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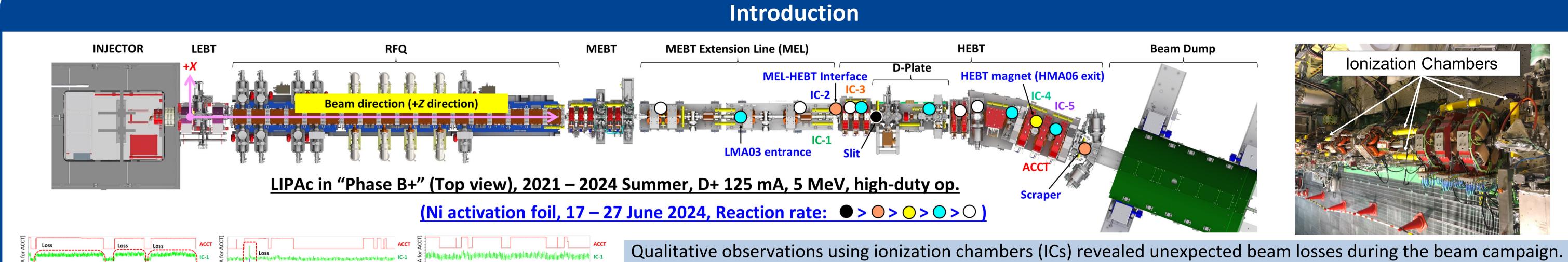
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Quantitative Evaluation of Beam Loss Based on Radiation Detection in **High-Duty Beam Commissioning of LIPAc RFQ**

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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 after the HEBT bending magnet for halo particles. Portable HPGe measurements indicated that the deuteron energy of halo particles was lower than core particles. Furthermore, activation foil measurements revealed beam losses of approximately 20 µA for core and 100 µA for halo particles.

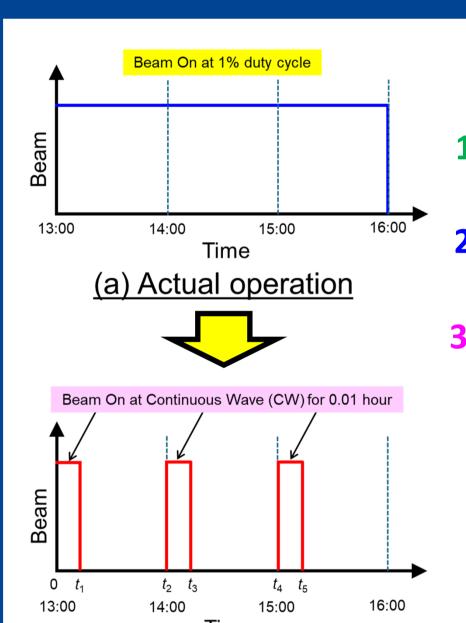


Qualitative beam loss measurements using Ionization Chambers (ICs)

- Detailed and quantitative beam loss analyses were not conducted until the end of the beam campaign.
- Nal(TI), portable HPGe, and activation foils measurements indicated significant beam losses at specific locations.

The objective of this is to quantitatively characterize beam loss for both core and halo particles, and to demonstrate the effectiveness of multi-modal radiation diagnostics.

Method



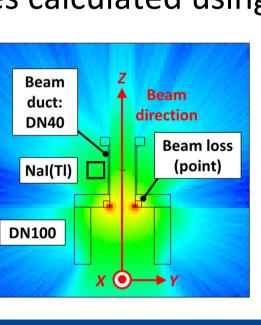
(b) Activation calculation

Pulsed beam operation operations (typically with a 1% duty cycle) during Phase-B+ were treated as short-duration continuous wave (CW) operations (e.g. 0.01 hours CW vs. 1 hour pulsed operation) in the activation analyses, considering unintentional beam interruptions caused by interlocks.

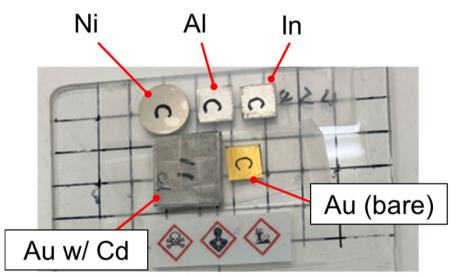
Nal(TI) survey meter: Its portability makes it an effective tool for identifying beam loss. An increase in dose rate following beam operation indicates the presence of

- beam loss. The amounts of loss was estimated by comparing measured and calculated dose rate, assuming a given deuteron energy. Portable HPGe detector: The energies of lost deuterons were estimated based on in-situ measurements of activated beamline surfaces. Differences in the cross
 - sections from the TENDL-2017 data library were used for deuteron-induced nuclear reactions producing Tc-96 (4.3 d), Co-55 (18 h), and Cu-61 (3.3 h). Activation foil method: Al, Ni, In, and Au foils (both bare and Cd-covered) were placed on the beamline surface. Beam loss was precisely estimated by comparing
- reaction rates calculated using MCNP, incorporating the latest prototype JENDL-5 deuteron sublibrary for Fe(d,xn) reactions with IRDF-2002.







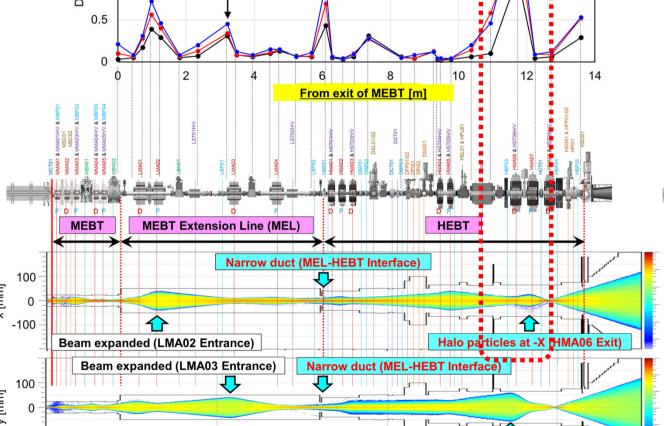


Foil	Dimension	Reaction	Threshold [MeV]	Half-life
Aluminium	10 x 10 x t1 mm	Al-27(n, α)Na-24	4.9	15.0 h
Nickel	φ15 x t1 mm	Ni-58(n,p)Co-58	1.9	71.6 d
Indium	10 x 10 x t1 mm	In-115(n,n')In-115m	0.5	4.5 h
Gold	10 x 10 x t0.05 mm	Au-197(n,γ)Au-198	0 (Exoergic)	2.7 d
(bare and w/ Cd cove	r) (Cd cover: t0.5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

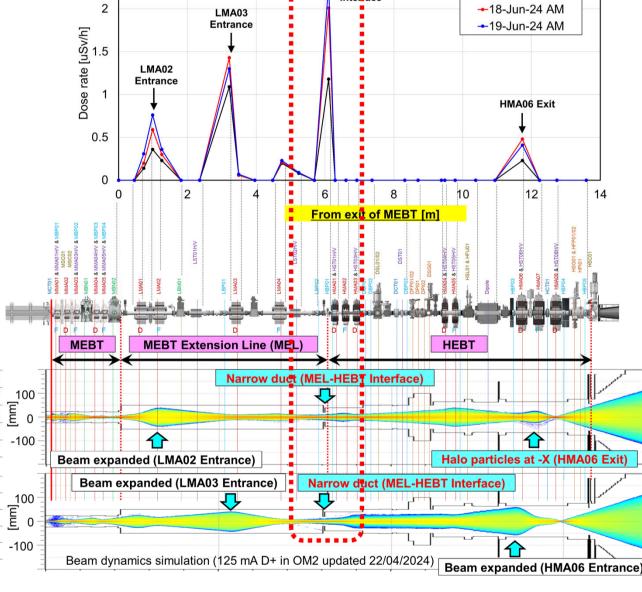
Results & Discussions

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

- Significant beam losses were observed at the following locations during Phase-B+ beam campaign:
- Regions where the beam expands transversely,
- The MEL-HEBT interface, where the beam duct narrows (from DN100 to DN40),
- The HMA06 exit, where halo particles are predicted to be generated in the -Xdirection according to beam dynamics simulations.
- Localized damage was observed in the Y-direction at the flange inside edge of the MEL-HEBT interface. This damage was attributed due to core particles (5 MeV [1]), where the pipe diameter narrows in a collimator-like fashion.
- The observed increase in dose rate at the MEL-HEBT interface suggests an average deuteron loss of approximately $10 - 40 \mu$ over a one-day beam operation, assuming a deuteron energy of 5 MeV.
- Beam loss at the HMA06 exit was attributed to halo particle generation in the energy range of 2.0 - 4.6 MeV [1], as indicated by beam dynamics simulations. [1] Hirosawa, K. et al., JINST 19 (2024) T05002.



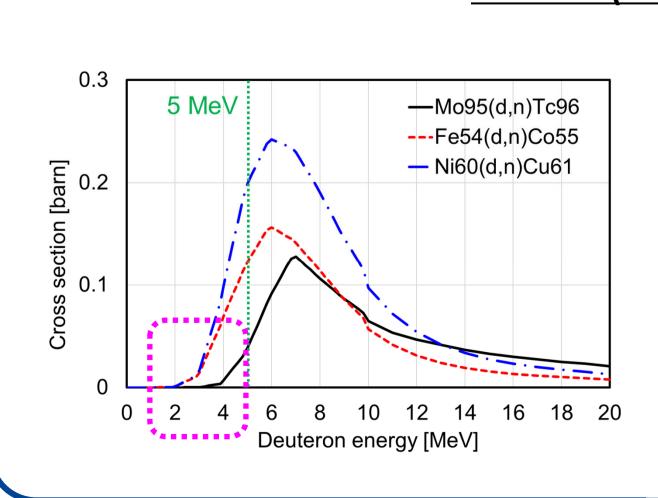
Horizontal X direction

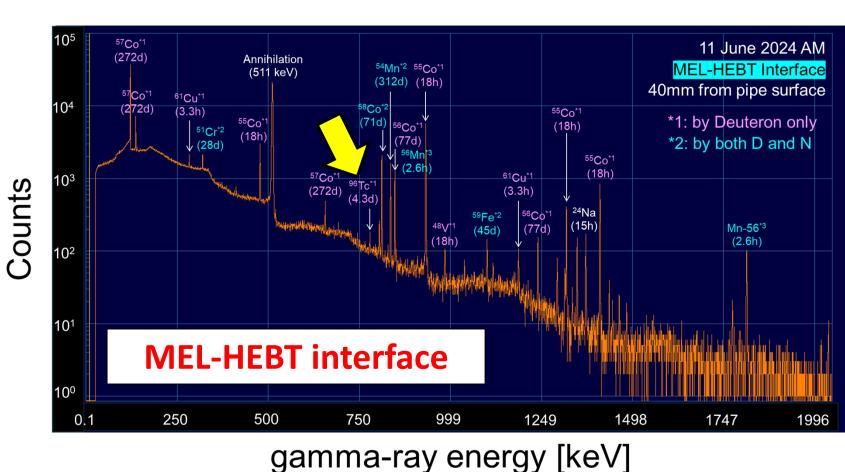


Vertical Y direction

Portable HPGe detector (Beam: June 10)

- While Tc-96, Co-55, and Cu-61 peaks were clearly detected at the MEL-HEBT interface, the Tc-96 peak was below the detection limit ($< 3\sigma$) at the HMA06 exit.
- The detection limit of Tc-96 was estimated to be 63 Bq/kg at the HMA06 exit.
- When deuteron energies of 3.3, 3.4, and 3.5 MeV were assumed at the HMA06 exit, the corresponding beam losses were estimated to be 280, 181, and 64 µA, respectively. Based on dose rate calculations using these values, the energy of deuterons lost at the HMA06 exit was estimated to be 3.4 MeV (i.e. 181 µA loss).

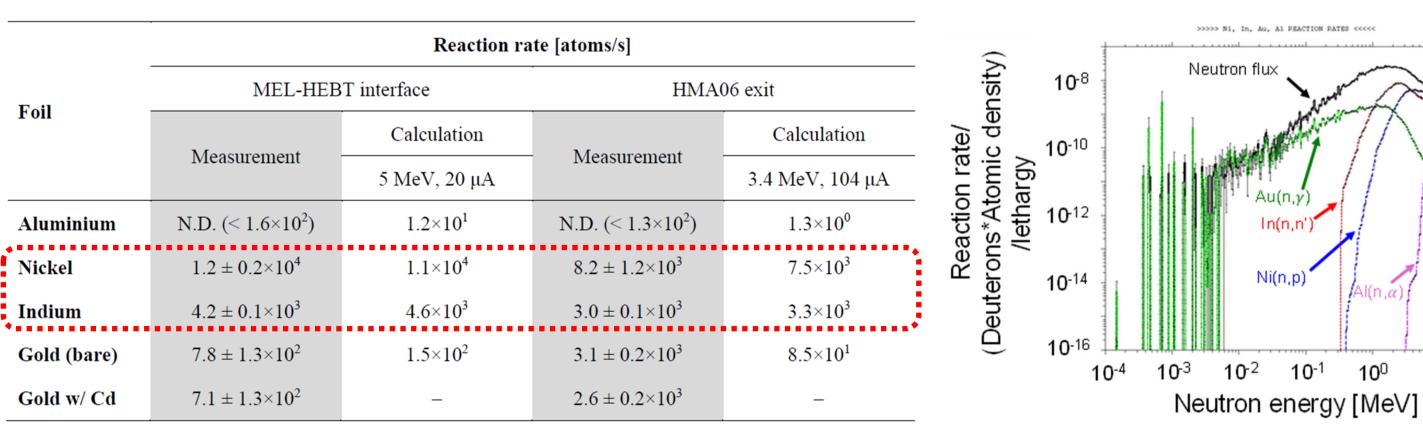




Activation foil measurement (Beam: June 18)

◆18-Jun-24 AM

→19-Jun-24 AM



- At the MEL-HEBT interface, the estimated beam loss was $18 21 \mu A$, based on daily averages over the June 18 beam operation, assuming a deuteron energy of 5 MeV for lost core particle.
- For the HMA06 exit, the estimated beam loss was $95 113 \mu A$, assuming a deuteron energy of 3.4 MeV for lost halo particles.
- These daily average losses during the June 18 beam operation correspond to deuteron loss fractions of approximately 1.6×10^{-4} and 8.3×10^{-4} , relative to the nominal 125 mA beam current, at the MEL-HEBT interface and the HMA06 exit, respectively.

Conclusion & Future works

Multi-modal radiation diagnostics for quantitative beam loss estimation demonstrated consistent loss characteristics in each measurement, in terms of both the amount and deuteron energy of core and halo particles. A significant loss of halo particles, approximately 0.1-0.2% relative to 125 mA at 3.4 MeV, was observed during the LIPAc 5 MeV beam campaign. Such substantial halo particle loss may pose more critical challenges for beam operations at higher energies, such as 9 MeV in LIPAc Phase-C/D and 40 MeV operations in IFMIF-DONES, where radiation diagnostics will play an increasingly important role.