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EXECUTIVE SUMMARY

This white paper will be submitted to the *U.S. FESAC Transformative Enabling Capabilities (TEC) Subcommittee* and the *Community Workshop on U.S. Magnetic Fusion Research Strategic Directions* seeking to raise awareness of the specific R&D needs to maintain a basic set of plasma diagnostics predicted to be necessary for the basic operation and control of a next-step-devices like FNSF or DEMO. Previous national panels and various reports recommended, where possible, adapt present standard diagnostic systems - for T_e & n_e (using Thomson Scattering), T_i, $v\phi$ & $v\theta$ (using Charge Exchange Recombination Spectroscopy), current density & q-profile (using the Motional Stark Effect) and radiated power (bolometers) - to the harsh environmental challenges of burning plasmas. However, in case the implementation of these diagnostic suites will become inadequate, a new development effort to replace conventional diagnostic systems will have to take place. The main issues constraining or even eliminating many conventional measurements presently installed in tokamaks and stellarators are lack of port access (due to space required for blankets, energy conversion systems as well as shielding from heat and neutrons), long-pulse operations, high neutron fluxes/fluences, gamma-induced noise and possibly, the presence of high-magnetic fields.

The harsh environmental conditions expected in next-step reactors will severely constrain or even eliminate many key diagnostics and measurements that are presently being used in D-D magnetically confined fusion plasma devices. Quite radical approaches will be needed for the management and control of the routine plasma operations by a relatively small number of diagnostics which do not rely on the presently used inductive magnetic sensors or wide-angle visible viewing optical detection systems. Additional funds (~6 M$/yr across the US diagnostic community) should be made available at DOE-OFES to foster a short- to medium-term development and implementation of key technology in support of adapting or replacing conventional diagnostics for a D-T nuclear environment. The strategy to consider must include a dedicated program for testing radiation-hardened components to withstand FNSF or DEMO-level neutron fluxes. A viable roadmap for development of x-ray sensors is presented as an example with five high-level recommendations, which include:

A) Foster community integration and interaction
B) Development of radiation-hardened semi-conductor and metallic sensors
C) Development of efficient light extractors
D) Testing sensors at ITER and FNSF/DEMO conditions
E) Developing new data analysis techniques

Each of the five high-level recommendations is also accompanied by specific guidance to foster the development of diagnostic solutions for burning plasmas. A similar path can be taken for fast-particle detection and fusion products (e.g. neutrons and NPAs), as well as microwave (e.g. reflectometry and ECE) and infrared (e.g. interferometer/polarimeter) technology. The field of diagnostic development using novel technologies for neutron, microwave, IR and x-ray measurements offers large potential for US leadership, because the tools needed for FNSF or DEMO control will likely involve engineer and scientific solutions and that have not been tested or yet developed.

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Burning-plasma diagnostics: photon and particle detector development needs

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Abstract

This white paper will be submitted to the *U.S. FESAC Transformative Enabling Capabilities (TEC) Subcommittee* and the *Community Workshop on U.S. Magnetic Fusion Research Strategic Directions* seeking to raise awareness of the specific R&D needs to maintain a basic set of plasma diagnostics predicted to be necessary for the basic operation and control of a next-step-devices like FNSF or DEMO. The *harsh* environmental conditions expected in D-T fusion reactors will constrain or eliminate many key measurements currently used in D-D experiments. A viable roadmap for development of x-ray detectors is presented as an example with five high-level recommendations. A similar path can be taken for fast-particle detection and fusion products (e.g. neutrons and NPAs), as well as microwave (e.g. reflectometry and ECE) and IR (e.g. interferometer/polarimeter) technology. Additional funds (~6 M$/yr across the US diagnostic community) should be made available at the Office of Fusion Energy Sciences (DOE-OFES) in order to assist in the short- to medium-term development and implementation of key technology in support of adapting or replacing conventional diagnostics for a burning plasma environment.

1. Motivation and Challenges.-

The US fusion community has been recognized to be a world leader in developing understanding of plasma physics and fusion plasmas due to the development of theoretical models, rapid advances in computer simulation techniques and our pioneering work in plasma diagnostics. A large fraction of such know-how is derived from a complete set of spectroscopic and particle diagnostics, which can be as costly as building fusion experiments. It is thus crucial to maintain the utilization of well-established plasma diagnostics techniques for basic diagnosis and operation of burning plasma experiments in the near future. This necessity is especially critical in the U.S. where conventional expertise, competitiveness and leadership in this domain are eroding at an alarming rate (see Greenwald panel report [1], ReNeW [2] and R. Boivin *et al*. [3][*]). Some of these reports recommended, where possible, adapt present standard diagnostic systems - for T_e & n_e (using Thomson Scattering), T_i, $v\phi$ & $v\theta$ (using Charge Exchange Recombination Spectroscopy), current density & q-profile (using the Motional Stark Effect) and radiated power (bolometers) - to the harsh environmental challenges of burning plasmas. However, in case the implementation of these diagnostic suites will become inadequate, a new development effort to replace conventional diagnostic systems will have to take place [4]; including a dedicated program for radiation hardening of new components to withstand high fluence while operating in high neutron flux. A valuable suggestion from our community has been for instance that, in addition to, or instead of magnetic measurements, FNSF/DEMO should make extensive use of neutron, microwave, infrared (IR) and soft x-ray (SXR) measurements [5]. We believe the field of diagnostic

[*] Specific needs for developing new diagnostics bridging the gap between computer simulations and experiments have been recognized by several national panels and white papers (see R. Boivin *et al*. [3]) but will not be addressed here.

development using novel technologies for neutron, microwave, IR and x-ray measurements offers large potential for US leadership, because the tools needed for FNSF/DEMO control will likely involve engineer and scientific solutions and that have not been tested or yet developed.

The main issues constraining or even eliminating many conventional measurements presently installed in tokamaks and stellarators are lack of port access (due to space required for blankets, energy conversion systems as well as shielding from heat and neutrons), long-pulse operations > 1000 s, high D-D and D-T neutron fluxes, gamma-induced noise and possibly, the presence of high-magnetic fields. Even if the diagnostic systems at ITER perform as expected, it is unlikely that those diagnostic systems will be installed on next-step burning plasma experimental devices. The stored energy in FNSF/DEMO devices will be at least 5× larger than the stored energy in ITER plasmas, which will already be 100× larger than stored energy in JET plasmas, so that the avoidance of disruptions will be absolutely necessary. As such, the consequences due to an insufficient set of diagnostics or particular diagnostic failures will be catastrophic and much worse than on present D-D machines. The objectives of physics measurements will therefore be quite different from the objectives of the physics measurements on present fusion devices, and measurements needed for plasma control towards optimizing reactor performance will become more important than measurements that are aimed at the validation and the understanding of the physics principles and concepts. Quite radical approaches will, for example, be needed for the management and control of the routine plasma operations by a relatively small number of diagnostics which do not rely on the presently used inductive magnetic sensors or wide-angle visible viewing optical detection systems. A DOE-sponsored R&D program is therefore needed to bring such new diagnostic solutions and developments to fruition and, where possible, adapt conventional diagnostics for a harsh nuclear environment. Typically, the development of a new diagnostic technique from a conceptual design to demonstration of its feasibility and maturity requires time of five to ten years. In these efforts, universities and national laboratories should be involved under the auspices of the Department of Energy. The development of new diagnostic techniques will require a rather long and dedicated R&D process ranging from basic laboratory experiments to a full implementation on ITER or an ITER-like experiment (e.g. JET-DT, JT60-SA) to then be prototyped for a FNSF/DEMO-equivalent burning plasma experiment.

2. THE X-RAY CASE

A) BACKGROUND.-

Since plasmas in large tokamaks (e.g. TFTR, JT-60 and JET) typically have core electron temperatures from few keV to few tens of keV, a significant fraction of their radiated power is in the SXR region of the spectrum. Recent simulations for ITER indicate that such fraction will be $\gtrsim$90% with a typical spectrum extending from the few keV to the hard x-ray (HXR) range[†]. It is therefore paramount to use the x-ray radiation emitted from thermonuclear plasmas - like ITER and beyond - to infer 1D profiles of key quantities such as electron and ion temperatures ($T_{e,i}$), toroidal and poloidal flow velocities ($V_{\phi,\theta}$), impurity densities (n_Z) and estimates of the effective plasma charge (Z_{eff}) [see x-ray imaging diagnostics shown in Fig. 1]. Our ability to extract 2D profile measurements of n_Z and $T_e(R,Z)$ will also be important additional tools for control and operation of a fusion power plant. Moreover, since the electron isotherms are flux-surface functions, one can gain information about the flux surface shape that can be used to constrain the current profile for reconstruction of the plasma equilibrium (e.g. safety factor [q] and current density [J(R,Z)]).

With recent advances in x-ray detector technology - especially, the manufacture of two-dimensional hybrid pixel arrays x-ray detectors of a large area and high single-photon count rate capabilities - it is now feasible to record spatially resolved x-ray photons in single or multiple energy ranges from highly charged ions in tokamak plasmas. Good examples for these new highly advanced x-ray sensors are the Pilatus and Eiger detectors, which are based on the silicon CMOS hybrid pixel technology developed by CERN [6] and the Paul Sherrer Institute [7], and which are commercialized by DECTRIS Ltd. [8]. These detectors were originally conceived for synchrotrons but have also been successfully used in our fusion community since 2005. In fact, the design of these pixelated large area detectors, which have 10^4-10^7 pixels, has revolutionized

[†] The core radiated power in ITER will be ~50 MW, similar to the input power of ~100 MW and second only to the neutron radiation of approximately 400 MW.

plasma diagnostics and contributed to the development of compact x-ray imaging crystal spectrometers (XICS) for T_i and Vϕ,θ profile measurements at Alcator C-Mod, KSTAR, EAST, LHD, W7-X and WEST. After a decade of experimentation the XICS concept has also been selected by the ITER organization to be a primary diagnostic for profile measurements of T_i and Vϕ and to be a secondary diagnostic for T_e and Vθ. An important feature of these x-ray detectors is that they have a variable lower energy threshold for photon detection that can be adjusted independently on each pixel. This feature offers an unprecedented flexibility for the design of multi-energy x-ray imaging x-ray cameras [8,9]. Imaging the plasma cross section at multiple energy ranges (e.g., $E>T_e^{av}$, $E>2T_e^{av}$, $E>3T_e^{av}$…, where T_e^{av} is the *line-of-sight average* electron temperature), provides a unique opportunity for measuring, simultaneously, a variety of important plasma properties. The energy resolved measurements can be used to produce images of impurity concentrations (n_Z and ΔZ_{eff}) - from the absolute image intensity at different energy bands - and the electron energy distribution function, both thermal (T_e) and non-Maxwellian ($n_{e,nM}$), from the variation of emissivity with x-ray energy. Runaway electrons are one of the major "Achilles heels" for ITER and tokamak reactors so that monitoring and control of the birth of runaway electrons is crucial, and measurements of the emitted photon-energy in the range of 50-500 keV are of the utmost importance. In summary, both the XICS and the ME-SXR camera techniques should be explored as a burning plasma diagnostic in-view of its simplicity and robustness.

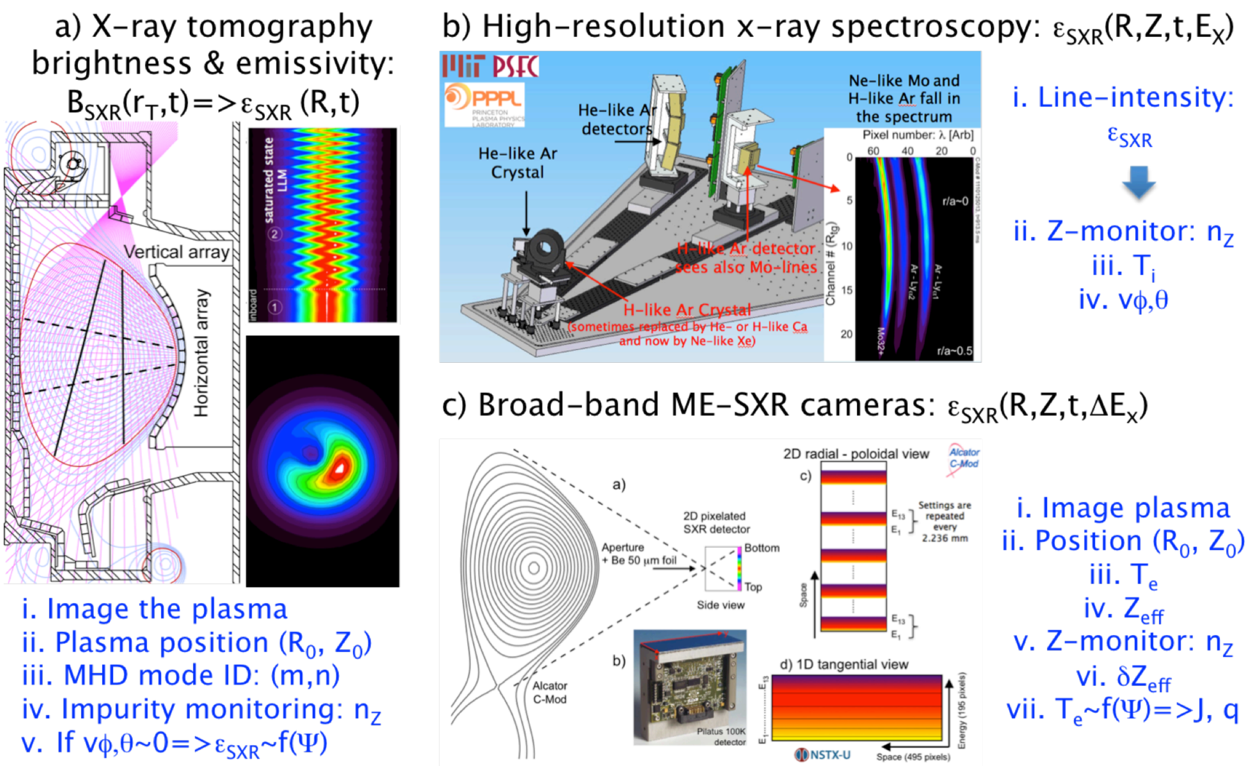


Fig. 1. An example of x-ray imaging diagnostics installed in tokamaks and stellarators worldwide: a) diode-based x-ray tomographic (XTOMO) system, b) core imaging x-ray spectrometer (CIXS), and c) multi-energy soft x-ray (ME-SXR) cameras. The examples shown are diagnostic systems prototyped at the Alcator C-Mod tokamak at the Massachusetts Institute of Technology - Plasma Science and Fusion Center (MIT - PSFC).

B) CURRENT DETECTORS AND LIMITATIONS.-

Conventional silicon detectors are used due to the availability of good quality homogeneous material, and high charge carrier transport properties. Unfortunately, these x-ray detectors can only withstand maximum neutron fluences in the range from few times 10^{13} up to 10^{15} neutrons/cm^2 (1 MeV-equivalent). The main concern in future uses of Si-detectors is, therefore, that their lifetimes could be severely shortened by neutron damage since future sensors will have to withstand fluences of 10^{15} up to 10^{17} neutrons/cm^2. Our community is thus forced to invest in new solutions that are compatible with very-high-luminosity experiments (up to 10^{16}-10^{17} neutrons/cm^2), using new kinds of radiation-hardened silicon sensors (e.g. 3D detectors, oxygen enrichments techniques, etc.) or semiconductor materials other than pure silicon like

Diamond, silicon-carbide, semi-insulating GaN, CdTe among others. The primary advantage of high-Z detectors is their high detection efficiency for high-energy x-rays since the photoelectric cross-section scales as Z^4-Z^5. For comparison, the cross sections for Compton scattering and pair production scale as Z and Z^2, respectively. The optimal spectroscopic detectors should favor photoelectric interactions and hence materials with a high atomic number will be preferred. Also, photon detectors with a dual-threshold capability and a "built-in" high-energy gamma-rejection option will be highly desirable; this gamma-rejection feature will enable "cleaner" and precise scans of the line- and continuum emissions for XICS and ME-SXR systems.

3. A DOE-SPONSPRED MULTI-STEP APPROACH

To make novel detector-solutions for a burning plasma environment possible, a new and long-term R&D program sponsored by DOE is needed. A multi-step approach for all members of our community in universities and national laboratories should take the following aspects into consideration:

A) STIMULATE COMMUNITY INTEGRATION AND INTERACTION (E.G. AVOID "*RE-DISCOVERING THE WHEEL*").-

Fusion researchers in the US should join or collaborate with members of the national and international community aiming at designing, building and testing novel radiation-hardened detectors. In particular, we would like to make the following recommendations:

i) Foster synergies between scientists supported by DOE offices of Fusion Energy Sciences (FES), High-Energy Physics (HEP) and Nuclear Physics (NP) which will have common interests aiming at designing, building and testing radiation-hardened detectors and associated electronics.

ii) Encourage interaction between small businesses and universities and national labs through the DOE Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs (https://science.energy.gov/sbir/) focused on various elements of burning plasma diagnostics.

iii) Join the RD50 collaboration (rd50.web.cern.ch/rd50/) and attend its bi-annual meetings; the RD50 is a CERN-sponsored community aiming at developing radiation hardened semiconductor devices for CERN's very high luminosity LHC experiments. The RD42 collaboration (http://rd42.web.cern.ch/rd42/) in particular, is developing radiation-hard pixel and strip tracking detectors based on thin-film CVD diamond for future collider detectors.

iv) Participate in the international conferences on Advances in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA, http://www.animma.com).

v) OFES should contact organizers of the High Temperature Plasma Diagnostics (HTPD) Conference and recommend including a "special-session" dedicated to the development of burning plasma diagnostics.

B) DEVELOPMENT OF RADIATION-HARDENED SEMI-CONDUCTOR AND METALLIC SENSORS.-

The US community should engage in a national and international effort aiming at developing novel radiation-hardened sensors capable of operating behind the blanket of a fusion reactor. SXR and HXR detectors with a dual-threshold capability and an intrinsic high-energy gamma-rejection option will enable a clear "scan" of the continuum and line-emission. The following recommendations are being made:

i) S*tate-of-the art* radiation-hardened detector technology (e.g. sensors and associated electronics) is mainly being developed mainly at European universities and European government research centers (see Fig. 2). An example of such a laboratory is the Microelectronics Institute of Barcelona at the National Center of Microelectronics (IMB-CNM) in Barcelona, Spain. This research facility leads the development of radiation hardened "3D" silicon detectors [11] for the 2020 high-luminosity experiments at CERN, currently providing PADs (Pixel Array Detectors) and strip detectors for ATLAS, CMS and LHCb. These novel detectors have not yet been tested in a fusion experiment. And it is therefore in our best interest to compare the photon sensitivity as

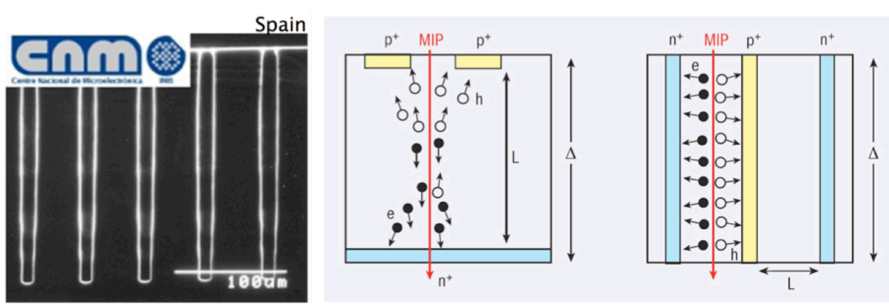


Fig. 2. "3D" detector technology being developed mainly in European universities and national laboratories.

well as neutron- and γ-induced noise characteristics between the conventional ("2D") sensors and the new "3D" silicon, silicon-carbide and diamond technology. Recent studies suggest that "3D" sensors – of the type used for LHC experiments – may withstand a 1 MeV-equivalent fluence up to 10^{17} neutrons/cm^2. This radiation tolerance level would enable survival of the ITER Core Imaging X-ray Spectrometer (CIXS) detectors for the full high-power DT operational phase of ITER. The CIXS detectors, however, require much lower electronic noise levels than those in the various LHC experiments, so it is imperative to further develop the "3D electrode" technology for lower noise, CIXS relevant PADs.

ii) In parallel with the R&D of new sensors is the development of radiation-hardened electronics, which is also an important component of radiation-hardened pixel-systems. Experience with the design of future systems for ATLAS at CERN suggests that hardening of electronic components has proven to be much more challenging than qualifying semi-conductor sensors.

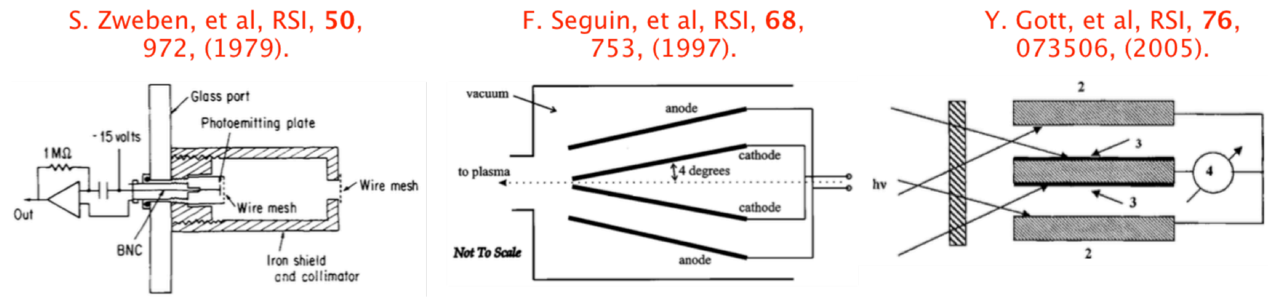


Fig. 3. UV and x-ray metal photo-diodes first design and prototypes for JET and ITER.

iii) Ultraviolet and x-ray vacuum photodiodes (VPD) made of high-Z metals have already been adapted for tokamak measurements by S. Zweben *et al*. (see Fig. 3) to measure UV emission in the Macrotor tokamak [11]. A special type of VPDs with modest x-ray efficiency, but intrinsically immune to radiation damage if built with high-Z cathodes and a small angle between the cathode surface and incident x-rays, was developed by F. H. Seguin *et al*., [12]. A somewhat modified concept - using Beryllium and Tantalum electrodes - was later proposed by Y. V. Gott and M. M. Stepanenko for x-ray tomography at ITER [13]; preliminary laboratory experiments demonstrated that the VPD has high sensitivity to thermal x-rays and low sensitivity to hard gamma rays and neutrons. As suggested by D. Stutman et al., efficient and radiation-resistant SXR sensors could be built using high-Z nano-structured photocathodes [5], coupled to an internal photocurrent amplification device [10]. Unfortunately, none of these feasible concepts have seen the "light" from a tokamak plasma due to lack of funding. The development of VPDs arrays should be explored aiming at designing and testing detectors for SXR and HXR measurements in multiple energy ranges; the energy sensitivity of these detector arrays can be tailored by choosing different thicknesses of the same metals or materials with distinct Z's.

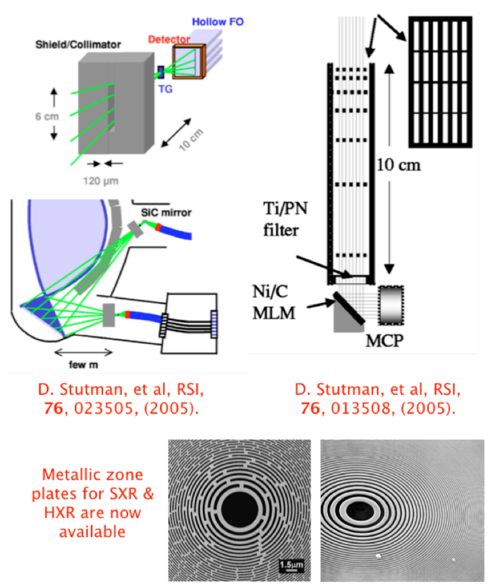


Fig. 4. UV and x-ray light-extractors using metallic transmission gratings, multi-layer mirrors and (Fresnel) zone plates.

C) Development of efficient (SXR & HXR) metallic light extractors.-

The 'first mirror' light extractor approach will encounter major difficulties already under ITER conditions. In essence, the plasma erosion and deposition, combined with the harsh radiation environment and the long pulse duration, will seriously degrade the first mirror reflectivity and polarization characteristics possibly rendering it unusable. The large benefit of working in SXR and HXR range is the presence of a 'front-end' low-Z metal filter, which also serves as a boundary vacuum wall eliminating plasma erosion and deposition of mirrors or reflectors along the detection chain. Therefore, the development and demonstration of light extraction technologies in the SXR and HXR range is equally important, or more, than the development of radiation-hardened sensors. Without efficient light extractors, our diagnostic community will not take full advantage of the rad-hard sensors since detectors will then need to have a direct view of the plasma, and in most cases, the radiation dose will likely exceed the limits of even a rad-hard sensor. As mentioned above, the gamma-induced noise will likely be unacceptable in that case, unless a double-threshold capability (with intrinsic gamma-rejection) is provided. An additional benefit of light extractors using diffractive-transmissive elements is that they can operate at various angles of photon incidence, which makes them less sensitive to misalignment and easier to replace by remote handling (e.g., through a simple translation of a fresh diffractive surface). Light extractors in the SXR and HXR range are, therefore, very attractive for ITER and beyond. Thus, the following recommendations should be adopted:

i) In particular, one should use UV and SXR diffractive extractor elements (e.g. free-standing 1D transmission gratings, synthetic multi-layer mirrors and 2D Fresnel zone plates [5,15]), where the light is deflected by a periodic array of slits instead of a solid surface (as is the case for mirrors; see various examples Fig. 4). Diffractive elements will, in principle, have a better chance of maintaining their optical properties during radiation and neutron exposure [5,14].

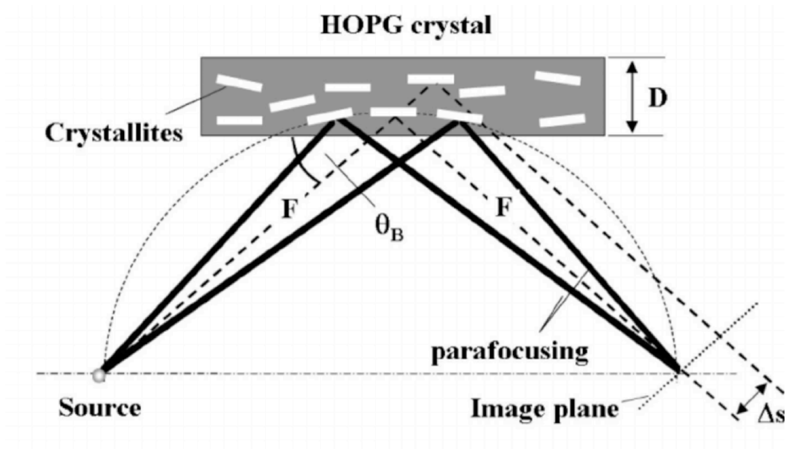
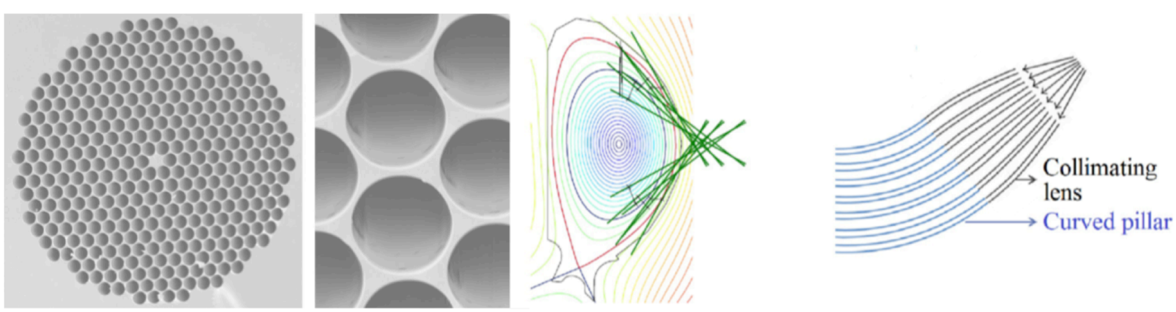


Fig. 5. HOPG x-ray pre-reflector.

ii) A two-crystal approach using pre-reflectors for imaging x-ray spectrometers will prevent direct neutron streaming from the 'first mirror' opening. Highly Oriented and Highly Annealed Pyrolytic Graphite crystals (HOPG and HAPG) are of particular interest for x-ray diagnostics of hot dense plasmas and can be used as a first crystal of choice followed by a 'dog-leg' optical train including a second crystal and neutron shielding (see HOPG example Fig. 5). The large benefit of these crystals is their broader angular range of reflectivity (0.1-0.4° instead of $1.5\text{-}5.1\times10^{-3}$ degrees for the typical Qz and Ge crystals) over a large wavelength range.



J. D. Joannopoulos, et al, Nature, **386**, 143, (1997). D. Mazon, et al, RSI, **87**, 11E302, (2016).

Fig. 6. Hollow fiber optics (in combination with efficient x-ray scintillators) or x-ray policapillary lenses should be used as efficient x-ray light extractors

iii) Light-extractors to transport the SXR information several meters away from the plasma in the complex port-plug geometry are also quite attractive. This concept can be explored by using either: a) efficient scintillators and radiation-resistant hollow-optical-fibers or newly developed Bragg fibers [5,15], or b) long polycapillary lenses [16]; see hollow fiber and policapilary examples in Fig. 6. The latter approach is appealing but may suffer from darkening since the capillaries are made out of borosilicate glass.

Moreover, the x-ray transmission is wavelength/energy dependent and varies significantly if the policapillaries are bent; in this case, a strong emphasis on the reliability and robustness of operation and calibration of diagnostic systems will be mandatory.

D) <u>TESTING SENSORS AT ITER AND FNSF/DEMO CONDITIONS</u>.-

An important component of this national program should encompass testing sensors in conditions approaching or similar to those in ITER-DT and FNSF or DEMO. A separate DOE-sponsored funding activity for maintaining or enhancing neutron irradiation sources should be considered. The following recommendations can be adopted:

i) Radiation-hardened sensors should be exposed to neutrons of relevant energies between 1-14.1 MeV. An example of such laboratory is The Neutron Radiation Effects Facility (NREF), which is one of the target stations at the Low Energy Neutron Source [LENS, see Fig. 6-a)]. The LENS facility at Indiana University is a pulsed neutron source that utilizes a low energy p-n reaction in Be coupled with a high-current, variable-pulse-width proton accelerator to produce either short or long neutron pulses [17-19]. The neutron flux at the device under test (DUT) is approximately $2x10^{10}$ neutrons/cm^2/sec in the range of 2-8 MeV, produced by a 13 MeV proton beam, and with low gamma contamination [see typical neutron spectrum in Fig. 6-b)]. NREF has been constructed to accommodate device and board level electronics testing with quasi-monochromatic high flux neutron beams [L.F.D.A appears in Fig. 6-c) installing a PILATUS 2 x-ray detector at NREF for neutron irradiation]. Worst case-scenarios of ITER-DT-like fluences can be achieved after one-two weeks of irradiation. Longer exposures will be needed to asses FNSF/DEMO conditions.

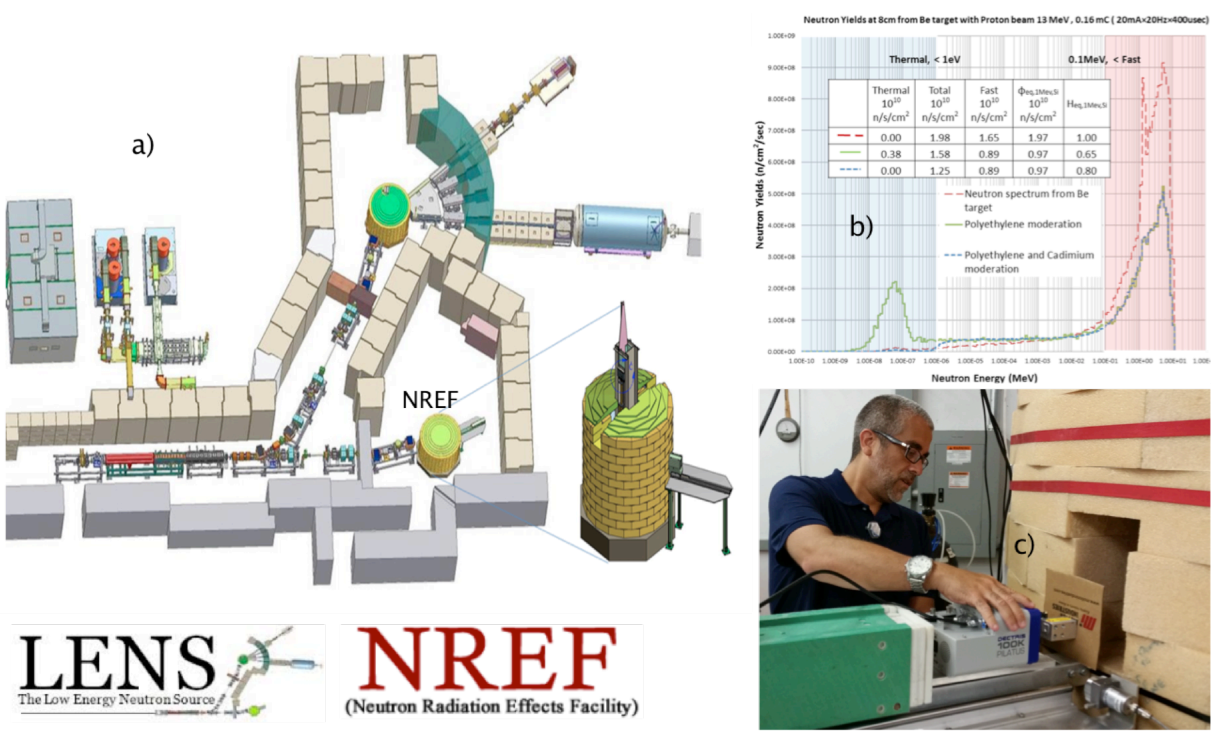


Fig. 6. LENS-NREF 1-10 MeV neutron irradiation facility in Indiana University.

ii) The US researchers can also make use of other intense neutron sources like the Spallation Neutron Source (SNS) at ORNL. The use of specific beam-lines capable of using fast neutrons in the range of 1-14.1 MeV should be addressed first.

iii) Here one can also envisage a progression from initial tests on JET-DT, to tests on JT-60SA, ITER and beyond. To this end, our diagnostic community should communicate with the ITER-IO to reserve a location behind the blanket for tests of ITER-DT, FSNF and DEMO relevant diagnostics.

E) DEVELOPING NEW DATA ANALYSIS TECHNIQUES.-

Considering that the diagnostic set of burning plasmas will be much reduced in comparison to those used on D-D experiments, we also recommend to pursue, concomitant with the development of new sensors, a further development of "Integrated data analysis (IDA)" tools to maximize the usefulness of the information recorded by a reduced set of diagnostics. The IDA method was first applied in W7-AS and TJII to density measurements [20-22] but has recently also been used in the RFP and Tokamak community [23-27] focusing to improve the data analysis for measurements of n_Z, Z_{eff} and T_e profiles‡. The IDA method takes advantage of diagnostic redundancies and the fact that multiple diagnostics (e.g. interferometers, polarimeters, ECE and SXR) have different dependences on fusion parameters (e.g. n_e, T_e) and thus improves the determination of parameters that cannot be accurately measured by any single diagnostic. IDA provides a systematic methodology for combining measurements based on the Bayesian probability theorem. The benefit for the US program lies in the ability to use the developed x-ray sensors to characterize both the metal x-ray line-radiation and continuum and their dependences on plasma density and temperature for measurements of n_Z, Z_{eff} and T_e profiles. The experience gathered in current machines with metal-plasma facing components and new x-ray detectors will be exported to future scenarios which will have to deal with the line-emission contaminations due to the use of metal walls.

4. SUMMARY.-

The harsh environmental conditions expected in next-step reactors will severely constrain or even eliminate many key diagnostics and measurements that are presently being used in D-D magnetically confined fusion plasma devices. Additional funds (~6 M$/yr across the US diagnostic community) should be made available at DOE-OFES to foster a short- to medium-term development and implementation of key technology in support of adapting or replacing conventional diagnostics for a D-T nuclear environment. In other words, a dedicated program for testing radiation-hardened components to withstand FNSF/DEMO-level neutron fluxes must be put in place. A viable roadmap for development of x-ray sensors is presented as an example with five high-level recommendations spanning from community integration, development and testing of radiation-hardened semi-conductor and metal sensors, light extractors and electronics, as well as support for novel data analysis techniques. A similar path can be taken for fast-particle detection and fusion products (e.g. neutrons and NPAs), as well as microwave (e.g. reflectometry and ECE) and IR (e.g. interferometer/polarimeter) technology. The field of diagnostic development using novel technologies for neutron, microwave, IR and x-ray measurements offers large potential for US leadership, because the tools needed for FNSF or DEMO control will likely involve engineer and scientific solutions and that have not been tested or yet developed.

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‡ IDA is part of a new series of IAEA Technical Meetings on Fusion Data Processing, Validation and Analysis (see https://www-internal.psfc.mit.edu/IAEA/index2017.html).

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