Frequency choice of the High Energy part of a Superconducting High Power Proton Linac

Application to the ESS and CONCERT cases

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1. Introduction

The superconducting option is now commonly chosen for the high energy part of most high power proton linacs due to the many benefits it may give compared to the conventional normal conducting copper coupled cavities [1]. However, there is still some open question concerning the choice of the frequency in the superconducting part. At low energies, the lower frequencies are generally favored, due to the easier fabrication of the RFQ (tight tolerances) for CW accelerators and to the chopper feasibility (fast rise time) for pulsed machines (ESS type). However, radiofrequency (RF) superconductivity generally favors the 1.0 GHz frequency domain (± 0.5 GHz) [2]. Therefore, there is usually a frequency jump between the low energy part and the high energy superconducting part (synchronism will impose a fixed integer ratio between these. The usual choice is to have 2:1 or 3:1). As a consequence, a couple of frequency is picked up. For example, the Spallation Neutron Source (SNS) project have chosen the 402.5 / 805 MHz couple, which means a frequency of 402.5 MHz for the low energy section and 805 MHz for the SCRF part [3]. The frequency question arise specifically in the European Spallation Source (ESS) case for which the 350 MHz / 700 MHz couple[*] was initially planned in the reference design [4]. Later on, additional work on the chopper located in the low energy section has pushed for lowering its frequency from 350 MHz to 280 MHz [5]. In the meantime, the superconducting option has proven to be adequate for the high-energy section of these linacs while the impact of the frequency couple choice on the high-energy part has not been fully analyzed. That is why, although trying to remain as much general as possible, this paper will essentially focus on the comparison between a 560 MHz and a 700 MHz frequency choice for the superconducting high energy part.

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[*] More precisely, due to the high H^- beam current required (100 mA), funneling was decided with two injectors working each at a frequency of 175 MHz (half of the low energy section frequency).

2. Advantages & Drawbacks of high vs. low frequency

Usually, superconducting accelerators in operation work in the 500 MHz-1500 MHz frequency range[*]. As stated earlier, this is due to a compromise in the physics of RF superconductivity. At high frequency, the global thermal instability will make the magnetic quench field – and therefore the accelerating gradient - decrease (for electron cavities β=1, the field typically fall down over 2 GHz). In the more realistic defect case, there is no threshold but the frequency trend is still valid [2]. But low frequencies have severe drawbacks as the cavity surface will increase (like the frequency square) making it more difficult to reach higher fields for two main reasons:

- First, the probability of finding larger defects will increase accordingly [6]
- Second, the field emission threshold will be lower due to area increase and particle contamination increase [7].

Discarding for the moment the cryogenic issues, which will be thoroughly addressed in the next section, it can be easily understood from the simple basic fact that the maximum field level in a SCRF cavity will suffer at both very low and very high frequency why any superconducting design will preferably stay in the vicinity of 1.0 GHz. In addition, the larger size of the low frequency cavities (the cavity volume rises inversely to the cubic of the frequency!!) put a heavy burden on handling during fabrication, cleaning and preparation steps. All the subsequent equipment should be dimensioned accordingly. This is important to bear in mind and not to be neglected. For example, all sizes for tooling, handling and testing should be exactly doubled when shifting from 700 MHz to 560 MHz. This immediately impacts large chemistry, clean room and cryogenic equipment costs. In the same manner, cryostat and mounting costs will also increase.

The low frequency solution offer some advantages like the larger bore aperture relative to beam size. One of the main benefits claimed for the superconducting option is its very large beam tube diameter, drastically reducing the threat of activation due to beam loss. Extremely low (if not zero) beam loss is expected in linacs using SCRF cavities as bore to rms beam ratio well over 10 can be chosen. Decreasing the frequency may increase even more this figure. But that should not be considered as a crucial issue as the general feeling is the bore radius is already high enough. Indeed, all beam dynamics simulations actually indicate no beam loss even including misalignment and errors in 700 MHz SCRF linacs [8]. A second possible advantage of the low frequency is the better filling factor (accelerating length divided by real estate length) due to the longer cell length (inversely proportional to frequency). That is true provided all other parameters are fixed (accelerating field, number of cells per cavity, etc…). But it has been shown above that this is not quite valid as for example the maximum field level expected will be lower, counteracting the benefit obtained from a better filling factor. As a matter of fact, each frequency choice will lead to a specific optimization taking in account the different parameter changes.

Another important issue to address is the main power coupler handling capability. This might be a very serious limitation in the overall design. The higher frequency will ask for a lower maximum power, making the power coupler more feasible. On the other hand, if a given maximum power coupler limit is set (as for example 600 kW, which is already quite challenging), the accelerating field will then be limited to a lower value for a lower frequency.

Finally, the operating working temperature will impact the cryogenic losses. It will be shown in section 3 why it definitely favors the 700 MHz frequency choice over the 560 MHz one.

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[*] There are some specific exceptions like the LEP at CERN running at a rather low 352 MHz and the S-DALINAC at Darmstadt at a rather high 3000 MHz.

The pro and cons of the low and high frequency are summarized in Table I.

High Frequency **700 MHz**	**Low Frequency** **560 MHz**
Area **Volume**	**Area x 1.58** **Volume x 2.00**
Higher Field limit Shorter Linac Higher FE threshold Higher Quench field **Smaller Area** Easier Handling & Mounting **Lower Power / Cavity** Power coupler capability Higher mechanical resonance frequency **Cryogenics** Lower optimum working temperature Lower cryogenic losses Less microphonics	**Larger bore radius** **Better filling factor**

Table I – Summary of the main advantages obtained for each frequency choice.

In particular, the higher mechanical resonance is an advantage for the high frequency choice as it eases the RF stability feedback control especially in a pulsed regime like ESS or CONCERT. Another advantage of the 700 MHz option listed is the lower expected amount of vibrations due to the helium bath upon using a superfluid regime. Induced microphonics have to be accounted for and will induce resonance frequency variations asking for additional input RF power. Of course, one may argue that the same working cryogenic temperature (i.e. the superfluid bath temperature) might as well be used for the low frequency option, but as it will be shown hereafter, that would be at the cost of an increasing (non optimal) thermal load. Trying to maintain some of the advantages of the higher frequency solution will therefore ask for some additional cost on another parameter.

3. Cryogenics Issues

3. 1 - Surface Resistance

The surface resistance of niobium can be divided in two terms. The first called the BCS part (after Bardeen, Cooper and Shriffer), increases exponentially with temperature. The second, called the residual resistance, is the ultimate resistance at T=0K. Theoretically, the residual resistance should in principle be zero. In reality, there are a number of different reasons causing this non-zero residual (static magnetic field, impurities, grain boundaries, residual hydride, end flanges, etc…). As a result, the surface resistance increases with temperature as shown in figure 1. While reducing the operating temperature results in lower losses for the cavities, it severely impacts the cryogenic plant, reducing its efficiency (for example, going down from 2.0 K to 1.8 K will have a tremendous impact on the cryoplant's cold compressors, a consequence of bath pressure reduction from 31 mbar to 16 mbar, while achieving very little reduction of the cavity losses). On the other hand, a high operating temperature would require a very high-power refrigeration, due to the strong dependence of the BCS surface resistance with temperature (for example, operating at 4.5 K, which is near the saturated liquid helium temperature, would require seven times more refrigeration power than for 2 K operation). Therefore, an optimal working temperature should exist in between these two limits. Cost, performance, and risk minimization should determine this optimum temperature.

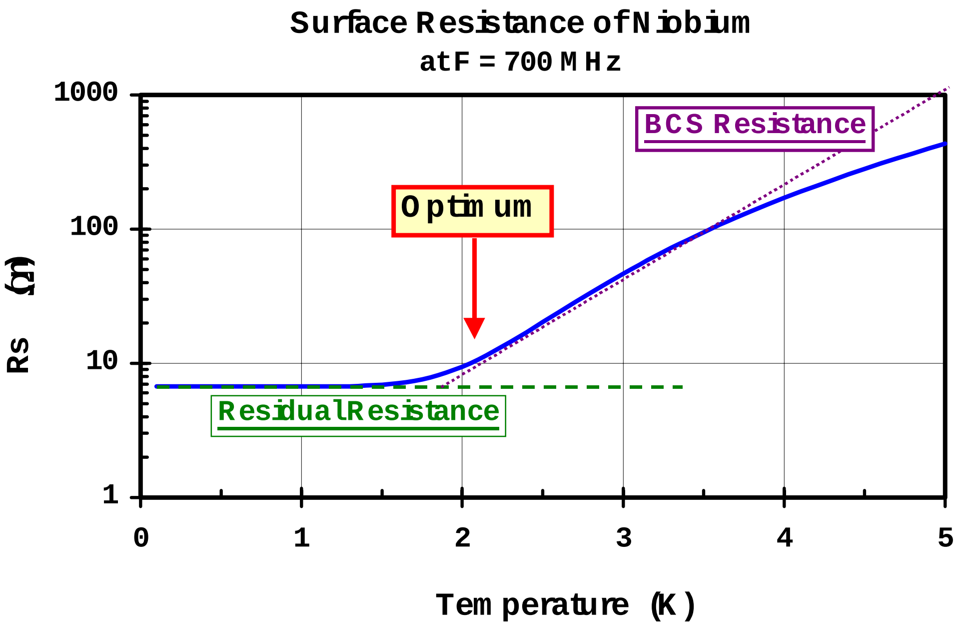

Figure 1- Surface Resistance increases exponentially with working temperature.

3. 2 - Optimum Working Temperature

The surface resistance will determine the dynamic cryogenic losses due to RF fields in the cavities. But this is not the whole story. First, there are static cryogenic losses due to the connections to the outside world. These are not power dependent. Second, one has to add static and dynamic losses coming from ancillary components. The most important component in terms of cryogenic impact is the main power coupler. In some cases, the main coupler might bring as much heat loads on the helium bath as the cavities actually do. This component is clearly power dependent and its influence is larger for long RF duty cycle (CONCERT case) than for short pulses (ESS case). Whenever adding all these loads together (static and dynamic), an optimum can be found for the operating temperature, optimizing the operating cryogenic cost of the linac. Then the cryogenic plant and the investment cost have to be accounted for. A new global optimum, slightly shifted from the one obtained for the operating optimum, will be determined [9]. In figure 2, the surface resistance of the niobium is drawn as a function of the operating temperature and the approximate position of the global working temperature for the two frequencies is shown. Of course, this optimum will slightly shift depending on the beam power and RF power. For example, increasing the RF duty cycle will put more emphasis on the dynamic heat loads. Therefore, the tendency will be to decrease the operating temperature in order to reduce the RF losses. Conversely, a low duty cycle will increase the weight of the investment cost of the cryoplant resulting in a higher operating temperature. But these differences are low enough to be neglected at first sight. In any case, the difference between the two optimum working temperatures will stay roughly the same. For example, if the optimum working temperature in the 700 MHz solution is 2.4 K, it will be around 2.8 K for the lower 560 MHz frequency.

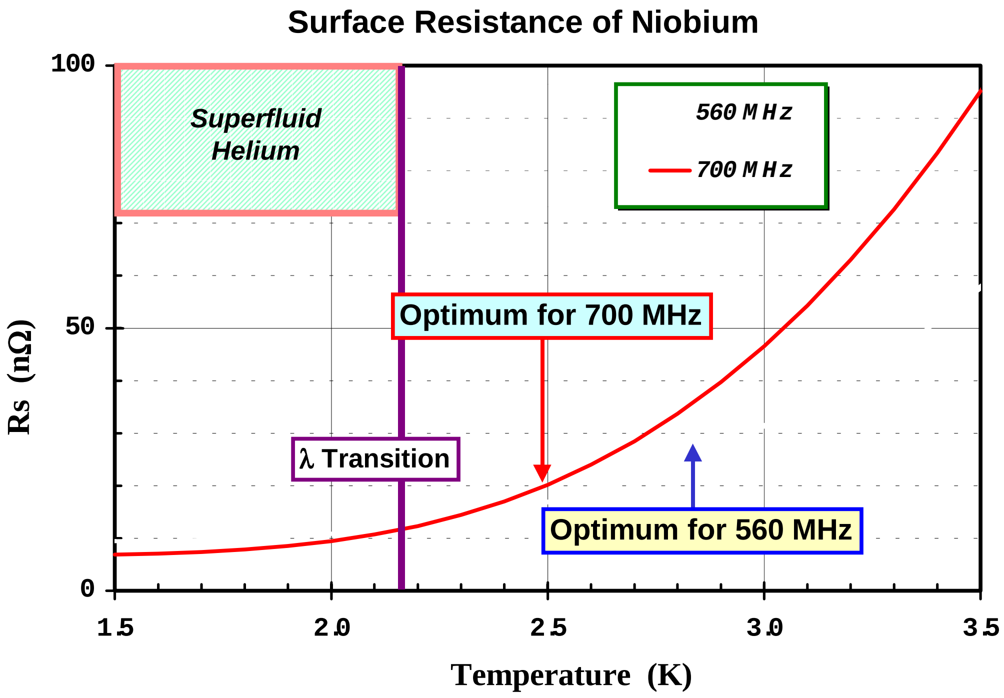

Figure 2 – Optimum working temperature for the two frequencies 560 MHz and 700 MHz. Real optimum might be slightly shifted from this value depending on the project scheme (ESS or CONCERT).

3. 3 - Discussion

The above discussion implicitly assumes the cavities will reach the desired accelerating fields without any problem (no field emission, no quenches). Although field emission will not be affected by the operating temperature, there will definitely be a difference in the quench field value while operating in the superfluid regime (He II at $T < T_\lambda = 2.17$ K) as compared to the normal liquid He I at above T_λ. In the superfluid bath, the thermal properties are much more effective. The heat conduction may be considered as infinite (isothermal bath). The quench field will be determined by the thermal properties of the niobium and the Kapitza interface (Nb/HeII). In a normal liquid bath, nucleate boiling can occur that will limit the cavity performance at lower fields. Boiling helium can also induce additional pressure vibrations enhancing the microphonics level induced in SCRF cavities. That will in turn affect the frequency stability and may result in a demand for additional RF input power.

The optimum working temperature for the 700 MHz option is close enough to the superfluid domain that the choice of a working temperature of 2.1 K will be very easy. The slight increase in cryogenic overall cost being well overcompensated by the benefits of the superfluid regime (higher fields, less microphonics). But in the 560 MHz option, the optimum is around 3 K, right in between the superfluid domain (2.17 K) and the atmospheric helium boiling point (4.2 K). Using a 4.5 K operating temperature might even be envisaged. As a matter of fact, at a slightly lower frequency like 500 MHz, most of the superconducting cavity accelerators have chosen the use of the atmospheric boiling helium (4.2 K) even though it is not the optimum. The main reason is the much more simple cryogenic system (cost effectiveness) and the absence of pumping items (which include the risk of leaks and air contamination) in the return flow piping. But as can be seen from our overall comparison in section 4, the atmospheric helium solution will induce a so unacceptable increase in the heat loads that it may be discarded here. Thus, only solutions at sub-atmospheric pressure are viable. And choosing a working temperature in the superfluid domain, moving further away from the optimum, will lead to a much higher overcost of the cryogenic system compared to the high frequency solution.

4. Overall Comparison

In the following, a full comparison have been made using the 2.0 K temperature for the 700 MHz frequency and three different temperatures 2.0 K (superfluid), 2.8 K (optimum) and 4.5 K (boiling) for the 560 MHz frequency. Calculations are done using two different beta sections ($\beta = 0.65$ and $\beta = 0.84$) in the high-energy part of the linac. Moreover, 5-cell cavities have been assumed in both cases. Changing the number of cells does not modify drastically the results. In fact, a 4-cell cavity at 560 MHz will approximately have the same length as a 5-cell 700 MHz. A 4-cell maybe chosen to actually reduce the disadvantage of having to increase the RF power level per cavity. But that will inevitably drag other disadvantages like reducing the filling factor (it will actually become even worse than that of the 700 MHz one) and increasing the cryogenic losses. So, for the sake of clarity, some of the parameters are fixed in the comparison like the beta values or the number of cells. The results are nevertheless typical and conclusions are still valid upon moving to another parameter set.

The calculated costs include the cryogenic helium plant (cryoplant) and the cryomodule fabrication cost. As a significant part of the overall investment cost is proportional to the linac length, this figure is also given for the high-energy part. However, operation cost is only given for the cryogenic heat loads, assuming that all other operation costs (like RF power) are not frequency dependent. Finally, no upper limit has been set to the main power coupler. So, the RF power needed per cavity is calculated along the linac and the maximum value (usually attained at the higher end of the linac) is quoted.

4. 1 - ESS Case

Table II gives some basic figures of concern in the case of the ESS project where the beam duty cycle is of the order of 6%, leading to a RF loss duty cycle between 6.9% and 7.5% depending on the choice of frequency and operating temperature.

One of the main results deduced from this study is that unacceptably high cryogenic losses are expected for the 560 MHz solution upon operation at boiling helium temperature (4.5 K). Choosing this operating temperature would lead to a cryogenic plant almost an order of magnitude higher in power when compared to the 700 MHz solution. It would be even twice more expensive in capital cost despite the lack of use of any cold pumping. This practically precludes any operation under these circumstances, which means that sub-atmospheric helium should be chosen no matter what.

One may notice the advantages mentioned above for the 700 MHz solution leading to a shorter linac and a lower cryogenic cost and consumption. Note equally that a 2 K solution in the case of the 560 MHz would require almost 40% of additional load on the main RF coupler, which is a heavy drawback. If the RF power limit is set to the same value in both cases, then the 560 MHz linac will be even longer. The optimum solution (minimum of capital + operating costs) for the 560 MHz option is obtained for a temperature around 2.8 K (the lowest electrical power for a slight increase in capital cost). As it clearly appears, all relevant figures (except maybe the bore ratio) are in favor of choosing the high frequency option (shorter linac, lower cryogenic costs both capital and operational, lower RF power per coupler, lower cryomodule cost).

Comparison of High Energy Superconducting Section

Beam Current	(mA)	70	70	70	70
RF Duty Cycle	(%)	7.1%	7.4%	**7.5%**	6.9%
Starting Energy	(MeV)	185	185	185	185
Ending Energy	(MeV)	1342	1 347	1 359	1 343
Frequency	**(MHz)**	**560**	**560**	**560**	**704**

Optimal Working Temperature	(K)	2.8	2.8	2.8	2.4
Temperature	(K)	4.5	3.0	2.0	2.0
Bpeak Max	(mT)	40	55	67	70
Eacc Max	(MV/m)	8.8	11.1	12.0	11.1
V real	(MV)	9.0	12.5	13.5	9.7
Number of Cavities 0.65		54	54	45	45
Number of Cavities 0.84		136	100	100	116
Cavity Active Length 0.65	(m)	0.870	0.870	0.870	0.692
Cavity Active Length 0.84	(m)	1.124	1.124	1.124	0.894
Cavity Surface	(m2)	2.48	2.48	2.48	1.57
Cavity Volume	(m3)	0.20	0.20	0.20	0.10
Bore Radius	(mm)	110	110	110	90
(Φbore / Φ beam)		22	22	22	**18**
RF Power Coupler (Max.)	(kW)	642	894	**963**	695
Filling Factor	(%)	45%	45%	45%	**40%**
Active Length	(m)	200	159	152	135
Linac Length (Superconducting part)	(m)	**442**	358	337	340
Number of Cavities		**190**	154	145	161
Cryogenic Losses	(W)	**10 988**	4 095	2 078	**1 366**
Cryogenic Cost	(MEuro)	**10.73**	7.04	6.41	**4.83**
Cryogenics Electrical Power	(MVA)	**3.7**	2.7	**3.0**	**2.1**
Cryomodule Cost	(MEuro)	**82.1**	66.6	62.7	**58.9**

Table II – Comparison between a 560 MHz and a 700 MHz solution for the superconducting cavity in the ESS project. Three different working temperatures have been studied for the 560 MHz frequency.

4. 2 - CONCERT Case

The CONCERT study is quite similar to the ESS case (same beam peak current, same final energy) except for the RF duty cycle that may increase to about 25%. Compared to the ESS case, the difference is mainly in the RF power needed per cavity (over 1 MW!!). From the cryogenics point of view, the plant is much larger (3 to 4 times) and as it has been shown above, the weight of the cryogenic losses is even more important. The main results for the CONCERT case are summarized in Table III. It can be immediately noticed that most conclusions drawn from the short duty cycle ESS study remain valid in the case of a longer duty cycle. That is the 700 MHz option offers much lower cryogenic costs (in investment as well as in operation), a shorter linac, lower RF power per cavity (this feature is even more problematic due to the very high RF power needed) than the 560 MHz option. Note also that the cryomodule costs are higher in the 560 MHz option for both the ESS and the CONCERT case due to the bigger cavity structures.

Comparison of High Energy Superconducting Section					
Beam Current	(mA)	100	100	100	100
RF Duty Cycle	(%)	25.8%	25.8%	26.0%	25.7%
Starting Energy	(MeV)	185	185	185	185
Ending Energy	(MeV)	1351	1 349	1 354	1 340
Frequency	**(MHz)**	**560**	**560**	**560**	**704**

Optimal Working Temperature	(K)	2.8	2.8	2.8	2.4
Temperature	(K)	4.5	2.8	2.0	2.0
Bpeak Max	(mT)	40	55	67	70
Eacc Max	(MV/m)	9.2	9.3	11.2	11.7
V real	(MV)	10.4	10.5	12.6	10.5
Number of Cavities 0.65		54	54	45	45
Number of Cavities 0.84		140	112	104	116
Cavity Active Length 0.65	(m)	0.870	0.870	0.870	0.692
Cavity Active Length 0.84	(m)	1.124	1.124	1.124	0.894
Cavity Surface	(m2)	2.48	2.48	2.48	1.57
Cavity Volume	(m3)	0.20	0.20	0.20	0.10
Bore Radius	(mm)	110	110	110	90
(Φbore / Φ beam)		22	22	22	**18**
RF Power Coupler (Max.)	(kW)	1 058	1 070	**1 283**	1 070
Filling Factor	(%)	45%	45%	45%	**40%**
Active Length	(m)	204	173	156	135
Linac Length (Superconducting part)	(m)	**451**	**386**	346	**340**
Number of Cavities		**194**	**166**	149	161
Cryogenic Losses	(W)	**44 981**	**7 881**	5 000	**3 650**
Cryogenic Cost	(MEuro)	**39.84**	**11.72**	**11.70**	**9.42**
Cryogenic Electrical Power	(MVA)	**13.0**	5.4	**6.4**	**4.9**
Cryomodule Cost	(MEuro)	**83.8**	**71.8**	64.4	**58.9**

Table III - Comparison between a 560 MHz and a 700 MHz solution for the superconducting section of the CONCERT project. Three different working temperatures have been studied for the 560 MHz frequency.

5. Conclusion

In conclusion, a full comparison study has been made using two different frequencies (560 MHz and 700 MHz) for the high-energy superconducting part of a high power proton accelerator. It appears that the high frequency option (namely the 700 MHz choice) gives the best performance in term of cryogenic costs (both in capital and in operation). Moreover, other advantages like a higher field limit, a smaller cavity surface, easier handling and mounting and a lower RF power per coupler make the 700 MHz option definitely more attractive for superconducting cavities.

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