RF ACCELERATOR FOR ELECTRON COOLING OF ULTRARELATIVISTIC HADRONS

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Abstract

New projects of high-energy hadron colliders could be improved by far by using the electron cooling technique. However, a source of high-current relativistic electron beam appears to be a technical challenge. Indeed, the intrinsic energy limitations of high-voltage DC accelerators lead to necessity to perform acceleration using not static but vortex electrical fields. Induction and radiofrequency (RF) accelerators employ such fields. Moreover, to keep the damping times small enough at high energies, it is necessary to increase the electron peak current to tens of amperes. The feasibility of RF energy recovery linac (ERL) application to electron cooling is discussed. The ERL of the Novosibirsk free electron laser facility is used as a reliable prototype.

INTRODUCTION

New projects of high-energy hadron colliders could be improved by far by using the electron cooling technique [1-7]. However, a source of high-current relativistic electron beam appears to be a technical challenge. Indeed, the intrinsic energy limitations of high-voltage DC accelerators lead to necessity to perform acceleration using not static but vortex electrical fields. Induction and radiofrequency (RF) accelerators employ such fields. Moreover, to keep the damping times small enough at high energies, it is necessary to increase the electron peak current to tens of amperes. As the duty factor of the cooler shall also be high, the desirable average beam current of the cooling electron beam is about 1 A or more.

Skipping at this point the betatron option, we will discuss the feasibility of RF energy recovery linac (ERL) application to electron cooling.

The necessity of high current and relatively low (less than 100 MeV) electron energy leads to the choice of an ERL with a low-frequency non-superconducting accelerating RF system. Indeed, the characteristic parameters for longitudinal stability of the average electron beam current I_{beam} and charge per bunch q are the ratio of the beam power to the power consumption in the RF cavities

$$\frac{P_{beam}}{P_{RF}} \approx \frac{I_{beam}U}{U^2/(2R)} = \frac{2I_{beam}R}{U} = \frac{QI_{beam}2(R/Q)}{U} \sim \frac{QI_{beam}}{10\,\mathrm{kA}} \qquad (1)$$

and the energy deposition per bunch to the stored energy of RF cavity

$$\frac{qU}{CU^2/2} = \frac{q\omega 2(R/Q)}{U} \sim \frac{q\omega}{10\,kA}, \qquad (2)$$

where R/Q, ω, $C = (\omega R/Q)^{-1}$, and U are the characteristic impedance, fundamental eigenfrequency, effective capacity, and voltage amplitude of single cavity, respectively. For the typical values U = 1 MV and $2R/Q$ = 100 Ohm, $U/(2R/Q)$ = 10 kA. Then Eqs. (1) and (2) give the following limitations for the average current and the bunch charge:

$$I_{beam} < \frac{10\mathrm{kA}}{Q} \qquad (3)$$

and

$$q < \frac{10\mathrm{kA}}{\omega}. \qquad (4)$$

For the non-superconducting cavities of the Novosibirsk free electron laser (FEL) facility [8, 9], ERL $Q = 20000$ and $\omega = 2\pi\cdot 180$ MHz, and Eqs. (3) and (4) give reasonable limiting values of 0.5 A and 10 μC, but for the superconducting cavities they are several orders of magnitude lower. For low-frequency non-superconducting RF systems, the transverse stability conditions are also much easier.

INJECTOR

To provide high charge per bunch, one can use a low-frequency RF gun. A 90 MHz CW RF gun with an average current of more than 0.1 A was built and tested at Budker INP [10]. In fact, in more than twenty years, Budker INP has manufactured tens of RF guns with electron energy of up to 1 MeV as industrial accelerators, referred to as ILU-8 [11]. The ILU-8 accelerators operate in a high duty cycle pulse mode and provide a peak current of up to 5 A.

For further gain in the bunch charge, it is necessary to increase the cathode diameter and decrease the RF and bunch repetition frequencies. A frequency of 30 MHz seems to be as a reasonable compromise between increasing the RF cavity size and obtaining more than 10 nC in each bunch. With a peak cathode current of 4 A and an initial bunch duration of about 4 ns, one can obtain a bunch charge of 16 nC. To have a significant accelerating gradient in an RF structure, it is necessary to use a higher RF frequency. Then, for further RF acceleration it is necessary to compress the bunch. In the consideration below, we will

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use the parameters of the RF system of the Novosibirsk ERL, which has been operated successfully at the Novosibirsk FEL facility [8, 9] for last 16 years. Its operating frequency is 180 MHz. To suppress the space-charge phenomena, we plan to accelerate electrons to a kinetic energy of 2 MeV in three similar 30 MHz RF cavities. The first one is the RF gun cavity and the two others are the accelerating ones.

The proposed compression system compresses the 2 MeV, 16 nC bunch from 4 ns to 0.5 ns duration. It uses the energy chirp of 2 MeV bunches, additional energy modulation in an auxiliary RF cavity, operating at a subharmonic of the main accelerating structure frequency of 180 MHz, and a magnetic buncher. For the required energy modulation to have an acceptable value (less than ±10%), the buncher shall have a high value of the longitudinal dispersion R_{56}. A second-order achromat is desirable for operation with large energy spread. The general scheme of the proposed magnetic buncher is presented in Fig. 1.

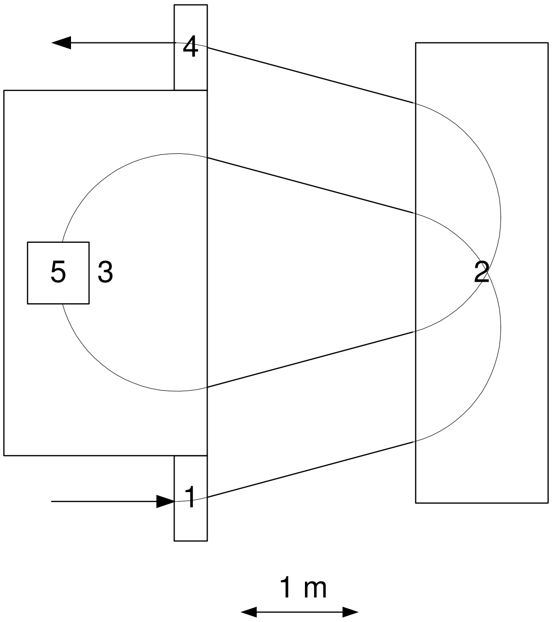

Figure 1: Magnetic buncher. 1 and 4 – parallel-edge magnets, 2 and 3 – magnetic mirrors, 5 – sextupole corrector.

It contains two magnetic mirrors with a homogeneous field and auxiliary magnets.

ERL

The above 2 MeV electron beam is to be accelerated further in an ERL. In the simplest case, the above-mentioned Novosibirsk ERL may be used to this end. In fact, this option is interesting in the context of improving the parameters of Novosibirsk FEL facility and will be considered in more details elsewhere. Below we describe a more advanced and expensive scheme of ERL with two accelerating structures [12]. It is more flexible and allows better control of the beam parameters.

The scheme of cooling ERL is shown in Fig. 2. Electrons pass each of the 30 accelerating cavities twice, obtaining energy of 50 MeV, are used in cooling section, are decelerated to 2 MeV in the same RF cavities, and are directed to the beam dump.

The estimated parameters of electron bunch are listed in Table 1. The bunch repetition frequency is limited by the average current of the electron gun and may exceed 10 MHz.

Table 1: Electron Bunch Parameters

Energy E, MeV	50
Charge q per bunch, nC	16
Number N_e of electrons	10^{11}
Longitudinal emittance ε_s, keV·ns	10
Normalized transverse emittances ε_t, mm·mrad	10

ELECTRON COOLING

The first successful demonstration [7] of the electron cooling of ion bunches using the RF electron linac at the RHIC shows clearly its high prospects. Let us estimate the cooling rate in the case of a long superconductive solenoid with a magnetic field $B = 1$ T.

Let the electron bunch length l_b be 60 cm. The longitudinal emittance ε_s = 10 keV·ns will define the energy spread of bunch $\sigma_E = c\varepsilon_s / l_b$ =5 keV, where c is the velocity of light. Then the longitutinal electron velocity spread in the beam rest frame is $V_{se} = c\sigma_E / E = 3 \cdot 10^6$ cm/s. For an ion beta function β_i = $3 \cdot 10^4$ cm and an ion normalized transverse emittance $\varepsilon_i = 10^{-4}$ cm, the transverse velocity spread in the beam rest frame is $V_{xi} = c\sqrt{\gamma\varepsilon_i / \beta_i}$ = $1.7 \cdot 10^7$ cm/s, and the transverse beam size is $a_i = \sqrt{\varepsilon_i \beta_i / \gamma}$ = 0.17 cm (γ is the Lorentz factor). Let the flat electron beam enter the flat solenoid edge. For a vertical beta function β_y = 100 cm, the vertical beamsize is $a_y = \sqrt{\varepsilon_t \beta_y / \gamma} = 0.032$ cm, and the vertical angular spread is $\theta_y = \sqrt{\varepsilon_t / (\gamma\beta_y)} = 3.2 \cdot 10^{-4}$. For a horizontal beta function β_x = 40000 cm, the horizontal beamsize is $a_x = \sqrt{\varepsilon_t \beta_x / \gamma} = 0.64$ cm and the horizontal angular spread is $\theta_x = \sqrt{\varepsilon_t / (\gamma\beta_x)} = 1.6 \cdot 10^{-5}$, which is much less than the r. m. s. horizontal kick $a_y/R = 2 \cdot 10^{-3}$ ($R = \gamma mc^2/(eB)$ = 17 cm) at the flat edge of the solenoid. Then the r.m.s. Larmor radius is equal to a_y. After transformation in solenoid we obtain a round beam with an r. m. s. sizes a_e of 0.15 cm, which exceeds the r.m.s. Larmor radius 5 times.

The peak electron current is $qc/(\sqrt{2\pi} l_b) =$ 3.2 A, and the electron rest-frame density is $n_e = N_e / (2^{3/2}\pi^{3/2} l_b a_e^2 \gamma)$ = $5 \cdot 10^7$. The cooling rate in the lab frame can be estimated as [1–3]

$$\delta_{cool} = \frac{2\pi n_e r_e r_i c^4}{\left(V_{xi}^2+V_{se}^2\right)^{3/2}}\frac{\eta}{\gamma}\ln\frac{a_e}{R}, \qquad (5)$$

where r_e is the classical radius of electron, r_i is the classical radius of ion, and η is the fraction of the collider perimeter occupied by the cooling section. For ions with the charge Z = 92, atomic weight A = 200, and $\eta = 0.01$, $\tau_{cool} = 1/\delta_{cool}$ = 100 s. This result shows good prospects for using this cooling system with a low-frequency ERL.

CONCLUSION

High energy electron cooling (>10 MeV) should use an RF linac for generation of electron beam. A low-frequency linac can produce an intensive electron beam for cooling ion bunches in the collider.

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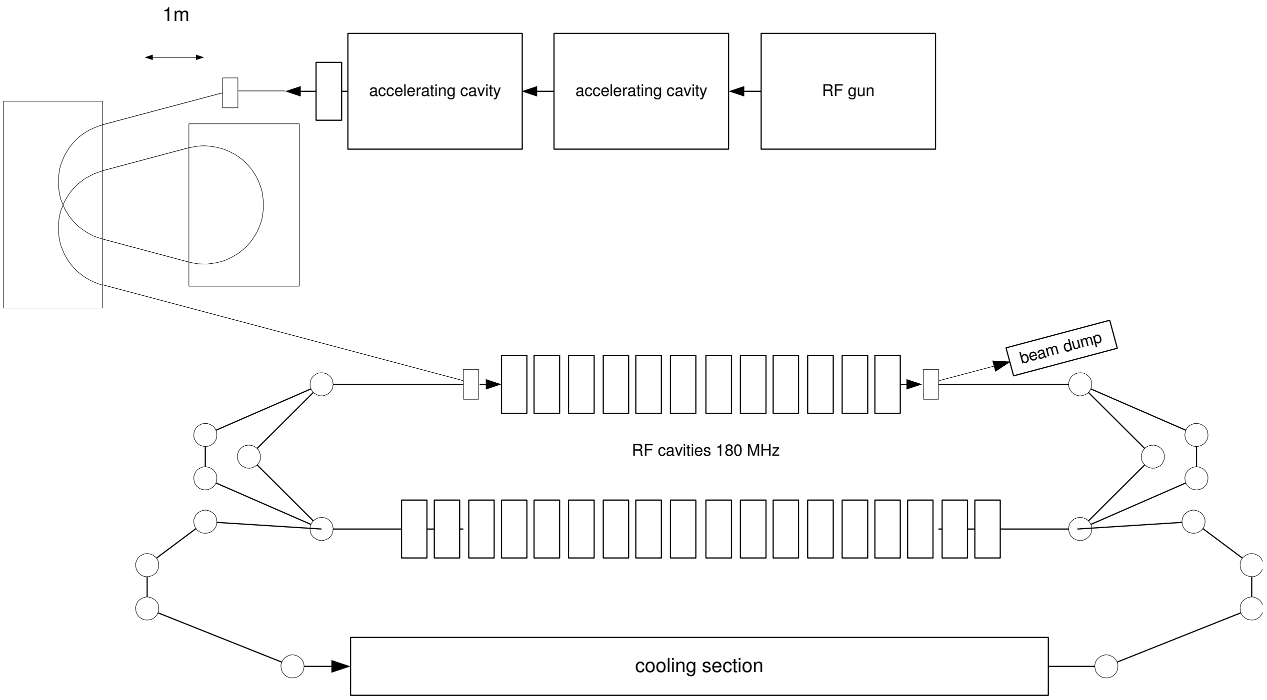

Figure 2: Scheme of cooling ERL.