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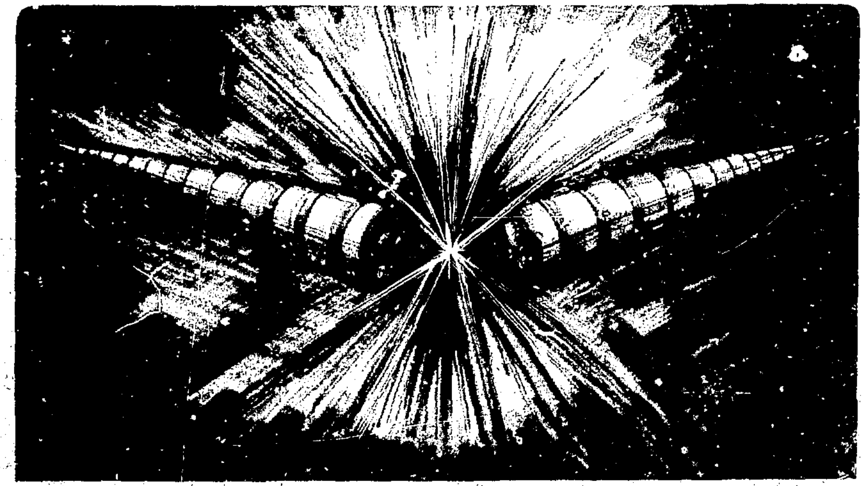

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THE CONTROL OF A HIGH-POWER NEUTRAL BEAM GENERATOR BY MEANS OF ARC-CURRENT REGULATION*

LBL-12723

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SUMMARY

Preliminary tests of a method for regulating the accelerator perveance of a high-power neutral beam, by controlling the plasma source have been conducted and are encouraging. The phase shifts and feedback paths were identified and quantified, and stabilization was achieved by adding an R-C snubber at the accelerator power supply output which reduced the destabilizing phase lags. The incorporation of such regulators into future systems is envisioned to make these high-power neutral beam systems cheaper and easier to operate.

MOTIVATION

The high-power beams of neutral particles used in fusion research are produced by accelerating ions (~250 mA/cm^2) through semi-transparent grids having high potential differences (~120 kV). As in any accelerated-beam system, neutral-beam (NB) sources have a specific design value of perveance ($I_{beam}/V_{accel}^{3/2}$) which is associated with optimum beam optics. When operated at this perveance value, there is minimal interception of the beam by the grids. It is particularly important to operate long-pulse multi-megawatt NB sources at or near this perveance value so that grid damage is avoided. Variations in voltage (such as ripple) in the power supplies used to operate the neutral beam can cause departure from optimum perveance. Deviation from the optimum perveance can also occur during beam "turn-on".

We report here the interim results of an investigation of a method for automatic beam current control. It has achieved essentially constant-perveance operation and can increase the ease and safety of operation.

BEAM CURRENT REGULATION

For a NB source, the beam accelerating potential is controlled by the accel PS. The beam current, however, is controlled by the arc power (i.e., plasma density). One can automatically and continuously maintain the beam current (by controlling the arc power) at a value consistent with a pre-requested perveance, even during accel voltage fluctuations. This is the method we have employed. It is implemented by a type of controlled closed-loop arc regulator.

Certain immediate advantages are notable:

1. An accel PS regulator is no longer needed. This can result in a real saving of (typically) 10 to 20% of required accel PS power.
2. An 80x reduction in the power-handling capability of the system controlling element (~100 kW versus 8 MW).
3. Automatic perveance matching during the beam "turn-on" transition.
4. Automatic compensation of accel PS and arc PS ripple.

In addition, such a system should be capable of compensating for "beam pumping"[1] of the ion output and for beam ripple caused by ac-heated filaments (presently under consideration).

IMPLEMENTATION

Figure 1 shows a block diagram of the beam current regulator used for the "proof-of-principle" tests on the NBSTF (the TFTR prototype beam line) at the Lawrence Berkeley Laboratory. The accelerator power supply[2] current (I_{accel}), being dominated by the beam current ($I_{beam} \approx 0.98 \times I_{accel}$, except during severe perveance mismatches) is controlled predominantly by the arc-current modulator,[3] (having a net transconductance $Y_{arc\ PS}$ and which incorporates the necessary 3/2-power dependence). Its control voltage is generated by summing an error signal and a "requested beam current" signal. The latter signal is obtained by scaling the instantaneous accelerator voltage ($V_{accel} = V_0 - Z_{accel} \times I_{accel}$) according to the requested perveance (G_{perv}, which is a linear gain adjustment). V_0 is the accel PS open-circuit voltage; Z_{accel} is the equivalent output impedance. The error signal is produced from a comparison of a scaled replica of the beam current ($Z_{probe} \times I_{beam}$, obtained from the saturated ion-collection current of a probe near the accelerator input) with the "request for beam current" ($G_{perv} \times V_{accel}$). This error signal ($-G_{accuracy}$) is amplified (with a frequency response given by $1/\ 1 + j\omega\tau_{error}$) before summing at the arc-current modulator input.

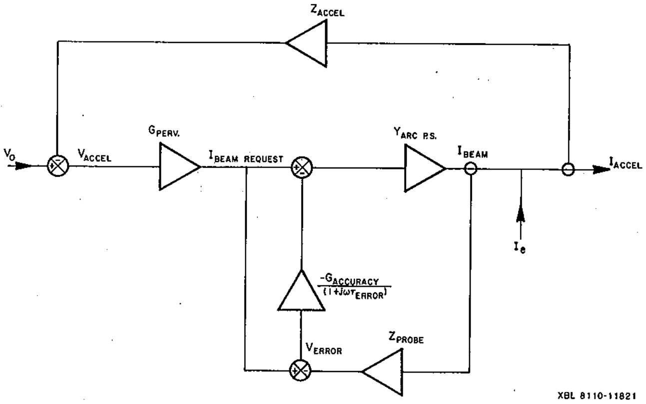

Figure 1 NBSTF Beam-Current Regulator Block Diagram The open circuit voltage (V_0) is modified by the output current (I_{accel}), the requested perveance (G_{perv}) and an error signal. The resultant controls the beam current by modulating the arc current.

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STABILITY CONSIDERATIONS

The complex admittance of the linear system shown in Figure 1 may be written:

$$\frac{I_{beam}}{V_0} = \frac{G \times Y_{arc\ PS}}{1 + (Z_1 + Z_2) Y_{arc\ PS}}$$

where

$$G = G_{perv} \left[1 + \frac{G_{accuracy}}{(1 + j\omega\tau_{error})} \right] ,$$

and

$$Z_1 = G \times Z_{accel} \text{ (accel PS output impedance)},$$

and

$$Z_2 = \frac{G_{accuracy}}{1 + j\omega\tau_{error}} \times Z_{probe}$$

The non linear electron current (I_0) has been neglected in these calculations.

One should expect stability problems near frequencies where $1 + (Z_1 + Z_2) \times Y_{arc\ PS} = 0$. Hence, the reduction of the Z_1, Z_2 impedances and/or phase lag may be expected to be stabilizing.

The arc-current modulator was made with the highest practical frequency response so as to permit control during the beam "turn-on" without increasing the transient accel energy reservoir. Two phase lags (Figure 2) were measured with the aid of a sine wave oscillator connected to the input of the arc-current modulator. The related observed delays are: ~4 μs in the arc current modulator (suspected to be dominated by the high current transistor switches) and ~6 μs (suspected to be composed of the transmission line's inductance[4] and the arc impedance, L/R ≃ 4 μsec, and an ion transit time of 2 μs).

The complex accelerator power supply output impedance (Z_{accel}) was computed from a lumped circuit model (Figure 3). It exhibited two resonances, one dominated by the accel transformer's leakage reactance (~3 H) interacting with the transmission line capacitance (~1 nF), and one dominated by the additional "short-circuit" inductance (1 H) interacting with a second transmission line and arc and filament power supply capacitances (1.5 nF). The calculated phase plot (Figure 4) shows a large phase lag above f = 10 kHz. (In this calculation, the lumped circuit is driven at the output terminals with a current source; V_0 is short circuited.)

OPERATION

The simplest feedback configuration ($G_{accuracy} = 0$), tried first, suffered from fluctuations (Figure 5) which increased during beam "turn-on". The initial rise in accelerator voltage was followed by increasingly large transient droops until the attempt for beam was aborted. The oscillation frequency was near the calculated 180° phase lag ($f_{180°} \sim 40$ kHz) frequency for $Z_{accel} \times Y_{arc\ PS}$.

The application of a 2.5 KΩ, 20 nF snubber across the output produced two fundamental improvements.

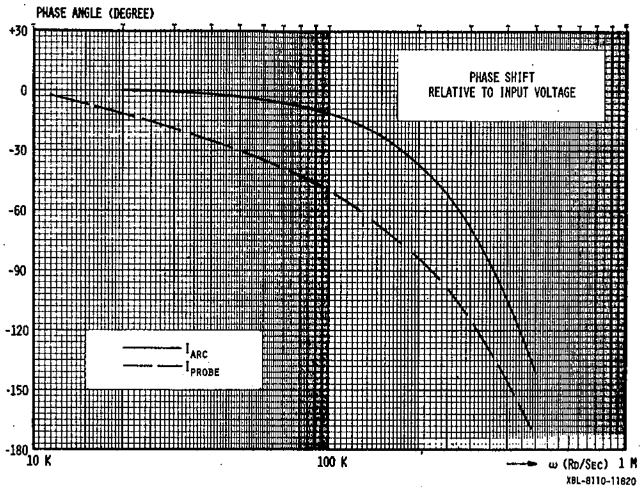

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Figure 2 Measured phase lags in the arc-current and the ion probe current. The ion probe current is proportional to the ion beam current.

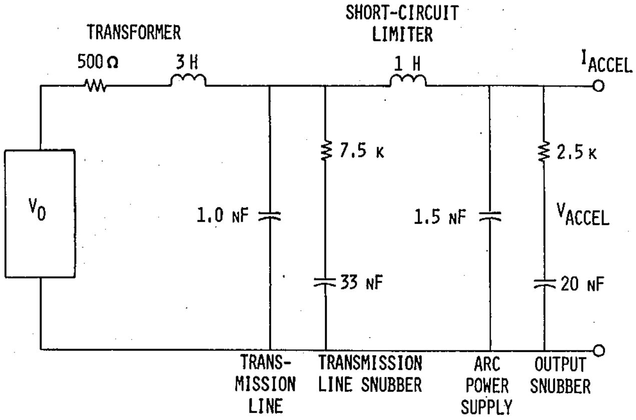

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Figure 3 Model of accel PS used in the calculation of complex Z_{accel}.

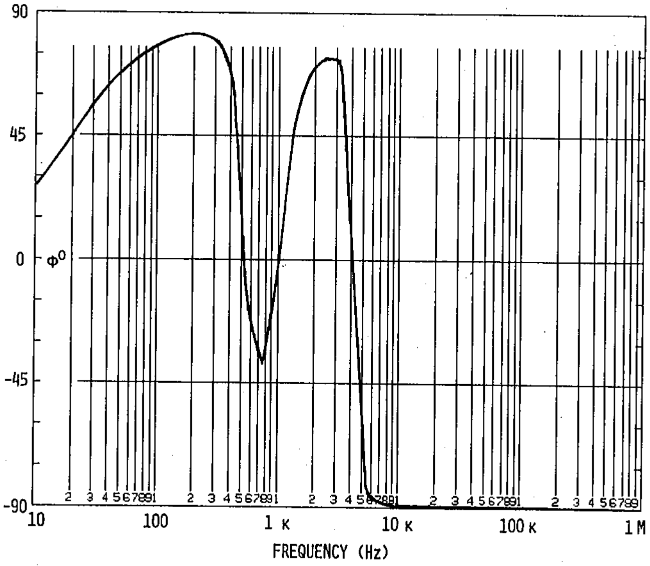

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Figure 4 Z_{accel} (Phase) Without Output RC Snubber.

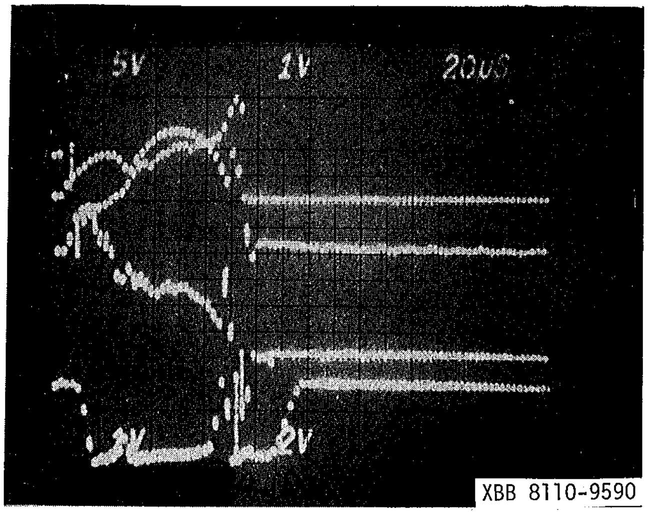

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Figure 5 Before the output snubber was installed, the V_{accel} fluctuations" increased until the beam attempt was aborted.

Trace No. 1 = Accelerator voltage
Trace No. 2 = Accelerator Current
Trace No. 4 = Suppressor Voltage

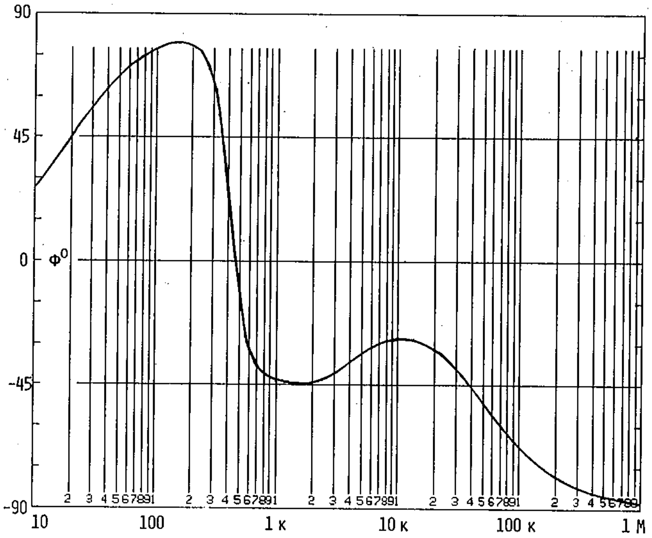

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Figure 6 Z_{accel} (phase), calculated with the output snubber 2.5 KΩ/20 nF RC . Phase lag at f = 40 kHz is -45°. (Z_{accel} was reduced 33%.)

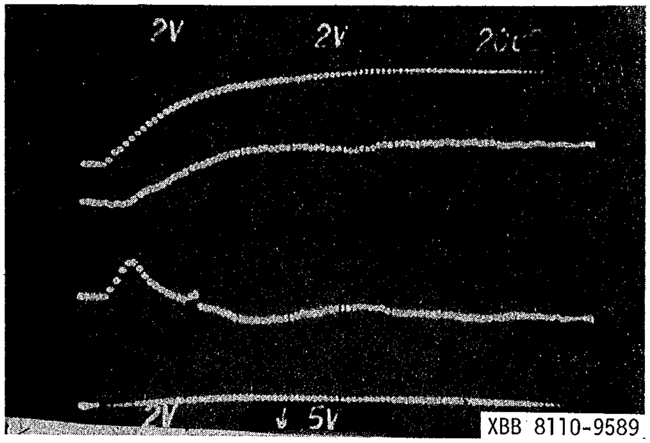

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Figure 7 Beam "turn-on" transient at V_{accel} = 90 kV with stabilizing RC snubber on the output.

Trace No. 1 = V_{accel}
Trace No. 2 = I_{probe} ($\approx I_{beam}$)
Trace No. 3 = $I_{gradient\ grid}$ (grid 2)
Trace No. 4 = $I_{suppressor}$ (grid 3),
(+) ≡ ion collection;
(-) ≡ electron collection

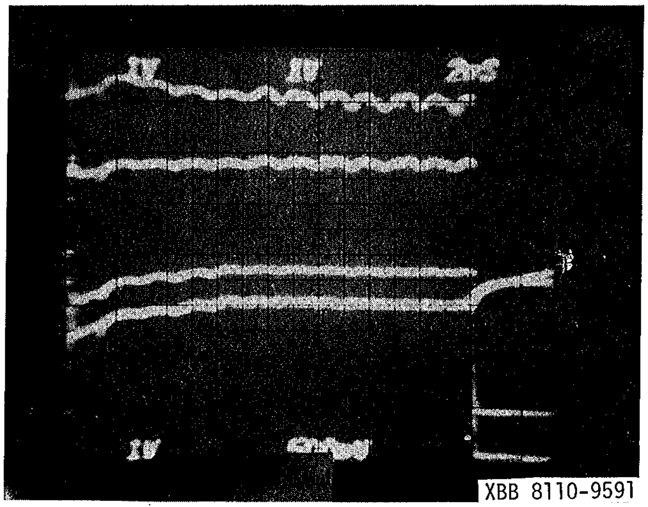

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Figure 8 First 7 ms: a time-varying error causes the beam current to increase; this loads down the accel voltage (top trace). The current regulator (Traces 3 and 4) saturates at 7 ms. Then unregulated operation is observed.

1. The calculated Z_{acc} phase lag at 40 kHz was reduced by 45° (Figure 6).

2. The calculated magnitude was reduced (~1.5X).

The resulting beam "turn-ons" were smoother (Figure 7) than those obtained during any prior standard operation.

The output drifted on a much slower time scale (Figures 8, 9), indicating that more feedback gain ($G_{accuracy} > 0$) was desirable. With the attempt to increase the feedback gain, oscillations were again observed around 40 kHz. In order to restabilize, the increased feedback gain had to be rolled off with a time constant (τ_{error}) of ~30-60 μsec. ($G_{accuracy}$ and τ_{error} have not yet been optimized.)

FUTURE PLANS

The 30 sec upgrade of the NBSTF[5] will attempt beam current regulation where the transient response is controlled in a manner similar to that above, but the slow time-scale regulation will take place in the arc power supply primary circuit.

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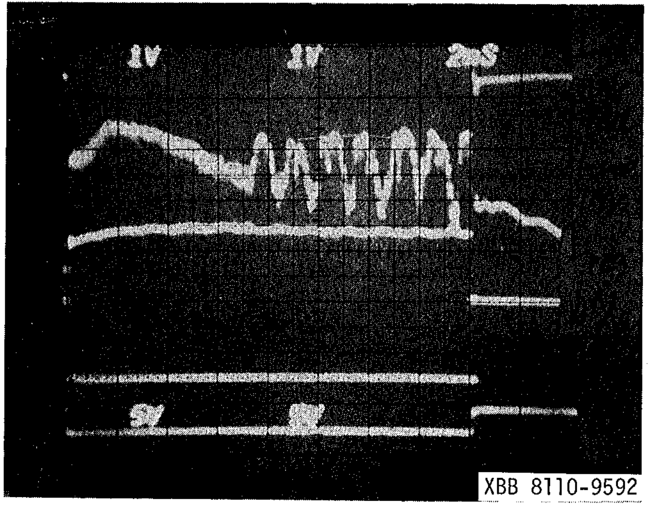

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Figure 9 The drift in the beam current (seen in Figure 8) increases the back-streaming electron bombardment of the second grid (I_{gg}, Trace 1). Unregulated operation (after 7ms) is observed.

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