Present Status of the R&D of the Superconducting Linac for the JAEA-ADS

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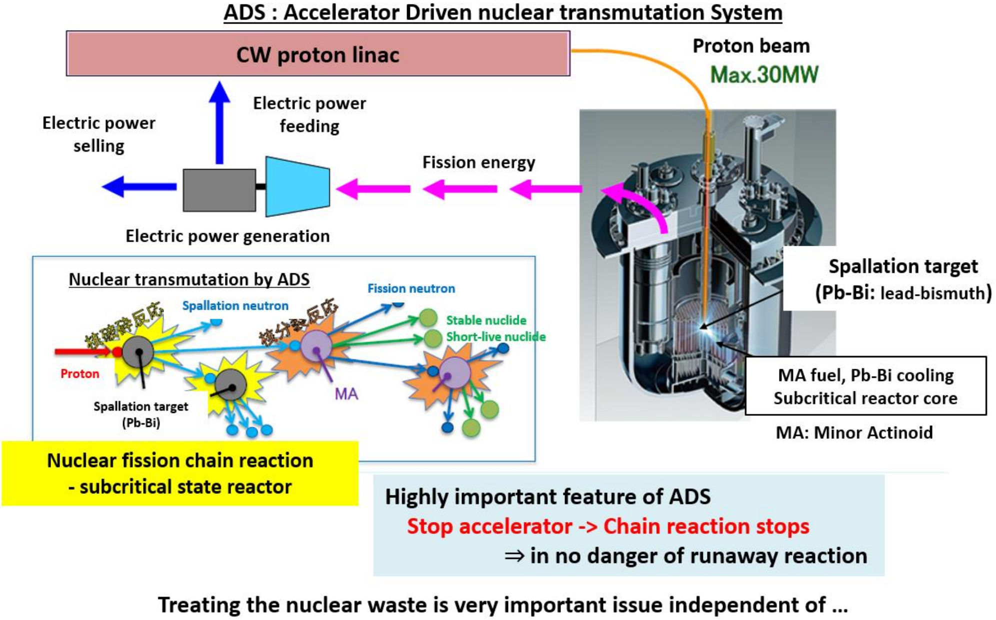
Contents

- Introduction
- Superconducting Radio Frequency Cavity (SRFC) models
  - Low beta cavities (Half-Wave Resonator (HWR) & Single Spoke (SS))
  - High beta (Elliptical cavity (Ellip))
  - SRFC EM models summary
- Prototyping SRFC
- Beam optics
  - Lattice design
  - Emittance growth study
  - Beam optics summary

Introduction

JAEA is proposing and Accelerator Driven Subcritical System (ADS).

The ADS designed by JAEA will consist of a 30 MW superconducting CW proton linac and a subcritical reactor core.



Requirements of the linac:

- <u>High beam power</u> (~ MW)
- <u>High reliability</u> (lower beam trip)

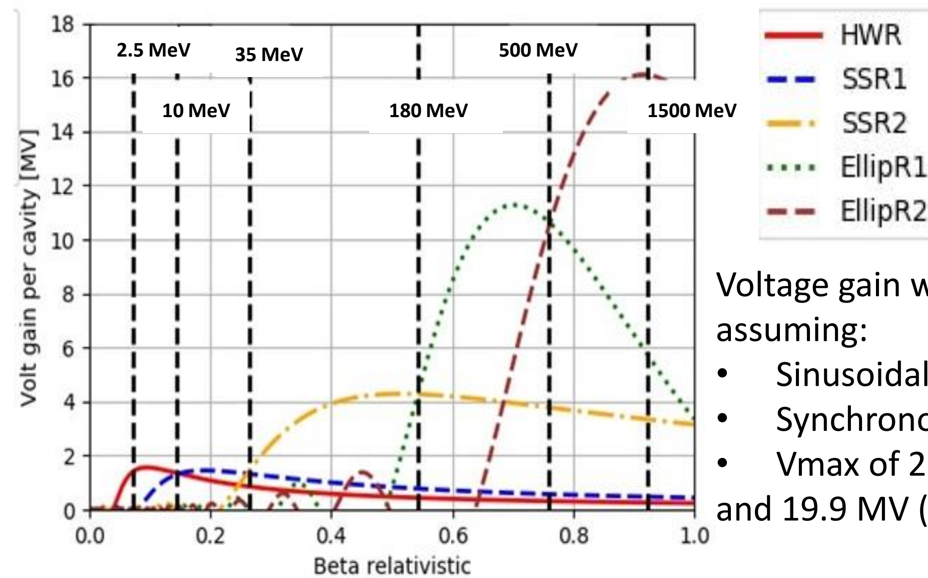
The goal is to design a **CW Superconducting proton linac** with a beam current of **20 mA** and a final energy of **1.5 GeV** with a **low beam loss**.

To achieve that goal two main tasks were developed: *<u>Cavity design</u>* and *<u>Beam optics studies</u>*.

SRFC baseline

SRF cavity start point model		
Cavity type	Freq [MHz]	# of Cell
HWR	162	2
SS	324	2
Elliptical	648	5

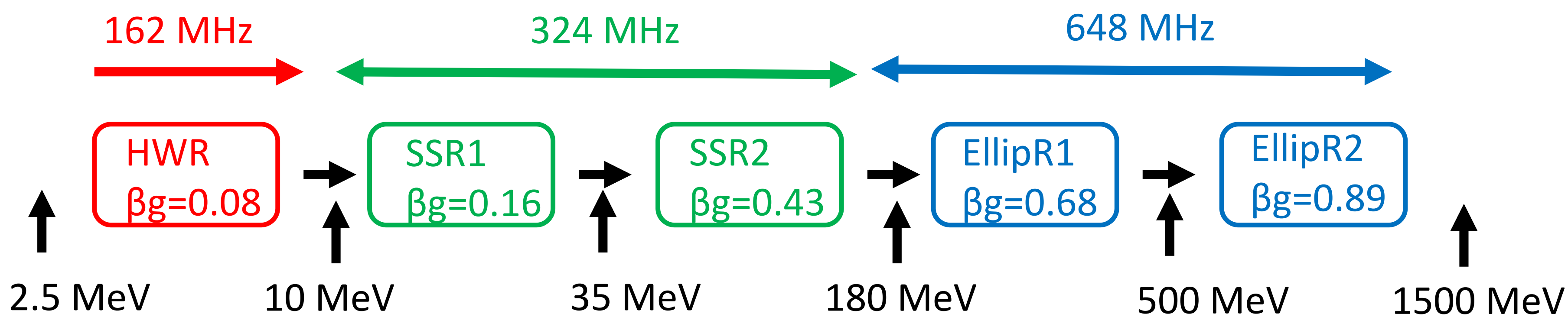
The optimization in the numbers of cavities and β_g were chosen to obtain maximum voltage gain per cavity + smooth transition



Voltage gain was computed assuming:

- Sinusoidal E fields
- Synchronous phase of -30°
- Vmax of 2.0,2.05,4.987,11.9 and 19.9 MV (values of PIP-II)

JAEA-ADS superconducting linac layout

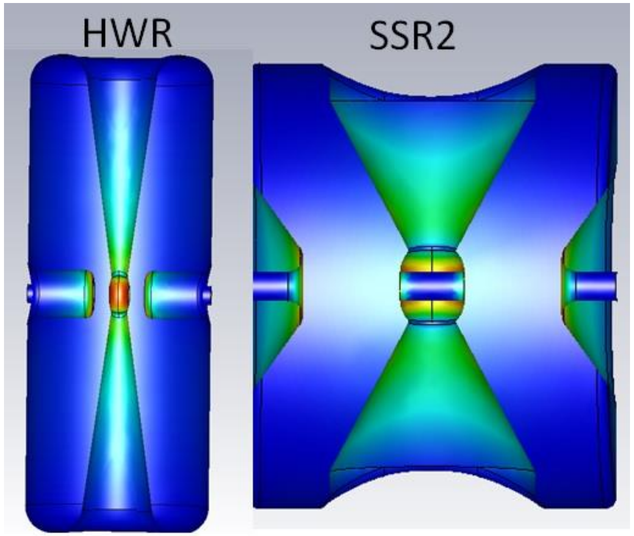


Low beta summary

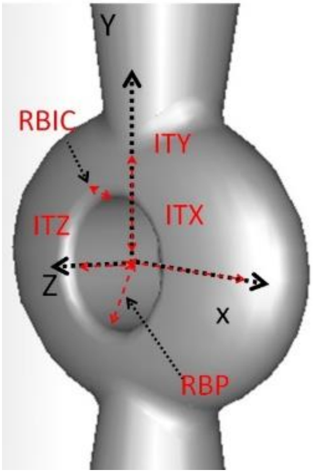
Design goals

- Lower Epk/Eacc & Bpk/Eacc (avoid electric breakdown, quench, etc.)
- Lower power dissipation (high value of R/Q and G)

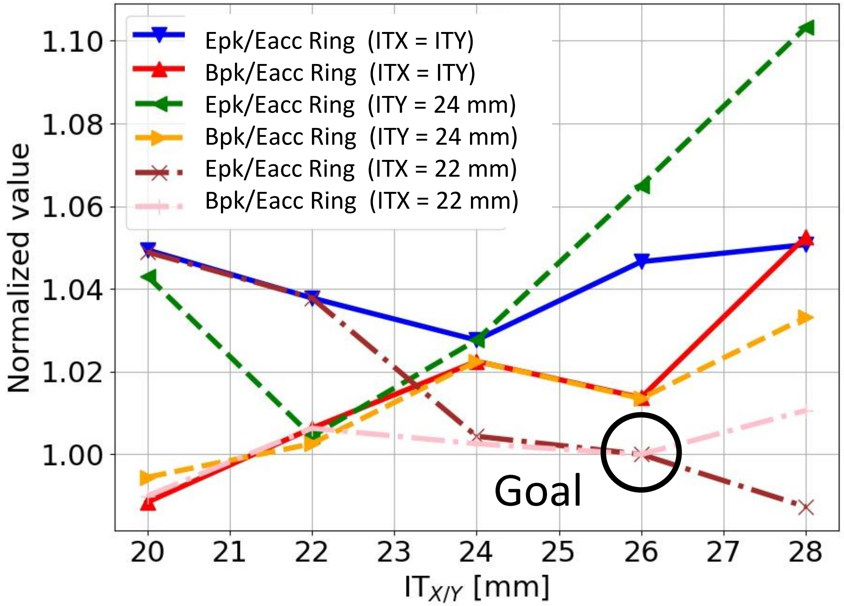
JAEA-ADS low beta Cavity Parameters			
Cavity type	Freq [MHz]	βg	Energy range [MeV]
HWR	162	0.08	2.5-10
SSR1	324	0.16	10-35
SSR2	324	0.43	35-180



HWR & SSR Electric field surfaces



Inner center conductor geometry



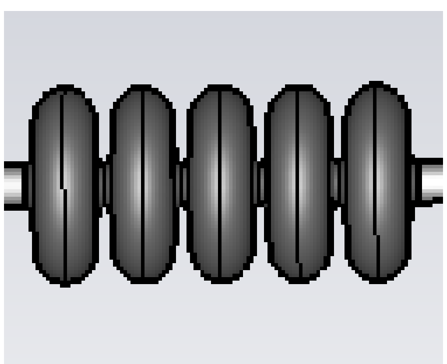
The values of Bpk/Eacc and Epk/Eacc as a function the transverse dimensions of the inner conductor shape.

[1] A. Facco "Tutorial on LOW BETA CAVITY DESING"
[2] G. Tae Park et al "ELECTROMAGNETIC DESING OF HALF WAVE RESONATOR WITH B=0.13, F=325MHZ FOR FUTURE HIGH POWER AND HIGH INTENSITY PROTON DRIVER KEK"

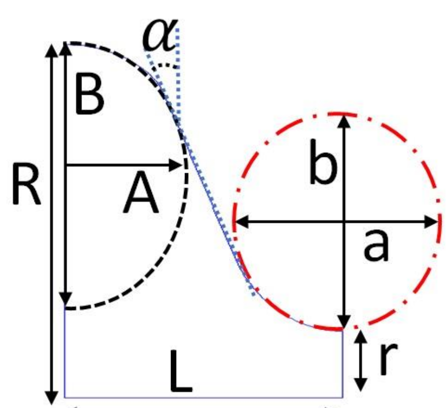
High beta summary

- Design goals
  - Lower electromagnetic peaks ratios:
    - Epk/Eacc < 2.60 & Bpk/Eacc < 4.6 mT/MV/m
  - Lower power dissipation (high value of R/Q and G)

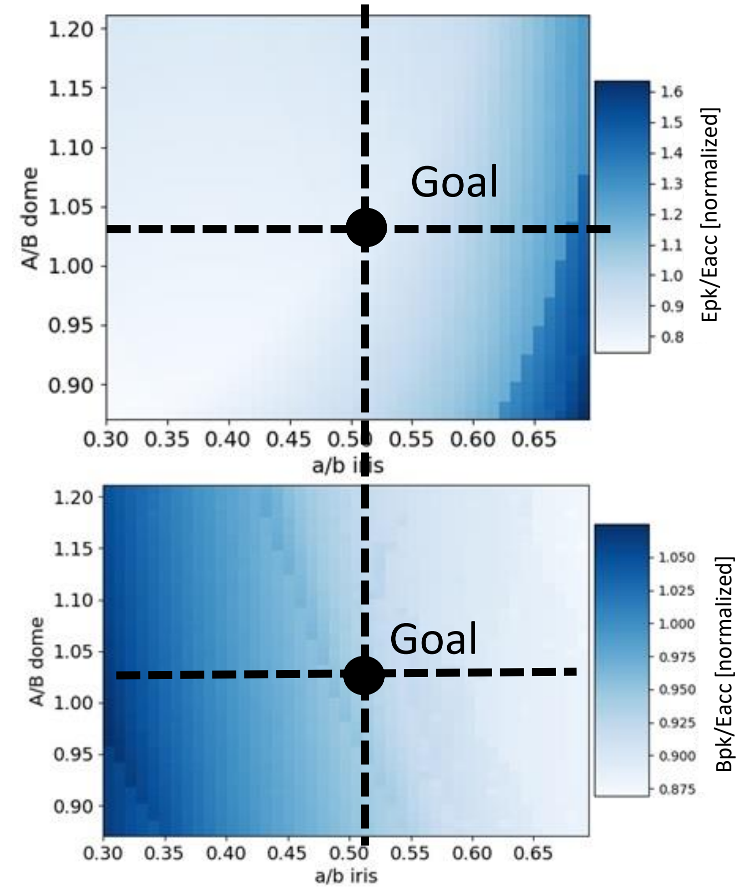
JAEA-ADS high beta (Elliptical) cavity Parameters			
Cavity Section	Freq [MHz]	βg	Energy range [GeV]
EllipR1	648	0.68	0.18-.050
EllipR2	648	0.89	0.5-1.5



5-cell elliptical cavity



Half cell parametrization geometry



The surface plot by changing the iris and the dome ratio to select the parameters to minimize the Epk/Eacc (top) and Bpk/Eacc (bottom).

SRFC summary

- The first EM design of the JAEA-ADS SRFC were developed [1,2], this is an important advance for several reasons:
  - SRFC is a key ingredient for the JAEA-ADS project (and necessary to design the beam optics)
  - The continuity & boost of the superconducting linac R&D in JAEA .
- The models present an efficient performance in terms of the figures of merits and their values are close with the ones obtained by similar projects (PIP-II and C-ADS).

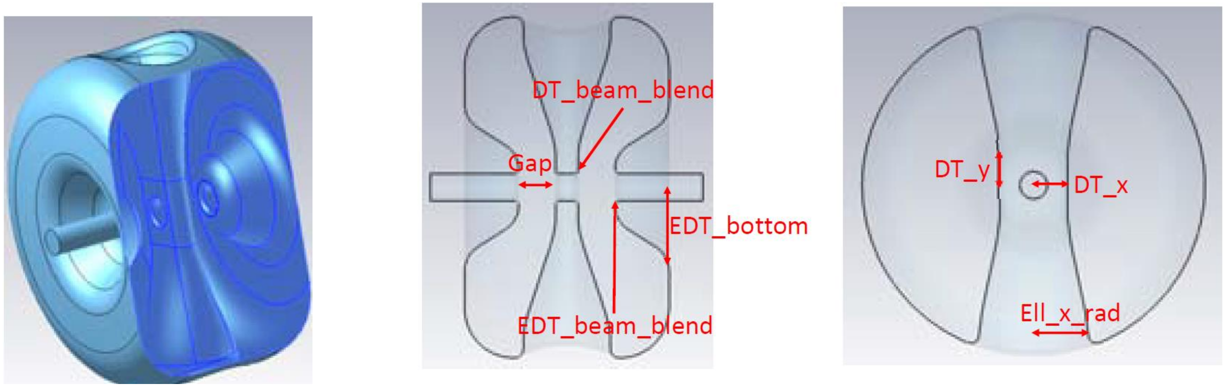
Parameters	HWR	SSR1	SSR2	EllipR1	EllipR2
Freq [MHz]	162	324	324	648	648
βg	0.08	0.16	0.43	0.68	0.89
Epk/Eacc	4.21	4.7	3.55	2.17	2.11
Bpk/Eacc [mT/MV/m]	3.41	6.68	5.13	4.22	4.07
R/Q [Ω]	285.39	212.72	285.80	443.22	619.73
G [Ω]	59.15	64.78	129.20	208.82	256.17

[1] B. Yee-Rendon, et al, "Electromagnetic design of the low beta cavities for the JAEA ADS", J. Phys.: Conf. Ser. Accepted (2019).
[2] B. Yee-Rendon, et al, "Design of the elliptical superconducting cavities for the JAEA ADS", J. Phys.: Conf. Ser. Accepted (2019).

Prototyping SRFC

The prototyping a low-beta single spoke resonator (SSR1) is under develop as the first step toward the detailed design of the JAEA-ADS linac [1,2].

Parameters	Value
Freq [MHz]	324
β_g	0.2



Design mode of the SSR1 with constraint.

[1] J. Tamura *et al.*, "ELECTROMAGNETIC DESIGN OF THE PROTOTYPE SPOKE CAVITY FOR THE JAEA-ADS LINAC", SRF2019, Dresden, Germany, TUP007 (2019).
[2] J. Tamura *et al.*, "RF Design of the Prototype Spoke Cavity for the JAEA-ADS Linac", The 3rd J-PARC Symposium (J-PARC2019), Tsukuba, Japan (2019).

Beam optics

- The ADS requires an excellent control in the beam loss, the main source of the beam halo, and emittance growth has a strong correlation with the beam halo.

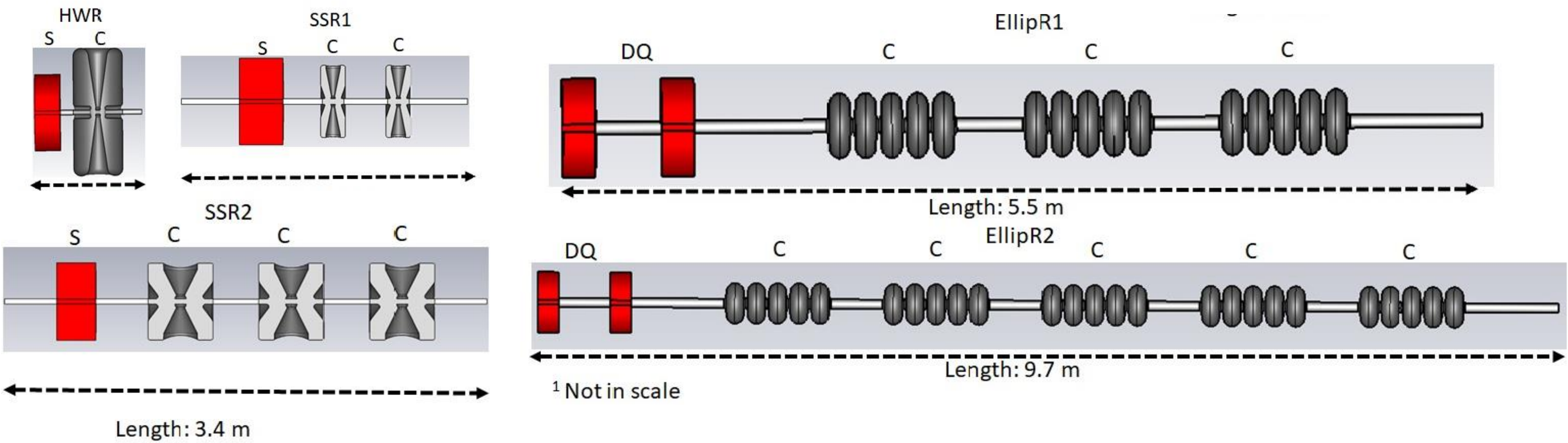
- To control the emittance growth, the next conditions are applied:
  - The phase advance ($k_{x/y/z}$) < 90^{o} to avoid parametric resonances
  - The beam should satisfy the equipartition condition ($\frac{T_{x/y}}{T_z} = \frac{k_{x/y}\varepsilon_{nx/y}}{k_z\varepsilon_{nz}} = 1$) to avoid emittance exchange between the transverse and longitudinal planes
  - Smooth envelope (an excellent beam matching between different cavity sections)
  - E_{peak} <= 30 MV/m (to ensure the stable operation in the cavities)
  - Continuity of the longitudinal acceptance (to reduce the emittance growth, specially in the region of frequency jump)

- This models is the upgrade version of the previous models of the JAEA-ADS Linac [1,2].

[1] B. Yee-Rendon, *et al* , "Beam optics design of the superconducting region of the JAEA ADS", J. Phys.: Conf. Ser. Accepted (2019).
[2] B. Yee-Rendon, *et al* , "CAVITY AND OPTICS DESIGN OF THE ACCELERATOR FOR THE JAEA-ADS PROJECT", TH0H10, PASJ19, Kyoto, Japan (2019).

JAEA-ADS Main linac layout

- The lattice scheme for the different SRFC section of the JAEA-ADS



[1] Not in scale

JAEA-ADS lattice layout. S= Solenoid, C = Cavity, DQ= Double quadrupole

- The summary of the main linac layout.

Parameters	Main Linac
# of Cavities	332
# of magnets[1]	170
Linac length	456.6

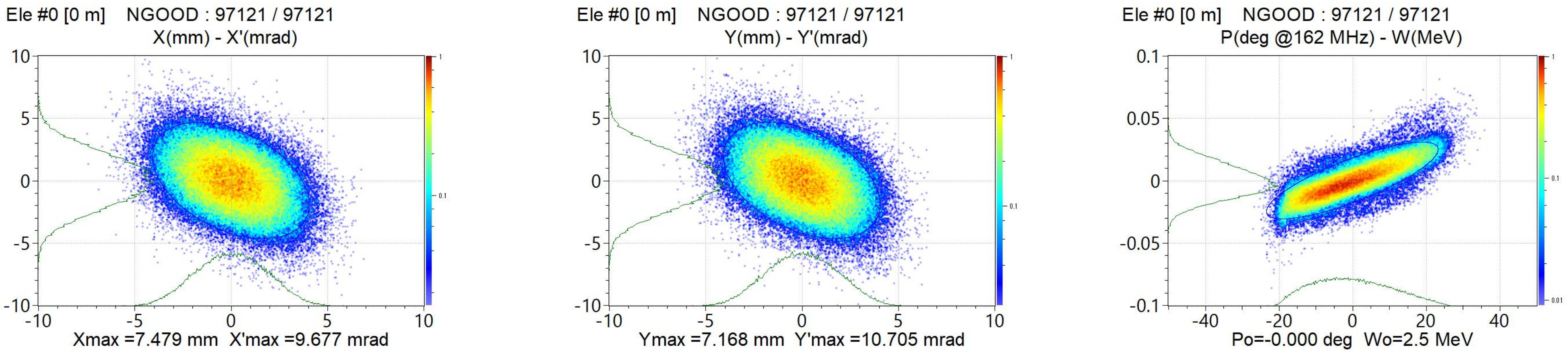
[1]Additional magnets were added to make the match at the section with frequency jump.

JAEA-ADS Beam emittance and distribution

- The RFQ's simulations provides the values for the emittance [1]. The next table presents the inputs emittance and the phase law used[A] in the studies.

Parameter	Main Linac
$\varepsilon_{x/ynormrms}[\pi\ mm\ mrad]$	0.252
$\varepsilon_{znormrms}[\pi\ mm\ mrad]$	0.4602
Phase law	$k_{0\parallel} = 0.66k0_{\perp}$

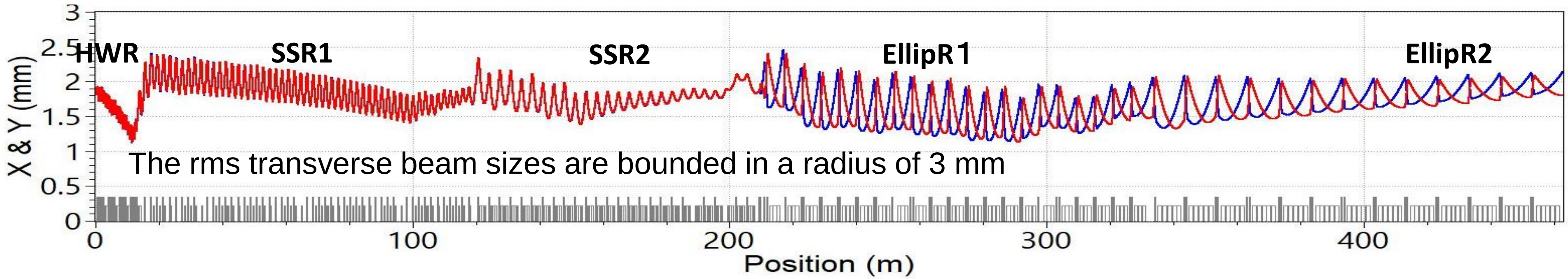
- Additional, the RFQ's studies provides also the beam distribution to the multiparticle tracking with about ~10^5 macroparticles.

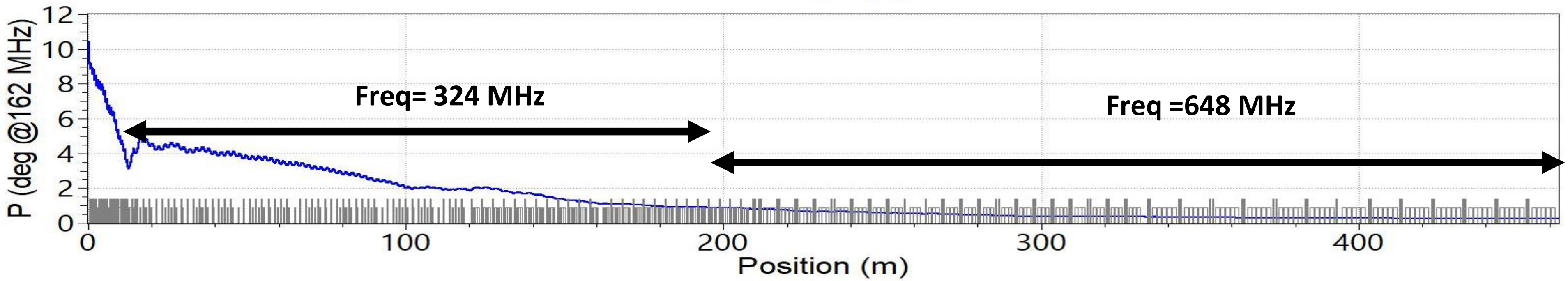


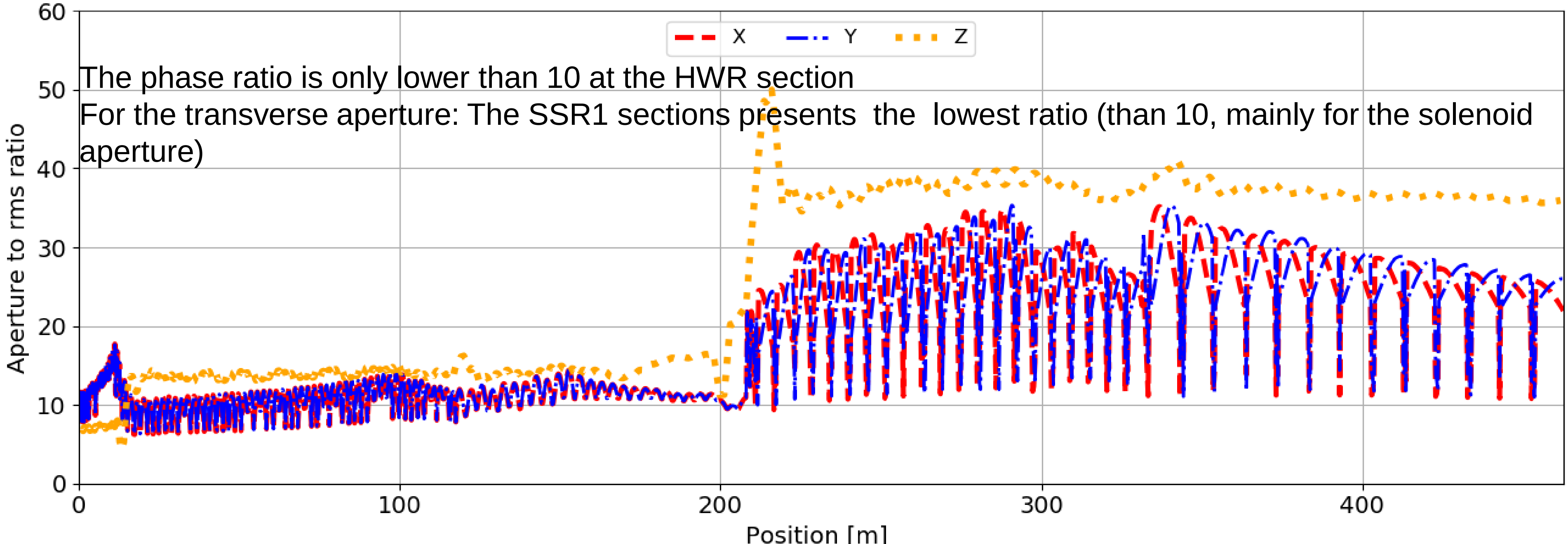
[1] Y. Kondo *et al.*, "Reference design of the RFQ for the JAEA ADS linac", The 3rd J-PARC Symposium (J-PARC2019), Tsukuba, Japan (2019).

[A]Several phase laws were testing $\frac{k_{0\parallel}}{k0_{\perp}} = 0.72, 0.7, 0.68, 0.66, 0.62,$ however, the one which keep the equipartition produce the lower emittance growth

JAEA-ADS rms envelope

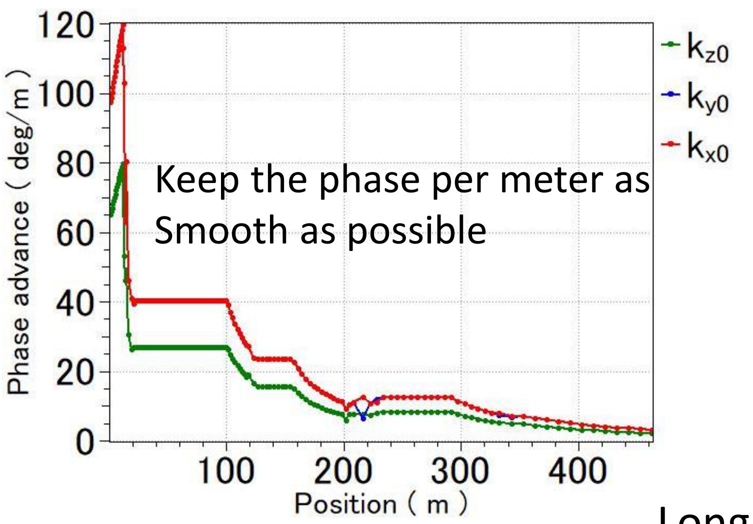






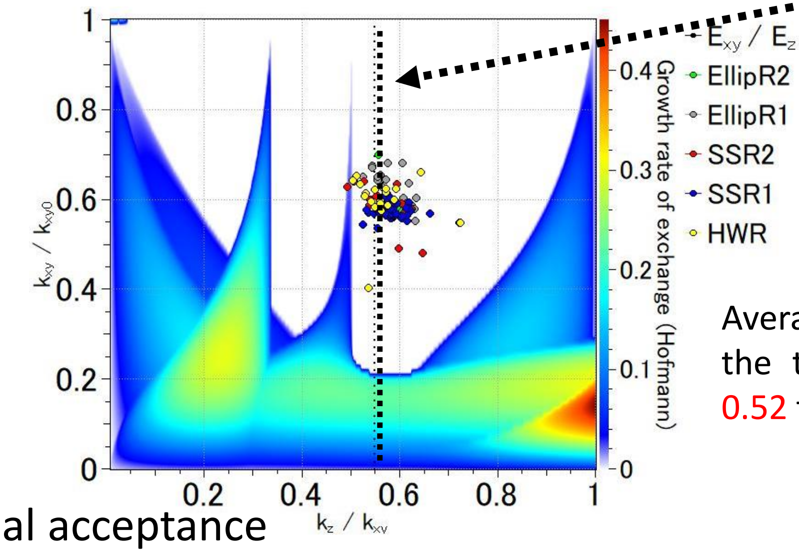
JAEA-ADS phase advance, Hofmann chart & longitudinal acceptance

Zero phase advance per meter



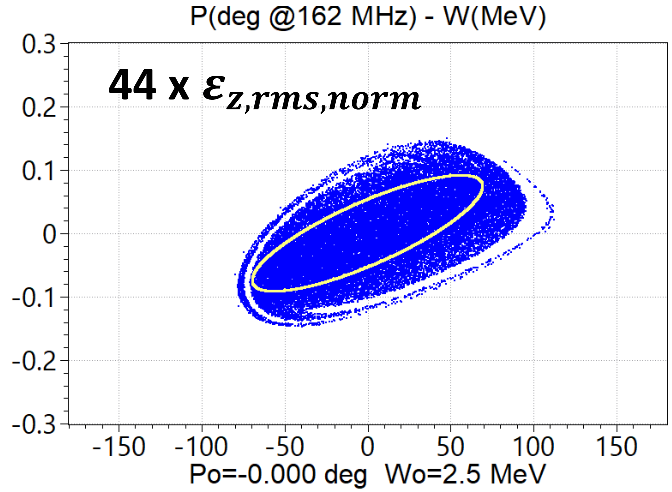
Hofmann chart

Equipartition region



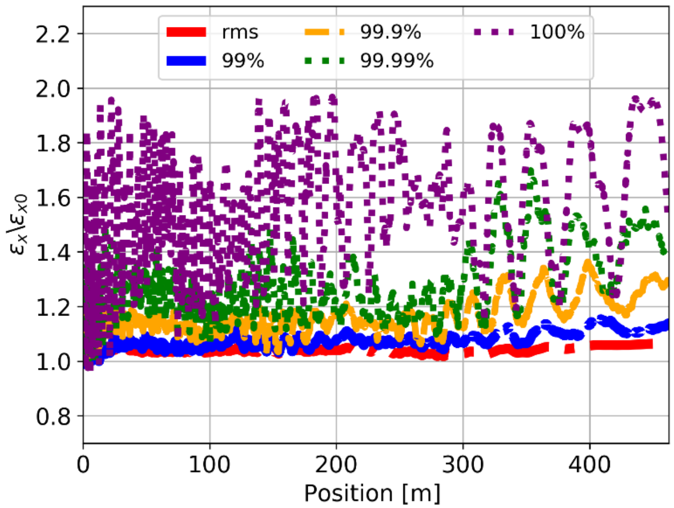
Average detuning is 0.6 for the transverse plane and 0.52 for the longitudinal

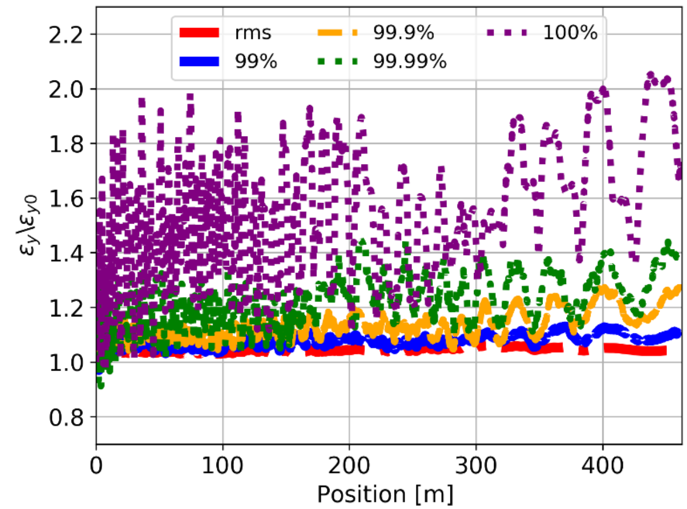
Longitudinal acceptance

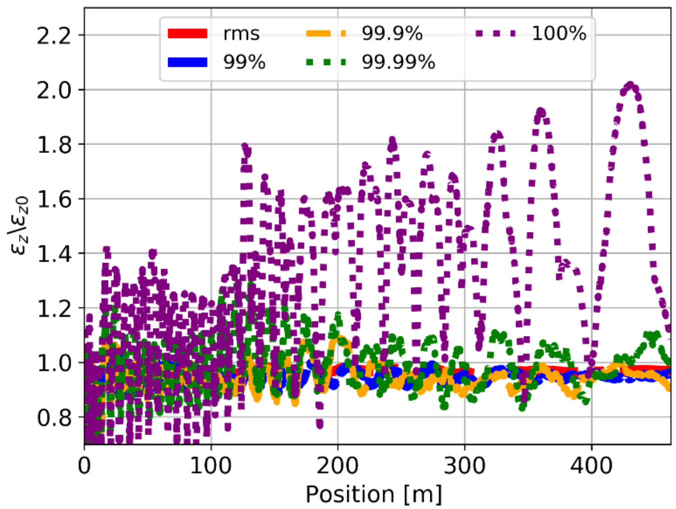


Large longitudinal is preferable when the fault compensation scheme is applied. In addition, it could help in the beam stability during the normal operation of the linac

Beam halo studies



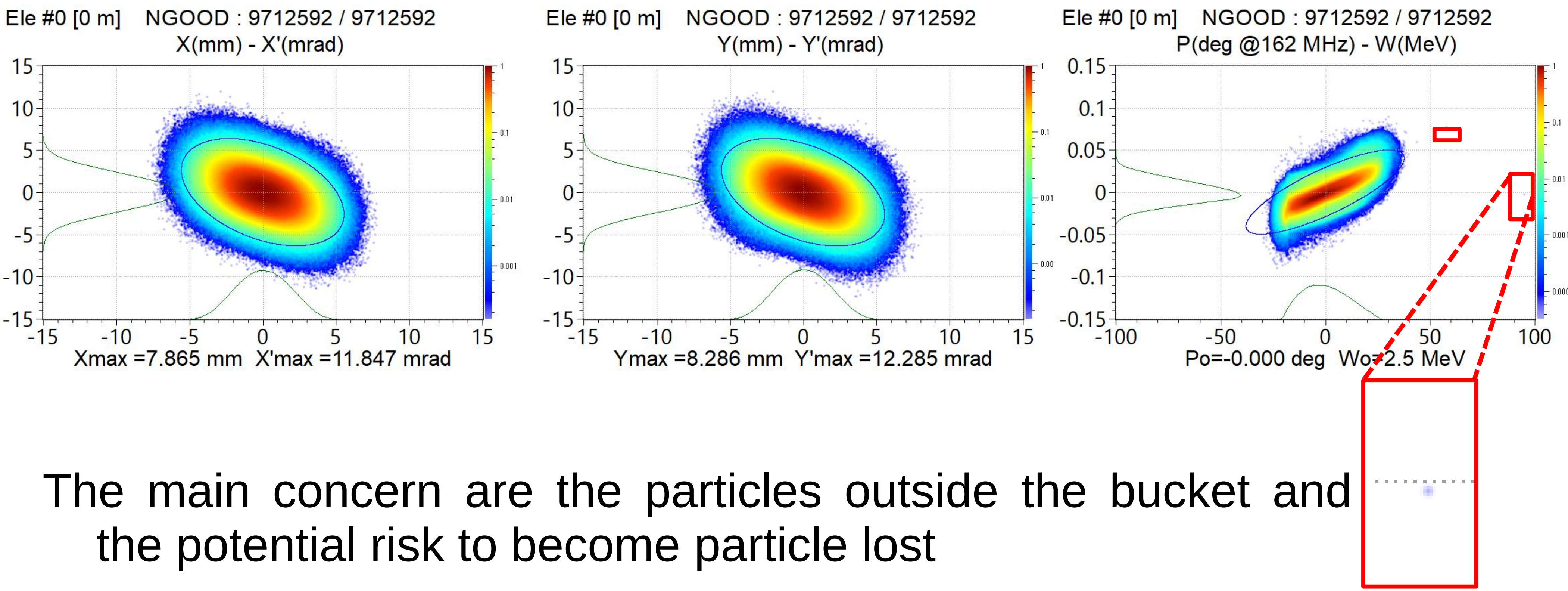




The maximum emittance growth (for the 100% of the emittance) is about the double, and for the rms emittance is about 6%. Particles below 100% of the emittance present a maximum emittance of 70% and below 99.99% is about 30%.

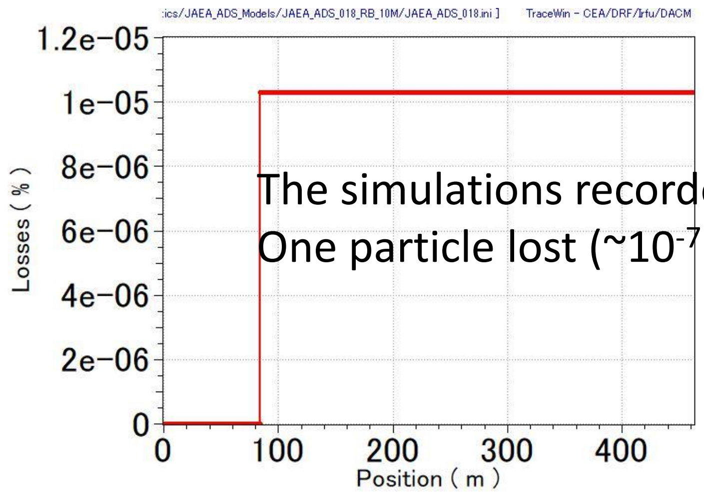
10 Million simulations tracking

The RFQ's output beam distribution was used for make beam dynamics studies using about ~10^7 particles

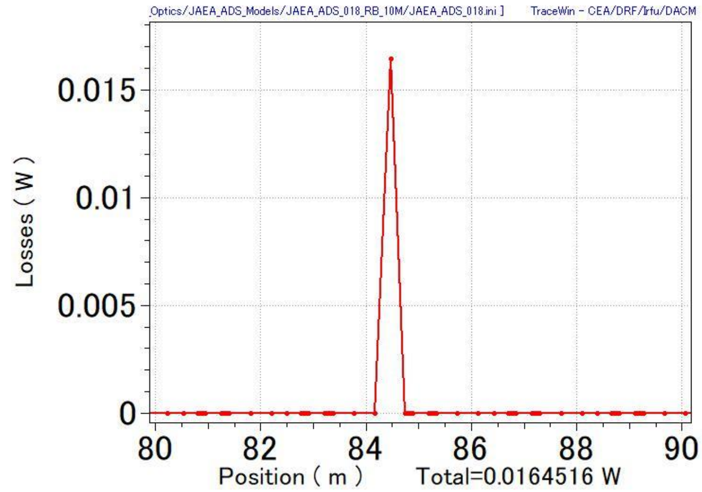


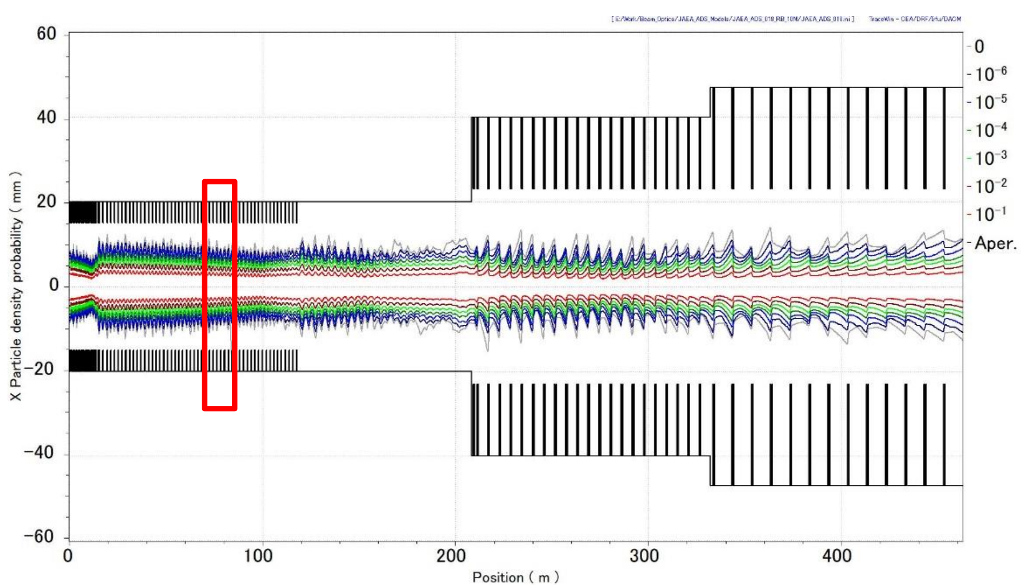
The main concern are the particles outside the bucket and the potential risk to become particle lost

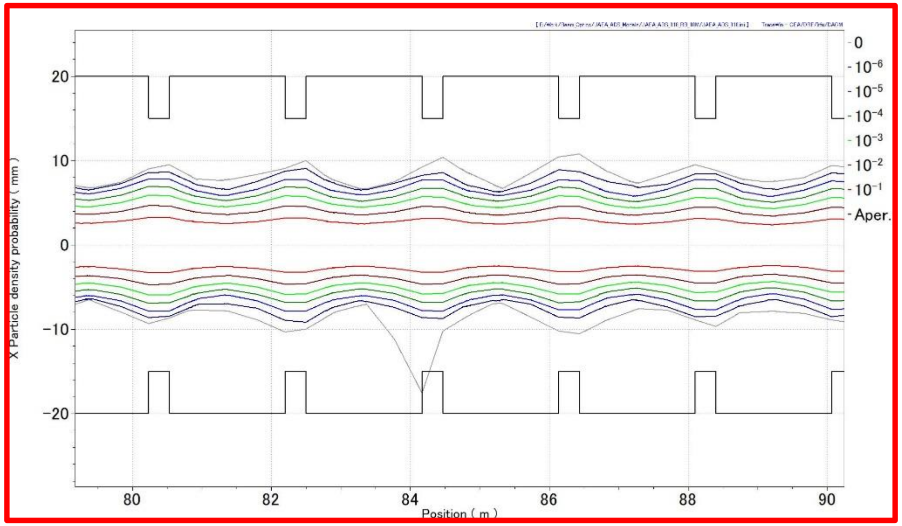
Beam loss



The simulations recorded
One particle lost (~10^{-7})

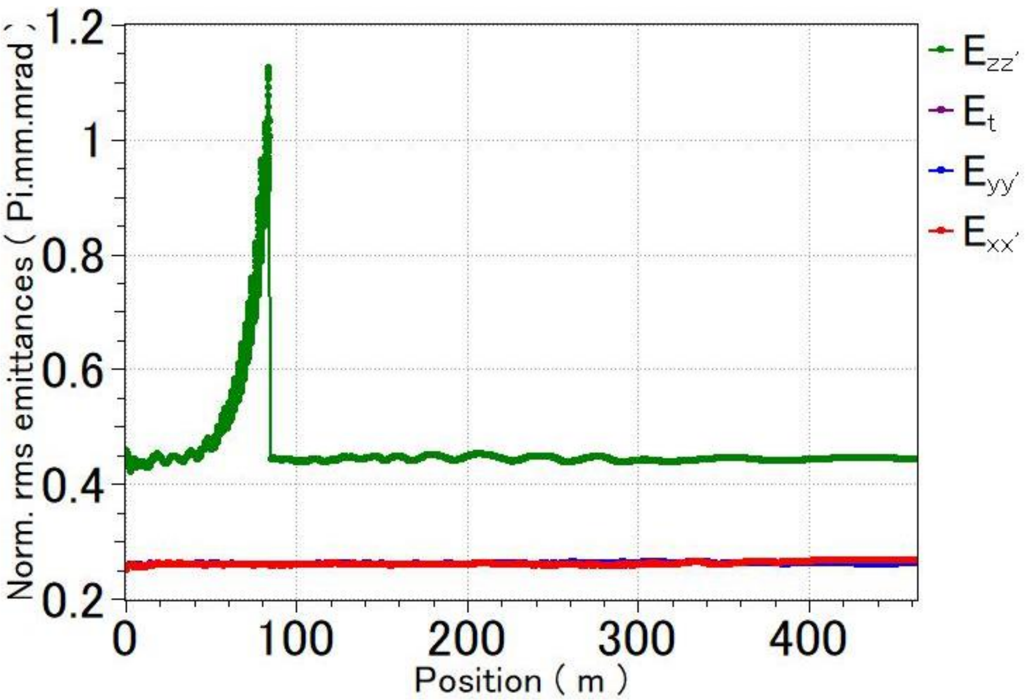






The particle is lost in the solenoid aperture of the SSR1 one particle lost

Rms emittance growth



The large longitudinal rms obtained is the result of the macroparticles outside the bucket.

Once the particle is lost the size of longitudinal return to similar values as the previous simulations 10^5.

Distribution	$\frac{\varepsilon}{\varepsilon_0}$X,rms	$\frac{\varepsilon}{\varepsilon_0}$Y,rms	$\frac{\varepsilon}{\varepsilon_0}$z,rms
10^5	1.066	1.044	0.968
10^7	1.069	1.043	0.965

Beam optics summary

- The beam halo studies using the RFQ output distribution (10^5 macroparticles) showed that the maximum emittance growth increase about the double for the ideal performance (no error). However, the final emittance growth is about 70%.

- A test case with 10^7 macroparticles, conclude that in *ideal conditions* the losses are lower than 1 W/m. The final rms emittance is agreed with the results of 10^5 cases. However, more cases are required to fully confirm it.

- In addition, the model required to implemented the error cases for the full validation.