2.

GA-A19756

BEAM CURRENT REGULATION OF DIII–D NEUTRAL BEAM LONG PULSE ION SOURCES

by
R. HONG, D. KELLMAN, G. SANTAMARIA,
A. COLLERAINE, J. KIM, R. LEE,
J. PHILLIPS, and J. WIGHT

NOVEMBER 1989

GENERAL ATOMICS

GA-A--19756

DE90 002914

BEAM CURRENT REGULATION OF DIII–D NEUTRAL BEAM LONG PULSE ION SOURCES

by

R. HONG, D. KELLMAN, G. SANTAMARIA, A. COLLERAINE, J. KIM, R. LEE, J. PHILLIPS, and J. WIGHT

This is a preprint of a paper to be presented at the 13th Symposium on Fusion Engineering, October 2–6, 1989, Knoxville, Tennessee, and to be printed in the *Proceedings*.

Work supported by
Department of Energy
Contract DE-AC03-89ER51114

GENERAL ATOMICS PROJECT 3466
NOVEMBER 1989

GENERAL ATOMICS

BEAM CURRENT REGULATION OF DIII–D NEUTRAL BEAM LONG PULSE ION SOURCES

R. Hong, D. Kellman, G. Santamaria, A. Colleraine, J. Kim, R. Lee, J. Phillips and J. Wight
General Atomics, P.O. Box 85608
San Diego, California 92138-5608

Abstract: An intrinsic characteristic of the neutral beam long pulse ion source installed on the DIII–D tokamak is the slow increase of arc and beam currents during the beam pulse. This ramping is attributed to the heating of the filaments by energetic electrons backstreaming from the accelerator into the arc chamber. The corresponding change in beam perveance causes the beam optics to vary during a beam pulse, often resulting in an overdense condition. A technique [1] which employs the idea of compensating the filament temperature rise by stepping down the voltage applied to the filaments at beam turn-on has proved to be somewhat effective and successful in regulating the beam current. The disadvantage of this technique is that the amount of filament voltage step-down varies from source to source and is dependent on beam energy. A new technique uses a Langmuir probe signal for feedback regulation in the arc power supply. Plasma density within the arc chamber is maintained at a constant value, as is beam current. This arc regulation method also features "arc notching" at beam turn-on to provide perveance matching during initial beam formation, which is crucial to obtaining smooth initial beam extraction, a high perveance beam, and thus higher power beam operation. The beam power achieved with this arc notching and regulation technique is about 10% higher than that obtained previously with the filament voltage step-down method.

Introduction

The Neutral Beam System installed on the DIII–D tokamak employs eight 80 kV Long Pulse Sources (LPS) mounted on four beamlines. These sources have been operated with high reliability for plasma heating experiments since 1987. The intrinsic characteristic of beam current ramping became troublesome in that the measured average beam power became a function of pulse length. Also, long pulse beam operation at high beam energy resulted in an unstable, overdense condition. Stepping down the voltage applied to the filaments at beam turn-on was helpful, but its disadvantages called for a better scheme to regulate beam current. In this paper, we will present the new beam regulation and arc notching technique, including its circuit development and functions. Test results of beam regulation will be presented and compared with the case of beam operation without regulation. Advantages of arc notching at initial beam formation will be shown, and arc discharge characteristics of the plasma generator with plasma density feedback regulation will be discussed.

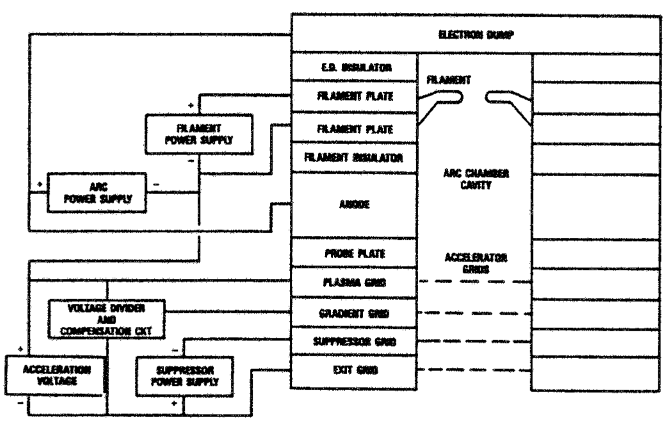

Fig. 1. Simplified block diagram of long pulse source and power supply system.

Regulation of Beam Current

Figure 1 shows the simplified diagram of a LPS and its power supply system. The timing sequence of various power supplies and the gas puffing system is shown in Fig. 2. Detailed descriptions of the power supply system are given in Ref. 2. The plasma generator (arc chamber) of the LPS is equipped with cusp magnets and operates in the emission limited regime. The accelerator has an actively-water-cooled tetrode configuration with a 10 m focus in one direction.

During source operation, the arc discharge level and beam current amplitude for various beam energies is controlled by a single command from a Langmuir probe signal for a fixed filament temperature. In the unregulated mode, we observed that the command setting served only as a reference for arc power level, and the plasma density required ≈3 sec to reach equilibrium. Both plasma density (Fig. 3) and beam current (Fig. 4)

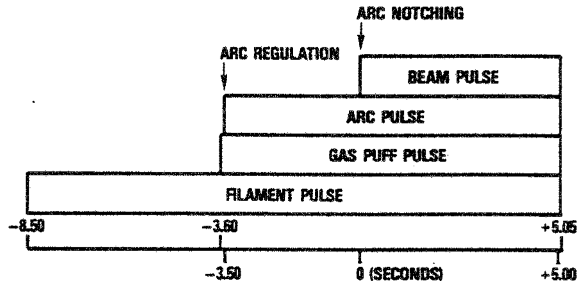

Fig. 2. Timing sequence for operation of a DIII–D LPS showing the on times of the various power supplies and the gas feed for a 5 sec beam pulse.

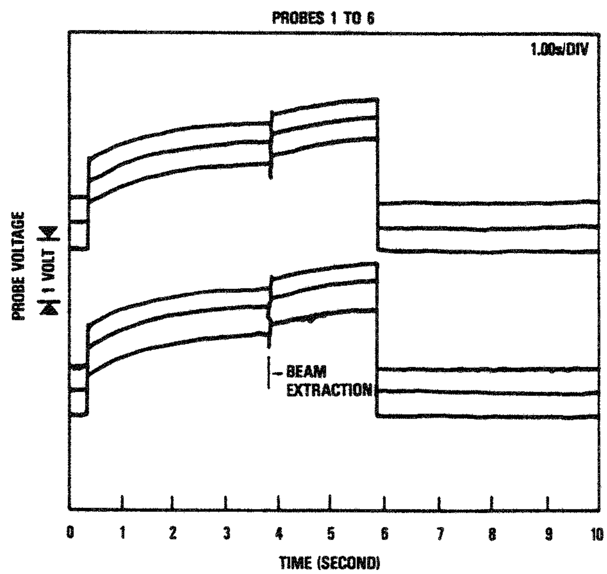

Fig. 3. Langmuir probe signals (proportional to plasma density) without arc regulation. The plasma density ramps up to a value of 1.7 volts just prior to beam turn-on but when beam extraction starts at 3.8 sec, the ramp up in density resumes.

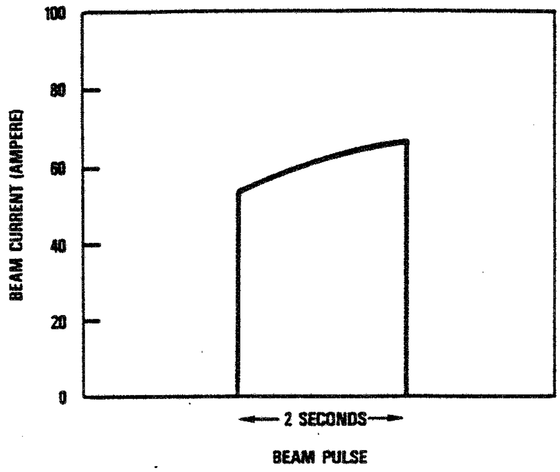

Fig. 4. Beam current without arc regulation. A clear rise in extracted current during the beam pulse is evident.

displayed strong ramping during the 2 second beam extraction period. In this test case, beam current ramped up to 66 A from 54 A in two seconds, a 22% increase.

In the regulated mode, one Langmuir probe signal is used for feedback regulation of plasma density in the arc chamber. Regulation starts at the initiation of the arc discharge, and plasma density is held constant (as set by the Langmuir probe command) through the entire discharge pulse, including the beam extraction period. The results are shown in Figs. 5 and 6. The time required for the probe signal to reach its commanded value is less than one second, and is found to depend on filament temperature, as well as commanded plasma density. Once the plasma density reaches its set value it stays constant through the entire shot, and beam current ramping is almost completely suppressed (about 1 A increase at the end of a 2 sec beam pulse). To further examine the effectiveness of this regulation scheme,we measured average beam perveance for various beam pulse lengths, with and without regulation. Figure 7 shows that average beam perveance increases only slightly with beam pulse length when regulation is in use. The variation in average perveance with pulse length is more drastic when the regulation circuit is disabled.

Arc Notching at Initial Beam Formation

To obtain the best beam optics and beam power transmission, the LPS needs to be operated at or near its optimum beam perveance. The required plasma density in the arc chamber for optimum perveance operation is always too dense for

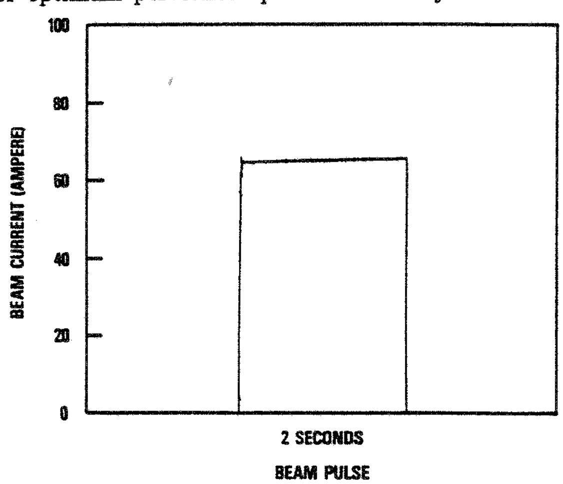

Fig. 6. Beam current with regulation and arc notching.

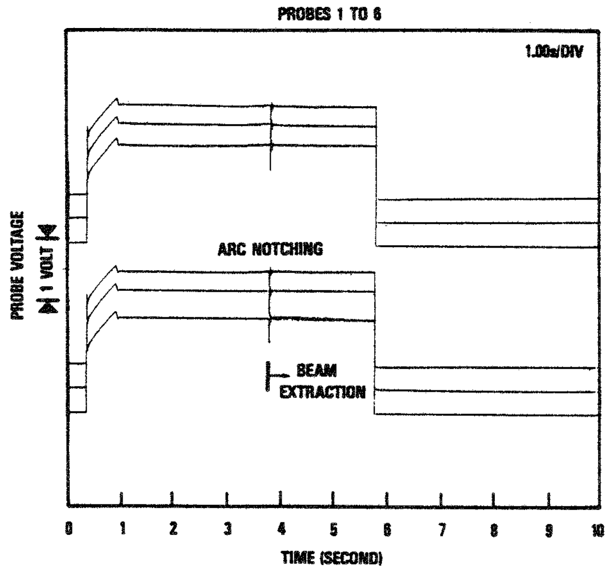

Fig. 5. Langmuir probe signal with regulation and notching. Note the stability of the plasma density prior to and during beam extraction.

the initial beam formation ($\approx$100 μs) during which the accelerating voltage is ramping up to its set value. This results in collapse of the voltage between the plasma and gradient grids of the accelerator, a condition under which the fault detection circuitry blocks the beam pulse. Adding a capacitive compensation network between the grids to stiffen up the voltage holding capability [1] has allowed us to operate the source at a beam perveance slightly lower than optimum with full arc power at initial beam extraction.

To operate the source at its optimum perveance and to take advantage of beam regulation, it is then necessary to "notch" the arc power to a lower level during initial beam turn-on, to obtain better perveance matching and to avoid collapse of the voltage between the plasma and gradient grids. This arc notching is accomplished by modulating the reference voltage in the arc regulator circuitry. The operation sequence proceeds as follows: the arc discharge is commanded and regulated such that plasma density is at a level required for optimum perveance operation; 10 ms before beam extraction, the arc power is notched down by about 25%; beam extraction then begins as arc power returns to its un-notched value. The level of arc power notching and the beam extraction point during the arc recovery period are both adjustable in the operation set-up to allow flexibility. This arc notching enables the source to operate at a higher beam

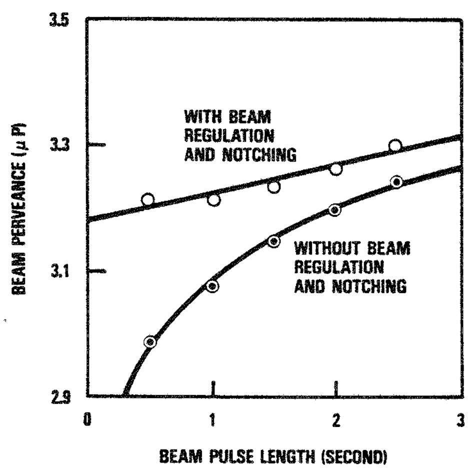

Fig. 7. Beam perveance vs. pulse length.

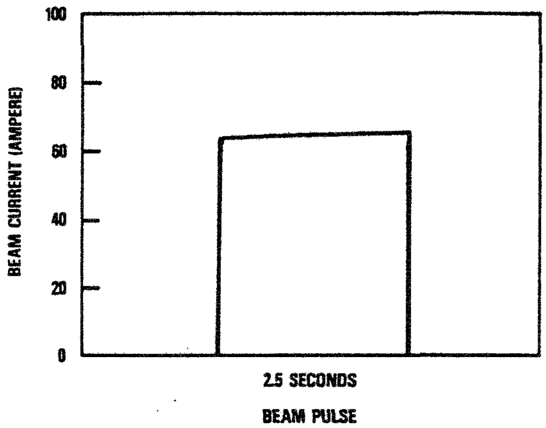

Fig. 8. Beam current with fast arc notching at beam turn-on.

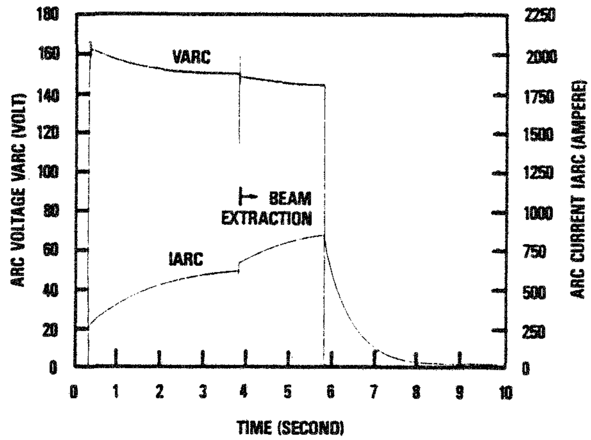

Fig. 9. Unregulated arc discharge waveforms.

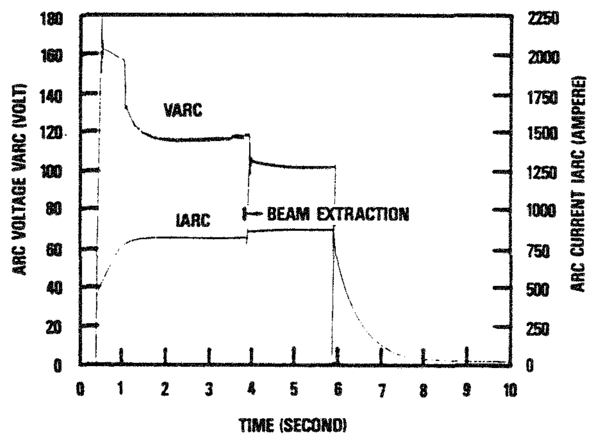

Fig. 10. Regulated arc discharge waveforms.

perveance, and thus higher beam power, without overdense beam termination at turn-on. Figure 7 shows that higher perveance is achieved even at short beam pulse lengths when arc notching is used.

We should mention here that this arc notching is a slow process compared to the turn-on time of the accelerating voltage. The duration of the arc notch and recovery is about 20 to 30 ms, or hundreds of times longer than the ramp-up time ($\approx 100\ \mu s$) of the accelerating voltage. Fluctuation of plasma density during the notch recovery phase (beam turn-on) was observed. This resulted in a corresponding beam current fluctuation during the first 10 to 20 ms of beam pulse, as shown in Fig. 6. Attempts to mitigate this problem have had only limited success. Recently, we experimented with a fast arc notching scheme, using a shunt switching network to divert a portion of the arc power through a resistive load during beam turn-on. The results have been very promising (Fig. 8) in that initial beam current fluctuation is avoided. After further testing and check-out, this fast arc notching scheme will be incorporated in all DIII–D neutral beam power systems.

Arc Discharge With and Without Beam Regulation

We have shown that both arc notching at beam turn-on and beam regulation have allowed sources to operate at higher beam perveance and constant beam current. It is important to examine the operational characteristics of the arc chamber and its power supply system with arc notching and beam regulation.

An arc discharge without regulation (Fig. 9) starts with low arc current and high arc voltage. As the discharge progresses arc current slowly increases to its equilibrium value, as does plasma density, while arc voltage ramps down to a smaller value. This slow decrease of arc voltage is attributed to the additional thermal electrons emitted from the filaments, which result from extra filament heating from arc current flowing through a portion of the filaments (arc chamber and filaments share the same common). With these additional thermal electrons, lower arc voltage is needed to sustain or to increase arc power. This is also true during the beam extraction period. The step-up in arc current and plasma density at beam turn-on is another intrinsic characteristic of the LPS and is presumably due to the modification of the discharge characteristics by energetic backstreaming electrons.

With plasma density regulation, we observe that the above characteristics are still present (Fig. 10), but the arc power supply provides more power at the early phase of the discharge, causing the plasma density to reach its set value quickly (Fig. 5). During the beam extraction period the arc regulator is able to compensate for the effect of energetic backstreaming electrons, maintaining plasma density, (and thus beam current) at a constant level. All eight ion sources have been operated in this beam regulation and arc notching mode for almost one year, and no ill effects on the arc chamber or its performance have been observed.

Description of the Arc Power Controller

As shown in Fig. 11, the arc power controller feedback loop includes control switches for turn-on initiation, notch generator, error amplifier, integrator, equalizer, arc power supply, arc chamber and Langmuir probe. The arc power supply includes SCR gating circuitry, an SCR controller, a Transformer/Rectifier (T/R) set and output filter network.

Considerations affecting the dynamic performance of the feedback loop include:

- The phase lag introduced by the SCR gating circuit and the phase-angle control process. This sets the ultimate dynamic performance limitations of the system.
- The gain rolloff introduced by the commutation reactances of the T/R set and output filter network. This introduces an underdamped second-order oscillatory response which is effectively cancelled by the equalizer. The equalizer possesses a frequency response characteristic which is the inverse of that due to the output filter.
- The thermal lag introduced by the extra filament heating due to the arc current. This affects system frequency response by introducing a lag-lead characteristic in the range of 0.1 Hz to 1 Hz. This is effectively countered by increasing the gain by approximately 20 db.

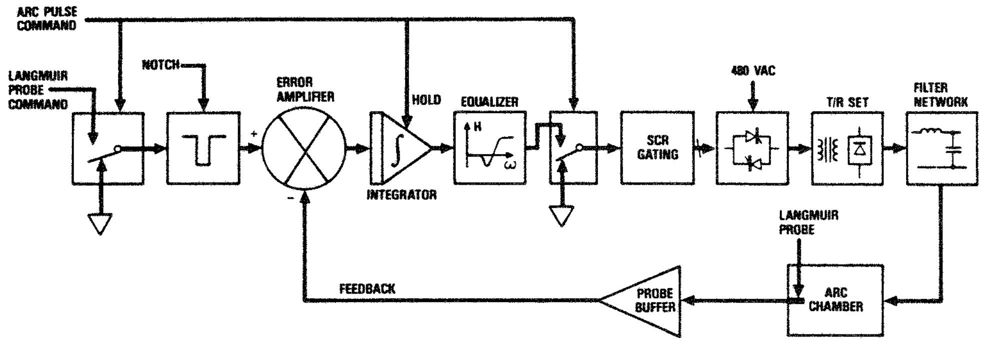

Fig. 11. Block diagram of Arc Power Controller

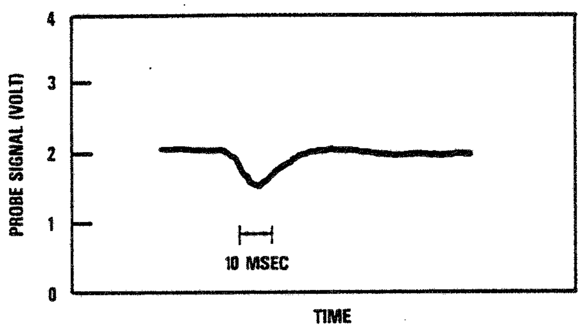

Fig. 12. Dynamic performance during arch notching.

Table 1
Results of Frequency Response Analysis Tests

Arc Power (kW)	Zero-Gain Crossover (Hz)	Phase Margin (°)	Gain Margin (dB)
60	17	50	>20
90	16	52	>20
110	15	54	>20

An integrator is used in the feedback loop to eliminate any dc drift effects. A hold control on the integrator and intermediate analog switches ensure that the system turns on with zero initial conditions. The integrator also has clamps incorporated to minimize overshoot due to saturation effects as the Langmuir probe feedback signal reaches its operating point at turn-on. Notching is performed by reducing the probe command input by a fixed percentage for an adjustable time delay, typically 10 to 20 msec. The duration of the notch input is extended somewhat by the dynamic response and inherent non-linearities in the system.

Dynamic performance was optimized for the fastest notch response consistent with minimal overshoot. Final gain adjustments were made by observing notch response over the full operating range with various gain settings. As shown in the waveform of Fig. 12, the probe signal drops 26% when a 24% notch is superimposed on the probe command signal.

The overall loop gain was measured with a commercial frequency response analysis system during operation with arc only. Frequency response was plotted between 5 Hz and 100 Hz and gain and phase margins were extracted from the data. The results shown in Table 1 serve to verify that the system has excellent stability margins.

Conclusions

Beam current ramping due to energetic backstreaming electrons is an intrinsic characteristic of the DIII–D long pulse sources with unregulated arc. Beam current regulation using Langmuir probe signal feedback regulation of plasma density in the arc chamber has proved to be very successful at eliminating this effect with improved ion source performance. Arc notching at initial beam formation is crucial to obtaining high perveance beam, and thus higher beam power operation. Testing has shown that the arc power controller has excellent stability margins and low overshoot when used with arc notching.

Acknowledgment

The authors would like to thank Dr. R.W. Callis for his encouragement and support. Special thanks go to neutral beam power supply technical staff, D. Clow, J. Morse and R. Brambila, and to neutral beam source operation staff, B. Scoville, M. Madruga and J. Gilgallon for their skillful work and dedicated support during the course of this project.

This work was sponsored by the U.S. Department of Energy under Contract No. DE-AC03-89ER51114.

References

[1] Hong, R., *et al.*, "Operational Experience with the DIII–D Neutral Beam 12 cm × 48 cm Common Long Pulse Source," *Proc. 12th Symp. Fusion Eng.*, 1133 (1987).

[2] Kellman, D., *et al.*, "Modification of the DIII–D Neutral Beam Power Systems for Operation of the Common Long Pulse Source," *Proc. 12th Symp. Fusion Eng*, 420 (1987).