Burning-plasma diagnostics: photon and particle detector development needs

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This white paper is submitted to the U.S. FESAC–TEC subcommittee 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.

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Outline

1. Technology to be assessed
2. Application of the technology for tokamaks and stellarators
3. Critical variables
4. Design variables
5. Risks and uncertainties
6. Maturity
7. Technology development for fusion applications
Technology to be assessed.– Development of burning plasma diagnostics

CHALLENGES:

a) National panels (e.g. RENEW, Greenwald, etc.) recommended, where possible, adapt present standard diagnostic systems (e.g. TS, CXRS, MSE & bolometers) – to the harsh environmental challenges of burning plasmas.

b) The main issues: 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.

c) The harsh environmental conditions expected in FNSF/DEMO–like devices will severely constrain or even eliminate many key diagnostics and measurements that are presently being used in DD MCF devices.

d) 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 inductive magnetic sensors or wide–angle visible viewing optical detection systems.
Technology to be assessed.– Development of burning plasma diagnostics

SOLUTIONS:

a) Additional funds should be made available at DOE–OFES to foster development and implementation of key technology in support of adapting or replacing conventional diagnostics for a DT nuclear environment.

b) Include a dedicated program for testing radiation-hardened components to withstand FNSF or DEMO–level neutron fluxes.

c) A viable roadmap for development of x-ray sensors is presented as an example with five high-level recommendations (& advice on each):
   i. Foster community integration and interaction
   ii. Development of radiation-hardened semi-conductor and metallic sensors
   iii. Development of efficient radiation-hardened light extractors
   iv. Testing sensors at ITER and FNSF/DEMO conditions
   v. Developing new data analysis techniques

d) 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 systems.
Technology for tokamaks & stellarators: The x-ray case, just an example

a) X-ray brightness & emissivity: $\varepsilon(R,t)$

b) High-resolution x-ray spectroscopy: $I_{SXR}(R,Z,t)$

i. Line-intensity: $\varepsilon_{SXR}$

ii. Z-monitor: $n_Z$

iii. $T_i$

iv. $v_{\phi,\theta}$

c) Broad-band ME-SXR cameras: $I_{SXR}(R,Z,t,E_x)$

i. Image plasma

ii. Position ($R_0, Z_0$)

iii. $T_e$

iv. $Z_{eff}$

v. Z-monitor: $n_Z$

vi. $\delta Z_{eff}$

vii. $T_e \sim f(\Psi) \rightarrow J, q$
Technology for tokamaks & stellarators: The x-ray case, just an example

**SXR based measurements:**

a) Plasma imaging and position ($R_0$, $Z_0$ and boundary).

b) MHD: $(m,n)$ mode ID

c) $T_e$, $T_i$

d) $v\phi$, $v\theta$ => $E_r$

e) Z-monitor (s): $n_Z$

f) $\delta Z_{\text{eff}}$ & $Z_{\text{eff}}$

g) $T_e \sim f(\Psi)$ => $J$, $q$

The development of radiation-hardened x-ray measurements will benefit *both* the tokamak & stellarator communities (the x-ray emission is an intrinsic property of hot plasmas & doesn’t dependent on the confinement configuration, aspect ratio or the intensity of B)
Critical variable(s): Not the physics but the neutron and gamma–induced noise!

Conventional Si–detectors are used due to the availability of good quality homogeneous material, and high charge carrier transport properties (these detectors can withstand a neutron fluence of $10^{13}$ up to $10^{15}$ n/cm$^2$).

- Lifetimes could be shortened by n–damage; sensors will have to withstand fluences of $10^{15}$ – $10^{17}$ n/cm$^2$.

- Forced to invest in new solutions that are compatible with very–high–luminosity experiments (~$10^{16}$ – $10^{17}$ n/cm$^2$), using new kinds of rad–hardened Si or semiconductor materials like Diamond, SiC, GaN and CdTe.

- Photon detectors with a dual–threshold capability and a “built–in” high–energy γ–rejection are highly desirable.
The U.S. fusion diagnostic community should join the international-lead efforts aiming at developing radiation-hardened sensors.

**STOP RE-INVENTING THE WHEEL**

i. *State-of-the art* radiation-hardened detector technology (e.g. sensors and associated electronics) is mainly being developed mainly at European universities and government research centers.

- Novel “3D” Si, SiC & diamond detectors have not yet been tested in a fusion experiment.

- “3D” sensors – of the type used for 2020 LHC run – may withstand a up to few $10^{17}$ neutrons/cm$^2$. 
The U.S. fusion diagnostic community should join the international–lead efforts aiming at developing radiation–hardened sensors.

STOP RE–INVENTING THE WHEEL

ii. Preliminary lab–tests of UV & x–ray metal vacuum photodiodes demonstrated a high sensitivity to thermal x–rays and low sensitivity to hard $\gamma/n$.


Q: Want brightness or emissivity measurements?  
A: R&D metal vacuum photodiodes!
Design variables: Radiation hardened light extractors, sensors & electronics

Light extractors can operate at various angles of photon incidence, which makes them less sensitive to misalignment and easier to replace by remote handling.

**STOP RE–INVENTING THE WHEEL**

iii. Diffractive elements will have a better chance of maintaining their optical properties during radiation and neutron exposure.

iv. Test efficient scintillators coupled to radiation–resistant hollow–optical–fibers, or Bragg fibers, or long polycapillary lenses.

v. A two–crystal approach using pre–reflectors for imaging x–ray spectrometers will reduce direct neutron streaming to the detectors of choice.

Metallic zone plates for SXR & HXR are now available.
Design variables: Radiation hardened light extractors, sensors & electronics

Light extractors can operate at various angles of photon incidence, which makes them less sensitive to misalignment and easier to replace by remote handling.

**STOP RE-INVENTING THE WHEEL**

iii. Diffractive elements will have a better chance of maintaining their optical properties during radiation and neutron exposure.

iv. Test efficient scintillators coupled to radiation-resistant hollow-optical-fibers, or Bragg fibers, or long polycapillary lenses.

v. A two-crystal approach using HOPG/HAPG pre-reflectors for imaging x-ray spectrometers will reduce direct neutron streaming to the detectors of choice.

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Risk and uncertainties: Lack of dedicated funding and loss of U.S. leadership

- Unfortunately, none of the feasible concepts mentioned above have seen the “light” from a modern tokamak or stellarator plasma due to lack of funding.

- 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]).


Risk and uncertainties: neutron hardening

An important component of a national program must include a plan for testing sensors in conditions approaching or similar to those in ITER–DT & FNSF/DEMO (Radiation-hardened sensors should be exposed to relevant $E_n = 1–14.1$ MeV).

- LENS is a pulsed (~1–10 MeV) neutron source that utilizes a low–E p–n reaction in Be.

- Neutron flux at the device under test (DUT) is $\sim 2 \times 10^{10}$ n/cm²/sec with low–$\gamma$ contamination.
Risk and uncertainties: neutron hardening

An important component of a national program must include a plan for testing sensors in conditions approaching or similar to those in ITER–DT & FNSF/DEMO (Radiation-hardened sensors should be exposed to relevant $E_n = 1–14.1$ MeV).

- NREF can accommodate device and board level electronics testing with quasi-monochromatic high flux neutron beams.
- Worst case-scenarios of ITER–DT fluences can be achieved after 1–2 weeks of irradiation.
Detailed measurements of the x-ray emission from tokamak plasmas are common since the early 70’s when sawtooth crashes were first reported.

- With recent advances in x-ray detector technology it is now feasible to record spatially resolved x-ray photons in single or multiple energy ranges.

- Good examples: Pilatus/Eiger detectors, based on the Si–CMOS hybrid pixel technology developed by CERN and PSI, and commercialized by DECTRIS Ltd.

- XICS: Alcator C–Mod, KSTAR, EAST, LHD, W7–X and WEST, and in the future, ITER.

- ME–SXR: Alcator C–Mod, NSTX–U, MST, and possibly, DIII–D and WEST.
Technology development for fusion applications.– From TRL4 to TRL7

The development of new diagnostic techniques will require a long R&D process from basic lab. experiments to a full implementation on ITER or an ITER-like experiment to then be prototyped for a burning plasma experiment.

From TRL4 → TRL6 or TRL7

a) Research and development of radiation-hardened light extractors

b) Build novel rad.-hard detectors capable of operating behind the blanket of a fusion reactor

c) Testing diagnostics & electronics in conditions approaching ITER–DT and FNSF/DEMO

- Additional funds (~6 M$/yr) should be made available at OFES to foster development and implementation of key technology for burning plasmas.

- Universities & national labs. should bring diagnostic solutions to fruition and, where possible, adapt conventional diagnostics for a harsh nuclear environm.
Summary

1. This white paper seeks 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.

2. The *harsh* environmental conditions expected in DT reactors will constrain or eliminate many key measurements currently used in D–D experiments.

3. A viable roadmap for development of x-ray detectors is presented as an example with five high-level recommendations (see ref. [6])
   i. Foster community integration and interaction
   ii. Development of radiation-hardened semi-conductor and metallic sensors
   iii. Development of efficient radiation-hardened light extractors
   iv. Testing sensors at ITER and FNSF/DEMO conditions
   v. Developing new data analysis techniques

4. A similar path can be taken for fast–particle detection and fusion products, as well as microwave and IR technology.

5. Additional funds (~6 M$/yr across the US diagnostic community) should be made available at 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.
Supplemental material
Recommend a DOE-sponsored multi-step approach: 1) Stimulate community integration & interaction

Recommendations:
1. Foster synergies between scientists supported by DOE FES, HEP & NP which will have common interests aiming at designing, building and testing radiation-hardened detectors and associated electronics.

2. Encourage interaction between small businesses and universities and national labs through the DOE SBIR/STTR programs focused on various elements of burning plasma diagnostics.

3. Join the RD50 collaboration; the RD50 is a CERN-sponsored community aiming at developing radiation hardened semiconductor devices for CERN’s very high luminosity LHC experiments.


5. 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.
Recommend a DOE-sponsored multi-step approach: 5) Developing new data analysis techniques

**FACT**: The diagnostic set of burning plasmas will be much reduced in comparison to those used on D–D experiments.

1. Concomitant with the development of new sensors, we also recommend further development of “Integrated data analysis (IDA)” tools to maximize the usefulness of the information recorded by a reduced set of diagnostics.

2. The IDA method was first applied in W7–AS & TJII to density measurements but has recently been used in the RFP and Tokamak community focusing to improve the data analysis for measurements of $n_Z, Z_{\text{eff}}$ and $T_e$ profiles.

3. 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.

4. IDA provides a systematic methodology for combining measurements based on the Bayesian probability theorem.

(See presentation by D. Den Hartog/L. Reush – UW–Madison, Thursday am)