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by

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ABSTRACT

The DIII–D tokamak employs eight neutral beam systems for plasma heating and current drive experiments. These positive ion source neutral beam systems have gone through several improvements in operational technique and in system hardware since the start of conditioning of the first long pulse ion source in December, 1986. These improvements have led to the routine operation in deuterium at beam power levels of 20 MW. The improvements in operational technique include filament power supply operating mode, accelerator grid voltage holding capability, and changes in grid potential gradients. The hardware improvements include installation of arc notching, arc discharge density regulation, and control of neutralizer gas puffing. Each of these improvements are discussed in this paper. Successful testing and operation of the ion source at 93 kV deuterium beam energy, well above the design value of 80 kV, also led to the possibility of enhancing system capability to 28 MW power level, nearly twice the original design value. Upgrading of the beam system to 60 second pulse duration at the currently achieved power level is under consideration. Studies have shown that this pulse length extension can be achieved with improvements in beamline heat handling components and auxiliary systems, especially the power supply system. The drift duct (the section between neutral beam beamline and tokamak) upgrade and protection for the long pulse duration present the greatest challenges, and are crucial to achieving long pulse beam injection into the tokamak plasma.

1. INTRODUCTION

The DIII–D neutral beam systems were converted to 5-sec pulse source operation (Ref. 1) in 1986. There are four beamlines, and each beamline has two ion sources in parallel focussed through a common drift duct. The ion sources (Refs. 2,3) were designed by Lawrence Berkeley Laboratory and manufactured by RCA. Conditioning of the first ion source began in December 1986. Hydrogen neutrals were first injected into DIII–D plasma in March 1987, and 10 MW of hydrogen beam was injected into plasma for 2 sec in May 1987. The eight-source system was developed to a capability of 14 MW in hydrogen, thus provided necessary heating power for plasma experiments on DIII–D tokamak. Deuterium beam operation has been used routinely since 1989, following the installation of DIII–D radiation shielding (Ref. 4). This allowed an increased injected beam power to 2.2 MW per ion source from 1.8 MW for hydrogen beam, and provided injection of deuterium neutrals into the deuterium plasma enhancing the plasma confinement time as compared to that of hydrogen beam injection. In the same year, the deuterium beam power was increased an additional 15% with new source optics by changing the voltage gradient between the grids of the ion source accelerator, thus achieving 2.5 MW per source beam injection into the plasma. This increase in beam power capability not only met the requirement for DIII–D experiments such as high-beta (Ref. 5) (achieved 11%) and divertor high heat flux (Ref. 6) (5.5 MW/m^2 obtained) programs which required higher heating power, it also enhanced the flexibility for program planning and system maintenance. System availability of better than 90 percent of the scheduled time has been consistantly achieved through the years. Following modification to the power supplies, successful operation of three ion sources at 93 kV deuterium beam energy last year demonstrated that the total system power output could be increased to 28 MW.

Specialized techniques for neutral beam operation have been developed to further increase the productivity of the neutral beam system. Techniques were also developed to successfully operated the ion sources in helium and argon providing beam injection for specific plasma experiments such as helium removal and L-H mode transition studies. Beam modulation has been frequently used for the CER (charge exchange recombination) diagnostic. Most recently, the average neutral beam power injected into the plasma was feedback regulated to control the plasma kinetic energy. This was achieved by using the advanced plasma control system, a system developed to digitally control key plasma parameters (Ref. 7), to monitor the plasma energy (using the diamagnetic flux) and generate control signals which were used to pulse modulate the neutral beam power. By controlling the plasma energy, VH–mode discharge which are unstable to increasing plasma energy were extended to duration of 1 sec. All these achievements are the cumulative results of experience, understanding, improvement in operational technique, and system hardware upgrades.

A system upgrade to 60 sec pulse duration, at 20 MW is currently being considered. We have identified the three major areas which need to be improved. The heat handling components (beam collimators and dumps) of the beamline need to be replaced by actively water-cooled components. Study of the heat dissipation on the existing power supply system indicates that the existing system can not support 60 sec operation, and tests will be performed to collect data for system upgrade. Protection of beamline drift duct for 60 sec operation is necessary, and will be done through both an improved monitor/interlock system and a scheme of reducing residue gas in the drift duct region.

2. IMPROVEMENTS OF TECHNIQUE AND HARDWARE FOR ION SOURCE OPERATIONS

In the very early stage of conditioning the first ion source, we learned that filament temperature is the most crucial parameter in obtaining a stable arc discharge for an ion source operated in the emission-limited regime. When the temperature is too hot (excessive thermal electrons), mode flipping, from emission-limited to space-charge limited operation, will occur resulting in extremely low arc current or no discharge at all. If the temperature is too cold, it requires higher arc voltage and arc power from the supply to obtain a desired arc density inside the discharge chamber, and thus results in poor arc discharge efficiency. The effect of the filament temperature on the ion beam extraction was observed (Ref. 8) and is shown in Fig. 1. It is seen that arc efficiency (defined as beam current over arc power) increases with the filament temperature within the operation range. This increase in efficiency is attributed to better particle confinement inside the arc chamber with increased numbers of thermal electrons. Thus, less arc power is required to supply ions for extraction. A power supply operated in the constant voltage mode with current clamping at turn-on serves very well for controlling the filament temperature. This enables the filaments to reach equilibrium temperature in a shorter period, and voltage regulation prevents drifting of filament temperature during pulsing. Waveforms of a typical filament and arc shot are shown in Fig. 2.

Beam extraction from these sources (Ref. 9) requires perveance matching (the need to set the arc discharge density properly corresponding to the accelerating voltage) during initial beam formation (within 100 μs). If we turn the accelerating voltage on against a full arc discharge, a large amount of ion current flows through the gradient grid such that voltage between the plasma and gradient grid becomes very small or collapses to near zero, resulting in beam termination. This problem is mitigated by adding a capacitive compensation network between the grids as shown in Fig. 3. The initial in-rush of ion current charges up capacitor C2 instead of flowing through R2, preserving the desired voltage potential between the plasma and gradient grid. Capacitor C1 serves to avoid over-compensation by

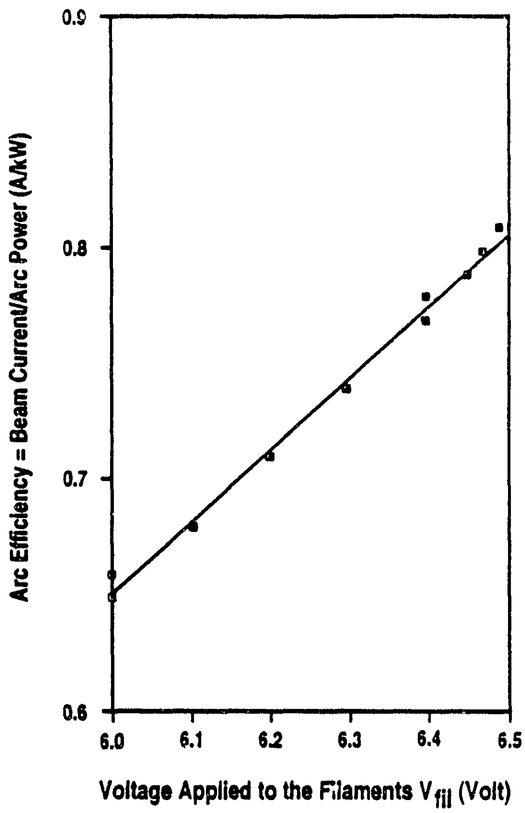

Fig. 1. Higher arc efficiency is obtained with hotter filaments for fixed beam energy.

preventing backstreaming electrons from flowing through resistor R1. This improvement in voltage holding capability between the plasma and gradient grids allows us to operate the source at higher beam perveance (higher beam power), which requires higher arc density and results in more ions flowing through the gradient grid during the initial beam formation.

Arc notching has also been used to improve perveance matching during initial beam formation. Arc notching is accomplished by diverting 20% of arc power to a resistive load 100 μs prior to the turn-on of accelerating voltage. Beam extraction is then started during the recovery of the arc to its desired power level. The total duration of arc notching and recovery is about 300 μs. With this arc notching ion source operation at higher beam power is much more reliable and overdense beam termination during initial beam formation is avoided.

The ion source was designed to run with the voltage between the plasma and gradient grids equal to 17% of the accelerating voltage ($V12 = 0.17\ V_{acc}$), and the optimum operating beam perveance is between 2.5 and 2.7 μp for deuterium beam operation. Based on the understanding that more ions can be extracted by increasing the value of V12 for a fixed value of V_{acc}, thus increasing the perveance and available beam power, source test operation was performed for higher value of V12 from 17% up to 21% of V_{acc}. The dependence of grid current on perveance (Fig. 4) shows that the optimum perveance, defined as the perveance at which

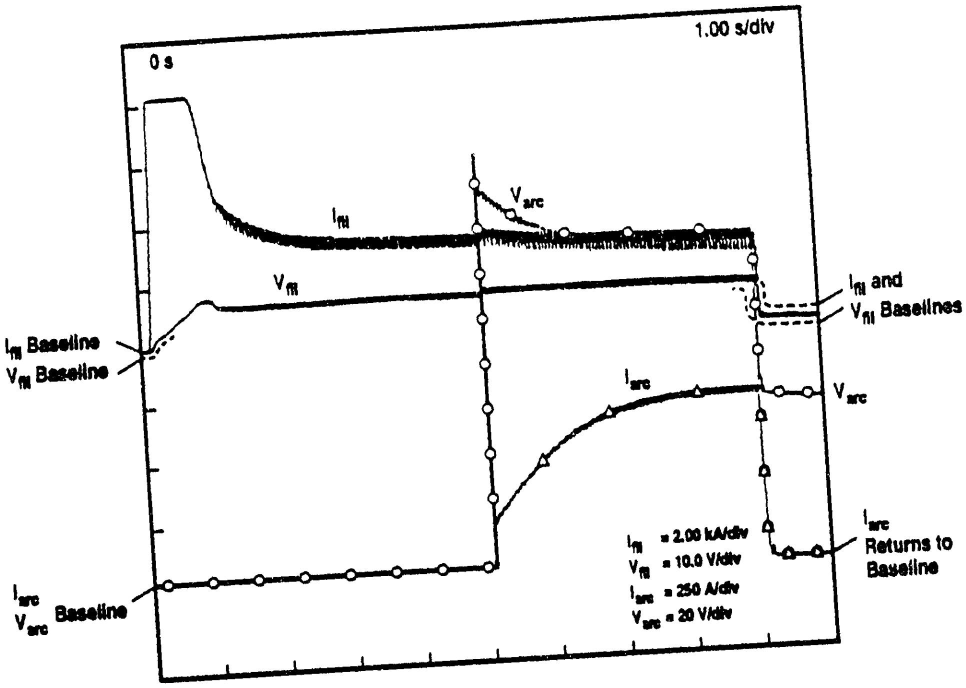

Fig. 2. Waveforms of a typical filament and arc shot with constant filament voltage

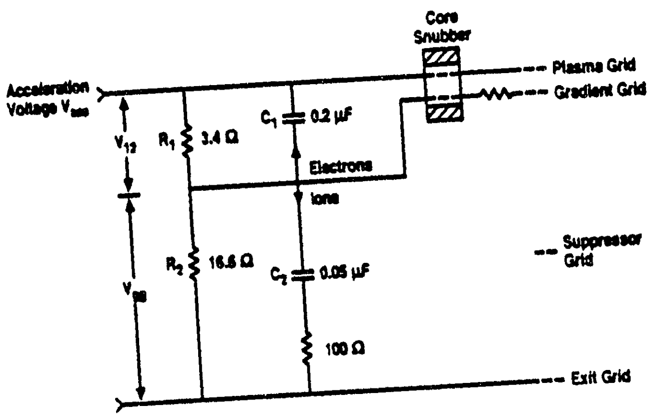

Fig. 3. Accelerator grids circuit with capacitive compensation.

normalized gradient grid current is minimum, shifts to higher value when V12 is increased. The beam divergence angle in the perpendicular direction does increase slightly (from 1.1° to 1.2°) while no change in the parallel direction is observed. This small increase in beam divergence has negligible effect on the beam transmission efficiency through the beamline. Ion source operations at the higher optimum perveance reliably produces an additional 15% beam power from each ion source, thus increasing the source capability to 2.5 MW deuterium beam power level.

Beam current ramping [Fig 5(a)] due to the backstreaming of energetic electrons from the accelerator into the arc chamber is an intrinsic characteristic of the DIII–D neutral beam ion sources. This ramping is attributed to the heating of filaments by the backstreaming energetic electrons, resulting in an increase of the arc discharge current inside the arc chamber and thus an increase in the beam current. The resulting change in beam perveance causes the beam optics to vary during a beam pulse, often resulting in an overdense condition and termination of a beam pulse. A technique (Ref. 10) which employes the Langmuir probe (six probes inside each arc chamber) signals for feedback regulation in the arc power supply has been very successful in regulating the beam current as shown in Fig. 5(b). In the regulated mode, plasma density inside the arc chamber is held constant through the entire discharge pulse, including the beam extraction period. This arc regulation has provided very consistant and reliable ion source operations at high perveance and beam power.

Neutralization efficiency of energetic ions is one of the factors which determine the neutral beam output power. The neutral gas density in the neutralizer cell of the beamline needs to be optimized to obtain maximum neutralization efficiency. Gas puffing through the arc chamber for arc discharge can provide a portion of the required gas density in the neutralizer region, but excessive gas flow will result in collisional loss of accelerated ions in the accelerator region and may cause damage to the accelerator grids. In our system (Ref. 11), additional gas is puffed directly into the neutralizer, and the flow rate was experimentally adjusted to obtain maximum neutralization efficiency.

3. ION SOURCE OPERATION AT BEAM ENERGY ABOVE THE DESIGN VALUE

In addition to reliable operation, improving the total beam power is one of the goals of DIII–D neutral beam operations. A study of the beam system capability

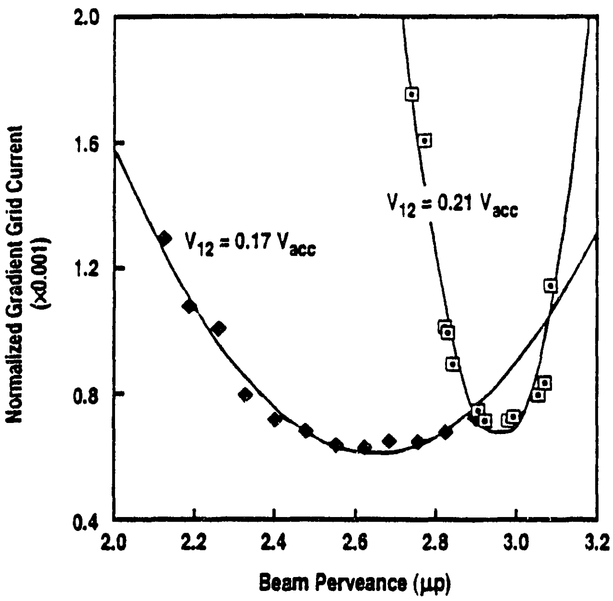

Fig. 4. Optimum grids circuit with capacitive compensation network.

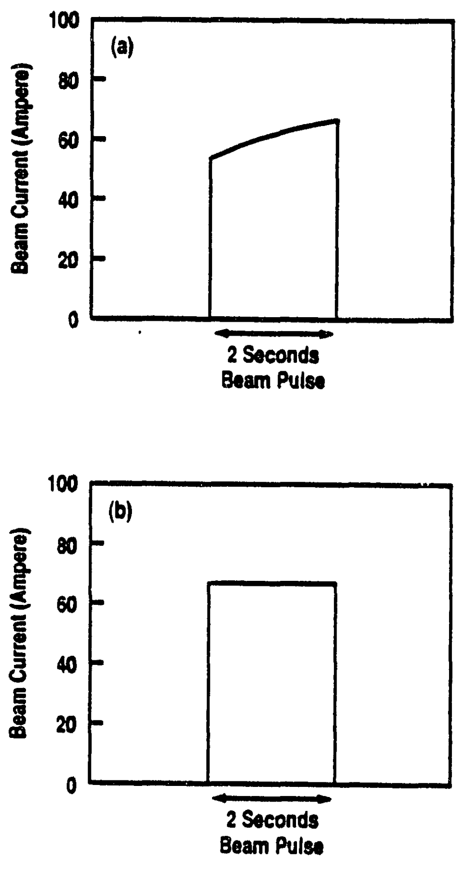

Fig. 5. (a) Beam current without arc regulation. A clear rise in extracted current during the beam pulse is evident. (b) Beam current with regulatio nand arc notching.

(Ref. 12) has indicated that the ion source can be operated in deuterium with the beam energy up to 93 kV based on the accelerator grid voltage holding capability. The corresponding arc power level is well within the design limit of the arc chamber. One high voltage transformer/rectifier unit of the power supply systems was refurbished and upgraded prior to the spring of 1991, and is now capable of supplying dc voltage (120 kV) high enough for 93 kV beam operation. The ion source performed very well during the test operation, and no ill effects on the ion source were observed. Injection of 93 kV, 1 sec deuterium beams, which yielded 3.6 MW beam power, injected into DIII–D plasma for heating was accomplished without any problem. Since then, two more ion sources have been conditioned up to 93 kV deuterium beam operation, giving us confidence that a total of 28 MW deuterium beam power from all eight ion sources could be achieved if the remaining transformer/rectifiers were upgraded.

4. POSSIBLE UPGRADE OF BEAM SYSTEM TO 60 SECOND PULSE LENGTH

The existing beam system was designed for 14 MW, 5 sec hydrogen beam operation. The pulse length has been limited to 3.5 sec for deuterium beam operation at 20 MW power level because of limitations on the internal heat handling components of the beamline. Beam power deposited on these beamline internal components which consist of beam collimators, beam dumps, and magnet and cryopanel protection plates, is removed by the cooling water between beam pulses. The maximum pulse length, limited by heat handling capability of beamline internal components, for various beam power is shown in Fig. 6. Figure 6 was obtained by extrapolating measured temperature rises of beamline internal components with various beam power and pulse lengths. It shows that shielding plates of the bending magnet pole faces set the limit on the beam pulse length in the higher beam power regime, and beam dumps and collimators are the limiting components at the lower beam power level. It is clear that these beamline internal componcnts need significiant upgrading to handle 60 sec beam pulse at source power level of 2.5 MW. The present proposed plan is to replace the existing beam collimators and dumps with components that are actively water cooled.

Damage to the beamline drift ducts by the high power deuterium beams with pulse length less than 5 sec has been observed. This has been attributed to the bending and focusing of the reionized energetic particles within the drift duct region by the DIII–D toroidal and poloidal magnetic fields. The reionization rate is directly proportional to the residual gas density within the drift duct region. A turbopump system which has been installed at one of the drift ducts will be used for experiment to measure and compare the reionization rate with and without additional pumping at the drift duct. Because the residual gas density is highly dependent on the cleanliness of the drift duct surface, duct surface conditioning using short pulse beams has been and shall be performed prior to long pulse operation. The existing drift duct photodiode system which monitors the reionization rate for beam interlock purpose has been very effective in protecting drift duct from severe damages, and has significantly reduced new damage to the duct after the maximum reionization rate allowed for continuing beam pulsing was lowered. This system shall be improved in hardware reliability and calibrations. Theoretical study to understand and quantify the trajectories and power deposition of the reionized particles is currently underway. This study shall provide information for drift duct protection.

Study of the heat dissipation in the existing neutral beam power supply system has shown that the existing power system components can not support 60 sec operation at a beam power level greater than 6 MW. The accelerator, filament, arc, and suppressor power supplies all need to be upgraded. The gradient grid resistor serves as the voltage divider between the plasma and gradient grids must also be upgraded for improved cooling or reduced heat dissipation. Transformers, both oil and air cooled, of these supplies appear to be the most critical elements in the power supply system when considering 60-sec operation. Tests will be performed to assess temperature rise and heat removal from critical components and structures. These tests would provide us the important and necessary data for system upgrade.

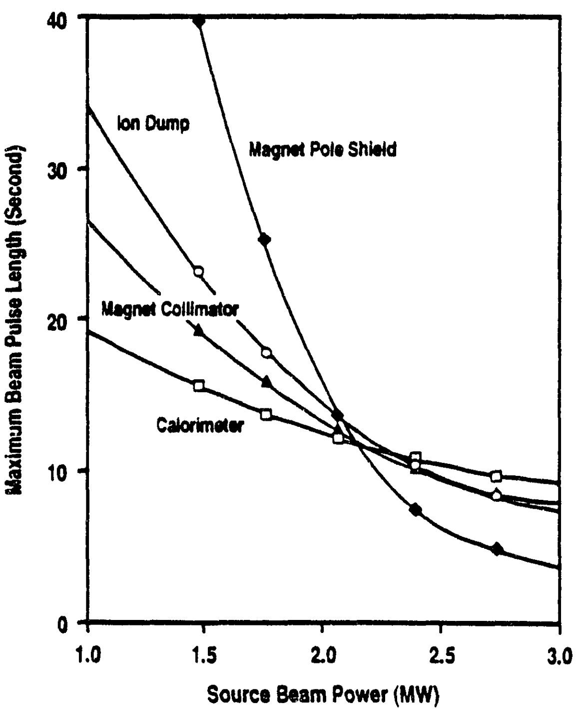

Fig. 6. Limits on beam system operation imposed by various beamline internal components based on the heat handling limitation. The source must be operated at pulse lengths less than all of the limiting components.

5. SUMMARY

Through years of neutral beam system operation, we have improved operational techniques and system hardware to achieve high reliability and availability of the DIII–D neutral beam system. A total deuterium beam power of 20 MW has been achieved and is the current capacity of the beam system which was originally designed for 14 MW hydrogen beam power. Increasing the accelerating voltage to 93 kV on three out of the eight sources has resulted in the possibility of enhancing the system capacity to 28 MW deuterium beam. The enhancement in beam power capability has enlarged the scope of experiments in DIII–D. In addition, helium and argon beam operation enabled DIII–D to perform unique experiments such as helium removal and L-H transition studies. Beam modulation capability along with a fast digital feedback plasma control system has been developed to control the plasma stored energy. Upgrading the system to 60 sec pulse operation is currently under consideration to support steady-state plasma experiments. The major upgrades will be the beamline internal heat handling components, the power supply system, and the beamline drift duct.

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