ECOLOGICALLY CLEAN ACCELERATOR FOR NUCLEAR PHYSICS RESEARCH

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Abstract

Rigid ecological requirements to human activity including industry and science force to search for specific technologies to reduce the undesired influence on nature. High intensity accelerators belong to the objects that produce radioactive waste. We have studied rf accelerator schema where the electron beam used is directed again into the same accelerator with appropriate phase in order to reduce beam energy down to acceptable level and in such a way to reduce radioactive problem for environment (beam energy recovering). In addition, this reduces background at experimental area as well as saves rf power in the case of superconducting rf cavities.

The following main processes have been taken into account while considering beam emittance degradation in a target: multiple electron scattering, ionization losses and bremsstrahlung. The first one results in transverse beam emittance growth while the latter two result in beam energy losses and energy spectrum width growth as well. Appropriate calculations have bean made and various plots have been presented. Critical target parameters namely target material nuclei charge as well as target thickness that allows leave a possibility the recovering process can be defines from these plots.

INTRODUCTION

The success in rf superconductivity resulting in accelerating gradient more than 25 MV/m opens quite new approach in accelerator technology for nuclear physics research. Really, in many experiments small part of beam power is used only. For example, in tagged photons experiments an intensity of ten millions photons per second is maximum value for apparatus to be resolved. In similar experiments, thin targets are used that do not disturb beam parameters significantly. The beam used might be directed into the accelerator again and decelerated down to low energy and utilized then thus resulting in experimental background reducing, rf power saving and hence total energy consumption reducing – up to hundreds kilowatts - and preventing surrounding from radioactive waste. It is quite evident a principal reliability of this method, because this technique is possible for very thin target at list. The purpose of this paper is to estimate beam emittance degradation in the case of electron beam as well as to discuss specific accelerators schemes for practical realization.

ELEMENTARY PROCESS IN A TARGET

As it was already mentioned, three elementary processes dominate in electron beam quality degradation after interactions with target atoms and molecules. These are multiple electron scattering, ionization losses and breamsstrahlung.

Multiple scattering results in appearance of angle gauss distribution of a beam being originally consisting parallel electrons. Mean square angle $\left\langle \vartheta^2 \right\rangle$ depends on beam energy E, target material and its thickness *x* as well [1]:

$$\left\langle \vartheta^2 \right\rangle = \left(\frac{E_s}{E}\right)^2 \frac{x}{X_0} , \qquad (1)$$

where X_0 is radiation length of target material and E_s is the constant, E_s=21 MeV. Beam emittance ε after scattering can be estimated as:

$$\varepsilon = \varepsilon_0 \sqrt{1+\theta_s^2/\alpha^2} , \qquad (2)$$

where ε_0 is transverse emittance of the accelerated beam, α is maximum angle coordinate of the phase portrait in transverse phase space. One can see that electrons should be focused on the target in order to minimize emittance degradation.

Electron emits photons of all energies up to the energy of a radiating electron. For this reason, breamsstrahlung results in beam energy widening. One can estimate electron beam spectrum after target with the next formula [1]:

$$w(E_o, E, t)dE = \frac{dE}{E_0}\frac{[\ln(E/E_0)]^{(t/\ln 2)-1}}{\Gamma(t/\ln 2)} . \qquad (3)$$

Hear $w(E_0,E,t)dE$ is the probability for an electron with initial energy E_0 to have the energy in interval from *E* up to *E+dE* after the target with the thickness t (in radiation length units), Γ is gamma function. Fig. 1 is an example of such a spectrum for energy beam of 1 GeV.

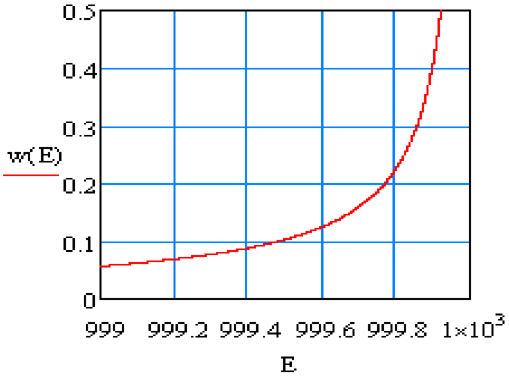

Fig.1. Electron beam spectrum after a target.

Relative number of electrons *n(ξ,t)* in energy interval *(E,E₀)* is given by the formula

$$n(\xi, t) = 1 - \frac{\Gamma(t/\ln 2, -\ln \xi)}{\Gamma(t/\ln 2)} , \qquad (4)$$

that follows from (3) by integration over energy interval mentioned. Here $\xi = E/E_0$ and $\Gamma(t/\ln 2, -\ln\xi)$ is complementary incomplete gamma function of two arguments [2]. Fig. 2 illustrates this dependence.

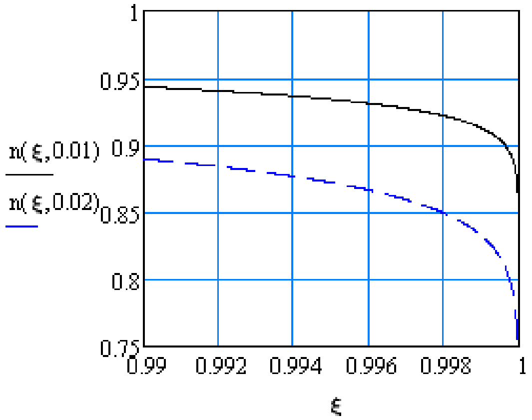

Fig.2.Relative electrons number in energy interval (E,E$_0$).

Electrons lose their energy also due to interactions with media electrons that results in media atoms excitation and ionization as well. The next formula takes place for average ionization losses of an electron with energy E [3]:

$$\frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} \approx \frac{E(MeV)Z}{800}, \tag{5}$$

where *dE/dx* stands for specific energy losses, Z is nuclear charge. It follows from the formula that one may neglect ionization losses for energies of the order 1 GeV and higher. It is worth while to note also that ionization mechanism of energy losses do not results in first approximation in energy spectrum widening.

Fig. 3 serves to estimate average beam losses in target material due to breamsstrahlung. This plot is the graphical representation of the formula:

$$W_{lost} = \int_0^{E_0} Ew(E_0, E, t)\,dE\,. \tag{6}$$

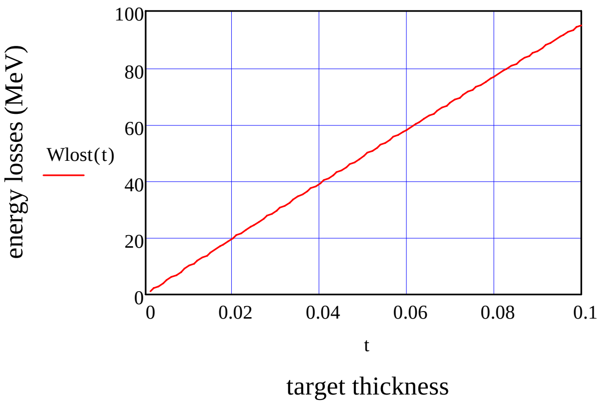

Fig. 3. Electron energy losses due to breamsstrahlung.

RF ACCELERATOR AND RECOVERY SYSTEM

Fig.4 represents one possible solution of the facility under discussion. The whole complex consists of superconducting rf electron linac and beam recovery system. The latter is formed by two achromatic translation magnet systems, experimental target and achromatic 180 degrees beam bending system. The first translation system provides parallel translation of the beam after linac and directs it onto a target while the second one provides return of used beam again into linac. With the appropriate rf phase adjustment the moving from the linac end to its beginning electron beam delivers its kinetic energy to the rf field in linac cavities. Low energy beam then is deflected by the last magnet of the injection system and directed to the beam absorber.

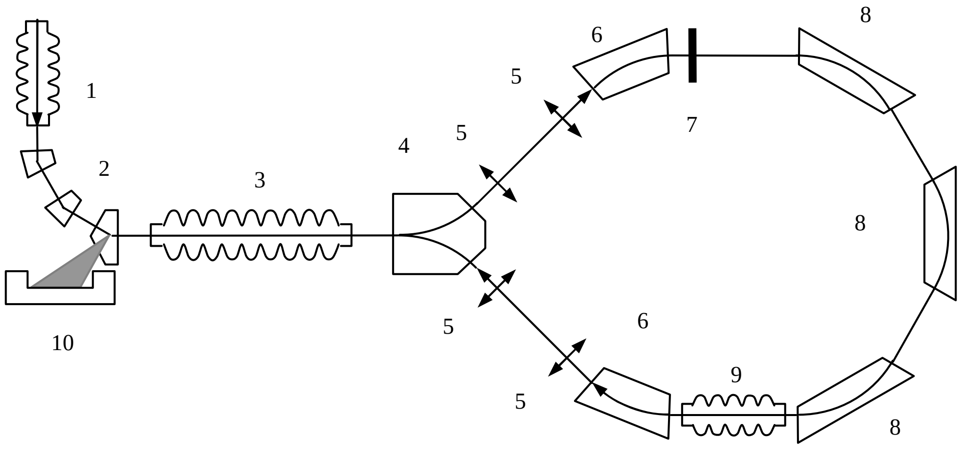

Fig. 4. Layout of the superconducting linac for nuclear physics research with beam energy recovery. 1 – injector linac; 2 –achromatic bending magnet system; 3 – main superconducting linac; 4,5,6 – achromatic translation system, including bending magnets 4 and 6 and magnetic lenses 5; target; 8 – achromatic bending system; 9 – energy and spectrum correction linac; 10 - low energy electron beam absorber.

Injection system consists of injection linac and an inflector. The latter serves to deliver injected beam into the main accelerator axis as well as to direct decelerated low energy beam to beam absorber.

Twofold effect is achieved by recovery system. First, beam utilized at low energy thus preventing of radioactive waste production. Second, rf power required for high energy high intensity beam production can be reduced significantly. Electron beam rf power consumption is reduced from the value *IE* for usual linac with the enery E and average beam current I to *kIE* for recovery scheme, where $0<k<1$ is recovery efficiency. Assuming, for example realistic value k=0.9 (90 percent of initial beam intensity is delivered to linac exit and decelerated successfully down to injection energy), E = 1 GeV, I= 100 μA one needs klystron power around 10 kW for recovery scheme instead of 100 kW for usual linac in order to have the beam of 1 Gev with the current 100 μA on experimental target.

USED BEAM EMITTANCE, DECELERATION AND RECOVERY EFFICIENCY

Transverse beam emittance after target can be estimated by formula (2). Assuming for estimation $\theta \sim \alpha$ that means that transverse beam emittance guarantees successful deceleration of used beam with very large optimism one can estimate maximum admissible target thickness. We obtain from formula (1) $x/X= (\theta E/E_s)^2 =0.01$ for $\theta=0.001$ and $E=2.Gev$. Quite evident considerations results in much higher admissible thickness.

For such target thickness, 95% of used beam intensity is confined in energy interval 1%, as one can see from fig. 2. Beam with such energy spread can be accepted by linear accelerator and decelerated successfully down to low energy that results in recovery efficiency 95%. Much higher energy acceptance (up to 5-10% and more) do not results to equivalent growth of recovery efficiency as it seen from appropriate plots, but one should maximize portion of successfully decelerated beam in order to reduce background and appropriate radioactive pollution of the environment.

Beam energy spread after target results in micro bunch lengthening after achromatic bending system if longitudinal dispersion is not equal to zero. This effect might be used to control beam parameters before deceleration in the main linac. Shown in recovery loop additional linac is used to compensate energy losses in the target and to correct longitudinal beam emittance before deceleration. The solution of the system (if exists)

$$\begin{aligned} eU[\cos(\varphi+\Delta\varphi)-\cos\varphi] &= \Delta E \\ eU\cos\varphi &= \Delta E \end{aligned} \qquad (7)$$

determines parameters *U* (voltage amplitude of the linac) and acceleration phase φ that compensate completely beam energy spread, linear energy spread in small phase spacing being assumed. For such a case evident solution

$$\tan\varphi = 1/\Delta\varphi;\; eU = \Delta E/\cos\varphi \qquad (8)$$

can be found. In general, such technique allows to compensate energy spread before beam deceleration. eU, ΔE and $\Delta\varphi$ in formulae (7,8) stand for the maximum energy of additional linac, energy spread and appropriate phase interval after passing bending magnet system.

With other important parameters of used beam, energy spread of the decelerated beam determines recovery efficiency as well. In order to avoid particle losses in the linac, the decelerated beam has to be extracted from the accelerator before maximum energy in beam bunches becomes equal to energy spread. This energy spread is the same as one immediately after target if non dispersive bending magnet schemes are used. In the case of achromatic bending with longitudinal dispersion energy spread results in bunch width lengthening, and this might be used for optimum matching of the longitudinal beam emittance with the linac acceptance.

CONCLUSION

We have discussed the accelerator complex for nuclear physics research scheme that uses a specific magnetic optics to direct electron beam after target again to the same accelerator in order to decelerate it down to low energy. This reduces rf power consumption since decelerated beam returns it into linac cavities. This if not prevents completely environment from radioactive waste production and background but reduces these significantly. The recovery efficiency might be as high as 90% and more. We have restricted ourselves by approximate formulae and estimation showing readability of the conception under discussion. With the approach have been developed calculations and simulation for specific schemes will make clear the details of the recovery process.

REFERENCES

[1] B.Rossy. High energy particles. State Publishing House of Technical and Theoretical Literature, 636 pp. Moscow 1955. (In Russian).

[2] Olver F.V.J., Asymptotics and Special Functions. Academic Press, 1974. 584 pp. Also Moscow, Nauka, 1990. 528 pp. (in Russian).

[3] K.N.Muchin. Experimental nuclear physics, in two volumes v.1, 616 pp. Energoatomizdat, Moscow 1983. (In Russian).