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Feasibility Study

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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1. Introduction and Scope of the Document [K. Hanke]

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, thus minimising risk and down time.

A very preliminary RCS layout with a suggestion of machine parameters was first presented at the Chamonix 2011 workshop [2]. 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 proposed, 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 for the LHC 25 ns beam, thus 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 baseline while keeping the option of higher harmonics open. The proposed site inside the PS ring was found to be not a viable option, which is why a site downstream of Linac4 was chosen. 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.

This document is a first feasibility study. We have found no show stoppers and conclude that the machine described in this document can be constructed and commissioned within 6-7 years from project approval. The cost figures given in this report are a best guess and would require a more detailed study to be confirmed. For the moment we have to assume an uncertainty of +20 % on these figures, where the cost is likely to increase and excluded to be below the figures given. Manpower resources have not been detailed either, and are bound to be a limiting factor for the groups involved.

In case this study is to be continued, we would require about one year to do a detailed study and to edit a design report before the real construction work can start.

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

2.1 Technical Description

The RCS will have to deliver the full variety of beams currently available from the PSB. Current beam parameters are summarised in tables 2.1 and 2.2. With Linac4 H$^-$ charge-exchange injection, extraction energy of 2 GeV, 10 Hz operation and Finemet cavities, beam production schemes will have to be completely revised and optimized for the downstream PS machine.

Table 2.1 — Main beam parameters of LHC-type beams currently provided by the PSB.

user/beam	h at extr.	PSB rings used	Protons per PSB bunch [E12]	rms ε* at extr. [mm mrad]	bunch length at extr. [ns]	matched area [eVs]
LHC25ns DB	1	1-4 and 3+4 (DB transfer)	1.65 and smaller (up to x10)	hor.: ≤2.5 vert.: ≤2.5	180	1.2
LHC50ns DB	1	1-4 and 3+4 (DB transfer)	0.85	hor.: ≤1.6 vert.: ≤1.2	180	1.2
LHC50ns SB	2+1	2-4	0.85	hor.: ≤2.4 vert.: ≤2.2	135	0.9
LHC75ns SB	2+1	2-4	<0.55	hor.: ≤1.6 vert.: ≤1.4	135	0.9
LHC150ns SB	2+1	2-4	0.27	hor.: ≤1.3 vert.: ≤1.1	100	0.6
LHCPILOT	1	3	0.005	hor.: 2.5 vert.: 2.5	85	0.3
LHCPROBE	1	3	0.005-0.023	hor.: ≤1 vert.: ≤1	75	<0.25
LHCINDIV	1	1-4	0.023-0.135	hor.: ≤2.5 vert.: ≤2.5	80-85	0.3

Table 1.2 — Main beam parameters of fixed-target physics beams currently provided by the PSB.

user	h at extr.	PSB rings used	protons per PSB bunch [E12]	rms ε* at extr. [mm mrad]	bunch length at extr. [ns]	matched area [eVs]
CNGS	2	1-4	up to 4.5	hor.: ~12 vert.: ~8 ~12/7 (MTE)	180	1.6
SFTPRO	2	1-4	up to 3	hor.: ~6-8 vert.: ~5-6 ~12/7 (MTE)	180	1.55
AD	1	1-4	<4.5	hor.: ~8	190	1.8

				vert.: ~6		
TOF	1	1-4	<9	hor.: ~10 vert.: ~10	230	2.3
EASTA/B/C	1	3 (+2)	~0.1-0.5	hor.: ~3 vert.: ~1	~160	~1.15
NORMGPS NORMHRS	1	1-4	up to <10	hor.: ≤15 vert.: ≤9	<250	2.3
STAGISO	1	2-4	<3.5	hor.: <8 vert.: <4	230	<1.6

While in the scope of this feasibility study we did not look into detailed beam production schemes, and we have reduced our analysis to some general considerations based on the availability of large frequency band Finemet cavities (see Chapter “RF Systems”) to provide harmonics h1 up to h4. The limit in bunch intensity per Linac4 shot is assumed to be 1E13 ppp at 10 Hz cycling rate. Beam production schemes and magnetic cycles used in the PS have been considered for this preliminary analysis.

Future detailed studies need to address how to achieve transverse emittance requirements (for example for the PS multi-turn extraction beams) and large longitudinal emittances (multiple splitting in the PS for certain beams). A mechanism to allow longitudinal blow-up will need to be an integral part of the RCS. Feedback from the PS will be essential to agree on production schemes for all beams and to foresee all necessary tools.

In general it should not be a problem to provide the PS and all the users with the requested beam intensity, but the main issue is the time needed for multiple injections into the PS ((n-1)*100 ms). This means that the injection plateau in the PS would need to be stretched for certain multi-bunch beams. This leads to the strong request that the rigid structure of the 1.2 s basic period should be adapted to a flexible basic period length to maximize proton delivery to the experiments. Single-bunch beams could be based on shorter cycles, and for certain multi-bunch beams (SFTPRO, CNGS, neutrino beam) the cycle length could be slightly longer than 1.2 s, but still much shorter than the otherwise required 2.4 s (see next paragraph).

2.1.1 Production of non-LHC beams

A prolongation of the PS injection plateau would be possible for the cycles of EAST (24 GeV/c) and AD beams (26 GeV/c), as some time is still available at the end of the cycle. For AD, 4 RCS cycles (h1) need to be injected, leading to a total injection time of ~300 ms.

The TOF cycle ramps up to 20 GeV/c, and with the new POPS PS main power supply it will be possible to obtain a flat top of only 200 ms. Therefore the required time should be available for the TOF beam (injection of 1 RCS bunch).

With the current 1.2 s basic period (BP) and an underlying h=1 harmonics at extraction of the RCS, it would on the other hand not be possible to produce SFTPRO, CNGS and a potential neutrino beam (combined with a TOF cycle) within one BP (8/9 injections from the RCS), even taking into account possible improvements of the magnetic cycle with POPS. Therefore it is under study if an h=2 production scheme in the RCS (plus an h=4 component at injection) could be a solution (5 injections into h=10 in the PS for SFTPRO, CNGS and the neutrino beam). It has to be checked if there would be enough acceptance available at RCS injection. That implies using simultaneously h=1 and h=2 at RCS extraction to provide the required bunch distance of 1/10 of the PS circumference, or accepting a bad phasing in the PS by +/-5 ns for an RF period of ~220 ns. In this context it has also to be confirmed that the degradation in beam quality would be acceptable for the users (ripple for North Area).

For ISOLDE beams, the intensity could be provided/exceeded and the number of RCS injections optimized, but the spill would have a different time structure (100 ms delay between the RCS pulses compared to the current ~700 ns - ~20 μs for one PSB ISOLDE cycle from 4 rings). This should be addressed in target simulations for HIE-ISOLDE.

2.1.2 Production of LHC-type beams

For the production of the LHC 25ns double batch beam 6 injections at h=2 are required to fill 12 PS buckets out of 14, yielding a total duration of 500 ms. Another scheme injecting into h=9 in the PS might also work within 2 BP and an optimized magnetic cycle related to the full exploitation of POPS. Please refer to the presentation of C. Carli at Chamonix 2011.

2.1.3 Proton delivery with the RCS

In order to study the gain or loss to individual experiments with an RCS replacing the PSB, it has to first clarified if it will be possible to have basic periods of variable length in the PS complex and the SPS. If positive, one can expect a gain for the experiments, which yet has to be quantified. It would become more stringent on the other hand for the composition of the supercycle, as the SPS cycle would have to be based on multiple PS complex basic periods, and the RCS and PS users would have to be added in the most efficient way based on their own cycle length.

In case the BP length would stay fixed at 1.2 s and h=2 beam production in the RCS would turn out to be feasible, there should be no loss in proton delivery to the individual end users compared to the current situation. HIE-ISOLDE might profit most from an increased proton flux.

A detailed study of the overall proton delivery efficiency has still to be conducted with the above-mentioned information as input and considering the individual magnet cycle requirements in the PS with POPS.

2.2 Budget Estimate

We tentatively allocate a budget of 50 kCHF for commissioning and operation issues as it was done for the Booster upgrade study. This will cover urgent hardware interventions (e.g. cabling, measurement hardware etc.) and potential subsistence for information exchange between personnel from CERN and from existing RCS facilities.

2.3 Time Estimate

The commissioning of the Linac4-RCS complex can be done in parallel with operation of the Linac2-PSB complex. The commissioning time is estimated to be 6 months. Once work starts on the RCS-PS and RCS-ISOLDE transfer lines and PS injection, all operation of the LHC injector chain must be stopped. The complete refurbishment of the transfer lines and the dismantling of parts of the Booster injection/extraction region means that there is no easy way back, but the risk is low due to prior commissioning of the RCS with Linac4. Once the transfer line to the PS and the new PS injection will be installed, we estimate 3 months for transfer line commissioning and re-commissioning of the PS with the RCS.

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

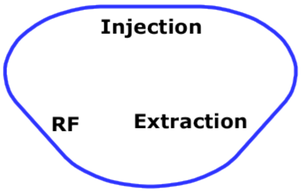
3.1 Technical Description

In the following we will describe the lattice option chosen as baseline design. Other designs have been studied [3], but will not be described in this report.

3.1.1 Lattice Layout

For civil engineering a triangular shaped ring is most advantageous and was chosen as baseline layout. As illustrated in Figure 1 injection, extraction and RF are each located in one straight section.

Figure 3.1 — Lattice Layout



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 space-saving for injection/extraction is a FODO cell structure as here the kick of one of the QDs in the straight sections can be exploited (chapter 4). In this lattice only two quadrupole families are used, one QF and one QD. Possible improvements, like the reduction of the vertical beta function and horizontal dispersion and more flexibility for the adjustment of the working point, are expected with more quadrupole families.

Injection, extraction as well as the RF system require dispersion free straight sections. The dispersion is suppressed by a phase advance of 2π per arc. Thus with only one QF family 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 powering the quadrupoles next to the straight section individually.

Figure 3.2 — Optics functions around the lattice: The horizontal/vertical beta function is shown in blue/red, the horizontal/vertical dispersion in dashed blue/dashed red.

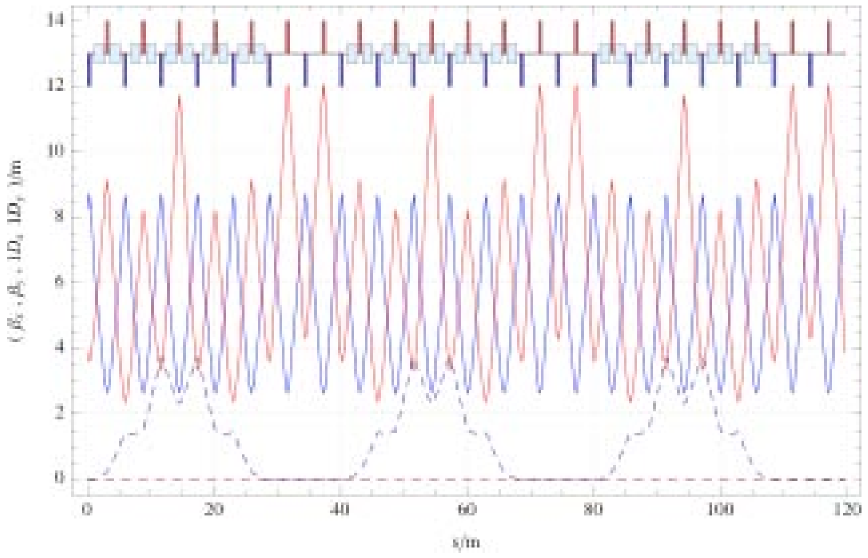
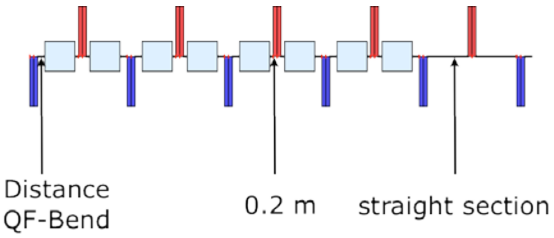


Figure 3.3 — Space Requirements



The complete lattice with a working point of Q_H= 4.205 and Q_V= 3.572 is shown in Figure 3.2. The horizontal tune of 4.205 is optimized for dispersion suppression in the straight sections. All lattice and optics parameters are listed in Table 3.1 and the distances indicated in Figure 3.3. The distance between (magnetic) ends of the QFs (blue in Figures 3.2 and 3.3) and bending magnets is 0.65 m, which leaves about 55 cm for equipment such as steerers, bumpers or instrumentation. The distance between (magnetic) ends of QD quadrupoles (red in Figures 3.2 and 3.3) and bending magnets of 0.20 m is the result of an optimization to reduce the dispersion in the arcs with as high as possible fractional horizontal tune and is just sufficient for magnet ends, but does not allow installation of additional equipment.

Table 3.1 — Design parameters

Circumference	119.68 m
Number of cells	21
Number of cells per straight section	2
Length of straight section	4×2.35 m
Distance QF-Bend	0.65 m
Phase advance per cell (hor.)	72.1°
Phase advance per cell (vert.)	61.2°
Q_H	4.20505
Q_V	3.57156
Gamma transition	3.60
$\beta_{H,max}$	8.73 m
$\beta_{V,\ max}$	12.06 m
$D_{x,\ max}$	3.73 m

3.1.3 Acceptance and Aperture Estimates

The RCS acceptance estimates are based on the known booster aperture and were downscaled in order to take the higher injection energy of the RCS into account. With this approach there is no acceptance margin facilitating the design of a collimation system.

As reference for the RCS dipoles, the scrapers in proximity of the Booster dipoles were taken and for the quadrupoles the vacuum chamber inside the Booster quadrupoles. The values are listed in Table 3.2.

Table 3.2 — Booster aperture

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

For h=1+2 the maximum momentum spread in the RCS is estimated to be around 0.75% (chapter 3.1.4), on which we based the calculation of the horizontal RCS acceptance. The dipole acceptance is listed in Table 3.3 and the quadrupole acceptance in Table 3.4.

Table 3.3 — RCS Acceptance Dipoles

Vacuum Chamber	5.5 mm
Half acceptance (vert.)	26.0 mm
Closed orbit distortion (vert.)	3 mm
Total half aperture (vert.)	34.5 mm
Half acceptance (hor.)	54.8 mm
Closed orbit distortion (hor.)	5 mm
Total half aperture (hor.)	65.3 mm

Table 3.4 — RCS Acceptance Quadrupoles

Vacuum Chamber	1.5 mm
Half acceptance (vert.)	35.7 mm
Closed orbit distortion (vert.)	3 mm
Total half aperture (vert.)	40.2 mm
Half acceptance (hor.)	67.3 mm
Closed orbit distortion (hor.)	5 mm
Total half aperture (hor.)	73.8 mm

Most challenging in respect to aperture requirements is the ISOLDE beam with a horizontal normalized emittance of 15 µm and 9 µm vertical at extraction. The beam size at injection assuming no additional blow up and a parabolic energy distribution (chapter 3.1.4) is given by:

$$\sigma_x = \sqrt{\beta_x \varepsilon_x + D_x^2 \sigma_E^2 / 5}$$

The RCS acceptance is given by the aperture minus the closed orbit distortion and vacuum chamber as listed in Table 5. The quadrupoles are built symmetrically and therefore the larger acceptance of 67.3 mm was taken for both planes. These values correspond to 3.49 σ horiz./5.04 σ vert. for the quadrupoles and 3.32 σ horiz./2.10 σ vert. for the dipoles.

3.1.4 Longitudinal Issues:

The RCS is confronted with conflicting requirements between injection and extraction. The main issue is the longitudinal emittance of the h=1 bunches.

- At 2 GeV: The PS requests bunches of 2 eVs for the LHC beams and of even larger emittance for TOF and CNGS beams. There are several options to overcome this difficulty: A fast emittance blow-up by an additional rf cavity in the VHF range. It applies phase modulation jumping between different higher harmonics of the basic rf system. The degree of blow-up achievable this way has to be studied by simulation and/or machine experiments with the new digital beam control system in the PSB.

- At injection: The technique of longitudinal painting with Linac4 foresees linear energy sweeps between ±1.2 MeV within 20 μs. This corresponds to a rectangular 'bunch' of 1.84 eVs; but a reasonably filled (painted!) h=1+2 bucket of this height can hold about only 1.2 eVs. A matched 2 eVs bunch has a height of about ±2 MeV.

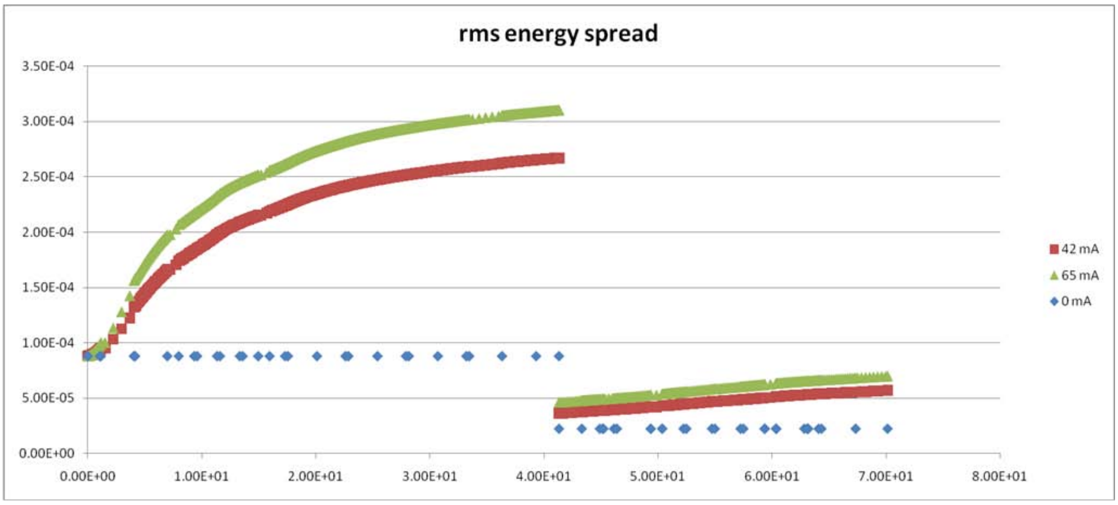
  Actually the existence of the limited energy spread entrains some benefits: As the excursions of the dispersion contribute significantly to the horizontal envelope and the ensuing aperture requirements, their reduction is welcomed.

  Injection on a rising cycle, as foreseen in the PSB to reduce the time spent in the high space-charge regime at low energies, would require even higher painting energy range. For this reason, a sinusoidal magnet cycle was assumed in this chapter.

  Nevertheless there may be a way out:

  The quoted Linac4 energy modulation range of ±1.2 MeV is limited mainly by the distortion of phase at the debuncher located at 42 m from Linac4 exit. In the present RCS implantation layout, this is about the distance from Linac4 to the RCS injection area. One could envisage dropping the debuncher and painting the bunch shape with a broader "brush". This would allow a modulation of ±2 MeV, allowing the creation of 2eVs bunches. The injection energy would be lowered to 158 MeV, which should not be a problem. The width of the brush is given by the space-charge driven blow-up in the injection line. Figure 3.4 shows the rms. width as a function of distance for the nominal average Linac4 currents of 40 mA and 26 mA. The latter one would be best for painting an LHC beam of 3.25E12 p within 20μs, i.e. within one sweep. Again, the consequences of painting with a 200-300keV wide brush would have to be studied by simulation.

Figure 3.4 — Blow-up of Linac4 rms Energy Spread along the Injection Line
Courtesy A. Lombardi



Another potential difficulty arises for the LHC beams from the fact that the PS requires bunch lengths up to 180 ns, corresponding to $\Delta\varphi=\pm77$ deg. The matched RF voltage of a bunch of area 2 eVs is about 2 kV and the synchrotron frequency as low as 150 Hz. Consequently, stretching the RCS bunches to this length near flat top is no longer an adiabatic process. It may be possible to produce these bunches by a carefully adapted RF voltage programme but it remains an operational burden. A safer approach consists in a fast bunch rotation preceding extraction: Dropping the voltage from 60 kV to 14 kV rotates the bunch from initially $\Delta\varphi=\pm36$ deg to the desired length in 0.8 ms.

3.1.5 Effect of Transverse Space Charge:

The defocusing due to space charge forces creates a tune spread which extends in general from the bare working point to a maximum tune shift, which is the one that experience the particles with vanishing betatron amplitudes. In the present PSB, it reaches values of about -0.5 in the vertical plane. From this experience one can infer that the RCS will allow tune shifts of this order, perhaps even a little more as the beam is accelerated much faster.

One practical form is given by the expression

$$\Delta Q_{s.c.} = -\frac{N_b}{\varepsilon_n}\frac{r_p}{4\pi\,\beta\gamma^2}\frac{F\,G\,H}{B_b} \qquad \text{with}$$

ε_n ... Normalised r.m.s. emittance
N_b...p/bunch
F ...Image Factor $\cong 1$
G ...Distribution Factor (transverse): Gaussian =2, uniform =1
H ...Aspect Ratio Factor: $H_x \propto \left\langle \frac{1}{a(a+b)} \right\rangle,\ H_y \propto \left\langle \frac{1}{b(a+b)} \right\rangle;$
a,, b ... Beam radii, hor. contains $< D_{x,rms}$ dp/p> added quadratically
B_b...Bunching Factor, average/peak line density of single bunch
β, γ...Lorentz Factors

The rather large radial dispersion in the arcs of the lattice (<Dx,rms dp/p >= 1.67m) together with a bunch height of up to dp/p $\cong \pm0.006$ helps to reduce the maximum tune shifts in both planes.

In Table 3.5 are compiled the computed tune shifts during the critical phase till 15ms for the most critical beams. Although better transverse distributions can be painted with H- injection, Gaussians have been assumed in both transverse planes to take into account possible redistributions. The emittances used in the calculations have been reduced by 20% w.r.t. the nominal ones to provide some margin for blow-up or minor losses.

Table 3.5 — Space Charge Tune Shifts during early Acceleration

Sinusoidal Magnet Cycle 50 ms rise			Bunch Area 1.2 eVs		LHC Beam		nTOF Beam	
					3.25E12 p/p $\varepsilon_{n\ x,z}$=2μm		1E13 p/p $\varepsilon_{n\ x,z}$=8μm	
t (ms)	Vrf (kV)	T(MeV)	Bunching Factor	Bunch Height (MeV)	-dQx	-dQz	-dQx	-dQz
0	10	160	0.482	1.29	0.36	0.52	0.37	0.45
2	20	165	0.421	1.77	0.33	0.54	0.39	0.48
3.2	22	172	0.424	1.70	0.32	0.52	0.37	0.46
5	25	189	0.428	1.96	0.29	0.46	0.33	0.40
8	35	237	0.427	2.33	0.22	0.34	0.24	0.30
15	60	443	0.337	4.15	0.12	0.18	0.13	0.16

The maximum vertical tune shift of -0.54 of the LHC beams appears somewhat risky, but it should be borne in mind that a transverse Gaussian is a pessimistic assumption compared with the distributions made possible by transverse painting.

3.1.6 Effect of Nonlinearities

In an RCS the effect of typical magnet non-linearities should be negligible compared to the effect of space charge. The effect of 2nd- and 3rd-order stopbands can be estimated from the results of magnet measurements from which the number and the placement of the correction magnets can be inferred. What remains to be checked is the effect of eddy currents in the dipole vacuum chamber.

Effect of the Vacuum Chamber:

For a thin vacuum chamber (wall thickness t) of rectangular cross-section 2 w × 2 h, the (dominant) sextupole component can be easily computed to be

$$k_2 = \frac{\partial^2 B}{\partial x^2} / (B\rho) = \frac{\mu_0 \sigma t}{\rho\, h} \frac{\dot{B}}{B}$$

with the usual denominations: σ ... conductivity, ρ...magnet bending radius.
For elliptical or super-elliptical cross-sections the differences should be minor, and the multipole components have to be computed numerically.
The impact of a (corrugated) Inconel625 vacuum chamber of 0.4 mm thickness has been checked with the ACCSIM code.
For a maximum $B/\dot{B} = 55\, s^{-1}$, the natural chromaticities of

$\xi_{x,\,y}$ = (-3.60, -3.84) are shifted to $\xi_{x,\,y}$ = (-1.78, -6.30). These chromaticity values should not require any correction.

However, some correctors appear to be indispensible: 2 skew quads for Qx-Qy=1 and 2 quads for 2Qv=7. Normally, the number of orbit correctors to be foreseen is comparable to that of the monitors, which is 16 in this case. In the PSB, up to now orbits were corrected by mechanical displacements only. Whether this works in an RCS is not evident.

A possible commissioning strategy could save lattice space and reduce cost: If a shutdown for complementary installation can be scheduled after first experimental runs, one may complement the basic correctors by installing those which turn out to be necessary.

4. **RCS Injection and Extraction** [W. Bartmann, B. Balhan, J. Borburgh, B. Goddard, L. Sermeus]

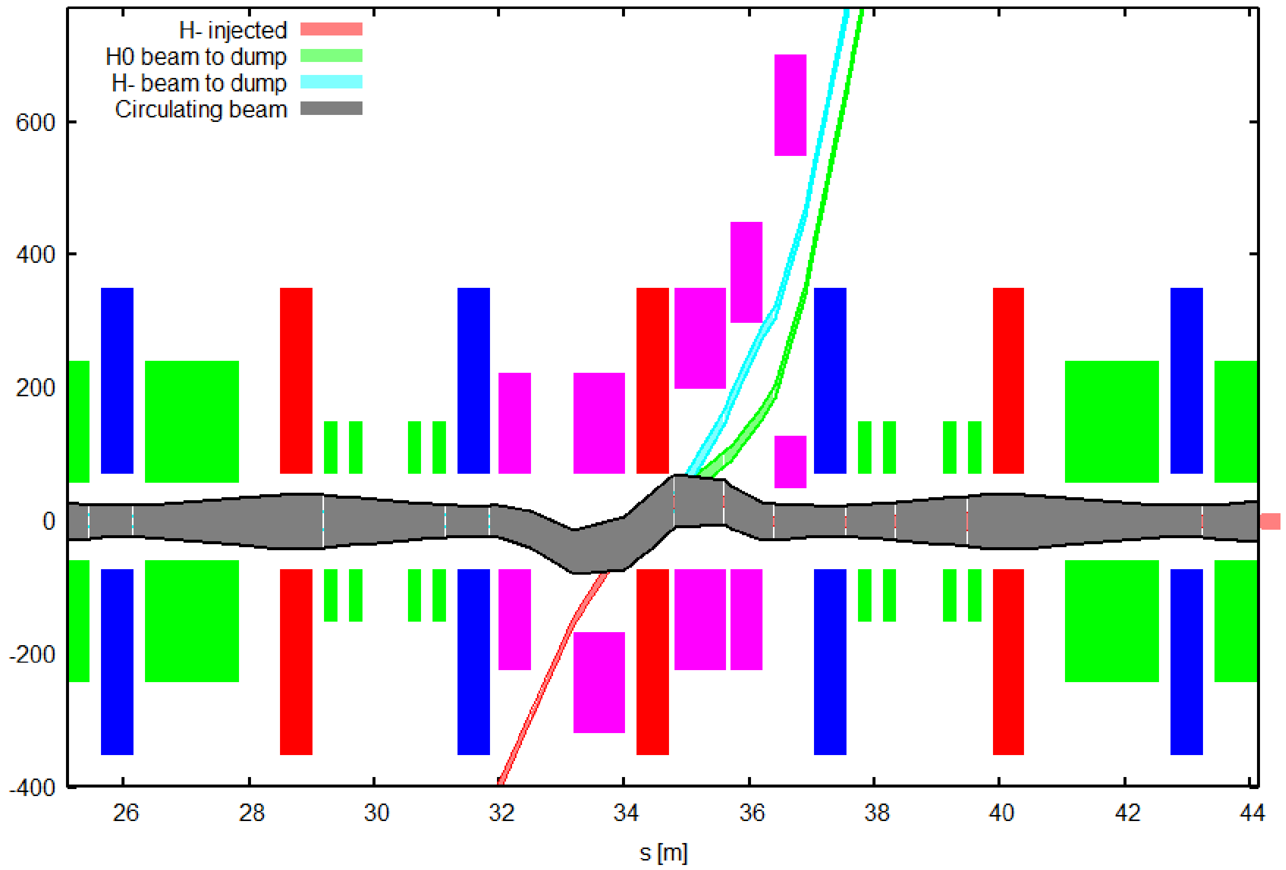
4.1 Technical Description

4.1.1 Injection system

The H^- charge exchange injection system comprises a horizontal 4 magnet chicane bump (D1-D4), one 4 magnet painting bump per plane (MKH1-MKH4 and MKV1-MKV4) and 3 stripping foils (F1-F3), see Fig. 4.1.

The injection system is a novel layout with a 2π chicane bump, housed in two empty FODO cells with a focusing quadrupole in the centre. The circulating proton beam (black) is bumped with an angle across the horizontal axis to be merged with the incoming H- beam (red) in the D2 chicane dipole. The D1 chicane dipole deflects only the circulating beam and will therefore be a septum like magnet. The bump shape minimizes the excursion in the central QF quadrupole and hence the aperture required, and allows the system to be accommodated in the FODO straight section.

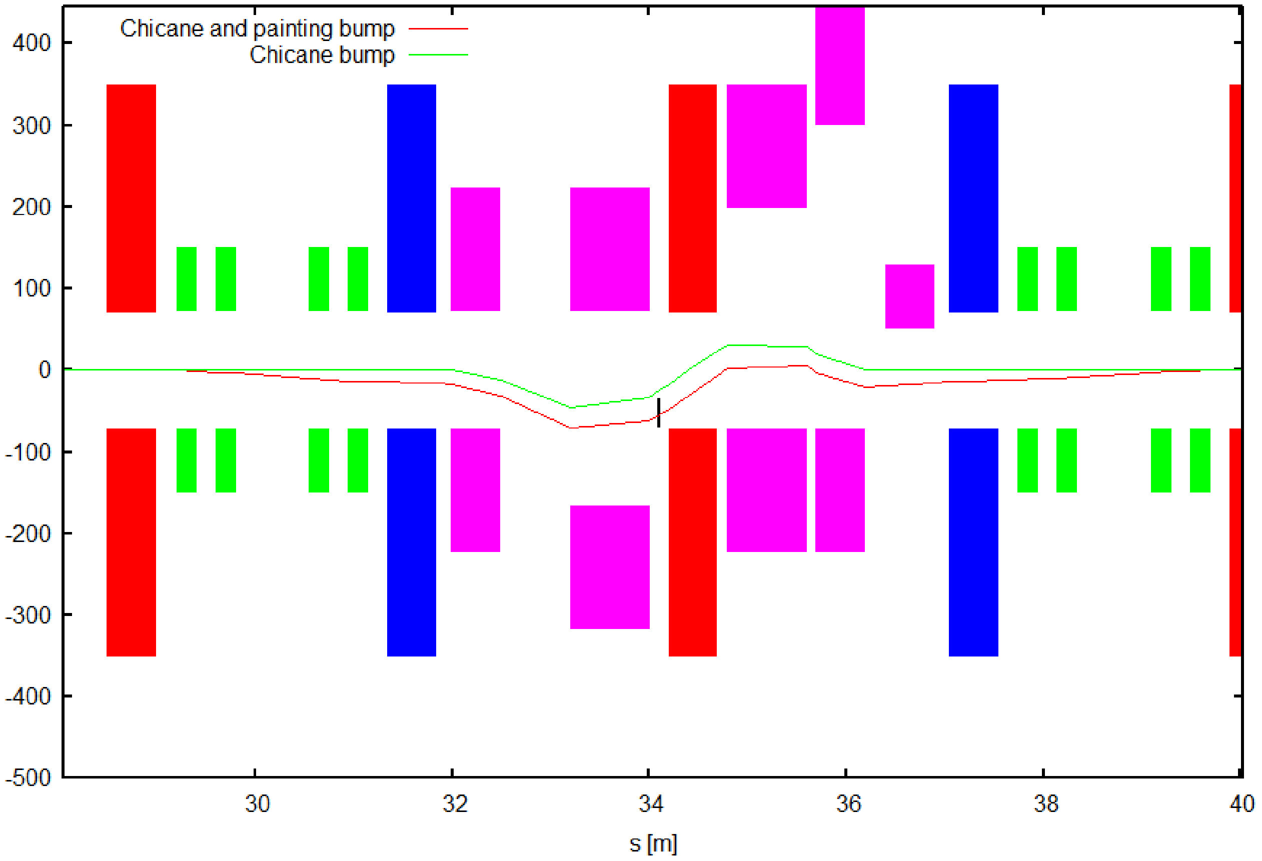
Figure 4.1 — [Layout of the H^- injection system with horizontal 3 σ beam envelopes in mm. Boxes indicate main bends (green, wide), focusing quadrupoles (red), defocusing quadrupoles (blue), horizontal and vertical painting bumpers (green, small) and chicane bumpers (magenta).]



The stripping foil F1 is placed downstream of D2 to strip the H^- ions to protons. The foil thickness has to be optimised with respect to stripping efficiency, foil heating and emittance blow up of the circulating beam. The unstripped H^- (turquois) or partially stripped H^0 (green) need to be deflected into a dump line. The D5 DC-dipole (septum) is required to deflect the H^0 waste beam only to clear the yoke of the downstream QD in the line to the dump. Open quadrupoles with a beam window at 350 mm as described in Section 7.1.3 are considered.

The painting bump amplitude reaches at the foil 30 mm in the horizontal and 32 mm in the vertical plane. 20 cm long magnets are needed for the horizontal painting bumpers with nominal fields of about 0.085 T (compared to 0.058 T in the 40 cm long KSW magnets of present PSB). The length of the vertical bumpers is increased to 40 cm to decrease the field below 200 mT and thus allow the use of ferrites. Figure 4.2 shows the shape of the chicane and painting bump in the horizontal plane.

Figure 4.2 — Horizontal bump shapes in mm.



Beta beating will result from the edge focusing of the strong chicane magnets. Its effect on the lattice focusing for full chicane strength is shown for SBEND and RBEND in Figures 4.3 and 4.4, respectively. This beating will change as the chicane is switched off, and a dynamic compensation will need to be considered as is being implemented in the PSB.

Figure 4.3 — Beta beating for RBEND chicane and painting magnets.

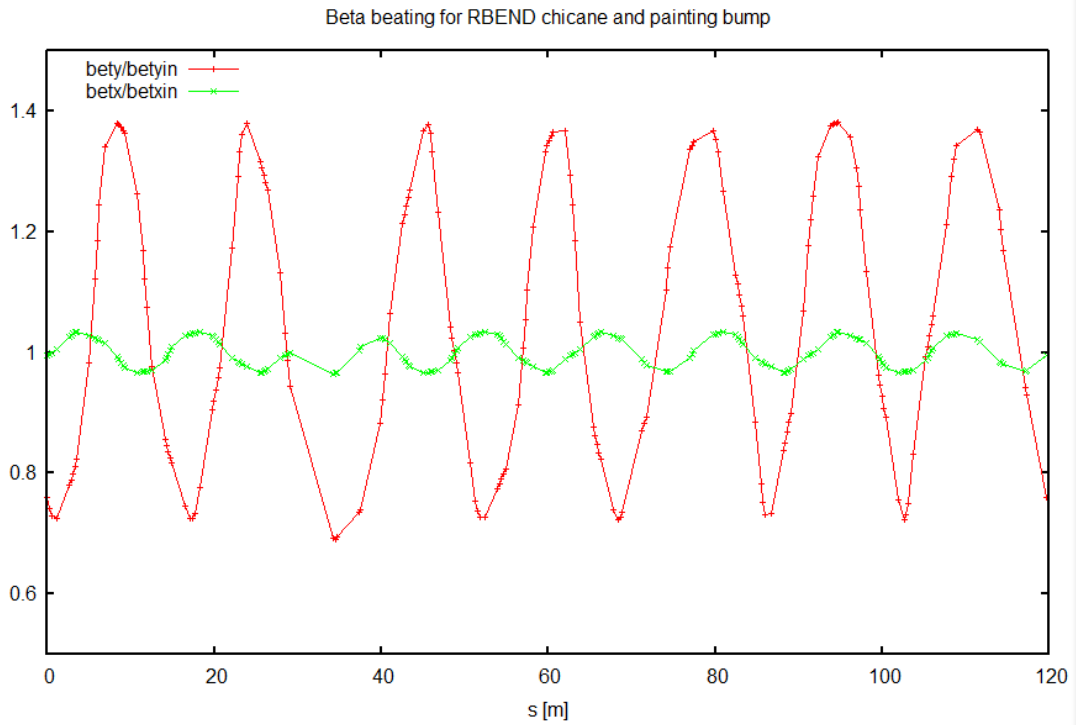


Figure 4.4 — Beta beating for SBEND chicane and painting magnets.

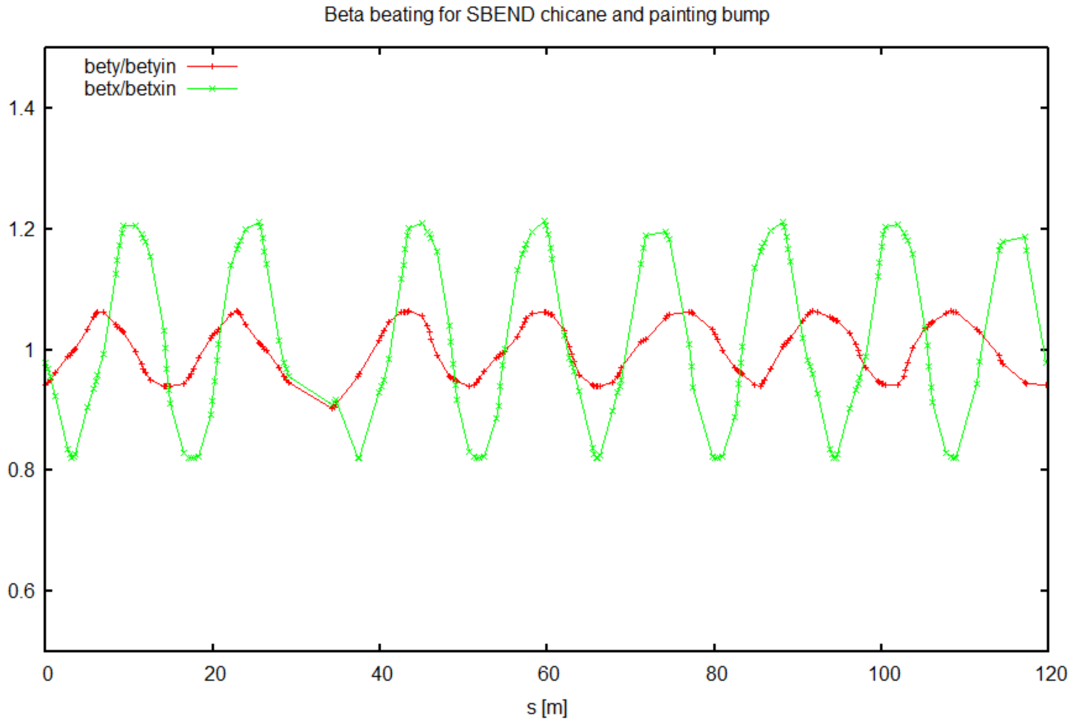


Table 4.1 — Chicane magnet kicks and integrated fields at 160 MeV kinetic energy.

Magnet	Kick angle [mrad]	Length [m]	Integral field B.dl [Tm]	Field [T]
D1	-48	0.5	0.09	0.18
D2	128	0.8	0.24	0.30
D3	-162	0.8	0.31	0.38
D4	84	0.5	0.16	0.32
D5	300	0.5	0.57	1.14

Table 4.2 — Painting magnet kicks and integrated fields at 160 MeV kinetic energy.

Magnet	Kick angle [mrad]	Length [m]	Integral field B.dl [Tm]	Field [T]
MKH1	-8.1	0.2	0.02	0.08
MKH2	7.4	0.2	0.01	0.07
MKH3	4.6	0.2	0.01	0.04
MKH4	-6.6	0.2	0.01	0.06
MKV1	39.9	0.4	0.08	0.19
MKV2	-30.6	0.4	0.06	0.15
MKV3	-20.3	0.4	0.04	0.10
MKV4	29.6	0.4	0.06	0.14

4.1.2 Extraction

The extraction is a fast bunch-to-bucket transfer with a kicker and septum system placed around a defocusing quadrupole, Fig. 4.5. The width of the downstream quadrupole in Fig. 4.5 indicates the use of open quadrupoles with a beam window at 350 mm as described in Section 7.1.3.

The septum system consists of two thick (25 mm) magnetic septa with a vertical gap height in the extraction channel of 40 mm.

The kicker system consists of 2 tanks filling two adjacent half cells. The required rise time is 40 ns (1-99%) to allow h=4 operation. The horizontal and vertical half-apertures are assumed to be 40 and 75 mm, respectively. The total required kick strength amounts to 28 mrad.

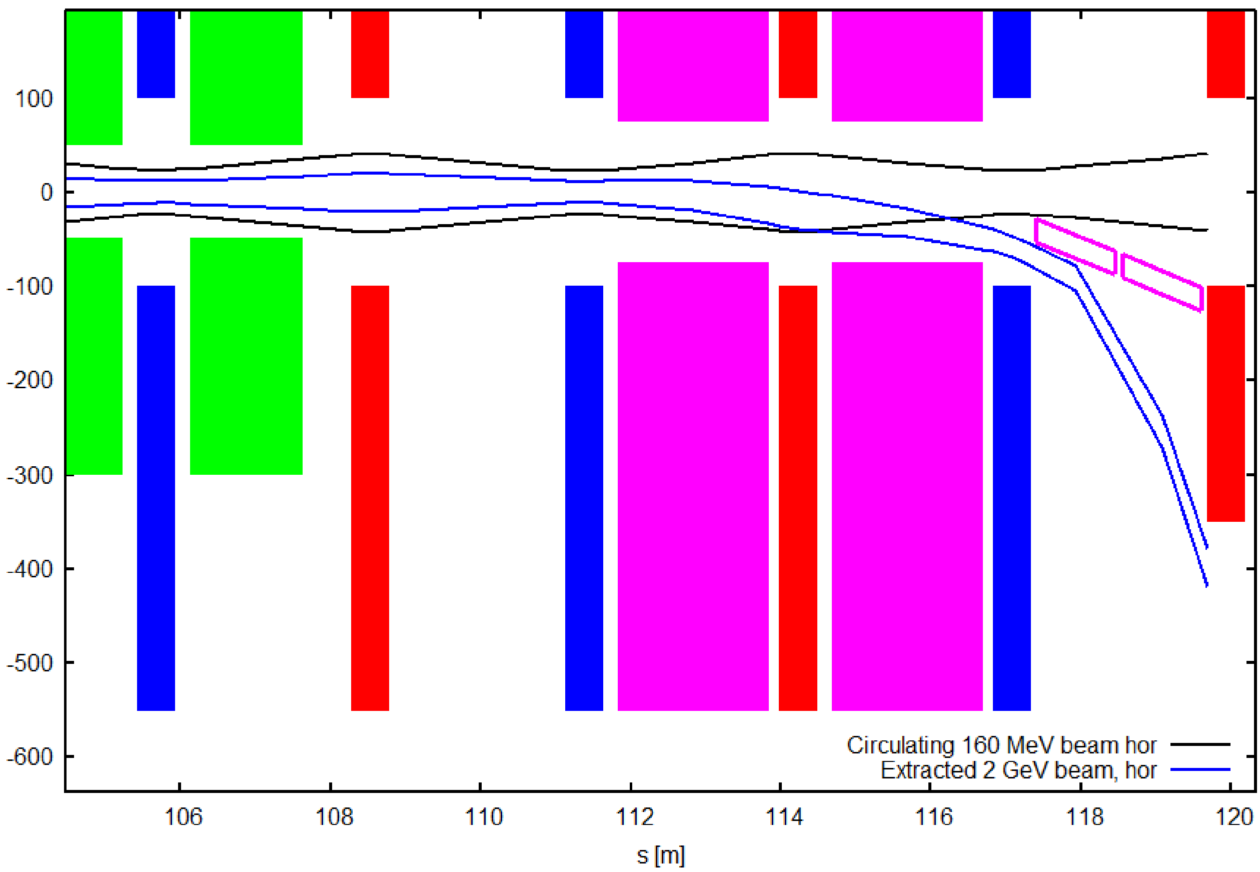
The RCS extraction kicker estimate is based on the assumption that 80 kV SF_6 cables will be used as Pulse Forming Lines as in other kicker systems of the PS complex. For the time being, this assumption is very optimistic because no potential interested cable manufacturer has been identified. As the total number of magnets to be used depends on a compromise between achievable kick rise time and magnet current, the unavailability of SF_6 cables may lead to use twice the amount of foreseen magnets powered from conventional RG220 cables at 40 kV. This would impact the total price accordingly.

Unless another solution is found in the future, the foreseen system requires 40 magnets with their dedicated generator.

Object to further iterations are:

- Using a bump for the circulating beam: This allows to decrease the kicker strength but also reduces the clearance between extracted and circulating beam and thereby the maximum allowable septum thickness.
- Adding a third kicker tank and reducing the kick strength of the other ones could also ease the feasibility of the system by removing the SF_6 cables constraint but will increase the total cost. Nevertheless this option should not be abandoned if it is combined with the previous ones because it adds the possibility of having one or two spare modules.
- Iterate the lattice design to provide longer drift space for extraction.

Figure 4.5 — Extraction at 2 GeV kinetic energy from the RCS. The filled boxes in magenta show the extraction kicker, the magenta lines the septum blades. Beam envelopes (blue for injection energy, black for extraction energy) are shown for a 3 sigma beam size including a closed orbit distortion of 3 mm.



The kick strengths and fields for the extraction elements are shown in Table 4.3.

Table 4.3 — [Kicker and septum strengths and fields at 2 GeV kinetic energy]

Magnet	Kick angle [mrad]	Length [m]	Integral field B.dl [Tm]	Field [T]
MKE (x2)	14	2	0.130	0.065
MSE (x2)	100	1	0.928	0.928

4.2 Budget Estimate

The RCS injection budget is based on the cost estimates for the PSB H^- injection.

In Table 4.3 the budget is compared for different operational modes. Harmonic 4 and a bunching factor of 60 % result in a required rise time of 40 ns. With a bunching factor of 50 % and thus increasing the rise time from 40 to 50 ns the kicker budget would be reduced by 25%.

Harmonic 1 or 2 (baseline) and a kicker rise time of 100 ns allow to use a more conventional configuration, not far from the foreseen PSB one at 2 GeV. The amount of systems would be reduced to 16, keeping the assumption that SF_6 cables will be available. Then the estimate is that the price will go down accordingly (Total=8800 kCHF). An option would also be to reuse a large part of the booster extraction and transfer kicker generators. This option would probably reduce the cost by another 2 MCHF.

Table 4.3 — Cost items for the injection systems.

Element	Cost in kCHF	Cost in kCHF
Injection magnets	3910	3910
Injection power generators	5610	5610
H- equipment (foil, dump, controls)	650	650
Total Injection	**10170**	**10170**

Table 4.3 — [Cost items for the extraction systems.]

Element	Cost in kCHF	Cost in kCHF
	h=4; t_{rise}=40 ns	h=1,2; t_{rise}=100 ns
2 DC extraction septa + 1 spare	500	500
MKE (40 systems with 550 kCHF/unit)	22000	6800
Total Extraction	**22500**	**7300**

The total budget for injection and extraction systems amounts to 32.67 MCHF in case of harmonic 4 with 40 ns rise time and to 17.47 MCHF in case of harmonic 1,2 with 100 ns rise time.

4.3 Time Estimate

The time line from project approval to be ready for installation of the injection equipment is about 3 years.

For the extraction a strong R&D program has to be launched immediately to focus on SF_6 cables, very fast and short ferrite loaded magnets with beam screen. The use of ferrite loaded steepening line may also be studied in this R&D program. The estimated R&D time is at least 4 years before a final system design could be launched. Another 3 years will be necessary to complete the installation.

If the magnet design and production is started already during the R&D program for the SF_6 cables, the system can be ready for LS2.

5. RCS-PS Transfer Line [W. Bartmann, B. Goddard, A. Kosmicki, L.A. Lopez-Hernandez, M. Meddahi, M. Widorski]

5.1 Technical Description

5.1.1 Beam line geometry

The RCS to PS transfer line joins the foreseen Linac4 to PSB beam line downstream its 70 deg horizontal bending next to Building 400, Fig. 5.1.

The main constraints for the RCS and transfer line siting come from radiation protection and civil engineering. Moving the ring closer to Building 400 and thereby reaching an almost straight extraction line into the existing beam line would require an open excavation below Building 400 and is therefore very difficult. Also the distance of the ring tunnel to Building 513 must not be decreased for radio protection reasons, see Chapter 19.

The suggested transfer lines, Fig. 5.1, are designed to have a minimum tunnel area housing both lines. The injection and extraction lines cross each other which might limit access possibilities.

As alternative the transfer lines can be designed not to cross each other having a clockwise rotating beam in the machine. For this option the extraction line will require an extended excavation north of Building 400.

Figure 5.1 shows the transfer lines for the incoming and extracted beam line with its crossing below Building 400.

Figure 5.1 — RCS transfer lines, the injected beam is coming from Linac4 (Bldg 400) and injected at the north LSS of the RCS. The extraction is placed at the south LSS and S-like bent into the existing tunnel between Linac4 and the PS, crossing the injected beam line next to Bldg. 400.

Downstream the connection point below Building 400, the existing beam line geometry is kept. At the crossing of PSB injection and extraction lines, a section of dipoles with 14 m bending length is considered to bend the beam at the BI-BT lines crossing.

The magnets foreseen for the 160 MeV H^- ion transport from Linac 4 to PSB, as well as the existing magnets in the PSB injection and extraction lines need to be redesigned and rebuilt for 2 GeV protons.

Table 12.1 shows the characteristics for the ten bending magnets foreseen in the extraction line until the jonction with the foreseen beam line Linac4-PSB.

Table 5.1 — Bending magnets characteristics for the upstream RCS-PS transfer line.

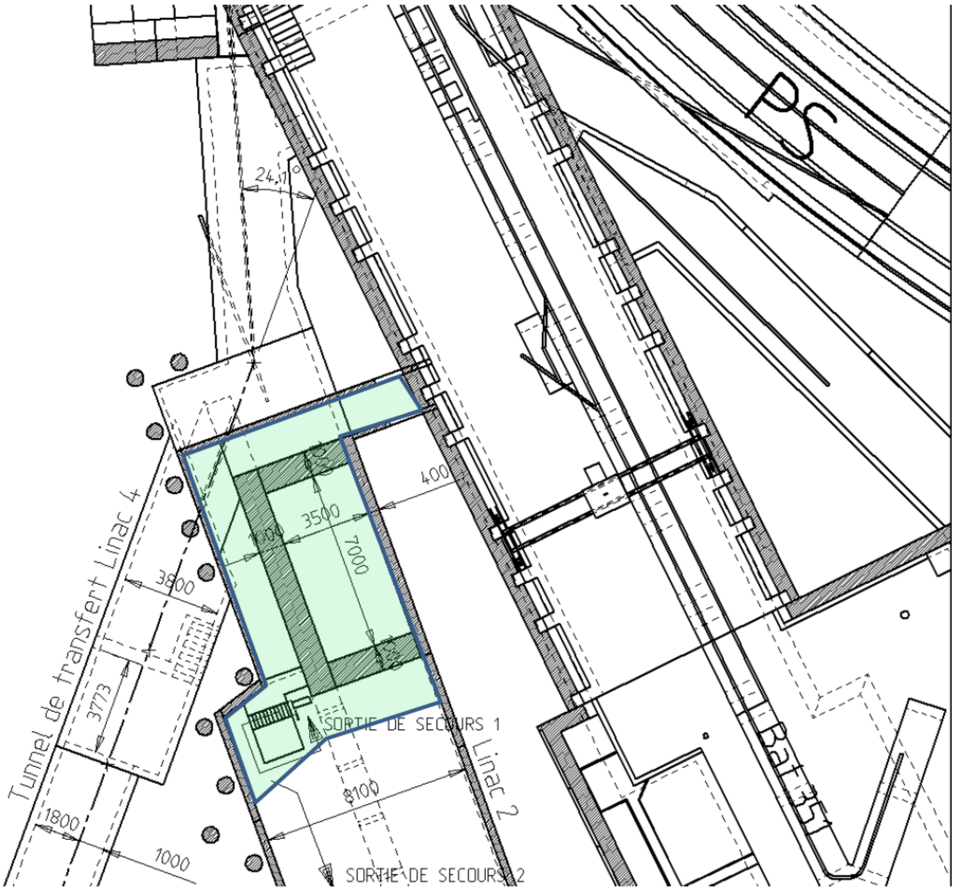
Magnet	Kick angle [mrad]	Length [m]	B.dl [Tm]	B [T]
MB1 x 4	180	1.75	1.67	0.95
MB2 x 6	216	1.75	2.00	1.15

5.1.2 Civil engineering and shielding

The foreseen beam line Linac4-PSB needs shielding reinforcement in the area of the jonction with the Linac2 beam line to cope with the increased beam power, see Chapter 19.

The earth coverage on top has to be increased by 2 m and parts of Building 363 need to be filled with concrete (420 m^3), Fig. 5.2.

Figure 5.2 — Concrete filling of Building 363 at the jonction of Linac4 and Linac2 beam lines.



5.2 Budget Estimate

The TL budget covers the transfer lines from RCS extraction to PS injection (total length of 253 m), not taking into account the emittance line (LBE) and the spectrometer line (LBS).

Civil engineering costs for the localised shielding as described in the previous section do not include the dismantling of equipment presently located in this area.

The assumed apertures for the TL magnets are 40 mm aperture height for the dipoles and 60 mm pole radius for the quadrupoles. A first iteration on the magnet design is necessary to make a detailed estimate for the power converter system.

Table 5.2 — Budget items for the RCS-PS transfer line.

Element	#	kCHF/unit	total kCHF
Quadrupoles	45	40	1800
Dipoles	25	60	1500
PC Quadrupoles	25	40	1000
PC Dipoles	10	40	400
Correctors	23	10	230
PC Correctors	23	10	230
BPMs	23	10	230
BTVs	5	20	100
BLMs	25	4	100
Controls	1	100	100
Vacuum	253	2.5	633
Cooling	253	0.6	152
Cabling	253	1.5	380
Interlock	1	150	150
CE	1	1070	700
Survey	1	50	50
Drawings	253	1	253
Installation	253	0.6	152
SUM			**8529**

The total RCS-PS transfer line cost is estimated to about 8.53 MCHF, based on recent projects. Recuperation of existing equipment has not been studied and could reduce this estimate.

5.3 Time Estimate

After project approval, 1 year of design phase and 2 years of manufacturing are estimated to have the elements ready for installation.

6. **PS Injection** [W. Bartmann, B. Balhan, J. Borburgh, S. Gilardoni, B. Goddard, M. Hourican, L. Sermeus, R. Steerenberg]

6.1 Technical Description

The use of conventional septa in DC mode - as is usually the choice for fast cycling hadron machines for reliability reasons – requires injecting into a long straight section (2.4 m) of the PS. A short extension of the existing PSB-PS transfer line would allow to inject into the long SS46 instead of the existing injection into the short SS42 (1 m). This implies a new geometric design of the transfer line and an important re-shuffling campaign of RF cavities, kickers and dumps in the PS.

As an alternative it is considered to inject into SS42 deploying eddy current (EC) septum technology for both the injection septum and the bumper. For this option the transfer line geometry remains unchanged and major modifications to the PS are avoided. Drawbacks are the reduction of the vertical septum gap height from 60 to 48 mm and the complexity of the under-vacuum eddy current device. A second kicker system needs to be installed in SS53, as it is also foreseen in case of the PSB upgrade to 2 GeV.

Figure 13.1 shows the horizontal beam size of a typical high intensity (HI) beam when injecting into SS42. The horizontal emittance assumed is 12 µrad (1 sigma normalised). The kicker (KFA) in SS45 cannot provide the 30% increase in kick strength for the 2 GeV high-intensity beams where a fall time of 68 ns (2-98%) is required. A second system is installed 180 degrees downstream to compensate for the kick leakage. Both kicker systems (the existing KFA45 and the foreseen KFA53) can be pulsed at 10 Hz.

Figure 6.1 — Horizontal beam size in [mm] for the HI beam at PS injection in SS42.

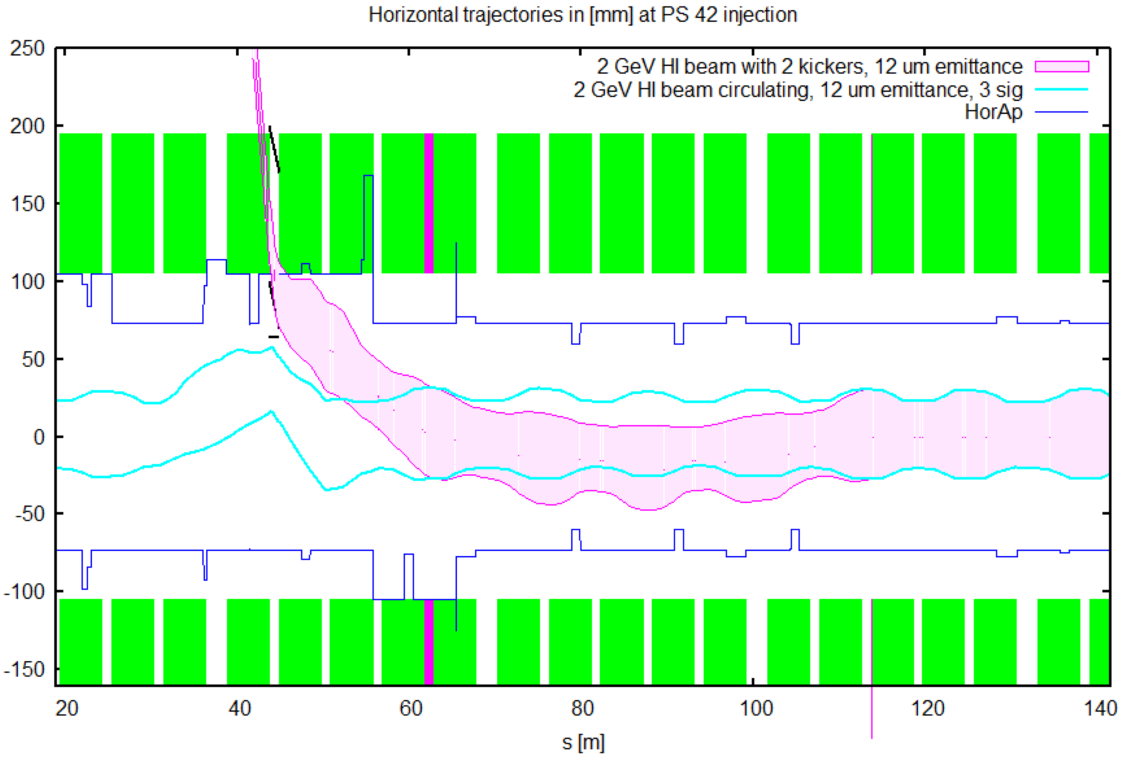


Figure 6.2 — Combined septum-bumper system with view from upstream end (left) and downstream end (right).

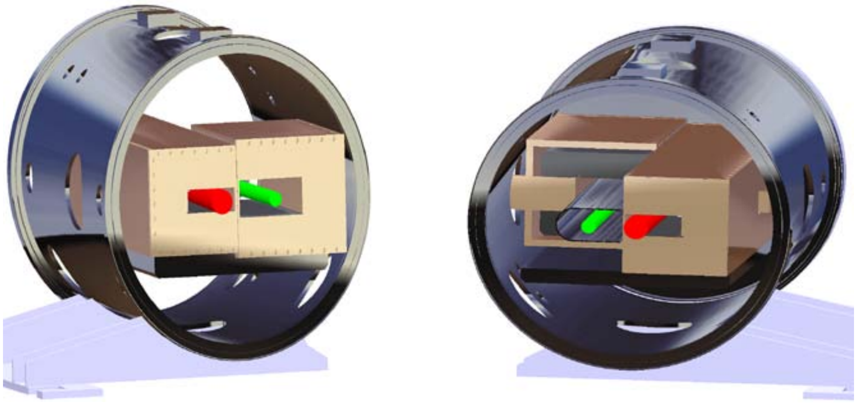


Figure 6.2 shows the combined under-vacuum septum-bumper system with injected beam (red) and circulating beam (green).

The main challenges of this system are magnetic and impedance screens, the internal support structure, vacuum pumping, the bake-out system, feedthroughs and the remote displacement system.

Simulations show that deploying a full sine current limits the field leakage from the septum into the circulating chamber at the circulating beam centre to about 1 permille. The field homogeneity in the septum is about 1%.

Table 6.1 — Septum and bumper characteristics.

	Unit	Eddy current under vacuum septum SMH42	Eddy current under vacuum Bumper Septum 42
Deflection	mrad	55	13
Septum Thickness	mm	5+1	5
Nbr Turn		1	1
Gap Height	mm	48	76 (70 for beam)
Gap Width	mm	120	165
Magnetic Length	mm	950	375
Induction in Gap	T	0.57	0.32
Required Current	A	21000	20000
Power Consumption	kW	< 0.4	<0.2
Magnet Resistance	mOhms	0.09	0.04
Magnet Inductance	uH	2.5	1
Mechanical aperture	mm	48 x 100	70 x 140

Differences to injection from an upgraded PSB that need to be studied:

- Reduced vertical acceptance for the injected beam in case of EC septum

  The emittances coming from the PSB or RCS have to be compared to the minimum beam acceptance in the PS which should allow to inject with a certain mismatch and still attain the target emittance in the PS. A possible improvement to reduce the losses on the septum itself is the addition of collimation in the transfer line. A change of the injection optics of the ring could be envisaged to create a sort of insertion and match a small vertical optical beta with the ring. This, however, risks to be limited by the PS optics flexibility.

  An analysis on the minimum emittances that the RCS could produce should be carefully done to quantify the losses on the septum and determine if they will be acceptable for high intensity beam operation.

- Continuous losses due to the injection bump in the PS ring

  Beam losses due to the circulating beam bumped to the aperture limits will occur 10 times more often in case of the RCS, however with a lower circulating intensity for the first injections. The total loss is expected to be about 5.5 times higher for a similar bump fall time, assuming that tails are repopulated in the 100 ms between injections.

- Lifetime of an eddy current device with respect to conventional septum technology

6.2 Budget Estimate

The PS injection equipment cost is estimated to about 3.285 MCHF. Table 6.2 shows the cost estimate for single items, not including controls and electronics.

Table 6.2 — Budget items for the PS injection.

Element	Cost [kCHF]
KFA45	430
KFA53	1850
Septum42	851
Bumper42	154
Total	**3285**

6.3 Time Estimate

The timeline for the kicker elements is from Jan-2012 to Jun-2017 and for the septa from Jan-2014 to Jun-2017.

7. **Magnets** [A. Newborough]

7.1 Technical Description

The magnets considered in detail for this feasibility study are the main bending and main quadrupole magnets for the RCS ring only, as they will contribute the most to the overall magnet budget. There will be several other magnet families required, such as the main ring correction magnets (dipoles, multi-poles etc...) and the transfer line magnets from the LINAC 4 to the RCS machine and from the RCS machine to the present ISOLDE experiment and PS machine. As the main ring correction magnets have not yet been specified the cost estimate will be based on the available number of adequately sized slots. The cost of the transfer line magnets will be included as part of the general transfer line estimation.

7.1.2 Main Bending magnets

Operating at a frequency of 10 Hz, it is envisaged that the main bending magnets will be able to achieve a field of up to 1.3 T. To achieve this field the magnets must be designed below saturation levels with special attention paid to the construction of the magnetic circuit. In particular it is planned to use a relatively thin lamination of grain orientated high silicon content steel. The use of this steel with the grain orientation in direction of the majority of the magnetic flux will have the effect of narrowing the hysteresis cycle and increasing the electrical resistance, thus minimising the adverse dynamic effects to within acceptable levels (delay between current and field, field quality perturbation, iron losses etc...).

The parameters shown in Table 7.1 have been calculated from the initial figures given for the required free vertical aperture of 71 mm (+/- 35.5 mm) and a horizontal good field region of 130 mm (+/- 65 mm). The total integrated bending field is 58.3 Tm, provided by 30 identical magnets each with an effective length of 1.5 m. The magnet characteristics provided are based around a magnet with 12 turns and an r.m.s. current density of 5 A/mm^2. If required, the number of turns can be altered to help in the design of the power supply by increasing or decreasing the required peak current, magnet inductance etc... However, a maximum voltage potential of 10 kV (+/- 5 kV to ground in normal operation) would dictate no more than 18 turns. Figure 7.1 shows a simple 2D magnetic field map of a preliminary design, while Figure 7.2 shows a possible magnetic cycle.

Figure 7.1 — 2D magnetic field map, main dipole.

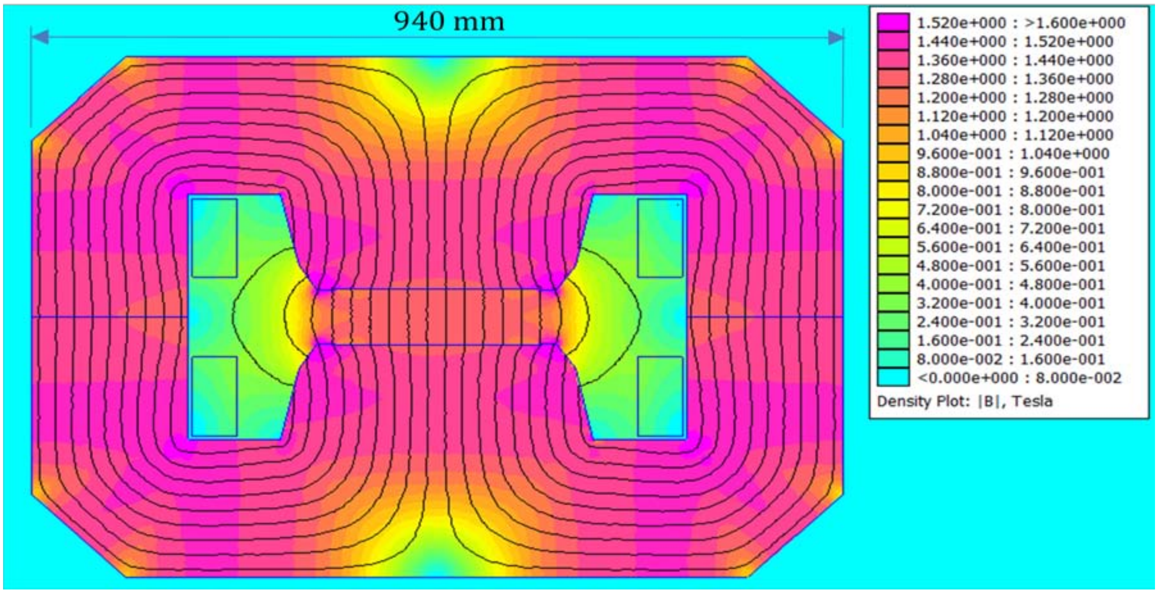


Figure 7.2 — Possible magnetic cycle

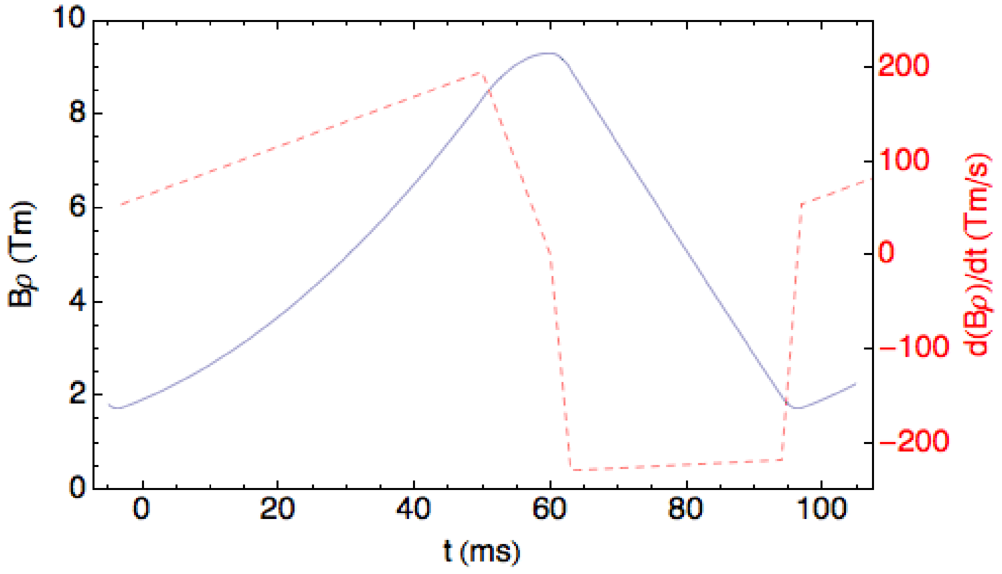


Table 7.1 — Main Bending Magnet Parameters

Approx. Magnet Dimension	
Iron length (m)	1.426
Total length (m)	1.626
Iron Width (m)	0.94
Iron Height (m)	0.66
Aperture height (m)	0.071
Aperture width (m)	0.27
Approximate weight (kg)	6000
Magnetic Parameters	
Magnet type	H – laminated, water cooled
Field (T)	1.3
Magnetic length (m)	1.5
Integrated field (Tm)	1.946
# turns per pole	6
# turns total	12
Electrical Parameters	
Current at peak field (A)	6106
Current at Injection (A)	1256
Current r.m.s. (A)*	3793
Resistance @ 20 °C (mΩ)	1.08
Resistance warm [ΔT = 30°C] (mΩ)	1.14
Inductance (mH)	1.36
Max. Volt-drop (V)**	226

Copper Losses, warm (kW)	16.4
Iron Losses (kW)	1.7
Total Dissipated Power (kW)	18.1
Cooling parameters	
Flow [ΔT = 20K] (l/min)	12
Required Pressure Drop (bar)	8
RCS Machine - Bending	
# Magnets in series (incl. Ref. magnet)	31
Total magnet resistance warm (mΩ)***	35
Total magnet inductance (mH)	42
Total dissipated power (kW)	562
Total volt drop (kV)	7.0

* Approximation from magnetic cycle (see figure.2)
** Assumes ramp down time of 0.03 seconds
*** Does not include connections and cables

7.1.3 Main Quadrupole magnets

As per the main bending magnets, the quadrupole magnets will be constructed from a thin lamination of high silicon content grain orientated steel. Limiting the pole tip field to approximately 0.80 T allows designing a magnet which operates below saturation. The required horizontal aperture radius of approximately 75 mm has been given as a baseline for the design of the magnet; this will dictate a minimum inscribed radius of 100 mm to be able to guarantee the field quality to within a few units in 10^{-4}. If the required field homogeneity is not as critical at the limit of the required aperture then a reduction could be made. For field quality issues a symmetrical design is desirable, however, it would be possible to use other designs if required. For example, if around the injection and extraction points of the machine it is seen that the symmetrical quadrupole magnet is too wide, then an open quadrupole could be considered allowing the passage of the injected or extracted beam through the upper and lower halves of the yoke. An example of this is shown in Figure 4; the magnet shown would use identical coils to standard type but would have an effective width of 700 mm, the separation would be made with non-magnetic blocks incorporating the beam window. The stray field within this beam window would be in the order of several gauss at peak current and although consideration to this should be made, it is understood that the effects on the beam would be negligible. As the gradient for these special magnets would vary slightly from that of the standard type, a separate powering configuration may be required. Alternative solutions may also be possible.

The maximum required gradient for the quadrupole magnets is approximately 8.0 T/m with an effective length of 0.5 m. Table 7.2 shows approximate parameters for the quadrupole magnet with a physical aperture radius of 100 mm. Figure 7.3 shows a simple 2D magnetic field map of a preliminary design.

Figure 7.3 — 2d magnetic field map, main quadrupole.

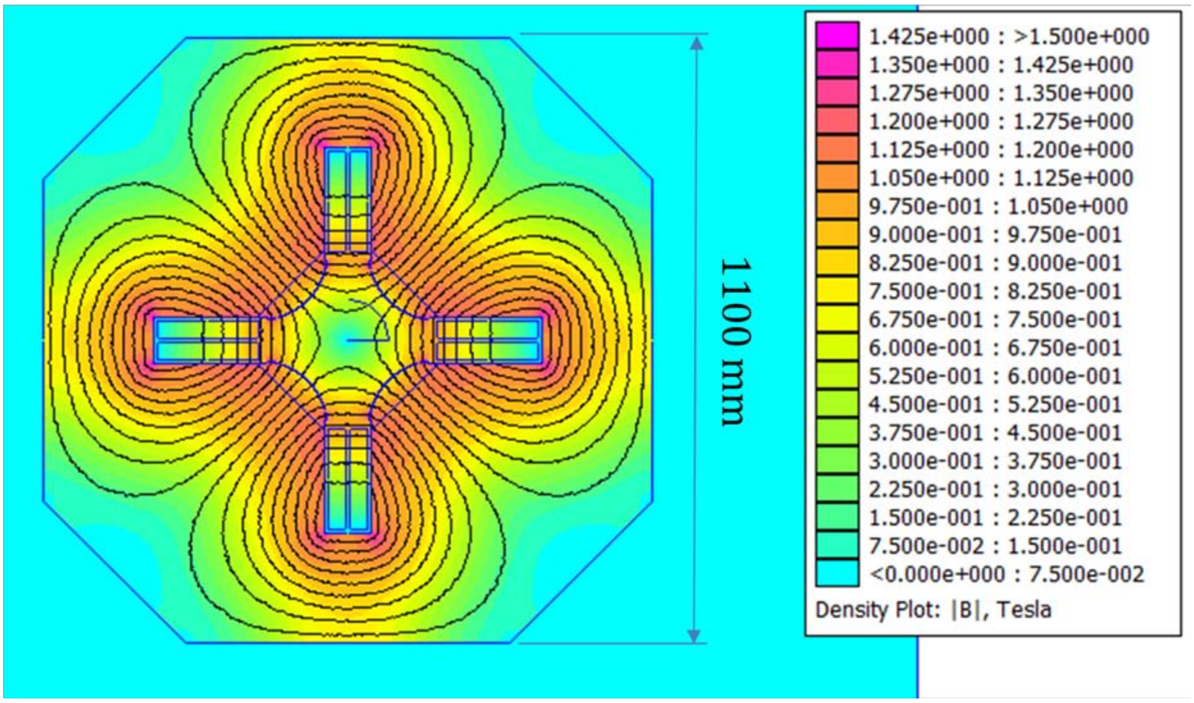


Figure 7.4 — 2d magnetic field map, injection/extraction quadrupole.

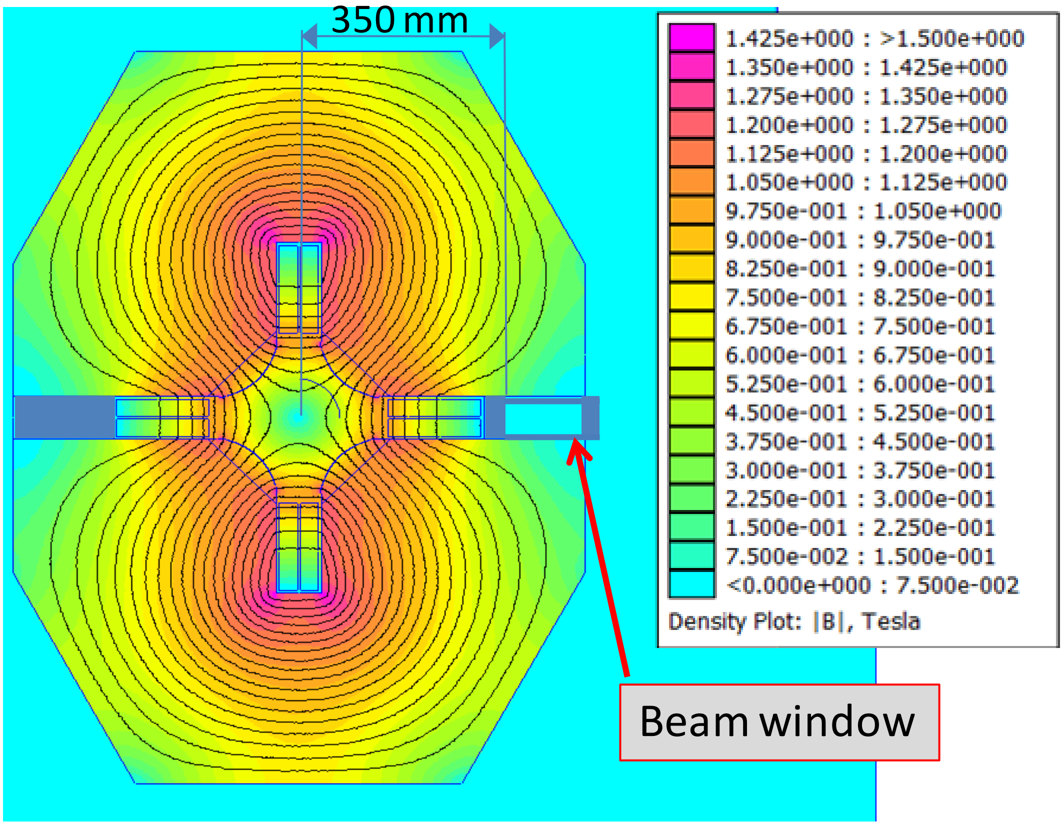


Table 7.2 — Main Quadrupole Magnet Parameters.

Approx. Magnet Dimension	
Iron length (m)	0.433
Total length (m)	0.6
Iron Width [overall] (m)	1.0 [1.1]
Iron Height [overall] (m)	1.0 [1.1]
Inscribed Radius (m)	0.1
Approximate weight (kg)	2950
Magnetic Parameters	
Magnet type	Tapered pole - laminated, water cooled
Gradient (T/m)	8.0
Magnetic length (m)	0.5
Integrated Gradient (T)	4
# turns per pole	8
# turns total	32
Electrical Parameters	
Current at peak field (A)	3979
Current at Injection (A)	815
Current r.m.s. (A)*	2470
Resistance @ 20 °C (mΩ)	1.79
Resistance warm [ΔT = 30°C] (mΩ)	1.89
Inductance (mH)	1.46
Max. Volt-drop (V)**	155
Copper Losses, warm (kW)	11.5
Iron Losses (kW)	0.7
Total Dissipated Power (kW)	12.2
Cooling parameters	
Flow [ΔT = 20K] (l/min)	8.5
Required Pressure Drop (bar)	8
RCS Machine – Quadrupole* **	
# Magnets in series	21 QF or 21 QD
Total magnet resistance warm (mΩ)****	40
Total magnet inductance (mH)	31
Total dissipated power (kW)	257
Total volt drop (kV)	3.4

* Approximation from magnetic cycle (see figure.2)

** Assumes ramp down time of 0.03 seconds

*** Values are stated per circuit, 21 QF or 21 QD magnets and are the maximum value.

**** Does not include connections and cables

7.1.4 Main ring correction magnets

When considering the proposed lattice in Chapter 3 of this report, it can be seen that in the arcs of the three fold symmetry machine there would be available space between the main quadrupole magnets and neighbouring bending magnets for additional equipment. The proposed optimized lattice would leave approximately 0.1 m free space (coil to coil) between defocusing quadrupole (QD) magnets and neighbouring bending magnets, and 0.5 m between the focusing quadrupole (QF) magnets and neighbouring bending magnets. Considering the dipole corrector and multi-pole magnets in the PSB machine today, the lengths vary from around 300 to 410 mm. Therefore, if similar designs were used, only the larger QF spaces would be adequate of which there would be approximately 36 around the machine. Although it is unlikely that all of these spaces can be dedicated to magnets, the following estimate will assume 36 units plus spares must be constructed.

7.2 Budget Estimate

7.2.1 Main units

The following estimate covers the cost of the main magnets only; it does not include supports, cabling, manpower, installation etc...

Magnet	Magnet	**Dipole**	**Quadrupole**	
	Number of magnets (incl.spares)	33	46	#
	Total mass/magnet	6000	2950	Kg
Total Costs	Total order mass	198	136	Tonnes
	Total fixed costs	215	170	kCHF
	Total Material costs	894	788	kCHF
	Total Manufacturing costs	3302	3335	kCHF
	Total magnet costs	**4411**	**4445**	**kCHF**
	Unit cost	**134**	**97**	**kCHF**
		8856		**kCHF**

7.2.2 Main ring correction magnets

Without specifications for the number or type of magnets required, the following estimate is based on the number of adequately sized available spaces in the machine arcs, 36 in total. It is assumed that a similar design to the current PSB corrector and multi-pole magnets are used. The estimate includes spare units but not supports, cabling, manpower, installation etc...

Corrector and multi-pole magnet unit cost – 25 kCHF

Total cost – 900 kCHF

7.3 Time Estimate

From the time of project approval, including design and manufacturing, an estimate for the availability of all the main units is approximately 36 months. This estimation would include the fabrication and evaluation of the pre-series magnets but does not included installation and commissioning.

As part of the study, the construction of a scaled version of the bending magnet is being built to evaluate the performance of the grain orientated high silicon content electrical steel. To achieve the results within a short time the yoke is to be designed around and assembled with an existing pair of spare coils, the construction and testing is planned for summer 2011. The construction of a scaled quadrupole will also be considered.

8. **Magnet Interlocks** [P. Dahlen, B. Puccio]

8.1 Technical Description

The Warm magnet Interlock Controller (WIC) solution is proposed. This system is currently deployed in LEIR, in Linac3, in the SPS-LHC-CNGS transfer lines and is also protecting the normal conducting magnets of the LHC.

The WIC solution is a PLC based system. It protects the normal conducting magnets from overheating by switching off the power converter when a fault such as overheating of magnets occurs. In order to optimise safety, the Siemens “F” Series PLC is used, offering a self checking safety environment that ensures system integrity. The WIC system performs self testing of its own hardware and software to detect failures and corruption, and goes into a safe state in the event of an abnormality. In the present case, it means that the Power-converters will be all the time switched off.

The study, the preparation of the material, the lab tests, the commissioning activities and the maintenance are handled by the Machine Interlock section of the TE/MPE group. The PLC software and the PVSS application are both managed by the EN/ICE group.

8.2 Budget Estimate

The cost will depend of many parameters: number of water-cooled magnets, number of additional sensors (water-flow meters, red-buttons, etc...) and the cables length for magnets and converters connections.

As a very first estimation, the budget will be between 300kCHF and 500kCHF.

8.3 Time Estimate

From the time of project approval, including study, ordering, manufacturing and testing in the lab, an estimate for readiness to a commissioning is approximately 12 months.

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

9.1 Technical Description

For this preliminary study, the power supplies for the RCS ring only have been studied in detail. With a 10 Hz machine, the preliminary design focuses on minimizing the impact on the 18 kV general network as well as minimizing the idle time between successive accelerations. Flexibility on the current waveform is also kept as an important feature for operation.

The costs of the transfer line power supplies will be included as part of the general transfer line estimation.

9.1.1 Main bending power supply

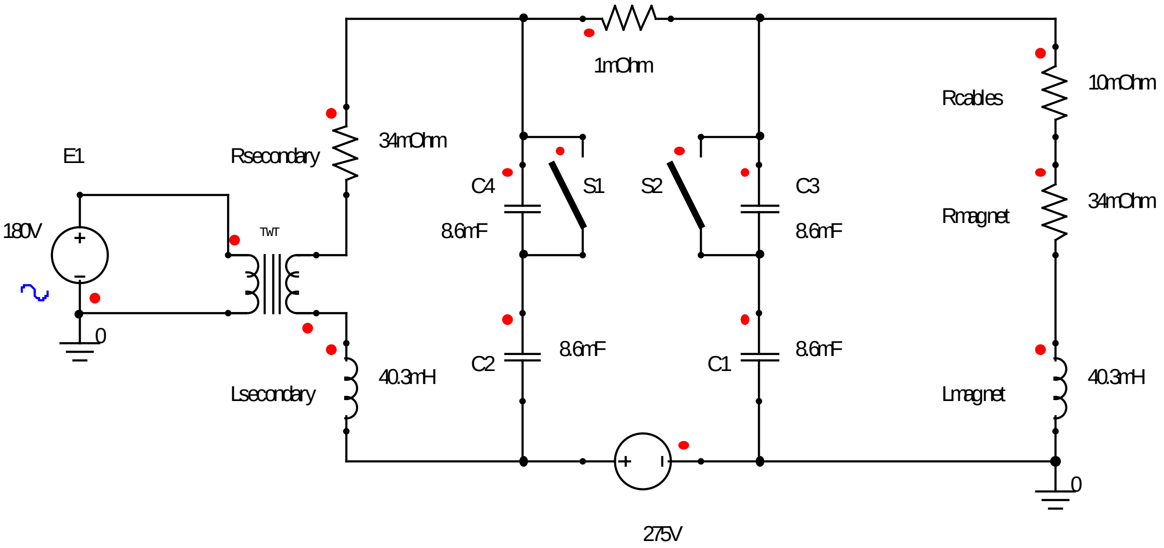
Considering the main bending magnets characteristics, two options can be considered and will be developed and quoted in this document. A detailed and long study would still be needed on each option to confirm the technical feasibility:

- A resonant system also called a White circuit is often used in fast cycling accelerators with a repetition rate of 10 Hz to 50 Hz (ESRF, SRS, J-PARC,...). This topology is highly cost effective but does not allow any freedom on the current waveform for operation.
- A semiconductor based 4-quadrant converter with local capacitive energy storage as developed for the PS. This topology is significantly more expensive but allows more freedom on the current waveform and is well known and understood at CERN.

9.1.2 White circuit option

The associated supply to this LC resonant circuit only compensates for the losses in the magnets and the cables and helps to “tune” the oscillation frequency. This notably decreases the rating of the power supply needed for a given current and voltage applied on the magnets. The main drawback of this system is that only sinusoidal waveforms with a predefined operating frequency can be produced. Furthermore several seconds are needed to change the minimal and maximal current, which excludes PPM operation with different energies. Adding some trimmers to shape some portions of the cycle significantly decreases the efficiency of this method and then its interest. Alternatives option would be to introduce low order harmonics (Fermilab synchrotron option) or to actively modify the resonant frequency within a basic cycle.

Figure 9.1 — Example of resonant circuit with “tuneable” capacitors.

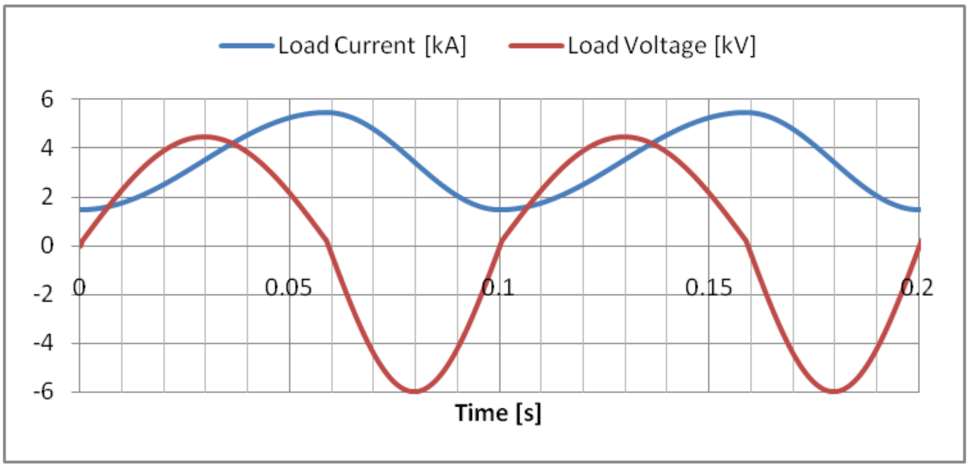


Switches S1 and S2 are closed when the voltage on C3 and C4 is at 0V and the current At its minimal value, increasing by this way the effective capacitance and slowing down the acceleration. The switches and related control must be designed carefully to avoid destructive discharge of the capacitors when charged.

This topology has never been implemented and the technical feasibility of asymmetric waveform still needs to be confirmed.

The magnet chain can be divided in n sub-modules in order to reduce voltage stress to ground by a factor 2n.

Figure 9.2 — Asymmetric sinusoidal waveform on the load (magnet + cables).



Only two “small” power supplies can induce the 14MVA needed on the load:
DC power converter ratings: 300V/3500A => 1MVA

AC power converter ratings: 200V/5000A => 1MVA including margin for 2% variation of the natural resonant frequency of passive components.
Space requirement: 400 m^2

9.1.3 POPS type option

This option was already considered for the upgrade of existing PS booster. The basic principle of a POPS-like topology is to manage the energy transfer between the magnets and a huge capacitor bank installed near the power converter. Only the power needed to compensate the electrical losses is driven from the 18 kV network, considerably reducing its stress. This would allow more flexibility on the MPS cycle without disturbing other users on the Meyrin site.

10 Hz operation of this system seems to be challenging but achievable. It still has to be demonstrated.

Figure 9.3 — General converter layout for POPS type alternative.

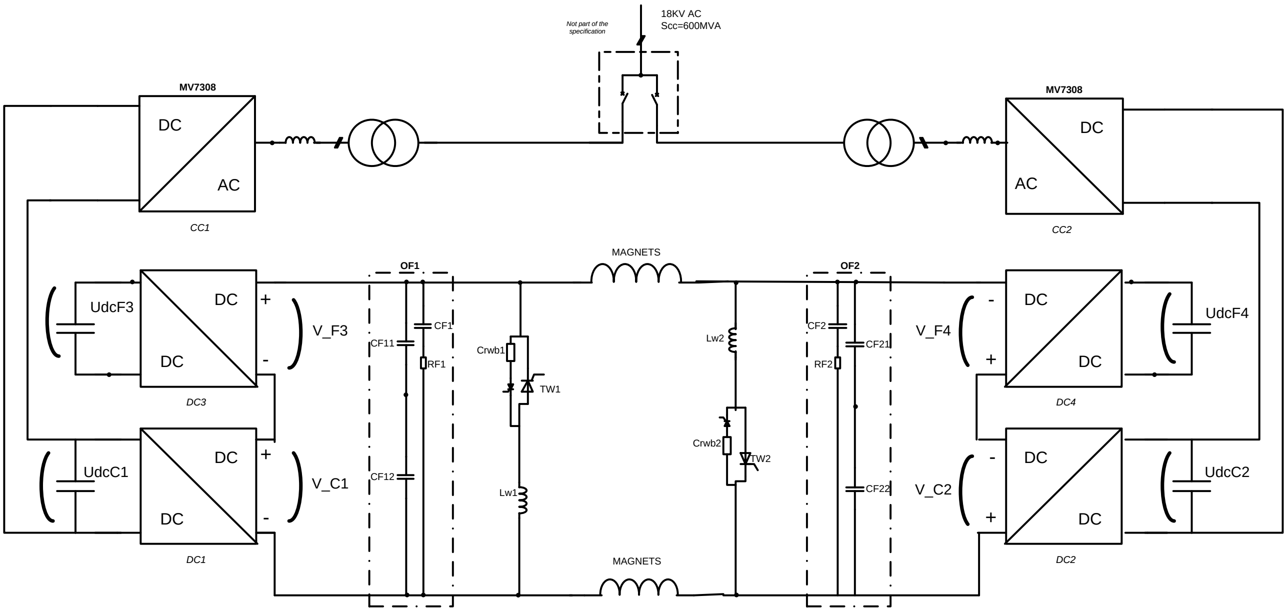
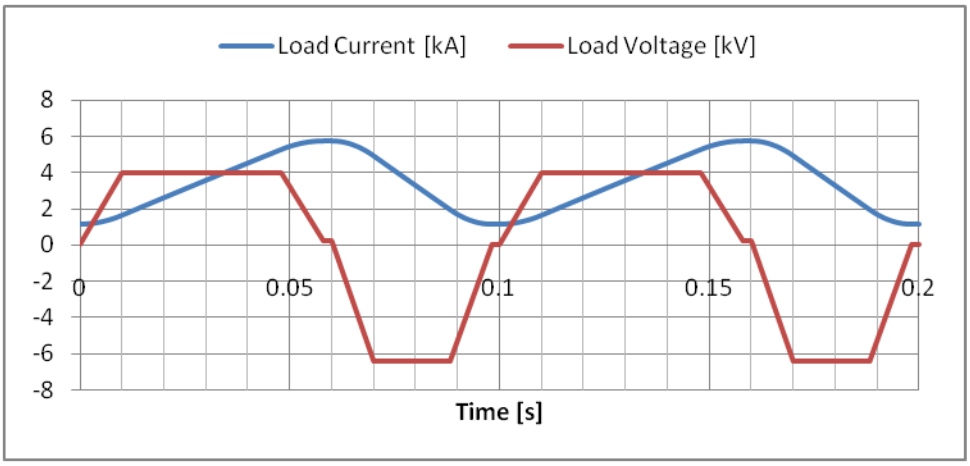


Figure 9.4 — Current cycle example with POPS alternative.



Active power from the 18 kV network: 700 kW
Power converter ratings: 6500 V/6000 A => 39 MVA
Space requirement: 400 m^2

9.1.4 Main quadrupoles power supply

Flexibility on the current adjustment is an important add-on to suppress the dispersion in the three machine straight section. One large 7000 V/4000 A main supply with active trimmers could be used, but the stability of such a system at a 10 Hz repetition rate is not confirmed yet. We then propose to split the focusing quadrupoles string in 4 similar sub-strings (3 times 6 magnets and 1 time 3 magnets).

In order to minimize the number of power converter families, the same strategy is applied to the defocusing magnets.
For each of the 8 quadrupole power supplies:
Active power from the 400 V network: 100 kW
Power converter ratings: 1000 V/4000 A => 4 MVA
Space requirement: 50 m^2

9.1.5 Correction magnets

Those magnets have to been specified yet, but the requirements can be extrapolated from comparable machines.

Assuming that all types of magnets are installed in the machine, only a part of them would be needed at the same time, reducing the number of converter to be installed.

Correction dipoles: 2 per 3 cells => 14

Quadrupoles, sextupoles and octupoles: 2 per cell => 42

Typical converter rating: 10kW

9.2 Budget Estimate

Civil engineering, services, water cooling, ventilation, 18kV feeders, magnet cables and fire detection not included.

Bending magnets power supply, asymmetric resonant option: 8MCHF.

Bending magnets power supply, POPS type option: 12MCHF.

8 Quadrupoles magnets power supplies (+1 hot spare): 12MCHF.

Correction magnets power supplies: 2MCHF.

9.3 Time Estimate

Starting from the formal approval of the project, 2 years would be needed for optimization, feasibility studies and converter pre-design. Another 3 years should be foreseen for production, installation and commissioning.

10. RF System [M. Paoluzzi]

10.1 Technical Description

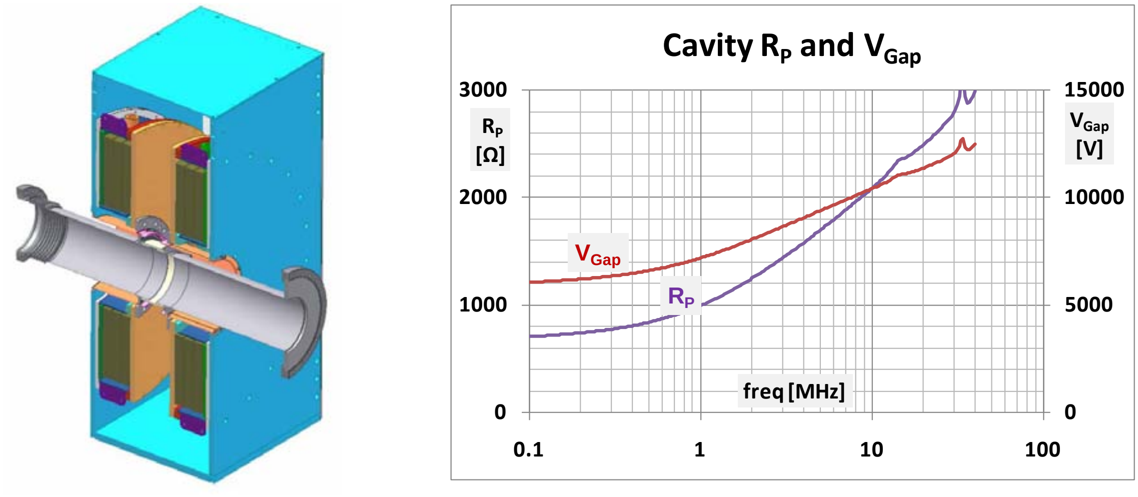
The main RCS parameters, from the RF system point of view, are listed in Table 10.1. The wide frequency range, the fast cycling and the limited available space in the straight sections, suggest the use of high-permeability materials and Finemet® is the magnetic alloy of choice because of the high value 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 10.1 — Main parameters.

Parameter	Value
Energy range	160 MeV to 2 GeV
Repetition rate	~10 Hz
RF voltage	60 kV
Revolution Frequency	1.3 MHz to 2.4 MHz
Harmonic numbers	h = 1 to 4
Frequency range	1.0 MHz to 10.0 MHz
Available length	2X2.35 m
Beam intensity	10^{13} 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. 10.1 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. 10.1 b). Limiting the low frequency duty-cycle to ~75 %, a nominal gap voltage of 8 kV can be achieved over the whole band.

Figure 10.1 — Cavity structure.

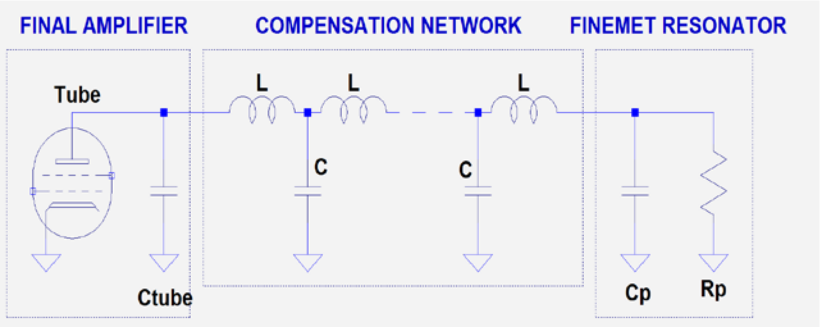


a **b**

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 (Figure 10.2).

Figure 10.2 — 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 two 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 10.3 plots the frequency response and table 10.2 lists the RF system parameters.

Figure 10.3 — Frequency response.

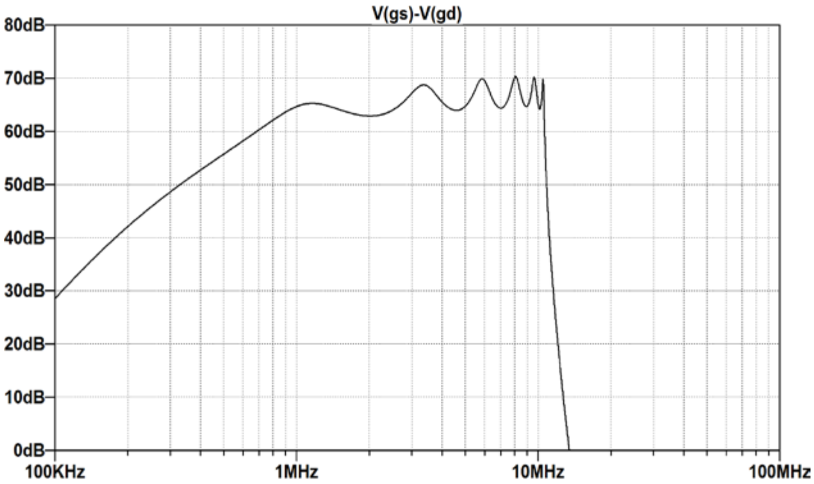


Table 10.2 — RF system parameters.

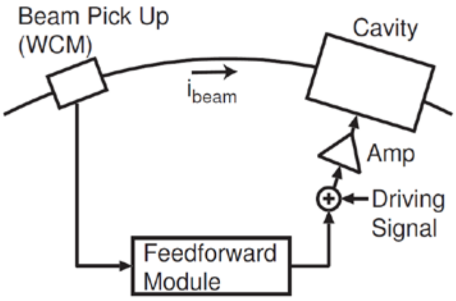
Parameter	Value
Cavity Gap Voltage	8 kV
Frequency range	1.0 to 10.0 MHz
Cavity power	26 kW
Cavity length	0.5 m
HV supply voltage	8 kV
HV supply current	~20 A

Plate power dissipation	55 kW
Driving power	250 W
Repetition rate	~10 Hz
Number of cavities	8
Total cooling water	60 m^3/hr
Cooling water ΔT	15 °C
Total required electrical power	~1500 kVA

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 sketched in Fig. 10.4 and successfully used in J-PARC[1]. The concept has proved its ability of reducing the beam induced voltages by more than 20 dB.

Figure 10.4 — Feed forward beam loading compensation.

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



10.2 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.

10.3 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.

---

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

11. Beam Intercepting Devices [O. Aberle]

11.1 Technical Description

For the RCS we consider the implementation of 1 beam dump + 1 spare and 2 beam stoppers + 1 spare. Other beam intercepting devices (collimators, scrapers...) are not included in this estimate. The beam parameters are beam energy of 2 GeV with Linac 4 intensities.

11.2 Budget Estimate

Based on the PSB studies the budget is estimated to 800 kCHF, including Fluka and thermo mechanical studies, design, material and manufacturing of 2 dumps and 3 beam stoppers.

11.3 Time Estimate

A period of 2 years is required for design, construction and testing of the objects.

12. Beam Instrumentation [J. Tan]

12.1 Technical Description

In [https://twiki.cern.ch/twiki/bin/view/PSBUpgrade/MinutesMeeting20April2011], a list of beams diagnostics for the RCS was proposed. In the following, a brief description of each instrument is given, without any detailed specification (resolution, precision, threshold...), and considering the new ring and its transfer line towards the PS. The transfer line between the Linac4 and the RCS is not included here as it uses most of the diagnostics systems which are already funded by the Linac4 project.

12.1.1 Synchrotron monitors

Beam position monitors

Orbit measurement is possible only with bunched beams. A couple of horizontal signals can be sent to the LLRF for radial loop. With the working point of $Q_H=4.2053$ and $Q_V=3.95$, it is proposed to implement 4 dual-plane BPMs per betatron wavelength, which gives a total of 16 units. The revolution frequency at 2 GeV being 2.37 MHz, one can estimate a maximum rms bunch length of 50ns for a filled bucket (h=1) and a minimum of 10 ns for the LHCPROBE beam. A capacitive BPM, in addition to its good linearity, is a broadband structure: it keeps information on the beam waveform and allows turn-by turn measurements. Due to space restrictions, it is proposed to use PS-type BPMs (see Figure 12.1), which would save significant space as they can be inserted into vacuum pump manifold.

Figure 12.1— Capacitive pick-up in the PS ring.

Wide band pick-up

A wide band pick-up is generally used for longitudinal phase space reconstruction. A wall current monitor with some hundreds of MHz bandwidth (300MHz for the PSB) is suitable for these applications. An operational unit and a spare one is recommended. About 400mm of machine space (flange to flange) is required.

Q-measurement

The FFT of the measured beam transverse oscillations gives the non-integer part of the tune. Again owing to space restriction, a set of dual-plane kicker and pick-up (stripline type) is proposed for this task. However they can be inserted inside quadrupole magnets.

Current transformers

In a synchrotron, a DC current transformer measures coasting beam currents while a semi-fast transformer allows studies of injection efficiency (turn by turn) : one of each monitor is needed in the RCS. About 550mm of machine space per monitor (flange to flange) is necessary. The transformers are integrated in the machine protection system (comparators...).

Beam Loss Monitors

BLMs are also integrated in the machine protection system. Fast monitors are required for a 10Hz cycling machine. From the proposed lattice, about of 20 BLMs would be spread around the ring.

Fast Wire Scanners

Beam profiles can be obtained with a Fast Wire Scanner (one device per transverse plane) for extracting the emittances. About 400mm of machine space per monitor (flange to flange) is necessary.

Scintillating screens

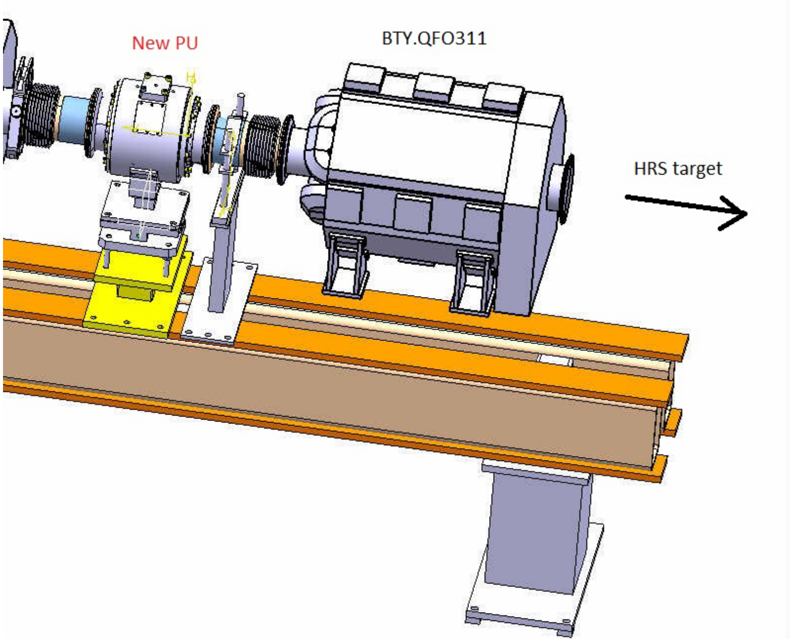
Such device is used for observing the beam nearby the injection foil.

12.1.2 Extraction line monitors

Beam trajectory measurements

For the RCS to PS extraction line, it is not possible to use the trajectory system foreseen for the Linac4, based on shorted striplines : wrong bandwidth and poor sensitivity in the MHz range are the main arguments to rule them out. It is proposed instead to equip the new transfer line with the inductive PUs, like those in the extraction-recombination line from the Booster to the PS (see Figure 12.2). With a set of 10 units which would be re-used from the decommissioning of the extraction-recombination line, about 15 additional monitors are needed to uniformly equip the RCS to PS extraction line.

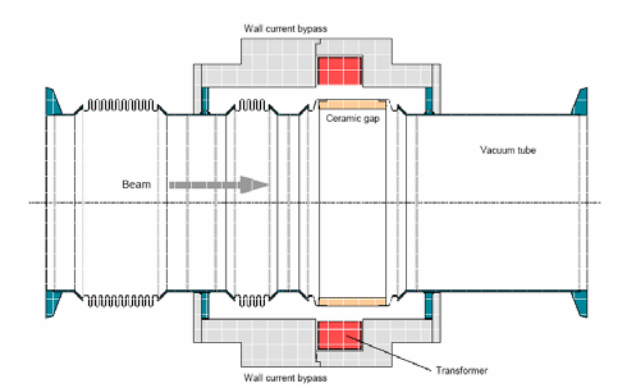
Figure 12.2 — Integration of the inductive pic-up in ISOLDE transfer line.



Current transformers

Fast transformers (see figure AA) are implemented in the transfer lines (injection and extraction). The present BT.TRA can be moved right downstream the RCS extraction point. The fast transformers are integrated in the machine protection system (watchdog). Basically the cost would be more related to the acquisition chain (electronics, cables, controls) than to the monitor itself.

Figure 12.3 — Principle of a fast current transformer.



Beam Loss Monitors

The number of BLMs in the transfer line depends on the optics. As a rule of thumb, they are placed nearby a septum, kicker or bending magnets. Ten BLMs as first guess seems to be a minimum prerequisite.

Scintillating screens

This monitor is generally housed in the extraction septum tank. A screen is associated with BLMs, which gives about 10 units placed along the extraction line.

SEM grids

In case the measurement line is kept, it is proposed to build new SEM grids, with integrated resistors for self testing, and shorter wire spacing for improved resolution. A set of three monitors has to be foreseen.

12.2 Budget Estimate

The total budget estimate is the minimum needed as some instruments shall be taken from the decommissioning of the PSB and its transfer line. The table below summarizes the request per instrument, including : the monitor, the tank and its support, the drawing office, the controls (crates, CPUs, timings), the acquisition chain (ADCs, amplifiers), the cables, and some external support (FSU). A spare is foreseen for critical instruments.

Instrument	Budget [kCHF]	Comments
Pick-ups	760 + 640	RCS + transfer line
Wide band pick-up	165	RCS
Q measurement	176	RCS
DCCT + Fast BCT	190	RCS
Beam loss monitors	205	RCS + transfer line
Fast wire scanners	205	RCS
Scintillating screens	366	RCS + transfer line
SEM grids	200	transfer line
TOTAL [kCHF]	**3,073**	

12.3 Time Estimate

The beam parameters in the RCS being similar to those in the PSB, the required resolutions and precisions from the new monitors might be improved but are not expected to be very challenging. Hence profiting from CERN’s sound knowledge of hadron machines, the time estimate for making the RCS instruments with standard technology is at least three years, provided the needed human resources are allocated.

13. **Controls** [S. Jensen]

13.1 Technical Description

The estimate is based on 40 VME crates, related CPUs, timing, OASIS, cabling and networks.

Excluded would be any cabling, networks and modules specific to each equipment group - this will fall under their budgets.

13.2 Budget Estimate

The estimate for the controls system of the RCS is 1 million ChF.

13.3 Time Estimate

Not considered a time driver.

14. Vaccuum System [J. Hansen]

14.1 Technical Description

The RCS will be designed with undulated stainless steel vacuum chambers similar to the vacuum chambers used in the PSB bending magnets. The machine will be a non baked and non coated vacuum system using Ion pumps as the main pumping.

14.2 Budget Estimate

The rough cost estimate for the RCS has been based on the latest cost estimate made for PS2 in November 2009 and the budget is estimated to be approximately 3 Million CHF. It is an estimation which is not based on a detailed knowledge of the machine and of its requirements.

Below is a list of items which were not included in the PS2 cost estimate nor in this estimate for the RCS, these are:

- Special machine equipment (kicker, septa, cavities) and their pumping.
- The interfaces expected integration issues with other beam components and contingencies must be foreseen for that.
- The 3D integration of the vacuum system.
- Tunnel infrastructure (electrical distribution, compressed air).
- The manpower for such machine is NOT and cannot fit within the existing MTP plan.

14.3 Time Estimate

Not considered a time driver.

15. Beam Interlocks [B. Puccio]

15.1 Technical Description

The Beam Interlock System (BIS) is a generic solution to protect CERN accelerators and facilities. It is currently in operation for the SPS ring, the SPS transfer lines and for the LHC. It will be deployed in LINAC4 and PSB.

The system is composed of remote User Interfaces (CIBUs) and Controller(s). The latter is embedded in VME crate: it receives the CIBUs information and evaluates the USER_PERMIT signals in order to produce a BEAM_PERMIT signal.

15.2 Budget Estimate

The cost will mainly depend of the number of connected systems, and their distance (=> cables length) with the Beam Interlock Controller(s).

For a first estimation, we assume that the number of User systems will be equivalent to the Booster and the BIS architecture will be the same as well. Therefore, the corresponding budget will be roughly 200 kCHF.

15.3 Time Estimate

From the time of project approval, including study, ordering, manufacturing and testing in the lab, an estimate for readiness to a commissioning is approximately 12 months.

16. Civil Engineering [L.A. Lopez-Hernandez, A. Kosmicki]

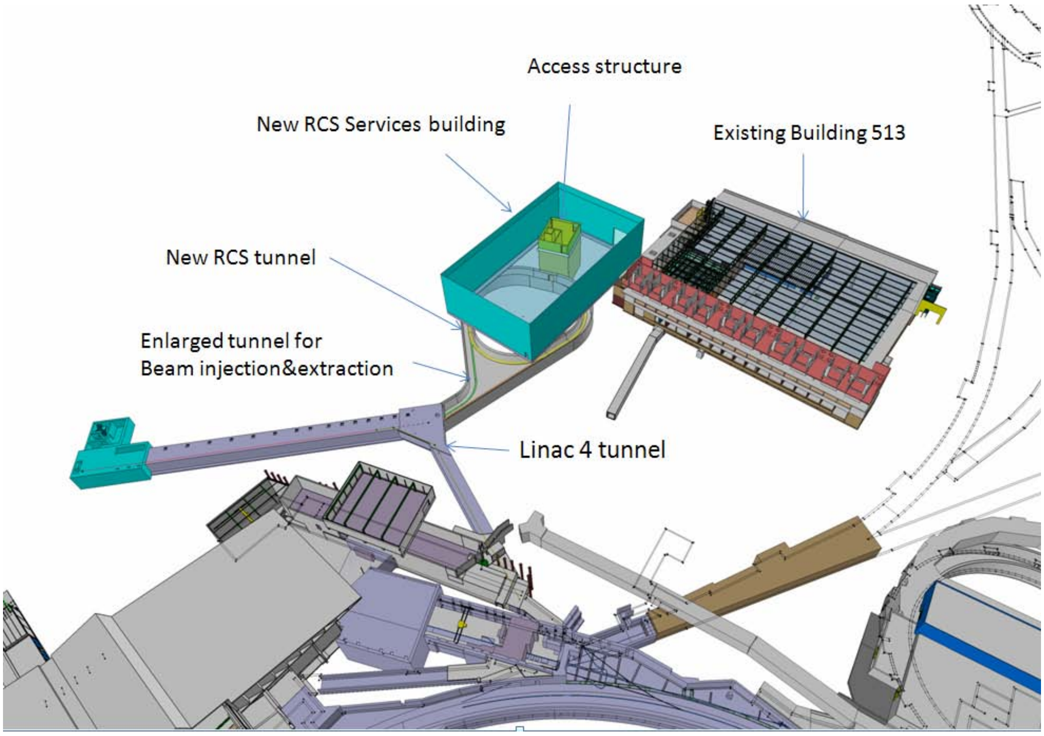
16.1 Technical Description

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 16.1 – RCS design May 2011.

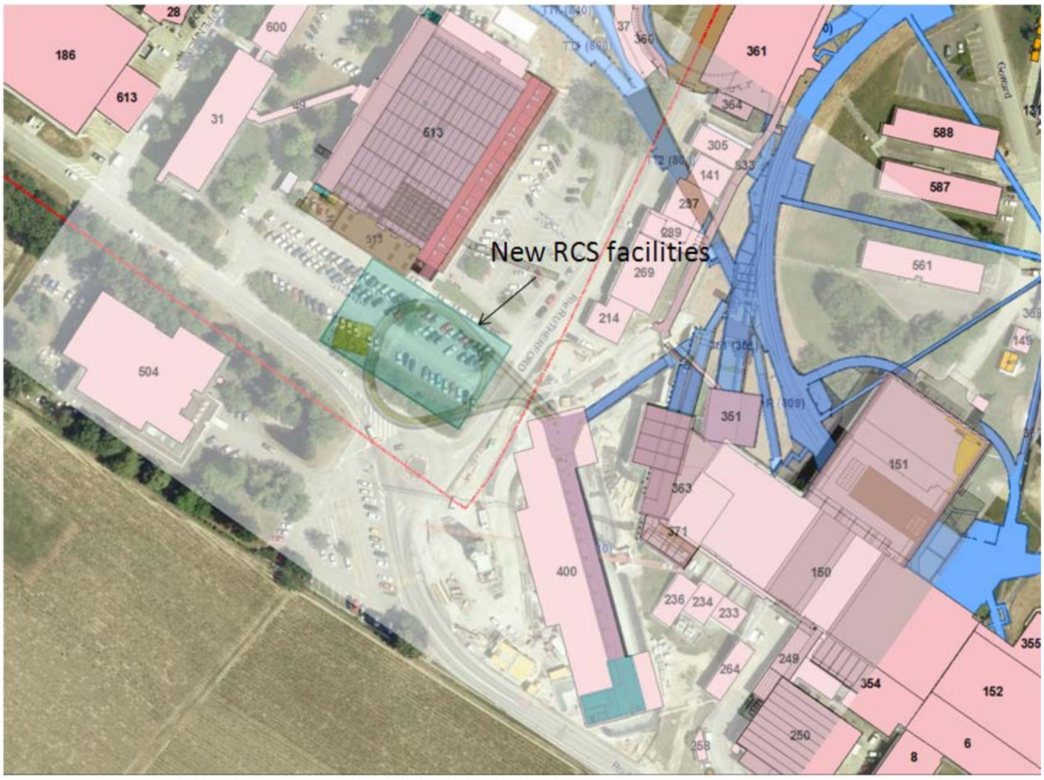


16.1.1 Description of the site and geotechnical aspects

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 16.2 - 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.

16.1.2 Description of the underground structures

16.1.2.1 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.

16.1.2.2 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.

16.1.2.3 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.

16.1.2.4 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.

16.1.2.5 Modifications to existing Linac4 tunnel

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

16.1.3 Description of the surface structures

16.1.3.1 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.

16.1.3.2 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.

16.1.3.3 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.

16.1.3.4 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:
-Cooling and ventilation
-Electrical infrastructure
-Handling and lifting equipment
-Access control, safety and interlock systems
-Mechanical features

16.2 Budget Estimate

16.2.1 Budget estimate

	Cost (CHF) (estimate may 2011)
Sub-surface works	10 890 000
Surface works	8 530 000
CE studies and site supervision	2 100 000
Miscellaneous	1 610 000
TOTAL	**23 130 000**

16.2.2 Spending profile

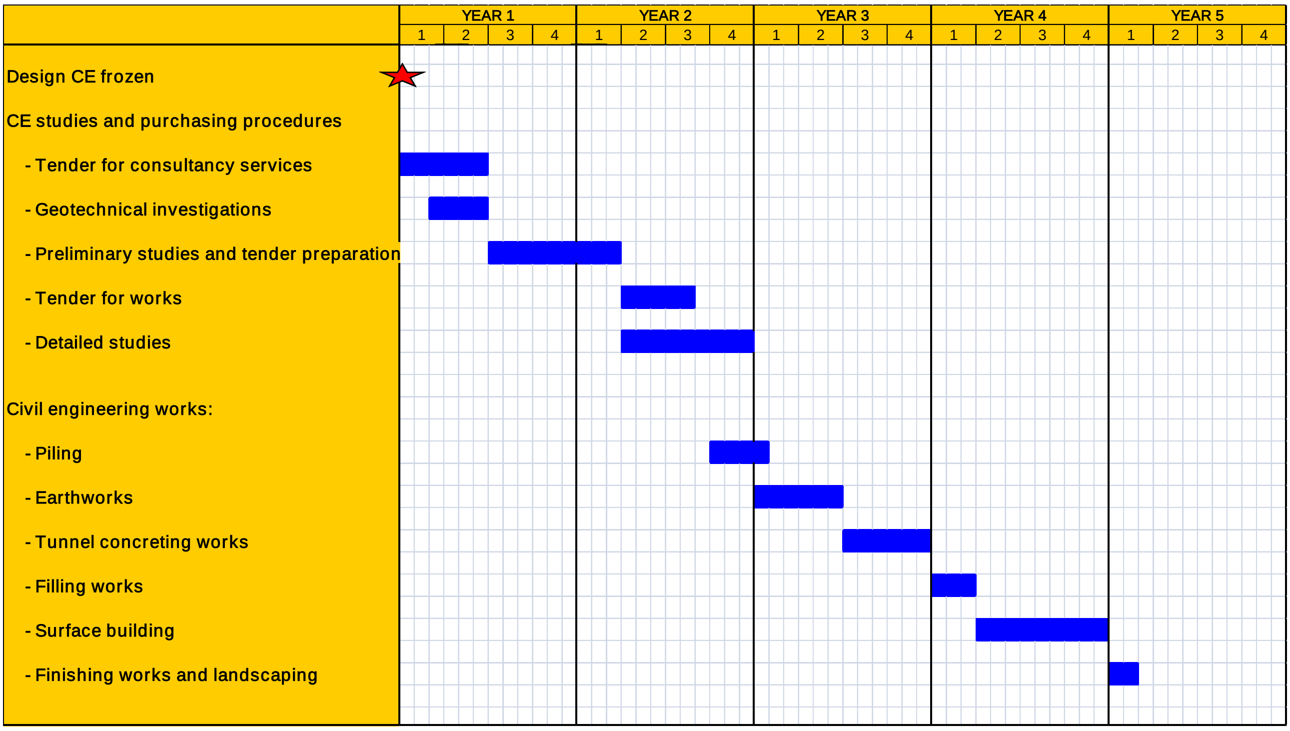
	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
KCHF	450 000	900 000	8 000 000	8 000 000	4 000 000	1 780 000

16.2.3 Manpower estimate

In FTEy	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Eng.	1.0	1.0	1.0	1.0	0.3	0
Tech.	1.0	1.0	1.5	1.5	1.0	0.5

16.3 Time Estimate

Figure 16.3 - Preliminary works schedule



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

17.1 Technical Description

The cooling of the RCS shall be ensured by a new station composed by a primary circuit with a set of cooling towers and 2 secondary circuits, one for the equipment in the surface building and the second for the equipment in the tunnel. The present solution is foreseen according to the estimated cooling loads that correspond to 1.5 MW for the magnets ; around 300 kW are accounted for the power converter. In case of any other additional load the technical solution might be completely modified. NO circuit separation has been requested for operational or risk of activation reasons.

The location of the RCD close to areas open to the public (restaurant no. 2 of CERN) will most probably require to use of dry cooling towers with the highest performace possible in terms of noise reduction and the related cost will be taken into account once a detailed study will be performed.

The ventilation system is requested for RP reasons to create in the RCS tunnel an overpressure with respect to LINAC 4 tunnel. No other needs or technical loads have been communicated in the tunnel as well as in the surface building, therefore any specific cooling is foreseen. Two units (N+1 redondance) will supply air in the tunnel that will be extracted on the other side of the tunnel by two extraction units (N+1 redondance). A separate ventilation system shall be installed for the surface building that, at present, is considered as a single volume.

17.2 Budget Estimate

According to the present state of knowledge of the thermal load to be removed by the cooling and ventilation plants the following costs are estimated:

Cooling plant: 1.4 MCHF

Ventilation plant: 1.3 MCHF

Ancillary costs for civil engineering and specific solutions such as the noise reduction system are not included in the estimate as well as all cost related to the distance between the emplacement of the future stations and the RCS premises.

The estimates cover only the demineralised water station and the ventilation system ; all other related plants such as the chilled water one and raising systems etc. are not taken into account since the solution that will be taken (independent station or connection to an existing one) cannot be defined at the present level of detail of the study.

A big uncertainty has to be taken into account on the estimate since the technical requirements provided are very few and several equipment groups have not expressed their need yet. Cost variations can therefore be more than 30%.

17.3 Time Estimate

The construction time for such stations will be the same as for the PSB upgrade, i.e. 6 months for design, 9 months for tendering and 6 to 9 months for work and commissioning; this last duration shall strongly depend on the complexity of the plant and the distribution system that, at this level of detail, is not yet known.

18. Electrical Systems [D. Bozzini, S. Olek]

18.1 Technical Description

A new 18 kV substation may be necessary. The 18 kV substation localization is near the future RCS services building because of the main power converters transformers close localization. The substation is composed of the following components:

- 18 kV switchgears (first one for general services loads and second one for machine loads),
- Protection relays for 18 kV switchgears;
- 18/0.4 kV power transformers for general services, cooling and ventilation, RF loads, and transfer line loads powering;
- LV switchboards for 400 V distribution;

- Monitoring and control system equipment (ENS SCADA system hardware);
- 48 DC power supply system composed of the batteries, battery chargers, and power distribution rack;
- UPS systems according to redundancy requirements;

The substation equipment will be installed on metallic false floor structure. Construction of new technical gallery or cable ducts will be necessary to connect the RCS substation building to existing Meyrin technical galleries network. New 18 kV cable lines will be installed to power the RCS 18 kV substation from existing 18 kV substations.

18.2 Budget Estimate

Based on the PS Booster upgrade studies and the description given above the preliminary budget for RCS is estimated to 3 MCHF.

The budget amount may increase as many factors are not known/confirmed at the moment namely:

- Position of the 18 kV substation;
- Additional power demand for transfer lines and CV system;
- 400 V distribution system requirement that will be larger in comparison to existing one (preliminary info from S. Pittet);
- Additional transformer for RF power increase from present several hundreds kVA to about 2.5 MVA (preliminary info from M. Paoluzzi);
- Technical gallery or cable ducts requirements to connect the RCS substation building to existing technical galleries;
- Power cables lengths according to project layout;
- Operation of the PSB during commissioning phase of the future RCS;
- …

18.3 Time Estimate

A period of approximately 2 years is required for electrical infrastructure design, material purchase, assembly, connection to existing systems, and system testing. As the electrical infrastructure is supposed to be installed in new RCS services building the construction works start time will depend on the building construction schedule.

19. **Transport Systems** [I. Rühl]

19.1 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.

19.2 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.

19.3 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

20. **Radiation Protection** [M. Widorski]

Radiation protection aspects have to be considered during all phases of the RCS project. Especially during the design phase sufficient manpower and time has to be allocated to the different work packages to consider the radiological aspects of their equipment.

The operational parameters for the RCS shall include a credible margin for future upgrades. The civil engineering and technical installations shall be based on these maximum parameters, currently assumed to be 32 kW at 2 GeV. These values will give the boundary conditions for the authorization of the RCS operation.

20.1 Technical Description

20.1.1 Radiation monitoring

The radiation monitoring required for the RCS installation comprises induced activity monitoring in the accelerator area, stray radiation monitoring in accessible areas close to the accelerator and at weakly shielded locations, monitoring of effluents like air and water, monitoring of eventual X ray producing devices and of radioactive storage areas as well as instruments for the control of radioactivity. The budget and schedule estimate are given in the tables in chapter 16.2 and 16.3.

20.1.2 Civil engineering aspects

The RCS will operate at an average beam power[2] of 32 kW provided by protons at 2 GeV kinetic energy. The shielding surrounding such an installation is the most important barrier to protect its environment against ionizing radiation originating from the stray radiation of the lost beam fraction. Shielding shall be foreseen providing sufficient protection against stray radiation during normal operation to meet given dose constraints and during accidental situations to limit radiation exposure below legal limits.

The RCS will be situated at the level of the Linac 4 installation (floor level 429.9 m) and has an approximate distance from beam to surface of 12 m. The distance to the closest building (B.513) will be about 15.5 m. The beam transfer line towards the PS ring bends up by about 2.5 m in order to join the PS beam level. The beam line points upwards just before entering building 363, the current Linac 2 building. No measurement beam line is considered in the current LTS/LTE line for the RCS beam. By entering the Linac 2 building the shielding situation becomes complex. The top coverage as well as the side shielding is weak towards building 353 (Linac 2 rack gallery), the emergency exit from building 353, the technical gallery TP9 and the area on top of the transfer line. When entering the PS tunnel, the top shielding is further reduced.

The appropriate radiation shielding thickness is a function of the operated beam power and the credible fraction of the lost beam as well as considerations on accidental beam loss. The position and layout of the RCS as proposed in this note provides a sufficient shielding around the accelerator structure for the operation at 32 kW beam power assuming a scenario of less than 10 W beam power lost and a maximum annual dose of 100 uSv on the CERN site or in proximate buildings. Specific loss points such as injection and dump areas need reinforced shielding and to be studied in detail. An

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[2] This value is based on pulses of 1E13 protons at a repetition rate of 10 Hz.

efficient beam loss management system including beam current watchdog, beam loss and radiation monitor interlocks must be implemented.

The beam transfer line towards the PS ring moves 2.5 m upwards in order to join the level of the PS ring. As this beam line is currently designed to contain the Linac 4 beam (160 MeV, 2.8 kW beam power), the level change has currently not been compensated in terms of shielding on top of the transfer line. The additional shielding foreseen in building 353 has only been designed for the Linac 4 beam power. Therefore, the complex layout at the junction of buildings 353 and 361, the technical galleries TP9 as well as the emergency exit from building 353, require important civil engineering works and exclusion zones to accommodate for the RCS beam in the transfer line. The proximate part of building 353 towards the transfer line will have to be partially filled with concrete, requiring the complete re-routing of cabling and fluent supply from building 353 towards the LT/LTB line and the PS tunnel. The emergency exit from the building has to be displaced and the current exit to be blocked. The parts of the galleries passing on top of the transfer line will have to be closed for access during beam operation. An additional earth hill will have to be installed on top of the RCS transfer line from where it joins the PS tunnel. The required amount of earth can be adapted as function of the accessibility of this area.

The shielding increase on top of the PS tunnel (SS16 ejection region) is planned to extend to areas where the RCS crosses the PS tunnel.

From the part where the RCS beam enters the PS Booster tunnel, the situation remains the same as for the PSB energy upgrade project with Linac 4 as injector, considering the same nominal beam power. It is considered that only about one fifth of the available RCS beam power will be delivered via the current BTP line to the PS (max. 2E13 protons per second). The remaining beam power could be provided to an upgraded ISOLDE installation.

Activation studies must be performed defining the required concrete liner thickness of the RCS tunnel.

20.1.3 Infrastructure aspects

All openings towards the RCS accelerator tunnel must be implemented such to provide approximately equivalent shielding coefficients as in the neighbouring solid sectors. All ducts have to be built sufficiently air leak tight and have to include chicanes to minimize radiation streaming through the openings.

A ventilation system shall be installed providing a dynamic air confinement of the RCS and transfer tunnel during beam operation. The air leakage rate shall be reduced to a minimum by civil engineering measures while maintaining a sufficient depression. Separate ventilation systems have to be foreseen for other areas as they cannot share that of the RCS tunnel. The RCS tunnel shall remain in over pressure towards the Linac4 tunnel, considering possible Linac 4 operation while the RCS remains in access mode.

Water cooling systems shall be exclusively used for systems located in the RCS tunnel and not connect to other devices, especially those located in areas where activation is negligible.

The routing and choice of ventilation ducts and water pipes shall consider the potential radioactive content in the fluids.

Sufficient premises shall be foreseen to buffer, store and maintain radioactive material removed from the RCS in proximity of the accelerator installation.

20.1.4 Radioactive waste

At the end of its lifetime the RCS will have to be completely dismantled. Radioactive waste costs are inherently linked to the RCS project, hence they have to be considered already at this stage. In this note, only an approximate cost estimate has been established to be considered for waste conditioning and elimination. Dismantling costs are not included.

20.2 Budget Estimate

20.2.1 Radiation protection monitoring

Induced activity monitoring (7 channels)	110 kCHF
Stray radiation surveillance (4 channels)	140 kCHF
Ventilation monitoring (1 station)	90 kCHF
Laboratory and X ray monitoring (5 channels)	70 kCHF
Personnel monitoring (2 channels)	40 kCHF
Total	**450 kCHF**

20.2.2 Infrastructure

Buffer area	40 kCHF
Radioactive material storage	100 kCHF
Total	**140 kCHF**

20.2.3 Radioactive waste from dismantling

RCS and transfer beam line equipment (194 m^3)	230 kCHF
Medium activated beam line equipment (20 m^3)	2.200 kCHF
Infrastructure (210 m^3)	250 kCHF
Civil engineering structures (420 m3)	500 kCHF
Waste conditioning (810 m3)	350 kCHF
Free release and activity measurements (810 m3)	500 kCHF

Total	**4.030 kCHF**

20.3 Time Estimate

20.3.1 Radiation monitoring

Definition and procurement	12 months
Installation and commissioning	6 months

21. Upgrade of Linac4 for 10 Hz Operation [M. Vretenar]

21.1 Technical Description

Linac4 has not been designed for operation at 10 Hz, and would need to be modified in case it was to inject into the RCS. The modifications are related to the ion source, electromagnetic quadrupoles, RF pulse length and cooling, power converters, as well as the Linac4-RCS transfer line. The impact on these items has been analysed and summarised in a separate document [4].

21.2 Budget Estimate

The cost of the modifications of Linac4 are summarised below.

Ion source	3.0 MCHF
Quadrupoles	0.7 MCHF
Power converters	3.9 MCHF
Transfer line	1.1 MCHF
Measurement lines	0.5 MCHF
TOTAL	9.2 MCHF

21.3 Time Estimate

No time estimate, but significant impact on the Linac4 construction and commissioning schedule is to be expected.

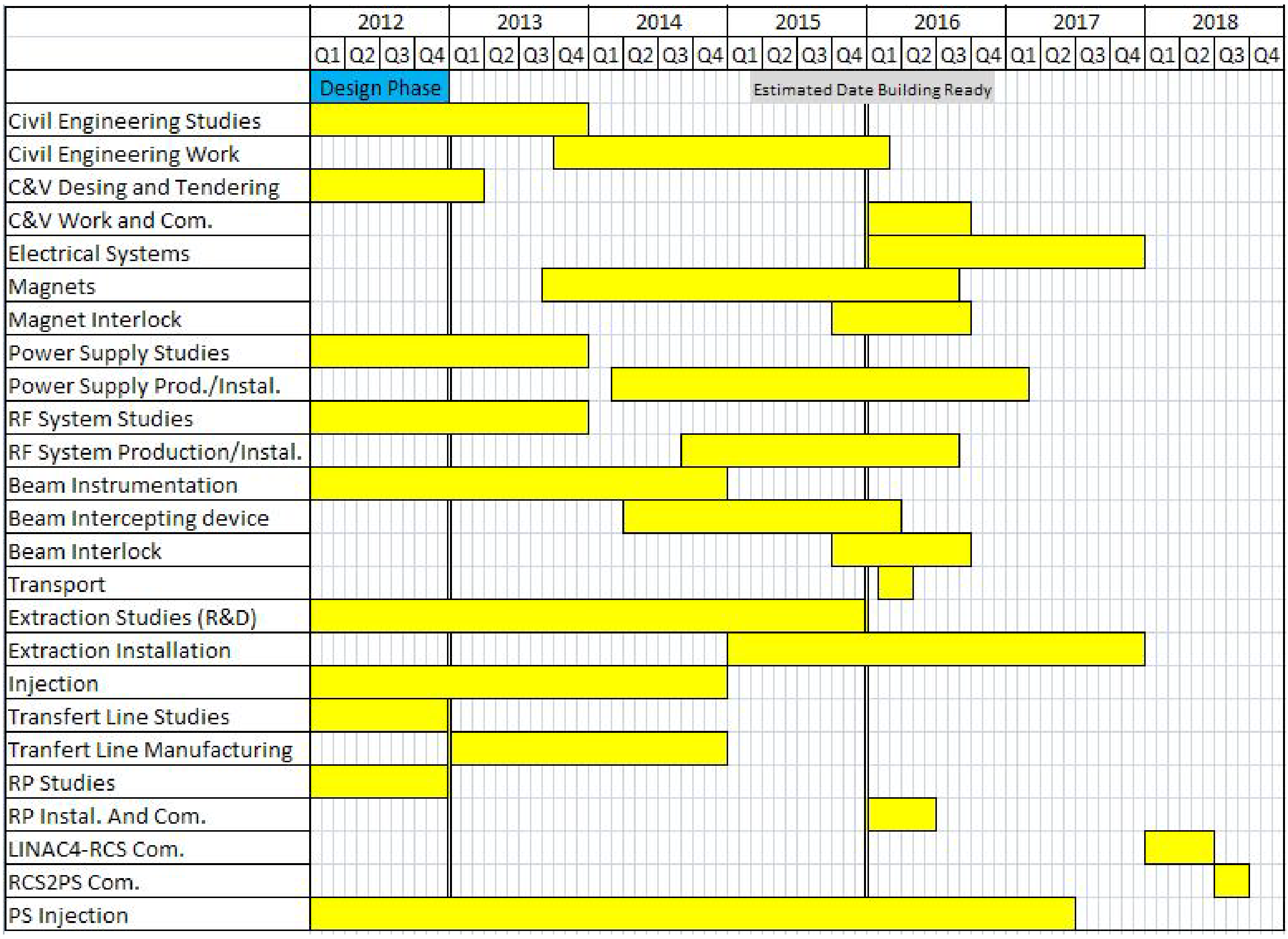
22. Budget Summary [K. Hanke]

system	cost estimate [kCHF]	time estimate (from project approval)
Operational Aspects	50	RCS commissioning: 6 m Transfer line and PS commissioning: 3 m
Design & Parameters	-	-
RCS injection and extraction	17470 (for h1,2 baseline) 32670 (for h4)	injection 3 y extraction 4 y R&D plus 3 y installation
RCS2PS Transfer Line	8529	1 y design phase 2 y manufacturing
PS Injection	3285	5 y
Magnets	9756	36 m
Magnet interlocks	300-500	12 m
Power supplies	22000 (resonant) 26000 (POPS type)	2 y study & design 3 y production, installation, commissioning
RF Systems	13000	2 y development 2 y production/installation
Beam Intercepting Devices	800	2 y
Beam Instrumentation	3073	not considered time driver
Controls	1000	not considered time driver
Vacuum System	3000	not considered time driver
Beam Interlocks	200	12 m
Civil Engineering	23130	4 y 2 m
Cooling & Ventilation	2700	6 design 9 m tendering 6 - 9 m work and commissioning
Electrical Systems	3000	2 y, building must be ready!
Transport Systems	890	3 m
Survey	-	-
Radiological Protection	4620	18 m

Linac4 Modifications	9200	impact on Linac4 construction and commissioning schedule to be analysed

23. **Planning Summary** [V. Raginel]

Below we give a preliminary project planning, assuming a project start in January 2012 with one year of design phase. Assuming that the building of RCS will be r in January 2016 and the chart shows an estimated date for the RCS to be ready on October 2018.



24. References

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[3] M. Benedikt, H. Burkhardt, C. Carli, R. Garoby, B. Goddard, K. Hanke, H. Schönauer, A.-S. Müller, “Lattice Design of a RCS as Possible Alternative to the PS Booster Upgrade”, IPAC’11, to be published.

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