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Energy recovery injectors ☆

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ABSTRACT

This article presents a novel design for a superconducting rf electron injector that incorporates energy recovery. This concept relaxes the demands of high power input couplers, improves essential beam parameters and energy efficiency and reduces the overall cost of a compact energy recovery linac machine.

1. Introduction

The requirements for the next generation of accelerators have been extensively discussed in the field of accelerator science. The recurring features of both high average beam current and efficiency coupled with low emittance and energy spread are mandatory within the realms of a compact Energy Recovery Linac (ERL) design. Continuous Wave (CW) operation using superconducting cavities have been shown to meet these expectations. Presently the most promising option for the associated ERL superconducting injector is a radio frequency (rf) photocathode gun combined with a booster linac to deliver via a merger the 6–10 MeV beam towards the ERL loop.

The design studies of the bERLinPro [1,2] project are used in this article as a typical example of a compact ERL with a goal to deliver beam of 50 MeV with an average current of 100 mA. Each of the three 7-cell linac cavities will be powered by 15 kW solid-state transmitters to control the 5 MW beam power.

The largest consumption of rf power is required in the ERL injector. Envisaged is 825 kW shared between three klystrons and an additional solid-state transmitter together consuming some 1.5 MW of wall-plug power. Proposed in this article is an injector that incorporates its own energy recovery process that is efficient enough to avoid the use of the klystrons and save at least 1 MW of power. This compact, lightweight and transportable accelerator design is compatible with the demands of future machines.

High rf power is necessary in conventional ERL injectors to produce the relatively high beam energy required to preserve beam quality. In order to safely dump the beam, the minimal beam energy is usually limited by the beam parameters after deceleration that often depend on the experimental setup in the ERL loop (e.g. high energy spread after FEL-process). This proposal takes advantage of the fact that the energy at the beam dump can be significantly lower than the injection energy. This energy difference will be recuperated, allowing one to considerably reduce the injector rf generator power.

As a worst case scenario one can consider bERLinPro with an additional FEL. This would generate a beam energy spread of $\Delta E_b \sim 0.3$ MeV at the beam dump assuming 10 kW FEL power [3]. With 15% energy acceptance of the dump transfer line [3], the beam must have at least 2 MeV energy after deceleration.

Experience of existing machines show that the output energy of an injector needs to be typically larger than 6 MeV in order to maintain high beam quality. This strict condition requires high rf power (e.g. 600 kW for 100 mA) through the input couplers. Presently there are no standard rf input couplers at a frequency of 1.3 GHz that produce more than 50 kW of power [4,5]. HZB reports on the development of a 115 kW coupler that will suffice for the bERLinPro injector [6]. Although promising, these projects are presently in a prototype stage and the proposal in this article of energy recovery in the injector could substantially relax the heavy burdens of such a project.

The underlying novel concept of this proposal is that the beam in the ERL should pass perpendicularly through the rf gun cavity. More specifically the returning beam traverses the axis of the iris between the cells (see Fig. 1). The beam is then decelerated under

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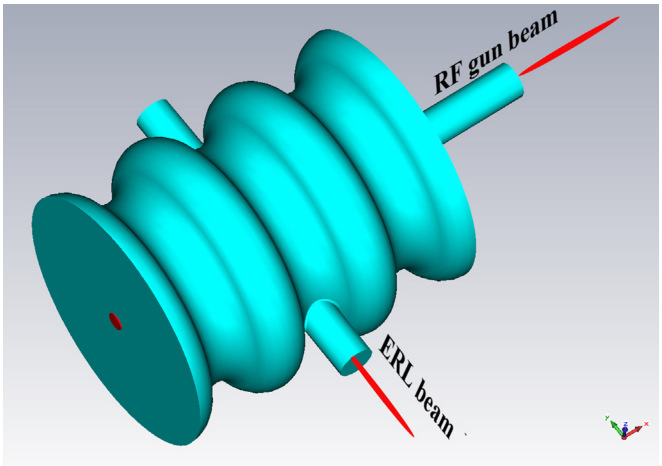

Fig. 1. Energy recovery SRF injector.

the influence of the transverse electric fields.

With bERLinPro in mind, the proposed scheme is to use the high energy beam in the returning loop to recover energy back into the injector (see Fig. 11). This natural position is convenient in terms of floor planning to deliver the returning beam perpendicular to the injector.

The amount of deceleration or shunt impedance depends strongly on the iris diameter. Commercially available rf cavity designs such as TESLA would only cause slight deceleration in the iris due to their small cross sections (typically 35 mm iris radius). Given this dependence, a critical iris radius can be found where the shunt impedance for the decelerating beam is equal to the shunt impedance of the adjacent accelerating cells (see Fig. 4). In order to achieve substantial deceleration and account for the usual transit time effects, the radius of the iris can be optimized. Through careful adjustment of the iris diameter one can adjust the ratio of the shunt impedance for the cross-propagating beams (acceleration on-axis, deceleration perpendicular to axis) and therefore control the degree of energy recovery.

In order to comprehensively describe the concept, machine integration and expectations of this energy recovery injector this article starts with design strategy in the following chapter. Even though the demand for large apertures limits the acceleration gradients compared to the standard techniques the energy gain on acceleration can remain high (in comparison with the high current DC injector see e.g. [7]) due to the absence of power limitations from the input couplers.

One promising effect of the rather large apertures is the natural propagation of Higher Order Modes (HOMs) from the cavity through the beam pipe to their designated HOM load. This reduces the number of trapped HOMs which plays a critical role in the suppression of Beam Break-Up (BBU) instability as discussed in chapter 3.

Chapter 4 presents the numerical design of a SRF energy recovery injector. The construction of such novel multi-cell cavity with a large iris and perpendicular extrusions for the recovery beam is based on the established techniques. We propose a series of precisely fabricated vacuum joints between the cells rather than the procedure described in [8]. The segmentation allows for high accuracy, improves the reparability of the rf gun and suppresses trapped HOMs. Furthermore a material with high rf losses could be used in the joints to significantly damp other unwanted higher order modes. A second article is planned to discuss the technical difficulties and the solutions due to the presence of HOM dampers in cavity cells which permit creating multi-cell accelerating structures with high suppression of trapped HOMs.

The machine integration in the form of layout is proposed in chapter 5 and the final chapter reiterates the lavish savings in power consumption for a compact ERL project such as bERLinPro. For completeness all cavity field calculations were undertaken with the codes SLANS and CLANS2 [9] and the beam dynamics were simulated using ASTRA [10].

2. Energy recovery SRF gun cavities

As is often the case, this study begins with a simple pillbox cavity. Rather than the typical accelerating TM_{010} mode where all the electric fields are parallel to the axis, the proposed injector requires transversal electric fields to decelerate the beam. Fig. 2a shows the cavity geometry and the TM_{011} mode that produces these fields. Such an example can be used as a starting point to model the energy recovery injector cavity.

The accelerating beam passes from left to right on-axis across the cavity, and the decelerating beam propagates perpendicular to the cavity axis through its center. At the *optimal* accelerating rf phase φ_{acc} the energy gain of the on-axis beam is V_{acc}. Authors use the notation of V for the energy to distinguish it from the electric

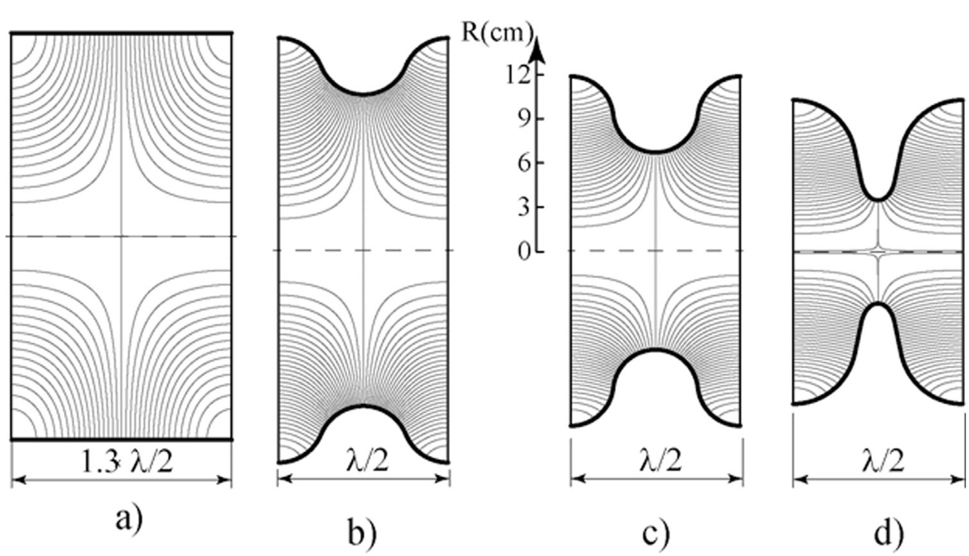

Fig. 2. Cavity sections of varied iris radii. Electric field lines of the TM_{011} mode of 1.3 GHz operating frequency are shown.