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

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Abstract

The extraction of a uniform and stable beam at a divergence below 7 mrad is a critical requirement for RF-driven negative ion sources used in neutral beam injection (NBI) systems planned for ITER, operating with both hydrogen and deuterium isotopes. Meeting this requirement calls for systematic assessment of the beam characteristics and its reproducibility under well-defined operating conditions. For that purpose, experiments are performed at the BATMAN Upgrade test facility, where beam footprints are diagnosed using a Carbon Fibre Composite (CFC) target and infrared imaging. The CFC images acquired during hydrogen and deuterium operation are analyzed using conventional fitting techniques, complemented by machine-learning-based methods. This combined approach allows correlations between beam parameters and their reproducibility to be thoroughly explored, beyond qualitative visual inspection of the beam footprints. Machine-learning-assisted analysis provides additional, subtle descriptors of the beam footprints, enabling robust comparisons across operating conditions.

1. Introduction

The production of stable and spatially homogeneous negative hydrogen and deuterium ion beams from RF-driven plasma sources is essential for neutral beam injection (NBI) systems in ITER. Achieving high beam transmission requires precise control of beam optics, including beam divergence, uniformity and beamlet deflection. ITER requirements specify that 85% of the beamlet power should remain within a core divergence below 7 mrad, while the remaining halo component should not exceed 15 mrad [1,2]. In addition, a uniform distribution of the extracted beam power across the extraction system is required to surpass 90%, while beamlet shifting errors should be below 2 mrad horizontally and 4 mrad vertically [1,2].

Several experimental campaigns have been conducted at the BATMAN Upgrade (BUG) test facility, a 1/8-scale ITER ion source with 70 extraction apertures (see Fig. 1a) [3], to investigate the observed beam characteristics, and assess how diagnostic and data-analysis methods affect the evaluation of the beam parameters. Among the available diagnostic techniques, beam properties can be examined using a Carbon Fibre Composite (CFC) calorimeter combined with infrared thermography [4]. The CFC provides spatially resolved measurements of the beam footprint, allowing individual beamlets to be analyzed in terms of divergence, deflection, and spatial structure.

Nevertheless, depending on the distance between the extraction system and the CFC target, different beam properties can be resolved more effectively. Larger distances make the beamlet broadening associated with beam divergence more pronounced on the CFC footprint, enabling a more accurate divergence characterization, whereas closer target positions provide a sharper picture of the beam uniformity. At the BUG facility, the selected geometry therefore represents a compromise between beamlet-resolved divergence analysis and overall beam uniformity evaluation. To mitigate the resulting overlap between neighboring beamlets, a checkerboard masking configuration can be applied, where only alternating extraction apertures contribute to the extracted beam, creating a pattern of 35 visible beamlets on the CFC target. The CFC-based analysis typically relies on fitting procedures applied to the measured heat-deposition profiles, commonly assuming a double-Gaussian profile of the beamlet angular distribution [5].

The resulting manifold of beam and source parameters contains a large amount of information that cannot be readily interpreted through individual parameter inspection alone. Examining how these quantities relate to one another can provide insight into the mechanisms governing beam formation and transport. To identify such relationships and highlight systematic differences between hydrogen and deuterium operation, multivariate statistical techniques, such as correlation-matrix analysis and Principal Component Analysis (PCA), are employed.

2. Methods

The recorded CFC temperature maps were used for beamlet-resolved analysis. After identifying the beamlet positions, a local region surrounding each beamlet was extracted from the CFC temperature map. Two-dimensional Gaussian fits were then applied to characterize its shape and spatial width. The horizontal and vertical beam divergence components were determined from the Gaussian widths assuming point-like beamlets at the last grid of the extraction system and linear beamlet expansion toward the CFC target, which represents a valid approximation at the 0.86 m CFC distance [6]. The asymmetry was defined as the difference between the horizontal and vertical divergence components. In addition, the horizontal and vertical deflection components were determined from the displacement between the expected beamlet positions defined by the extraction-grid geometry and the corresponding fitted beamlet centers on the CFC target. It should be noted that these deflections occur by the magnetic filter field and by the embedded Co-extracted Electron Suppression Magnets (CESMs), which introduce a characteristic zigzag beamlet pattern. The resulting deflection can be compensated by Asymmetric Deflection Compensation Magnets (ADCMs).

To investigate relationships between the parameters, a correlation matrix was constructed, which provides an overview of how different beam properties evolve relative to each other and to the source operating conditions, allowing coupled trends and structures within the beam to be identified. In that table, each matrix element corresponds to a correlation coefficient describing whether two quantities tend to increase or decrease together. Its value ranges between −1 and +1, where values close to +1 correspond to similar trends, values close to −1 to opposite trends, and values close to 0 to weak or no correlation.

Principal Component Analysis (PCA) algorithm [7] was further applied to identify the trends within the dataset by combining information from all investigated beam parameters. This approach enables similarities and differences between hydrogen and deuterium operation to be visualized more clearly. The corresponding principal-component (PC) loadings describe how strongly each original beam parameter contributes to a given principal component. Positive and negative loading values indicate whether a parameter shifts the clustering toward higher or lower values along the corresponding principal component axis. The magnitude of the loading reflects the importance of a parameter in reinforcing the observed clustering and separation.

3. Results

During the latest experimental campaign at the BUG facility, the influence of source operating conditions on the extracted beam properties was investigated. For both isotopes, RF power values between 40 and 60 kW were examined, while additional measurements up to 75 kW were performed for hydrogen operation due to the lower RF power coupling efficiency to the plasma compared with deuterium operation. Additional measurements down to 20 kW were also performed for deuterium operation. The source pressure was varied between 0.3 and 0.6 Pa, whereas the extraction and acceleration voltages were fixed at 6 kV and 35 kV, respectively.

Fig. 1a) illustrates the extraction system and the beam propagation toward the CFC target located downstream of the grounded grid. The corresponding thermal footprint recorded on the CFC target (at an RF power of 60 kW and a source pressure of 0.3 Pa) is shown in Fig. 1b), where each localized hotspot corresponds to the impact position of an individual beamlet. A vertical profile extracted along the central beamlet column (dashed line in Fig. 1b) is presented in Fig. 1c), together with the associated multi-Gaussian fit used for beamlet reconstruction. The good agreement between the experimental profile and the fitted model demonstrates that the fitting procedure reproduces the beamlet structure with sufficient accuracy for subsequent extraction of beam parameters.

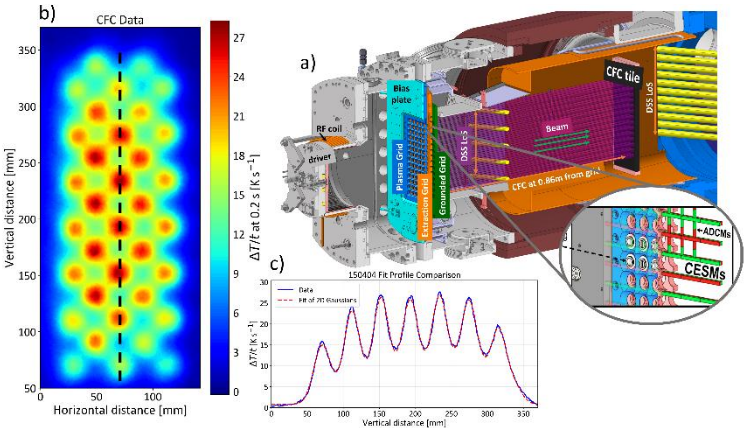

Figure 1. a) Schematic of BUG experimental setup [3], b) Measured CFC temperature rise for 35 beamlets, c) Fitted profile of central CFC column.

Fig. 2a) presents the correlation matrix for hydrogen (upper blue triangle) and deuterium (lower red triangle) operation. Distinct correlation structures are observed both between source parameters and beam properties, and among the beam properties themselves. In both isotopes, the horizontal and vertical divergence components exhibit strong positive correlations, indicating a coherent broadening behavior across the extraction system. Strong correlations also occur between divergence and deflection, suggesting that beamlets experiencing stronger shifting effects also tend to exhibit broader spatial profiles. The comparatively weak correlation between horizontal and vertical deflection implies that horizontal and vertical beamlet shifting do not follow a systematic directional coupling. Moreover, RF power and pressure exhibit predominantly negative correlations with divergence and asymmetry, indicating a tendency toward reduced beam broadening and asymmetry at higher operating values. A comparison of the two matrices shows that beam properties and source parameters are correlated differently in hydrogen and deuterium operation, indicating differences in the underlying beam behavior.

The corresponding PCA analysis is shown in Fig. 2b). Despite partially overlapping operating conditions, hydrogen and deuterium operation form two distinguishable clusters in the PCA space, indicating that the extracted beam parameters contain systematic isotope-dependent structures. Since the separation between the two isotopes occurs along the PC2 axis, the corresponding PC2 loadings are presented in Fig. 2c). These loadings reveal that vertical deflection contributes most strongly to the positive PC2 direction, whereas horizontal deflection contributes predominantly to the negative PC2 direction. RF power and vertical divergence also play an important role in the separation, while asymmetry has only a minor influence. Since beamlet deflection is influenced by the magnetic filter field and the CESMs/ADCMs configuration, the isotope separation appears to be primarily linked to differences in deflection behavior, with secondary contributions from divergence-related effects.

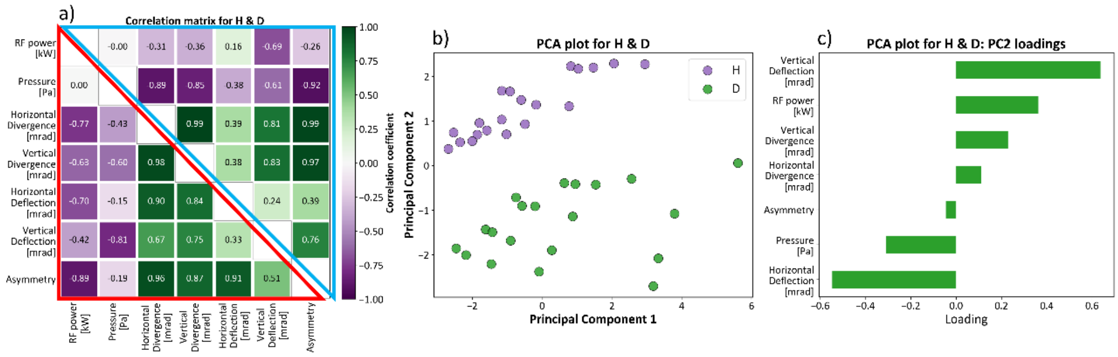

Figure 2. a) Correlation matrices for hydrogen (upper blue triangle) and deuterium (lower red triangle), b) PCA clustering of hydrogen and deuterium shots, c) PC loadings associated with the PCA separation.

4. Conclusions

Correlation-matrix analysis revealed distinct relationships between beam properties and source operating conditions for hydrogen and deuterium operation. The PCA algorithm further demonstrated a clear separation between the two isotopes, confirming the presence of systematic isotope-dependent differences in the extracted beam characteristics. Combined, these findings establish multivariate analysis as a valuable tool for studying hydrogen and deuterium beam behavior in RF-driven negative ion sources.

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