EFFECTS OF HIGH FREQUENCY DISRUPTIONS ON THE JET DIVERTOR CRYOPUMP, INCLUDING POTENTIAL JET TOROIDAL FIELD UPGRADES

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ABSTRACT

The JET Divertor Cryopump System was designed several years ago and the design took account of thermal and eddy current stresses. The design calculations were based on static analyses for disruptions with poloidal magnetic field variation of 110T/s and a toroidal magnetic field (TF) of 3.4T. The cryopump operated during the 1994-95 experimental campaign without any failures. Subsequently detailed endoscope inspections indicated no distortion or damage in any of the cryopump areas.

During this last experimental campaign, a significant portion of plasma disruptions were of high value and relatively high frequency. The eddy current stresses are in principle proportional to both the velocity of the disruption and the TF. The cryopump system was able to withstand these severe disruptions and in order to explain this ability, an analysis has been performed to investigate the dynamic/impact nature of the load, together with the natural frequencies of the structure. In addition, the transient nature of eddy currents, the 'skin' effect and the current decay time have been quantified.

The calculations indicated that, although any damping characteristics of the structure have no significant effect for these high value disruptions, the high stress areas of the pump have a natural frequency much smaller (~4%) than the frequency of the severe disruptions. Therefore, the dynamic effect of these impact loads is approximately 30% of an equivalent static load and resulted in no failure. These analyses confirmed the demonstrated and expected high reliability of the cryopump even for a possible upgrade of the TF to 4T.

1. INTRODUCTION

The JET Divertor Cryopump System (Fig 1) was designed several years ago and the design took account of thermal and eddy current stresses during normal operation and abnormal events like severe disruptions, loss of water, cryogen flow and loss of vacuum [1], [2], [3]. The cryopump was designed to slide on the divertor coil 4 and incorporated expansion devices (bellows, expansion/elongated holes) in order to minimise the thermal stresses. The mechanical, thermal and electrical properties of the materials used [3], [4] were such as to further reduce the thermal gradients and stresses, and in addition to minimise the eddy current stresses. Eddy current stresses are generated during plasma disruptions.

2. STATIC ANALYSIS OF DISRUPTIONS

The design calculations of the pump were based on static analyses for disruptions with rates of change up to 110 T/s for the radial and vertical magnetic field and a TF of 3.4T. The radial and vertical magnetic fields before disruption were 1T. Finite Element models simulated the system geometry and the predicted stresses were rather high in certain places, but were accepted because it was felt that the assumed value of 110 T/s for a disruption was conservative.

The maximum stresses in the pump were predicted to be in the large stainless steel backplate and cryoclamps. (Fig 2). In particular, in the backplate ends and last toroidal cryoclamps; large eddy currents (~ 1kA) generate large bending moments. Specially designed cut-outs at the backplate ends and terminal cryoclamps with increased width reduce the eddy current stresses to acceptable levels.

3. IMPACT ANALYSIS OF DISRUPTIONS

During the 1994-95 experimental campaign, a significant portion of disruptions had high values of field rate of change (450 T/s) and high frequency (1 kHz). However the majority of disruptions was still much below 110 T/s and of lower frequency $\leq$ 100 Hz.

Despite these events, the cryopump operated for more than a year without failures. Subsequently detailed endoscope inspections indicated no distortion

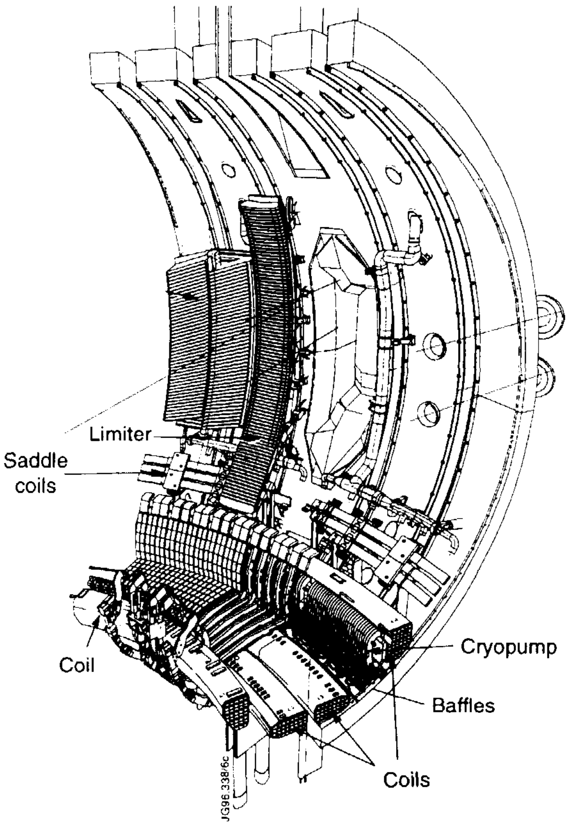

Fig 1. A Three Dimensional View of the JET Torus with a Mk1 Pumped Divertor

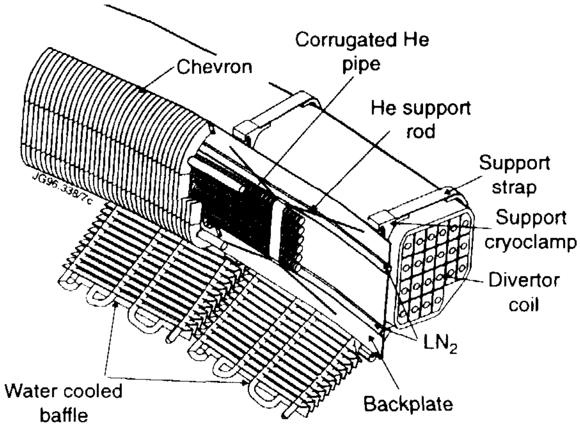

Fig 2. A Three Dimensional view of the JET Divertor Cryopump with associated water cooled baffles and divert coil No 4

or damage in any part of the system. The eddy current stresses are in principle proportional to both the velocity of the disruption and the TF. The cryopump was able to withstand these severe disruptions and in order to explain this ability, an analysis was undertaken to investigate the dynamic/ impact nature of the load. In addition, this analysis accounted for a potential TF field upgrade to 4T.

In dynamic/impact phenomena, the higher the ratio of the load period to the natural period of the structure, the more severe the effect. In addition the maximum response to a very fast impulsive load will be reached in a very short time, before any damping forces can absorb much energy [6].

Therefore we investigated the highly stressed areas of the system, with relatively high natural frequencies and simulated these structures under impact/disruption loading with a single degree of freedom undamped models. The end cryoclamps were typical. They were particularly suited, due to their geometry, to one degree of freedom models. Their basic natural frequency is approximately 43Hz. The response of the cryoclamps to an impact load of 1kHz (1 ms) is divided into two phases, the interval, during which the load acts, and the subsequent free vibration stage. The ratio of the natural frequency of the structure to the load frequency is 4.3% and Fig 3 shows the predicted dynamic effect (D) of impact square loads as a function of this frequency ratio [6]. This effect D is 0.27. Due to the very short duration of the loading the maximum response occurs during the free vibration phase of the structure (after 1ms) [6].

Figure 4 shows in addition to the JET MK1 In-Vessel Pumped Divertor Geometry, the direction and measured values of a typical high value, high frequency disruption.

Accounting for orientation, the maximum value of the radial magnetic field rate, $\dot{B}_r$, is given by

$$\dot{B}_r = 450 \sin\theta_1 \pm 200 \,\mathrm{Sin}\theta_2 \le 310 \text{ T/s}$$

For a potential TF increase to 4T, the dynamic analysis above, when compared to the initial static analysis of the design phase, produces a stress magnification factor of

$$0.27 * \frac{4\mathrm{T}}{3.4\mathrm{T}} * \frac{310\mathrm{T/s}}{110\mathrm{T/s}} < 1$$

It is therefore clear that the static analysis performed during the design phase with 3.4T and 110T/s is more severe than the effect of disruptions with maximum rate of field change of 450T/s, for 1ms, even accounting for a possible increase of the TF to 4T.

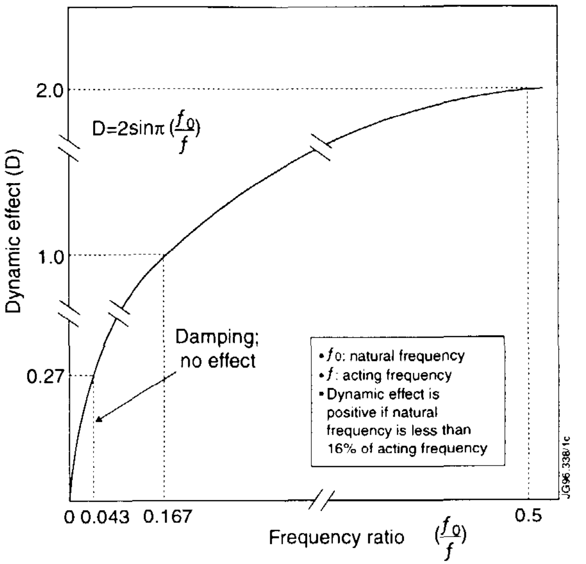

Fig 3. Dynamic Effect (D) of impact Square loads as action of the ratio between the natural and acting frequencies.

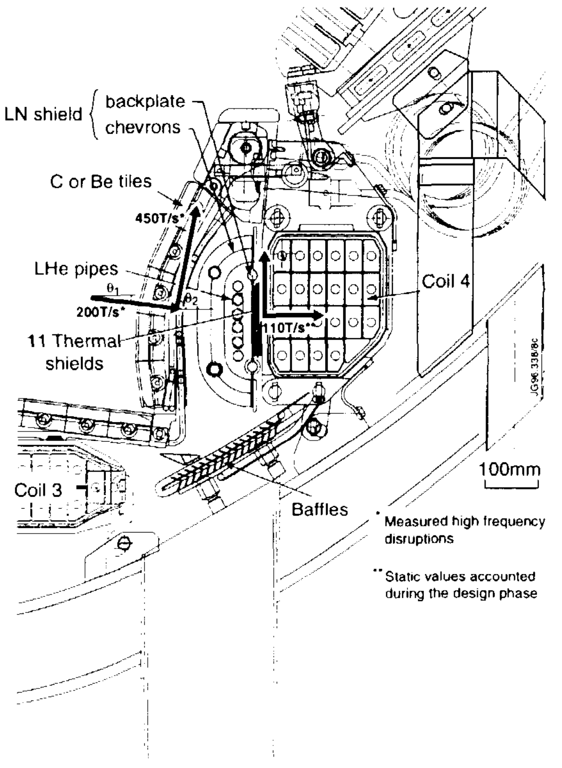

Fig 4. Cross Section of the JET MkI Pumped Divertor indicating measurements of high frequency descriptions

4. SECONDARY DYNAMIC EFFECTS

4.1 Skin Effect

The eddy current penetration in a component is proportional to the square root of the ratio of the component's electrical resistivity to the frequency of the disruption [7]. Therefore high frequency disruptions may not penetrate fully components with low electrical resistivity. It can be shown that a 1kHz disruption results to a penetration in Cu of less than 2mm. This phenomena may be present in parts of the Liquid Nitrogen (LN) circuit of the cryopump but the effect in terms of stresses is marginal because of the small thickness (2mm) of the chevrons of this component (Fig 4).

4.2 Eddy Current Decay Time

Eddy currents decay with a time constant which is proportional to the component thickness or skin depth, the electrical conductivity and the square root of the area in which the currents are flowing [7]. For high frequency disruption of ~1kHz and poor conductors (i.e. stainless steel) the current decay time is of the order of only 1-2ms; again not particularly significant to affect the conclusions of the dynamic analysis of the high value, high frequency (1 kHz, 1ms) disruptions on the stainless steel cryoclamp.

5. EFFECTS OF LOW VALUE, LOW FREQUENCY DISRUPTIONS

It can be shown that the dynamic magnification factor D varies as a sine function of the load pulse length ratio to the natural period of the structure and can reach a maximum value of 2 (Fig 3). [6]. This value can be reached only with a rectangular step load, zero damping and for a load pulse ratio of a greater or equal to 0.5.

Therefore for the highly stressed terminal cryoclamps, with a natural frequency of $\simeq$ 43 Hz, disruptions with a frequency of less than 86 Hz (or duration of more than 12ms) and value more than 55 T/s, result in higher stresses than accounted in the static analysis of the design phase. Such disruptions occurred and were really the most severe ones (not the 450 T/s, 1ms events). These could result in stresses very near or just above the component yield point but the detailed endoscope inspection indicated no such deformation.

This analysis ignores structural damping and is therefore conservative. Damping may have a significant mitigating effect in low frequency disruptions. Critical damping (equal to the square root of the stiffness multiplied by the mass of the system) can reduce the parameter D ,by a factor of up to two [6]. The cryoclamps are supported on the casing of one of the Divertor coils. Underneath the casing there is the epoxy and copper structure of the coil which would effectively introduce some damping in the structural response.

In addition to structural damping, the effect of structural support position on eddy currents can be very significant indeed. If the system geometry permits, the choice of support points should result to lower stiffness/frequency components. Furthermore careful positioning of supports to minimise the bending moments in the structure can result in a stress reduction of up to a factor of 20 [9]. All these effects result in lower eddy current stresses and explain also the ability of the cryopump to survive the most severe, relatively low frequency and lower absolute value disruptions.

Finally, global sideways displacements of the Torus, up to ~5mm due to disruptions were observed during the 1994-95 experimental campaign. These phenomena are particularly pronounced at Octants 1 and 5, where the cryopump is fed cryogens by the cryofeeds. Such events could damage the concentric thin wall tube cryofeeds and were not predicted during the design phase of the cryopump. However in the design and installation phases adequate gaps between the cryofeed and the vacuum vessel were incorporated to account for baking of the vacuum vessel, to assist installation and to accommodate geometrical inaccuracies of the system. These gaps proved also adequate to protect the cryofeeds against the torus sideways displacements.

CONCLUSIONS

It is the value and relationship of the frequency of the disruption to the component natural frequency and not only the rate of change of field in the disruption that determines the severity of the event. High velocity disruptions may be severe for some components and not for others.

The dynamic analysis performed in the cryopump under the very high value, high frequency disruptions experienced during the JET Experimental Campaign of 1994-95 explained the ability of this component to withstand these events and to cope with a potential increase of the TF to 4T. The high stress areas of the system have still relatively low frequency compared to the high frequency of the applied impact load and therefore the generated dynamic stresses are mitigated and are smaller than equivalent static stresses under similar conditions.

Finally significant global sideways movements of the vessel during disruptions resulted in no major effects on the cryopump feeds.

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