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A REVIEW OF ERL PROTOTYPE EXPERIENCE AND LIGHT SOURCE DESIGN CHALLENGES

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INTRODUCTION

Energy recovery as a concept dates back to as early as 1965 [1]. As with many innovative accelerator ideas the practical realisation of the concept took many decades to materialise. The first appearance was through demonstration experiments conducted initially at the SCA FEL machine at Stanford [2] and MIT-Bates [3]. However the real impact on accelerator developments was the operation at Jefferson Lab of DEMO-FEL [4]. This inspired various groups throughout the world to explore the potential of energy recovery for various applications, including pushing the boundaries of existing technology to deliver highly-advanced light sources encompassing both FELs and spontaneous sources.

The experience of developing and operating existing light sources is a fruitful source of knowledge that is invaluable to the designers of future ERL-based light sources. This experience can be measured against the design goals of future sources, for instance the 4GLS light source concept, in order to identify the major challenges to be addressed in the realisation of these sources. A number of prototype projects have already been initiated to address these challenges, with many centres working towards the dual goals of a high-average current injector and suitable CW superconducting RF linac design.

The principal advantages of ERL accelerators over linacs and storage rings are now well recognised and some of these points are summarised below:

Advantages over storage rings - ERLs are not restricted to the equilibrium longitudinal and transverse emittances of storage rings; the electron beam characteristics are determined by the injector; ERLs are able to produce shorter bunches with a flexible bunch pattern.

Advantages over linacs - improved efficiency; increased average currents and light source power; reduced dump activation.

OPERATIONAL LIGHT SOURCES

There are currently three operational ERL-based facilities driving FEL sources across the globe. These ERLs provide powerful oscillator FEL sources which operate in the IR and THz region.

The BINP Recuperator FEL (Russia)

This is the only one of the three operating ERL FEL sources to be based on normal conducting RF. The accelerator is injected from a thermionic gun with an RMS normalised emittance of ~20 mm mrad [5]. The beam is accelerated from 2 MeV to 12 MeV using the 180 MHz linac. A record 20 mA of circulating current has been achieved and the FEL source has operated at 400 W, a record for the achieved wavelength and line width. The source is characterised by its unconventional vertical orbit plane.

The JAERI/JAEA ERL FEL (Japan)

This ERL source operates with a 500 MHz superconducting linac injected from a thermionic gun [6]. As with the previous operating source the performance of this facility is undergoing development and improvement [7,8]. The average current obtained in the 1 ms macro pulses, which occur at 20 Hz, has recently reached 10 mA, due to improvements in the injector. Improvements to the RF system have also been carried out, towards the goal of achieving CW operation. Currently the duty cycle is limited by the capacity of the installed cryogenic system.

The JLAB ERL-FEL (USA)

The programme of ERL-based IR-FEL projects at JLAB started with the JLAB DEMO-FEL [4]. This pioneering source featured the two main components now characteristic of most new ERL light source concepts and designs; an advanced photoinjector and a CW superconducting RF linac.

The latest upgraded machine is currently driving a record 10 kW class IR-FEL laser [9]. The accelerator is now routinely and reproducibly providing both powerful IR-FEL and THz output for user experiments. There are still challenges to operating and optimising such high power FEL sources; for instance the FEL power has been observed to roll off from 1.7 kW/mA at 2 mA to 1.1 kW/mA when operated at high currents of around 5 mA. The cause of this roll off is not fully understood and is currently under investigation [10]. The operation of the JLAB FELs has provided a wealth of experience and knowledge which form an important basis for the realisation of future practical designs. Perhaps as important has been a series of systematic physics experiments which have taken place during the commissioning and development of these facilities. These experiments have provided vital information on topics at the heart of ERL operation, such as beam break-up instability (BBU) [11], beam loss and linac control [12].

As well as these studies on the ERL-driven FEL machines there has been an important series of experiments on the high energy CEBAF accelerator. This was modified specifically to allow operation in energy recovery mode for accelerator studies. An example of an experiment run in this mode is the investigation of recovery at high final-to-injection energy ratio. Ratios as large as 50:1 were examined and the results and experience obtained are highly relevant to the design of feasible future high-energy ERL accelerators [13].

Operating Light Source Summary

The existing FEL sources based on energy recovery provide an extremely successful demonstration of the application of this type of accelerator, driving world-record sources in both the IR and THz regions. The importance of these machines lies not only in their demonstration of operation as successful sources of radiation but in that they have provided, and continue to provide, a vital test bed for future ERL facilities.

FUTURE ERL-BASED LIGHT SOURCES

Proposed Concepts and Designs

Inspired by the success of the existing sources, many new proposals have been developed over the last few years. Some are designed to drive high-power oscillator FELs such as those at KAERI [14] (similar to JAERI, IR-FEL), National High Magnetic Field Lab (Florida) [15], PKU-FEL [16] (using 9-cell TESLA cavities in a Rossendorf/Stanford module) and the 4GLS VUV-FEL [17,18].

Although there are some proposals for ERLs to drive high-gain FELs, including developments of both BESSY-II [19] and the European XFEL [20], the repetition rates of such machines are generally low, making the complexity of using recovery unattractive, e.g. the XUV-FEL within the 4GLS facility.

Finally there are a growing number of proposals to run ERLs as spontaneous sources of photons into the X-ray region, for example the innovative MARs proposal [21] (which uses a combined energy recovery and recycling concept), Cornell [22], KEK and JAEA [23] (all operating around 5-6 GeV) and 4GLS [18] and Arc-En-Ciel [24], similar proposals which combine a high-average current ERL loop driving spontaneous undulator sources with one or more FELs and/or other sources of radiation.

WHY ERL LIGHT SOURCES?

At lower energies, the high repetition rates of ERLs are powerful drivers for oscillator FEL sources as illustrated by the design output of some of the facilities listed above. The 4GLS spectral output shows the wide range of high quality photon output obtainable from an intermediate energy machine [18]. This is achieved using a high-average current, 600 MeV ERL loop, driving a suite of spontaneous undulator sources together with a high-power VUV oscillator FEL. The facility also includes a beam of high peak charge (1 nC) bunches, which shares the same main accelerating linac and provides an advanced XUV HHG-seeded FEL as well as an integrated IR-FEL driven by a separate linac which uses the same superconducting RF technology.

At the high-energy end of photon output, the attraction of ERL sources can be summarised by examining the three operating modes of the proposed Cornell X-ray facility [25]. The first is a high-flux mode run at 100 mA average current. Although this is broadly typical of the currents achieved in third-generation storage ring-based sources, the ERL-based facility can benefit from the combination of very long 25 m undulators with small gaps and short periods.

The second mode is the so-called ultra-fast mode. With bunch lengths unrestricted by equilibrium dynamics, in contrast to storage rings, it is realistic to assume that these sources could reach bunch lengths as small as 50-100 fs. This is far smaller than the typical 10 – 20 ps achievable in third-generation storage ring-based sources.

Finally there is the high-coherence mode. The transverse emittance in ERLs is set essentially by the injector properties. The use of such advanced photo-injectors will allow the radiation from such a source to reach the diffraction limit in both the vertical and horizontal planes at X-ray wavelengths. In modern storage rings the horizontal source size cannot reach these limits, and is typically of the order of 100 times greater. This is an unavoidable consequence of the emission of synchrotron radiation in an equilibrium system.

CHALLENGES OF ERL LIGHT SOURCE DESIGN: THE 4GLS CONCEPT

The realisation of such promising future output potential from these ERL-based light sources is not without its difficulties and challenges. Many of the major issues faced by future projects generally can be illustrated by presenting the design of the futuristic 4GLS facility, which has at its heart an ERL-driven accelerator.

Introduction to 4GLS

The 4GLS facility is a combination of three integrated accelerators. There is a 100 mA, ERL-driven, high-average current loop; high-peak charge 1.5 A, 1 kHz repetition rate bunches driving an XUV-FEL; and an integrated IR-FEL, operating at 13 MHz and based on the same superconducting linac technology.

The 4GLS ERL High-Average Current Loop

The high-average current loop is contains a beam of 77 pC bunches giving a 100 mA average current when operating at the maximum repetition rate of 1.3 GHz. The 100 mA beam is produced by an advanced photoinjector and quickly accelerated to 10 MeV in a superconducting RF booster accelerator. The beam is then merged into the shared 590 MeV superconducting RF linac. The chirped bunches that emerge from this linac are then compressed around a 150-degree FODO arc. These bunches then undergo further progressive compression as they traverse around the ID arc, passing through a series of undulators. Maximum compression is achieved at the VUV-FEL, where the 300 A peak current achieved is used to drive a powerful, low Q, oscillator FEL. The beam then re-enters the linac before being dumped at 10 MeV

Challenges of Beam Generation

The 100 mA average current is ten-times the record achieved at the upgraded JLAB IR-FEL facility and 4GLS requires that this high average current is delivered simultaneously with a small transverse normalised emittance of less that 2 mm mrad. The laser required to operate at 1.3 GHz repetition rate will demand state-of-the-art technology. Although a DC gun seems the most probable solution for the 4GLS project because of the maturity of its development, there are still significant challenges in achieving the high voltages required for low emittance, and developing a practical cathode system that will reliably deliver 100 mA. Many groups are active in developing DC guns toward a performance which would meet the requirements of 4GLS [26].

There is a promising alternative technology based on superconducting RF technology, which is being pursued in parallel [26]. One of the major R&D efforts on this type of gun has been in the area of cathode design: these injectors require a cathode system which is compatible with the superconducting environment within which it has to operate.

Challenges of Acceleration

Superconducting RF technology for electron linacs is maturing with a considerable amount of effort having been applied over recent years, for example towards accelerators suitable for a future linear collider. Most of this effort, however, has been focussed on the achievement of high gradients in pulsed systems. The requirement for the ERL main accelerator is for CW operation and demands the use of efficient (high Q), controllable cavities, with designs which minimise HOMs and extract their power efficiently. In 4GLS, the shared linac has the added complication of coping with three different energy beams, the ERL accelerating and decelerating beams and the high-charge XUV-FEL beam. The superconducting injector booster accelerator requirements are also demanding; the 100 mA low-emittance beam has to be quickly accelerated to ~10 MeV, preserving the emittance in the presence of space charge. The injector accelerator has to supply the high input power (~ 1 MW) in a stable manner which avoids disrupting the quality of the sensitive low-energy beam.

Challenges of Electron Beam Transport

The production and acceleration of these beams is only part of the challenge and these high quality beams also have to be transported to the source points without significant degradation of the transverse emittance. The longitudinal properties of the beam have to be manipulated to produce highly-compressed beams, capable of producing sub-picosecond sources and driving a powerful FEL.

At low energies, space charge presents a challenge as the beam is transported and merged into the ERL loop before the main acceleration. The beam transport also has to be designed to minimise the disruption by instabilities such as CSR through the arcs and wakefield effects in the linacs and the many tens of metres of small gap undulators.

The beam power in the 100 mA, 600 MeV 4GLS machine is 60 MW. Losses have to be minimised to manage radiation, to avoid damage to components and to allow efficient recovery.

As with many accelerators, the success of the facility will require good diagnostics and the development of tuning procedures which can use those diagnostics to achieve and maintain the demanding operating performance. Even after deceleration to 10 MeV the 4GLS beam has a power of around 1 MW. Handling such a low-energy high-power beam has its challenges both in the transport of the highly disrupted decelerated bunches and in the engineering design of a high-power, low-energy dump.

Challenges of Free Electron Lasers

The 4GLS facility includes three FELs covering wavelengths from the far IR to 100 eV (soft X-rays). The recovery loop drives a novel low-Q oscillator FEL operating in the VUV region. One of the limitations of the output of this device is the capability of the mirrors to withstand the extremely high peak powers. The XUV-FEL, which uses a high-charge 1 kHz beam accelerated in the shared linac, requires a peak current of around 1.5 kA. It is seeded by a state-of-the-art HHG laser system. The undulator tolerances to achieve the required performance are demanding.

Challenges of Combining Sources

The realisation of the science vision for 4GLS requires the combination of the various light sources at the user experiments. This presents challenges for both timing and synchronisation. The aim is to design the facility such that all the sources can be synchronised to better than 100 fs and particular combinations to around 10 fs. Sources of jitter such as the photoinjector laser, RF signals, RF acceleration, electron and photon transport will have to be tightly controlled. This produces demanding specifications on the equipment and the stability of the environment within the accelerator hall.

Outlook

The 4GLS concept and the challenges outlined here have been recently published in the 4GLS CDR [18]. The next stage of the project is to carry out the detailed design and prototype work towards achieving the delivery of this advanced facility in the early part of the next decade.

PROTOTYPES

To meet and address these challenges a number of laboratories are developing prototype facilities.

The Cornell Injector Prototype Project

To develop technology for delivering a 100 mA, 5 GeV ERL-based light source, Cornell University, in collaboration with JLAB, has instigated a prototyping programme [27]. The injector stage of this programme has been funded and is currently under construction, with the gun now in the early stages of commissioning. It consists of a 100 mA injector system driven by a DC photoinjector, and includes a normal-conducing, copper buncher cavity, an advanced, CW superconducting RF accelerator consisting of five 2-cell cavities [28], a merge section and a high-power dump [29]. The accelerator will be capable of accelerating 100 mA to 5 MeV, or lower currents up to 15 MeV. The status of the gun and the accelerator are described briefly below.

(1) Photoinjector Gun

Simulations of the injector have indicated that at high voltage this injector design can deliver 77 pC bunches with a transverse emittance of less than 0.1 mm mrad [30]; driven at a repetition rate of 1.3 GHz this will produce a 100 mA beam. The prototype gun components, including an advanced load-locked cathode preparation chamber, have been fully assembled and the gun is ready for first test with a low voltage power supply.The pump down and bake required to achieve the XHV vacuum conditions for reasonable cathode lifetime have started. A Yb fibre laser system which can provide 100 nJ per micro-pulse is being built and the full voltage, 750 kV, 100 mA DC supply will be available from the manufacturer in the autumn.

(2) Two-Cell SRF Booster Cavity

A two-cell superconducting 1.3 GHz cavity capable of accelerating 100 mA has been designed. This design features two symmetrical input couplers to cancel induced kicks to the low-energy beam, enlarged apertures for HOM extraction, and 80 K cooling in a ferrite HOM load. The first cavity has undergone successful vertical tests and it is intended that at least two full cavity assemblies will undergo horizontal tests next year.

The gun tests with beam are planned initially at low voltage and then with the high-voltage power supply. The five superconducting RF cavities will be constructed and tested over the next two years with the full cryomodule assembly installed ready for testing with beam early in 2008.

The KEK-JAEA Facility

Both KEK and JAEA propose separate X-ray sources based on ERLs. Together they are planning an ERL test facility at KEK, which would include lower energy ERL ring operating with 100 mA average current [23]. Like the Cornell proposal, key features of the facility are a DC photoinjector and superconducting RF accelerator. A 245 kV photoinjector gun development is already underway, including cathode tests to develop a suitable cathode material.

The BNL Test Facility

Prototyping relevant to light source development is not restricted to the laboratories involved in such projects. Relevant R&D is taking place for both ERL and other accelerator-based projects in many centres. An illustration of this is the ERL test facility being constructed at Brookhaven [31], as a prototype of the ERL technology to be used in the RHIC electron cooler, which is based on a 200 mA ERL.

In this project the photoinjector is based on an advanced superconducting RF gun design operating at 703.75 MHz. The main accelerating module is based on a 703.75 MHz five-cell cavity; the HOM power is extracted at room temperature.

THE DARESBURY ERLP PROJECT

This paper finishes by reviewing the status of the Energy Recovery Linac Prototype (ERLP) at Daresbury. This project contains all the components of an advanced ERL accelerator: a photoinjector gun system, two superconducting RF accelerating modules, an arc design including sextupole correction and a compression system delivering sub-picosecond bunches to an FEL wiggler. The injector produces relatively long 100 μs trains of 80 pC bunches at 81.25 MHz, chosen so that the bunch charge matches well that demanded by 4GLS machine to produce 100 mA at 1.3 GHz.

The laser system has been commissioned. The gun is a copy of the JLAB one but uses a single, bulk-resistive ceramic. Delivery of this large ceramic from the manufacturer was delayed due to difficulties in brazing the end flanges. This was overcome by adopting a Cornell design where the previous external kovar ring braze was replaced with a copper ring brazed on the inside of the vessel. The gun is now fully assembled, as is the test diagnostic line, and with vacuum bake and pump down currently underway first electrons are expected in August 2006.

The accelerating modules consist of two TESLA 9-cell cavities integrated into a Stanford/Rossendorf cryo-module. These systems have been manufactured by Accel, the booster module was delivered in April and the linac module is due for delivery in early July.

All the magnets for the beam transport system and the ERL ring have been mounted on a modular girder system and it is expected that the whole accelerator will be assembled by October this year. Commissioning of the 4 K cryogenic system has already taken place and the full 2 K system will be commissioned in the autumn along with the RF for the linac and the booster modules.

Demonstration of energy recovery in the prototype is planned for spring next year. The exploitation of this prototype for both accelerator and photon science is being planned. A Compton back-scattering source will be installed to produce short-pulsed X-ray photons. The TESLA cavities used in the ERLP are not optimised for CW operation and as part of a wide international collaboration there are plans to install two Cornell-designed cavities in a Stanford cyromodule and test these cavities with beam within the ERLP.

SUMMARY AND OUTLOOK

The three operational light sources have provided a wealth of operational experience of ERL-based facilities. They have provided, and will continue to provide, a vital test bed for the study of ERL issues relevant to the design of future sources. There is active prototyping activity in many centres addressing the particular issues related to high-average current photoinjector and CW acceleration. The major aims of producing and accelerating 100 mA beams should be achieved in the near future at these facilities. Advanced light sources based on 100 mA average current beam are now a realistic proposition for the early part of the next decade.

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