A TORIDAL CONFINEMENT FACILITY STUDY AND EVENTUAL EXPERIMENTAL DEVICE TO INVESTIGATE A RANGE OF LIQUID METAL DIVERTOR AND FIRST WALL CONCEPTS

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Abstract

A Toroidal Confinement facility study and development of a characteristic experimental device was undertaken to investigate a range of liquid metal divertor and first-wall concepts build on past and expected results from liquid metal experiments: the Lithium Tokamak Experiment (LTX), the National Spherical Torus Experiment Upgrade (NSTX-U), and the Experimental Advanced Superconducting Tokamak (EAST). The device configuration is driven by the need to adequately provide the concept details that depicts component features, space allocations, plumbing arrangements, thermal insulation, etc. of liquid metal (LM) systems. Of equal importance is to validate that the developed designs are upward compatible to exist within a blanket system of a DEMO or an eventual fusion power plant design. The proposed studies also builds upon recent low-A High Temperature Superconductor (HTS) tokamak pilot plant studies that incorporated a liquid metal divertor for high-heat-flux mitigation and as a means of reducing poloidal field coil current and simplifying the magnet layout and maintenance schemes. Tokamak aspect ratios in the range of A = 1.8 to 2.5 would be considered based upon recent pilot plant studies indicating this range would be optimal for fusion power production if high-current-density HTS magnets (or other high current density magnets) were utilized. This aspect ratio range is subject to change pending the results of the first 1 - 1.5 years of the study.

This paper will provide the design details of the Toroidal confinement facility – defining the general arrangement of the device configuration, details of high current density magnet systems and all LM system details investigated along with any engineering defined limitations or issues that may be expected when attempting to migrate the designs into the environment of a DEMO operated blanket defined system.

1. INTRODUCTION

The liquid metal Toroidal Confinement (TC) facility study was initiated to incorporate physics and technology advancements to enhance the development of a fusion device. The Spherical Tokamak (ST) was used as the confinement option to evaluate size conditions and height limitations in locating a TC facility within the Princeton Plasma Physics Laboratory (PPPL) test cell. An earlier set of ST design studies investigated a range of machine sizes and design parameters which formed the background to the TC facility study that helped to establish the starting machine size and aspect ratio [1]. It was found that as the ST development moved into the DEMO class with requirements of tritium breeding ratios greater than one and larger number of component features on the plasma inboard side the machine aspect ratio increased from the traditional ST values of smaller experimental sized device (1.6 – 2.0) to values as high as 2.5; more indicative of low aspect ratio rather than the recognized ST value. Section 2 will provide the physics and engineering background that establishes the current TC facility design point, build dimensions and general discussions of conditions that impact the device size.

One important condition found in developing an ST DEMO design is the need to operate with a high field on axis, which corresponds to a high peak TF field and the need for high TF winding current density for the ST. This fostered the need to investigate conductor designs that meet these conditions with details presented in Section 3. Section 4 will detail the two LM options currently being investigated at this time. This includes a fast flowing liquid metal divertor/FW option, a slow-flow, thin film divertor system and a possible combination of the two. Finally Section 5 will provide some summary information defining physics and engineering issues that need to be addressed and future direction planned for this Toroidal Confinement Facility study.

2. TOROIDAL CONFINEMENT FACILITY DEVICE DESIGN POINT AND BUILD DETAILS

2.1 Mission objectives

The Toroidal Confinement facility has two major mission objects. First, the development of critical technologies that will address key liquid-metal wall and divertor science questions to help understand fuel & material retention in liquid metals; liquefying temperature-controlled first-walls for lithium and other liquid metals, studying hydrogenic retention and permeation in bare and LM-covered high-Z walls. Working within an ST defined device can be used to establish required B_T, I_P, P_{AUX}, plasma stability margin, pulse duration, and duty factor to provide high P/R, P/S, q-parallel, particle fluence and other key PMI parameters within a hot wall - liquid-metal capacity of a high-performance plasma Second, the development of high current density superconducting winding designs for the OH and TF coils which is required for any future operation of a compact ST DEMO device. This includes high temperature superconductors (HTS) and a new CIC technology development that uses present SC materials within a layer wound design. On a longer term the Toroidal Confinement facility mission can be expanded to include blanket technology development, especially of interest is the DCLL blanket which offers the simplest system design of the various blanket options. Fusion technology development within an integrated system design allows all components to be defined based on the proper interaction of interfacing systems while operating with magnetic fields that effectively provide the proper environment.

2.2 Configuration definition

A current snapshot of the 1-m, Toroidal Confinement Facility is illustrated in Figure 1 highlighting the general arrangement with a TF cavity sized for an HTS magnet along with a fast flowing liquid metal divertor/FW system. Table 1 defines an early set of physics parameters and Table 2 list the component build dimensions starting from the machine axis to the plasma centre. The TC facility will operate in hydrogen and D-D within a cryogenic enclosure that supports liquid helium conditions for superconducting TF and PF coils located external to the TF, in an array that forms the elongated double-null plasma shape. Large vertical ports (top and bottom) are used to run the liquid metal piping services and extract divertor and metal surfaces of the LM system, in an arrangement similar to configurations developed in a number DEMO designs. With the design based on the spherical tokamak confinement system with low aspect ratio, high plasma elongation / triangularity values brings about conditions of less space on the plasma inboard side for machine components. ST DEMO designs that require a thin inboard blankets to reach a breeding ratio greater than 1, component and space requirements for TF inboard leg structural material, interior piping, thermal barriers and blanket support structure all moves the ST aspect ratio outside its typical range of 1.6 – 2.0 to a value closer to 2.5.

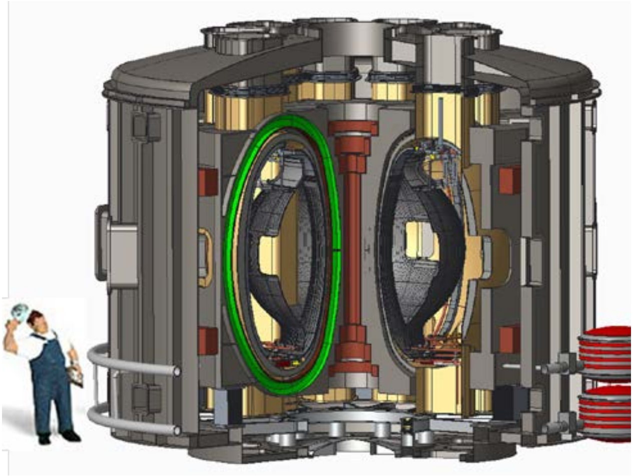
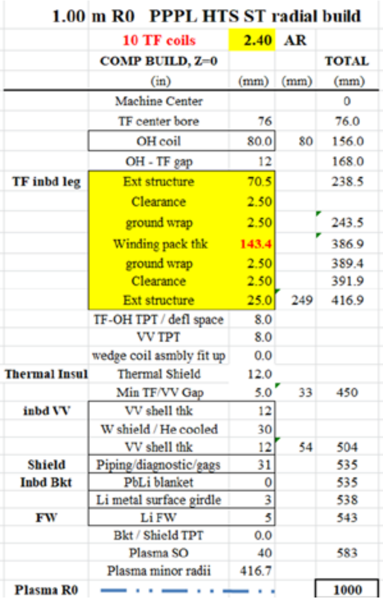


FIG 1. *Toroidal confinement facility to study LM systems within an HTS-ST*

TABLE 1. Preliminary TC Facility machine parameters

Parameters	Values
Major radius (R)	1.0 m
Minor radius (a)	0.42 m
Divertor operation	Double-null
Aspect ratio	2.4
Elongation (k_x)	2.5
Triangularity (δx)	0.50
Magnetic field (B0)	4.75 T
Maximum TF field (Bmax)	12.2 T

Table 2



	1.00 m R0 PPPL HTS ST radial build			
	10 TF coils	**2.40**	**AR**	
	COMP BUILD, Z=0			**TOTAL**
	(in)	(mm)	(mm)	(mm)
	Machine Center			0
	TF center bore	76		76.0
	OH coil	80.0	80	156.0
	OH - TF gap	12		168.0
TF inbd leg	Ext structure	70.5		238.5
	Clearance	2.50		
	ground wrap	2.50		243.5
	Winding pack thk	143.4		386.9
	ground wrap	2.50		389.4
	Clearance	2.50		391.9
	Ext structure	25.0	249	416.9
	TF-OH TPT / defl space	8.0		
	VV TPT	8.0		
	wedge coil asmbly fit up	0.0		
Thermal Insul	Thermal Shield	12.0		
	Min TF/VV Gap	5.0	33	450
inbd VV	VV shell thk	12		
	W shield / He cooled	30		
	VV shell thk	12	54	504
Shield	Piping/diagnostic/gags	31		535
Inbd Bkt	PbLi blanket	0		535
	Li metal surface girdle	3		538
FW	Li FW	5		543
	Bkt / Shield TPT	0.0		
	Plasma SO	40		583
	Plasma minor radii	416.7		
Plasma R0				**1000**

In the development of the liquid metal TC facility the machine aspect ratio has moved to 2.4. Leading factors that raised the value was the desire to supply sufficient solenoid space for an ohmic start-up, sufficiently high field on axis and space within the TF inboard leg for the conductor winding and supporting structure. The ST confinement option requires high current TF windings. Another design driver was the need to limit the overall height of the device to allow it to be located within the existing test cell of the PPPL Tokamak Fusion Test Reactor (TFTR) building, constructed to house a higher aspect ratio copper device. This condition limits the ST Major radius to be around one meter given the desire to construct the device with superconducting coils and fit with the TFTR test cell. Why superconducting coils and not copper coils? With an extensive background carried out investigating different ST experimental options using copper coupled with recent ST superconductor coil designs incorporating a Super-X divertor with a PF arrangement that extends the divertor flux length to keep the divertor heat loads within acceptable values for the Tungsten surface material [1][2], it was recognized that the success of the ST confinement option rests on high current density TF and OH windings to meet low aspect ratio physics conditions and the incorporation of higher heat capacity LM divertors will simplify the PF arrangement to establish sufficient clearance to meet device maintenance requirements.

3. TF CONDUCTOR OPTOINS AND WINDING DESIGN DETAILS

3.1 Background investigation of HTS conductors

High Temperature Superconductors (HTS) was identified by the US Fusion Energy Sciences Advisory Committee (FESAC) as the potential “game changer” for reducing fusion device size by increasing the allowable magnetic field, overall coil current density, and the operating temperature. HTS magnets with high current density are particularly beneficial for low-aspect-ratio “spherical” tokamaks and the compact stellarators due to their space constraints. Successful HTS magnet development may enable the design of smaller and cheaper fusion devices with a mission of demonstrating net electricity. Given this inducement set the early AC facility development looking at different HTS conductor options that would best fit with the design parameters of the AC facility ST design.

Recent configuration studies [3] in the US show that high current density cables of multi-layered REBCO tapes could be further developed into a viable magnet solution for low-aspect ratio ST pilot plants. Existing cable configurations such as twisted stacked-tape cable (TSTC), conductor on round core cable (CORC) and the Roebel cable, however, doesn’t provide the packing factor needed for a compact reactor magnet. An alternative concept using rectangular or square shape cable with a conductor aspect ratio of 1.6-2 can be more attractive to meet the current density needs for the compact ST magnets.

HTS conductor technology need a major breakthrough to reduce AC losses. The lack of a multi-filamentary structure is a key weakness of REBCO tapes for the application in high-field fusion magnets especially in the central solenoid where transient losses are of greatest concern. The next generation advanced HTS cable development should be focused on the innovative design of multi-filamentary REBCO coated conductors directly integrated into the design and fabrication of high current, low AC loss cables. Compared to the CORC and other cables presented earlier, the fabrication of the fully-stabilized multi-filamentary coated conductors is promising but is still in an early stage of the development.

The small inner bore of an ST device leaves little room for a solenoid to meet the plasma start-up requirements. It may be possible to use a series of <0.2 m small HTS central solenoids stacked up together with each solenoid wound directly with YBCO tapes or Bi-2212 wires, providing a much higher winding current density to facilitate plasma start-up. The required flux swing from plasma operation is sufficiently low and Bi-2212 solenoids with lower intrinsic AC losses can be particularly attractive to meet a significantly reduced flux swing (a few Weber’s) required to facilitate the non-inductive start-up of plasma (largely from bootstrap currents).

A number of HTS options have been investigated in this early Toroidal Confinement facility development phase. The increased current carrying capability and fabrication process improvement would continue to bring down the price if a market for fusion devices were to develop and the production level of HTS cable were to increase; however this is not happening with any expedience especially related to fusion applications. At present HTS conductors are an order of magnitude more expensive than the LTS conductors making an early application for a near term experimental device problematic, especially for a low aspect ratio ST design that requires a high current density magnet windings to meet component space requirements within the device inboard region.

3.2 Texas A & M University Cable-in-Conduit (CIC) development

An opportunity arose in a meeting at PPPL with a high energy researcher at the Texas A & M (TAM), where a new CIC technology development was presented that has the potential of providing a near term solution to the high current densities windings needed for the Advance Confinement facility design at a lower cost than HTS [4]. The central motivation in TAM CIC development is to preserve the full performance of the SC wire [5]. The approach involves a single layer of wires cabled with a twist pitch around a perforated thin-wall center tube. A stainless steel tape is then spiral-wound onto the cable and pulled into a seamless sheath tube. Finally the sheath is drawn onto the cable to compress the wires against the center tube where they are immobilized.

Texas A & M research is focused on developing the CIC technology for a 40kA application:

- developing 2-layer CIC using Nb_3Sn and Bi-2212 strands
- capability to make U-bends on a 2 inch radius yet preserve I_c
- demountable spice joints for interconnects and leads

Several advantages derived with the TAM CIC can be attributed to: (1) supporting the wires in a layered structure that spring-loads them against the sheath, immobilizing them yet they cannot be crushed by small deformations in the sheath and (2) locking the twist pitch of the wires so that each wire traverses an integer number of twists around each bent of the cable with all wires traversing the same catenary length. No tension or compression is created in the neighboring regions of the winding.

PPPL has proposed a Lab Directed Research and Development (LDRD) project to investigate the application of this technology as it pertains to the operating conditions of magnetic fusion. In addition, the TAM CIC conductor is being incorporated within the TC facility design as an option to be considered for use in the TF and central solenoid.

To increase the TF coil winding overall current density and lower its cost a layer winding scheme is also being investigated. A recent design developed for the NFRI K-DEMO study included a two-winding pack, low field/ high field TF design to increase the overall winding current density to 35 MA/m^2 and reduce the winding cost; savings over one billion dollars. Further cost reductions and higher current density values are expected with greater gradation within the winding pack using a layer winding approach. This option will be investigated as part of the TC facility study and if successful the approach would be applicable to all magnetic confinement options. An initial concept definition has been developed given the TF cavity space allocated for the winging in the TC facility build dimensions and shown in Figure 2.

The size of the TAM CIC conductors range from 7 mm diameter at the low field side to 11mm at the highest field region which resulted in an overall winding pack current density (to the outside of the ground wrap) of 85 MA/ m^2. The operating field on axis is 4.75 T (12.2 T peak field) with an analytically calculated 600 Mpa average Tresca stress. A more detailed FEA analysis of the full TF coil structure and winding will be performed to fully assess this design along with alternate arrangements to determine the most economical design. To complete the assessment TF conductor joint design and analysis details will be developed along with a layer wound solenoid with grading of the conductor from high field to low field.

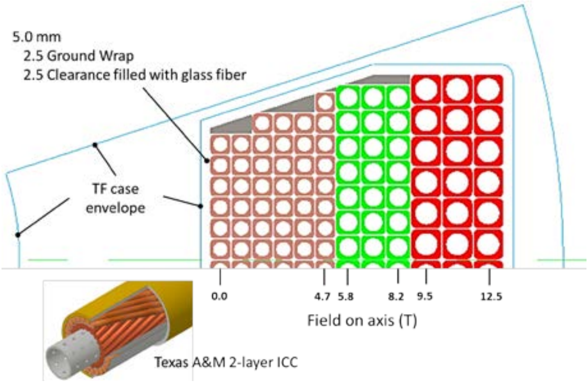


FIG 2. *TF coil winding pack using a layer wound TAM CIC conductor*

4. LIQUID METAL UNDER INVESTIGATTION

4.1 Fast flowing liquid metal divertor/FW option

The early emphasis in defining a LM system centered on the engineering design of LM fast flowing divertor/FW concept [6] as defined for a 1m experimental device but with upgrade compatibilities for operating within an integrated blanket system of a DEMO design. With the TC facility in a concept definition phase design details focused on the major components of each LM option as they impact the general arrangement of full device. Details for the fast flowing LM approach focused on the following:

- The flowing LM divertor/FW system shell structure.
- Definition of the required piping arrangement.
- Back-of-the-envelope calculation of the Li pumping system
- Defined LM maintenance approach.
- Defined interface definition of external NB systems.

The main component of the fast flowing Li system consists of the structural shell that comprises 20-18° outer panels and 10-36° inner panels that includes lower divertor surfaces. Electromagnetic EM Li pumping units are located at the bottom, in-line with each ten TF coils that supply Li to the 10 segmented inboard/outboard divertor surfaces. From here Li flows to the FW panels. Concept details are shown in Figure 3. A full complement of Li surfaces, supply / return lines and the external Li reservoirs is shown in Figure 4.

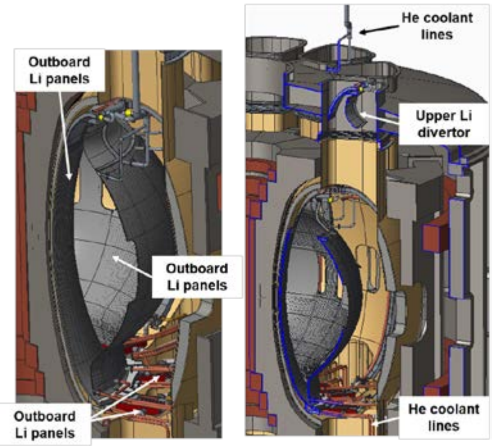


FIG 3. *Fast flowing Li system internal features*

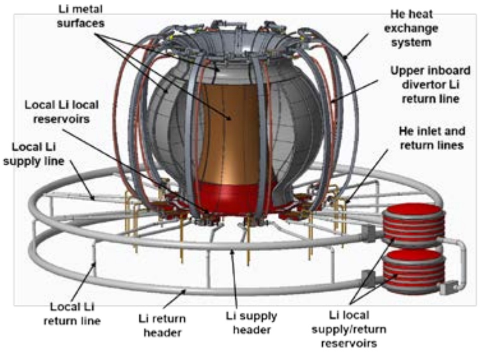


FIG 4. *FF Li system general arrangement*

The Li panel arrangement provides maintenance through the upper ports with all flow orifices located on the upper connected inboard/outboard divertor system. The flow system defined moves Li from the high field to low filed side with basic flow details depicted in the line diagram of Figure 5. The system has been divided into ten units following the basic division of the device operating with ten TF coils. Estimates were made to define the volume and pumping required to flow the lithium through the system within the 1m sized experimental device, assuming a 2mm lithium surface depth. Each of the subdivided ten Li flow sectors were designed with a Li containment capacity of 0.18 m^3 at the bottom to collect the 0.14 m^3 of liquid Li that flows within each sector; or 1.4 m^3 for the all ten lithium supply sectors. Each EM unit supplies a Li flow rate of 10 m/sec, operating within a 1.7T local field with 2 kA supplied current. A single EM unit operating power is approximately 3 MW's; 30 MW's for all ten sectors. Additional pumping power will be required to support the helium flow system within the different Li surface panels and the He heat exchange system.

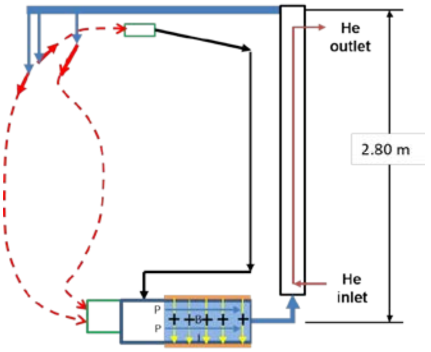


FIG 5. *Single sector Li flow line diagram*

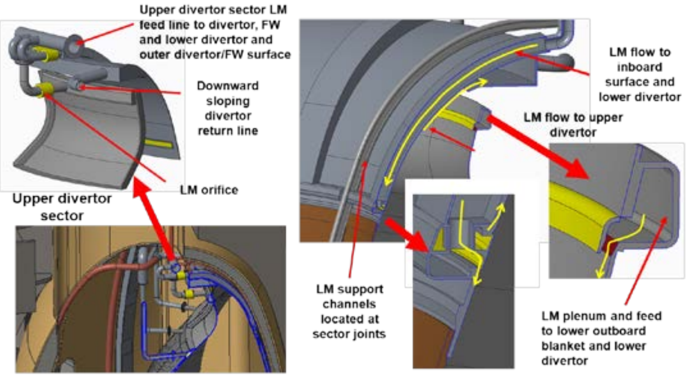
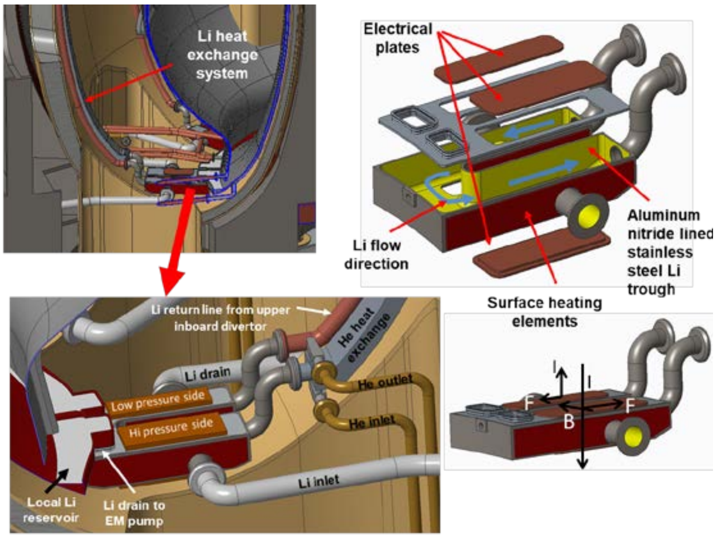


FIG 6. *Upper divertor Li flow details*

The planned maintenance of the Li system follows the vertical maintenance approach used in developing the ST arrangement for a DEMO operation. The Li system consists of an integrated upper inboard/outboard divertor system that contains the Li nozzles that supplies Li to the inboard divertor (flow from high to low field), a separate nozzle that supplies Li to the inboard surface and on to the lower divertor region. A third nozzle system is located at the base of the upper outer divertor to supply Li flow to the outboard surface and the lower divertor. Figure 6 defines details of the upper divertor and illustrates Li piping and flow details. The EM Li pumping unit is shown in Figure 7 with an exploded view calling out internal components and an assembled unit with field, current and force vectors indicating the direction of flow. The EM pumping assembly has two chambers, a low pressure side (low applied current) where Li is returned from the upper inboard divertor, and a high pressure side (high applied current). Between the two chambers Li that accumulates in the base of the lower divertor drains into the EM chamber and moves to the high pressure side as part of the flow from the Li coming from the low pressure side. To maximize the flow pressure the EM unit was located as close as possible to the high field region given the limitations provided by the Li reservoir.



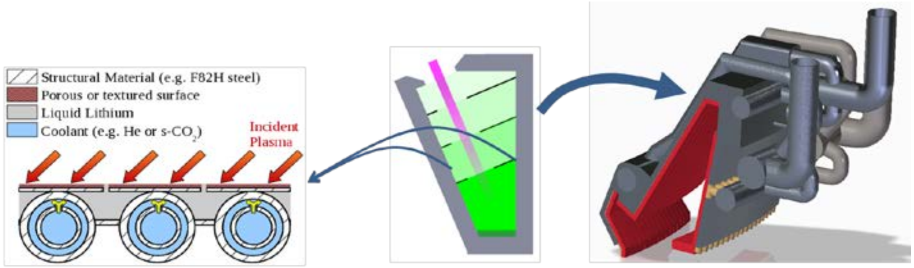
Local Li exchange / reservoir arrangement

FIG 7. *EM pumping unit details*

4.2 Slow flow, thin-film systems

The clamed benefits of liquid metal PFC's is the protection of the substrate from plasma erosion processes. The slow flow, thin-film systems employ capillary forces to wick the surface. The capillary restrained forces provide a powerful means of stabilizing surfaces against various instabilities and provide a general design strategy for slowflow, thin-film systems to avoid ejection into a confinement device. The initial slowflow, thin-film concept design was patterned from a schematic diagram of the actively-supplied, capillary-restrained systems with a T-tube [7] shown in Figure 8a along with a lithium vapor box divertor [8] 8b, shown in a poloidal cross-section and the corresponding concept model in 8c. The vapor box divertor design is developed with walls coated with capillary porous material, soaked with liquid lithium that's continually replenished.

The concept behind the Lithium Vapor Box Divertor is to control the location and density of the gas-phase material that absorbs the plasma heat flux. It uses local evaporation and strong differential pumping through condensation while moving through the vapor box, rather than allowing this to occur "naturally" through recycling of fuel gas and injected impurities. The configuration contains lithium vapor along the divertor plasma to extinguish the maximum expected heat flux. Its bottom can be wetted with a layer of lithium to handle the highest transient heat fluxes. The upper region of the box is much cooler than the bottom box, so lithium is redeposited there, limiting the out flow of lithium to the plasma. The required flow and inventory of lithium is modest, requiring minimum amount of re-supply to thin layers of capillary porous material along the surfaces, with some of the recirculating flow extracted for purification.



a) Schematic diagram of the actively-supplied, capillary-restrained system

b) Vapor box divertor

c) T-tube heat exchanger design concept

FIG 8. *Vapor box divertor concept based on a Capillary Pores System (CPS)*

Figure 9 illustrates an early divertor box concept design showing the piping system arranged to distribute helium and a local detail of lithium supplies lines to the porous Li surfaces. The divertor box inboard and outboard divertor channels has been sized given the space provided within the region of the vacuum vessel; set by the plasma elongation and triangularity along with preliminary sizing of the TF and VV shell structure. Given the available space, a 90 mm inboard and 300 ml outboard null point to surface distance can be defined. Further iteration is needed to fully establish the proper divertor box design.

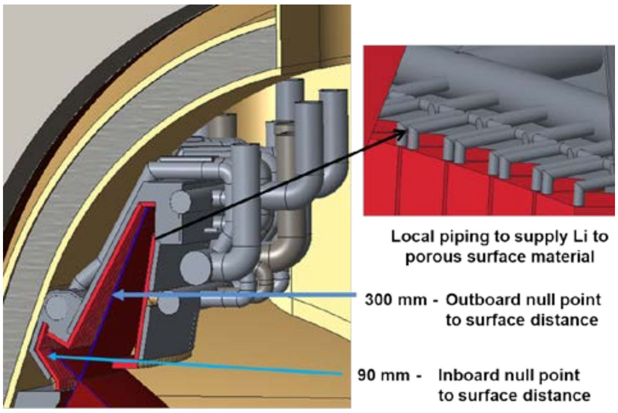


FIG 9. *Local divertor box details*

5. Summary comments

A Toroidal Confinement facility study was undertaken to investigate a range of liquid metal divertor and first-wall concepts and develop of a characteristic experimental device. This device can be used to address physics issues and assess the performance and operating characteristics of both the fast and slow flow LM divertor approaches. With the study centred on an ST, double null configuration a planned next phase is to develop a combined slow – fast flow LM system where a fast flow arrangement would be located at the bottom with a divertor pumping system included and a slow flow system located at the upper divertor position (with no pumping) and a slow flow LM design developed for the inboard and outboard surfaces. The final assessment will also include the upward ability to effectively integrate the TC facility design features within a DEMO fusion device and the definition of superconducting OH and TF coil systems that can meet planned performance and cost objectives.

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