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## DISCLAIMER

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# Development for Extending the Beam Pulse Length of the DIII-D Neutral Beam System

R.-M. Hong, H.K. Chiu and J.T. Scoville
General Atomics
P.O. Box 85608
San Diego, California 92186-5608 USA
hong@fusion.gat.com

***Abstract*—The DIII-D fusion research tokamak utilizes seven neutral beam ion sources for plasma heating and current drive. These ion sources and the neutral beam system have performed with high availability and reliability since 1987. Experimental research has accomplished extensive understanding and insights of plasma physics, and requires more beam system capability to provide flexibility and enhancing scope of physics experiments. Extending the beam pulse length without lowering the beam power is one of the goals for the next 5 years. Currently, deuterium beam pulse length of ion source operated at 80 keV is limited to 3 s due to heat handling capability of some beamline internal components, which are used to collimate beam or to protect other beamline components from being damaged by residual (unneutralized) energetic ions. A systematic study based on actual heating of beamline internal components has been performed to develop a plan for extending the beam pulse length to more than twice the current operating limit. This study using temperature rise of thermocouples embedded in the beamline internal components and data extrapolation obtained the beam pulse limitation for each beamline internal component identified that the pole shield of the residual ion bending magnet is the component that limits the beam pulse length to 3 s for 80 keV beam operation. Beam pulse length at 80 keV can be doubled with the upgrade of the magnet pole shield alone. Temperature rise measurements also showed that a drift duct (the section connecting beamline and tokamak vessel) made of stainless steel will be able to handle the heat from the re-ionized neutral particles. In addition to beamline internal components, long pulse beam operation of ion sources and other beam subsystems need to be operationally confirmed. Tests have shown ion source, control system, pumping and cooling systems, and power supply system operated flawlessly at beam energy of 60 keV for 10 s. It gave us confidence that the current DIII-D neutral beam system could operate at least twice the current beam pulse length after upgrade of the magnet pole shield.**

***Keywords: neutral beam, ion source, long pulse, DIII-D***

## I. INTRODUCTION

The DIII-D neutral beamlines (Fig. 1) were designed for 80 keV, 5 s hydrogen beam operation. Ion sources have been routinely operated with deuterium beams since 1989 following the installation of DIII-D radiation shielding roof. In the same year, deuterium beam power was increased from 2 MW per ion source with 80 keV beam energy to 2.5 MW and beam pulse length was reduced to less than 5 s due to the concern of overheating some of the beamline internal components. An additional 10% reduction in beam pulse length was implemented in 2003 after several magnet pole shields were damaged. Currently, beam pulse length is limited to 3 s for 80 keV deuterium beam operation. To achieve the goal of doubling the beam pulse length, we need to prove that ion source and subsystems can run at least 6 s or longer and to develop a plan for upgrading beamline internal components to handle additional heat from longer pulse operation. We have operationally proved that stable arc discharges can be obtained at a power level appropriate for 80 keV beam operation with all subsystems performing flawlessly, including power supplies, gas puff system, water cooling system, and cryogenic system. To determine the beam pulse limitation of beamline internal components one ion source was operated at various beam energies (60, 65, 70 and 75 keV) and pulse lengths (up to 10 s depending on beam energy), and data from thermocouples embedded in these components were collected. Analyses of thermocouple data showed that upgrading the magnet pole shield alone would allow the beam system to operate for 6 s of 80 keV deuterium beams. The magnet exit collimator (and possibly the louvers) would also need to be upgraded for longer than 6 s beam operation. In the process of taking thermocouple data, the ion source was operated to 10 s beam of 60 keV, with all subsystems performing flawlessly. This was the first time that DIII-D ion source produced 10 s beam at any beam energy. Drift duct thermocouple data were obtained when beams were injected into plasmas of several physics experiments to include

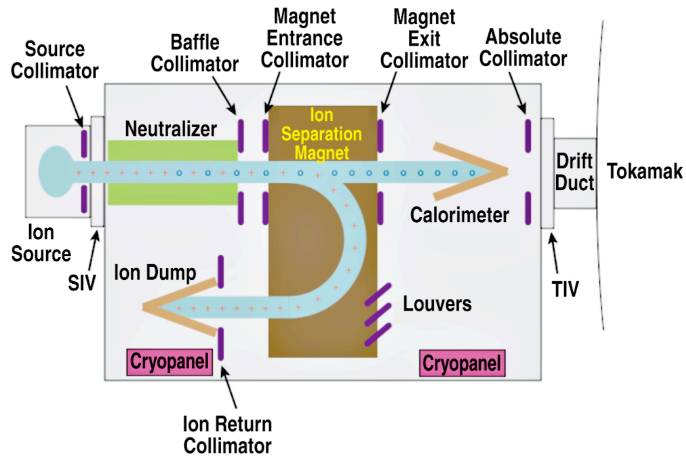


Figure 1. Beamline internal components and paths of neutrals and residual ions.

effects of various tokamak operation parameters (producing different stray magnetic fields that steer re-ionized particles to the drift duct walls) on the re-ionized neutral particles. It shows that drift duct can handle long pulse beam operation.

## II. 10 SECOND BEAM OPERATION

The first step in developing a DIII-D long pulse neutral beam system is to prove that the existing system can operate at lower beam energy with long beam pulse. It removes the beamline internal components overheating concern while checking out all other beam subsystems for long pulse operation capability. The timing sequence of ion source beam operation requires turn-on of filament and arc power supplies and puffing gas into ion source before beam extraction, thus their pulse lengths are longer than the beam pulse length. One ion source was operated at 60 keV deuterium beam for 10 s. It ran extremely well without any beam blocks during the entire 10 s beam pulse. Fig. 2 shows the filament, arc and gas waveforms of this 10 s shot. Fig. 3 shows the beam current waveforms. Near constant beam current throughout the whole beam pulse was achieved by regulating the arc discharge level (ion density) inside the arc chamber of the ion source. Current oscillations are the result of arc current and voltage oscillations (360 Hz from arc power supply), which varies the ion density, and spikes on the suppressor and gradient grid currents are either due to perveance mismatch at initial beam formation or a small change in beam current. Note that gradient grid current is very sensitive to the amplitude and change of beam current. Continuous high gradient grid current (> 300 mA) may cause damage to the grid rails over the long term; however, very short spikes will not do any harm to the grid rails. We also observed that cryogenic panels inside the beamline pumped the residual gas from the ion source extremely well and returned the beamline vacuum to its pre-arc discharge state within a minute.

## III. TEMPERATURE RISE OF BEAMLINE INTERNAL COMPONENTS AS FUNCTION OF BEAM PULSE LENGTH

To experimentally determine beam pulse length limitation of beamline internal components, we measured the peak temperature rise of thermocouples embedded on these components while operating the ion source at various beam energies and pulse lengths.

DIII-D neutral beamline components and paths of neutral beam and residual ions are shown in Fig. 1. Fig. 4 shows the peak thermocouple temperature rise of three beamline internal components with highest temperature rises. We concluded that magnet pole shield has the highest bulk temperature rise and is the first beamline component that requires upgrade for long pulse beam operation. Thermal study of ion power deposited on the magnet pole shield after structural failure of several pole shield plates concluded that in order to avoid the start of surface melting the pole shield temperature rise should not exceed 275°C (for baseline temperature of 25°C). This limits the 70 keV deuterium beam pulse to 5.6 s. The magnet exit collimator has the second highest temperature rise and is able to handle the heat of 70 keV, 9.1 s deuterium beam pulse with

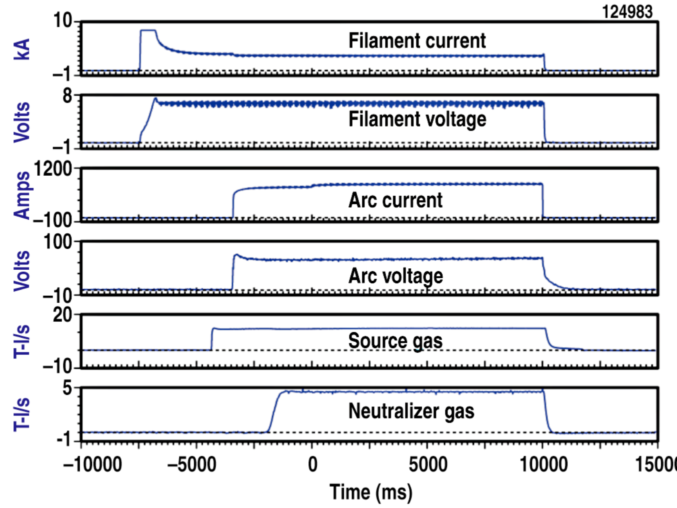


Figure 2. Arc, filament, and gas waveforms of a 60 keV, 10 s deuterium beam shot.

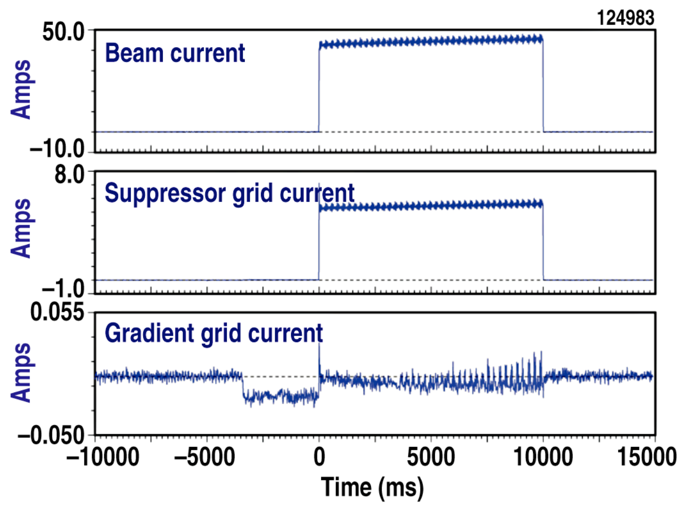


Figure 3. Beam current waveforms of a 60 keV, 10 s deuterium beam shot.

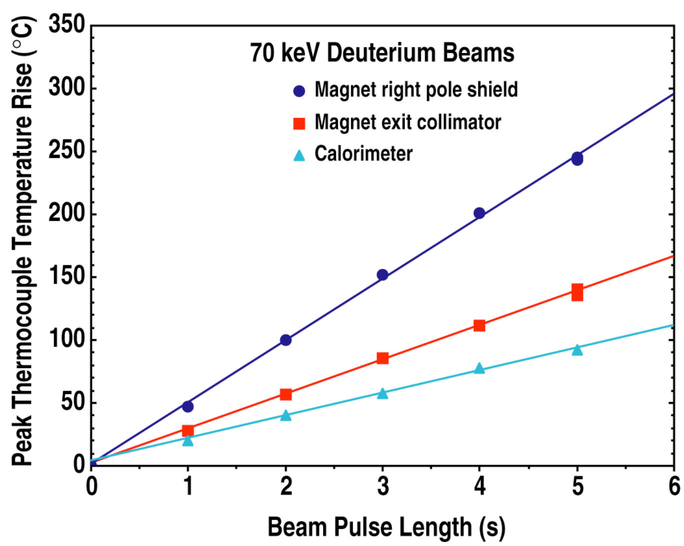


Figure 4. Peak thermocouple temperature rise of three beamline internal components as a function of beam pulse length.

the bulk temperature rise limit of 250°C to prevent surface melting. Then, this becomes the beam pulse-limiting factor if magnet pole shield is upgraded to long pulse operation. Using this same analysis and thermocouple data for four different beam energies (60, 65, 70, and 75 keV) operation with various beam pulse lengths, we obtained beam pulse limitations as determined by these two beamline internal components. Fig. 5 shows the results and the comparison with the existing beam pulse limitation for DIII-D neutral beam system operation. It shows that beam pulse length limits match well between the existing limitation and that based on the magnet pole shield temperature rise at higher beam energy (>70 keV) and that the existing limitation becomes too conservative at lower beam energy. The existing limitation used total beam energy (IVt) of 80 keV, 68 A, 3 s beam as the reference to obtain pulse length limitation for beams at other energies. Neutralization efficiency of energetic ions was not considered in the calculations and since lower energy ions have higher neutralization efficiency, which in turn have fewer non-neutralized ions depositing power on the pole shield, the existing limitation for low energy beam is too conservative. We also observed that at lower beam energy, the magnet exit collimator temperature rises faster than the magnet pole shield and is the component that determines the beam pulse length limitation. However, the most important result from this measurement is that beam pulse length can be doubled from the existing operation limitation if the magnet pole shield is upgraded to long pulse operation (>6 s, 80 keV beam pulse). This can be a very economical way of extending the capability of the DIII-D neutral beam system in supporting plasma physics and fusion science research.

## IV. HEATING AND COOLING OF ION SOURCE FOR LONG PULSE BEAM OPERATION

DIII-D neutral beam ion sources were designed (by Lawrence Berkeley Lab for MFTF) for 80 keV, 30 s beam operation with the ion source being actively cooled. Water cooling system for DIII-D ion sources meets the cooling requirements with high quality water to prevent corrosion of ion source components. Temperature rise of the cooling water was measured during beam operation to monitor heating of ion source (arc chamber and accelerator grids). Fig. 6 shows the cooling water temperature of arc chamber and accelerator grids as function of time for 60 keV, 10 s beam operation. Cooling of arc the chamber is not really active as temperature continues to rise during the beam pulse; however, its amplitude is small enough that over heating is not anticipated even it needs to operate at a higher arc discharge for long pulse 80 keV beam operation. Cooling water temperature rises of all the accelerator grids (4 grids, each grid has 4 modules, 2 modules in 1 cooling channel, a total of 8 cooling channels) approached a plateau value, indicating the effect of active cooling and temperature rises are also very small — well within design limits. Power deposited on ion source, arc chamber and accelerator grids, was measured by water flow calorimetry. Results for the 60 keV, 10 s operation show that power deposited on each grid rail (14 grid rails per grid module, each accelerator grid has 4 grid modules) is less than 100 W, which is one-tenth of the design value. Ratioing the beam power to predict deposited power for 80 keV beam operation, we obtain 205 W on one grid rail. The highest measured power deposited on one grid rail for 80 keV, 3 s beam operation is 250 W, which is still well below the design limit of 1000 W and in reasonable agreement with the value scaled from 60 keV.

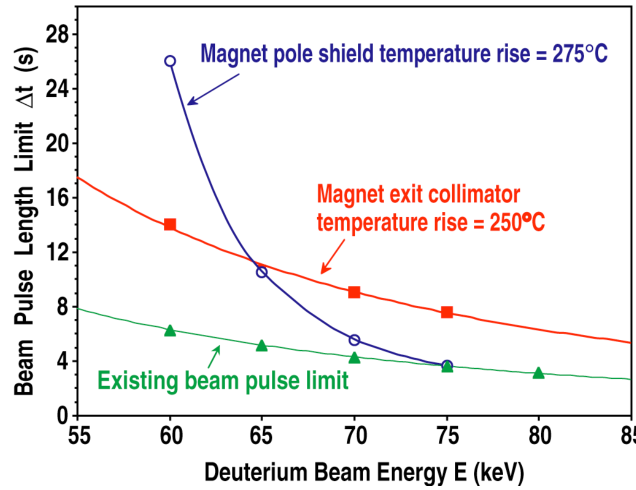


Figure 5. Beam pulse limitations based on temperature rises of magnet pole shield and magnet exit collimator, and the existing limitation in beam system operation.

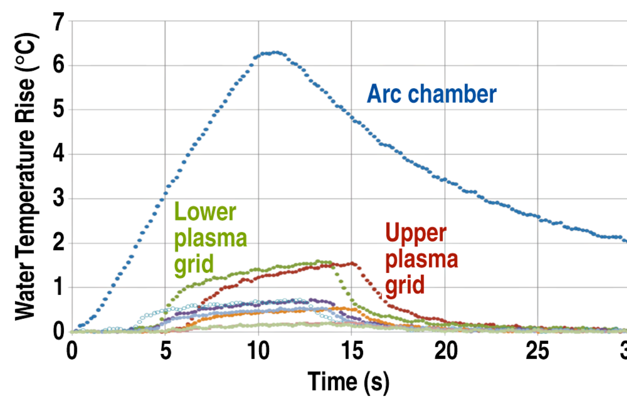


Figure 6. Water temperature rises of ion source cooling channels for 60 keV, 10 s beam pulse.

## V. HEATING AND COOLING OF BEAMLINE INTERNAL COMPONENTS FOR LONG PULSE BEAM OPERATION

The water cooling system for beamline internal components is designed to cool down components between beam shots, e.g. 10 minutes between 80 keV, 3 s beam shots. The temperature rise of the cooling water was measured during beam operation to monitor heating of beamline internal components and to measure heat deposited on these components by water flow calorimetry method. Fig. 7 shows the cooling water temperature of beamline internal components as a function of beam pulse length for 80 keV operation. It shows that if we extrapolate to 6 s beam operation, only two channels (calorimeter and magnet pole shield and louvers) will have a temperature rise above 35°C, but below 40°C. There should be no water over temperature concern during beam pulse. A 10 minute cooling down time between beam shots would be sufficient to return the component temperature to pre-beam shot value.

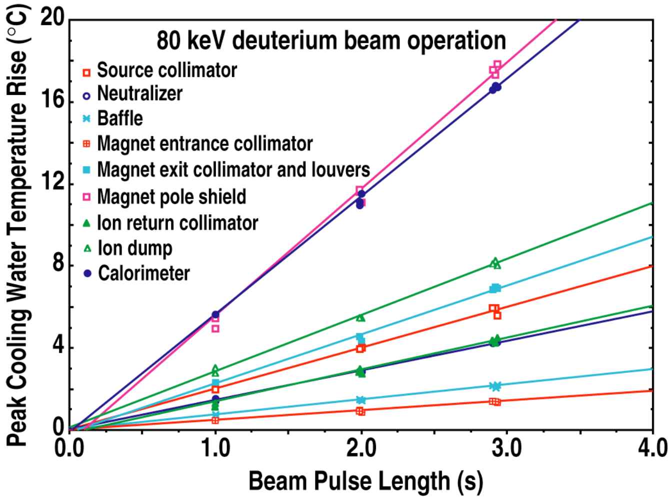


Figure 7. Peak cooling water temperature rise as a function of beam pulse length for beamline internal components.

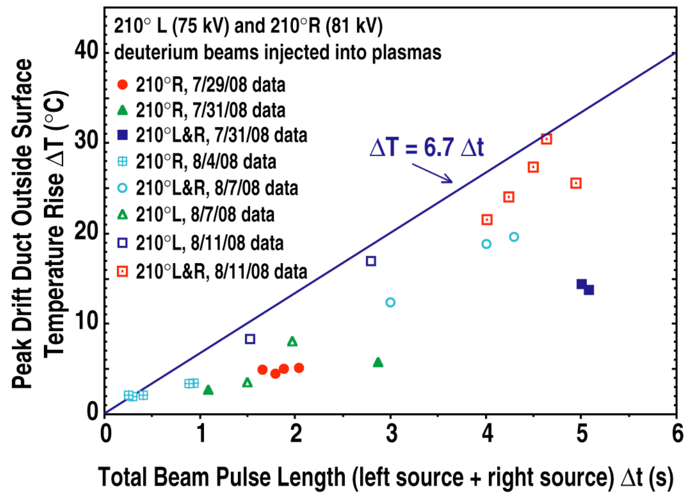


Figure 8. Drift duct thermocouple peak temperature rise as function of pulse length of injected beams.

## VI. HEATING OF DRIFT DUCT DURING BEAM INJECTION INTO TOKAMAK PLASMAS

The drift duct is the conduit that connects the beamline with the tokamak vessel. Its walls are heated by the re-ionized neutrals which that are bent to the drift duct walls by the stray magnetic fields from the tokamak coils and plasma current. Since the stray magnetic field varies with tokamak plasma operating parameters, heat deposited on the drift duct walls varies too. Fig. 8 shows the peak thermocouple temperature rise as a function of total beam pulse length of many beam plasma injection shots on different days of plasma experiments. It is observed that peak temperature rise of the drift duct outside walls are on or bellow a linear line of $\Delta T \approx 6.7\ \Delta t$. We can conclude that drift duct outside wall temperature rise will reach about 67°C for 10 s beam pulse and will be 134°C if both ion sources of the same beamline inject 10 s beams into a plasma. Engineering study assuming 3/8-in. thick stainless steel drift duct with no cooling and a heat load of 0.25 MW/m$^2$ for 20 s pulse calculated a temperature rise of 135°C at the outside surface of the drift duct. The maximum surface temperature of the inside of the drift duct will occur at the end of the pulse and be approximately 209°C. This study shows that the existing drift duct made of 3/8-in. thick stainless steel will be capable of handling 20 s beam pulses.

## VII. CONCLUSIONS AND SUMMARY

It has been confirmed that the pulse length of existing DIII-D neutral beam is limited to 3 s for 80 keV deuterium beam due to heat handling capability of the magnet pole shields. Beam pulse length can be extended to 6 s when the magnet pole shield is upgraded. To operate 80 keV, 10 s deuterium beams, the magnet exit collimator needs to be upgraded in addition to the magnet pole shield. All beam sub-systems such as gas, vacuum, cryogenic, water, and power supply systems are sufficient to support 6 s beam operation. Cooling of the calorimeter is not a concern, since no long pulse beams will be fired into the calorimeter during ion source conditioning and beam calibration, and the calorimeter will be moved away from the beam path when beams are injected into tokamak plasmas. A recent study has also shown that high voltage power supply system can reliably support 10 s beam operation at 80 keV.

## ACKNOWLEDGMENT

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