

Beam Physics Design of the Injector for the JAEA-ADS

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Introduction

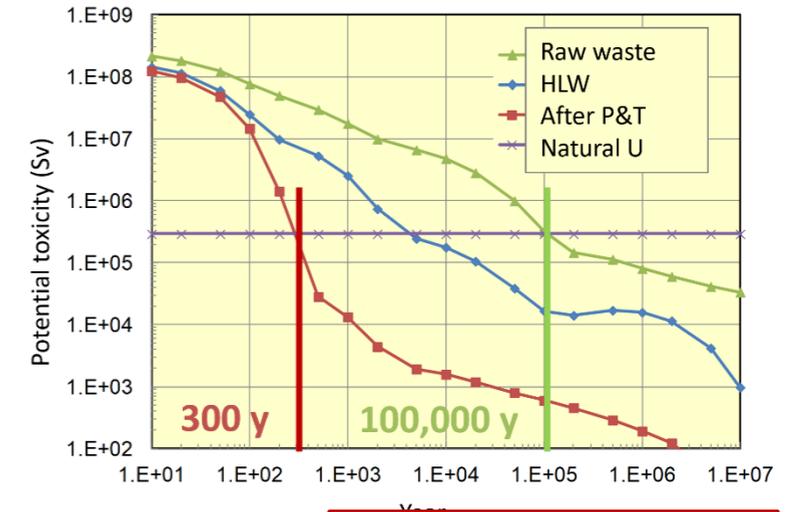
Motivation: Nuclear waste is a common worldwide problem

Japan's case

- Already existing 18,000 tons
- Nuclear plants have been restarted, 1000 tons newly generated (/year/40 plants)

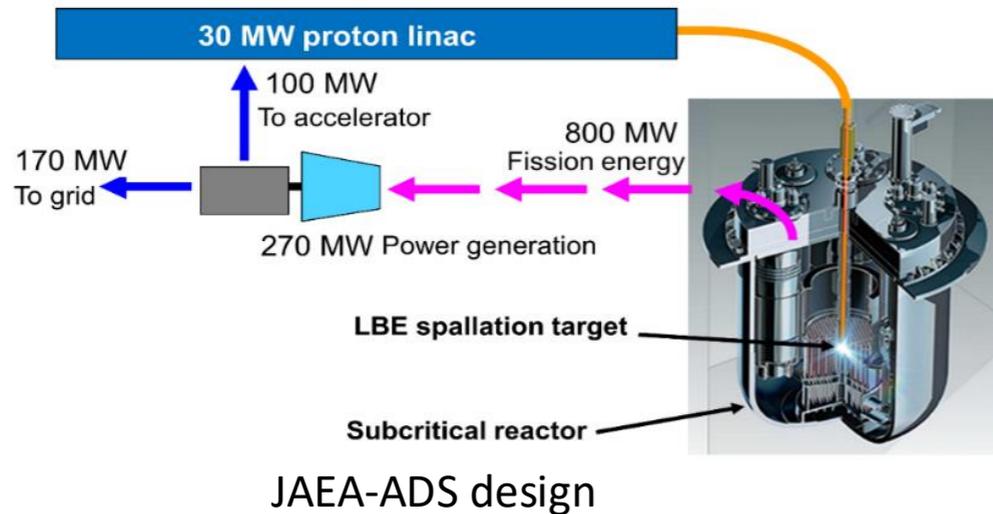
Potential solution

Accelerator-Driven System (ADS)



Toxic period 1/300

JAEA proposes an ADS for the reduction in volume and radiotoxicity of nuclear waste (Nuclear x Renewable)



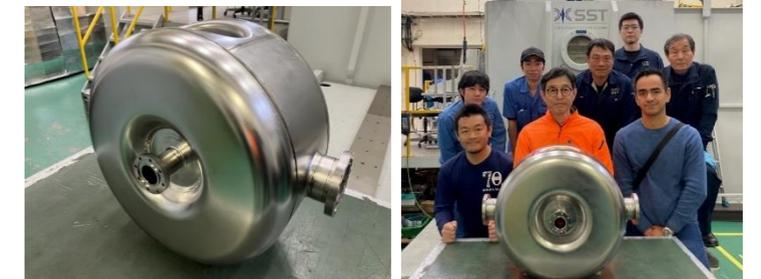
Accelerator's R&D topics:

1) Linac's design & operation strategies

2) Prototyping SRF cavities



Today's presentation

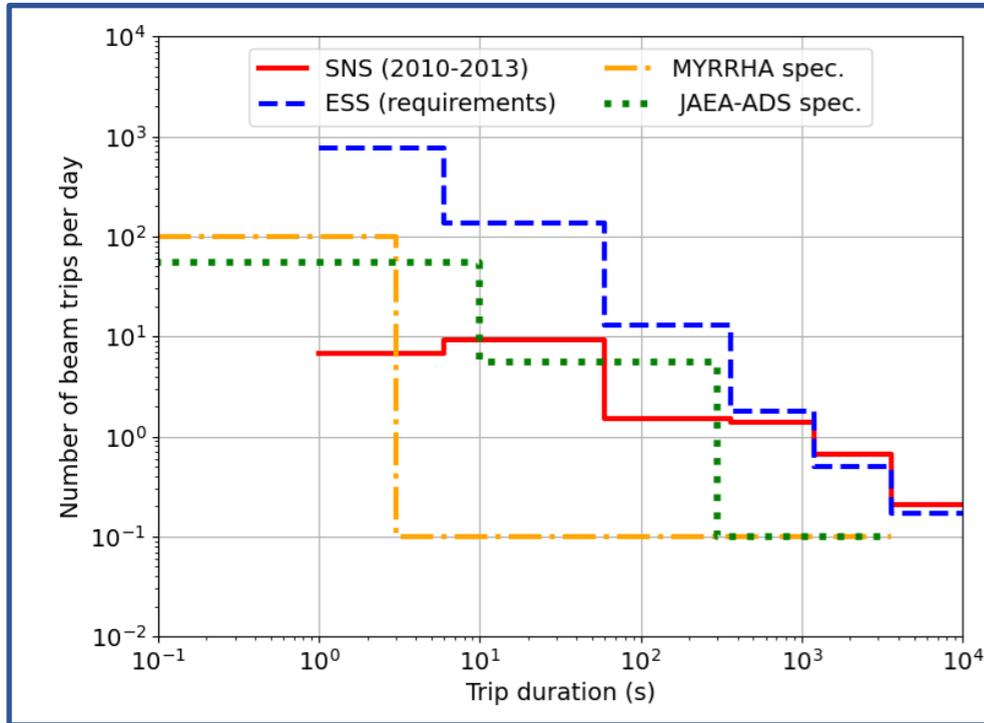


Assembly completed (Feb 2025)_{3/12}

High availability requirement

One main challenge:

Low beam trips beyond the current linacs

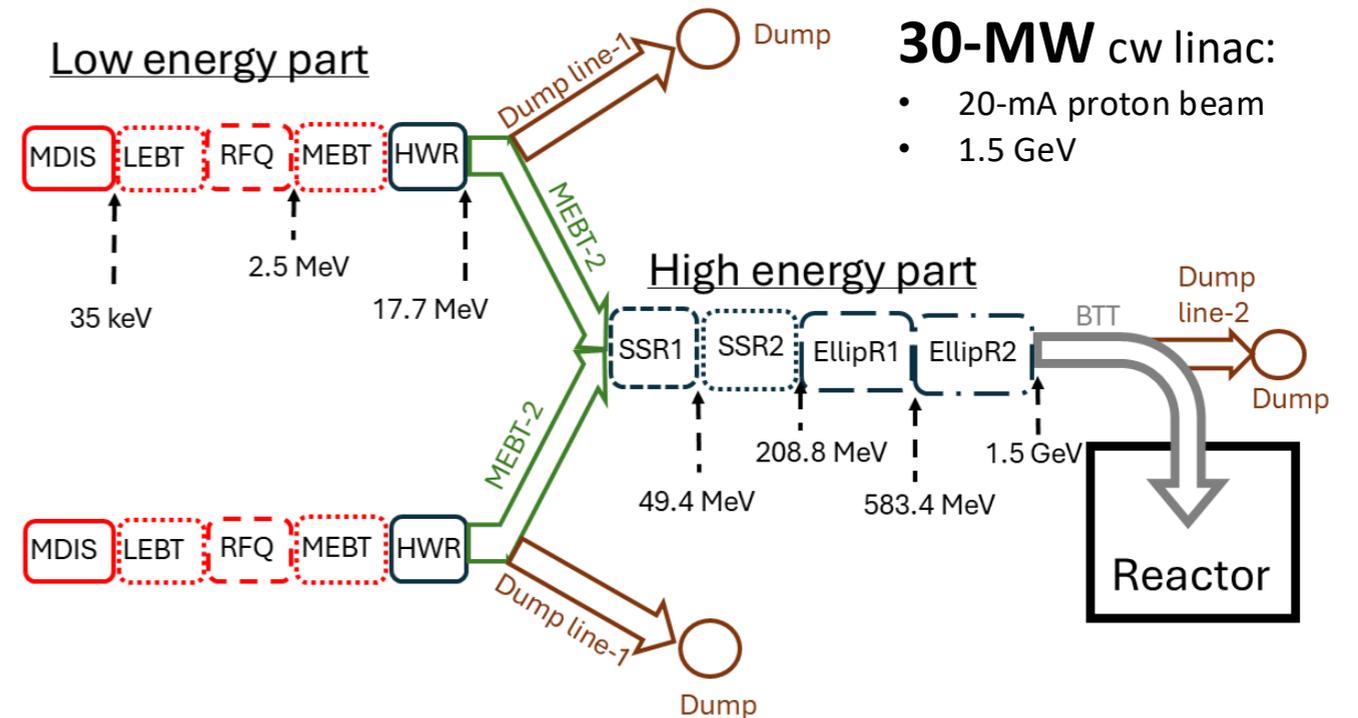


B. Yee-Rendon et al, LINAC2022, TU2AA01,p. 310 (2022).

Active strategy:

- A **hybrid redundancy** scheme [1-2]:

Hot standby + **local compensation** [1,3]
 (based on parallel) (based on k-out-of-n)



30-MW cw linac:

- 20-mA proton beam
- 1.5 GeV

JAEA-ADS linac layout

[1] B. Yee-Rendon et al, PRAB 25,08001 (2022).

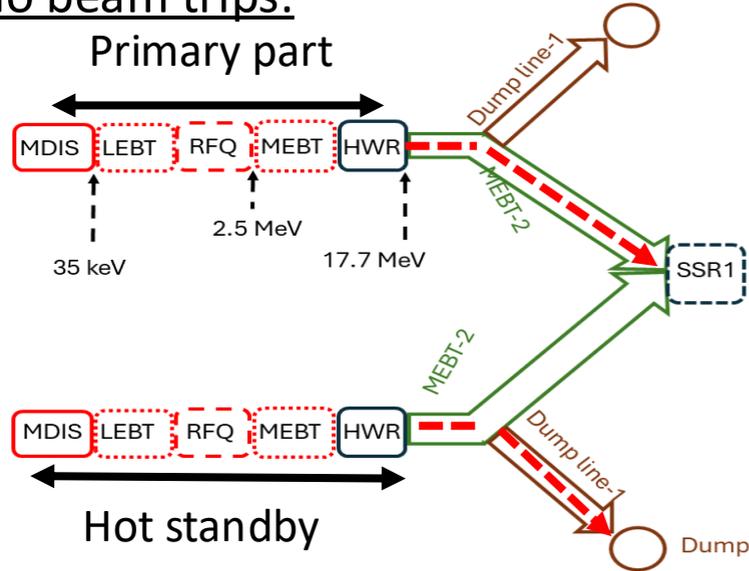
[2] B. Yee-Rendon et al, PASJ2022, TUPOO6,p. 286 (2022).

[3] B. Yee-Rendon et al, PASJ2021, TUOAO1,p. 61 (2021).

Injector design considerations: Hot standby operation

Definition: **Injector** part starts from the source to the HWR section including the MEBT-2 and dump line-1

No beam trips:

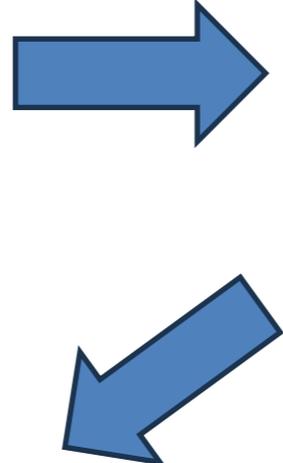


Failure in the primary part:

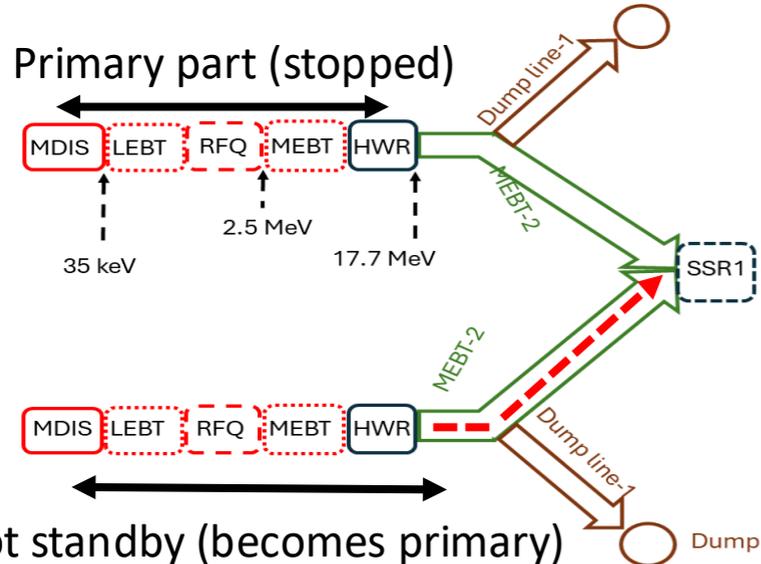


Protocol application[1]

1. Failure is detected
2. Machine protection system will stop the beam within 10 μ s
3. Dipole switch changes polarity is about 1.5 s [2]
4. Check performance in 3 s



Failure case:



The **dipole switch time** is short enough that **hot standby** can **manage all** (or almost all) the beam trips concerned

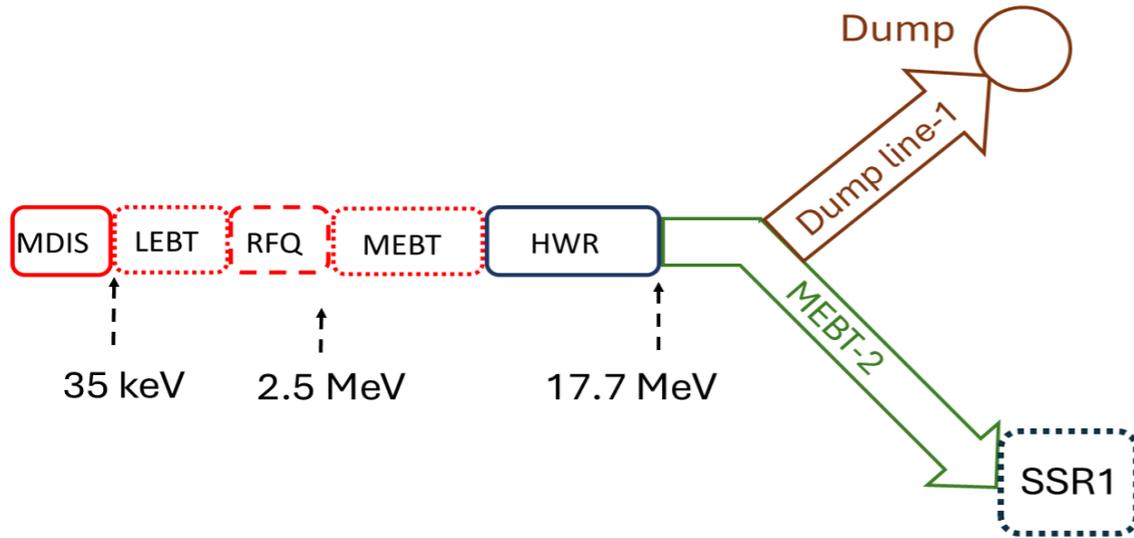
[1] Similar strategy is pursued by other ADS linac
 [2] E. Froidefond, et al., IPAC-2021, 2356(2021)

Injector design criteria: lattice design

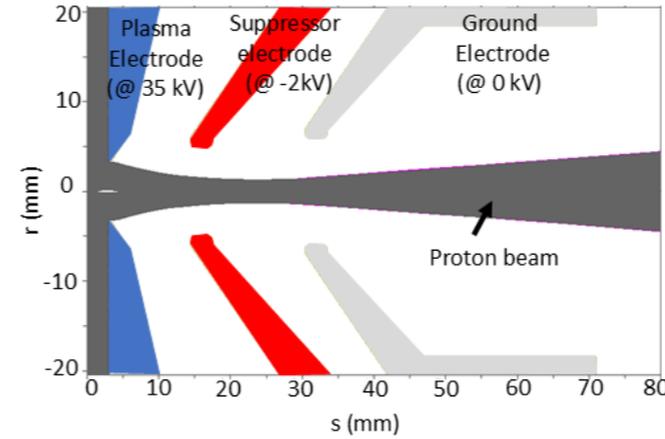
Criteria	Strategy
Low beam loss control: $< 1 \text{ W/m}$	<ul style="list-style-type: none"> • <u>Emittance growth control</u> • <u>Reduce mismatch</u> • <u>Achromatic</u> bending
Enough transverse space for shielding between linacs: $> 4 \text{ m}$	<ul style="list-style-type: none"> • <u>Trade-off</u> between dipole angle, transport length and beam loss
Handle high beam power dump: 354 kW	<u>Pulse mode operation</u> [1]: <ul style="list-style-type: none"> • <u>99.5%</u> beam <u>stopped</u> at the <u>LEBT</u>: $\sim 800\text{W}$ (peak current and power are manageable) • <u>0.5%</u> [1] beam <u>transmitted</u>: 1.7 kW beam power dumped (manageable)

[1] 0.5% of the pulse length is sufficient to operate at nominal current. Thus, the linac elements in hot standby can be adjusted to nominal current, ensuring that a quick and safe ramping to nominal operation. Similar strategy adopted for J-PARC beam commissioning (H. Hotchi et al., PRAB 20, 060402(2017))

Injector design



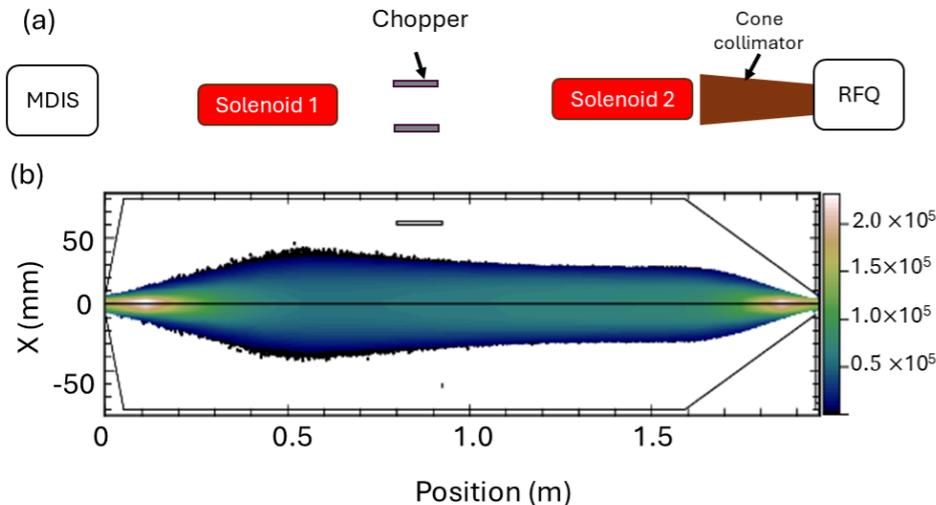
Microwave Discharge Ion Source (MDIS):



- 35 keV proton beam
- Triode configuration

B. Yee-Rendon et al, IPAC2023, TUPA121, 1591 (2023)

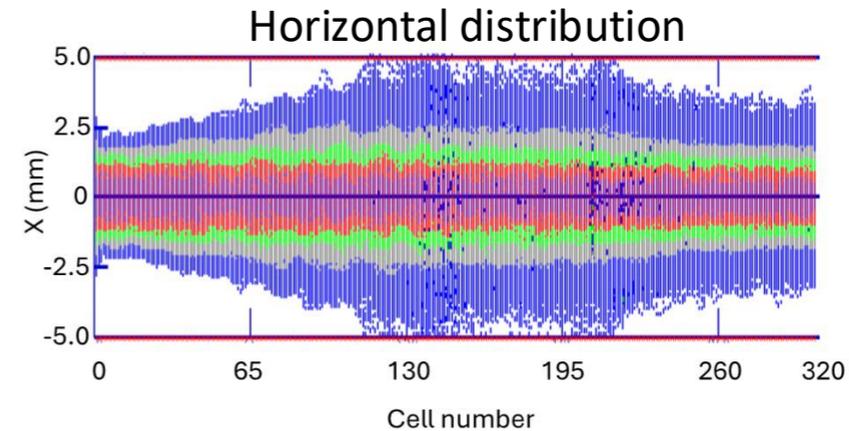
Low-Energy Beam Transport (LEBT):



- Space-charge compensation
- Chopper used to power ramping

B. Yee-Rendon et al, LINAC2024, TUPB076, 488 (2024)

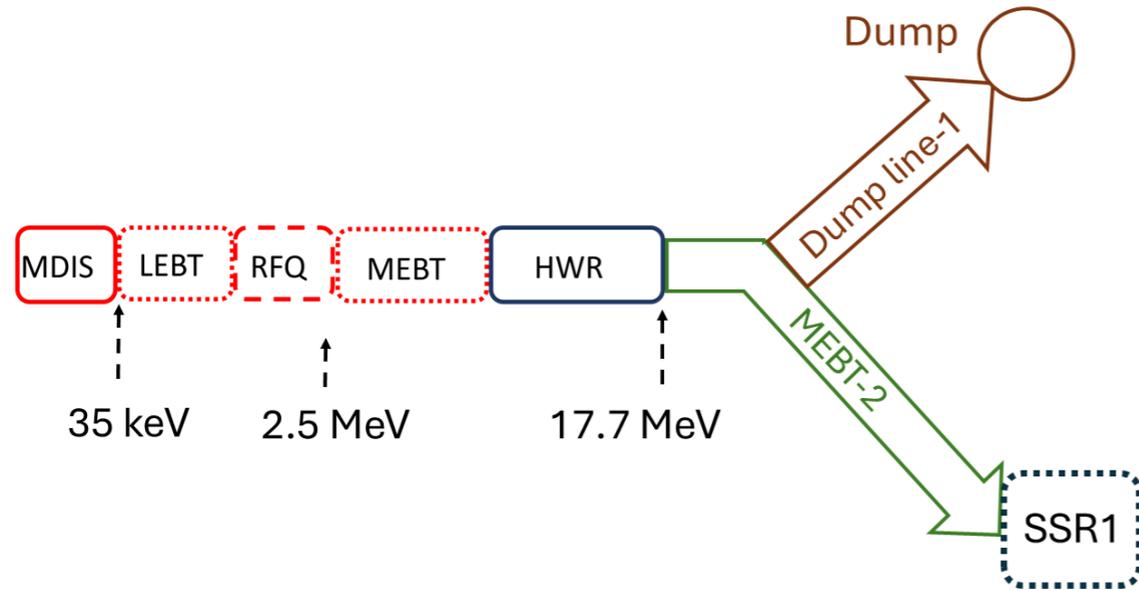
Radio Frequency Quadrupole (RFQ):



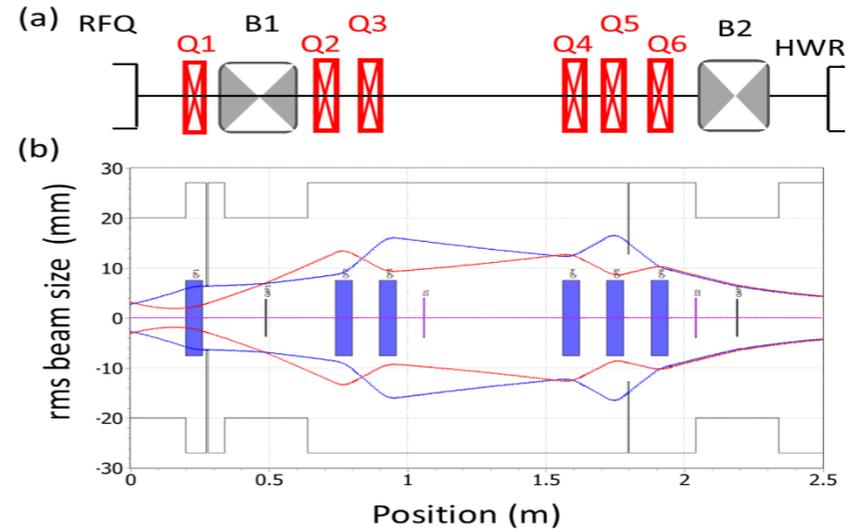
- 162-MHz RFQ
- Low surface field: 12.2 MV/m

Y. Kondo et al, J. Phys. Soc. Jpn. Conf. Proc. 33, 011015 (2021)

Injector design-II

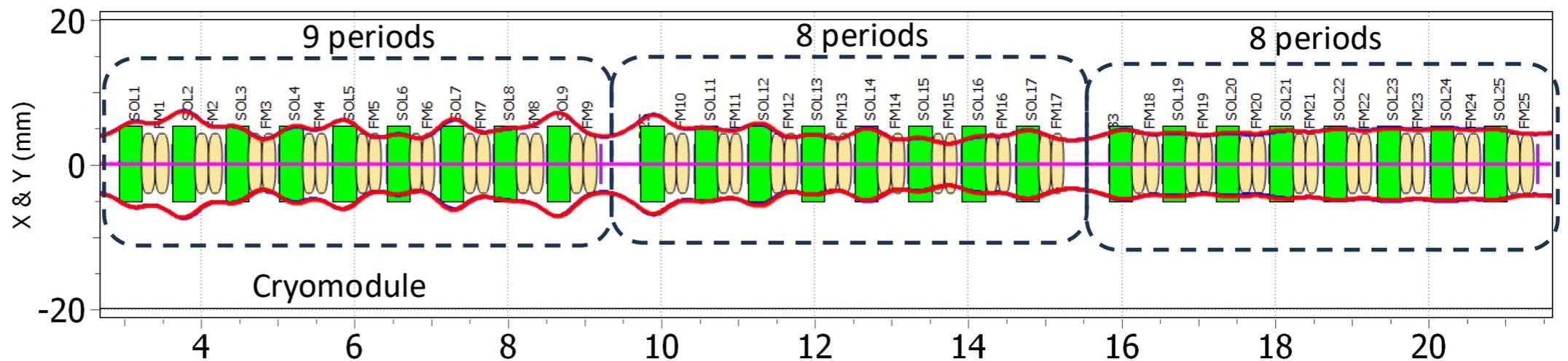
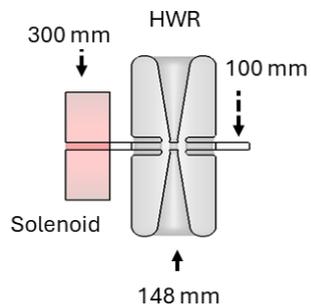


Medium Beam Transport Line (MEBT):



- Collimator system control beam size

Half-wave resonator (HWR) section:



HWR's lattice period

B. Yee-Rendon et al, PRAB24, 120101 (2021)

MEBT-2 design

Matching section:

- **Triplet quadrupoles** to adjust beam sizes + two **normal conducting buncher cavities**

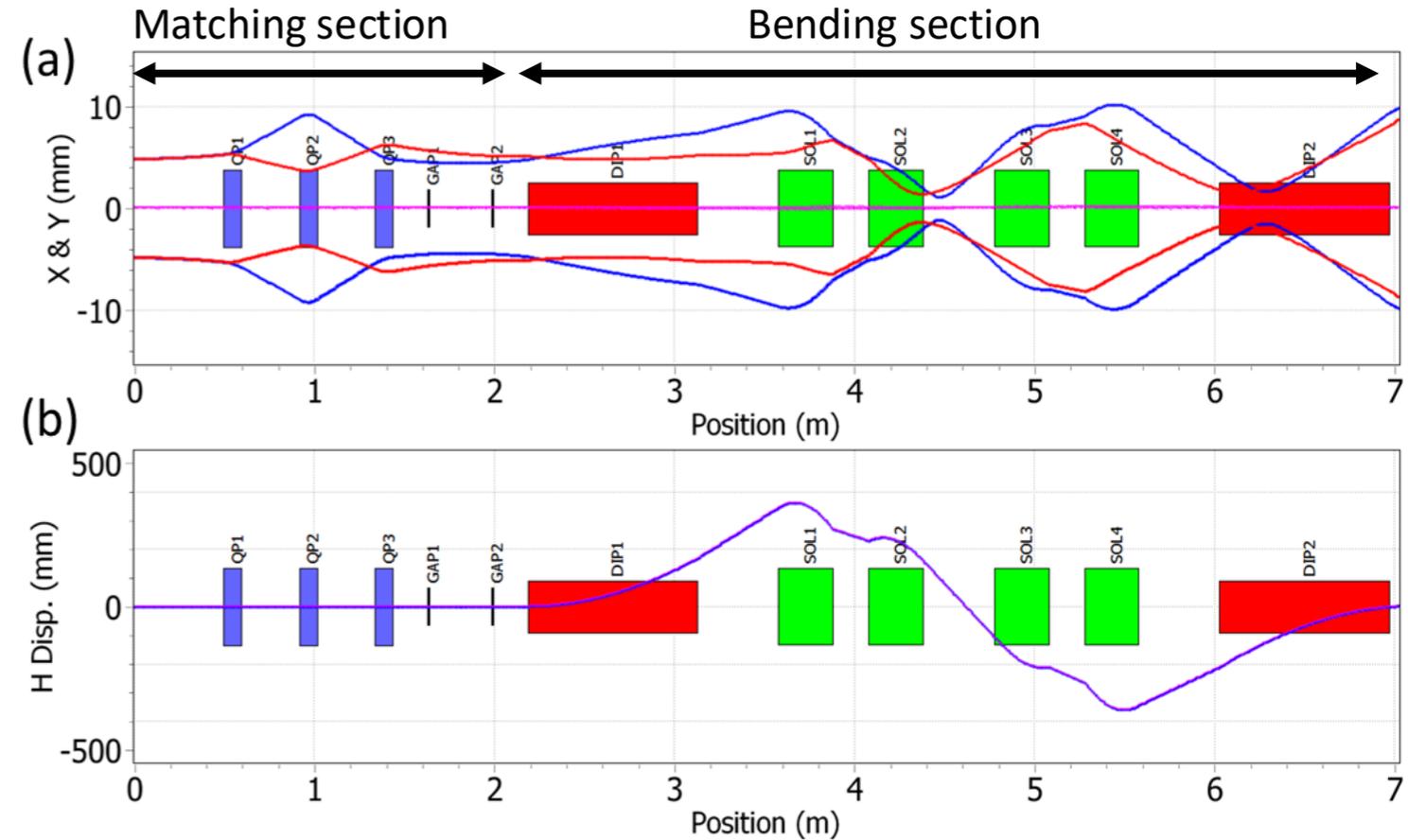
Bending section:

- **Achromatic**: using two **45-degree double switch dipoles** and four **superconducting solenoids** (same type as HWR and SSR sections)

Main parameters of the MEBT-2

Element[1]	Length (mm)	Gradient (T/m), Field (T), Effective voltage(kV)
QP1	100	-7.9
QP2	100	14.3
QP3	100	-10.2
Gap-1 & 2	300	145
DIP 1 & 2	942	0.5
Sol-1 & 4	300	2.9
Sol-2 & 3	300	-2.8

[1] QP stand for quadrupole, Gap for buncher cavity, DIP for double switch dipole, and Sol for solenoid.

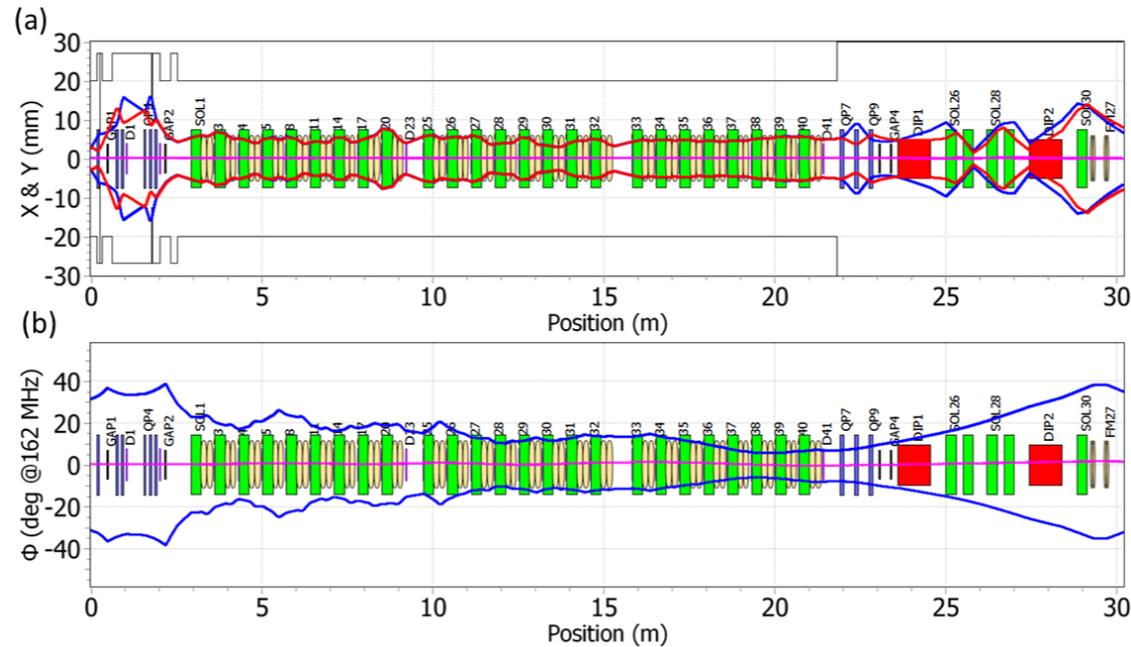
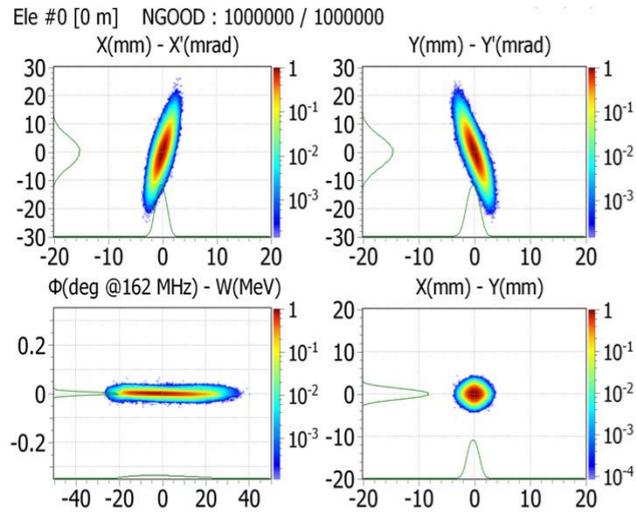


Total length: ~ 7 m
 Transverse distance: > 5.4 m

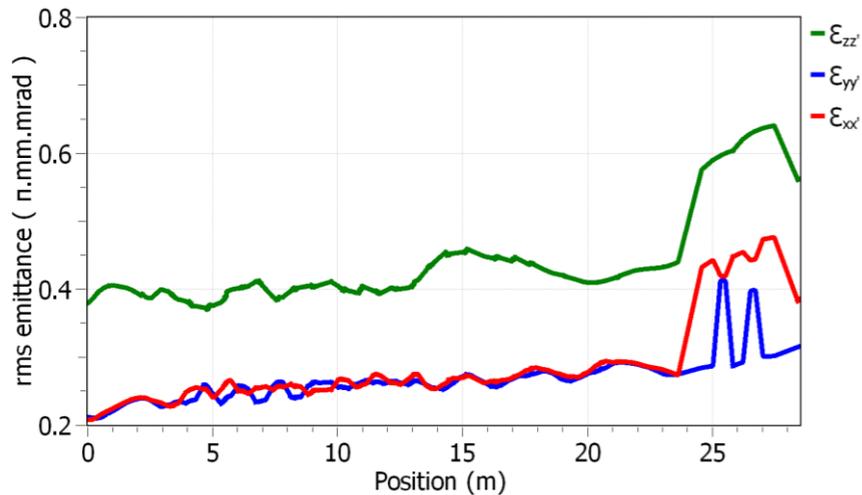
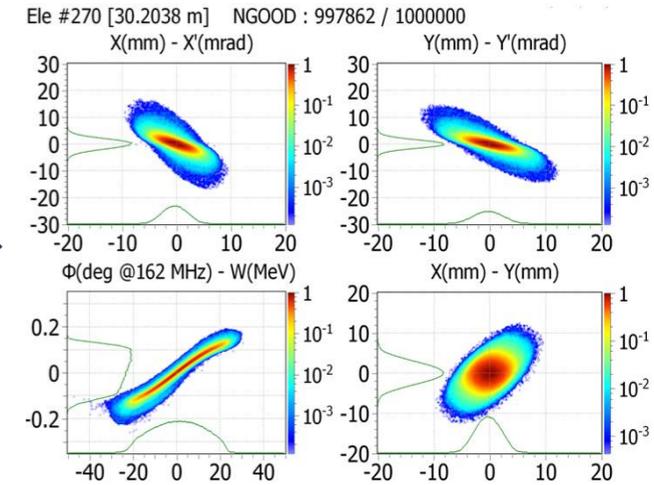
Injector beam dynamics studies

MEBT to first SSR1 period:

Input distribution



Output distribution



No beam losses [1] were registered, but the rms emittance growth at the MEBT-2 section was about 33%

[1] The beam that is scrapped by the collimators at the MEBT are not considered beam loss.

JAEA Dump line-1 design and beam dynamics results

Bending section:

- **Achromatic:** using two **45-degree double switch dipoles** and four **superconducting solenoids** (same as MEBT-2)

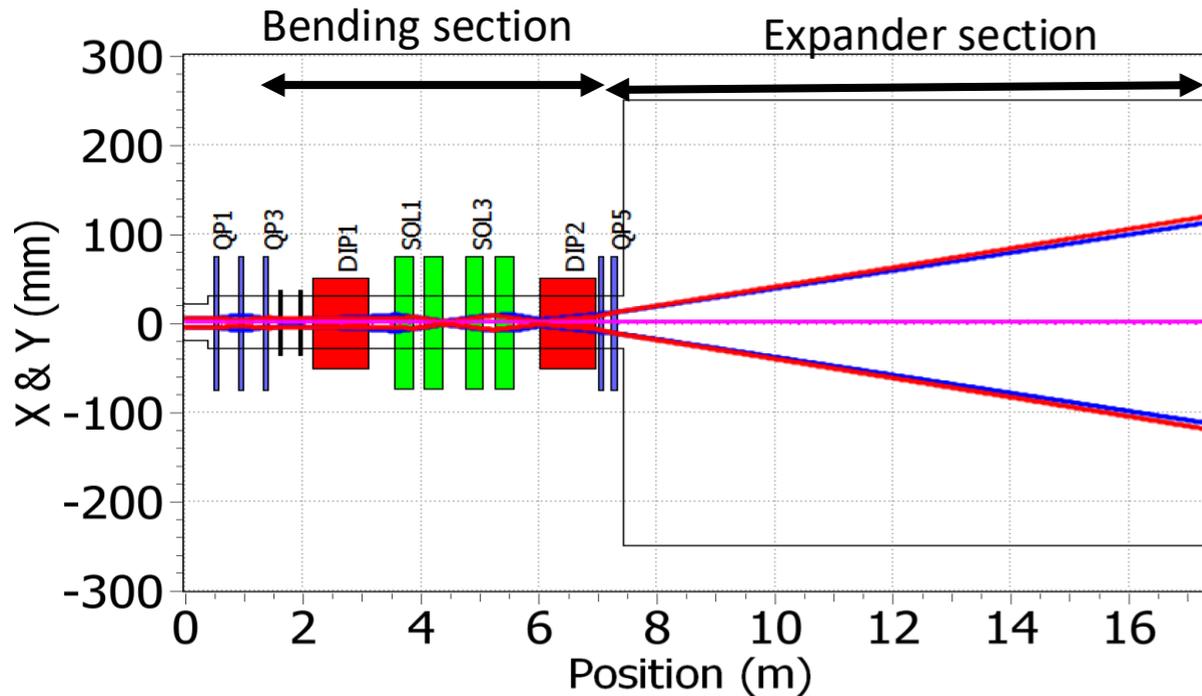
Expander section:

- **Doublet quadrupoles** and **10-m drift space**

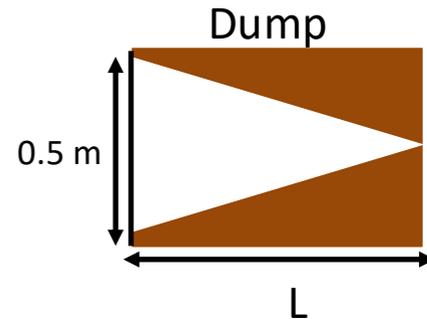
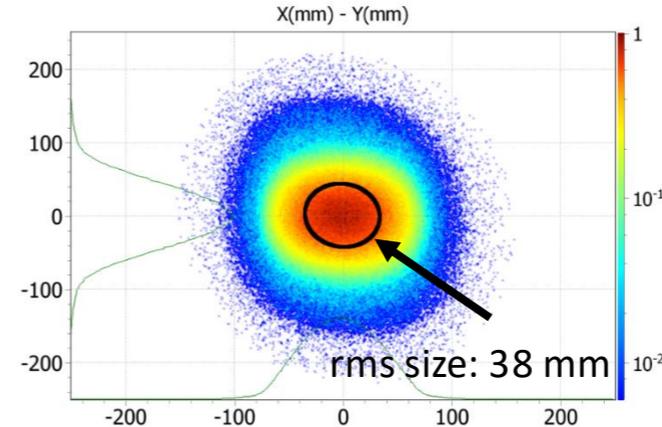
Main parameters of the Dump line-1

Element [1]	Length (mm)	Gradient (T/m), Field (T)
DIP 1 & 2	942	0.5
Sol-1 & 4	300	2.9
Sol-2 & 3	300	-2.8
QP4	100	3.4
QP5	100	-3.1

[1] DIP for double switch dipole, Sol for solenoid, and QP stand for quadrupole.



Beam size at the dump



For a 1.7 kW beam:

- The peak power density is **4.6 W/cm²** for a 1-m length dump (two order lower than other high power beam dumps)

Conclusions

- To achieve **high availability ADS linac operation**, we pursue **hot standby** redundancy at the **low-energy part**, referred to as the injector.
- **Hot standby** operation introduces new **challenges** in **beam transportation** from the low-energy part to the high-energy one. Additionally, it imposes requirements of **transverse space for shielding** and **high-power beam dumps**.
- A **double achromatic** design **facilitates beam transport** to the high-energy section or the beam dump. Furthermore, using a **pulse mode** for the hot standby part reduces beam power dump, **simplifying the dump** design.
- The **current injector design meets the requirements** of zero beam loss, sufficient shielding space, and reasonable peak power density in the dump.