SC CAVITIES R&D FOR LHEC AND HE-LHC

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Abstract

The new machines HE-LHC and LHeC (whether or not linac-ring and ring-ring options will be favoured) rely on new RF systems. The talk will analyse the synergies or competitions between the R&D strategies. The first steps foreseen for 2012 will be highlighted.

SUPERCONDUCTING RF R&D THEMES

High Gradient

The supreme discipline for superconducting RF R&D definitely is to reach the highest possible accelerating gradient. It is limited by the maximum tolerable surface fields, but different from normal-conducting RF where the electric field enhancement on the curvature of the iris may lead to field emission, the main limiting factor in SCRF is the surface magnetic field near the equator of the cavity; the surface magnetic field is equal to the RF surface current density, which has to be kept below a threshold for sustained superconductivity.

The global projects requiring high gradient are primarily ILC and X-FEL; the dedicated R&D for these projects have brought the field continuously forward and very advanced technologies have been invented and implemented over the last 20 years. Fig. 1 summarizes this progress [1].

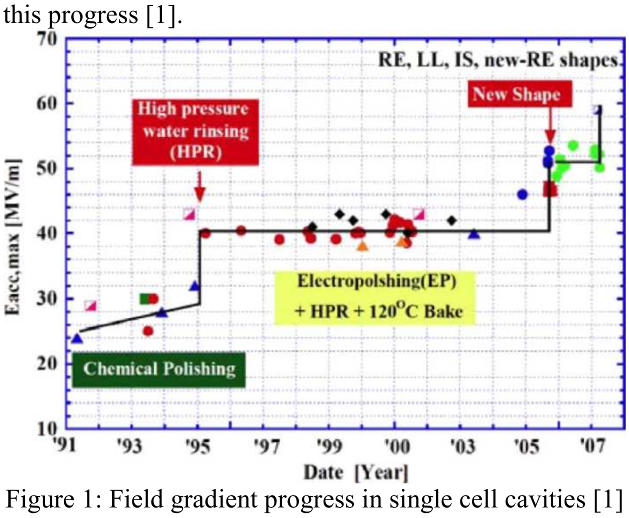

Figure 1: Field gradient progress in single cell cavities [1]

The main steps during this development are marked by the advent of now well established technological processes in SCRF: chemical polishing (CP), electropolishing (EP), high-pressure water rinsing (HPWR), large-grain Nb and shape-optimization reducing the peak magnetic field.

Reproducibility, industrialisation

The achievement of accelerating of beyond 50 MV/m is by all means remarkable, but for a large scale project like the ILC it is necessary to demonstrate what values can be obtained in a reproducible and reliable fashion. For an ILC with $\sqrt{s} = 500$ GeV e.g., a gradient of 35 MV/m would have to be sustained of 15 km (length of accelerating structures only); this also implies that accelerating structures have to be fabricated and tested in an industrial fashion. The present ILC goal is to have a yield of 90% of industrially produced cavities at the design gradient of 35 MV/m [2], a goal which the Global Design Effort is slowly approaching.

RF Losses, Q-slope, Q-drop

It is generally observed that the quality factor Q decreases with increasing field. A possible explanation of this generally observed behaviour is sketched in [3]: material imperfections lead to nucleation centres in the bulk material near the surface; in these areas, unpaired (normal-conducting) electrons exist. With increasing surface field the conducting layer gets thicker and more and more of these normal-conducting electrons contribute the current and consequently losses increase.

New SC Materials

The materials used for superconducting RF are mainly Nb and Pb. Some other materials that have shown interesting behaviour in DC have been tried for RF (Nb_3Sn, MgB_2) with limited success. There is however a large variety of possible candidates with potentially better performance in either maximum surface field (current density) or Q_0 that would require dedicated R&D to evaluate their potential; these include high-temperature superconductors, alloys like Nb_3Sn or molecular superconductors like alkali-doted C_{60} fullerene. These new materials might also become interesting in view of thin-film techniques described in the following.

Sputtering Nb on Cu

The technique of sputtering Nb on Cu was first developed at CERN around 1980 [4] and significantly contributed to the success of LEP. Compared to bulk or sheet niobium, this technique has the following potential advantages: 1) less Nb is needed, which may reduce overall cost, 2) due to its high thermal conductivity, the copper substrate hinders the forming of hot spots and thus increase the quench resistance, 3) the thickness of the copper can be chosen such that also the mechanical stability of the cavity is increased. In spite of these potential advantages, the maximum gradient in sputtered SC cavities has not reached the record peak fields of sheet niobium cavities. It does not seem however that this is an intrinsic limitation, so the technology has still large potential. Both diode sputtering and magnetron sputtering techniques have been developed and later refined, leading to advanced techniques known as HiPIMS [5] or Arc-PVD.

Many laboratories (JLAB, LNL Legnaro, CEA/IRFU Saclay, University Sheffield and CERN) develop these techniques further and recent progress is remarkable. Sputtered cavities are successfully used e.g. for the ALPI project (LNL), the Soleil light source and at CERN both LHC and HIE-Isolde.

Synergy with other SC RF R&D

At CERN and elsewhere, superconducting RF is of high importance for a large number of operating and planned accelerator facilities: all large proton drivers for a number of applications (spallation neutron sources, accelerator driven systems, neutrino physics, muon colliders, irradiation facilities) are based on large and advanced superconducting RF installations. The ILC as example for a planned lepton collider was mentioned earlier and it has in fact driven the research on SCRF over many decades; but also HIE-Isolde, the post-accelerator for radioactive isotopes in construction at CERN is based on SCRF technology. The LHC RF system is relatively insignificant on this scale, but the luminosity upgrade HL-LHC is relying on superconducting crab cavities to compensate for luminosity losses arising from a crossing angle at small β^*. These cavities have novel geometries and R&D for them is in full swing.

LHEC – MOST EXCITING

LHeC Options

The LHeC lepton-hadron collider uses one of the LHC beams for protons, while the electron (or positron) beam is accelerated either in a new ring inside the LHC tunnel (ring-ring option) or in a separate linear accelerator (linac-ring option). In both cases one aims at a 60 GeV, 100 mA lepton beam at collision with 7 TeV protons. For both options, substantial RF systems are required [6].

For the ring-ring option with a 100 mA electron beam, synchrotron radiation losses add up to approximately 44 MW, which have to be reconstituted from the RF system. The conceptual design estimates the need of 56 klystrons at 721.4 MHz, providing 1 MW CW each, grouped in 14 RF power stations; a single such station would consist of 4 klystrons feeding 8 cavities in one cryostat. The cavities could run at a moderate gradient of 12 MV/m. The sheer size of these power stations would require housing them in bypasses near ATLAS and CMS. Apart from their size however, the RF systems for the ring-ring option are relatively "conventional" and will not be discussed further in this paper – for more details please refer to [6]. The total power consumption is estimated to be around 80 MW.

For the linac-ring option, the beam current for the same luminosity would be 6.4 mA, but still a conventional linac without energy recovery has to be discarded because of excessive power consumption (6.4 mA · 60 GV = 384 MW beam power!). An energy recovery linac (ERL) however would bring the overall power consumption in the same ballpark as in the case of the ring-ring solution, with the distinct advantage compared to the ring-ring option that it could be constructed, installed and commissioned while LHC continues its proton-proton physics run. The ERL would consist of two 10 GeV linacs in the opposite straight sections of a racetrack geometry, which are passed 3 times during acceleration and 3 times during deceleration.

ERL

In a recirculating linac, electrons are kept on a racetrack in order to pass through the same accelerating structure for a number of passes – this makes more effective use of the linac. For every pass, there is a separate arc adapted to the correct energy. An ERL is also a recirculating linac, but in addition the beam, after this acceleration and after passing the interaction region, is recovered and brought back onto this racetrack again, but in the opposite RF phase, such that it is decelerated in the linac by exactly the correct amount for again a multiple passage. In continuous operation of an ERL, accelerating and decelerating buckets in the cavity are filled with (approximately) the same charge, thus the RF current loading of the cavity is almost zero – the decelerated beam converts its power into the power needed for the accelerated beam. This almost looks like a perpetual motion machine, but of course we were idealizing – in reality there will be particles lost and particle energy lost by synchrotron radiation in the arcs – but it remains true that, in the LHeC case, the necessary beam power of 384 MW can be produced with around 80 MW of total electrical power – still a fantastic "efficiency".

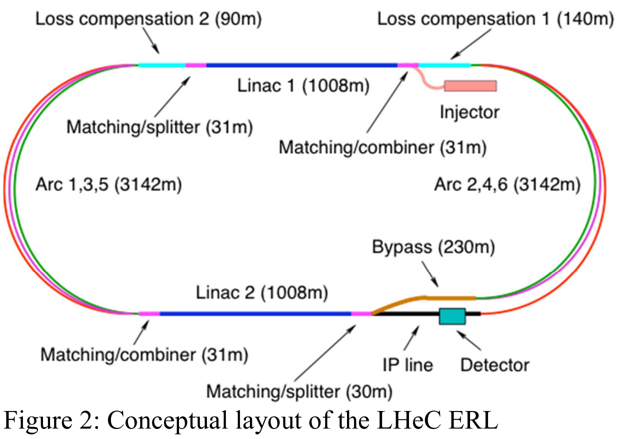

Figure 2: Conceptual layout of the LHeC ERL

In addition to this, an energy recovery linac seems to combine advantages of storage rings with advantages of a linac. I cannot formulate better than Merminga [7]: *In a storage ring, electrons are stored for hours in an equilibrium state, whereas in an ERL it is the energy of the electrons that is stored. The electrons themselves spend little time in the accelerator (from ~1 to 10's of µs) thus never reach equilibrium. As a result, in common with linacs, the 6-dimensional phase space in ERLs is largely determined by the electron source properties by design. On the other hand, in common with storage rings, ERLs* *have high current carrying capability enabled by the energy recovery process, thus promising high efficiencies.*

ERLs are considered for 4-GLSs, for electron-coolers and for electron-proton colliders like LHeC.

A caveat of the 60 GeV LHeC ERL of course is that now the synchrotron radiation losses in the arcs are not negligible anymore (a total of 24 MW is estimated); this requires additional loss compensation accelerators – their power cannot be recovered, it is however significantly smaller than for the ring-ring option.

The high efficiency is achieved by extracting power from the decelerated beam into RF to convert it to the power for the accelerated beam. In order to stabilize this process, the R&D should aim at a maximum possible Q_0 – this would slow down every beam current transient. The coupling to the generator and thus the required RF power is determined by the stability of the cavity and the necessity to go through transients when switching the beam on or off – it can be small compared to a conventional SC linac where this power is converted to beam power. The RF parameters for LHeC RF are summarized in the upper part of Table 1.

Table 1: RF parameters of LHeC ERL main linacs and preliminary total power estimates

	Unit	721.4 MHz	1322.6 MHz
Main Linacs:			
R/Q	Ω	500	1036
Q_0 @ 2 K		4.5E10	2E10
V/cavity	MV	15.7	16.3
P_{RF}/cavity	kW	24.6	12.8
n_{cav}		1260	1318
total RF power	MW	31	16.9
P_{AC}	MW	50	28.2
Synchrotron radiation compensation:			
total RF power	MW	10.5	
P_{AC}	MW	18	
Heat load (assuming Q_0 @ 2 K, conversion factor 600):			
P_{AC}	kW	4.5	5
P_{AC}	MW	5.7	6.1
HOM's	MW	1.7	5.4
Static, coupler, interconnects	MW	3	3
0.3 GeV injector:			
P_{AC}	MW	5	
Total P_{AC}	**MW**	**83.4**	**65.7**

As already noted in Table 1, two possible frequencies are at present considered for the LHeC ERL, namely 721.4 MHz and 1322.6 MHz. These frequencies are harmonics of 120.237 MHz, resulting from the requirement to have 3 equally spaced bunches in 25 ns for the 3 passages through the accelerator; the decelerated beam will have to be delayed by $n + 1/2$ RF periods. The frequency of the SR compensation RF system would be chosen that all bunches are in the correct accelerating phase, for example by choosing exactly the double frequency. The frequencies are also chosen in order to be of similar technology as existing projects: the ILC and the X-FEL, but also a number of existing ERL's are using 1.3 GHz; ESS, eRHIC and the SPL are using 704 MHz. So for either frequency, the project could use technology already developed and successfully demonstrated.

Cryomodule layout

Building on the existing experiences at 704 MHz and 1.32 GHz, one would consider a cryomodule layout similar to those projects. This would result in a conceptual cryomodule layout for both frequencies as sketched in Fig. 3.

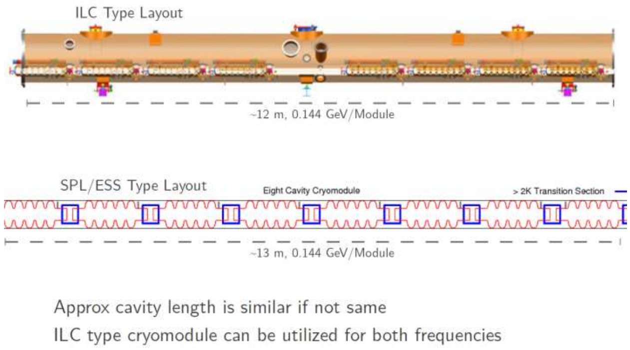

Figure 3: Conceptual cryomodule layout for 1.32 GHz (top) and 721 MHz (bottom)

It can be stated that with 9-cell cavities for 1.32 GHz and 5-cell cavities at 721 MHz, the length of an individual cavity would be roughly identical and in both cases one could consider a cryomodule of approximately 12 to 13 m length. In both cases, around 160 cryomodules are needed.

Frequency choice

The synergy with on-going projects is certainly an important argument for the choice of operating frequency. There are however other arguments which may make one or the other frequency preferable. The following thoughts were taken into consideration:

High Q_0 is one main design goal – this implies small surface resistance. For a small residual resistance, the surface resistance is dominated by the BCS resistance, which increases with frequency; this would clearly favour the lower frequency. Experimental results have demonstrated very large Q_0 values (in excess of 5E10) with moderate Q-slope however for both frequencies, so they don't strongly support this simplified model.

When simply scaling a cavity the longitudinal short range wakes per unit length scale with f^2 (or a little less if the beam pipe is widened). The dipole wakes scale with f^2. Both will lead to a larger excitation of modes at higher frequency. In addition, a 9-cell cavity has a denser mode spectrum than a 5-cell cavity, which will reduce the stable beam current for the higher frequency cavity – this would be a strong argument to stay at the lower frequency. On the other hand, the larger impedance at the higher frequency means that less RF power is needed at the higher frequency (cf. Table 1!); also the physical size of the cavity (and the diameter of the cryostat) could be smaller.

Power consumption

Summarizing the above, the RF power to the main linac cavities will be determined by the necessity to handle microphonics and mechanical instabilities of the cavities, it is also required to ramp the ERL up or down. When we assume an identical Q_{ext} of 1E7 for the two frequencies, the RF power per cavity is 25 kW at 0.7 GHz and about half this at 1.3 GHz. This would call for a total AC power consumption of 50 MW and 28 MW for 721 MHz and 1322 MHz, respectively. The synchrotron radiation compensation would add 18 MW for either case. For the heat load, we have assumed a slightly large Q_0 at the lower frequency and a temperature of 2 K. The resulting total cryogenic powers can be found in Table 1. The overall power consumption of the LHeC ERL RF systems including cryogenics is thus estimated to be around 84 MW for 721 MHz and slightly lower (66 MW) for 1322 MHz. These numbers should however be understood as preliminary rough estimates.

HE-LHC

The HE-LHC looks at the energy upgrade of the LHC from its nominal $\sqrt{s} = 14$ TeV to 33 TeV. It constitutes a major R&D effort for the magnets, but it is not significantly different from the present LHC in terms of RF requirements. Considering that for a constant RF voltage, the bucket area is increasing with energy as $E^{1/2}$; one can state that less RF voltage is required at larger energy. In order to have the same Landau damping at 16.5 TeV as presently at 7 TeV, the longitudinal emittance should also be increased as $E^{1/2}$. Even at 16.5 TeV, the synchrotron radiation losses per turn would still remain at manageable 200 keV. Consequently one would obtain the same bunch length with the same voltage as the LHC (16 MV); so to first order, the HE-LHC could use exactly the same RF system as today's LHC.

Independent of the higher energy, a higher harmonic RF system can be considered to have a better handle on the control of the bunch length and shape. A conceptual design of single-cell cavities scaled to 800 MHz has started.

CONCLUSIONS

There are a number of challenging subjects ahead in the field of superconducting RF R&D, which are important for a large number of accelerator projects. These include the next generation of high energy colliders but also spallation neutron sources, protons drivers for neutrino physics and muon colliders. Interesting subjects include the minimisation of losses, the maximisation of the accelerating field gradient, mechanical stability, improved fabrication techniques and new materials. Synergies between these projects must be identified and SCRF R&D should be well coordinated, test infrastructures could be shared.

The SCRF R&D for LHeC is concentrating on an energy recovery linac, which promises very high efficiency generation of high energy, high current and high quality electron beam. The main design goal is a very large Q_0, which is also desirable for other projects. The frequency choice is not yet final, but 700 MHz will probably allow larger stable beam current than 1.3 GHz, at the expense of larger RF power.

The HE-LHC RF system is to first order identical to the present LHC RF system. A possible improvement (both for LHC and HE-LHC) could be a harmonic RF system; it would allow better control of the bunch length and shape.

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