POSSIBLE SCENARIOS FOR THE LHC INJECTOR UPGRADE*

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Abstract

The possible upgrade of the LHC injector chain is a crucial step towards the LHC luminosity upgrade beyond 10^{34} cm^{-2}s^{-1}. It is also a mandatory requirement for the LHC energy upgrade well beyond the ultimate value of 7.56 TeV per beam. By pushing the accelerator parameters to the ultimate performance we can increase to 1.7×10^{11} the bunch population and eventually reach a peak luminosity of 2.3×10^{34} cm^{-2}s^{-1}. To go beyond, a considerable improvement of the LHC parameters, such as ß*, beam intensity, bunch length, number of circulating bunches is required. Finally, the upgrade of the injector complex and of the injection energy is another important ingredient to upgrade both peak and integrated luminosity up to an order of magnitude above the nominal value.

LHC PERFORMANCE LIMITATIONS

In Table 1 we show two intermediate scenarios towards nominal luminosity. One of them assumes 75 ns bunch spacing and ß* = 1 m, in view of exploring and mastering multibunch operation, beam pipe cleaning mitigating the electron-cloud effect, ß-squeezing and collisions with finite crossing angle. The other scenario with 25 ns bunch spacing and less than half of bunch population is intended to investigate and control operation with nominal values of ß*, crossing angle and bunch spacing at reduced current. Reaching the nominal performance may last up to four years, also in consideration of the staged installation of collimators and dilution kickers in the beam disposal system and of the progressive cleaning of the vacuum pipe. Refs. [1-2] describe in details the phenomena inducing performance limitations in LHC and the possible way to nominal and ultimate performance.

MOTIVATION FOR A LUMINOSITY UPGRADE

The LHC is the result of the High Energy Community's effort, lasting more than two decades and involving enormous intellectual and financial resources. Launching a vigorous programme for the luminosity upgrade to exploit the full potential of the LHC seems a rather obvious decision.

Indeed, the expected run-time halving the statistical errors is a rather steep function of elapsed LHC lifetime. We can evaluate it, assuming that the first-year luminosity is a tenth of the nominal one, and that its increase is almost linear over four years, up to the nominal value of 10^{34} cm^{-2}s^{-1}. Four years after the LHC start-up when the nominal luminosity is reached, less than two years will be required to multiply by four the set of collected data. Another three years later, however, more that five years will be requested for a fourfold increase of the data. In these conditions, the stability of the experimental apparatus and the consistency of the data set may become serious issues.

On the other hand, collision debris will induce cumulative radiation damages in the inner triplet eventually reducing their expected lifetime. In the LHC insertions, the damage threshold typically corresponds to 700 nb^{-1} integrated luminosity. This limit is eventually reached in about seven years. In this eventuality, installing new quadrupoles with higher gradient and larger aperture will also ensure a tighter beam focusing and hence a substantial increase of the LHC peak luminosity.

Table 1: main steps to nominal performance in LHC.

Parameter	Units	75 ns	25 ns	Nominal
No. of bunches	n_b	936	2808	2808
Proton per bunch	N_b [10^{11}]	0.9	0.4	1.15
Normalis. emittance	ε_n [μm]	3.75	3.75	3.75
rms bunch length	σ_s [cm]	7.55	7.55	7.55
rms energy spread	σ_E [10^{-4}]	1.13	1.13	1.13
IBS growth time	τ_x^{IBS} [h]	135	304	106
Beta at IP	β^* [m]	1.0	0.55	0.55
Full crossing angle	θ_c [μrad]	250	285	285
Luminosity lifetime	τ_L [h]	22	26	15
Peak luminosity	L[10^{34}cm^{-2}s^{-1}]	0.12	0.12	1.0
Events per crossing		7.1	2.3	19.2
$\int_{\text{over 200 runs}}$ L dt	L_{int} [fb^{-1}]	9.3	9.5	66.2

BEYOND THE NOMINAL LUMINOSITY

Table 2, discussed in Ref [1], shows parameters and expected performance of the nominal scenario and of the so-called ultimate luminosity scenario, with a bunch population of 1.7×10^{11} protons and a peak luminosity of 2.3×10^{34} cm^{-2}s^{-1}. It also contains three possible upgrade scenarios: (1) with 12.5 ns bunch spacing, (2) with a large Piwinski angle and 75 ns bunch spacing, and (3) the so-called superbunch scheme, with a single very long and dense bunch per beam. In all of them the peak luminosity is expected to become about 10 times larger than nominal, provided the β^* is reduced by a factor 2 to 0.25 m and the crossing angle increased by an appropriate amount. In addition, the circulating current will increase by at least a

*Work including discussions following the LHC-LUMI-05 workshop and supported by the European Community-Research Infrastructure Activity under the FP6 "Structuring the European Research Area" programme (CARE, contract number RII3-CT-2003-506395).
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Table 2: Possible scenarios for the LHC luminosity upgrade.

Parameter	Symbol	Nominal luminosity	Ultimate luminosity	Shorter bunch	Longer bunch	Super bunch
No of bunches	n_b	2808	2808	5616	936	1
Proton per bunch	N_b [10^{11}]	1.15	1.7	1.7	6.0	5600
Bunch spacing	Δt_{sep}[ns]	25	25	12.5	75	89×10^3
Average current	I [A]	0.58	0.86	1.72	1.0	1.0
Normalized emittance	ε_n [μm]	3.75	3.75	3.75	3.75	3.75
Longitudinal profile		Gaussian	Gaussian	Gauss.	flat	flat
rms bunch length	σ_s [cm]	7.55	7.55	3.78	14.4	6×10^3
ß* at IP1&IP5	β^* [m]	0.55	0.50	0.25	0.25	0.25
Full crossing angle	θ_c [μrad]	285	315	445	430	1×10^3
Piwinski parameter	$\theta_c\, \sigma_s/(2\sigma^*)$	0.64	0.75	0.75	2.8	2.7×10^3
Luminosity	L [10^{34}cm^{-2} s^{-1}]	1.0	2.3	9.2	8.9	9.0
Events per crossing		19	44	88	510	5×10^5
l_{rms} of luminous region	σ_{lum} [mm]	44.9	42.8	21.8	36.2	16.7

factor 1.7, the crossing angle by at least a factor 1.5 and the number of events per crossing by at least a factor of 2.3.

In the superbunch scenario the latter quantity will have the prohibitive value of 5×10^5, incompatible with the state of the art of today's particle detector technology.

UPGRADE OF THE LHC INJECTION ENERGY

Motivations to upgrade the LHC injection energy are based on the well-known argumentations. At higher energy, the adiabatic damping is larger and the ratio of the injected beam area over the available mechanical acceptance smaller than in the today's nominal conditions. On the other hand, the injection field in the LHC dipoles is larger and the relative value of the field shape harmonics, induced by dynamics effects, proportionally smaller.

Therefore, higher injection energy should guarantee from one side a *larger circulating current* and hence a larger peak luminosity, from another side a *shorter turnaround time*, i.e. the average time elapsed between two consecutive runs, with a consequent increase of the integrated luminosity. Indeed, the expected luminosity gain should be larger if the collimation and the protection systems have no constraints in handling larger currents and if, reducing the dynamic effects in the superconducting magnets and the filling time of the LHC rings, we can substantially shorten the turnaround time. The operational experience of LHC will clarify these issues in due time.

In addition, increasing the injection energy is a necessary step to *increase the LHC beam energy* beyond the ultimate value presently achievable of 7.56 TeV per beam, without changing the energy swing and hence the span of magnetic field during the ramp of the LHC main magnets. However, increasing the LHC beam energy needs replacing all the LHC magnets and hence will be a major investment, both in terms of needed R&D and new resources.

Reduction of the turnaround time

In a superconducting ring, such as LHC, the checks and the adjustments requested between two fills will strongly depend on machine reproducibility and should be somehow reduced when increasing the energy of the injection plateau and of the snap-back. Indeed, the range of variation of the cable magnetization should decrease at least proportionally to the injection energy, with a consequent reduction of all kind of dynamic effects in superconducting cables.

By doubling the LHC injection energy we should have a more stable and reproducible magnetic cycle, and most likely a shorter turnaround time. Presently we expect a turnaround time of 10 hours in LHC. By injecting at 1 TeV, we may hope reducing it by a factor of two, from 10 to 5 hours.

In Table 3 we consider two situations, one with nominal luminosity and another with ten times higher peak luminosity, and we show how a twofold shortening of the turnaround time may affect the LHC performance.

Table3: integrated luminosity versus turnaround time

L_0 [$cm^{-2}s^{-1}$]	t_L [h]	$T_{turnaround}$ [h]	T_{run} [h]	$\int_{200\ runs}$ L dt [fb^{-1}]	gain
10^{34}	15	10	14.6	66	1.0
10^{34}	15	5	10.8	85	1.3
10^{35}	6.1	10	8.5	434	6.6
10^{35}	6.1	5	6.5	608	9.2

We based our calculation of the gain on the hypothesis that the luminosity decay is exponential and hence the *optimal run time* T_{run} will be computed using equation (1):

$$1+\frac{T_{run}+T_{turnaround}}{\tau_L}=e^{\frac{T_{run}}{\tau_L}}, \qquad (1)$$

where $T_{turnaround}$ is the turnaround time and τ_L is the e-folding decay constant of the instantaneous luminosity.

In these circumstances, the integrated luminosity per run is:

$$\int_0^{T_{run}} Ldt \approx \frac{L_0\tau_L}{T_{run}+T_{turnaround}+\tau_L}. \qquad (2)$$

Increase of the beam current

Injecting in LHC more intense proton beams with constant brightness, within the same physical aperture will increase the peak luminosity. Indeed, at the beam-beam limit regime, the peak luminosity is proportional to the normalized emittance $\varepsilon_n = \gamma\varepsilon$, as shown in the approximate formula (3):

$$L \approx \gamma\Delta Q_{bb}^2 \frac{\pi\varepsilon_n f_{rep}}{r_p^2\beta^*}\sqrt{1+\left(\frac{\theta_c\sigma_s}{2\sigma^*}\right)^2}, \qquad (3)$$

where ΔQ_{bb} is the linear tune shift induced by beam-beam interactions, f_{rep} is the collision repetition rate, r_p is the classical radius of the proton, σ^* is the rms transverse beam size, and σ_s, θ_c, β^* have the same meaning as in Table 2.

By increasing the LHC injection energy, it is possible to inject beams with larger normalized emittance within the same physical aperture. The beam will be more intense and of a larger size at the collision energy, thereby imposing some compensation scheme for the far beam-beam interaction effects [3-4] or a larger crossing angle satisfying the equation (4):

$$\frac{d_{sep}}{\sigma} \approx \theta_c\sqrt{\frac{\gamma\beta^*}{\varepsilon_n}}, \qquad (4)$$

where d_{sep} is the full size beam-beam separation induced by the crossing angle, whilst the other symbols have been defined above.

At 1 TeV injection energy, the peak luminosity should double and, without compensation, the crossing angle should increase by a factor √2.

Increase of the beam energy

The LHC collision energy is expected to slowly ramp up to the ultimate value of 7.56 TeV corresponding to a peak field of 9 T in the main dipoles. Any farther energy increase will require replacing the main magnets probably introducing Nb_3Sn superconductors to reach 15 T in the main dipoles and 320 Tm^{-1} in the main quadrupoles.

Should this approach become of interest for the high-energy physics community, it would be mandatory to increase the injection energy in view of reducing the energy swing during the acceleration ramp. Main dipoles of 15 T will at least require doubling the LHC injection energy and installing twice more powerful transfer lines.

SCENARIOS TO UPGRADE OF THE LHC INJECTOR CHAIN

In this section we present initial considerations to upgrade to 1 TeV the energy of the LHC injector chain.

Basic assumptions

We assume that the low-energy part of the injector chain, including the PS booster (PSB), will be refurbished to provide bunches of the appropriate intensity, emittance and brilliance, with the required inter-bunch separation. In particular, the PSB should be able to provide a bunch population of 2×10^{11} within 3.0 µm emittance and of 4×10^{11} within 6 µm.

We also assume that the upgrade scenario should progress in stages, aiming at a minimal duration of the needed shut down. To bring the high intensity and brilliance proton beams from 1.6 GeV/c momentum, at the exit of the PSB, to 1 TeV/c, at the entrance of the LHC, we may need building some new and more performing accelerators. Their construction may last several years during. To avoid an unsustainably long interruption of the CERN accelerator complex, the upgrade path should be made compatible with the existing PS and SPS. This choice may impose some detrimental consequences, such as additional severe constraints and most likely non-optimal compromises in the parameters and performance of the new accelerators.

Scenarios

There are several possible scenarios to feed LHC with 1 TeV/c momentum protons. The optimal solution will strongly depend not only on the real performance and limitations of LHC itself, but also on the other physics priorities that the CERN accelerator complex will be requested to fulfil. At this stage, the most important issue is to define fundamental options and to identify R&D programmes. The final definition of the optimal scenario will result from more thorough investigations, which will be eventually launched in the near future.

At present, our basic option is to first replace the PS with a superconducting (SC) synchrotron, of about the same size and about twice the momentum, located in an underground tunnel, possible under or close by the actual PS building. Doubling the injection energy in the present SPS will eventually mitigate limitations induced by space charge, electron-cloud instability and transverse mode coupling instability (TMCI). The SPS cycle will be shortened and will avoid transition crossing not only for protons but also for light ion. At the same time, the RF frequency swing during acceleration will be reduced. We will call PS+ such a new ring.

To finally reach 1 TeV/c momentum, one or two additional rings should be added.

A new single ring, build with superconducting magnets, located in the SPS tunnel, coexisting with the present normal conducting ring during the construction phase, is at present our preferred option to reach 1 TeV/c. In our opinion this is the best and simplest way to use the existing infrastructure. The only drawback will be the rather large value of momentum swing requested in the new ring (a factor of twenty). We will call SPS+ the new ring.

We can consider alternative scenarios, proposing a SC ring of intermediate energy in the ISR tunnel, complemented by a SC ring in the SPS tunnel: both of them will cover a rather small momentum swing. We can also suggest using the present SPS up to say 150 GeV/c, complementing it with a SC ring in the SPS tunnel, to reduce the swing in the SC magnets. We can finally propose a revamped normal conducting PS complemented by a normal conducting (NC) ring in the IRS tunnel feeding a SPS+ at about 60 GeV/c momentum.

The optimal choice will depend not only of the feasibility of fast ramping SC magnets, but also on the following issues:

- Is the PS+ fully compatible with the present PS? is it easy to switch from one to the other?
- Is it possible to host an additional SC ring in the SPS tunnel? Is it possible to inject particles from the present SPS into the SPS+ at some intermediate energy?
- Is it possible to re-use the ISR tunnel for a new NC or SC synchrotron?

More investigations will be required to answer these questions. In the following sections we will mostly concentrate on the PS+ and SPS+ options.

Superconducting magnet aperture

To compute the magnet aperture we should make assumptions on lattice and beam parameters of the PS+ and the SPS+. Starting from the latter, we expect the optical layout to be very close to the present one in the SPS, with $\beta_{max} \approx 100$ m, $D \approx 4$ m and a peak value for the closed orbit of about 5 mm. We also assume a normalized emittance of $\varepsilon_n \approx 7$ µm and a relative bucket height of $\delta_{bucket} \approx 10^{-3}$.

The rms transverse beam size will be of $\sigma \approx 2.2$ mm at injection and ≈ 0.8 mm at top energy. The dispersive beam size will be at most of $D\delta_{bucket} \approx 12$ mm, the betatron beam size (at $6\times\sigma$) ≈ 13 mm at injection and ≈ 5 mm at top energy. If a slow extraction will be required, the resonant separatrix size should be ≈ 20 mm long. Finally a radial clearance of at least 6 mm should be kept from the beam pipe.

Adding in quadrature the betatron and the dispersive beam size and linearly the closed orbit, the separatrix size, and the clearance one will need a radial aperture of at least 29 mm at injection and 44 mm at top energy.

Our conclusion is that an inner coil diameter of 80 mm should be adequate for the SC magnets of the SPS+.

With similar considerations the SC magnets for the upgraded PS+ should have an inner coil diameter 150 mm.

Ramp rate and cycle duration

The ramp rate and cycle duration of the PS+ and of the SPS+ will be determined by the envisaged use of the accelerator complex, beyond the pure LHC filling. We expect that a high duty cycle and a fast ramping rate will be required to maximise the availability of test beams and the potential physics reach with extracted beams.

A possible arrangement of the interleaved cycles of PS+, SPS and SPS+ is shown in Figure 1. In the presented scenario, the PS+ dipoles have a maximum field of 3.5 T and a ramp rate of 3.15 T/s, the cycle duration is of 3.6 s, i.e. three times the PSB cycle (when shortened from the present 1.2 s to 0.9 s) and the momentum swing of 31, implying an injection field of 0.11 T. These are very challenging requirements calling for a vigorous R&D. The SPS+ dipoles have a maximum field of 4.5 T and a ramp rate of 1.2 T/s, with a momentum swing of 20. Also these requirements are rather challenging and will require an intense R&D effort.

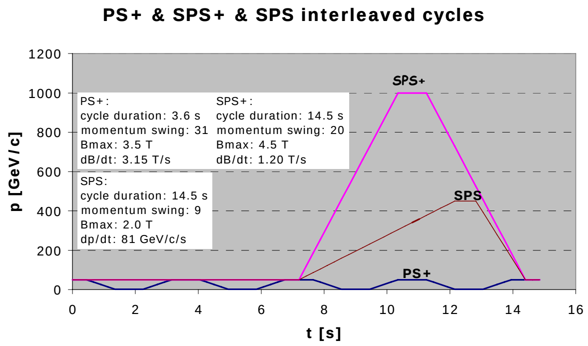

Fig. 1. An example of interleaved cycles for PS+, SPS+ and SPS.

One of the crucial issues for both magnets will be the cryogenic load induced by the ramp transient and by beam loss. Ideally the two contributions should be as small as possible and eventually of the same order of magnitude.

For instance, in the SPS+, with a well thought collimation system, we hope reducing to about 20 kW the beam loss in the superconducting material. This corresponds to about 10^{12} protons of 1 TeV escaping from the collimation system per cycle. The escaping halo will be lost in the whole accelerator, depositing about 5 W per meter of superconducting magnet. Correspondingly, the thermal loss induced by the magnetic cycle should be of the same order of magnitude, which is by far not an easy goal. With the present SC technology at the requested ramp rate the thermal loss are an order of magnitude larger and an aggressive R&D program will be necessary to master the problem [5].

Other open issues

The scenarios of LHC upgrade presented here are still superficial sketches needing several clarifications and improvements. A non-exhaustive list of the open issues is given below and may need an important effort to be fully addressed.

- Installation staging in the SPS tunnel: it is required to propose scenarios to minimise the SPS shutdown during the upgrade of the injection chain.
- Lattice design: a realistic lattice design of the SPS and of its injector should be investigated, also considering the partial use the present SPS ring.
- Slow extraction design: we need a realistic simulation of the resonant extraction process in the 1 TeV SPS, also to compute the expected extraction loss and to refine the estimate of the magnet aperture.
- Injection optics: this issue is relevant both for the 1 TeV SPS and for the LHC itself since the space available in the extraction/injection regions is limited.
- Optimal extraction/injection channel: extraction kickers and septa will operate on more energetic particles within serious space occupancy constraints.

- Optimal design for the SC magnets: nominal parameters should be proposed for the SC pulsed magnets and a road map for the requested R&D presented.
- Cryogenic system: solution should be investigated for the installation of cryogenics in the SPS tunnel.
- RF systems: the optimal choice of the RF parameter is not yet available. We expect serious constraints, which may require a full iteration both on lattice design, on the choice of the injector energy and of the ramp-rate of the magnetic cycle.

SUPERCONDUCTING FAST CYCLED MAGNETS

We still need gaining experience on fast cycled superconducting magnets. The design and manufacture of such magnets shall take into account many aspects resulting in a balanced compromise between at least different contributions to thermal losses, temperature and field margin, life-time under the cyclic operation in a radioactive environment.

Considerations on magnet development

Magnets for PS+ and for SPS+ may apparently fall into two well separate categories requiring two different parameter sets and development lines:

- Moderate peak field (3.5 T), fast ramp rate (more than 3 T/s), short cycle (3.6 s), large aperture (Φ = 150 mm) for the PS+;
- Higher peak field (4.5 T), slower ramp rate (less than 1.5 T/s), longer cycle (14 s), moderate aperture (Φ= 80 mm) for the SPS+.

In reality other aspects, such as beam losses and cryogenic consumption, may suggest carrying out a common development for both magnet types.

Due to the much higher ramp rate and short cycle, the magnets of the PS+ would show, if built with the same technology and components as those of the SPS+, much higher losses essentially coming for the superconduting wires and cables. We may then assume for example that PS+ would need a much stronger effort in wires and cable development than SPS+.

However when considering the beam losses the scenario changes and we may observe that the beam losses would in any case be at the limit of the heat load which can be evacuated from the magnets and that in both cases the magnet losses have to be kept much lower than today's available technology allows.

In our opinion, any effort and development on magnets for a PS+ would strongly benefit also to a SPS+.

Superconducting cables

We consider two main options for the cable development: the first using Rutherford cables, the second using internally cooled cables such as the Nucleotron type.

When using Rutherford cables, the total losses (magnet and beam) have to be kept typically below 10-15 W per meter of magnet length to allow the magnet operating in the superconducting state.

With the use of internally cooled cables this limit can be raised above 50 W/m. However, internally cooled cables make magnet manufacture (in particular the interface with connections and interconnections) and operation much more difficult and less reliable than with Rutherford cables. For long magnets, the hydraulic impedance may even become not acceptable for an efficient cooling. Finally, in particular for the SPS+, losses of the order of 50 W/m would not be acceptable for the budget allowed by the refrigeration system: on about 5000 metres of magnets the heat to be evacuated would amount to 250 kW, much more than for the LHC!

In our opinion, we have to focus our developments on Rutherford cable, which has to be considered the first choice for a safe and durable operation.

SC conductor issues

Thermal loss is one of the main concerns in SC conductors for rapid cycling magnets. The sources of losses are mostly related to three phenomena:

- hysteresis losses
- matrix losses
- losses due to interstrand currents.

To sustain the ramp rates requested in the PS+ or in the SPS+ we certainly need a resistive matrix (CuMn or CuNi) with filament diameters much smaller than the 6 μm used for the LHC and resistive coating on the strands or resistive core in the cable to limit interstrand currents.

Designing the optimal conductor for fast cycling SC magnets is a task involving many competences including magnets design, cryogenics and beam physics. Indeed, trimming various parameters (including machine requirements) may open new opportunities for a simpler and more efficient design.

As an example, the losses due to interstrand coupling currents strongly depend on the cable width (to the cube for a given strand diameter) so that using a small cable, instead of wide one, affects the allowed interstrand resistance. Similarly, the peak field in the coil and the coil volume affects the hysteresis losses.

The fatigue behaviour of the magnet has certainly to be addressed in particular for the wires and cables, since the cyclic operation may change the electrical and thermal properties of the interfaces between the superconducting strands, potentially affecting interstrand current redistribution, thermal losses and stability.

Source and computation of wire/cable losses seem sufficiently well established for overall estimate, in particular once strand measurement data are available. Concerning heat transfer mechanisms, they are known in principle, but difficult to model and to quantify. A new facility, being set-up in Saclay (cryostat provided by WUT) to measure heat transfer coefficients from cable to helium through different insulations, will be an important tool to quantify the thermal efficiency of different possible magnet cross sections, in particular the cable insulation scheme.

Other issues

Powering may become a challenge in case of large energy swings, as could be the case of a PS+. In particular the magnet inductance and dynamic behaviour shall be carefully iterated and optimized with the power supply system.

Quench detection and protection does not seem to represent a major challenge with respect to existing systems: the high voltage to ground during energy extraction can be avoided by subdivision. More dump resistors, current breakers, and current leads would be needed.

Finally, magnetic measurements systems have to be developed to measure with sufficient accuracy magnetic field harmonics over a large field swings (up to 30) in a second.

Recommendations for R&D

The requirements for superconducting pulsed magnets suitable for the upgrade of PS and of SPS are certainly in reach of present technology provided the necessary R&D and industrialization of wires is carried out in the coming years.

In particular it is recommended to investigate in details the following issues:

- explore in detail and quantify beam losses in the magnets for different possible machine layouts
- procure, with moderate R&D, NbTi wires with 3 μm filaments in resistive matrix to study and set-up wire manufacture and performance with resistive matrix, low losses cables (higher interstrand resistance) and stability
- manufacture 1-meter models with such a wire, fully instrumented to explore behaviour low losses wire/cable in operational condition, fatigue issues (including possible degradation of strand coating), measurement of thermal losses
- consolidate, by theory and experiments, heat transfer mechanisms from cable to helium
- develop and industrialize, by intensive R&D, very low losses NbTi wires with 1 μm filaments in resistive matrix

- conceive an integrated magnet design approach iterating machine optics, magnet requirements (peak field, aperture), beam losses
- study in detail powering of such magnets, in particular in case of the large energy swing of a PS+
- develop appropriate magnetic measurements systems
- propose layout for the PS+ (and the SPS+) to validate the magnet parameters and their possible use in upgraded injectors.

ACKNOWLEDGEMENTS

We would like to acknowledge the suggestions, contributions and information provided by several colleagues. In particular we would to explicitelly mention Daniel Leroy, Arial Werveij, Luc Oberli, Davide Tommasini, Gianluigi Arduini, Remo Maccaferri, Elena Shaposhnikova, Francesco Ruggiero.

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