RF REQUIREMENTS FOR THE 4GLS LINAC SYSTEMS

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Abstract

The 4GLS facility at Daresbury will combine energy recovery linac (ERL) and free electron laser (FEL) technologies to deliver a suite of naturally synchronised state-of-the-art sources of synchrotron radiation and FEL radiation covering the terahertz (THz) to soft X-ray regimes. CW-mode operation at high acceleration gradients are needed for the various 4GLS accelerator systems and here is where Superconducting Radio Frequency (SRF) cavities excel. Since resistive losses in the cavity walls increase as the square of the accelerating voltage, conventional copper cavities become uneconomical when the demand for high CW voltage grows with particle energy requirements. After accounting for the refrigeration power needed to provide the liquid helium operating temperature, a net power gain of several hundred remains for SRF over conventional copper cavities. This paper details the RF requirements for each of the SRF accelerating stages of the 4GLS facility, outlining techniques necessary to cope with CW-mode operation and HOM power generation.

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 Fig. 1).

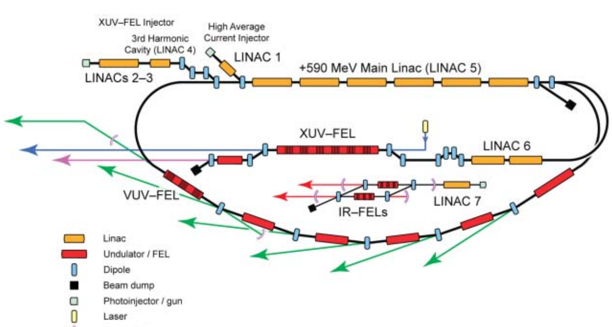

Figure 1: 4GLS Conceptual Layout and SRF Linacs.

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 rate operation for the majority of the 4GLS Linacs. 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.

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SRF APPLICATION FOR 4GLS

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 with particle energy requirements. 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 results 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.

The accelerator system design for 4GLS requires the study of multiple bunches accelerating through a single Linac with different charges, and assessments made on the effects of potential beam break-up [3].

4GLS SRF LINACS

Linac1

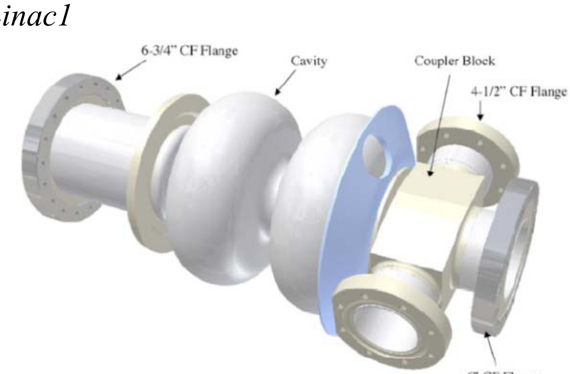

Figure 2: Cornell 2-Cell CW Injector Cavity Design.

For Linac1, the requirement here is not for high accelerating gradients, but to deliver enough RF power to accelerate the high average current beam (100 mA) up to 10 MeV. The cavity scheme proposed, developed by Cornell, operates at 1.3 GHz and a cavity gradient of 4.3 MV/m (see Fig. 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.

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 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.

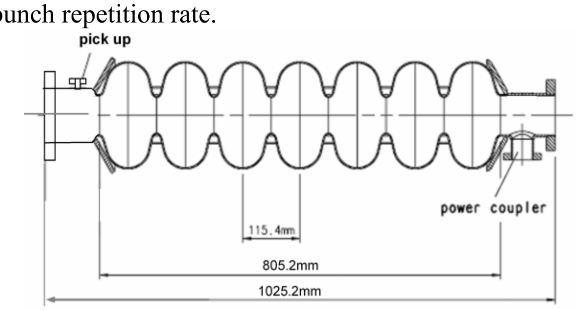

Figure 3: Modified TESLA/TTF Cavity Configuration.

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, 7-cells will be employed (see Fig. 3) and the longitudinal space recovered will be utilised to house improved beam-pipe HOM absorbers of the type developed for the Cornell ERL injector cavities. 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 ERLP at Daresbury [4].

Linac4

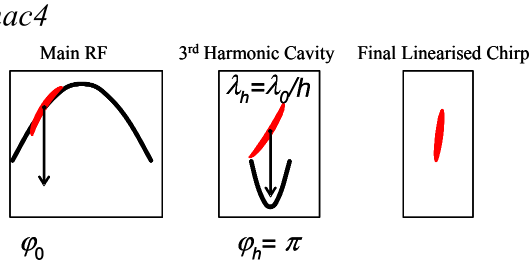

Figure 4: Harmonic RF, Energy Linearisation Schematic.

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 (see Fig. 4). 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.

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 Fig. 5) to be used on FLASH at DESY for this very same application [5], which may become a viable solution for 4GLS.

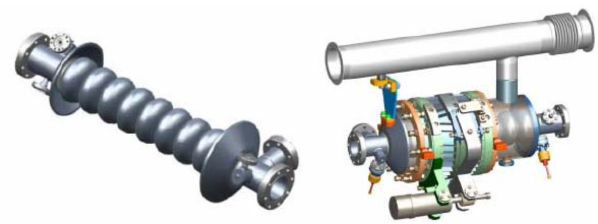

Figure 5: FNAL Developed 3.9 GHz Module for FLASH.

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 Fig. 6).

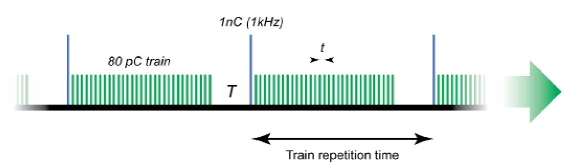

Figure 6: Possible Bunch Structure for 4GLS.

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.

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

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 4GLS. 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 simply derived from the product of the average beam current and the total Linac accelerating voltage, plus a nominal amount for generating the required V_{acc} (see Table 1).

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
Avg. Current (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	4.7×10^4	1.3×10^7	5×10^6	2.6×10^7	1.3×10^7	1.3×10^7
Power/Cav. (kW)	100	13	13.3	9.85*	14.9	19.5

** Includes CSR losses*

LLRF SYSTEMS

For the photoinjector and low energy Linac sections, the phase stability of the RF fields will need to be kept to 0.01° (~ 21 fs at 1.3 GHz) and to 10^{-4} in amplitude due the electron bunch acceleration being off-crest. Errors in phase and amplitude at this point will produce energy modulation and hence timing jitter of the pulse to pulse structure of the beam. This level of phase stability control has been shown at TJNAF using the Cornell LLRF control system [6]. In the main Linacs the beam will be accelerated almost on-crest, reducing the required phase stability to 0.1° (or ~ 0.1 ps at 1.3 GHz) and 10^{-3} for amplitude. The 4GLS feedback system will comprise a phase comparator and regulation loop to maintain a phase error of < 0.01° with reference to the desired working point for each RF station. The amplitude loop will consist of a proportional integral controller taking inputs from the cavity probe and amplitude set point for that acceleration structure and controlling the drive level to the RF amplifier using vector modulation techniques.

For 4GLS the dynamic range of the controller will need to be higher and less susceptible to noise and environmental effects. The current state of the art, Field Programmable Gate Array (FPGA) based digital feedback systems can stabilise the RF to enable 10 mA to circulate in an ERL. The same LLRF system will enable mechanical tuning of the SRF module for slow field changes to allow both setting and control of the required accelerating field.

IOT RF POWER SYSTEMS

Klystrons and triodes have been the traditional power source for particle accelerators because they produce high power RF and offer high gain (50 dB) with efficiencies > 50%. IOTs however have recently become available at L-band frequencies with efficiencies up to 65 % with gains in excess of 20 dB. The use of IOTs is being demonstrated on the ERLP at Daresbury [7] and Table 2 lists the operating parameters and outputs of suitable RF power sources for 4GLS.

Table 2: Suitable RF Power Sources for 4GLS

Type / Device	**IOT**	**IOT**	**IOT**	**Klystron**
Manufacturer	CPI	e2v	Thales	e2v
Frequency (GHz)	1.3	1.3	1.3	1.3
Beam Voltage (kV)	34	25	28.5	45
Beam Current (A)	1.58	1.13	0.88	5.5
Power CW (kW)	29.5	14	16	120
Gain (dB)	22.5	20.9	20	45
Efficiency (%)	54.9	63	59	51

REFERENCES

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

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