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Progress on Development of SPIDER Diagnostics

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Abstract. SPIDER experiment, the full size prototype of the beam source for the ITER heating neutral beam injector, has to demonstrate extraction and acceleration to 100 kV of a large negative ion hydrogen or deuterium beam with co-extracted electron fraction $e^- /D^- <1$ and beam uniformity within 10%, for up to one hour beam pulses. Main RF source plasma and beam parameters are measured with different complementary techniques to exploit the combination of their specific features. While SPIDER plant systems are being installed, the different diagnostic systems are in the procurement phase. Their final design is described here with a focus on some key solutions and most original and cost effective implementations. Thermocouples used to measure the power load distribution in the source and over the beam dump front surface will be efficiently fixed with proven technique and acquired through commercial and custom electronics. Spectroscopy needs to use well collimated lines of sight and will employ novel design spectrometers with higher efficiency and resolution and filtered detectors with custom built amplifiers. The electrostatic probes will be operated through electronics specifically developed to cope with the challenging environment of the RF source. The instrumented calorimeter STRIKE will use new CFC tiles, still under development. Two linear cameras, one built in house, have been tested as suitable for optical beam tomography. Some diagnostic components are off the shelf, others are custom developed: some of these are being prototyped or are under test before final production and installation, which will be completed before start of SPIDER operation.

INTRODUCTION

Within the path towards the development of ITER heating neutral beam injectors (HNB), a key role is played by SPIDER, the full size prototype of the HNB source under construction at Consorzio RFX [1]. SPIDER is a 100 kV negative hydrogen/deuterium RF source, with a multi-grid accelerator, made of 1280 apertures distributed over an area of 1.5x0.6m^2, in 4x4 groups of 5x16 apertures each. Its specifications are: 285 A/m^2 extracted deuterium current density at 0.3 Pa in the source, ratio of co-extracted electrons to negative deuterium ions <1 and beam uniformity within 10%, for up to one hour beam pulse. SPIDER is the necessary step before MITICA, the full size 1 MV ITER injector with 40 A extracted current and < 7 mrad beam divergence [1]. SPIDER will take advantage of the experience gained in ELISE, the test facility in operation at IPP, which is half size the ITER source and is designed to produce up to 60 keV, 10 s, beam pulses [2].

Inside this challenging development path it is proving essential to well diagnose both the RF source and the accelerated beam, in particular a) to characterize the source extraction region, next to the plasma grid, where negative ions are mainly produced and extracted, specifically measuring the D^- density and the cesium dynamics over the wide grid surface and during long pulses and b) to estimate the beam uniformity and divergence from its intensity profile. Overall injector performance can then be studied by correlating the physics of the source with the beam characteristics in the actual HNB geometry, investigating the optimum operational space. This can only be performed at full extent in SPIDER or in smaller sources, using a complete set of diagnostics [3], because on the

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ITER HNB only a much reduced set of measurements will be available, mainly thermocouples (TCs), due to the very little accessibility and to the harsh nuclear environment. Even MITICA will suffer some of these limitations, with much less source access than SPIDER, through either the high voltage (HV) bushing or the viewports on the vacuum vessel, and with a neutron flux at the viewports of about 10^8 n/cm^{2}s, originating from the d-d reaction between deuterons implanted on the beam dump and ERID and the incoming beam deuterons, marginally critical for electronic components and optical detectors [4]. On ITER HNB the neutron flux is 100 times higher, due to the facing burning plasma, making impossible to install electronic components, while refractive optics like windows, lenses and fibres are at risk. In SPIDER, with about 10^6 n/cm^{2}s, no serious radiation compatibility issue is expected. SPIDER diagnostics are listed in Table 1 with the corresponding measured quantities.

TABLE 1. List of SPIDER diagnostics and corresponding measured quantities

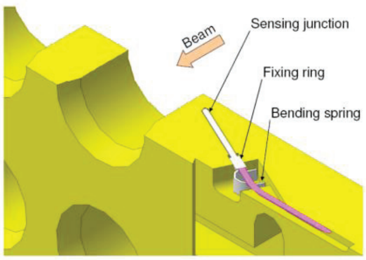
Source diagnostics	**Measured quantities**
Electrical currents	Current balance at power supplies
Calorimetry & surface thermocouples	Power load on source components
Electrostatic probes	Plasma uniformity, T_e, n_e
Source Optical Emission Spectroscopy	Source plasma T_e, n_e, n_{H^-}, n_{Cs}, n_H, impurities
Cavity Ring Down Spectroscopy (CRDS)	Negative ion density n_{H^-}
Laser absorption	Atomic Cesium density n_{Cs}
Beam diagnostics	
Calorimetry & surface thermocouples	Beam uniformity, divergence, aiming, vert. resolution 7 cm
Instrumented calorimeter STRIKE	Beam uniformity over 2D profile & divergence, resolution 2mm, < 10 s beam pulses, SPIDER only
Beam Emission Spectroscopy (BES)	Beam divergence, stripping losses, beam uniformity
Optical tomography	Beam uniformity over 2D profile, resolution 1/4 beamlet group
Neutron Imaging	Beam uniformity horizontal profile, resolution 3-4 cm, D only

SPIDER diagnostics design has been finalized and they are currently in the procurement phase through an F4E contract. Their final design is described here with a focus on some key solutions and most original and cost effective implementations. Some of these diagnostics, like spectroscopy, use well established techniques routinely employed in other sources like in ELISE [5,6] or at the NIFS test bed [7], and they are replicated in SPIDER with a tailored layout and state of the art components. Other diagnostics are new in concept, like STRIKE, beam tomography and neutron imaging.

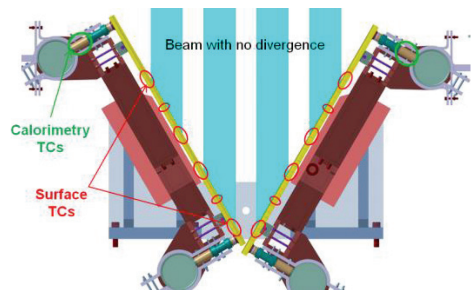
THERMOCOUPLES

Thermocouples (TC) will be installed in-vacuum on all components of the beam source and on the beam dump panels made of 31 water cooled hypervapotrons (HPV) vertically stacked. 20 of the 144 TCs on the beam source will be fastened to the outlet pipes of the cooling system, whereas the remaining ones will be inserted at a given depth in the body of specific components (accelerator grids, source walls, driver plates and Faraday shields) to measure their local temperature. The former TCs will be used for calorimetry, the latter ones will help studying the thermal load distribution and evaluating the uniformity of plasma generation and beam extraction. 68 of the TCs on the beam dump have been fastened to the manifolds and the outlet pipe of each HPV, which will provide two power deposition vertical profiles, one for each panel. Another 112 TCs are inserted at 3 mm from the beam heated surface of the central HPV of each beamlet group, to characterize with smaller thermal inertia both vertically and horizontally the power distribution of the beam (Fig.1). The thermal measurements system may also act as a slow protection system since all source components are exposed to high thermal loads [8]. Steady state thermo-hydraulic analysis by finite elements simulations of the HPVs under nominal heat loads and water flow rate, have shown that beamlet groups with 3 and 7 mrad divergence are clearly distinguishable and information on divergence and horizontal aiming can be retrieved from the slope and position of edge gradients [9]. Conversely at reduced power load with no cesium operation, the water flow rate must be reduced to achieve sufficient sensitivity.

N type thermocouples (NiCrSi/NiSiMg - Nicrosil/Nisil), similar to the ones used in ITER HNBs, have been selected. TC cables have been manufactured by Mineral Insulated Cable (MIC), with Inconel 600 sheath and conductors insulated with magnesium oxide, to ensure that the cable is vacuum compatible and is able to withstand the effects of plasma environment while maintaining a good reliability at high temperature. The MI cable is terminated with a transition to a Kapton insulated pair of wires, more suitable for crimping on connectors. Differently from ITER HNBs, where custom ceramic sealed transitions are being considered for higher radiation hardness, more standard epoxy sealed transitions are used here because of the milder environment and budget constraints. TCs installed in SPIDER source have grounded junctions to minimize the overvoltage during transient phenomena, in particular during accelerator breakdowns, while those on the beam dump have isolated junctions because this configuration is less susceptible to noise and there is no risk of breakdown. MI cable external diameter has been chosen to be 0.8 mm in the source, to ease the complex routing, and 1.5 mm in the beam dump, to match the same diameter holes in the HPVs.



(a)



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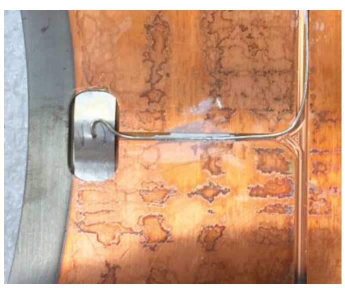

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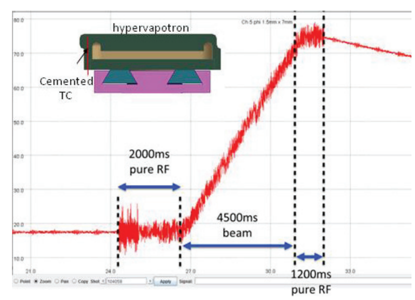


(d)

FIGURE 1. (a) Fixing of a TC head inside the extraction grid and (b) on the source back plate; (c) position of embedded TCs along central hypervapotron of each beamlet group and of calorimetry TCs on outlet pipes; (d) measurement of a cemented MIC TC subject to BATMAN beam and section of a hypervapotron with position of the cemented TC head

All TCs have been procured as well as the extension cables, both inside and outside vacuum, and the vacuum feedthroughs while installation is starting. Vacuum cables are Kapton insulated twisted pairs shielded in bundles by nickel plated copper braids, while cables in air are shielded multipair cables. Shielding and grounding have been carefully managed, especially in the RF source, to avoid multiple referencing, ground loops and minimize pickup noise. Source TCs sit at the HV of the source or of the extraction grid and these cables are routed out of the vessel through the HV bushing, then inside the transmission line, to be terminated in the acquisition cubicles in the HV deck. TCs on the grounded grid (GG) instead have their custom conditioning and acquisition electronics onboard of the grid, with isolated power supply and optical signal transmission, to avoid the up to 20 kV spikes of the GG during HV breakdowns.

The front-end conditioning electronics are of two types: a well established commercial solution, standard for industrial application, for source TCs and beam dump surface TCs, and a custom solution for GG and beam dump calorimetric TCs. The commercial system is intended to benchmark the cheaper and equally or better performing custom system, which can then be used with more confidence in MITICA, where about 1000 TCs will monitor the heat load on source and beam line components.

The commercial system is based on Isolated Thermocouple Input Modules, type Analogue Devices 5B37-N-08, whose output signal is digitized by acquisition boards type National Instruments NI PXI-6259. The 5B37-N-08 modules have internal cold junction compensation, 1500 V rms, 2100 V peak input to output insulation and 4 Hz low pass filter. A prototype diagnostic complete of all components from TC sensor to acquisition system has been assembled and tested inside the BATMAN RF source [10].

The custom front end conditioning electronics and digitization board is realized in 3U high Eurocard format with 8 TC inputs. Up to 10 boards are hosted in a single crate, each addressed through an RS232 terminal server. For each input channel, a Cold-Junction Compensated Thermocouple-to-Digital Converter (MAX31855) digitizes the data from the thermocouple. On each board a microcontroller (PIC) periodically selects each channel through a multiplexer and reads the full serial-data output from the Thermocouple-to-Digital Converter. Once all channels have been read out by the microcontroller, it sends the collected data through the internal UART (Universal Asynchronous Receiver-Transmitter). Output data pass then through an optocoupler before reaching the RS232 serial transmitter and being distributed via a terminal server over Ethernet LAN. This board has been developed through a number of prototypes and successfully tested on the NIFS test bed and on the NIO1 RF source [11].

The most recent update of the custom electronic front end is based on the newest Cold-Junction Compensated Thermocouple-to-Digital Converter, MAX31856, which supersedes the MAX31855, with improvements in resolution (19 vs 14 bits), on-board temperature reference (6 vs 4 bits), and compensation (fully compensated vs offline nonlinear correction), with digital output in °C featuring ±0.15% accuracy, while maximum acquisition frequency is 10 Hz. The thermocouple inputs are protected against overvoltage up to ±45V. In addition, the ground loop detection does not generate a fault, which was an issue with the previous version as grounded TCs installed on components at the same potential caused a fault unless converters sharing one board were isolated from each other with a DC/DC power supply. To reduce pickup noise, the amplified signal is lowpass filtered before being fed to the ADC, which provides further digital lowpass and notch (the line frequency) filtering to attenuate input noise. Four pins are used for SPI-compatible communications, which make the MAX31856 interfaceable to microcontroller devices like Arduino and Raspberry PI. Thanks to this feature MAX31856 is already available integrated into small and cheap commercial boards, like Thermopar Nanoshield from Circuitar [12]; up to 15 modules can be simultaneously controlled by a single Arduino, which can then feed the data to the network through an ethernet interface.

ELECTROSTATIC PROBES

In the extraction region close to the exit of the source, a system of electrostatic probes is being installed to measure the homogeneity of plasma parameters such as plasma density, electron temperature, and plasma potential. As described in [13], the sensors will be distributed over the surfaces of the plasma grid (PG) and of the bias plate (BP), which face the plasma. The design was constrained by the need to embed the sensors in the PG and BP, taking into account the cooling channels and the grid supports. The insulating component of the exposed electrode has been specially machined to avoid sensor short circuit due to continuous exposure to cesium deposition. The robustness of the probes design and its immunity to cesium deposition were successfully tested in BATMAN [14].

Basically two kinds of measurements are available related to the sensor configurations: a) single sensor configuration: in this case the ion saturation current, Isat, collected by the sensor biased at a given voltage of about -100V, will be provided; b) single sensor coupled with a larger floating reference electrode exposed to the plasma: in this case the I-V Langmuir characteristic is available. One of the main issues for the probe measurements facing the SPIDER plasma is the RF oscillation of the plasma potential, due to the 1 MHz power supply. The I-V characteristic is expected to be affected in these conditions by a distortion of the electron branch, inducing an overestimate of the measured electron temperature; this effect is expected to be larger for larger amplitude plasma potential oscillations. Different methods are documented in literature to deal with this issue: in this specific case, given the mechanical constraints provided by the installation of sensors on the plasma facing grids, the method based on a passive compensation has been chosen. Following this approach each sensors is terminated in vacuum, in the position as close as allowed to the sensor location, through a circuit board based on passive components. The role of this RF adaptation is to increase the probe impedance with respect to the sheath impedance in order to minimize the RF distortion of the characteristic. Each sensor cable and the respective circuit board is properly RF shielded up to the ex-vessel front end channel and to the acquisition system. A prototype probe system employing this RF compensation scheme was successfully tested in BATMAN [15]. Each sensor on the PG and on the front side of BP can in principle host either a probe or a reference sensor: this will make it possible to tailor their configuration to the experimental operation needs. Initial setup is organized with the maximum number of available reference electrodes (12 in PG, 6 in BP), so that 18 probes will acquire V-I characteristic and 48 probes will acquire current saturation.

The signal is then sent through Kapton isolated extension cables to the vacuum feedthroughs of the HV bushing and into the HV transmission line to the acquisition cubicles in the HV deck. The ion saturation current will be acquired continuously at a sampling rate up to 100 S/s, whereas V-I characteristics will be acquired with a pre-programmed burst acquisition at a sample rate up to 20 KS/s. The acquisition system modules allow also higher sampling rates of up to 2 MHz, which are available for selected signals and on operator request for monitoring faster phenomena. The custom developed ex-vessel front-end signal conditioning electronics are conceived on the basis of drawers hosting 8 channels: each channel includes I and V output signals and the power supply (internal or external) for probe polarization. The front-end circuit has been designed to minimize the adverse effects caused by arcs and voltage spikes often found in probe measurement, which in the worst cases can cause damages to the probe itself and to the connected components. In general when the probe is polarized, the interaction with the plasma can produce an arc, practically causing a short circuit, and thus a current limiting mechanism to avoid excess power and erosion was implemented. At low plasma densities, supra-thermal electrons can cause voltage spikes on the probe that can exceed the voltage ratings of standard components causing a number of failures. Furthermore in the specific case of SPIDER, two more design constraints are present. To start with the zero reference of the probe measurement can be at different voltages with respect to the reference ground of the plasma grid because of the polarization and the currents flowing in the accelerator grids. Secondly, due to the presence of RF power, the long cable paths between the probe and the measurement electronic, if not properly handled can act as antennas producing undesired e.m.f. induced offsets. In order to counteract all these adverse effects, i.e. avoid ground loops, reduce RF interference and protect the DAQ system from voltage spikes, the polarizations and the power supplies have been separated for each and every channel, using galvanically isolated low capacitance DC/DC converters, and each probe input has been galvanically isolated from the outputs to DAQ system (Fig.2). Both single ended and differential outputs are provided.

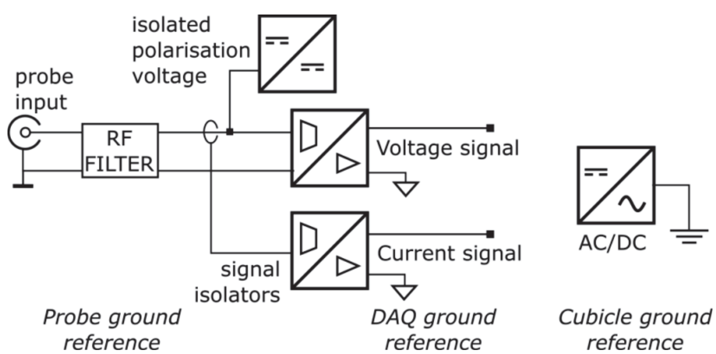


FIGURE 2. Block scheme of a probe input channel.

SOURCE AND BEAM EMISSION SPECTROSCOPY

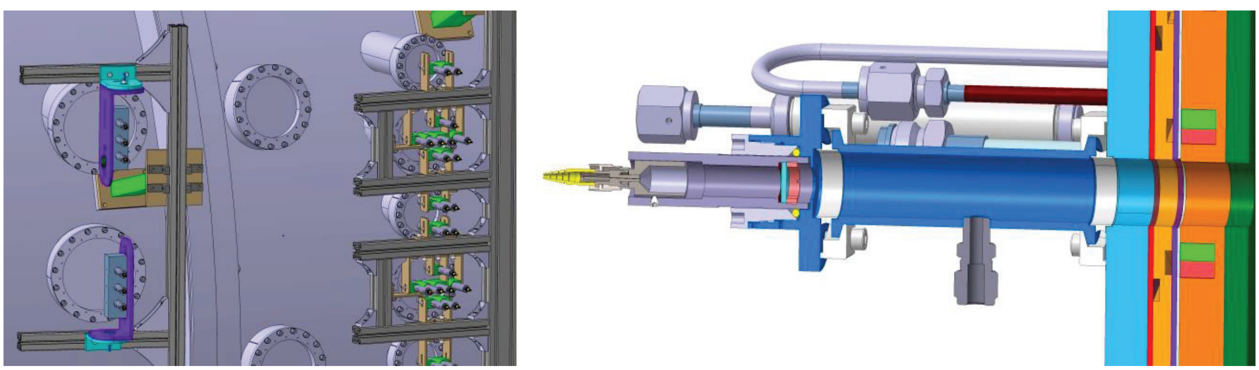
Optical emission from the plasma in the RF source is collected along lines of sight (LOS) parallel to the grids, through 10 mm diameter holes on the side components of the source case and perpendicularly to the grids, across larger holes on the source and drivers back plates. The light across silica viewports on the vacuum vessel is focused by optical heads with collimating silica lenses (Fig.3) onto 400 μm diameter high OH silica fiber optics and brought outside the bioshield to spectrometers or single channel detectors [16]. Optical emission spectroscopy (OES) can measure most plasma parameters with the support of a collisional radiative model [17]. Beam emission spectroscopy is also set up with 40 LOSs intercepting the beam both horizontally and vertically at 75° to the beam direction, to measure beam divergence, uniformity and stripping losses [18]. The two systems share the same design for optical heads, fibers and spectrometers. These are well established diagnostic techniques [19], so that here only the peculiar characteristics of the systems on SPIDER are highlighted.

On SPIDER the LOSs are collimated over a distance > 3m using f=120mm, 10 mm diameter lenses, for compatibility with the small apertures on the source case and to allow alignment through the opposite hole, by backilluminating the fibers. For BES the small collection angle is instead limited by the required accuracy on divergence at the expected low divergence values of 3-7 mrad [18]. The drawback is a reduction in collection efficiency, which was measured to be about a factor 20 less than the optical heads installed in ELISE: this is normally not a problem for OES except for weaker lines but it can be for BES, where longer exposure times and improved efficiency detection must be conceived. In addition, 8 fibers, one for each driver, are installed in-vacuum, routed through the HV bushing and transmission line, and used for protection to detect driver malfunctioning: the same set will be the only perpendicular LOSs available in MITICA and possibly in the ITER HNB.

OES detection, broadband or filtered at specific lines (e.g. Cu at 515 nm and Cs at 852 nm), is performed for some fibers with OSI-020UV photodiodes [20], equipped with an embedded transimpedance amplifier featuring an external feedback resistor, followed by a voltage amplifier with remotely selectable gain in the range 1-1000. The first stage in the custom detector module has a bandwidth of 50 kHz with 1MΩ gain (1 MHz with 10 kΩ), with a 4000:1 dynamic range, reducing to 4 kHz and 200:1 at 1000 further voltage gain. Acquisition will be performed by a National Instruments PXI-6259 board, with 32 analog input channels, 16 bit, 1 MS/s multiplexed.

Other OES fibers will be fed into one low and one high resolution spectrometers, the first for wide spectral survey (300 – 900 nm) to detected Balmer series, impurity and Cs lines, the second to resolve the molecular Fulcher bands. Newly designed IsoPlane SCT320 imaging spectrometers from Princeton Instruments [21] with different gratings have been chosen for both cases. A grating with 150 grooves/mm blazed at 500 nm for survey and an holographic one with 1760 or 2000 grooves/mm for molecules have been selected, opening the possibility to perform both measurements using the same fiber by just swapping grating. The Isoplane has much less aberrations than a Czerny-Turner (CT) spectrometer, allowing higher spectral resolution and more fibers on the input slit: 11 fibers with the selected Pixis camera mounting a 28x7mm (2048x512 pixels) thermoelectrically cooled CCD. Two spectrometers of the same type are used also for BES, where otherwise an f=750mm CT spectrometer would have been chosen, as for high resolution OES. A 2400 grooves/mm, highest compatible density, holographic grating will be mounted, achieving sufficient resolution and efficiency at 656 nm. With a ProEM camera using a 14x14mm (1024x1024 pixels) thermoelectrically cooled CCD, 22 fibers can fit the slit height. The other advantage of Isoplane is the higher luminosity: F/4.6 against F/10 of an equivalent 750 mm CT spectrometer, thus partially compensating the lower efficiency of the optical head; in fact the fiber exits towards the spectrometer with F/4.5.

Two other active spectroscopy diagnostics are being procured: a cavity ring down spectroscopy system to measure the negative ion density [22] and a laser absorption spectroscopy system [23] to measure the atomic cesium density, following the design developed at IPP and presented respectively in [24] and [25].



(a) (b)

FIGURE 3. (a) optical heads installed on the side of SPIDER vessel for source OES (right set) and BES (left set); (b) section of optical head installed in vacuum at the back of an RF driver

INSTRUMENTED CALORIMETER STRIKE

STRIKE is an inertially cooled calorimeter comprising an array of 16 tiles, made of 1D-CFC, which intercepts the entire ion beam, one tile for each beamlet group: due to the preferential heat conductivity across the tiles, the power load footprint is transferred with little distortion to the rear face, where the resulting temperature map is measured by two IR cameras [26]. STRIKE is the main beam diagnostic in SPIDER, as it measures the entire beam intensity distribution, and thus its uniformity, with the highest spatial resolution, limited by the 2 mm resolution of the IR camera and the heat transfer function of the tile. In addition, thanks to the possibility to move along the beam, the divergence will be estimated by comparing the beam footprint at two distances from the GG. Even if, differently from the water cooled copper beam dump, STRIKE can only work with short pulses, < 10 s at nominal power, it will serve as a benchmark for other beam uniformity diagnostics without such limitation like the beam dump thermocouples, BES and optical tomography, that have lower resolution or are not local measurements but line-of-sight averaged and as such require data inversion. It is particularly important to understand the capabilities and operational limits of these diagnostics in view of their use in MITICA, where STRIKE is not foreseen: in fact STRIKE would not sustain the 10-fold increase of beam power, but it would still be useful to diagnose the initial lower power operational phase.

So far mini-STRIKE systems using small old prototype tiles have been used in BATMAN at IPP [27], at NIFS test bed [28] and more recently at QST [29], where characterization of the beam down to the single beamlet, was unachievable with other diagnostics. The simple approach of fitting the data with a superposition of as many Hubbert peaks as the number of beamlets, which is particularly successful when they are distinguishable, helps describe beam optics uniformity and deflection, providing useful information to optimise voltages or magnetic field configuration. Such procedure can be improved using a transfer function technique, applied successfully to data from NIFS test-stand and BATMAN [30]: the tile can be modeled as an operator providing a defined output (a temperature map on its rear surface) to a certain input (the power flux by the beam), through a transfer function, measured using as input a focused laser beam. By inverting this transfer function the heat flux related to a certain temperature map can be retrieved. The feasibility of applying this technique to non-stationary heat loads is currently under investigation. The reconstructed heat flux has a lower beamlets superposition and fitting is found to be easier.

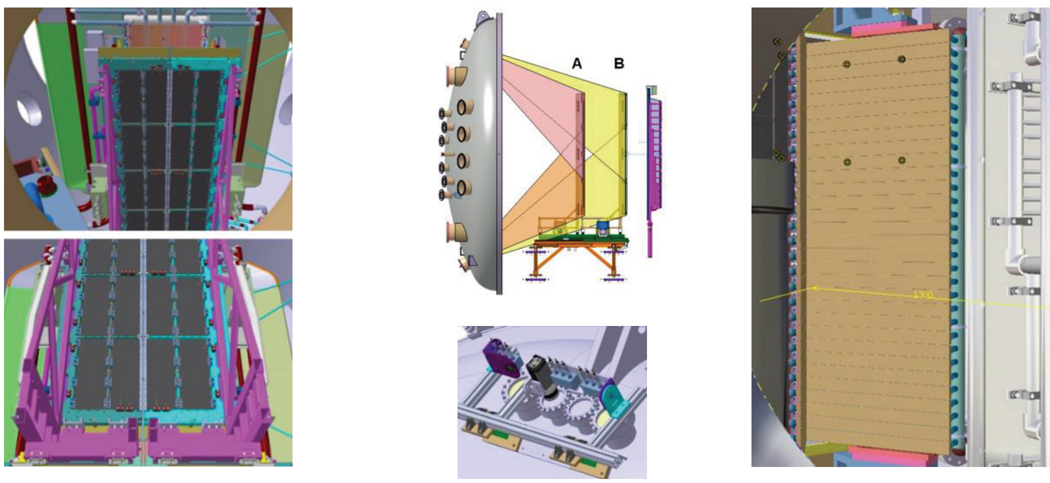
The main problem with STRIKE is that the manufacturer of original 1D-CFC tiles stopped production more than 20 years ago, the manufacturing expertise was lost and no company would commit to procurement without first a best effort R&D program to demonstrate that the original specifications could be reproduced. Such R&D has been undertaken by Toyo Tanso, within the F4E procurement contract. After a 9 months manufacturing process, in June 2016 they have delivered a full size 142 mm x 376 mm, 20 mm thick prototype tile and two half size tiles, 142 mm x 188 mm, with a thermal conductivity ratio (parallel to perpendicular) ranging from 20 at room temperature to 15 at 1200 °C and with all other mechanical and thermal properties suitable for this application. The tiles have been successfully tested with a high power CO_2 laser beam focused down to a 2 mm diameter spot to verify the thermal properties and the symmetry of conductivities in the tile plane [31]. Prototype tiles will then be tested under the high power beam of GLADIS test bed to verify if they can sustain the high gradient power load expected in SPIDER at nominal power and divergence. The rationale behind the two prototype sizes is that half size tiles should be less susceptible to breakage, also because they are much less elongated, and thus they will be a backup solution in case the full size one will break, with the acceptable limitation that the central rows of each beamlet group cannot be measured as it will be at the edge of the tile. If both prototypes will fail, the alternative concept is a castellated tile [32], which has however reduced performance and is similarly limited in maximum power load. The full set of tiles will be ordered after successful test on the prototypes and will be installed in SPIDER in time for the initial operational phase.

Another important component of STRIKE is the in-vessel mechanical support and positioning system for the array of tiles. The tiles are mounted on two symmetrical panels, left and right, which are closed to intercept the beam during measurement and positioned between 0.5 m and 1.1 m from the GG to estimate the beam divergence. Conversely the panels will be left open in long beam pulses to allow the ion beam through, to the water cooled copper beam dump. The mechanical system is now being manufactured and was designed to be vacuum compatible to 10^{-5} Pa, with suitable welding procedures, carefully avoiding trapped volumes and guaranteeing clean surfaces, using in-vacuum stepper motors to move the two panels both along and across the beam.

Two IR cameras view respectively the top and bottom half of the CFC panels, with some overlapping to cross-validate the measurements (Fig. 4a,b). They are installed on the front lid of the vacuum vessel and look through ZnSe viewports, with > 98% transmission in the 7.5-14 μm spectral range of the camera. The IR cameras have been selected with the following main specifications: detector array with at least 640x480 pixels, to achieve a spatial resolution of 2 mm or 2.5 mm when the tiles are respectively at 1.1 m or 0.5 m from the GG; radiometric camera calibrated with 2% accuracy from room temperature to 2000 °C, as for pulse repetition rates of 20 minutes the maximum temperature at the back of the tiles is expected to swing between 220 °C and 1700 °C at each 10 s pulse; frame rate of ≥25 Hz, considered sufficient to follow the relatively slow dynamics of the temperature evolution; ethernet interface for reliable and standardised central control and data acquisition from outside the SPIDER bioshield at distances > 25 m. Cameras with uncooled microbolometer detector array have been preferred to cooled

InSb detectors because they can meet the specifications with about 1/3 the cost and with acceptable limitations: in particular model A655sc from FLIR has been chosen. In fact STRIKE does not require the much faster frame rate and higher accuracy of InSb cameras, and it can tolerate an external trigger with 1 frame accuracy and operation with one of the three selectable temperature ranges: -40°C to 150°C, 100°C to 650 °C and 300°C to 2000°C for each beam pulse. This is the most penalising restriction as in some cases the higher temperature at the beamlet centre might be saturated or the higher range might not cover the tail of the beamlet, but this can be improved by the fitting routines or merging similar pulses with different ranges. Alternatively, a second double focal length lens is available to improve the spatial resolution to < 1mm but waiving the full spatial coverage.

When STRIKE is open, the same IR cameras will be used to monitor each of the two copper beam dump panels, by repositioning them on different viewports (Fig. 4c). To this purpose the front surface of the dump, with expected temperature up to 350 °C, will be coated with a suitable black molybdenum disulphide coating, i.e. Molykote D-321R, made by Dow Corning, to overcome the problem of the low copper emissivity, as effectively achieved at IPP [33], and in this case also to reduce the reflection from the opposite panel.



(a) (b) (c)

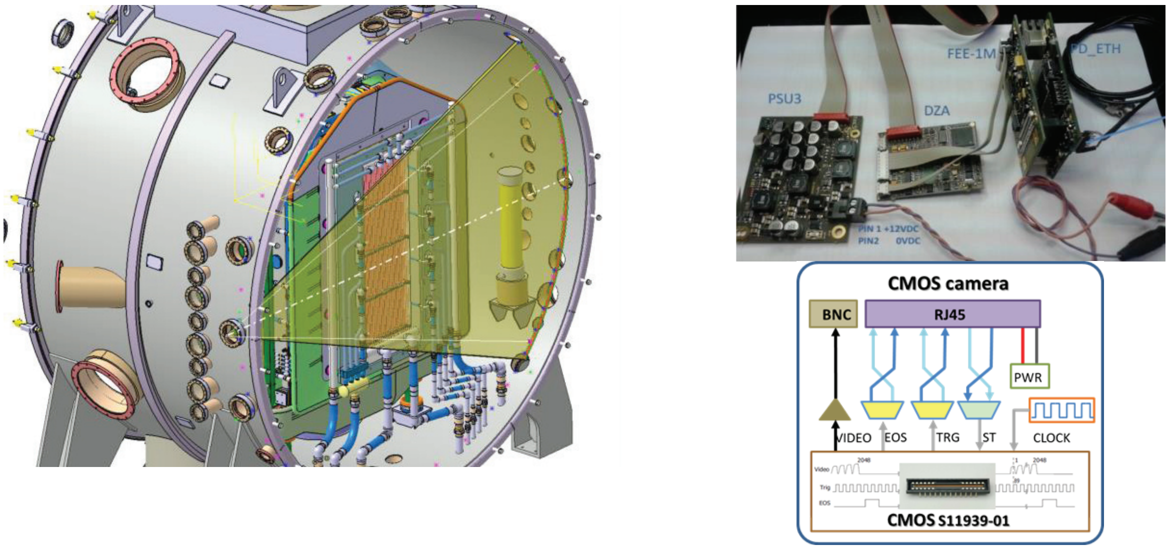
FIGURE 4. (a) View of the STRIKE panels from the top and bottom IR cameras; (b) STRIKE positions (500 & 1100 mm from GG) and IR views (top) and top IR camera installation together with BES optical heads (bottom); c) view for IR camera of one panel of water cooled beam dump from side viewport

OPTICAL BEAM TOMOGRAPHY

An optical tomography diagnostic has been designed to measure the beam intensity profile and its uniformity. The layout comprises a set of 15 linear cameras looking perpendicularly or at a small angle to the beam through a corresponding set of viewports all around the vacuum vessel [34]: total 3000 LOSs allow to achieve a good tomographic reconstruction with a resolution of ¼ the beamlet group [35], improvable down to a couple of beamlets with suitable filtering [36].

The layout and the inversion procedure require a sufficiently large linear sensor, with > 1000 pixels, good sensitivity and high dynamic range to compare LOSs collecting from one to about 20 beamlets and able to discriminate 10% deviations from a uniform profile. Only a small selection of linear CCDs for spectroscopy applications can satisfy such requirements, as most of the linear cameras market is tailored for inspection and production line measurements or for scanning applications, which are all based on a strong external illumination and characterized by smaller sensors with lower dynamic range, typically < 1000:1, and much faster frame rate than required. Two suitable solutions are CCD S11071-1104 and CMOS S11639-01, both from Hamamatsu, respectively with 2048x16 pixels 14x14 μm and 2048 pixels 14x200 μm. The former is sold by TEC5 in a OEM camera module comprising a set of four stacked boards, with ethernet interface, 6000:1 dynamic range, 400 Hz maximum frame rate. The latter is controlled by 3 digital lines and has an analog video out, so that a simple custom board has been built for it, performing 5000:1 dynamic range and 4 kHz maximum frame rate. Both can be externally triggered for mutual synchronization. Both prototype cameras have been tested and found suitable for the application, but the

CMOS camera, with much simpler electronics, is likely more radiation hard and significantly cheaper, which would make it more appealing for its future use in MITICA, where radiation damage is an issue for detectors and electronics and consumable cameras might have to be used.



(a) (b)

FIGURE 5. (a) Fan of lines of sight of one linear camera on a section of SPIDER vessel; (b) pack of 4 boards for linear camera from TEC5 with linear CCD Hamamatsu S11071-1104 (top) and schematic of linear camera with CMOS S11939-01 (bottom).

NEUTRON IMAGING

In deuterium operation, fusion reactions between beam deuterons and deuterons implanted in the copper beam dump will produce about 10^{12} neutrons/s spread over 1 m^2. Hence information about the beam intensity profile and its uniformity can be retrieved from the neutrons flux density distribution over the dump. To this purpose a Gas Electron Multiplier detectors equipped with a cathode that also serves as neutron-proton converter foil (nGEM) is used, positioned just behind the dump at about 3 cm from the dump surface [37]. A 230x352 mm^2 nGEM with 256 pixels has been built and will be installed in SPIDER to measure the footprint of a beamlet group with an expected resolution of about 3 cm [38]. Since the detector must operate at atmospheric pressure, it is enclosed inside a vacuum sealed box, which is inserted inside the SPIDER vacuum vessel and connected to the outside through an umbilical pipe that also routes cabling to the detector. The vacuum box and connection pipe have been designed and are currently being manufactured. Prototype detectors have been built to optimize manufacturing process and to test directionality capability, neutron detection efficiency, beam profile reconstruction capability, uniformity over the active area, gamma rejection capability and time stability [38]. Some of these tests were performed with an X-ray source, others on the ROTAX beam-line at the ISIS spallation source.

In this application the deuteron absorption in the beam dump is still a debated issue and to investigate it a calibrated liquid scintillator was installed in ELISE to measure the time evolution of neutron emission from the copper dump during deuterium operation [39]. Preliminary results show some agreement with simulations based on a local mixing model and 20% deuteron concentration at saturation, but further experiments are under way.

CONCLUSIONS

The status of procurement of SPIDER diagnostics has been described with focus on specific design solutions and original components. While procurement of components is being completed, systems assembly and installation in the test facility is going to start, with the aim to complete interfacing to the central control and acquisition system and finally commissioning before start of SPIDER operation. Some subsystems and analysis programs will be preliminary tested in NIO1, at IPP or at NIFS.

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