# DEVELOPMENT OF THE CYCLONE®KEY:

## HOW INTEROPERABILITY LEADS TO COMPACTNESS

V. Nuttens, M. Abs, J. Caulier, Q. Flandroy, W. Kleeven, E. Kral, J. Mandrillon, O. Michaux, N. Mine, E. Van der Kraaij

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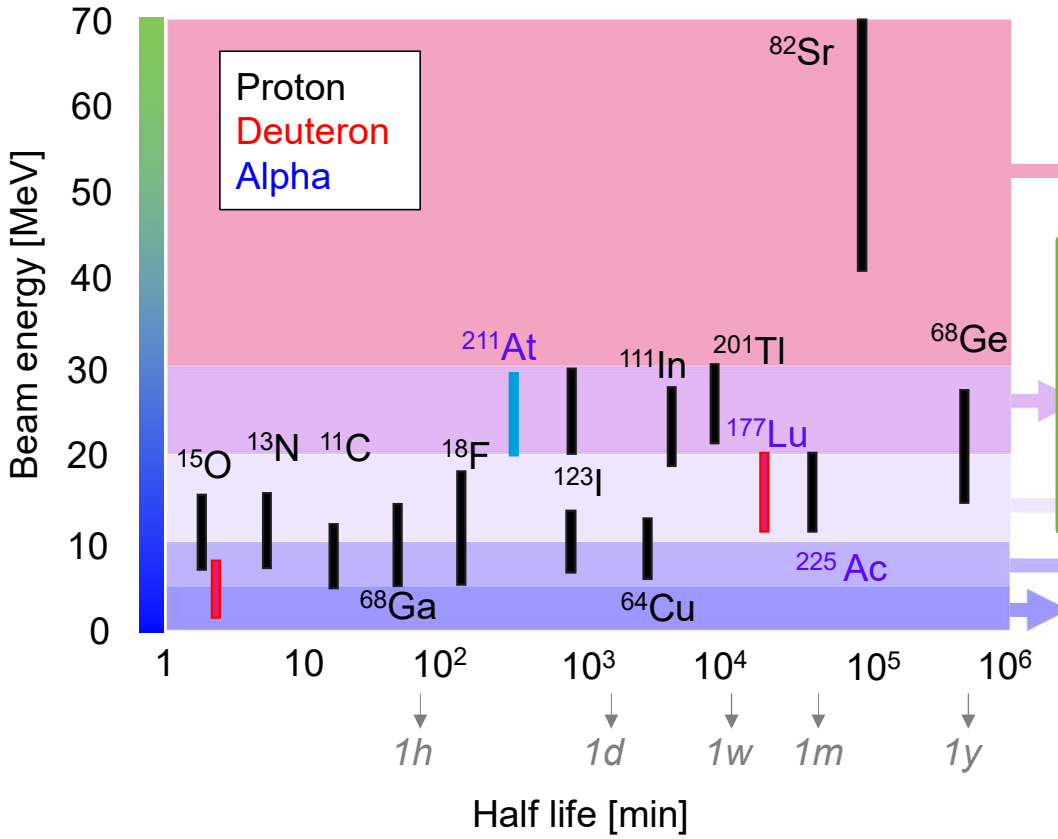
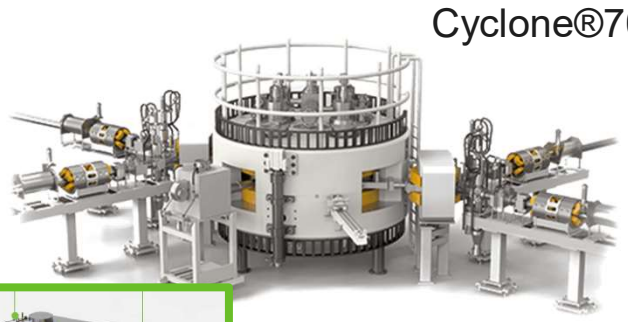
# Energy ranges & example of cyclotrons



Cyclone®70

Cyclone®IKON

Cyclone®KIUBE

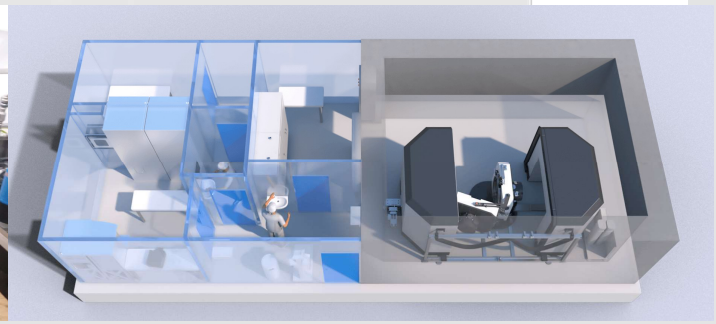
Cyclone®KEY

# The Cyclone®Key

- Design constraints:
  - Simple to install and operate
  - Compact (self-shielded & low activation concrete enabled)

| Parameter | Value |
|---|---|
| **Accelerated ions** | $H^-$ |
| **Ion source** | Internal PIG |
| **Number of sectors** | 4 |
| **RF frequency** | 41MHz |
| **RF mode** | 2 |
| **Dee angle** | 40deg |
| **Dee voltage** | 32kV |
| **Extraction** | Stripper (1+5 spares) |
| **Extracted energy** | 9.2MeV |
| **Cyclotron footprint (L×W×H)** | 1.5m×1.4m×1.35 m |

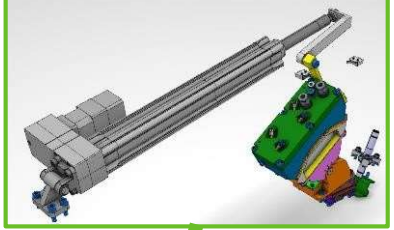
The Cyclone®KEY, the little brother of the Cyclone®KIUBE



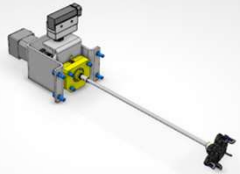
# Cyclotron subsystems

Pop-up

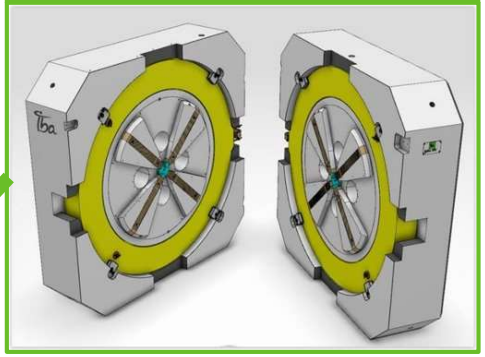
Target changer



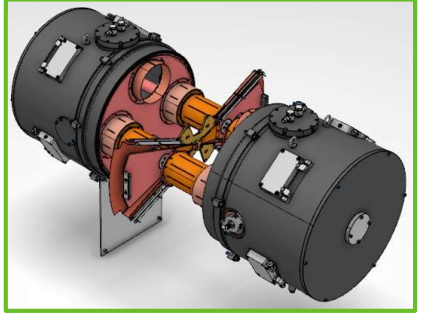
Strippers

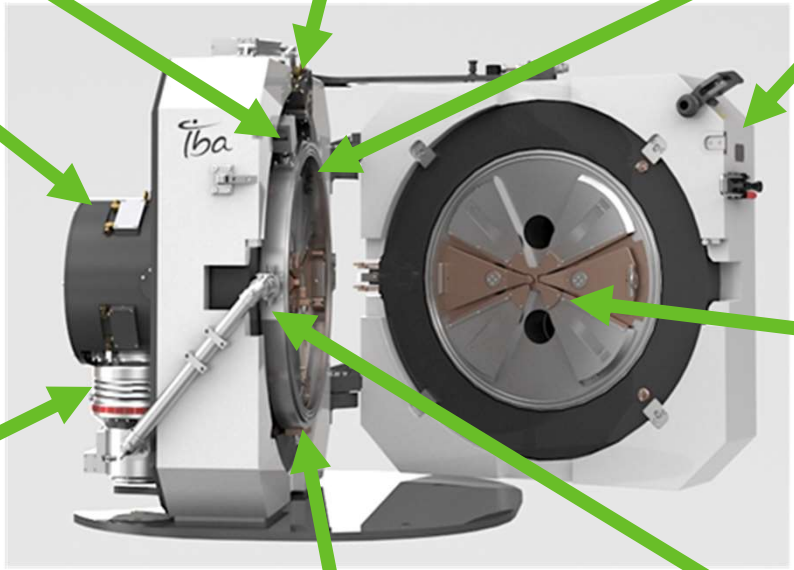


Magnet

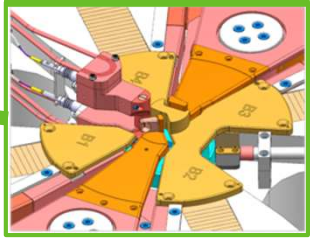


RF



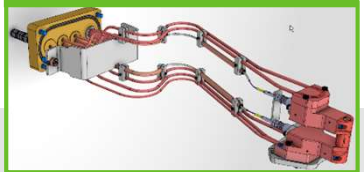


Central region

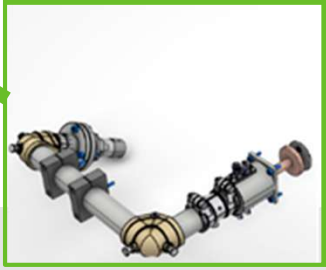


Vacuum

Ion source



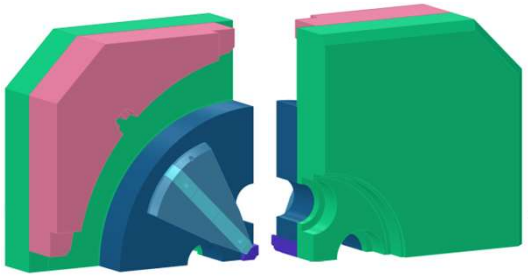
RF coupling &



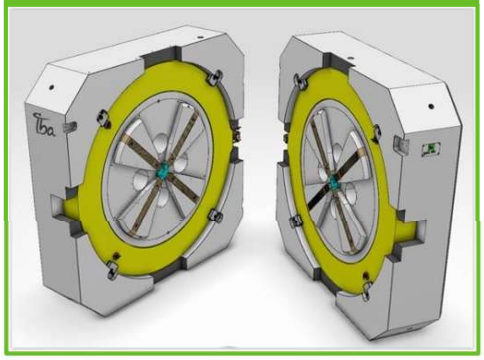
tuning

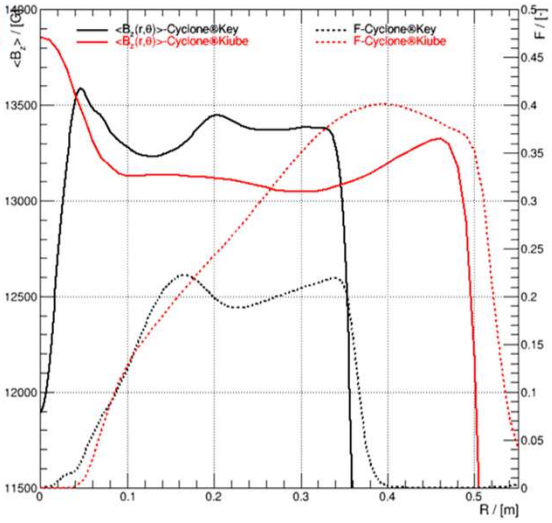
# Magnet design with OPERA

- Vertical median plane : no yoke lifting system, door opening
- Cyclone®KIUBE inheritance
  - 24mm of pole gap to optimize coil power consumption
  - Square shape: iron only where it is needed
  - Symmetry of yoke penetration for
    - RF coupler (left)
    - Coil connections (right)
    - Ion source (bottom)
    - Target (top)
  - Pole insert for cyclotron isochronisation during mapping
  - Vacuum chamber sits on the sectors
- Each half of the magnet is milled from a single plate of iron
  - Precision machining -> very low level of harmonic imperfection
  - High impact on vacuum performance (no virtual leak, faster pumping)
- Hole in the return flux for vacuum and RF system



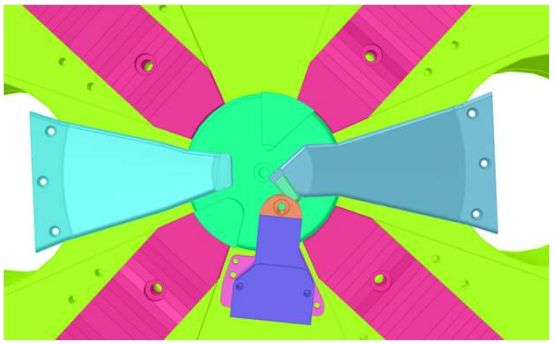
Magnet



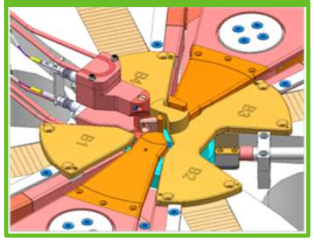


# Ion source and central region with AOC

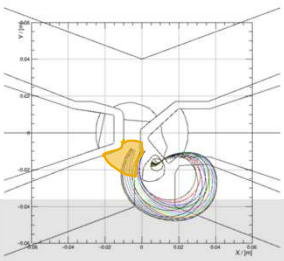
- Design constraint: same ion source as the Cyclone®KIUBE
  - PIG internal ion source for $H^-$ production
  - Consequence:
    - Central plug gap is fixed but too low field if flat
    - 2 magnetic extensions have been added to locally increase the magnetic field and keep isochronism
    - Not too close to the ion source to avoid plasma column deformation
- Central region design based on particle tracking with our tracking code AOC
  - Dee tip geometry has been optimized to provide
    - Orbit centering
    - Good phase acceptance
    - Horizontal and vertical electric focusing
  - Beam stop for protons

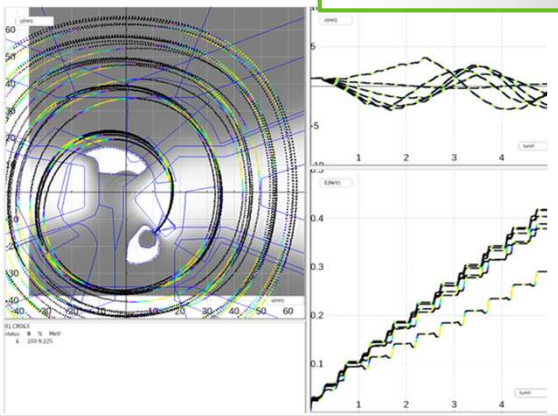


Central region



Ion source

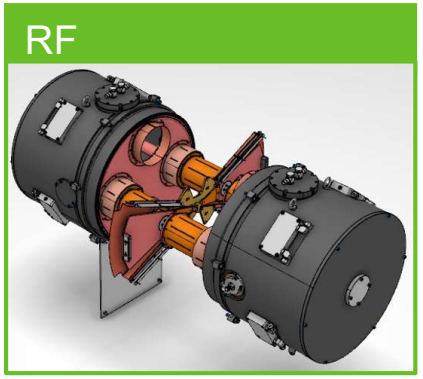


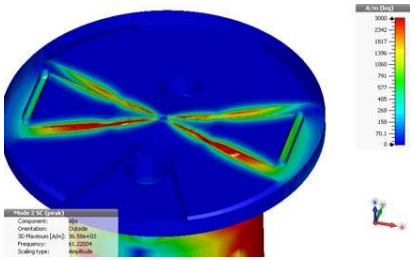


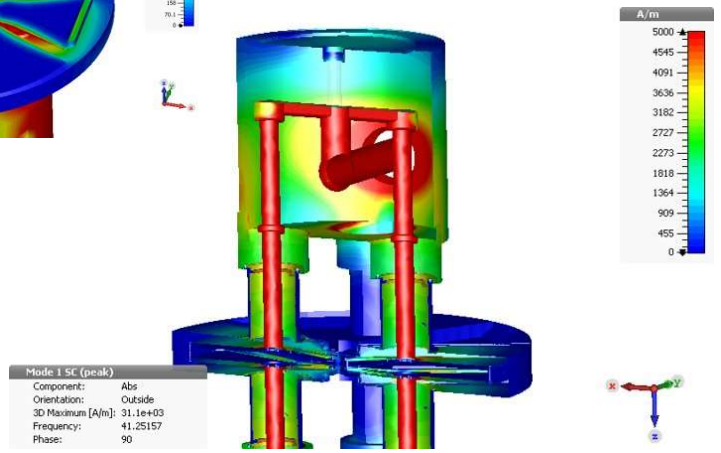
# RF system design with CST

- Design constraint: combine the RF system with the vacuum box
- H2 mode at 41MHz and 32kV
- Compatible with Cyclone®KIUBE RF amplifier chain
- Symmetric wrt cyclo median plane
  - Slightly higher power consumption (5,3kW)

  BUT
  - No RF current in the poles (no heating of the poles) and vacuum chamber
  - No RF field on the stripper
  - No need for good RF contact between upper and lower parts in the CR
  - More stable and reliable during operation

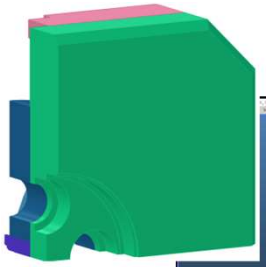


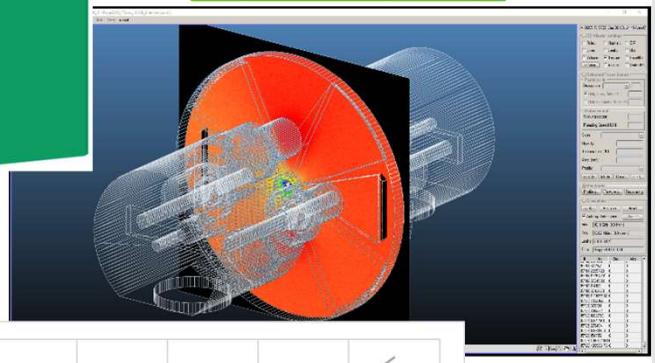



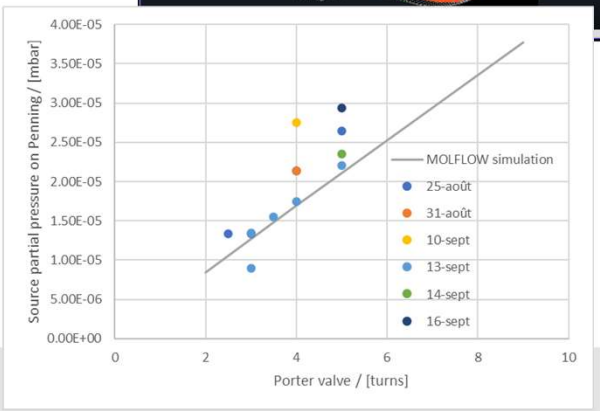


# Vacuum system with MolFlow+

- Design constraint: combine the RF system with the vacuum box
- Turbo molecular pump (TMP) HiPace2300
  - Compact and low maintenance requirements
  - Lower power consumption wrt ODP
  - S(N2)=1900L/s - S(H2)=1850L/s
  - Possibility to install one or two pumps
- 3D model of the vacuum system
  - $H_2$ gas from source only
  - After validation with the Cyclone®KIUBE design
  - Holes dimensions in the valleys optimized for vacuum conductance, RF power and magnetic field
  - Measurement: primary pump was limiting the TMP
  - (note: Penning pressure corrected for $H_2$)

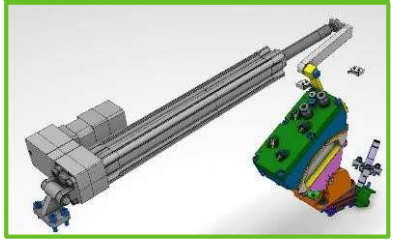




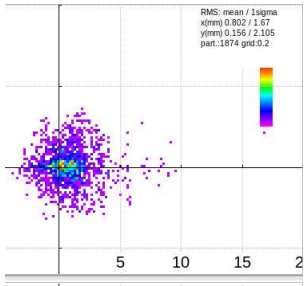
# Extraction system and target changer

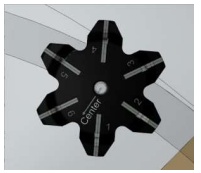
- Design constraints: 3 targets inside the yoke
- Stripping extraction:
  - 1 exit port with target changer
  - stripper carousel with up to 6 strippers
- Beam tracking from the ion source up to extraction was performed in AOC. At 32kV, in target:
  - Expected ($1\sigma$) beam sizes: X:2.1 and Y:1.7mm
  - Energy ≥9.2MeV  - Energy spread ($1\sigma$) 150keV

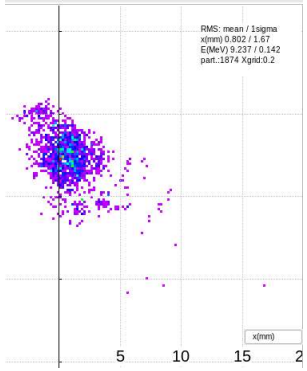
Target changer

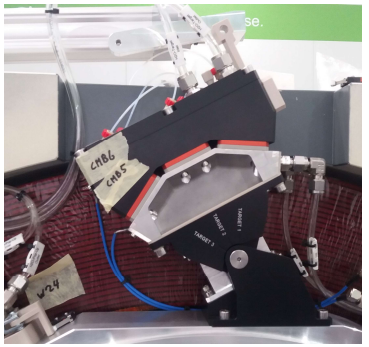


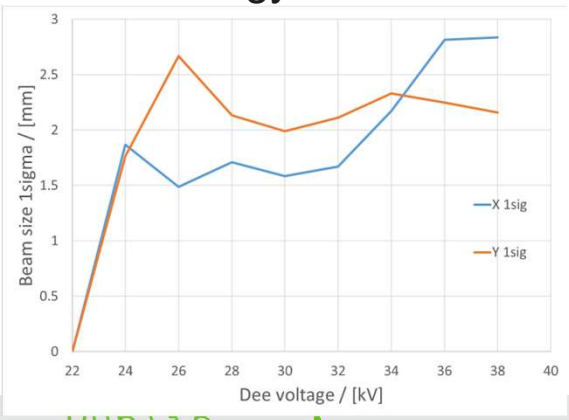
Strippers

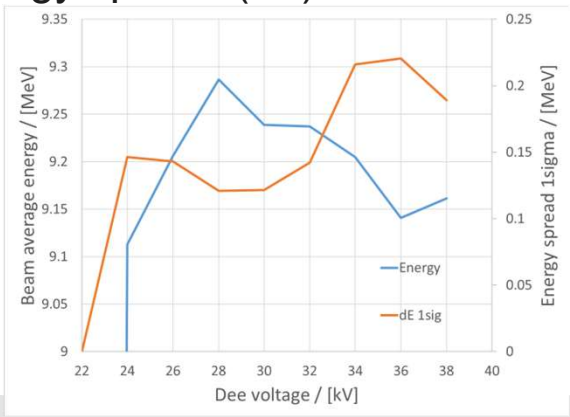




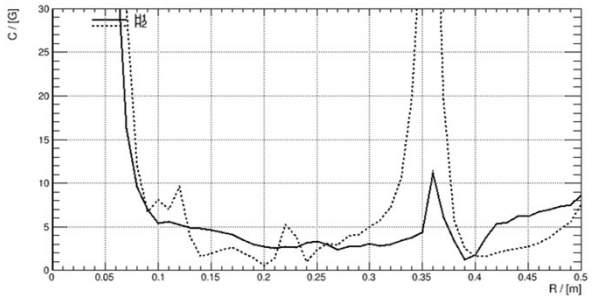





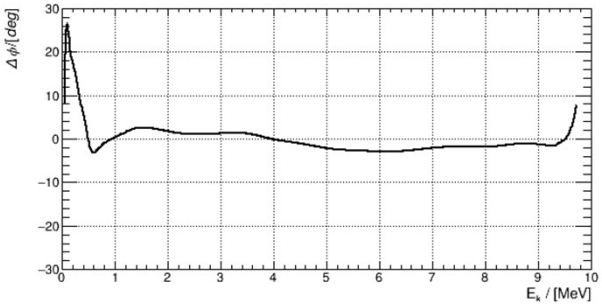



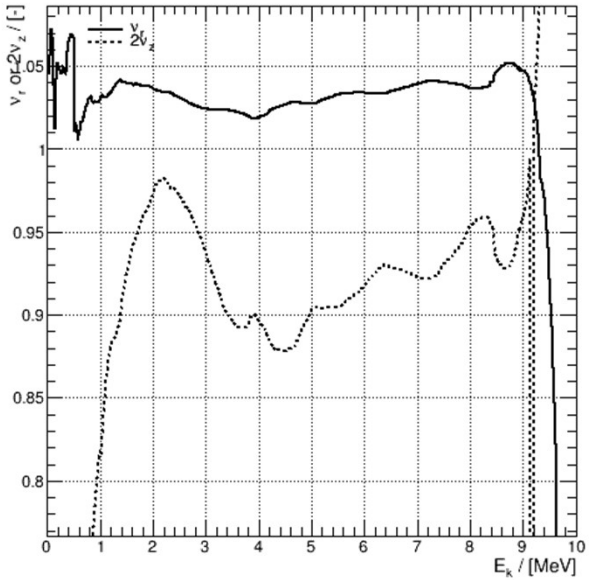
# Tests results

- Successfully mapped
  - Very low imperfection harmonics



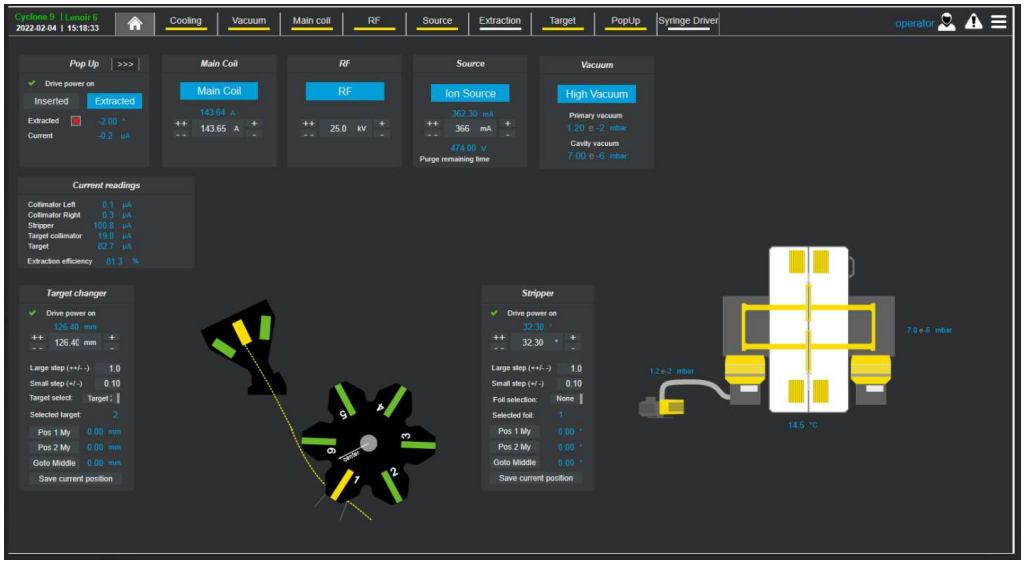

  - Excellent isochronism
    - Confirmed by beam test with $H^+$



# Tests results

- Beam tests (with 2 TMP)
  - Base vacuum: 5,3E-7mbar
  - Source on vacuum: <1,2E-5mbar
  - Stripper current: 100µA for 2h
  - Transmission Pop-up/Stripper: 60-67% (depending on source gas quantity and source current)
  - Extraction ratio: 81%



# Conclusion

- In parallel of the Cyclone®IKON, IBA has successfully design, develop & test its new compact cyclotron for the low energy range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