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ABSTRACT

Since 1987, the DIII-D tokamak has utilized up to eight neutral beam ion sources on four beamlines for plasma heating and current drive. Extending the beam system capability will provide additional experimental flexibility and enable the experimental program to achieve new understanding of fusion physics. Upgrading two beamlines to provide off-axis beam injection [P.M. Anderson and R. Hong, Fusion Engin. Design **84** (2009), p. 404] capability and extending the beam pulse length without lowering the beam power are two of the goals for the next 5 years. Currently, the pulse length of deuterium beam ion sources operated at 80 keV is limited to 3 s due to the heat handling capability of some beamline internal components, especially the pole shields in the magnets used to bend the residual energetic ions back to the ion dumps. A narrower ion beam has higher probability of being bent back to the ion dump through the bending magnet without hitting the magnet pole shield, thus reducing the power deposited on the pole shields. With the reduction of deposited power on the pole shields, their lifetime can be increased and the beam pulse length may be extended beyond the current limitation without the need for active cooling of the shield. The reduced heat flux has been confirmed by a performance test of a modified ion source with a narrower ion extraction area. Operating the ion source with higher beam energy can compensate for the reduction in beam power from the smaller extraction area.

Off-axis beam injection requires tilting the entire beamline from the horizontal position, including the ion sources. Physics experiments require an adjustable beam injection angle and deposition location in the plasma with comparable injected power at each angle. To meet this requirement, we need to be able to tilt the ion source with respect to the horizontal midplane, and a more strongly focused beam is also necessary for the off-axis beam to clear the tokamak vessel port into the plasmas with optimum beam transmission efficiency. Modeling of the beam divergence has shown that we need to modify the existing DIII-D ion source to increase the focusing of the beam in order to get transmission of the full 2.5 MW beam through the smaller port needed for off-axis aiming. Performance testing of a tilted ion source was successfully completed and a more strongly focused ion source was fabricated and tested in late Spring 2010. This paper summarizes the test results and compares them with an unmodified ion source.

1. INTRODUCTION

One of the four DIII-D neutral beamlines (Fig. 1) is being upgraded to add the capability to inject off-axis beams into the plasmas. This off-axis beamline requires two ion sources that meet three requirements: operate 80 kV deuterium beams at pulse length longer (2x) than the current limit of 3 s, increased heat loads on the beamline collimators due to beams from a tilted ion source are within design values, and produce stronger focused beams to clear the vessel port of the tokamak. Two ion sources were modified to prove that these three requirements can be satisfied. One ion source was modified by reducing the ion extraction area from 12 x 48 cm to 10 x 48 cm, and tested to verify that less beam power would be deposited on the magnet pole shields, thereby permitting longer beam pulse lengths. This ion source was also tilted downward relative to the midplane at two angles to measure its effects on the beam power deposited on beamline collimators. Another source was modified not only by reducing the extraction area to 10 x 48 cm, but also by increasing the tilt angle of the accelerator grid modules inward towards the beam center to enhance beam focusing.

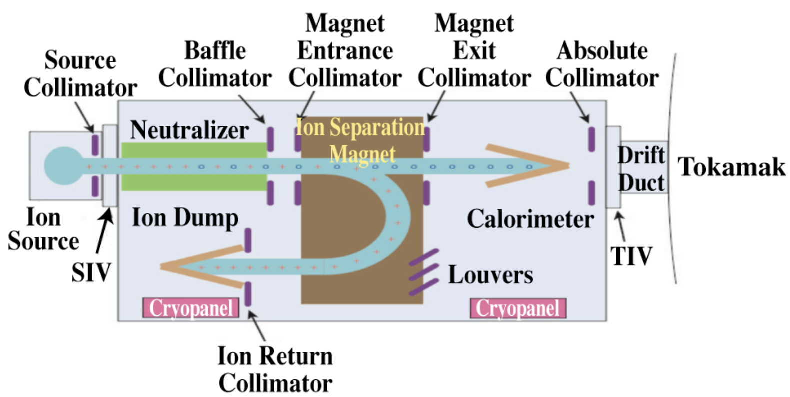

Fig. 1. A DIII-D neutral beamline.

2. LONG PULSE ION SOURCE

Fig. 2 is a cutaway of a DIII-D neutral beam ion source. A masking plate between the arc chamber and the accelerator defines the ion extraction area; 12 x 48 cm for the existing DIII-D sources. Residual energetic ions (not neutralized ions) have caused damage to the magnet pole shields (copper plates used to protect the magnet poles). The pulse length of 80 kV beams is limited to 3 s to prevent future damage to the pole shields.

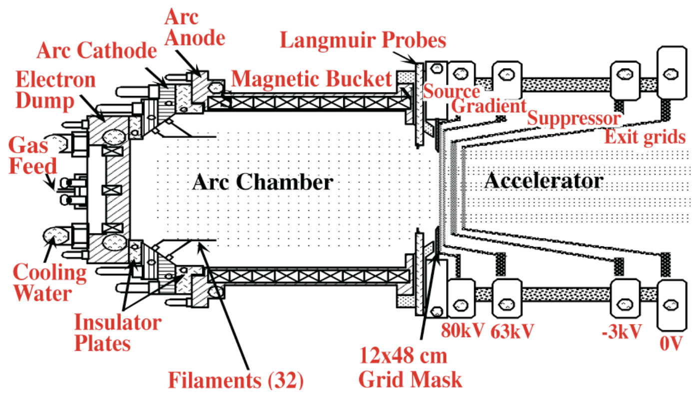

Fig. 2. Cutaway view of a DIII-D ion source.

An ion source modified to 10 x 48 cm ion extraction area (called reduced aperture source) runs as well as the unmodified ion source (called normal aperture source). With the smaller extraction area, it is expected that a reduced aperture source would extract and accelerate fewer ions from the arc chamber at same beam energy than the normal aperture source. This is shown by the total beam power curves in Fig. 3. The total beam power from the reduced aperture source is 7% less than that of normal aperture source. Operating the reduced aperture source at higher beam energy can easily make up the loss in beam power due to a 7% loss in beam current (= perveance x beam energy$^{3/2}$). The beam power of an 84 kV deuterium beam from the reduced aperture source is equal to an 80 kV beam from a normal aperture source.

Peak temperature rises of magnet pole shields as a function of beam pulse length for the normal and reduced aperture sources were measured and are shown in Fig. 4. An engineering study has set the maximum temperature rise at 275°C to protect the magnet pole shields from damage due to overheating. Using this guideline, the normal aperture source can operate 80 kV deuterium beams with beam pulse lengths a little more than 3 s. However, the reduced aperture source can operate 80 kV deuterium beams at beam pulse lengths of more than 6 s. This meets the goal of extending the beam pulse length to twice the 3 s limit for 80 kV deuterium beam operation.

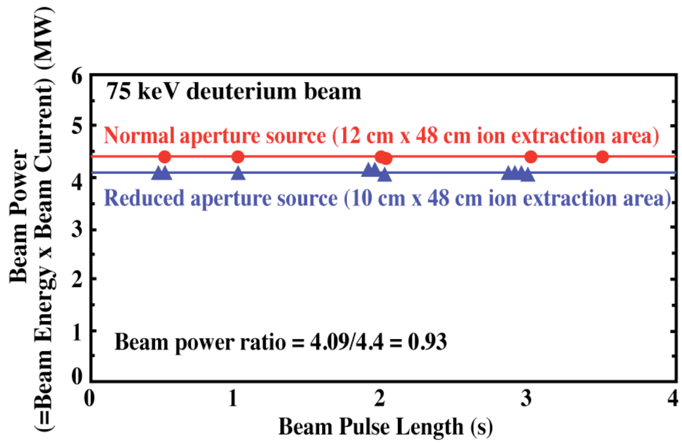

Fig. 3. Beam power comparison for the reduced aperture and normal aperture sources.

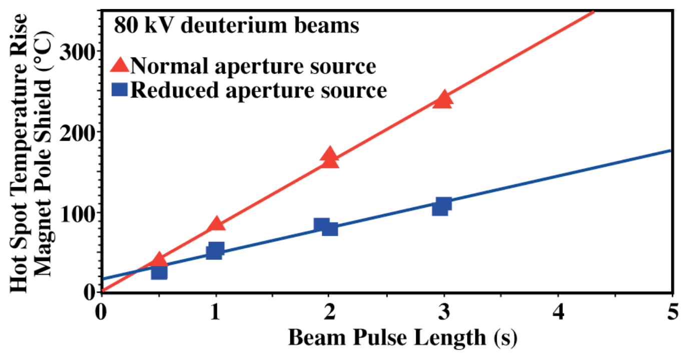

Fig. 4. Magnet pole shield peak temperature rise as function of beam pulse length.

3. EFFECT OF A TILTED ION SOURCE

The DIII-D off-axis beam system requires the ion sources to be operated between the horizontal position and a downwards tilt of 35 minutes without changing the positions of the beamline internal components. Measurements were made to confirm that the increase in beam power deposited on the lower components of the collimators due to a tilted source did not result in overheating. Fig. 5 shows the temperature rises of the collimators normalized to that of an ion source in horizontal position. The increase in temperature is less than 30% on the lower component of collimators when the source tilt angle is 35 minutes. The temperature rise of the top component of the baffle collimator drops by about 30% at a source tilt angle of 35 minutes. New collimators in the off-axis beamline were upgraded to a thickness of 3 in., twice that of existing collimators, and are capable of handling the 30% increase in deposited beam power.

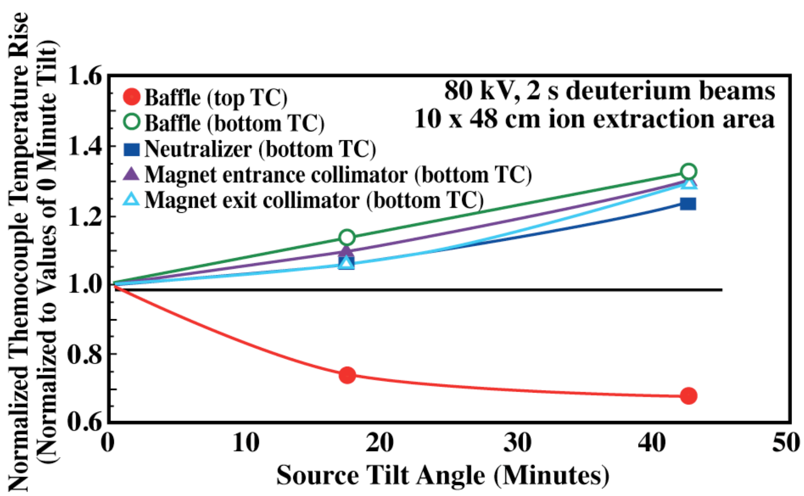

Fig. 5. Normalized temperature rises of collimators vs. source tilt angles.

4. STRONGER FOCUSED ION SOURCE

The DIII-D off-axis beamline requires stronger focused beams to safely pass through the vessel port and into the plasmas when the beamline is tilted upwards at the higher angles (up to 16.5 deg). A study of the beam layout including divergence angles of individual beamlets has shown that tilting the accelerator grid modules of the existing DIII-D ion source toward the beam center would increase the beam focusing and the beam would clear the vessel port. An ion source was modified to have a 10 x 48 cm ion extraction area and tilted accelerator grid modules. Fig. 6 shows the tilt angles of the accelerator grid modules. The accelerator has four grids, which are parallel to each other, and each grid is divided into four modules. This stronger focusing ion source (SFIS) was tested to demonstrate that it can operate well with 80 kV deuterium beams and that it produces more strongly focused beams when compared to the existing normally focused ion source (NFIS). The SFIS achieved stable operation at 80 kV deuterium beam, and the time required to achieve this was very similar to that experienced when conditioning an NFIS. Figs. 7 and 8 are arc discharge and beam current waveforms for the SFIS during a stable beam shot.

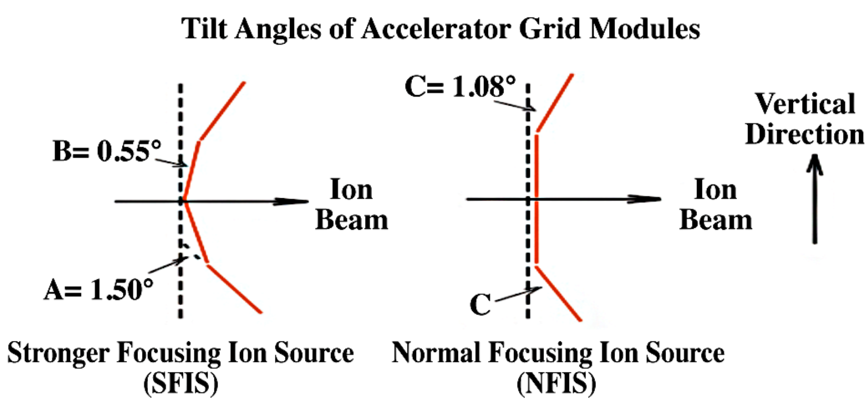

Fig. 6. Tilt angles of accelerator grid modules for SFIS and NFIS.

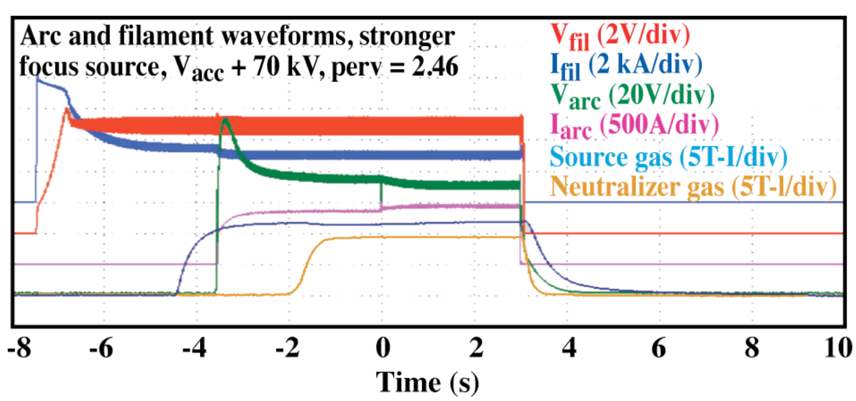

Fig. 7. Waveforms of an arc discharge.

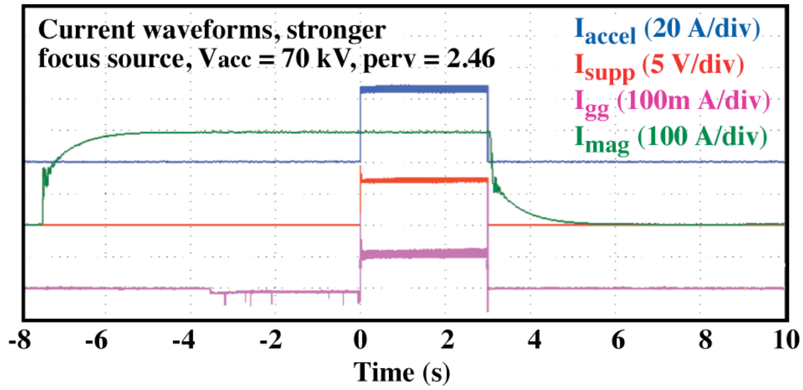

Fig. 8. Waveforms of beam currents.

The temperature rise of the thermocouples embedded in the beamline collimators and dumps and of the water cooling these internal beamline components were measured for the SFIS and the NFIS and compared to each other to determine if the SFIS had produced more strongly focused beams. From Figs. 9 and 10 it was concluded that the SFIS has more beam lost to the neutralizer and collimators and should have less beam deposited on the calorimeter, showing lower temperature rise. However, the calorimeter hot spot has higher temperature rise (see Fig. 11) for the SFIS than for the NFIS. It could be that SFIS, with the beam focused towards the beam center, has a local hot spot that is hotter than the hot spot for the NFIS, even though the SFIS has less total beam deposited on the calorimeter.

The temperature rise of the cooling water can be used to measure beam power deposited on beamline collimators and beam dumps. The peak temperature rise of cooling water is a direct comparison of beam power deposited on beamline collimators and beam dumps. From Figs. 12, 13, and 14, we conclude that the SFIS has lost more beam to the collimators and confirm that SFIS has less beam deposited on the calorimeter.

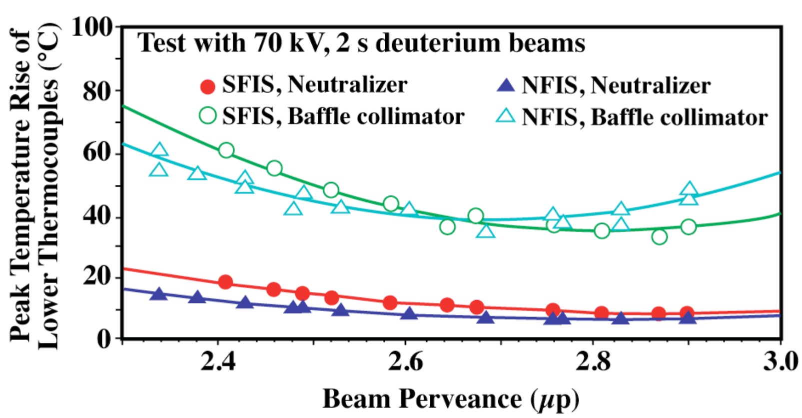

Fig. 9. Neutralizer and baffle collimator temperature rises.

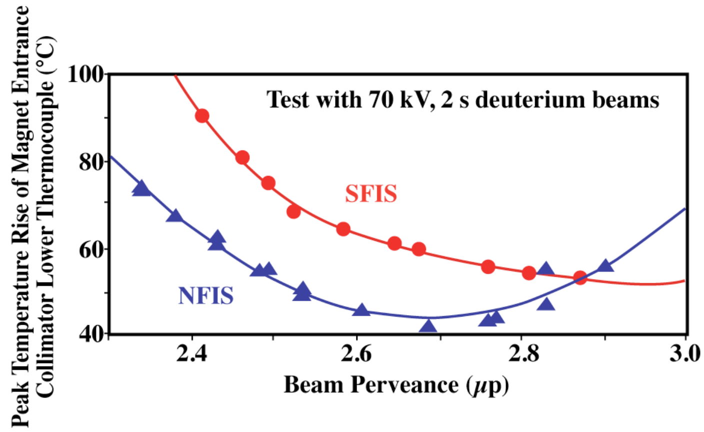

Fig. 10. Magnet entrance collimator temperature rise.

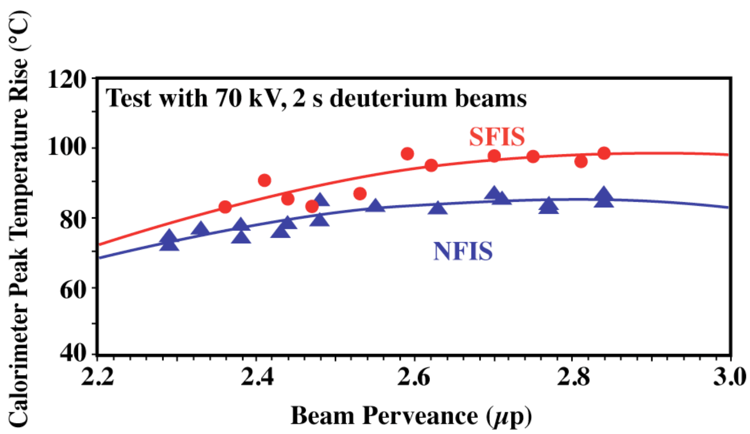

Fig. 11. Calorimeter temperature rise.

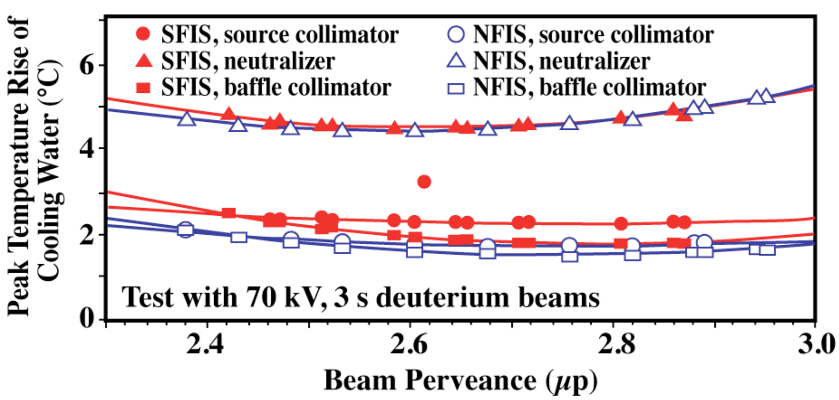

Fig. 12. Peak temperature rise of cooling water for source collimator, neutralizer, and baffle collimator.

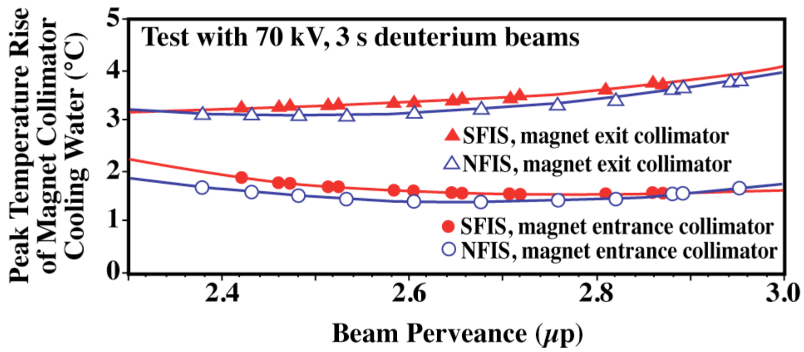

Fig. 13. Peak temperature rise of cooling water for magnet collimators.

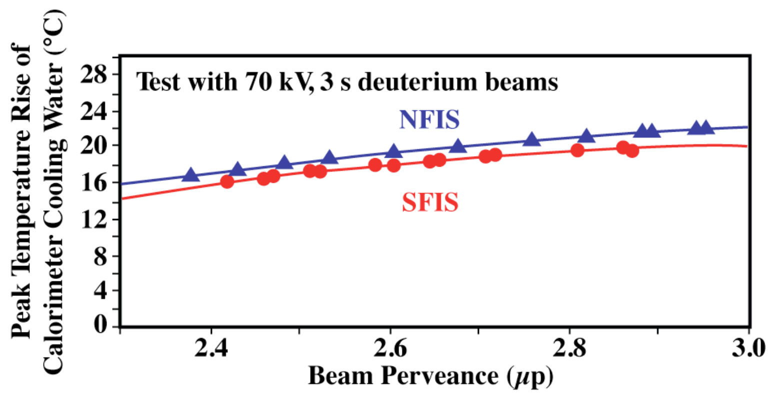

Fig. 14. Peak temperature rise of cooling water for calorimeter.

To prove that the SFIS produces a more strongly focused beam than the NFIS, a comparison was made of the beam profiles on the calorimeter using the temperature rise of thermocouples embedded in the calorimeter. Fig. 15 is the calorimeter thermocouple pattern, and highlighted thermocouples will be used to obtain beam profiles. Figs. 16 and 17 show vertical and horizontal beam profiles for SFIS and NFIS, respectively. The SFIS has stronger focusing only in the vertical direction, and that there is little difference in the horizontal FWHA (Full Width Half Amplitude) between the SFIS and the NFIS. However, the SFIS has smaller FWHA than the NFIS by 5.6 cm, which agrees very well with an estimate using the difference in the tilt angles of the outer grid modules and the distance between the ion source and the calorimeter: 2 x 358 cm x tan (1.5° – 1.08°) = 5.2 cm.

A hypothesis on the vertical profiles of beams exiting the ion source is used to explain that SFIS has more beam loss to the collimators, less beam to the calo–rimeter, but has a stronger focused beam. The SFIS profile has a larger tail (see Fig. 18), possibly the result of increasing the tilt angles of the accelerator grid modules. Beams in this tail are lost to the collimators and do not reach the calorimeter; however, the beam that reaches the calorimeter is within a tighter profile.

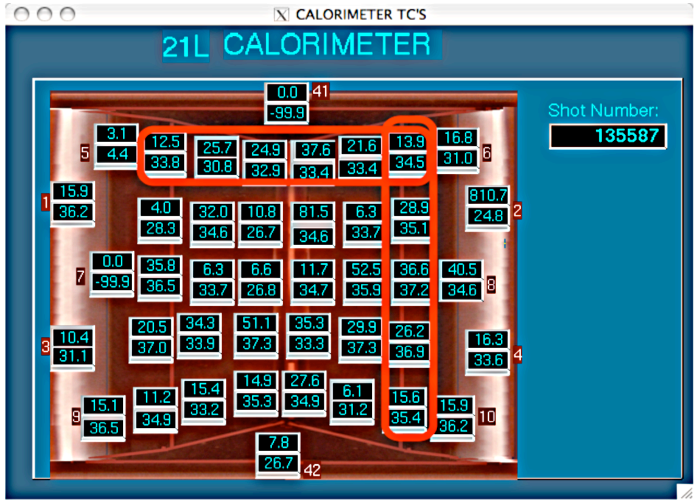

Fig. 15. Calorimeter thermocouple pattern.

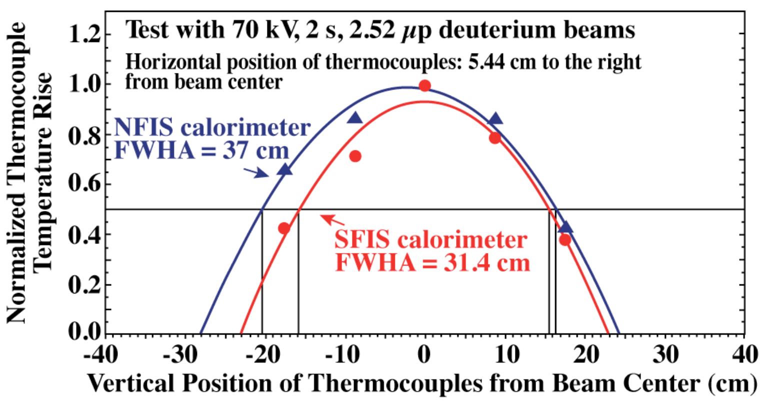

Fig. 16. Vertical beam profiles at the calorimeter.

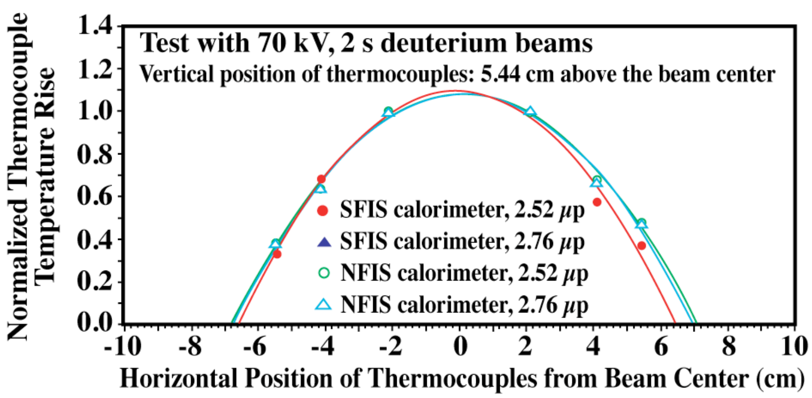

Fig. 17. Horizontal beam profiles at the calorimeter.

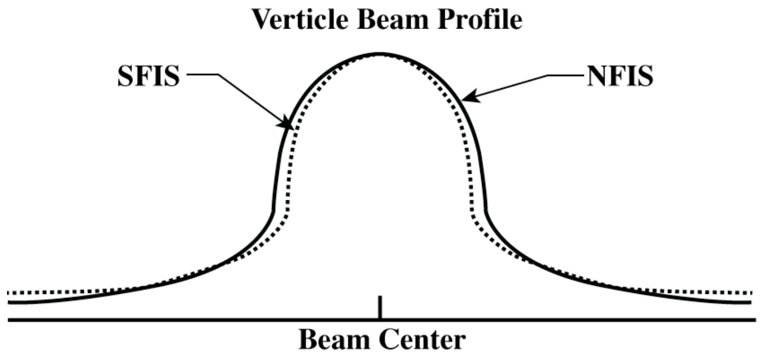

Fig. 18. Hypothetical beam vertical profiles.

5. CONCLUSIONS

An ion source with a reduced ion extraction area was built and proved fully capable of generating 80 kV, 6 s deuterium beams. New internal components in the off-axis beamline can handle the increase in the deposited beam power from a tilted ion source. An ion source with stronger focusing was built, conditioned, and tested. It has larger beam loss to the collimators with less beam to the calorimeter, and a stronger focused beam at the calorimeter.

The results of these three tests ensure that the modified ion source can be safely used on the off-axis beamline, and that the off-axis beamline can meet its physics objectives.

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