Columbia Plasma Laboratory
DOE/ER/53222-107

DOE/ER/53222--107
DE93 007140

High Beta Tokamak Research Progress Report

November 1991 – December 1992

by

T. H. IVERS, M. E. MAUEL, G. A. NAVRATIL, M. K. VIJAYA SANKAR, E. EISNER, A. GAROFALO, D. GATES, R. KOMBARGI, D. NADLE, , AND QINGJUN XIAO

Plasma Physics Laboratory
Department of Applied Physics
Columbia University
New York, N. Y. 10027

December 1992

MASTER

* Work supported by US DoE Grant No. DE-FG02-86ER53222 .

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HBT-EP Status Report
11 December 1992

1. Basic Machine Operation

The HBT-EP tokamak has been fully operational since the installation of the basic diagnostic set and impurity control systems which was completed this past summer. Successful reduction of oxygen impurities in HBT-EP using a combination of GDC in deuterium, heating the vessel to 70° C, and sputter source boronization, has resulted in the production of discharges of about 10 msec duration (twice the design value) with central temperatures in excess of 100 eV. At somewhat higher density and shorter pulse length (4-5 msec), discharges with a central temperatures in excess of 100 eV (magnetic Reynolds number, $S \geq 10^5$) which reach β values above the Troyon beta limit ($\beta/\beta_c > 1$) have been achieved which also show the onset of strong MHD activity when β approaches β_c. This satisfies our primary project goal for this first year of experimental operation. HBT-EP has been operated in all its basic circular configurations with the minor radius ranging from 14 cm to a maximum of 20 cm and the conducting shell structure varied between its extreme positions both close to the plasma edge (about 1.5 cm away) to distant from the plasma edge (about 8 cm away). All toroidal and poloidal field capacitor bank systems have been tested to full power and their reliability in experimental operation has been excellent with over 1500 shots already taken on the machine.

Shown in Figure 1 is a time history of the measured and calculated parameters of a typical $a = 15$ cm plasma with $B_T = 3$ kG. The toroidal plasma current is initiated at a value less than 10 kA ($q^* \sim 5$), and we ramped the current up to our design value of nearly 20 kA ($q^* \sim 2.2$) at this field. At this time the loop voltage was less than 2 Volts, and the average conductivity weighted temperature exceeded 50 eV. Also shown in Figure 1 is the onset of a strong MHD event at about 2.0 msec when $\beta/\beta_c \sim 0.7$ with a large negative loop voltage spike and a large drop in plasma temperature. The plasma recovers from the first event, although there appears a growing MHD oscillation. As $\beta/\beta_c > 1$, a very strong MHD instability terminates the discharge. These are routinely observed as we push to higher plasma current and higher values of β_N. Magnetic analysis of some of these discharges have identified the dominate mode numbers of the precursors to the strong MHD events as $n = 1, m = 2$. Since our emphasis up until now has been on optimizing the machine performance, we have not yet begun a systematic study of these modes. However, having achieved our high beta, high temperature goals for operation which exhibit MHD instabilities, we are now ready to move on to the next phase of our program where the stabilization and control of these instabilities will become the dominant focus of our studies.

In Figure 2 is a photo of the HBT-EP tokamak as it appears today. Not visible in the photo are the Thomson scattering system and CO_2 laser interferometer.

2. Operational Parameter Space

A primary goal of the current project is to document the capability of the HBT-EP tokamak to achieve a value of $\beta/\beta_c \sim 1$ (a 'normalized' beta $\beta_N \sim 2.8$ corresponding to the Troyon Limit) in plasmas which are sufficiently collisionless. Following the recommendations of the 1989 DOE Review Panel chaired by Noah Hershkowitz, this implies reaching the beta limit with a magnetic Reynolds number, S, of about 10^5 which corresponds to central temperatures of about 100 eV for HBT-EP parameters. Prior to the construction of HBT-EP, extensive modeling with 0D and 1D transport codes indicated the importance of reducing the impurity levels to 0.1% to 0.2% oxygen in order to achieve the necessary level of performance. The steps taken to reduce the impurity levels are summarized in the next section. Here we will describe the parameters achieved in HBT-EP.

We employ two methods of determining the electron temperature. The first which is available on all discharges is to calculate the conductivity temperature based on the loop voltage and plasma current derived plasma resistivity. Assuming a $Z_{eff} = 1.1$ and using the Spitzer resistivity, the 'average' temperature can be calculated. The choice of a very low value of Z_{eff} and the assumption of no neo-classical enhancements gives us a lower bound on the conductivity weighted average temperature. These measurements are benchmarked against Thomson scattering measurements of the central electron temperature. Shown in Figure 3 is a plot of the conductivity temperature and the Thomson scattering measurement of central temperature as a function of the deuterium fill density. For higher fill pressures the plasma is not able to push through the oxygen barrier, the loop voltage is high (> 10 Volts) and the conductivity temperature is below 15 eV. The Thomson scattering measurements for these plasmas show a central temperature of about twice the conductivity calculated 'average' value. As the deuterium fill pressure is reduced, the plasma burns through the oxygen barrier producing a conductivity temperature of about 25 eV with the central temperature measured to be about 80 eV. This gives a ratio of about 3 to 1 between peak and the average temperature in plasmas above the oxygen barrier. Unfortunately, we are unable to make reliable measurements at lower fill densities with the present Thomson scattering system, although conductivity temperatures at somewhat lower density have exceeded 60 eV. If we extrapolate the peak to average ratios measured at somewhat higher density, the peak temperatures in these plasmas are inferred to be somewhere between 120 eV and 180 eV.

In addition to achieving $S \sim 10^5$ with collisionless, 100 eV plasmas, these must be produced near the Troyon limit so that the beta limiting instabilities can be excited for stabilization studies. Our primary method of determination of the value of β_N is from a force balance analysis with input from the basic magnetic diagnostics. Shown in Figure 4 is a plot of the value of β_N achieved as a function of conductivity temperature for a large number of discharges in HBT-EP under a wide variety of fill pressures and plasma size. This includes both early shots before the impurity control clean-up procedures were used on vacuum vessel and the more recent data after clean-up. We see that the best performing shots have reached the Troyon Limiting beta with conductivity temperatures in the 40 eV to 50 eV range. These plasmas satisfy the primary criteria for plasma parameters as defined by the Hershkowitz Panel of "$T_e \sim 100$ eV at β's approaching the Troyon limit" needed to proceed with the next phase of the program which concentrates on passive stabilization of external kink modes with the conducting shell.

3. Plasma Impurity Control

As discussed previously, our modelling analysis for HBT-EP performance indicated that reduction of the oxygen (and other high Z) impurities in the ohmically heated plasma in HBT-EP is critical to allow us to reach the beta limit for stabilization studies. This was identified by the Hershkowitz Panel as a critical element for the HBT-EP machine design and we spent a great deal of time and effort in the design to address these concerns. The machine was constructed out of stainless steel with metal seals in most locations. Where 'o'-rings were used they are all double with a vacuum pumped space between them to minimize oxygen permeation and residual leaks. The basic systems installed on HBT-EP for impurity control are a Glow Discharge Cleaning (GDC) system, a vacuum vessel heating system to allow bake out up to 100 °C, and a sputter source boronization system (replacing the Titanium getter system originally proposed). Shown in Figure 5 is a time history of the total pressure and partial pressures of the constituent gasses in HBT-EP. Through a succession of trials of various combinations of conditioning schemes we have moved from relatively high 5 x 10^{-7} Torr base pressures with an oxygen partial pressures of 10^{-8} Torr and a water partial pressure of 10^{-7} Torr to a much cleaner machine whose best base pressure is now about 4 x 10^{-8} Torr with water partial pressures down to about 3 x 10^{-9} Torr and the oxygen partial pressure down to 10^{-10} Torr. The most successful procedure includes several days of GDC in deuterium at 6 mTorr which converts most of the oxygen to D_2O with the possible help of the nickel plated shells as a catalytic agent. We then bake for about 1 day to drive off the heavy water produced by GDC as well as boronize for a few hours using our sputter source operating in 25 mTorr of helium. It is this combination which has resulted in our ability to produce discharges lasting almost 10 msec with conductivity averaged temperatures of 80 eV.

We are continuing to develop our conditioning procedure and we believe that further clean-up is possible. In any case the improvement in the performance of the plasma after implementing the procedures is substantial and are clearly necessary to generate the plasma conditions needed for the proposed work. The remaining element in our clean-up procedures is to use pulse discharge cleaning PDC after GDC and boronization with the possibility of implementing PDC between shots in deuterium to maintain a very high degree of conditioning on all the limiter and wall surfaces which directly view the plasma.

Figure Captions

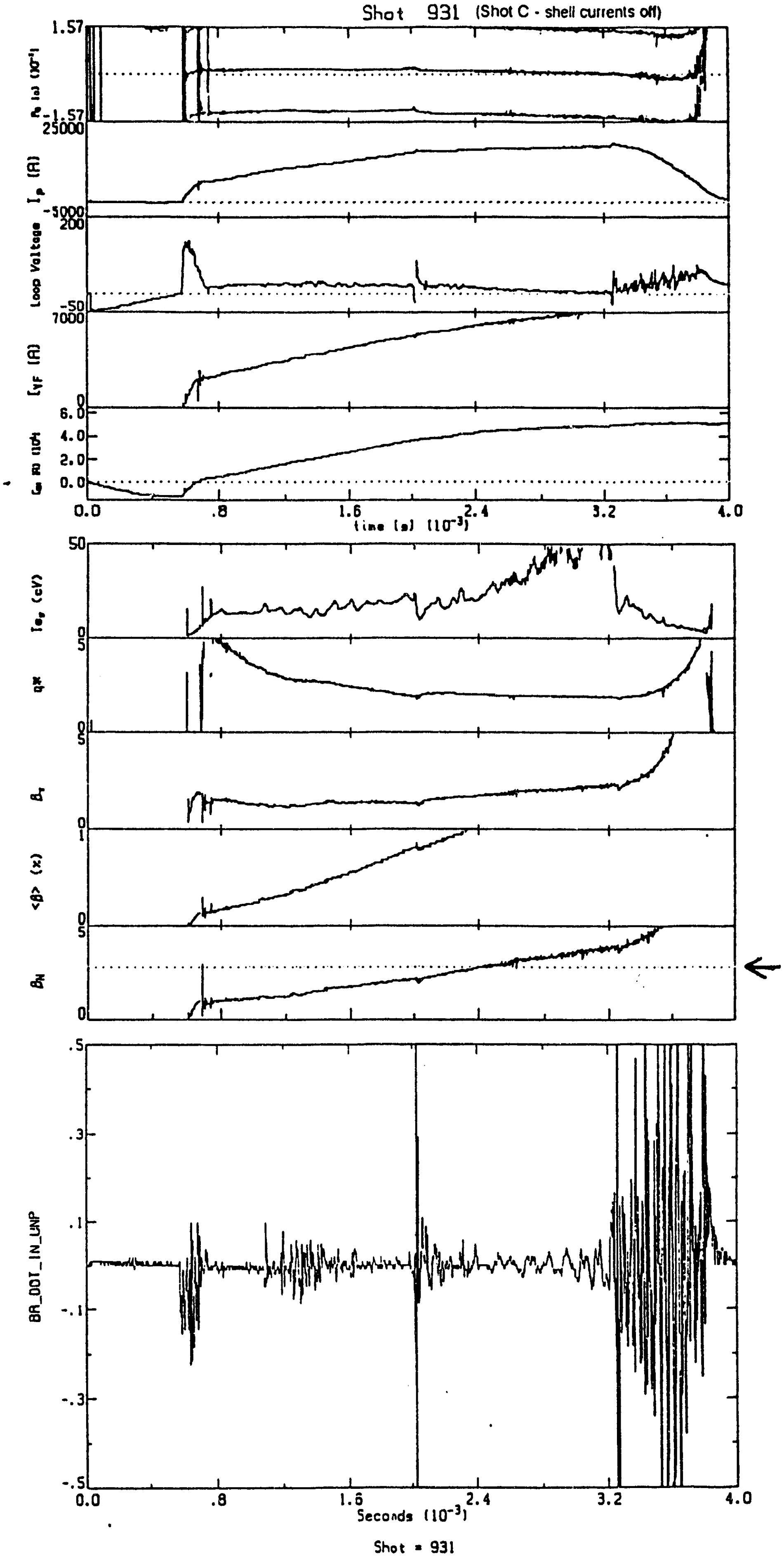
Figure 1. A typical HBT-EP discharge exhibiting MHD instabilities in a hot plasma with $\beta/\beta_c \sim 1$.

Figure 2. A photograph of the HBT-EP tokamak. Not shown are the Thomson scattering and CO_2 laser interferometer.

Figure 3. Comparison of the electron temperatures measured from conductivity and the Thomson scattering diagnostic.

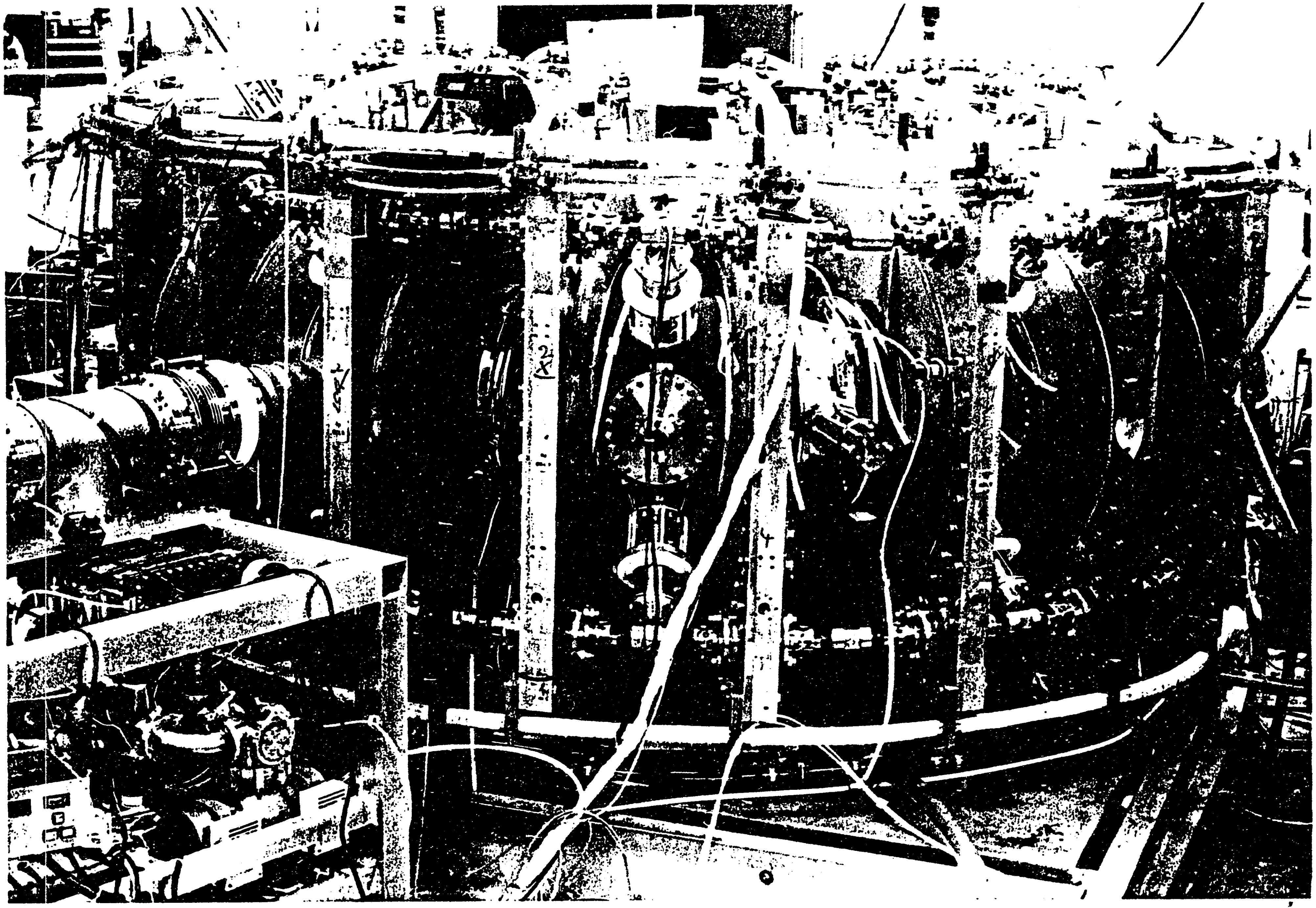
Figure 4. A scatter plot of a wide variety of HBT-EP discharges. At low-temperatures, discharges similar to HBT are produced—enabling internal magnetic probe measurements. As the machine cleanliness has improved, the temperature and beta of the discharges has improved.

Figure 5. The vacuum history of HBT-EP showing various partial pressures and the techniques used for cleaning.



← $\beta/\beta_c = 1$

FIG. 1



Comparison of Conductivity and Thomson Scattering Electron Temperatures

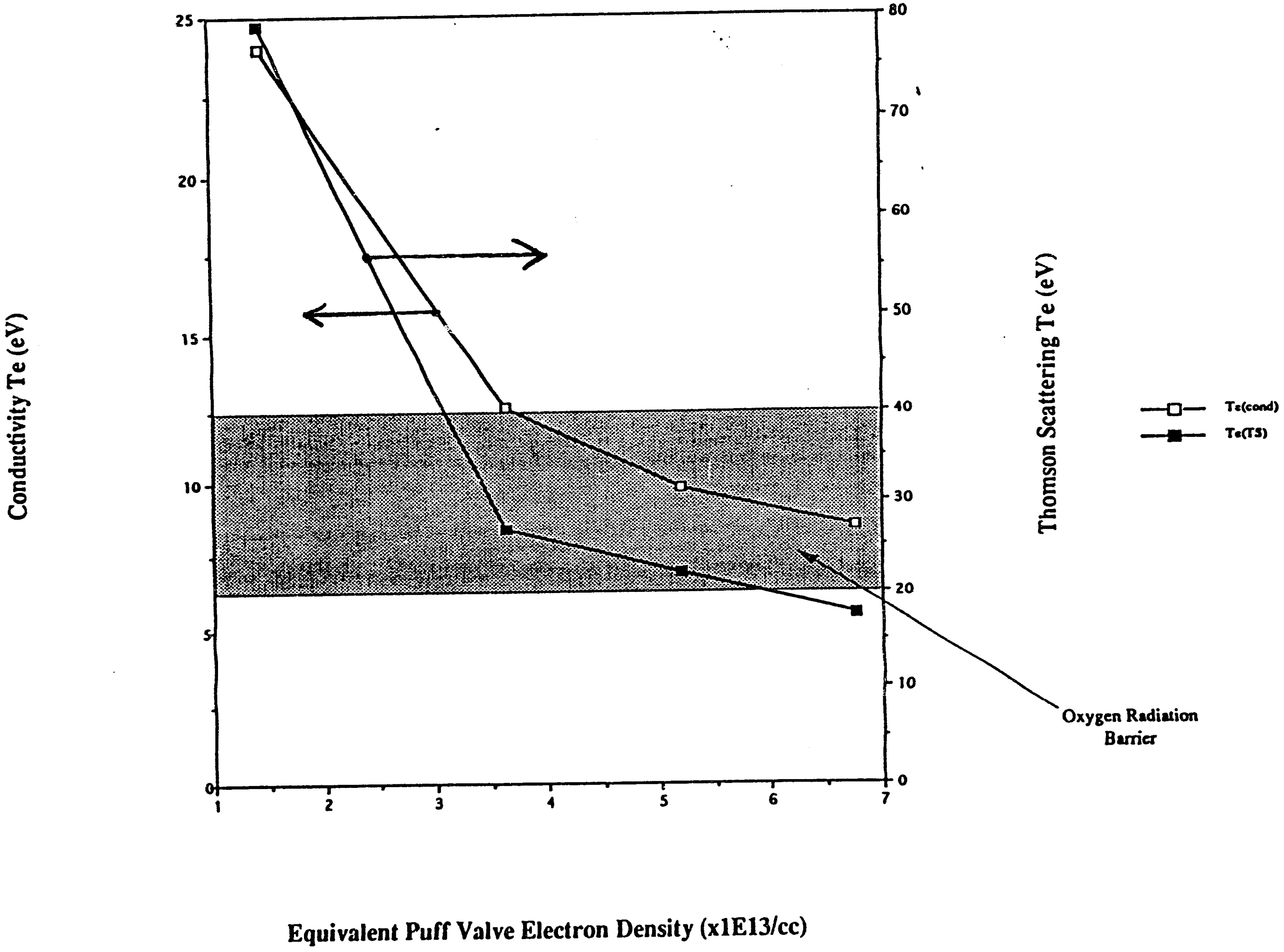
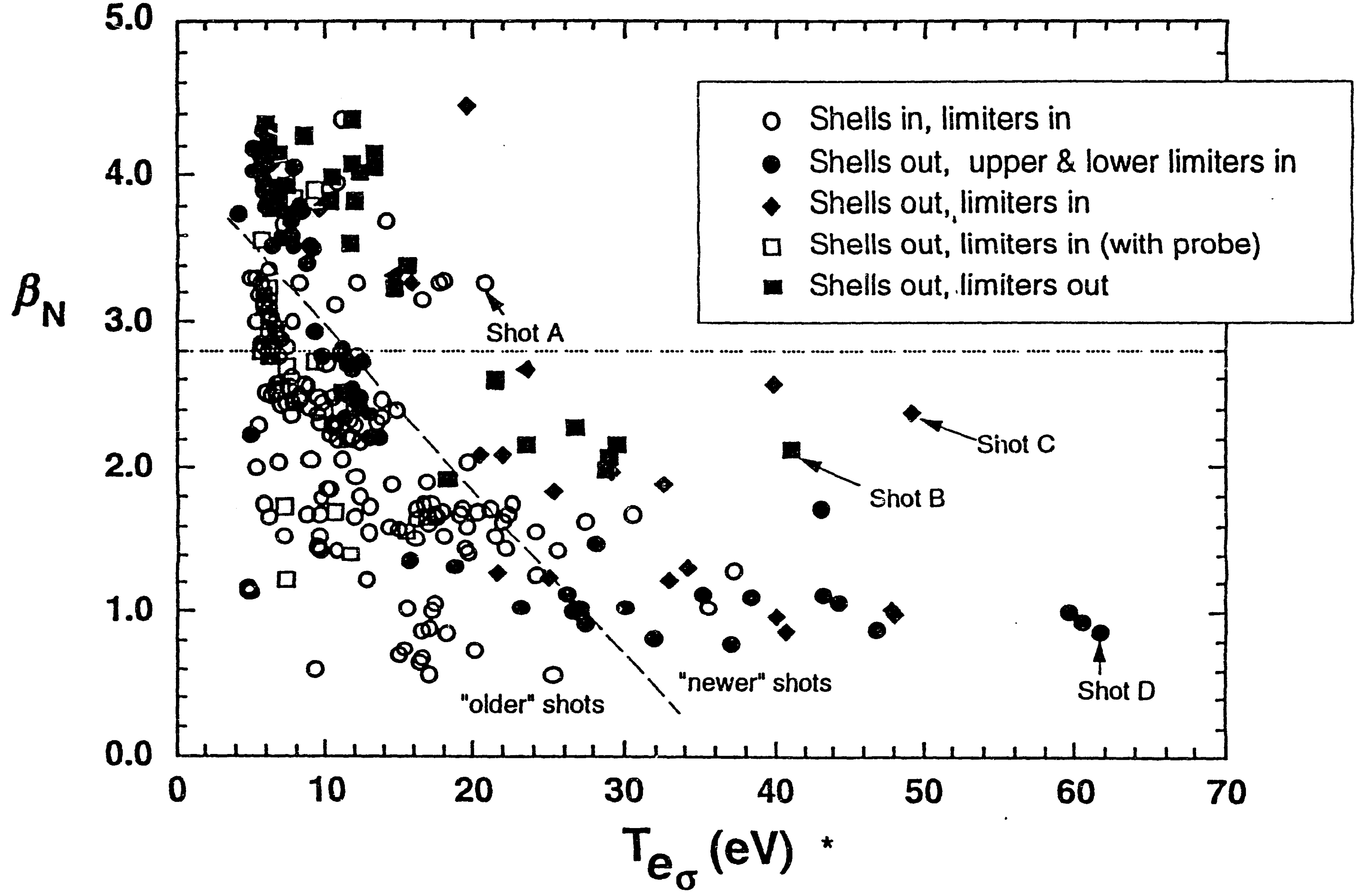


FIG. 3



* 1) Temperature determined from plasma conductivity
2) Thomson Scattering indicates Te (0) ≈ 2 x Teσ

Fig. 4

HBT-EP VACUUM HISTORY

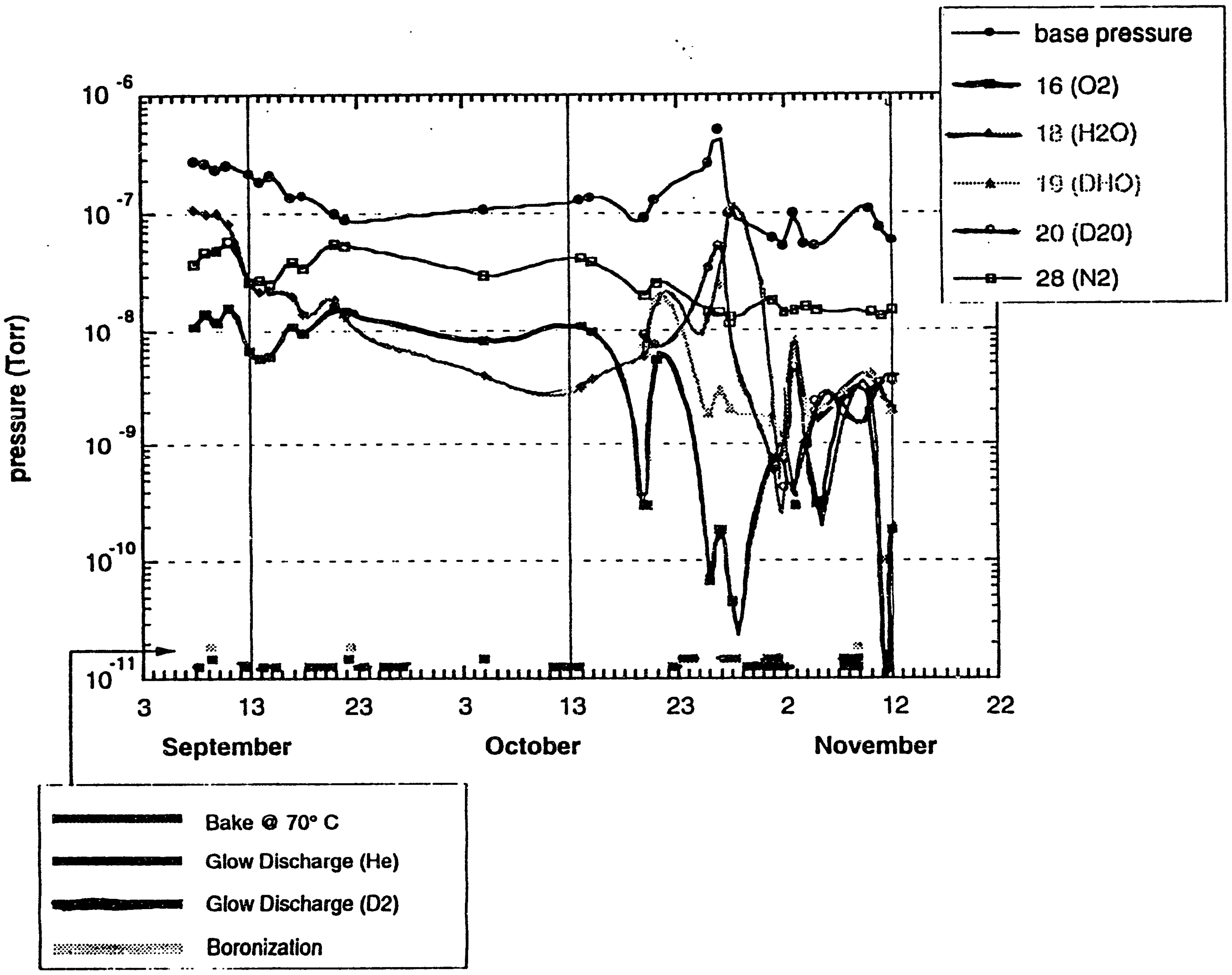


Fig. 5

END

DATE FILMED

3/23/93