Development of HECRAL-C: A Cryogen-Free Hybrid Superconducting ECR Ion Source for Milliampere-Level C^{4+} Ion Beam Production

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- Develop a new ECR ion source producing high-current C^{4+} beams for next generation heavy-ion therapy facility.
- A superconducting magnet (axially conduction-cooled) and a NdFeB hexapole (radial Halbach array) for 18 GHz operation.
- It was named HECRAL-C and was commissioned to produce over 1.3 emA of C^{4+} ion beams in both CW and AG modes.
- It delivers 1.2 emA C^{4+} beams to the RFQ accelerator with 0.23 π·mm·mrad normalized emittance with a compact LEBT.

Designing

Design Parameters of HECRAL and HECRAL-C

Parameters	HECRAL	HECRAL-C
f (GHz)	24.0	**18.0**
Pw (kW)	5.0	2.4
B_z (T)	3.4 - 0.5 - 1.7	2.8 - 0.4 - 1.4
B_{rad} (T)	1.4	1.2
Lm (mm)	420	400
Dp (mm)	100	100
HV (kV)	30	30
Cooling	LHe Bathing	**Conducting**

Beam parameter requirements at the RFQ entrance

Parameters	Requirements
Current	≥1.2 emA
Energy	10 keV/u
Normalized RMS Emittance	≤0.25 πmm·mrad
TWISS parameter	αx=αy=0.73, βx=βy=2.39cm/rad
Mismatch factor	≤10%

Beam parameter requirements at the DTL exit

Parameters	Requirements
Current	≥1.0 emA
Energy	4 MeV/u

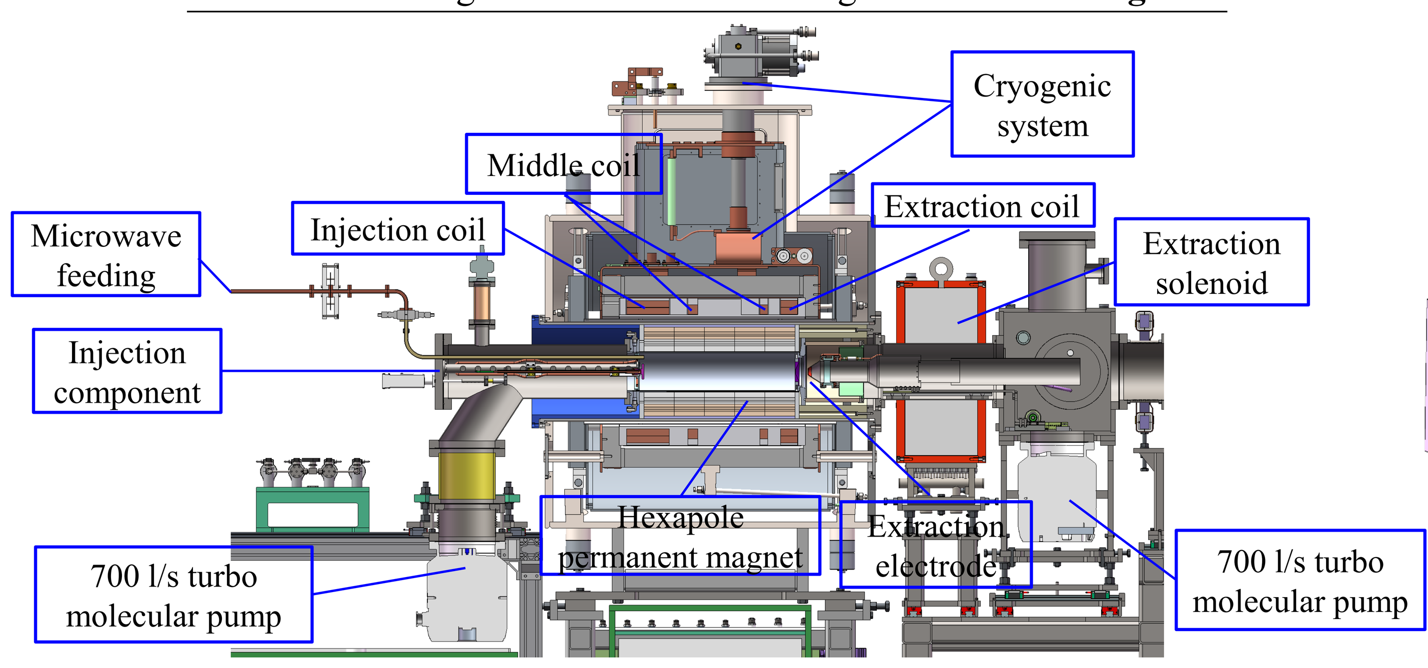


Fig. 1. Layout of HECRAL-C ion source

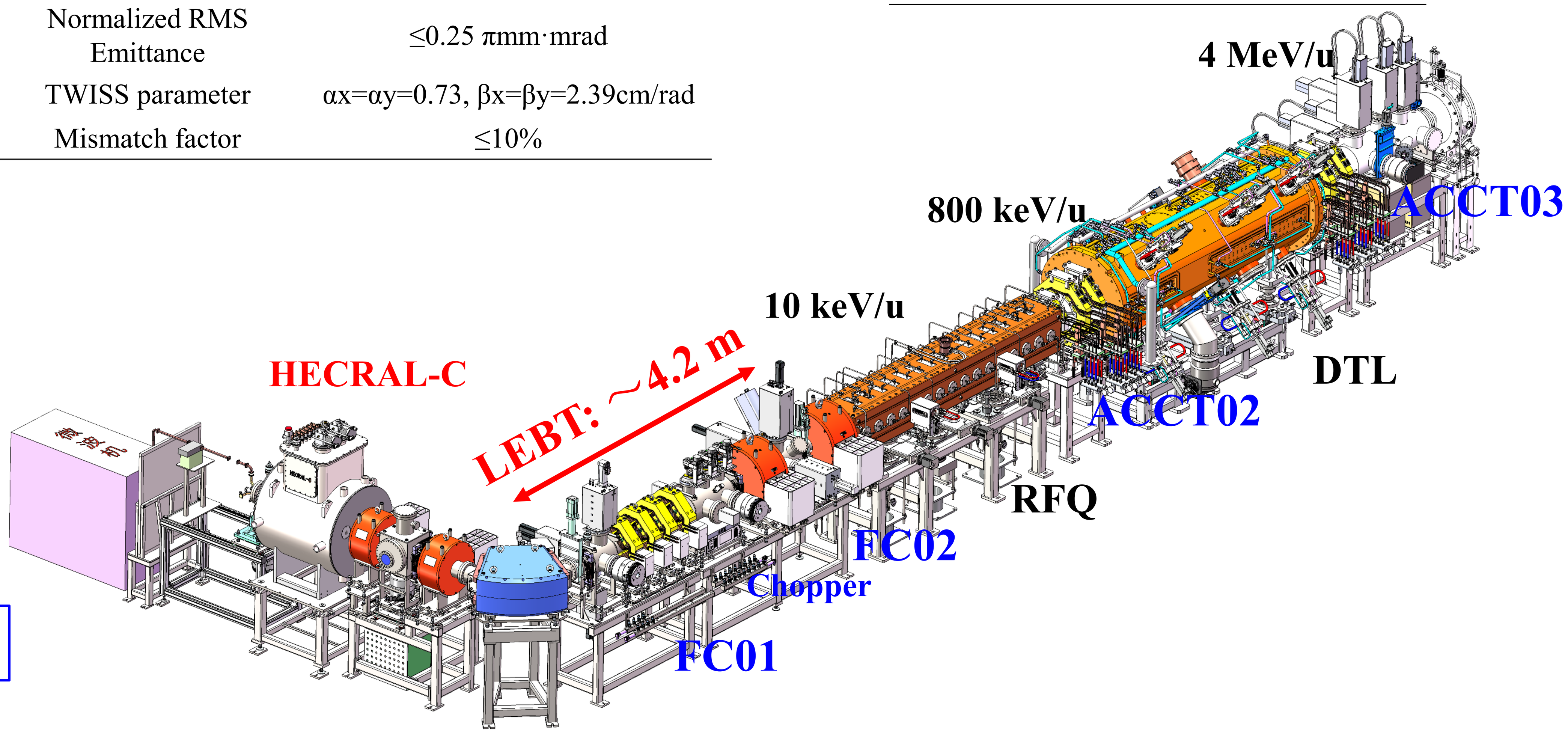
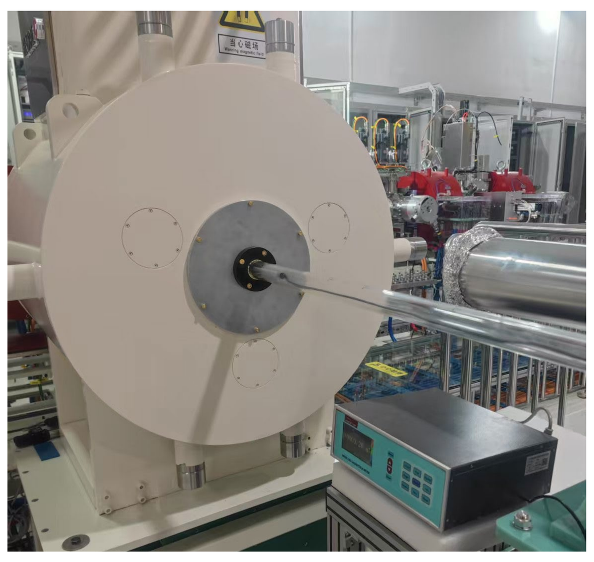


Fig. 2. Overview of Ion Source and Linac

Testing

42W@50K*2, 1.8W@4.2K*2

300 K→4.0 K ～120 Hours



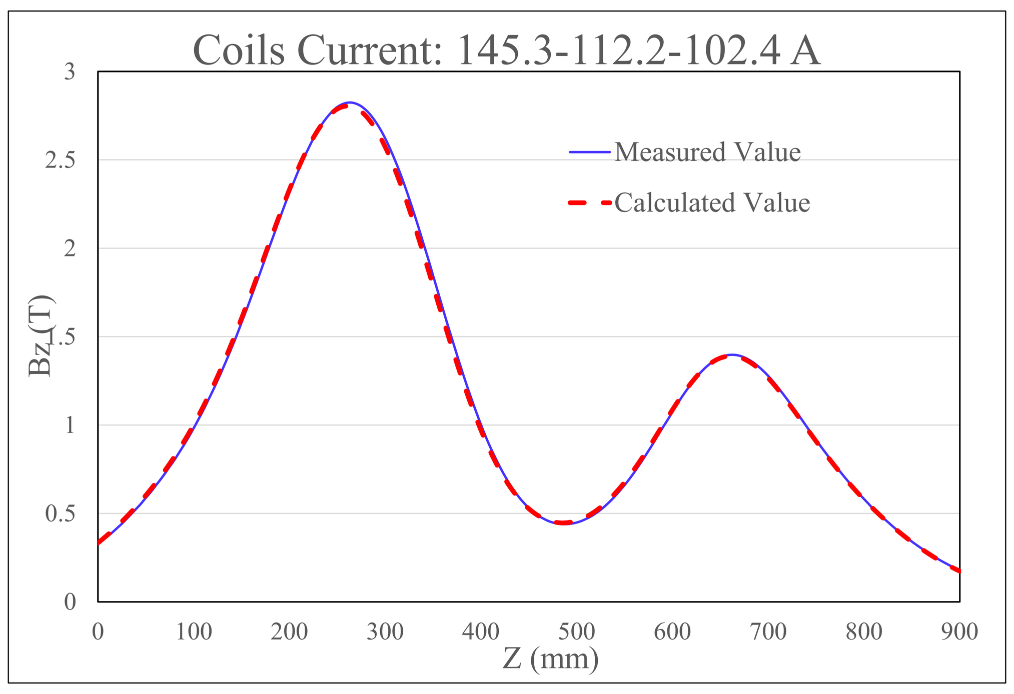
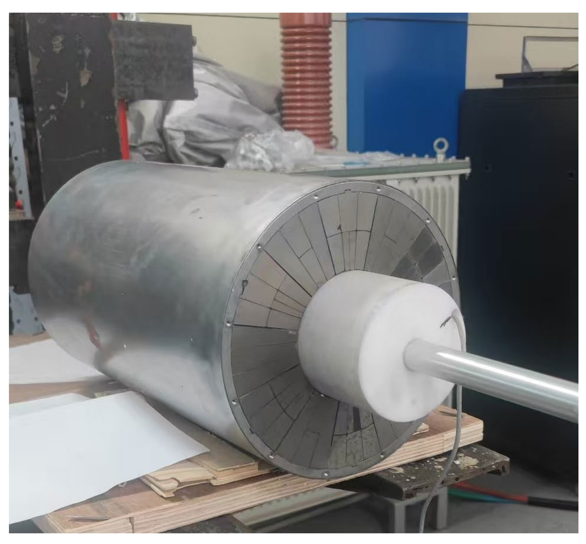


Fig. 3. Axial magnetic field distribution

N45SH(Br=1.32T/Hcj=-20kOe)

N33EHS(Br=1.13T/Hcj-35kOe)



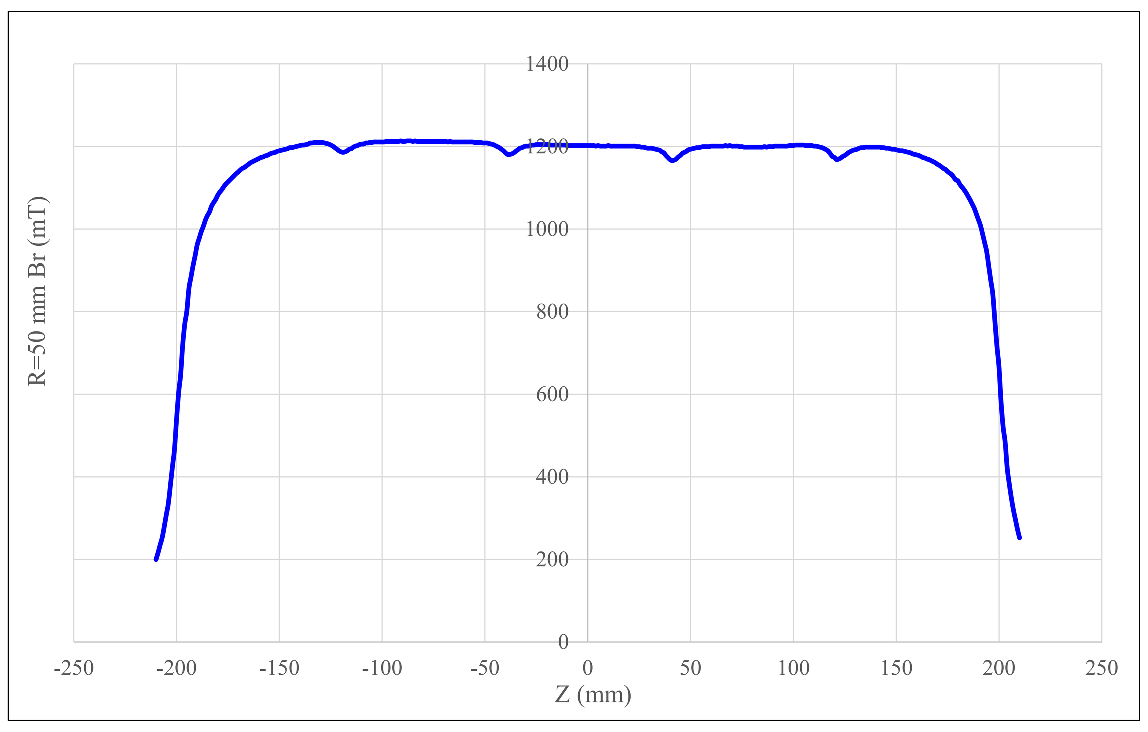


Fig. 4. Radial magnetic field distribution

Commissioning

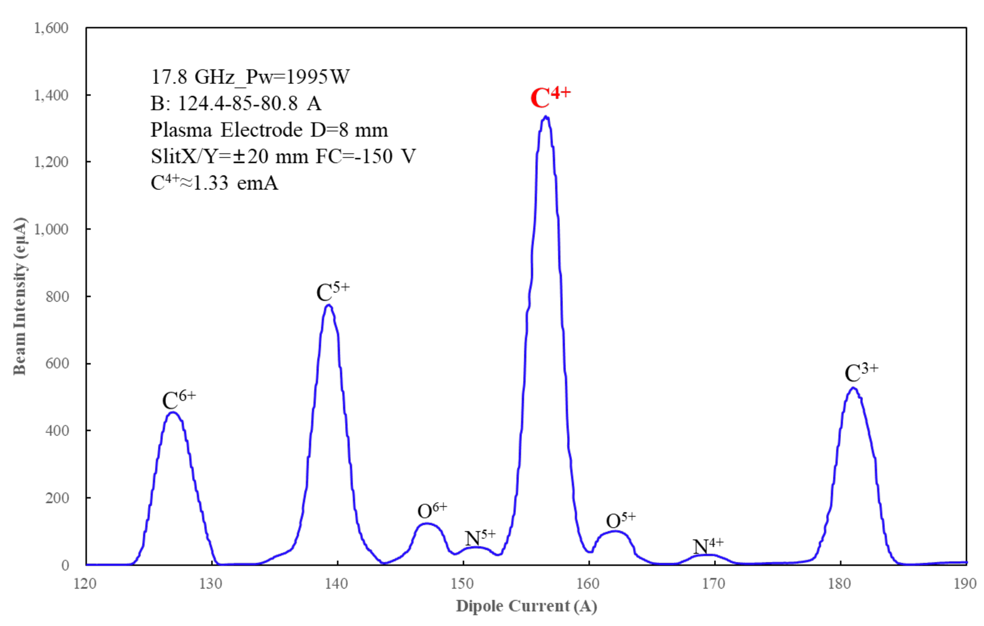


Fig. 5. Charge State Distribution at FC01 in CW Mode

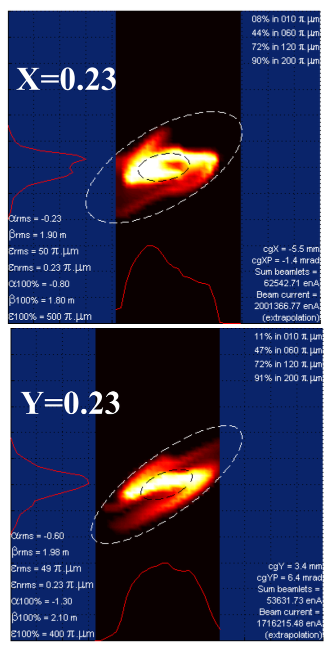


Fig. 6. X&Y Emittance at FC02 in CW Mode

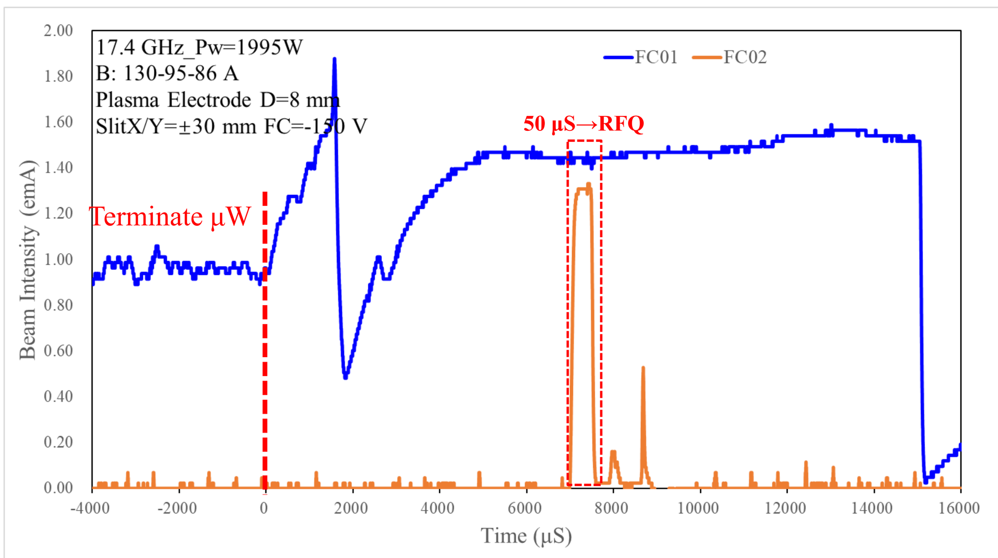


Fig. 7. Beam Monitoring at FC01 and FC02 in AG Mode

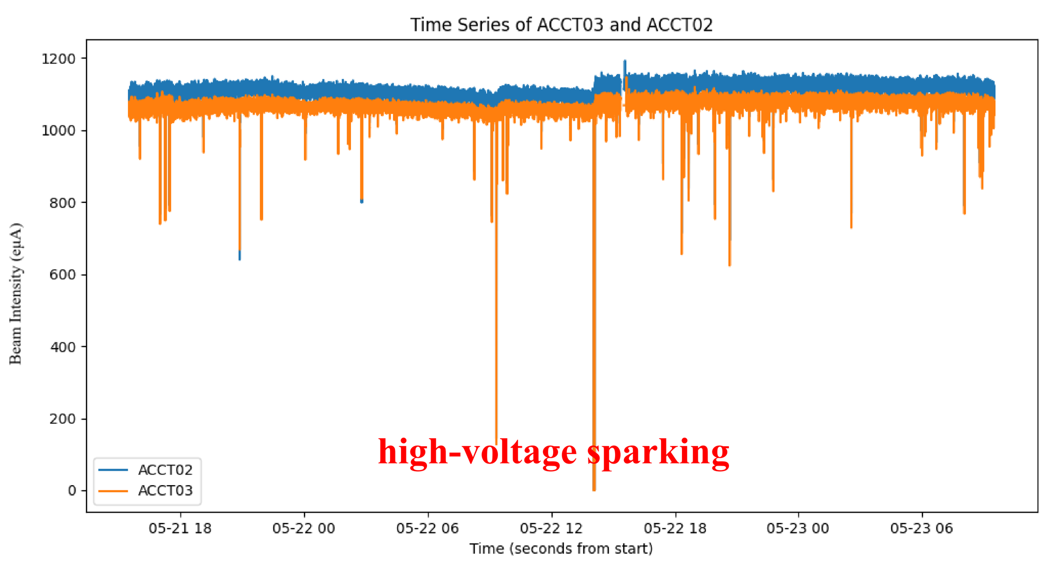


Fig. 8. Beam Stability Monitoring at ACCT02 and ACCT03 (Linear accelerator provided)

- The HECRAL-C combines high-frequency, high-magnetic-field, and large-volume plasma chamber with low cost and low power consumption, delivering stable and reliable performance.
- The HECRAL-C has successfully provided high-intensity C^{4+} beams in both standalone tests and during linac commissioning (RFQ and DTL), meeting the requirements of advanced heavy-ion cancer therapy systems.

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