CFC-Based Assessment of Beam Quality in Negative Ion Sources using Machine Learning

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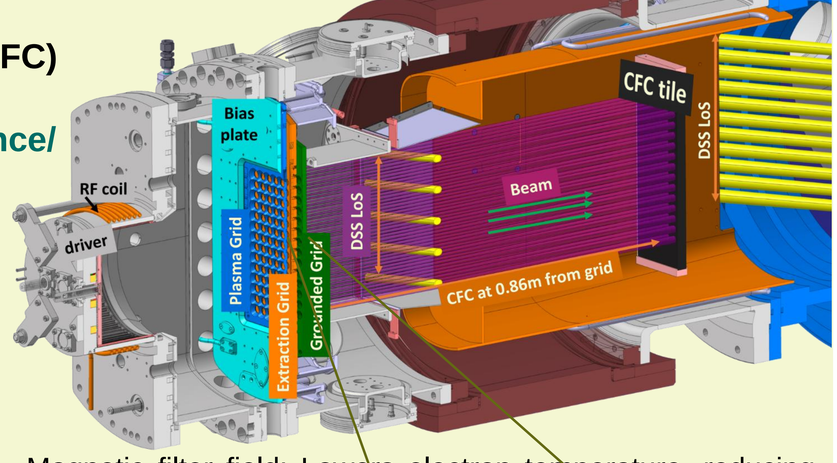
Goals

- Beam characterization and ML-assisted analysis in negative ion sources.
- Beamlet-resolved properties: divergence, deflection, homogeneity.
- **ITER requirements[2]:** Uniformity > 90%, Divergence < 7 mrad.

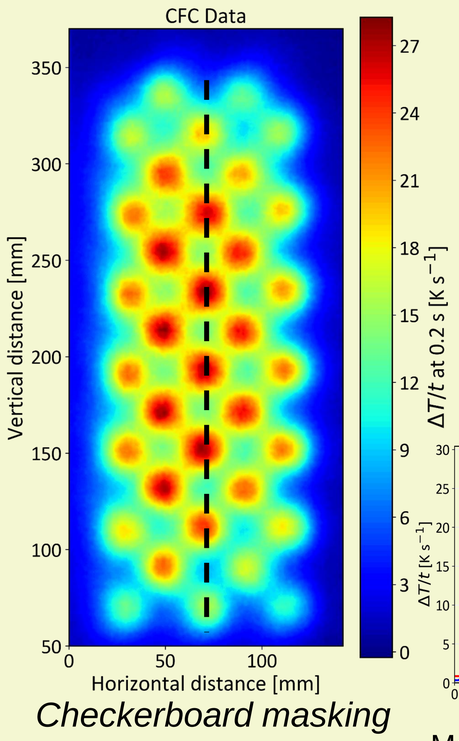
Beam Diagnostics

Carbon Fibre Composite (CFC) Calorimeter[1]
→ **Beam footprint/ Divergence/ Uniformity/ Deflection**



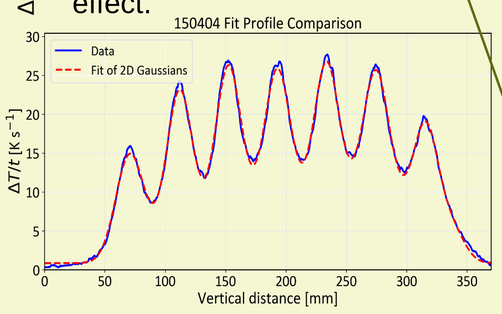
Magnetic filter field: Lowers electron temperature, reducing negative-ion destruction and influencing beamlet deflection.

CESMs* + ADCMs*: Deflect co-extracted electrons and introduce zigzag beamlet deflection; ADCMs mitigate this effect.

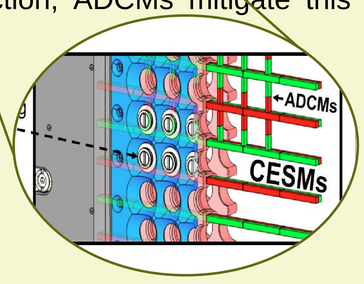


Checkerboard masking

CFC thermal footprint of 35 beamlets.



Measured and fitted beamlet profile used for parameter extraction.



**Co-extracted Electron Suppression Magnets*

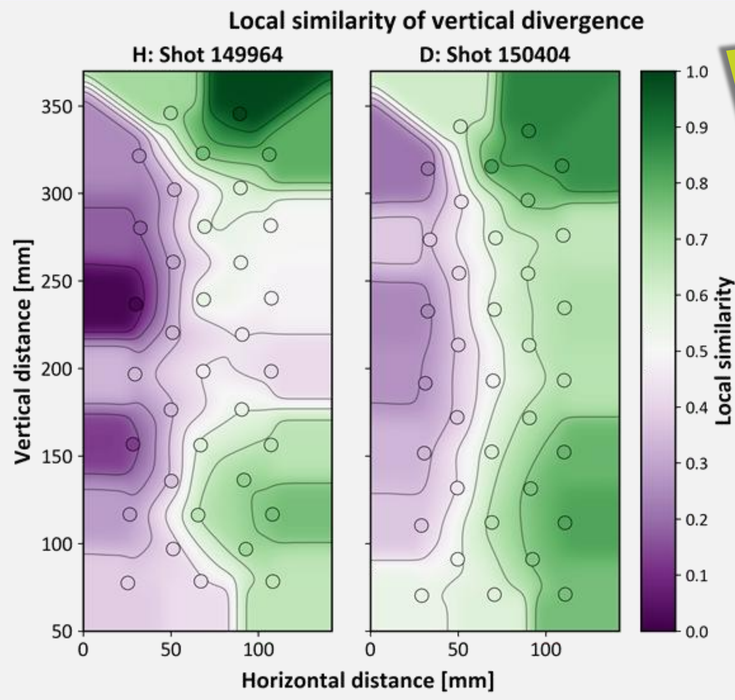
**Asymmetric Deflection Compensation Magnets*

TERMINOLOGY

Divergence: Angular spreading of a beamlet.
Deflection: Beamlet shift from the expected position (on the CFC).
Asymmetry: Difference between horizontal and vertical divergence.

Correlation matrix: Pairwise correlation between parameters.
+1 → two quantities increase together
0 → no relation
−1 → one increases, the other decreases
Local similarity: How similarly neighboring beamlets behave.
0 → no similarity
+1 → high similarity
Sensitivity: Response of beam properties (q) to source parameter change (e.g., for pressure variation (0.3 – 0.6 Pa) → $S = \partial q/\partial P$).

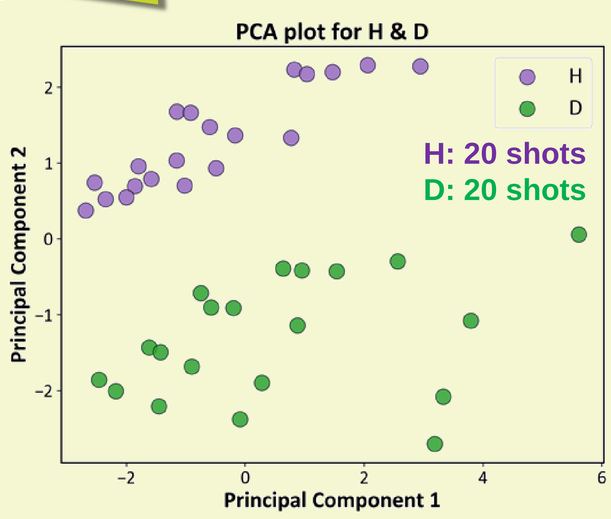
Beamlet Behavior



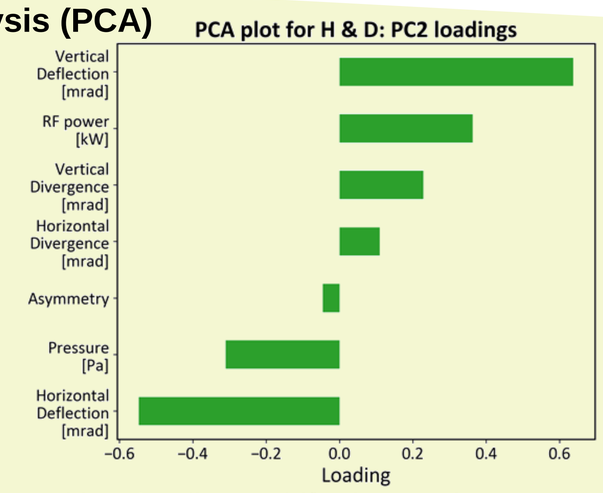
- Neighboring beamlets form vertically correlated similarity structures.
- Deuterium exhibits smoother column-like behavior than hydrogen.

Machine Learning

Principal Component Analysis (PCA)



PCA combines the extracted beam (& source) parameters into a single global representation, reproducing the systematic differences observed between H & D.



Positive loadings shift data points toward positive PC2 values, while negative loadings shift them toward negative PC2 values.

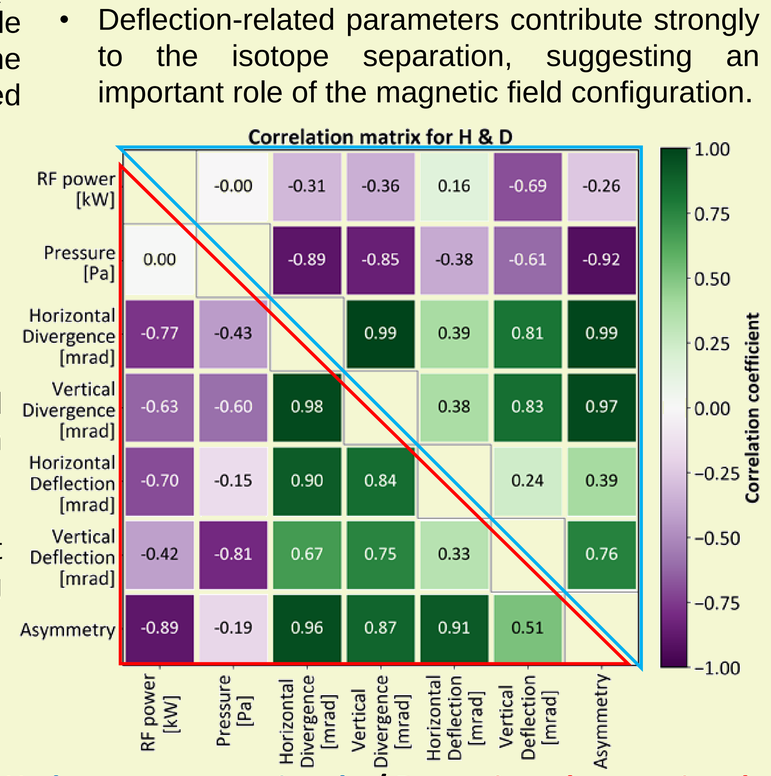
- Deflection-related parameters contribute strongly to the isotope separation, suggesting an important role of the magnetic field configuration.

Parameter Relationships

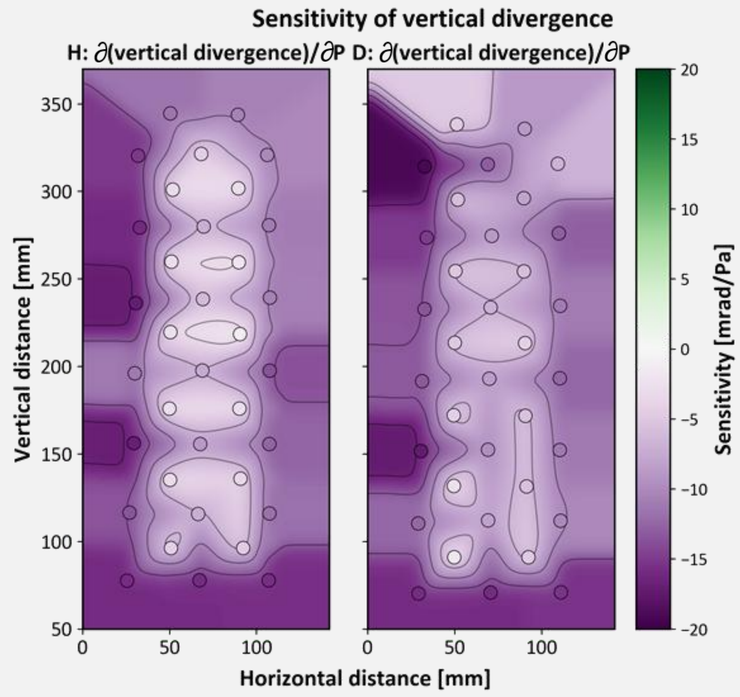
Correlation analysis reveals coupled behavior between source operation and beam properties.

- Hydrogen and deuterium exhibit distinct parameter coupling structures.

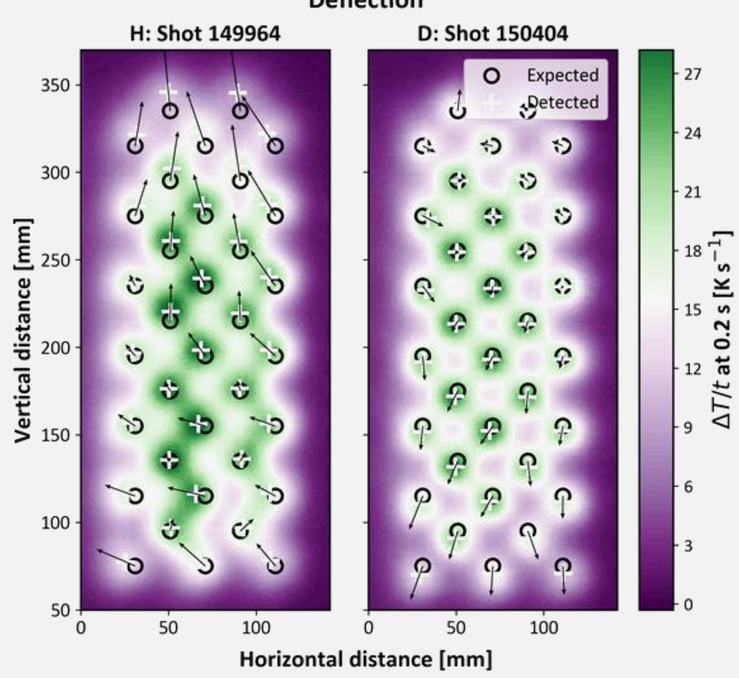
Source conditions:
- RF power: 20 – 75 kW
- Pressure: 0.3 – 0.6 Pa
- $U_{extraction}$: 6 kV, $U_{acceleration}$: 35 kV



Hydrogen: upper triangle / Deuterium: lower triangle



- Central beamlet columns exhibit weaker sensitivity to pressure variations.
  - Stronger pressure response is observed toward the beam edges.



- Hydrogen exhibits a stronger zigzag-like beamlet deflection pattern.
- Alternating row-to-row shifting is linked to the magnetic field configuration.

Beamlet-resolved analysis reveals systematic differences between hydrogen and deuterium operation, which are captured by the PCA.

(1) G. Orozco, F. Bonomo, N. den Harder, B. Heinemann, A. Hurlbatt, R. Nocentini, R. Riedl, and C. Wimmer, Fusion Engineering and Design 165, 112225 (2021)

(2) R. S. Hemsworth, D. Boilson, P. Blatchford, M. D. Palma, G. Chitarin, H. P. L. De Esch, F. Geli, M. Dremel, J. Graceffa, D. Marcuzzi, G. Serianni, D. Shah, M. Singh, M. Urbani, and P. Zaccaria, New J. Phys. 19, 025005 (2017)

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