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## DESIGN MEETING ON REDUCED TECHNICAL OBJECTIVES/ REDUCED COST ITER OPTIONS

**by Dr.W. Spears, ITER Garching Joint Work Site**

The ITER Council, at its 14th Meeting in July 1998, requested the Director to establish option(s) of minimum cost aimed at a target of approximately 50% of the direct capital cost of the present ITER design, while maintaining its overall programmatic objective, endorsing the revised technical objectives delineated by the Special Working Group (SWG), in its first task. The above meeting was convened at Garching JWS on 25-28 January 1999 to allow the JCT and Home Teams to exchange views on machines with such objectives, and to discuss in detail the design issues. More than 50 participants (List of Participants at the end of the article) sat together for the four days. This meeting, chaired by the ITER Director, Dr. R. Aymar, was a follow-up of a meeting in Naka in October 1998, which described generically some of the problems and identified further work necessary before reaching a conclusion. The current meeting was aimed at updating the earlier analyses, but not yet at reaching a recommendation for conclusion on the single parameter set on which to base future ITER construction.

The studies on the Reduced Technical Objectives/Reduced Cost ITER (RTO/RC ITER) showed that reducing the technical objectives without changing the nature of the design was not enough on its own to achieve the 50% cost target. Further design changes, compared to the design of ITER documented in the Final Design Report (FDR) of ITER in July 1998, would be necessary. They consisted mainly of reductions, as far as was reasonable, in technical margins, and in improving/optimising engineering design towards reduced manufacturing costs, while at the same time, and very importantly, seeking to benefit fully from R&D results in physics and technology. The main changes proposed come from:

- the need to take maximum advantage of high plasma elongation and triangularity within physics limits suported by the experimental database;
- the need to engineer suitably robust plasma vertical stability to take advantage of such elongation and triangularity, ranging from the use of a close fitting passive shell, to copper cladding on the vessel, towards passive internal saddle coils, and ending with the use of active coils inside the vessel;
- the use of wedged toroidal field (TF) coils with a segmented central solenoid and poloidal field (PF) coils linked above and below the equatorial plane to handle a higher plasma elongation and triangularity within power supply limits;
- the need to maintain the largest plasma volume, at the expense of a reduced divertor volume, increased neutron heating of the winding because of reduced shield thickness, and the elimination of the blanket backplate, with the bolting of blanket modules and the welding of their coolant channels directly to the vessel;
- the need to maintain the largest possible port access, at the expense of a reduced intercoil mechanical structure;
- the newly expected need to provide means to stabilise very long time scale MHD instabilities which can be detrimental to confinement.

Although significant progress had been made on understanding the implications of the above design requirements, it was clear from the meeting that there were a number of outstanding issues that would require further assessment:

- the degree to which high elongation plasmas were supported by the physics database, and the most appropriate level of complexity and operational risk to allow in the engineering design to support such plasmas;
- the machine parameters providing an optimal compromise between Q=10 inductive operation and Q=5 steady state operation;
- the overall machine cost impact of eliminating the blanket backplate;
- the level of cost savings that could be achieved by adopting different design solutions in the magnets, e.g. reduction in conductor strand stability margins, conductor grading, alternatives to Incoloy;
- whether manufacturing methods for in-vessel components could lead to a design that is improved further to minimise costs;
- whether it was possible to make further cost reductions in building layout and balance of plant.

In summarising the meeting as a whole, the Director emphasised the need to resume the joint design work, between the JCT and Home Teams, to the aims agreed by the ITER Council. This had been so efficient up to July 1998. He indicated that there was a need for a process to reach convergence of views among ITER participants. Such a process would have to be managed through a common approach by the Home Team Leaders (HTLs) with the Director for it to be successful. The EU HTL expressed the need for a sound documentation of the rationale for reaching a final set of parameters. Unified actions by JCT and HTs would be needed to achieve this. The JA HTL indicated that there was a little time to reach convergence, but that there must be full acceptance of that convergence for it to carry support at the political level, and in parallel there must be convergence on an agreement on how to go on and construct ITER. These important issues were discussed in preparation for consideration at the March ITER Meeting in Cadarache.

**LIST OF PARTICIPANTS**

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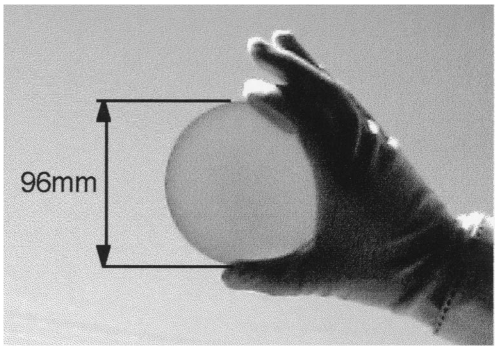
# DIAMOND WINDOW AND ITS APPLICATION TO ITER GYROTRON

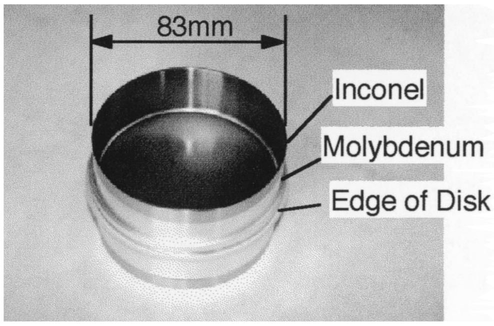
**by K.Sakamoto, Project Leader of Gyrotron and Window development, JA HT**

### Background

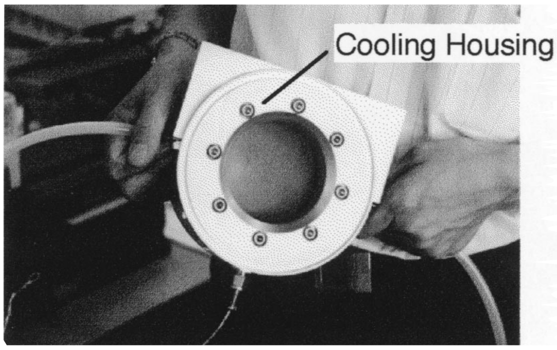
Electron cyclotron resonance heating and current drive (ECH and ECCD) is a major candidate as an additional heating and current drive method in ITER. In the design work of an ECH/ECCD system, 50 MW injection at 170 GHz was proposed. As a power source of the ECH/ECCD system, a gyrotron of 170 GHz/1 MW/CW was demanded, and its development was selected as an R&D item of ITER EDA. In the development of a high power gyrotron, an output window made of ceramic has been regarded as the most serious and annoying problem. A ceramic window capable of 1 MW/CW RF power transmission at continuous wave (CW) is indispensable, not only for the gyrotron but also for tritium shielding near the ITER vacuum vessel. However, as the RF frequency increases, the absorption coefficient of the window materials due to dielectric loss (the so called loss tangent, tan d) becomes significant. Conventional materials such as sapphire cannot withstand a 1 MW/CW operation at 170 GHz. Therefore, the development of a window capable of such operation was also selected as an R&D item of ITER EDA, in parallel with the gyrotron development. Up to now, several window materials and concepts (cryogenic sapphire window, distributed window, boron nitride window, silicon nitride window and synthetic diamond) have been proposed and tested.




(a) Diamond disk before brazing




b) Metal bonded diamond disk with Inconel cylinders




(c) Assembled diamond window with water cooling housing

**Fig.1: Several steps of development towards diamond window assembly**

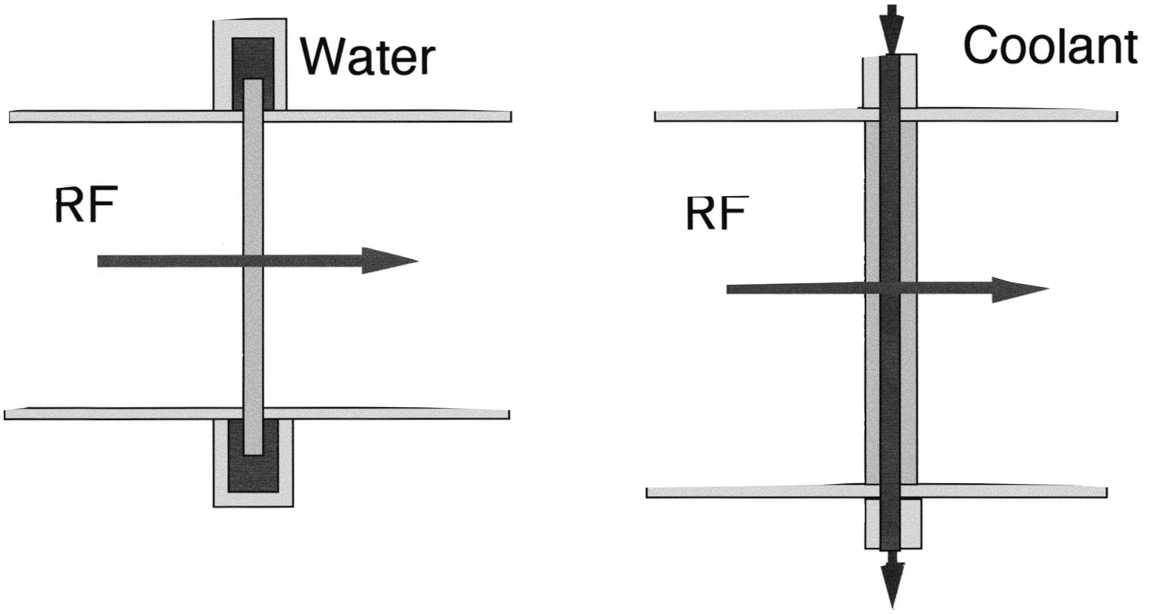
In the JAERI gyrotron, sapphire and silicon nitride were used as a window material until 1996. An output power of 0.5 MW was obtained, but the window temperature exceeded 100o C after 0.8 s because of the large dielectric loss due to the window material. It was concluded experimentally that long pulse operation is only possible below 170 GHz; therefore, an innovative window was desired.

### Synthetic Diamond

Owing to recent progress in plasma processing technology, the production of large diameter polycrystalline diamond disks is now possible. The most successful method of production is a chemical vapor deposition of carbon plasma produced by a microwave from gaseous hydrocarbons, such as methane or acetylene, in a hydrogen-rich atmosphere. The diamond layer grows on the heated substrate. It is well known that the diamond has an extremely high thermal conductivity and a low value of tan d. The diamond is the hardest material, and it is chemically inert to all acids. If the diamond disk is used for high power millimeter wave windows, ideal windows, i.e. with low loss and a simple configuration, will be realized.

To develop a diamond window, JAERI, the Forschungzentrum Karlsruhe(FZK), and DeBeers have cooperated. The main challenge in the creation of the high power millimeter wave windows has been manufacturing diamond disks with diameters of about 100 mm, thicknesses of ~2 mm and low dielectric loss. It was also necessary to manufacture a flange assembly for vacuum and tritium shielding and for water cooling.

Fig. 1 shows the photographs of the several steps of development towards a diamond window assembly. Fig. 1 (a) shows a diamond disk. Its diameter is 96 mm, the thickness is 2.23 mm, which corresponds to three wavelengths in the material at 170 GHz. The surfaces are polished with a roughness of 250~280 nm. In an RF power transmission experiment at short pulse, tan d ~1.3 x 10-4, and a thermal conductivity of ~1800 W/mK were confirmed. The thermal conduct-ivity is four times higher than that of copper. Utilizing this high thermal conductivity, a diamond window assembly with edge cooling by water was designed as shown in Fig. 2 (a). The disk periphery is left for water cooling. Fig. 2 (b) shows a conventional double disk window, where the coolant (fluorocarbon) flows between the disks for face cooling since the thermal conductivity of the conventional material is poor. This window permits only a 0.2 MW level of power transmission in CW operation.




(a) Single Disk Diamond Window with edge cooling by water (>1 MW)

(b) Conventional Double Disk Window (Si3N4, Sapphire), surface cooling (>0.2 MW)

**Fig.2: Conceptional view of window.**

In the next step, Inconel cylinders are bonded on both sides as shown in Fig. 1 (b). The aperture of the cylinders is 83 mm. Molybdenum rings are put on in order to compensate for the difference of thermal expansion between diamond and cylinder at the bonding and baking phases. Fig. 1(c) is an assembled diamond window with water cooling housing. Fig. 3 shows the cross section of the assembled diamond window. The cooling water flows at the periphery of the disk, realizing effective cooling. A heat transfer coefficient of 20 kW/($m^2$K) was confirmed at a flow rate of 19 liter/min in the RF power penetration experiment.

## Installation of the diamond window on the 170 GHz gyrotron

The diamond window assembly was installed on a 170 GHz gyrotron. In the fabrication process of the gyrotron, high temperature baking is necessary for the purpose of degassing. Before installation, baking was optimized while using another brazed diamond. It was confirmed that a baking temperature of 450o C is acceptable. In a large baking oven, gyrotron baking was carried out at a temperature of 450o C, for two days flat top, with two days heating up and four days cooling down. As a result, a good vacuum was obtained (less than 1 x 10-8 Pa). The window receives a maximum bending stress of 40 MPa from the atmospheric pressure. However, this value is much lower than the limitation value of the diamond disk, which is higher than 400 MPa. In Fig. 3, the diamond window gyrotron is shown. In the gyrotron operation, the output power is measured calorimetrically by the temperature increase of the cooling water of the RF dummy load. The flow rate of the window cooling water is 20 liter/min.

In Fig. 4, the time dependence of the central temperature of the window (closed circle) is shown. The temperature is measured by an infrared camera with a detecting wavelength of 3-5.4 mm. The output power is 520 kW. The dashed line is a simulation result with tan d ~1.3x10-4, a thermal conductivity of 1800 W/mK at room temperature. These values show a good agreement. This also indicates that the diamond loss tangent did not change through high temperature baking. Since the loss tangent of the used diamond is relatively high, tan d~1.3x10-4, the window temperature was stabilized at 150o C. However, no trouble such as an arcing was found on the gyrotron. As the quality of the diamond is being improved, we have already fabricated a second window with tan d~2x10-5. If this window is used, the temperature increase is less than 50 o C with 1 MW, CW, as shown in Fig. 4. This suggests that a window of multi-megawatt transmission is very well possible. Up to now, the maximum output energy has been 3.6 MJ (0.45 MW, 8 s).


**Fig.3: 170 GHz gyrotron with diamond window**

The total number of operations greater than 1 s was ~1300. The total penetration energy was ~1.8 GJ. After the experiment, the diamond window was inspected, but no damage was found. It is concluded that the synthetic diamond window is reliable and constitutes the solution to the window problem that had been the most serious problem in ECH technology.

**Cost considerations**

The cost of the diamond disk assembly is now roughly three times higher than that of a conventional double disk window system, capable of a power transmission of less than 0.2 MW. So, it might be concluded that, even at present, the cost effectiveness of the diamond disk in the ITER 170 GHz ECH system is acceptable. However, it should be noted that this diamond window developed for the ITER system constitutes the first application of the high quality, large sized diamond disk. Other applications of such disks are very likely. Since the synthetic diamond is an industrial product and not a jewel, its price will surely go down with an increase of its applications. Furthermore, since the power limitation due to the window has decreased, gyrotron power increase becomes possible. Then, the total number of gyrotrons in the ECH system could be reduced, which will contribute to a cost reduction of the system.

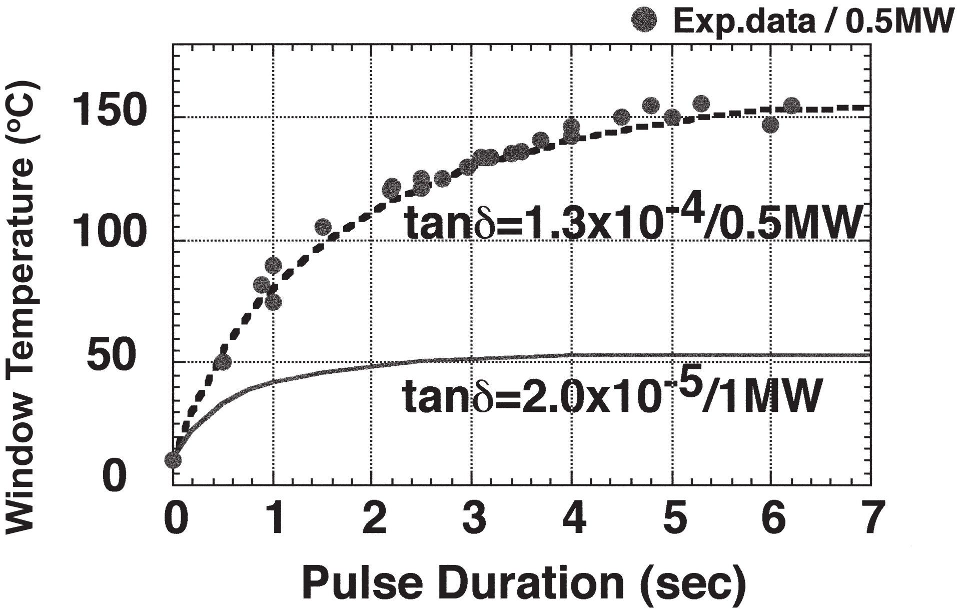



**Fig.4: Time dependence of window temperature** (Closed circles are experimental data at 0.5 MW power transmission. Dashed and solid lines are simulation results)

Items to be considered for inclusion in the ITER Newsletter should be submitted to B. Kuvshinnikov, ITER Office, IAEA, Wagramer Strasse 5, P.O. Box 100, A-1400 Vienna, Austria, or Facsimile: +43 1 2633832, or e-mail: c.basaldella@iaea.org (phone +43 1 260026392).

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