SRF LINAC SOLUTIONS FOR 4GLS AT DARESBURY

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Abstract

The proposed 4th Generation Light Source (4GLS) facility, anticipated to be located at Daresbury Laboratory in the UK, will extensively utilise Superconducting RF (SRF) Linacs for each stage of its multi-beam acceleration. IR, XUV and VUV FEL devices, and particularly the ability to combine these sources for users, provide a unique capability for this Energy Recovery Linac (ERL) based accelerator. The CW mode of operation for the SRF Linacs necessitates that adequate provision is made for delivering the required RF power and also damping of the beam induced HOMs to manageable levels. This paper outlines the RF requirements and proposed solutions for each of the 4GLS Linacs.

INTRODUCTION

Superconducting RF (SRF) technology has been chosen as being the most appropriate solution for CW or high repetition rate accelerators, particularly those employing Energy Recovery Linac (ERL) techniques, such as that being proposed for 4GLS [1] (see Figure 1).

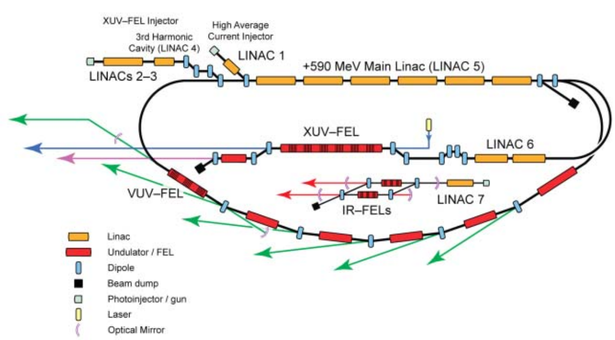

Figure 1: 4GLS Conceptual Layout and SRF Linacs.

Providing the required acceleration for each Linac stage of 4GLS appears to be achievable using predominantly the same cavity/cryomodule configuration. Based on TESLA/TTF technology at 1.3 GHz, cavity/cryomodule modifications are required for this conventional 9-cell cavity scheme to sustain CW and/or high repetition rates. For the 100 mA High Average Current Linac (HACL) injector, substantially more RF power is needed and so an alternative cavity/cryomodule system is proposed based on a solution developed by Cornell University [2].

Effective damping of the higher order modes (HOM) for each of the 4GLS Linacs will be critical in maintaining the high degree of beam stability required for optimal lasing at the Free Electron Laser (FEL) insertion devices. Precise Low Level RF (LLRF) amplitude and phase stability (and subsequent synchronisation) of each Linac accelerator must be maintained, requiring sophisticated state-of-the-art digital feedback and feed-forward systems.

SRF cavities excel in applications requiring continuous wave (CW) or long pulse operation at high accelerating gradients (E_{acc}), such as that for 4GLS. Since resistive losses in cavity walls increase as the square of the accelerating voltage, conventional copper cavities become uneconomical when the demand for high CW voltage grows. SRF has the major advantage that the surface resistance of a superconductor is five orders of magnitude less than that of copper. The geometry of SRF cavities also result in reduced wakefields and therefore reduced collective effects on the beam. Typically, after accounting for the refrigeration power needed to provide the liquid helium, a net gain factor of several hundred remains (in terms of the total AC power) for SRF over conventional normal conducting (NC) copper cavities in providing the required RF power.

4GLS SRF LINACS

Linac1

For Linac1, the requirement here is not for high accelerating gradients, but to deliver enough RF power to accelerate the 80 pC, high average current beam (100 mA) up to 10 MeV. The cavity scheme proposed, developed by Cornell, operates at 1.3 GHz, with a cavity gradient of 4.3 MV/m (see Figure 2). Linac1 for 4GLS will utilise ten of these 2-cell cavities, each with a dual RF input coupler which is employed to cancel any asymmetric kick that may be imparted to the low energy beam.

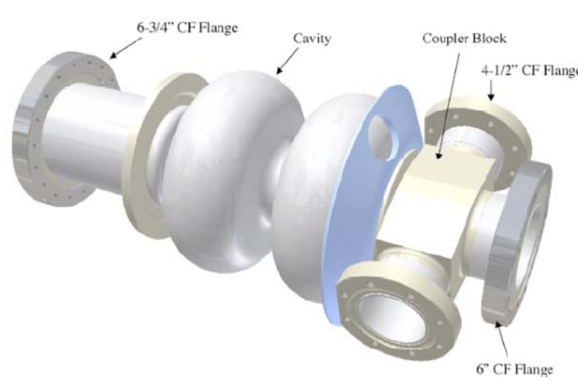

Figure 2: Cornell 2-Cell CW Injector Cavity Design.

Linac2 and Linac3

Linac2 and 3 in combination will accelerate a 1 nC bunch charge beam, at a repetition rate of 1 kHz, up to

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190 MeV. As the fill-time for the SRF cavities is long (~ 1.6 ms), the accelerating field will be generated in CW-mode, whilst actual beam acceleration occurs at the 1 kHz bunch repetition rate.

It is proposed for all 4GLS Linacs (except Linac1 and Linac4) that a modified TESLA cavity configuration is employed, which allows for high gradients whilst also providing improved HOM damping capability. Instead of the conventional 9-cell configuration, a 7-cell baseline configuration will be employed and the longitudinal space recovered will be utilised to house improved beam-pipe HOM absorbers, of the type developed for the Cornell ERL injector. The accelerating gradient required for Linac2 and 3 is 14.7 MV/m. A collaboration has been set-up between CCLRC, Cornell and Stanford Universities, LBNL and FZR Rossendorf to develop such a cavity/cryomodule system, which can be proven on the Energy Recovery Linac Prototype (ERLP) at Daresbury [3].

Linac4

For the high peak current injector feeding the XUV-FEL, the beam is run off-crest from the peak RF voltage in order to create a particle time versus energy correlation. The correlation is used to compress the bunch when it is run through a subsequent bunch compressor (BC) chicane. The sine-wave profile of the RF waveform sets the correlation by running the bunch off crest and is non-linear.

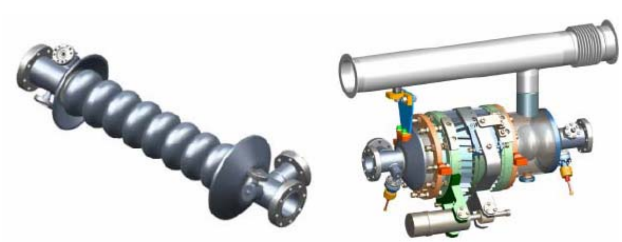

Figure 3: FNAL Developed 3.9 GHz Module for FLASH.

A third harmonic Linac with its higher frequency, has a much steeper RF voltage gradient versus time. The beam is run on the decelerating phase through the harmonic RF waveform (at close to -180^o) to remove most of the second order, non-linear part of the correlation, whilst imparting a net deceleration of ~ 30 MeV. Fermilab have developed a 3.9 GHz accelerating module (see Figure 3) to be used on FLASH at DESY for this very same application [4], which may become a viable solution for 4GLS.

Linac5

The main accelerating Linac for 4GLS (Linac5) is used to simultaneously accelerate both the 80 pC, CW (HACL) beam up to 600 MeV and the 1 nC, 1 kHz (high peak current) beam up to 750 MeV, whilst also decelerating the energy recovered beam before it is dumped (see Figure 4). The injected 1 kHz beam will be accelerated to 160 MeV before entering Linac5 to provide a clear distinction in beam energies, enabling beam separation into two paths within the first bending magnet separator. After Linac5, the HACL electron bunches excite a variety of spontaneous sources before returning back through Linac5 again for energy recovery (ER). When operated in ER-mode, the beam loading imposed on the Linac5 cavities will cancel in the accelerating and decelerating phases. For this reason, the power required to re-accelerate is orders of magnitude lower compared to the equivalent RF power needed to accelerate in a single pass.

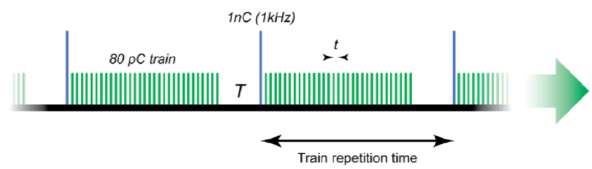

Figure 4: Possible Bunch Structure for 4GLS.

Linac6

The extracted 750 MeV, high peak current beam is further accelerated up to 950 MeV by Linac6 which operates at 15.5 MV/m, before passing through the XUV-FEL. There is no requirement for energy recovery of this ~ 1 kW beam and so it is dumped at high energy.

Linac7

For the IR-FEL Linac, the average accelerated beam current will be 2.6 mA, based on an electron bunch charge of 200 pC operating at a repetition rate of 13 MHz. Although this Linac will operate at a relatively conservative gradient of 9.3 MV/m, the higher average beam current will increase the RF power requirements beyond that of all other 4GLS Linacs, to ~ 20 kW/cavity.

SRF LINAC RF POWER REQUIREMENTS

Table 1: 4GLS Linac RF Parameters

	Linac1	**Linac2 Linac3**	**Linac4**	**Linac5**	**Linac6**	**Linac7**
Bunch Charge (pC)	77	1000	77	77 1000	1000	200
Bunch Rep. Rate	1.3GHz	1kHz	1kHz	1.3GHz 1kHz	1kHz	13MHz
I_b (mA)	100	0.001	0.001	100 0.001	0.001	2.6
Cells/Cav.	2	7	9	7	7	7
Cav./Module	5	8	2	8	8	8
Modules	2	1	1	6	2	1
Energy Gain (MeV)	10	95	-30	590	200	60
E_{acc} (MV/m)	4.3	14.7	14.5	15.2	15.5	9.3
Q_e	$4.7x10^4$	$1.3x10^7$	$5x10^6$	$2.6x10^7$	$1.3x10^7$	$1.3x10^7$
Power/Cav. (kW)	100	13	13.3	9.85*	14.9	19.5

** Includes CSR losses*

The generator power (P_g) required to maintain the required accelerating voltage (V_{acc}) for the ER Linac5 is given by:

$$P_g = \frac{V_{acc}^2}{4\frac{R}{Q}Q_e}\left\{1+\left(\frac{2\Delta\omega Q_e}{\omega_c}\right)^2\right\} \quad (1)$$

Where $\Delta\varpi$ is the microphonic tolerance bandwidth, which has been assumed to be 25 Hz for the 4GLS accelerating modules. Additional power overhead is also required for this linac to account for Coherent Synchrotron Radiation (CSR) losses. The RF power requirements for all other Linacs is derived from the product of the average beam current (I_b) and the total Linac accelerating voltage (see Table 1), plus a nominal amount for generating the cavity accelerating voltage at the required Q_o of 1 x 10^{10}.

Figure 5 shows how the magnitude of the microphonics can impact heavily upon the required RF operating budget. Having flexibility in adjustment of cavity Q_e is clearly advantageous when trying to minimise the RF power needed when a number of cavities are powered, each with their own microphonic sensitivities.

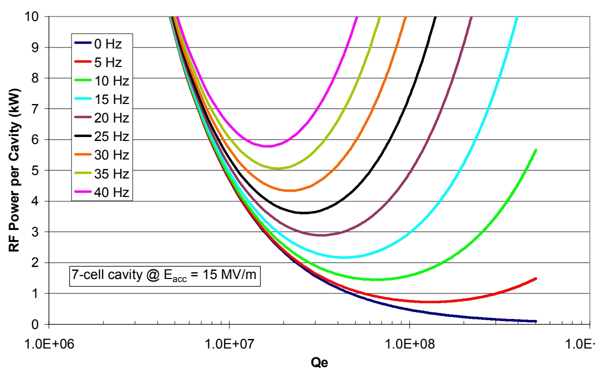

Figure 5: Microphonics Impact on Q_e and RF Power.

HOM ABSORBERS

Strong damping of the beam induced HOMs is essential to preserve beam emittance, minimize impedance driving the BBU instability, and to reduce the total HOM losses. Loaded quality factors (Q_L) of between a few 100 and a few 1000 are therefore required. To achieve this demanding goal, RF absorbing material will be placed in the beam tube between (and at the ends of) each cavity in each linac module. Cornell has developed such a device (see Figure 6) for their ERL injector module [5], which becomes an attractive solution for 4GLS.

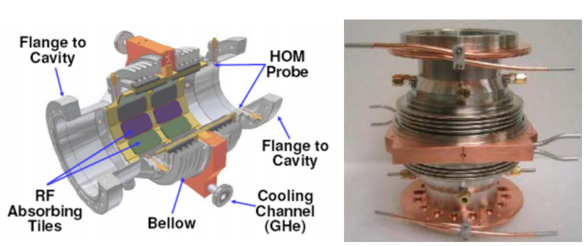

Figure 6: Cornell ERL Injector HOM Absorber.

The operating temperature of the HOM absorbers will be <80 K and a combination of three different RF absorbing materials provide efficient RF absorption from 1.4 GHz up to 50 GHz.

MAIN LINAC R&D

Stanford University have provided a cryomodule which has an identical layout to that of the modules available on ERLP, such that the completed module can be incorporated onto ERLP and its associated support services to allow for beam verification. The fundamental challenge facing this collaboration has been to confirm that the three Cornell HOM absorbers can physically fit inside the Stanford cryomodule, whilst interfacing with the two 7-cell cavities, such that the input couplers exit via the existing cryomodule aperture.

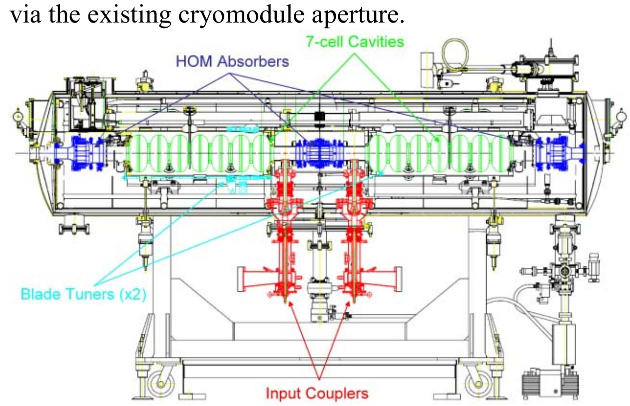

Figure 7: Modified Stanford Cavity/Cryomodule.

Two different Cornell HOM absorber geometries are employed; the first being 267 mm long and 78 mm diameter which is located between the two cavities, the second being 308 mm long and 106 mm diameter which are located at both ends of the cryomodule. The larger, high power Cornell ERL injector input coupler has been integrated, with only minor modification to the existing Stanford module. Figure 7 shows the modified Stanford cryomodule, incorporating 2 x 7-cell cavities, 3 x HOM absorbers, 2 x Cornell ERL injector input couplers and 2 blade-type tuners incorporating piezo actuators. Further development and integration of these various components will take place over the next 12–18 months, with possible first beam tests on ERLP occurring in early 2008.

REFERENCES

[1] 4GLS Conceptual Design Report, April 2006, found at: http://www.4gls.ac.uk/documents.htm#CDR

[2] M. Liepe *et al*, "Design of the Cornell ERL Injector Module", PAC05, Knoxville, 2005, pp 4290-4292.

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