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Title: **NEUTRON ACTIVATION FOR ITER**

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Neutron Activation for ITER

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Abstract

There are three primary goals for the Neutron Activation system for ITER: maintain a robust relative measure of fusion power with stability and high dynamic range (7 orders of magnitude); allow an absolute calibration of fusion power (energy); and provide a flexible and reliable system for materials testing. The nature of the activation technique is such that stability and high dynamic range can be intrinsic properties of the system. It has also been the technique that demonstrated (on JET and TFTR) the highest accuracy neutron measurements in DT operation. Since the gamma-ray detectors are not located on the tokamak and are therefore amenable to accurate characterization, and if material foils are placed very close to the ITER plasma with minimal scattering or attenuation, high overall accuracy in the fusion energy production (7%--10%) should be achievable on ITER. In the paper, a conceptual design is presented. A system is shown to be capable of meeting these three goals, also detailed design issues remain to be solved.

I. Introduction

The International Thermonuclear Experimental Reactor (ITER) is intended to be a long-pulse burning plasma experiment capable of providing the physics and technology database necessary to implement a demonstration fusion reactor. The 1.5 GW fusion power device will place extreme requirements on its plasma diagnostic systems. Central to the mission of the machine is the ability to accurately and precisely monitor the fusion power. Neutron activation has been the technique that demonstrated (on the JET[1] and TFTR[2,3] tokamaks) the highest accuracy neutron measurements in DT operation, and without the need for *in-situ* source calibration. This paper describes issues relevant to a conceptual design for a neutron activation system for ITER.

II. System Requirements

There are three primary goals for the neutron activation system on ITER:

1. Maintain a robust relative measure of fusion power with stability and high dynamic range.
2. Allow an absolute calibration of fusion power (energy).
3. Provide a flexible system for materials testing. Such materials testing can include accurate measurements of some weak reactions previously not accessible on present neutron sources at accelerators.

There are two problems in determining the total neutron yield and fusion energy production from neutron activation. First, the "efficiency" of the neutron activation detectors can be separated into two parts: the activation cross-sections which are "physical" and unchanging and (for dosimetric reactions) are well-known with quantified uncertainties; and then the efficiencies of the gamma-ray detectors which live in a lab and, unlike other neutron counting systems, not on the tokamak. Thus the efficiencies of the gamma-ray detectors tend to be a well-characterized and they remain stable. The second problem is that of determining the fluence-to-yield ratio at a given location. This problem has succumbed to operating with detectors (foils) in close-proximity to the plasma and to careful neutronics modeling[4]. Assuming we can get material foils very close to the ITER plasma with minimal scattering or attenuation, we should be able to achieve similar 7%-10% accuracy (or better) on ITER in the neutron production.

A. Response Sensitivity and Mass of Foils

Given the higher fusion power level and assuming elemental foil locations near the surface of the blanket/shield modules, despite the larger size of ITER the expected activation rate is about 10 times greater than TFTR or JET *per second!* For operation at full power less mass can be used; however, there is a minimum amount of sample mass (or sample mass density in a fluid system) that one can use before contamination and background become issues[5]. Removing the irradiated sample material from the encapsulation for counting can mitigate contamination, but with significant engineering issues to avoid personnel dose. One cannot choose to use arbitrarily small cross-section reactions as they are not dosimetry standards and one looses the absolute calibration. Such reactions could be used after cross-calibrating to dosimetric standard reactions; even so, only about a factor of 100 in sensitivity can be expected from using small cross-sections before signals are overwhelmed by competing reactions Thus we expect to end up with very radioactive samples. If we use short half-life activities, then the samples are very hot (must be counted far from detectors which can be problematic). If we use long half-life (10^6 --10^8 seconds!) activities then we cannot reuse the samples. However, samples with medium half-lives (of order one day) for 1% efficient detection (very reasonable) works. Assuming the transfer time of a sample is of order one second, we would want to leave samples near the plasma many times that duration (a new sample every 100 seconds). The activation desired for a sample should be similar to that provided by a standard source used for absolute calibration of the gamma-ray detectors. A typical maximum value for modestly safe handling would be 100 μCi. Figure 1 shows the source strength of neutrons needed to create 100 μCi samples in 100 second exposures for various reactions at a typical location around ITER. Operation at low mass (to the left of the figure) are problematic because of contamination. Above 100 grams the self-absorption of the samples and the increased and varying sample-detector distance makes adding mass not as effective, and the calibration looses accuracy. The silicon reaction is too sensitive; the nickel reaction is very long-lived (70 days) and thus creates samples which create a modest waste problem. But iron, aluminum, and titanium foils appear to allow for reasonable sensitivity without creating sources too hot, especially if samples may be sent and retrieved from the discharge to limit the exposure duration. Other non-dosimetric reactions can also be used after cross-calibration.

B. Location of Irradiation Ends

To maintain the high accuracy, the system needs to maintain insensitivity to profile and position dependence of the neutron emitting region. On TFTR, a circular tokamak held in the z-plane, this was relatively easy. There was a ~15% decrease in signal from the single re-entrant irradiation end on the top of TFTR from an increase in major radius of ~0.6 m of the plasma[4]. Any toroidal variation of the neutron fluence can be ignored. Multiple measurements at different poloidal locations are needed for ITER because of the asymmetric, elongated plasma. Figure 2 shows a cross-section elevation of ITER and the location of the blanket/shield modules. As on JET, ITER will need probably 3 (with a 4th for redundancy) poloidal locations instrumented for neutron activation. Another set of irradiation ends at a different toroidal location (for 8 total irradiation ends) would also be desired for redundancy against failure.

The sensitivity of locations at each module to movement of the neutron emitting region can be estimated analytically. The approximation that the neutrons are emitted from a toroidal line source is a relatively good one[6]. While the absolute value of the activation response depends on detailed scattering calculated from neutronics models, the relative trends of the response as the plasma source is moved around follow the analytic formula of Zankl[6] quite well[4]. It is also found that the trends are insensitive to the breadth of the neutron profile. Figure 3 shows the percentage relative change in the analytic response per meter of movement of a toroidal line source for a location at the center surface of each blanket/module, plotted as the poloidal angle of the module. In general, one needs to measure in the direction of movement to be sensitive. If two irradiation ends were at -50° and 110° then dResp/dR is +10% for the first one and -10% for the second and dResp/dz is about -25% for the first and about +25% for the second. Simultaneous irradiation in these two ends would allow averages to be taken which would cancel out movements of the plasma even when both occurred at the same time. These positions avoid proximity to the divertor and the attendant problems for neutron transport calculations. Two more irradiation ends could be positioned at 0° (no sensitivity to dz) and 80° (no sensitivity to dR). These irradiation ends could be used to check dResp/dR and dResp/dz for the other two irradiation ends. Quite possibly "extreme" radius (or height) plasmas will be run to quantify neutron camera calibrations and scattering; these should be prepared for. 4 typical blanket/shield modules that would need to be instrumented to provide the up/down and in/out measurements for neutron activation are highlighted in Figure 2.

To achieve the goal of high accuracy with neutron activation will require the foils to be positioned relatively close to the plasma. The thickness of material between the plasma and foil must be minimized, both to reduce attenuation but more to minimize scattering. What is worse than material thickness is variations in mass density along different lines-of-sight toroidally (or poloidally). Thus, buried inside a shield module may be satisfactory *if* a relatively uniform (and very well characterized!) amount of material surrounds the irradiation end.

C. Equipment in Blanket/Shield Modules

The activation of "solid" material samples, or "foils", does a time-integrated measurement. We will want to move samples in and out *during* the ITER pulse, to make measurements during only fractions of the shot duration (both for some time-dependence but primarily to avoid foils too hot to count). Thus we will need to worry about timing problems and monitoring the position of the foils. Moving magnetic samples (like iron) might be problematic, but the masses will be very low. We thus will probably want robust monitors of sample position near the machine, to insure the foils remain in place and to provide the timing information when they arrive and leave. For an irradiation end on the bottom of the machine where gravity will pull the foils down and away from the plasma, the foils will need to be held in place by air constantly on, as JET does.

If material samples are placed and removed during a pulse, we need to worry about the duration the foil spends near the plasma during the transfer. However, the fluence drops tremendously with further distance from the plasma, and at the desired fast transfer speeds the resulting few milliseconds in transit won't matter. Again, assurances that the foil was in position and stayed there during the exposure will be more important.

The irradiation ends should be located just behind the first wall cooling pipes in amongst the support structure cooling pipes. If they were located back at the shield surface there would be 122 mm of material to the plasma which would cause too much attenuation. Using one of the 23 mm OD, 20 mm ID support structure cooling pipes *instead* as a transfer tube for the activation system may not be consistent with power handling needs. Also, the number and sharpness of bends in the cooling pipes are not conducive to a pneumatic transfer system, where typically the radius of curvature of any bend must be many times the length of the capsule. A special pipe may be needed, with extra cooling around it.

Flowing or liquid-activation systems[7] have been considered. In general the coolants (in the coils or blankets) are too far from the plasma to achieve any accuracy in such a measurement. The technique of marrying neutron activation and fluid flow is generally used as a method to use a *known* neutron source to measure fluid flow. A flowing system might be able to sample all around the plasma in a single channel and achieve some insensitivity to variations in neutron emission location. We still think it would be easier to have separate signals to do analysis on rather than integrating a single channel.

D. Other Design Considerations

We want a system that not only provides a calibrated signal, but also can be used for materials tests. A reaction of only 1 mbarn cross section, a year half-life, and only 5% isotopic abundance in a 10 gram sample will still give over 10 counts per second after exposure to a 1000 second full-power ITER discharge. Thus pneumatic capsules capable of no more than 10 gram samples (similar to that used on TFTR and JET and requiring about 1 inch diameter plumbing) is desired. The 2 cm ID of the support structure cooling pipes are consistent with this mass and sample size; a 1 cm ID system would also still be big enough.

At least one detector of high energy sensitivity and very low background is desired for flexible purposes, with low background more important than high efficiency. Such a detector needs to be placed in a low background counting area. The other detectors can be simpler with lower resolution for routine measurements. Those routine measurements should have plenty of activation, so again low efficiency is allowed. There must be plans to do "renormalization" procedures and routine absolute calibration of system components.

There may be a problem with capsule contaminants and achieving low-mass samples[5] with small dose from manual handling. At the intense fluences of ITER, capsule contaminants (for example, sodium that might interfere with the $^{27}Al(n,\alpha)^{24}Na$ reaction) may provide a lower bound on the mass of the foils used (so that the signal from the foil is much greater than the "noise" from the contaminant). But this lower bound mass may be too large to allow manually handling of the foils for a considerable time. Measuring and quantifying the contaminants in the capsules may be difficult given again the intense fluences expected on ITER. The transfer system should thus be designed to insure entirely remote handling, but while maintaining flexibility in the order and timing of the irradiations and counting.

The JET "carousel" system for switching between irradiation ends and counting stations seems the best type of solution for flexibility and operation. By placing the carousel inside the tritium containment boundary, the complex purging of pneumatic tubes and switching to remove activated air may be minimized or at least simplified. However, maintenance access to the carousel will almost certainly be required. The design of the pneumatic system should maintain a modular approach to counting room and pneumatic layout so it is easy to change and upgrade. A desirable requirement would be to engineer very fast transfer times of samples to at least one counting station. This won't be routinely needed, but strongly increases the system usefulness for materials testing, and other special work. (An example is detection of the 800 msec beryllium decay from knock-on neutrons.) The TFTR system operates at about 10 m/sec transport speed. If the counting room for the NA system is located 100 meters from the tokamak we might want an order of magnitude faster transport speed. We should strive for relatively automated operation, with a documented audit trail of which foils sent where and when. The overall system emphasis is two-fold: robust routine operation, and otherwise a flexible system to maximize scientific usefulness. However, careful consideration of safety issues with both hardware and procedural controls will be necessary.

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Figures

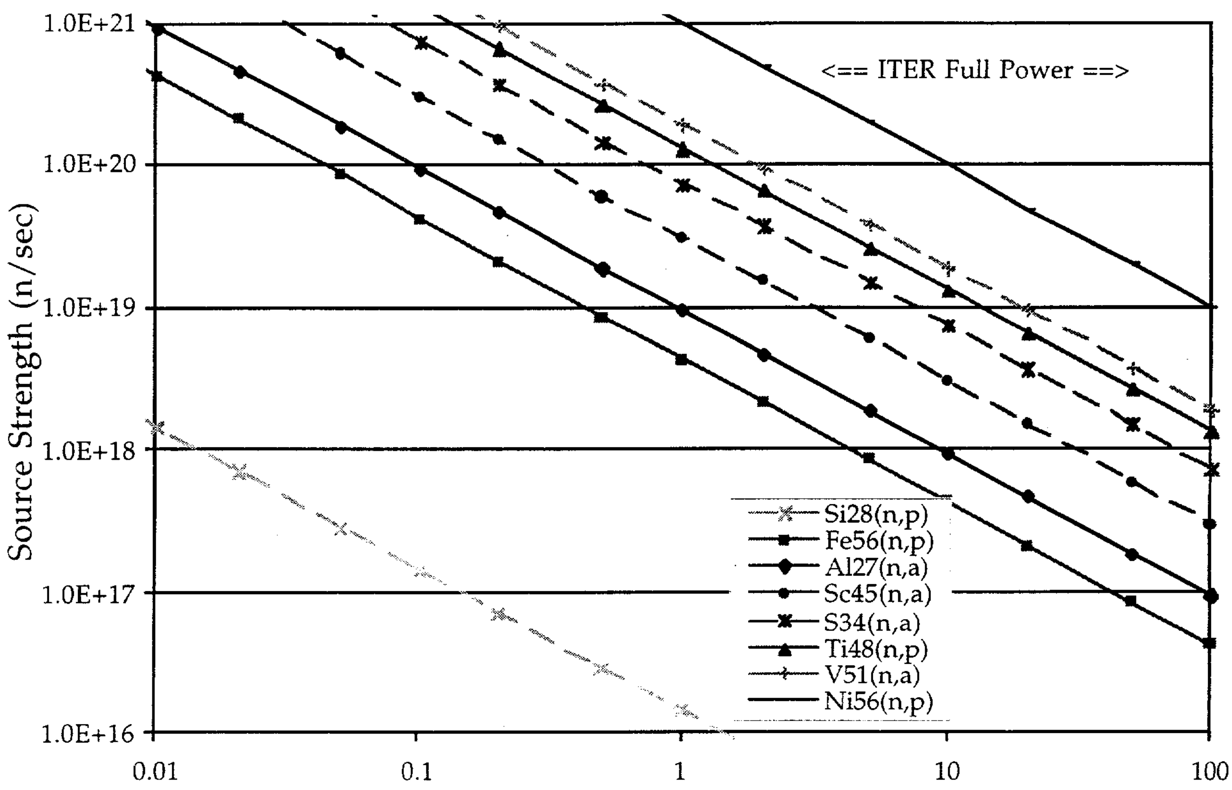

Figure 1: Source strength required to create 100 microCuries of activity in a 100 second exposure for a given mass of material. Irradiation location at top of machine (foil radius 8.7 m, foil height 6.0 m, poloidal angle 85°). Reactions are listed from most sensitive to least.

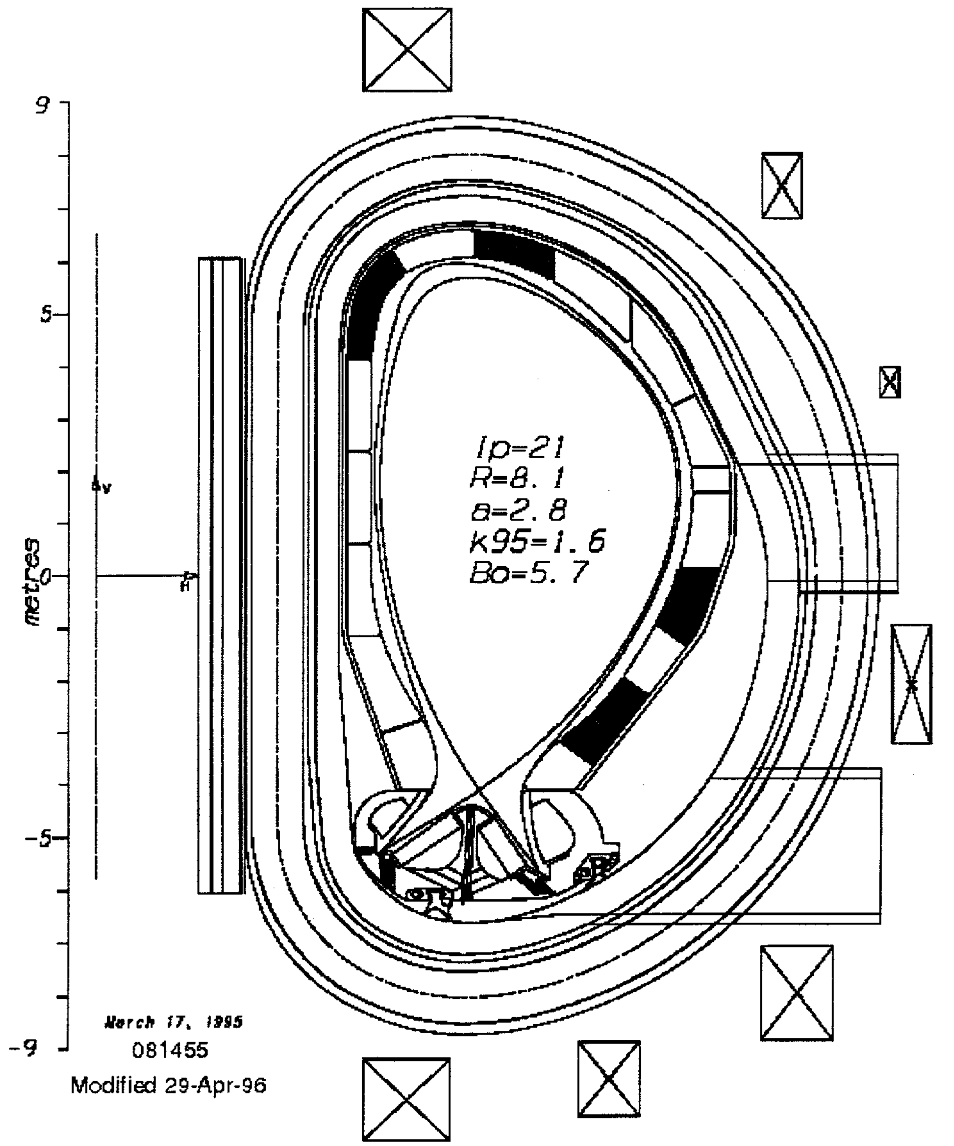

Figure 2: Cross Section elevation of ITER. Shaded regions show suggested locations of activation irradiation ends.

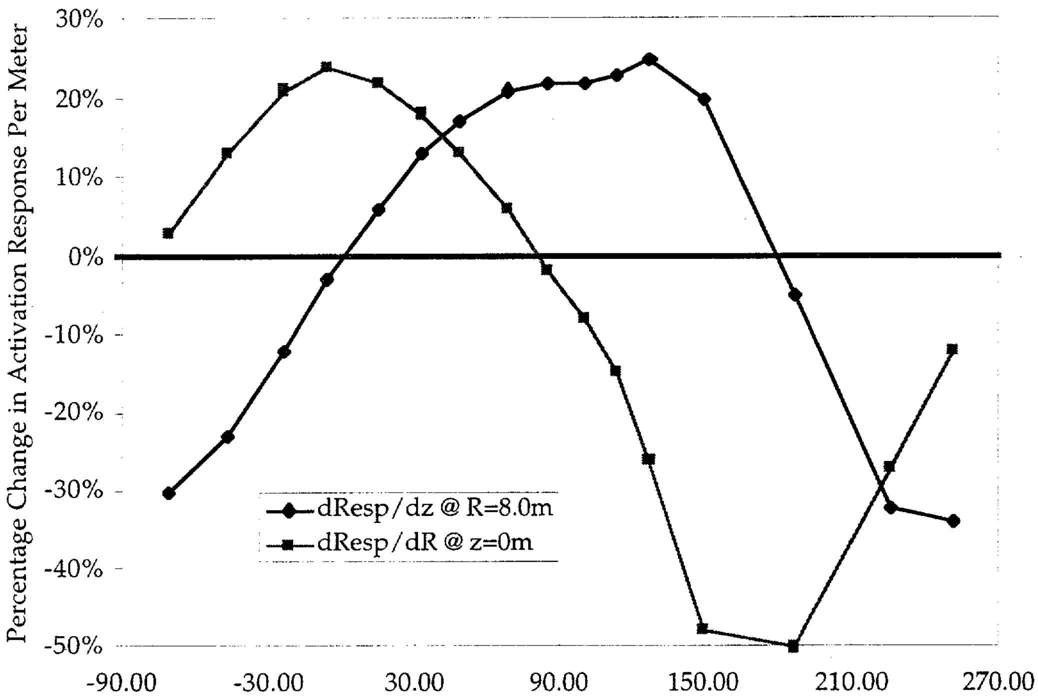

Figure 3: Percentage change in activation response per meter as toroidal line source of neutron emission is moved. The diamonds are caused by variation in the z direction, and the squares are for variation in the R direction. Zero degrees is the outboard midplane.

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