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A GENERAL PURPOSE INFRASTRUCTURE AT CERN FOR R&D AND TEST OF SUPERCONDUCTING RADIO-FREQUENCY CAVITIES AND CRYO-MODULES

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Abstract

This document outlines the status of a possible SC RF infrastructure at CERN made-up with the presently existing equipments. It presents the technical specification of such a facility for the manufacture, processing and testing of superconducting RF cavities and fully equipped cryo-modules and the service it could provide to users. It finally estimates the necessary M&P resources to refurbish the present equipments as well as the M&P resources to operate and use the facility. The information given is intended, following an iterative process, as basis for users to suggest possible upgrades for their specific needs. These upgrades would be analysed in a forthcoming document.

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INTRODUCTION AND OBJECTIVE

This document is issued in the framework of the initiative to establish a European facility to "build and test high performance SCRF[1] structures and to integrate them into modules", as recently proposed in the "Letter of Intent about a European SC RF Facility" [i]. It shall detail the present possibilities at CERN for manufacture, processing, and testing of superconducting RF cavities, to assemble them and their ancillary equipment, such as power and HOM[2] couplers and tuners, etc., into cryo-modules and test them as such. The document is based on the technical information of existing facilities at CERN so far collected [ii].

The document assesses what CERN is able to contribute to such an infrastructure by its existing installations and equipment, evaluate possible important shortcomings, and, in a second iteration to be published later, propose a completion of the existing equipment, according to the needs of the user collaborations, including an estimate on resources for investment and operation.

The high performance SCRF structures that could potentially be built and tested in a European facility and assembled into cryo-modules cover a wide range of frequencies (the typical frequency in brackets):

- Radioactive ions beam (REX-ISOLDE[3], 100 MHz),
- e^-/p storage ring (350 - 500 MHz[4]),
- Super-conducting proton linac (SPL, 700 MHz)
- e^-- linac (ILC, energy recovery linac, … , 1.3 GHz),
- Singular cavities for R&D, or other purposes (1.0 - 3.0 GHz).

For convenience, the various applications are grouped into two classes: "low frequency" cavities (e/p storage ring, radioactive ion beam) and "high frequency cavities" (super-conducting proton linac cavities, e^-- linac cavities, singular cavities for R&D or other purposes). This grouping goes essentially along with

- two different technologies: niobium coated as a thin film on a cavity body manufactured from copper (Nb/Cu) for "low frequency" cavities and niobium cavities manufactured from bulk sheet metal for "high frequency" cavities; and
- different requirements for the cryogenics installation: "low frequency" cavities can be operated at 4.2 – 4.5 K, whereas "high frequency" cavities need to be operated at a lower temperature (1.8 – 2.0 K), which requests additional cryogenic equipment;
- different beam currents: "low frequency" cavities go along with relatively high beam currents, and are limited by the transfer of RF power through the power coupler, hence do not make use of the highest gradients, whereas "high frequency" cavities are pushed to the technological limits in gradient and Q-value.

1. SCOPE OF FACILITY AND ORGANISATION

As outlined by CERN's Director General in his contribution to the "European SCRF Infrastructure" meeting at Milano - LASA on 14 September 2006 and described in the white

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1 Super-Conducting Radio Frequency
2 HOM = Higher Order Mode
3 REX = Radioactive Beam Experiment, ISOLDE = Online Isotope Mass Separator
4 The frequency of the proposed ILC damping ring is 650 MHz

paper on “Scientific Activities and Budget estimates for 2007 and Provisional Projections for the Years 2008-2010 and Perspectives for Long-Term”, presented at the Scientific Policy Committee (SPC) on 16/10/06, the Finance Committee (FC) on 18/10/06 and the Council on 19/10/06, CERN is willing to provide, as a generic facility, its existing installations, as set up for the LEP2 and the LHC collider RF systems [iii]:

- CERN is committed to maintain an operational facility and the users are organized in collaborations providing the equipments to be tested and operating the tests with their own resources;
- It allows envisaging a generic central facility for multi-user purposes, at a reasonable cost, by reusing as much as possible the available equipments and complemented when possible by equipments of national laboratories;
- In case the technical specification of the above (basic) facility does not fulfil the requirements of one (or several) of the users, the facility would have to be upgraded with resources provided by the corresponding user(s).

2. STATUS OF THE EXISTING EQUIPMENT

2.1. Introduction

As the existing facilities were built up in the frame of the LEP energy upgrade (LEP 2) and the LHC project, they consequently date back to the 1990ies. The major part of the LEP cavities consisted, and all LHC cavities consist, of Nb/Cu cavities. Only a small number were manufactured from bulk niobium sheet metal for the early phase of the LEP 2 project. As the LEP storage ring was dismantled since, CERN’s manufacturing and testing facilities, in their actual state, are compatible and complete as far as the Nb/Cu technology for LHC is concerned. During an intensive R&D programme focussed onto 1.5 GHz Nb/Cu resonators several installations and techniques specific for high frequencies had also been developed, while allowing the build-up of considerable expertise in surface preparation and analysis techniques.

Any specific installation for sheet metal niobium cavities was since dismantled or transferred elsewhere (e.g. electro-polishing equipment developed for 1.3 GHz single cells). Irrespective of this, all general purpose equipment, such as the equipment available at the main workshop, as used for brazing, electron-beam welding, chemical etching, and a large part of the specific surface processing equipment, such as water rinsing and clean room assembly installations, can be used for either of these two technologies.

The flexibility of CERN’s installations is also documented by the fact that, in a collaborative effort between CEA, DESY and CERN, a large number (about 100) of 1.3 GHz single cell niobium sheet metal cavities were processed at CERN by an improved surface treatment, including electro-polishing, and tested in parallel to the ongoing programme for production and test of the LHC cavities.

2.2. General-purpose installation

The general-purpose facilities are the following:

- Mechanical manufacturing equipment including several kinds of lathes, grinding and milling machines (manual and CNC), sheet-working equipment and welding;

- Brazing in a large vacuum furnace, with 5.5 m height and a diameter of 0.95 m: the brazing temperature, dependent on the chosen brazing alloy, can be up to ~1100 ºC and can be maintained at a pressure of 10^{-6} Torr at 950 ºC. A brazing cycle takes typically several hours[5];
- Electron beam welding: Two EBW machines are available. One has beam energy of 150 kV and a total power of 7.5 kW, with a small vacuum vessel of less than 1 m^3. The largest one has a beam energy of 70 kV and a total power of 70 kW and is more suitable for cavity welding having a vacuum vessel of about 1 m diameter and several meters long, pumped to less than 10^{-4} mbar by means of cryo-pumps. An older EBW machine used for the welding from the inside of the LEP and LHC – type cavities has since been dismantled.
- Degreasing in ultrasonic (US) bath: Several installations exist within the surface treatments workshops, the biggest being ones up to 16 m long by 0.6 m wide and 7 m long by 2 m wide. The available US agitation devices can be easily fitted to tanks of any size.

2.3. Water rinsing stations

Water rinsing under strict quality control is essential to guarantee surfaces free from any chemical and particulate residuals. For niobium sheet metal cavities this requirement must be strictly obeyed to before the cavity is tested at low temperature. Any thermal breakdown (quench) initiating at localized surface defects or any parasitic emission of electrons (electron loading) can thus be avoided. For the Nb/Cu cavities the requirement applies as well, but the cavity surface must in addition be kept free from residuals a second time, namely before coating. Any poor adhesion of the niobium film resulting in a poor removal of the heat and thermal runaway can thus be avoided.

Studies showed that an abundant rinsing with ultra-pure water at low pressure (LPWR) or at a pressure of 100 bar (HPWR[6]) was essential to avoid electron loading. It also turned out to be useful to recover a cavity of poor performance. Quality assurance criteria could be established for, to give an example, the resistivity of the outlet water from the cavity, in order to reliably suppress electron loading. Other parameters of importance were the particle/bacteria content and the TOC[7]. For these reasons the water rinsing stations available at CERN have following features:

- Demineralized water supply (resistivity > 10 MΩ·cm);
- Low pressure ultra-pure (resistivity > 18 MΩ·cm) water rinsing station, kept under protective gas and equipped with particle filters of small pore size and UV light disinfecting equipment;
- High pressure (100 bar) ultra-pure water rinsing stations, with nozzle specifically designed for the individual application, and water flow in excess of 1 m^3/hour;
- Monitoring of resistivity, TOC, and particle/bacteria content of water at inlet and outlet to and from cavity, respectively;
- Housed in clean room (class 1000) for LPWR operations, and in closed cycle for HPWR operations.

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[5] There are other furnaces available at CERN featuring the following parameters: (i) T_{max} = 1400 ºC, 1m high, 0.24 m diameter, 10^{-11} (10^{-7}) Torr ultimate pressure at room (maximum) temperature; (ii) T_{max} = 2000 ºC, 1m high, 0.15 m diameter, 10^{-12} (10^{-7}) Torr ultimate pressure at room (maximum) temperature

[6] LPWR = Low Pressure Water Rinsing; HPWR = High Pressure Water Rinsing

[7] TOC = Total Organic Carbon

2.4. Clean rooms and "grey" assembly areas

As important as rinsing the cavities with ultra-pure water is their dust-free assembly into cryo-modules, and the dust-free assembly of all ancillary parts (couplers, RF probes, flanges), after an appropriate removal of dust particles off the surface. Re-circulating the air through HEPA[8] filters provides dust-free conditions. Any reflux of contaminated air towards the clean room of highest standard from the adjacent "grey" area must be avoided by maintaining an appropriate overpressure at all times. The clean room installations and "grey" assembly areas have the following features:

- Clean room (class 10) in Building SM 18 assembly and test hall, clean room (class 100) in B. 252 assembly hall and in B 118 surface treatment hall, all with a buffer entry zone (class 1000);
- Monitoring of airborne particle content;
- Whenever possible vertical airflow to minimize the contamination of the objects under assembly by particles emitted by the operator's activity;
- On-line monitoring of differential pressure between adjacent clean rooms of different class, particle content, air speed as well as humidity and temperature for reasons of well-being of the operator;
- Work space (class 10000) in Building SM 18 and in B. 252 for LPWR;
- Appropriate access management and control;
- Appropriate operator equipment (clothes, gloves, fog generator, cleaning pistol, etc.).

2.5. Surface preparation (polishing and coatings)

The surface preparation installations have the following features:

- Surface plating workshop: all plating needed prior to brazing can be deposited in-house, on pieces of sizes up to 1 m.
- Chemical polishing (CP) of the surface (SUBU[9]): can be performed either with a fully automatic system that allows performing in sequence the operations of: deoxidizing with sulfamic acid, chemical etching, surface passivation, each step followed by water rinsing, for cavities of sizes up to those corresponding to 200 MHz of frequency (volume >1 m3); or by a manual procedure that can be adapted with ad-hoc fittings to cavities of any size and shape;
- Electro-polishing (EP): equipment has been conceived for the EP of copper 1.3 - 1.5 GHz single cell cavities in vertical position. Detailed numerical simulations prove it to be superior to classical horizontal EP. However equipment for horizontal copper EP is still available.
- Magnetron sputtering: three different installations are available for cavities from 1.5 GHz down to 200 MHz. The sputtering cathode mounting onto the cavity is performed in a class 100 clean room.

2.6. Cryogenics

The main cryogenic plants for cavity and cryo-module testing are housed in Building SM 18. Once the tests of series and spare LHC main magnets will be completed, SM18 will be kept in reduced operation for the needs of the LHC off-line Fast Measurement system (FaMe). This will take approximately half of the liquid helium production of the existing Linde/Sulzer 6 kW refrigerator.

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[8] High Efficiency Particulate Air

[9] SUBU = chemical polishing by 20 μm with solution of sulfamic acid, n-butanol, hydrogen peroxide, and ammonium citrate

The remaining liquid helium production can be used to test in turn, if any, refurbished magnets from the future LHC Magnet Rescue Facility, some other LHC spare components (superconducting links, bare magnets) or LHC repaired RF cavities or cryo-modules.

The major weak points of the cryogenic infrastructure are:

1. lack of helium purification capacity;

2. no central remote control for all the cryogenic subsystems;

3. prohibitive heat loads on the network of lHe transfer lines to the RF test cryostats.

Items 1 and 2 need improvements for LHC operation and maintenance (FaMe requirements). The related consolidations have to be studied, finalized and launched as soon as possible (neither decision nor budget yet). Nevertheless, item 3 is not critical for LHC as far as the testing LHC RF repaired cavities or cryo-modules may only occur exceptionally.

Assuming that the test of refurbished LHC components will eventually remain an ancillary activity, nearly half (typically 12 g/s lHe) of the liquid helium production of the 6 kW refrigerator and the capacity of one of the two existing gaseous helium pumping units (gHe 18g/s @ 30 mbar) will be available for SCRF testing.

These numbers, however, even under the optimistic but unrealistic assumption of negligible losses in the cryogenic transfer lines, correspond to 240 W cooling capacity at 4.5 K. It should be noted that neither the losses in the cryogenic distribution system nor the requirements for cooling down the various test objects are precisely known. This fact enhances the margin of uncertainty in the estimation of available and required cryogenic power.

This would allow the RF testing at 2 K in continuous wave mode of, say, one single accelerating structure of 1 m length at 700 MHz and for a Q-value of $5 \cdot 10^9$, which is marginal. In addition, any recurrent SCRF testing at 2 K in Building SM18 will require the improvement (redesign) of the network of lHe transfer lines to the existing RF test cryostats (item 3). The new system would require actively cooled thermal shields for all lHe headers and vessels, additional heat exchangers and valves, additional headers for gaseous helium pumping and the doubling of the purification capacity for the pumped gaseous helium.

2.7. RF testing at low temperature

2.7.1. Cryogenic equipment

As outlined in the preceding chapter, the fraction of the installed cryogenic power available in Building SM18 in total for the RF tests at low temperature (4.2 – 4.5 K) is about 12 g/s, sufficient to cool by evaporation 240 W of heat dissipation in the cavities or cryo-modules.

The two vertical 4 m deep cryostats available in Building SM18 allow for testing at 4.5 K of cavities up to a useful depth of 3 m and down to frequencies of about 300 MHz. The two shorter vertical cryostats (2.5 m deep) allows for testing at 4.5 K of cavities up to a length of 1.5 m and down to frequencies of about 300 MHz. It also fits the needs of testing singular cavities for R&D or other purposes at 2 K.

The RF testing of the cryo-modules in horizontal position can only be performed at 4.5 K, because the volume and geometrical layout of the lHe reservoir precludes the lowering of the temperature below 4.2 K by pumping.

2.7.2. Temperature mapping

Testing includes the possibility to detect "hot spots" or regions of anomalous temperature increase at the outer cavity surface indicating enhanced RF losses at the cavity inner surface (temperature mapping). This technique allows the identification of the origin of the anomalous losses by optical inspection of the inner surface. It is considered as essential to ensure "a posteriori" quality control to detect hidden flaws that might have occurred during the sequence of the various production steps.

The temperature sensors (e.g. carbon resistors or different ones) are mounted in a distance of about 1 cm from each other on top of a motor-driven arm and slide in steps of a few degrees, in close contact with the cavity surface, azimuthally along its outer surface. They thus provide a signal of the temperature increase near the cavity surface when powered with RF. This "resistor arm" must closely fit to the shape of the individual cavity and should therefore be provided together with the cavity, if temperature mapping should be performed.

Temperature mapping can be performed on the vertical cryostats of both depths by decreasing the temperature of the liquid helium to about 2.2 – 3.5 K by pumping and then again re-pressurizing the lHe bath to atmospheric pressure. This action leaves the lHe in "sub-cooled" state, i.e. in a lower temperature than corresponding to its vapor pressure. It avoids boiling of the helium bath and impedes the heat removal off the hot spots or off the surface regions of anomalously high power dissipation, allowing detecting more easily the resulting temperature increase under RF.

2.7.3. Autonomy for testing at T < 4.2 K (vertical position)

2.7.3.1. In temperature-mapping mode (sub-cooled helium)

However, during this mode the lHe supply is shut off and the lowering of the temperature is obtained by evaporation during pumping of a fraction of the lHe bath (about 40 % of the helium volume remains after pumping down to the lower temperature). This reduces significantly even more the useful length of the cryostat from 3 m to 1.2 m (for the deeper cryostats) and from 1.5 m to 0.6 m (for the shorter cryostats). In addition, the useful temperature range for taking temperature maps is between 2.5 and 3.5 K, thus limiting in time the autonomy for this mode of operation. The autonomy amounts to about to 1.5 hours for the shorter cryostat for a 352 MHz cavity, per 100 W power dissipation. It doubles for the deeper cryostat and so it does for cavities of smaller size (1300 MHz). Evidently a second refilling of lHe is always possible, should the RF test be extended in time.

2.7.3.2. In evaporation cooling mode

The autonomy is also restricted if the cavity is to be tested when cooled by evaporation in lHe at 1.8 K under its saturated vapor pressure (15 mbar)[10]. This is the lowest pressure that the installed pumps can achieve. The corresponding total cooling power for the mass flow of 18 g/s amounts to about 400 W. Also in this mode of operation, the cryostat is shut off from the lHe supply, and the temperature is lowered by evaporation when pumping the lHe bath. At 2.0 K, as already stated before, 40 % of the lHe volume remains. Under these conditions, the lHe level will further drop by 14 cm within one hour when testing a 1300 MHz cavity at 100 W RF dissipation.

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[10] The cryostats V3 and V4 (1.1 m diameter) were upgraded with additional pumps to be able to pump down to 16 mbar.

2.7.4. Duration of RF tests

One whole cycle in the vertical cryostat from assembling the cavity at room temperature, pumping, cool down, RF testing at low temperature including temperature mapping, and for one single filling cycle of lHe, warm-up and disassembling again at room temperature takes about a week as fastest.

One whole cycle of RF test of the horizontally positioned cryo-module in one of the two bunkers, from assembling the cryo-module at room temperature, including the ancillary equipment, pumping, cool down, RF testing at 4.5 K, warm-up to room temperature takes about two weeks as fastest.

2.8. RF test equipment

The RF test equipment is adapted to the needs of vertical and horizontal tests in radiation-shielded bunkers at low and high RF power, including conditioning of the fully equipped cryo-module including power couplers. The equipment available is the following:

- Several solid-state amplifiers at 300 W and bandwidth of 340 – 355 MHz;
- Several solid-state amplifiers at 300 W and bandwidth of 390 – 410 MHz;
- 1 high power klystron at 352 MHz with bandwidth of 2 MHz;
- 1 high power klystron at 400.8 MHz with bandwidth of **2** MHz;
- 2 large band solid-state amplifiers at 100 W between 1 – 2 GHz;
- 1 solid-state amplifier at 300 W and bandwidth 480 to 850 MHz.

2.9. Surface analysis tools for samples including RF tests at low temperature

The surface analysis tools available at CERN that are used for, or are in close relation with, the manufacture of the SC cavities are the following:

- Optical inspection of inner cavity surface;
- Scanning electron microscope coupled with EDX composition analysis;
- X-ray diffractometer fitted with Eulerian cradle;
- XPS chemical surface analysis and Auger composition analysis;
- RF characterization of samples with quadrupole resonator [iv];
- DC or LF SC characterizations (T_c, RRR).

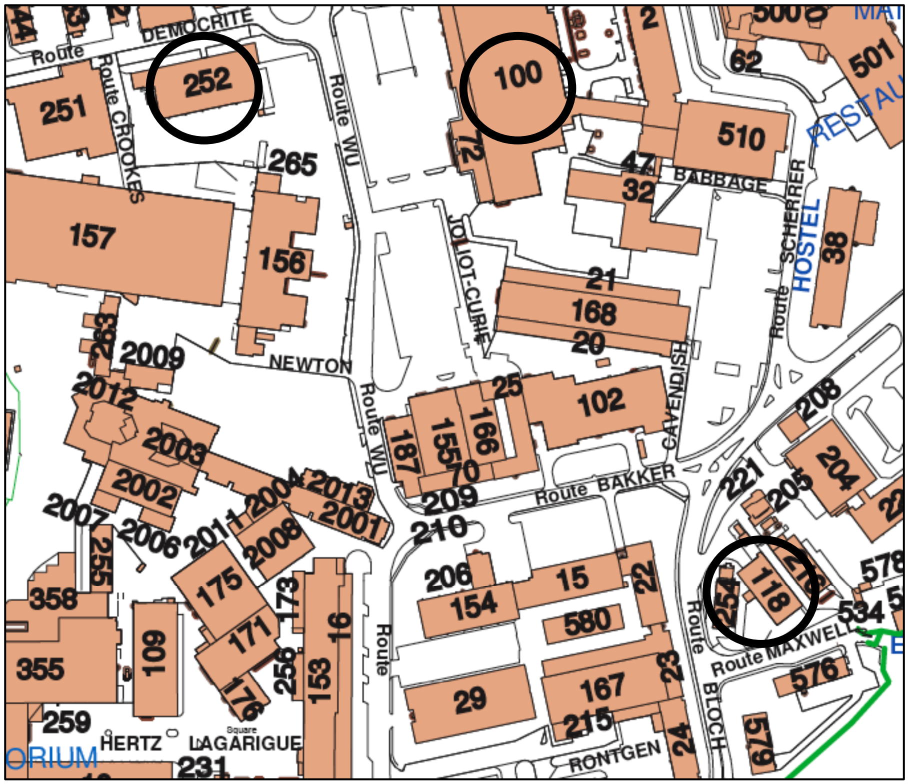
3. PERFORMANCE SPECIFICATION OF AN SCRF INFRASTRUCTURE MADE-UP WITH EXISTING CERN EQUIPMENTS

3.1. Localities

The facilities existing at CERN shall now be assessed by correlation of the main premises of manufacture, processing, assembly and test for the two technologies in use. Only installations will be considered in more detail that allows the industrial handling of genuine accelerating structures.

The principal installations (localisation on CERN site shown in Fig. 1) are housed in the

- CERN central workshop (B. 100);
- Surface treatment hall (B. 118);
- Assembly hall (B. 252);
- Assembly and testing hall (Building SM18) including the bunkers for the vertical tests and the horizontal tests, as well as the clean room for the cryo-module assembly.



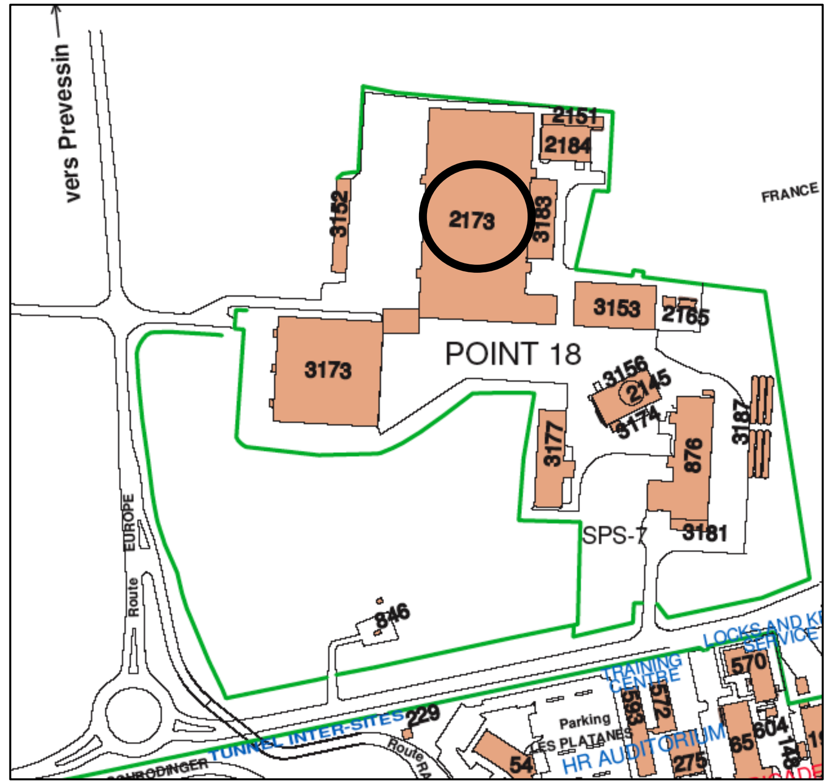


Fig. 1: Geographic localisation of principal installations: buildings 100, 118, 252, 2173 (SM18)

The CERN central workshop as general-purpose facility is not considered as specific for the standard manufacture of industrial-like cavities and, therefore, is not further specified. The same is true for the surface-processing laboratory (B. 101), the surface analysis installations (B. 101), and the Cryo-lab (B. 165), all being typical non-industrial installations. They are, however, essential for any parallel investigations, if necessary, such as R&D that might be needed to identify flaws occurring during the production of cavities.

“Non-industrial” cavities (mono-cell “high frequency” cavities, quadrupole resonator) can be tested in the shorter cryostats (2.5 m depth), which is marginal from the point of autonomy and useful length for “industrial like” accelerating structures.

3.2. Performance specifications

Taking the hypothesis that the cavity will arrive at CERN from the workshop, the performance of the essential equipment needed for processing, testing and assembling into cryo-modules is specified as follows.

3.2.1. B. 118/Surface treatment hall

This hall is essentially equipped to handle with noxious chemicals. The installations concerned with cavity production are (Table 1):

- Chemical polishing installation for “low frequency” Nb/Cu cavities;
- High-pressure ultra-pure water rinsing stations for Nb/Cu and niobium sheet metal cavities in closed cycle operation, including equipment for monitoring the water quality;
- Clean room facility for high pressure water rinsing of small ancillary equipment (RF components).

Table 1: Facilities in B. 118 for SCRF Infrastructure

Installation	Characteristics	
High pressure water rinsing station	Max. pressure [bar]	100
	Resistivity [MΩ·cm]	18
	Particle content [per ml]	< 1000
	Pump capacity [m^3/h]	1.25[11]
	TOC [ppb] (average)	35
	Range of nozzle movement [m]	3
High pressure water rinsing glove box	Max. pressure [bar]	100
(Connected to clean room class 100)	Resistivity [MΩ·cm]	18
	Particle content [per ml]	< 1000
	Pump capacity [m^3/h]	1.25
	TOC [ppb] (average)	35
	Chamber dimensions [m]	~1
Chemical polishing apparatus	Type of polishing solution	SUBU
	Volume of polishing solution [m^3]	1.3
Clean room	Class	100
	Size (L x W) [m x m]	5 x 5
	Class of entry zone	1000
	Size of entry zone (L x W) [m x m]	3 x 3
	Air flow direction	vertical

3.2.2. B. 252/Assembly hall

This hall is essentially equipped to assemble the magnetron-sputtering cathode into the cavity, to perform the sputter coating, to rinse the cavity with ultra-pure water at low pressure, to dry it by alcohol, and to assemble the RF probes for the low power test before being transported to the RF test premises (SM18). The installations concerned with cavity production are (Table 2):

- Ultra-pure water rinsing stations for Nb/Cu and niobium sheet metal cavities, including equipment for monitoring the water quality;
- Niobium sputter coating equipment for “low frequency” cavities;
- Class 100 clean room and “grey” assembly area including equipment for monitoring air quality.

[11] The real mass flow depends on the hole size and the number of nozzles and can drop to 0.4 m^3/h or below

Table 2: Facilities in B. 252 for SCRF Infrastructure

Installation	Characteristics	
Low pressure water rinsing station	Max. pressure [bar]	6
(open rinsing in front of laminar flow class 10000)	Resistivity [MΩ·cm]	18
Clean room	Class	100
	Size (L x W) [m x m]	8 x 5
	Class of entry zone	10000
	Size of entry zone (L x W) [m x m]	4 x 5
	Air flow direction	vertical
"Grey" assembling area	Class	10000
(equipped with low pressure water rinsing and alcohole/IN_2 drying station)	Size (L x W) [m x m]	4 x 4
	Air flow direction	horizontal
Sputter coating equipment	Diameter of cathode [m]	up to 130 mm
	Length of cathode [m]	up to 2.5 m
	Sputtering rate [micron/hour]	From 1.8 (352 MHz) to 6 (1.5 GHz)
	Pumping equipment	UHV with TMP pumping and differentially pumped RGA
	Sputtering discharge pressure (Ar or Kr) [mbar]	~ 10^{-3}
	Minimum pressure range before start of coating [mbar]	~ 10^{-10}

3.2.3. B. SM18/Assembly and testing hall

This hall is essentially equipped to perform the low power RF tests in vertical position of the individual "low frequency" cavities including temperature mapping, assembling in their horizontal vacuum tank, in a class 10 clean room, the individual cavities into cryo-modules, including couplers, RF probes, etc. and to perform the low or high power RF tests, depending on whether the power coupler is mounted or not. The installations concerned with cavity testing are (Table 3):

- Three vertical cryostats of different depth including radiation shield (bunker) for cold low power RF tests with lHe supplied in closed cycle "liquefier mode" [12];
- Temperature mapping system in vertical test cryostats for 2.5 – 3.5 K operation;
- Class 10 clean room for assembly of cryo-module including equipment for monitoring air quality;
- Horizontal radiation shielded testing installation at low or high RF power of cryo-modules (bunker) in "liquefier" mode.

[12] The cold helium gas is warmed up to room temperature before being liquefied again.

Table 3: Facilities in B. SM18 for SCRF Infrastructure

Installation	Characteristics	
Clean room	Class	10
	Size (L x W) [m x m]	15 x 4
	Class of entry zone	1000
	Size of entry zone (L x W) [m x m]	15 x 4
	Air flow direction	vertical
"Grey" assembling area	Class	10000
	Size (L x W) [m x m]	6 x 6
	Air flow direction	vertical
	Circulating air flow [m^3/h]	vertical
Cryogenics	Cooling mode for vertical/horizontal cryostats	Closed loop liquefier operation
	Max. lHe production @ 4.5 K [g/s] with shared utility	32
	Number of pumping units available for SCRF infrastructure	1
	Capacity of pumping unit at 30 mbar [g/s]	18
Vertical cold RF tests	Number of cryostats (corresponding physical/useful depth [m])	2 (4.0 / 3.0)
	Number of cryostats (corresponding physical/useful depth [m])	2 (2.5 / 1.5)
	Inner diameter of cryostats [m]	1.1
	Lowest frequency of (β = 1) cavity under test [MHz]	300
	Cooling capacity of liquefier @ 4.5 K [W]	640
	Cooling capacity of pumping unit @ 2.0 K [W]	400
	Cooling mode for horizontal cryostats	Closed loop liquefier operation
	Autonomy for T-mapping[13] [h]	3
	Volume of lHe [l] (for deeper cryostat)	1500
	"Low frequency" solid state low power RF amplifiers	2
	Frequency range [MHz]	340 - 355
	Output power [W]	300
	"High frequency" solid state low power RF amplifiers	1
	Frequency range [MHz]	1000 - 2000
	Output power [W]	100
	RF large band signal generator	4
	Frequency range	10 kHz – 1.35 GHz
Cryo-module cold tests	Bunker	2
	Length of bunker [m]	15
	1st Klystron	1
	Frequency [MHz]	352 ± 1 MHz
	Output power [MW]	1[14]

[13] for 350 MHz cavity and 100 W RF dissipation and for the useful range for temperature mapping between 2.5 and 3.5 K

Installation	Characteristics	
	2nd Klystron	1
	Frequency [MHz]	400.8 ± 1 MHz
	Output power [MW]	0.3

3.3. Throughput of cavities/cryo-modules

The throughput per month achievable in the existing facility depends on a number of features. One of these is the layout of the cryo-module, in particular the number of individual cavities housed in one cryo-module. It is therefore evident, in order to avoid a limitation of the achievable throughput for the cryo-modules, that the provision of their individual elements (cavities, couplers, tuners, vacuum vessels, etc.) is adapted accordingly.

As a typical example, the throughput per month shall be exemplified for LEP type cryo-modules (Table 4).

It was estimated from the (longest) retention times (or shortest throughput rates per production step), taking into account parallel production lines (last column of Table 4).

The estimation of the retention time for the manufacture of the cavity body in the central workshop is subject to large uncertainties. That is why the total throughput is determined in two ways, one including the manufacture in the central workshop, the other without.

The throughput for niobium sheet metal cavities should be similar, because the electro-polishing step is to be added but the sputtering step is not necessary.

Inspecting Table 4, the (maximum possible) throughput amounts to four cryo-modules per month. This number is determined by the assembly time of about 1 week in the clean room per cryo-module. Provided that the cryo-modules consist of 4 individual cavities (as for LEP2), a smooth matching between the number of cavities passing the vertical tests and their assembly into cryo-modules is achieved, if 16 cavities per month will successfully pass the performance specification in the vertical tests. To achieve this rate, the number of vertical cryostats must be at least four[15].

For cryo-modules with twice this number of individual cavities (as proposed for ILC), in order to keep the same total throughput per month of 4 cryo-modules, the rate of parallel tests in the vertical test cryostats must be increased accordingly to 32.

It should be kept in mind that no contingency is considered throughout the production, except for the margin in performance below specification in the vertical tests of 4 cavities out of 20, and that the cryogenic power available or required is uncertain.

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[14] 1 MW nominal power, but presently 220 kW CW, limited by RF circulator and water cooling system
[15] At present there are three cryostats operational

Table 4: Assessment of CERN facilities: Estimation of maximum throughput (exemplified for Nb/Cu LEP type cryo-modules16)

Sequence of industrial manufacture: Building no./name	Description of activity[17]	Number of parallel production lines	Characteristic duration per production step [days]	Throughput (number of objects per month for 1 production line)	Throughput (number of objects per month for existing number of production lines)
100/CERN central workshop	Manufacture of cavity body	1	> 10	< 2	< 2
118/Surface treatment hall	CP and HPWR	1	1	20	20
252/Assembly hall (mainly used for sputter-coating)	MS, WR, and magnetron assembly	1	3	6	6
SM18/Bunker for vertical tests of cavities	Cold RF tests of large scale cavities at low RF power (solid state amplifier, TM)	4[18]	5	4	16
SM18/Clean room	Assembly of cavities into cryo-module	1	5	4	4
SM18/Bunker for horizontal tests of cryo-modules	Cold RF tests of large scale cavity cryo-modules at high RF power (klystron)	2	5	4	8
TOTAL (including manufacture)		n/a	> 29	< 0.7	< 0.7
TOTAL (without manufacture)		**n/a**	**19**	**4**	**4**

[16] A LEP type cryo-module consists of 4 individual cavities
[17] CP = chemical polishing, MS = magnetron sputtering of niobium, TM = temperature mapping, WR = ultra-pure water rinsing at low pressure, HPWR = high pressure ultra-pure water rinsing at 100 bar
[18] Presently available are 1 vertical cryostat with 2.5 m depth with marginal autonomy, 2 vertical cryostats with 4.5 m depth

3.4. Assessment of CERN facilities with regard to various accelerator applications of superconducting cavities

The standard recipe for the surface treatment of Nb/Cu cavities at "low frequency", as realized at CERN, consists in chemical polishing before sputter-coating its inner surface with niobium. No equipment exists at CERN for electro-polishing an entire cavity at industrial scale, both for the Nb/Cu and for the niobium sheet metal technology.

Though not equipped to comply with the standard recipe for the surface treatment of "high performance" niobium sheet metal cavities, which consists in electro-polishing, CERN, in the past, contributed significantly to its development [v] and has the know-how in house.

The flexibility of the CERN's installation was already proven by a parallel production and test program for LHC Nb/Cu cavities on one hand and 1.3 GHz niobium sheet metal cavities on the other.

Tables 5 and 6 list the principle production steps (rows), as required for Nb/Cu cavities and niobium sheet metal cavities, respectively. They correlate them with the particular application (columns).

Inspecting these tables the following conclusions can be drawn.

1. **Nb/Cu cavities**

   a. e^-/p storage ring (350 - 500 MHz) cavities can be manufactured and tested vertically without restriction in the deep cryostats (4 m depth); they can be horizontally tested as cryo-modules in the bunkers without restrictions;

   b. Quarter-wave resonators for radioactive ion beams can be manufactured in CERN's general-purpose workshops, but for coating, surface processing and testing new equipment must be acquired or existing equipment must be adapted[19];

   c. SPL cavities (700 MHz) and e^--linac cavities (1.3 GHz) can be tested vertically in the deeper cryostats and also – with marginal autonomy at temperatures below 4.5 K – in the shorter cryostats. They cannot be tested horizontally in the bunkers as cryo-modules, because the high power RF equipment is missing and the temperature cannot be lowered to 2.0 K;

   d. Singular cavities for R&D (1.0 - 3.0 GHz) can be produced and tested vertically in the short cryostats (2.5 m depth) without restrictions;

2. **Niobium sheet metal**

   a. RF cavities of whatever application cannot be produced according to the standard

[19] A proposal for developing, building and testing Nb/Cu quarter wave resonators of different shape is in preparation at CERN

recipe, because of the electro-polishing equipment is missing;

b. Quarter-wave resonators for radioactive ion beams can be manufactured in CERN's general-purpose workshops, but for surface processing and testing new equipment must be acquired or existing equipment must be adapted;

c. e^-/p storage ring storage ring (350 - 500 MHz) cavities can be produced (under the restraint a.) and tested vertically in the deep cryostats without restriction; they can be tested horizontally as cryo-modules in the bunkers without restrictions;

d. SPL cavities (700 MHz) and e^--linac cavities (1.3 GHz) can be tested in the deeper cryostats and also – with marginal autonomy at temperatures below 4.5 K – in the shorter cryostats. They cannot be tested horizontally as cryo-module in the bunkers because the high power RF equipment is missing and the temperature cannot be lowered to 2.0 K;

e. Singular cavities for R&D (1.0 - 3.0 GHz) can be produced (under the restraint a.) and tested vertically without restrictions in the short cryostat.

Table 5: Assessment of CERN facilities (for Nb/Cu cavities)

Sequence of industrial manufacture: Building no./name	Description of activity[20]	e-/p storage ring (350 - 500 MHz)	REX-ISOLDE ion beam (100 MHz)	SPL (700 MHz)	e- linac (1.3 GHz)	Singular cavities for R&D (1.0 - 3.0 GHz)
100/CERN central workshop	Manufacture of cavity body	yes	yes	yes	yes	yes
118/Surface treatment hall	CP[21] and HPWR	yes	no	yes	yes	yes
252/Assembly hall	WR, MS, drying and cavity assembly	yes	no	yes	yes	yes
SM18/Bunker for vertical tests of cavities	Cold RF tests at low RF power including TM diagnosis	yes	no	no	no	yes
SM18/Clean room	Cryo-module assembly	yes	no	yes	yes	yes
SM18/Bunker for horizontal tests of cryo-modules	Cold RF tests at high RF power	yes	no	no	no	n/a
TOTAL sequence possible?		**yes**	**no**	**no**	**no**	**yes**

[20] CP = chemical polishing, MS = magnetron sputtering of niobium, TM = temperature mapping, WR = ultra-pure water rinsing at low pressure, HPWR = high pressure ultra-pure water rinsing at 100 bar

[21] CERN does not have available a electro-polishing installation for multi-cell cavities, but only for mono-cell cavities

Table 6: Assessment of CERN facilities (for Nb sheet metal cavities)

Sequence of industrial manufacture: Building no./name	Description of activity[22]	e-/p storage ring (350 - 500 MHz)	REX-ISOLDE ion beam (100 MHz)	SPL (700 MHz)	e- linac (1.3 GHz)	Singular cavities for R&D (3.0 GHz)
100/CERN central workshop	Manufacture of cavity body	yes	yes	yes	yes	yes
118/Surface treatment hall	CP[23] and HPWR	yes	no	yes	yes	yes
Not existing	Electro-polishing	no	no	no	no	no
SM18/Bunker for vertical tests of cavities	Cold RF tests at low RF power including TM diagnosis	yes	no	no	no	yes
SM18/Clean room	Cryo-module assembly	yes	no	yes	yes	n/a
SM18/Bunker for horizontal tests of cryo-modules	Cold RF tests of large scale cavity cryo-modules at high RF power	yes	no	no	no	n/a
TOTAL sequence possible?		**no**	**no**	**no**	**no**	**no**

[22] CP = chemical polishing, MS = magnetron sputtering of niobium, TM = temperature mapping, WR = ultra-pure water rinsing at low pressure, HPWR = high pressure ultra-pure water rinsing at 100 bar
[23] CERN does not have available a electro-polishing installation for niobium sheet metal cavities

4. NECESSARY REFURBISHMENT OR UPGRADE OF THE EXISTING EQUIPMENTS AND M&P RESOURCES

The possible refurbishment or upgrade of the existing equipment should be subdivided into three classes (Table 7).

The first class comprises generic existing equipment that is not or only partially working properly. If not repaired or replaced by other adequate equipment the production and test of cavities as outlined in Table 5 is severely impaired. To this category belong clean rooms, which are no more operational, or control and monitoring equipment for clean rooms or RF test stands, temperature mapping equipment and controls, etc.

To the second class of generic equipment belong items that are needed but missing, or that reduces considerably the performance and capacity of the whole facility. This equipment should also be acquired, modified or replaced as soon as possible. The reduction of the cryogenic losses in the lHe distribution system or the fourth vertical cryostat including cryogenic, RF and its control equipment belong to this class as well as characterization of superconducting materials by DC or RF methods.

The third class of equipment is also generic in the sense that it upgrades the utility of the facility, as required by a particular application. This category includes cryogenic equipment that would allow testing of cryo-modules at 2.0 K, centralized control system that would allow effective use of the cryogenic installation, electro-polishing equipment for niobium sheet metal cavities, RF low and high power equipment for a particular frequency, e.g. for SPL cavities, singular RF cavities for characterization of samples by RF (quadrupole resonator), etc.

All other equipment is very specific for the particular application and should therefore be provided by the user of the facility. A typical example is the diagnostic tools for RF testing (e.g. temperature mapping system).

Table 7 also includes an estimation of the manpower and investment resources for the different items foreseen for refurbishment or upgrade.

Table 7: Equipment for refurbishment or upgrade (M & P costs)

Class	Building	Generic installation	Equipment item	Total investment costs [kCHF]	Manpower for refurbishment or upgrade [man-months][24]	Total costs [kCHF]	Responsible group
1	118	Clean rooms	Clean room for HPWR of couplers, etc.	250	2	276	AB-RF
1	118	Surface preparation	Chemical polishing of LEP/LHC copper cavities	10	1	23	TS-MME
1	118	Surface preparation	EP of 1.3/1.5 GHz copper mono-cell cavities	25	3	64	TS-MME
1	118	Water rinsing stations	Upgrade of monitoring equipment (TOC, particle content)	150	3	189	TS-MME
1	118	Water rinsing stations	Upgrade of HPWR stations for 1300 MHz cavities (nozzle, etc.)	60	3	99	TS-MME
1	252	Clean rooms	Upgrade of monitoring equipment	50	2	76	AB-RF
1	252	Water rinsing stations	Upgrade of monitoring equipment (particle counter, etc.)	100	2	126	AB-RF
1	SM18	Clean rooms	Upgrade of monitoring equipment	50	3	89	AB-RF
1	SM18	RF testing at low temperatures	Temperature mapping equipment (without resistor arm)	100	6	178	AB-RF
1	SM18	RF testing at low temperatures	352/700 MHz test stand controls and cabling (bunker)	200	12	356	AB-RF
1	SM18	RF testing at low temperatures	352/700 MHz test stand controls and cabling (vertical)	100	12	256	AB-RF
1	SM18	RF testing at low temperatures	400 MHz test stand controls and cabling (bunker)	40	3	79	TS-MME

[24] The assumption is made that 1 man-month costs 13 kCHF.

Class	Building	Generic installation	Equipment item	Total investment costs [kCHF]	Manpower for refurbishment or upgrade [man-months][24]	Total costs [kCHF]	Responsible group
1	SM18	RF testing at low temperatures	Water distribution equipment for high power RF equipment	150	6	228	AT-ACR
1	SM18	RF testing at low temperatures	Controls upgrade of the existing power converters	50	3	89	AB-RF
1	SM18	RF testing at low temperatures	Re-cabling and upgrade of control system of three existing vertical cryostats	200	12	356	AB-RF
1	SM18	Water rinsing stations	Upgrade of ultrapure water rinsing stations (revamping of filters, UV, additional de-ionizing)	30	1	43	TS-MME
1	SM18	Water rinsing stations	Upgrade of HPWR stations (cleaning, computer controls)	30	1	43	TS-MME
2	101	Surface analysis tools (DC & RF)	DC characterization of samples (T_c, RRR, …)	200	3	239	TS-MME
2	252	Surface preparation	High peak power magnetron sputtering	160	3	199	TS-MME
2	SM18	Cryogenics	Upgrade of cryogenic installation (counter flow G/L Heat exchangers, JT valves, pumping header, redesign of interface distribution system - cryostats)	1000	12	1156	TS-MME
2	SM18	RF testing at low temperatures	Cabling and refurbishment of 4th vertical cryostat	100	4	152	AT-ACR
2	SM18	RF testing at low temperatures	RF equipment for 4th vertical cryostat	100	4	152	AB-RF
2	SM18	Surface analysis tools (DC & RF)	RF characterization of samples (e.g. quadrupole resonator)	200	2	226	AB-RF
3	118	Surface preparation	Electropolishing apparatus for niobium sheet cavities	200	6	278	TS-MME

Class	Building	Generic installation	Equipment item	Total investment costs [kCHF]	Manpower for refurbishment or upgrade [man-months][24]	Total costs [kCHF]	Responsible group
3	SM18	Cryogenics	Upgrade of cryogenic installation (remote control, including helium pumping and helium purification processes)	1000	24	1312	AT-ACR
3	SM18	RF testing at low temperatures	RF low and high power equipment at 1300 MHz	400	1	413	AB-RF
3	SM18	RF testing at low temperatures	Upgrade beyond 200 kW up to 350 kW of circulator load and water cooling for 352 MHz	100	3	139	AB-RF
3	SM18	RF testing at low temperatures	Pulsed high power equipment at 352, 700 (1 MW) or 1300 MHz	1200	12	1356	AB-RF
			SUM	**6255**	**149**	**8192**	

In conclusion, the refurbishment of "class 1" equipment is needed to comply with the assessments as outlined in Table 5. In particular would it make possible again to produce Nb/Cu e^-/p storage ring cavities (350 - 500 MHz) and allow the rapid start up of production and test or singular cavities.

The refurbishment of "class 2" equipment would again permit the usage of the forth vertical cryostat, in case a more rapid throughput of cavities should be required. Such a step is only expedient if accompanied by an upgrade of the existing lHe distribution network. It would also allow the characterization by DC or RF of superconducting materials for R&D activities.

The acquisition, repair or upgrade of "class 3" equipment must be considered as a first extension of the existing infrastructure to other applications beyond Nb/Cu e^-/p storage ring cavities. It would allow production and test of Nb sheet metal "high frequency cavities", including horizontal tests of cryo-modules, or pulsed high power tests at different frequencies. This "class 3" equipment is still "generic" equipment in the sense of (i) providing service to a broad spectrum of specific applications and (ii) being equipment of stationary nature and difficult to move that should be most reasonably installed in the central infrastructure.

5. OPERATIONAL COSTS

The total operational (Material and Personnel) costs are composed of

- recurrent costs for maintaining the facility operational as base load without any significant project related activities, and
- ad hoc costs related to the specific project that depend on the workload with regard to full capacity of the facility.

The recurrent costs incur by the base load and do not depend on the throughput of cavities for a specific project: operation of cryogenics installations and related electrical power, maintenance of water stations and clean rooms, consumables, etc. (Table 8). They are imputable to CERN's budget.

Table 8: Recurrent operational costs per year of SCRF facility (base load in M & P)

Generic Installation	Cost relevant parameter	Value of cost relevant parameter	Costs per year [kCHF]
Cryogenics	Manpower base operation costs per year		250
	Refrigerator power [kW]	3	
	Costs per kWh electricity [CHF]	0.05	
	Running time per year [h]	8000	
	Total cryo-power warm [kW]	1200	
	Electricity per year		480
	Maintenance material and other consumables		250
	SUM		980
Surface preparation	Maintenance manpower costs per year		50
	Consumables		50
	SUM		100
Clean rooms	Maintenance manpower costs per year		80
	Clean room power demand kW/m^2]	0.1	
	Total area of clean rooms [m^2]	214	
	Total clean room power [kW]	21	
	Running time per year [h]	8000	
	Electricity per year		9
	Consumables		20
	SUM		109
Water rinsing stations	Maintenance manpower costs per year		20
	Consumables		10
	SUM		30
RF testing at low temperatures	Maintenance manpower costs per year		10
	Consumables		10
	SUM		20
Surface analysis tools (DC & RF)	Maintenance manpower costs per year		10
	Consumables		10
	SUM		20
TOTAL SUM			**1259**

The ad hoc project dependent costs depend largely on the requested throughput of the facility and shall be imputed to its user. In Table 9 these costs are estimated, based on the maximum throughput as indicated in Table 4, broken down for the different production steps as indicated there.

It should be noted that the cost evaluation does not include any contingencies, be it by the need to reprocess cavities of poor performance, to keep pace with new technological developments or simply by items still missing.

Table 9: Project related operational costs (for maximum possible throughput)

Sequence of industrial manufacture: Building no./name	Description of activity	Characteristic duration per production step [days]	Throughput (number of objects per month for existing number of production lines)	Consumables per month [kCHF]	Number of operators needed per production step (FTEs)	Costs per month [kCHF]
118/Surface treatment hall	CP and HPWR	1	20	14	2	40
252/Assembly hall (mainly used for sputter-coating)	MS, WR, and magnetron assembly	3	6		2	23
SM18/Bunker for vertical tests of cavities	Cold RF tests of large scale cavities at low RF power (solid state amplifier, TM)	5	16		3	156
SM18/Clean room	Assembly of cavities into cryo-module	5	4		2	26
SM18/Bunker for horizontal tests of cryo-modules	Cold RF tests of large scale cavity cryo-modules at high RF power (klystron)	5	8		3	78
TOTAL		**n/a**	**4**		**n/a**	**323**

6. OUTLOOK

The description of the CERN SCRF infrastructure as provided so far outlines the basic refurbishment needs to obtain the performance as subdivided into three classes (c.f. chapter 5). Any further upgrade, such as high power tests in the second bunker of cryo-modules of 350, 700 or 1300 MHz cavities, would require a major investment into the ancillary infrastructure (cryogenics, test premises, cooling capacity, power converters, …). If needed so, such an upgrade shall be described in a forthcoming document.

7. STAGED APPROACH AND POSSIBLE SCHEDULE

The classification for the refurbishments and possible upgrades as suggested in ch. 5 allow an approach staged in time towards a general purpose SCRF infrastructure within the frame of the available funds, the priority of the various projects, the requirements of the users and the possible setting up of dedicated SCRF infrastructures elsewhere. Apart from the repair capacity possibly needed for LHC cavities and the highly demanding requirements for a SCRF infrastructure dedicated to the ILC, possible and already identified projects are related to the

- LHC upgrade: R&D for the 1.2 GHz bunch shortening system and 160/240 MHz capture system;
- SPL: 700 MHz SCRF cavity R&D and prototyping;
- HIE[25]-ISOLDE: low beta quarter wave structures and components;
- EUROν[26]: RF developments and R&D for SCRF cavities and high power equipment;
- 4th generation light sources: development and test of SCRF cavities, cryo-modules, couplers and tuners.

A staged approach towards a general-purpose infrastructure could be funded according to the classification of Table 7: class 1 in a first and second step (each about 30 % of the total costs), and class 3 in a third step (about 40 %). Such a funding profile would be compatible with a total duration of the project of 4 years.

8. CONCLUSION

In this document a staged approach is presented, based on the SCRF facilities existing at CERN, towards an infrastructure for producing and testing individual SCRF cavities and fully equipped cryo-modules. The first stage comprises the repair or replacement of rotten or obsolete equipment that is needed for the start up of any exploitation for tests of storage ring cavities (LHC) and singular cavities for R&D purposes. Further stages of refurbishment extend the performance of the existing infrastructure towards cavities and cryo-modules for other applications.

[25] HIE = High Intensity and Energy
[26] European accelerator neutrino facility

The costs to execute the staged refurbishments are also provided. A distinction is made between investment costs on one side and operational costs on the other side. The latter are further split into basic costs for maintenance, services, energy, etc., and project related costs that depend on the throughput required.

The cost estimations do comprise neither contingency nor extra costs for retesting of cavities or cryo-modules of poor performance.

REFERENCES

[i] Letter of Intent about a European SC RF Facility of 15 March 2006 sent by Prof. A. Wagner on behalf of the European partners of the TESLA Technology Collaboration and other interested institutions to the CERN Council Strategic Planning Group.

[ii] S. Calatroni, B. Vullierme, J. Tuckmantel, CERN Facilities for Superconducting RF, presented at "Electron Accelerator R&D for the Energy Frontier", Orsay, 2006;

A SCRF Infrastructure for Europe, edited by E. Elsen, N. Walker and L. Lilje, after discussion on the occasion of "Electron Accelerator R&D for the Energy Frontier", Orsay, 2, 06;

S. Calatroni, J. Tuckmantel, B. Vullierme, Note on CERN Facilities for Superconducting RF, https://ab-div.web.cern.ch/ab-div/Info/2006/SCRF_WebSite/index.htm.

[iii] J.-P. Delahaye, Personal conclusions about a European SCRF infrastructure following the meeting held at Milano on 14/09/06.

[iv] E. Mahner et al., Rev. Sci. Instr. **75** (2003) 3390.

[v] L. Lilje et al., Improved Surface Treatment of the Superconducting TESLA Cavities, Nucl. Instr. Meth. A 516 (2004) 213.