CONSTRUCTION OF A 700 MHz PROTOTYPICAL CRYOMODULE FOR THE EUROTRANS ADS PROTON LINEAR ACCELERATOR *

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Abstract

Accelerator Driven system (ADS) are being considered for their potential use in the transmutation of nuclear waste. Such a device typically requires a 600MeV to 1GeV accelerator delivering a high intensity beam. Because of the induced thermal stress to the subcritical core, the high-power proton LINAC will have to fulfill stringent reliability requirements. One working package of the EUROTRANS project is dedicated to the design, realization and tests of a prototypical cryomodule, operating at 2K, for the LINAC high energy section. Elliptical cavities will compose this accelerator section. A full scale cryomodule with a beta 0.47 TRASCO cavity and its cold tunning system will be tested at IPNO, early 2010. Experiment aims to evaluate the cavity performances (E_{acc}=8.5 MV/m) but above all the whole cryomodule reliability to fulfill ADS stringent requirements.

INTRODUCTION

According to the World Energy Council, conventional fossil fuel are the main resources for the world energy supply [1]. Since the demand in power has drastically increase the past decades, those fuel reserved are significantly decreasing. As a consequence, one can notice a growth of interest for nuclear power all over the World [2], especially for its high efficiency in electricity production without greenhouse gases emissions. However, High radio-toxicity waste production remains a major environmental topic. Concerning European Union, 2500 tons of used nuclear fuels are produced, every year, including 3.5 tons of minor actinides and 3 tons of long-lived fission products.

Accelerator Driven system (ADS) is one solution to enable the reduction of nuclear waste radio-toxicity before their deep ground storage. Based on the transmutation process, such a device allows to decrease the radioactive waste life time and consequently to relax the constraints on the geological disposals.

Towards this goal, the EUROpean research program for the TRANSmutation of high-level nuclear waste in accelerator driven systems (EUROTRANS), wish to demonstrate the technical feasibility of Transmutation in an ADS (XT-ADS concept) through the construction of an experimental facility MYRRHA[3].

An ADS transmuter system is composed of a sub-critical reactor, neutron supplied by a spallation source which provides the appropriate flux to keep the nuclear chain reaction going on. The spallation target is subject to an high proton flux to provide the neutron energy spectrum required to burn the minor actinides. The design of the MYRRHA proton accelerator will be definitely frozen for mid-2010. Its concept (see Figure 1) [4] leads to a superconducting linac in CW mode, ranging from 2.4MW (XT-ADS demonstrator operation) up to 16MW for the future industrial application (EFIT). To minimize the thermal stress in the transmutation reactor, beam trips longer than 1 second should not exceed 5 per 3 months operating cycle [5]. This extremely high reliability requirement can immediately be identified as the main technological challenge to achieve.

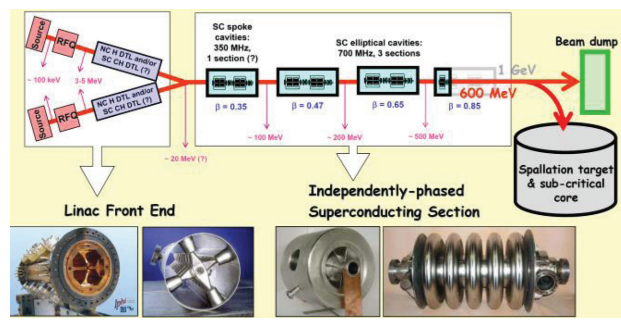

Figure 1: European ADS accelerator conceptual scheme.

The Linac High energy part will be composed of 5-cell superconducting cavities (β = 0.47 & β = 0.65) operating in CW at 704.4MHz. A prototypical cryomodule, is presently being built in view of a full scale cavity test in an accelerator coupling configuration. The status of R&D activities concerning the Cryomodule as well as the Power Couplers design will be recounted in the following lines. Experimental perspectives and a preliminary discussion in terms of reliability evaluation of the whole device, with its digital Low Level RF (LLRF) feedback loop system, will end this paper.

SUPERCONDUCTING ACCELERATING MODULE

The development of an accelerating superconducting cavity requires the prototyping of all the auxiliary systems needed for its operation in a real environment. In this context, R&D activities involve INFN and CNRS resulting in the design and fabrication of a cryogenic real scale module dedicated to be tested in new experimental area. INFN contributed in the development of the Cryomodule and make available its beta 0.47 TRASCO cavity equipped with a cold tuning system. IPN Orsay

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(CNRS/IN2P3) participated in the development of the cryogenic valve-box, one of the power couplers and makes available its new facility SUPRATech dedicated to the preparation (chemistry, clean room) and cavity tests (experimental area set up in progress) with an 80 kW RF power supply.

The Cryomodule

The Cryomodule design (see Figure 2) has been performed by considering reliable aspects for the assembly, and the cavity handling, derived from the experience accumulated by the TESLA Test Facility (TTF) and the Spallation Neutron Source (SNS). Its construction is now in progress.

The module is 1.5 m long, for a diameter of about *1.4 m* with the cold box assembled on top of it. The module was designed to operate at 2K for a nominal accelerating gradient of 8.5 MV/m and an assumed conservative quality factor value of $Q_0=5.10^9$ for computations. At 2K, the dynamic Heat Load has been estimated to 25W for 4W in static conditions. More details concerning the thermal design are given in Reference [6].

Static losses are kept in the module by minimizing the heat flow toward the 2K helium bath. Therefore, the thermal radiation, flowing from surfaces at room temperature, is intercepted by a thermal shield at intermediate temperature (Nitrogen at *77 K*) and minimized by using multilayer insulating blanket (doubly aluminized Mylar® sheets separated by a low thermal conducting material).

The cryogenic cold valve box, derived from the IPN Orsay EURISOL design, has a nominal cooling capacity of 50W at 2K. A 20 liters helium buffer is placed inside the box to prevent from pressure perturbations in the cavity Tank. The cold box thermal shield, made of copper and covered with multilayer insulation, is able to evacuate 60W at around 80K.

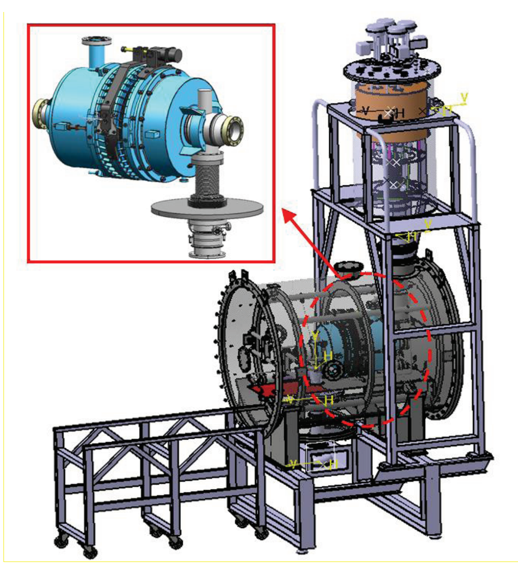

Figure 2: The prototypal EUROTRANS 700MHz cryomodule, with its dressed cavity inside.

The Dressed Cavity

The cryogenic module will be equipped with one of the two TRASCO cavities (geometrical β=0.47) fully "dressed". A magnetic shield made of 1 mm Cryoperm10® sheets encloses the cavity and is located inside the helium Tank [7]. Magnetic shield measurements showed that the contribution to the surface resistance by trapped magnetic field is estimated to be below 10 nΩ which guarantee a quality factor higher than 5.10^9.

The cavity and its shield are placed in a titanium helium tank which provides the low pressure He bath for 2K operations.

A coaxial blade tuner derived from the one successfully tested at TTF [8] has been developed and fabricated. This device, mounted on the tank, will allow slow and fast tuning compensation. A rotation torque provided by a stepper motor is transferred into longitudinal strength by means of bending blades and allow static compensation of Lorentz forces detuning. This coaxial device is also assisted by piezoelectric actuators which allow dynamic cavity frequency adjustments.

POWER COUPLER RF DESIGN

A Fundamental Power Coupler (FPC) development has been carried out at IPN Orsay. Based on the SNS Power Coupler design [9] it was adapted and optimized to transmit to the cavity up to 150 kW RF power at 704.4 MHz with a capacitive coupling of $Q_{ext} = 1.10^7$,adpted to the experimental needs (i.e without the beam).

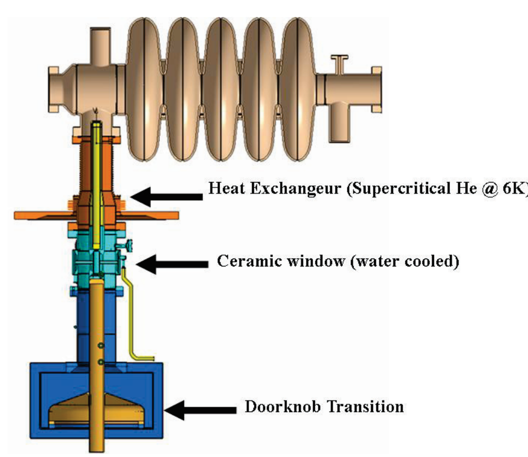

Figure 3: Section view of the power coupler connected to the cavity.

The Figure 3 is a section of the final Coupler design. A Doorknob type transition performs the waveguide geometrical transition. In order to minimize thermal losses (Joule and dielectric losses), the inner conductor and the ceramic window are water cooled [10]. The FPC outer conductor RF and static losses are removed by a supercritical helium heat exchanger (P=3bar, T=6K) in order to minimize heat loads to the cold extremity of the cavity maintained at 2 K, to ensure the transition between

300K and 6K. A dedicated test facility named SUPERCRYLOOP was developed and successfully operated at IPN Orsay for measuring the performance of the cold heat exchanger and the first experimental results have confirmed its excellent performances [11].

Doorknob Transition

To ensure the waveguide geometrical transition between rectangular waveguide (WR1150) and the coaxial power coupler a Doorknob type impedance matching structure was designed. The transition alone must have good impedance matching to enable good performances when integrated with the RF ceramic window.

Simulations showed that even a small change inside the structure can result in a significant change in the RF performances. The transition was computer simulated using the Ansoft HFSS® code. The doorknob height, the radius, the radius of the rounded corner and its positions to the short circuits were optimized to get the better transmission performances. Those different parameters were adjusted with a precision of one tenth of a millimeter. Such a study requires some carefulness as regard to the structure meshing. Since The HFSS® code frequency solver is using tetrahedral mesh, with "(semi)automatic" refinement for precision adjustments it was then decide to compare results with another calculation code.

The CST Microwave studio® code using its time domain solver with PBA® (Perfect Boundary Approximation) on a hexahedral mesh structure was employed. The optimized transition designed with HFSS® was implemented in the CST® code. The Figure 4 shows that simulations results, regarding the reflection (S11) and transmission (S21) coefficients are in agreements. With CST-MS® the "reflection peak" slightly shifted to lower frequency, but the -30dB bandwidths are appreciably similar.

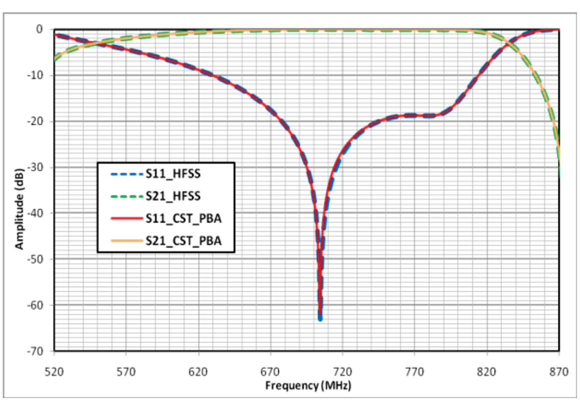

Figure 4: RF simulation results for the doorknob transition design.

The waveguide to coaxial transition can have either a "flat" or a circular rounded short circuit at the end of the rectangular waveguide. Simulations were made for transitions with both short circuit shapes and the results showed that both types have similar RF performances. A manufacturing cost study showed that "flat" short circuits would be a smaller expense. Furthermore, once the doorknob is manufactured, its position to the short circuits is the only re-adjustable parameter.

Consequently the short circuit is mechanically realized by flat aluminum flange screwed on the waveguide, with an adaptable entering part. The doorknob and the internal conductor are in copper. First low power measurements, using an N to WR1150 transition and an coax-to N transition, showed that at 704 MHz the reflection coefficients is around -35dB.

RF Window

The coaxial window is a planar annular disk made of 97% aluminium ceramic. The windows were manufactured by the French company SCT. A deposit of TiN [12] was made on one of the two windows. Influence of this deposit on multipacting effect will be evaluated out during the Power Couplers conditioning. The Chokes shape and size were adjusted to optimize there inductive influences to get the lowest return loss. The coaxial structure with the ceramic window and the doorknob waveguide transition were integrated in simulations. Figure 5 shows the electric field distribution in the whole structure. The field was calculated for 80kW TW signal passing through the coupler. The maximum peak field is located at the chokes extremity near the ceramic. The results showed that the doorknob transition is the limiting part for the signal transmission while the calculated values at 704 MHz for the ceramic window (alone) were : reflection < -70 dB and transmission >-0.005 dB.

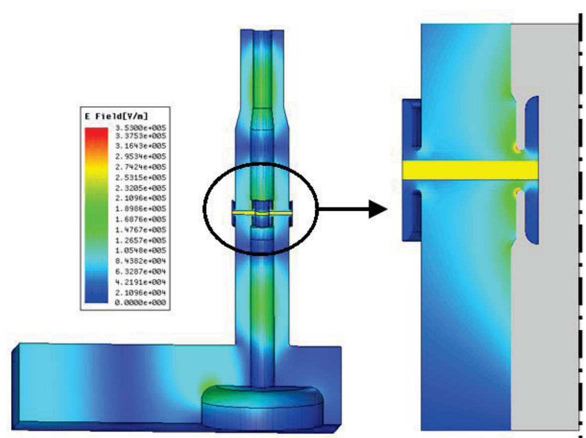

Figure 5: Electric field distribution in the transition & the coaxial coupler for an 80 kW RF power. The time instantaneous peak field is localized at the chokes extremity.

External Coupling

The external coupling Q_{ext} was fixed to the value of 1.10^7. The coupler external and internal conductors' radius were set by the size adaptation to the cavity aspect and the impedance of the coaxial line. So, the only free parameter to adjust the FPC coupling is the antenna penetration into the cavity. CST-MS® simulations were done to evaluate this penetration depth. A final value of -18mm was then chosen, e.g. an antenna length of 281 mm.

Future Conditioning Experiment

All the power coupler elements presented above were manufactured and delivered at IPN Orsay. The conditioning cavity was designed and its fabrication is presently in progress. According to RF calculations the cavity return loss at 704 MHz should be around -60 dB with a bandwidth of 1 MHz at -30dB. FPC will be conditioned [13] in a travelling wave mode at an RF power of 80 kW.

EXPERIMENT & RELIABILITY

Experiment & Facility

During the Power Coupler conditioning, it is foreseen to proceed to the first low power tests of the cavity inside the Cryomodule (early 2010). Those tests will help in evaluating the cavity quality factor with its new "clothing". It is also plan to evaluate the Lorentz Factor and to identify all the microphonics disturbances. This first test will also be useful to check the good functioning of the whole cryogenic device.

The first results will help in defining a procedure for the ramping up of the field in the cavity during high power test and the controlling of the tuning system. For all the experiments the Cryomodule will be set up in the former IPNO cyclotron pit. The cavity will be RF fed thanks to a Thales Electron Devices® Induced Output Tube (IOT) able to provide an 80 kW Continuous Wave signal at 704 MHz. This IOT requires a 36 kV cathode voltage and the electron beam intensity in the tube can reach 3.3A. Therefore, it is DC power supplied thanks to a 160kW (40kV-4A) alimentation provided by Brucker®. The RF low power signal injected in the IOT is piloted by a synthesizer signal which is beforehand amplified by a 1kW Brucker® amplifier (Gain of 60 dB).

The entire power supply chain has been installed, tested and is now fully operational. The Thales® IOT was successfully tuned, and an expected average gain of 21 dB was measured (The gain is slightly changing as function of the output power, maximum: 21.5dB for 60kW).

The high power tests will be a second evaluation of the module cryogenic efficiency. But, above all it is the capability of the piezo-based tuning system coupled with the prototypical digital LLRF I/Q feedback loop which will be evaluated. The reliability of the entire installation and its response time for fast set points update of the entire installation will be tested.

Preliminary Reliability Study

EUROTRANS Linac reliability analysis estimates the number of malfunctions that could cause beam/plant shutdowns per 3-month operation cycle [14]. Results show that such linacs have a high potential for reliability improvement. For the XT-ADS, the objective is to only admit a maximum of 5 beam trips (longer than 1s) per cycle.

To reach this goal a fast fault recovery scenario has been established [5]. When a cavity or its supply fails, the philosophy is to re-adjust the accelerating fields and phases of some non-faulty RF cavities, for a short beam interruption of about 100 ms, to recover the nominal beam characteristics.

To forecast future reliability tests of the 704 MHz Cryomodule and evaluate the technical feasibility of such retuning, we computed a model of the cavity with the main characteristics of its LLRF system in the MATLAB Simulink® environnement.

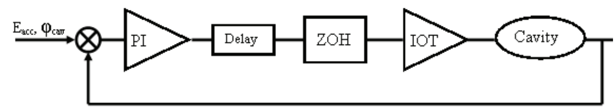

Figure 6: Simple model base for the sample feedback analysis

Table 1 : Simulations Parameters

Parameter	Value	Parameter	Value
Frequency	704.4 MHz	Microphonics frequency	600Hz max.
(r/Q)	160Ω	Beam current	10 mA
Coupling Q_L	$\sim 1.10^7$	Synch. Phase	-30°
Lorentz Coeff.	-10Hz/(MV/m)	Loop Delay	2μs
Acc. Field	8.5 MV/m	Sampling time	1μs
Acc. Gap	0.5 m	Max. power	80 kW
Mechanical const.	1ms	IOT average gain	21 dB
Tunning System response time	10ms	Correction gain	120
Microphonics amplitude	10 Hz max.	Integration time	400 μs

We established our calculation on a simple model (see Figure 6) in the frequency analysis to estimate the gain and the integration time of the corrector (PI), taking into account the sampling operation in a digital system. A delay and sampling time (Zero Order Hold function, ZOH) were introduced [15]. The IOT gain variation as function of the power delivered and non linearity are also taken into account. The cavity voltage is deduced by modeling the cavity as an RLC resonant circuit [16]. The detuning induced by the Lorentz forces and microphonics perturbations were also implemented as well as the fast cold tuning system control loop. Table 1 sums up the principal calculations parameters values.

The figure 7 presents the simulation results during a fast fault recovery procedure where the cavity field has to be increased by 15% and its phase changed by 3 degrees.

The process for this scenario is described by the following steps:

1- The cavity accelerating field and phase was set to the nominal working points (*8.5 MV/m, -30°*); the beam is switched- on.
2- A failure on another accelerating device is detected the beam is switched-off.
3- The accelerating field set point is updated (*10MV/m*)
4- The phase set points is updated (*33°*)
5- The cavity field is stable the beam can be injected again.

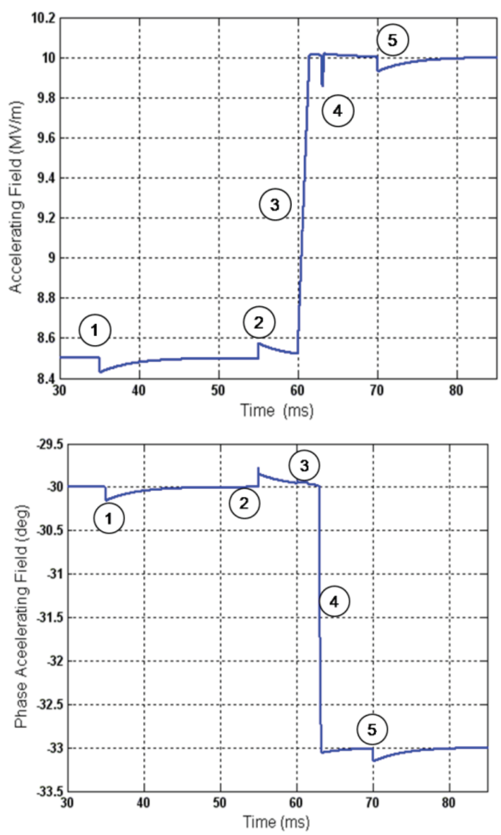

Figure 7: simulations results for the update of the accelerating field and cavity phase during a fast fault recovery scenario.

Results from this preliminary simulations study shows that during a short beam trip, the phase and the field amplitude in the cavity could be updated in around 15ms, with a good control of the feedback loop. When the phase set point is changed deviation of 0.1MV/m is observed but quickly compensated. The real transient effect, due to beam loading, is observed when the beam is switched-on (or switched-off), but one can see that it is also under control and corrected in 10 ms.

CONCLUSION

The experimental campaign on the EUROTRANS 700MHz full scale Cryomodule should start in 2010. In the long run, the experiment will be able to provide a testing bench for specific sequences of the XT-ADS fast fault-recovery reference scenario. The aims of reliability tests will be to recover similar results than computations for the set points updating and validate an efficient and safe procedure.

ACKNOWLEDGMENT

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