ESS ELLIPTICAL CAVITIES AND CRYOMODULES

G. Devanz, N. Bazin, M. Desmons, P. Bosland, P. Hardy, F. Leseigneur, M. Luong, F. Peauger, J. Plouin, D. Roudier, Irfu, CEA-Saclay, Gif-sur-Yvette, France
G. Olivier, IPN Orsay, France.
G. Costanza, Electrical and Information Technology, Lund University, Lund, Sweden

Abstract

The accelerator of the European Spallation Source (ESS) is a 5 MW proton linac to be built in Lund Sweden. Its superconducting section is composed of 3 cavity families: double spoke resonators, medium beta and high beta elliptical multi-cell cavities. This paper presents the electromagnetic and mechanical design of the elliptical cavities. Both elliptical families are housed in 4-cavity cryomodules which share a common design and set of components which will be described here.

INTRODUCTION

The superconducting linac of the ESS operating at 2 K is composed of a spoke resonator section running at 352.21 MHz which brings the proton beam energy up to 220 MeV, followed by two 704.42 MHz elliptical cavity sections. The first one, based on 6-cell β=0.67 cavities accelerates the beam to 570 MeV. The higher energy section is using 5-cell β=0.86 cavities to increase the proton energy to 2 GeV [1].

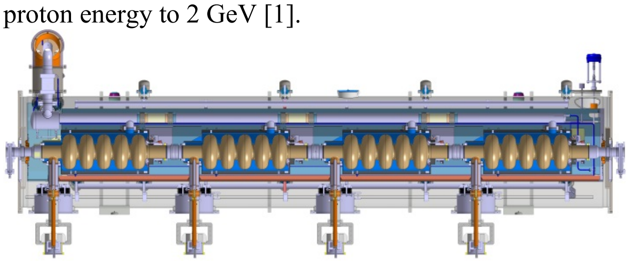

Figure 1: Cut view of the high beta cryomodule.

In both medium and high beta sections, cavities are hosted in 6.6 m long cryomodules grouping 4 units as shown on figure 1.Using a single type of cryomodule was made possible thanks to the similar length of the medium and high beta resonators. Their design is detailed in [2].

ELLIPTICAL RESONATORS

Table 1: RF Requirements of Elliptical Cavities

	Medium	High
Geometrical β	0.67	0.86
Frequency (MHz)	704.42	704.42
Number of cells	6	5
Operating temperature (K)	2	2
Maximum surface field in operation (MV/m)	44	44
Nominal Accelerating gradient (MV/m)	< 16.7	< 19.9
Q_0 at nominal gradient	> 5e9	> 5e9
Q_{ext}	$7.5\ 10^5$	$7.6\ 10^5$

High Beta Cavity

Figure 2: The first bare high β prototype.

The RF design of the high beta cavity and the study of its coupled RF-mechanical behaviour have been presented in [3]. Recently, requirements on the cavity have been made stronger, with a 10% increase on the beam current and accelerating gradient (table 1)

Table 2: RF Properties of High β Cavity

Iris diameter (mm)	120
Cell to cell coupling κ (%)	1.8
π and 4π/5 mode separation (MHz)	1.2
E_{pk}/E_{acc}	2.2
B_{pk}/E_{acc} (mT/(MV/m))	4.3
Maximum. r/Q (Ω)	477
Optimum β	0.92
G (Ω)	241

An important design driver is the RF power transmitted to the beam which amounts to 1.2 MW maximum through the fundamental power coupler (FPC). A large beam tube diameter is needed to be able to reach the required Q_{ext} with a single FPC while limiting the coupler antenna penetration in the beam pipe. The 140 mm diameter adopted for the cavity beam pipes has the benefit of lowering the cut-off frequency which favours the propagation of high order modes (HOM) from one cavity to normal conducting (NC) components of the beam pipe like bellows, or to the power coupler of an adjacent cavity. This way, a better damping of HOMs is achieved in addition of what is already obtained by RF dissipation on a single cavity power coupler NC parts and by transmission to the RF waveguide. Different scenarii have been studied to check that combinations of Q_{ext} and Q_0 estimates and non-propagating longitudinal mode impedances were not the cause of significant cryogenic loads. The highest risk is for the first longitudinal HOM at 1420.7 MHz. If arbitrarily set at 1 MHz from the nearest machine line (instead of a theoretical 11.8 MHz), its RF dissipation would amount to a maximum of 10 mW.

Two prototypes of the β=0.86 cavity are being manufactured from high purity Nb (measured RRR>300). These prototypes include extra RF ports on the beam tubes which were fitted in place of hypothetical HOM couplers. Despite HOM couplers have been discarded for future cavities, the ports have been kept on prototypes for RF measurement purposes. The first bare cavity has been completed in industry (fig. 2). The first steps of the RF frequency monitoring on dumbells have been tested during this first production. The helium vessel will be welded after the preparation and vertical tests which will be performed at Saclay.

Medium Beta Cavity

The number of cells of the medium β cavity has been changed to 6 recently in order to make better use of space while having medium and high beta cryomodule designs converging to a single design.

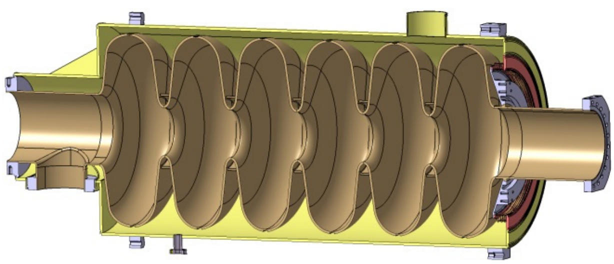

Figure 3: 6-cell β=0.67 cavity 3D model.

The medium β cavity RF design is more constrained due to the relative steeper wall angle compared to the high beta cavity. The wall angle has been kept greater than 7° in order to limit the detrimental effects on the mechanical stability and cavity preparation. The cell-to cell-coupling κ was chosen at 1.8% for the high β cavity as a trade-off between efficiency and mode separation. For the β=0.67 cavity, it was limited to 1.22% to prevent a dramatic reduction the cavity efficiency with increasing κ.

Table 3: RF Properties of Medium β Cavity

Iris diameter (mm)	94
Cell to cell coupling κ (%)	1.22
π and 5π/6 mode separation (MHz)	0.54
E_{pk}/E_{acc} @optimal. β	2.36
Bpk/E_{acc} @ optimal. β (mT/(MV/m))	4.79
Maximum. r/Q (Ω)	394
Optimum β	0.705
G (Ω)	196.63

The FPC-side end-group RF design is dominated by the technical challenge of placing the FPC port (100 mm in diameter) not closer than 35 mm from the cell iris. The beam pipe diameter was chosen at 136 mm in order to ensure the required Q_{ext} could be obtained in this condition. The RF parameters of the optimized cavity pictured on fig. 3 are summarized in table 3.

The HOM have been studied using COMSOL to check that no longitudinal modes exist near multiples of beam frequency (352.21 MHz).

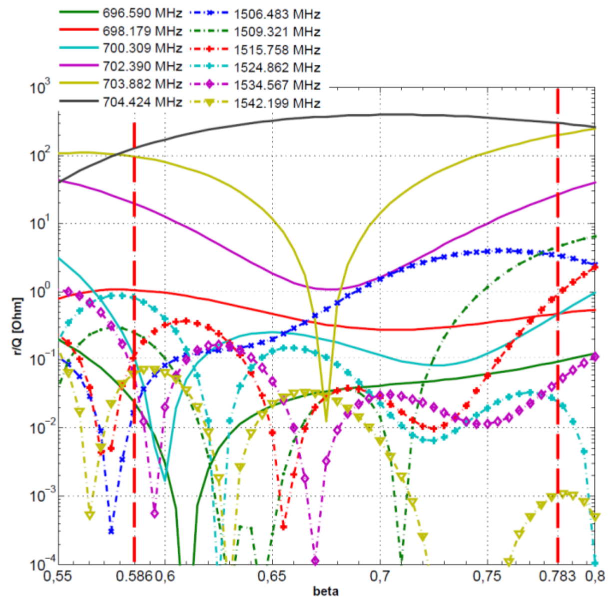

Figure 4: r/Q with respect to the proton β=v/c for fundamental and first longitudinal HOM passbands.

The variation of non-propagating longitudinal modes r/Q over the whole range of proton reduced velocity β=v/c in the medium beta section is shown on figure 4 between the two vertical red dashed lines. As far as the longitudinal HOMs are concerned, only the first passband L1 was found to be non-propagating. The characteristics of its 6 modes are shown in table 4.

Table 4: L1 HOM Passband Characteristics

Frequency (MHz)	r/Q (Ohm)	QL estimate
1506.48	0,444	13000
1509.32	0.0021	7000
1515.76	0.0020	5000
1524.86	0,127	3000
1534.57	0.0001	2000
1542.20	0.0032	3000

The listed r/Qs correspond to the maximum in the cavity range of use mentioned earlier. The Q_L has been estimated with HFSS on a single cavity surrounded by two normal conducting bellows and equipped with a 50 Ω terminated coaxial power coupler (fig. 5).

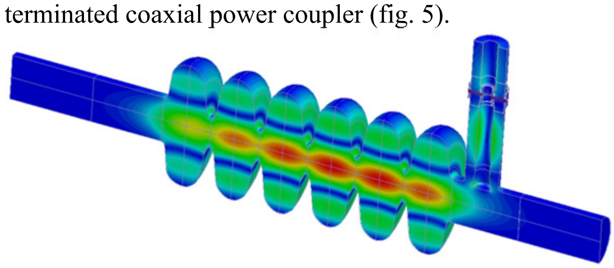

Figure 5: HFSS model used to estimate the QL of HOMs showing the 1506.48 MHz mode of the β=0.67 cavity.

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The model includes the RF window, so that its transmission characteristics are taken into account. This is also required to check that no resonance occurs in the ceramic disk for any of the HOMs. The simulations indicate that the natural damping of the L1 modes is adequate. The accurate study of higher frequency longitudinal HOM passbands requires the simulation of a full cryomodule and has been started.

Mechanical/RF Aspects

The cavity wall thickness is determined taking into account both the mechanical loads related to pressure or tuning, but also the cavity sensitivity to Lorentz force detuning (LFD). The cavity wall thickness of 4 mm is chosen, combined with stiffening rings 70 mm in radius. It has been found that the sensitivity of the static LFD coefficient K_L to the exact ring radius is rather weak.

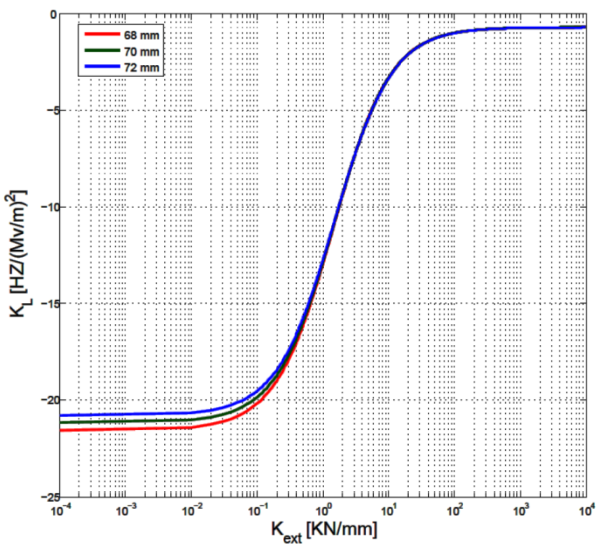

Figure 6: Sensitivity curve for K_L.

Figure 6 shows the variation of K_L with respect to the external stiffness K_{ext} (combined stiffness of the He vessel and the cold tuning system) for three values of the ring diameter. K_{ext} is expected to be 21 kN/mm in our case, combining expected 30 and 75 kN/mm stiffness of the tuner and tank respectively. For $K_{ext}<10^{-2}$ kN/mm the cavity can be considered in the free ends condition. For $K_{ext} > 10^3$ kN/mm, the fixed ends condition is met. The mechanical parameters of the cavity are summarized in table 5. The maximum working pressure in the helium circuit of the cryomodule is chosen at 1.5 bar absolute, and it therefore used as a reference in the table. This has been done in an effort to limit the impact of European directive on Pressure Equipment on the certification process of the cryomodules.

Table 5: RF/mechanical Properties of Medium β Cavity

Cavity wall thickness (mm)	4
Tuning sensitivity (kHz/mm)	217
Stiffness (kN/mm)	1.47
K_L static Lorentz coefficient (Hz/(MV/m)^2) (fixed ends)	-0.71
K_L static Lorentz coefficient (Hz/(MV/m)^2)	-21.1
K_L static Lorentz coefficient (Hz/(MV/m)^2) for Kext=21 kN/mm	-2.06
Maximum pressure (bar) in He vessel at 300K limited by Von Mises stress in cavity wall < 40 MPa (fixed ends)	2.2
Maximum Von Mises stress (MPa) in cavity wall with 1.5 bar in helium vessel	28

Mechanical Design

Medium and high β cavities include the following characteristics, most of them being typical of the X-FEL technology:

- A Ti helium vessel including a hydro-formed bellow on the tuning system side
- NbTi flanges for use with Al alloy hexagonal seals.
- The main cylindrical part of the helium vessel is connected to the two-phase line of the cryomodule through a welded joint. This helps minimizing the required opening in the magnetic shield located near the cell equators. The two-phase line is located above the cavity (see fig. 7).
- The alignment tools are anchored on the beam flanges on which reference boreholes are machined.

The helium tank is attached to the FPC-side beam flange and reinforced on this side using four winglets. On the opposite side, a titanium cone closes the helium and supports the tuning system. This cone is welded directly to a Nb ring which is part of the beam pipe, without resorting to an additional NbTi transition part. The actual implementation of the tank design for the medium and high beta cavity has only minor differences, the only significant ones being the longitudinal extension of the main cylinder of the vessel and the position of the helium inlet

The feasibility of most of the technological aspects of the cavity fabrication has already been tested beforehand on the very similar SPL type β=1 5-cell cavity of the Eucard R&D programme [4].

MAGNETIC SHIELD

We decided to limit the contribution of the trapped flux to the surface resistance to 4 nΩ (half the expected low field surface resistance) , and thus to limit the external static field to B_{ext} = 1.4 µT =14 mG. Since the earth magnetic field is 500 mG, this corresponds to a required shielding efficiency equal to 35.

The design calculations were performed with a material permeability equal to 20000, corresponding to the estimated expected value for cryogenic shield materials. Indeed the chosen solution is a cold magnetic shield enclosing the helium tank. The target value for the magnetic field on the cavity walls is reached for a shield with 1.5 mm thickness, provided that an appropriate cylinder of magnetic shield is placed around the pipe connecting the helium vessel to the two-phase line.

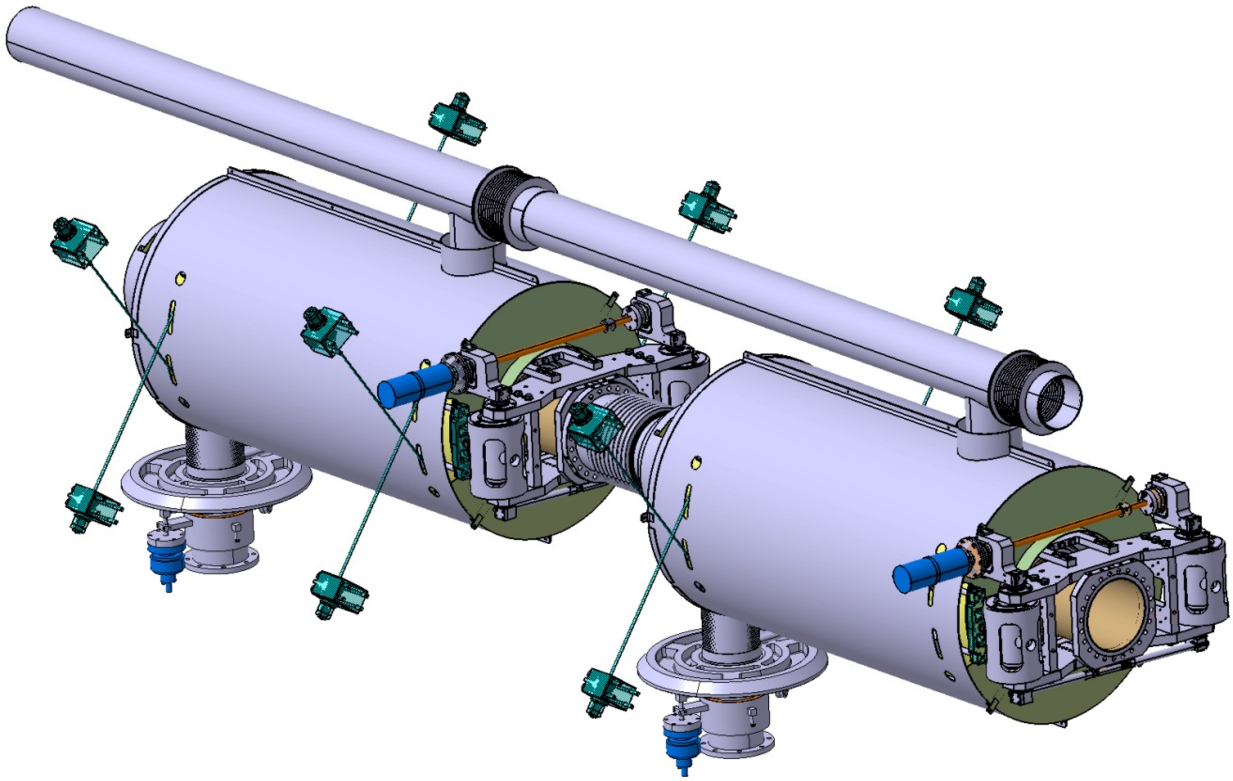

Figure 7: Arrangement of a pair of cavities in the 4-cavity string showing the bottom position of the power coupler, cold tuning system, inter-cavity bellow, TA6V tie-rods which are part of the cavity supporting systems, magnetic shields and two-phase cryogenic pipe connected to the top of the helium vessels.

The magnetic shield has been broken down into 7 parts to enable the pre-assembled cavity string, on top of the MLI surrounding the helium vessel (fig. 8).

COLD TUNING SYSTEM

The cold tuning system (CTS) is based on the proven mechanical design principles of Saclay tuners (fig. 9). It combines lever arms and excentric shafts actuated by a motor gear box and main screw assembly to provide the slow mechanical tuning action. The motor and the gearbox are working under vacuum at cryogenic temperatures. It is an evolution from the previous tuners for pulsed proton cavities [4] and includes the additional possibility to use one or two piezo actuators simultaneously for fast Lorentz force detuning compensation.

The already existing high β cavity tuner design has been modified to fit both medium and high beta, taking into account the integration of such elements as the magnetic shield and cavity supporting system. The tuner provides a maximum slow tuning range of +/- 3mm. Its

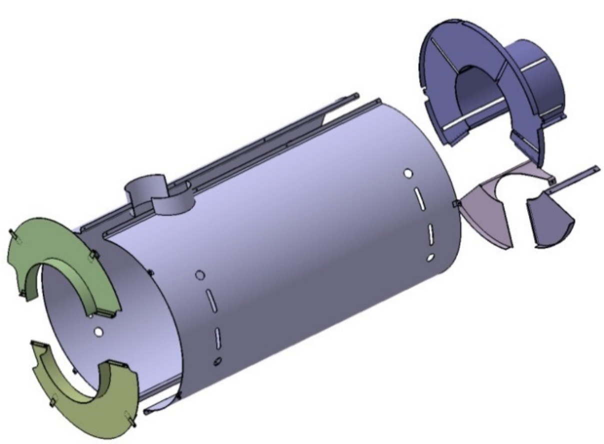

Figure 8: Elements of the magnetic shield.

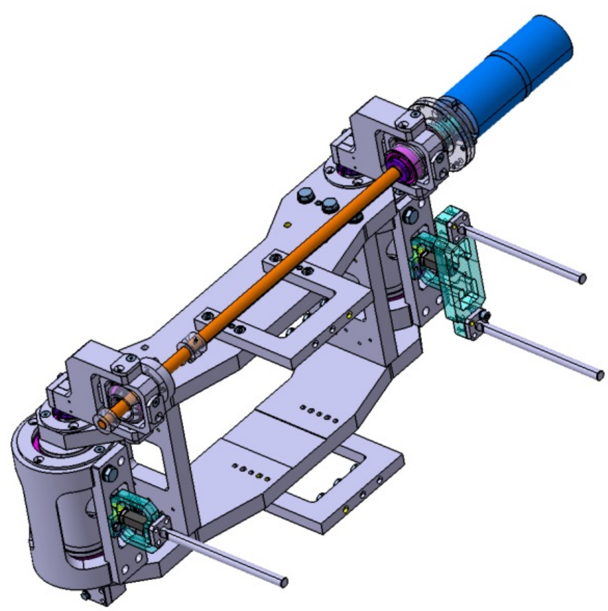

Figure 9: 3D model of the CTS.

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use will be restricted to cavity elongation. The corresponding tuning range will be of 650 kHz and 590 kHz for the medium and high β cavities respectively. The cavities will be pre-tuned in such a way that bringing them to the operation frequency will require a positive frequency tuning with the CTS of about 100 kHz. This way, all plays in the mechanical system will be closed, enabling the CTS to achieve its design stiffness. Based on pneumatic bench measurement on existing Saclay tuners of the same type, we expect the tuning system to reach a minimum stiffness of 30 kN/mm.

The piezo support and preload frame is customized for each family of β according to the cavity stiffness. Let alone their task of holding the 30 mm long piezo stacks in place, the role of these supports is to apply a preload on the actuators. This load is set up at room temperature, using a set screw. The frame design is aiming at maintaining the correct preload at the working temperature of the tuner which lies between 2 and 30 K. The support is designed such that its stiffness is ten times greater than the cavity stiffness. This way, the piezo load is maintained within a 10% variation throughout the full slow tuning range irrespective of the reaction force of the cavity.

FUNDAMENTAL POWER COUPLER

The power coupler (fig. 10) design is an adaptation of the 704 MHz, 1.2 MW peak power FPC developed in the framework of the European program CARE/HIPPI. The later has been tested on a conditioning bench up to full power at a duty factor of 10%. It has also been tested in full reflection on superconducting cavities in the horizontal test cryostat Cryholab at Saclay [5]. The peak power requirement is also 1.2 MW for ESS, the RF duty factor being lower at 4.2%.

The room temperature window of this coupler is derived from the KEK-B ceramic disk window. The design has been modified to obtain RF matching at a frequency of 704.42 MHz, and adapted to a 50 Ω coaxial line, 100 mm in diameter.

A new coaxial to waveguide doorknob transition has been designed to add a high voltage (HV) biasing capability to the existing coupler. Both HV connection and water cooling connection are located at the antenna en on the waveguide side. In order prevent the RF leaks in the coupler surroundings through the kapton capacitor, the new transition includes a RF trap. The presence of water in the cooling hoses has been taken into account in the design. Resistors have also been integrated in the HV connection to provide RF attenuation and protect the HV power supply.

The cooling scheme of the HIPPI coupler has been retained with 3 parallel supercritical helium cooling spiralling channels in the cold outer conductor and improved water cooling for the inner conductor of the window and the antenna.

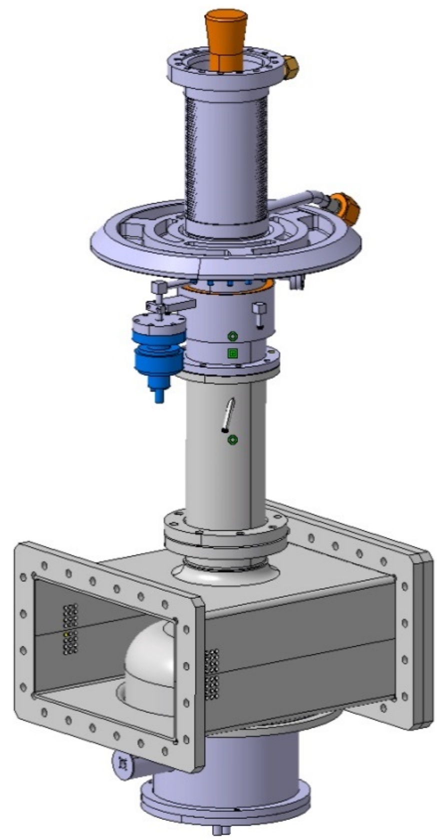

Figure 10: Model of the fundamental power coupler.

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