Cavity and optics design of the accelerator for the JAEA-ADS project

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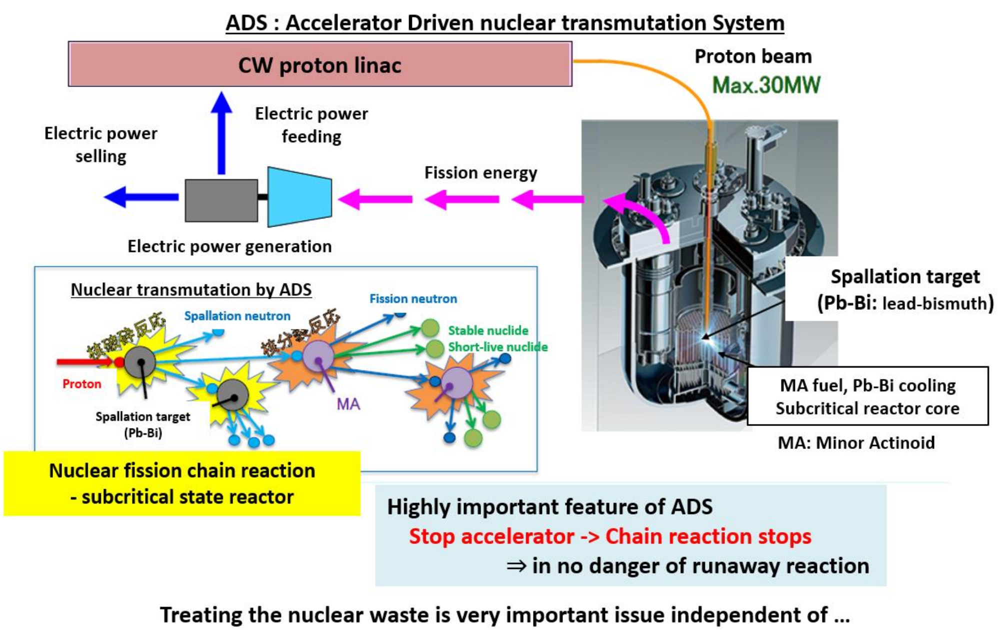
Goal

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

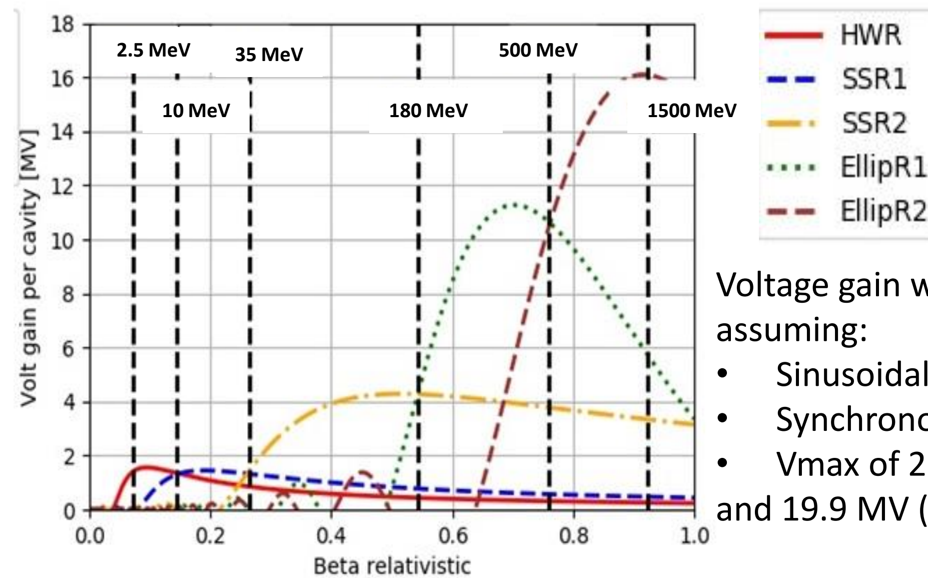
The goal is to design a **CW Superconducting proton linac** with a beam current of **20 mA** and a final energy of **1.5 GeV** with a **low beam loss**.

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

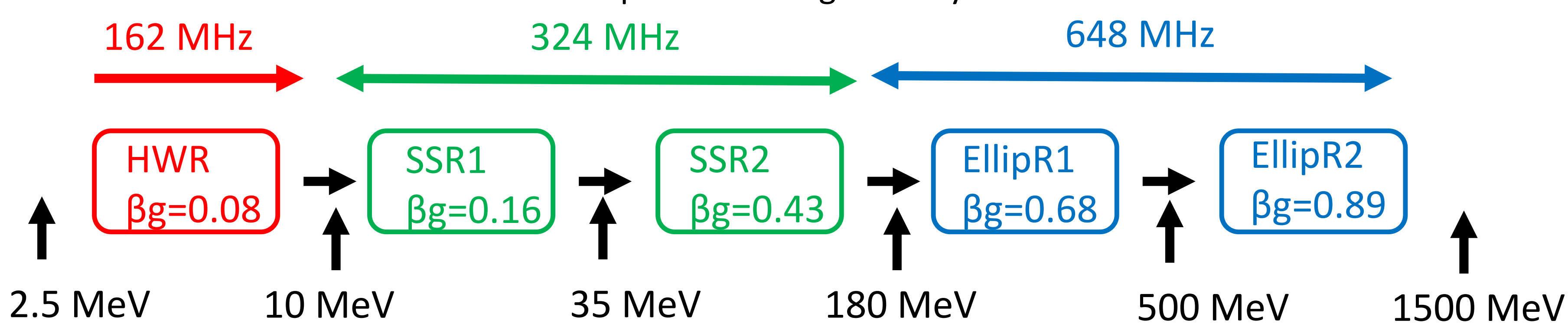
The optimization in the numbers of cavities and β_g were chosen to obtain maximum voltage gain per cavity + smooth transition



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

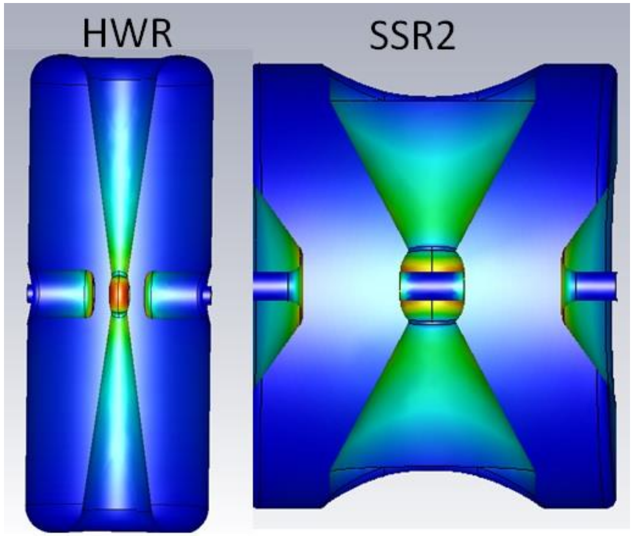


Low beta summary

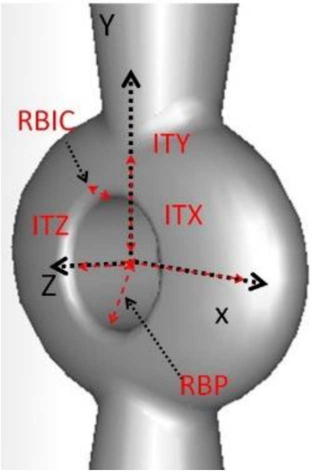
Design goals

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

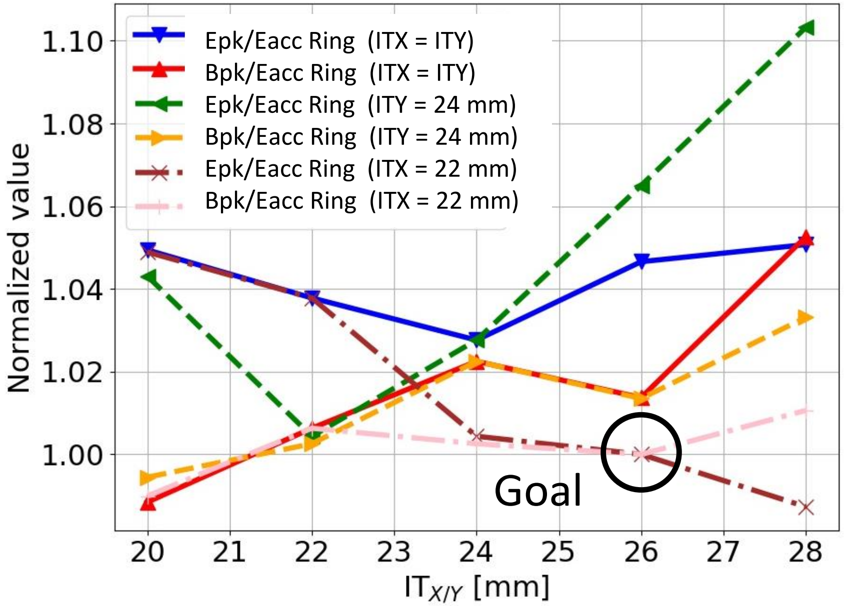
JAEA-ADS low beta Cavity Parameters			
Cavity type	Freq [MHz]	βg	Energy range [MeV]
HWR	162	0.08	2.5-10
SSR1	324	0.16	10-35
SSR2	324	0.43	35-180



HWR & SSR Electric field surfaces



Inner center conductor geometry



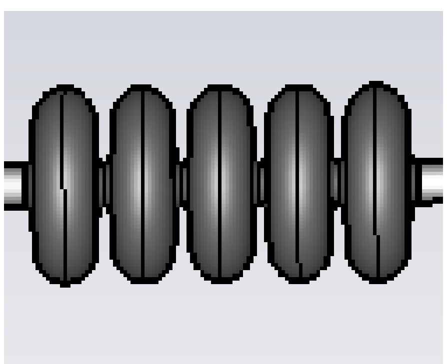
The values of Bpk/Eacc and Epk/Eacc as a function the transverse dimensions of the inner conductor shape.

[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"

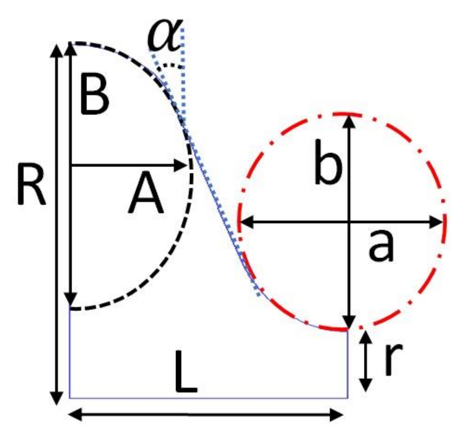
High beta summary

- 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)

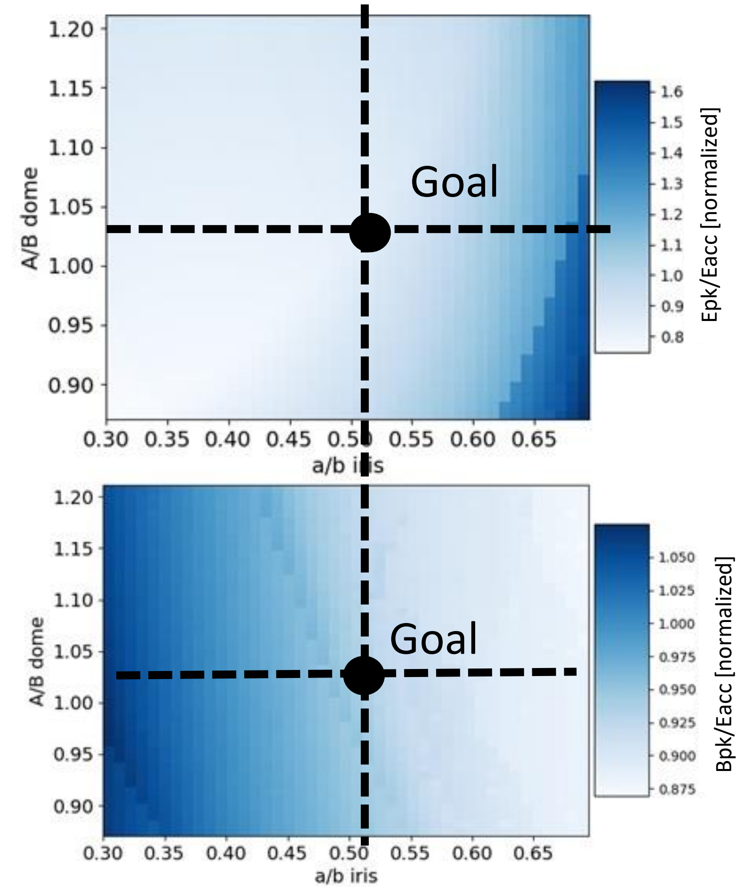
JAEA-ADS high beta (Elliptical) cavity Parameters			
Cavity Section	Freq [MHz]	βg	Energy range [GeV]
EllipR1	648	0.68	0.18-.050
EllipR2	648	0.89	0.5-1.5



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).

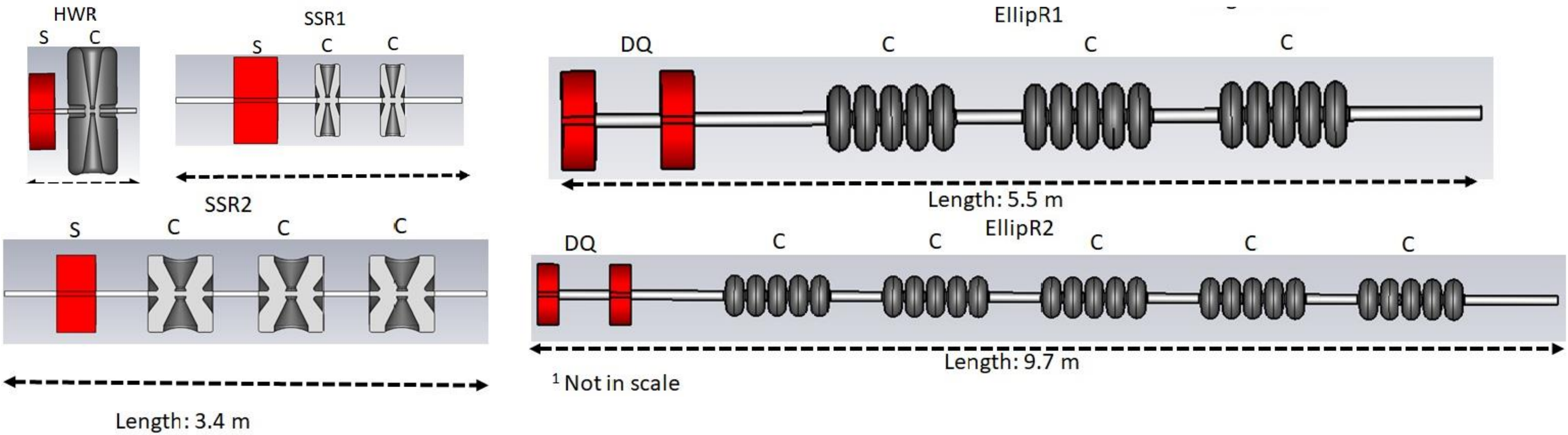
Beam optics

- 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)
- After the first beam optics studies[1] (called in this work as previous study), the last two conditions were added.

[1] B. Yee-Rendon, et al, , "Beam optics design of the superconducting region of the JAEA ADS", J. Phys.: Conf. Ser. Accepted (2019).

JAEA-ADS scheme upgrade

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



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

- The initial emittance were changed, consequently emittance ratio changed too. Thus, a new phase law was implemented to keep with the equipartition condition.

Parameter	New studies	Previous study
$\varepsilon_{x/ynormrms}[\pi\ mm\ mrad]$	0.25	0.36
$\varepsilon_{znormrms}[\pi\ mm\ mrad]$	0.46	0.40
Phase law	$k_{\parallel} = 0.54 k_{\perp}$	$k_{\parallel} = 0.85 k_{\perp}$

[1] IPAC19 model

JAEA-ADS cavity summary & beam tracking setup

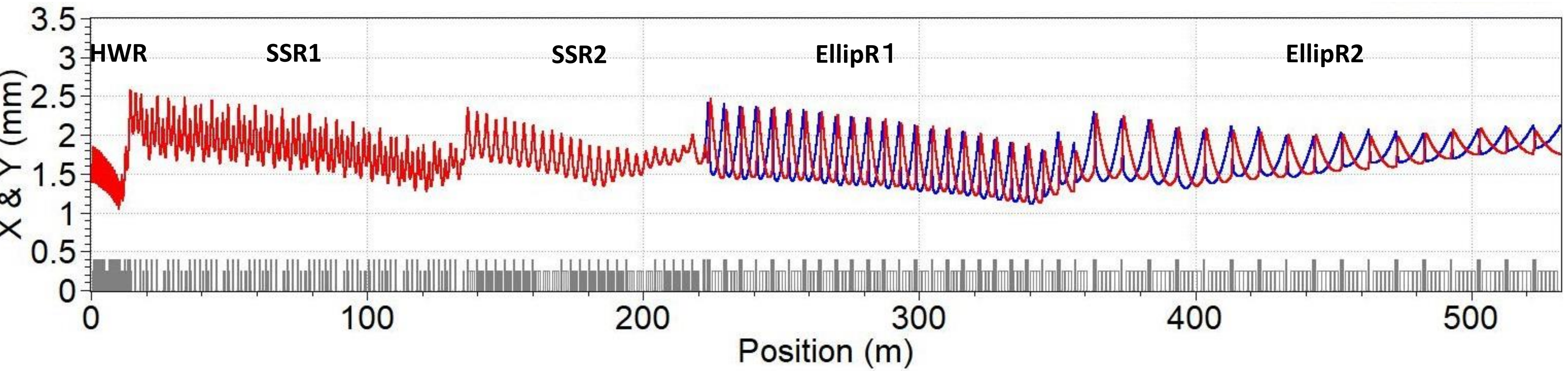
- The effect of the new two conditions (E_{peak} & Continuity of the longitudinal acceptance) were studied in detail by developed two schemes. The description and some of the results are summarized in the next table.

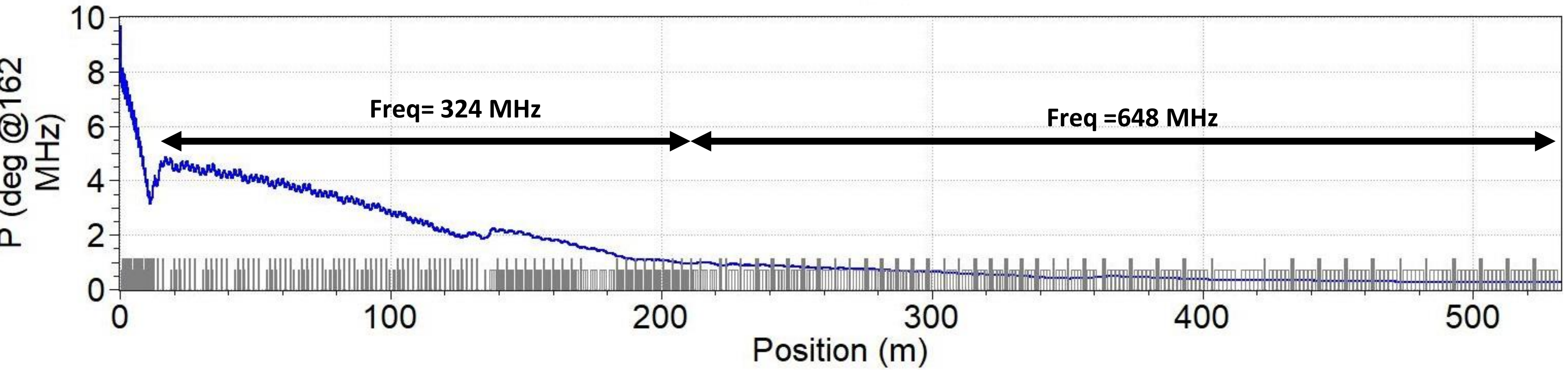
Parameter/condition	Model A[1]	Model B
$E_{peak} = 30\ [MV/m]$	Yes	Yes
Continuity of the longitudinal acceptance	No	Yes
# of Cavities	278	374
# of magnets	138	190
Linac length	423.102	532.155

- The beam dynamics studies were developed by tracking 6-Dimensional Gaussian distributions (3σ cut) with 100,000.

[1] This model is similar as the IPAC19 model

JAEA-ADS Model B rms envelope



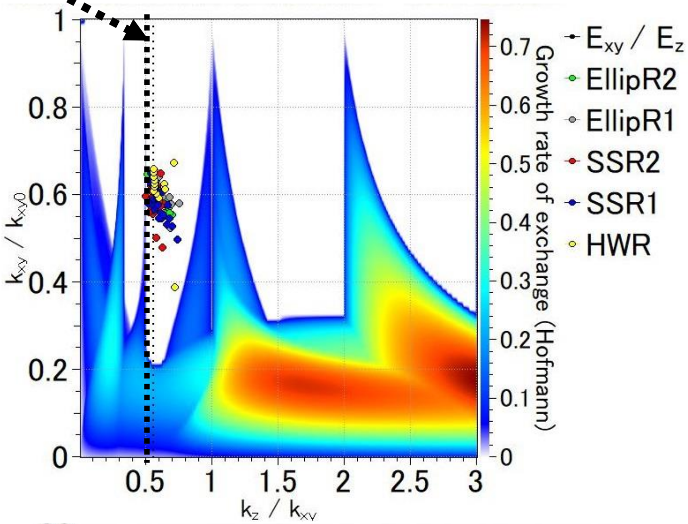


On the top the rms beam size envelopes along the length of the linac, on the horizontal plane (red) and vertical (blue) one. The ratio between cavity radius and rms beam size are from 8 to 19, the lattice has quasi-periodic envelope. On the bottom, the rms phase is below 10 degree.

JAEA-ADS Hofmann chart & longitudinal acceptance

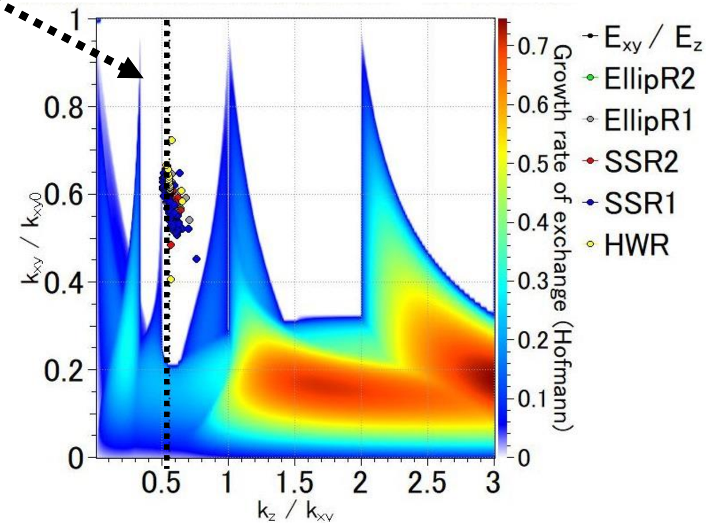
Equipartition region

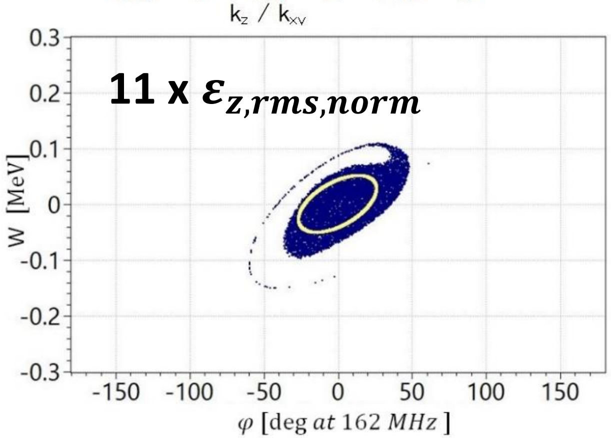
Model A

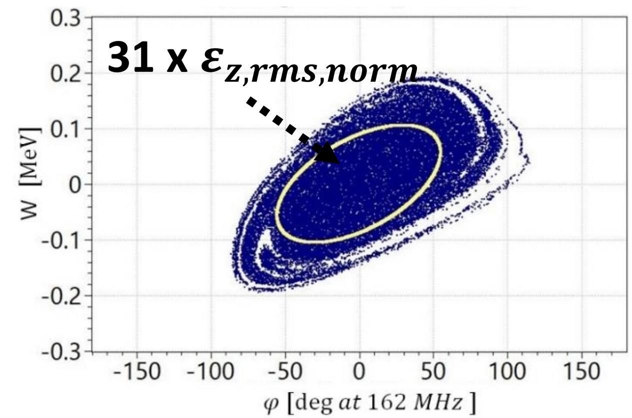


Equipartition region

Model B

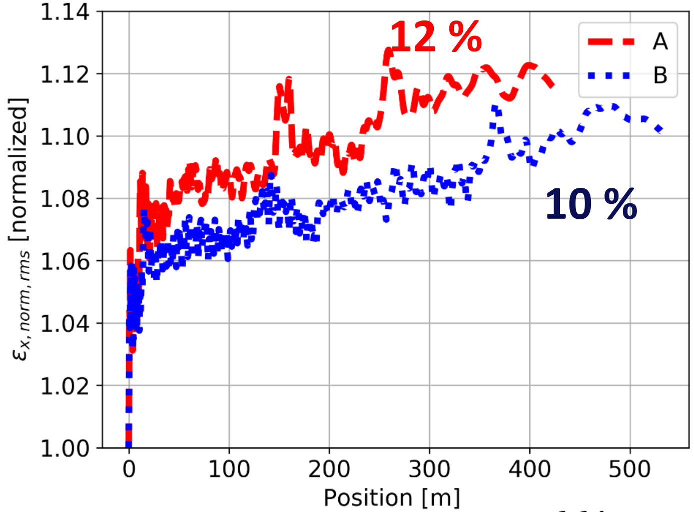


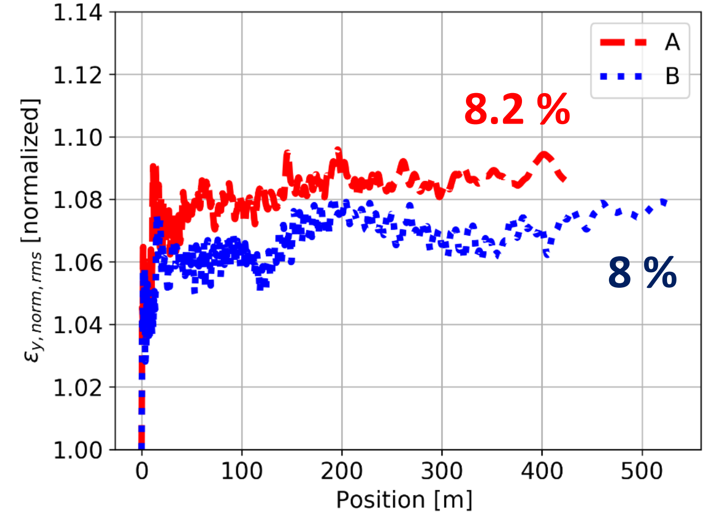


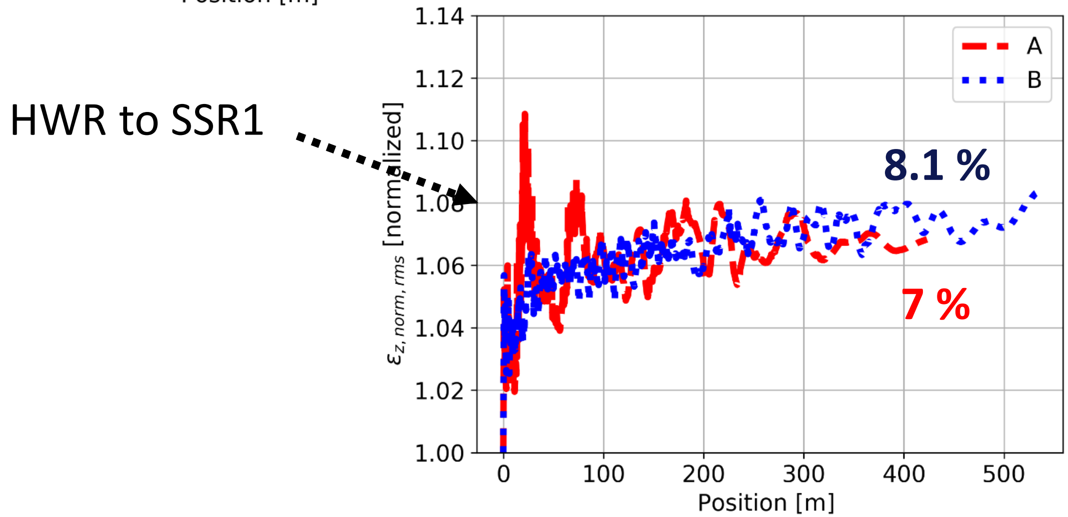


The Hofmann charts (top) that both model A (left) and B (right) operate in the equipartition region (growth of emittance exchange is zero) and both models are space charge dominant beams ($k_{x/y}/k_{x/y0}$ < 0.7). The longitudinal acceptance plots (bottom) show that Model B has almost 3 times larger than A .

Norm rms emittances evolution







Model B presents a better control of the RMS normalized emittance ratio ($\frac{\varepsilon}{\varepsilon_0}$) along the length of the linac than A (top plots). It can be seen a large longitudinal emittance growth (bottom plot) at the beginning of the linac in special during the transition between HWR and SSR1.

Beam optics summary I

- The JAEA-ADS linac is the highest beam power linac proposal so far. The control of the beam loss, halo and emittance growth are big challenges for the success of the project.
- The most relevant characteristics of the linac design are:
  - High beam current (20 mA) → strong space charge → emittance growth
  - The double frequency jump (162MHz-324MHz-648MHz) → emittance growth
- From the previous model (IPAC19) new inputs and conditions were implemented to improve the design:
  - New initial (ratio) emittances → New phase law → changes in phase advance (k) & the synchronous phase of the cavities (φ_s)
  - E_{peak} = 30 MV/m → decrease the E_{acc}
  - Continuity longitudinal acceptance → affects φ_s
- Two models were developed:
  - Model A : E_{peak} = 30 MV/m (similar as the previous model)
  - Model B : E_{peak} = 30 MV/m & Continuity of the longitudinal acceptance

Beam optics summary II

- The summary of the results are:

Models	Cavities	Len [m]	Growth (X,Y,Z) [%]	Acceptance long [$\varepsilon_{z,norm,rms}$]
A	278	423.102	12/8.2/7	11
B	374	532.155	10/8/8.1	31

- Both models are space-charge beam which operates near the equipartition region.
- Both models have longer linac length and emittance growth comparing with old model. These are consequence of the E_{peak} & Continuity of the longitudinal acceptance conditions and the new emittance inputs (new phase law).
- Model A and the previous model have similar longitudinal acceptance about 10 x $\varepsilon_{z,rms,norm}$, on the contrary, Model B has almost 3 times that value.
- Model B has a better emittance growth control than A, specially in the transverse plane. This is due to the emittance interchange between the longitudinal plane and the transverse one (see the rms emittance plot). This show the advantage of the continuity of the longitudinal acceptance.
- The study is a step forward in the JAEA-ADS linac design which will help to the development of the JAEA-ADS project and the future of the high intensity linacs around the world.