THE PROTOTYPE CRYOMODULE FOR THE EUROTRANS PROGRAM*

S. Barbanotti, N. Panzeri, P. Pierini, INFN Milano – LASA
J.L. Biarrotte, S. Bousson, C. Commeaux, E. Rampnoux, M. Souli - IPN Orsay

Abstract

EUROTRANS is a research program funded by the EURATOM (EC) in the 6th Framework Programme for the assessment of a nuclear waste transmutation system driven by a high intensity superconducting linac.

The design of the high energy end of the linac (above 100 MeV) is based on low beta multicell elliptical cavities. A prototype cryomodule containing a single 5 cell cavity (built and tested successfully at INFN) is being developed jointly by INFN and IPN-Orsay. This paper describes the module layout and its implementation plan at Orsay.

INTRODUCTION

The EUROTRANS program objective is to develop an advanced design for an eXperimental facility demonstrating the technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS) and a generic conceptual design of a modular European Facility for Industrial Transmutation (EFIT). Its objective is to provide also an experimental evaluation of the reliability figures for the main modular components of the accelerator configuration. One of the tasks in the accelerator working package of the Eurotrans project is dedicated to building and testing a full prototypical cryomodule of the high energy section of the superconducting proton linac.

A cryomodule is the basic building block of the superconducting accelerator section and has the main role to provide to the cavities both a mechanical support and their cryogenic environment for operation. The XT-ADS linac, which main parameters have been briefly reviewed in Reference [1-2], on the basis of the high availability/reliability requirements and maintenance considerations, needs a cryomodule designed for easy disconnection both from the beam line and the cryogenic fluids distribution plant [3]. The aim of the work here briefly presented is to deliver an operational prototype cryomodule, which can be extensively tested (without beam, but at high RF power levels as in its realistic operating condition), to assess its main reliability characteristics.

The test cryomodule will be a prototypical module of the beta 0.5 section containing one single elliptical multi-cell superconducting niobium cavity with all its auxiliary equipments. In the high energy section of a proton linac, consisting on a few families of elliptical cavities with gradually increasing lengths, the technological complexities decrease gradually with the increase of the cavity length (that is, with the increase of the velocity, and energy, for which the proton cavity is designed). It is felt by the accelerator designers that the lowest limit for the elliptical cavity technology is a cavity design for proton velocities at half the speed of light (beta=0.5), which has been indeed chosen for the first family of the high energy section of the XADS linac.

Besides the development of the bare superconducting cavities, it is important to prototype each auxiliary system needed for the cavity operation in a real environment (frequency tuner, power coupler, RF source, power supply, RF control system, cryogenic system, cryostat…), and relative procedures of assembly and alignment. The construction of a fullscale module with a β=0.5 cavity (100-200 MeV energy range) can be considered as a rather general proof-of-principle of the technology and a test stand for determining its reliability characteristics.

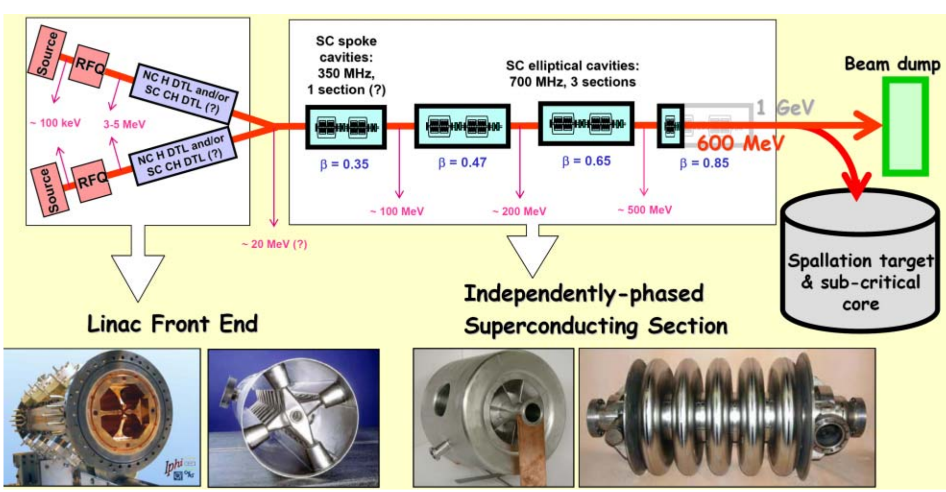

Figure 1: XT-ADS reference accelerator scheme: a doubled linac front end is followed by a fully modular spoke and elliptical cavity SC section, upgradeable from 600 MeV up to 1 GeV for the EFIT needs. Typical cavity prototypes are shown in the lower part: from left to right RFQ, CH structure, Spoke, Elliptical 5-cell.

The development of the cryomodule relies heavily on prior R&D results, existing infrastructures and investments of INFN, CNRS and CEA. INFN will make available its two beta 0.47 (geometrical length) TRASCO [4] cavities equipped with the cold tuning system [5], which have outperformed the EUROTRANS specifications during vertical tests [6-7]. CNRS will contribute with clean room for cryomodule assembly, cryogenic infrastructure for test at 2 K, manpower for the cold box study and integration, assembly and tests. CEA will contribute with the cavities chemical treatments.

The final installation and testing of the cryomodule will be done at the Supratech infrastructure under preparation at IPN/Orsay, where the following hardware and facilities will be available:

- High power RF sources: a 350 MHz source (for EURISOL and EUROTRANS spoke cavities, a 10 kW unit developed by INFN/Legnaro) and a 700 MHz source (80 kW IOT unit)
- A clean room for cryomodule assembly (85 m^2 clean room, with 45 m^2 of class 10/100 for cavity assembling and handling).
- Ultra-pure water production system and HPR facility.
- An Helium liquefier.
- A cavity chemistry facility.

LAYOUT OF THE MODULE

The actual layout of the module is shown in Figure 2. The vessel of the module for a single cavity has a diameter of about 1.2 meters (namely 48", as the SNS vessel) and a length of about 1.4 meters.

The design has been performed on the following reliability-based considerations:

- As a general request, easy and reliable connection interfaces to the cryogenic and RF system and fast and reliable cold mass alignment strategies are needed to guarantee a short mean time to recover in the case of a module exchange in the linac.
- As in the SNS experience, in order not to produce mechanical stresses on the warm ceramic RF window the fundamental power coupler is positioned vertically. Furthermore, in order to avoid the possibility of contamination of the inner cavity surface during the coupler assembly with dust particles, the warm RF window is positioned below the cavity.
- The actual layout simplifies the handling of the subassembly coming out of the clean room. As shown in a later paragraph, the suspension of the dressed cavity to a room temperature "spaceframe" with tension tie rods does not require any vertical movement of the cavity during assembly. In more details the cavity, with its ancillary components, will be supported by 8 tension rods in a symmetric X pattern to a room temperature "spaceframe" support cage similarly to the SNS concept. The spaceframe acts also as the support for the thermal shield that protects the cold mass at 2 K from the room temperature surfaces of the vacuum vessel, intercepting the thermal radiation at higher temperatures.
- This design allows the connection to the cold box providing the liquid cryogenic circuits at different temperature levels already developed by IPN Orsay and similar to the CM0 coldbox used for the spoke cryomodule. The coldbox will be located above the module, connected through a big flange on the top of the vacuum vessel.

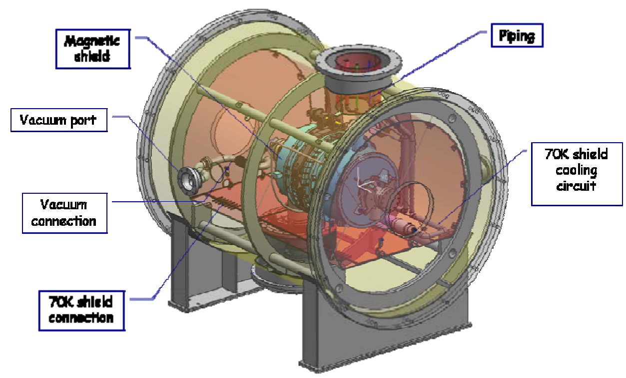

Figure 2: The EUROTRANS module layout.

As a last consideration, it seems important to borrow, as extensively as possible, proven technologies from existing state-of-art cryomodule designs, again with the perspectives of reaching the ADS reliability goals. Most of the technical solutions, and the underlying superconducting RF technology, outlined for the module layout have been derived from the huge experience accumulated by the TESLA Test Facility (TTF) and the Spallation Neutron Source (SNS) experience [8]. These technologies represent the state-of-art in the design of a large superconducting RF infrastructure with perspectives of reaching an unprecedented high operational availability, necessary for an acceptable economical cost of the underlying applied and fundamental physics experimental programs for which both accelerators have been designed.

The dressed cavity

The module will be equipped with one of the two TRASCO cavities, fully "dressed" with the components required for their operation in a linac cryomodule (Fig. 3)

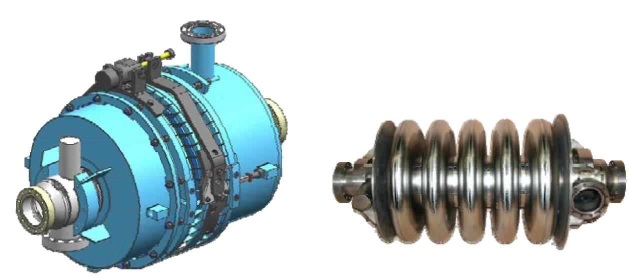

Figure 3: A view of the TRASCO cavity, complete with tank and tuner assembly.

In particular, the cavity will be equipped with a Ti He reservoir (which provides the low pressure bath liquid He for the operation at 2 K) and with a jacket of a high-permittivity (at low temperatures) material (Cryoperm) that provides the required shielding from the earth magnetic field in order to guarantee low values of surface resistance for RF losses minimization. A simple solution for using a magnetic shield at the inside of the helium reservoir has been analyzed and is under development [9].

A coaxial blade-tuner [5], based on the prototype tested on the TTF linac, provides the slow tuning and fast piezo-assisted actions. The mechanism has been fully engineered and fabricated. The Ti He tank and tuner system will be integrated on the cavity after acquisition of the magnetic shield.

Figure 4 shows the tank and tuning system during the mechanical acceptance tests in LASA.

Figure 4: The blade tuner for the TRASCO cavity during mechanical testing at LASA.

The cavity, which demonstrated the required performances during vertical tests at JLAB [6], has been tuned to the warm frequency of 702.7 MHz, in order to meet the 704.4 MHz IOT frequency of the module tests with the necessary preload conditions on the piezo elements for operation (Figure 5).

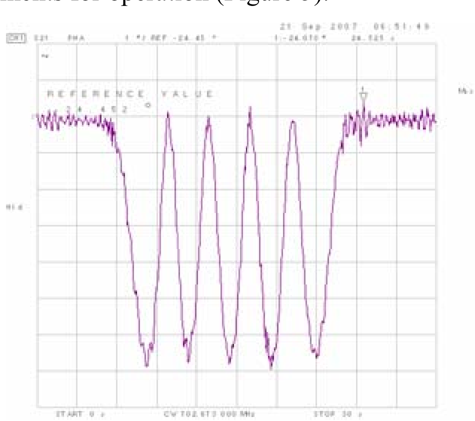

Figure 5: Field flatness profile of the cavity atfter tuning to the nominal frequency.

THERMAL DESIGN

One of the main issues driving the technical design of a cryomodule is the heat load budget at low temperatures. This either comes from a static contribution (thermal radiation, heat conduction or convective heat transfer from the room temperature environment) or from the dynamic contribution driven by the presence of the RF fields sustained by the accelerating cavities.

Static heat loads

Static losses are handled in the modules by minimizing the heat flows towards the 2 K He bath and intercepting it at higher temperatures, thus gaining in thermodynamic efficiency. The thermal radiation flowing from surfaces at room temperature is intercepted with a thermal shield fixed at intermediate temperature, and minimized by using multilayer insulating (MLI) blankets (layers of doubly aluminized mylar sheets separated by a low thermal-conducting spacer material). Ideally, a single thermal shield level in the temperature range between 35 and 50 K would be the best solution to minimize effectively these sources of static inleak. This solution, however, requires a cryogenic system with the ability to mix warm helium gas at the module entrance, in order to produce the desired temperature coolant for the shields. The actual cold box system that will be used during testing lacks this feature and thus an independent circuit using nitrogen gas has been assumed in the design. Direct heat conduction paths from the room temperature environment to the 2 K circuit need to be carefully intercepted at intermediate temperatures.

Finally, convective effects are prevented by providing a good insulating vacuum between the cold mass and the external vessel at room temperature.

For the estimation of the static heat load budget, and its proper handling, a thermal analysis of each direct path from the room temperature vessel to the cold mass environment has been performed, by taking into account the proper temperature-dependent material properties. Estimation based on simplified geometries and tabulated material data has been verified with finite element calculations on the model geometry.

Dynamic loads:RF losses

A superconducting cavity deposit the power P_{cav} on its walls according to the relation

$$P_{cav} = \frac{\left(E_{acc} L_{active}\right)^2}{R/Q \; Q_0}$$

where E_{acc} is the accelerating field level, L_{active} the active cavity length, Q_0 the quality factor of the resonator and R/Q is a geometrical parameter, determined only by the shape of the resonator.

For the TRASCO cavity operation at its design parameters (E_{acc}=8.5 MV/m, $Q_0=10^{10}$, with L_{active}=0.5 m and R/Q=160 Ω), this estimation gives 11.3 W of dissipated power at each cavity. For comparison, in the SNS case, the two cryomodules types (medium beta and high beta) have a nominal RF dynamic load of 10 and 13 W, respectively. Even if the vertical tests performed on the existing structures were able to exceed these limits, for the heat load computations, a conservative value of Q_0=5 10^9 has been assumed.

Heat load budget

Table 1 reviews the overall heat load budget on the module. Only the 2 K main circuit and the shield circuit have been taken into account. The overall heat load estimates, even with the uncertainties arising from a few missing contributions from the table, seems to be well within the capacity of the CM0 coldbox (~ 50 W).

Table 1: Heat load budget on the module.

	2 K circuit		70 K circuit
	Static	**Dynamic**	**Static**
RF load @ 8.5 MV/m & 5 10^9		22.58	
Tie rods connections and shield supports	0.12		25.00
Thermal radiation[1]	0.40		15.10
Cabling	0.10		
Coupler[2]	1.00	6.77	1.00
Total [W]	**1.62**	**29.35**	**49.24**

[1] Based on 0.1 W/m^2 from 77 K surfaces and 2 W/m^2 from 300 K.
[2] Static from SNS estimates (30% conduction, 70% radiation) Dynamic based on SNS estimate, 30% of RF load

On the basis of the heat load assessment reported above have been calculated the required mass flow for the shield and cavity circuits. For these calculations, it has been assumed that the shield circuit is cooled by nitrogen gas. The calculation does not take into account the additional heat losses in the coldbox. Even using a conservative estimate for the dynamic heat loads and a 30% overcapacity budget for the coolant mass flow, a total requirement of 1.4 g/s at 2 K is needed for the LHe circuit, consistently with the 2.2 g/s capabilities of the CM0 cold box.

For the moment, the estimation of the cryogenic needs does not include the cooling circuit for the coupler, since the details of this component are still under finalization. Nonetheless, for comparison, the SNS coupler requires a flow of 5 K, 3 atm He of 0.0375 g/s, of which 2/3 is used to handle the static losses and the rest handles the dynamic losses at 6% RF duty cycle. In terms of cold box capabilities, the extra flow needed for the coupler cooling should be compatible with the existing CM0 coldbox flow limitations.

The cryogenic cold box

The cryogenic cold valves box is derived from the IPN Orsay CM0 design, which has a nominal cooling capacity of 50 W at 2 K. The cold box supplies 3.3 g/s of liquid helium for the cavity cooling, 2.5 g/s of liquid helium at 4.3K and a Joule Thomson valve for the 2K operation (it can produce a maximum flow rate of 2.2 g/s at 1.9K, ~50W).

A ~ 20 liter helium buffer is placed inside the valve box to prevent from pressure perturbations on the cavity when feeding liquid helium. A thermal shield, able to evacuate around 60 W at around 60K, made of copper and covered with multi layer insulation, surrounds the cold internal parts of the valve box. The present design of valve box has no specific cryogenic loop for the power coupler cooling, but a supercritical loop will be added in the final design.

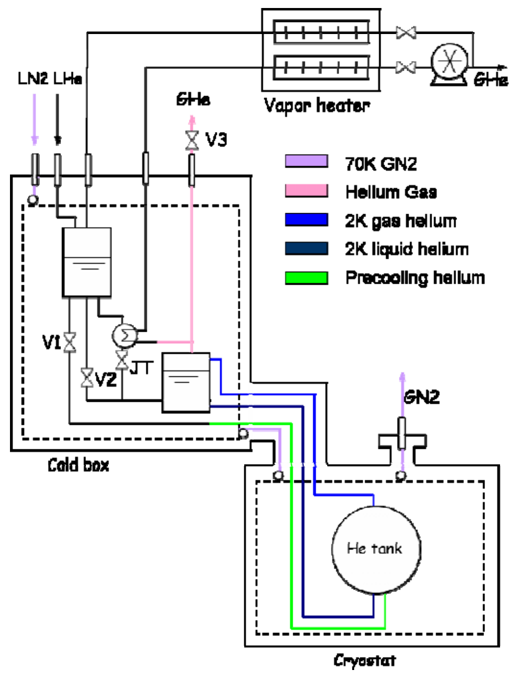

Figure 6: The main cryogenic scheme.

THE COUPLER

The 704.4 MHz power coupler is under development at IPN Orsay and is based on the SNS design, adapted and optimized for the needs of this design (different frequency, more CW power, additional cooling provisions included).

The main characteristics of the coupler are the following:

- Capacitive coupling to the cavity
- Coaxial geometry of the antenna
- Ceramic window geometry: disk with chokes
- Doorknob to perform the transition from the coaxial to the waveguide geometry
- Capable to transmit up to 80 kW of RF power to the cavity
- Inner cooling of the antenna with room temperature water or He gas (both options)
- Window cooling by water @ 300 K
- Cooling of the outer conductor between the ceramic and the cavity by supercritical liquid helium @ 4.5 K.

The clean room cavity-coupler assembly

The cavity, the helium tank and the coupler window need to be assembled inside a clean room in order to seal the cavity volume and to avoid any contamination that could limit the RF performances. The assembly procedure inside the cryomodule has to allow the insertion of the complete cavity-coupler assembly.

The following procedure is envisaged for the assembly of the cavity in the module:

STEP 1 Pre-assembly of the cold mass on the spaceframe. The cavity and cold coupler part (up to the room temperature window) are connected in the clean room and the entire assembly, translated on a temporary support, is attached to the spaceframe via the tension tie rods.

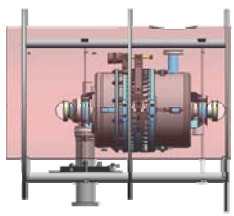

Figure 7: Preassembly of the cavity+coupler in spaceframe.

STEP 2 The spaceframe is rolled into the vessel.

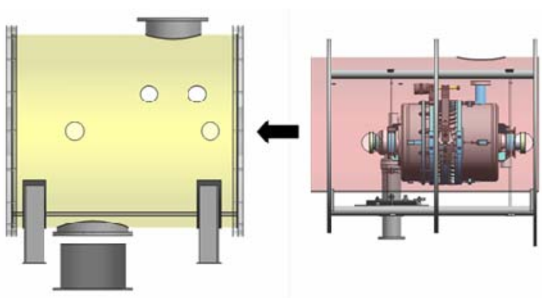

Figure 8: Introduction of the whole cavity + coupler assembly inside the cryostat (horizontal translation).

STEP 3 The vacuum closure which separates the warm coupler part from the cryostat vacuum is slid from below to separate the two environments.

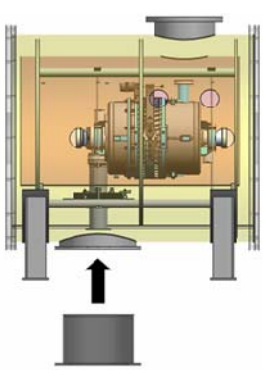

Figure 9: Insertion of the vacuum closure separating the warm coupler window and extension.

FUTURE WORK

The next step in the design activities will be the finalization of the following aspects in the cryomodule layout:

- Final choice of vacuum pumping system components for the cavity and coupler environments and the module insulation vacuum.
- Definition of all service ports for instrumentation, service and alignment references.
- Adaptation of the present design to the final coupler choice under development and to the RF system infrastructures that will be installed at IPN/Orsay.
- Review and finalization of the cryogenic piping and interface with the cryogenic facility and infrastructure under development at IPN Orsay.

The expected timeline for the cryomodule production, including cold mass integration after tuning, cleaning and tests, and installation at the IPN/Orsay facility is:

- 12/2007 final engineering and start procurement.
- Fall 2008, assembly in Orsay.

ACKNOWLEDGMENTS

This work is supported by the EURATOM 6th Framework Program of the EC under contract FI6KW-CT-2004-516520.

REFERENCES

[1] J-L. Biarrotte, “Status of the Eurotrans R&D activities for ADS Accelerator Development” Proceedings of the 5th HPPA Workshop, Mol, OECD/NEA Publication, in press.

[2] P. Pierini, “The Accelerator Activities of the EUROTRANS Programme”, in Proceedings of APAC 2007, Indore, India, p. 852.

[3] P. Pierini, C. Pagani, “Task 1.3.3. Preliminary Report: Specifications of the Prototype Cryomodule”, EUROTRANS report, Deliverable 1.15 of EU contract FI6W-516520, April 2006.

[4] M. Napolitano et al., “Status Of The High Current Proton Accelerator For The TRASCO Program”, in Proceedings of EPAC 2002, Paris, France, p. 251.

[5] P. Pierini et al., “Report on Tuner Design”, CARE-Note-2006-003-HIPPI, available from http://www-dapnia.cea.fr/Documentation/Care/index.php.

[6] A. Bosotti et al., “RF Tests Of The Beta=0.5 Five Cell TRASCO Cavities”, Proceedings of EPAC 2004, Lucerne, Switzerland, p. 1024.

[7] A. Bosotti et al., “Characterization of an Elliptical Low Beta Multicell Structure for Pulsed Operation”, in Proceedings of the 12th SRF Workshop, Cornell, USA.

[8] I. Campisi, “Testing of the SNS superconducting cavities and cryomodules”, in Proceedings of PAC 2005, Knoxville, USA, p. 34.

[9] P. Pierini, S. Barbanotti, L. Monaco, “Design of the magnetic shield for TRASCO low beta elliptical cavities”, these proceedings, contribution WEP61.