ST-Q3b: **How does the program envision reaching solutions for the technological issues associated with the goal – especially those particular to the ST approach – NBI, magnets, etc.?**

Larry Grisham, Jim Tsai (magnet issues moved to input for Q1)

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 ST beam requirements of about 100 keV D^o or 150 keV T^o would be met with positive ion based neutral beams, while the higher beam energy requirements (up to 300 keV D^0 or 450 keV T^0) would be met by negative ion based neutral beams.

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. Most other aspects of long pulse operation in this energy range will be demonstrated by the KSTAR beam program, which is using 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.

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.

The one ST 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 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 other more immediate priorities. Thus, if the ST program 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.

The scientific principles of a lithium jet neutralizer are well established, based upon measurements done decades ago [see refs contained in ref 1]. However, producing a neutralizer which can run reliably over long periods of time with no maintenance requires an engineering development program. A quarter size engineering test model would be a logical first step, and would not require a negative ion beam to address any of the engineering issues. These issues include optimization of the lithium nozzle and the lithium recovery and recirculation system, implementing, if needed, a lithium purification system to either remove or regenerate refractory lithium compounds which form, and finding the most reliable combination of components and operating temperatures. Based upon previous metal jet work, the nozzle would probably be a carefully shaped heated slot running the full width of the incident negative ion beam, with the flow ordered by a heated central cone running along the center of the slot. The width of the slot would only be at most a few cm along the direction of negative ion beam propagation. However, it is expected that the total neutralizer unit might stretch a meter along the beam path, in order to accommodate a wide recovery basin in case of lithium jet spreading, and to have room for cooled surfaces to reduce vapor migration.

After the engineering model has established robust reliability, a full size neutralizer would need to be tested with a full power full energy negative ion beam, such as will be available at the ITER neutral beam test facility in Padua. This would permit measurement of any lithium jet spreading due to deceleration of the jet through charge exchange with plasma formed by beam impact ionization. As discussed in reference 1, this is not expected to be a large effect, but it should be checked. Once the magnitude of this effect was measured for one neutralizer configuration, it would probably not be necessary to measure it again on designs for future systems.

An additional factor that will need to be considered if relatively low energy negative ion neutral beams are used for any application is that usable (what gets through the accelerator) D^- current densities from MFE-relevant sources are much lower (a factor of 15 – 20) than usable D^+

current densities. If one is using megavolt beams, the large energy per particle makes up for the low current density. However, at energies appreciably below 500 keV, the power density becomes a concern. It is also the case that, if all other factors remain the same, the single beamlet divergence is inversely proportional to the beam velocity.   Thus, if one used negative ion beams of about a quarter of the planned ITER beam energy, there is a good chance that one would need at least 4 times the port access planned for ITER, although the exact comparison would depend on the details of the design. Alternatively, one might try to significantly increase the usable D^- current density, but this would require a basic source physics development program.

There are two possible approaches to increasing the usable negative hydrogen current density. One is to reduce the stripping of negative ions to neutrals within the extractor and accelerator, which produces a divergent low energy tail. This requires reducing the source operating pressure. This is part of the ITER development work, but if successful, will probably result in at most a 10 -20% increase in usable beam current, and would require eliminating the gas efflux from the neutralizer by replacing it with a lithium jet to achieve the full possible improvement. The other approach is to increase the negative hydrogen density extracted from the source. There is at this time no proven way to do this for MFE-relevant sources, although there is at least one speculative possibility which would require testing to evaluate.

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