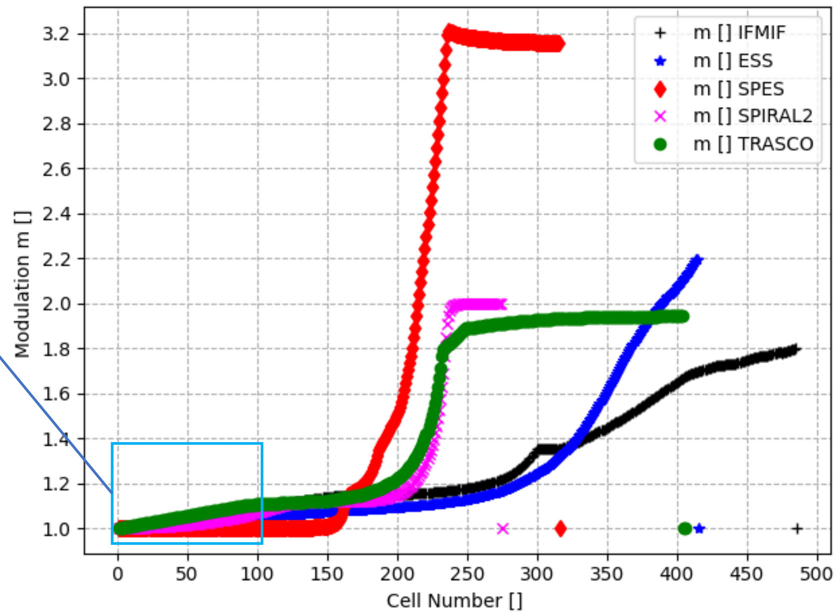
$\Psi(\phi_s) \rightarrow$ Separatrix Phase amplitude

Voltage, Modulation, Focusing Force and A10 along the RFQs

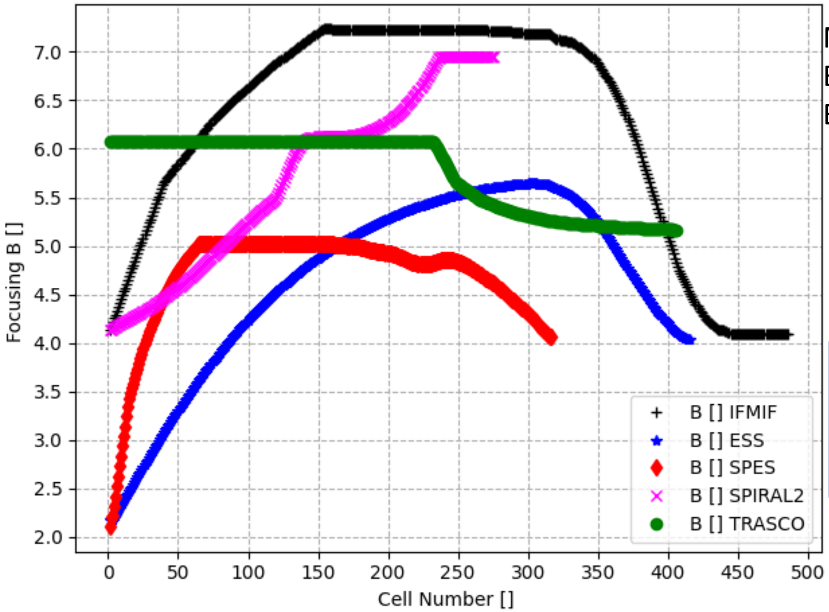


V is constant on TRASCO
V is linear with z on SPES
V shape nonlinear for SPIRAL2, ESS, IFMIF



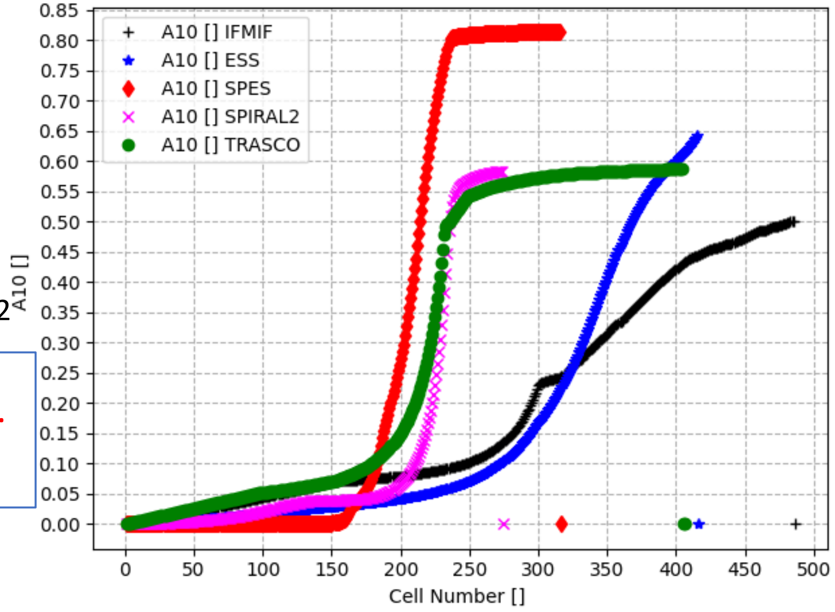


Max m of 3.2 for SPES, with very rapid change, min m of IFMIF
Linear change of m, but SPIRAL2, m=1 constant for SPES on the first 100 cells



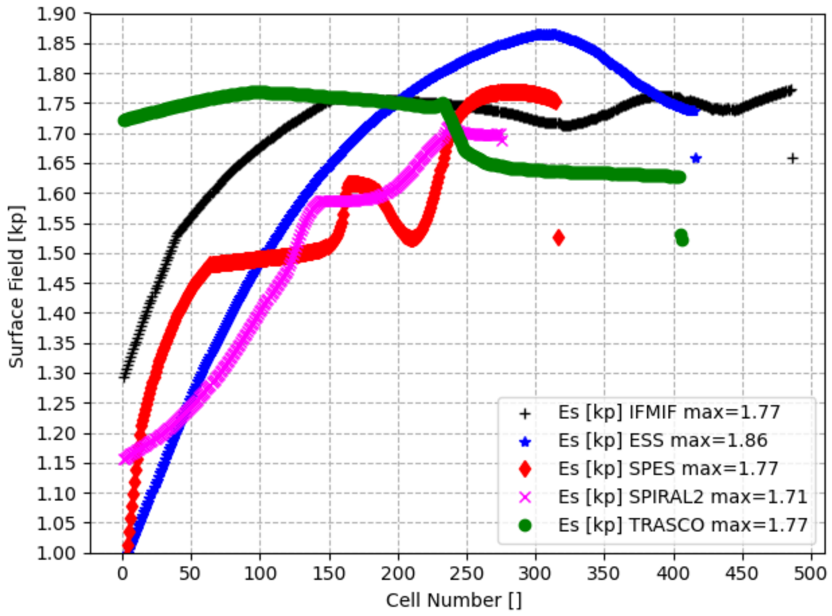
Max B on IFMIF, due the high current.
B decreased at end, but SPIRAL2.
B decreased at begin, but TRASCO.

Largest acceleration on SPES, min on IFMIF, linear change on the first 100 cells, but SPIRAL2



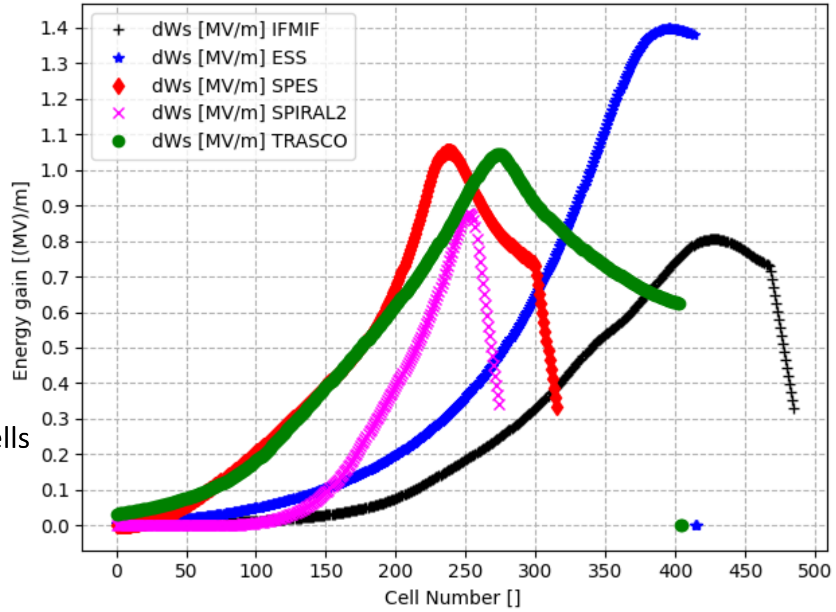
- **With a ramped V(z) the efficiency is improved.**
- **The law for m(z) in the shaper does not influence the efficiency.**
- **Modulation can be bigger than 2 in the Accelerator.**
- **Not smooth B does not influence the efficiency.**

Surface Field, Energy gain, R0, Energy along the RFQs

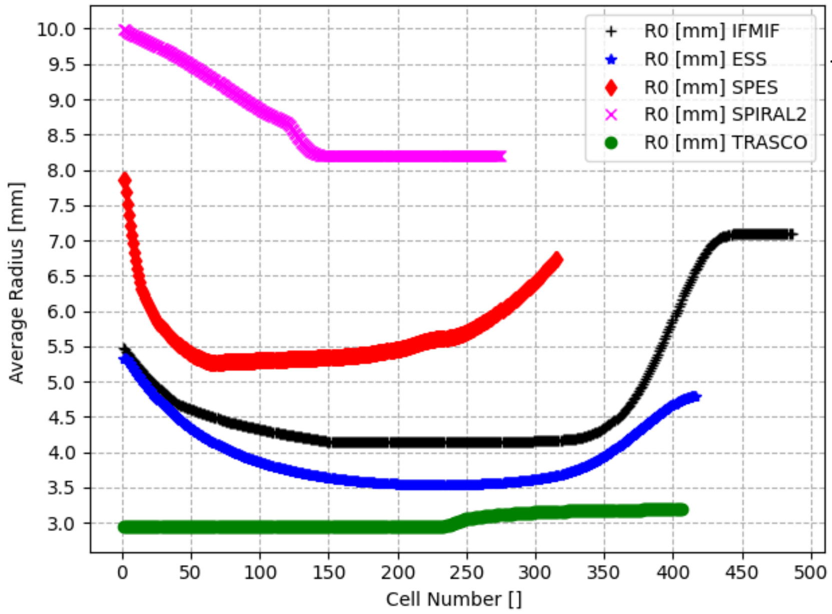


Es always below 1.8,
but ESS, which is 4% max d.c.

- Es <1.8 for CW, Es<1.9 for pulsed
- Large R0 for large transmission
- For Energy gain/m is more efficient V vs m
- Do not increase energy in the shaper

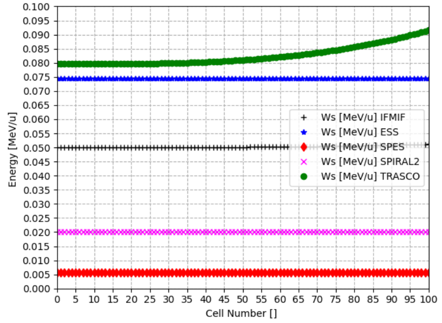


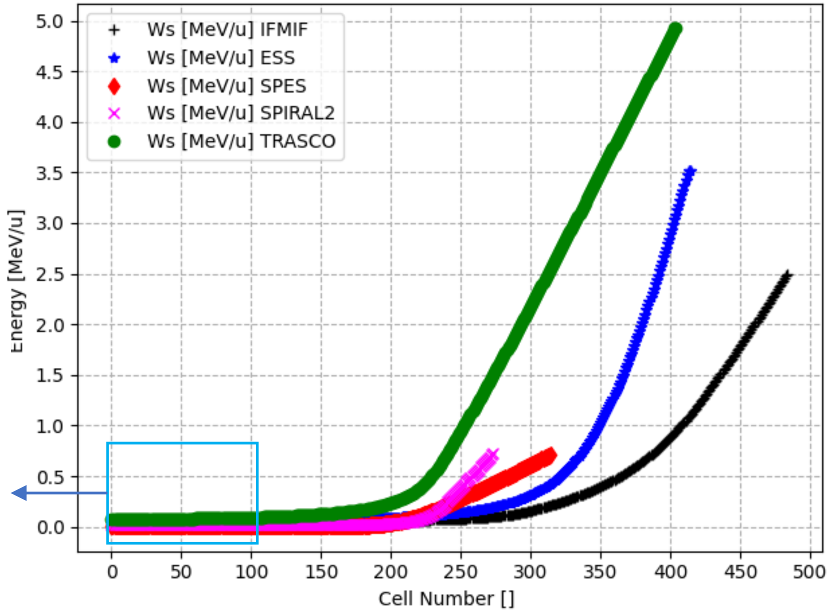
Max energy gain/m on ESS,
Min on IFMIF, in the few last cells
is reduced a lot.



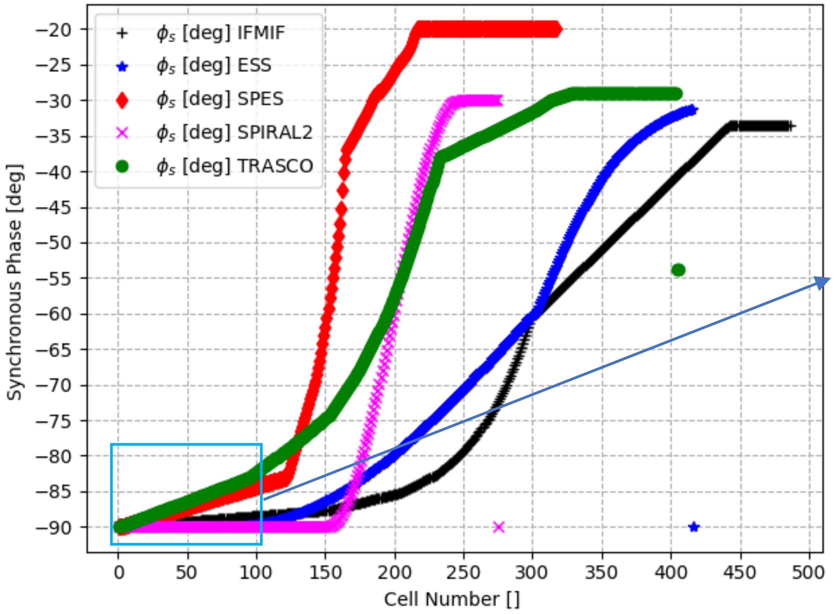
Max aperture on SPIRAL2,
for handle larger emittance.
Min on TRASCO.

Linear change on energy vs cells on
TRASCO and ESS. No energy increase
on the first 100 cells

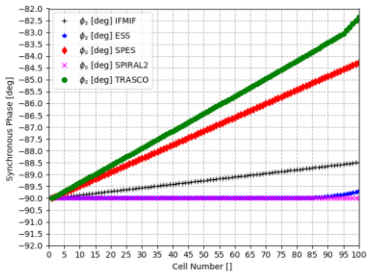


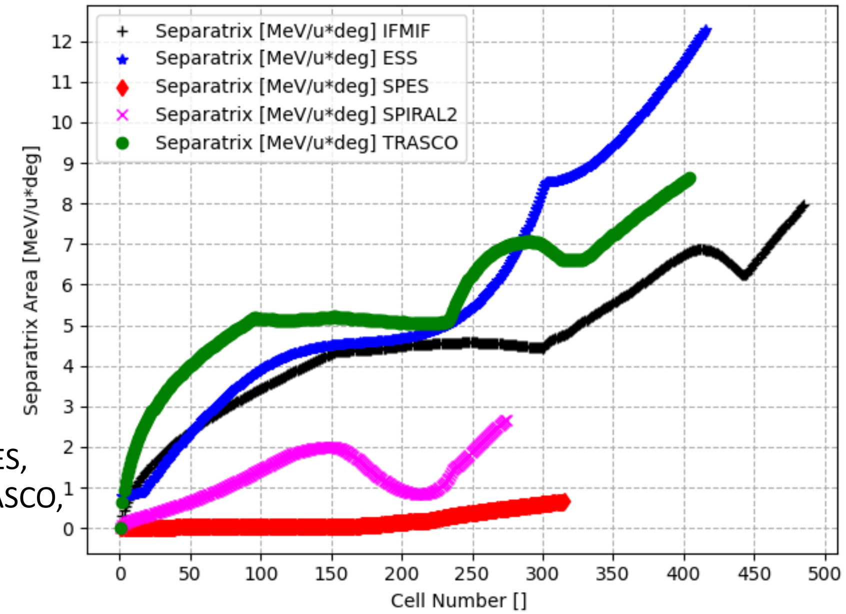


Phase, Separatrix, Phase advance at zero current along the RFQs

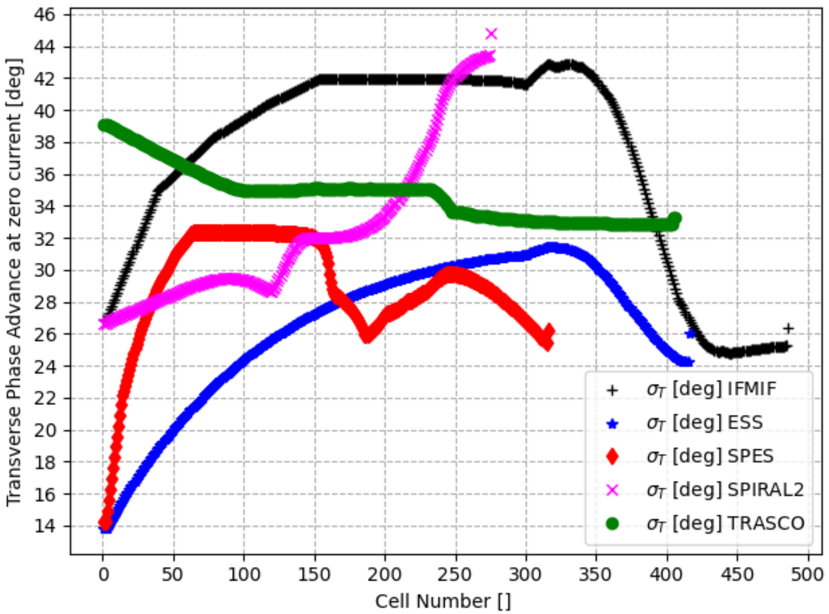


Linear change on the first 100 cells on TRASCO,IFMIF,SPES
Phase=-90° on SPIRAL2,ESS on first 100 cells.





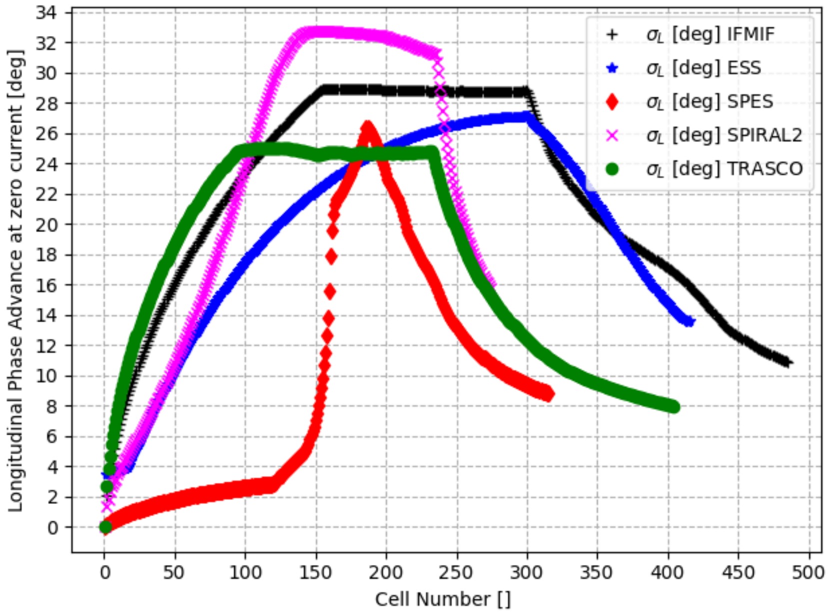
Small Separatrix on SPES, SPIRAL2, larger on TRASCO, ESS.



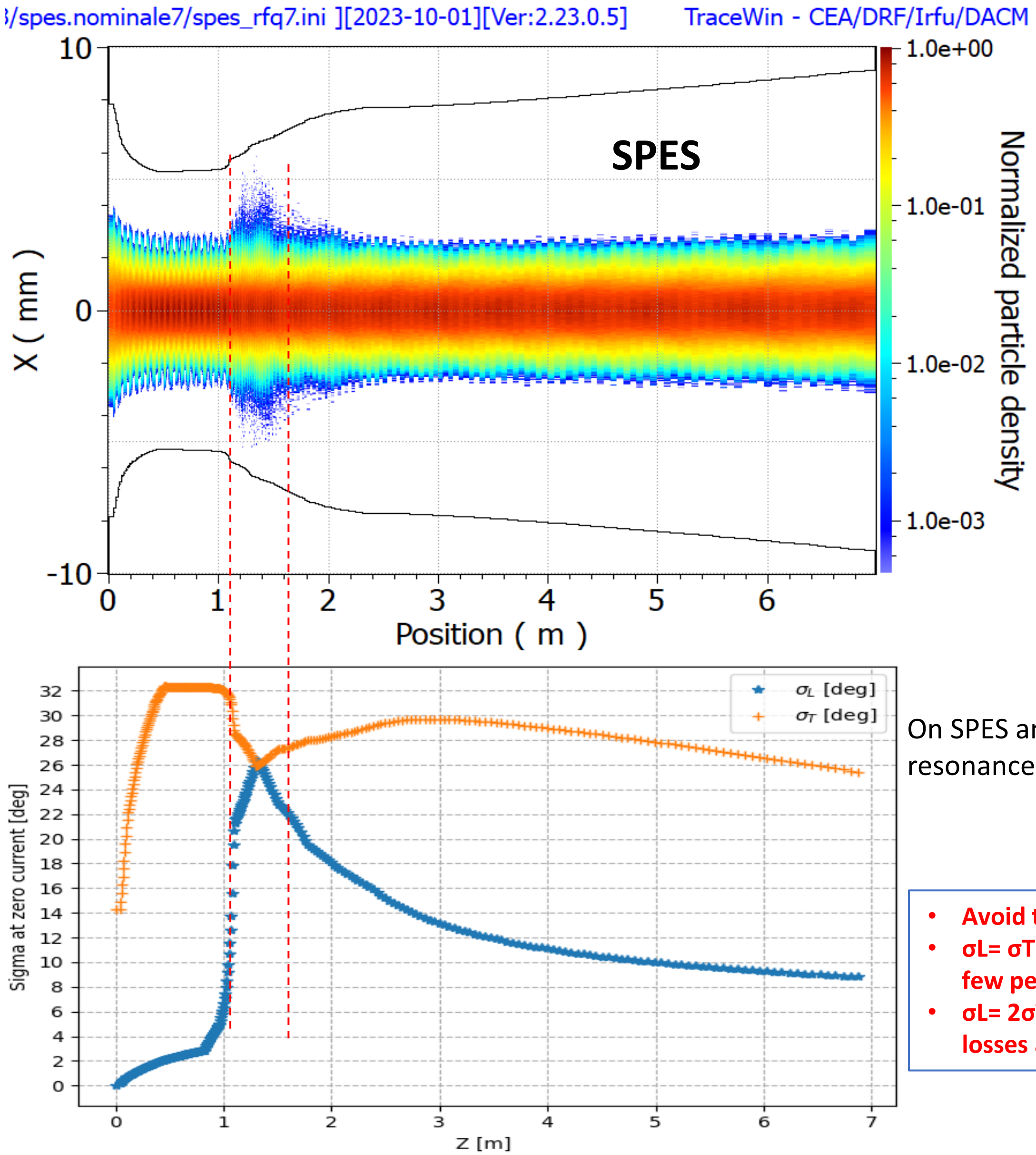
σT Decrease on TRASCO, small and smooth on ESS.

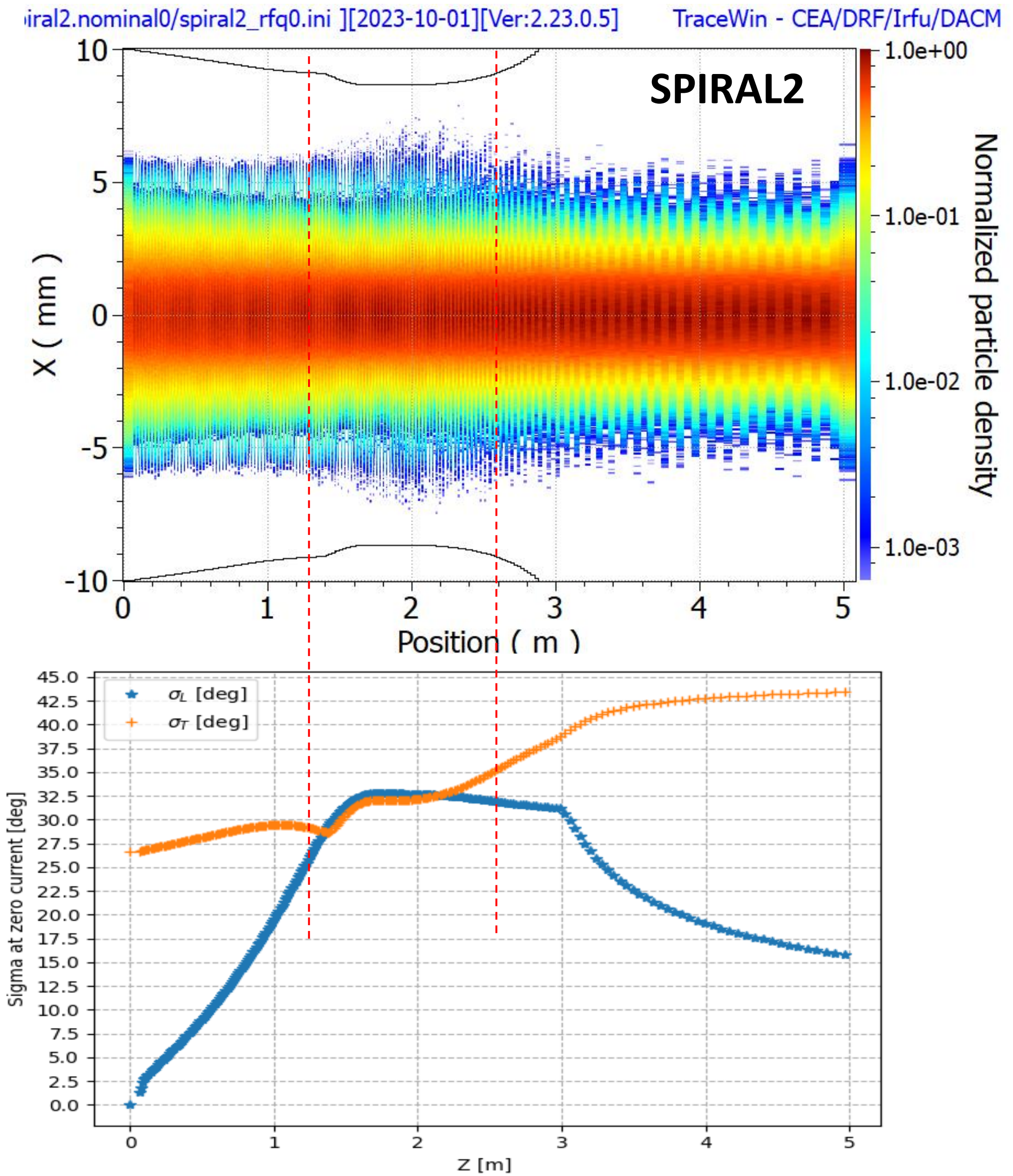
σL Rapid increase on SPES and SPIRAL2, slow and smooth on ESS.

- **Different law for Phase in the shaper can be chosen.**
- **At the begin and end of RFQ decrease the σT, σL to better match the LEBT and MEBT.**
- **Not need to change smoothly σT, σL.**
- **Large Separatrix creates large Long. Emittance**



Parametric resonance along the RFQs at zero current

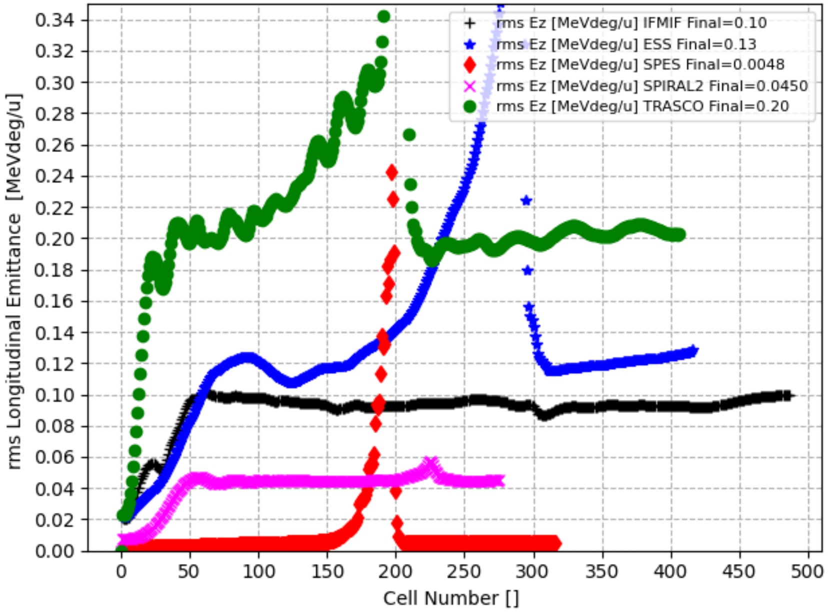




On SPES and SPIRAL2, the parametric resonance σT= σL is visible.

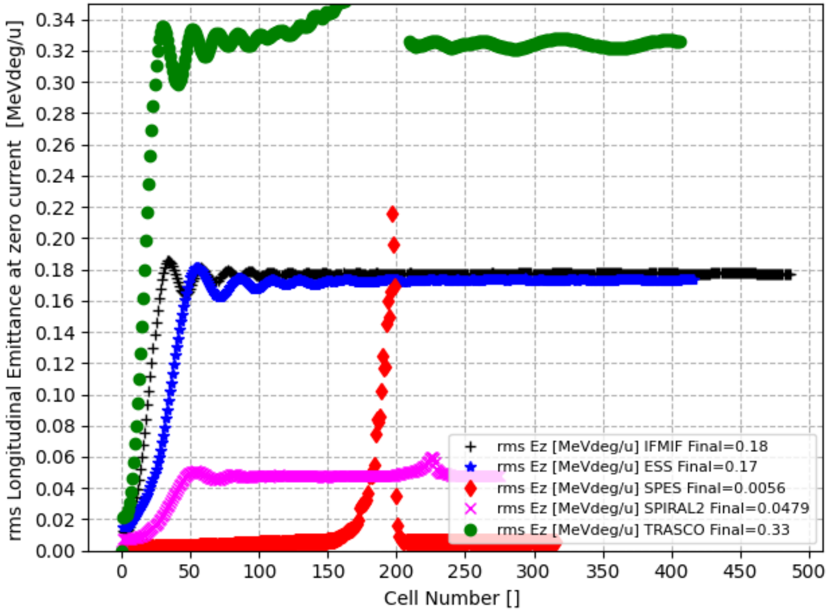
- **Avoid the parametric resonance.**
- **σL= σT not so dangerous, not losses in few periods.**
- **σL= 2σT Very dangerous, can lead losses also in few periods**

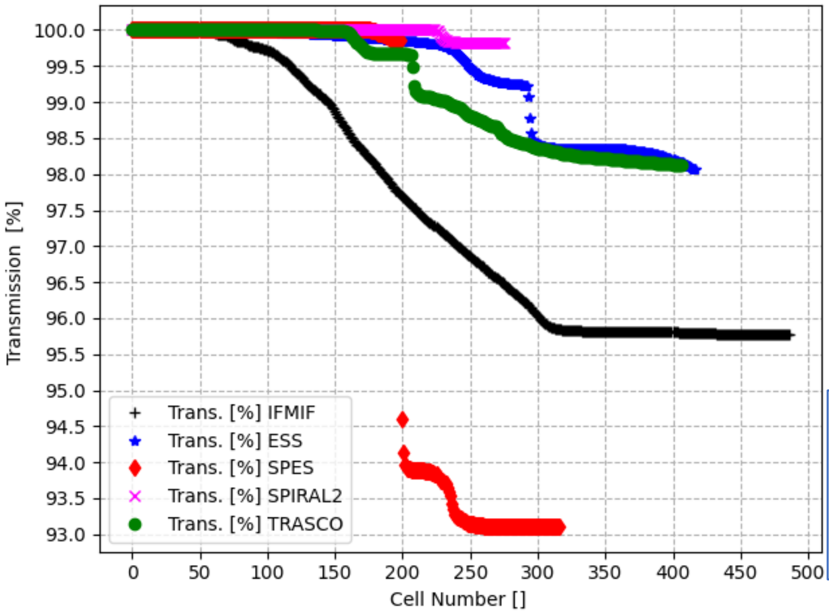
Longitudinal Emittance and Transmission along the RFQs



rms Ez similar for ESS,IFMIF,
Low for SPES,SPIRAL2,
High for TRASCO.
Elimit +/- 0.2MeV

At zero current: same rms Ez for ESS,IFMIF, low for SPES, SPIRAL2 and high for TRASCO.

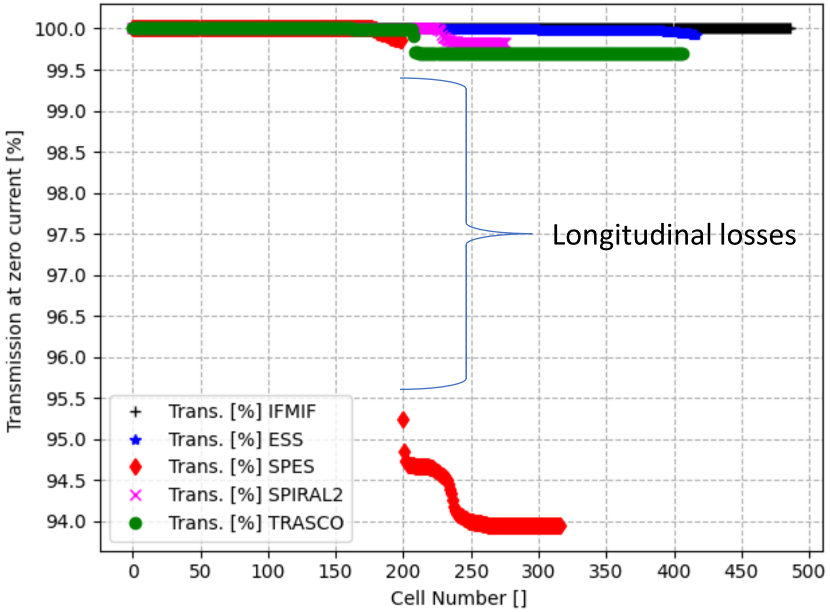




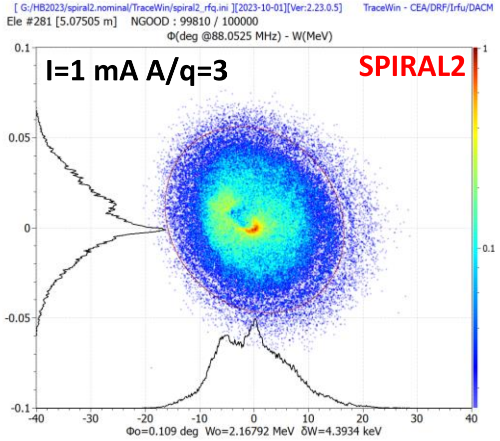
High transmission for SPIRAL2.
Similar for ESS,TRASCO.
Low for SPES,IFMIF.

At zero current: very high transmission for ESS, TRASCO, IFMIF,SPIRAL2, Low for SPES.

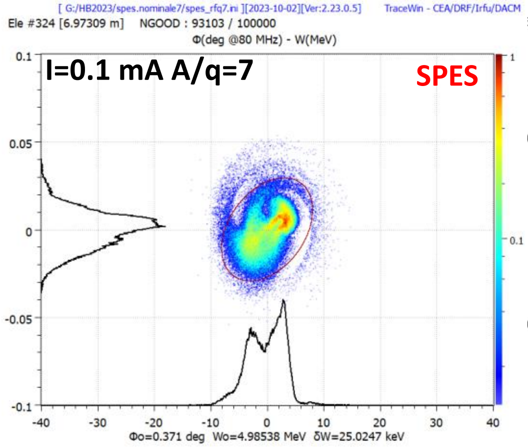
- **High current -> High Long. Emittance**
- **Low Long. Emittance at low current possible with long shaper**
- **At zero current higher long. Emittance for the RFQs designed for high current**



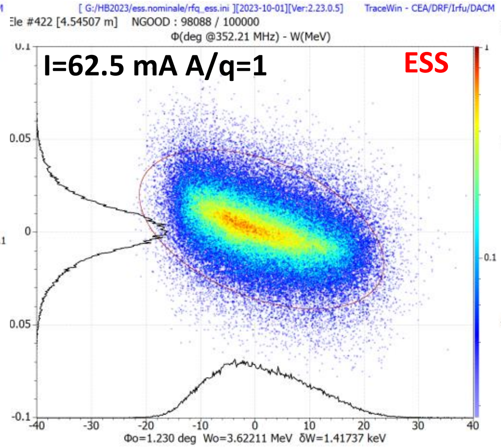
Full Current and zero current Longitudinal Phase Space at the RFQs end



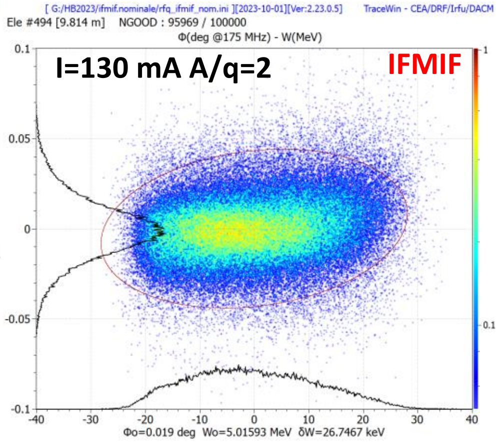
rms Ez=0.1351 MeVdeg
95% Ez=0.84 MeVdeg



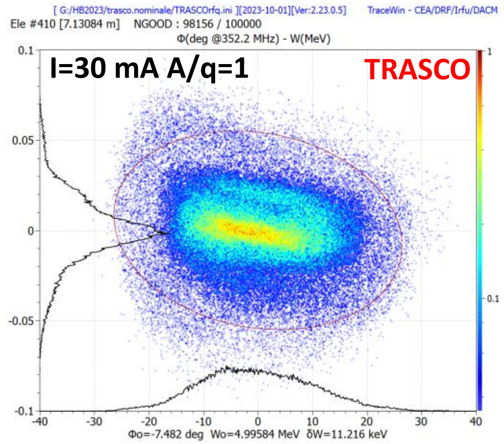
rms Ez=0.0336 MeVdeg
95% Ez=0.2195 MeVdeg



rms Ez=0.1287 MeVdeg
95% Ez=0.8678 MeVdeg

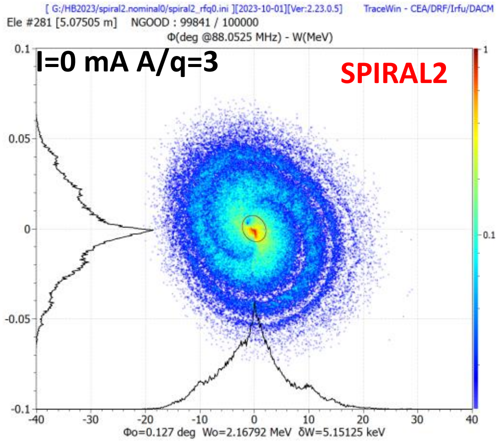


rms Ez=0.2017 MeVdeg
95% Ez=1.2175 MeVdeg

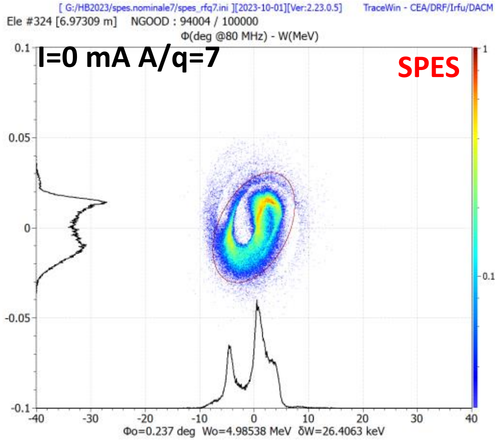


rms Ez=0.2024 MeVdeg
95% Ez=1.4379 MeVdeg

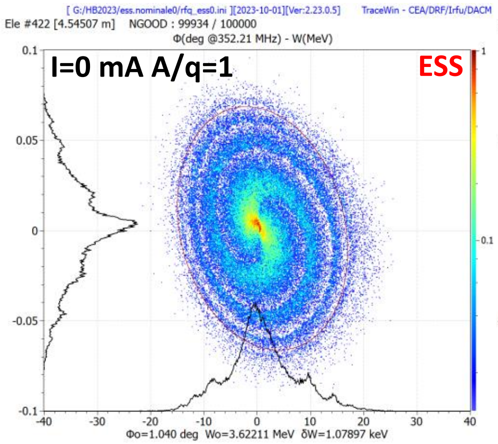
- At zero current higher long. Emittance for phase space filamentation



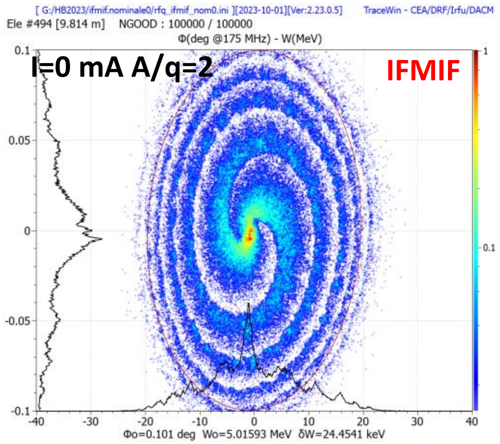
rms Ez=0.1428 MeVdeg
95% Ez=0.8575 MeVdeg



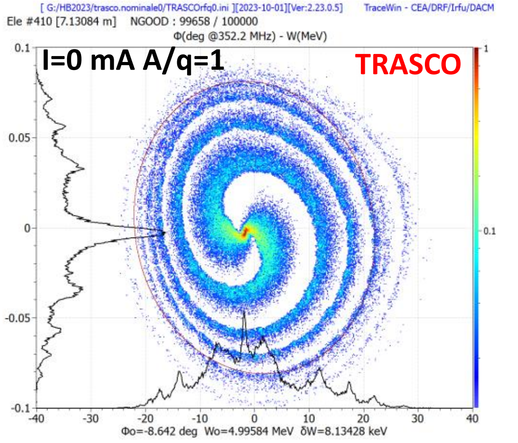
rms Ez=0.0391 MeVdeg
95% Ez=0.2113 MeVdeg



rms Ez=0.1735 MeVdeg
95% Ez=1.0589 MeVdeg

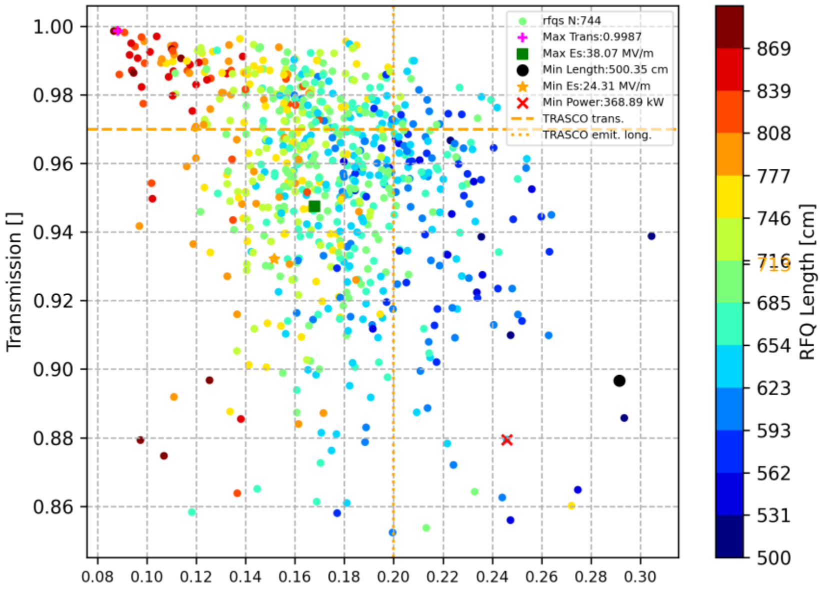


rms Ez=0.3532 MeVdeg
95% Ez=1.9553 MeVdeg



rms Ez=0.3250 MeVdeg
95% Ez=1.7864 MeVdeg

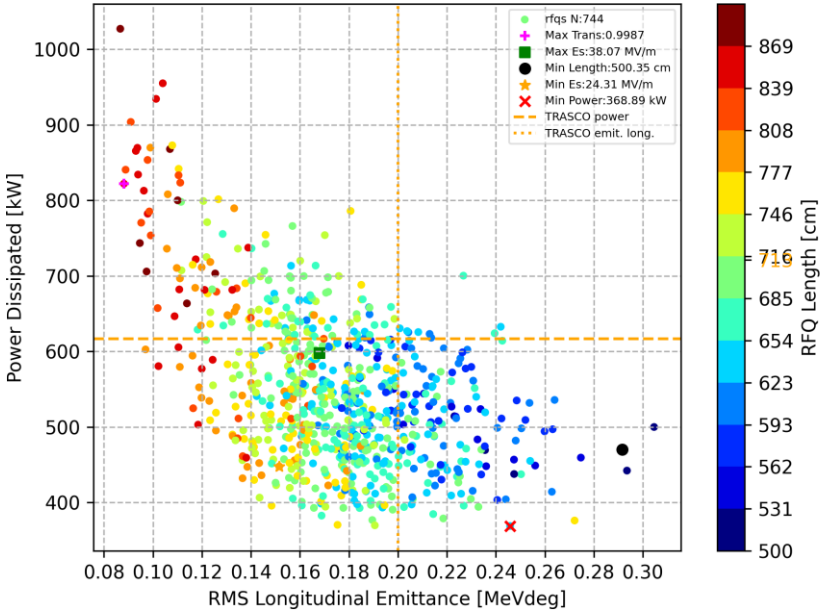
Example of TRASCO redesign: each dot is a full multiparticle simulation



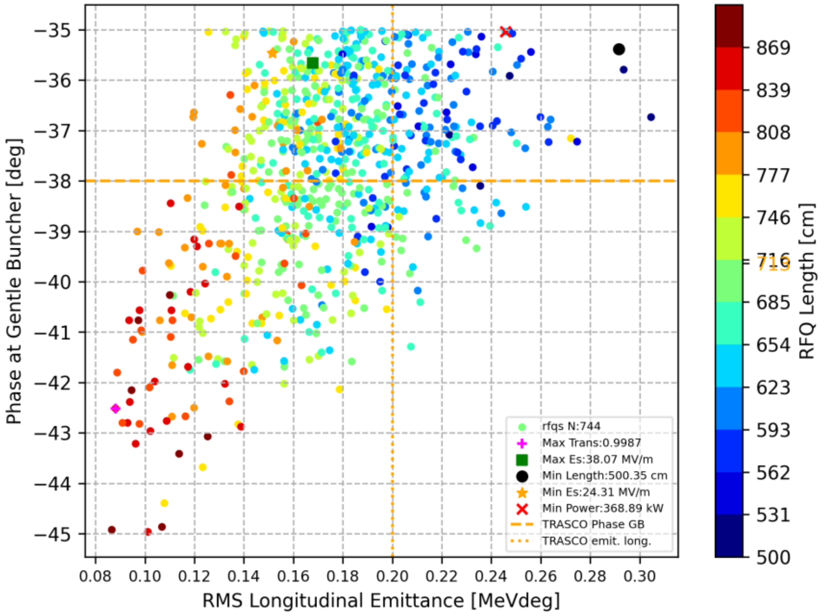
The method used for RFQs optimization is NSGA (https://pymoo.org/algorithms/moo/nsga2.html) with goals on minimum Power dissipated, maximum beam transmission and length.

No correlation of Ez with transmission

To reduce the Ez is necessary to increase the RF power dissipated

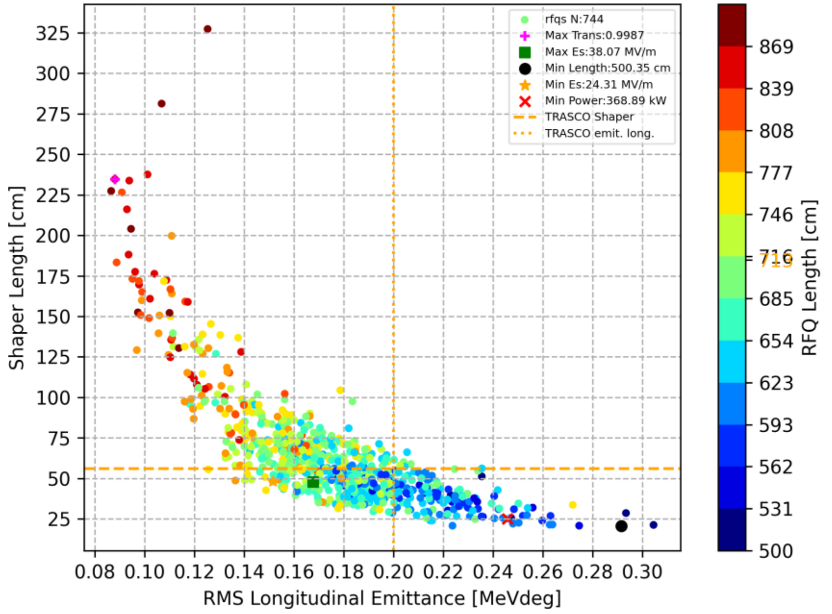


With the new algorithm is possible to improve the TRASCO RFQ design.
The RFQ power reduction can be in the order of 30%,
with shorter RFQ length (7.1 -> 6.9 m),
With same longitudinal emittance (0.2 MeVdeg)
and less surface field (1.77 -> 1.7kp).



To reduce the Ez is necessary to reduce the phase at Gentle Buncher

To reduce the Ez of a factor 2, The shaper length is increased of a factor 3.



Conclusion

- The simulations codes(*) can well define the beam dynamics inside any RFQs.
- The simulations codes has been compared with success with the experimental results, in terms of transmission and longitudinal emittance.
- There are no general common rules about how to do an RFQ design.
- In general way, the voltage can be ramped along the RFQ, like the modulation, R0 etc..
- The RFQ parameters must be carefully defined at the end of Gentle Buncher to get a good degree of longitudinal capture.
- A low longitudinal emittance can be obtained with a longer shaper; however, this will cost in increase the RFQ length and may decreases the transmission.
- Typically, a longitudinal emittance formation is done on about 50 RFQ cells. For getting a very low longitudinal emittance in SPES RFQ the number of cells used is about 100.

(*) TraceWin/Toutatis and PARI/PARTEQM

Reference

[1] M. Comunian et al. “TRASCO RFQ DESIGN”, THP6B13, EPAC2000.

[2] M. Comunian et al. “BEAM DYNAMICS REDESIGN OF IFMIF-EVEDA RFQ FOR A LARGER INPUT BEAM ACCEPTANCE”, MOPS031, IPAC2011.

[3] M. Comunian et al. “THE NEW RFQ AS RIB INJECTOR OF THE ALPI LINAC”, THPWO023, IPAC2013.

[4] R. Ferdinand et al. “SPIRAL 2 RFQ DESIGN”, WEPLT076, EPAC2004.

[5] A. Ponton “THE ESS RFQ BEAM DYNAMICS DESIGN”, THPB029, LINAC2012.

ACKNOWLEDGEMENTS

Thank you very much at Mamad Eshraqi, Aurelien Ponton,
Robin Ferdinand, Normand Guillaume, for the RFQ inputs files of ESS and SPIRAL2.