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FIRST TECHNICAL MEETING ON ITER NEUTRAL BEAM INJECTION

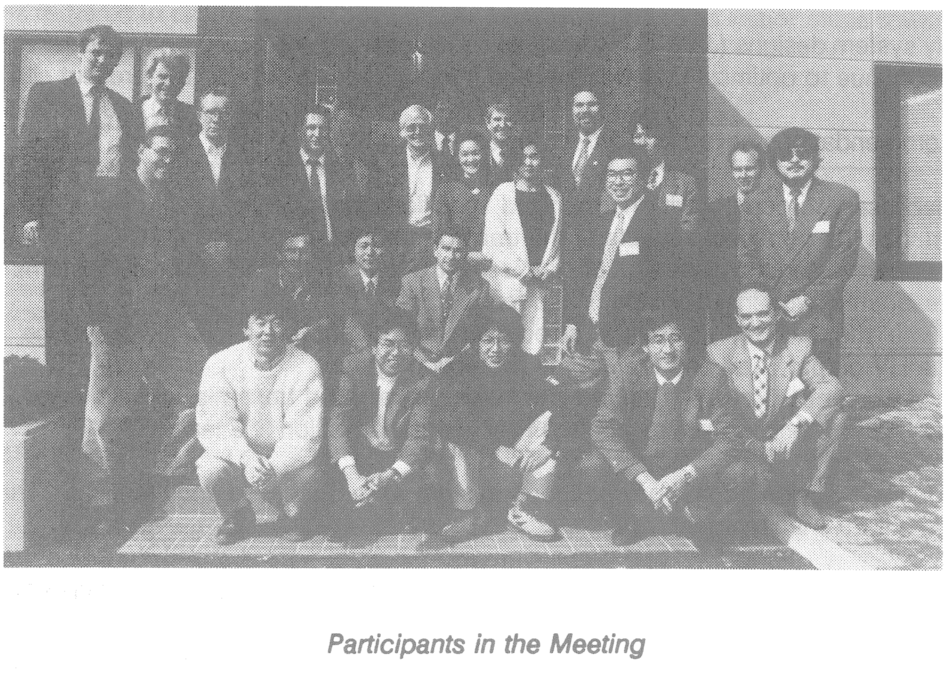
by Dr. P. L. Mondino, Head, Plasma and Field Control Division, ITER Naka JWS

The first Technical Meeting on Neutral Beam Injection (NBI) was held on 13 - 16 February 1996 in Naka, Japan, with representatives of three Home Teams (HTs) - EU, JA and RF - involved in the design and R&D of the NBI, and with JCT members attending. The US HT did not participate as it is involved in neither the design nor the R&D for NBI. The list of attendees is shown at the end of this article.

The Meeting was called to review the work done and to plan the future activities, with the following aims:

1. To assess the status of neutral beam injection development and design work for ITER.
2. To identify and prioritize future needs in both design and R&D and to suggest a co-ordinated R&D and design programme.
3. To establish areas of possible cost reductions or R&D that could lead to cost reductions.
4. To review the layout and the design integration taking into account the various interfaces identified so far.

The Meeting covered three main topics. Power supplies for the NBI system were covered on the first day. The second day was entirely given over to presentations on the design of the NBI system (HTs and JCT) and preliminary cost assessments from of the three HTs. The third day was devoted to presentations on the status of the NBI R&D programme and to discussions on the future needs, R&D strategy and establishing of



Participants in the Meeting

R&D priorities. The last day was used for preparation of the written summaries of the R&D and design sessions, and presentations of the summaries to the whole meeting. An unplanned, additional session was held on Monday, 19 February, with the Task Area Leaders (J. Pamela, Y. Ohara and V. Kulygin) and with Y. Okumura and A. Panasenkov, in order to complete the summaries of the design and R&D sessions. In total, nine papers were presented on NBI power supplies (including three on cost), twenty-two papers were presented on the design and cost of the NBI system, seventeen on the NBI R&D and the R&D programme.

NBI Power Supply System Designs

Power supply system designs were presented by the European and Japanese HTs, to which Design Tasks were allocated on this subject. Both systems were well designed and compliant with the ITER EDA technical objectives. The basic designs converged to identical configurations with differences existing in the design and application of individual components.

For the major differences see the chart below.

	EU	JA
HV transformer	Cascade type with five series transformers (200 kV insulation level, chosen to reduce HV insulation risk)	Multi-transformer (all 1 MW insulation level) with 5 series bridges (chosen to improve electrical performance)
Input invertor	1300 V, 400 Hz, GTO type	2300 V, 150 Hz, GTO type
Transmission line	Multi-axial low (atmospheric) pressure gas insulated	Multi-axial high pressure gas insulated

The cost estimates for the NBI power supplies, provided by all three HTs, were consistent with each other.

There were some differences in design assumptions. These included grid currents, allowable voltage ripple, transmission line length, and arc voltage during breakdown. The matter was discussed during the meeting. JCT staff presented proposals for common specifications that were accepted by the HTs and will be assumed in the future work.

It was noted that the recent changes in NBI location and building design need to be accommodated with the present designs.

Both power supply system designs (JA & EU) were well conceived and are based on previous work in the field. Both HTs should continue to optimize their designs and integrate the layout into the present site architecture.

The following recommendations have been agreed upon:

- Redesign as necessary to comply with harmonized specifications;
- Further characterize the non-ideal aspects of the transformer system;
- Include the stray parameters (leakage inductance, self capacitance, etc.) in circuit simulations and evaluate any possible resonance with invertor input wave form;
- Carefully evaluate the invertor frequency selection considering the implications to the invertor, the transformer, the HV output filter, and the source protection system;
- Re-evaluate the HV output ripple filter requirement with the required transmission line length;
- Re-evaluate the fault protection system with the required transmission line length.

Requirements for future R&D for the NBI power supply system were discussed and identified. The JCT should propose them to the ITER management.

The JCT recommended that the HTs proceed in the detailed analysis of the proposed concepts so that different designs can be compared when both design tasks are completed.

NBI Design

The design of the "common reference concept" of the ITER NBI system and the associated R&D priorities were agreed among the JCT and the JA, EU and RF HTs during the Design Review Meeting held in July 1994, at the Naka JWS, following the conceptual studies done by the three HTs. Four beam lines were considered at that time to deliver 50 MW to the plasma.

The reduction of the ports from 24 to 20, decided early in 1995, reduced the beam lines to three. Therefore, the power from each beam line had to increase from 12.5 MW to 16.7 MW.

The main parameters, chosen as reference, are:

beam energy = 1000 keV,
pulse duration > 1000 s,
source pressure = 0.3 Pa,
beam current > 40 A,
source current density > 20 (D^-) mA/cm^2,
$I_e / I_{D^-} < 2$.

During the meeting the design was reviewed considering the physics aspects and the analysis in progress (physics design). Then the various components (engineering design) were reviewed, and for each item the connection with the R&D was assessed. Priorities were identified for each activity and for each component, and actions were assigned to the JCT and the HTs. The remote handling and the safety aspects were also assessed: routine maintenance is required on a yearly basis to the source to replace filaments and to add cesium (Cs).

R&D Results

The main objectives of the R&D are:

- To address and solve the outstanding issues for the reference concept of the ITER NBI injection system.
- To examine possible improved concepts.
- To provide a solid basis for a decision on the ability to produce the 1 MeV beams for ITER, and eventually for the choice of NBI as a heating and current drive scheme for ITER.

The results from the 1 MV accelerator research are very encouraging, with negative ion beams of >800 keV being produced at both JAERI, Naka, Japan, and the EURATOM-CEA, Cadarache, France. The ion source development is proceeding extremely well, with the ITER design current density being reached in the prototype "concept" source at near the design source operating pressure. Additionally, world record D^- beam production currents and power (13.5 A at 400 keV, 5.4 MW) have been achieved with the JT-60U source and accelerator. Further work is required in all areas, but these results can be regarded as major steps towards being able to realize the ITER injectors.

The status of R&D in JA, the EU and the RF is given in the following boxes:

JA

1 MeV Accelerator: A high energy H-beam of 805 keV, 150 mA (measured at the power supply), 1 s was accelerated in the multi-aperture, multi-stage accelerator. Deterioration of voltage holding capability was not observed after breakdowns. Once the accelerator had been conditioned without the beam, it was easy to accelerate the negative ions up the energy even in the Cs seeded operation.

Large Area D^-source: A D^- ion beam of 13.5 A, 400 keV (5.4 MW) was successfully produced for 0.12 s with a D^- current density of 8 mA/cm^2 at a source operating pressure of 0.22 Pa. The ratio of extracted electron current to extracted negative ion current was less than unity ($I_e / I_{D^-} < 1$). The source plasma was produced uniformly over the wide extraction area of 106 cm x 45 cm at low pressure, 0.1 - 0.3 Pa.

Low Pressure Source (Kamaboko): A high current density of 30 mA/cm^2 (H^-) was demonstrated at a low operating pressure of 0.2 Pa.

Alumina Insulator: A new method for the fabrication of a large Al_2O_3 ceramic insulator was developed. A scalable model of the insulator will be fabricated by this method and tested.

EU

__SINGAP Accelerator__: Simplified concept of high-energy electrostatic accelerator which could constitute an alternative to the conventional multi-gap, multi-aperture systems.

The use of only one HV acceleration electrode would simplify the construction, the alignment, and the remote handling procedures. Also, the HV power supply would have only one HV terminal and the transmission line one HV conductor.

The management of the stray electrons represents the main issue for SINGAP. Therefore, trapping of extracted electrons in the pre-accelerator and reduction of the source operating pressure are both important. The results obtained so far are the following:

- *Suppression of electrons leakage from the pre-accelerator to < 1/1000;*
- *1 MV voltage hold-off demonstrated on the single vacuum gap after only 20 min of voltage on-time;*
- *100 mA, >900 keV, electron beams were accelerated in the single gap;*
- *Up to 60 mA of H^-beams have been accelerated at 860 keV (beam power measured on the target at 3 m from the source), with an efficiency of the accelerator (I_{H^-} on target/I_{drain}) higher than 95%, with an overall beam divergence <10 mrad, and with breakdowns free-operation during 1.5 s pulses;*
- *No deconditioning breakdowns in the HV vacuum gap have been observed.*

__MANTIS Negative Ion Source Test Bed__: Two sources have been tested. The former "Dragon" source yielded up to 14 mA/cm^2 of D^- beam, with Cs seeding, at an arc power of 140 kW (1.75 W/cm^3) and at a pressure of 0.7 Pa. In collaboration with the Japanese HT, the low pressure Kamaboko source was tested in D^- operation. 20 mA/cm^2 of D^- beam (1.4 total D^- current on the calorimeter), with a good beam uniformity was accelerated at 0.35 Pa, with only ~25 mg of Cs injected in the source. The co-extracted electron current ($I_e/I_{D^-} > 4$) needs to be further reduced, and, therefore, an optimization of the magnetic filter has been started.

RF

Investigations of a plasma neutralizer included:

1. *Model plasma neutralizer experiments (PNX-1) and theoretical investigations.*
2. *Construction of an upgraded model plasma neutralizer (PNX-U).*

The conceptual design of a plasma neutralizer using a superconducting magnetic confinement system for ITER (PN-ITER) has also been developed.

__PNX-1__: This experiment has a plasma volume ~0.07 m^3, and a microwave power of up to 5 kW, at a frequency of 2.45 GHz. It has been used to demonstrate plasma confinement in agreement with scaling predictions. The maximum density was 5×10^{11} cm^{-3}, which gives a line integrated plasma density of 3×10^{13} cm^{-2}. The maximum density was not limited by plasma cut-off of the microwaves. It was found that microwave power is absorbed by surface wave excitation, the propagation being along a waveguide formed between the wall and the plasma surface; absorption is with the assistance of plasma resonance transformation.

Experiments on the niobium wall pumping effect were arranged at PNX-1, and the possibility of this approach, with an efficiency not less than 0.35, was demonstrated.

__PNX-U__: An upgraded model neutralizer, PNX-U, was designed and is now under construction having the following status: Vacuum system is under commissioning. Magnetic coils are under fabrication. Microwave system: under assembly and adjustment.

The results obtained in the present R&D tasks are encouraging for the realization of the NBI system for ITER. Especially, two intensive experiments are being conducted in JA and in EU on the accelerator, which already show the capability of high-energy acceleration of negative ion beams at more than 800 keV. Additionally, the joint experiment between JA and EU demonstrated a D^- current density of 20 mA/cm^2 at 0.35 Pa, which are near the design values for ITER. (Note that, since the meeting, the ratio of extracted electrons to negative ions has been reduced to <1 at 2.5 mA/cm^2 of accelerated D^- by increasing the source magnetic filter field.)

The R&D tasks already allocated and the ones under discussion are adequate to give a sufficient database to make a choice among the heating and current drive methods.

There is no duplication on R&D, except for 1 MeV accelerator development, Multi-GAP at JA and SINGAP at EU. These accelerator concepts are studied as the reference design and the alternative design, respectively.

Collaborations among the HTs are very useful and effective to reduce the cost and the time to complete the R&D. The present collaboration between JA and EU has produced excellent results. Future collaborations, foreseen in the NBI R&D Requirements for the Rest of the EDA should be conducted intensively.

LIST OF PARTICIPANTS

EU: J.-M. Bottereau, A. Cheyne, E. Kussel, J. Pamela, A. Simonin, M. Watson
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JCT: I. Benfatto, E. Bowles, E. Di Pietro, M. Hanada, R.S. Hemsworth, C. Holloway, M. Huguet, A. Krylov, P.L. Mondino, A. Roshal

FIRST WORKSHOP ON ENERGETIC PARTICLES AND HEATING AND CURRENT DRIVE

by Dr. J. Jacquinot, JET, and Dr. S. Putvinksi, ITER JCT

The First Workshop on Energetic Particles, Heating and Current Drive in ITER was held on October 2 - 6, at the Kurchatov Institute, Moscow, Russia. A list of participants follows at the end of the article.

In the opening session, the Chairman of the Expert Group and the Head of the ITER Physics Integration Unit, F. Perkins, discussed the most important scientific issues in the area of plasma heating and current drive systems related to the recommendations of the ITER Technical Advisory Committee. The general physics context reviewed at the TAC-8 meeting stresses the importance of reaching the L to H mode transition with less than 100 MW of total heating power and demonstrating the plasma regime which can combine adequate plasma confinement quality and purity together with conditions tolerable for the divertor: e.g., with minimum ELM size and high radiation in the divertor channel to reduce the thermal loading of the target plates to an acceptable level.

The following agenda included session on all four candidate H & CD systems and on energetic particles. Results of the subgroups' discussions are given in the following boxes:

Electron Cyclotron Resonance Heating (Chairman M. Makowski)

The design has focused on 170 GHz driven by 1 MW CW gyrotrons. Two ports are used to deliver 50 MW. The angle of the microwave beams can be adjusted from 20 to 40 degrees to allow heating and current drive up to $r/a=0.7$. A greater steering angle could be provided if necessary.

The physics of ECRH is well understood and codes describe the details of ITER geometry. The system fulfils the GDRD requirements providing both power localization and off-axis current drive. These two functions are strongly coupled for each individual beam, and it may be desirable to provide several injection angles simultaneously in order to decouple these two functions suitably. These aspects will receive further consideration. The maximum accessible density is 3.5×10^{20} m^{-3} for ITER.

H-modes, efficient electron heating and current drive have been demonstrated in experiments confirming the theoretical expectations. MHD modes (sawtooth or $m=2$ modes) have been controlled by local deposition.

The main uncertainty lies in the availability of suitable gyrotrons and windows. Integrated reliability tests with these two elements are expected to be available towards the end of the ITER EDA.

In addition, two preionisation systems are proposed in order to increase the operating range of the plasma breakdown phase. Power sources of 3 MW at 90 and 3 MW at 140 GHz are required.

Ion Cyclotron Resonance Heating (Chairman P. Bosia)

The ITER proposal is based on conventional coupling straps grouped in 4 x 2 array modules. Four ports are required to couple 50 MW. The voltage is 38 kV at 60 MHz for a plasma 15 cm away with a 2 cm density scrape-off layer. The frequency range (40 to 70 MHz) allows compliance with the required magnetic field range using resonance at second harmonic of tritium cyclotron frequency ($f = 2f_{C,Tritium}$) and permits CD and sawtooth stabilization scenarios. Matching elements are incorporated in the launcher in order to accommodate load variations due to ELMs. The system meets all GDRD requirements.

The physics of fast wave heating and CD is well supported by a number of tokamak experiments and by theory. A code comparison effort has made good progress in resolving differences in ITER projections. The reference ITER scenario (radiating divertor with grassy ELMs) has been demonstrated in JET up to 16.5 MW. TFTR has demonstrated efficient ion heating in a D/T plasma at $2f_{C,Tritium}$, and central CD has been found in accordance with theory in several experiments.

Monopole excitation would allow the antenna voltage mentioned above to be substantially reduced. However, discrepancies in plasma heating results have been found indicating a need to continue testing ITER-relevant antennas on tokamaks.

The unique features of ICRF, in ITER conditions, are a) the possibility of direction ion heating (up to 60%), which provides additional alpha heating power that helps the L-H transition and b) the decoupling of the heating and CD functions by phase and frequency control.

R&D aiming at increasing the power density per module by up to a factor of 4 has been performed but now requires in vivo tests in relevant plasmas. Physics R&D on off-axis CD with mode conversion CD is being pursued on TFTR and TS.

Lower Hybrid Heating (Chairman G. Tonon)

Robust couplers capable of launching more than 25 MW per port at 5 GHz have been designed by the EU HT. The active-passive structure which uses thick plates (13 mm) is optimized for $N_{\parallel} = 2 \pm 0.3$. Coupling requires a density of 10^{18} m^{-3} at the grill mouth. It has necessitated a 1 cm antenna-separatrix gap for JET H-modes with giant ELMs. A much larger distance (up to 15 cm) can be used in other conditions. The power deposition and CD codes which have been accurately benchmarked in recent experiments predict a power deposition at mid-radium at 3 x 10^{19} m^{-3}/10 keV and a narrowly peaked profile at r/a = 0.7 for 1.25 10^{20} m^{-3}/20 keV.

Experiments have established LHCD as the most efficient current driver (3.6 MA in JT60-U, 3 MA in JET), with efficiency between 2 x 10^{19} and 3.5 x 10^{19} $Am^{-2}W^{-1}$. It will remain the most efficient far off-axis driver in ITER due to the property of fast electron generation. Reverse shear and the related improvement of central confinement have been produced with LHCD in steady-state conditions in large tokamaks. R&D is required to substantiate the coupling requirements including divertor physics R&D to project the expected edge density in ITER.

Neutral Beam Injection (Chairman R. Hemsworth)

The proposal is to use 3 negative ion beam lines at 1 MeV. The beams are tangential in the co-direction at R=6.5 m requiring 3 ports. The overall efficiency (plug to torus) is >35%. Good progress is being made in testing key elements of this new heating method. Experimental results with plasma from the 0.5 MeV system of JT60-U are expected at the end of 1996. In addition to technical demonstration, these tests are particularly ITER-relevant since the heating and CD performance and TAE physics will be assessed in the electron heating regime without the large central beam fuelling and ion heating characteristics of present experiments.

Beam heating physics is supported by present positive NBI experiments in a large variety of conditions including D/T experiments in JET and TFTR. A unique feature of NBI is the possibility of driving much more rotation than in RF systems. This allows extending the range of operation with error field and possibly to reach higher pressure needed in advanced scenarios. This may, however, require counter injection which gave doubtful results in present experiments. The relative merits of co-, counter-, or mixed injection should be studied.

Energetic Particles (Chairman S. Putvinski)

The D/T experiments in TFTR have not revealed any alpha-driven instabilities or associated losses. The largest observed effect is that alphas can be expelled by 20 cm after a sawtooth crash. It has also been found that alphas are driven towards the bottom of the tokamak during disruption. The consequences of such an event should be taken into account in the design of the first wall.

The theory of AE instability in ITER-relevant conditions (high n modes) has progressed substantially. The reference ITER burning scenario is stable at least up to n=10. Fully non-perturbative analyses of ITER scenarios will be available by the end of 1996.

Other effects such as the losses due to fishbones and to energetic particle continuum modes (EPM) are more difficult to predict. New capabilities are available to describe the non-linear development of these modes. They should first be validated on experiments. The physics of ripple losses is now well understood and benchmarked against experiments. It is urgent to apply this knowledge to the ITER 20 coil configuration.

In the area of steady-state scenarios, participants noted that a sophisticated feedback method is likely to be necessary in order to avoid unacceptable relaxation of the high bootstrap current regime. The EG stressed the need for the diagnostic requirements of real time current profile measurements. Far off-axis current drive is an essential requirement for steady-state operation. Rotation is also an important element according to MHD theory for maintaining stability at the required high beta values. The stabilization mechanism needs to be confirmed in experiments.

In general, experiments have focused on the issues identified by the EG, and a considerable amount of new information was discussed at the meeting. ITER JCT representatives thanked the major devices for assisting ITER in a timely manner.

The EG recommended to adopt a multi-system strategy and identified the following reasons:

a) No single system accomplishes all the required functions for ITER: localized heating and CD, in heating for H-mode access, rotation and efficient off-axis CD for AT operation. A particular system may accomplish two or three of these functions, but not in an independent way.
b) It is very likely that new needs will arise from operating in an ignited plasma. A multi-system approach offers such flexibility, reducing the risks.
c) The strategy provides options for the step following ITER (DEMO).

d) The science extracted from ITER will be increased both in depth and variety as clearly demonstrated by discoveries in present tokamaks, which used several heating systems.

The merits and additional cost associated with this strategy should be evaluated with the perspective that the total cost of the heating system is only about 5% of the construction cost.

It was agreed that the next meeting will coincide with the 1996 IAEA Fusion Energy Conference and will be dedicated to the assessment of physics R&D on heating and CD and related fast particle effects.

Closing the meeting, the Chairman, on behalf of the participants, conveyed to the host, the Kurchatov Institute, very warm thanks and congratulations for the excellent organization and the pleasant atmosphere which prevailed during the entire meeting.

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* N. Fujisawa	JCT, San Diego
* A. Fukuyama	Nagoya Univ., JA
* R. Hemsworth	JCT, Naka
* J.G. Jacquinot	JET, EU (Chair)
R. Koch	EURATOM-ERM/KMS, EU
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V. Kulygin	Kurchatov Inst., RF
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