Misalignment on Multi-Aperture Particle Beam Properties
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D Cric, J. J. Milnes and E Surrey,

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, U.K

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ABSTRACT
Accurate accelerator grid alignment is a major factor governing the properties of multi-aperture particle beams. It is particularly important for JET Positive Ion Neutral Injectors (PINIs), where accelerators are constructed of two grid halves. Grid misalignment can lead to increased power loading of beam intercepting components, to reduced beam transmission, and, finally, to reduced neutral beam power injected into plasma. A new PINI accelerator assembly procedure, which utilises a robotic arm measuring device, was recently developed at JET. PINI alignment data are used as input to a beam simulation code to predict beam properties prior to testing at the Neutral Beam Test Bed. Since the new PINI assembly procedure and the associated computer code have been implemented the alignment of JET PINIs has been considerably improved.

1. INTRODUCTION
Clear experimental evidence of misaligned beams extracted from JET PINIs was obtained at the Neutral Beam Test Bed (NBTB) in 1993, during high heat flux testing of high conductivity unidirectional Carbon Fibre Composite (CFC) samples. It was recognised that unidirectional property of this material can be combined with infrared imaging to obtain high-resolution power density distributions of particle beams extracted from JET PINIs [1]. Since 1994, CFC calorimeters are routinely used at JET NBTB for PINI characterisation (Fig. 1).

The CFC calorimetry diagnostic proved to be extremely valuable in detecting PINI grid misalignment and in deciding whether PINIs were suitable for installation on the JET Neutral Beam Injectors. The technique alone did not help to reduce the number of misaligned PINIs - on average, 60% of tested PINIs were found unsuitable for the use on the JET machine and required realignment before final installation.

Irregularities in beam profiles (Fig. 1) are attributed to accelerator grid misalignment, bowing of the grids due to heat load and to ion source plasma non-uniformity.

The origin of misaligned beams is in the aperture offset technique, which is used to combine 262 individual beamlets from a JET PINI into a single beam. Beamlets are steered to a focal point by transversal electric field introduced by variable offset of individual apertures. Beam steering is usually described through the steering constant, which for the two JET PINI types (triodes and tetrodes) vary between 20 and 42 mrad/mm. This means that an error in transversal grid alignment of 0.1 mm will displace the beam by 20 to 42 mm over a distance of 10 metres.

Misaligned beams increase the power loading on beam intercepting components (scrapers) which, in some cases, can limit the neutral power injected into JET plasma. Due to misaligned beams, PINIs on JET Octant 4 Neutral Injector are usually operated below the maximum voltage and current that can be delivered by the high voltage power supplies.

2. PINI ACCELERATOR ASSEMBLY PROCEDURE
To minimise the grid misalignment, a new accelerator assembly procedure was recently developed
at JET. PINIs are assembled with the aid of the FaroArm (model G04-02, FARO Technologies Inc., USA) – three-dimensional coordinate measuring device with 25\(\mu\)m accuracy (Fig. 2).

Coordinates of nine grid holes are measured for each grid half (Fig. 3). The measurement of a total of 54 data points (triode PINI) requires \(\sim30\) minutes.

A log file containing all measured data points is automatically created during the assembly procedure and is used as input data set for the PINI Simulator computer code to construct a three-dimensional map of the entire PINI accelerator. The PINI Simulator code creates various reports and graphs to check and visualise accelerator misalignment: grid aperture pattern, aperture offsets, rotation of the grids, angles between grids, projections of individual beamlet centre lines (Fig. 4).

Graphs on Fig. 4 illustrate the change of the beam shape at several locations along the beam axis. For an ideally aligned accelerator, individual beamlets will have a horizontal focus at the distance of \(z^\dagger=11\) m from the accelerator. Note the distortion of the actual beam shape, which is caused by the misalignment between plasma grid and deceleration grid. The case in Fig. 2.b corresponds to the central aperture horizontal misalignment of 121 and 28 \(\mu\)m, and grid half rotation of 1.4 and 1.1 mrad for upper and lower grid halves, respectively.

The PINI Simulator code is installed on the computer, which is used to control the robotic arm, and the operator can verify the alignment at the end of the PINI assembly. A few misalignment tolerances are checked to establish whether the PINI is acceptable for further tests at the Neutral Beam Test Bed, and assembly procedure is repeated until a satisfactory result is achieved.

3. BEAM SIMULATION CODE - ALGORITHM
One module of the PINI Simulator code is used to generate the beam power density distribution at various distances from a PINI accelerator. In addition to measured accelerator aperture coordinates, the code also takes into account other physical parameters that can affect the properties of multi-aperture particle beams: beam divergence, ion source-plasma non-uniformity and stray magnetic field. The algorithm of the model is outlined below.

Two-dimensional beam profiles at specified distance from the accelerator are generated by summation of 262 individual beamlets. Measured accelerator aperture coordinates are used to calculate actual locations (starting points) and orientations (aiming angles) of individual beamlets. Offset aperture steering constants were determined using analytical models and Kobra3-INP three-dimensional ion trajectory tracing code [2].

Power density distribution of each beamlet is treated separately by assuming: a common shape (Gaussian); common initial waist diameter; variable peak power density and divergence. Perveance scan data are included to calculate beamlet divergence. The variation of beam divergence with beam perveance is obtained using NBTB multi-channel Doppler shift optical spectrometer [3]. A source plasma non-uniformity function is introduced to calculate power density profile for each individual beamlet - variation of peak power density and divergence across the aperture array. This function can be derived from the Doppler shift spectroscopy diagnostic [3].
Beam intercepting components (Neutraliser, Magnet Liner, Box Scraper) can be included in the calculation.

From a given ion source species composition and neutralisation target, power density profiles can be calculated for composite beam, neutral beam, full energy ions and fractional energy ions (H, D, T and He beam species).

The effect of stray magnetic field on charged particle trajectories is also included in the calculation. Beam profiles can be generated at specified distance and a sequence of profiles can be used to calculate beam envelopes, perveance scan curves, beam transmission and power loading of beamline components.

The PINI Simulator code was developed for the MS Windows operating system. Results of the simulation can be presented in tabular (spreadsheets), or graphical format (2D graphs, contour plots or 3D surface plots).

4. BEAM SIMULATION CODE – RESULTS

4.1. Comparison to experimental profiles
To test the adequacy of the PINI assembly procedure and verify the predictions of the beam simulation code calculated profiles are compared with two-dimensional profile obtained using CFC calorimetry. This is illustrated in Fig. 5 and Fig. 6, which show the comparison between calculated and measured profiles for two high current triode prototypes with slightly different accelerator geometry (gap and aperture offset).

There is a remarkable similarity between measured and calculated profiles. The beam simulation code predicts well most of the features of a complex beam power density distribution. It should be noted that there is also a very good match on the absolute scale, which can only be obtained if all parameters influencing the beam power density distribution (non-uniformity, divergence, accelerator geometry) are taken into account. Similar agreement was obtained for all PINIs, which were assembled by using the new alignment procedure and which were subsequently tested at the Neutral Beam Test Bed.

4.2. Beam interception and transmission
Beam intercepting components (scrapers and liners) can be included in the beam simulation code to generate realistic beam profiles at various locations along the beam centre line. This is illustrated in Fig. 7, where simulated neutral beam profiles are shown at various points of interest along the Neutral Injector beam centre line.

By integrating the power density distribution over the area of the beam profile window, the total transmitted power at a specified location along the beam line can be calculated, as illustrated in Fig. 8.

The code can be also used to generate horizontal and vertical beam envelopes by plotting the width and height of the 1/e power density contour as a function of distance along the beam centre line.
4.3. Optimum perveance and ion source non-uniformity

Optimum beam perveance of a multi-aperture beam is often defined as a ratio of beam current and beam voltage \((I/V^{3/2})\) that corresponds to the minimum beam width/height, and is usually determined by calorimetric methods. Optimum perveance can also be determined using optical spectroscopy by measuring the width of the Doppler shifted beam emission lines, which is a measure of the beam divergence.

Optimum beam perveance is often measured by varying the beam current (i.e. ion source plasma density) at fixed beam voltage, and this procedure is usually called a perveance scan. One such sequence was simulated using the PINI Simulator code for a standard JET triode PINI assuming typical non-uniform ion source plasma. The results of this simulation are shown in Fig. 9. Perveance scan data were generated by analysing two-dimensional beam profiles at 4.8 metres and 11 metres from the source. These two locations correspond to the Inertial Calorimeter position on JET Neutral Injectors and to the Beam Dump position at JET NBTB [4]. Data are also compared to beam divergence values, which are used in the simulation and are derived from Doppler spectroscopy measurements.

It can be seen from Fig. 9 that the optimum perveance value, corresponding to the minimum of the perveance scan curve, depends on the location at which the measurement is taken. This explains the long-standing discrepancy between optimum perveance values measured at JET Neutral Beam Test Bed and at JET Neutral Injectors. In the case of uniform ion source plasma, all measurements will result in the same optimum perveance of \(0.56\times10^{-6} \text{ A/V}^{3/2}\), i.e. the spectroscopic value.

5. CONCLUSIONS

- The new PINI assembly procedure and associated beam simulation code allow prediction of beam properties prior to actual conditioning and characterisation at the JET Neutral Beam Test Bed.
- A few established figures of merit are sufficient to decide whether the PINI is suitable for further testing.
- Since the procedure was adopted, in November 2000, 100% of tested PINIs were found suitable for installation on the JET machine - in the past only 40% of tested PINIs were acceptable, at the first attempt.
- Beam simulation predicts that, in addition to good accelerator design, grid misalignment and ion source non-uniformity are two major factors that determine the properties of multi-aperture beams.
- Global beam shape and power distributions are predicted with good accuracy.
- The code is particularly useful for examining the influence of various source and/or accelerator parameters (ion species composition, plasma non-uniformity, beamlet divergence) on global beam properties.
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REFERENCES


Fig. 1. Power density contour plots of particle beams extracted from various JET PINIs: high current tetrodes (left and middle) and high current triode (right). PINI numbers, measurement distance and beam parameters are indicated on graphs. Contour labels indicate power density in MW/m².

Fig. 2. PINI accelerator assembly in the JET PINI workshop.

Fig. 3. Characteristic grid holes (1-9) used for PINI alignment measurement - upper grid half.
Fig. 4. Projections of characteristic beam centre lines on planes perpendicular to global beam axis: (a) ideal case (high current triode) and (b) actual case (high current triode PINI 01CT). Distances from the accelerator (z coordinate) are indicated on top of the figure.

Fig. 5. Simulated (left) and measured (right) power density distributions for a composite (ions + neutrals) beam extracted from the high current triode PINI 01CT. Data correspond to 100kV/37A deuterium beam. Contour lines indicate power density corresponding to 1/e fraction of the peak power density.

Fig. 6. Simulated and measured power density distribution for composite beam extracted from the prototype high current triode PINI 02CT. Data correspond to 90kV/32A deuterium beam.
Fig. 8. Simulated transmitted neutral beam power as a function of distance from accelerator electrodes. A reduction in transmission occurs at various beam intercepting elements.

Fig. 7. Simulated power density distributions of a 130 keV neutral deuterium beam (upgrade triode 01CT) at the exit of the Neutraliser (z = 2 m), after Inertial Calorimeter Back Panel (z = 4.8 m), exit of the Box Scraper (z = 5.1 m) and exit of the Duct Scraper (z = 8.3 m). Contour lines indicate 1/e fraction of the peak power density.

Fig. 9. Variation of simulated beam height at 11 metres from the source (squares), simulated beam width at 4.8 metres from the source (circles) and beamlet divergence (solid line) with beam perveance. Data are derived from simulated power density profiles and from Doppler shift spectroscopy measurements. “Optimum” perveance values are apparently dependent on the measurement method and position along the beam centre line.