EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

CERN-ACC-2013-0181

A PROPOSAL FOR AN ERL TEST FACILITY AT CERN

R. Calaga, E. Jensen, CERN, Geneva, Switzerland

Abstract

An energy recovery linac at 300-400 MeV is proposed as a test facility using a two-pass double cryomodule concept. This facility will be designed to serve as a validation and a test bench for the electron linac with energy recovery foreseen for the LHeC. Furthermore, the test facility can be used as the injector to the main linac in future. Some aspects of the ERL test facility and preliminary choices of the RF system are outlined.

Presented at the International Particle Accelerator Conference (IPAC'13) –

May 12-17, 2012, Shanghai, China

Geneva, Switzerland, May 2013

A PROPOSAL FOR AN ERL TEST FACILITY AT CERN

R. Calaga, E. Jensen, CERN, Geneva, Switzerland

Abstract

An energy recovery linac at 300-400 MeV is proposed as a test facility using a two-pass double cryomodule concept. This facility will be designed to serve as a validation and a test bench for the electron linac with energy recovery foreseen for the LHeC. Furthermore, the test facility can be used as the injector to the main linac in future. Some aspects of the ERL test facility and preliminary choices of the RF system are outlined.

INTRODUCTION

A 60 GeV superconducting CW energy recovery linac (ERL) is presently considered as the baseline for a future electron-hadron collider, the LHeC [1]. It should be noted that only 96% of the energy is recovered in the LHeC due to losses from synchrotron radiation. A proof of principle ERL test facility is proposed as a vital R&D step to validate the technology for the ERL mode of operation with a primary goal of improving the efficiency of the entire RF system. Relevant beam parameters for the LHC, LHeC and the proposed ERL test facility are listed in Table 1.

Table 1: Some relevant parameters for the protons in the LHC and the electrons in the LHeC compared to the proposed ERL test facility.

Parameter	LHC	LHeC	ERL-TF
Species	Protons	Electrons	
Inj energy [MeV]	4.5×10^5	400	5
Max energy [GeV]	7.0×10^6	60	0.3-0.4
Beam current [mA]	500	40	40-100
Charge/Bunch [p/e]	1.7×10^{11}	2.0×10^9	
N. Emitt [μm]	2.5	50	50
Bunch length [mm]	75.5	0.3	0.3-2.0
Duty Factor	CW	CW	CW
Energy recovery eff	-	96%	>99.95 %

The primary constraint on the RF frequency comes from the LHC bunch repetition frequency of 40.079 MHz or any harmonic multiple (where $h > n_{pass}$) of it. A high enough harmonic will allow for a flexible system. Furthermore, to preserve the symmetry in the ERL, one can suppress all harmonics that are not a multiple of $n_{pass}.f_0$, where $n_{pass} = 3$ corresponding to 120.24 MHz. This allows for a equal spacing of the 3 bunches in 25 ns. However, this criteria of equal spacing is not mandatory. Initial choices of 721.42 MHz ($h = 18$) and 1.322 GHz ($h = 33$) were considered due to the proximity of the frequencies to current state of the art SRF developments elsewhere in the world [2]. A final choice of $h = 20$ (801.58 MHz) is now presently the baseline due to the relevant advantages described in the following sections and synergy with present RF system developments at CERN [2]. Fig. 1 shows the ERL scheme with a slightly asymmetric bunch patterns for the accelerating bunches with 3 and 4 passes.

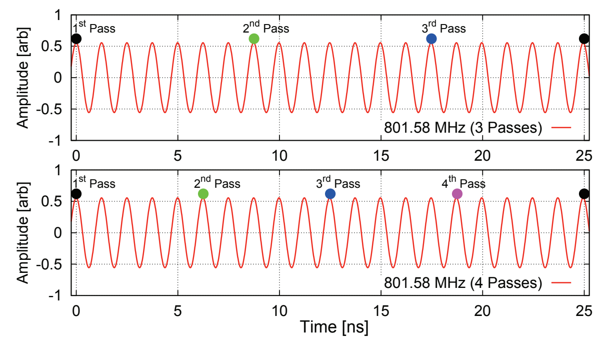

Figure 1: Top: Asymmetric bunch patterns with $h = 20$ with subsequent bunches spaced by 25 ns. The colored dots red represent the location for subsequent passes, 3 passes (top) and 4 passes (bottom) with a maximum of 20 passes.

FREQUENCY CHOICE & RF SYSTEM

The ability to stably accelerate and decelerate high current beams in CW mode with the atmost efficiency, both RF and cryogenic, is paramount. A frequency range of approximately 600-800 MHz is a reasonable choice to fulfill the sometimes contrary constraints of high accelerating gradients and high current beams. In addition, the latest developments in the SRF technology and RF power systems are a key driving factor.

Cavity Aspects

The field flatness and therefore the linac efficiency can be conveniently parameterized into a field sensitivity factor a which is proportional to the $N_c^2 k_c$. N_c is the number of cells and k_c is the cell-to-cell coupling. A lower frequency (for e.g. 600-800 MHz) allows a natural reduction of a (hence more robust) due to fewer cells and increased cell-to-cell coupling as a result of the larger apertures. This principle also works for higher order modes (HOMs), therefore leading to fewer trapped modes.

For CW operation, to truly benefit from an ERL, the dynamic cavity losses are highly important. As the losses scale quadratically with the voltage and inversely with the cavity quality factor (Q_0), high-Q at medium gradients is optimum. Taking advantage of the exponential scaling of the BCS resistance with temperature and the quadratic scaling with frequency, a reasonably lower frequency is an attractive option assuming good control of the residual resistance. The aim is to achieve a total surface resistance of $\leq$3 nΩ (effective $Q_0 = 10^{11}$) which is feasible but challenging at frequencies of 600-800 MHz and 2 K operation. This will amount to a dramatic reduction (approximately ×4) in dynamic losses compared to the present state-of-the-art. An ERL test facility will therefore enable the R&D to validate the technology choice, operating temperature and cryomodule design to maximize the overall efficiency.

High Q_L Operation

Assuming zero beam loading, the minimum RF power required to maintain the cavity voltage is proportional to the peak detuning. Fig. 2 shows the generator power as a function of Q_L for different peak detuning at 801.58 MHz. A $Q_e = 1.5 \times 10^7$ and a cavity voltage of 18 MV requires RF power of only 30 kW. Therefore, the cavity detuning cannot exceed 50 Hz for stable operation. The lower frequency and the fewer number of cells inherently provide better mechanical stability. The design choices for the cavity and cryomodule assembly should minimize the sensitivity to external forces both mechanical and electromagnetic. Active feedback devices such as piezo tuners may become necessary. The use of single amplifier powering a single cavity for precision amplitude and phase control is an appropriate choice. The available installed power is generally always larger to accommodate for transients during beam injection, phasing errors and RF failures. Therefore, the maximum achievable stability and high Q_L operation at moderate gradients is an important goal for the test facility.

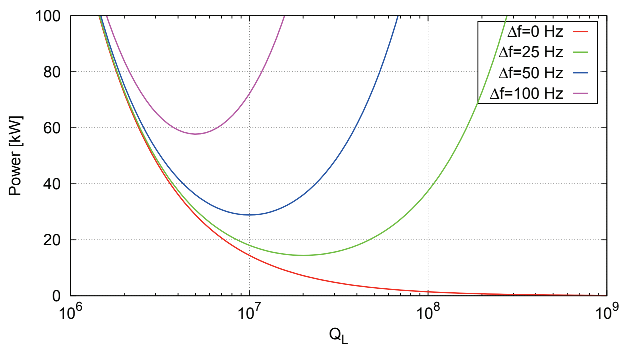

Figure 2: Generator power as a function of Q_L for different peak cavity detuning assuming zero beam loading.

RF Power

For frequencies at 800 MHz or below and RF power less than 80kW, Inductive Output Tubes (IOTs) and solid state amplifiers (SSA) become quite attractive (for example see Ref. [5]). The efficiencies of IOTs and SS devices can be 70% or higher compared to klystrons with approximately 45% efficiency. The high efficiency, availability in the commercial market and the compact nature make them ideally suited and economical for ERL applications. SSA devices have added advantages due to the low maintenance, tuning, and low voltage power supplies to increase the efficiency and reduce the overall costs. Due to the dramatic improvement of SSA in the recent years, amplifiers up to 60 kW were demonstrated recently [6] and could become the choice for the future.

Higher harmonic system

Synchrotron radiation (SR) losses in the 60 GeV LHeC ERL is significant (see Table 2). This can be compensated by simply pre-injecting power into the main RF system. A conceptually more efficient solution would provide for an additional RF system at e.g. twice the main RF, in which both the accelerated and the decelerated beam could be re-accelerated to compensate for the SR energy loss. For the frequency a dedicated SR compensation RF system to remain reasonable, a maximum frequency in the range of 800 MHz for the main RF system is chosen.

Table 2: RF power requirements due the synchrotron radiation losses in the final LHeC ERL. The efficiency of the power source is not included.

Parameter	Arc 2-3	Arc 4	Arc 5	Arc 6
E [GeV]	20-30	40	50	60
SR Losses [GeV]	0.084	0.23	0.53	0.57
RF power [MW]	0.6	1.7	4.0	4.2

Higher Order Modes

The beam power deposited into a longitudinal HOM with resonant excitation is proportional to square of the beam current and linearly with the impedance of the mode. For example, a HOM with a $Z_{||} = 1-10$ MΩ (moderately damped) can already lead to HOM powers of 1.6-16 kW. Although, resonant excitation maybe avoided, a large amount of beam power has to be carefully extracted from the cryogenic environment due to the short range wakes excited by the beam which scales roughly as $f^2.\sqrt{N_c}$ [3]. Other parasitic effects such as energy spread and emittance growth also have a similar scaling, thus supporting the lower frequency choice in the 600-800 MHz range. Analogous to the longitudinal plane, short range transverse

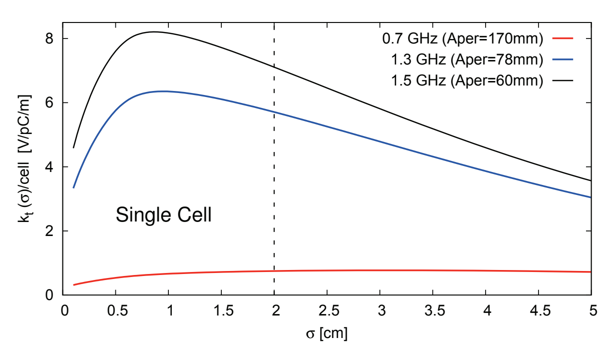

Figure 3: Transverse loss factor as a function of bunch length for three different cavity shapes from 0.7-1.5 GHz with their respective apertures.

effects can be quantified by a loss factor ($k_\perp \propto \sqrt{N_c}/A^n$). The scaling with aperture (A^n) where $n = 2-3$ in the bunch lengths of interest is quite dramatic. Fig. 3 shows

ISBN 978-3-95450-122-9

the transverse loss factor numerically calculated as a function of bunch length for three different cavity shapes from 0.7-1.5 GHz with their respective apertures. For high Q (or trapped modes), multibunch instabilities are of primary concern where a wake excited by one bunch can form a feedback loop on its recirculating path and with subsequent bunches to rapidly become unstable beyond a threshold current. This threshold, in a simple model is inversely proportional $Z_\perp$ of the HOM [4]. The threshold current has a strong frequency dependence (ω^{-3}... ω^{-5}) both due to aperture and the number of cells. The actual threshold has to be numerically estimated from the HOM spectra of the cavity and the exact ERL configuration. Therefore, a comprehensive cavity higher order mode characterization and the stability thresholds for beam breakup at high currents is a vital demonstration step in the test facility to ensure stable operation for a LHeC like machine.

ERL TEST FACILITY LAYOUT

Several proposals already exist for the use of energy recovery linacs as electron-ion colliders, high brightness light sources, FELs and test facilities [7]. A 300-400 MeV prototype superconducting ERL at 801.58 MHz at CERN is proposed as a demonstrator for the future realization of the 60 GeV e^- ERL for the LHeC and other . A conceptual layout of such a test facility using two 4-cavity cryomodules is shown in Fig. 4. The test facility will use a two-

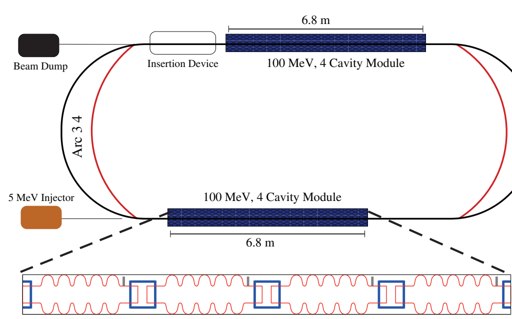

Figure 4: Preliminary schematic of an injector ERL. A sketch of the continuous 4×5-cell cavity layout is shown.

cryomodule two-pass energy recovery configuration similar to that of the LHeC. Alternative layouts are also under study to find the most flexible system to fully exploit the test facility [8]. In addition to the technological validation, several physics uses in the form of a free electron laser or a Compton γ-ray or X-ray source using appropriate insertion devices at various energies could be conceived.

The test facility could also be directly adapted as an injector to a future LHeC. Using the nominal beam current of 6.6 mA and an injector energy of 300-400 MeV, the RF power required to transmit to the beam is 2-3 MW. Using such an energy recovery concept, the RF power can be reduced to 50 kW or less. A schematic of such an ERL injector feeding into the high energy LHeC is shown in Fig. 5. This injector would also be applicable to the ring-ring type LHeC machine. However, the feasibility of energy recovery down to injection energy of the spent beam should be studied in details. The beam dump system should become significantly simpler at these reduced energies of 5 MeV.

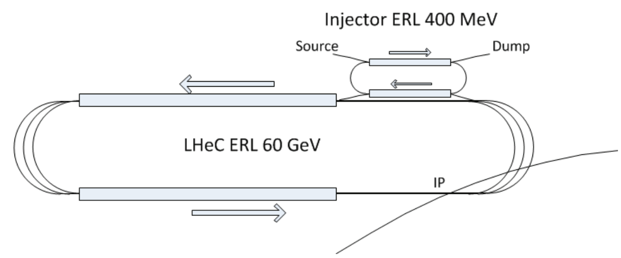

Figure 5: Preliminary schematic of the injector ERL combined with the LHeC.

DC and RF injectors sources for high brightness and high average current electron linacs have been a subject of intense R&D over several decades [9]. For beam currents within the 100 mA range, the DC gun coupled to an SRF injector is a well established approach. However, significant R&D is ongoing at several laboratories in the world to develop RF injectors for future high current sources. The test facility can also serve as a demonstrator for the final electron injector source to the LHeC and beyond. A 3-5 MeV injector should be sufficient to inject into the test facility for appropriate phasing and matching of both accelerating and decelerating beams.

CONCLUSION

A 300-400 MeV medium energy ERL test facility is proposed as a demonstrator for a future ERL based LHeC electron linac. The test facility will not only serve as an important validation tool for several technological and physics aspects of ERLs, but can be directly adapted as an efficient injector to a future LHeC and other accelerators in the horizon. The flexibility both in RF and optics layouts of the test facility and the R&D to push the state-of-the-art of SRF will be key to exploit the various aspects such a test facility.

ACKNOWLEDGMENTS

The authors would like to thank M. Klein and J. Tuckmantel for valuable discussions and suggestions.

REFERENCES

[1] M. Klein *et al.*, LHeC Design Report, J.Phys. G39 (2012) 075001 [arXiv:1206.2913].
[2] R. Calaga, *et al.*, CERN-LHeC-Note-2012-006 ACC, 2012; E. Jensen, LHeC meeting, Daresbury, 2013.
[3] R. Calaga *et al.*, ERL 2005 workshop, Newport News, USA.
[4] L. Merminga *et al.*, Annu. Rev. Nucl. Part. Sci. 2003. 53:387429.
[5] J. Jacob, EPAC2006, Edinburgh, Scotland.
[6] M. Gasper, RFTech workshop, Annecy, 2013.
[7] G. Hoffstaetter, V. Litvinenko, ERLS for light sources, HEP and NP, ERL2011, Tsukuba, Japan.
[8] A. Valloni *et al.*, these proceedings.
[9] A. Todd *et al.*, PAC2005, Knoxville, USA.