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ENERGY RECOVERING FOR LINAC RF INJECTORS

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Abstract

The article presents a new design of a CW RF high average current superconducting injector cavity. This design allows recovering energy in the injector, improving beam parameters and energy efficiency, reducing injector size, cost and avoiding high average power coupler problem.

INTRODUCTION

Modern science has certain requirements for novel accelerators, main of which are high efficiency, small size, high average beam current, and CW operation, preserving the high beam quality – low emittance, energy spread, etc. Superconducting ERLs meet these requirements perfectly. Photocathode RF gun equipped with a linac booster with the energy of about 10 MeV on base of superconducting cavities is the best injector option for an ERL. Due to extremely low losses in superconducting RF cavities relatively low RF power of generators is required.

The relevant example of an ERL is BERLinPro project [1] with the beam energy of 50 MeV and average beam current of 100 mA driven by a RF injector with 6 Mev beam energy. The beam power of the ERL is 5 MW. A 45 KW transmitter based on solid state technology is foreseen for the ERL linac. The RF generator power is required mostly to accelerate the beam in the injector – 890 kW generated by four klystrons consumed 1.5 MW of a power outlet. Thereby, in perspective, there is a possibility to waive a klystron usage in a ERL with energy recovering in the injector to economize 1.5 MW.

But really, the economy has to be lower due to a wide beam energy distribution appearing after e.g. free electron laser (FEL) (or any other kind of beam application). The absolute value of the energy spread does not change during the recovery process in the ERL but its relative value raises inverse proportionally to its energy. The highest possible energy spread in the beam dump is about 15% [3]. In our example of ERL the energy spread of the beam becomes 300 keV if the FEL power is about 10 kW. To keep energy spread under 15% the energy of the recuperated beam transported to a beam dump must be about 2 MeV (200kW). Let us suppose ~50% of the beam dumping power (100 kW) could be regenerated by a special normal conducting RF cavity embedded to the beam dump. In all, we can reduce power consumption of injector to 145 kW instead of 1.5 MW, i.e. several times enhance the energy efficiency of the ERL RF system.

For physical reasons the beam injector energy of more than 6 MeV is needed to keep the beam quality. The typical problem of such injectors is the high power RF couplers. At present there are no RF input couplers at 1300 MHz frequency with RF power more than 50 kW [2]. The recovery of ERL beam energy in the injector can reduce the requirements for couplers. But there are two main obstacles to recovery in RF injectors.

Firstly, the beam energy cannot be recovered efficiently just before the beam dump because of the large beam energy spread.

Secondly, the decelerating beam cannot be transported along the RF gun axis because the photocathode is located on this axis.

Figure 1 demonstrates solutions for these problems. The first suggestion is that energy recovering in the RF gun be done before the energy recovering in the linac, when the beam has its maximal energy and relatively small energy spread (0.6% in case of BERLinPro). The second suggestion is that the ERL beam should pass the RF gun cavity across its axis, between its cells. Directly between cells, in the iris, there is only transverse electric RF field and this field can be used for the beam deceleration. However, usual accelerating cavities (e.g. TESLA type) cause only minor deceleration due to small iris radius (35 mm). The shunt impedance for decelerating beam is higher, if the iris radius is increased. Thus, at some iris radius shunt impedance for decelerating beam can be equal to the shunt impedance for accelerating beam in one (at radius ~80 mm) or even two (at radius ~110 mm) accelerating cells.

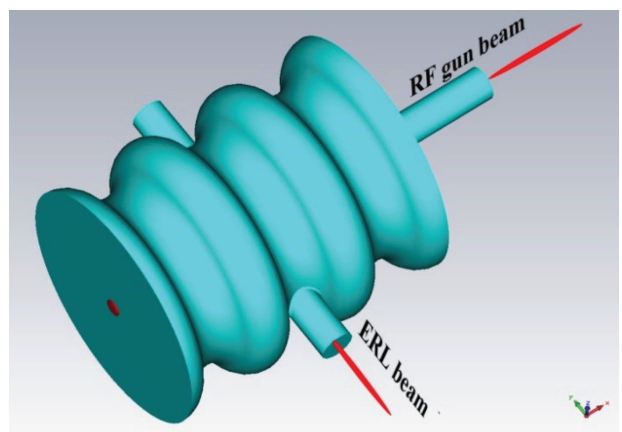

Figure 1: Energy recovery SRF injector.

Therefore, energy recovery injectors require cavities with large apertures. Such cavities have several new unique features. They can be segmented with vacuum joints between cells. This improves the repair ability of the RF gun. The accelerating mode quality will not be changed due to the absence of RF currents in the joint. Moreover, some of high order modes will be dumped significantly, especially if absorbing materials will be used in the joints. The presence of HOM dampers in a cavity permits creating multicell accelerating structures. Now, high average current cavities can have two cells [4].

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Possible designs of such joints will be considered in a separate paper.

Suggested cavities with large apertures rich approximately 30% lower acceleration gradient due to higher RF field at its surface. Nevertheless, beam energy gain can be higher due to the absence of input coupler limitations and a shorter length of the accelerating cavity. Out coupling of high order modes (HOM) from the cavity with large aperture to an RF load becomes easier. This is crucial for suppression of BBU instability that is destructive especially for low energy high current electron beam in injectors. At the same time, energy recovery injectors do not affect the linac BBU because there is no beam related connection between transversal HOMs of both RF gun and linac.

ENERGY RECOVERY SRF GUN CAVITIES

The simplest example of a gun cavity with the energy recovery is a pillbox cavity with TM_{011} mode (Fig.2a). The decelerating beam propagates perpendicular to the cavity axis. The on-axis beam gains the maximal energy $\mathcal{E}_{acc}$ at the *optimal accelerating* RF phase. The recovering beam loose the energy $\mathcal{E}_{dec}$ at the *optimal decelerating* RF phase. Electric field distributions along the both trajectories have approximately the same form. They are shown in Fig.3. There is no magnetic field along the both trajectories. If $\mathcal{E}_{acc}= \mathcal{E}_{dec}$ the recovery is full. The cavity radius in Fig.2a is optimized to get a maximal ratio ($\mathcal{E}_{dec}/\mathcal{E}_{acc}$)=*0.65* (see Table 1). As can be seen, the recovering is not full in a pillbox cavity.

The ratio ($\mathcal{E}_{dec}/\mathcal{E}_{acc}$) can be varied in a wide range if there is aperture in the middle of the cavity with some iris radius (see Fig.4). Such 1.3 GHz cavities with section length of λ/2 and different iris radii are shown in Figs. 2b, 2c, 2d with $\mathcal{E}_{dec}/\mathcal{E}_{acc}$=*2, 1, 0.25* respectively. The case Fig. 2b presents a cavity geometry, in which recovered power is sufficient for beam acceleration in two cells. The case Fig. 2d is the TESLA type cavity.

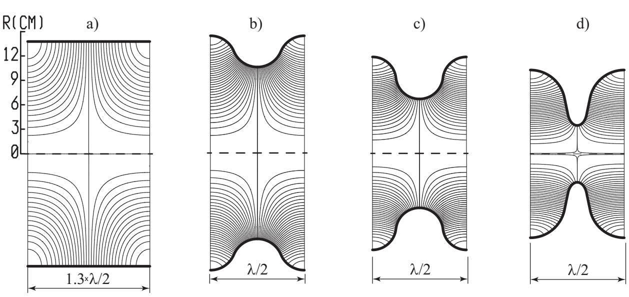

Figure 2: Cavity sections with different iris radii. 1.3 Ghz TM_{011} Mode.

Main RF parameters of the cavities, shown in Fig.2, are presented in Table 1.

At the on crest phases of decelerating and accelerating beams the beams collide directly at the cavity axis at RF phase of 180 degrees. To avoid that, the beams have to be either interlaced at different RF periods or to be accelerated/decelerated off crest. In the first case the maximal bunch repetition frequency will be the half of RF frequency. In the second case a small additional RF generator power is needed.

Table 1: RF Parameters of Cavity Sections of Fig.2

Figures	2a	2b	2c	2d
$\mathcal{E}_{dec}/\mathcal{E}_{acc}$	0.65	2	1	0.25
E_{peak}/E_{max}	0.63	1.74	1.16	1.06
B_{peak}*, T	0.15	0.23	0.17	0.11
$\mathcal{E}_{acc}$*, MeV	4.1	2.88	2.89	3.05

* at E_{max} =50 MV/m – maximal axis electric field, E_{peak} and B_{peak} – maximal surface electric and magnetic fields.

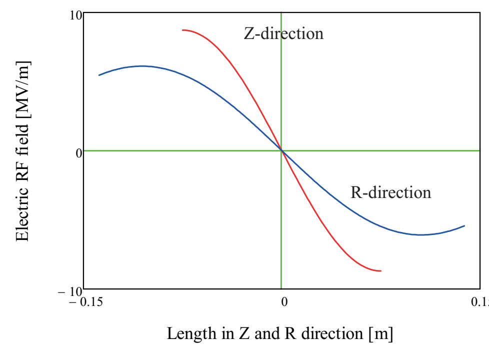

Figure 3: Electric field distribution of pillbox cavity along the axis (Z) and the decelerating trajectory (R).

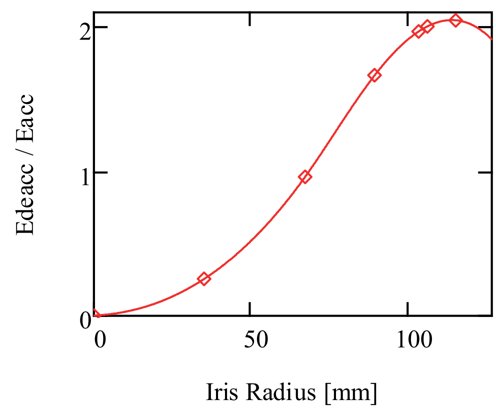

Figure 4: The Dependence of the Ratio $\mathcal{E}_{dec}/\mathcal{E}_{acc}$ on the Iris Radius of Cavity Sections, Shown in Figs. 2b-2d.

A possible scheme of energy recovery SRF gun is shown in Fig.5. Here the cavity cell geometry shown in Fig. 2b is used. A moderate power (about 1/3) comes through the input coupler, the balancing 2/3 come from the energy recovery. HOM suppression is guaranteed by two HOM loads – coaxial and waveguide types – that have established reputation as a perfect method for BBU suppression in the normalconducting cavity of VEPP2000 accelerator with 200 mA average beam current [5]. HOMs are directly coupled to the HOM loads but the accelerating mode is separated from coaxial load by the choke filter and from waveguide load by evanescent section of the beam pipe. Practically, all types of HOMs can be deeply suppressed by choosing the radii of the coaxial and waveguide loads there.

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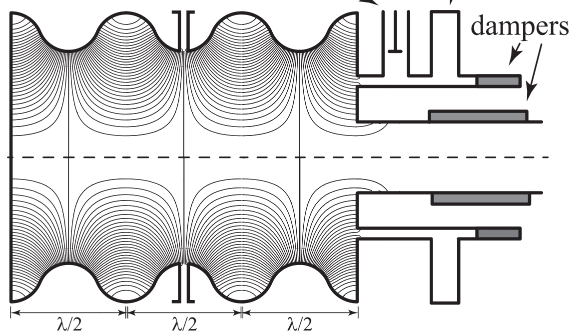

Figure 5: Energy recovery SRF gun based on the cavity cell, shown in Fig.2b.

Parameters of the SRF gun are presented in Table 2.

Table 2: Main Characteristics of the SRF Gun of Fig.5

Parameter	Value
$\mathcal{E}_{acc}$	4.4 MeV
$\mathcal{E}_{dec}\approx 2/3\cdot \mathcal{E}_{acc}$	2.9 MeV
RF generator power	(4.4-2.9)·100=150 kW
E_{max}	25 MV/m
E_{peak}	43.4 MV/m
Optimal accelerating phase	49 degrees

Consequently, beam emittance of double charge bunches in this RF gun has to be the same as single bunch charge bunches in the BERLinPro RF gun due to the higher energy gain at the shorter accelerating gap [6]. This allows half repetition frequency and reduces the cost of a photocathode laser. One can consider an SRF gun with a frequency reduced by a factor 2 with respect to the main linac (e.g. 1.3 GHz mani linac and 650 MHz injector). In this case the RF gun size is doubled, as well as the beam energies: $2\cdot\mathcal{E}_{dec,}$=5.8 MeV and $2\cdot\mathcal{E}_{acc}$ = 8.8 MeV. Such an injector does not require a booster.

Figure 6 shows the possible layout of an modernized ERL with energy recovery in SRF gun. At first, 100 MeV ERL beam comes through the SRF gun recovering 5 Mev there. Then it passes through the linac to recover 90 Mev. Then the beam with the remained 5 MeV energy goes to the beam dump.

CONCLUSION

The possibility of developing energy recovery SRF gun injectors is discussed. Two main ideas (immediate recovery in a SRF gun, and transverse propagation of the recovering beam) are presented .The role of large aperture multicell accelerating cavities with strong HOM suppression to avoid BBU instability of low energy high current beam is shown. The layout of an ERL with energy recovery in SRF injector is presented. A high quality beam is predicted by dynamic calculation of simple variant of SRF gun.

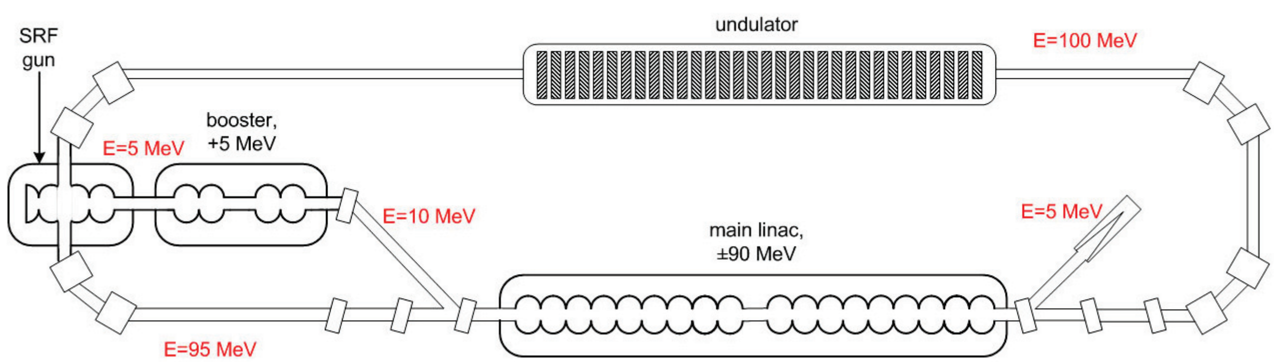

Figure 6: Schematical Layout of an ERL with the Energy Recovery SRF Gun.

ACKNOWLEGMENTS

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