# CHOICE OF FREQUENCY, GRADIENT, AND TEMPERATURE FOR A SUPERCONDUCTING PROTON LINAC

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*Abstract*

The construction of a Superconducting Proton Linac is planned at CERN during the next decade. It is foreseen to be constructed in two stages: a low duty cycle, low-power linac (LPSPL) as an injector for a new 50 GeV synchrotron (PS2) replacing the present PS, which could be upgraded to a high-duty cycle, high-power linac (HPSPL), for the needs of future facility(ies) requiring a multi-MW beam power. In this paper we present the criteria which were used to choose the frequency, gradient, and cryogenic temperature of the SPL. Since these questions are common to other proposed high-power proton linacs, they may also be of use for other projects with similar specifications. The various design options are discussed as well as their impact on beam dynamics, cavity performance, power consumption, cryogenics, and overall efficiency.

## INTRODUCTION

The first designs (1999) for a superconducting linac at CERN [1] were based on the technology of the LEP accelerating modules (Niobium sputtered Copper cavities), operating at 352 MHz in a bath of 4.5 K. With the advance of bulk niobium cavities the design was revised in 2005 to use 704 MHz bulk niobium cavities operating at 2 K and assuming a challenging gradient of 25 MV/m [2]. This year, the basic parameters such as electric gradient, cryogenic temperature, and RF frequency have been reviewed again, in order to prepare a technical design report which is due in 2011 and which will be the basis for a decision on construction of the SPL. The main motivation for the review is the question whether the SPL could profit from the extensive R&D effort that was made for the TESLA/ILC/XFEL cryo-modules and cavities. Since Linac4, the SPL front-end, which is now under construction at CERN, is operating at 352 MHz, only multiples of this frequency were considered, i.e. 704 MHz, 1056 MHz, or 1408 MHz. The last one seems most attractive since it is close to the ILC frequency and one can expect that many technical solutions can be applied with little changes to the existing ILC hardware.

The required SPL parameters are given in Table 1. For this review we will focus on the “nominal” operation, which is relevant for the equipment design and a representative layout of the infrastructure.

Table 1: Main SPL parameters for low-power (LP-) and high-power (HP-) operation.

| | LP-SPL | HP-SPL* (nominal) | HP-SPL* (5 GeV) |
|---|---|---|---|
| E [GeV] | 4 | 5 | 2.5 |
| $P_{beam}$ [MW] | 0.192 | 4 | 4 |
| $f_{rep}$ [Hz] | 2 | 50 | 50 |
| $I_{average}$ [mA] | 20 | 20/40 | 40 |
| $I_{source}$ [mA] | 40 | 40/80 | 80 |
| chopping | yes | yes | no |
| $t_{pulse}$ [ms] | 1.2 | 0.8/0.4 | 0.8 |
| p.p.p. [$10^{14}$] | 1.5 | 1 | 2 |
| $t_{fill\ PS2}$ [ms] | 1.2 | 1.2/0.6 | n.a. |
| main user | PS2/ Isolde2 | PS2/ neutrinos | EURISOL |

* If needed the SPL can be configured to deliver beam to 2 high-power users, such as EURISOL and a neutrino facility simultaneously.

## LAYOUT OPTIONS

For the performance comparison three different layouts have been considered: i) one slightly improved version of the nominal design of the 2006 conceptual design report [2], ii) a version based on 1408 MHz elliptical cavities, and iii) a mixed option using 352 MHz spoke cavities up to an energy of 758 MeV and then switching to 1408 MHz elliptical cavities. The main characteristics of the three options are listed in Table 2. In the high-frequency option the number of cells per cavity has been increased from 5, which is used at 704 MHz, to 9, so that the packing factor (ratio of accelerating structures over total length) remains similar to the nominal option. In the 2006 report [2] it was concluded that the maximum accelerating gradient for bulk niobium cavities only depends on the quality of the applied surface treatment techniques and not on the RF frequency. After a survey of recently achieved test results, that was conducted in the framework of this study, this statement is still considered as true. It is therefore assumed that all elliptical cavities can reach the same maximum gradient of 25 MV/m in cavities with a geometrical $\beta = 1$. For $\beta < 1$ the gradient was scaled according to the changing ratio of peak surface fields over accelerating gradient.

From Table 2 one can see that both, the high-frequency option and the spoke option are longer than the nominal (704 MHz) one, by 14% or 10%, respectively. This is mainly caused by longer matching sections, which are

Table 2: Main parameters for three possible SPL architectures.

| option: | nominal | high-frequency | spoke/elliptical |
|---|---|---|---|
| frequency [MHz] | 704 | 1408 | 352/1408 |
| $\beta_{\text{geometrical}}$ | 0.65/0.92 | 0.6/0.76/0.94 | 0.67/0.8/0.94 |
| cells/cav | 5/5 | 7/9/9 | 4/5/9 |
| input energies/section [MeV] | 160/581 | 160/357/884 | 160/392/758 |
| output energies [MeV] | 5122 | 5144 | 5075 |
| accelerating gradient* [MV/m] | 19.4/24.2 | 18.1/21.7/24.2 | 8.5/9.5/24.2 |
| cavities per cryo-module | 6/8 | 4/4/8 | 3/4/8 |
| cavities per focusing period | 3/8 | 2/4/8 | 3/4/8 |
| number of cavities | 42/200 | 30/40/208 | 27/24/216 |
| total number of cavities | 242 | 278 | 267 |
| length of the SC linac [m] | 439 | 499 | 485 |

* The gradients for elliptical cavities all correspond to 25 MV/m for cavities with a geometric beta equal 1. They have been scaled for $\beta < 1$, to account for the increased ratio of peak surface field over on axis field.

needed to adapt the beam for the 4x frequency jump. Due to the increased phase slippage in 9-cell cavities, the high-frequency options needs 3 families of cavities rather than 2, which means an increased R&D effort for this architecture.

## BEAM DYNAMICS

The beam dynamics performance of all options is compared in terms of r.m.s. emittance growth for the nominal beam and the sensitivity to longitudinal errors. Transversely the length of the focusing periods was made similar in all architectures and thus we expect no major differences for the transverse dynamics. Each option was matched carefully across the transitions and has an approximately constant ratio between transverse and longitudinal phase advance to avoid space charge resonances. From Table 3 we can see that the spoke option seems to perform best, which can probably be attributed to the high energy (760 MeV) at which the frequency transition takes place. In the two other options the frequency jumps are at 160 MeV. For the same reason we conclude that the large longitudinal emittance growth for the high-frequeny option can be explained by the relatively low energy of 160 MeV at which the 4x frequency jump takes place.

Table 3: R.m.s. emittance growth for the different linac options.

| $\varepsilon$-growth | nominal | high freq. | spoke/ell. |
|---|---|---|---|
| $\Delta\varepsilon_x$ [%] | 5.6 | 6.3 | 1.5 |
| $\Delta\varepsilon_y$ [%] | 8.2 | 7.8 | 5.3 |
| $\Delta\varepsilon_z$ [%] | 6.8 | 12.1 | 2.5 |
| losses | - | - | - |

To further assess the longitudinal stability of the layouts statistical error simulations were made with PATH [3] for various error limits using 500 simulations for each value. We report here the results of one representative case, assuming an energy jitter of $\pm 125\,\mathrm{keV}$ and $\pm 1\ \mathrm{deg}$ (1 sigma values) from Linac4 and RF errors related to the SPL klystrons of $\pm 1\%/\pm 1\ deg$ in amplitude and phase. The simulation results in Table 4 show that the resulting r.m.s. emittance growth is negligible for all options. The only losses in the longitudinal plane were observed for the high-frequency case, which we attribute again to the 4x frequency jump at 160 MeV.

Table 4: Additional r.m.s. emittance growth (with respect to Table 3) and energy and phase jitter for the different linac options assuming an input jitter from Linac4 ($\pm 125\,\mathrm{keV}/\pm 1\ \mathrm{deg}$) and klystron related RF errors of $\pm 1\%/\pm 1\ deg$. Errors are quoted as average $\pm$ 2x standard deviation.

| | nominal | high freq. | spoke/ell. |
|---|---|---|---|
| $\Delta\varepsilon_x$ [%] | $0.21 \pm 0.41$ | $1.02 \pm 1.11$ | $0.24 \pm 0.49$ |
| $\Delta\varepsilon_y$ [%] | $0.59 \pm 0.53$ | $0.42 \pm 0.75$ | $0.33 \pm 0.50$ |
| $\Delta\varepsilon_z$ [%] | $1.13 \pm 1.33$ | $1.90 \pm 1.88$ | $0.81 \pm 0.76$ |
| $\Delta$E [MeV] | $\pm$3.8 | $\pm$3.5 | $\pm$3.5 |
| $\Delta\phi$ [deg] | 0.57 | 0.61 | 0.61 |
| lossy runs | - | 21/500 | - |

Losses in the transverse plane due to halo development or r.m.s. emittance growth should not be an issue for any of the designs, since even for 1408 MHz the ratio of beam pipe over r.m.s. beam radius is always above 20. A value that can be considered as safe, even for strong halo development due to mismatch. In case of mis-steering of the beam, however, the larger apertures of lower frequency cavities may be an advantage.

## FUNDAMENTAL CAVITY PARAMETERS AND HIGHER ORDER MODES

Higher order modes (HOMs) are excited by the passage of the beam and their amplitude is therefore directly proportional to the beam current. For long beam pulses the amplitudes of HOMs can increase to levels where they influence the beam or even destroy the bunches. The crucial parameter here is the Beam Break-Up threshold current above which the machine can no longer be operated. It should be noted that a linac does not have the quasi-periodicity condition with the revolution frequency as it exists in rings. On one hand this means that the threshold current values in a one-pass linac are certainly higher than in a circular machine. On the other hand this also means that an instability can be excited at any HOM frequency, it must not be close to a machine line! Since absolute values are difficult to define, we conduct a risk analysis for the simplified case of doubling the frequency and the number of cells in a superconducting cavity. The analysis is done in three steps: i) doubling the frequency in ideal cavities, ii) doubling the number of cells in ideal cavities, iii) considering imperfect structures (including production scatter). We present here a summary of the results. The complete analysis will be published separately.

### *Doubling the frequency in ideal cavities.*

In this first step we keep the number of cells constant and from simple geometrical scaling one finds all lengths are reduced by a factor of 2, all areas by a factor of 4, and all volumes by 8. Therefore also the stored energy is reduced by a factor of 8. One finds that the $(R/Q)$ and the external $Q$ of any coupling device remains invariant. However, the induced voltage per cavity doubles since it is proportional to $\omega(R/Q)$. The impedance per cavity remains constant, but the impedance per length (or total impedance when doubling the number of cells) doubles. For the scaling of dipole wakes, the transverse offset for particles from the beam axis was kept constant, resulting in twice the transverse momentum kick per cavity or 4 times the kick, when it is considered per length. A summary of the changes for the HOM characteristics, when doubling the frequency are listed in Table 5.

Table 5: Relative HOM properties when doubling the frequency of an ideal SC cavity (keeping $n_{\text{cells}}$ constant.

| **HOM properties** | **704 MHz 5-cell** | **1408 MHz 5-cell** |
|---|---|---|
| $(R/Q)_{\|\|}$ | 1 | 1 |
| $Q_{\text{ex}}$ | 1 | 1 |
| $V^{\dagger}_{\text{ind}}$ | 1 | x2 |
| $Z_{\|\|}/L^{\ddagger}$ | 1 | x2 |
| $\Delta p_x$* | 1 | x2 |
| $Z_{\perp}/L$** | 1 | x4 |
| $I_{\text{BBU}}$ | 1 | /4 |

† monopole, short range, per cavity
‡ monopole, long range
* dipole, long range, per cavity
** dipole, long range

### *Doubling the number of cells in ideal cavities.*

In addition to the previous step we now increase the number of cells by a factor of 2. By doubling the stored energy, the external $Q$ of all modes immediately increases by a factor of 2. The coupling factor of HOM couplers located on the end-cell cut-off tubes is proportional to the square of the HOM field in the end-cells. Due to the increased cell number the normalised squares of these fields scale as 8:1 in favour of the shorter cavity. Depending on the HOM in question we obtain the scaling given in Table 6.

Table 6: Relative HOM properties for linear frequency scaling and doubling the number of cells of an ideal superconducting cavity.

| **HOM properties** | **704 MHz 5-cell** | **1408 MHz 10-cell** |
|---|---|---|
| $V^{\dagger}_{\text{ind}}$ | 1 | x4 |
| $Z_{\|\|}/L^{\dagger}$ | 1 | x4 . . . 16 |
| $\Delta p_x$* | 1 | x8 . . . 32 |
| $Z_{\perp}/L$* | 1 | x8 . . . 32 |
| $I_{\text{BBU}}$ | 1 | /(8 . . . 32) |

† monopoles
* dipoles

### *Imperfect structure*

The end-cell correction, which adjusts the end-cell frequencies of the accelerating mode and thereby also corrects the field flatness in the cavities, changes the field distribution of the HOMs. In some cases this may be beneficial but in other cases it will make things worse when it comes to coupling to these modes with a HOM coupler. The same is true for the correction of all the single cells, which is necessary due to the inevitable scatter in the production of the cavities. While these corrections certainly improve the field flatness of the accelerating mode, they are unlikely to flatten the HOMs and are thus making it more difficult to i) discover the HOMs, since the risk for trapped modes is rising, and then ii) to damp the HOMs via HOM couplers. The mathematical problem can be formulated identically to a quantum mechanical perturbation problem and as a result one can state that the sensitivity to field profile perturbations is increased by a factor of 2 to 4.

### *Cavity loading*

During the filling of the cavities with RF energy, most of the RF power is being reflected into an RF load. Once the appropriate voltage level is reached in the cavity the beam passes the cavity. At the end of beam pulse the RF generator is switched off and the stored energy of the cavity is “decaying into” an RF load. The “wasted” energy scales as the filling time and thus one finds that for a 10-cell, 1408 MHz cavity the “wasted” energy is only 1/4 than in the case of a 5-cell, 704 MHz cavity.

Transient beam loading due the chopping of the beam at low energy does not lead to any significant effects. For all chopping scenarios, which are under consideration for injection into the PS2 or a neutrino factory accumulator ring, the observed voltage swing is below 0.1% and thus much smaller than the accuracy demanded from the RF system ($\approx 0.5\%$).

## CAVITY PERFORMANCE

### *Accelerating gradient*

A critical parameter for the overall design and costs of the SPL is the expected average accelerating gradient in the linac. Table 7 summarises recent results from DESY and SNS [4], giving also an indication of the production yield, which can be expected for the given gradients.

Table 7: Summary of test results of superconducting cavities from DESY (9-cell, 1.3 GHz) and ORNL/JLAB (SNS, 6-cell 805 MHz).

| **cavity** | **gradient $E_a$ [MV/m]** | **$E_a$ [MV/m] @ 90/50 [%] production yield*** |
|---|---|---|
| DESY (all) | 28 | 22/28 |
| (quench) | 30 | 23/30 |
| SNS | | |
| $\beta = 0.61$ | 17.1 | 15/17 |
| ($\beta = 1^\dagger$ | *23.0* | *20/23*) |
| $\beta = 0.81$ | 18.2 | 15/18 |
| ($\beta = 1^\dagger$ | *20.0* | *16/20*) |

*90/50% yield corresponds to 11/100% of reprocessing needed.
$^\dagger$ extrapolated from the $\beta < 1$ results

In conclusion, these test DESY results imply that, for the present state-of-the-art processing sequence, accelerating gradients of up to 23 MV/m (at $\beta = 1$) can be achieved with a production yield of 90%, while the SNS results point at more conservative values of 16 MV/m. Higher gradients are within reach but they entail a lower production yield and one has to compare the cost of re-processing the cavities with the civil engineering costs for tunneling to choose the gradient for a superconducting linac.

### *Obtainable $Q$-value*

The $Q$-value is crucial to estimate the cryogenic cooling capacity that needs to be installed for the different frequency options at different temperatures. The classic theory, which can be found in various text books, models the surface resistance as the sum of the BCS-surface resistance $R_{BCS}$, which is dependent on the frequency and temperature, the value $R_H$ coming from the part of the Earth's magnetic field, which gets trapped during the cool-down, and a loosely defined residual resistance $R_{res}$. The $Q$-values calculated from this model, however, do not reflect the $Q$-slopes, which are observed during the testing of superconducting cavities. Since this behaviour is not yet fully understood we extend the classic theory with a field-dependent part of the surface resistance, which is found by analysing a large variety of test data from different cavity shapes (spoke, elliptical, quarter wave) at different frequencies (80 - 1300 MHz) and various temperatures. With this addition we calculate $Q_0$ as $Q_0 = G/R_s$ with $G$ being the geometry factor, which has a numerical value of around 280 Ω for $\beta = 1$ cavities. $R_s$ is then calculated from

$$R_s = R_{BCS}(f,T) + R_H(f,T,B_{tr}) + \underbrace{R_s'(f,T,B_p)}_{\text{phenomenological addition}} + R_{res}$$

Using the phenomenological addition of $R_s'$ the $Q$-slopes for a 704 MHz cavity at various temperatures are plotted in Fig. 1.

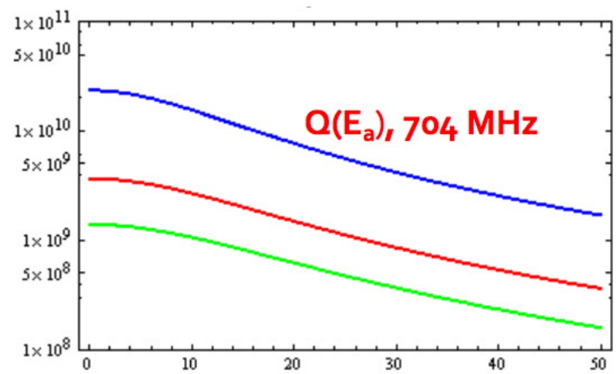


Figure 1: Approximated $Q$-slopes for a 704 MHz cavity for 2.2, 3.3, and 4.5 K (top to bottom).

Furthermore, for a maximum surface field of $\approx 100$ mT (corresponding to an electric surface field of $\approx 50$ MV/m) we find that there is a factor of $\approx 21(26)$ between the $Q$ values at 2 and 4.5 K for 704 (1408) MHz. At 2 (4.5) K the difference in $Q_0$ between 704 and 1408 MHz is 2.5 (3.0) in favour of 704 MHz. Table 8 lists the cavity properties, which are used for the estimates of the cryogenic loads and the cavity filling time, which has a large influence on the electric power consumption of the RF system.

Table 8: Expected parameters of superconducting cavities at 704 and 1408 MHz.

| **f [MHz]** | $\beta_{\text{geom}}$ | $(R/Q)$ [Ω] | $Q_0$ [$10^9$] @ 4.5/2 K | $E_{\text{acc}}$ [MV/m] |
|---|---|---|---|---|
| 704 | 0.65 | 285 | 0.30/5.8 | 19.4 |
| 704 | 0.92 | 501 | 0.40/7.7 | 24.2 |
| 1408 | 0.60 | 441 | 0.10/2.3 | 18.1 |
| 1408 | 0.76 | 671 | 0.12/2.5 | 21.7 |
| 1408 | 0.94 | 931 | 0.15/3.2 | 24.2 |

Reaching the desired gradient of 25 MV/m seems feasible for both temperatures in the 704 MHz case. For 1408 MHz the situation is not completely clear, especially for pulsed operation. As we will see towards the end, a temperature of 4.5 K would lead to an excessive cryogenic heat load and it therefore an unlikely choice for both frequencies when considering high duty cycle operation.

## RF HARDWARE

When faced with the choice of different frequencies for an RF system one generally assumes that the size of the components shrinks with rising frequencies. Also one can usually hope for higher peak power from the klystrons. However, in case of high average power needs, RF components are limited by the average power density in the components. This applies for all elements with losses, such as circulators, ferrite based phase shifters, water loads, klystrons, etc. Indeed, klystron manufacturers so far confirmed this view when asked for devices that can supply reliably 5 MW of peak power with 10% duty cycle at either 704 or 1408 MHz. The manufacturers feel that these ratings are feasible with single beam klystrons at the lower frequency, even though a multi-beam approach would make things simpler and probably more reliable. At 1408 MHz, however, even the multi-beam approach is considered as very challenging due to the resulting high average power density in the loads. The same problem arises for circulators and RF loads, where suitable devices are available at 704 MHz but not at 1408 MHz. It is thus very unlikely that 1408 MHz will lead to more compact, or even cheaper elements for the RF power system.

Looking at the question of RF couplers, we consider that solutions can be found at both frequencies. At 1408 MHz one can build on existing modifications of the XFEL/ILC coupler, which are used in high duty cycle electron machines. At 704 MHz little hardware exists, but the larger volume should be able to cope with the high average power. The necessary R&D effort for an SPL type machine is considered to be very similar for both frequencies.

## CRYOGENICS

### *Cryo-modules*

The ILC cryo-module with its extensive development and testing history is considered as state of the art in cryo-module design for superconducting linacs. The long cryo-modules yield a high packing factor (active cavity length over linac length) and keep the static cryogenic losses to a minimum. The static losses are further reduced by having the Helium supply lines as well as the pumping return line inside of the modules. Another special feature is to use the pumping return line as a structural element, which acts as a "backbone" for the whole set-up. An analysis of the pumping flows for the SPL duty cycle showed that the diameter of the return line would be suitable for SPL operation at 2 or 4.5 K. Using only one thermal shield instead of two it should also be possible to use the outer vessel for both frequencies without changing the static heat loss significantly. Nevertheless, for use in the SPL the ILC cryo-module has to be modified considerably for the following reasons:

- The liquid helium level control and flow pattern in the two-phase line have to be adapted to cope with the SPL slope of 1.7 $\mathrm{deg}$ (maximum ILC slope: 0.6 $\mathrm{deg}$).
- In case of the SPL the average cryogenic load per cryo-module is approximately 10x times higher than in the ILC.
- At both frequencies, the port openings for HOM and RF power couplers have to be adapted to the layout of the SPL cavities.

In conclusion it is clear that many features of the ILC cryo-module will be re-used for the SPL. However, it will not be possible, neither for 704 nor for 1408 MHz, to carbon copy the ILC design, even if, in the case of the higher frequency, it should be easier to re-use certain elements. It is clear, however, that one cannot expect large savings on the cryo-modules, when using 1408 MHz instead of 704 MHz.

### *Cryogenic infrastructure*

The size and type of the cryogenic infrastructure depends on the chosen operating temperature of the superconducting cavities. The choice of temperature depends on i) whether the temperature has an influence on the performance of the cavities (see "CAVITY PERFORMANCE"), and ii) the resulting cooling capacity, which is required to keep the cavities at a stable operating temperature. It is clear that operating in the saturated pool boiling regime at 4.5 K offers the advantage of being at a higher pressure than atmospheric (1.3 bars), thus limiting the risk of helium contamination due to air leaks. However, this would require venting of helium vapour bubbles from the uppermost point of all closed envelopes, and therefore means a specific design of helium vessels, considerably different from the ILC design. In the frame of the whole project the price difference between a 2 K and a 4.5 K helium transport system is considered as minor.

Using the $Q$ estimates, which are given in Table 8, together with the static loads [2] and applying the CERN standard safety margins we get the cryogenic loads given in Table 9.

From the values in Table 9 it is clear that operation at 4.5 K is out of question, since it would demand an excessively large cryogenic installation, with an electric power consumption rivalling that of the RF system. One can also see that the difference between the two frequencies is almost negligible, which means that (for cryogenics) the difference in filling time (see section on "FUNDAMENTAL CAVITY PARAMETERS...") is more or less compensated by the difference in $Q_0$.

Table 9: Cryogenic load at different temperatures and frequencies assuming the nominal operational parameters from Table 1 (with 0.4 ms beam pulse length).

| f [MHz] | $T_{\text{cryo}}$ [K] | $Q_{eq,4.5\,K}$ [kW] | $P_{\text{el}}$ [MW] |
|---|---|---|---|
| 704 | 2 | 20.8 | 5.2 |
| 704 | 4.5 | 95.4 | 23.9 |
| 1408 | 2 | 18.3 | 4.6 |
| 1408 | 4.5 | 81.9 | 20.5 |

## FACILITY OPTIMISATION: ELECTRICAL POWER CONSUMPTION

Finally, taking into account the different layout of the architectures at 704 and 1408 MHz (number of cryomodules/cavities), the different filling times of the cavities, the dependance of the cavity $Q$ on temperature, gradient, and frequency, the cooling efficiencies, etc, one can estimate the electric power consumption of the facility (cryogenics and RF) as a function of frequency (see Fig. 2) and cryogenic temperature (see Fig. 3).

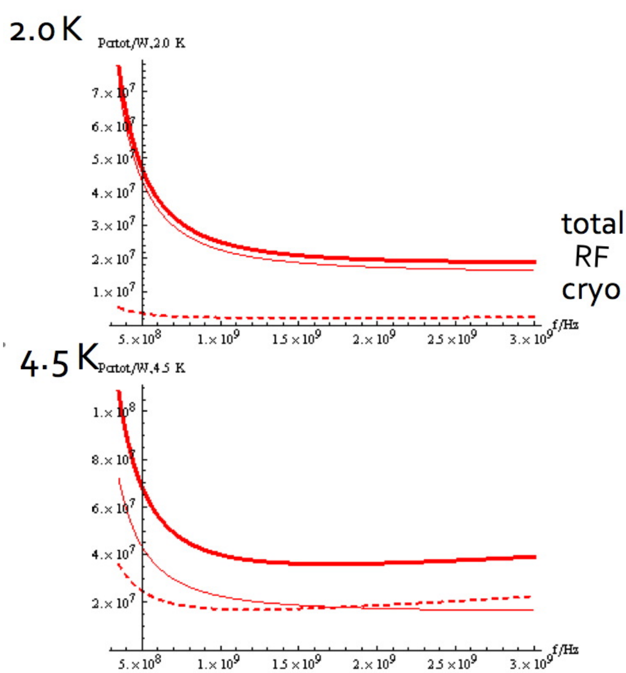


Figure 2: Electric power consumption as a function of frequency (arbitrary units). The curves show the cryogenic power, RF power, and the sum (bottom to top).

Table 10 summarises the power consumption for the "nominal" and "high-frequency" options of the SPL at the nominal operation parameters quoted in Table 1.

One can see that, due to the difference in filling time the 1408 MHz option uses more than 30% less power from the grid than the 704 MHz option.

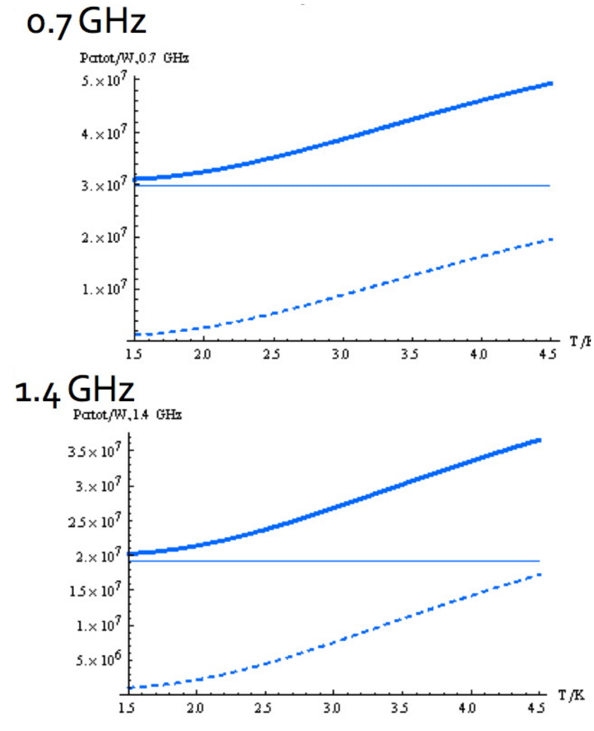


Figure 3: Electric power consumption as a function of temperature (arbitrary units). The curves show the cryogenic power, RF power, and the sum (bottom to top).

Table 10: Electric and cryogenic power consumption at 704 and 1408 MHz for the "nominal" operation of the SPL with 0.4 ms beam pulse length and 2 K cryogenic temperature (see Table 1).

| | 704 MHz | 1408 MHz |
|---|---|---|
| $P_{\text{RF}}$ [MW] | 25.5 | 16.3 |
| $P_{\text{cryo}}$ [MW] | 5.2 | 4.6 |
| $P_{\text{total}}$ [MW] | 30.7 | 20.9 |

## SUMMARY

The pros and cons for operating a superconducting linac at 704 or 1408 MHz have been evaluated for two different cryogenic temperatures: 2 K and 4.5 K. As a typical high-power linac design, the layout of the CERN SPL has been used as a reference. In the CERN context the option of using spoke and elliptical cavities in one linac seems less attractive. Linac4, the 160 MeV front-end of the SPL is now being built at CERN and at this point in time the SPL is not yet approved, which is why Linac4 uses "traditional" normal conducting cavities in the medium energy range of ≈100 - 160 MeV. If the SPL were already approved, then it would seem attractive to use spoke cavities already from lower energies and to extend their use up to several hundred MeV. As it now, spoke cavities would require an additional R&D effort for the SPL and are therefore not considered.

The original question whether we can save costs and/or R&D effort when going to 1408 MHz can be answered with a clear "**no**" for the following reasons:

- Even though the cryo-module design will have many features of the ILC design, the SPL needs a specific design to adapt for the 1.7% slope, the different layout of cavities and couplers, and the increased duty cycle.
- At 1408 MHz the linac becomes $\approx 15\%$ longer.
- The risk of having trapped modes and to suffer from beam break up is considerably larger for higher frequencies and increased cell numbers.
- The cost of the cryogenic system is similar for both options.
- The cavity design will certainly adapt the methods learned in the ILC cavity development, but for both frequencies the design needs to be modified and tested. Furthermore the 1408 MHz option needs 3 ($\beta$) families of cavities, while only 2 are needed for 704 MHz.
- The beam dynamics performance is similar, but the higher frequency option is more sensitive to longitudinal emittance growth.
- High-power RF equipment capable to operate at high duty cycle is very difficult to design at 1408 MHz. This applies to klystrons in particular but also to hybrids and amplitude/phase shifters and is due to limits in the average power density, which can be sustained in the equipment.
- The lower frequency option offers the possibility to collaborate with other high-intensity linac projects (such as ESS). It is unlikely that projects, which rely on high beam currents will choose a high-frequency option due the problems related to HOMs.

The advantages of 704 MHz have to be "bought" by an increased power consumption of the RF system, which is caused by longer filling times for the larger cavities, but this seems like a reasonable price for the prospect of sound equipment design and reliable operation. It should be noted that the above arguments were derived for a high-duty cycle proton machine (40 mA average current, 50 Hz, $> 0.4$ ms beam pulse length), and that they have to be reviewed in case of lower average beam power.

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