CEFDA04-1140

Task Title: TW4-THHN-ADSD2: DEVELOPMENT OF THE NEGATIVE ION SOURCE (ARC DRIVEN) FOR THE ITER NEUTRAL BEAM INJECTORS FOR LONG PULSE OPERATION.

INTRODUCTION

In Cadarache development on negative ion sources is being carried out on the KAMABOKO III ion source on the MANTIS test bed. This is a model of the ion source designed for the neutral beam injectors of ITER. This ion source has been developed in collaboration with JAERI, Japan, who also designed and supplied the ion source. Its target performance is to accelerate a D^- beam, with a current density of 200 A/m^2 and <1 electron extracted per accelerated D^- ion, at a source pressure of 0.3 Pa. For ITER a continuous ion beam must be assured for pulse lengths of 1000 s, but beams of up to 3,600 s are also envisaged. [1] The ion source is attached to a 3 grid 30 keV accelerator (also supplied by JAEA) and the accelerated negative ion current is determined from the energy deposited on a calorimeter located 1.6 m from the source.

2005 ACTIVITIES

During previous campaigns, continuous beam pulses of duration up to 1000 s have been demonstrated both in hydrogen and in deuterium, however the current density of both beams were found to be low in comparison to the specifications of 200 A/m^2. The D- accelerated beam is collected on a calorimeter, made of water cooled copper, which is located at 1.6 m or 1.4 m downstream of the accelerator. A large discrepancy exists between measured accelerated currents and that which is transmitted to the calorimeter. The discrepancy in these values and the possibility that the accelerated current included electrons, either from extraction or stripping was investigated. The objective of experiments in 2005 was to investigate the loss of ≈50 % of the accelerated negative ion current between the the last grid of the accelerator and the calorimeter on MANTIS.

Beam Transmission

The negative ion current density extracted from a negative ion source is best derived from the beam energy and the power deposited on a remote target or targets. With the Kamaboko III ion source on MANTIS during long pulse operation the power arriving at the calorimeter is determined from the temperature rise of the cooling water and the measured flow rate. The current arriving at the target is typically only 45 – 60 % of the current taken from the high voltage acceleration power supply. “Bad” beam transmission has been previously measured and reported on the MANTIS test-bed. [2] Intensive investigation into the loss of 50 % of the accelerated current has been carried out and a number of possibilities eliminated. These possibilities were as follows:

- that the accelerated current included extracted electrons.
- Electrons created from stripping or back-streaming ions were being included in the accelerated current measurement.
- That the space-charge of the accelerated ion beam was causing the beam to blow up and diverge.
- That the loss of beam is due to bad beam optics, i.e. that errors in extraction and acceleration gaps, grid misalignment and negative ion current density and magnetic field effects were causing the loss of beam.

Each of the above were individually examined and subsequently eliminated. [2]

A partial explanation was thought to be power loading to the extraction or acceleration grids. A deterioration in the beam optics could occur during the long pulses if one, or both, grids were bowing under the thermal load, the beam optics would change until the grids reach thermal equilibrium. Results that indicate a substantial change in beam transmission with the pulse length seems to support this theory. Figure 1 shows the transmission as a function of the pulse length, for shorter pulse lengths the transmission is significantly higher that for long pulse operation.

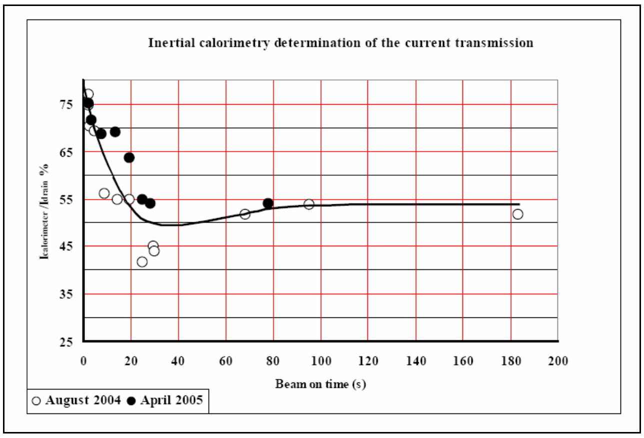

Figure 1

On the MANTIS test-bed the accelerated ion beam propagates inside the walls of a drift duct, which fills the space between the accelerator and the calorimeter. A schematic of the MANTIS layout is shown in figure 2. If poor beam optics are the cause of the poor transmission, then the lost current would fall on the walls of the drift duct. To measure the current falling on the duct walls a new drift duct and calorimeter were constructed and installed.

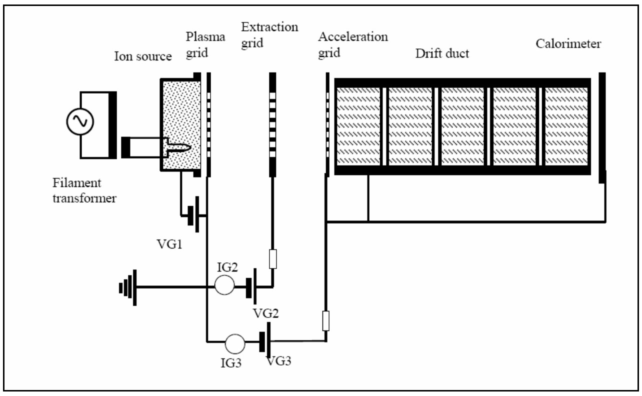

Figure 2

The square cross section duct is made up of 24 copper panels each 20 cm x 25 cm mounted on a stainless steel support frame, see figure 3, making a duct of 25 cm x 25 cm cross section, ≈1.2 m long. A new, un-cooled, calorimeter is installed at the downstream end of the duct.

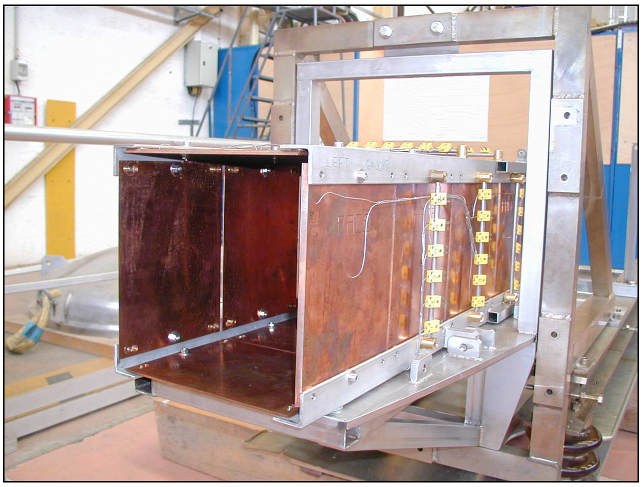

Figure 3

The current intercepted on the target and on the drift duct is measured from the thermal data collected by thermocouples embedded into the copper. Also an infra red (IR) camera was set up to view, through a sapphire window, the rear of the beam target (the side not hit by the beam). Some of the target was partly hidden from the IR camera, so the camera is able to give information about the beam optics, but only an estimate of the power incident on the target.

To obtain a measure of the beam divergence the difference between two profiles is obtained, the profile just before the beam pulse and the profile 10 s later. Lateral diffusion during 10 s is significant, therefore simulations which take account of this thermal diffusion have been performed for beams with various values of the beamlet divergence, and these are used to deduce the actual beamlet divergence from the measured profiles. An IR image collected by the IR camera located 3 m from the rear of the graphite painted copper target is shown in figure 4, the resulting Gaussian profiles in the horizontal and vertical are also shown for a typical beam profile on MANTIS.

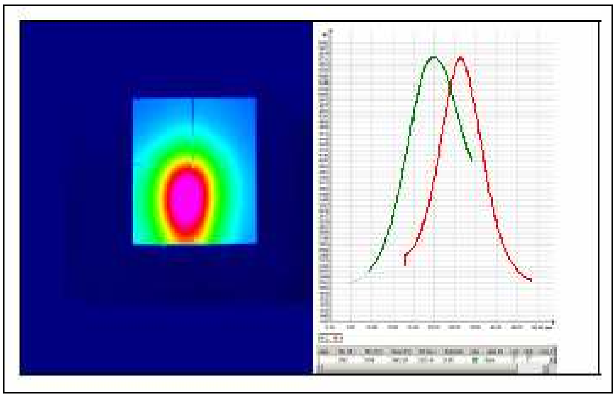

Figure 4

Using the new duct and calorimeter, it was typically found that 64 % of the accelerated current arrives at the calorimeter and 30 % falls on the duct. Thus it can be concluded that >90 % of the current taken from the high voltage power supply, Idrain, is accelerated negative ions, but that ≈30 % of the accelerated beam is carried by a very divergent “halo”. Preliminary estimates suggest a halo divergence of ≈200 mrad. This is to be compared to the divergence of the central part of the beam, the “core” divergence, which has been measured to be <50 mrad [3].

To asses if the poor divergence is a characteristic of the accelerator, or particular to negative ion acceleration, the potentials on the accelerator were reversed and positive ions extracted and accelerated, from the same ion source, with the same magnetic fields etc., and the beams were analysed with the same diagnostics [3]. It is found that the transmission of positive ions to the calorimeter is ≈96 %, therefore it seems that the beam halo is particular to the negative ion acceleration.

Now that the presence of a halo has been determined the question remains as to why these large halos exist. One hypothesis is that the beam halo is caused by the bad beam optics due to distortion of the grids with power loading. To this end a new accelerator grid and extraction grid have been designed, which are designed to accept the power load without thermo-mechanical distortion. They have recently been installed on the MANTIS test-bed, and experiments are due to start in march 2006.

CONCLUSIONS

A low H- or D- current density measured at the calorimeter on the MANTIS test bed during long pulse operation cannot be explained by lost accelerated electrons arising from either extraction from the ion source or creation by stripping in the accelerator and is partially attributed to poor transmission due to thermal loading leading to distortion of the acceleration grid.

A new drift duct and calorimeter were installed to investigate the lost current, It was found that 30% of all accelerated current was being intercepted by the drift duct in a halo. The power accountability was in excess of 90%.

Using the same optics, and reversing the polarity of the power supplied, the MANTIS test bed was operated with positive ions. In this case >96% of the beam was intercepted on the target, and no halo seen.

The presence of a beam halo is observed only in the negative ion beams, to determine whether the distortion in optics due to thermo-mechanical loading of the grids is causing this halo, a new accelerator has been designed and installed.

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[3] Characterization of the ITER model negative ion source during long pulse operation R S Hemsworth, D Boilson, B Crowley, D Homfray, H P L de Esch, A Krylov, and L Svensson. To be published in Rev. Sci. Inst., Vol. 77 (2005)

REPORTS AND PUBLICATIONS

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[3] Characterisation of the ITER model negative ion source during long pulse operation R. S. Hemsworth, D. Boilson, B. Crowley, D. Homfray, H. P. L. de Esch, A. Krylov, and L. Svensson. To be published in Rev. Sci. Inst., Vol. 77 (2005)

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CEFDA04-1182

Task Title: TW4-THHN-IITF2: FIRST ITER NBI AND THE ITER NB TEST FACILITY: PROGRESS IN THE DESIGN

INTRODUCTION

The key conclusion of the final review meeting for the previous contract on this topic (TW3-THHN-IITF1), held in july 2004, was to bring the alternative SINGAP configuration for the accelerator and the negative ion source (RF or arc driven) to a level of design comparable to the reference design of the MAMuG accelerator and the arc driven source as in the ITER documentation. Therefore the objective of the 2005 activity was to make progress with the conceptual design of the first ITER NB injector in the SINGAP configuration. The Euratom-CEA association was involved in the conceptual design studies of both SINGAP ion source and SINGAP accelerator supporting systems.
The second part of the task was aimed to the detailed design studies of the ITER Neutral Beam Test Facility (NBTF) with completing the design of the generic installation (i.e. beam line vessel, cryoplant, cooling system).
The Euratom-CEA Association is involved in this EFDA workprogram in close collaboration with ENEA, FZK, IPP, CIEMAT and UKAEA European Associations.

2005 ACTIVITIES

POWER LOAD TO THE BEAMLINE FROM A SINGAP ACCELERATOR

A study has been launched to examine the influence of the known physical parameters that affect the beam optics on the power and power density that will impinge on the beamline components.

The sensitivity of the beam optics to the parameters listed below has been studied:

- Manufacturing tolerances.
- Voltage variations on the ion source and accelerator.
- Changes in manufacturing tolerances due to operation, e.g. thermal expansion.
- Differences due to idealised physics assumptions: axial and radial gas pressure profiles, magnetic fields, ion temperature.
- Source uniformity. Conceptual design of the SINGAP NB Ion Source supporting system.

The next step in this work is to integrate the results of this study into a computer code that wile calculate the power and power density on selected components.

ELECTRONS FROM SINGAP

A disadvantage of the SINGAP accelerator is that electrons created by stripping in the main acceleration gap are accelerated from their birth position up to ground potential where they exit the accelerator through the large apertures in the grounded grid.

The power carried by these electrons is calculated to be 2.7 MW, and their average energy is 720 keV. Without any modification to the system these electrons hit either the inside of the neutralizer channels or the leading edge elements of the neutralizer. The power density impinging on the leading edge elements is calculated to exceed the power density limit of the elements in the basic design, and no alternative has been found that can accept the power density and have an acceptable fatigue life.

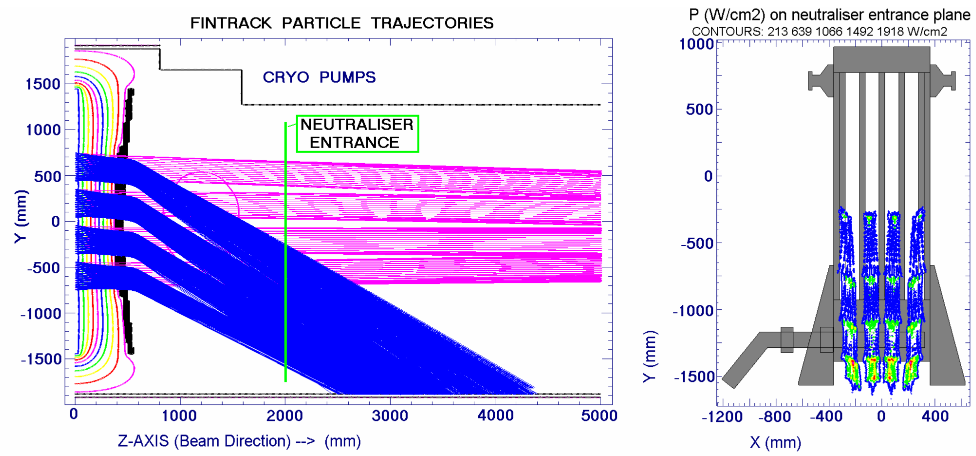

Figure 1: To the left: deuterium (purple) and electron (blue) trajectories. The picture on the right gives the electron power density contours overlaid on a picture of the neutraliser. Contours are plotted at 10% (blue), 30% (green), 50% (yellow), 70 % (red) and 90% (purple) of the peak power density in the graph (1.97 kW/cm^2)

The solution proposed by the CEA is to add a horizontal field at the exit of the accelerator by placing columns of permanent magnets just downstream of the grounded grid that are placed either side of the beams from the apertures in the grounded grid. The additional magnetic field has a negligible on the D- beams, but deflects the electrons onto the floor of the neutraliser and a vertical dump placed below the neutraliser entrance. figure 1 shows the deflected beams and the calculated power density at the neutraliser entrance.

The resulting power density is significantly reduced compared to the undeflected situation, but there are still some “hot spots” created by overlapping beamlets. It is proposed to ameliorate the situation by sweeping the electron beams in an oscillatory fashion on the vertical dump and neutraliser floor. A sweep of ±12 cm on the vertical dump and the neutraliser leading edge elements is achieved simply, and in a fail safe manner, by choosing a PG filter current power supply with ±10% ripple.

ION SOURCE AND NEUTRALISER GAS SYSTEM

The gas supply system for ion sources and the neutralisers on the NBTF and for the injectors on ITER have been designed by the Euratom-CEA-ssociation. The system that is proposed for the NBTF is slightly different from the one proposed for ITER since the flow rates need to be adjustable on the NBTF in order to optimize the ion source operation and the neutralization of the accelerated ions. In principle the flow rates can be fixed on ITER injectors although a small range of fine adjustments is foreseen. A particular difficulty is posed by the source gas system as the source will be at –1 MV. The design proposed takes account of this, it provides fine control of the gas flow (±5%) and the gas acountability that is necessary for the operation of the cryopumps (regeneration etc.).

CONCEPTUAL DESIGN OF THE SINGAP NB ION SOURCE SUPPORTING SYSTEM

The SINGAP ion source body and the plasma, extraction and pre-acceleration grids are designed by the ENEA Association.

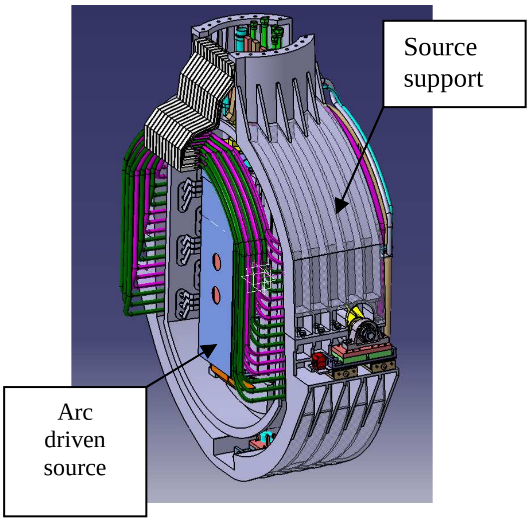

Figure 2: Isometric view of the SINGAP source support

The arc driven/RF ion source and support has a dead weight of ≈15 tonne that is hung from the high voltage SINGAP bushing. The setting up and alignment of the source is made during the assembly phase. The conceptual design of the 1 MV source supporting system, and the structural analysis of the support, was carried out by the Euratom-CEA Association. This support fulfils both static and dynamic loading conditions.

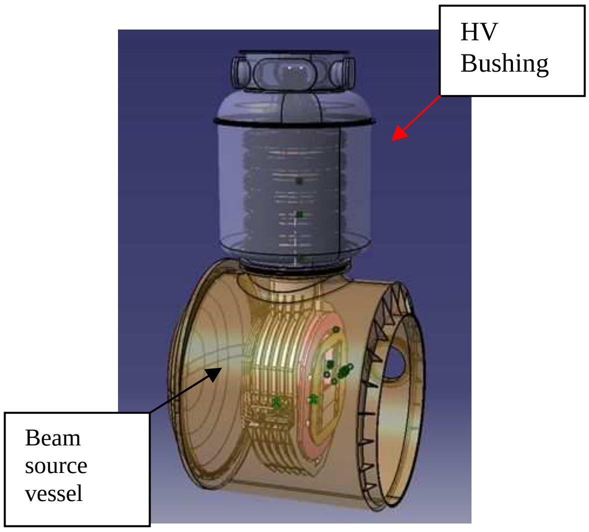

Figure 3: The SINGAP source integrated in the ITER beam source vessel, hanging from the bushing

CONCEPTUAL DESIGN OF THE SINGAP ACCELERATOR SUPPORTING SYSTEM

The SINGAP acceleration grid (or grounded grid) is designed by ENEA and is located 350 mm from the pre-acceleration grid. The conceptual design of the accelerator support system was studied by the Euratom-CEA Association. The proposed system can be adjusted in all directions and rotations towards the ion source and/or beam line components. The mechanism for moving the SINGAP electrode to provide the accurate lateral and vertical beam steering is considered in the design of the supporting system (see figure 2). The study included the structural analysis. The mechanism will operate under vacuum, using magnetic transmission drivers for both vertical and lateral motions.

DETAILED DESIGN OF THE BEAM LINE VESSEL

The current design of the beam line vessel (BLV) allows mixed vertical and horizontal access to the beam line components (BLCs). The detailed design of the BLV and associated large rectangular top flange was performed during 2005 by the Euratom-CEA Association. The upper large opening (9.50 m x 2.55 m) allows vertical maintenance as shown in the figure 5. The BLV is a cylindrical elliptic shape that allows the integration of two halves split cylindrical cryopumps designed on the basis of the ITER cryopump reference. The elliptic shape vessel is connected to the beam source vessel (BSV). The vessel global volume is almost 200 m^3.

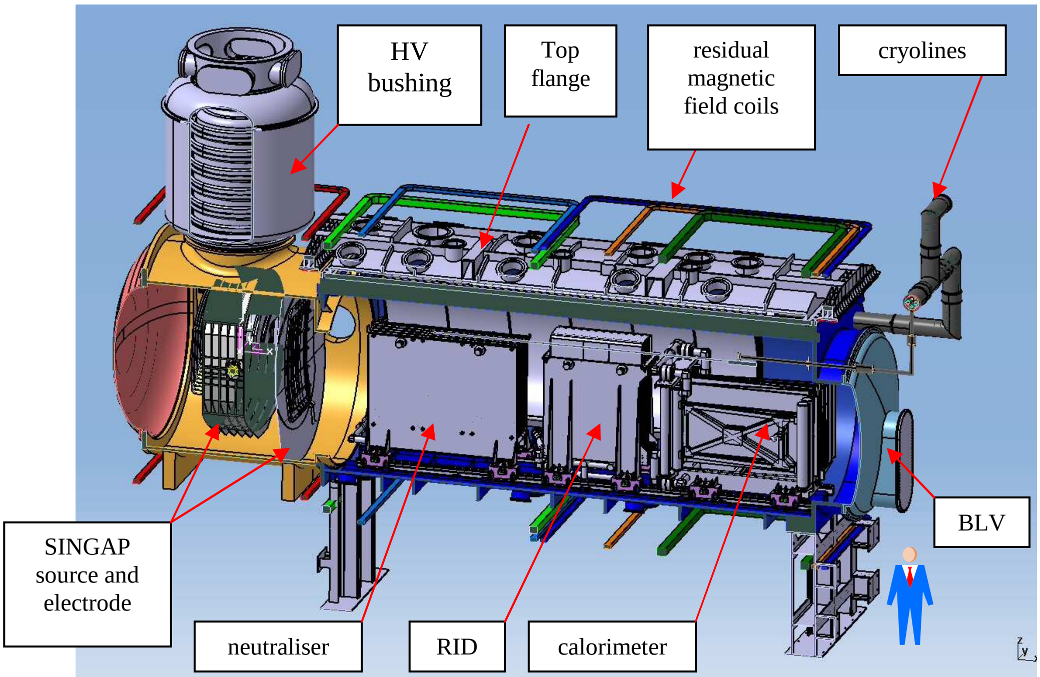

Figure 4: Isometric view of the NBTF and injector components

DETAILED DESIGN OF THE CRYOLINES

Detailed design of the cryogenic lines and interfaces with the cryopump inside the BLV are studied by CEA. The main specification of the cryolines is to feed the cryopanels with supercritical helium at 4.5 K and to feed the chevron baffles and thermal shields with helium gas at 80 K. The lines are composed of modules which are classified in 4 main categories: “T” section, “Elbow” section, “Straight” line and “Junction” section. The modular concept of the design is helpful for manufacture and assembly procedure.

DETAILED DESIGN OF THE COOLING SYSTEM

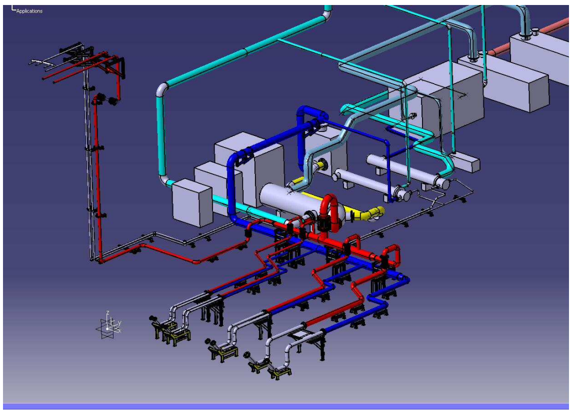

Figure 5: Isometric view of the NBTF PHTS

The cooling plant for the NBTF consists in a primary heat transfer system (PHTS) and a heat rejection system (HRS) that includes a 60 MW cooling tower. The full thermal power produced by the injector and the power supply system can be exhausted in a steady state regime.
The detailed design of the PHTS was performed during 2005. It includes the low voltage loop (inlet temperature 80°C) that feeds the beam line components (BLCs) and the high voltage loop for the feeding of the 1MV ion source (inlet temp. 20°C) and associated pre-accelerator (inlet temp. 55°C). figures 5 and 6 illustrate the design of water manifolds and feeding pipes in the experiment building.

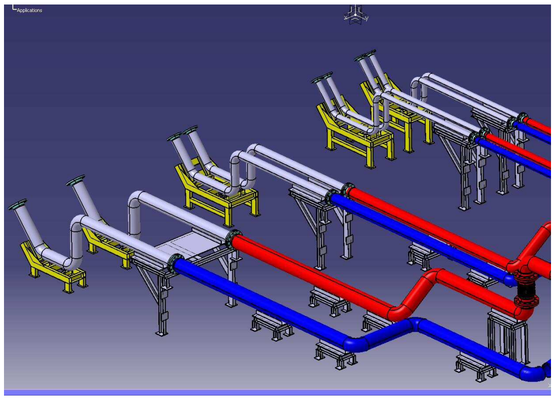

Figure 6: View of the BLCs feeding pipe

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CEFDA04-1182RHpart

Task Title: TW4-THHN-IITF2: FIRST ITER NBI AND THE ITER NB TEST FACILITY: RH DESIGN FEASIBILITY ANALYSIS OF NBI INSPECTION

INTRODUCTION

Recent developments of an inspection device able to operate under vacuum and temperature, the Articulated Inspection Arm (AIA), were made at CEA/LIST. The main interest of such devices is to avoid long lasting reconditioning periods when vacuum is broken. The AIA is made of five segments linked in a serial manner and each having two degrees of freedom. It will perform in the Tore Supra Tokamak some visual inspection, sampling and a set of other operations. Although the kinematics and architecture used to build that kind of robots was already known at CEA/LIST and developed for inspection of fuel reprocessing cells (PAC project), the new constraints induced by the operating conditions (ultrahigh vacuum, temperature) required the complete development of specific actuators.

The feasibility of an inspection carrier for the Neutral Beam Test Facility (NBTF) was demonstrated in a very preliminary study after examination of the requirements and the inspection tasks.

2005 ACTIVITIES

INSPECTED ZONES

Due to the thermal heat flux of the beam, some areas of the facility could be damaged during the lifetime of the project. It is therefore important to perform careful examination of the critical areas.
The interfaces between the main elements are the critical zones of the facility (see figure 1).

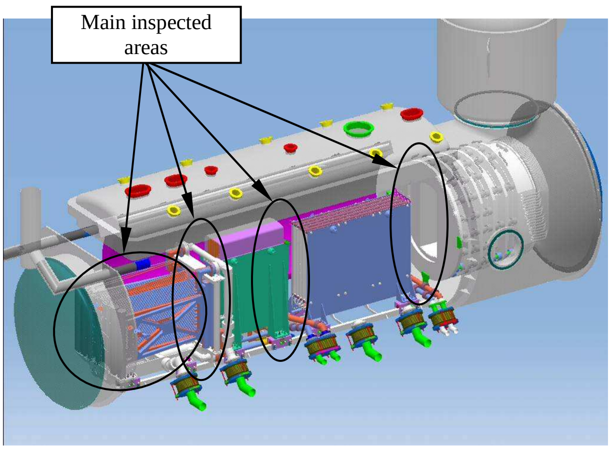

Figure 1: NBTF vessel: inspected zones

The standard inspection tasks will therefore be carried out in these areas:

- interface between the source and the neutralizer
- interface between the neutralizer and the RID
- interface between the RID and the calorimeter
- calorimeter zone (inside)

Although the cryopumps are not directly submitted to the heat flux of the beam, inspection of these elements will be necessary to check if they are not submitted to arcs.

ROBOT ARCHITECTURE

Previous work proposed an inspection robot concept based on articulated segments all with the same architecture and linked in a serial way to build a carrier. According to the size of each segment, the number of degrees of freedom and the strokes of each actuator, inspections can be carried out in all the operating area with help of a camera located at the end of the carrier.
In a first stage, the study aimed to define the kinematics of a robot and its architecture considered as the minimum required to reach all important zones of the facility.

Design of the carrier was made with the following requirements:

- Minimise the number of degrees of freedom, so that:
  - Control is made easier
  - Breakdown probability increase with the number of actuators
  - Cost is reduced
  - Stiffness is increased

- Minimise the number of segments

- Minimise length

- Dimension range should remain close to the existing prototype:
  - Diameter 160 mm
  - Segment length close to 1.5 m

- Use the existing actuators without new R&D

- Carrier will be inserted through the cover plate along a vertical axis.

The following assumption was taken:
2 degrees of freedom camera and turret designed for vacuum and temperature exists and will be used for the inspection.
The payload of the carrier is 10 kg.

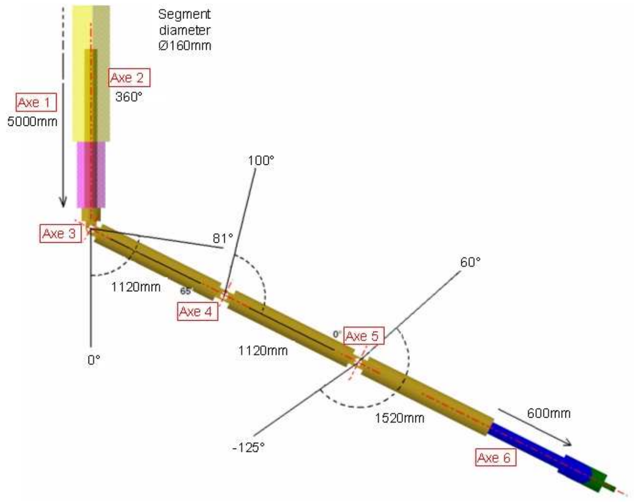

Figure 2: Dimensions and strokes of the carrier

Simulations of inspections tasks in 3D CAD models identified the architecture of figure 2 as a good candidate for inspection in the NBTF vessel when two access ports are available. Attention was paid to locate the entry point apart the vertical symmetry plane in a location where deployment of the carrier is not affected by the position of the main components.
Strokes and loads applied on all articulations are compatible with those already tested during R&D work of the AIA. Only minor adaptations without uncertainties should be needed to deal with these new requirements.
Inspections carried out with a carrier from a single access port located in the middle of the cover plate were assessed with the assumptions that only the number and length of the segments were supposed to change.
In this case 1400 mm is the maximal length of a segment (estimation made according to the existing performances of the AIA actuators). In that case, one carrier composed of three 1400 mm long segments and a 1520 mm end segment similar to the previous concept is feasible. In that case, design margins will be significantly reduced and a reduction of the 10 kg payload should be considered.

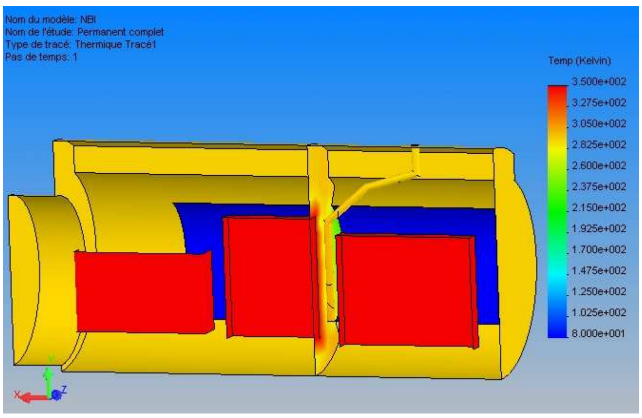

Figure 3: Steady state thermal calculations

Both steady state and transient thermal calculations were made to analyze heating of the carrier and its potential impact on the behaviour. Although temperature elevation in steady state of all scenarios stays below 35°C (meaning that thermal stresses in the carrier should remain at an acceptable range) the evaluation of the benefit of a reflecting coating clearly shows an improvement compared to a version without any reflective layer. This could be a good answer to limit the clearances modifications in the assembly due to temperature elevation and to prevent any early wear of the mechanical components already running without any grease.

ELECTRONICS

Prototypes already developed (PAC, AIA) are all using integrated electronics to drive each segment of the robot. To reduce the volume of wiring a dedicated network was developed for these applications. Boards used for Cogema carrier are rad hardened to a cumulative dose of 10 kGy with a maximal 10 Gy/h radiation flux. Introduction of the electronic boards in boxes to cope with the vacuum environment of the NBTF vessel will probably lead to overheating of the components. Possible solution could be:

- To provide a cooling system
- To use components of the military series but their availability needs to be checked.

CONTROL

Control of the NBTF inspection device would be similar to that of AIA and its family and based on real-time dynamic simulations. A 3D CAD model of the facility is used to drive the robot in its environment. Virtual views can be provided to the operator in order to ease the task. A collision avoidance algorithm can also be run to avoid any undesired contact of the robot with its environment. Due to high flexibility, absolute precision of such robots is poor. On the other hand their repeatability is good.

The use of a scale 1 training facility is therefore necessary if one wants to achieve thorough inspections of the different elements with accuracy. Teach files are then defined and played in the facility to improve safety margins regarding to the components of the vessel and defined the optimal trajectories.

CONCLUSIONS

This feasibility study was based on all the latest results from the R&D work for the Articulated Inspection Arm (AIA) performed under the EFDA Remote Handling Activities. The proposed carrier for NBTF inspection is therefore made of a defined number of segments all linked in a serial manner. Articulations are driven with vacuum tight actuators developed to withstand high vacuum and high temperature conditions. This option has been chosen to base the study on existing results and minimize the risks of a brand new conception.
Two intervention schemes have been assessed. First one where access to the Beam line components is provided through two ports on both sides of the baffle. For the second option access is provided from a central position that requires initial baffle removal. Although design margins are small in the study with two access ports, they

could be easily increased with a reduction of the payload that will carry the inspection tool.

During this NBI carrier conceptual design study, implantation of neighbor diagnostics was not defined and no attention was paid to avoid any interface issue with diagnostics in the vessel during deployment of the carrier. Space reservation for these elements may have a direct impact on the definition of the carrier and feasibility of the inspections.
Duration of an inspection should not last more than a couple of hour (in case of a two access ports study) according to the performances of the existing actuators. For that reason thermal effects on the carrier should be limited during inspections.
Rad-hardened electronics developed for inspection of fuel reprocessing hot cells would be preferable to that of AIA because thermal conditions are less stringent.
A first generation of control system was already developed for the carrier navigating in fuel reprocessing hot cells. Adaptation of this control system to the new carrier is feasible. Both rough and fine control can be achieved with this system. But fine control of the system can only be achieved by means of teach and repeat procedures defined in scale 1 test facility.
Design of a carrier that can inspect in an acceptable time all major NBTF components and operate under vacuum is feasible without any major R&D developments. Design margin of a solution with a central access with removing the baffle is close to the limits of the present performances and further investigations would be necessary to increase margins.
Nevertheless, further conceptual then detailed design studies of the NBTF inspection robot should be launched when the final design of the beam line vessel and internal components will be frozen. The present feasibility study will have first to be revised.

REPORTS AND PUBLICATIONS

Feasibility of an inspection device
DTSI/SCRI/LPR/05RT.072

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