Quantitative Evaluation of Beam Loss Based on Radiation Detection in High-Duty Beam Commissioning of LIPAc RFQ

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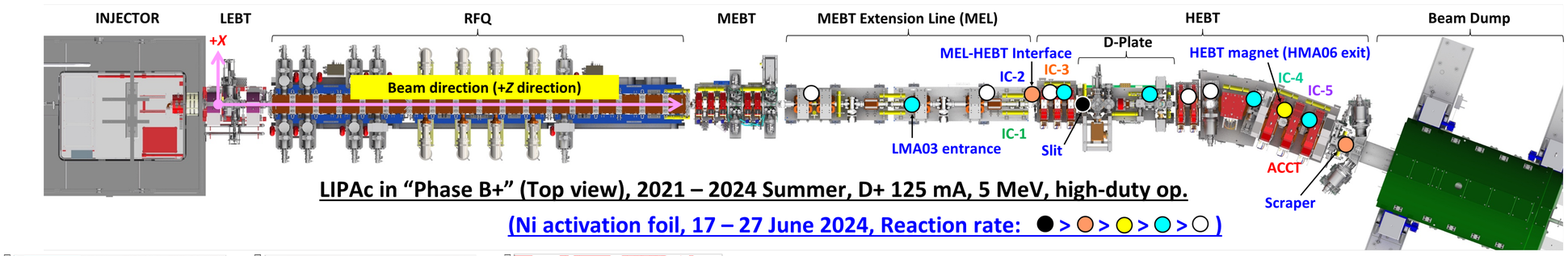
Abstract

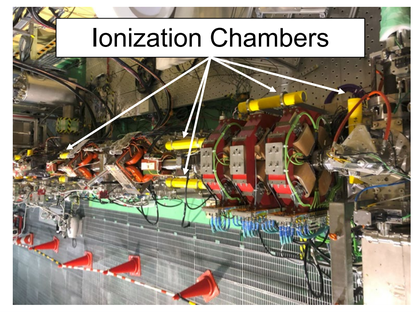
Using the LIPAc deuteron accelerator, beam loss characteristics were quantitatively assessed through multiple radiation measurement techniques. Significant losses of high-energy deuterons were observed at the interface between the MEBT Extension Line (MEL) and the HEBT for core particles, and at the HEBT magnet for halo particles. Portable HPGe measurements indicated that the deuteron energy of lost halo particles was lower than that of core particles. Furthermore, activation foil measurements revealed beam losses of approximately 100 μA for halo and 20 μA for core particles.

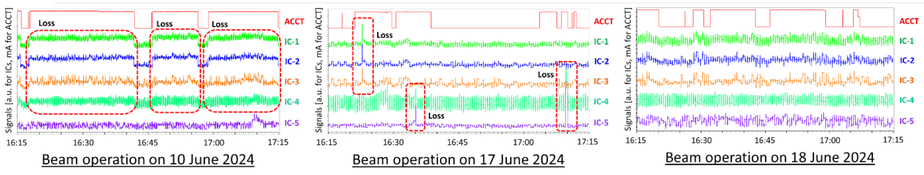
Introduction



LIPAc in "Phase B+" (Top view), 2021 – 2024 Summer, D+ 125 mA, 5 MeV, high-duty op.

(Ni activation foil, 17 – 27 June 2024, Reaction rate: ● > ● > ● > ● > ○)





Beam operation on 10 June 2024 | Beam operation on 17 June 2024 | Beam operation on 18 June 2024

Qualitative beam loss measurements using ionization chambers (ICs)

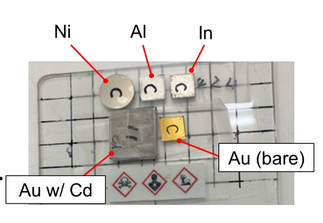
Qualitative observations using ionization chambers (ICs) revealed unexpected beam losses during the beam campaign.

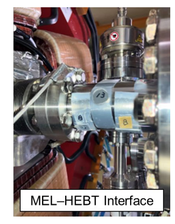
- While dose rate and Ni activation foil measurements were intermittently performed, comprehensive quantitative assessment of beam loss and corresponding deuteron energy were not carried out during the beam campaign.

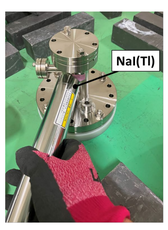
This study aims to quantitatively characterize beam loss and to examine the spacial differences in the loss behavior of core and halo particles.

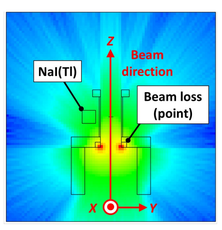
Method

1. **NaI(Tl) survey meter**: Daily dose rate measurements on the beamline surface enabled identification of beam loss locations. Quantitative analysis of dose rate differences pre- and post-operation provided compelling evidence of beam loss. Comparison between experimental data and MCNP simulations allowed estimation of both the beam loss magnitude and associated deuteron energy.
2. **Portable HPGe detector**: In-situ measurement near the beamline surface enabled estimation of lost deuteron energies.
   The production of Tc-96 (4.3 d), Co-55 (18 h), and Cu-61 (3.3 h), resulting from interactions between lost deuterons and SS beam pipes, were quantitatively compared with FISPACT-II calculations based on the TENDL-2017 nuclear data library, facilitating deuteron energy estimation.
3. **Activation foil method**: Al, Ni, In, and Au foils were placed at multiple locations along the beamline surface. These foils were activated by secondary neutrons generated through interactions between lost deuterons and SS beam pipes, with activation levels depending on the neutron energy spectrum.

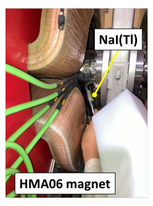


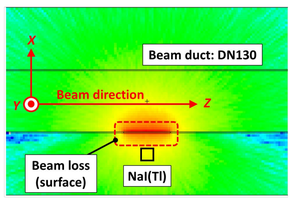


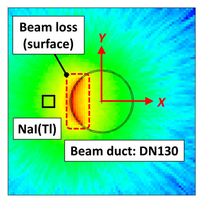




(a) MEL-HEBT Interface

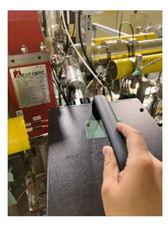






(b) HEBT magnet (HMA06 exit)

NaI(Tl) survey meter



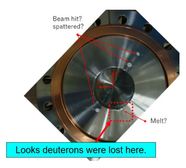
Portable HPGe detector

Activation foil method

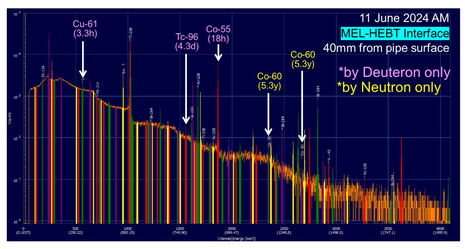
Foil	Dimension	Reaction	Threshold [MeV]	Half-life
Aluminium	10 x 10 x t1 mm	Al-27(n,α)Na-24	4.9	15.0 h
Nickel	φ15 x t1 mm	Ni-58(n,p)Co-58	1.9	71.6 d
Indium	10 x 10 x t1 mm	In-115(n,n')In-115m	0.5	4.5 h
Gold (bare and w/ Cd cover)	10 x 10 x t0.05 mm (Cd cover: t0.5 mm)	Au-197(n,γ)Au-198	0 (Exoergic)	2.7 d

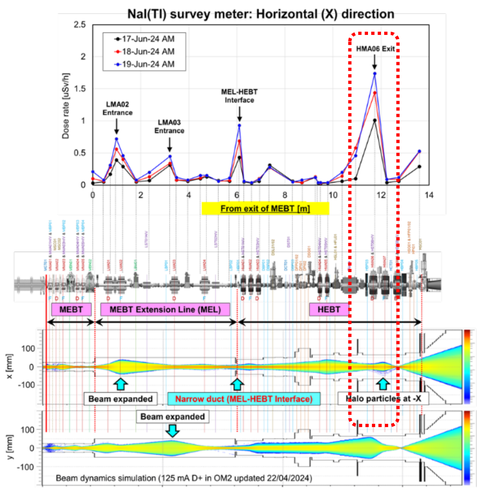
Results & Discussions

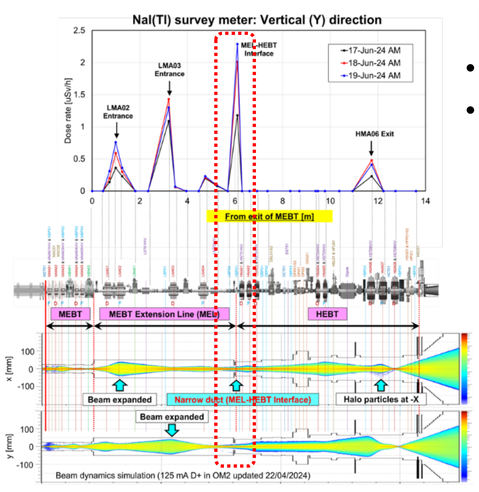
NaI(Tl) survey meter (Beam: June 17, 18)



- Significant beam losses were observed at the **MEL-HEBT interface** (-*Y* direction) and the **HEBT magnet** (**HMA06 exit**, -*X* direction).
- **At the MEL-HEBT interface**, the edge of the flange was found to be melted by **core particles**, suggesting that it may have unintentionally worked as a collimator due to the narrow duct size.
- **At the HMA06 exit**, the beam loss was attributed to **halo particle** generation, as indicated by beam dynamics simulations.







Dose rate change at the MEL-HEBT interface (Calc: 10 μA)

No.	Beam	Dose rate [μSv/h] Measurement	Calculation 4 MeV	Calculation 5 MeV	Calculation 6 MeV
(0)	June 16	1.18	1.18 (= Measurement)	1.18	1.18
(1)	June 17	2.01	1.24	1.39	1.64
Difference: (1) – (0)		0.83±0.35	0.06	0.21	0.46
(2)	June 18	2.29	1.32	1.67	2.29
Difference: (2) – (1)		0.28±0.46	0.08	0.28	0.65

Dose rate change at the HEBT magnet (HMA06 exit, Calc: 10 μA):

No.	Beam	Dose rate [μSv/h] Measurement	Calculation 4 MeV	Calculation 5 MeV	Calculation 6 MeV
(0)	June 16	1.01	1.01 (= Measurement)	1.01	1.01
(1)	June 17	1.44	1.28	1.89	2.85
Difference: (1) – (0)		0.43±0.26	0.27	0.88	1.84
(2)	June 18	1.74	1.66	3.11	5.43
Difference: (2) – (1)		0.30±0.34	0.38	1.22	2.58

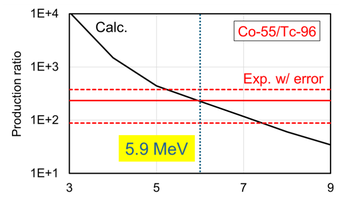
Portable HPGe detector (Beam: June 10)

- At the HMA06 exit, **Tc-96** signal was not detected (< 3σ), while that was clearly detected at the MEL-HEBT interface.
- The detection limit of Tc-96 was estimated to be 63 Bq/kg from the measured spectrum. Using TENDL-2017 data of Mo-95(d,n)Tc-96 and beam loss estimated based on NaI(Tl) measurements:
  → Deuteron energy of **halo particles** lost at HMA06 exit must be **< 3.5 MeV**.

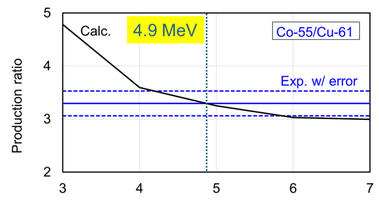
[1] Hirosawa, K. et al., JINST **19** (2024) T05002.

However, deuteron energy of **core particles = 5.0 – 5.1 MeV** measured using the TOF technique in the previous study [1].

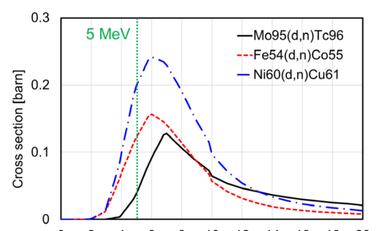
✓ Production ratios of Tc-96, Co-55, and Cu-61 also indicated a tendency for the energy of deuterons lost at the MEL-HEBT interface are higher than that at the HMA06 exit.



MEL-HEBT interface



HMA06 exit



Deuteron reaction in TENDL-2017

Activation foil measurement (Beam: June 18)

Foil	Reaction rate [atoms/s] MEL-HEBT interface Measurement	MEL-HEBT interface Calculation 5 MeV 20 μA	HMA06 exit Measurement	HMA06 exit Calculation 3.5 MeV 100 μA
Al	N.D. (≤1.6×10^{2})	1.2×10^{1}	N.D. (≤1.3×10^{2})	2.3×10^{0}
Ni	$1.2\pm0.2\times10^{4}$	1.1×10^{4}	$8.2\pm1.2\times10^{3}$	7.7×10^{3}
In	$4.2\pm0.1\times10^{3}$	4.6×10^{3}	$3.0\pm0.1\times10^{3}$	3.2×10^{3}
Au (bare)	$7.8\pm1.3\times10^{2}$	1.5×10^{2}	$3.1\pm0.2\times10^{3}$	8.5×10^{1}
Au w/ Cd	$7.1\pm1.3\times10^{2}$	–	$2.6\pm0.2\times10^{3}$	–

MEL-HEBT interface

- When the deuteron energies = **5 MeV, beam loss = 20 μA.**
- Good agreement with NaI(Tl) measurements.

HMA06 exit

- When the deuteron energies = **3.5 MeV, beam loss = 100 μA.**
- Discrepancies in Factor 3 from the NaI(Tl) results in dose rate.
  → Calculation assumptions may need to be corrected.

The first quantitative demonstration of beam losses of approximately 20 μA at the MEL-HEBT interface and 100 μA at the HMA06 exit, providing a critical benchmark for future beam transmission diagnostics and operational optimization.
A clear tendency for halo particles to have lower energy (3.5 MeV) than core particles (5.0 – 5.1 MeV [1]) was observed, which may be used to validate beam dynamics simulation.

Conclusion

In this study, beam loss characteristics were quantitatively evaluated using multiple radiation diagnostics in the LIPAc deuteron accelerator. Core particles lost at the MEL-HEBT interface exhibited higher deuteron energy than halo particles lost at the HEBT magnet (HMA06 exit). However, the experimental results indicated that significantly larger quantities of halo particles were lost compared to core particles. The first quantitative demonstration of beam losses at the LIPAc provides a critical benchmark for future beam loss diagnostics and operational optimization.

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