ROBUST AND COMPACT DESIGN OF A 30-MW BEAM TRANSPORT LINE FOR AN ACCELERATOR-DRIVEN SUBCRITICAL SYSTEM

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Goal

- Accelerator-driven system subcritical systems (ADS) are an advanced option to face the problem of nuclear waste storage.

- The beam transport to the target (BTT) carries out the beam from the end of the linac to the beam windows and onto the spallation target, with specified beam characteristics, performance, and design considerations.

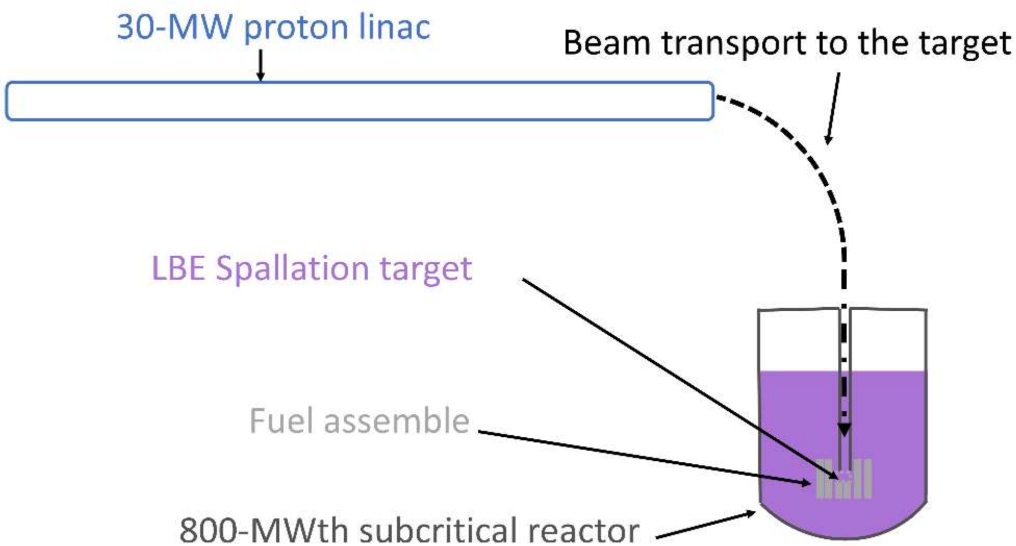

Fig.1: JAEA-ADS scheme.

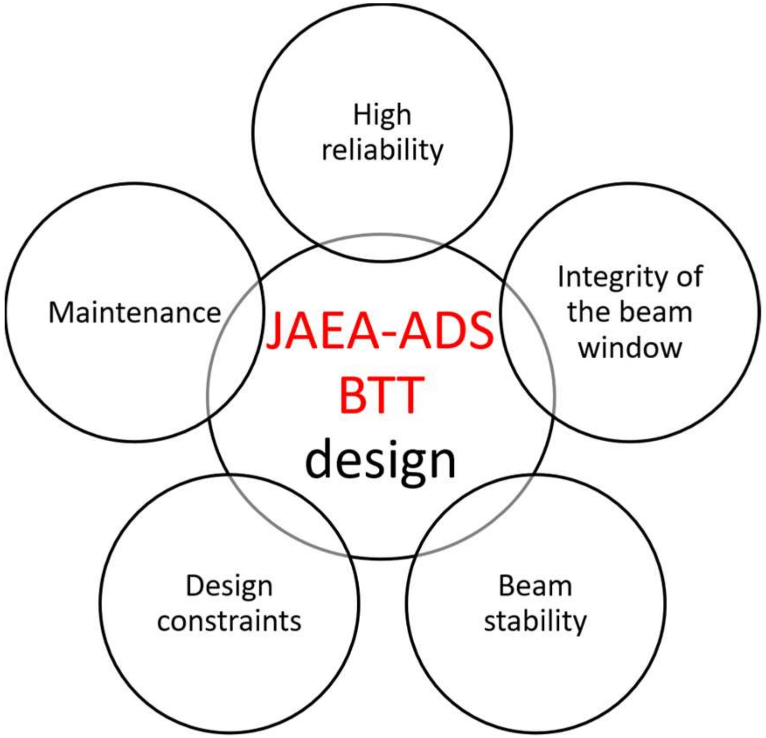

Fig.2: JAEA-ADS BTT requirements.

Introduction

The BTT must transport a 30-MW with high-reliability and fulfill all the requirements of Table 1 [1-3].

Table 1: Main characteristics of the beam transport to the target for the JAEA-ADS project

Parameter	
Particle	Proton
Beam current (mA)	20
Beam energy (GeV)	1.5
Beam power (MW)	30
Beam loss outside the reactor part (W/m)	< 1
Beam power stability	$\pm$ 1%
Beam energy stability	$\pm$ 1%
Peak current density (μA/mm^2)	< 0.3
Footprint stability at the beam window	better than $\pm$ 10%
Final beam pipe aperture(mm)	< 450
Length (m)	≈ 27

Thus, we adopted a robust and compact design to satisfy the specifications.

[1] T. Sugawara and K. Nishihara, private communication, Nov. 2021.
[2] H. Iwamoto et al., "Radiation shielding analysis of the upper structure of an accelerator-driven system", JAEA, Tokai, Japan, Rep. JAEA-Research 2021-012, Dec. 2021 (Japanese).
[3] T. Sugawara et al., "Conceptual Design Study of Beam Window for Accelerator-Driven System", J. Nucl. Sci. Techol., 47, 953 (2010).

Design considerations

- Compact:
  - Decreasing the number of element, the reliability is increased for a series configuration.
  - Design reactor.
- Robust:
  - Beam stability.
- Simple:
  - Avoid complex or risky configurations that are prone to error or harmful failures.
- Beam window feasibility:
  - Low beam peak density.
- Maintenance:
  - Confined the beam losses inside the reactor part.
  - Dipole aperture are set to 100 mm to allow the easy exchange of the fuel.
- Among others…

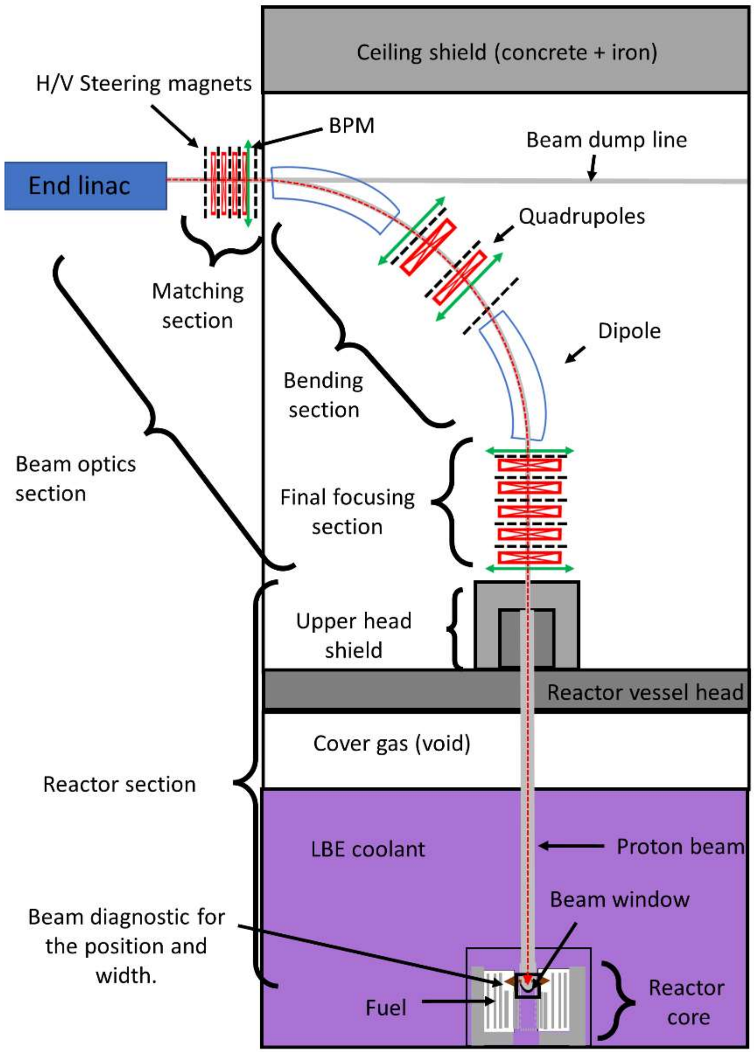

Fig.3. Schematic view of the JAEA-ADS BTT.

BTT beam optics

- Information of the elements that composes the BTT and its envelopes.

Table 2: Magnet parameters that composed the beam transport to the target. For the quadrupoles, the gradient is presented. The positive sign in the quadrupole gradients indicates that the beam is focused on the x direction

Element	Length (mm)	Gradient (MW)/ Bfield (T)
Quad1	80	11.69
Quad2	80	-2.52
Quad3	80	-1.08
Quad4	80	-13.99
Dipole1	3543	1.60
Quad5	300	-13.01
Quad6	300	1.58
Dipole2	3543	1.60
Quad7	300	-12.55
Quad8	300	4.55
Quad9	300	14.79
Quad10	300	14.99
Quad11	300	14.85

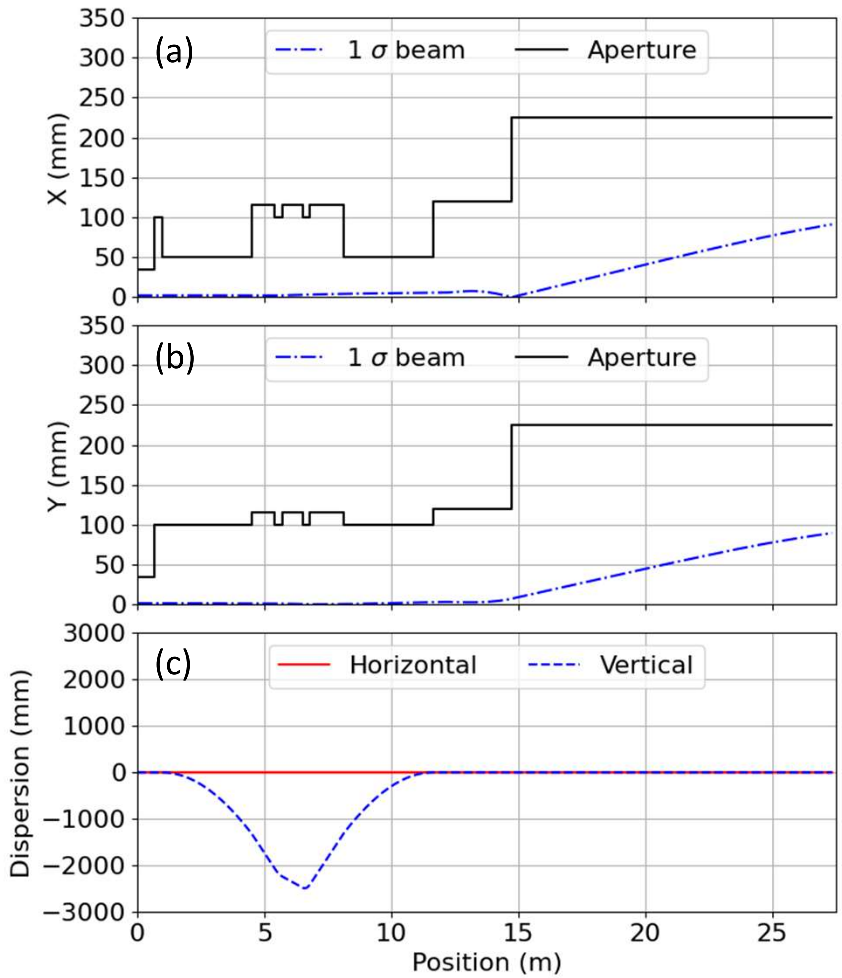

Fig.4. Horizontal (a), vertical (b) rms size and dispersion function (c) along the BTT.

BTT baseline design

- Smooth beam scraping confined in the reactor part, where it has proper shielding.
- The beam profile has a lower peak and lower percentage of beam scraping than the accepted Gaussian profile [1].

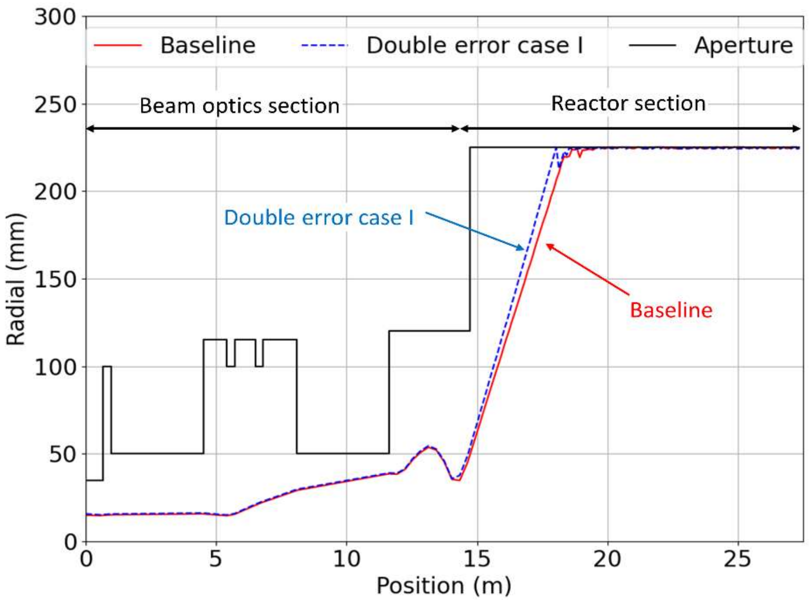

Fig.5. Maximum transverse envelope for the baseline and the double error case.

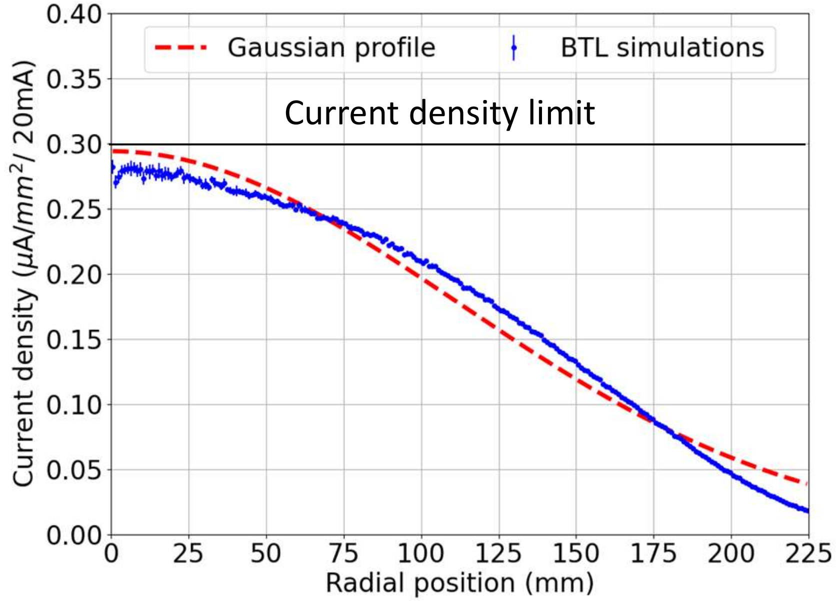

Fig.6. Radial current density from the beam tracking simulations and the accepted Gaussian profile.

[1] T. Sugawara et al., "Conceptual Design Study of Beam Window for Accelerator-Driven System", J. Nucl. Sci. Techol., 47, 953 (2010).

Errors

- To achieve a stable beam operation, the BTT must be evaluated in the presence of errors to improve its design.
- Errors are divided into statics (long time) and dynamics (jitters).
- Error for the components that integrate the BTT (elements errors) and from the beam delivered for the JAEA-ADS linac (input beam errors)
- The below tables show the element errors based on the JAEA-ADS linac [1] and other beam transport lines [2].

Table 3: Summary of the static element errors for the beam transport to the target

Element	Quadrupole	Dipole
$\Delta x, \Delta y$ (mm)	0.45	0.5
$\Delta\theta x, \Delta\theta_y$(mrad)	1.2	2.4
$\Delta\theta_z$ (mrad)	6	2.4
Magnet field (%)	0.5	0.05

Table 4: Summary of the dynamic element errors for the beam transport to the target

Element	Quadrupole	Dipole
$\Delta x, \Delta y$ (mm)	0.01	0.01
$\Delta\theta x, \Delta\theta_y$ (mrad)	0.01	0.02
$\Delta\theta_z$ (mrad)	0.06	0.02
Magnet field (%)	0.05	0.005

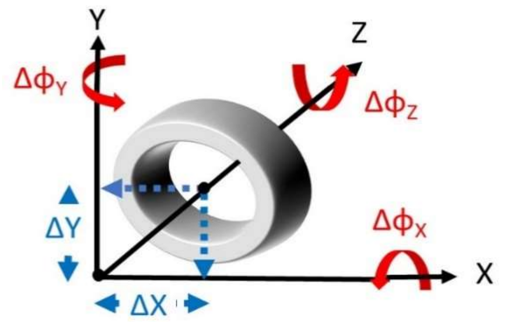

Fig.7. Misalignments errors. The blue arrows show the transverse offset. The red arrows are the phase rotation errors.

[1] B. Yee-Rendon, et al, "Design and beam dynamic studies of a 30-MW superconducting linac for an accelerator driven subcritical system" Phys. Rev. ST. Accel. Beams 24, 120101 (2021).
[2] B. Branhas et al, "Design, manufacturing and tests of the LIPAc high energy beam transport line", Nucl. Fusion 61 (2021) 015001.

Input beam errors

- To increase the reliability of the system, JAEA-ADS adopted local compensated schemes to achieve a fast beam recovery [1].
- Compensation schemes were developed for single SRF cavity failures (SSRFC), multiple SRF cavity failures (MSRFC), and magnet failures (Magnet).

Table 5: Summary of the input beam errors for the BTT

Parameters	SSRFC	MSRFC	Magnet	Dynamic
$\Delta x, \Delta y$ (mrad)	1	1	1	0.02
$\Delta\phi$ ((deg))	1	1	1	0.02
$\Delta x', \Delta y'$ (mrad)	1	1	1	0.02
Δ Beam energy (keV)	0.4	0.4	0.4	0.1
$(\Delta\epsilon/\epsilon_0)_t$[2] (%)	4	28	27	1
$(\Delta\epsilon/\epsilon_0)_l$ (%)	28	192	21	1
M_t (%)[3]	5	15	14	1
M_l (%)	11	28	14	1

[1] B. Yee-Rendon *et al.*, "Beam dynamics studies for fast beam trip recovery of the Japan Atomic Energy Agency accelerator driven subcritical system", *Phys. Rev. Accel. Beams.*, vol. 25,080101(2022).
[2] The final normalized rms emittance growth with respect to the baseline.
[3] The final beam mismatch with respect to the baseline.

Error studies

- The error studies consisted of 1000 independents runs with more than 9 million macroparticles.
- In each run, the amplitude for each of the errors associated with each element was chosen independently.
- The types of errors are divided into statics and dynamics.
- We simulated double errors: errors in the elements (misalignments, etc.) + errors in the input beam (emittance growth, mismatch).

Table 6: Double error description

Case	Type	Definition
I	Static	Element errors + SSRFC input beam errors
II	Static	Element errors + MSRFC input beam errors
III	Static	Element errors + Mag input beam errors
IV	Dynamic	Element errors + input beam errors

Error case I

- Error case I : Static element error + input error from compensation of single SRF cavity failures.
- This case is considered the most likely error case among all.

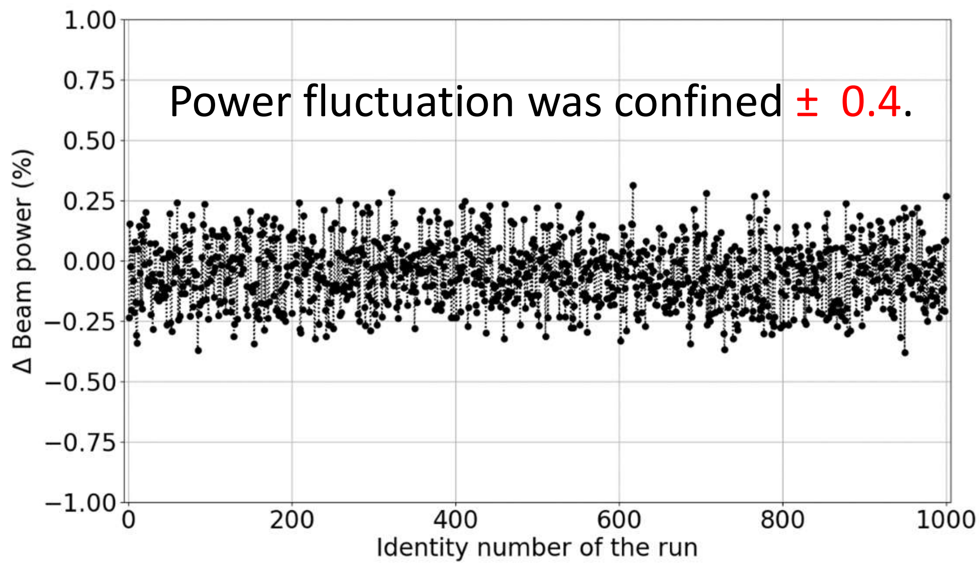

Fig.8. Beam power fluctuations to the baseline for double error case I.

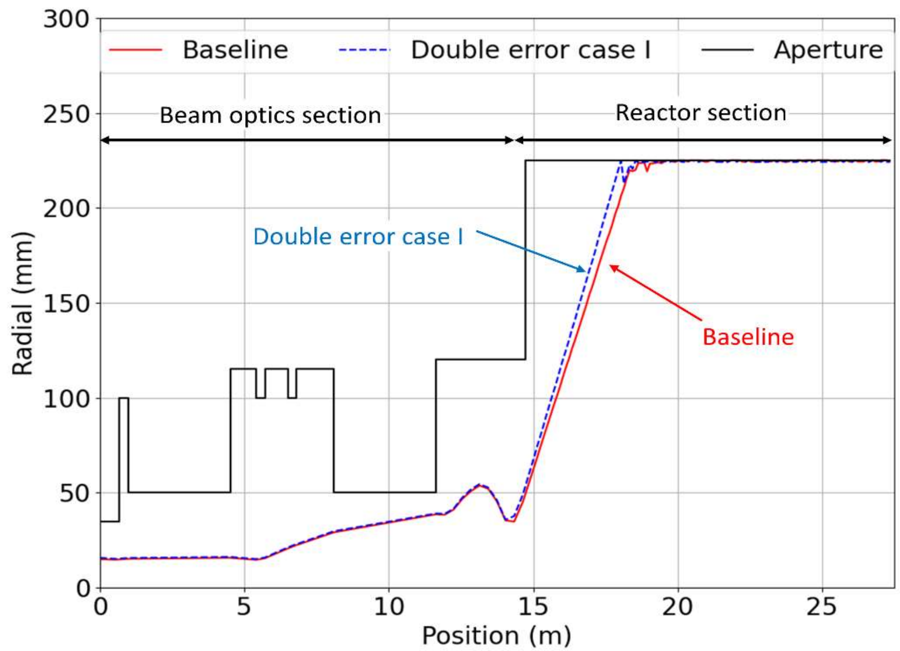

Fig.9. Maximum transverse envelope for the baseline and the double error case.

Summary of the beam stability for double errors

The required target stability is showed by the red lines in the subplots.

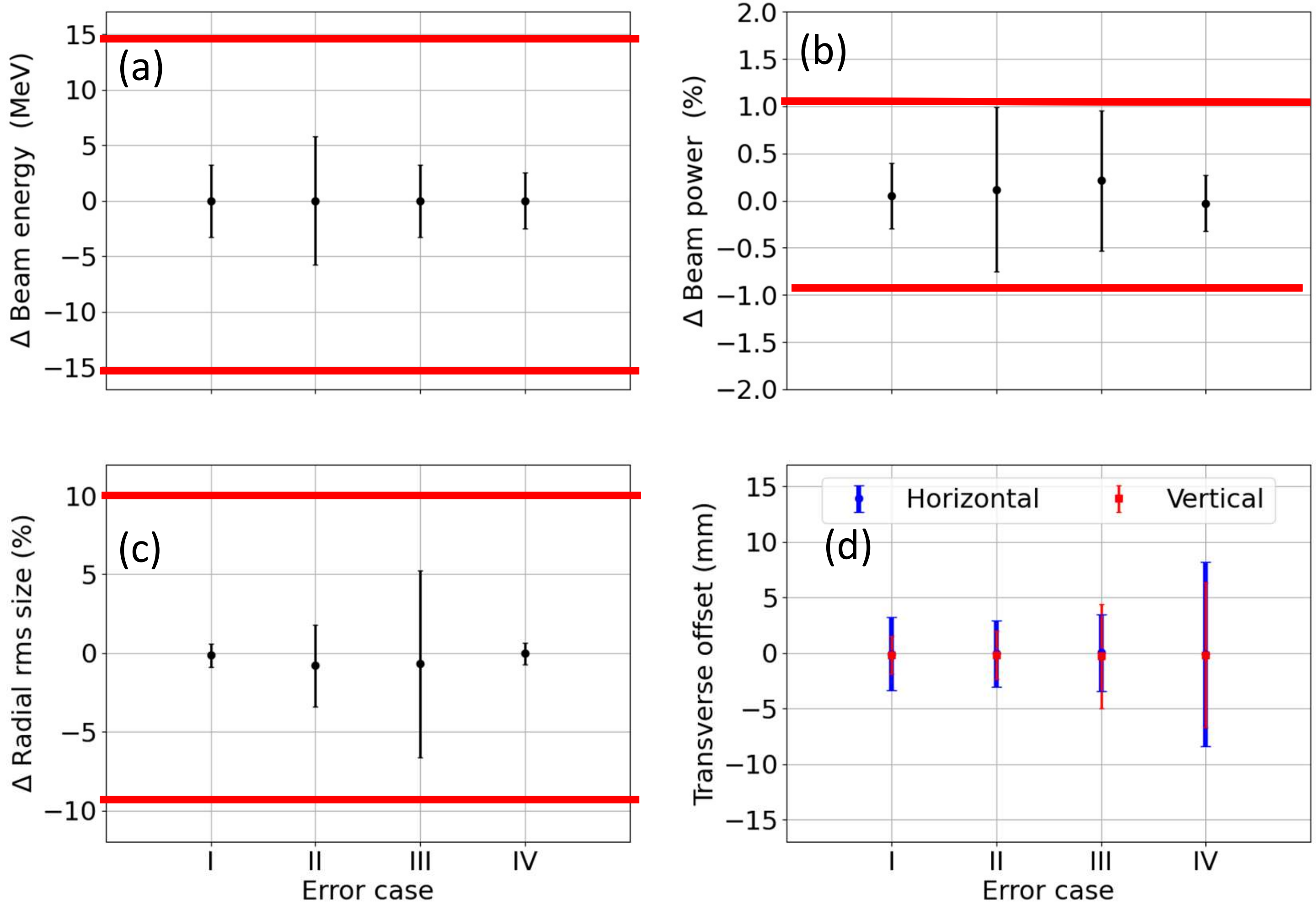

Fig.10. Summary of the beam error degradation for different error cases defined in Table. The plot (a) is the difference in kinetic energy, (b) beam power, (c) radial rms size, and (d) transverse offset. The error bars denote a 99% confidence interval.

Summary

- The JAEA-ADS BTT efficiently transports a 30-MW beam from the end of the linac to the beam window while fulfilling stringent conditions of beam stability and engineering specifications.
- A suitable beam profile is delivered, which satisfies the feasibility of the beam windows and small beam scraping.
- The error analysis showed that the BTT meets the stringent beam window stability of the JAEA-ADS [1].
- In the future, beam expander methods (non-linear optics and beam rastering) will be evaluated.

[1] B. Yee-Rendon et al., "Beam physics design of a 30-MW beam transport to the target for an accelerator-driven subcritical system", JINST, vol. 17, P10005 (2022).