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SOURCE STRENGTH MONITORS
FOR ITER

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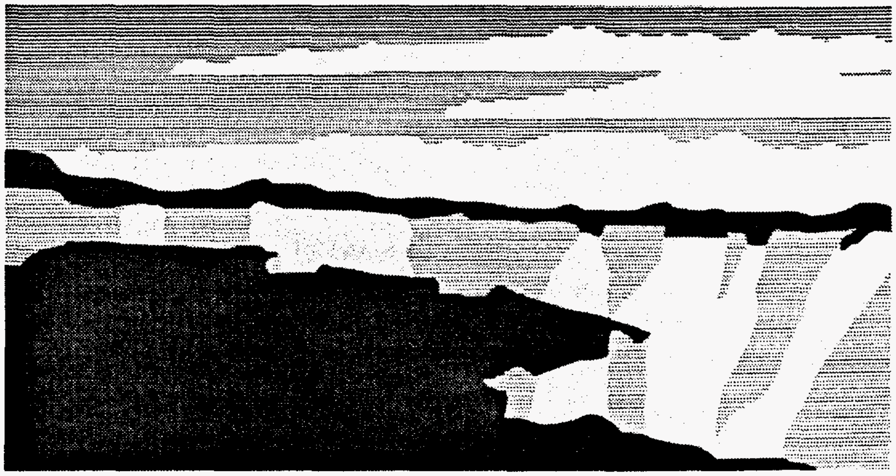

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DESIGN CONSIDERATIONS FOR NEUTRON ACTIVATION AND NEUTRON SOURCE STRENGTH MONITORS FOR ITER

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INTRODUCTION

The International Thermonuclear Experimental Reactor[1] will require highly accurate measurements of fusion power production in time, space, and energy. Spectrometers in the neutron camera could do it all, but experience has taught us that multiple methods with redundancy and complementary uncertainties are needed. Previously, conceptual designs have been presented for time-integrated neutron activation[2] and time-dependent neutron source strength monitors[3], both of which will be important parts of the integrated suite of neutron diagnostics for this purpose.[4] The primary goals of the neutron activation system are: to maintain a robust relative measure of fusion energy production with stability and wide dynamic range; to enable an accurate absolute calibration of fusion power using neutronic techniques as successfully demonstrated on JET[5] and TFTR[6,7]; and to provide a flexible system for materials testing. The greatest difficulty is that the irradiation locations need to be close to plasma with a wide field of view. The routing of the pneumatic system is difficult because of minimum radius of curvature requirements and because of the careful need for containment of the tritium and activated air. The neutron source strength system needs to provide real-time source strength vs time with ~1 ms resolution and wide dynamic range in a robust and reliable manner with the capability to be absolutely calibrated by *in-situ* neutron sources as done on TFTR[8], JT-60U[9], and JET[10]. In this paper a more detailed look at the expected neutron flux field around ITER is folded into a more complete design of the fission chamber system. Overall issues of neutron calibration for ITER will be presented elsewhere[11].

Neutron Activation

Irradiation End Location

The locations of the neutron activation irradiation ends are a critical choice in creating a working, maintainable system that can be accurately calibrated using neutronics modeling of the local geometry. In the previous Phase II design[2] a location in the front surface of the blanket/shield module (BSM) was desired. However, pneumatic access to any such location through the BSM would be very difficult, and the resulting "unique" BSMs were rejected because of the heavy requirements on remote handling and installation procedures that made special modules extremely undesirable. As the design of the BSMs continues to evolve, the need for "toroidal filler modules" to plug gaps between BSMs from the curvature of the torus has been recognized. Placing neutron activation irradiation ends in such special toroidal filler modules at the intersection of four BSMs should allow remotely maintainable units with a good view of the neutrons from the plasma.

The primary design concern for the neutron activation system is achieving the necessary wide angle of view of the neutron emitting region. If the field of view to a significant number of neutrons is cut by the edge of a BSM, then the geometry of the activation location relative to that edge becomes the dominant effect in the neutronics uncertainty. This was the case on TFTR where the location of the RF limiter relative to the re-entrant irradiation end determined the toroidal cut-off of the field of view and created a 5% uncertainty.[6] The field of view should clearly include the center of the plasma and out to approximately the half-radius, and also a considerable distance toroidally. If one wants to see ±1.4 m at 2.8 m distance one needs an angular field of view of 26°. If the activation location is set back a distance d from a gap of radius 10 cm with corner of radius e the viewing angle is $\min(\mathrm{atan}(10/(d-e)),\mathrm{atan}((10+e)/d))$. For $e\sim7.5$ mm, d must be less than 29 mm to achieve this 26° angular field of view; for $e\sim10$ mm then d must be less than 32 mm. This simple calculation says the activation location needs to be within 2-3 cm of the front face of the BSM.

Figure 1 is a scale drawing of a typical proposed irradiation end in a toroidal filler module. An actual Catia CAD working model of the BSMs was used as the source. One nice aspect of this drawing is that the rounded corners of blanket are significant and give a better field of view than the above calculation would imply. As in the previous Phase II design, the pneumatic transport for ITER will be 1.1 cm inner diameter tubes carrying 1 cm diameter capsules. A coaxial design at the irradiation end as used on TFTR with a 2 cm outer diameter allows the return air to be transmitted to the inner tube. Figure 2 shows a close-up of the irradiation end. While the inside of the irradiation end does not need to be in vacuum, a secondary vacuum seal and tritium containment is needed further down the pneumatic system (see the next section).

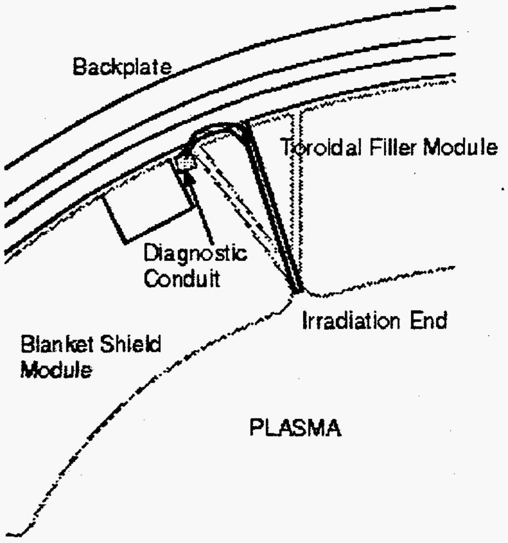

Figure 1: Schematic of a Neutron Activation Irradiation Location in a Toroidal Filler Module. A tube of radius-of-curvature greater than 10 cm is drawn going into the backplate diagnostic conduit.

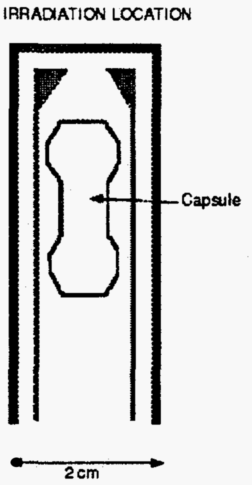

Figure 2: Close-up view of neutron activation capsule inside of irradiation end. The capsule self-plugs the return air hole at the end, providing a pressure change signal used to determine arrival of the capsule.

A critical issue will be heating of irradiation end components and cooling. The nuclear heating into the toroidal filler module region has been analyzed.[12] Nuclear heating will be 10 W/cm^3 in this region and the plasma heating probably only 10%-20% of that. The inner wall of the irradiation end is made quite thin for low total nuclear heating. Thick connecting "fins" from the inside tube to the outside transfer heat; the outer tube is then mounted to the BSM for thermal contact. There exist "lucky" and "unlucky" BSMs depending on whether the neighboring BSM also needs to be removed during remote handling because of the system of keys. The irradiation ends would be attached to "unlucky" BSMs to provide thermal contact. Then during remote handling procedures the neighboring BSM will have to be removed anyway, allowing access to the toroidal filler modules with irradiation ends. There is still some worry about the nuclear heating of the capsule itself which will be in poor thermal contact with anything. Presently we do not plan to have any significant flow of pneumatic gas past the capsule; on the contrary, we hope to use plugging of the channel by the capsule and resulting pressure changes as a robust radiation-insensitive monitor of capsule arrival at the irradiation end. We still may be able to use polyethylene since it may not get too hot. Any capsule components will need to be made of low activation material. The tube itself could be 316 SS or Inconel or Tungsten or even possibly copper; eventually the relative thermal coefficients of expansion will need to be considered in a detailed design.

Which exact filler modules are to be used needs to await the final design of the BSMs. The poloidal angles of the four irradiation locations at each of two toroidal angles would be driven by the sensitivity issues raised in Ref. 2. The toroidal angles will be chosen within constraints of use of the backplate diagnostic conduits by other systems and routing concerns (see next section).

Routing of Pneumatic System

We have considered whether the system should be hydraulic (using water to push the capsules) rather than pneumatic. Water does gives one better thermal conduction. But air moves the capsules much faster, can operate at lower pressure, and is easier to "airlock" to provide secondary vacuum and tritium containment. Our actual preference is to use helium which has good heat transfer, reduced problems on the vacuum if the system fails, low activation, and good availability in the ITER plant.

The critical issue in routing the pneumatic system is the minimum radius of curvature allowed and available. Consider a capsule of diameter d and length l in a hose of inner diameter d+ε. Choose a radius of curvature R such that the hose just touches the ends of the capsule. For ε/d~10% one can support about a 10 cm radius of curvature for a 1 cm capsule. (This translates to minimum 10 inch radius of curvature for 1 inch capsules in 1-1/8" I.D. tubes on TFTR, which agrees with experience.) Thus our pneumatic routing scheme will be plausible as long as we can negotiate any necessary turns with greater than 10 cm radius of curvature.

The initial problem is getting out of the irradiation end in the toroidal filler modules. On Figure 1 is illustrated a path with the minimum radius of curvature defined above. The irradiation end will be centered over a feature in the backplate known as the backplate diagnostic socket (see paper by C. Walker in these proceedings for figure and details[13]). The tube can then curve into the backplate wiring conduit[13] (actually a conduit in the BSM) and following its routing. This backplate wiring conduit was initially designed for electrical diagnostics (such as magnetics) and is also used by the bolometer system. Thus our principle is to use features already existing in the backplate, and then don't be affected by small changes in its design.

The route can get out of the wiring conduit at water manifolds either at the top or midplane of the machine. Figure 3 shows the present backplate design, both in cross-section and 3-D view, illustrating that there is plenty of room to pass the 1 cm tubes through. An extra pipe can be placed through the double wall construction for the pneumatic tubes. If we have 20 mm diameter pipes (12 mm ID) then we can have two of them (transfer and return air) in a 50 mm diameter sheath; it could probably be even smaller.

At least 2 toroidal locations are desired to have poloidal arrays of irradiation ends for redundant backup. We propose to put this system in toroidally at locations of the so-called "in-situ welds of multi-sectors"; that is, sector joints that are welded together in the pit rather than welded before being lowered into place. Electrical diagnostics should not be on

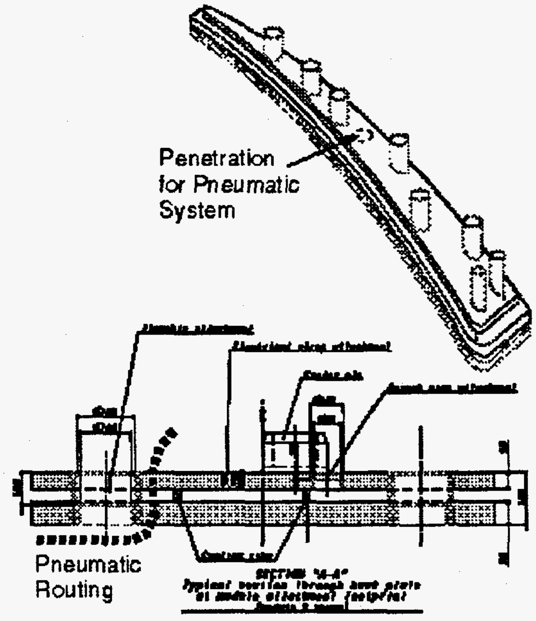

Figure 3: Views of backplate near vertical pipe assemblies showing where activation system pneumatic routing exits from primary vacuum vessel.

this critical path of the construction, but our pneumatic system can be. Eight out of the 20 sector welds are like this. We could conceptually use any pair of in-situ weld sectors and collect the tubes toroidally in the Heat Transfer System (HTS) Vault and thence to Diagnostic Hall (on south side). Sectors 13 and 17 on the south side are our initial preferred choice.

Routing of the pneumatic system into either the HTS vault or the neutral beam injection (NBI) vault provides a location for airlocks and secondary tritium containment. The need for two different toroidal locations implies they (probably) both cannot use NBI vault and also be at in-situ welds, besides which the NBI vault only applies to routing out near the midplane which is problematic for inboard locations. Hence the primary design route is along vertical water manifolds to the HTS vaults. Once into the vertical pipe extensions our pneumatic tubes can follow the same routing as the water pipes[14], using their primary and secondary containment.

Once the tubes penetrate into the HTS vault the problems of providing secondary containment and removing activated air from inside the pneumatic tubes must be solved. Figure 4 is a schematic of the pneumatic system. Capsules are routed to and from loaders, drop outs, and counting systems in the Neutron Activation Laboratory in the Diagnostic Hall to a special room with a "carousel" multiple-in / multiple-out queuing device. The carousel room in the tokamak building would be "off-limits" usually, but the analysis room in the diagnostic hall probably only needs partitions to provide controlled access and distance from the counting stations. All the lines from the carousel to the tokamak go through a single penetration into the HTS vault, and are then routed toroidally[15], all using insulated (plastic) piping to prevent shorting sectors. The radiation dose inside the HTS vault should not be any greater than the TFTR Test Cell itself, and this non-metal piping will not fail from radiation damage. Inside the HTS vault are located "shoebox-size" airlock devices which provide primary containment and ability to purge the air lines. We

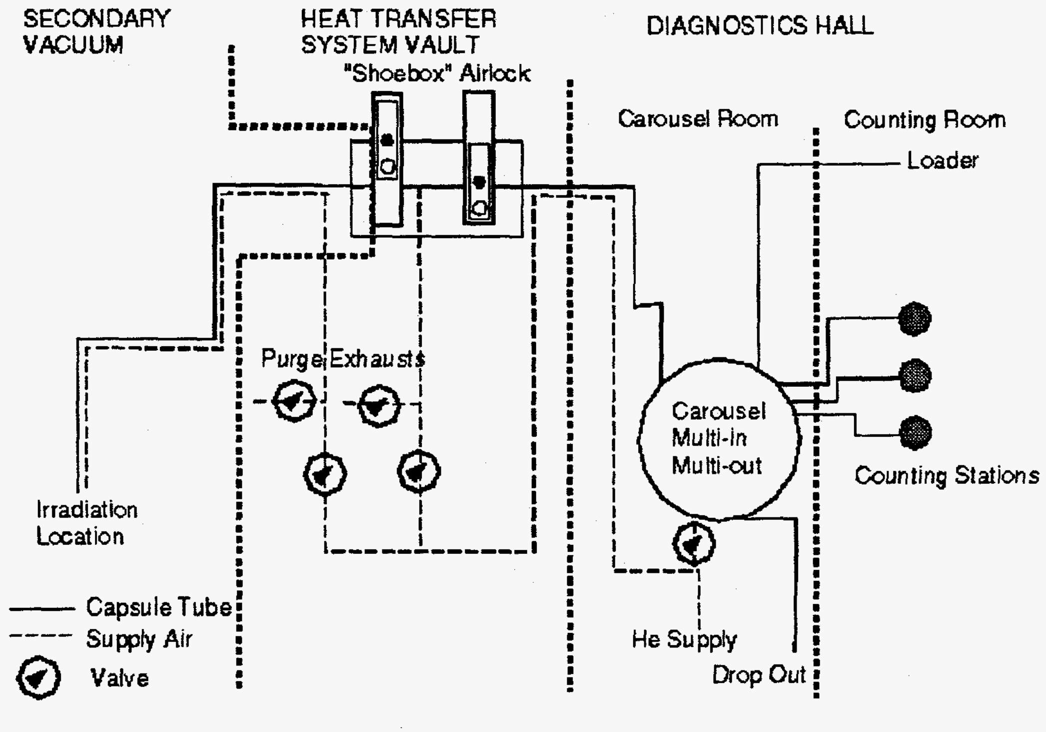

Figure 4: Generalized layout of pneumatic system from counting room to carousel to one irradiation location illustrating tritium containment and activated air control. The "shoebox" airlocks feature two valves each with three positions: open, closed with air holes, and fully closed and sealed. Activated air is purged via exhausts in the Heat Transfer System vault.

thus plan to vent the activated air in the pneumatic system into the HTS vault.

There are other options available for variations of the pneumatic routing if necessary. There are "HTS upper and lower communication shafts" or "pipe chases" which run between the upper and lower HTS vaults (to allow twice the volume in loss-of-coolant accident). These provide communication between top and bottom cooling systems. Cooling water from the "outer blanket limiter" (outboard below midplane port) and from the divertor go *down* to the lower HTS vault, but the piping at the midplane goes to the pipe chases and then down (or for the neutron activation system up to connect to pipes at top). A possible alternative location for the airlock shoeboxes would be on the walls of the pipe chase at the cryo(pump) handling level or diagnostic level and thence out. Exact details can be worked out during construction as long as the concepts are sound and space for the airlock shoeboxes is available.

An issue recognized during the conceptual design was how to measure the presence of capsules in the pneumatic system in a way that could withstand the radiation and heat of the environment. Operation of the pneumatic system on TFTR has led us to recognize that pressure changes occur when the capsules reach the irradiation ends and "stopper" the flow of gas. This method can provide a very robust measurement technique for arrival and departure timing and determination of the presence of the capsule at the irradiation end. More usual electrical and optical techniques can be used at the airlocks and in the HTS vault and beyond where the environment is not as intense.

A similar system needing pneumatic access to the inboard side is the pellet injection system. However, that system uses a smaller pipe, probably needs a much larger radius of curvature, and only needs one or two specific routings and cannot be generalized to multiple poloidal locations. Its primary vacuum seal must be pulled out to the pellet injection cask, and not just its secondary seal. Thus the pellet system is more difficult and not as general, and cannot be used as a template for the neutron activation system.

Key Outstanding Issues

Before final design and construction of the neutron activation system, there are still several outstanding projects that must be addressed.

1. The basic design must be modeled in the MCNP neutronics code and its sensitivity to location determined. The field of view and its uncertainties must be carefully considered.
2. A thermal model should be developed to confirm that sufficient heat transfer to the BSMs and the toroidal filler module itself and their cooling is achieved so that no active cooling of the irradiation end is needed.
3. Each irradiation location will need to have its pneumatic system routed through the final backplate design. No "jogs" or bends of small radius of curvature can be allowed, and there may need to be a special circumstance or two.
4. In particular, it is not clear from present drawings whether irradiation ends on the outboard lower side can be routed past the midplane ports to be collected in the upper vertical pipe assembly. A special routing out at the midplane ports and up through the pipe chases may be necessary.
5. Neutron Activation Laboratory space for both the analysis / counting room and for the carousel needs to be allocated by Naka Joint Work Site team in the Diagnostics building.

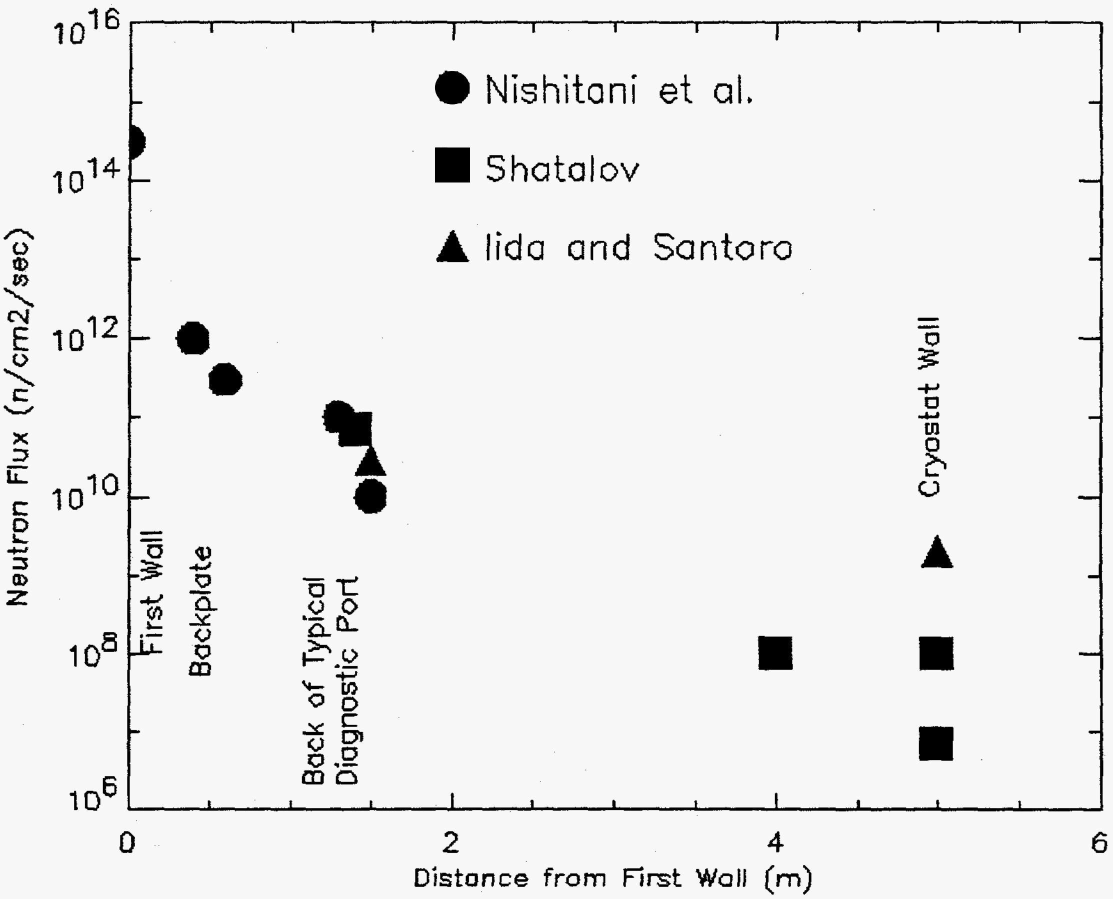

Figure 5: Summary of expected neutron fluxes at full power (typically 1 MW/m^2 at wall) at different distances from the ITER plasma.

Neutron Source Strength Monitors

Location of Detectors in Neutron Field

Further detailed design of the neutron source strength monitor system has required some estimate of the local neutron flux within the bioshield of ITER. Figure 5 summarizes a variety[16,17] of MCNP neutronics calculations done for ITER. There is an outstanding question of whether there is more than 1 order of magnitude drop in (total) neutron flux from outside of the vacuum vessel to the bioshield and whether the source strength monitors will need to be placed behind toroidal field coils to get more shielding. However, we believe that we will *not* need the shielding of the TF coils and can use a limiter (remote handling) port shield plug instead.

As argued previously[3], 7 orders of magnitude detector efficiency dynamic range is needed in the system with a factor of no more than 25 between sensitivity of detectors, and hence 6 detectors in a complete set. We need three different locations because we cannot get the needed dynamic range of detectors in one physical location. One detector (the most sensitive) must go "close" to the plasma to allow *in-situ* calibration. As long as a detector responds to neutrons from at least one toroidal field "bay" or more (and is not effectively collimated to significantly less than one bay) the calibrations of that detector should be meaningfully related to the total plasma volume emission. We plan to place two 200mm x 50mm fission chamber detectors in the neutron collimator pre-shield[18] following lines of a

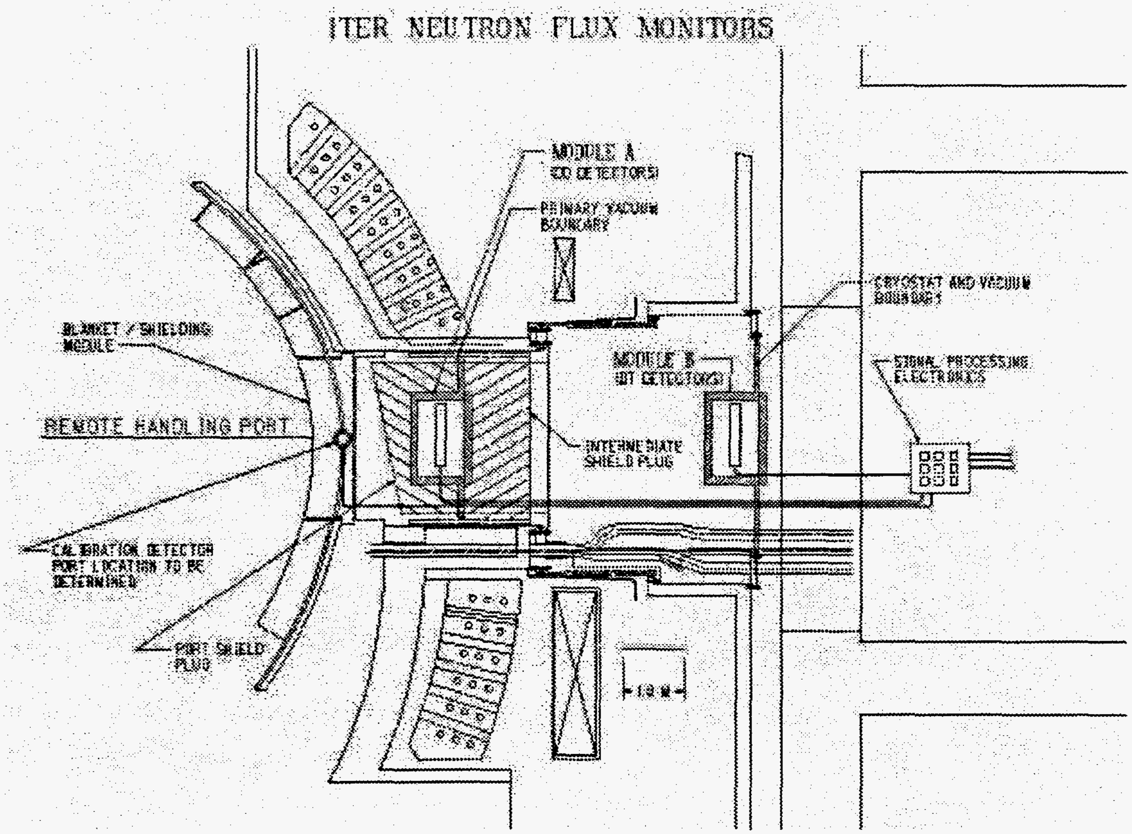

Figure 6: Elevation view of remote handling port depicting locations of one set of neutron source strength monitors. Module A contains 2 fission chambers for DD operation and is re-entrant into the primary vacuum shield block. Module B contains 3 fission chambers for DT operation and is re-entrant into the cryostat vacuum boundary. A calibration detector located near the plasma is the sixth fission chamber in the set.

bolometer channel also to be placed there. We may also try to use one of the micro-fission detector[17] locations at the back of the blanket shield module (BSM). Our "calibration detectors" are thus not in "limiter/Remote handling" (RH) ports and they can be calibrated by a source held *in-situ* by standard RH equipment. No special track inside the vessel would be needed. Three detectors (the least sensitive for DT operation) can go into a module "topologically outside the interspace vacuum" (see Module B in Figure 6) on a coverplate of the secondary vacuum wall in a re-entrant configuration. They are thus outside of any vacuum (but inside bioshield). A variation of sensitivity of a factor of 25x25 can be achieved between these three detectors by changes in fissionable mass. Commercially available fission detectors with up to 10 grams now exist.

This leaves two detectors (the middle range of sensitivity, for ohmic and/or DD operation) which must go into a different module (Module A of Figure 6) with less shielding in front of it than the least sensitive ones in the module B outside the interspace vacuum. The module of two detectors of intermediate sensitivity would need to be in the interspace vacuum, just outside the primary vacuum shield block. The need for three locations (most sensitive, least sensitive, and middle sensitivity) is dictated by the desire to use count mode over the entire dynamic operating range of ITER and by the requirement to use machine shielding (and distance) to provide some of the dynamic range. The least sensitive and middle sensitive modules can hopefully be part of the plug assembly for the limiter/RH ports.

Two similar sets of six detectors are then required at two different toroidal locations. In addition to basic redundancy, two arrays of monitors are needed to: control for local changes in shielding and hence detector efficiency over time; control for local noise sources like RF interference; and control for localized neutron production from runaway electrons or disruptions.

Details of Fission Chambers in Modules

Each detector is inserted into a double-walled stainless steel module box with hydrogenous material for moderation (polyethylene, about 8 cm thick between the walls), attached to the lid of the module for easy removal by remote handling. The stainless steel provides fireproofing as well as radio frequency shielding. The modules need not be vacuum tight. From each module, through a vacuum penetration in the cryostat, runs a single 10-cm diameter electrical conduit containing the electrical connections. No electronics are needed in the detector modules, because modern fission chambers operate with low-capacitance, low-leakage cables many hundreds of feet long.[19] The electronics can be outside the reactor hall in the diagnostics building. In each module there will be one "blank" or fissionable-material-free detector to help identify noise issues. In general, the renormalization (radioactive) sources can just be built-in to the modules, and not have to have any technique to insert or remove them. They provide a constant background of a low counting rate that can be subtracted from the signals. However, each detector may require its own source because of the wide variation in sensitivity of detectors in a module.

Module Name	Detector	Mass (g)	Maximum Source Strength (n/sec)	Efficiency (counts/ neutron)
Cal	NE-1	10	4.0e14	2.5e-10
A	NE-2	10	1.3e16	8e-12
A	NE-3	5	2.6e16	4e-12
B	NE-4	6	6.6e17	1.5e-13
B	NE-5	0.25	1.6e19	6e-15
B	NE-6	0.01	4.0e20	2.5e-16

Table 1: Representative set of 6 detectors for the ITER Neutron Source Strength Monitors.

Table 1 shows a representative set of six detectors for the neutron source strength monitor array. The maximum source strength is that which provides 100-kHz count rate at the detector. The 100-kHz count rate is chosen as a rate where pileup and dead time effects are small and easily accounted for. This set will measure a range of source strength all in counting mode from 4×10^{20} n/sec to below 10^{14} n/sec with lower counting rates in NE-1. Following Figure 5 the flux is assumed to decrease by a factor of 30 between the calibration detector location and Module A, and by another factor of 30 between Module A and Module B. The actual detector array for ITER will be different, depending on final design and exact location and neutronics analysis. This table does reflect how the design conditions can be met.

In practice the efficiencies of some detectors may have to be adjusted in the field to achieve the required ranges of sensitivity. Such adjustments are readily made with thin sleeves of cadmium, which has an exceptionally high absorption cross section for very slow (<0.4 eV) neutrons. The detector efficiency can be reduced as required by wrapping the detector body in a cadmium sleeve of appropriate thickness. With the expected degree of neutron thermalization in the modules, a factor of 2 reduction in efficiency is achieved with 0.5 mm of cadmium.

It will be important also to have time-dependent monitors of the DT neutron emission rather than just the total emission, for initial triton burnup work but more importantly for trace-tritium shots and tracking tritium clean-up in DD shots. Possible threshold detectors for this purpose are radium-based fission chambers, silicon surface barrier diode detectors, scintillating fiber detectors, and natural diamond detectors. Additional types of threshold detectors are presently under development.[20] The fission threshold of ^{226}Ra at 3.0 MeV makes a radium-based fission detector all but impervious to D-D neutrons that have nominally 2.5 MeV. (One would still detect the extremity of the D-D tail in the case of beam-target reactions.) Such a detector could in principle measure only the D-T neutrons in a mixed DD-DT flux. However, the fission cross section $\sigma_f = 0.02$ barn at 14 MeV[21] is very small (more than 5000 times smaller than the thermal cross section for ^{235}U), so that a large mass or huge neutron flux is needed for adequate sensitivity. Because ^{226}Ra is an intense alpha emitter (half-life = 1620 yr), the noise discrimination problems would be much more severe than with uranium-based detectors. Alpha pileup is also a serious issue. A study at ORNL concluded that it is not practical to put more than 10 mg of radium in a single detector, both because of alpha pileup and because of safety problems in fabrication. However, several radium-based detectors could be used in parallel for increased sensitivity. A 0.1-g radium detector array at the location of Module A would require a neutron source strength of $2x10^{19}$ n/s (56 MW fusion power) to generate a minimal count rate of 500 c/s. That means that the detector would be useful only when the D-T neutron flux is so large that there is no need to discriminate against D-D neutrons. Silicon surface barrier diodes[22] are sensitive to neutrons with E_n>4 MeV and generally use a system threshold set at 5.5 MeV. The efficiency to neutron detection is typically 0.001 counts per unit flux. At the front of module A this would enable useful operation with a D-T source strength of $5x10^{16}$ to $5x10^{18}$ n/s which is ideal for trace-tritium operation in ITER. One would like a factor of 10-100 higher sensitivity for D-D triton burnup which would imply a location near the close-in calibration detectors. SBDs have a lifetime of about 10^{12} n/cm^2; at the cryostat wall with a neutron flux of 10^8 n/cm^2/s they would only last 10 full-powered 1000-sec long discharges. Such detectors would still provide valuable information on ITER during the period prior to full-power operation; they could be installed in the source strength monitor module boxes and sacrificed when full-power tritium operation begins. Scintillating fiber detectors[23] use a directional array of fibers and pulse-height analysis to reject Compton recoils from gamma interactions and low-energy proton recoils from DD neutron interactions. They have been successfully used for triton burnup and 14-MeV neutron dectection with better efficiency and time response than silicon diodes. Diamond detectors[24] are also radiation resistant; in addition to use in the neutron cameras they might be useful as DT source strength monitors.

Key Outstanding Issues

1. Different neutronics calculations of the ITER environment[16] have reached conclusions about the drop off in neutron flux to the bioshield that differ by a couple orders of magnitude. This difference needs to be resolved to better determine the location of the source strength monitors. Also, the effect on the neutron flux of the shield plug in the limiter port needs to be ascertained.
2. The exact location of the calibration detectors needs to be negotiated.
3. The selection of complementary energy-sensitive (DT only) flux monitors needs to also be made.

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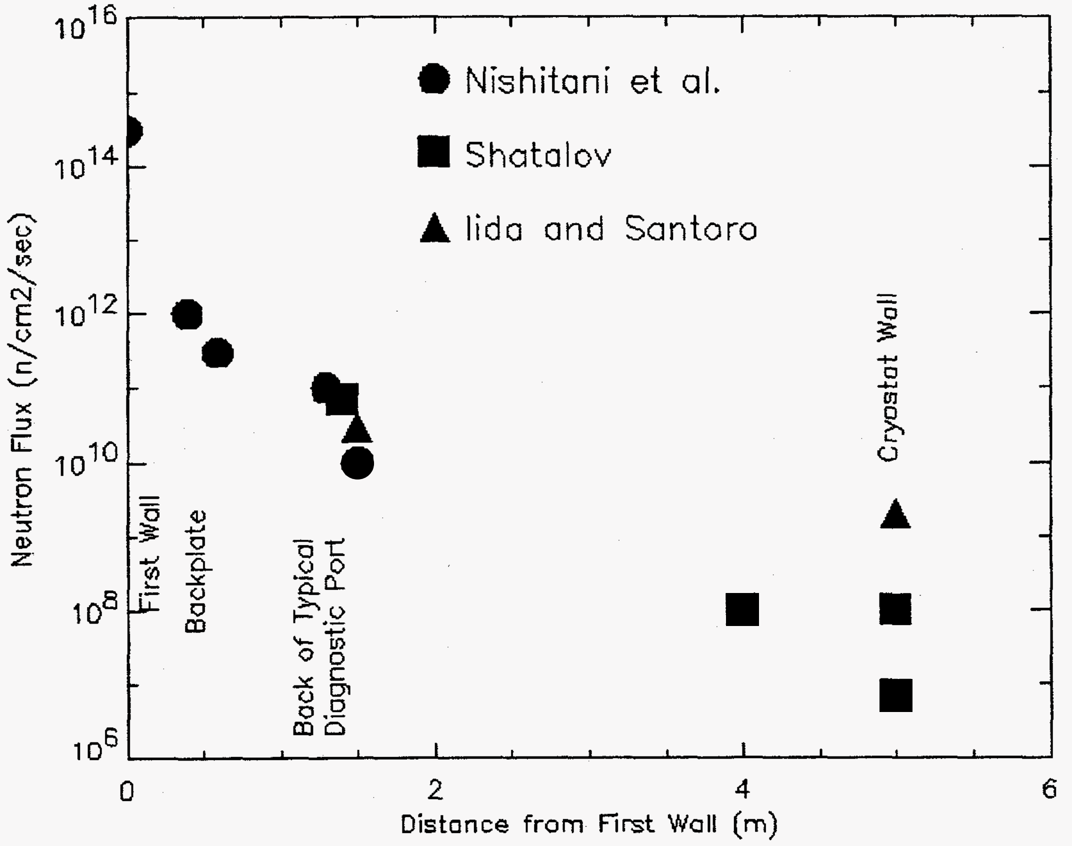
Neutron Flux (n/cm2/sec)
10^16
10^14
10^12
10^10
10^8
10^6
0
2
4
6
Distance from First Wall (m)
● Nishitani et al.
■ Shatalov
▲ Iida and Santoro
First Wall
Backplate
Back of Typical Diagnostic Port
Cryostat Wall