SUPERCONDUCTING OPTIONS FOR THE UK'S NEW LIGHT SOURCE PROJECT

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Abstract

The UK's New Light Source (NLS) project was officially launched on April 11th 2008 [1], which will be based on advanced conventional and free electron lasers, with unique and world leading capabilities. User consultation exercises have already been initiated to determine the fundamental photon output requirements for such a machine. In order to match possible requirements for high repetition rates (> 1 kHz), a series of Superconducting RF (SRF) linac options have been investigated, reflecting varied beam loading conditions and possible beam energy scenarios.

INTRODUCTION

Superconducting RF (SRF) is becoming the technology of choice for the next generation of particle accelerators, both for basic energy science programmes such as conventional synchrotron radiation sources (i.e. diamond, TLS, SSRF and SOLEIL), and also for high energy physics collider machines (i.e. LHC and ILC). This paper assesses possible existing SRF cryomodule design solutions for a number of SRF linac based accelerators that have been developed specifically for FEL applications around the world; which include single-pass (XFEL and BESSY-FEL), recirculating (CEBAF) and energy recovery (ALICE) configurations. A companion paper deals with alternative normal conducting linac solutions for NLS [2].

The design requirements for an SRF linac differ for every application, as typically for single pass configurations, beam-loading is relatively weak and RF infrastructure costs are not as significant compared to more heavily beam-loaded linacs. It then becomes more cost effective to recirculate and/or to remove the beam-loading component completely by operating in energy-recovery mode. Dynamic RF cryogenic loads will typically dominate for these types of linacs and so considerable cost savings can also be gained using multi-pass schemes to attain higher energies. A recirculating option is also being investigated for NLS in order to assess potential capital and operational cost savings.

CEBAF UPGRADE CRYOMODULE

A series of three cryomodules have been constructed as part of JLab's efforts to increase CEBAF's availability and reliability. These provide additional acceleration for the FEL and produce prototypical cryomodules for the 12 GeV Upgrade. The first two constructed were based on the initial "Upgrade Cryomodule" design [3,4]. Both containing 7-cell cavities based on the original CEBAF cavity cell shape operating at 1.5 GHz, with a design expectation of > 70 MeV of acceleration. The third cryomodule, dubbed "Renascence," incorporates several design changes in order to provide more than the 108 MeV capability required for the 12 GeV upgrade of CEBAF [5] (see Figure 1).

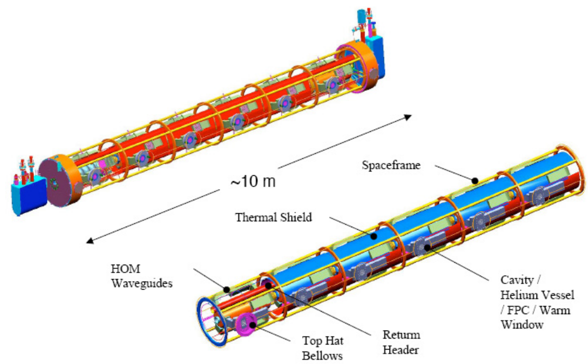

Figure 1: JLab Renascence Cryomodule.

XFEL CRYOMODULE

The XFEL Cryomodule consists of eight TESLA cavities in a string with a large helium gas return pipe as the backbone of the structure which the cavities are supported from (see Figure 2). Optimisation of the cryomodule design has been taken place to develop the module capable of reaching nearly 280 MV of acceleration, fed by a MW class multibeam klystron. In order to minimise the cryogenic load, XFEL is pulsed with a 1% duty factor to achieve a final operating energy of 20 GeV [6].

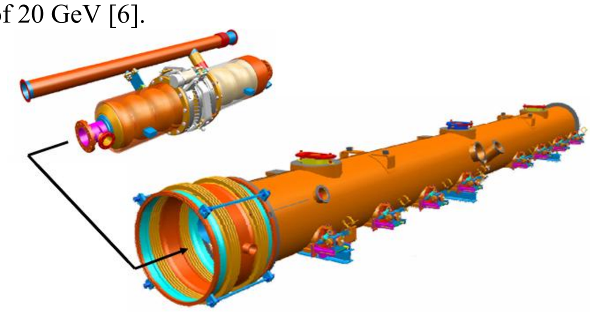

Figure 2: XFEL Cryomodule.

BESSY-FEL CRYOMODULE

The TESLA/XFEL cavity and cryomodule technology was developed for pulsed operation, although most of the system is equally suited for CW mode. There are a number of modifications that must be implemented to

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achieve modest CW gradients and BESSY's approach has been to maintain the TESLA design philosophy and only make changes were necessary; to sustain reliable CW operation, and/or if significant cost savings can be realised [7].

Since the BESSY-FEL has a much reduced final beam energy of 2.3 GeV, optimisation of the cryogenic load and analysis of the construction cost versus gradient and helium temperature, lead to a relatively flat optimum between 15 – 18 MV/m. (15.4 MV/m actually chosen) at a Q_0 of 2e10, with an operating temperature of 1.8 K. Since it is intended to run the module CW and at a higher Q_0, the cavities are very sensitive to microphonics and in order to mitigate this, the diameter of the helium fill pipe is increased to allow a higher heat load to be dissipated. Modifications to the existing XFEL coupler are also planned in order to achieve the higher average powers required for the BESSY-FEL linac.

ALICE CRYOMODULE

The remit of the ALICE facility is to provide a R&D facility for advanced accelerator systems; from high-intensity electron sources, CW SRF linac cryomodules, short pulse FEL undulators, to Electro-Optical diagnostics [8]. The SRF cryomodule employed on ALICE (see Figure 3) was developed in collaboration between FZD-Rossendorf and Stanford University, and first operated on the SCA facility at Stanford University in 1979, then at the ELBE facility from 2001 and is now commercially licensed by ACCEL GmbH in Germany. It comprises two, 1.3 GHz 9-cell cavities; each having a pair of HOM couplers (á la XFEL), modified to utilise sapphire ceramics (developed at JLab [9]) to improve the power handling capability upto 10 W (from the original 5W), plus a single non-adjustable 10 kW CW coaxial input coupler.

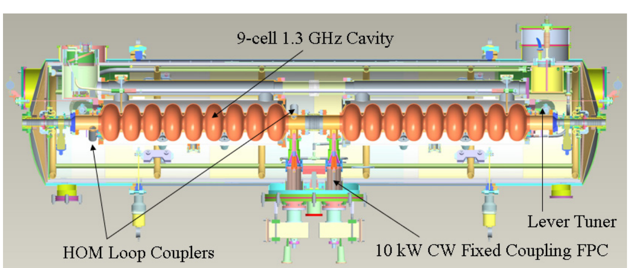

Figure 3: ALICE Cryomodule.

DARESBURY INTERNATIONAL CRYOMODULE COLLABORATION

A collaboration between Daresbury Laboratory, Stanford and Cornell Universities, LBNL and FZD Rossendorf has been developed to design and build an improved cryomodule, which can facilitate modest CW gradients and provide increased power handling capability, with improved field stability control. The intention is to develop a cryomodule design, based upon the ALICE cryomodule. The reason for choosing this module is to enable its installation on the ALICE facility to allow for full beam test validation on an operational ERL accelerator, albeit at relatively low average beam current (~13 µA). These tests will enable the evaluation of modest accelerating gradients (up to 20 MV/m) with an input coupler Q_{ext} reaching beyond 10^8, at temperatures down to 1.8 K.

Modifications to this cryomodule (see Figure 4) include adopting two 7-cell TESLA super-structure cavities and widening its beam pipes to allow improved propagation of the HOMs, which are then dissipated in beam-pipe ferrite based HOM absorbers developed by Cornell. The Cornell ERL injector coupler is also adopted, which is optimised for lower average power (~25 kW). Finally, an upgrade to the tuning system will allow piezo actuators to be introduced, to allow fast tuning of the cavity to compensate for microphonics [10].

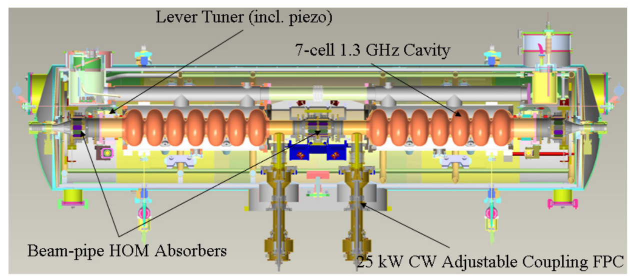

Figure 4: DICC Collaboration Cryomodule.

MODULE SUMMARY

Comparing the operational parameters for each of the cryomodule designs highlighted here, we can see when applied to what may be needed for NLS (at 1 GeV), an active linac length of ~ 100 m would be required for ¾ of the CW optimised cryomodules (see Table 1). The BESSY FEL cryomodule clearly provides the most optimum solution overall; requiring fewer SRF cryomodules, the shortest active linac length and a significantly lower total linac dynamic load.

Table 1: SRF Module Comparison and NLS Application

Accelerator	CEBAF Upg.	XFEL	BESSY FEL	ALICE	DICC
Average Cavity Gradient (MV/m)	19.2	23.6	15.4	13	20
Frequency (GHz)	1.5	1.3	1.3	1.3	1.3
Qo	8.0E+09	1.0E+10	2.0E+10	5.0E+09	1.0E+10
Input coupler Qe	2E+07 (fixed)	4.6E+06	3.0E+07	5E+06 (fixed)	1E+07 – 1E+08
Max Input Coupler Power (kW)	13	169 (pulsed)	5	10	25
Cavities per cryomodule	8	8	8	2	2
Module Energy Gain (MeV)	108	196	128	27	32
Cryomodule Length (m)	10	12	12	3	3
	Application on NLS				
Number of Cryomodules (1GeV)	10	PULSED	8	48	32
Active Length of Linac (m)	100		96	144	96
Dynamic RF load per cryomodule (W)	199.8		98.6	70.3	64.7
Total Linac Dynamic load (W)	1997.6		788.9	3372.9	2069.2
Cryomodule dynamic load/energy gain (W/MeV)	1.8		0.8	2.6	2.0

POTENTIAL NLS REQUIREMENTS

The NLS project is very much in its infancy in terms of machine layout and defined parameters. Figure 5 shows a possible NLS machine layout for 1 GeV operation, based upon a BESSY-FEL cryomodule, operating at 17.2 MV/m; chosen to ensure at low energies (for $\phi_b = \pm 30^o$) that peak gradients do not exceed 20 MV/m.

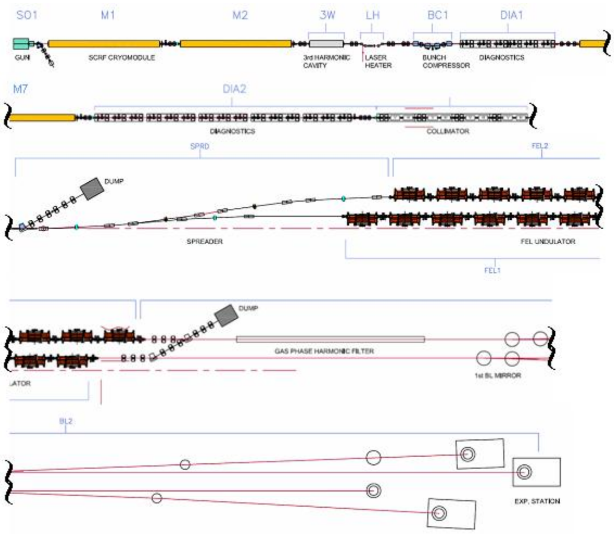

Figure 5: Possible NLS facility layout (1 GeV shown).

This review of many existing and/or under development cryomodules, potentially suitable for an FEL based light source has highlighted a clear understanding of the capabilities for each. For NLS, operating at possible repetition rates of between 1 kHz and 1 MHz, Table 2 shows how the nominal SRF parameters would vary for a linac based upon the BESSY-FEL type cryomodule, operating at 1, 2 and 3 GeV.

Table 2: Possible SRF Linac Parameters for NLS

	1GeV		2GeV		3GeV		Units
RF Frequency	1.3	1.3	1.3	1.3	1.3	1.3	GHz
Bunch Charge (max)	200	200	200	200	200	200	pC
Repetition Rate (max)	1	1000	1	1000	1	1000	kHz
Average Current (max)	0.0002	0.2	0.0002	0.2	0.0002	0.2	mA
Number of cells/cavity	9	9	9	9	9	9	
Number of Cavities	56	56	112	112	168	168	
Number of Modules	7	7	14	14	21	21	
Cavity R/Q	1036	1036	1036	1036	1036	1036	Ω
Qo	2.0E+10	2.0E+10	2.0E+10	2.0E+10	2.0E+10	2.0E+10	
Energy Gain	1	1	2	2	3	3	GeV
Eacc	17.2	17.2	17.2	17.2	17.2	17.2	MV/m
Qe	5.0E+07	5.0E+07	5.0E+07	5.0E+07	5.0E+07	5.0E+07	
Cavity Filling Time	6.121	6.121	6.121	6.121	6.121	6.121	ms
RF Power per Cavity	6	6	6	6	6	6	kW
Total RF Power per Linac	0.345	0.345	0.689	0.689	1.034	1.034	MW
Dynamic load per Cavity	14.3	14.3	14.3	14.3	14.3	14.3	W
Dynamic load per Linac	803.0	803.0	1606.0	1606.0	2408.9	2408.9	W
Static load per Linac	70	70	140	140	210	210	W
Total CW load at 1.8K	873.0	873.0	1746.0	1746.0	2618.9	2618.9	W
Total Linac Active Length	84	84	168	168	252	252	m
Total Machine Length	370	370	510	510	640	640	m

For the 200 pC bunch charge and 1 kHz and 1 MHz repetition rates, beam loading is relatively low, with average beam currents (I_b) of only 0.0002 mA and 0.2 mA respectively, which for on crest acceleration ($\phi_b = 0^o$) gives an optimum Qe of 8.6e10 and 8.6e7 using Equation 1:

$$Q_e = \frac{V_{acc}}{R/Q \, I_b \cos\phi_b} \quad (1)$$

For LLRF and microphonics stability reasons, Qe's at this level will be difficult to sustain and so a conservative value of 5e7 is proposed for each repetition rate. For information, Cornell have demonstrated stable operation at Qe = 1e8 on the JLab IR-FEL [11].

Whilst the use of SRF technology minimises the amount of RF power required to generate the accelerating voltage, the total efficiency gain is also dependant on the load to the cryogenics. Table 2 also highlights the anticipated module count and total cryogenic load at 1.8K (Qo = 2e10) for 1, 2 and 3 GeV final operating energies. Note that these figures do not include the customary operational safety factor (typically 50%), to ensure machine performance can be maintained.

CONCLUSIONS

Having compared the various cryomodules available for potential use on NLS, a number of important issues have been identified. The first of which being that pushing up the CW gradient in these cryomodules impacts heavily on the dynamic capacity needed from the cryogenic system. The second being the maximum energy gain a module can deliver, whilst minimising its real estate footprint. On both counts, the proposed BESSY-FEL cryomodule appears to be the most optimum choice of extensively developed cryomodules available at present, which could effectively match possible high repetition rate operation for NLS in the UK.

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