Management of High Current Transients in the CWDD Injector 200 kV Power System*

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Abstract

The injector for the Continuous Wave Deuterium Demonstrator is designed to deliver a high current CW negative deuterium ion beam at an energy of 200 keV to a Radio Frequency Quadrupole [1]. The injector comprises a volume ion source, triode accelerator, high-power electron traps and low-energy beam transport with a single focusing solenoid. Some 75 Joules of energy are stored in stray capacitance around the high voltage system and discharged in a few microseconds following an injector breakdown. In order to limit damage to the accelerator grids, a magnetic snubber is incorporated to absorb most of the energy. Nevertheless, large current transients flow around the system as a result of an injector breakdown; these have frequently damaged power components and caused spurious behavior in many of the supporting systems. The analytical and practical approaches taken to minimize the effects of these transients are described. Injector breakdowns were simulated using an air spark gap and measurements made using standard EMC test techniques. The power circuit was modeled using an electrical simulation code; good agreement was reached between the model and measured results.

I. INTRODUCTION

High current ion injector systems have frequently suffered from reliability problems associated with grid conditioning of the dc accelerator. As requirements head towards higher ion currents, higher duty factors, and increased energies, the reliability problems have become more evident and seemingly more difficult to overcome.

During initial testing of the injector system at Culham Laboratory, reliability problems occurred when operating above 150 kV, with both power and control circuits being frequently damaged. A program was initiated to solve these problems after the system was installed at Argonne National Laboratory. The nature of these problems are now better understood, and hardware modifications have been implemented to improve reliability. The system is now operating routinely at and above the design energy of 200 keV. In this paper, the High Voltage Power Supply (HVPS) is used to illustrate techniques and solutions that were implemented. These same techniques and solutions were also used on other subsystems of the injector.

II. TEST METHODOLOGY

When a breakdown occurs, energy stored in stray capacitance of the high voltage circuit is discharged, exciting resonances in the low megahertz range. The result is a radio frequency transient of several hundreds of amperes flowing around the power circuit, generating huge RF voltages across stray inductances and coupling into all parts of the system. The currents are so large that even very weakly coupled circuits can be catastrophically affected.

Bulk-Current Measurement and *Bulk-Current Injection* are used in Electromagnetic Compatibility (EMC) testing to measure conducted emissions and conducted susceptibility of equipment [2]. It has been established in previous tests at Culham and in similar tests at JET [3] that conducted interference was by far the most significant problem on this equipment, even though radiated levels in excess of 140 dBμV have been measured. *Bulk-Current* techniques were used to measure RF currents flowing in power and control circuits during actual breakdowns and simulated breakdowns at low voltage to allow measurements within the high voltage equipment, and quantify the level of susceptibility of various equipment. In order to provide a consistent test scenario, an air sparkgap was used to simulate injector breakdowns.

Figure 1 shows the main components of the injector high voltage power circuit. Transient currents are shown for a sparkgap setting of 56 kV; peak breakdown currents are in amperes. The current transient is principally a damped sinusoid at 1 MHz lasting approximately 6 μs, produced as stray capacitance in the high voltage isolation transformer and the high voltage feedthrough are discharged through the busbar system.

Surprisingly large currents were measured in the high voltage power supply switched-mode electronics (HV Controller). These can be explained when it is realized that considerable voltages are generated along the machine *ground* busbar. The busbar between the machine *star-point* and the HVPS 0v connection had an inductance of 15 μH. At 1 MHz, the impedance of this connection was 94 Ω and could, therefore, be expected to develop approximately 20 kV across it. This voltage then appeared as a differential across the HVPS isolation transformer, which coupled the transient by way of stray capacitance and an imperfect primary screen.

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Significant transients (up to one ampere) were measured on control cables between the injector and the control room, even though they are DC isolated. However, for RF, these cables are in parallel with the busbar connecting the machine star-point to building ground and, therefore, carry a portion of the feedthrough discharge currents.

III. CIRCUIT ANALYSIS

A simplified equivalent circuit of the injector high voltage power system is shown in Figure 2. Most of the capacitance values were obtained by measurement, whereas the inductance values were calculated.

An analog circuit analysis program for personal computers, Micro-Cap IV [4], was used to generate current and voltage waveforms for various nodes of the circuit. For comparison, generated waveforms are shown in Figure 2 at the same locations as the measured waveforms in Figure 1. Both the measured and calculated waveforms decayed exponentially, reaching equilibrium in 6-10 μs. Overall, the analysis agreed well with reality, although peak values of the calculated waveforms were generally higher than those of the measured waveform. One possible reason is that small resistive components were not included in the model, except around the HV controller.

A major component of the HV circuit is the magnetic snubber. This device is designed to absorb much of the available energy generated during an arc discharge. The energy is dissipated by means of eddy current losses in a transformer core. The CWDD snubber is similar to the snubber developed by Lawrence Berkeley Laboratory [5]. In the analysis, the snubber has been represented by a resistor in parallel with an inductance.

The Berkeley paper assumes a nonoscillatory current suggesting that the value of inductance, L, is so large that it can be neglected, and that the resistance is a function of time. For large values of L, breakdown transients should decay exponentially, similar to overdamped or critically damped circuits. However, observed transients on the CWDD injector are oscillatory, similar to that of an underdamped circuit. Attempts to measure the snubber inductance produced values in the 10 to 40 μH range. Using the lower value of L in the circuit analysis resulted in calculated waveforms more closely resembling measured waveforms than when using higher values.

IV. SOLUTIONS

It became clear that the grounding system must be modified to minimize impedances and, hence, voltage drops. To reduce currents in the HV controller, the HVPS elements must all be connected to the same ground point. Breakdown current paths must be localized as much as possible, to reduce coupling to other circuits.

An existing aluminum skin covering the walls and floor of the high voltage areas offered a low impedance ground system and was close to an ideal *coaxial* arrangement. Power system ground connections were removed from the bus bar and connected to this skin. Since this skin is so wide, the limiting factor in minimizing ground impedance became the connections from the equipment to the skin. In addition to ground system modifications, each subsystem was modified to improve internal grounding for radio frequencies, and filtering was installed to shunt transient currents to ground.

Sparkgap testing was repeated at 56 kV and then at 200 kV. Unwanted currents had been reduced by at least a factor of four, and in the case of the busbar currents to ground, a factor fifty improvement had been made. Indeed, at 200 kV, the HVPS currents are now lower than previously measured at 56 kV.

Modeling of the new arrangement was made in order to predict improvements in unwanted currents. Accurate modeling was found to be more difficult since the new ground system impedance was difficult to calculate. However, the model did predict improvements comparable to those seen when sparkgap tests were performed.

V. SUMMARY

Conventional power system approaches are clearly inadequate when designing high voltage systems for today's injectors. Further considerations are necessary to successfully manage the transients resulting from dc accelerator breakdowns.

Breakdown transients have been measured on the CWDD injector and their effects are now understood. Dramatic improvements have been made in the reliability as a result of modifications, such that the high voltage systems now operate more reliably at 200 kV than previously at *any* voltage.

The system's behavior has been modeled to first order using relatively simple circuits. These proved helpful in understanding failures caused by breakdowns. Proposed modifications were tested on the model before implementation on the real system. Overall improvements predicted by the model compared favorably with those obtained in practice.

The effect of the magnetic snubber on a *resonant* circuit needs further work. At 1 MHz, the CWDD snubber is clearly less effective than expected--far less energy is dissipated, and peak currents appear to be limited as much by stray inductance as by the snubber itself.

Experience on CWDD has shown that with proper management of transients, a high level of reliability can be achieved on high voltage, high power injector systems.

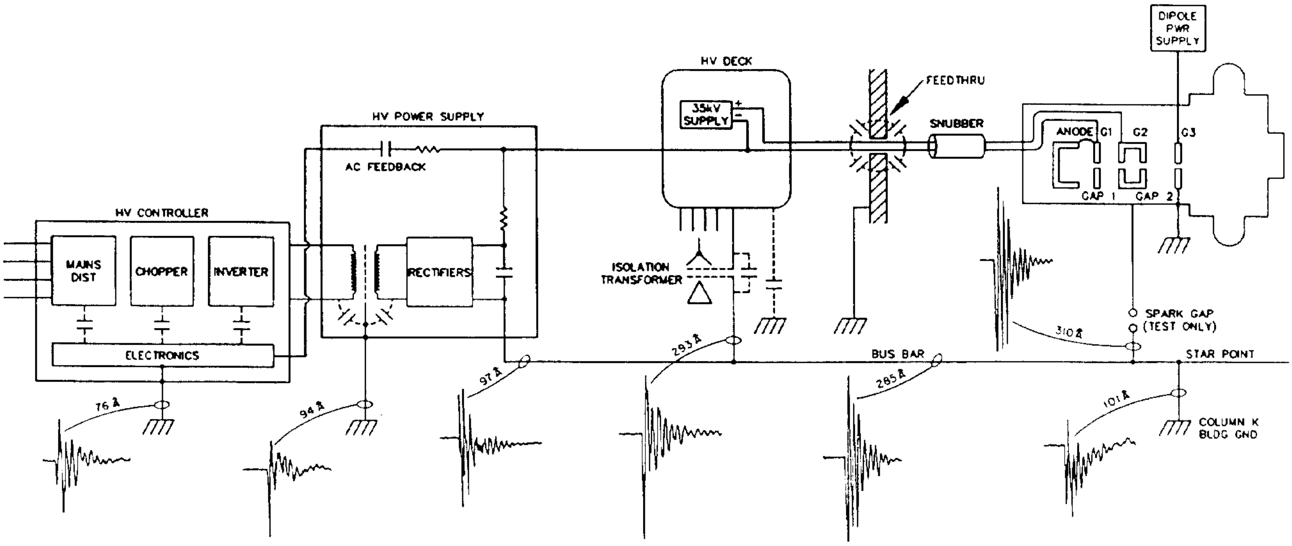

Figure 1. Injector High Voltage Power Circuit

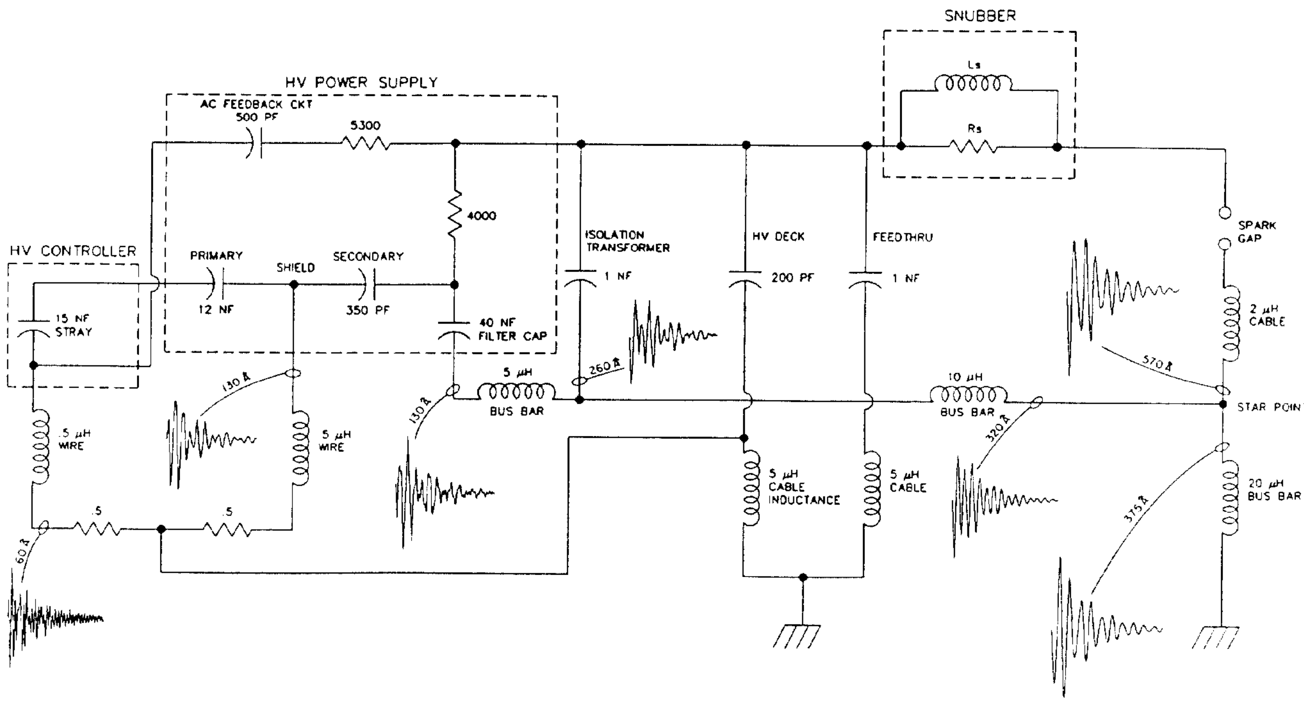

Figure 2. Equivalent Circuit of Injector High Voltage Power Circuit

VI. ACKNOWLEDGMENTS

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