JET–R(97)06

Power Handling in the JET Lower Hybrid Launcher

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August 1997

Abstract

The LHCD system is described and the power handling of the Launcher during the 1994/5 experimental campaign is analysed. The most important limit in power handling is found to be the electric field in the small waveguide at the grill mouth. A system to limit this electric field is described. With an electric field of 400 kV/m there is a 50% chance that a trip and re-application of the power will be triggered. This is a significantly lower operating limit than that reported by other machines.

1. Introduction: LHCD Generator and Launcher

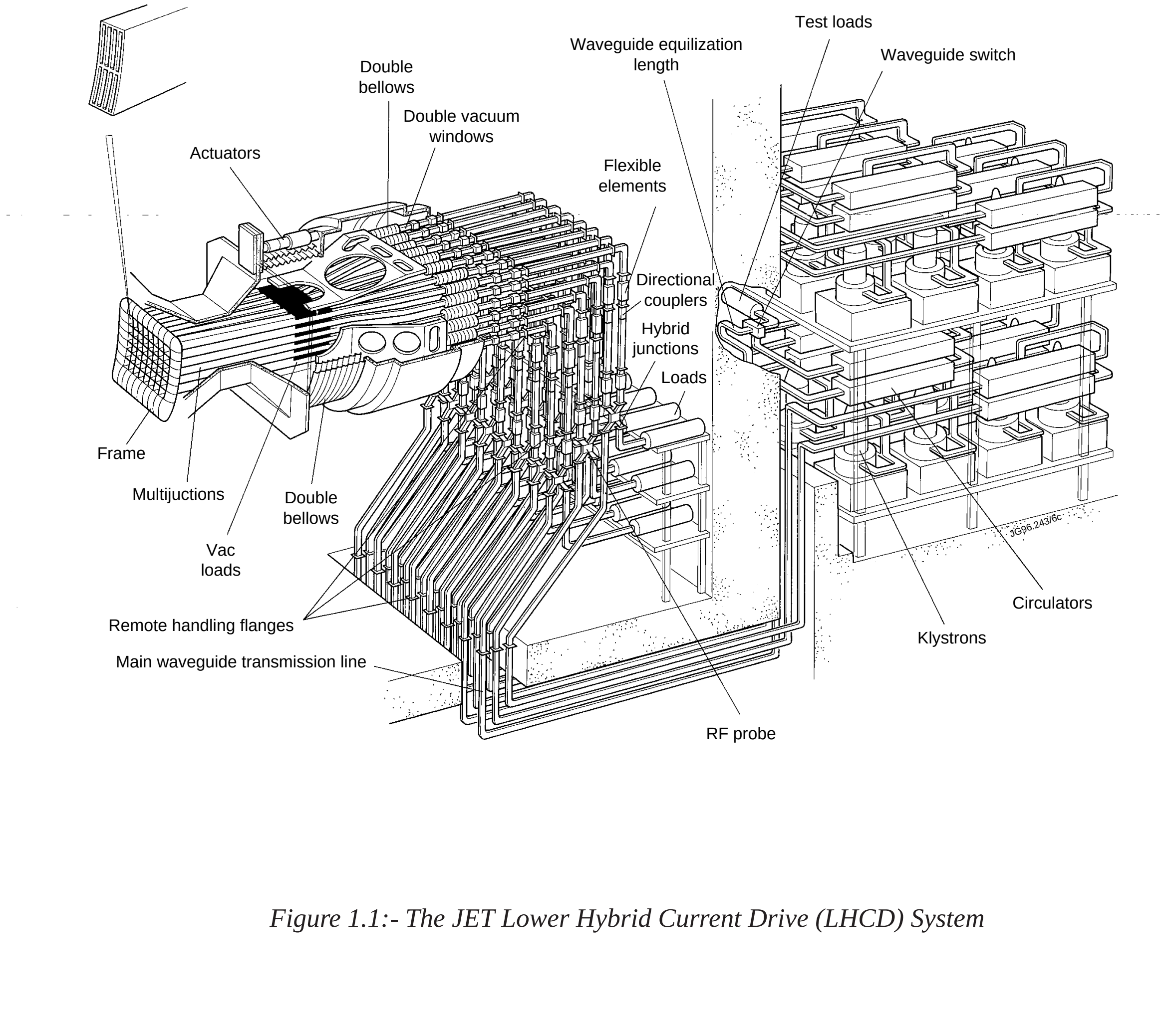

Figure 1.1:- The JET Lower Hybrid Current Drive (LHCD) System

The JET LHCD system consists of 24 klystrons feeding a phased array of waveguides mounted on the main horizontal port of Octant 3 of the JET machine. The klystrons are fed from an outdoor power supply at -65 KV and up to 25 A each. They are grouped in modules of 4 fed from a common HVPS. Each module has its own cooling system that transfers the losses to the JET site water network. Each klystron is protected by a circulator on its output which absorbs any power reflected back from the Launcher. The klystron power can be directed by a waveguide switch to either a test load or to the waveguides that lead to the Launcher. The waveguides are pressurised to 1 bar over pressure with SF6 to improve their power handling.

At the rear of the Launcher the power from the klystrons is split by a hybrid junction and transmitted through flexible waveguide elements that accommodate radial movements of the Launcher. At the back plate of the Launcher vessel are 48 windows. These have two ceramic discs with a pumped interspace to provide the double containment required for tritium operation. The Launcher houses 48 multijunction assemblies. These split the power in one H plane and two stages of E plane junctions from one input to eight output in two rows of four waveguides each. The waveguides have mechanical phase shifters to produce a slow travelling wave across the grill mouth.

The electron density at the grill mouth must be of the order 1 x 10^{18} m^{-3} for the Lower Hybrid wave to propagate into the plasma. This means that the distance between the grill mouth and plasma boundary must be precisely controlled or a large fraction of the power is reflected back into the multijunctions causing arcs at high power. To do this the Launcher is driven by a hydraulic system. This has two circuits. The first simply offsets the 12 Tonnes vacuum pressure while the second servo loop is used for control against the spring action of the double bellows connecting the Launcher to the main horizontal port. The position of the grill mouth can be controlled to within a few millimetres by a feedback loop that controls the power reflection coefficient to a preset value.

The inner most position to which the Launcher can move is limited by three ‘legs’. These are movable buffers that can be positioned remotely. They are driven from the offset hydraulic circuit. They prove a means of ensuring that the Launcher cannot be driven into the plasma and means of ‘parking’ the Launcher behind the Poloidal Limiter when it is not in use and the hydraulic system is depressurised.

The Launcher has its own cryopump to limit the rise in pressure in the multijunctions during a pulse. The multijunction waveguides have small holes in their top and bottom surfaces to improve the conductance to the cryopump. Outgassing is also reduced by baking the Launcher vessel and multijunctions to up to 350 ^{o}C.

The main parameter of the LHCD system are given in Table 1.

The spectrum of the launched power is shown in Figure 1.2 for 0^{o} phasing between adjacent multijunctions. The 32 waveguides in each row result in a good directivity of the wave. The wave spectrum ($n_{//}$) can be varied between 1.4 to 2.3 by varying the phase between multijunctions which is determined electronically by controlling the phase at the generator output.

Parameter	
Operating Frequency	3.7 GHz
Number of Klystrons	24
Generator Nominal Power for 10 s Pulse	15 MW
Generator Nominal Power for 20 s Pulse	12 MW
Duty Cycle	1/30
Klystron Efficiency	42%
Phase Control	$\pm$ 10^o
Maximum VSWR at Generator	1.8
Length of Transmission Line	40 m
Estimated Insertion Loss of Line	1 dB
Number of Waveguides at Launcher Grill Mouth	384
Waveguide Dimensions at Grill Mouth	9 x 72 mm
Grill Material	Stainless Steel
Grill Coating	Copper
Grill Normal Operating Temperature	250 ^{o}C
Total Launcher Weight	15 Tonnes
Stroke of Launcher Position Control	300 mm
Maximum Speed of Launcher	5 mm in 100 ms
Acceleration of Launcher	0.2 g
Pumping Speed of Cryopump	80,000 l/s
Cryopump Operating Temperature	4.2-4.5 ^{o}K
Reservoir of LHe	60 Litres

Table 1:- Main LHCD System Parameters

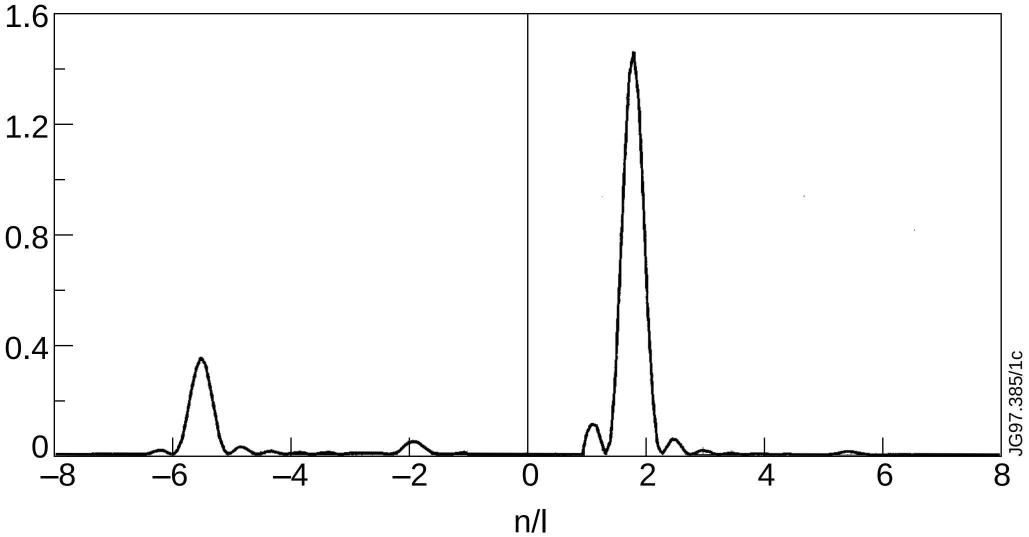

Figure 1.2:- Launched Power Wave Spectrum

2. The Multijunction Assemblies

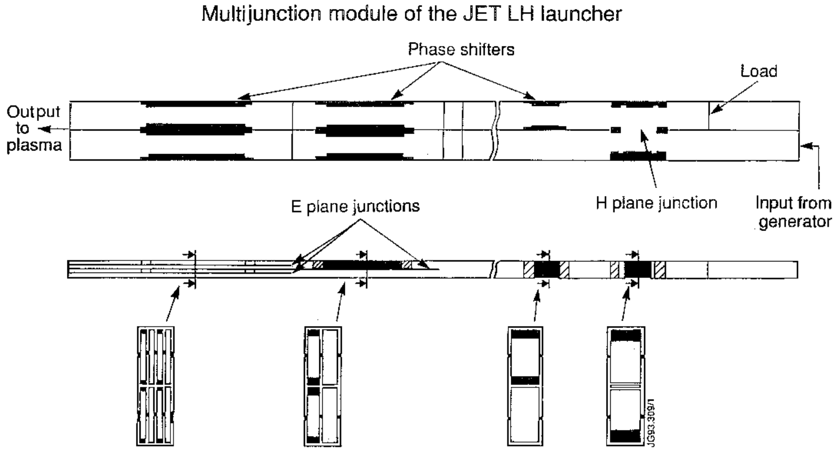

Figure 2.1 Multijunction Module

The LHCD launcher (L1) uses the main horizontal JET port (0.4 x 1 m) on Octant 3. At the mouth of the launcher is an array of waveguides (32 columns x 12 rows). Each waveguide is 9 mm wide and 72 mm high with a wall thickness of 2 mm. The array is profiled to match the plasma shape in a standard X-point configuration.

The array of waveguides is split into multijunction modules. Each multijunction module consists of an array of 4 columns x 2 rows. The total of 48 modules are assembled in 6 rows x 8 columns. Each multijunction module is one vacuum wavelength (44 mm) wide and two wavelengths high.The mode within the waveguides is the normal TE_{10}.The resulting module is shown in figure 2.1.

The estimated loss in the launcher is 3%. With the normal duty cycle, radiation cooling is sufficient. The launcher is therefore not actively cooled.

The multijunction modules are fed through stainless steel silver plated vacuum waveguides. These connect through the back plate of the vacuum tank that contains the multijunctions to the double vacuum windows.

The multijunctions are manufactured from stainless steel and then internally electroplated with 15 microns of copper to reduce the electrical losses.

The H-plane junction has a vacuum matched load fitted to the fourth port to reduce the circulating power within the multijunction. This uses silicon carbide as the absorbing material in a weakly resonant configuration. It is rated at 20 kW for the JET duty cycle and 300 kW for 100 microseconds. The operating temperature is 20°C to 500°C. Cooling is by radiation only.

The temperature rise in a multijunction should be less than 25°C per pulse. The maximum temperature rise will be at the grill mouth where radiation cooling is least effective.

Each module is equipped with one thermocouple at its H plane junction, as is each vacuum load.

3 The Electric Field in the Multijunctions

The electric field in the multijunctions can be related to the forward power and reflection coefficient measured on the directional couplers at the rear of the Launcher as follows:-

$$r_{mp} = r_{mv}^2$$

$$r_{bp} = r_{bv}^2$$

where
r = reflection coefficient
v = voltage
p = power
m = grill mouth
b = back of window

$$r_{bp} = r_{mp}^2$$

$$r_{bv} = r_{mv}^2$$

Therefore

$$r_{mp} = \sqrt{r_{bp}} = r_{bv}$$

$$r_{mv} = \sqrt[4]{r_{bp}}$$

$$E_{\max} \le (1 + r_{mv})^2 E_f$$

$$\le k(1 + \sqrt[4]{r_{bp}})^2 \sqrt{P}$$

Where E_f is the forward electric field in the multijunction
P is the forward power in the multijunction (~1/16 the klystron power)
k is a constant determined by the waveguide dimensions

The relationship between peak electric field and power is given by:-

$$P = \frac{a.b}{4\mu}\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}\; E_p{}^2$$

$$P = 3.55x10^{-7} E_p^2$$

Where a is waveguide width (72 mm)
b is waveguide height (9 mm)
λ_0 is wavelength in free space
μ is 120π
E_p is the peak electric field in the waveguide

Thus $$E_{\max} \leq 1678(1+\sqrt[4]{r_{bp}})^2\sqrt{P}$$

$$E_{\max} \leq 595 \text{ kV/m}$$ for P = 31.25 kW (500/16) and r_{bp} = 0.03

4 Multijunction Conditioning

The multijunctions are normally baked to 250 ^{o}C by radiation from the Launcher vessel which is held at 350^{o}C and the JET vessel that is held at 250-320 ^{o}C. At the start of an experimental campaign or after venting of the Torus the multijunctions are further baked and conditioned with RF power until the pressure rise during a pulse on one klystron has been reduced to about 1 x 10^{-7} mbar. At the start of the 1996 campaign the pressure rise after 1 hour of conditioning pulses on all klystrons was about 2 x 10^{-5} mbar. This dropped to about 1 x 10^{-6} mbar after 2 days of conditioning.

Grill conditioning in vacuum uses a system of automatic pulsing. This pulses each klystron module for 3 seconds in turn and adjusts the power up or down depending on the number of trips on each klystron. An interlock on the temperature of the vacuum load limits the temperature of the load to 380^{o}C.

5 Operation During the 1994/5 Campaign

The LH system operated on 2130 plasma pulses during this campaign. This is about 33 % of all plasma pulses. The maximum power coupled to the plasma was 7.3 MW. Clean pulses without trips of more than 5 MW for more than 4 s were achieved on several occasions when the reflection coefficient was low enough (<3%) and the grill well conditioned. To achieve the low reflection coefficient (Rc) feedback control was used. With this Rc feedback the grill mouth was moved as the plasma boundary conditions changed to maintain a constant reflection coefficient. During an in-vessel inspection in September 1994 melting of the grill mouth was observed. This was at the mid-plane of some elements of the multijunctions. This corresponds to the peak in the electric field. The top left quadrant of the grill viewed from inside the JET vessel was also melted more generally. The picture frame protection tiles was advanced 1 mm in this area to improve protection.

Figure 5.1 shows the average number of trips per pulse for each klystron. There are five possible triggers for a trip:-

- High VSWR at the generator.
- Light on the vacuum side of one of the two Launcher windows.
- An out of balance between the power reflected by the two multijunctions (REFPA/B) fed by one klystron.

There are a relatively large number of trips per pulse: about 15 on average for each klystron. After each trip power is reapplied after 100 ms so that on average 1.5 seconds of each pulse are lost.

The REFPB trips dominate in the upper and lower rows (klystrons A1-B4 and E1-F4) while REFPA trips occurred more often in the middle row (klystron C1-D4). The rate of VSWR trips is fairly constant.

The RF trips were generally effective in preventing arcs propagating back to the windows although a few klystrons showed some window trips. These probably originated at the windows.

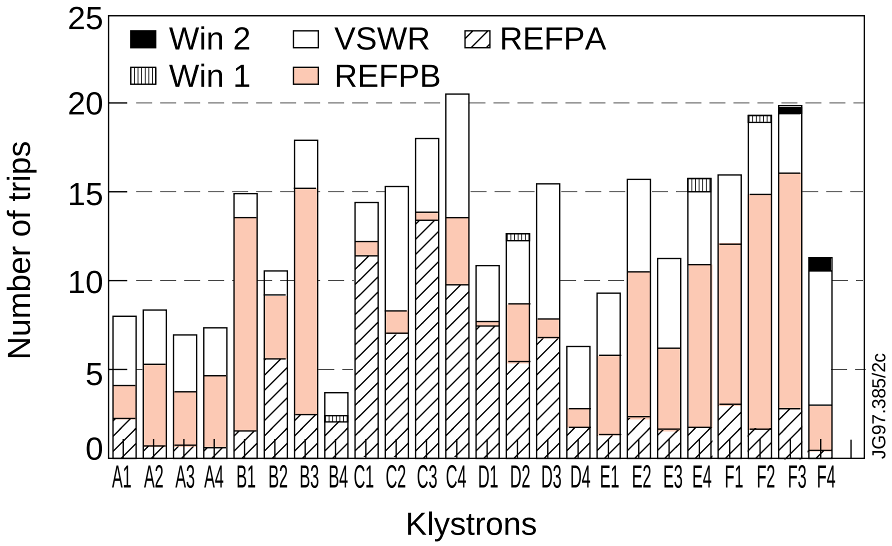

Figure 5.1:- Average Number of Trips per Pulse for Each Klystron. Pulses with more than 2 MW Coupled for more than 0.9s (544 pulses).

Figure 5.2 shows how the electric field of two multijunctions varied during the campaign. After an initial conditioning period of about 1000 pulses there was no further increase in the electric field although high powers were transmitted by operating at reduced reflection coefficient. This is shown in Figure 5.3

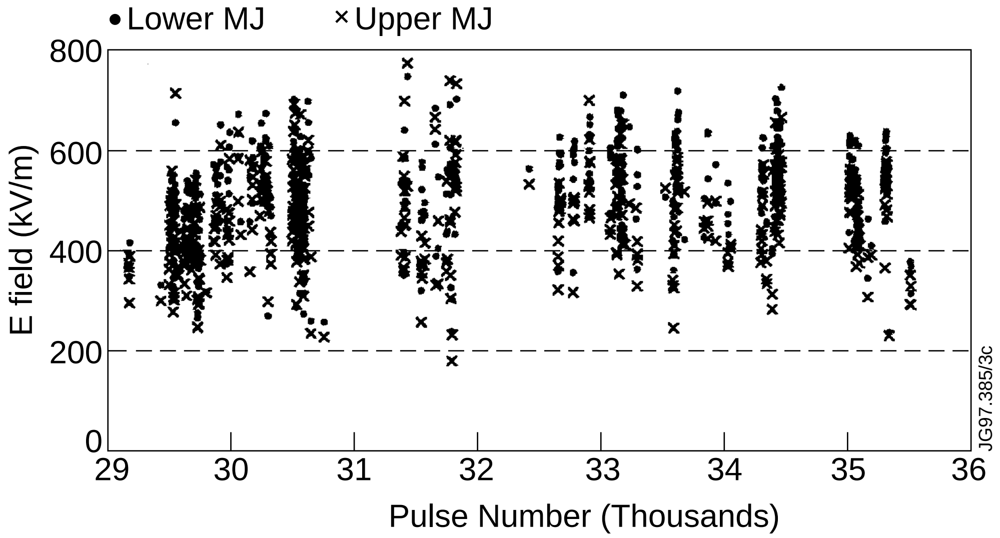

Figure 5.2:- Electric Field in Multijunctions fed by Klystron A3. Pulses with more than 2 MW coupled for more than 0.9s (512 pulses).

As can be seen the power handling improves rapidly as the reflection coefficient is reduced to a few percent. The majority of points are below a line of constant electric field, consistent with this being the factor limiting power transmission.

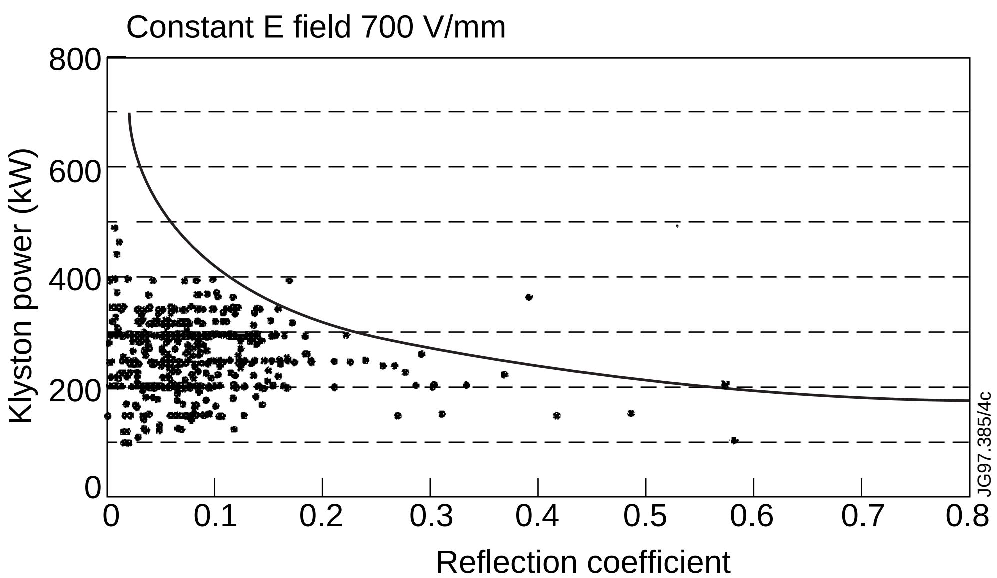

Figure 5.3:- Klystron power against the Higher of the Multijunction Reflection Coefficients. Klystron A3

In Figure 5.4 the time the electric field was above a given value is plotted for klystron A3 together with the cumulative number of trips normalised to 1.

For the plot of ‘Proportion of Time above Electric Field Value’ the electric field is evaluated for each data point of each pulse to produce a distribution curve, built up by adding the total time the electric field was within each band of 16 kV/m. A total of 50 bands are used to cover the range 0 to 800 kV/m. The cumulative distribution can then be calculated. This is normalised by dividing by the total time. For the plot of ‘Cumulative Distribution of E Field at a Trip’ the electric field just before each trip is evaluated and the distribution and cumulative distribution built up in a similar way. The cumulative distribution scale is normalised by dividing by the total number of trips (2846 in the case of A3).

These plots shows that there is not a hard limit above which the multijunctions will not operate but rather an increasing probability that an arc will be produced and the power tripped as the electric field value increases klystron A3 clearly operates reliably at an electric field up to 300 kV/m but with increasing difficulty up to about 600 kV/m. Above this level little operating time was achieved.

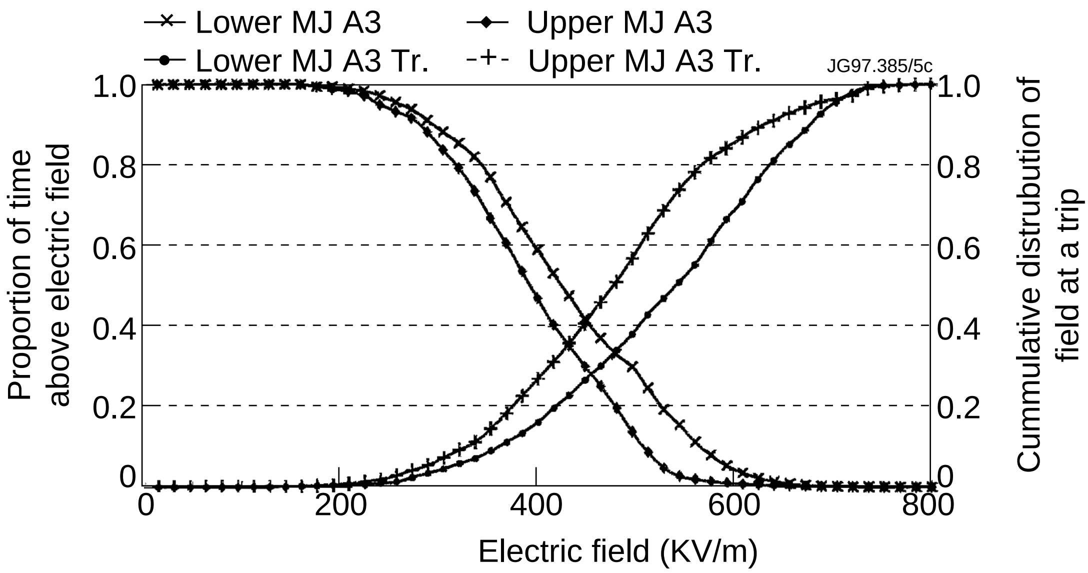

Figure 5.4:- Time Above Electric Field Value Integrated over 544 pulses for Klystrons A3.

The mean electric field just prior to a trip is shown for all multijunctions in Figure 5.5. This was calculated in the same way as the curves for A3. The power handling of the top row (modules A and B) is somewhat better than that of the others. Module D is also relatively good. This pattern is consistent with the qualitative impression reported by the operators during the campaign. Across all the multijunctions on average, an electric field of 400 kV/m seems to be the level at which a trip has a 50% chance of developing.

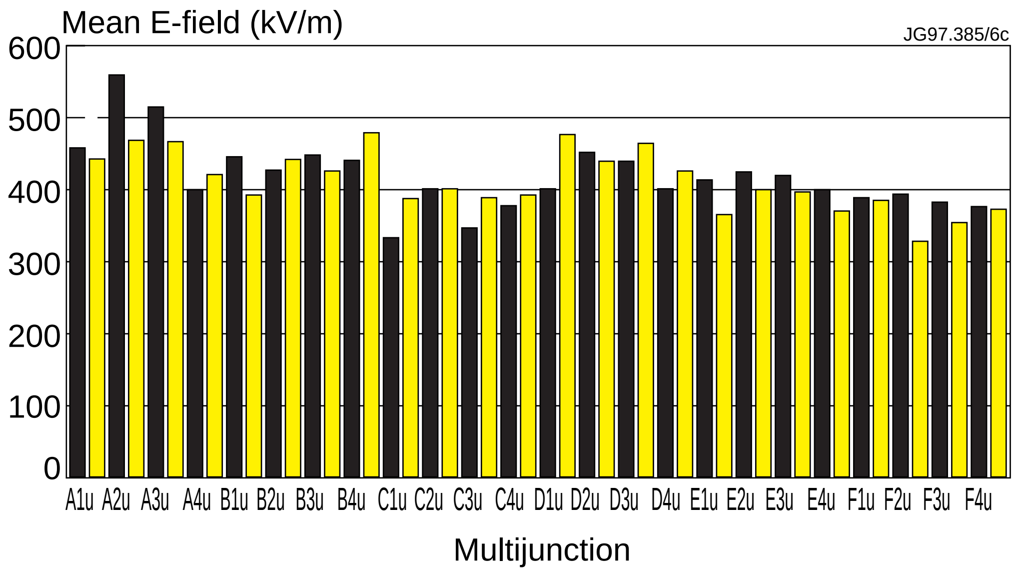

Figure 5.5:- Mean Electric Field Prior to a trip for all 48 multijunctions. A1u - A1 upper: A1 lower shown adjacent(unlabeled).

6 Discharges in the Multijunctions

A variety of different patterns of reflected power have been observed associated with trips. Figure 6.1 shows the result of a ramp in the input power to a pair of multijunctions operating in vacuum. At a power of about 200 kW (100 kW per multijunction) the lower multijunction starts to show a non-linear reflection coefficient. At about 300 kW the upper multijunction clearly develops a discharge. This is cross coupled to the lower multijunction.

This type of behaviour is consistent with a multipactor effect. It is particularly dangerous for the multijunction as it will tend to be stationary and is too low a level for the detection system to trip, resulting in strong local heating: possibly enough to produce melting of the stainless steel.

By operating during the test pulse that is performed each morning before the start of plasma operation it was possible to see that the detailed behaviour of the discharge was modified by the presence of the Tokamak magnetic fields. It is less sensitive to changes in neutral gas pressure measured in the Launcher vessel up to 1.4 x 10^{-6} mbar, as the electron mean free path remains long relative to the waveguide dimensions.

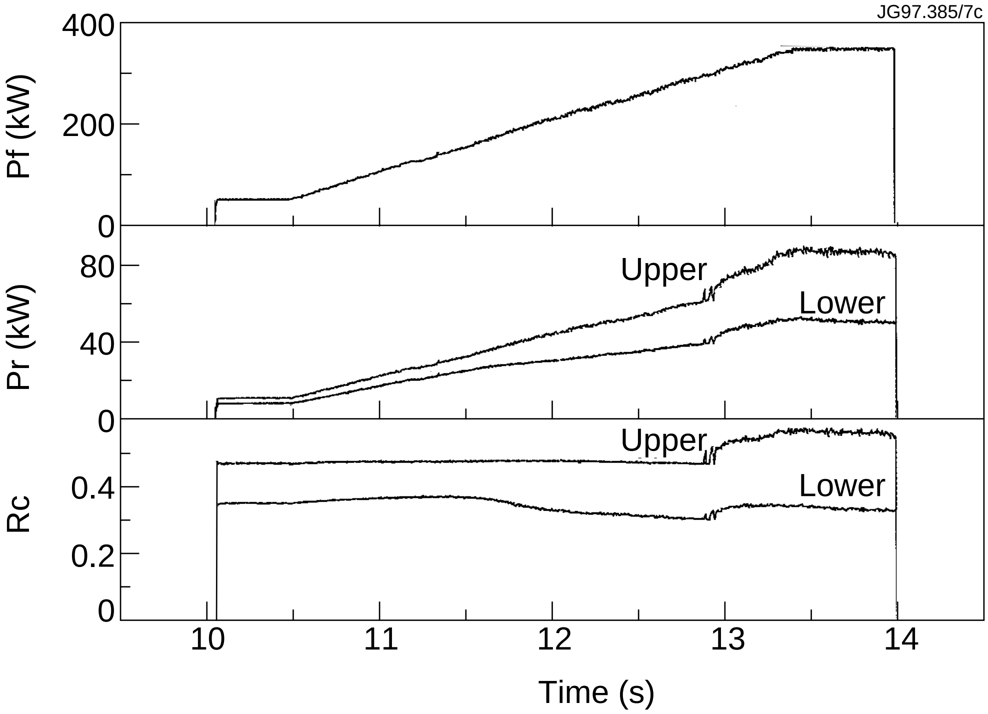

Figure 6.1:- Forward power, Reflected powers and Reflection Coefficient of D1 multijunctions operating in vacuum.

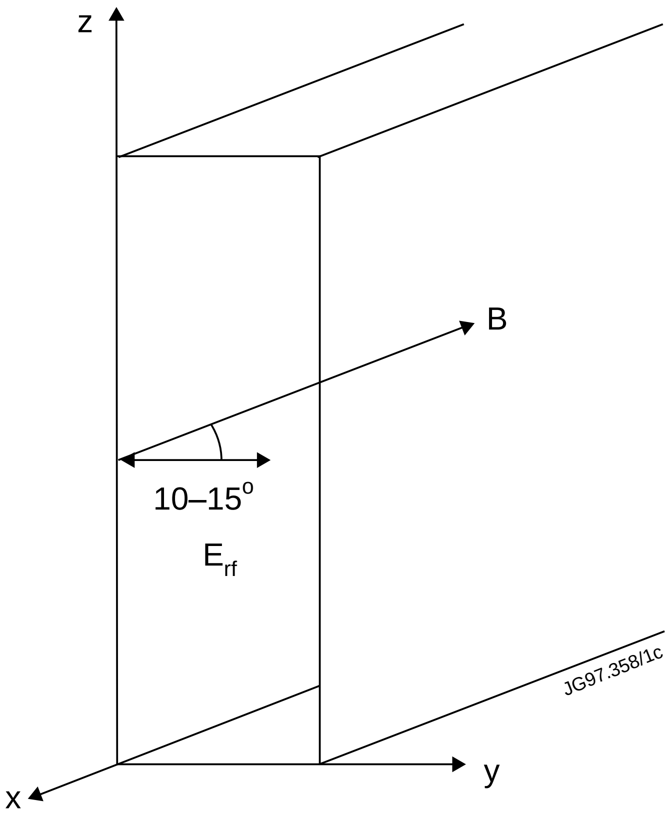

Figure 6.2:- Cross section of waveguide and co-ordinates.

The kinetic equation for an electron in the waveguide is:-

$$m_e dv/dt = e(v \times B + E_{rf} \sin(2\pi ft + \phi) + E_{st})$$

where m_e is the mass of the electron
v is the electron velocity (v_x, v_y, v_z)
B is the magnetic field (B_x, B_y, B_z)
e is the electron charge
E_{rf} is the RF electric field (0, E_{rf}sin(2pft +ϕ), 0)
f is the RF frequency
ϕ is the RF initial phase
E_{st} is the static electric field due to space charge

A necessary condition for a multipactor breakdown to occur is for a single electron emitted from one surface to result in more than one electron emitted when it hits another surface. That is the secondary emission coefficient, δ >1. The resulting electron population could result in an avalanche breakdown. A carbon layer was deposited on the prototype L0 Launcher as an anti-multipactor coating. However it tended to flake off and was not applied to L1.

The magnetic field along a multijunction for a standard JET plasma is shown in figure 6.3. This field is along the central axis of the horizontal port. Given the close proximity of the coils to the port there will be considerable variation in magnetic field for the different waveguides, which would clearly move the multipactor regions but probably not to a different cross section of waveguide.

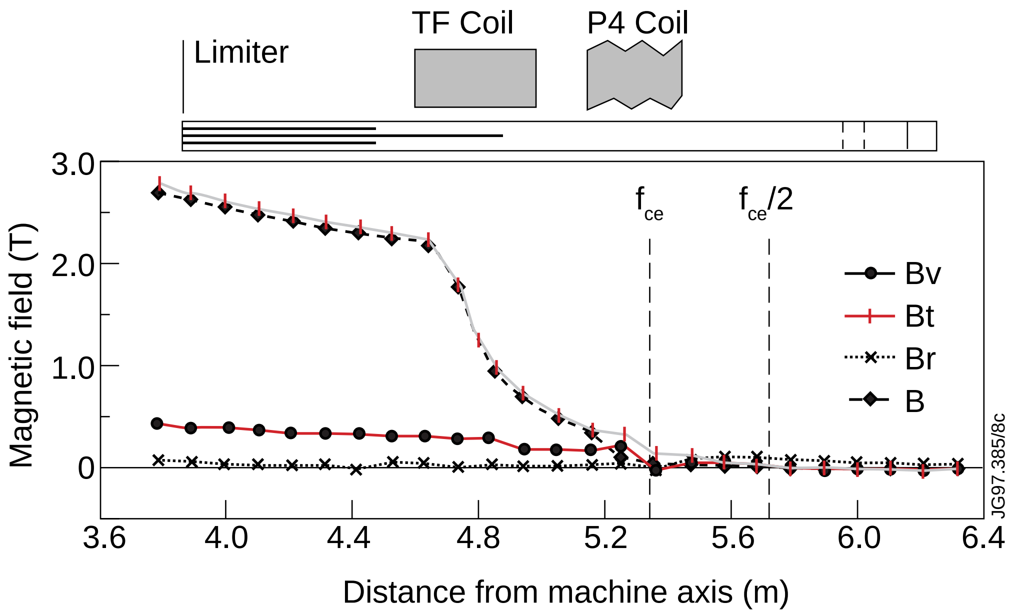

Figure 6.3:- The magnetic field along a central multijunction for a standard fat divertor plasma. At f_{ce} = 3.7 GHz B = 0.123 T.

Analysis and computer simulation of the electron motion at three different locations has been performed (1). The waveguide cross sections in the regions studied were:-

At the grill mouth	X=3.856 m,	Y = 9 mm,	Z = 72 mm.
At f_{ce}	X=5.35 m,	Y = 42 mm,	Z = 72 mm.
At $f_{ce}/2$	X=5.715 m,	Y = 42 mm,	Z = 72 mm.

This studied indicated that multipactor would not occur at f_{ce} or $f_{ce}/2$ but that an avalanche breakdown could occur at the grill mouth if the secondary electron emission coefficient was that of 'as received copper'. As the surface is conditioned however the maximum secondary electron yield drops and a threshold is reached at which multipactor breakdown no longer occurs. This threshold is about midway between the 'as received' and 'well conditioned' cases.

7 Electric Field Limiting System

As a result of this analysis a system to limit the electric field in the multijunctions was devised. This uses a look up table to limit the klystron output power according to the reflection coefficient of the multijunctions fed by each klystron. The general arrangement is shown in figure 7.1. The look up table, giving the maximum allowed forward power, is calculated from the required electric field limit. This can be set by the operator in the range 0-800 kV/m.

During the pulse the reflected powers are sampled at about 50 ms intervals and the maximum forward power is derived from the look up table. The reference power sent to the RF power control loop is the lower of the requested power and the output of the look up table.

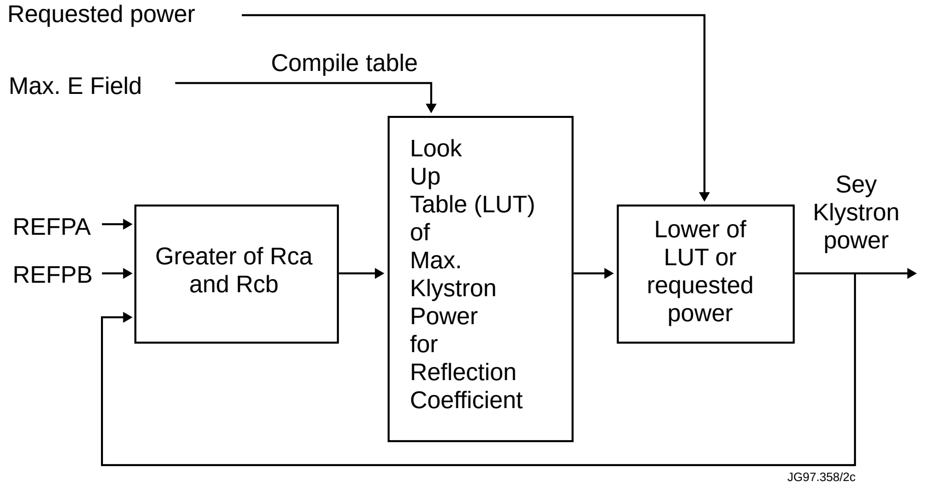

Figure 7.1:- Klystron Control and Protection System Software to limit the Electric field in the multijunctions.

The result of this electric field limit is shown in figure 7.2. The forward power is limited throughout the pulse, while the higher of the two electric fields is held fairly constant. The electric field control switches between the upper and lower multijunction during the pulse. The ripple on the electric field is a result of the 50 ms sampling time which is relatively slow compared with the fluctuations in the electric field.

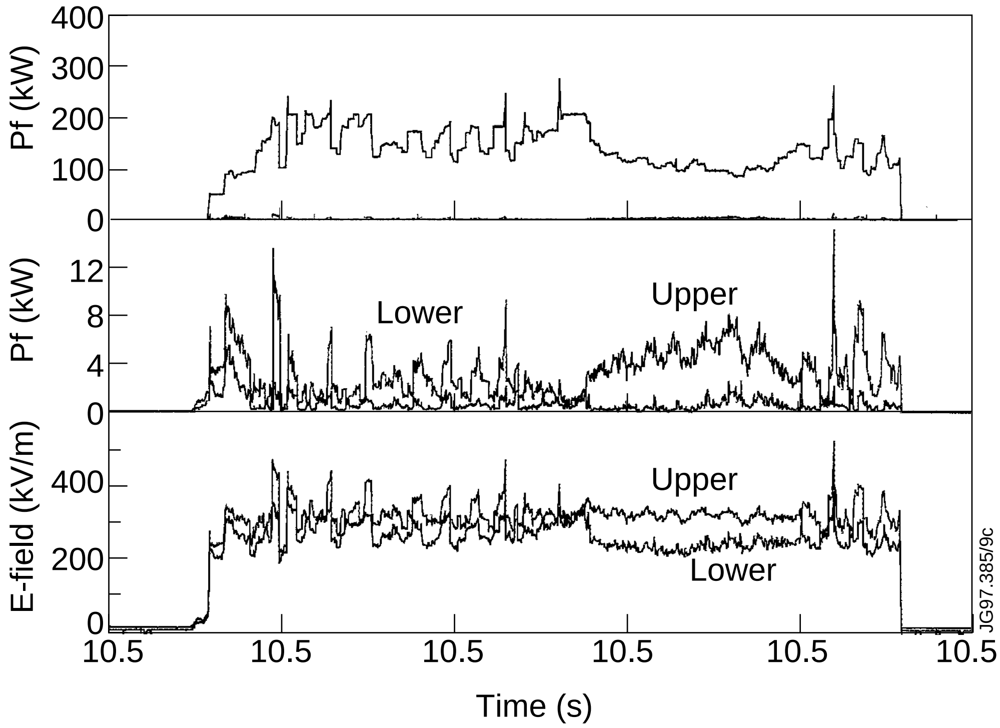

Figure 9.1:- Power Limiting to maintain a constant Electric Field. Klystron E3, #36733

8 Melting at the Grill Mouth

The upper left hand quadrant of the grill, viewed from inside the torus vacuum vessel has shown progressive melting during the campaign, while the lower half has remained in good condition. The erosion has removed metal from the grill mouth up to a depth of about 5 mm in places and opened some of the brazed min-plane joints. The most probable cause is electrons accelerated by the electric field just in front of the grill mouth. This effect is more pronounced on a wide grill of the JET design, as the electrons can be accelerated to high energy by the near field in front of the grill (4,5).

9 Conclusions

There is some evidence of multipactor discharges at the grill mouth of the multijunctions. This is supported by computer simulations. Both the model and operational experience indicate that the multipactor effect is reduced to acceptable levels by conditioning. The melting observed at the grill mouth is attributed to electrons accelerated by the near field.

The electric field at which the multijunctions can operate reliably is limited to 400 kV/m even after extensive conditioning. At this level there is a 50 % chance of a trip developing. This corresponds to a power density of 21 MW/m^2; a significantly more conservative figure than that reported by other machines (6).

A system to limit the electric fields in the multijunctions has been developed and reduces the number of trips by limiting the forward power. This system allows the forward power to be adjusted to the maximum sustainable power under varying coupling conditions.

10 References

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