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Summary II – Fusion Ion sources, Beam Formation, Acceleration and Neutralisation

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Abstract. The 11th International Symposium on the Production and Neutralization of Negative Ions and Beams was held in Santa Fe, New Mexico on 13th – 15th September 2006 and was hosted by Los Alamos National Laboratory. This summary covers the sessions of the Symposium devoted to the topics listed in the title.

Keywords: Accelerator, Ion Source, Negative Ions, Hydrogen, Computer Modeling, Magnetic Fusion, Plasma heating, Space-charge-dominated beams

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GENERAL COMMENTS

This report is the second part of an overall summary of the Symposium. Part I of the summary by D P Moehs accompanies this report in the conference proceedings. The PNNIB included contributions from the accelerator, fusion and industrial fields. The ion sources and accelerators discussed therefore spanned a wide parameter range in current, energy, pulse length and duty cycle. The requirements in terms of fundamental beam parameters such as emittance and brightness vary widely between these different applications. However, a number of important common issues exist and were brought out during the workshop. This summary is given more from the fusion applications perspective than part I which is more accelerator oriented. The author echoes the acknowledgements given in part I of the summary, and wishes to express thanks to all the participants at the Symposium, to the International Organizing Committee, and especially to LANL and the Local Organizing Committee for hosting the conference. The result was a highly successful meeting and an enjoyable stay in Santa Fe for all.

SUMMARIES

Fusion Ion Sources

There has been a long and successful history of application of high-power positive-ion based neutral beam injection for heating and current drive on magnetic fusion devices at typical beam energies of 100keV, multi-megawatt power levels and multi-second pulse duration. Large next step devices, in particular ITER, require much

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higher beam energies (1MeV D^0 for ITER) which can only be produced from negative ion sources, with long pulse lengths measured in units of hours rather than seconds. The realisation of the 1MeV ITER beam systems for ITER is the main drive for ongoing R&D in high current (multi-ampere) negative ion sources and large multi-aperture accelerators. Such ITER-oriented R&D on test facilities within Europe was reported in by D Boilson, P McNeely (this session), and by B Crowley (see Part I summary) and R S Hemsworth (session on Beam Formation, Acceleration and Neutralisation). The key design parameters for the ITER ion source is $20\text{mAcm}^{-2}\text{ D}^-$ current density over a large extraction area, to achieve 40A D^- total extracted ion current, at pressures $<0.3\text{Pa}$ to minimize stripping losses. Negative ion based neutral beam injectors have also been operated on the JT-60U tokamak (JAERI, Japan) and on the Large Helical Device (LHD) stellarator (NIFS, Japan) for several years. Operating experience on these systems has highlighted the need to improve the ion source and accelerator design in order to achieve high performance and reliability. Y Takeiri opened this session with a comprehensive account of the developments of the ion source and accelerator of the LHD negative ion neutral beam injectors.

Y Takeiri's report on the LHD neutral beam injectors showed that these systems had now exceeded their original design parameters, and could be regarded as 'mature' technology having undergone a number of developments since initial operation. The key limitations of the filamented ion source (uniformity) and accelerator (beam optics) have now been overcome very successfully. The optimisation of ion source uniformity has required two changes. Firstly, redesign of the magnetic configuration has been carried out based on electron trajectory calculations, which showed that the original filter field was connecting strongly with the cusp field and producing local trapping of primary electrons. Secondly, improvement to the control of the 12 individual arc power supplies, connected to 12 pairs of filaments, has been implemented. The original accelerator design with conventional multi-apertures (round shape) suffered from voltage hold-off degradation; this has now been greatly improved by replacing the grounded-grid with a multi-slot design with significantly increased transparency. The slotted-grounded grid improved the transmission, but introduced horizontal/vertical anisotropy in beamlet focusing. However, this has been successfully compensated for by adopting 'racetrack' shape apertures in the intermediate steering-grid electrode, and is the first use of this novel technique.

P McNeely reported on the R&D activities at IPP Garching, Germany in support of the RF driven ion source option for ITER. A key design decision needs to be taken of whether to adopt the RF source as an alternative to the present filamented arc-driven source (the current ITER reference design). This would have significant advantages of lower maintenance and simplification e.g. of the ion source power supplies and HV transmission line. Major advances in RF ion source development have been achieved at IPP through the evolution of various test stand facilities. The simplest 'physics' test stand (BATMAN) has the flexibility to apply extensive plasma and atomic physics diagnostics to improve the understanding of H^- production in the caesiated RF source. One of the key problems for long-pulse operation in the caesiated source is stability, and significant improvements have been achieved by using temperature control of the plasma grid using heated air flowing through the cooling channels. A 600s pulse has been obtained at 0.3Pa with $20\text{mAcm}^{-2}\text{ H}^-$ achieved (measured electrically) for low

voltage small-area extraction through a few apertures. The MANITU shielded test stand, presently under commissioning, is intended to demonstrate ITER parameters of required current density and pressure for 1hour with large-area extraction (200cm^{-2}) at $<100\text{kV}$ from an RF source. The RADI test stand (also under commissioning) will operate a larger ion source (half ITER-size) source, eventually with extraction though not initially.

D Boilson reported progress on long-pulse (1000s) demonstration of all the key ITER parameters for a filamented H^- ion source with beam extraction on the MANTIS facility at CEA Cadarache, France. An important objective has been to confirm the achieved current density calorimetrically at the target, due to the difficulties of interpreting current measurements resulting from the presence of co-accelerated electrons. However, in long pulses a degradation in the calorimetrically measured value has always been observed, reducing to $<15\text{mA}\text{cm}^{-2}$ compared with $>30\text{mA}\text{cm}^{-2}$ in short pulses or when inferred from electrical measurements. The new results have shown that the degradation is due thermal distortion of the grids, confirmed by observing power losses on specially designed calorimetric diagnostics in the drift duct, thus reducing the power measured at the target. Excellent power accountability is now obtained, for both negative and positive ion extraction, which confirms the values of j^- obtained. Subsequent checking of the extraction and acceleration grids showed that these had deformed plastically; an improved design grid with better cooling is now being installed.

Beam Formation, Acceleration and Neutralisation

Another crucial design choice that must be made for the ITER neutral beam injector concerns the accelerator. The reference design is a conventional Multi Aperture Multi Gap grid arrangement (denoted MAMuG) but the alternative SINGAP (SINGAP) arrangement, in which a group of pre-accelerated beamlets (or hyperbeamlet) is accelerated through a single large-aperture and gap, has many key advantages for ITER. Progress from a prototype SINGAP accelerator (1MeV, 30mA) at Cadarache was reported by R S Hemsworth. The SINGAP accelerator benefits from better lateral pumping (hence lower stripping losses) and considerably simpler engineering, especially the HV transmission line. The SINGAP test stand at Cadarache features a 1MV, 100mA power supply and a single extraction aperture in the plasma, extraction and pre-accelerator grids. A particular feature of the test stand is its grounded source, with target at +HV potential. Important progress has been made since the last PNNIB, supporting the choice of SINGAP for ITER. Current density substantially increased (170Am^2 achieved) and a key issue concerning an apparent unacceptable beam 'halo' has finally been resolved by very careful elimination of instrumental effects in the measurements. The remaining halo fraction is within the 15% upper-limit specified by ITER, and a possible explanation for this halo was put forward. It was suggested that Cs can migrate to surfaces of accelerator, and H^0 can also reach these surfaces after few bounces. H^- produced in some locations (e.g. counterbore) would be accelerated with very poor optics, as shown by simulations. Further simulations showed that modifications to the aperture geometry could largely eliminate the remaining halo. One drawback of SINGAP is that stripped electrons can be accelerated to the full

potential of the main gap. This could have posed a serious threat, but a simple conceptual solution has been identified to collect these electrons at acceptable power density, by deflecting the electrons vertically using a transverse horizontal magnetic field from permanent magnets downstream of the grounded grid. Dark current effects limit maximum voltage achievable on test since the HV power supply reaches its current limit. 750kV is presently the maximum operating voltage, but improvements including better materials, vacuum cleanliness and optimisation of electric field distribution are being implemented. It is instructive to note that although such dark current problems may be a particular problem of the specific SINGAP test stand configuration, they illustrate a basic requirement for long-pulse systems, namely that even components seeing low power density (e.g. from dark current effects) *must* be cooled. Reliance on radiation or long-path conduction will lead to very high temperatures and thermal stresses that are likely to exceed material limits.

A J T Holmes described, through the use of analytical theory, how the plasma meniscus controls the beam focusing and extracted current through its shape. His analysis took as its starting point the expression for the convergence angle at the extraction plane, which includes terms for the focusing, the effects of plasma non-uniformity, and spherical aberration. From this an expression for the squared emittance (using the Lapostolle definition) in terms of the current density and geometrical parameters was derived, which embodies a thermal term and all the aberrations and non-uniformity effects. The derived expression for the squared emittance was compared with various sets of data from a filamented bucket ion source in linear plots of squared emittance versus $(j/d)^{2/3}$ (for j = current density, d = first gap length). In these plots, the offset is a measure of the thermal term and the slope represents the aberrations and non-uniformity effects. The cases presented included H^- and He^+ extraction for various filter field strengths and marked differences in the slope and offset could all be explained by effects of non-uniformity, ion mass and the role of momentum transfer/resonant charge exchange collisions. The filter field produces two distinct deleterious effects on the optics: firstly it leads to non-uniformity, and secondly the random distribution of the velocity angle of ions in the filter field at the instant of extraction represents a stochastic “heating” effect. Momentum transfer and charge-exchange collisions act to reduce the thermal term; this was considered to be especially important for sheath-accelerated H^- in caesiated sources.

Two papers were presented on the subject of space-charge compensation of negative ion beams:

In the first paper, I Soloschenko considered the general case where the neutral density n_0 could vary from low values ($n_0 < n_{crit}$) resulting in a 2 component system with $n_e \ll n_i < n$ and Φ negative, to high values with $n_0 > n_{crit}$ resulting in a 3 component system with $n_i > n$, $n_e < n_i$ and Φ positive. This paper highlighted the problem of unstable ion oscillations for beams propagating at low pressure, due to collective effects in the plasma column. For positive space charge potential at high pressure, the experimentally observed oscillation amplitude drops in accordance with non-linear theoretical estimations. Data was presented on the suppression of oscillations in the low-pressure case by injection of electrons into the beam.

E Surrey considered the two specific cases of the ITER 1MeV D⁻ heating neutral beams (DNB) and 100keV H⁻ diagnostic neutral beams (HNB), within the drift region

extending from the accelerator into the neutraliser. The purpose of this study was to check whether over-compensation is likely to affect the beam optics, which is an important question for the beamline design, for maximising transmission of the HNB, and for achieving sufficient current density in the plasma for the DNB and consequent ITER plasma diagnostic performance. The results, based on an analytical model, showed that $n_i > n_e$ is likely to occur for both HNB and DNB i.e. over-compensation. A steady-state balance between focusing and defocusing forces is thus possible, depending on the value of the “over-compensation parameter” $\alpha = (n_i - n_e)/n_e$, as is also the possibility of oscillations although the scale-length in the axial direction of such oscillations is expected to be very long compared with the ITER beamline. In the case of over-compensation, a Bennett beam profile is expected to develop, and data was shown from the LHD neutral beam system for which a Bennett profile fitted better than a Gaussian which tends to support the predictions in this beam parameter range.

It is important to note a key difference between the models adopted in the two papers by I Soloschenko and E Surrey. In the former, the steady-state is defined by the energy deficit of electrons leaving the beam being balanced by electron heating from beam-electron Coulomb collisions. Calculations based on this assumption were presented, performed analytically and also by PiC plasma computations, showing good agreement with experimental data. In E Surrey’s model, the electron heating directly by the beam or by stripped electrons was found not to be significant; the electron power balance was found to be determined mainly by the birth energy of electrons produced by ionisation.

E Chacon-Golcher’s contribution on a MC-PIC model of a negative ion source, from surface production through to extraction, is also discussed by D Moehs in part I of the summary. This model fully integrates all processes, including a simplified surface chemistry model. The particle behaviour is fully described in the electromagnetic field using e.g. the canonical angular momentum. The physics content of the code is still being refined and the performance is still being improved, but results such as sheath parameters at the convertor are all shown to agree well with analytical theory, and emittance plots can be output from the code.

M P Stockli presented a detailed overview of the H^- injector requirements for the SNS Power Upgrade. He firstly presented the very successful results from the SNS baseline ion source and LEBT in which the milestone performance levels agreed with US DoE in 1998 were obtained in April 2006 (33mA at 60Hz achieved, which is sufficient for 1MW at target). LBNL developed the multi-cusp caesiated source to meet baseline requirements. Minor modifications of the ion source should increase current to 41mA needed for 1.4MW. The 2-lens electrostatic LEBT is predicted to suffer no losses for up to 70mA, but an R&D programme, now started, is needed to extend robustness of the second lens for high power although minor modifications should be enough for the 41mA current level. SNS upgrade demands higher current (up to 95mA) and longer pulse-length. Because emittance generally tends to increase rapidly with current, the RFQ transmission needed to obtain a more realistic emittance requirement has been calculated. Despite the impressive performance achieved with the many working H^- sources, only the JAERI source [Rev Sci Instr 73 (2002)] can achieve $0.21\pi \cdot mm \cdot mrad$ with 100% of 60mA and comes close to meeting the SNS

upgrade needs. The combination of high currents and low emittances required for future developments is likely to require use of caesium. The LEBT also has to be redesigned to handle the losses at high power. A magnetic LEBT is capable of handling the losses, but the design must allow the beam to become space-charge neutralised to avoid associated non-linear effects; BNL has a 2-solenoid design that meets these requirements. The magnetic LEBT will have an electrostatic chopper just in front of the RFQ. Finally, the LEBT will be designed to accommodate two ion sources to mitigate ion source reliability problems for high system availability.

R Keller described modelling of a high current LEBT oriented towards the needs of the SNS upgrade discussed above: 65keV, 60mA beam transmitted with $0.2\pi.\text{mm.mrad}$ rms emittance. Beam formation was modelled using the 2D PBGuns code. The beam was modelled through the LEBT structure using the Lorentz-EM 3D code. Results including emittance plots were shown for a new LEBT layout featuring electron removal at intermediate energy with electrostatic beam steering/chopping. The predicted LEBT parameters are suitable for SNS upgrade.

Finally in this session, J Dietrich presented a conceptual design for an electron removal system based on 90° deflection of the electrons using a transverse magnetic field. In order to compensate the deflection of the H⁻ beam, a first pair of Helmholtz coils was proposed to deflect the electrons, with a second identical pair to compensate for the initial ion deflection. An interesting feature is that the electrons deflected from the 60keV/100mA beam are retarded to 5keV at the collector plate. Trajectory calculations for ions and electrons were presented, computed using a new code GUN-3D consisting of a 3D Poisson solver, trajectory integrator and a space charge allocator. The code iterates to obtain self-consistent potentials and trajectories. A novel feature of the GUN-3D code is that it is implemented in Java, which overcomes all platform-dependency problems and permits an entirely open-source tool. Despite being in Java, the code is not as slow as might be expected and was stated to be about 50-60% of the speed of an equivalent compiled code using e.g. FORTRAN. One point to be noted is that in the arrangement modelled, the beam enters the system through a 3mm diameter aperture; when transformed back to the accelerator the beam would have a ~1mm diameter i.e. an enormous current density.

SOME FINAL COMMENTS FROM A FUSION PERSPECTIVE

The physics design basis for the next generation of negative ion neutral beam heating systems has developed significantly:

- very good progress on the test stands for ion sources and accelerators
- improvements in physics understanding
- better diagnostics
- reliable models
- excellent performance from LHD negative ion neutral beam heating system as a result of significant re-optimisation; useful lessons from this may be learned for large-area ion sources, especially concerning uniformity

The progress demonstrated from all these results provides reassurance that negative ion neutral beam heating can provide routine reliable performance and should be seen as a strong encouragement in the development of neutral beams for next step devices like ITER.