SPIRAL2 cryomodule production result and analyses

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SPIRAL2 CRYOMODULE PRODUCTION RESULT AND ANALYSIS

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Abstract

The production and qualification of the SPIRAL2 cryomodules are close to the end. Their performances are now well established. This paper will explain the path followed to the good achievements, and show some statistical analyses to be used for future projects. How far can we push the performances? What cryogenics consumption shall we take as design values?

INTRODUCTION

The SPIRAL 2 [1] linac is based on superconducting (SC), independently-phased resonators. In order to allow the required broad ranges of particles, intensities and energies (see table 1), it is composed of two families of short cryomodules developed by CEA/Irfu (Saclay) and IN2P3/IPN-O (Orsay) teams. The first family is composed of 12 quarter-wave resonators (QWR) with β_0=0.07 (one cavity/cryomodule), and the second family of 14 QWR at β_0=0.12 (two cavities/cryomodule). Resonance frequency is 88.0525 MHz and maximum gradient in operation of the QWRs is $E_{acc} = V_{acc}/\beta\lambda = 6.5$ MV/m. Developed by IN2P3/LPSC (Grenoble), the RF power couplers shall provide up to 12 kW CW beam loading power to each cavity. The transverse focusing is ensured by means of warm quadrupole doublets located between each cryomodule, in so-called "warm sections" also equipped with beam diagnostic and vacuum equipments.

Table 1: Beam specifications.

Particles	H^+	$^3He^{2+}$	D^+	ions	ions
Q/A	1	3/2	1/2	1/3	1/6
Max. I (mA)	5	5	5	1	1
Min. energy (MeV/A)	0.75	0.75	0.75	0.75	0.75
Max energy (MeV/A)	33	24	20	15	9
Max. beam power (kW)	165	180	200	45	54

PRESENT STATUS

SPIRAL2 Phase 1 project status

SPIRAL2 Phase 1 project is presently in installation phase. Construction phase is close to the end, and reception operations of the building are almost finished.

The sources and most of the low energy beam lines have been installed. All supporting frames for the accelerators are in place and cabling operations are proceeding smoothly. Linac components installation will start as soon as the linac tunnel is dust cleaned.

First beam inside the linac is scheduled for mid-2015.

Cryomodules status

Low beta cryomodules are assembled and tested at Irfu in Saclay. Out of twelve cryomodules, eight have been tested and qualified. Clean room assembly of the remaining four ones has begun this summer; the last one shall be delivered during the first quarter of 2015.

High beta cryomodules are assembled and tested at IPN-O in Orsay. Five out of seven cryomodules have been successfully qualified. Assembly of the sixth cryomodule is well advanced and the last two cryomodules are scheduled for delivery in GANIL before the end of the year.

Power couplers for both families are prepared and conditioned at LPSC in Grenoble. All power couplers but spare ones have been processed.

CAVITIES AND CRYOMODULES DESIGN

SPIRAL2 cryomodules design has been extensively described in previous papers [2][3]. Both models are short cryomodules (one or two cavities per cryomodule) with no focusing element inside. Due to beam dynamics requirements, cryomodules are very compact. Cavities are bulk niobium QWR.

Cavity body is cylindrical and stem is conical, with toroid-shaped stem-to-body top. Helium jacket doesn't cover the bottom part of the cavities. Cavity is working at 4.5 K; copper, thermal screen is cooled at 60 K using 15 bar He gas. Insulation vacuum and beam vacuum are separated.

Power coupler is of fixed type, located on the bottom of cavities. Couplers are similar for both types of cavities. Coupling factor is optimized for each family of cryomodules (5.5 10^5 for low beta cavities and 1.1 10^6 for high beta cavities), considering the peak intensities of the various particles to be accelerated through the linac.

Both families of cavities are prepared using standard BCP chemical treatments, followed by 18 MΩ water high pressure rinsing (HPR) in clean room. None has been heat cured against 100 K effect.

Low-beta cryomodules specificities

Low beta cavities are closed by a removable bottom plate, intended to ease HPR cleaning of these small cavities. This plate is made out of OFHC copper (see reference [2]).

Tuning system is mechanical. Deformation of the cavities by squeezing its outer body perpendicularly to the beam axis provides a 13 kHz tuning range.

As there is only one cavity per module, no helium buffer reservoir is fitted inside the cryomodule. Phase separation is performed directly above the cavity, inside the helium vessel, and is enhanced by using porous metallic filters.

Magnetic shielding is made of room-temperature, Mumetal® plates located around the outer vessel.

High-beta cryomodules specificities

High beta cavities tuning is performed by a niobium plunger, moving up and down inside the cavity. This system, located on top of the cavity in the maximum magnetic field area, provides a tuning range of slightly more than 10 kHz.

Windows, sights and rods allow checking and adjusting the cavity alignment from outside both at room and at cold temperature.

Magnetic shielding is located around the cavities and made of Cryoperm® and A4K® material. It is cooled by the same circuit as the cavity, to ensure that the permeability of the material is as high as possible when niobium transits to the SC state.

Cavities are baked while under vacuum in clean room (120°C for 48h). This baking proved to enhance Q_0 by 50% (mean value). This effect was not observed on low beta cavities for reasons still unclear.

CRYOMODULES PRODUCTION HISTORY

Strategy

Design of both cryomodules and cavities families has been performed independently in two different laboratories, with only minimal standardization (power couplers being one of the few common components).

Manufacturing of cavities and cryomodule components has been subcontracted to private companies, mainly from France, Germany and Italy.

Testing of the cavities, and then assembling and testing of the cryomodules have been performed by the same two laboratories that did the designs.

Power couplers have been designed by a third laboratory (LPSC from Grenoble) and manufactured by the French SCT company. LPSC then prepared and conditioned the couplers on a dedicated, standing wave bench. Then couplers have been shipped to the respective teams in charge of the cryomodules assembling. The careful optimization of the power couplers preparation and RF conditioning is detailed in reference [4].

Prototyping stage included one cavity of each family plus power couplers, and in a second phase one full cryomodule of each family. For planning purposes, several series orders were placed before ending qualification tests.

Implementation

Prototype cavities of both families achieved the specifications and performed very satisfactorily. Neither power coupler nor tuning system was tested on cavities at this stage, and the cavities were not fitted with helium vessels. None of the prototype cavities were intended for use in cryomodules.

Prototype of the low beta cryomodules remained unsatisfactory during a long period. Q_0 of the pre-series cavity was one order of magnitude below specifications (and below the prototype's). Extensive troubleshooting helped solving the problem, related to the bottom plate and flange. For the prototype, these were made out of niobium titanium, with Helicoflex® seals (acting as RF seals as well). For economical reasons, they were replaced with a niobium bottom plate with a stainless steel, non-standard CF flange, using a copper seal with a special RF knife as used by CERN. On SPIRAL2, RF sealing failed because of the flange design, leading to high RF losses on the stainless steel flange. To solve the problem, CF sealing was replaced by Helicoflex®. This, in turn, led to extensive leak problems, mainly after cool-down to 4 K. Finally, Helicoflex® seals were replaced by double indium sealing around a copper disc, fitted inside the Helicoflex® grooves. Indium being not easy to remove, it was decided not to high pressure rinse the cavities between the vertical cryostat (VC) test and assembling inside the cryomodule. This is the standard procedure now used.

Cooling of the bottom plate was also optimized. It makes used of a thermosiphon system connected to the plate through copper braids. Niobium bottom was replaced by OFHC copper bottom, enhancing thermal stability at the cost of 1.6 W additional RF losses at nominal gradient.

Prototype of the high beta cryomodule achieved good performances and was extensively tested, fitted with pre-series cavities. It showed nevertheless high field emission and high cryogenic consumption, the latter problem leading to some optimizations.

Series assembling of the high beta cryomodules started very quickly, but all assembling operations were stopped after the first three cryomodules tests. None of these three cryomodules achieved the nominal gradient (whereas the prototype did), and field emission was extremely strong. Moreover, the tuning system was showing frequency overshoot when its direction was changed [5].

After long and extensive troubleshooting, field emission and gradient problems were solved by optimizing the preparation procedures. Cleaning of the power couplers was also optimized and all antennas were electropolished. From this point, and for all SPIRAL2 cryomodules, all components connected to the beam vacuum were systematically checked against dust contamination using particle counters. Pumping and venting speeds controls were hardened and high beta cavities HP rinsed twice before their installation inside the cryomodule. Tuning system problem was also understood and solved [6].

Conclusions

Most of the problems which happened during phase production arose from changes between prototypes and

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series phases: bottom plate's flange for low beta cavities, tuning system for high beta ones. These shall therefore be limited to the utmost and thoroughly tested before implementation. More generally, in our experience, anything untested was prone to be the source of problems.

Similarly, optimization of the preparation phases and procedures shall be performed as early as possible during the development phase.

The low number of prototypes was also a drawback. It hampered defect analyses, because it was not possible to distinguish between defects related to the basic design or to manufacturing problems.

Lack of standardization during design phase will certainly be a drawback for maintenance and operation purposes. It is advisable to standardize designs and preparation procedures as much as possible in order to share studies, ease maintenance and lower costs of components and tooling.

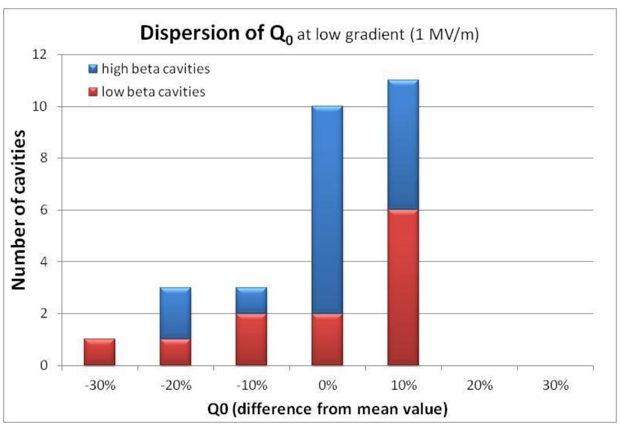

Figure 1: Dispersion of cavities' performances with respect to Q_0 at low gradient (1 MV/m) in VC.

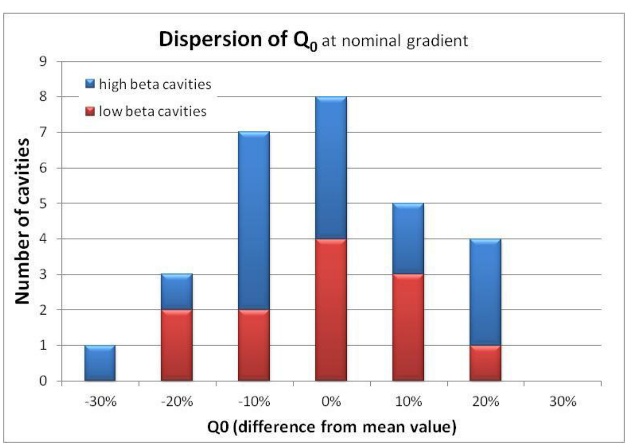

Figure 2: Dispersion of cavities' performances with respect to Q_0 at nominal gradient (6.5MV/m) in VC.

PERFORMANCES AND ANALYSIS

Cavities

All SPIRAL2 cavities were qualified first in VC. During these tests, these cavities performances proved to be very homogeneous. They all met the project objectives (no more than 10 W of RF losses at 6.5 MV/m accelerating gradient).

Computed Q_0 is 7.6e8 for low beta cavities (with niobium Rs=20 nΩ and including normal conducting bottom). Mean Q_0 value achieved in VC is 1.0e9 at low field (1 MV/m gradient) and 5.9e8 at nominal gradient (6.5 MV/m). For high beta cavities, theoretical Q_0 is 2.7e9 (with Rs=10 nΩ); mean Q_0 value achieved in VC is 8.2e9 at 1 MV/m and 3.7e9 at 6.5 MV/m.

During VC tests, 86% of cavities are within ±15% of the mean Q_0 value at low gradient (figure 1). At nominal gradient, 71% of cavities are within ±15% of the mean Q_0 value (figure 2). Q_0 dispersion is therefore small after VC tests.

Figure 3 shows the maximum gradients achieved during VC tests. The dispersion is as small as for Q_0: 82% of cavities have a maximum gradient within ±15% of the mean value.

Maximum gradient achieved in VCis around 15% higher for low beta than for high beta cavities, which roughly corresponds to the peak magnetic field to gradient ratio difference (8%). Moreover, simulation codes used to compute this ratio were not the same for both cavities families (see table 2).

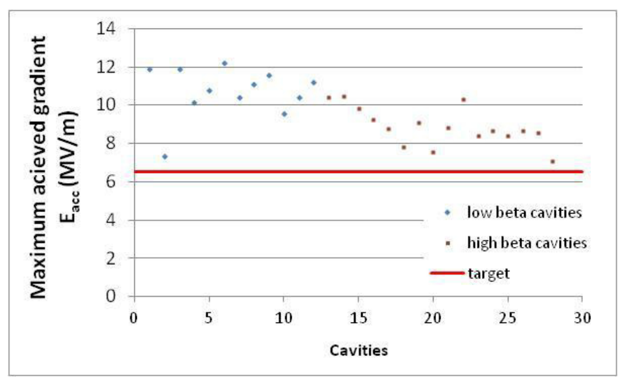

Figure 3: Maximum gradient achieved in VC.

Table 2: Computed ratios of surface fields to accelerating gradient.

	low beta cavities	high beta cavities
E_{peak} / E_{acc}	5.4	4.8
B_{peak} / E_{acc} [mT/(MV/m)]	8.7	9.4

Cavities have been manufactured by three separate companies (SDMS from France and Zanon from Italy for low beta cavities, RI from Germany for high beta ones); it is not possible to distinguish any performance difference.

Cryomodules

Since the problems described above were solved, not a single cryomodule test failed, indicating that the preparation procedures are now well optimized, and that the technical staff in charge is highly skilled.

Performance comparison of cryomodules with respect to tests done in VC is hampered mainly by several factors.

First, the statistical population is very small: only 18 cavities have been tested in cryomodules.

Another factor is that measurements performed in cryomodule conditions are much less precise than in VC. Calibration is tricky and power coupler coupling factor is high (5.5 10^5 for low beta cavities and 1.1 10^6 for high beta ones), so RF losses in cavities can only be estimated by cryogenic measurements [6].

Moreover, in order to avoid quenches that might degrade performances of cavities, it was decided not to push cavities beyond an "8 MV/m administrative gradient limit". Actually, among the 18 cavities which have been tested in their dedicated cryomodules, only one didn't reach the administrative limit. This particular cavity was one of the better performing low beta cavities during the VC test. All other cavities did reach the administrative limit inside the cryomodules, and all of these cavities actually had VC performances higher than this limit. In conclusion, one can assess that for all but one cavity, cryomodule operation does not lead to a significant loss of maximum gradient (so far).

Q_0 drop between VC and cryomodule operation is measured through. Cryogenic losses are measured with RF power off, then with RF power on, either by measuring the return gas flow or by closing the inlet cryogenic valves and measuring the helium level decrease in the buffer reservoir. The difference is giving RF losses inside the cavity and thus the Q_0 factor in cryomodule operation. The precision of this measurement is estimated around 30% for gas flow measurements, and around 20% for helium level ones.

Our measurements indicate a mean performance decrease in terms of Q_0 of 38%. If one does not take into account a particular low beta cryomodule (one which is still fitted with a Helicoflex® bottom seal and a non electropolished coupler, and assembled first before final optimization of preparation procedures), the mean degradation of Q_0 is 33% and identical for both families of cryomodules. One should obviously not take this value for a very general behavior of all cavities and cryomodules, but this is certainly an interesting indication for linac designers, as both types of cryomodules are of significantly different designs (tuning systems, magnetic shielding, cryogenic circuits, HPR treatment of cavities, etc.).

The X-rays dose rate emitted by cavities in operation is a key parameter measured during qualification tests. This parameter is important because it may lead to malfunction of two diagnostics used in the SPIRAL2 linac tunnel (Beam Extension Monitors, BEM; and Beam Loss Monitors, BLM) which rely on X-rays measurements, and might thus be noised by the cavities. Because of this concern, one BEM has been tested in real conditions, connected to a running high beta cryomodule [7].

X-rays dose rate has been measured during VC tests and during cryomodule qualification. For high beta cavities, acquisition is always performed in the direction of maximum emission. For low beta cavities, it is also done so during cryomodules test, while the VC design forbids such a position of the probe. Various commercial detectors have been used, showing differences of up to a factor 3 in terms of dose rates values. Table 3 summarizes these results for both families of cavities.

Results are difficult to compare from one cavity family to another because of the difference of setup and of probe. Nevertheless, their general behavior is obviously very different. Low beta cavities have a more homogeneous behavior, especially in cryomodules, while high beta cavities are more "all-or-nothing". One reason is certainly relating to the fact that high beta cavities have been high pressure rinsed between VC test and cryomodule assembly phases, while the low beta ones have not. Therefore there is no "memory" effect in the case of the high beta cavities. Indeed, cavities emitting strongly in VC and in cryomodules are not necessarily the same in the high beta family; one observes at least one cavity emitting strongly in VC which is very "quiet" in cryomodule, and vice versa. On the opposite, low beta cavities emitting significantly in VC still do so in cryomodules.

Table 3: X-ray dose rates emitted by SPIRAL2 cavities (in µSv/h)

Conditions	value	low beta cavities*	high beta cavities**
In vertical cryostat, at nominal gradient	min	0	0,1
	max	2,1	4 970
	median	0,1	1,7
	mean	0,4	660
In cryomodule, at nominal gradient	min	1,4	0
	max	730	22 000
	median	293	0
	mean	325	2 223

*Probe on top of cavity in vertical cryostat, close to the beam axis in cryomodule operation.
** Probe close to beam axis in both tests conditions.

It proved difficult to achieve design coupling Q_i for the power couplers, especially for low beta cavities (see table 4). Computations and room temperature RF calibration tests with power coupler and cavities were performed to optimize the penetration depth of the antenna. In the end, low beta cavities are slightly less coupled than planned while high beta cavities are slightly more.

Computations proved pessimistic as far as pressure sensitivity to helium pressure variation is concerned (see table 4). This parameter is mainly driven by the thickness of the cavity top torus (connecting the stem to the cavity body). Therefore difference of behavior from one cavity to the other shall be attributed to manufacture discrepancy (these parts are deep drawn, not machined) but also to BCP chemistry "intensity"; indeed, coarse frequency tuning has been done by chemistry, and therefore some cavities have seen longer chemical etching than others, and have thus thinner top torus than others.

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Table 4: Achieved coupling factor and pressure sensitivity compared to target values.

Data	Value		low beta cavities	high beta cavities
Q_i	target		5,5E+05	1,1E+06
	achieved	min	6,7E+05	8,4E+05
		max	1,0E+06	1,0E+06
		mean	7,7E+05	9,2E+05
Pressure sensitivity [kHz/mbar]	Target		> - 8.0	> - 8.0
	computed		- 2,5	- 7,0
	achieved (in cryomodule)	min	- 1,1	- 4,5
		max	- 1,7	- 7,3
		mean	- 1,4	- 5,4

All cryomodules but one are consuming less cryogenic power than the project objectives (see figure 4). Static cryogenic losses estimation proved to be very reliable for low beta cavities (see figure 5). The best cryomodule is performing exactly to the computed values, while the mean cryomodule is less than one third above. Performances are further from the expectations for high beta cryomodules, but they remain below the target value thanks to the low RF consumption of the cavities.

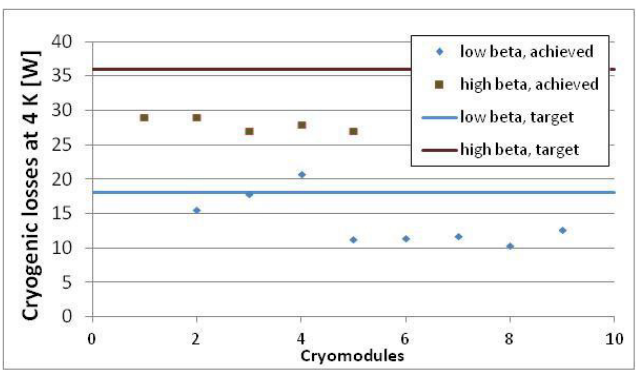

Figure 4: Total cryogenic losses of cryomodules at 4 K.

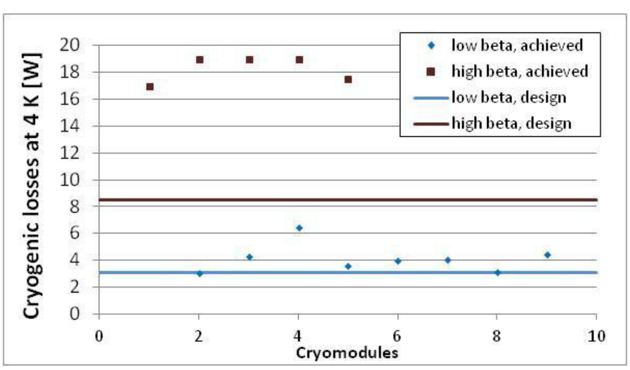

Figure 5: Static cryogenic losses of cryomodules at 4 K.

CONCLUSION

Despite its reduced number of cavities, the SPIRAL2 project provides some interesting information regarding the achievable performances of low beta cavities: surface peak fields, Q_0, cryogenic losses, etc. The achieved performances provide some hint for today's linac designer. One should nevertheless take into account the fact that these cryomodules have yet to be put into operation on the linac, connected to their warm sections; test stand operation is different from linac operation, and some more margins need to be taken into account.

On the other hand, the SPIRAL2 linac is now a ten years old design. Latest progresses in low beta cavity design and cavity preparation (like EP) should allow designers to go one step beyond the performances achieved on SPIRAL2.

PERSPECTIVES

Installation phase is a critical stage of the project. In order to keep the very good performances achieved by the cryomodules on the test stands, extensive precautions will be taken during this phase. The critical step is the connection of the cryomodules to the inter-cryomodule warm sections. It will be performed using a moveable laminar flow to cover the area but, because of the extreme compactness of the design, the operation will anyway be difficult. Therefore, a connection test has successfully been performed in Orsay, using a qualified high beta cryomodule, to demonstrate that this operation does not degrade the cavities performances.

Similarly, road transportation of the cryomodules from the test stands to GANIL (~250 km) was identified as a risky step. Therefore, a successful transportation test was performed: one qualified low beta cryomodule was transported from Saclay to GANIL, unloaded, reloaded and transported back to Saclay. There it was once again tested to check that its performances (maximum gradient, RF losses, field emission and cavity alignment) were not degraded by the transportation.

Installation process will start as soon as possible. The goal is the cool down the linac during spring 2015.

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