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LHC Upgrade Scenarios – Preliminary Estimations for the RF Systems

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Abstract

Possible scenarios for upgrading the LHC machine beyond its so-called "ultimate" performance have been proposed.

We try to detail the RF system changes that could be needed and to give a resource and schedule plan to implement these changes based on data available at this time. We also identify research and development areas that are essential for all future projects again estimating the resources and times required to do this work. Finally we identify, and outline en-route, some particular experiments that can be done on existing machines to lower uncertainty when extrapolating.

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Introduction

Possible scenarios for upgrading the LHC machine beyond its so-called "ultimate" performance have been proposed [1, 2]. They fall into two categories, not mutually exclusive, a luminosity upgrade and an energy upgrade. The energy upgrade in the LHC does not in itself imply changes to the RF system in the LHC, (e.g synchrotron radiation energy loss becomes ~100 keV/turn), but due to the change of injection energy needed in the LHC does require significant changes to the SPS and PS injectors and their RF systems. The luminosity upgrades involve possible changes to increase the intensity, reduce the bunch length and improve the IR regions, all with consequences to the RF systems in the LHC, and the intensity increase implying changes in the SPS and PS machines as well.

We try to detail the RF system changes that could be needed and to give a resource and schedule plan to implement these changes based on data available at this time. We also identify research and development areas that are essential for all future projects again estimating the resources and times required to do this work. Finally we identify, and outline en-route, some particular experiments that can be done on existing machines to lower uncertainty when extrapolating.

Luminosity Upgrade

The existing bottle-necks that compromise achieving the "ultimate" intensity in the LHC are at injection in the PSB and SPS [3]. Both could be improved by an increase in injection energy. In the first case LINAC4 has been proposed and in the second PS2 or PS+. Below we will not attack these changes.

● Reaching Ultimate intensity

The increase to "ultimate" intensities / bunch should be possible without the 200 MHz capture system originally foreseen for the LHC. At the moment the SPS can provide the nominal longitudinal beam in a longitudinal emittance of 0.6 eVs which does not necessitate the use of the capture system. An increase to ultimate intensity should be possible with an increase of longitudinal emittance to 0.73 eVs to maintain stability in the SPS. This should also be acceptable without a capture system. It is also believed that, as operational experience is obtained and the intensity slowly increases, the injection errors, energy and phase, will slowly decrease and consequently the modest longitudinal damping provided by the 400 MHz system will remain sufficient. This will release the pressure on the emittance. If all this proves to be false then a longitudinal damping system may have to be introduced to attain ultimate intensities. It is not clear that the present design of the 200 MHz system would be optimum for this function.

- *Nonetheless efforts must continue now in the injector chain to provide the ultimate beams to prove that 0.7 eVs is obtainable.*

● Above Ultimate intensity

To go above ultimate, as mentioned above, there are three lines of attack for the luminosity upgrade.

(1) *To provide shorter bunches* [4, 5, 6] allowing a lower $\beta*$ which requires a lower collision length in the IRs. The present proposal is to install a high harmonic RF system at 1.2 GHz with sufficient voltage to reduce the bunch length in the coast by a factor 2 (0.26 ns to 0.14 ns rms).

(2) *To increase the total intensity* [6]. The present proposal for increasing the intensity is to keep the bunch intensity constant at the ultimate (nominal) level and double the number of bunches. Increasing the bunch current would lead to increased risk of TMCI in the SPS plus increased space charge. For the TMCI it is not yet known whether the ultimate bunch will suffer from TMCI and the ultimate beam from nefarious effects from the electron cloud.

- *Ultimate bunches must be injected into the SPS to study TMCI thresholds and ultimate beams to study electron cloud emittance increase.*

Apart from the problem of incompatibility of the present RF systems with the different bunch spacing proposed, doubling the number of bunches has two effects on the RF in the injector chains. It doubles both the beam-loading and the bunch spacing frequency.

In the LHC the beam-loading implies doubling the RF power capability of the existing 400 MHz plant or doubling the number of cavities and working at half the voltage. In the first case we need to rebuild the main power and HOM couplers, in the second we only need to improve the HOM couplers. Doubling the number of cavities doubles the HOM impedance seen by the beam from this source – not recommended for beam stability considerations especially when the intensity is being doubled.

The doubled intensity also raises the question again about the need for a capture/ damping system. It is not at all clear that the limitations on emittance for loss-free capture are not exceeded. In this case a system with double the power capability of the 200 MHz capture system designed would also be required.

In addition the move to double the bunch spacing frequency from 40 MHz to 80 MHz, although allowed by the 400 MHz system, precludes the use of a 200 MHz system. The frequency must be an integer multiple of the bunch spacing frequency. 160 MHz or 240

MHz can be discussed. The beam-line spacing in the LHC would certainly favour 240 MHz, 200 MHz cavities just fit in point 4 where the spacing is maximum, 160 MHz would be very difficult due to their size.

These last arguments also apply to the SPS cavities, both the main 200 MHz and the Landau damping 800 MHz. The 200 MHz cavities must be replaced by cavities at n x 80 MHz and must have the power capability associated with the double beam current. This implies new power systems and power couplers. In addition if ions are considered either the cavities should be broad-band, as they are at present due to their traveling wave design, or they should include fast tuning systems. The 800 MHz system can accept the 80 MHz bunch spacing but must be upgraded for the power requirements. In addition a serious study as to the probable final stable longitudinal emittance achievable has to be carried out. Coupled bunch instability limits at twice the ultimate intensity are a serious concern. The use of a new RF accelerating system in the SPS would allow a reduction in HOM impedance to be attempted – R&D on the HOMs required.

An additional problem arises when other beams, such as FT or CNGS, are considered. In this case where every bucket is filled, the frequency of the Landau damping system should be an integer multiple of the main accelerating system. This implies 160 MHz for the main accelerating system, 800 = 5 x 160. An alternative could be to scrap the 800 MHz system and install the same 1.2 GHz system as foreseen for the LHC, and then the main accelerating system would be at 1200 / 5 = 240 MHz. In this case the 1.2 GHz system would need to be tuned if also used at low energies.

A further consideration is that fast RF feedback should be used with the 160/240 MHz system. This implies the drilling of a parallel gallery in the SPS ring – over a distance of ~ 50 m. It could also be advisable even if the 200 MHz cavities are retained.

To provide the 12.5 ns bunch spacing the 80 MHz already existing in the PS can be used. Some of the PS systems have to be upgraded to cope with the new intensity and the bunch splitting at 80 MHz. Certainly the power of the 10 MHz cavities should be increased by 2. The fixed tuned systems can be different. The 13/20 cavities should be upgraded by a factor two in power also to compensate the beam loading. The power in the 40 and 80 MHz systems is at present dominated by the need to raise the voltage rapidly during the beam gymnastics. With the 12.5 ns “ultimate” beam the beam loading will rise to typically 200 kW. In this case the 400 kW available may not be sufficient. Without complete studies we assume that an upgrade to 00 kW would be advisable. For the 200 MHz system there is, in principle, no beam-loading component at 200 MHz and so the system can remain as it is.

Another consideration in any ring with decreased bunch spacing, is with respect to the need to damp coupled bunch instabilities if a Landau damping system is either not available or insufficient at high intensity. In the nominal/ultimate machine a bandwidth of ± 20 MHz is required. This will double when the bunch spacing is halved. Producing bandwidths of ± 40 MHz in the RF damping systems may be problematic.

(3) *For one option to improve the IR region performance* crab cavities are required. These are not studied in detail here. Requirements on phase stability are very difficult to attain and the basic system parameters have not been determined. Crab cavities are to be installed at KEK and results from here will be important. What is certain is that both a vigorous R&D and design effort is required and an estimate for the resources for this effort has been made.

Energy upgrade

The idea is to at least double the collision energy in the LHC – this has direct consequences for the injectors as well. It implies an increase in injection energy by the same factor to 1 TeV (magnet field range). No new RF systems are needed in the LHC provided the current remains below ultimate.

The extraction energy of 1 TeV from the SPS implies that the SPS itself will be rebuilt with new magnets, and for the same reasons as for the LHC, the SPS injection energy will be raised to ~ 50 GeV. This does not necessarily need a new RF system if the acceleration time of 7.5 s is maintained. However in building the new machine it would be good to upgrade the RF so that faster cycle times are possible.

The increased injection energy into the SPS also implies more powerful magnets in a new PS of the same size or similar strength magnets to those existing in a machine larger in diameter by at least a factor 2 (maximum magnetic field). Probably the injection energy into this new PS would increase as well – an injection at 3.5 GeV is considered. If the new PS is twice as large and ramps at the same rate then the existing capabilities of the RF systems have to be doubled in number also. However it is clear that a serious amount of work needs to be done to optimize all the parameters in these different machines. No RF systems are considered at the present time for new machines with the energy upgrade.

- *Design study for increased energy chain – will lead to first specification for RF systems in the PS.*

Transverse feedback systems

In principle the power requirements for the transverse damper systems depend upon the injection errors into the machines and the speed at which they have to be corrected. The filamentation times may decrease with intensity and increased beam size requiring faster action. The injection errors should not change significantly however instability rise-times will certainly get faster – this means more feedback gain for stability and this feeds back into the power via the injection errors.

- *Study of expected instabilities in this higher intensity regime*

The decreased bunch spacing implies doubling the bandwidth of the systems. We make the conservative assumption that for all machines except the LHC, the transverse feedback systems need to be doubled in kick strength and the bandwidth in the PS, SPS and LHC doubled. A serious limitation exists in the LHC dampers which have un-cooled copper electrodes. The doubling of intensity will certainly push the temperature of the electrodes beyond acceptable limits. This means a complete re-design of these kickers – at the same time kickers and power amplifiers can be upgraded for double kick strength.

In conclusion the RF systems which will be discussed here are:

a) 1.2 GHz for bunch shortening in the LHC – also designed as possible Landau damping system for the SPS and LHC (tuning capability may be needed in the SPS).
b) Double 400 MHz power system in the LHC
c) 160/240 MHz capture/damping system in the LHC
d) 160/240 MHz wide range tuning system in the SPS
e) Double power 800 MHz system in the SPS
f) Double power 10 MHz system in the PS
g) Double power 20 (13) MHz system in the PS
h) Increased power 40 MHz system in the PS
i) Increased power 80 MHz system in the PS
j) Crab cavity in the LHC – only R&D and design studies
k) Transverse feedback systems (LHC, SPS, PS, PSB)

RF systems – cost and Schedule

The estimates for cost and schedule are only approximate; the different systems need a much more detailed analysis in the future.
The costs given are today's prices. They should be increased according to the probable start date of the project using average inflation figures. Also included is an estimate for the disposal of the equipment. This is based on 20 kCHF per m^3 of radioactive material and should also be increased by the inflation over the estimated length of life before dismantling. It is assumed that electricity, water cooling and cryogenic capacity of sufficient capacity is provided nearby the new RF systems or upgrades.

While FSU costs are included this is not true for the CERN staff. Here FTE are given for engineers (E) and technicians (T). Note that the RF feedback systems need highly qualified CERN technicians. We are at present developing digital beam control systems which may be more easily re-usable in the future and would then require less manpower. However against this is the constant evolution of digital devices which leads to completely new developments.

The time scales estimated depend on the amount of skilled manpower available. To a limited extent they might be shortened by increasing the manpower. This does not probably apply to research and development. Note too that the rate at which industry can manufacture new tubes may be determinant.

The estimates are given in Appendix 1.

Research and development

To achieve the goals above a vigorous research and development programme is required. This programme should not necessarily be targeted at the moment to produce hardware with specific parameters. Rather it should be exploratory to enable a better definition of what can be done while at the same time attacking particular requirements as projects are approved. The following areas have been identified.

High Power Couplers

For high intensity machines the number of cavities required is in direct relation to the power capability of the power coupler. Note that this is continuous power and not pulsed. At present we can manage typically 1200 kW at 400 MHz for a variable coupler in the LHC SC environment. At 200 MHz we get ~700 kW / coupler in our warm TW cavity in the SPS – an older design. Simple scaling (F^2) to 1.2 GHz (power density) gives 130 kW and 20 kW respectively. Note that Cornell are struggling to get 50 kW through their 1.2 GHz couplers.

R & D on high power couplers assumes an appropriate RF source is available. This probably means in most cases that the high power source R & D has to be done first.

Power couplers are a main area where aggressive R & D is required.

High Power HOMs

R & D is also required for the HOM couplers – getting the coupled power out of the cavities becomes progressively more difficult as the frequency and intensity rise. SC cavities pose particular problems as do crab cavities where the fundamental frequency damping is an issue.

High Power Sources

At the present time below ~ 400 MHz tubes are used and above klystrons. However new types of (unproven) sources being developed by industry, e.g. the “diacrode” or the “IOT”, can offer new possibilities Experience at CERN has shown that RF systems are cheaper if they are made of a small number of high power amplifiers rather than many amplifiers at lower power. It can be argued that multi-tube systems allow some redundancy albeit at reduced performance. In the LHC a tube loss would mean dumping the beam and then continuing with lower power and hence intensity or repairing the amplifier. Bearing in mind the long cycles it does not seem advantageous to take advantage of this possibility. Also a system with many amplifiers will also have higher maintenance costs in terms of manpower. Hence it seems better that, whatever the frequency, the highest power devices should be used. This is an area where R & D in conjunction with industry is very interesting.

Wide range tuning systems

Acceleration in the lower energy machines, especially with heavy ions, requires tuneable cavities. Ferrite tuned systems are well known at the lower frequencies (10s of MHz). At higher frequencies plungers can be used, with life-time issues, or in super-conducting cavities mechanical deformation is used at the moment to avoid moving parts and multipactoring. For fast cycling medium range energy machines accelerating both protons and heavy ions there is no obvious solution. This is also an area where R&D would be necessary.

Superconducting RF

Programmes to study high power high frequency systems (e.g. at 1.2 GHz or higher) are needed. Extending to lower frequencies (e.g. 240 MHz) is also interesting.

CERN is ideally placed to do research on superconducting RF. We not only have experts in various associated domains such as surface conditioning, sputtering, chemical cleaning and clean room use, but we also have the facilities available, clean rooms, vertical cryostats, concrete bunkers with cryogenic capability etc. In any case we need to keep these possibilities and expertise to cope with future problems with the existing LHC cavities let alone future LHC upgrade RF requirements.

Cost and manpower estimates are given in Appendix 2.

Note that these estimates are for a program independent of the specific R&D that would be necessary for a given project. Nonetheless the different estimates can be combined.

References

1. Many references are given at http://paf.web.cern.ch/paf/
2. HHH-2004. Ed. F.Ruggiero, W.Scandale F. Zimmerman. CERN-2005-006
3. High brilliance and closer bunches from the LHC injectors, E. Shaposhnikova http://care-hhh.web.cern.ch/CARE-HHH/LUMI-05/
4. LHC Luminosity and Energy Upgrade: A Feasibility Study, O.Bruning et al, LHC Project Report 626
5. RF and Feedback for Bunch Shortening, J. Tuckmantel, HHH-2004, CERN-2005-006
6. LHC beam parameters and IR upgrade options, F. Ruggiero, http://care-hhh.web.cern.ch/CARE-HHH/LUMI-05/

Appendix 1: Material cost and manpower estimates for the different RF systems

a) 1.2 GHz system LHC for ultimate beam (Landau in SPS – with possible tuning)

The analysis in [4] gives the parameters for a bunch shortening system in the LHC assuming ultimate intensity. Note that in [5] less cavities, 16 instead of 22 per beam, were assumed with more power per cavity. Optimisation will depend on the R&D results on the areas of High Power Couplers and High Power sources. If this bunch shortening system is also required with the higher intensities assumed beyond ultimate then the power increases proportionally. This will require more cavities at lower voltage and the same power or yet higher capability power couplers etc.
To get the required bunch length reduction we need 43 MV/beam. This can be supplied by 22 SC cavities/beam with an RF power per coupler of 500 kW.

Subject	Cost MCHF	Comments
Cavities plus cryostats inc. vacuum tank, He tank, Tuners, HOMs, non-staff manpower	15	R & D required
Couplers	2	R & D required
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	43	R & D required
Beam control	2	
Disposal	0.5	
TOTAL	62.5 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1	1	0.5								High Power Source and Couplers, SC
Design and prototyping			0.5	0.5							
Manufacture				3	12	15	15	11	0.5		
Instal								1	1		
Commission										0	Operating costs and disposal not in breakdown
TOTAL (MCHF)	1	1	1	3.5	12	15	15	12	1.5		
Manpower FTE (E+T)	2 +3	2 +3	3 +3	3 +3	3 +3	3 +4	3 +6	3 +6	3 +6	3 +5	

b) <u>New double power 400 MHz system in the LHC</u>

The double power requirement, 600kW per existing cavity, comes directly from the doubling of intensity assumed in the upgrade when the number of bunches is doubled.
Several variants exist:
1) The same type of cavities is used and two of the same power couplers are used per cavity. Implies redesign of nearly everything – might be able to re-use the cavities. Could use twice as many of the same power sources (space problems and also phasing problems at the cavity – where does all the power go if offset phase) or have a new power source development at twice the power.
2) Twice as many cavities are used at half the voltage and the same power. Not efficient on space, impedance increases.
3) A new coupler is used in place of the existing one at twice the power. This also needs a cavity, He tank and cryostat re-design and rebuild but maybe not as dramatic as for variant 1. The comments on the high power source are as for variant 1.
For the estimate we assume variant 3 where effectively everything is new.

Subject	Cost MCHF	Comments
Cavities plus cryostats inc. vacuum tank, He tank, Tuners, HOMs, non-staff manpower	12	R & D required for 2400 kW couplers, and HOMs.
Couplers	2	R & D required
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	29	R & D required for 600kW sources
Beam control	2	
Disposal	0.5	
TOTAL	45.5 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1	1	0.5								High Power Source and Couplers
Design and prototyping			0.5	0.5							
Manufacture				3	9	9	10	8	0.5		
Instal								1	1		
Commission										0	Operating costs and disposal not in breakdown
TOTAL (MCHF)	1	1	1	3.5	9	9	10	9	1.5		
Manpower FTE (E+T)	1.5 +2	1.5 +2	2 +3	3 +3	3 +3	3 +4	3 +6	3 +6	3 +6	3 +5	

c) <u>160/240 MHz capture/damping system in the LHC</u>

There are 4 cavities per beam at 750kV. RF power per cavity including injection damping is 600kW. Assume a warm system but R & D on SC could lead to the possibility of an SC system even at 160 MHz.

Subject	Cost MCHF	Comments
Cavities (plus cryostats inc. vacuum tank, He tank), Tuners, HOMs, non-staff manpower	5	R & D required for 2400 kW couplers, and HOMs. NB synergy with d) and possible SC. Full bandwidth system +-40MHz precludes SC?
Couplers	2	R & D required
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	14.5	R & D required for 600kW sources. Nb synergy with d)
Beam control	2	
Disposal	0.7	
TOTAL	24.2 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1	1	0.5								High Power Source and Couplers, SC cavity?
Design and prototyping			0.5	0.5							
Manufacture				2	4	4	4	3	1		
Instal								1	1		
Commission										0	Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	1	1	1	2.5	4	4	4	4	2		
Manpower FTE (E+T)	2 +3	2 +3	3 +3	3 +3	3 +3	3 +4	3 +6	3 +6	3 +6	3 +5	

d) <u>160/240 MHz wide range tuned system in the SPS</u>

10MV total accelerating voltage is assumed to give fast ramp capability, 10 warm cavities of 1MV each taking 750 kW. Same tube and cavities as in c)

Subject	Cost MCHF	Comments
Cavities (plus cryostats inc. vacuum tank, He tank), Tuners, HOMs, non-staff manpower	6.5	R & D required for 3000 kW couplers, HOMs. And fast tuners, possible SC. Full bandwidth system +-40MHz precludes SC?
Couplers	2	R & D required
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	22.5	R & D required for 750kW sources. NB synergy with d).
Civil engineering	1	
Beam control	2	
Disposal	0.8	
TOTAL	34.8 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1.5	1.5	0.5								High Power Source and Couplers, Fast tuners SC cavity?
Design and prototyping			0.5	0.5							
Civil Engineering				1							
Manufacture				2.5	6	7	7	3	1		
Instal								1	1		
Commission										0	Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	1.5	1.5	1.0	4.0	6	7	7	4	2		
Manpower FTE (E+T)	2.5 +3	2.5 +3	3 +3	3 +3	3 +3	3 +4	3 +6	3 +6	3 +6	3 +5	CE manpower not included

e) Double power 800 MHz system in the SPS

The present system is capable of 250kW per cavity. This is more than adequate for the nominal LHC beam - 100 kW requires. Doubling the intensity could be possible within the present design of power amplifier. However, it is not prudent to assume a simple scaling since the power requirement is a function of the 800 MHz beam component wich is a function of the bunch parameters. In addition it is known that the 800 MHz system must be modernized – new tubes / klystrons must be found. We assume that the power will increase to 500 kW per cavity.

Subject	Cost MCHF	Comments
Cavities, HOMs, non-staff manpower	0.3	Possibly no change, cooling upgrade
Couplers	0.7	R & D required for new waveguide couplers
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	4	R & D required for 500kW sources.
Beam control	0.5	
Disposal	0.5	
TOTAL	6 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1	0.5									High Power Source and Couplers,
Design and prototyping		0.5									
Manufacture			1.5	1.5							
Instal					0.5						
Commission						0					Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	1	1	1.5	1.5	0.5						
Manpower FTE (E+T)	0.5 +2	1 +2	1 +2	1 +2	1 +2	1 +2					

f) <u>Double power 10 MHz system in the PS</u>

11 cavities installed, each capable of 20 kV. Power to be upgraded to120 kW/cavity.

Subject	Cost MCHF	Comments
Cavities, HOMs, non-staff manpower	0.5	Cooling uprade – HOMs to be looked at
Couplers	1	R & D required for new couplers
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	4	
Beam control		
Disposal	0.5	
TOTAL	6 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	0.2										Couplers,
Design and prototyping		0.5									
Manufacture			2	2.5							
Instal					0.3						
Commission					0						Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	0,2	0.5	2	2.5	0.3						
Manpower FTE (E+T)	0.5 +0.5	0.5 +0.5	0.5 +2	0.5 +2	0.5 +2						

g) Double power 20 (13) MHz system in the PS

2 cavities, switched between 13 and 20 MHz, 20kV per cavity and 60 kW per cavity. (Power doubled)

Subject	Cost MCHF	Comments
Cavities, HOMs, non-staff manpower	0.1	Cooling upgrade – HOMs to be looked at
Couplers		Should be OK
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	0.5	
Beam control		
Disposal	0.1	
TOTAL	0.7 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D											
Design and prototyping	0.1										
Manufacture		0.45									
Instal		0.05									
Commission		0									Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	0,1	0.5									
Manpower FTE (E+T)	0.5 +0.5	0.5 +0.5									

h) Double power 40 MHz system in the PS

2 cavities at 300 kV/cavity and 600kW/cavity

Subject	Cost MCHF	Comments
Cavities, HOMs, non-staff manpower	0.5	Cooling – HOMs to be looked at
Couplers	0.5	R & D required for new couplers
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	2	We assume a new power source and power supply is necessary but that the infrastructure can largely be re-used.
Beam control		
Disposal	0.2	
TOTAL	3.2 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	0.3										High Power Source and Couplers,
Design and prototyping		0.2									
Manufacture		0.4	1	0.9							
Instal				0.2							
Commission					0						Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	0,3	0.6	1	1.1							
Manpower FTE (E+T)	0.5 +0.5	0.5 +1	0.5 +2	0.5 +2	0.5 +1						

i) <u>Double power 80 MHz system in the PS</u>

3 cavities at 300 kV/cavity and 600kW/cavity

Subject	Cost MCHF	Comments
Cavities, HOMs, non-staff manpower	0.5	Cooling – HOMs to be looked at
Couplers	0.5	R & D required for new couplers
Power amplifiers inc. power supplies, infrastructure, cabling, RF feedback electronics, non-staff manpower	3	We assume a new power source and power supply is necessary but that the infrastructure can largely be re-used.
Beam control		
Disposal	0.2	
TOTAL	4.2 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	0.3										Couplers, High Power Source?
Design and prototyping		0.2									
Manufacture		0.4	1.5	1.4							
Instal				0.2							
Commission					0						Operating costs and disposal not in cost breakdown
TOTAL (MCHF)	0,3	0.6	1.5	1.6							
Manpower FTE (E+T)	0.5 +0.5	0.5 +1	0.5 +2	0.5 +2	0.5 +1						

j) <u>Crab cavity in the LHC</u>

We only consider the R&D and design necessary to define the crab cavity (and this is very approximate.) It is impossible to determine the configuration of such a system without this preliminary work.

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
R & D	1.0	1.0	1.0								SC Cavities, couplers, high power sources
Design and prototyping		0.5	1.0	0.5							
Decision on construction					000						
TOTAL (MCHF)	1	1.5	2	0.5							
Manpower FTE (E+T)	2 +3	2 +3	2 +3	2 +3							

k) Transverse damping systems

a) LHC (double existing system by adding same)

Subject	Cost MCHF	Comments
Kickers	3	Cooled structures, higher hold-off voltage
Power amplifiers, infrastructure and cabling	6	High power amplifiers to give twice kicker voltage. Power supply capability doubled
Beam control	0.5	
Disposal	0.5	
TOTAL	10 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
Design and prototyping	0.7	0.7									
Manufacture		0.8	3	3	0.8						
Instal					0.5						
Commission						0					
TOTAL (MCHF)	0.7	1.5	3	3	1.3						Not disposal
Manpower FTE (E+T)	1 +1	1 +2	1 +3	1 +3	1 +3	0.5 +2					

b) SPS (double existing system by adding same)

Subject	Cost MCHF	Comments
Kickers	1.4	
Power amplifiers, infrastructure and cabling	2.8	
Beam control	0.5	
Disposal	0.5	
TOTAL	5.2 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
Design installation	0.2	0.5									
Manufacture	0.5	1.0	1.7	0.3							
Instal				0.5							
Commission					0						
TOTAL (MCHF)	0.7	1.5	1.7	0.8							Not disposal
Manpower FTE (E+T)	0.5 +2	1 +3	1 +3	0.5 +3							

c) PS (double existing system by adding same)

Subject	Cost MCHF	Comments
Kickers	0.2	
Power amplifiers, infrastructure and cabling	0.5	
Beam control	0.2	
Disposal	0.1	
TOTAL	1.0 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
Design installation	0.2										
Manufacture	0.1	0.4									
Instal			0.2								
Commission				0							
TOTAL (MCHF)	0.3	0.4	0.2								Not disposal
Manpower FTE (E+T)	0.5 +2	1 +3	1 +3	0.5 +3							

d) PSB (double existing system by adding same)

Subject	Cost MCHF	Comments
Kickers	0.2	
Power amplifiers, infrastructure and cabling	0.5	
Beam control	0.2	
Disposal	0.1	
TOTAL	1.0 MCHF	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Comments
Design installation	0.2										
Manufacture	0.1	0.4									
Instal			0.2								
Commission				0							
TOTAL (MCHF)	0.3	0.4	0.2								Not disposal
Manpower FTE (E+T)	0.5 +2	1 +3	1 +3	0.5 +3							

Appendix 2: R & D material cost and manpower estimates for a general programe to cover 5 years intensive work

High Power couplers;

	Year 1	Year 2	Year 3	Year 4	Year 5
R&D cost	0.5MCHF	1MCHF	1MCHF	1MCHF	1MCHF
R&D Manpower FTE	0.5 eng, 2 tech	0.5 eng, 2 tech	0.5 eng, 2 tech	0.5 eng, 2 tech	0.5 eng, 2 tech

High power devices and amplifers;

	Year 1	Year 2	Year 3	Year 4	Year 5
R&D cost	0.5MCHF	1MCHF	1MCHF	1MCHF	1MCHF
R&D Manpower FTE	0.5 eng. 1 tech. plus industry	0.5 eng. 1 tech. plus industry	0.5 eng. 1 tech. plus industry	0.5 eng. 1 tech. plus industry	0.5 eng. 1 tech. plus industry

HOMs;

	Year 1	Year 2	Year 3	Year 4	Year 4
R&D cost	200kCHF	300kCHF	300kCHF	300kCHF	300kCHF
R&D Manpower FTE	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech

Fast Tuning of cavities;

	Year 1	Year 2	Year 3	Year 4	Year 5
R&D cost	200kCHF	300kCHF	300kCHF	300kCHF	300kCHF
R&D Manpower FTE	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech	0.5 eng. 1 tech

Super conducting cavity development

	Year 1	Year 2	Year 3	Year 4	Year 5
R&D TOTAL cost	0.5MCHF	1.0MCHF	1.0MCHF	1.0MCHF	1.0MCHF
R&D TOTAL Manpower FTE	2 eng. 3 tech	2 eng. 3 tech	2 eng. 3 tech	2 eng. 3 tech	2 eng. 3 tech