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FUSION PHYSICS & TECHNOLOGY

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ADVANCED FUSION DIAGNOSTICS**FINAL TECHNICAL REPORT**

JULY 15, 1991 TO JULY 14, 1993

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ION CYCLOTRON EMISSION (ICE) STUDIES

1.0 INTRODUCTION

Key among various issues of ignited plasmas is understanding the physics of energy transfer between thermal plasma particles and magnetically confined, highly energetic charged ions in a tokamak device. The superthermal particles are products of fusion reactions. The efficiency of energy transfer by collisions, from charged fusion products (e.g., α -particles) to plasma ions, grossly determines whether or not plasma conditions are self-sustaining without recourse to auxiliary heating. Furthermore, should energy transfer efficiency be poor, and substantial auxiliary heating power is required to maintain reacting conditions within the plasma, economics may preclude commercial viability of fusion reactors. The required charged fusion product information is contained in the energy distribution function of these particles. Knowledge of temporal variations of the superthermal particle energy distribution function could be used by a fusion reactor control system to balance plasma conditions between thermal runaway and a modicum of fusion product energy transfer. Therefore, diagnostics providing data on the dynamical transfer of alpha-particle and other charged fusion product energy to the plasma ions are essential elements for a fusion reactor control system to insure that proper plasma conditions are maintained. The objective of this work is to assess if spectral analysis of rf radiation emitted by charged fusion products confined in a magnetized plasma, called ion cyclotron emission (ICE), can reveal the vital data of the distribution function of the superthermal particles.

Not all ICE is generated by fusion products. Copious amounts of ICE is produced in nonignited magnetized plasma, which may well be generated by thermal ions and microinstabilities or anomalies occurring within the plasma. In most cases, however, electromagnetic radiation in the ion cyclotron frequency range arises in a magnetized plasma from magnetic forces which cause charged particles to gyrate about flux lines. The accelerated charged particles radiate electromagnetic energy at their angular gyration or cyclotron frequency ω_{ci} and, if the charge particles are sufficiently energetic, radiation is produced, also, at harmonics ($n = 2, 3, \dots$) of the gyration frequency. Charged particles are a result of fusion reactions during ion-ion collisions within the plasma. These charged, fusion products are born with energies far exceeding the thermal

energies of the plasma ions. Hence, it is reasonable to expect that the rf spectrum radiated by charged fusion products will be rich in higher harmonics of the ion cyclotron frequencies and will dominate the small amount of ICE power emitted by thermal plasma ions in this frequency range. The fundamental and harmonics of the angular cyclotron frequency are determined using the expression,

$$\omega_{ci} = -\frac{nZ_ieB}{m_i} \quad , \quad (1-1)$$

where $-Z_ie$ is the ionic charge, m_i is the mass of the ion, and $B \equiv |\vec{B}|$ is the magnitude of the local magnetic field intensity. For typical fusion devices, magnetic field intensities are in the range of 3 to 10 T, so that the fundamental frequency $f_{ci} = -\frac{eB}{2\pi m}$ of cyclotron emission of alpha particles ($m_\alpha = 4$ AMU) trapped in these fields will be in the range of roughly 20 to 75 MHz.

In a D-T "burning" plasma, superthermal charged particles are the products of the primary reactions,

and

The branches in the last reaction, (B) and (C), occur with equal probability. A secondary reaction,

also contributes superthermal alpha particles to the plasma. In an initially pure deuterium plasma, (B) and (C) are the primary reactions and (A) and (D) are secondary, while a plasma mixture of ^2D and ^3He , results primarily in highly energetic ionic particles as indicated by reaction (D), but some neutrons are generated by reaction (B).

Reacting ions in a magnetically confined D-T plasma have kinetic temperatures of approximately 10 to 20 keV; whereas, alpha particles, the charged products of reaction (A), will be born with energies of 3.6 MeV. Based on the large difference of temperature between the charged products and the deuterium plasma ions, the total power radiated at the common cyclotron

frequency by the alpha particles could exceed that radiated by the more populous deuterium (plasma) ions, depending on the production and loss rate of the alpha particles. More importantly, we expect that the power radiated by alpha particles at the higher harmonics of the fundamental cyclotron frequency to easily dominate that radiated by the plasma ions at the same frequencies.

2.0 DOUBLET III ICE STUDIES

FP&T specified and purchased four balun transformers from Prodyne Corporation, New Mexico, to couple rf receivers to the balanced ICRF loop antennas on DIIID. These broad-band transformers also provide 3 kV dc isolation between machine ground of the tokamak and the diagnostics and control room instrumentation ground. Additionally, the Prodyne baluns have a large common mode rejection ratio for signals impressed on the balanced inputs. The transformers exhibit approximately -50 dB of isolation between 20 and 700 MHz, with roughly -5 dB insertion loss. The standoff voltage of each unit was tested by applying 3 kV dc across primary to secondary windings. High voltage insulation tests were performed between the primary circuit ground and the secondary circuit ground to assure that the units meet TFTR 3 kV isolation requirement. In all test cases, no breakdown between balanced and unbalanced connectors was observed. These transformers are installed on DIIID, and they have been employed in the DIIID ICE, ICRF, and the UCI studies stability and fast-ion loss during TAE mode since December, 1990, to the present day.

Fusion Physics and Technology began their Doublet III-D ICE studies at General Atomic during May 1991 with only four, two-week periods of operation remaining. Dr. K. Moses was placed on temporary assignment at GA during the four, two-week periods that DIIID operated and he started the experimental investigations of fusion-product ICE on DIIID at that time. The first two week period began on May 15, 1991. This time was used as an orientation period to familiarize Dr. Moses with the DIIID device, diagnostics, and computerized data archival system. During these experimental runs, signals at several discrete frequencies within the ICE frequency band were observed. The antenna signals were impressed on several tunable narrow-band filters, so that the time history of the emission amplitude at several discrete frequencies could be observed and recorded. In addition, the ICE band was divided into a low (10 - 100 MHz) and a high (100 - 200 MHz) frequency range by paralleling the antenna signals to two spectrum analyzers operated in continuous sweep mode. The ICE emission was observed throughout the ICE band, and strong ICE signals were observed at frequencies equivalent to the tenth harmonic of the cyclotron frequency ascribed to DIIID magnetic field. The spectral content changed with plasma conditions, but, due to the short period of DIIID operation in May, an insufficient database was collected to afford correlating emission characteristics with plasma conditions.

2.1 DIID VH Mode Discharges

The experimental ICE investigations on DIID during June and August 1991 centered on investigating VH-mode of tokamak operation. We present an examples of VH-mode data from several diagnostics in Figure 1. The traces appearing in the figure were obtained during the DIID discharge number 73310, taken on August 28, 1991. This particular deuterium discharge is one that is presented by DIID researchers as a reference VH mode shot. The toroidal flat top current is 165 MA, and the toroidal field on axis is 2.06 T. The signal from a photodiode (designated by PHDO4) exhibits a quiescent period after an initial rise. The quiescent period begins at about 2050 ms after the experiment is initiated, and it persist till 2550 ms. After this period of time, the PHDO4 signal displays large amplitude spikes which signal the onset of ELMS activity. During the quiescent period, the plasma density and the production of neutrons (represented by the signal designated PLASTIC in Figure 1) increase with time, until the start of ELMS activity at 2550 ms into the discharge. After that point the plasma density levels off, and the neutron production rate begin to drop rapidly with time.

The signal designated ICE3, at the top of Figure 1, is the vertical deflection voltage as a function of time of a Hewlett-Packard Spectrum Analyzer, model 141, produced by signals from a single-turn balanced loop antenna. This area of this antenna is oriented to receive poloidal inductive signals. The periodic fast-rising signal, reaching the top of the maximum amplitude, is self-generated by the frequency sweep return of the spectrum analyzer ("zero" markers). The trailing edge of this strong signal marks the initiation of a frequency sweep that lasts for 100 ms. This arrangement permits conversion of the time base to that representing frequency, without recourse to a separate, independent trace of the spectrum analyzer sawtooth sweep voltage. Combining the amplitude and frequency axis on one trace yields some efficiency and advantage in displaying and archiving spectrum analyzer data. Vertical signals appearing on the trace between two adjacent zero markers represent the Fourier components of ICE signals from the plasma. The receiver reference level was set at - 30 db, and the attenuator is set at 10 db/div of the spectrum analyzer display. At any given instant of time during the sweep, the acceptable bandwidth of the frequency window Δf covered 3 MHz. A video filter of the spectrum analyzer is used in this system to filter out low-frequency (<30 kHz) noise. The time period between any two of these large signals is linearly proportional to the frequency range swept by the spectrum analyzer. For this shot, the rate of frequency ramping is 2 MHz/ms giving a 1 to 200 MHz frequency range. Thus, to determine the frequency of any vertical signal appearing between any two zero markers, one multiplies the time interval from the start of the analyzer frequency sweep to the peak of the ICE component by 2 MHz/ms.

Consider the ICE3 trace of Figure 1. Here we see rf signals that commence close to the start of the VH mode. A trace of the ICE3 signal with an expanded

time base is shown in Figure 2, together with the ICE7 and PHDO4 signals. Notice that the trailing edge of the PHDO4 signal levels off at 2054 ms. The first small spike, that can be seen in the ICE3 trace in Figure 1, appears at 2069 in Figure 2. Taking the start of the sweep to be 2057, the frequency of the first peak in the spectrum analyzer signal is 34 MHz. The next analyzer sweep, shown in Figure 3, begins at 2189 ms; and signals appear at roughly 23, 31 and 49 ms after the start time, corresponding to 46, 62, and 98 MHz, respectively. More rf signals appear in the third analyzer sweep after the VH mode began. Frequencies at 44, 58, 74, and 96 MHz can be seen in the expanded time scale trace in Figure 4. Also a signal appears 98 ms after the initiation of the sweep and it is at a frequency of 186 MHz. Figure 5 shows very broad-band emission with spikes appearing predominately at the higher frequencies roughly 120 to 200 MHz. As a counter example, the VH mode is not observed in the next discharge of the day, number 73311 (Figure 6), and very little signal is present on ICE7.

The trace designated as ICE7 in Figure 1 and subsequent figures of the data with expanded time bases is derived from a similar spectrum analyzer system. This spectrum analyzer is operated with the same dial settings as those used in obtaining the ICE3 data, which were presented above, but the ICE7 apparatus is attached to a different set of antenna loops. The area of these loops (ICE7) are oriented to receive inductive signals incident from the toroidal direction. As can be observed in the figure, the gain of the ICE7 data channel is an order of magnitude less than the gain setting for ICE3. It was found necessary to maintain this gain differential due to the high noise level found on the ICE7 antenna in this series of discharges. Since we could not resolve any ICE signal from this noise, we shall not discuss the ICE7 signal any further.

Consider the qualitative manner in which the frequency of the ICE varied during the VH mode period. In Figure 1, the ICE resided mainly in the low frequency end of the spectrum analyzer 1 - 200 MHz sweep band. As the VH mode continued, the frequencies of ICE tended toward the center of the band, and then as the mode approached its termination, the emission bandwidth increased with the components displaying the greatest amplitude residing toward the upper end of the band. This qualitative temporal behavior of ICE3 data during VH mode, i.e., shifting the frequencies of maximum intensity from low to high ends of the band, and increased emission over a broader bandwidth, toward the termination of the mode is found in other reference VH mode type discharges in DIIID. For example, the ICE3 data appearing in Figures 7 and 8 obtained during DIIID discharges number 73221 and 73290, respectively, were taken under the same conditions of toroidal field (2.06 T) and toroidal current (1.65 MA) as VH mode discharge number 73310; and these data all exhibit similar ICE temporal characteristics. Additionally, some ICE can be resolved from the noise on the ICE7 (toroidal) traces during the VH mode period of the discharges in Figures 7 and 8. However, it is not clear that the toroidally inductive ICE signals exhibit

the same qualitative temporal behavior as that of the poloidal ICE signals on the ICE3 data channel.

2.2 Broadband ICE From DIIID Discharges

Using the same spectrum analyzer settings as used in the VH mode studies, we observed very strong, broadband ICE from deuterium discharges at slightly reduced toroidal currents (1.33 MA), while the toroidal field was maintained at the same value of 2.06 T. The data shown in Figure 9 were obtained from DIIID discharge number 73295, performed on August 17, 1991. Consider the ICE3 data appearing in Figure 9 during the time interval from 2000 to 2750 ms in which the plasma density is increasing to its peak value of approximately $8 \times 10^{13} \text{ cm}^{-3}$. Here we see that strong ICE occurs throughout the 1 to 200 MHz band. ICE7 channel, also exhibits some ICE during this time period, although this emission is not as intense nor is it as frequency component rich as the emission seen in the ICE3 channel. Looking at Figures 10 through 14, which display the ICE data on expanded time scale, we see that the ICE emission not only appears across the full frequency band of observation, but it tends to be grouped and centered about discrete frequencies throughout the band. Qualitatively, the emission during the period of increasing plasma density shows the same temporal behavior. The characteristics of the ICE shown on Figures 10 to 14 resembles the emission observed on TFTR by J. C. Dooling, FP&T and G. J. Greene, PPPL, which we reported earlier. [1] However, later in the discharge, when the density drops to a smaller and relatively constant value about a medium of $6 \times 10^{13} \text{ cm}^{-3}$, then ICE emission is no longer observable on the trace.

2.3 ICE Filter Array

The pattern of the spectrum analyzer signals displayed in Figures 10 through 14, which exhibit multiple broadband peaks centered on several frequencies, could be representative of the actual spectrum of ICE or indicating that the ICE is changing frequency of emission on the time scale of the analyzer sweep time of 100 ms. In order to determine the actual temporal behavior of the ICE it was decided to use an array of narrow bandpass filters to monitor the emission frequency on a continual basis. Figure 15 is a schematic representation of the narrow bandpass filter array specified by FP&T. Two filter systems were constructed: 1) 1 to 100 MHz constructed by the University of California, Irvine, researchers led by Dr. Heidbrink, and 2) 100 to 210 MHz constructed by FP&T. Referring to the ICE filter array shown in Figure 15, the signal from an ICE antenna is coupled by a Prodyne balun transformer, model BIB-120J, to a fixed + 20 db MITEQ preamplifier, model AV-1A-0520. The frequency bandwidth of the MITEQ amplifiers extends over the range from 1 to 200 MHz. The output signal from the preamplifier is divided into 12 parallel paths. A 10 MHz bandpass filter in series with a MITEQ preamplifier and Hewlett-Packard planar-doped barrier diode detector, model HP8471D, is placed in all but one path. The center frequency of each successive bandpass filter differed by 10 MHz,

providing 5 MHz overlap between successive filters. Eleven bandpass filters are used to provide continuous frequency coverage over the range from 1 to 100 MHz. As power dividers must have an even number of output terminals, the twelfth path is terminated with the characteristic impedance ($50\ \Omega$) of the coaxial cable. The detected ICE signals are digitized and archived by the DIIID diagnostic computer system. A similarly constructed second array, covering the frequency range of 100 to 210 MHz with eleven 10 MHz wide bandpass filters, was built to observe the high frequency end of the ICE spectrum.

An example of the rf signals from the low frequency array of bandpass filters is shown in Figure 16. These data were obtained from the antenna oriented to receive inductive signals in the poloidal direction. This example is DIIID discharge number 75606, taken in a study of stability and fast-ion loss during TAE modes. Only eight channels of the ICE filter array are used in collecting this set of data. The center frequency of the first of eight bandpass filters is 5 MHz, while the center frequency of the successive filters are spaced 10 MHz apart, up to a center frequency of 75 MHz for the eighth filter. It follows that the associated 3 db down passbands of the ICE data channels shown in Figure 16 are:

ICE1	1 to 10 MHz
ICE2	10 to 20 MHz
ICE3	20 to 30 MHz
ICE4	30 to 40 MHz
ICE5	40 to 50 MHz
ICE6	50 to 60 MHz
ICE7	60 to 70 MHz
ICE8	70 to 80 MHz

All signals in Figure 16 are plotted as functions of time. The signal designated IP in Figure 16 is the toroidal current in the tokamak, and the trace identified as beams represents the beam power injected into DIIID. In this figure, the traces labeled density and plastic represent the time histories of plasma density and rate of neutron production measured by a plastic scintillator, respectively. The ICE signals display a dichotomy in the temporal emission between two low frequency (1 - 10 MHz and 10 to 20 MHz) channels and the six higher frequency channels. The emission is observed only in the two low frequency channels after the density transition from 2.5×10^{13} to $3 \times 10^{13}\ \text{cm}^{-3}$. The plasma density increase coincides with the start of neutral beam injection, although with time, the density falls off slowly. During the slow decay of plasma density, the low-frequency ICE emission increases in intensity, occurrence and persistence. This low-frequency emission is thought to be related to the TAE mode which is under investigation by Dr. Wm. Heidbrink, UCI. Later in time, at

approximately 2500 ms into the discharge, the density rises once more; and the ICE emission shifts to the higher frequency bands, predominately to the range of 40 to 80 MHz, with a small amount of ICE activity in the 20 to 30 and 30 to 40 MHz bands. Some emission is found to persist in the 10 to 20 MHz range, also. It is clear in Figure 16 that all ICE ceases after the beams signal drops from 3 to 1 units, and although the plasma density continues to increase after a small drop, the neutron production rate decays rapidly.

We were not able to obtain data with the 100 -210 MHz filter array, due, in part, to operating difficulties on DIIID, and operating parameters were conducive to ICE during the last two experimental runs in which FP&T was a participant.

3.0 CONCLUSIONS

There are many interesting situations under which ICE emission has been observed. The frequency of the emission exhibits complex behavior in time and varies under diverse plasma conditions. We have presented a very limited number of examples of experiments in which ICE has been observed in DIIID. We offer this raw data only as observations of ICE activity, without interpretation, in the hope that it might stimulate others to investigate this interesting phenomena and to find the understanding that has escaped us in the rather chaotic climate in which it was undertaken. The limited nature of this study is mainly due to the complexity of ICE, and our inability to find a meaningful explanation of observations relating them directly and unquestionably to some physical aspect of tokamak confinement. However, we do not view the discontinuance of the FP&T ICE program as a failure since some progress has been made, and we have made a small contribution to the DIIID program. Rather, we see it as falling short to demonstrate understanding on a time scale consistent with the needs of the fusion program and the expectations of its directors. It may have been possible for this project to generate greater interest in and understanding of rf emission observed in the range of ion cyclotron frequencies had we embarked upon the investigation of ICE on the DIIID device at the outset instead of TFTR; or had we received the same cooperation from the TFTR group that we received from our colleagues at GA; or had we received support from PPPL and/or DOE at the time we first proposed the existence of ICE in 1982-83 (long before the observation of ICE on the JET machine). Perhaps as plasma in magnetic fusion devices matures to the point of ignition, ion cyclotron signals generated by charged fusion products will increase in intensity and be clearly observable as we expect, and the understanding of ICE phenomenology will be more readily obtainable.

28-AUG-91 12:08:38

Figure 1, VH mode Discharge No. 73310, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal, DENSITY trace is the time history of the plasma density, and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

28-AUG-91 12:30:34

Figure 2, VH mode Discharge No. 73310, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal. Expanded time base (2050 - 2160 ms) is counted from the initiation of the discharge.

28-AUG-91 16:12:31

Figure 3, VH mode Discharge No. 73310, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal. Expanded time base (2180 - 2290 ms) is counted from the initiation of the discharge.

28-AUG-91 16:16:01

Figure 4, VH mode Discharge No. 73310, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal. Expanded time base (2320 - 2430 ms) is counted from the initiation of the discharge.

28-AUG-91 10:24:13

Figure 5, VH mode Discharge No. 73310, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal. Expanded time base (2450 - 2560 ms) is counted from the initiation of the discharge.

28-AUG-91 11:18:57

73311

SHOT 73311 BT(set) = -2.06 T GAS = D2/--/--/D2
 28-AUG-91 IP(max) = 1.84 MA PREFILL = 150 ms
 10: 8: 8 LIM = 0.50/-1.00 cm FAULT = IPMIN

Figure 6, Discharge No. 73311 for comparison with data of Figure 1, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, PHD04 is the photodiode no. 4 output signal, DENSITY trace is the time history of the plasma density, and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

21-AUG-91 12:55:46

Figure 7, VH mode Discharge No. 73221, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, DENSITY trace is the time history of the plasma density, and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

Figure 8, VH mode Discharge No. 73290, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

27-AUG-91 17:42:58

Figure 9, Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band during 2000 - 2750 ms, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, Ip is the toroidal current and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

28-AUG-91 09:41:28

Figure 10, Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, I_p is the toroidal current and PLASTIC is proportional to the neutron production rate. Expanded time base, 2100 - 2210 ms, is counted from the initiation of the discharge.

Figure 11, Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, I_p is the toroidal current and PLASTIC is proportional to the neutron production rate. Expanded time base, 2220 - 2330 ms, is counted from the initiation of the discharge.

28-AUG-91 09:17

73295

SHOT 73295 BT(set) = -2.08 T GAS = D2/--/--/D2

27-AUG-91 IP(max) = 1.33 MA PREFILL = 150 ms

14:11: 8 LIM = 0.50/-1.00 cm FAULT = IPMIN

Figure 12, Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, I_p is the toroidal current and PLASTIC is proportional to the neutron production rate. Expanded time base, 2350 - 2460 ms, is counted from the initiation of the discharge.

28-AUG-91 09:40:20

Figure 13. Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, Ip is the toroidal current and PLASTIC is proportional to the neutron production rate. Expanded time base, 2470 - 2580 ms, is counted from the initiation of the discharge.

27-AUG-91 17:54:28

Figure 14, Discharge No. 73295, ICE3 and ICE7 vertical voltage of spectrum analyzer, bandwidths 1 - 200 MHz showing strong ICE across the band, DIAMAG3 is the diamagnetic loop signal, DENSITY trace is the time history of the plasma density, I_p is the toroidal current and PLASTIC is proportional to the neutron production rate. Expanded time base, 2600 - 2710 ms, is counted from the initiation of the discharge.

Figure 15, ICE FILTER ARRAY

TWO SYSTEMS - CENTER FREQUENCIES 5 TO 95* & 105 TO 205 MHz

* UCI equipment

Figure 16, Discharge No. 75806, I_p is the toroidal current. All ICE traces are filtered output signals from 10 MHz passband filters with center frequencies, ICE1 5 MHz, ICE2 15 MHz, ICE3 25 MHz, ICE4 35 MHz, ICE5 45 MHz, ICE6 55 MHz, ICE7 65 MHz, ICE8 75 MHz. BEAMS is the neutral beam injection signal, DENSITY trace is the time history of the plasma density, and PLASTIC is proportional to the neutron production rate. Time base is counted from the initiation of the discharge.

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