Neutral Beam Development Plans and Needs for ITER

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The efficiency of neutralization of a positive hydrogen ion by charge exchange declines rapidly as the beam velocity exceeds the Bohr velocity (the classical velocity of a hydrogen electron). The corresponding beam energy at which this rapid decline commences is about 40 keV/amu, and past about 55-60 keV/amu, the neutralization efficiency becomes prohibitively low. The neutralization efficiency of negative hydrogen ions in a neutralizer cell of optimum thickness remains acceptable at higher velocities, and is nearly independent of beam energy above 100 keV/amu.

Thus beam requirements of energies up to about 110 keV D^o or 165 keV T^o would be met with positive ion based neutral beams, while the higher beam energy requirements would be met by negative ion based neutral beams. Because the electron affinity of hydrogen is only 0.75 eV, it is much more difficult to form negative hydrogen ions than positive ions, and they are more easily destroyed by collisions at low energy in the initial stages of acceleration than are their positive counterparts. As a consequence, the usable accelerated current density obtainable from large area negative hydrogen ion beam systems is typically a factor of 15 to 20 less than would be obtainable from a positive hydrogen ion beam system. Thus, if the beam energy requirements of a fusion device are low enough that they can be met by positive ions, one almost always wants to do so. Negative ions do have the advantage that they produce neutral beams which have only a single major energy component arising from the neutralization of D^-, whereas D beams produced from positive ions have three energy components (full, half, and one-third) arising from the dissociation and neutralization of the D_2^+ and D_3^+ ions that accompany the D^+ extracted from the ion source.

The accelerator technology for such positive ion beams was demonstrated on TFTR and DIII-D in the 1980's and 1990's with the Berkeley common long pulse accelerator. The water cooled grid rails had a thermal time constant of about 0.1 seconds. Since these sources fired beam pulses of 2 seconds and more on many occasions, and even 5 seconds, they reached 20 - 50 thermal time constants without difficulties. This many thermal time constants is indistinguishable from steady state. The remaining aspects of long pulse operation in this energy range, principally involving active water cooling of all components hit by the beam, will be demonstrated by the KSTAR beam program, which is using a substantially modified version of the conceptual design of the 1000 second TPX beamline to produce a beam system capable of beam pulses of 100 seconds and more, far beyond the thermal time constants of any of the beamline or source components.

The JT-60SA development program has as its goal a 500 keV 10 MW 30 second beam. It is the successor to the JT-60U negative ion program, which encountered many difficulties due to the lack of a test stand. Because the JT-60SA program will have the experience of 13 years of negative ion operations on JT-60U to draw upon, it is expected to offer better performance, although it will still not have a test stand in order to resolve design and operational problems away from the tokamak. It will incorporate improvements to the JT-60SA design, including a better accelerator, incorporating a much more viable beamlet steering design, and improved insulators characterized by much lower outgassing than their predecessors.

The ITER negative ion neutral beam program is developing beamlines with a planned capability of 16.5 MW at 1 MeV for 1000 seconds. Since this program will have both a full size ion source test facility and a full power long pulse neutral beam test facility, and since it draws upon the experiences of the first generation of negative ion systems at JT-60U and LHD, it is expected to produce a fully acceptable megavolt beam system. Cathode filament lifetime has been a problem in the present generation of negative ion sources due to the inadequate suppression of unipolar arcs across the cathode sheaths, but this could be addressed by better fault detection. In any event, an RF-driven negative ion is being developed for ITER which will not need filaments, and will also need far fewer and less massive connections, rendering it easier to install in disconnect for maintenance.

The principal DEMO beam requirement which none of these development programs is addressing is continuous beam operation. In all of these systems, the cryopumps must be regenerated after they have accumulated about half the explosive limit of hydrogen, which, depending upon the beam isotope, ion charge state, and beamline volume, corresponds to at most a few thousand seconds of beam time. Because negative ion beam systems presently need all the available surface area for pumping, it is difficult to envision installing sufficient excess pumping to allow isolating and regenerating some pumps while others continue to pump. A lithium jet neutralizer [1] which has been proposed as an upgrade to the ITER neutral beamlines would solve this problem by eliminating 75 – 80 % of the gas input into the beamline, while simultaneously increasing the neutralization and electrical efficiency, and greatly reducing heat loads on the accelerator and ion source backplate. The remaining gas load from the source would require less pumping capacity, so that continuous operation would be possible using either sector-regenerable cryopumps or cryogenic turbopumps. While generally endorsed, the lithium vapor jet neutralizer would require a development program, which is not at present being funded. Although the EU has expressed interest in funding its development, it at present has more immediate priorities. Thus, if DEMO requires very long pulse or steady state beams, it may need to develop this neutralizer. As discussed in reference [1], other types of advanced neutralizers do not seem immediately applicable for reducing beamline gas load.

Alternatively, it might be possible to develop a laser photodetachment neutralizer for DEMO. Like a lithium vapor jet neutralizer, this would add no gas load to the beamline, and it would permit a higher neutralization efficiency than a gas neutralizer, potentially much higher. However, unlike the lithium jet neutralizer, there is no clear development path forward for a photodetachment neutralizer capable of operating and surviving in the DEMO environment.

An additional issue which historically was considered important for neutral beams was damage to high voltage insulators by neutrons. This has been solved for the ITER beam by placing these insulators above the beamline, well out of the main neutron flux. If this proves viable on ITER, then much the same strategy should be appropriate on DEMO.

[1] “Lithium jet neutralizer to improve negative ion neutral beam systems,” L. R. Grisham, Physics of Plasmas **14**, 102509-1-8 (2007).