# 4GLS AND THE PROTOTYPE ENERGY RECOVERY LINAC PROJECT AT DARESBURY

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*Abstract*

The 4GLS project is a novel next generation solution for a UK national light source proposed to be sited at Daresbury. It is based on an energy recovery linac (ERL) operating at high average beam currents up to 100mA and with compression schemes producing pulses in the 10-100 fs range. This would provide a unique spontaneous emission source with high average brightness output both from undulators and bending magnets. In addition to this operating regime a high peak current mode would also be possible at lower duty cycle, enabling a high gain FEL amplifier to generate XUV radiation. Longer wavelength FELs are also planned. This challenging accelerator technology, new to Europe, necessitates a significant R&D programme and as a major part of this a low energy prototype, the ERLP, is being constructed at Daresbury. The paper summarises the ERLP design specification, describes the component solutions adopted and explains the 4GLS project status and plans.

## THE 4GLS PROJECT

The 4GLS project is a proposed national light source for the UK, optimised for the low energy user community and exploiting 4$^{th}$ generation concepts in order to extend the capabilities of existing 3$^{rd}$ generation designs. It abandons the traditional electron storage ring solution and replaces this with an electron linac, taking advantage of the combination of transverse and longitudinal brightness that can thereby be achieved. Use of such a linac also permits incorporation of advanced free electron laser (FEL) devices to supplement the spontaneous emission sources. This multi-source concept originated at Daresbury in 2001 and has been developed significantly since then [1, 2, 3].

A key feature of such a light source is the need to provide transverse brightness competitive with that at the 3$^{rd}$ generation facilities: a combination of low emittance and high beam current that implies a high brightness injector and an average beam current capability of at least 100mA. This latter requirement necessitates adoption of an Energy Recovery Linac (ERL) solution, as successfully demonstrated at both the Jefferson [4] and JAERI [5] Laboratories. A novel feature of the Daresbury proposal is that the electron return path, needed to return the beam for deceleration in a second pass through the linac, is also utilised to provide a range of photon sources, including various undulators and FELs.

An ERL is no longer restricted by the dynamic equilibrium properties of a storage ring. Its high energy beam properties are determined by those of its injector, together with the ability then to preserve or manipulate them during the subsequent processes. A noteworthy result is the consequent capability to generate sub-picosecond bunches and this is a key feature of the science case for such a novel facility, allowing fast dynamic measurements from nanoscale samples. With its synchronised undulator and FEL sources offering the opportunity for advanced pump-probe experimental exploitation the 4GLS project provides the possibility of a breakthrough in the development of advanced light sources. UK funding agencies are therefore presently supporting the development of 4GLS design concepts into a realistic and fully costed project proposal.

## PROJECT CHALLENGES

The novelty of the 4GLS concept poses many R&D challenges of beam dynamics and accelerator technology that will need to be addressed for project success. These include the following:

- flexible electron beam optics solutions
- optimised bunch compression
- overall layout selection following start-to-end simulations
- CW linac operation up to 100 mA
- efficient cryogenics design
- CW injector operation up to 100 mA
- variable pulse train operating modes
- sub-ps synchronisation of electron and photon sources
- high brightness photogun for FEL mode
- seeded XUV FEL solutions

## PROTOTYPE DEMONSTRATOR

As a necessary precursor of a 4GLS project approval decision a formal R&D phase was initiated during 2003, with the aim to resolve major design uncertainties and to make progress towards a Technical Design Report. This phase will last 3-4 years and is centred on construction at Daresbury of an Energy Recovery Linac Prototype (ERLP) at low energy that will provide experience of all of the relevant technologies and also an opportunity to optimise beam dynamics design aspects and component specifications.

The ERLP will initially employ a high average current photogun together with a buncher cavity. The injector will be completed by a superconducting booster cavity to raise the beam energy to about 8 MeV for injection into the main linac structure. The main linac, also a superconducting RF structure, will accelerate the beam to about 35 MeV after which it will be transported through a

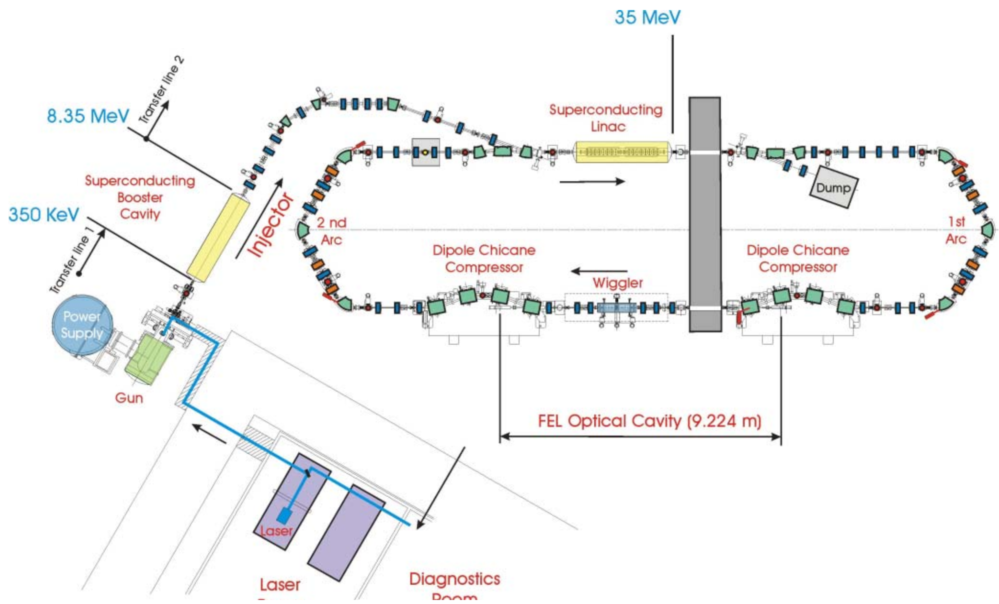


Figure 1: Layout of Daresbury Energy Recover Linac Prototype.

180 degree arc and into a beam compression system. This electron beam will then drive an infra-red FEL oscillator whose principal purpose will be to disrupt the beam by introduction of a large energy spread that must be successfully transported around a second 180 degree bend for reinjection into the main linac at an appropriate decelerating phase. After deceleration the beam is then dumped. The overall layout of the ERLP is illustrated in Fig. 1 and shows all of the principal features.

The ERLP contains many of the challenging features of the full 4GLS project, albeit at much lower energy since that eventual project is anticipated to operate at up to about 1 GeV. Energy recovery will be demonstrated for the first time on a European accelerator. High average current photoinjector technology will be developed, as will high duty cycle superconducting RF structures. Beam optics solutions have been reached that have improved understanding of optimisation issues, including low energy space charge effects [6]. When operational the ERLP will also enable a series of experimental tests such as efficient energy recovery in the presence of FEL disruption; controlled bunch compression and associated CSR; high duty cycle operation of RF structures; and pulse synchronisation.

Not all of the key technical challenges of 4GLS can have solutions directly demonstrated on the ERLP. The project team has been establishing a series of international collaborations with other groups that provides simultaneous access to parallel experimental programmes, including participation in a recent EU Framework 6 Design Studies bid.

## PROTOTYPE DESIGN OVERVIEW

In order to operate an ERL by 2006, which is necessary to meet the proposed timescales for the full 4GLS project, the ERLP is being constructed initially from components that can be produced and installed as rapidly as possible.

For this reason the first photogun will be copied from the 500 kV Jefferson DC gun employing a GaAs cathode [7]. In parallel a gun test facility and associated laser laboratory will be included to study future improved designs and for development of the high brightness RF gun that will be essential for eventual 4GLS FEL operation (eg CsTe or other cathode type). Consideration will also be given to a superconducting gun for CW mode operation. The present plan is to commission the first gun early in 2005 and both its power supply and 5W (80 MHz at 60 nJ) mode locked laser driver are already under test.

With a DC gun it is necessary to add a single cell buncher cavity immediately downstream to decrease the long (20-30 ps) output pulse from the GaAs cathode. Comparison [8] of some alternative designs, including beam modelling with ASTRA, has led to selection of one based on the proven ELBE cavity geometry, which is both compact and easy to manufacture.

For the same reason of minimising delay an existing design of high duty cycle SRF linac structure has also been adopted. To simplify and economise procurement the low energy booster cavity in the injector line is an exact copy of the main linac but operates at a very modest gradient of only 4 MeV/m. These two linac modules are discussed further in the next section.

Modelling of the beam from cathode through to booster exit [9] confirms a satisfactory solution even though the booster structure is not fully optimised for the low energies at its upstream end. The injection line that then takes the beam through a chicane into the recirculating linac has been optimised [10] for the 8 MeV beam and includes an achromatic bend and careful control over the $R_{56}$ term. This line is designed with 1 % energy acceptance.

The two 180 degree arcs are a major design feature [11] of the ERLP and dominate the overall layout. A compact solution is required since the available space within the building is limited and there are also additional geometrical restrictions. Comparison of a standard Bates bend [12] with a TBA structure has resulted in selection of the TBA: it is a little wider and shorter, the greater $R_{56}$ tunability of the Bates design is not needed and its component manufacture is simpler. Overall $R_{56}$ in the ERLP can be controlled by varying dispersion in the central TBA dipole to offset the contribution arising from the two magnetic chicanes upstream and downstream of the FEL interaction area; additional phase control will be provided mechanically in the second arc. Note that these chicanes also provide spaces for the two mirrors of the FEL cavity. The complete ERL loop has been modelled and flexible, optimised solutions, including sextupole control of $T_{566}$ non-linear characteristics, obtained. The bunch compression system has been shown to achieve sub-ps bunches at the FEL interaction region. The downstream arc is also able to transport a 5% energy bandwidth disrupted beam back to the linac entrance.

## SUPERCONDUCTING LINACS

Superconducting RF linac structures have been developed in a number of centres, with recent progress on L Band (1300-1500 MHz) operation. A number of options were considered for the ERLP and the decision to adopt a design based on the 1300 MHz TESLA modules was a result of their early delivery availability. Because TESLA runs at low duty cycle (0.1%) the original cryostat design was not acceptable for CW (or even duty cycles above 1%) so a modified design from the ELBE team at Forschungszentrum Rossendorf (FZR) was selected. This is a reduced length version with a cryomodule containing two 9-cell cavities capable of delivering about 30 MeV energy gain from its 2m of active structures. An order has been placed with ACCEL Instruments GmbH for two of these modules, to be delivered in the second half of 2005; the booster module will be operated at a modest 4 MeV/m and the main linac at up to 15 MeV/m, so the maximum ERLP energy will be about 35 MeV.

The linac structures must operate at 1.8K and this means a very large cryogenic system. The static loss is up to 7 W per module and the dynamic loss over 50 W at 15 MV/m. Taking the two modules plus transfer lines this leads to total operational losses of approximately 150W (this may be pessimistic but is a commercial guarantee) and a liquid helium requirement of some 250 L/hour. As an R&D prototype experiment a decision has been taken to purchase a 4K liquefier (Linde TCF50) and employ supplementary pumping to lower this temperature. This leads to an operational duty cycle that will permit running for 10 hours daily with the liquefier working nonstop over the 24 hours.

## PROGRESS AND MILESTONES

The final layout in Fig. 1 is now under construction in an existing experimental area that has been cleared and most shielding is already in place. All major contracts have been placed and detailed final design is under way. Many of the transport magnets have been made available under a collaboration with Jefferson Laboratory, which also loaned its first FEL undulator magnet for inclusion in ERLP. Gun commissioning will commence early in 2005 and the ERLP transport lines should be in place soon afterwards. Finally the arrival of the booster module and cryogenic system in mid-2005 will allow injector commissioning, followed by 35 MeV main linac beams early in 2006. It is hoped to demonstrate Energy Recovery by the end of the project third year (April 2006) and move on quickly to FEL operation.

## ACKNOWLEDGEMENTS

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