SUPERCONDUCTING RF ELECTRON RECIRCULATOR FOR NUCLEAR PHYSICS RESEARCH AT LEBEDEV PHYSICAL INSTITUTE

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Abstract

Conceptual design of the superconducting rf accelerator is discussed. This machine is supposed to be used in the field of low and intermediate energy nuclear physics. Four pairs of dipole magnets at the vertexes of square and four superconducting rf linacs between them form a configuration that allows multiple electron beam acceleration from the injection to the final energy, synchronism being provided by proper orbit lengthening in bending magnets after each turn. Additional superconducting rf linac is used for injection into the main accelerator. Special design of dipole magnet makes it possible to stop recirculation in order to guide beam to experimental area. Thin target is used for experiments in order to recover beam energy. This allows to save rf energy and to provide safe radiation conditions of the accelerator as well.

Synchronism conditions as well as dipole magnet design dictate the energy gain per turn in the accelerator. For field strength about 14 kGs in dipoles the energy gain per turn is 600 MeV for TESLA type superconducting cavity (f=1.3 GHz), and the maximum electron energy 2GeV might be realized with 3 turns. Taking into account the working accelerator gradient 25 MeV/m of TESLA type cavity the accelerator might be placed in existing accelerator hole of the high energy physics department in Troitsk where electron synchrotron to the energy 1.3.GeV is under operation now.

The main arguments in favor of accelerator schema suggested are given in the paper. Beam optics as well as recovery problems are discussed followed the appropriate beam envelope calculations.

INTRODUCTION

There are still many problems in low and intermediate energy elementary particle and nuclear physics to be solved in order to make clearly fundamental interaction nature. We refer anyone to appropriate literature for details restricting ourselves pointing out the energy range of accelerator for these purposes. CW electron accelerator with the maximum energy 300-500 MeV might be useful for one group of the problem of interest, while electron beam in energy range 1-2 GeV is necessary for other class of the problems to be solved.

With the appropriate upgrade Lebedev Physical Institute electron synchrotron with the maximum energy 1.3 GeV might be used to solve some problems in the energy interval mentioned above. This concerns accelerator intensity and beam quality as well first of all. Taking into account synchrotron age (more than 30 years of operation), many of accelerator systems should be replaced with more modern and reliable. These considerations lead us to conclusion to build up completely new accelerator maximally using existing synchrotron environment namely accelerator building, power supply, control rooms, experimental holes.

Due to considerable success of rf superconductivity – accelerating gradient more than 25 MV/m – reticulating schema with rf superconducting multi cell accelerating cavities seems to be quite reasonable solution in order to feet the whole accelerator or its main part to existing synchrotron hole. Its dimensions namely square geometry 25*25 m^2 dictate possible accelerator geometry. This might be recirculator of politron type of the order 4, or the one of the CEBAF type with orbit separation in horizontal plane.

Assuming the planed electron beam energy of order 1GeV and accelerated current 100 μA one obtains average beam current 100 kW, the main part of this power being absorbed in beam burial thus resulting in pollution of the environment and radiation background. Below, we discuss the possibility of electron beam energy recovering that partially allows avoiding the problem mentioned and saving the total accelerator energy consumption as well.

RF ACCELERATING UNIT

Our conceptual design is based on modern rf superconducting accelerator technology that have being developed in the world during mainly last two decades of 20^{th} century. While CEBAF project is the most impressive example of large scale production and use of superconducting cavities in large facility, the TTF (Tesla Test Facility) at DESY is not less impressive example of R&D success resulting in industrial ready technology of large scale production high gradient multi sell superconducting cavities.[1]. Accelerating gradient had been increased up to 25 MV/m due to improving niobium sheets for cavity production and post production cavity preparation. Niobium with RRR of 300 is nowadays industrial standard. RRR is the ratio of resistivity at room temperature and 4.2 K (with applying magnetic field in order to keep niobium in normal conducting state) and characterizes the material purity and hence its high thermal conductivity at low temperature, that prevents quench (thermal break down). The main cavity parameters are collected in table 1.

Table 1. Main parameters of the superconducting TESLA cavity

Resonance frequency	1300 MHz
Number of cells	9
Shunt impedance $R/Q = V_{ac}^2/P_{dis}*Q$	1 kOm
Quality factor Q at bath temperature 2.0 K	> 5*10^9
Accelerating gradient (MV/m)	> 25
Iris diameter	70 mm
Equator diameter	206.6 mm
Active length	1.038 m

RECIRCULATOR

Recirculation schemes are used to optimize capital and operational cost of the accelerator complex. In ore case, square hall geometry results in appropriate accelerator geometry in order to adjust maximum electron beam energy to space available. At conceptual design step, two schemes are under discussion.

Polytron of 4th order (octutron) [2] with four accelerator sections and four pairs of bending dipole magnets is possible solution. In general, polytron is circular electron accelerator with k periodic element, each being formed by accelerating structure and pair of dipole magnets that provide achromatic transition of electrons from the last structure to the next one. The synchronism condition in the accelerator is provided by lengthening trajectory in any magnet doublet by integer number of wavelength λ after each turn:

$$\Delta L = g\lambda \,, \qquad (1)$$

g=1,2,3,…

One can obtain easily from geometry:

$$\Delta L = 2\Delta R(\vartheta - \sin\vartheta), \quad \vartheta = \pi / k \,, \qquad (2)$$

and the next formulae follow for trajectory radius increase ΔR, orbit spacing d and energy increase ΔE:

$$\Delta R = g\lambda \frac{1}{2(\vartheta - \sin\vartheta)}, \quad d = \frac{g\lambda}{2}\frac{1-\cos\vartheta}{\vartheta - \sin\vartheta},$$

$$\Delta E(MeV) = 1.5B(T)g\lambda \frac{1}{\vartheta - \sin\vartheta}, \qquad (3)$$

where B is magnetic field strength. The main accelerator parameters estimated with formulae (1-3) are listed in table 2; accelerator scheme is presented on fig. 1.

Table 2. The main parameters of the octutron.

Total energy	2050 MeV
Energy increase per turn	600 MeV
Energy increase in one linac	150 Mev
Injection energy	100 MeV
Number of turns	3
Magnetic field in dipoles	1.36 T
Dipole pole dimensions	0.4 m*3.6 m
Minimum radius of electron trajectory	0.6 m
Maximum radius ol electron trajectory	4.7 m
Linac frequency	1.3 GHz

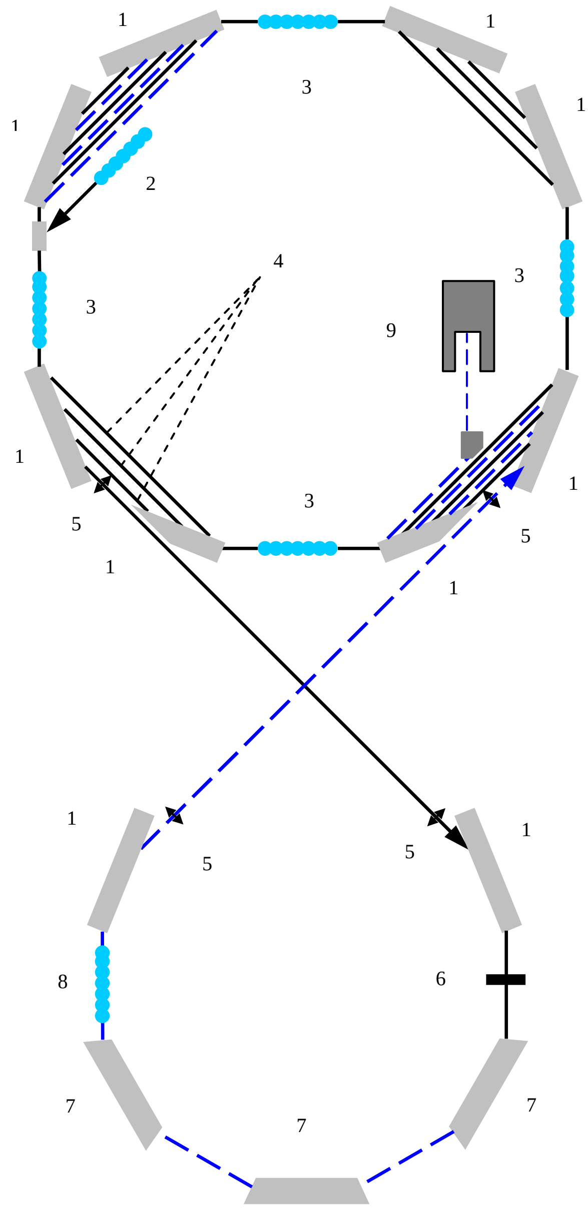

Fig. 1. Forth order politron with beam energy recovery system. 1 – magnet doublet, 2 – injector, 3 - superconducting linac, 4 - electron trajectories (dashed lines correspond to recovery beam), 5- magnetic lens, 6 – target, 7 – achromatic magnet bending system, 8 – energy and spectrum correction linac, 9 - low energy electron beam absorber.

Double side recirculator is formed by two parallel rf superconducting linacs and six independent recalculating arcs that provide achromatic electron beam translation from the exit of one linac to the entrance of the other one. Dipole magnets after each linac split beams of different energy and direct these to individual arc, while that before linac collect trajectories with different energies. Beam extraction in its direction to experimental area is provided in manner just described in previous paragraph. In spite of seeming inconvenience this scheme seems to be more flexible because provides independent adjustment of each turn.

BEAM ENERGY RECOVERING

In many modern experiments only small part of beam energy is used to study nuclear and elementary particle interactions. Unused beam energy absorbed is special beam burial, additional background being produced both for experiment itself and surrounding as well. To avoid this, electron beam energy recovery scheme might be used.

At high energy, two processes result in beam quality degradation mainly. These are multiple electrons scattering as well beam bremsstrahlung that lead to beam emittance growth. Details of calculations one can find elsewhere in these proceedings [3], while appropriate formulae are given below. For electron scattering:

$$\theta_s^2 = \left[\frac{21}{E(MeV)}\right]^2 \frac{x}{X_0}, \qquad (4)$$

where θ_s^2 is mean-square scattering angle, E – electron energy, x – target thickness, X – radiation length of target material. Beam emittance ε after scattering can be estimated as:

$$\varepsilon = \varepsilon_0 \sqrt{1+\theta_s^2/\alpha^2}, \qquad (5)$$

where ε_0 is transverse emittance of the accelerated beam, α is maximum angle of ellipse in transverse phase space. It is seen from the last formula, that electron should be focused on target in order to minimize beam admittance degradation.

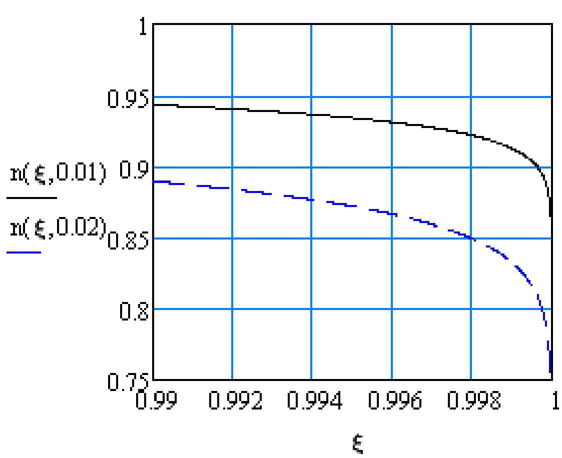

Fig. 2. The relative electrons number in definite energy interval

Bremsstrahlung results in electron beam energy spectrum widening. The next formula gives the relative number of electrons after interaction with a target that have normalized energy not less the definite value:

$$n(\xi,t) = 1 - \frac{\Gamma(t/\ln 2, -\ln\xi)}{\Gamma(t/\ln 2)}. \qquad (6)$$

Here $\xi = E/E_0$, t is target thickness in radiation length units. Fig.2 lustrates this dependence for different target thickness.

To recover rf energy stored in the electron beam, a achromatic system of three magnets is used after target that provides 180 degree utilized beam rotation. Together with additional bending dipole magnet this system directs interacted electrons to the second dipole magnet of dipole pair as it is seen from fig.1. If the phase of used beam is adjusted in such a way that electrons see the decelerating rf field in cavity as well as the difference between accelerated and used bunches is close to π used beam looses the energy. One can make accelerator design in such a way, that decelerated trajectories coincide with those of accelerated bunches in odd dipole pair while are between the main beam pipe in even dipole pairs. To have this, an adjustable decelerating linac in beam recovery loop is used as it can be seen in fig. 1. Details of recovery system performance one can find in [3]. After the used beam energy decreases down to definite value, low energy beam is deflected in dispersive part area of dipole pair and directed into beam absorber.

Of course, recovery efficiency depends strongly on beam quality after target. As one can see from the above formulae, it seems that energy spectrum widening is much more sensitive to target thickness and hence more worrying that transverse beam heating. On the other hand, one can control first process – achromatic bending results in longitudinal dispersion and energy spread phase dependence appearance, that in turn makes it possible to decrease absolute energy spread of used beam and thus to reduce beam lost during deceleration [3].

CONCLUSSION

We have discussed one possible solution for new electron accelerator at Lebedev Physical Institute. Modern accelerator technologies make it possible to accommodate cw accelerator complex into existing environment. Beam energy recovering allows to reduce rf power consumption significantly and to minimise radioactive background as well. Detailed beam longitudinal and transverse beam dynamics studying as well as engineering of the complex are foreseen.

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