KEY CRYOGENICS CHALLENGES IN THE DEVELOPMENT OF THE 4GLS

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Abstract

The fourth generation light source (4GLS) is a uniquely flexible source of ultra-high brightness continuous and pulsed radiation covering the IR to XUV range of the spectrum. It is the first light source in the world that is planned from the outset to be a multi-user, multi-source facility combining ERL (energy recovery LINAC) and FEL (free electron laser) technology. 4GLS will require seven different sets of superconducting LINACs. Each of the LINAC modules consists of 4 to 8, 1.3 GHz superconducting RF cavities of the TESLA design operating at 1.8 K. The overall cooling power necessary to cool the cavities is estimated to be around 3.5 KW demanding the super fluid liquid helium flow rates around 183g/s. Even though the technology of the superconducting RF cavities is well understood, the design and reliable operation of the cryogenic system/Cryo modules is an extremely complex task.

In this paper we highlight the key cryogenic challenges of the 4GLS project and our approach in identifying solutions to meet them.

INTRODUCTION

Fourth generation light source (4GLS) [1] is the leading energy recovery proposal in Europe and the most comprehensive in terms of utilisation of combined sources. It is complementary to DESY- XFEL, to table-top lasers and to third generation sources available to the UK research community *i.e.* ESRF, SRS (now) and DLS (near future). 4GLS will be a multi-user facility utilising the strengths of undulator sources, capturing the potential of FELs and harnessing the advantages of combining both. The use of Superconducting RF (SRF) cavities based on the technology developed by TESLA collaboration at DESY [2] has been identified as the most appropriate solution to achieve desired acceleration of the electron bunches. However major modifications will be required to the SRF structures to sustain high beam current at 100 mA in the CW mode (or high repetition rate), particularly employing the Energy Recovery LINAC (ERL) [3] technique.

The proposed scheme (Figure 1) for the 4GLS utilises three electron sources:

1) a high peak current for XUV-FEL,
2) a high average current for VUV-FEL and number of spontaneous synchrotron sources and
3) a modest current for IR-FEL.

To reduce the development time and costs, and taking advantage of the similarities among the TESLA, XFEL at DESY [2], BESSY FEL [4] at BESY, we are planning to use the proven TESLA cavity and cryomodule technology. The three electron beams will be simultaneously accelerated through a combination of SRF LINACs operating at a temperature ≤ 2 K and at 1.3 GHz. This requirement however demands major modifications to the existing SRF structures to sustain high beam current at 100 mA in the CW (or high repetition rate) mode of operation.

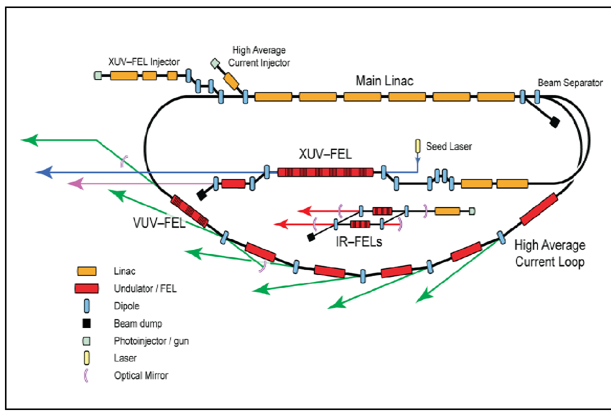

Figure1: Layout of the 4GLS facility

The technology of the SRF cavities and the helium liquefiers operating at temperatures below 2K is still evolving. In order to create the extreme operating conditions necessary for the proposed light source there are many issues (*challenges*) which must be resolved before the final design is defined. In this paper we highlight some of the key challenges, particularly from the cryogenics point of view, and our approach in identifying the solutions to meet them.

SRF CRYOMODULES

Assuming a conservative maximum acceleration of E_{acc} = 20 MV/m, the cavity cryomodule configuration is chosen to provide enough operational flexibility. Table 1 shows the estimated heat load distribution anticipated for all the LINACs.

High Dynamic Losses

Due to the CW operation the average dynamic load experienced by an 8 cell cavity is estimated to be around 19.5 W which is about 5 times higher than a typical TESLA cavity.

Table 1: Heat Load Estimates

LINAC	Modules	Cavities	Total Load at 1.8K	HOM Load at 80K
			W	W
LINAC 1 *(10 MeV) High Avg Current Injector*	2	10	214.5	1694.0
LINAC 2 *(95 MeV) XUV-FEL Injector*	1	8	165.6	1355.2
LINAC *3 (95 MeV XUV-FEL Injector)*	1	8	165.6	1355.2
LINAC 4 *(XUV FEL 3rd Harm.)*	1	4	*	*
LINAC 5 *(590 MeV Main Linac)*	6	48	993.6	8131.2
LINAC 6 *(200MeV XUV-FEL)*	2	16	331.2	2710.4
LINAC 7 *(60 MeV IR-FEL)*	1	8	165.6	1355.2
Total >>	14	90	2036.1	15246.0
Distribution Losses			500.0	W
Total heat Losses @ 1.8K			2536.1	W
Total refrigeration @1.8K With safety factor of 1.5			3499.8	W

* *Assumed to be negligibly small.*

Overall helium flow rate for the complete system is estimated to be of the order of 183 g/S. The helium liquefier required will be comparable with the largest cryogenic facilities (operating at 1.8 K) in the world (See Figure 2). Also whether a single Joule Thomson (JT) valve, as implemented in the TESLA cooling scheme, can operate reliably at such a high flow rate is questionable. The estimated heat loads for the 4GLS are comparable with the BESSY- FEL proposed by BESSY. BESSY has suggested [5] to use one JT valve for each cryomodule and to increase the diameter of the chimney connecting the helium reservoir housing the cavities and the two phase line to achieve the desired flow control.

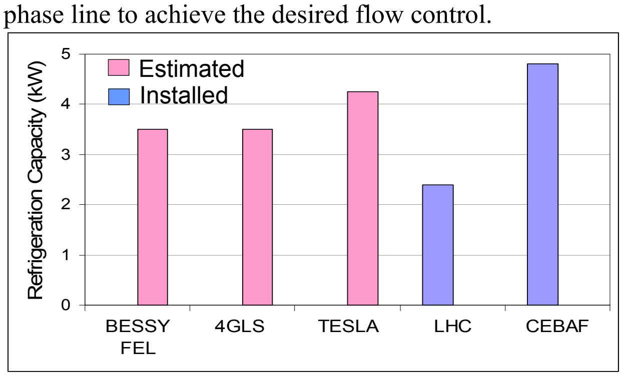

Figure 2: Comparison of 1.8K helium liquefiers

Microphonics

High flow rates coupled with the CW operation tend to create microphonics which affect the Q value and the stability of cavities and consequently the stability of the beam. One solution is to use the pressurised helium gas for the shield cooling at 80K and avoid microphonic generated due to boiling liquid nitrogen. The two phase helium flow through the JT valve could also be a source of microphonics. A study of mechanical design of the cryomodule and its effect on microphonics is needed to identify and understand the related issues.

Higher Order Modes

CW operation and extremely small bunch lengths create higher order modes (HOM) in the cavities. These HOM must be extracted out of the cavities to avoid their interaction with the beam. The TESLA cavity design will have to be modified to accommodate the ferrite absorbers [6] to capture the extracted HOM power which is estimated to be 15kW at 80 K. As in the case of cooling of the radiation shields, the use of high pressure cold helium gas, instead of liquid nitrogen is recommended [7].

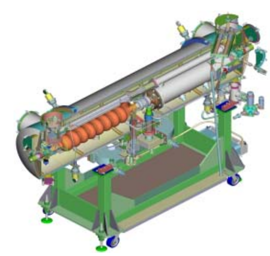

Figure 3: SRF Cryomodule for ERLP

ERLP and Cryomodule Collaboration

In order to understand some of the above issues, the ERLP [3] being commissioned at Daresbury laboratory, UK, will be used as a test bed to investigate the new technology and resolve many issues related to the 4GLS. Figure 3 shows a SRF cavity developed for ERLP. Also international cryomodule collaboration has been set up [8] specifically to look into the issues of the SRF cavities operating in CW mode.

LIQUID HELIUM PLANT

Initial estimates indicate that the liquid helium circulation rate to maintain all 14 cryomodules for 4GLS with 90 cavities at 1.8K will be close to 183.7 g/S. See table 2. Over the last forty years, accelerator physics has been instrumental in pushing the helium refrigerator technology in the direction of higher reliability, better efficiency and lower cost. Experience with the large scale cryogenic facilities operating at CERN, DESY and CEBAF (figure 3) indicate that such a high refrigeration requirement can be met by a single large liquefier integrated with a series of cold compressors. The liquefier of the type used at CERN [9] or the one chosen for the TESLA [10] will be suitable for the 4GLS.

Table 2: Parameters of the Cryogenic system

Parameter	Value	
Operating temperature	1.8	K
Number of modules	14	
Number of LINACs	7	
Total dynamic heat load	2.03	kW@1.8K
Heat load at 80K shields	3.75	kW
Heat load on HOM	15.2	kW
Heat Load on Radiation screen @ 4-10K	642	W
Operating Mode for RF	CW	
Safety factor	1.5	
Mass Flow rate for Liq He	183.7	g/S at 1.8 K
Size of the helium liquefier	5250	l/hr @ 1.8 K

Cold Compressors

Cold compressors [9, 11] are required to control the operating pressure in the helium vessel(s) that contain the SRF cavities. The required pressure is nominally 15 mbar for 1.8K operation. Currently available compressor designs have a limited dynamic range (less than 10 %), which means they can only operate within a limited flow range. However depending upon the characteristics of the SRF cavities, actual flow rates could vary by 100%. One solution to this problem is to design the cold compressors for the highest flow rate and create a by-pass to drive the excess flow away from the cavities. This fact however demands the use of a liquefier with a large margin over the required capacity which obviously impacts on the system costs. It is therefore desirable to develop new techniques and designs of the cold compressors to increase the dynamic range of operation.

Process Optimisation

Accelerating gradients as high as 30 MV/m have been obtained from the SRF cavities in laboratories but industry can reliably produce the cavities with gradients of only around 15 MV/m to 20 MV/m. As a result, in practice, the associated variation in the Q values and subsequently the heat load can vary by a factor 2 or 3. This situation forces us to keep a high safety margin (1.5 in our case) on the cryogenic consumption. This obviously increases the cost of the cryogenic system and operation significantly.

The entire cryogenic load is distributed among 7 different linacs. Four distinct cooling loops at 1.8K, 5K, 80K *(Radiation shields)* and 80K *(HOM)* will be required in the cryogenic distribution layout. We propose to use a single liquefier to serve all the four cooling loops. Even if the radiation shield and the HOM absorbers both have to be cooled to the same temperature (~ 80K), it is necessary to have independent controls for both, for two reasons: 1) The heat load on the HOM absorbers will be concentrated and 2) the thermal coupling between the HOM absorbers and the cavity is much stronger and can affect the performance of the cavity significantly. Thus 4GLS will require an additional cooling loop as compared to the other large cryogenic systems mentioned earlier.

The size of the Joule Thomson valve and its location which separates the high and low pressure region in the cryomodule highly affects the stability of the cavities. It is necessary to keep the pressure (and in turn the temperature) stability of the liquid to within 0.1 mbar to ensure that microphonics are kept within acceptable limits. More investigations in this area are being undertaken using the ERLP and the cryomodule collaboration.

SUMMARY

SRF technology has now been accepted among the scientific community [12] as the preferred technology to create high accelerating gradients for electrons, economically and reliably. However the high dynamic loads, microphonics and HOM impose heavy constraints on the overall operation of the cryomodules. The requirement of CW mode of operation coupled with the ERL technology in the case of 4GLS has identified several issues in incorporating the SRF technology. Further investigations are being undertaken to resolve these issues using the ERLP and the Cryomodule Collaboration.

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