Contribution aux exercices de prospective nationale 2020-2030

Accélérateurs et instrumentation associée

POWERFUL ENERGY RECOVERY LINAC AT ORSAY

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*Contribution à rédiger en français ou en anglais et à envoyer à PROSP2020-GT07-COPIL-L@IN2P3.FR avant le **1er novembre 2019***

1. Informations générales

Titre : Powerful Energy Recovery Linac Experience at Orsay

Acronyme: PERLE@Orsay

Résumé :

Accelerator community shows a growing interest in beam-energy recovery machines. This concept allows the construction of electron accelerators capable to handle average beam currents similar to those provided by storage rings with the superior beam quality typical of linacs. PERLE is a proposed multi-turn ERL, based on SRF technology, being as a compact machine uniquely covering the 10 MW power regime. Apart the applications it could host, PERLE could be a hub to validate a broad range of accelerator phenomena and to develop ERL technology for the upcoming energy frontiers machines. FLUO is leading the effort within an international collaboration to study and later host PERLE at Orsay.

Préciser le domaine de recherche

- *Physique des accélérateurs (nouveaux concepts machines, optique et dynamique des faisceaux…)*
- *Sources d'électrons et cibles associées*
- *Supraconductivité accélérateur (cavités SRF et cryomodule)*
- *Développement durable de la discipline (efficacité énergétique, fiabilité…)*

Préciser la motivation principale visée par la contribution :

- *Accélérateurs à Récupération d'énergie (ERLs)*
- *Accélérateurs pour la physique nucléaire*
- *Accélérateurs pour la physique des particules*

2. Description des objectifs scientifiques et techniques

Energy-recovering electron linear accelerators (called Energy-Recovery Linacs, or ERLs) share many characteristics with ordinary linacs, as their six-dimensional beam phase space is largely determined by electron source properties. However, in common with classic storage rings, ERLs possess a high average-current-carrying capability enabled by the energy recovery process, and thus promise similar efficiencies. The efficient recovery of power, to re-excite cavities from a used beam, was suggested first in 1965 by Tigner [1], and experimented only twenty years later by Stanford [2] and LANL [3] for normal conductive facilities accelerating beams at rather low power. The concept become really viable thanks to the major advances in SRF technology within the last decades (quantified by cavity quality factors $Q_0 \geq 10^{10}$) enabling high average current operation, in addition to the consideration of multi-pass recirculation allowing high beam energy in relatively compact machine. These two aspects have paved the way to the green generation of high energy, high brightness, high average current electron beams. Their unique combination of linac-like beam quality, extremely flexible time structure, unprecedented operating efficiency and compact footprint open the door to previously unattainable performance regimes. Thus, ERLs are just beginning to assert their potential as game changers in the field of accelerators used in synchrotron radiation sources, high-energy electron cooling devices, electron-ion colliders, and other applications in photon science, nuclear and high-energy physics.

In order to develop and acquire expertise in design, studies, construction and operation of ERLs, the future Orsay lab-FLUO, strengthen by an international collaboration, is aiming to involve local accelerator experts around an ambitious and federating project: PERLE@Orsay [4]. PERLE is a proposed high-power Energy Recovery Linac, designed on multi-turn configuration, based on SRF technology, to be hosted at Orsay-France in a collaborative effort with an international collaboration involving today: CERN, JLAB, STFC-ASTeC Daresbury, Liverpool University and BINP Novosibirsk. Four of these international partners have been pioneering the development of ERL technology, the other are leading laboratories on SRF technology and accelerator physics. The collaboration still open to new comers.

The PERLE accelerator complex is arranged in a racetrack configuration (*Cf. Figure 1*) hosting two cryomodules (containing four, 5-cell cavities operating at 801.6 MHz), each located in one of two parallel straights completed with a vertical stack of three recirculating arcs on each side. Spreaders and recombiners are matching the linacs and the circulating arcs.

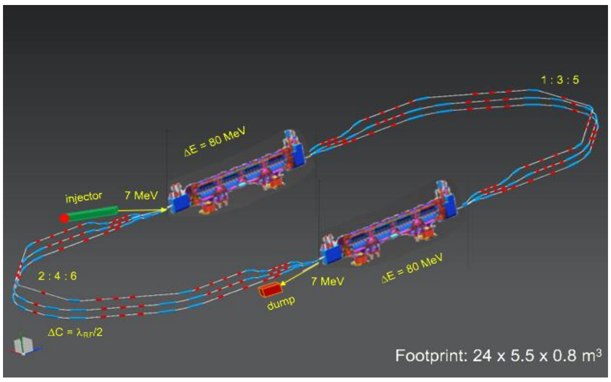

Figure 1: PERLE Layout featuring two parallel linacs each hosting a cryomodule housing four 5-cell SC cavities, achieving 500 MeV in three passes.

In its final configuration, a high average current electron beam (20mA) is accelerated through 3 passes to the maximum energy (500 MeV) in the superconducting RF CW linear accelerators. The beam is then used for its intended purpose (photon generation by Compton back-scattering, a cooling source for ion beams or a beam for colliding against ions). This process may significantly increase the energy spread or emittance of the electron beam but the major part of the beam power remains. The beam is then sent back through the accelerators again only this time roughly 180 degrees off the accelerating RF phase so the beam is decelerated through the same number of passes and then sent to a beam dump at around the injection energy. Several benefits accrue from this manipulation: the required RF power (and its capital cost and required electricity) is significantly reduced to that required to establish the cavity field and make up minor losses, the beam power that must be dissipated in the dump is reduced by a large factor, and often the electron beam dump energy can be reduced below the photo-neutron threshold so that activation of the dump region can be reduced or eliminated.

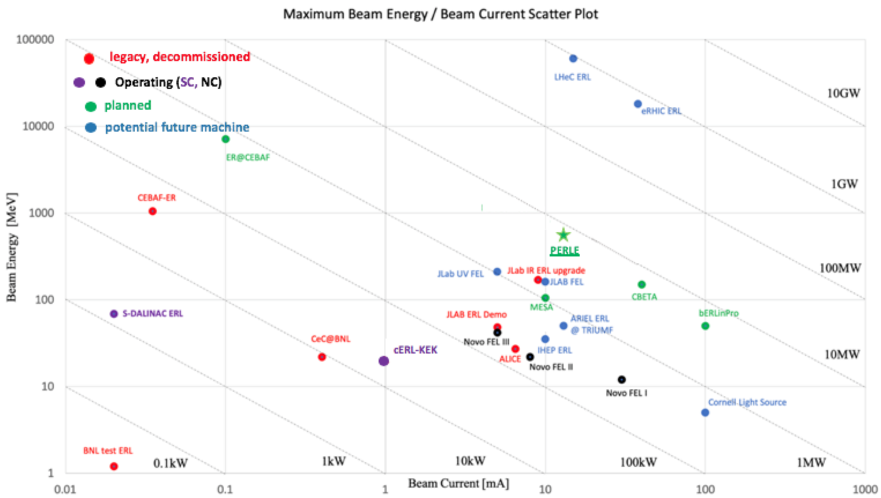

Figure 2: Global landscape of ERL projects worldwide

By scrutinising the global landscape of ERLs projects worldwide (*Cf. Figure 2*), we note that a relatively high number or ERLs are decommissioned, very few are currently operating (S-DALINAC in Darmstadt University [5], cERL in KEK [6] and Novo FEL in BINP-Novosibirsk [7]) and relatively important number are proposed or under construction/commissioning. Among these later, two future potential projects (LHeC [8] and eRHIC [9]) are at very high power (1GW limit) far beyond state-of-the-art machines, and three planned projects are bridging the gap at a power frontier of 10MW: CBETA in Cornell University [10], bERLinPro at Helmholtz Zentrum-Berlin [11] and PERLE@Orsay. All of them are based on SRF technology (1.3Ghz cavities for CBETA and bERLinPro Vs. 802MHz cavities for PERLE), one is a single pass machine (bERLinPro) and the two others are multi-pass machines. All of them share the same concerns: the CW operation, the high beam average current handling, the low delivered beam energy spread and the low delivered beam emittance.

Two new proposed projects have chosen the PERLE technology and configuration: DIANA in Daresbury (a user facility for industrial applications) and DICE in Darmstadt University (for Photo-Nuclear Physics R&D, to replace the old s-DALINAC). Possibility of collaboration between PERLE and these two projects in several field was discussed with project leaders.

3. Développements associés, calendrier et budget indicatifs

In the following, we list the important items that need to be studied and the main development required to meet the PERLE requirement. The list is obviously not exhaustive:

- Development of high-average-current, low-emittance guns (collaboration with STFC-AsTEC Daresbury): upgrade of existent DC gun, photo-cathode development for both unpolarized and polarized electron beam.
- Injection line design (collaboration with STFC-AsTEC Daresbury and University of Liverpool): design of a buncher, an SRF booster and a merger matching the injector and the main linac.
- Design and prototyping of a full dressed SRF cavity (collaboration with CERN and JLAB): demonstration of level of SRF performance required in CW, high-average current environment, adequate damping of HOM.
- Design and prototyping of input power coupler (collaboration with CERN).
- Linac cryomodule design (collaboration with CERN): study the possibility of SPL cryomodule adaptation to PERLE need, complete design of a cryomodule for PERLE later.
- BBU study in high average current environment (collaboration with CERN and JLAB): cavity design optimization for an efficient extraction of HOMs considering PERLE parameters: bench pattern recombination, current threshold, cryogenic efficiency…
- Recirculation arcs design (collaboration with JLAB and BINP): optimization of arcs and switchyards lattice, study of optics tolerances, prototyping of main magnets.
- Collective effects study: effects of coherent synchrotron radiation on beam quality, Ion cloud mitigation, start to end simulation.
- Particle tracking studies of halo formation and control of beam loss:
- LLRF and feedback system development: RF control and stability under maximum practical Q_{Load}, development of multi-bunch BBU feedback systems.
- Beam diagnostics development

We are aiming to include all the outcomes of these studies and the test results of prototypes in a Technical Design Report to be published end of 2021- beginning of 2022.
The PERLE configuration (*Cf. Figure 1*) entails the possibility to construct PERLE in stages, starting by installing a single linac in the first straight and initially replacing the second one by just beam lines. The second phase is for the realisation of PERLE at its design parameters, as a 10MW machine. We estimate the construction schedule of PERLE within the next decade.
A tentative cost estimation of PERLE facility was undertaken and the global cost of the machine was evaluated at about 25MEuros. This estimation did not include manpower cost, nor infrastructure and related equipment (Shielding, water cooling, fluids, electrical power, safety protection system, etc.) implementation cost. A request to CPER-Phase 2 program will be made to support the infrastructure cost. Moreover, this value did not take into account any possible in-kind contribution from the collaborators.

4. Impact

Like indicated previously, PERLE configuration and its beam parameters place it at the far front of new generation of compact, but powerful ERLs, that have the opportunity (and the responsibility) to bridge the gap between state-of-the-art machine and future large-scale research infrastructures at the energy frontiers. Particularly, design challenges and beam parameters are chosen to enable PERLE as a testbed for the injection line and SRF technology development, as well as multi-turn and high current ERL operation techniques for the Large Hadron Electron Collider (LHeC: An ERL reaching 60 GeV in three turns providing electrons that collide with the LHC protons) [8]. While the concept and promise of ERL's has been kick-started by demonstration machines based on existing accelerator technology, PERLE will be the first machine designed from the ground up to use fully optimized ERL-specific designs and hardware. In another hand, new proposal of compact machine (DIANA and DICE), using PERLE configuration and technologies start to raise, presenting a wide spectrum of applications (industrial and academic). We are already talking about close collaboration between these machines where PERLE is considered as a locomotive.

From the strategic point of view, PERLE is considered as the federative project of the new Orsay lab that could structure its accelerator activity and contribute to its visibility worldwide.

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