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EDMS NO.	REV.	VALIDITY
0000000	**0.0**	**DRAFT**

REFERENCE
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Date : 201x-xx-xx

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Feasibility Study of a Rapid Cycling Synchrotron to replace the PS Booster

ABSTRACT:

This document summarises the outcome of a feasibility study and resource estimate to construct a 2 GeV Rapid Cycling Synchrotron (RCS) to replace the CERN PS Booster.

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HISTORY OF CHANGES

REV. NO.	DATE	PAGES	DESCRIPTIONS OF THE CHANGES
0.0	201x-xx-xx	n	

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1. Introduction [K. Hanke]

1.1 Introduction

Following the feasibility study and cost estimate for an upgrade of the existing PS Booster to a beam energy of 2 GeV [1], the question was raised whether a new machine to replace the Booster would be a viable option. The obvious advantage of such a scenario would be not only to replace a 40 year old machine by a new one, but also to commission the machine off-line before connecting it to the downstream PS and SPS synchrotrons and thus minimising risk and down time.

1.2 Design Choices

A very preliminary suggestion for an RCS lay-out with a suggestion of machine parameters was the outcome of internal discussions and first presented at the Chamonix 2011 workshop [1]. The proposed machine circumference was 1/7 of the PS circumference (89 m), with a three-fold symmetry. A site inside of the PS was suggested, with injection into the PS from the inside. It was suggested that the machine would run at h=3 and fill the PS at h=21 with 6 injections, avoiding the triple splitting in the PS.

Further investigations led us to modifying these initial assumptions. The details are laid out in the following sections. First of all, a circumference of 89 m appeared to leave insufficient space for diagnostics, injection and extraction elements, correction elements, vacuum equipment etc. Therefore a longer variant with 4/21 of the PS circumference was chosen. This would allow operation at h=1 and h=4, where in a first step h=1 is considered the base line while keeping the option of higher harmonics open. The machine would pulse at 10 Hz as originally proposed. The machine parameters are listed in more detail in the following sections.

As for the geometry of the machine a three-fold symmetry appears preferable, with the straight sections assigned to injection, extraction, and accelerating structures. As an alternative solution a race-track and a rectangular geometry were studied...

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   - [Bullet sub-list]
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Figure 1 — [Caption of the figure]

Table 1 — [Caption of the table]

2. Operational Aspects and Performance [K. Hanke, B. Mikulec]

3. RCS Parameters [H. Schönauer, M. Fitterer, C. Carli]

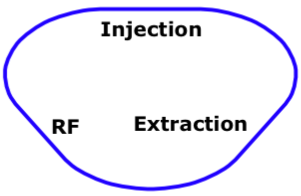
3.1 Technical Description

A variety of options has been considered. In the following we will describe the one option chosen as baseline design. All other options are described in chapter 0.

3.1.1 Lattice Layout

For civil engineering a triangular shaped ring seems to be advantageous and was chosen as baseline layout. As illustrated in Figure 2 injection, extraction and RF are each located in one straight section.

Figure 2 — [Lattice Layout]

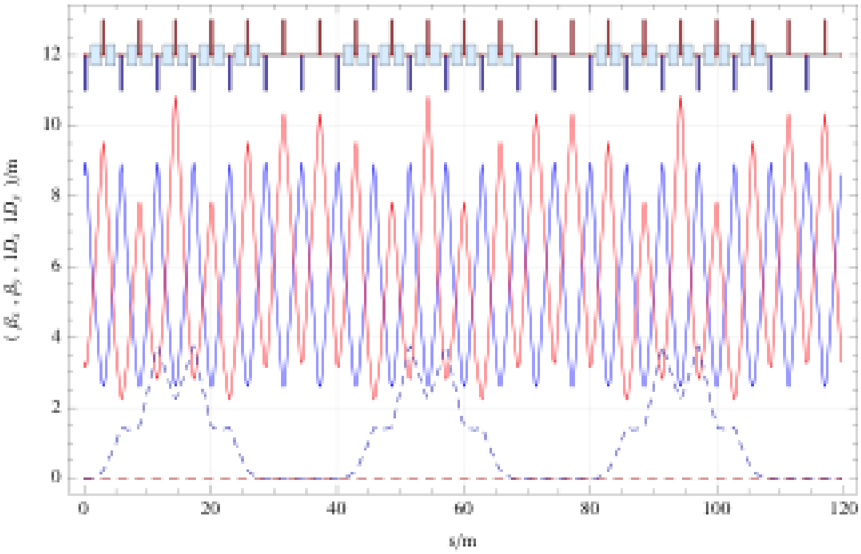


[1] [Foot note]

3.1.2 Optics

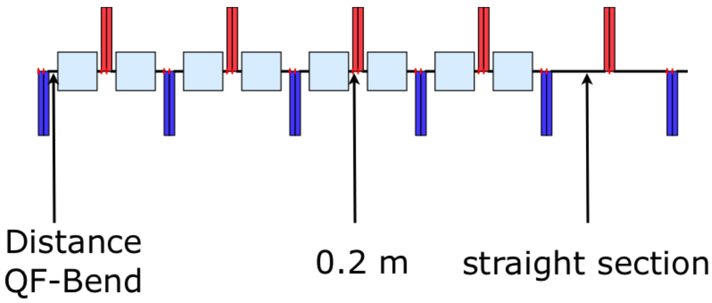
The lattice consists of 21 cells – 5 per arc and 2 per straight section - with a cell length of 5.6993 m. Most advantageous for injection/extraction seem to be a FODO cell structure as here the kick of the QD in the centre of the cell can be exploit (chapter **Error! Reference source not found.**). Alternative cell types are described in chapter **Error! Reference source not found.**. In the baseline version only two quadrupole families are used.
Injection, Extraction as well as RF require dispersion free straight sections. The dispersion is suppressed by choosing a phase advance of 2π per arc. With only two quadrupole families thus one family of QF quadrupoles the dispersion cannot be fully suppressed in the case of working point adjustments, but stays small for small changes. A full suppression could be achieved by introducing one additional family of QF quadrupoles with similar strength located next to the straight section.
The complete lattice with a working point of Q_H= 4.2053 and Q_V= 3.95 optimized for dispersion suppression in the straight sections is shown in **Figure 3**.

Figure 3 — [Optic]



The horizontal/vertical beta function is shown in blue/red, the horizontal/vertical dispersion in dashed blue/dashed red.

Figure 4 — [Space Requirements]



All lattice parameters are listed in Table 2 and the distances indicated in **Figure 4**.

Table 2 — [Design Parameters]

Circumference	119.68 m

Number of cells	21
Number of cells per straight section	2
Length of straight section	4×2.45 m
Distance QF-Bend	0.75 m
Phase advance per cell (hor.)	72.1°
Phase advance per cell (vert.)	67.7°
Q_H	4.2053
Q_V	3.95
Gamma transition	3.64
$\beta_{H,max}$	8.98 m
$\beta_{V, max}$	10.84 m
$D_{x, max}$	3.75 m

3.1.3 Acceptance Estimates

The RCS acceptance estimates are based on the known booster acceptance and were downscaled in order to take the higher injection energy of the RCS into account. As reference for the RCS dipoles, the scrapers in proximity of the booster dipoles were taken [Reference to technical drawing] and for the quadrupoles the vacuum chamber inside the booster quadrupoles [PS-SI-3-49-1063.tiff]. The values are listed in Table 3.

Table 3 — [Booster Aperture]

Half gap height Scrapers (vert.)	29.5 mm
Half gap height Scrapers (hor.)	61 mm
Radius vacuum chamber booster quadrupoles (vert.)	60.5 m
Radius vacuum chamber booster quadrupoles (hor.)	67.5 m

For h=1+2 the maximum momentum spread in the RCS is estimated to be around 0.75%, on which we based the calculation of the horizontal RCS acceptance. The dipole acceptance is listed in Table 4 and the quadrupole acceptance in Table 5.

Table 4 — [RCS Acceptance Dipoles]

Vacuum Chamber	5.5 mm
Half acceptance (vert.)	25.1 mm
Closed orbit distortion (vert.)	3 mm
Total half aperture (vert.)	33.6 mm
Half acceptance (hor.)	54.3 mm
Closed orbit distortion (hor.)	5 mm
Total half aperture (hor.)	64.8 mm

Table 5 — [RCS Acceptance Quadrupoles]

Vacuum Chamber	1.5 mm
Half acceptance (vert.)	33.9 mm
Closed orbit distortion (vert.)	3 mm
Total half aperture (vert.)	38.4 mm

Half acceptance (hor.)	68.1 mm
Closed orbit distortion (hor.)	5 mm
Total half aperture (hor.)	74.6 mm

Most challenging in respect to aperture requirements is the nTOF beam with a horizontal emittance of 15 μm and 9 μm vertical at extraction. The current RCS acceptance correspond to minimum 1.79 σ horiz./1.55 σ vert. for the quadrupoles and 1.69 σ horiz./1.65 σ vert. for the dipoles, which is rather tight.

3.2 Alternative Scenarios

To be written later

4. **Injection and Extraction** [B. Goddard]

4.1 Technical Description

4.2 Budget Estimate

4.3 Time Estimate

5. **Magnets** [A. Newborough]

5.1 Technical Description

5.2 Budget Estimate

5.3 Time Estimate

6. **Power Supplies** [S. Pittet]

6.1 Technical Description

6.2 Budget Estimate

6.3 Time Estimate

7. **RF System** [M. Paoluzzi]

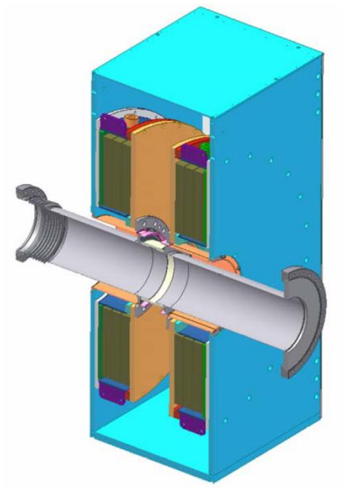
7.1 Technical Description

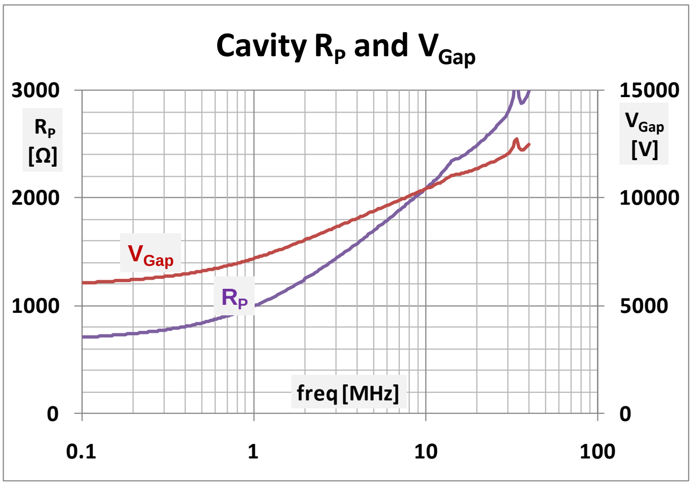
The main RCS parameters, from the RF system point of view, are listed in table X. The wide frequency range, the fast cycling and the limited available space in the straight sections, suggest the use of high-permeability materials and Finemet® is the magnetic alloy of choice because of the high value of its figure of merit, $\mu_p Qf$, which translates into limited losses and high accelerating gradients. In addition, its very low quality factor, *Q*, allows the entire frequency range to be covered without any tuning system which would, at the specified 10 Hz repetition rate, introduce a substantial additional complexity. Moreover, the wideband characteristic enables multi-harmonic operation.

Table X — Main parameters

Parameter	Value
Energy range	160 MeV to 2 GeV
Repetition rate	~10 Hz
RF voltage	60 kV
Revolution Frequency	1.1? MHz to 3.3? MHz
Harmonic numbers	h = 1 to 4
Frequency range	1.?? MHz to 10.?? MHz
Available length	4.5 m ??
Beam intensity	1e13 ppp
Energy increase	~ 3 kJ
Required power	60 kW (acceleration in 50 ms)

The foreseen RF cavity (similar to the LEIR ones) is a coaxial resonator with the accelerating gap in the centre (see Fig. Y-a). Each cavity contains 6 Finemet® rings (OD=670 mm ID=305 mm, T=25 mm), is 0.5 m long and at the proven water cooling capabilities (620 kW/m^3 of Finemet®) the CW gap voltage will span from 7.2 kV at 1 MHz to 10.4 kV at 10MHz (see Fig. Y-b). Limiting the low frequency duty-cycle to ~75 %, a nominal gap voltage of 8 kV can be achieved over the whole band.





a **b**

Figure Y — Cavity structure

The cavity is basically a push-pull device with a very loose coupling between the two cavity halves that imposes a differential drive and thus a push-pull configuration for the final amplifier.

At low frequency, the cavity gap impedance is mainly dependent on the Finemet® characteristics and is strongly affected by the number of cores. At high frequency the response is primarily driven by the system capacitance which mostly depends on the resonator geometry. To achieve the required wideband response the system capacitances have to be compensated and this is achieved including them into a multi-section filter (Fig ZZ).

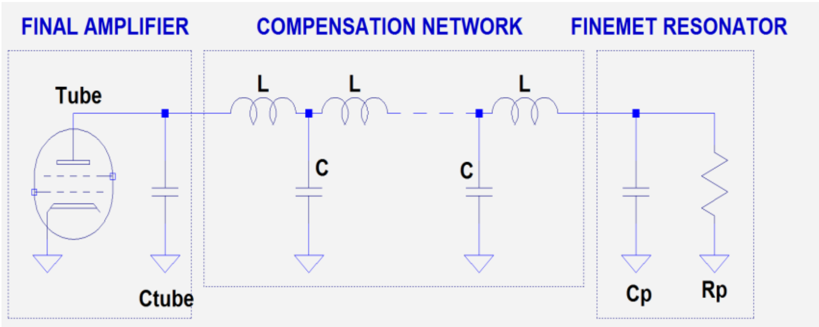


Figure ZZ — System capacitances compensation scheme

As a counterpart some ripples appear in the transfer function and its amplitude, phase and delay behavior are a compromise among the different system components.

Each cavity will be driven by a push-pull final stage built around 80 kW Thales tetrodes type RS1084CJ. This is a water cooled device widely used in the PS complex for which simulation and testing tools are readily available.

System simulations have been carried-out showing that the expected performances can be achieved. Figure Z plots the frequency response and table W lists the RF system parameters.

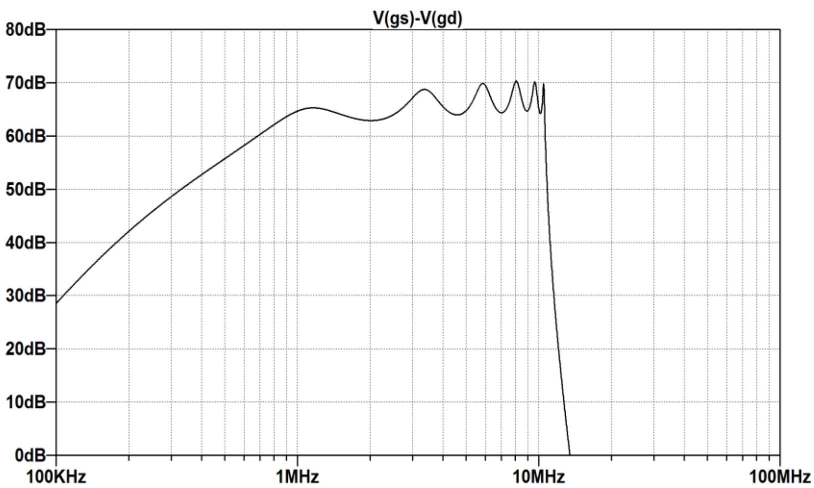


Figure Z — Frequency response

Table W — RF system parameters

Parameter	Value
Cavity Gap Voltage	8 kV
Frequency range	1.0 to 10.0 MHz
Cavity power	26 kW
Cavity length	0.5 m
HV supply voltage	8 kV
HV supply current	~20 A
Plate power dissipation	55 kW
Driving power	250W
Repetition rate	~10 Hz
Number of cavities	8

The circuit configuration selected to cover the wide frequency range does not allow the implementation of a fast RF feedback loop for beam loading compensation. Nevertheless alternatives exist such as the feed-forward scheme schetched in fig. ZZZ and successfully used in J-PARC[2]. The concept has proved its ability of reducing the beam induced voltages by more than 20 dB.

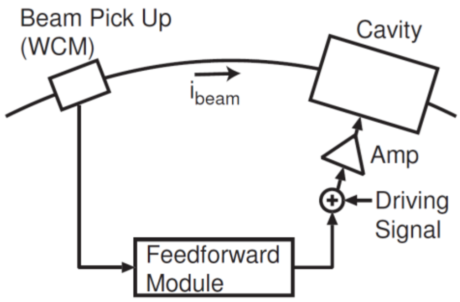


Figure ZZZ — Feed forward beam loading compensation.

(Courtesy Dr. F. Tamura, J-PARC)

7.2 Budget Estimate

The cost of the complete RF system composed of 8 cavities and amplifiers, power supplies, spares, ancillary equipment and a test stand has been estimated to approximately kCHF 13,000.

[2] Fumihiko Tamura, J-PARC RF group, private communications.

7.3 Time Estimate

Provided a Finemet® FT3L production facility is made available for the required ring size (presently the only possibility is in J-PARC), 2 years are required for the prototype design, development and testing. Two additional years are needed for the final production and installation.

8. Beam Intercepting Devices [O. Aberle]

8.1 Technical Description

8.2 Budget Estimate

8.3 Time Estimate

9. Beam Instrumentation [J. Tan]

9.1 Technical Description

9.2 Budget Estimate

9.3 Time Estimate

10. Civil Engineering [L.A. Lopez-Hernandez]

10.1 Technical Description

The civil engineering to be carried out is at the CERN site of Meyrin and consists of one tunnel (approx 127 m long), situated 13m below finished ground level, and one surface building (approx 54 m long by 32 m wide).

Several concrete ducts will connect the tunnel and the building and a concrete structure will provide access for personnel and equipment at the tunnel by means of a lift shaft and stairwell.

The existing tunnel Linac4 will be modified to allow for connection of the new RCS tunnel.

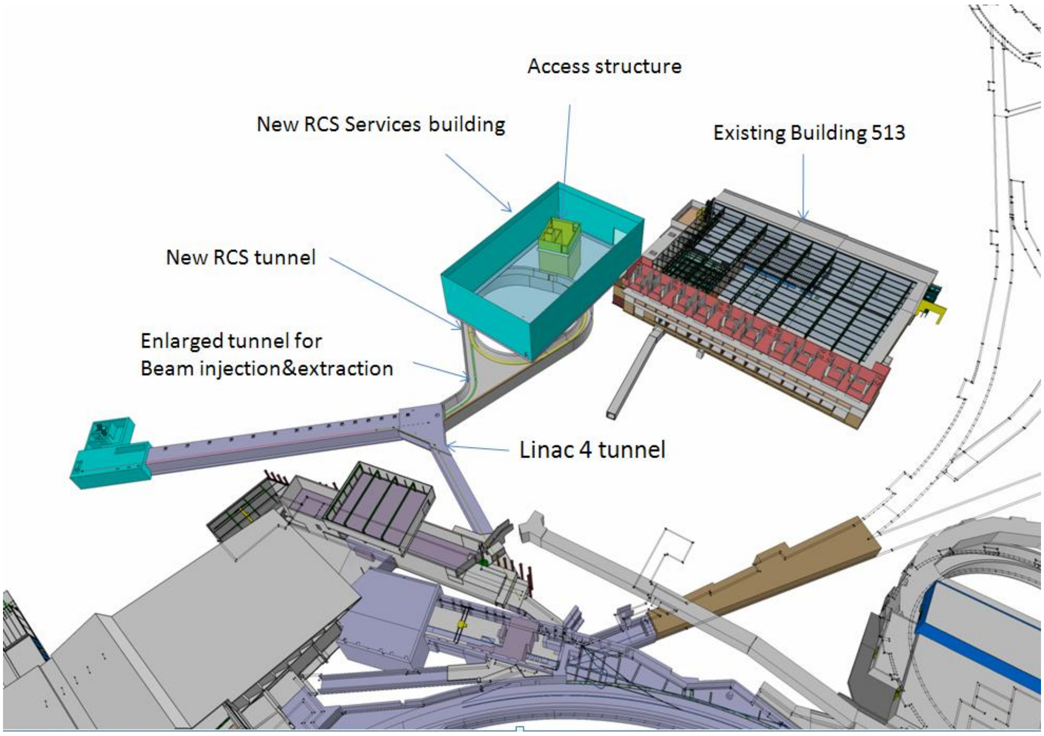


Figure 1 – RCS design May 2011

10.1.1 Description of the site and geotechnical aspects

The RCS site is located in the CERN site of Meyrin, on French territory, between building 513 and the Rutherford road.

The work area site covers the southern area of the parking building 513 but it also crosses the road Rutherford and part of the road Feynman.

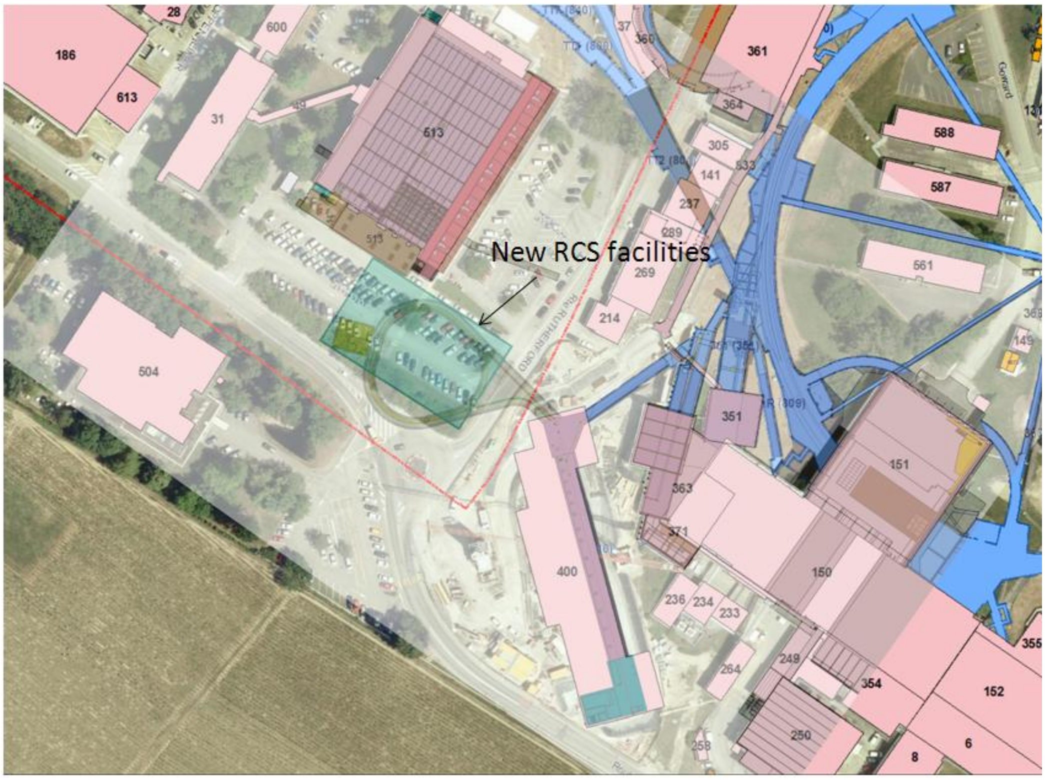


Figure 2 - RCS location

The ground through which and in which the underground structures will be excavated consists of a relatively thin superficial deposit of glacial moraine above a mixed sequence of molasse.

The molasse consists of irregular, sub-horizontally bedded tenses of rock with lateral and vertical variations from very hard and soft sandstones, to weak marl. Significant property variations occur between and within each gradational lens, making it difficult to assign parameters which are truly representative of the rock mass. It is possible that certain contaminants such as hydrocarbons could be found within the molasse which are to be selectively loaded and disposed in a certified dump.

Several networks are present on the site. These networks will have to be diverted before the start of the works.

10.1.2 Description of the underground structures

10.1.2.1 Introduction

The structures designed from a CE point of view are listed below. Each structure has a description, function and particular specification. All structures must have a design life of fifty years.

All underground structures will be provided with an inner lining of concrete and be totally free from all visible signs of water ingress either from joints, cracks or elsewhere.

It is foreseen to carry out the excavation works using piled walls anchored with prestressed anchor bolts and supported on the molasse. The excavation for each pile shall be made by drilling through the soils and into rock. After the piles have been installed, the earth is excavated along the piles wall and protected by means of projected shotcrete.

Instrumentation and monitoring of excavations and of the existing structures, particularly the buildings 513 (Computer center) and 400 (Linac 4) are key elements of the construction process.

The possibility to carry out this work using underground methods has yet to be evaluated. Indeed, while being very costly in view of the lengths of structures and their depth, this option would allow to preserve the existing networks and it significantly reduce the nuisance to the Meyrin site such as the deviation of roads Rutherford and Feynman.

10.1.2.2 RCS Tunnel

The function of this tunnel is to house the RCS machine.

The RCS tunnel is envisaged to be approximately 120 m long and have internal dimensions of 3.00 m width and 3.50 m height. It will be situated 13 m below finished ground level.

The tunnel is connected with the surface via one access structure, and with the Linac 4, via an enlarged tunnel approximately 40 m long, containing the transfer lines for the injection and extraction of the beam.

10.1.2.3 Enlarged tunnel for beam injection and extraction

The purpose of this tunnel is to transfer the H– ion beam from the Linac4 to the RCS and from the RCS to the PS.

This tunnel is envisaged to be approximately 40 m long and have internal dimensions of 3.5 m height and between 6.0m and 20m width. It will be horizontal and situated 13 m below finished ground level.

This tunnel will connect into the Linac4 tunnel and will pass under the existing building 400 which will have to be suspended above the open excavation and remain operational.

10.1.2.4 RCS access structure

The function of the RCS access structure is to provide an access for personnel, equipment and services into the RCS tunnel.

The RCS access structure will house a lift shaft and a stair well.

10.1.2.5 Modifications to existing Linac4 tunnel

The concrete wall of Linac4 tunnel will be partially demolished for the connexion of the injection/extraction tunnel.

10.1.3 Description of the surface structures

10.1.3.1 Introduction

There is one surface structure associated with this project. This building will be similar to existing CERN buildings, i.e. steel frame with cladding.

10.1.3.2 RCS building

The function of this building is to house the equipment, the racks and services needed for the RCS operation.

It will be a steel frame with cladding and have the dimensions shown on the drawings. The building will be equipped with a 10 t capacity gantry crane.

10.1.3.3 Car parks, roads and services

Car parking, roads, surface water drainage and landscaping of the area around the new Klystrons building will be part of the civil engineering works for this project.

10.1.3.4 Architectural Building work and finishes

The amount of building and finishing Works is minimal, consistent with industrial type structures. Internal architectural building and finishing works will include:

-Concrete block partition walls with rendering and gypsum plaster

-Doors and windows

-Sanitary ware and waste water disposal

-Supply of potable water

-Fire doors, industrial doors and access doors

-Stairs, walkways, balustrades and footbridges

-Rainwater gutters

NOT INCLUDED IN THE SCOPE

-Cooling and ventilation

-Electrical infrastructure

-Handling and lifting equipment

-Access control, safety and interlock systems

-Mechanical features

10.2 Budget Estimate

10.2.1 Budget estimate

	Cost (kCHF) (estimate may 2011)
Civil engineering studies	
Main CE works	
Minor CE works	
Site supervision	
Finishing works/contingency	
TOTAL	

10.2.2 Spending profile

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
KCHF						

10.2.3 Manpower estimate

In FTEy	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Eng.						
Tech.						

10.3 Time Estimate

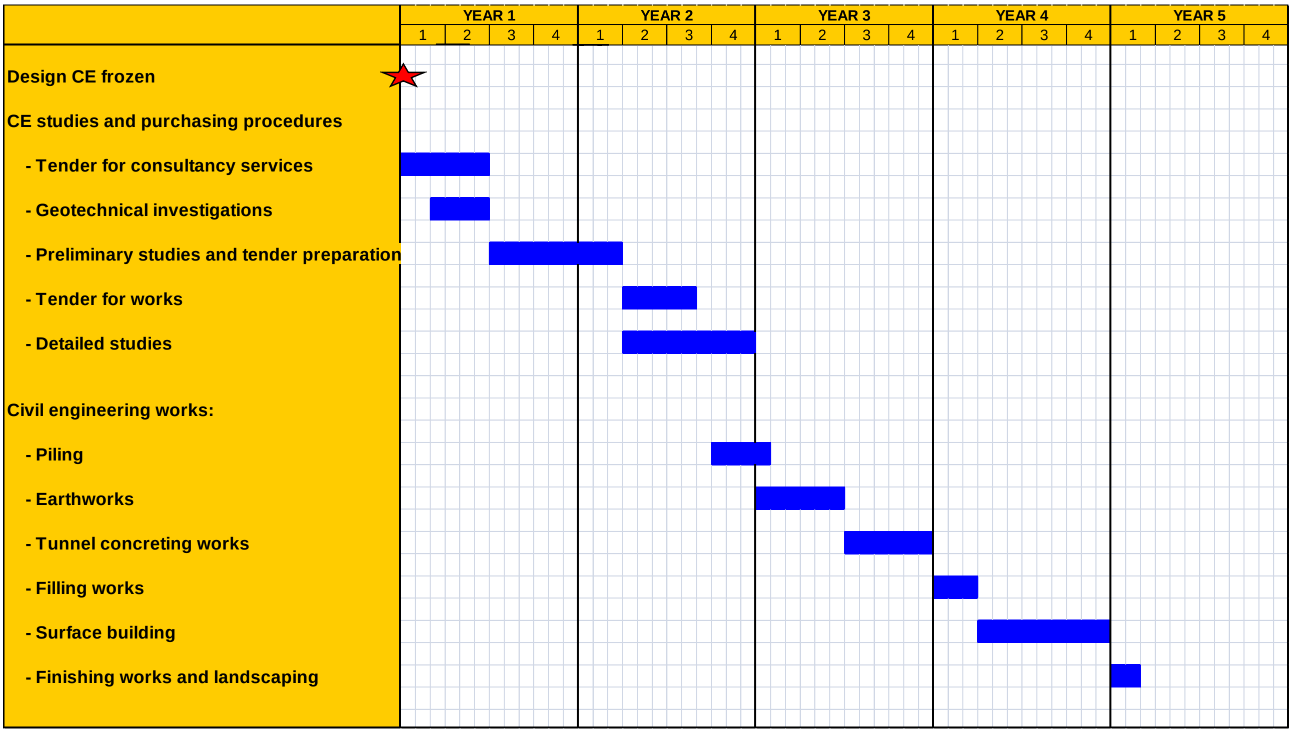


Figure 2.- Preliminary works schedule

11. **Transfer Line** [K. Hanke, M. Widorski, L.A. Lopez-Hernandez]

11.1 Technical Description

11.2 Budget Estimate

11.3 Time Estimate

12. **Cooling and Ventilation** [M. Nonis]

12.1 Technical Description

12.2 Budget Estimate

12.3 Time Estimate

13. **Transport Systems** [I. Ruehl]

13.1 Technical Description

The installation of a lift with 2t capacity will allow the transfer of people and goods from the surface to the accelerator zone. The lift access will have to form an integral part of the interlock system.

The surface building will be equipped with a double girder Electrical Overhead Travelling (EOT) crane of 20t capacity.

The accelerator zone will be equipped with three 10t capacity EOT cranes of which two can be coupled to lift loads of up to 20t.

The floor transport equipment in the accelerator zone will be a standard electrical tractor with a pulling force of 20t. A set of trailers with capacities ranging from 1t to 20t will be required to transport the miscellaneous machine components. No guiding system required provided that there is enough clearance available. This requires detailed integration studies and a sufficiently reserved big transport zone.

13.2 Budget Estimate

1 Lift	2t capacity	interlocked	200kCHF (depending on floor levels)
1 EOT crane	20t capacity	double girder	200kCHF (depending on span)
3 EOT cranes	10t capacity	single/double girder	300kCHF (depending on span)
1 Tractor	20t capacity	battery vehicle	60kCHF
Set of trailers 1-20t			80kCHF
Auxiliary handling equipment			50kCHF
TOTAL cost estimate			890kCHF

Please note that the estimated costs for the installation of the four EOT cranes do not include the crane rails. These are normally provided via the civil engineering works.

13.3 Time Estimate

Installation and commissioning of 2t lift	3 months
Installation and commissioning of 20t EOT crane	1 month
Installation and commissioning of three 10t EOT cranes	1.5 month

14. Radiological Protection [M. Widorski]

14.1 Technical Description

14.2 Budget Estimate

14.3 Time Estimate

15. Budget Summary [K. Hanke]

15.1 [LEVEL 2 TITLE]

system	**cost estimate [kCHF]**	**time estimate**
RF Systems	13,000	2y development 2y production/installation

16. Planning Summary [K. Hanke]

16.1 [LEVEL 2 TITLE]

17. References

[1] K. Hanke et al, PS Booster Energy Upgrade Feasibility Study - First Report, https://edms.cern.ch/document/1082646/3
[2] C. Carli et al, Alternative / complementary possibilities, Chamonix 2011 LHC Performance Workshop, Session 9, http://indico.cern.ch/conferenceOtherViews.py?view=standard&confId=103957
[3] xx