

SRF LINAC DEVELOPMENT FOR THE NEW LIGHT SOURCE PROJECT IN THE UK

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Abstract

A design optimisation has been performed for an L-band, SRF linac adopting cryomodule technology developed as part of the TESLA Technology Collaboration (TTC). A conventional XFEL cryomodule has been adopted as a baseline design and modified to allow for modest CW operation at a nominally high Q_0 level. An assessment of appropriate operating gradient, based upon expected sub-system component costs and SRF linac operating costs, has been performed. The associated cryomodule modifications to accommodate such a large dynamic load are also highlighted, along with identifying an appropriate RF control architecture which can achieve the stringent phase and amplitude stability requirements for NLS.

INTRODUCTION

The proposed superconducting RF (SRF) linac solution for NLS has been arrived at based on technology availability, demonstrated performance, reliability and anticipated capital and operational costs. The fundamental SRF system design choices for RF frequency, operating temperature and gradient are highlighted, whilst also identifying appropriate hardware solutions for each technology sub-system, to not only meet NLS operating specifications, but also to ensure a robustness and reliability commensurate with modern user requirements for such a 4th generation light source [1].

TECHNOLOGY AND FREQUENCY CHOICE

The fundamental advantage of SRF technology over normal-conducting is the extremely low surface resistance (R_s) that can be achieved with appropriately prepared niobium structures. At 2 K operating temperatures, $R_s \sim 10$ n Ω have been demonstrated, enabling Q factors $> 10^{10}$. This compares with $Q \sim 10^4 - 10^5$ for normal conducting cavities, giving a reduction in equivalent RF loss of 6 orders of magnitude. Even accounting for the low Carnot efficiency of conventional cryogenic refrigeration systems, considerable operational cost savings are still evident using SRF technology (typically ~ 200). Another major advantage of SRF technology is that it does not require the structure r/Q_0 to be maximised, resulting in larger, more open cavity beam-pipes. This has the benefit of reducing the trapped Higher Order Mode (HOM) impedances, such that beam instability and/or breakup thresholds can be increased compared to normal-conducting cavities, with both longitudinal ($W_{||}$) and

transverse (W_{\perp}) wakefields scaling as f^2 and f^3 respectively.

For the intrinsic losses associated with SRF accelerating structures, when $R_{BCS} \gg R_{res}$ then R_s scales with f^2 , when $R_{BCS} \ll R_{res}$ then R_s is independent of f . At an operating temperature of 1.8 K the BCS term dominates above 1.93 GHz and hence the losses grow linearly with f , whereas for frequencies below 500 MHz the Residual Resistance (R_{res}) dominates and the losses grow with $1/f$ (see Figure 1).

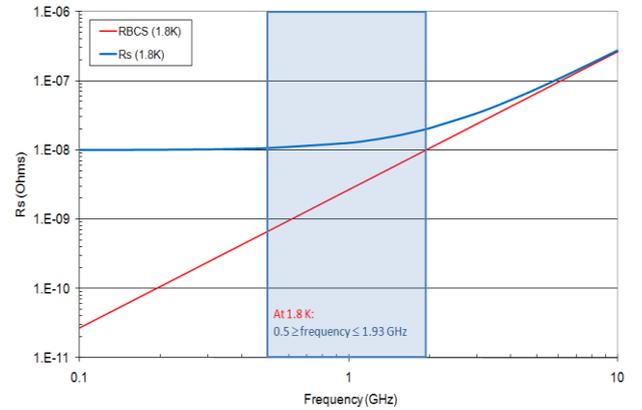


Figure 1: Preferred Frequency Band for an SRF Cavity with $R_{res} = 10$ n Ω at an Operating Temperature of 1.8 K.

The choice of frequency for NLS is based upon technology availability within this frequency band, not only in terms of the accelerating structures and associated cryomodules, but also in terms of high power RF infrastructure to match the design requirements. For these reasons, L-band technology has been adopted, taking advantage of the decades of development for the TESLA, ILC, TTF, FLASH and XFEL accelerator facilities, whilst also witnessing the implementation of TESLA technology for many other existing and proposed accelerator projects around the world; such as ALICE, ELBE, Cornell-ERL, JAERI ERL, BESSY-FEL and 4GLS.

GRADIENT CHOICE

The choice of gradient for NLS is dependent upon many factors; of primary consideration is the anticipated cavity performance and the associated effect on costs. As E_{acc} is increased for a SRF cavity, invariably the Q_0 reduces and rolls off until a fundamental limitation is reached. For NLS it is proposed to utilise TESLA L-band structures [2], processed using conventional Buffered Chemical Processing (BCP) techniques. Figure 2 shows the predicted performance for such a cavity at 1.8 K,

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based upon typical DESY measured performance at 2 K [3].

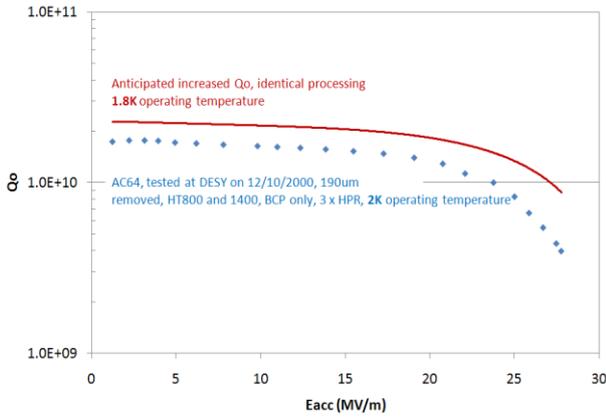


Figure 2: Predicted Q_0 vs E_{acc} Performance for a BCP Processed TESLA Cavity, Operating at 1.8 K (red curve) Based on Measured Data at 2 K (blue diamonds).

The cavity in question (A64) is one which was vertically tested at DESY in October 2000 following a BCP process to remove 190 μm of material, with two high temperature bakes and three stages of High Pressure Rinsing (HPR). This structure reached 23.8 MV/m at a very respectable Q_0 of 10^{10} , albeit in pulsed mode for TTF. Extrapolating to what may be expected if the operating temperature is reduced to 1.8 K is shown by attributing a conservative 30 % increase in Q_0 across the same range of E_{acc} .

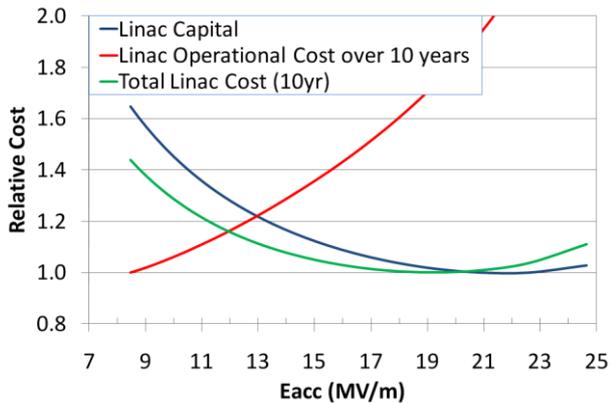


Figure 3: Relative Total Capital and 10-year Operational Linac Costs.

The choice of nominal operating gradient for NLS has been decided based upon anticipated total system costs (i.e. including cryomodules, RF amplifiers, cryopant, tunnel installation and integrated system operational costs), coupled with best operational reliability. The relative major linac sub-system cost scalings have been determined based upon information sourced from industry and other national laboratories who have performed similar L-band technology assessments for their own respective accelerator designs. Accumulating these costs and adding linac operational costs over a 10 year period, shows that there is a broad E_{acc} minimum, centred at around 19.4 MV/m (see Figure 3). This analysis however

utilises energy costs at 2010 rates ($\pounds 0.07/\text{kWh}$) and assuming 6000 hrs/year of RF operation with 8400 hrs/year of cryopant operation. Realistically however electricity costs are increasing and by the time NLS is ready for first operation energy costs will be undoubtedly much higher. Figure 4 shows how a doubling of the energy costs between now and then could significantly alter the optimum gradient, reducing it to ~ 17.5 MV/m.

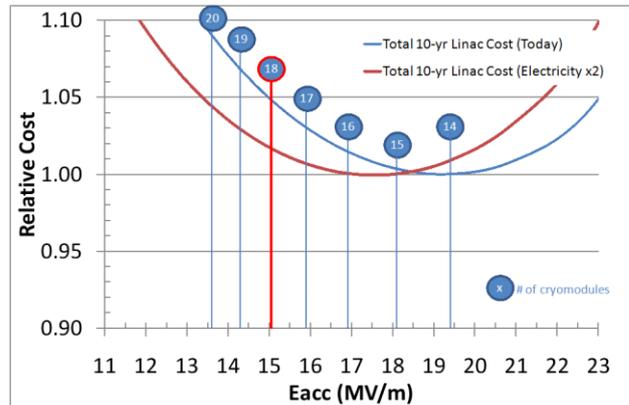


Figure 4: Effect of Increased Energy Cost on E_{acc} Optimisation over 10 years

From Figure 4 it can be seen that 14 cryomodules operating at 19.4 MV/m would give a minimum total cost for a machine operating with today's electricity costs. Minimising capital and operational costs however is not the only imperative, but also reducing the technical risks associated in achieving the required E_{acc} . It is therefore proposed to employ 18 cryomodules operating at a nominal gradient of 15 MV/m, for which the total linac cost is within 5 % of the cost minimum at today's energy rates and within 2 % for potentially doubled energy costs in the future. In reducing the operating E_{acc} to this level a number of associated benefits prevail:

- Reduced risk of poor cavity performance, especially field emission limitations.
- Cheaper cavity processing, using conventional BCP:HPR techniques.
- Increased reliability and availability.
- Increased intrinsic redundancy, as each cavity will have a larger operational overhead capability.
- Increased production yield from industry.

RF OPERATING PARAMETERS

Based on a frequency choice of 1.3 GHz for the 2.25 GeV NLS linac, operating at a temperature of 1.8 K with a nominal gradient of 15 MV/m and reaching a Q_0 of 2×10^{10} , the SRF parameters for both the baseline repetition rate of 1 kHz and a later upgrade to 1 MHz operation are given in Table 1. An optimum Q_L is determined by defining the expected peak detuning (or microphonics) level (δ) from the integrated cryomodule cavities, for which a minimum RF generator power (P_g) is achieved from Equation 1, assuming on-crest acceleration and $\beta \gg 1$ [4].

Table 1: NLS SRF System Operational Parameters.

| Parameter | 1 kHz | 1 MHz | Units |
|---|---------|---------|-------|
| Bunch Charge | 200 | 200 | pC |
| Repetition Rate | 0.001 | 1 | MHz |
| Beam Current | 0.0002 | 0.2 | mA |
| RF Frequency | 1300 | 1300 | MHz |
| Gradient | 15.05 | 15.05 | MV/m |
| Q_0 | 2.0E+10 | 2.0E+10 | |
| Cavity Length | 1.038 | 1.038 | m |
| R/Q | 1036 | 1036 | Ohms |
| Number of Cryomodules | 18 | 18 | |
| Number of Cavities | 144 | 144 | |
| Q_{ext} | 3.7E+07 | 3.7E+07 | |
| RF power per Cavity | 2.6 | 4.6 | kW |
| Total RF power | 374 | 662 | kW |
| 1.8 K Dynamic load per Cavity | 11.7 | 11.7 | W |
| Total 1.8 K Dynamic Load | 1.7 | 1.7 | kW |
| 1.8 K Static Load per Cavity | 2 | 2 | W |
| Total 1.8 K Static Load | 0.288 | 0.288 | kW |
| Total 1.8 K Cryogenic Load (incl 50% safety factor) | 3.0 | 3.0 | kW |
| RF AC Power | 0.69 | 1.23 | MW |
| Cryo AC Power | 2.98 | 2.98 | MW |
| Total AC Power | 3.67 | 4.21 | MW |

$$P_g = \frac{L}{4 Q_L \kappa / Q} \left\{ \kappa_{acc} + I_b Q_L \kappa / Q \sum + \left(2 Q_L \frac{\delta f}{f_0} E_{acc} \right)^2 \right\} \quad (1)$$

Figure 5 highlights for a relatively conservative microphonics level of 15 Hz, that an optimum $Q_L = 3.7 \times 10^7$ would require an RF power of 4.6 kW/cavity.

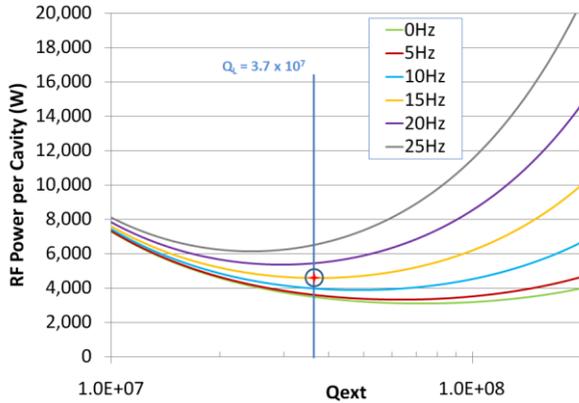


Figure 5: RF Power per Cavity as a Function of Anticipated Microphonics for 1 MHz Operation.

CRYMODULE DESIGN

The XFEL cryomodule design is chosen as a reference to develop a suitable cryomodule for the NLS linac. However, due to its CW-mode of operation, the dynamic heat load experienced by the NLS cryomodule will be about 10 times higher than for XFEL.

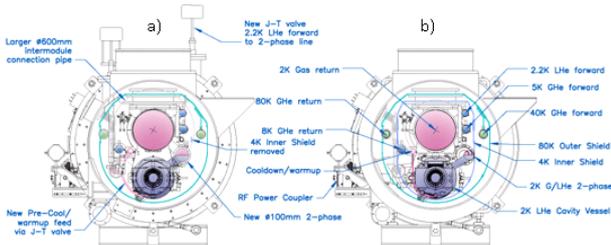


Figure 6: Modifications Performed for a) an NLS Cryomodule Compared to b) XFEL Cryomodule.

Consequently the XFEL cryomodule must be modified to handle much higher mass flow with higher GHe pressure stability at a lower operating temperature of 1.8 K. In order to address all of the related issues, a conceptual engineering design has been developed incorporating the associated changes as identified in Figure 6, with a more detailed description already documented elsewhere [5].

RF POWER AND CONTROL

The RF system architecture for NLS is to use one amplifier for each cavity, in order to provide highest uncorrelated stability in terms of LLRF performance, control and machine availability (see Figure 7). Each cavity therefore has its own control loop with feedback and feedforward, with an intention for providing RF stability at the level of 0.01° phase and 2×10^{-5} amplitude.

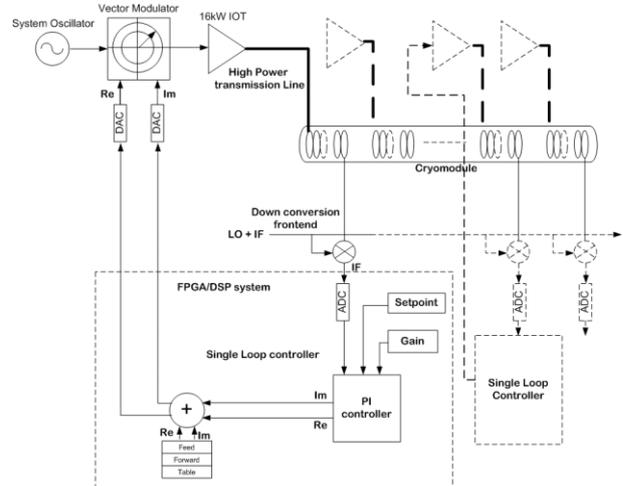


Figure 7: Independent Amplifier LLRF Architecture Solution for NLS.

SUMMARY

The SRF linac proposed and its operating parameters described, demonstrate a viable baseline design achieving a modest CW gradient operation, for a beam repetition rate of 1 kHz, with potential to accelerate at higher repetition rates (>1 MHz) without the need to modify the fundamental cryomodule design. For more information, refer to the NLS Project: Conceptual Design Report.

REFERENCES

- [1] 'NLS Conceptual Design Report', May 2010.
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