NEW RF SYSTEMS FOR THE SUPER-SPS AND SUPER-ISR

Joachim Tuckmantel, CERN

Abstract

The RF system requirements necessary to fulfil the desired specifications for a possible new set of LHC injectors and the consequent technical implications are examined.

INTRODUCTION

It is assumed that the upgraded LHC injector chain will consist of a reliable and cost-effective set of machines starting with protons at rest and ending with a high brightness beam of about 1000 GeV injected into LHC. Some of the existing machines at CERN are stretched to the (maybe ultimate) limit, some are already old and will need refurbishing to ensure the continued availability of a reliable injector chain for the life of LHC. Furthermore, even if LHC is CERN's top priority, there are and will be other requests from the physics community to the laboratory that may influence choices so that the injector chain can efficiently work for other physics experiments while LHC itself is in coast.

Due to this situation at the present time the details of a future injector chain are still vague with several dissimilar variants proposed; for each of them there are several options for RF systems having certain advantages and disadvantages. Therefore, we have – in the spirit of a first iteration – collected together some general considerations as well as limitations, advantages and disadvantages of certain classes of RF systems and components. This opens the door for a second iteration where the constraints of other ingredients such as existing tunnels, bending- and focussing magnets, collimators, kickers and different physics requests are merged with the information on the RF systems, illuminating the road towards a design where the total effort to design and build such a chain is minimized and non-LHC physics is incorporated as far as possible.

We have considered as a concrete example an injector chain of two machines in the present SPS tunnel [1], the lower energy machine – called 'SPS' – receiving bunches, as presently, from the PS at 26 GeV/c and accelerating them to 150 GeV/c. There they are transferred to a second machine called HPS with superconducting (sc) magnets that accelerates them to 1 TeV/c.

TRAVELLING WAVE CAVITIES

In TW cavities an RF wave is injected at one end, travels along the structure and is partially absorbed by the beam, the remainder being absorbed by a load at the opposite end; no inverse wave exists. Also any beam-induced RF wave travels towards the load and is absorbed there. TW cavities have the property that although without tuner they have a relatively large usable frequency range allowing a large frequency swing during acceleration. The SPS 200 MHz system can accelerate protons between 14 (theoretically 10) and 450 GeV/c corresponding to about 700 kHz frequency swing. TW cavities react 'fast', i.e. the so-called filling time is low, about 600 ns in the SPS. This allows, e.g., the 'trick' of fixed frequency acceleration for ions in the SPS [2] where the classical integer harmonic acceleration would not be possible since the necessary frequency swing would exceed the TW cavities' possibilities. A batch of ion-bunches with a gap at its end longer than the cavities' filling time is accelerated at each turn with a suitable *invariant* frequency, not adapted to the change of speed of the ions. But each time the batch has passed the cavities, the dead time during the beam-gap is exploited to bring the RF voltage vector into the correct state for receiving the head of the batch at its next arrival.

Also the efficiency in transferring RF power to the beam is good at the design beam current. In the SPS the CNGS beam takes up practically all the injected RF energy; but this means also that a further current increase with the same voltage would not be possible without rearranging the structure lengths (and adding RF power transmitters).

The great disadvantage of TW cavities in CW-mode* is their relatively low accelerating gradient, i.e. for a given RF voltage the structure is long and has a correspondingly large parasitic impedance; also HOM damping is difficult. There is no point in considering a *sc* TW cavity, aside from the technical difficulties in building and operating one.

* Pulsed linacs use (preferably small) TW structures filling them with a large amount of RF energy that is nearly completely taken out during a relatively short beam pulse before the surface losses truly start to count, an operational mode that cannot be used in circular machines with quasi-continuous beam

STANDING WAVE CAVITIES

One can imagine that in a standing wave cavity a wave travels back and forth in the cavity, being completely reflected at each end. At resonance the two waves superimpose to give a standing wave pattern that has zero electric (maximum magnetic) field at one temporal instance and maximum electric (zero magnetic) field at another instance simultaneously over the whole cavity volume. Due to this resonant process SW cavities have a relatively small bandwidth. They have to be tuned when the driving frequency changes, as during acceleration of low energy protons, but offer a higher voltage compared to TW cavities in CW mode. Since they have no load, in high current machines the RF energy possibly stripped-off from the beam has to be handled somehow. Therefore systems with klystrons or similar transmitters that cannot support larger amounts of 'reflected' power without destruction, have to be protected by a 'circulator' which deviates the reflected wave towards a load. Systems equipped with gridded tubes can absorb a certain amount of reflected power and may work without circulator.

Mult-Cell Standing Wave Cavities

To reduce the number of ancillaries as couplers, tuner, controls-electronics and so on, standing wave multi-cell cavities are convenient as long as field-flatness can be conserved along the structure, i.e. the cells must be very similar in frequency requiring tight fabrication tolerance. In high current machines such as LHC and its injectors we need a high gain RF vector feedback on the accelerating mode to reduce its apparent impedance. Such a feedback system needs a reference probe in the cavity to determine the present field level. To avoid direct cross-talk this probe should not be located next to the power (input) coupler but preferably far away. N-cell cavities have pass-bands of N modes closely grouped in frequency, each mode having its (different) pattern of field polarity in different cells. This leads to the inevitable situation that apart from the designated accelerating mode at least one other mode with not very different frequency exists, having for the same polarity at the exciting power coupler an *opposite* polarity at the probe. This situation corresponds to positive feedback[†] and this mode would auto-oscillate with maximum available power, leading to immediate beam loss.

[†] assuming that the accelerating mode was adjusted to negative feedback as it should be

Such a configuration existed e.g. when a few sc LEP cavities with four cells each were installed in the SPS as LEP injector. To sufficiently reduce the impedance for the SPS proton beam also passing these cavities, a complex filter system with very narrow bands had to be designed, built, shielded and adjusted so that all four pass-band modes could be treated individually. Such a filter increases the complexity of the whole feedback loop, complicates its overall stability and, worse of all, will increase the RF feedback loop-delay, requiring a corresponding reduction of the loop-gain.

Furthermore the feedback tries to enforce the field at the probe antenna, the latter being a superposition of all pass band mode fields so that the sum-voltage *seen by the beam* is not necessarily the desired one, even at infinite gain.

For the present LHC feedback loop (without additional filters due to the choice of single-cell cavities) we are on the safe side concerning feedback gain but there is not a very large margin. Therefore, single-cell cavities are preferred in this context.

Frequency Swing

The speed of lower energy (heavy) particles still changes by a non-negligible fraction and for standing wave cavities the frequency has to be tuned correspondingly. The following table shows the frequency difference at $f_{RF,\infty}$=200 and 400 MHz for particles with momentum p compared to particles with speed of light (infinite momentum). To accelerate from p_1 to p_2, the frequency has to be changed by the difference of the corresponding frequency values.

p/e GeV/c/e	p/200 MHz f-f. [kHz]	p/400 MHz f-f. [kHz]	Pb/200 MHz f-f. [kHz]	Pb/400 MHz f-f. [kHz]
26	130.0984	260.1969	832.6792	1665.3585
150	3.9124	7.8249	25.1697	50.3395
450	0.4347	0.8695	2.7971	5.5942
1000	0.0880	0.1761	0.5664	1.1328
7000	0.0018	0.0036	0.0116	0.0231

Tab 1: RF Frequency difference with respect to particles with v=c ('p': protons; 'Pb': fully stripped lead ions) for $f_{RF,\infty}$=200 and 400 MHz

For protons injected at 150 GeV/c the tune change is easily obtainable but considerable technical problems might arise at 26 GeV/c. For ions (fully stripped Pb) injected at 150 GeV/c/e the change is not negligible but at 26 GeV/c/e probably impossible to realize in a high field cavity.

SUPERCONDUCTING VERSUS NORMAL CONDUCTING

The advantage of a sc RF system that comes to to everybody's mind is its capability to produce the same total accelerating voltage for less mains power and in less space, essential points for LEP or TESLA/ILC. LHC and consequently its injectors are high current machines and both the resistive (acceleration) and the reactive (bunch stabilization) power have to be transferred through a power coupler into the cavity. These power couplers are sensitive, complex and expensive elements[‡] and may cause an operational interruption more often than the cavity itself. For reliability reasons these couplers should not be operated too close to the design limit but with some margin, to avoid arcing and overheating, causing shut-down of this RF system. Since the power to be transmitted is proportional to the product of beam current and cavity voltage, the latter is voluntarily limited in LHC to the modest 5.5 MV/m (2 MV per 400 MHz single-cell cavity). At this (for linear collider standards) low field and also because of the low number of cavities, the argument of energy saving is not essential for LHC. This also means that no special R&D is necessary to increase peak field and Q_0 for our purpose, we can very well live with today's standards, but possibly profit from advances in cost and reliability made in the framework of other machines. However, even with this minimalist attitude a team with extensive experience in sc cavities has to be in-house, otherwise false manipulations or incorrect operational actions will lead rapidly to problems or even hardware destruction.

For a high current machine with tight tolerances, the inevitable impedance that any RF system presents is of critical importance, limiting the stable beam current and ultimately the luminosity. In this context there are two facts in favour of sc cavities.

First, since each sc cavity produces much more voltage than its normal conducting (nc) twin (assume the same shape for simplicity), fewer cavities have to be installed for the desired voltage, reducing parasitic impedance by the same factor.

Second, nc cavities are optimized for maximum shunt impedance R_s, i.e. minimum internal losses for the same cavity voltage (square). They are often built as nose-cone cavities with beam holes as small as possible and hence large (R/Q) on the fundamental and also for the higher order modes (HOM). R_s can be understood as the product $(R/Q)\cdot Q_0$, with the pure geometrical constant (R/Q) and the resonator's *internal* quality factor Q_0, the latter depending on the RF properties of the cavity material. These R_s-optimized copper cavity shapes, apart from other problems, do not allow good surface cleaning and hence such a cavity used as sc would have a lower than necessary Q_0. Therefore sc cavity optimization gives away a considerable margin in the geometrical (R/Q) but this is more than compensated by the increase in Q_0, leading then to the required R_s, and the lowest dynamic cryogenic losses. These designs with generally much larger beam tubes have also intrinsically lower (R/Q) for the HOMs.

The shunt impedance for HOMs is the product of the – already reduced – geometrical (R/Q) times the corresponding quality factor $Q_{0,HOM}$, the latter being very high for a sc cavity. Therefore, in high current machines, sc cavities have to be equipped with HOM couplers, loading down the natural $Q_{0,HOM}$ to a much lower value. Once such couplers have to be added, the best is done to get the strongest damping. Then sc cavities with HOM couplers have overall lower HOM impedances than copper cavities without such couplers.

Finally there is a last point that ultimately tilted the balance in favour for sc cavities in LHC – the reactive beam loading.

REACTIVE BEAM LOADING

Bunches passing a cavity leave an induced voltage behind, changing the instantaneous cavity voltage. If bunches do not pass at maximum (or minimum) cavity voltage, this newly induced voltage not only causes an amplitude change (energy transfer) but also a phase-shift of the total cavity voltage, an effect called reactive beam loading. Without countermeasures the next bunch will not see the design voltage, hence the reactive beam loading has to be compensated to conserve the design bunch spacing. There are two ways to do so, either by brute force injecting an opposite RF wave, very costly in RF power for high current machines, or by slightly detuning the cavity in such a way that the beam-induced phase jump just drifts back to zero again as the next bunch arrives; the latter method costs (in the ideal case) no additional RF power.

Since the tuner is much too slow to change its state during a fraction of a machine turn, tuning has to be considered constant. Therefore the above

[‡] citation (I. 'Ricky' Campisi, JLAB) in a relatively recent review talk on sc RF: today a coupler can be more expensive than a – cost-optimized – cavity

method only works to perfection for an absolutely regular bunch pattern all around the ring and perfectly identical charges for every bunch. With the classical tuner loop – comparing the phase of the cavity field and the driving RF wave – applied in most machines, the above method still works relatively well even with gaps in the beam since the tuning is adjusted (and averaged by the tuner inertia) automatically to an average position such that only a minimum average excess power is required and bunches only deviate modestly from their theoretical position, in itself not critical for a fixed target accelerator.

In a high current injector chain, however, at transfer the bunch has to hit exactly the centre of the bucket, hence the perfect bunch and bucket spacing has to be enforced even with gaps in the beam[§]. Then the RF phase has to be maintained using a strong correcting RF wave. However, cavity detuning can be used as a 'free parameter' to at least minimize the unavoidable excess power, ending in heating the cooling water.

There are two criteria of minimisation: the average power and the peak power for one machine turn. For a klystron, which converts any DC power either in RF power or collector heat, the peak power is the decisive quantity. In reality there will be *significant transients* at the instant when the cavities encounters a train followed by a gap or vice versa. To first order we neglect these, but have to keep in mind that the installed *RF power has to be even larger* to cope with these transients. For the *same* – yet undefined – cavity detuning $\Delta\omega$ we calculate the transmitter power to keep the design cavity voltage V for the two cases, once while a (long) train passes (P_+) and once while a (long) gap passes (P_0). The optimum $\Delta\omega$ is the one where the *maximum* of these two cases has its *lowest value*, i.e. we search for $\min(\max(P_0,P_+))$.

We can write [3] the generator current I_g in a beam-cavity-generator model needed to create an accelerating voltage V (for sc cavities $Q_L=Q_{ext}$) as

$$I_g = \underbrace{\left(\frac{V}{2(R/Q)\cdot Q_L} + I_{b,DC}\, f_b \sin(\phi)\right)}_{real\ \ part\ (resistive)} + \ i\cdot \underbrace{\left(I_{b,DC}\, f_b \cos(\phi) - \frac{V\ \Delta\omega}{\omega\,(R/Q)}\right)}_{imaginary\ \ part\ (reactive)}$$

V defines the real axis with $\phi=0$ at rising zero-crossing[**], $I_{b,DC}$ is the DC beam (train) current and f_b the (normalized, =1 for point bunches) bunch form factor. This generator current corresponds to the (measurable) generator power

$$P_g = \frac{1}{2}(R/Q)\cdot Q_{ext}\left|I_g\right|^2 = \frac{1}{2}(R/Q)\cdot Q_{ext}\left(\mathrm{Re}\left[I_g\right]^2 + \mathrm{Im}\left[I_g\right]^2\right)$$

Reactive beam loading in coast

In coast with (above transition energy) $\phi=180°$ the optimum detuning is easily found since then

$$I_{g,coast} = \left(\frac{V}{2(R/Q)\cdot Q_L}\right) + \ i\cdot\left(-I_{b,DC}\, f_b - \frac{V\ \Delta\omega}{\omega\,(R/Q)}\right)$$

The real part of $I_{g,coast}$ is identical if there is a train ($I_{b,DC}\neq 0$), or a gap ($I_{b,DC}=0$), hence choosing the detuning term in the imaginary part of $I_{g,coast}$ corresponding to (minus) *half* the beam current term – called 'half-detuning' [4] – with

$$\Delta\omega_{opt,coast} = -\frac{\omega\,(R/Q)\ \ I_{b,DC}\, f_b}{2\ V}$$

yields

$$I_{g,coast,opt} = \left(\frac{V}{2(R/Q)Q_L}\right) \pm\ i\cdot\frac{I_{b,DC}\, f_b}{2}$$

where the imaginary part keeps the same magnitude but simply changes sign between gap and train. Any change of detuning would increase the absolute value of $I_{g,coast}$ for one of the two cases, hence we have in fact found the optimum.

The power is identical for both cases

$$P_{g,coast,opt} = \frac{1}{8}\left(\frac{V^2 Q_{ext}}{(R/Q)Q_L^2} + \ (R/Q)Q_{ext}\left(I_{b,DC}\, f_b\right)^2\right)$$

and – apart from the transients in the real RF system – there will be constant RF power independent of whether there is a train or a gap passing the cavity. For sc cavities $Q_L=Q_{ext}$, i.e.

$$P_{g,coast,opt} = \frac{1}{8}\left(\frac{V^2}{(R/Q)Q_{ext}} + \ (R/Q)Q_{ext}\left(I_{b,DC}\, f_b\right)^2\right).$$

We see that $\Delta\omega_{opt,coast}$ is lower if (R/Q) is smaller and V larger, two properties where sc cavities clearly have an advantage compared to nc cavities. For the LHC sc cavities the required detuning is still small compared to a revolution frequency while for nc cavities detuning may correspond to several revolution frequencies, i.e. cavities will be detuned across several revolution frequencies off the principal RF line.

The LHC sc cavities are equipped with an adjustable coupler to adapt Q_{ext}. Looking for the optimum $Q_{ext,opt}$ for the power consumption calculated above we find

$$Q_{ext,opt} = \frac{V}{(R/Q)\cdot I_{b,DC}\, f_b}.$$

For the LHC sc cavity we have $(R/Q)=45\Omega$, with $f_b\approx 0.9$ at 400 MHz, an effective current (nominal, 'in train') of about 0.6 A and V=2 MV in coast, leading to $Q_{ext,opt}$=75,000; this is perfectly (as it was built for

[§] For the LHC in coast a different method with RF vector feedback active is under preparation but it is incompatible with a (fast cycling) injector.

[**] 'proton machine convention'

this) in the range of the adjustable coupler; the corresponding power is then 300 kW.

Reactive Beam-Loading with Acceleration

In LHC during the 20 min ramp from 450 GeV to 7 TeV particles increase their energy per turn by about 0.5 MeV, i.e. about 60 kV per cavity are necessary. This amount is, compared to the cavity voltage of 1 to 2 MV, still small enough for the detuning choice above to be about optimum. However, for a rapid cycling machine the accelerating term can no longer be neglected in the optimization. The detailed optimization is more complicated [5] and will not be shown here but we apply these results later in the example.

Tuning Range of Superconducting Cavities

This parameter is important at the lower particle energy end where the proton/ion speed still changes considerably with the particle energy. Nc cavities may be tolerant to some weak multipacting (MP) but not sc ones – a quench will be triggered, instantaneously disabling the cavity – and therefore all types of MP-prone plunger tuner – where piston-like objects penetrate more or less the cavity volume – are to be avoided in sc cavities.

For some (heavy ion) machines, in which cavities with relatively low frequency (100 MHz range) and low stored energy are used, 'RF tuners' can be applied. These can be seen as a capacitance (inductance) coupled over a (second) power coupler parallel to the resonator and switched on or off by fast semi-conductor (PIN) switches. However, with the large stored energy in voluminous and high-field cavities the reactive energy to be shuffled twice per RF oscillation over these switches becomes prohibitive even for small tuning ranges. The reactive power also overloads the (second) coupler much more than the power (input) coupler for the usual tuning ranges of these cavities.

Therefore all larger high field cavities (as at CEBAF, LEP, LHC, SNS, TESLA, …) are tuned by (longitudinal) *elastic* deformation of the whole cavity body, the only principal difference being the way this deformation is enforced (step-motors with gears using blades or cables, piezo-crystals, magnetostrictive bars, thermal expanding bars). However, the cavity body cannot be deformed too much, or we will exceed the elastic limit, permanently deforming the cavity. Furthermore tuners are presently used to correct relatively small frequency deviations but for the planned rapid cycling machines, with one large tuning stroke for each energy ramp, material fatigue on the cavity (and helium tank) becomes an important issue. It should be noted that the cavity material (today) is either high RRR niobium or OFHC copper (with Nb film). As an example, the LEP cavities had an operational tuning range of 50 kHz on 352 MHz ($1.5\cdot10^{-4}$) and the LHC cavities about 200 kHz on 400 MHz ($5\cdot10^{-4}$); the stiffer LHC cavities approach their elastic limit while the softer LEP cavities had an elastic limit corresponding to roughly 300 kHz ($8\cdot10^{-4}$). Without further positive R&D results, concerning material studies or a different tuning method, a relative (repetitive) tuning range not more than $5\cdot10^{-4}$ has to be accepted. This has to be compared with the data in Tab. 1.

Variable Input Coupling for Sc Cavities

The input coupling strength determines the cavity field level created by a given RF input power but also the bandwidth of the system and with it the so-called 'filling time'. At injection, errors in energy and time between one machine and its injector are inevitable. If high charge bunches (even slightly) miss the bucket centre, there will be a considerable energy transfer between cavity and beam, in one way or another. As the induced voltage is proportional to the shunt impedance $(R/Q)\cdot Q_{ext}$ of the RF system, we have every interest in having a low Q_{ext} at injection. Therefore the LHC sc cavities are equipped with an adjustable power coupler that is set to low Q_{ext} during injection.

Furthermore, to avoid significant filamentation creating tails and halos, the injection oscillations should be damped as rapidly as possible. This can be done by an additional (with additional impedances in the machine) purpose-designed (capture and) damping RF system. In LHC we achieve this goal for the initially limited beam intensities directly with the main RF system alone (simulations indicate that it will be possible) but cavities have to be as fast as possible, i.e. also have a low Q_{ext}. Once the injection oscillations damp away, energy ramping needs increasing cavity field levels. In order to create these without excess RF power, the Q_{ext} of the main coupler has to be increased, corresponding to a decrease in coupling strength. This is practically realized by mechanically retracting the antenna part (inner conductor) of the power coupler, while stretching/compressing the bellows between air and the cavity/machine vacuum. The LHC adjustable coupler works without sliding RF contacts.

The ramp in LHC lasts 20 min allowing a smooth mechanical movement, realized by turning a screw with low pitch thread with a step motor drive over many turns against the vacuum forces. However, to ramp the particle energy within a few seconds would require a change of the antenna position in the same time, excluded with the present design. This is another area for R&D work.

One – very unattractive – way out would be to apply brute RF power with a fixed power coupler, but the necessary RF power increase would be considerable and, on top of this, this fixed power coupler would have to withstand these increased levels reliably without arcing or overheating.

Design Frequency Range for Sc Accelerator Cavities

The highest frequency used in a major sc particle accelerator is 3 GHz (S-Dalinac, TU Darmstadt), the lowest (was) 352 MHz in LEP with several other machines distributed between, i.e. a solid common technological base for this frequency range exists. For LHC and its injectors, even lower frequencies, e.g. 200 MHz, are of interest; however, extrapolation is not straightforward.

The 'spherical' shape of β=1 sc cavities cannot be modified drastically (risk of multipacting, deadly for sc cavities), hence a 200 MHz cavity compared to the existing 400 MHz design will be twice as large in all dimensions.

Practically this means that the wall strength of the cavity has to be increased (vacuum pressure) with a corresponding rising material price for the high RRR niobium. Also the fabrication technique of spinning and welding (no projections!) has to be adapted – today all cavities start from about 3-4 mm thick sheets. Furthermore the niobium industry, delivering today up to about 1x1 m^2, 3-4 mm thick sheets would have to deliver sheets 2x2 m^2 in flat dimensions, provided the rolling machines are available.

One might also use the Nb/Cu sputter technology, certainly saving in material cost, but then the sputter conditions are different from the proven 352-400 MHz range and film may grow differently on the more distant, thicker and differently treated copper substrate cavity. There was a first attempt in this direction, aimed at μ-acceleration and financed by Cornell-University, a 200 MHz Nb/Cu single-cell prototype studied and developed at CERN, exploiting part of the still existing sputter installations. After several tests the best performance was about [6] 10 MV at $Q_0=0.8\cdot10^9$, below expectations for this application; for the time being the development is suspended.

Fig. 1: 'Virtual reality' of a sc cavity module at 200 MHz. The cryostat would have a diameter of about 2 m with couplers and cryogenic domes sticking out. The technician (on his knees, left) shows the size of a man in the same scale.

The doubling in size will also have other inconveniences: the cryostat will be twice the diameter (cost, cryogenic losses, handling) and the technique of waveguides applied down to 350 MHz becomes impracticable due to their large size (proportional to the wavelength). Coaxial lines have to be employed, more difficult to use (bends!), and, more seriously, the 'warm' part of the variable power coupler, presently exploiting nicely the waveguide's door-knob transition to naturally incorporate the antenna's variability, may have to be redesigned and tested from scratch.

This means that a frequency significantly below 400 MHz is 'terra incognita' for *sc* cavities and serious R&D concerning cavities, cryostats and couplers has to be undertaken before envisaging its application.

EXISTING LHC/SPS RF CAVITIES

There are two types of LHC cavity that exist. The first are 400 MHz sc cavities. They have a single cell with (R/Q)=45Ω and a quality factor Q_0 in excess of 10^9 in sc state. The power coupler has a variable coupling with Q_{ext} between 10,000 and 200,000. The design voltage is 2 MV, corresponding to 5.5 MV/m with a design RF power up to 300 kW. Four cavities are grouped together in one module, equipped with all ancillaries, cryogenic supply and connected to the RF power sources ready for operation during commissioning of LHC.

Fig. 2: 400 MHz sc cavity module

The foreseen nc 200 MHz capture and damping system has been staged[††]. But the eight copper cavities (four per beam) have already been ordered and have been successfully manufactured. They are single-cell cavities with $(R/Q)=192\Omega$, $Q_0=30000$, design coupling fixed with $Q_{ext}=6100$, and design voltage 0.75 MV in CW (possibility to go up to 1MV for a short time, e.g. during capture and injection damping). The design power is 240 kW produced by four combined 60 kW gridded tube amplifiers (which can give more power for a fraction of a second).

Fig. 3: 200 MHz capture cavity (right) and parts of it before brazing (left).

These relatively expensive RF power amplifiers, the tuner and the power- and HOM couplers do not yet exist but similar equipment has been built for other cavities. This hardware will have to be produced later when higher beam current will make these cavities necessary.

In the SPS, the injector to LHC at 450 GeV/c, there are 2x2 travelling wave cavities with a total RF voltage of about 7 MV. The necessary RF power is about 800 kW per cavity.

[††] after confirmation by simulation that the 400 MHz sc system can - at the limit – handle injection of the initially limited intensity beam with only low capture losses

Fig. 4: SPS 200 MHz travelling wave cavity

HIGH POWER RF TRANSMITTER

At lower frequencies high power transmitters work with gridded tubes but the stray capacities become more important for higher frequencies so that the dimensions of the tubes become smaller, in contrast to the request for larger size to handle high power. Hence efficiency and maximum power decline for rising frequency. Therefore, to obtain a *single* power source with high power the outputs of several gridded tube amplifiers have to be combined by RF-hybrids. This was done in the SPS for each of the four SPS TW cavities; one design (realized for two cavities) contains in the final stage 32 tubes of 35 kW nominal, the other (realized for the other two cavities) contains eight tubes of 130 kW each 'in parallel' yielding in practice 800 kW [7]. Both designs produce complex construction. This implies considerable maintenance and adjustment and hence manpower.

Fig. 5: Racks with 4x2 gridded tubes of 35 kW (nominal) at 200 MHz (SPS)

Fig. 6: RF hybrids ‘joining’ the RF power flux (SPS)

Fig. 7: Amplifier of 135 kW (right, tube below the ‘hat’) coaxial RF lines and hybrids (SPS)

Furthermore its size forces the SPS high power system to be located in a hall on the surface and long (coaxial) lines leading down into the tunnel to be used. Such long lines would severely limit the maximum loop-gain of a direct RF vector feedback. For this reason the 400 MHz LHC RF system (using klystrons) is integrally housed underground and designed with klystrons physically as close as possible to the cavities. Also the gain of gridded tubes at high frequencies is not very high, requiring correspondingly higher input power, and a chain of pre-amplifiers with increasing output power is necessary, further increasing the loop-delay.

Thales has built a prototype of a tube (diacrode® [7][8]) that can deliver up to 1 MW at 200 MHz but the price of this very special tube is (presently) in the same order of magnitude as the sum of all classical tubes for the same power; besides, only one amplifier with this tube has been built and was tested for 1000 hours, no further follow-up is under way.

For higher frequencies tubes using electron drift effects such as klystrons are used. For evident reasons these tubes scale with the wavelength and hence these tubes get bigger at lower frequencies, limiting their application to the higher frequency range. Klystrons have the advantage of high gain so that a single solid-state amplifier can drive the klystron, avoiding a chain of pre-amplifiers.

There is no absolute limit to push any of these technologies further up or down in frequency but practically today the changeover is between 200 and 400 MHz. This is reflected in the ‘catalogue offer’ from industry, an important point concerning cost.

There is another new type of tube (IOT), a merger of gridded tube and klystron but today the power limits are such that a single tube could not supply e.g. an SPS TW cavity.

Due to the ever-rising prices for klystrons (see below), it is planned for Soleil, working at 352 MHz, to use a power transmitter combining a multitude of solid-state amplifiers of 330 W each. A prototype sub-module with true 30 kW [9], was built and tested successfully for at least 1500 hours.

SOME ASPECTS OF THE FUTURE OF HIGH POWER RF

In the past most of the really high power CW RF installations were built for television transmitters, a large number of them being distributed all over the world. Nowadays nearly all television channels are transmitted either by cable or by satellite, neither technique depending on truly high power RF. The emerging GSM technology also relies on a multitude of well-distributed relatively low power transmitters, more acceptable with respect to electromagnetic smog than a few sparse large emitters. This means that today only a few scientific instruments such as large accelerators and fusion test sites (and maybe a few secret military set-ups) rely on truly high power CW RF. Therefore the corresponding hardware such as e.g. klystrons becomes more and more expensive and older technologies, e.g. glass power tubes, are being discarded as the last experts retire, no new people being trained. This brings for CERN the problem that spare parts will not be available any more (we are already stockpiling critical parts) and CERN’s hardware may have to be modified – requiring a non-negligible effort in precious manpower – to fit different equipment made by newer technologies and/or other companies. Furthermore, industry is less motivated to do R&D in this domain; advances have to be pushed either by the laboratories on their own or with a considerable financial contribution from them.

But worse of all is the lack of young people attracted to the field of high power RF, both engineers and technicians, and CERN has in fact difficulties recruiting correspondingly trained good staff.

Therefore, as an example, even if pure financial arguments might point in the opposite direction, it should be pondered very carefully if it is not better to keep the existing 200 MHz RF system and to mass-produce electronics cards for the detectors compatible with 10 and/or 15 ns bunch spacing instead of discarding the 200 MHz RF system and designing and building a new system compatible with a 12.5 ns bunch spacing.

Evidently, if a decision is taken to replace the present SPS by a completely new system anyway, this argument is no longer valid and either 160 MHz or 240 MHz might be chosen. However, even then, much existing low power hardware and many proven methods will have to be redone requiring the corresponding training of staff and time to do it.

SUPERCONDUCTING CAVITY DEVELOPMENT AT CERN

The development work for the LEP sc cavities took off in 1979 and was entrusted to an existing experienced RF team (sc particle separators) with a few new recruits, in total about 20 people of medium age-profile. Knowledge of vacuum techniques, cryogenics, surface treatment and radio-protection was steadily expanded and collaboration with experts in these multiple fields was established, considerably increasing the total manpower working for this project. The work relied on the then still existing numerous in-house workshops of different kinds with direct access to technicians and mechanics being an integral part of the group. The niobium/copper sputter technique was developed and brought to industry production maturity. In parallel the necessary ancillaries for a true accelerator cavity such as horizontal cryostats, power couplers, HOM couplers and tuners, to name but a few, took shape. Finally complete knowledge was transferred to European industry. Modules were produced in industry, acceptance tested at CERN and installation started in LEP around 1995. After many successful physics runs, finally pushing the system performance well above the design values, LEP finally closed down in September 2000.

The LHC sc modules were developed and built in more recent years, largely based on the LEP technology and experience, exploiting partly the LEP team and installations serviced by them. However, today (2005) the core of the R&D team is nearly completely retired, especially the technicians with the invaluable hands-on experience, and the few remaining people, no longer young, have taken up completely different tasks as their main activities. Only a minimum number of technicians directly necessary for LHC modules have been kept. These have been trained to replace absolutely essential retiring staff. This mixed team is now very busy finalizing and collaborating in the installation and running-in of the LHC sc modules.

From the companies producing the LEP modules only one is still conserving and increasing its initial expertise (producing also the bare LHC cavities), the others have partly stopped this activity due to lack of orders, and one important sub-contractor (HOM couplers) has even gone bankrupt due to the decrease of orders from the nuclear industry, their main activity.

Having this situation in mind, it is difficult to imagine finding staff for a larger R&D program concerning sc cavities inside CERN before LHC is reliably producing its design luminosity. Considerable collaboration or support will be essential either coming from laboratories having continued to push (e.g. in the framework of the TESLA project) the technological development while recruiting and educating younger staff or in collaboration with specialized industry.

AN EXAMPLE INJECTOR COMPLEX

A possible scheme of two superposed rings in the present SPS tunnel has been proposed in [1]. We will now examine various RF systems for realizing this scheme.

Bunches are injected from the PS at 26 GeV/c (as is done today) in the lower energy machine, called ‘SPS’, possibly even (partly) identical with the present machine, and are accelerated to 150 GeV/c. Bunches are then injected into the higher energy machine, which is equipped with fast ramping sc magnets and called HPS, where they are accelerated to 1000 GeV/c before being ejected towards LHC.

There are four crucial steps to be considered

- capture from the PS into the ‘SPS’
- acceleration in the ‘SPS’ to 150 GeV/c
- bunch to bucket transfer ‘SPS’ to HPS
- acceleration in the HPS to 1000 GeV/c

Furthermore, since the new system should present a luminosity upgrade, we have considered a beam current twice the nominal one. The emittance assumed in [1] for the nominal current is no longer strictly valid for this case but we assume nonetheless the same emittance and hence the same cavity voltage in order to contain the bunch.

We neglect possible difficulties during the bunch to bucket transfer into the 'SPS' and into the HPS which might require a separate damping system for higher currents or at least some reserve power with a low enough Q_{ext} (requiring possibly a *fast* ramping variable coupler which today does not exist even as a prototype).

We use in this example as alternative frequencies only 200 MHz and/or 400 MHz. The latter is the LHC main frequency and hence a natural choice. 200 MHz is an evident alternative being half the LHC frequency and the present SPS is already equipped with it, together with an 800 MHz higher harmonic 'Landau system'. This state perfectly matches the presently envisaged bunch distances of 25 and 75 ns.

A frequency of 200 MHz in the injectors would still be compatible with the bunch distances of 10 ns or 15 ns. The physics experiments are now discussing a bunch distance of 12.5 ns – half the present nominal one – which would make an upgrade to shorter bunch distance easier for them. However, this bunch distance is incompatible with the present RF system at 200 MHz in the SPS[‡‡], it would ask for an RF system at a multiple of 80 MHz such as 160 MHz or 240 MHz. In this case the SPS cavities and RF power plants have to be completely rebuilt, with the corresponding financial and, more crucial, manpower requirements.

For our considerations, we have to distinguish two voltages. The first is the total accelerating voltage V of the cavity to contain the bunch when under acceleration as given by [1]; the second is the projection of V on the beam current, i.e. the voltage component $V_{beam}=V\cdot\sin(\phi)$ used to accelerate the beam. It determines the power taken up by the beam to be supplied by the RF transmitter and passed along the power coupler, both limited in performance.

V_{beam} can be determined from the (maximum) ramp-rate in MeV/s divided by (e and) the revolution frequency – about 43 kHz in the SPS tunnel, i.e. for both machines. For the faster ramping low energy machine ('SPS') data are given in [1] with 160 MeV/s and 80 MeV/s at 1 and 2 s total ramp time; for the HPS we estimate the (maximum) ramp rate by the ratio of particle energy difference and ramping time, somewhat optimistic since in reality the ramp starts and ends with a smooth lower slope to avoid transients, therefore requiring a correspondingly steeper centre slope.

The nominal beam current to be considered is the 'in train' current which amounts, for bunches with $1.15\cdot10^{11}$ p/bunch at 25 ns bunch distance, to about $I_{b,DC}$=0.74 A. The <u>normalized</u> bunch form factor f_b is somewhat smaller than unity hence for our estimation we set $I_{b,DC}\cdot f_b$=0.7 A.

We assume the use of SW cavities similar to the 200 MHz ACN cavities with 0.75 MV peak voltage and a power coupler that can carry up to 300 kW CW. Therefore we have to respect two limitations. First we divide the necessary total voltage by 0.75 MV, yielding the number of cavities that can supply this voltage. However for the cases of increased beam current this voltage would require an RF power overloading the power coupler and we have to lower the cavity voltage, increasing the number of cavities correspondingly, till the RF power does not exceed the power coupler rating.

There remain two technical problems to be resolved, the necessary <u>frequency swing of about 130 kHz</u> (see Tab. 1) in the 'SPS' and the <u>required strong coupling</u>, i.e. low Q_{ext}, for higher beam currents. We assume that these can be solved by corresponding R&D.

Concerning the choice of Q_{ext} and the static detuning of the cavities – differing from 'half-detuning' [4] for accelerated beam [5] – we adapt them to be about optimum. However, in reality these optimal values cannot be determined easily. Errors will be the norm and – most of all – this 'two state' estimate does not take into account the strong RF transients between gaps and trains. Therefore in reality a good safety margin has to be added to the power values given here.

Capture from PS into SPS

As is the case today, bunches from the PS are too long to be captured at 400 MHz, hence the 'SPS' has to have (at least) a 200 MHz system. Therefore acceleration has also to be done using this system. A possible additional 400 MHz system will be discussed during the transfer considerations.

Acceleration in the 'SPS'

At 200 MHz for bunches of 0.5 eVs two cases were considered in [1], a total ramp of either 1 s or of 2 s. The first one asks for a maximum voltage of 9.2 MV and a peak ramp rate of 160 GeV/s (V_{beam}=3.7 MV), the second for 6 MV and a ramp rate of about 80 MeV/s (V_{beam}=1.85 MV). We do not consider the use of the existing 200 MHzTW system since it has no direct RF vector feedback and

[‡‡]A complex 'bunch gymnastics' scheme compatible with a 200 MHz main RF system was proposed by [10], but requiring a sizable 'lower harmonic system' at 80 MHz, requiring probably an effort in the same order of magnitude as the replacement of the 200 MHz system.

is limited in beam current capability. We summarize the different cases/options in Tab. 2; text in red shows overloading of the main coupler, the case has to be realized by more cavities running at a voltage below their capabilities, row below.

t_{ramp} [s]	I/I_{nom}	V_{tot} [MV]	V_b [MV]	n_{cav}	V_1 [MV]	Q_{ext}	P [kW]
1	1	9	3.7	12	0.75	6000	270
2	1	6	1.85	8	0.75	6000	230
2	**2**	6	1.85	8	0.75	3000	**420**
2	**2**	6	1.85	**12**	**0.5**	3000	300
2	**3**	6	1.85	8	0.75	1500	**620**
2	**3**	6	1.85	**20**	**0.3**	1000	240

Tab. 2: Ramping time from 26 to 150 GeV/c, beam current and required RF power per cavity for different cases in the ‘SPS’.

Conclusion is that we need at least 12 cavities for I/I_{nom}=2 and 20 cavities for I/I_{nom}=3 for the 2 s ramp.

Transfer ‘SPS’ to HPS

As shown in [1], the bunch-to-bucket transfer is ‘transparent’ if we inject from a 200 MHz bucket into another 200 MHz bucket, 4.5 MV in both machines assuming the same transition energy. Such a voltage would be available in both machines for acceleration in any case so that no additional hardware would be necessary. However, in this case LHC has to capture the bunch from a 200 MHz bucket in the HPS.

If we intend to operate the HPS at 400 MHz, either the HPS needs an additional 200 MHz capture system or bunches have to be shortened previously in the ‘SPS’. This bunch shortening could be done either by increasing the ‘SPS’ 200 MHz voltage or by adding a 400 MHz system there. For these three scenarios we find the required voltages in [1]. Comparing then the hardware additionally required for transfer to that necessary in any case for acceleration, we see that the effort for a transfer into a 400 MHz bucket in the HPS is completely disproportionate. There might still be one small advantage for acceleration in the HPS at 400 MHz: the necessary voltage [1] would indeed be about twice that needed at 200 MHz but might be generated using more efficient sc modules identical to those in LHC (except with higher power capability). However, we continue with a pure 200 MHz system in the HPS.

Acceleration in the HPS

For bunches with 0.6 eVs in the HPS from 150 GeV/c to 1 TeV/c at 200 MHz a voltage of 13 MV would be necessary for a ramping time of 3 s (i.e. V_{beam}≈6.6 MV) or 7 MV for 6 s ramping time (i.e. V_{beam}≈3.3 MV). Again we assume the same emittance and hence same total voltage for higher beam current.

t_{ramp} [s]	I/I_{nom}	V_{tot} [MV]	V_b [MV]	n_{cav}	V_1 [MV]	Q_{ext}	P [kW]
3	1	13	6.6	18	0.72	5000	300
3	**2**	13	6.6	18	0.72	3000	**560**
3	**2**	13	6.6	**35**	**0.37**	2000	300
6	2	7	3.3	10	0.7	2500	500
6	2	7	3.3	**18**	**0.39**	2000	280

Tab. 3: Ramping time from 150 to 1000 GeV/c, beam current and required RF power per cavity for different cases in the HPS. Red text indicates overloading of the power coupler, the case has to be realized by more cavities running at reduced voltage (row below).

Conclusion from Tab. 3 is that for I/I_{nom}=2 and a 3 s ramp 35 cavities are necessary, for a 6 s ramp 18 cavities. Due to power limitation in the coupler the operational voltage cannot be larger than about half the cavity design voltage.

Superconducting 200 MHz Cavities in the HPS

For completeness we might study a *sc* 200 MHz RF system in the HPS; but as already shown the cryostat would be very bulky (see Fig. 1) and there is no prototype yet. Extrapolating from the existing 400 MHz sc cavities we will have the same (R/Q) and can assume that a gradient of 5.5 MV/m (or slightly more) will also be obtained, i.e. due to the double length the voltage would be 4 MV per cavity. Then 13 MV could be produced by three cavities (at 6 MV/m) and 7 MV by two (at 4.8 MV/m).

t_{ramp} [s]	I/I_{nom}	V_{tot} [MV]	V_b [MV]	n_{cav}	V_1 [MV]	Q_{ext}	P [kW]
3	1	13	6.6	3	4.333	150000	**1550**
3	1	13	6.6	**4**	**3.25**	100000	1200
3	1	13	6.6	**11**	**1.2**	35000	420
3	**2**	13	6.6	3	4.3	75000	**3100**
3	**2**	13	6.6	**8**	**1.63**	20000	1200
3	**2**	13	6.6	**22**	**0.6**	10000	420
6	2	7	3.3	2	3.5	70000	**2400**
6	2	7	3.3	**4**	**1.75**	25000	1200
6	2	7	3.3	**11**	**0.64**	10000	420

Tab. 4: Sc 200 MHz cavities (extrapolated). Ramping time from 150 to 1000 GeV/c, beam current and required RF power per cavity for different cases in the HPS. The red text indicates overloading of the power coupler for the nominal cavity field: the case has to be realized by more cavities running at reduced voltage (two lines below, once with 1.2 MW couplers, once with 450 kW couplers).

Concerning the corresponding power coupler, there are two extreme estimates. Considering a coupler also scaled from 400 MHz by a factor 2 in all dimensions might – for the same internal field levels – allow four times the RF power, i.e. 1.2 MW, which would have to be confirmed by R&D. If the coupler were scaled only slightly and considering that surface resistance scales as the skin-effect, we might consider 450 kW as acquired. Tab. 4 gives the number of cavities required for different allowed power levels in the couplers.

We see that without a power coupler withstanding about 1 MW the sc option is not significantly better than the nc one, but on the other hand 200 MHz sc cavities have a very large size, need a cryogenics installation and require further R&D.

Location of the RF power transmitters

To allow direct RF vector feedback – necessary for the high beam current – the total loop delay has to be low enough to allow a sensible gain. This requires that – in contrast to the present SPS situation – the power transmitter has to be physically close to the cavities under ground (as in LHC). Excluding any new excavations next to the tunnel, the only locations of perhaps corresponding size might be the experimental caverns of the UA-1 and UA-2 ppbar experiments. However, the necessary infrastructure for electrical high power supply, cooling and possible cryogenics have to be studied in more detail.

Conclusion

It has become clear that the main bottleneck for a high performance RF system for new injectors is the power coupler. Without significant progress cavities have to be operated far below their voltage capability which requires more cavities to obtain the total design voltage; the parasitic impedance and the cost of the RF system grow correspondingly.

There are two other aspects of the power coupler to be studied: the coupling to the cavity field has to be larger the higher the beam current, not a trivial enterprise, and – should injection damping become necessary – this power coupler would even need to be variable. A variable coupler is already in operation on the sc LHC cavities but only with a slow (20 min) ramp time while here the coupler has to ramp with an acceleration within 1 to 6 s.

Furthermore, to allow the large gain RF vector feedback necessary for the high beam currents, the ‘power plants’ have to be underground close to the cavities. This requires, in particular at frequencies at (or close to) 200 MHz, a much more compact implementation than was done for the SPS with the technology of the ‘70s. New technologies are appearing at the horizon but further R&D in collaboration with industry is necessary.

If SW cavities are to be applied at the low energy end, the classical cavity tuning range requirements have to be increased due to the large frequency swing – in particular for ions – and the tuner has to withstand the repetitive stroke over the full range once per acceleration cycle.

Finally, should a sc cavity option be considered seriously – except if an exact copy of the existing 400 MHz modules is used – a corresponding multi-disciplinary team with experience, based on the existing minimum team, would have to be built up.

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