A high-resolution neutron spectroscopic camera for the SPARC tokamak based on the Jet European Torus Deuterium-Tritium experience

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Dedicated nuclear diagnostics have been designed, developed and built within EUROFUSION enhancement programs in the last ten years for installation at the Joint European Torus (JET) and capable of operation in high power Deuterium-Tritium (DT) plasmas. The recent DT Experiment campaign, called DTE2, has been successfully carried out in the second half of 2021 and provides a unique opportunity to evaluate the performance of the new nuclear diagnostics and for understanding of their behavior in the record high 14 MeV neutron yields (up to $4.7 \cdot 10^{18}$ n/s) and total number of neutrons (up to $2 \cdot 10^{19}$ n) achieved on a tokamak.
In this work we will focus on the 14 MeV high resolution neutron spectrometers based on artificial diamonds which for the first time have extensively been used to measure 14 MeV DT neutron spectra with unprecedented energy resolution (FWHM of ≈1% at 14 MeV). The work will describe their long-term stability and operation over the DTE2 campaign as well as their performance as neutron spectrometers in terms of achieved energy resolution and high rate capability.
This important experience will be used to outline the concept of a spectroscopic neutron camera for the SPARC tokamak. The proposed neutron camera will be the first one to feature the dual capability to measure i) the 2.5 and 14 MeV neutron emissivity profile, via the conventional neutron detectors based on liquid or plastics scintillators, and ii) the 14 MeV neutron spectral emission via the use of high-resolution diamond-based spectrometers.
The new opportunities opened by the spectroscopic neutron camera to measure plasma parameters will be discussed.

I. INTRODUCTION

Dedicated nuclear diagnostics have been designed, developed and built within EUROFUSION enhancement programs in the last twenty years for installation at the Joint European Torus (JET) and capable of operation in high power Deuterium-Tritium (DT) plasmas[1]. In a DT plasma, fusion neutrons are emitted in the reactions $D+D \rightarrow He^3+n$ (2.5MeV) and $D+T \rightarrow He^4+n$ (14.1 MeV). Neutron measurements are used to determine the DT fusion power and to assess the fuel ions (D or T) distribution functions, including the effects of external heating. The recent JET DT Experiment campaign, called DTE2, has been successfully carried out in the second half

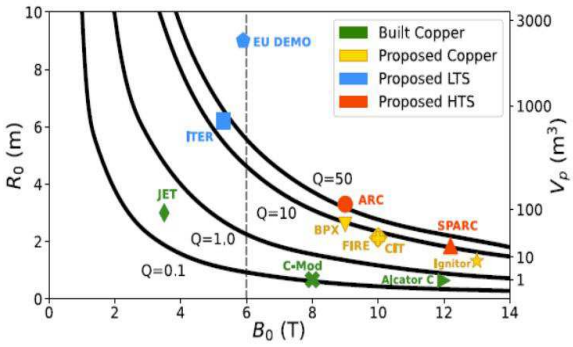

Figure 1: Calculation of the expected fusion gain Q as a function of the main toroidal magnetic field B_0 and major radius R_0. See the text for details of the plotted points.[8]

of 2021 and provides a unique opportunity to evaluate the performance of the developed nuclear diagnostics in the record high 14 MeV neutron yields (up to $4.7 \cdot 10^{18}$ n/s) and number of neutrons (up to $2 \cdot 10^{18}$ n) ever achieved in Magnetic Confinement Fusion (MCF)[2]. The JET neutron diagnostic suite consists of: i) counters (U235 and U238 fission chambers and activation foils) which are used for the measurements of the total 2.5 and 14 MeV neutron yields and fluences[3]; ii) neutron/gamma ray cameras for spatial profile measurements of the radiation emission[4,5]; and iii) high resolution neutron spectrometers for measurements of the neutron energy spectrum[6].

We propose here to develop the next generation of neutron camera which combines spatial profile and spectroscopy measurements for a DT tokamak. This would be possible by employing CVD (Chemical Vapour Deposition) single crystal diamond detectors that can offer high energy resolution in a compact size[7]. During the last JET DT campaign CVD diamond detectors have been extensively and successfully used along collimated and non-collimated lines of sights.

Starting from the objective of the SPARC tokamak[8], the paper will describe the predicted performance of the diamond detectors for the expected neutron fluxes at the camera position and will outline the enhanced plasma diagnostic information that can be achieved.

II. SPARC TOKAMAK

SPARC is a Deuterium-Tritium (DT) tokamak which will be built by the private fusion startup Commonwealth Fusion Systems in collaboration with the Plasma Science & Fusion Center of Massachusetts Institute of Technology[8]. SPARC combines the unique features of a compact size (major radius of 1.85m) with high magnetic fields (toroidal field up to 12.2 T in the center), thanks to recent advances in high-temperature superconducting magnets.

The main goal of SPARC is to demonstrate for the first time - and within this decade - that a tokamak can achieve an energy gain. The best result at present has been

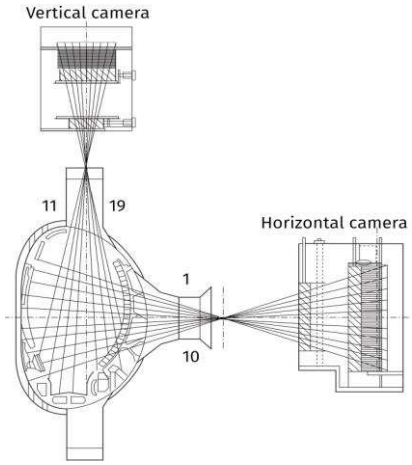

Figure 2: Schematic of the JET neutron camera and of the 19 lines of sights into the plasma shown on a poloidal plane[4].

achieved by JET and is a Q value equal to 0.7 for a short transient time. Conservative extrapolation indicates (see Fig. 1) that the SPARC machine should achieve a Q value above 2, with the possibility to reach up to Q value larger than 10 and fusion power in excess of 100 MW[8]. SPARC would be the first tokamak to approach and study the so-called burning plasma regime, and the large expected neutron yields (up to about $5 \cdot 10^{19}$ n/s) offer a unique opportunity for a neutron diagnostic system to provide high time, space and energy resolution diagnosis of the plasma.

III. JET NEUTRON CAMERA

The JET neutron camera was built in the early 90's and consists of two cameras, one horizontal and one vertical with 10 and 9 collimated lines of view, respectively, that measure the neutron emission (see Fig. 2). Two concrete shieldings protect the detectors from background radiation from γ-rays and scattered neutrons. The collimator cross sections are rectangular measuring 44x25 mm^2 (horizontal camera) and vary from 25x18 mm^2 (channel 11) to 25x25 mm^2 (channel 19) for the vertical camera. Collimator inserts make it possible to reduce the aperture. The collimator arrays are placed in blocks made of high-density concrete. Two sets of neutron detectors are used: liquid scintillators (NE-213, of diameter 2.5 cm) which measure the 2.5 and 14 MeV emission in D plasmas and can separate neutron from γ–rays via pulse shape discrimination; plastic scintillators (BC-418, of 1 cm thickness) which were installed before the first DTE1 campaign for 14 MeV measurements in DT[4]. There is a movable slit in front of the cameras, into which gamma ray detectors (LaBr3 scintillators coupled to SiPM) can be inserted. This allows the measurement of gamma rays in experiments dedicated to the study of fast ions and of bremsstrahlung X-ray radiation from runaway electrons[5]. The aim of the neutron camera is to measure the spatial neutron emissivity from the JET plasma. An example of

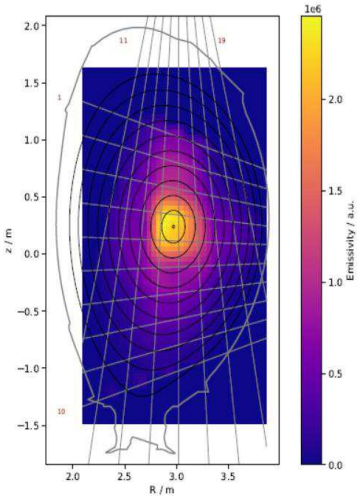

Figure 3: Example of neutron tomographic reconstruction for JET DT discharge #99608.

tomographic reconstruction is shown in Fig. 3 for a DT discharge. In general, very limited or no information about the neutron energy spectrum is available from the camera due to the characteristic flat response of the scintillator to incoming neutrons and some instrumental effects.

IV. NEUTRON EMISSION SPECTROSCOPY

The most advanced neutron diagnostic is called Neutron Emission Spectroscopy (NES). By using custom high-resolution spectrometers, NES measures the neutron energy spectral shape, which is related to the fuel ion (D and T) velocity distribution. If the plasma is thermal, the 2.5 MeV and 14 MeV neutron spectra have Gaussian shapes, and the broadening can be directly related to the ion Temperature T_i. In general, the presence of external heating in the form of Neutral Beam Injection or Radio Frequency modifies the velocity distribution of the ions and in turn creates specific features in the neutron spectrum, such as the appearance of high energy tails. By the use of suitable plasma models, it is still possible to separate this non-thermal from the thermal emission[9].

The state-of-the-art high-resolution neutron spectrometers in MCF are the Magnetic Proton Recoil Upgrade (MPRu) for 14 MeV neutrons and Time of Flight Optimized Rate (TOFOR) for 2.5 MeV neutrons, in DT and D plasmas, respectively[6,7]. MPRu and TOFOR are installed at JET on individual lines of view into the plasma and have successfully operated over several experimental campaigns. These advanced instruments offer very good spectral resolution, but their complexity and size limit the possibility of installing them on multiple lines of sight.

In recent years, compact 14 MeV neutron spectrometers based on Chemical Vapor Deposition (CVD) single crystal diamonds 10 were installed within various JET enhancement projects1[1,12]. Among these, there is the 12-pixel matrix on a vertical line of view, and single-pixel diamonds on two collimated lines of views in well shielded locations (see Fig. 4).

The first use of a diamond natural crystal for 14 MeV neutron spectrometry on a DT plasma was done by

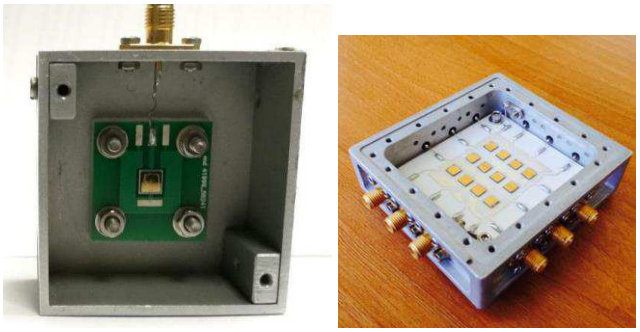

Figure 4: Photographs of prototypes of single crystal diamond detectors developed for the JET tokamak in a single-pixel (left) and 12-pixel (right) configuration[16].

Krasilnikov on the TFTR tokamak in 1996[13]. Later artificial CVD diamonds have been used at JET by Pillon mainly as neutron yield monitor in D plasmas[14]. In recent years the availability of high quality single crystal CVD diamond combined to custom developed preamplifiers and fast digital data acquisition has allowed to perform 14 MeV neutron measurements at very high energy resolution and count rate capabilities above 1 MHz[1].

Neutron detection in diamond sensors is based on the collection of the pairs of electrons/holes produced by either the charged products of nuclear reactions between fast neutrons (above about 5 MeV) and ^{12}C ions, e.g. the $^{12}C(n,\alpha)^{9}Be$ reaction, or recoil ^{12}C ions generate via neutron scattering. A typical response of single crystal CVD diamonds to quasi-monoenergetic 14 MeV neutrons, shown in Fig. 5, features several peaks and structures, associated with the various possible reaction mechanisms[9]. The peak centered at 8.5 MeV, equal to the incoming neutron energy minus the Q value of about 6 MeV, is due to the collection of the energy deposited by the α and ^{9}Be charged particles of the reaction $^{12}C(n,\alpha)^{9}Be$ and is used to perform high-resolution neutron spectroscopy. Thanks to the narrow response (a FWHM of about 1% can be achieved), details of the neutron spectrum can be studied. For 2.5 MeV neutrons, their interaction with the diamond is only via elastic scattering reactions and features a broad response, similar to liquid scintillators. Due to this flat response only a limited spectroscopy is possible[15].

While the quality of the commercial CVD single crystal diamond is very high in terms of purity, the available crystal sizes are still small (the largest size is 5.0x5.0x0.5 mm^3). In order to increase the detection efficiency, a matrix configuration of detectors has been realized (see Fig. 4)[16]. Yet there are specific issues that must be taken care of and optimized, starting from the realization of the diamond contacts to extract the charge through the preamplifier/electronics and the handling of so-called polarization effects which can affect semiconductor detectors at high irradiation rates.

The experience during the JET DT campaign has demonstrated that the CVD diamond technology is reliable

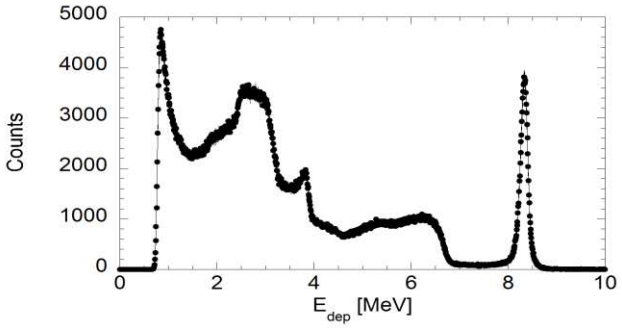

Figure 5: Response of a single crystal diamond detector to monoenergetic 14 MeV neutrons. The peak centered at 8.5 MeV is used for high resolution neutron spectroscopy of the incoming neutron spectrum[19].

and can be used in the high neutron fluxes of a DT plasma. The data collected have shown that, when equipped with suitable fast charge preamplifiers and digitizers, counting rates up to 1 MHz can be reliably sustained in pulsed mode operation.

V. SPARC NEUTRON CAMERA

The SPARC neutron camera is in its preliminary design and currently consists of 11 line of views with collimators embedded in the concrete biological shield, at a distance of about 14 m from the tokamak center. The expected neutron fluxes at the end of the collimators cover several orders of magnitude, namely 10^6-10^8 n/cm^2·s in D and 10^7-10^{10} n/cm^2·s in DT experiments for the central midplane channel (line of view #6). Such high fluxes are the basis for designing a neutron camera which can achieve high time resolution with compact diamond detectors that typically feature a detection efficiency of 1% or less. Based on JET experience, it is proposed to use at the end of each collimator a set of neutron detectors, based on traditional plastic or liquid scintillators optimized for 2.5 MeV measurements in D plasmas and CVD diamond crystals for 14 MeV neutron spectroscopy in DT.

Expected total count rates for a single pixel CVD diamond (4.5x4.5x0.5 mm^3) crystal have been calculated in Table 1 based on the MCNP-simulated neutron fluxes and a reference detection efficiency of 10^{-2} as reported in ref [17] for both 2.5 and 14 MeV neutrons. The results indicate that rates well above 10 MHz are expected for the most optimistic plasma performance in DT and around two orders of magnitude less in D plasmas. In order to keep the highest counting rates below 2 MHz, to limit pile up and other instrumental effects, it is possible to use smaller crystals (e.g. 1.8x1.8x0.3 mm^3) with reduced volumes and thus efficiencies by a factor of 10. Combining a few of such pixels in a matrix would provide redundancy and guarantee the desired efficiency for D plasmas measurements as well.

Performing neutron spectroscopy on each channel of the neutron camera would enable the measurement of the ion temperature spatial profile.

LOV	DD Max	DT Min	DT Max
1	1.4E+03	2.9E+02	6.0E+05
2	1.0E+04	1.9E+03	3.9E+06
3	4.0E+04	7.3E+03	1.5E+07
4	1.2E+05	1.8E+04	3.7E+07
5	2.1E+05	3.1E+04	6.4E+07
6	2.4E+05	3.6E+04	7.5E+07
7	2.1E+05	3.1E+04	6.4E+07
8	1.1E+05	1.8E+04	3.7E+07
9	4.2E+04	7.3E+03	1.5E+07
10	1.1E+04	1.9E+03	4.0E+06
11	1.5E+03	3.2E+02	6.6E+05

Table 1: Expected count rates (cps) in a single pixel diamond detector for three different SPARC scenarios.

The expected SPARC neutron spectrum is expected to be mainly thermal. The only external heating is ICRH which in a burning plasma heats the bulk ions and can create high energy tails in the neutron spectrum but at the level of a few percent of the total neutron emission. We can reasonably assume here that the line integrated T_i can be directly inferred from the broadening of the neutron spectrum by the expression $W=177\sqrt{T_i}$[18] where both W, the Full Width at Half Maximum (FWHM), and T_i are expressed in keV. Assuming 1 MHz as the as maximum total counting rate in DT experiments, each pixel at the end of a collimator would feature 50 kHz signal rates under the $^{12}C(n,\alpha)^9Be$ peak. This would allow us to measure the 14 MeV neutron spectrum with a time resolution of about 100 ms and 5000 counts. Since the contribution of the detector energy resolution to the spectral broadening is negligible (about 1% FWHM), the relative uncertainties on T_i can be expressed as $\Delta T_i/T_i=2/\sqrt{(2N)}$ where N is the number of counts[18]. This means, for instance, that T_i can be measured with 2% (4%) statistical uncertainty and 100 ms (25 ms) time resolution. Additional diamond pixels on the same line of view would allow achieving the same time resolution at better statistical uncertainties. Systematic uncertainties due for instance to energy calibration are not considered here.

Concerning the data acquisition system, it is proposed to use a hybrid system that provides both real-time information of selected plasma parameters (eg. neutron emission and ion temperature profiles) and the full pulse height time-resolved spectra for advanced analysis to be performed offline.

VI. CONCLUSIONS

The development of compact, high-resolution 14 MeV neutron spectrometers based on CVD diamonds has opened the possibility to make measurements of neutron energy spectra along multiple lines of sight into a DT plasma. A spectroscopic neutron camera is proposed for the SPARC tokamak, providing both the neutron emission spatial profile and a high-resolution measurement of the neutron spectrum. The SPARC neutron camera can be designed to provide real time information of the neutron emission and of the ion temperature profiles which could be used for feedback control of the plasma.

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