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Compensation for Non-linear Interaction between JET NBI Deflection Magnets for Simultaneous D_2/T_2 Beamline Operation

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1. INTRODUCTION

Each Neutral Beam Injector at JET is capable of injecting around 10MW D^o or T^o from 8 PINI ion sources through one port [1]. There are four Deflection Magnets (one per quadrant) spaced close together. A schematic drawing of a quadrant is shown in fig.1. Each magnet deflects the unneutralised ions from the beams onto a V- shaped Full Energy Ion Dump (FEID) and Fractional Ion Dumps (not shown). Thermocouples in the FEID monitor the power footprint.

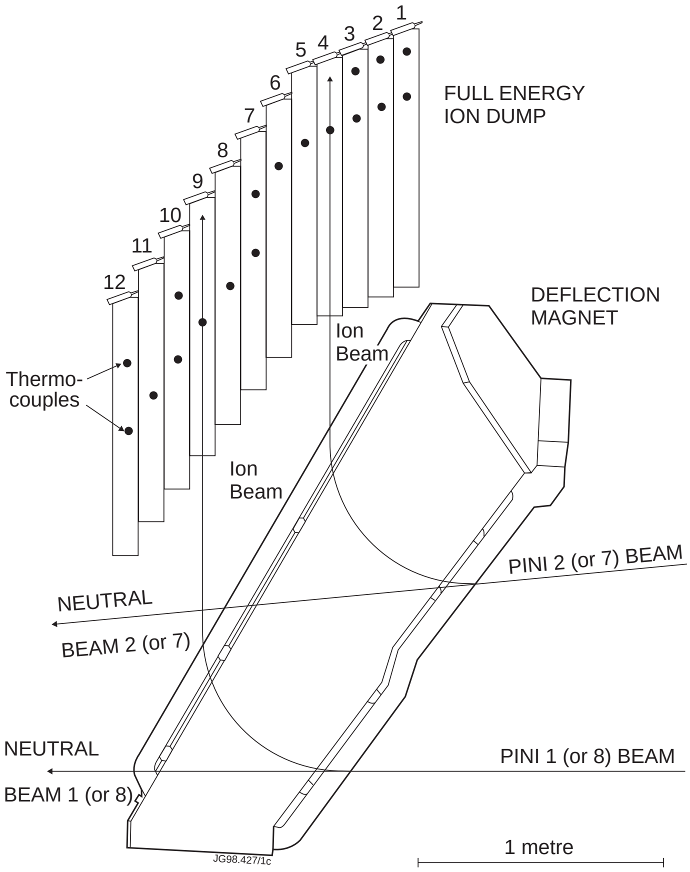

Fig. 1: Beam quadrant with Deflection magnet, Full Energy Ion Dump, thermocouples and beam trajectories.

At the high magnet currents necessary to deflect the 160 kV T^+ beams (~800A) onto the dumps, significant flux leaks from one magnet into the other. This is schematically shown in fig. 2. The flux leakage is no problem if all four magnets are operating at the same current, as the flux leaking out from one magnet is compensated by the flux leaking in from the others. However, in order to conduct an experiment to measure plasma self heating from α-particle production [2], it was necessary to inject a mix of 160 kV T^o and 140 kV D^o beams from ***one*** beamline. To accomplish this the interaction between the four deflection magnets had to be characterised, as the deuterium beams require only 550A deflection current.

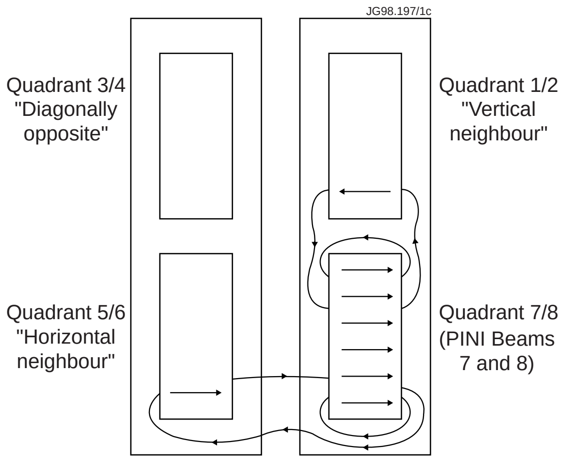

Fig. 2: Schematic of the four bending magnets indicating the flux leakage from quadrant 7/8 to the other magnets.

Fig. 3 overlays the quadrant 7/8 thermocouple data from two 140kV deuterium shots. In one shot all magnets were energised and the power was deposited in the middle of the FEID. In the second shot the magnet deflecting the ions from PINIs 7 and 8 was operating alone at the same current. A clear 1-element shift can be identified in fig. 3. Concerns that due to iron saturation this effect would be worse in tritium operation led to the present study to compensate for its magnitude.

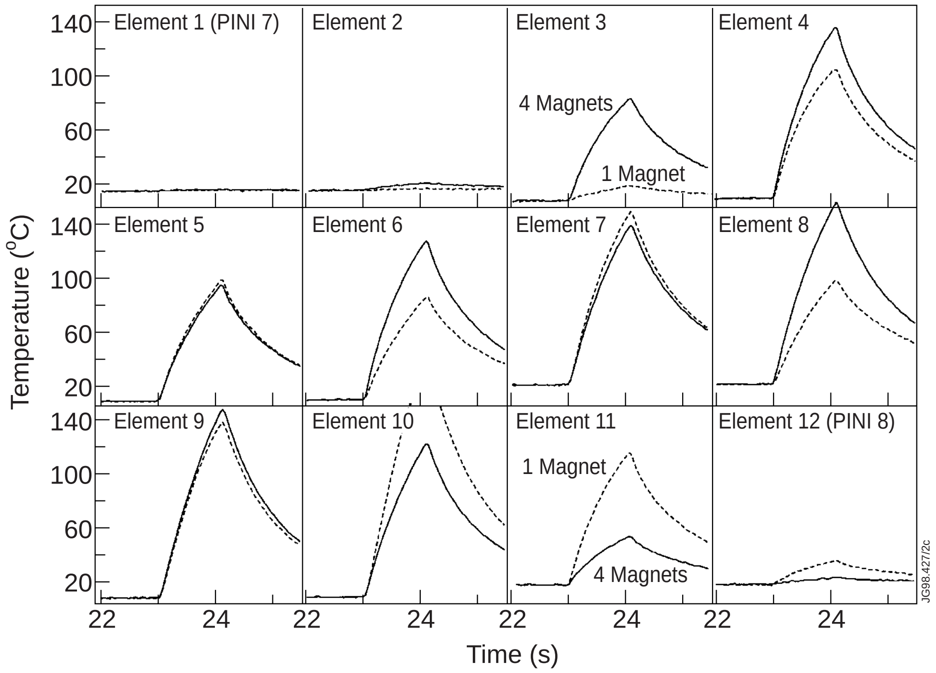

Fig. 3: Time traces from the thermocouples in the quadrant 7/8 FEID. 140 kV D beams were fired from 23 to 24.1 second. ***Solid lines:*** *all four deflection magnets energised.* ***Dashed lines:*** *Only one deflection magnet energised. The reduced bending power for the latter case can clearly be seen.*

2. MODEL FOR THE MAGNET INTERACTION

The influence of a vertical, horizontal or opposite neighbour (F_V, F_H, F_O, respectively) carrying a current I_V, I_H, I_O, respectively, need not be linear. It is *assumed*, however, that the addition of their contributions is linear; ie the effect of two neighbours switched on is assumed to be equal to the sum of the effects when each neighbour is switched on individually. Moreover, from measurements it has been found that the influence of the opposite magnet is very small. In this paper it is taken to be zero: F_O=0.

The existing magnet calibration prescribed the magnet current I(E,m) required to deflect ions with mass m at energy E without considering neighbouring magnets and is accurate if all four magnets are energised at the same current ($I_H=I_V=I_o=I$). Thus, the magnet interaction correction must yield 0 for cases when all magnets are operating at equal current. The following expression meets all requirements listed above:

$$\Delta I(I_V, I_H, I) = F_V(I_V, I) - F_V(I,I) + F_H(I_H, I) - F_H(I,I) \qquad \text{(formula 1)}$$

Formula 1 can be seen as a measure for the difference between the magnetic flux leaving the magnet ($F_V(I,I)+F_H(I,I)$) and magnetic flux from the neighbours entering the magnet ($F_V(I_V,I)+F_H(I_H,I)$).

A further simplification is to assume that the dependence of flux leakage on I is the same for all magnets: $F_V(I_V,I)=f_*(I)\cdot f_V(I_V)$ and $F_H(I_H,I)=f_*(I)\cdot f_H(I_H)$. Formula 1 then becomes:

$$\Delta I(I_V, I_H, I) = f_*(I) \times \left[f_V(I_V) - f_V(I) + f_H(I_H) - f_H(I) \right] \qquad (formula\ 2)$$

This requires the measurement of a set of one dimensional functions, rather than scanning a multi dimensional space of variables.

3. MEASUREMENTS

Because of limited experimental time, only two values for I were chosen: 551A (140kV D^+) and 780A (154kV T^+). I_V and I_H were varied between 0 and 875A. A reference shot with $I=I_V=I_H$ was done first. Then I_V and I_H were gradually changed. For each setting of I_V and I_H, I was adjusted in such a way that the power density footprint from the reference shot was reproduced. In this way ΔI was obtained with a 1A-2A accuracy. The D^+ measurements were done on quadrant 1/2, the T^+ measurements on quadrant 7/8.

4. MODEL CURVES

We have measured $F_V(I_V,I)$ and $F_H(I_H,I)$ at two values of I and many values of I_V and I_H. We need to find functions f_*, f_V, f_H that fit the data at both values of I and can be used for interpolation as well. It was assumed that $f_*(I)=(I/I_{cal})^\gamma$ where I_{cal} is the value at which a measurement was done. I_{cal}=780A was used, but we could equally well have chosen I_{cal}=551A. The magnet interaction correction adopted is:

$$\Delta I = \left(I/I_{cal}\right)^\gamma \times \left[f_V(I_V) - f_V(I) + f_H(I_H) - f_H(I) \right] \qquad (formula\ 3)$$

The parameters in this formula are listed in Table 1. Interpolation must be used for values of the current not listed in Table 1. The model curves have been drawn in figures 4 and 5 for I=780A and 551A, respectively. Also the measured data (section 3) is plotted in figures 4 and 5. It can be seen that the agreement is quite good. The maximum deviation from the curves to the data (10A for T^+, 6A for D^+) corresponds to a shift on the dumps of less than _ element. The average deviation is less than 1/8 element. The high value for γ (γ=1.5) means that at lower current I the interaction from the neighbours is small, which is observed indeed.

Table 1 Adopted Magnet Interaction Compensation curves, to be used with Formula 3.

I, I_V, I_H (A)	**f_V (A)**	**f_H (A)**
0	33	32
300	23.2	31
550	15	23
780	0	0
900	-7.8	-12

Ical	780 A
γ	1.5

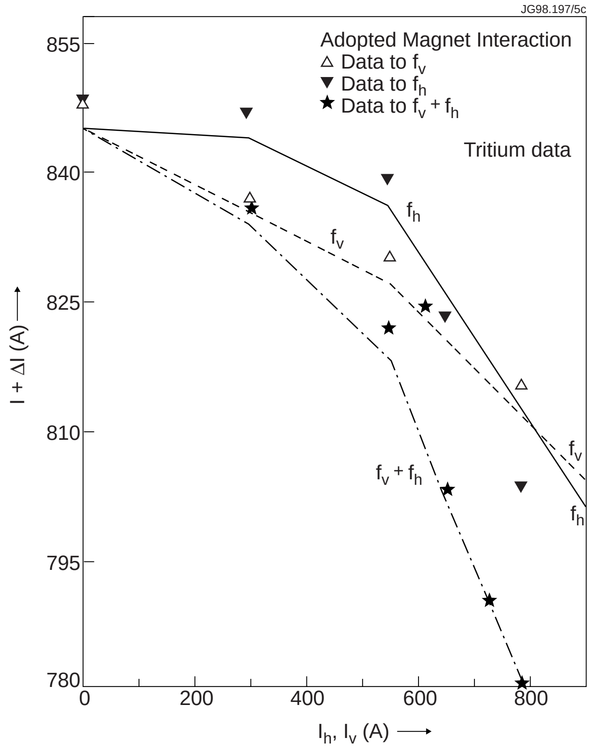

Fig. 4: ***Magnet Interaction at 780A.*** *Model curves f_V, f_H and f_V+f_H (drawn lines). Measured 154kV T^+ data belonging to the model curves (individual points).*

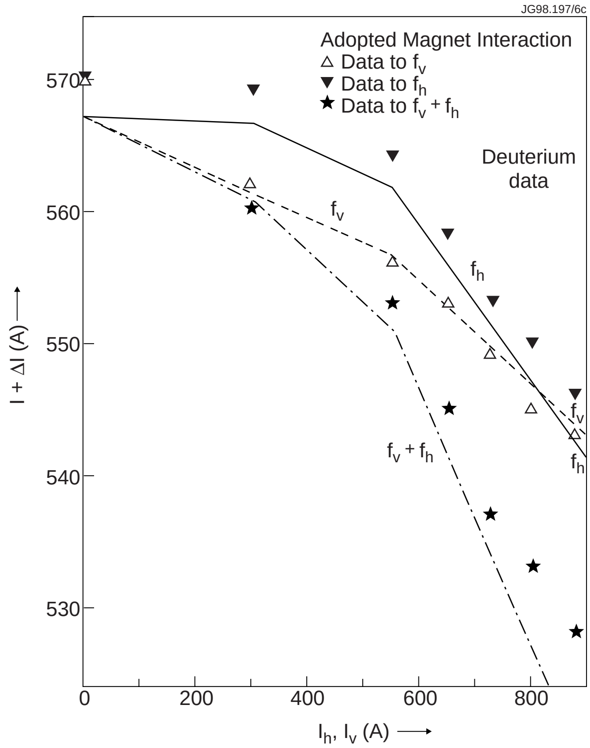

Fig. 5: ***Magnet Interaction at 551A.*** *Model curves f_V, f_H and f_V+f_H (drawn lines). Measured 140kV D^+ data belonging to the model curves (individual points).*

The model curves were installed on the beamlines in 1997 and both beamlines have run with the magnet interaction compensation operative ever since.

5. ADDITIONAL VERIFICATION

A series of test shots was run on all the four quadrants to verify the validity of the model in cases that were not used to derive it. It was especially important to know that what was measured on quadrants 1/2 and 7/8 (section 3) also applies to the other quadrants. Permutations of 765A, 551A and 0A were run on all the quadrants and the Magnet Interaction Compensation (formula 3, Table 1) was active throughout. The footprints that deviated most from the reference shot are given in fig. 6.

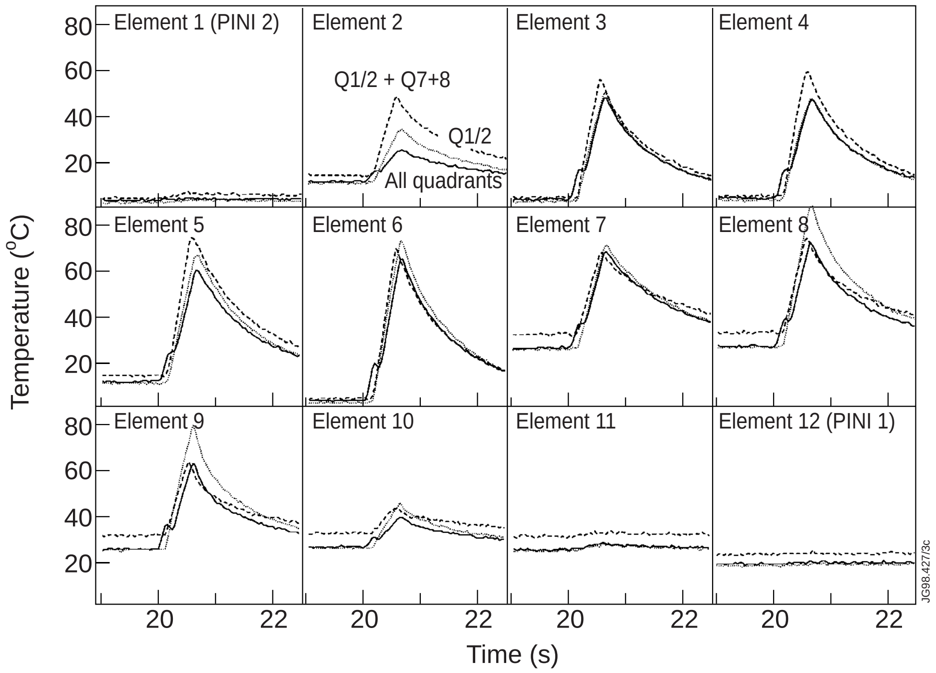

Fig. 6: Temperature profiles on the quadrant 1/2 FEID. ***Magnet interaction compensation is active. Solid lines:*** *Ref. shot. All 4 magnets are at 765A.* ***Dotted lines:*** *Only one magnet active (Quadrant 1/2). The beam footprint is wider, but not shifted.* ***Dashed lines:*** *Quadrant 1/2 and 7/8 active (opposite quadrants). The beam footprint is slightly shifted.*

6. CONCLUSIONS

The interaction between the NBI deflection magnets was successfully modelled and the compensation for it implemented on both beamlines. The Magnet Interaction Compensation is given in formula 3, which uses the parameters in Table 1. The Compensation algorithm was installed on the beamlines in 1997 and is operative ever since.

REFERENCES

1. Duesing, G. et al, *Fusion Technology* **11** 163-202 (1987)
2. Thomas, P.R. et al, *Physical Review Letters*, in print (1998)