INTRA-BUNCH ENERGY SPREAD OF ELECTRONS IN POWERFUL RF LINACS FOR NUCLEAR PHYSICS RESEARCH*

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Abstract

There are some particles in RF electron linacs with energy that may be significantly different from that of particles within a core of the bunch. Loss of these particles at average beam power of tens of kilowatts can cause radiation and thermal problems. Filtration of such particles during the initial stage of acceleration, at energies below the threshold of photonuclear reactions, is important. The paper analyzes several ways to perform such type of filtration in the injector part of a powerful electron linac using a RF chopper or magnetic systems.

INTRODUCTION

A facility with subcritical nuclear assembly driven by an electron linac is under construction at NSC KIPT. To drive the assembly it is necessary to get 100 kW of beam power at particle energies about 100 MeV. There were several projects of the linac developed since 2005 when the work was started. The main problems concerning the electron beam that complicated the task were beam blow-up, transients and intra bunch energy spread. The present paper is mainly devoted to consideration of ways to diminish intra bunch energy spread for the linac, which design is described in [1].

DESCRIPTION OF THE LINAC

Configuration of the linac was chosen on a base of numerical simulation of particle dynamics. Self consistent simulation taking into account excitation of high order modes (HOMs) was studied with technique described in [2]. Detailed transversal and longitudinal dynamics of particles were simulated using EGUN, PARMELA, MADX codes as well as technique [3] and COUPLEREZ code. As a result of simulation following linac configuration was chosen. The linac consists of an injector and five accelerating sections. Evanescent wave buncher [4] was chosen as an injector of the linac. As travelling wave acceleration sections we chose 3.7 m long S-band disk loaded waveguide (DLW) with 120° phase advance per a cell. The base section has a linear taper of iris radii from 14 mm to 12 mm. To diminish cumulative effect of HOMs excitation initial part of the sections (first 20 cells) has different taper. Initial iris radii (a_0) are 15 mm, 14.75 mm, 14.5 mm, 14.25 mm and 14 mm. Filling time of the section is about 0.6 µs. At RF power supply of 19 MW and beam current of 0.6 A energy gain of the sections are about of 24 MeV.

It seems more economically to place linac in horizontal plane but the subcritical assembly needs vertical lead-in of the beam. For this purpose the linac is equipped with a 90° achromatic bend (see Fig. 1).

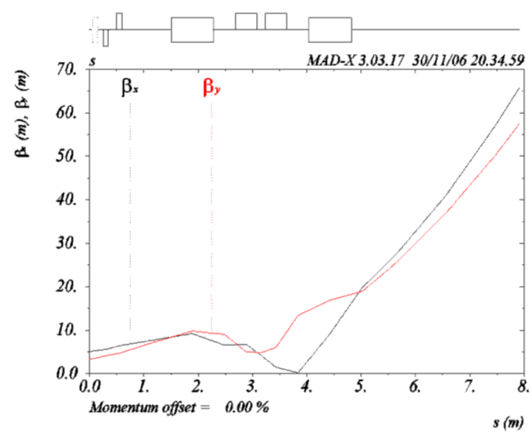

Figure 1: Optic functions of a 90° achromatic bend.

It is almost impossible to avoid particles in “tail” of phase–energy distribution under bunch formation at single RF frequency in axially-symmetrical electromagnetic fields. At perfect alignment such particles can travel enough far along the linac causing radiation and thermal problems. To partially eliminate such problems we decided to use magnetic chicane installed between the first and the second sections. Bending radius of magnets is 436 mm, which corresponds to the field in magnets of 1872 Gauss at the energy of particles 24 MeV. Bend angle of magnets is 23.8°, middle magnet has a double angle. The leading and trailing edge angles on the first and the last bending magnets are zero correspondently. The exit angle of the first magnet and the entry angle of the last magnet are equal to 3.1°. The middle bend magnet has the same edge angles of 32.7°. A collimator to limit the energy spread of particles is installed at the exit of the middle magnet. Coefficient R_{56} of a chicane transport matrix that is responsible for longitudinal motion of particles equal to 0.1 m. A couple of quadruple doublets provide beam matching with transportation channel (see Fig. 2). Beam transportation through a rest part of the linac is provided with quadruple doublets at the exits of each accelerating sections.

SIMULATION RESULTS

Simulation shows that at initial energy 1 MeV of point like bunches and RF power of 19 MW the accelerating section with a_0=14 mm. has starting current of HOM

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instability excitation that equal to 0.6 A. This value for the section with maximal initial iris radius a_0=15 mm is 1.2 A. To minimize HOM excitation it is necessary to place section along the linac in a reverse order on value of the starting current. In this case initial incidental displacement of bunches do not lead to instability build-up inside one section. Although bunch displacement grows in order of magnitude along the linac due to cumulative effect of HOM excitation, this growth is lower in order of magnitude than that in case of identical sections with maximal initial iris radius. Therefore the linac with such configuration has low value of displacement amplification and one can hope to get good transversal beam characteristics.

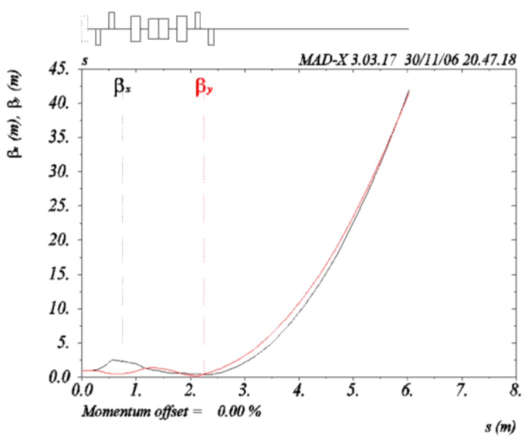

Figure 2: Chicane optic functions.

At self-consistent simulation of particle motions with technique [3] we used following parameters. RF power feeding of each section was 20 MW. Leading and trailing edges of current pulse were 0.21 µs, flat-top part of this pulse was 2.3 µs, leading and trailing edges of RF pulse were 0.42 µs with full width at half of magnitude (FWHM) of 3.57 µs. To compensate influence of beam loading current pulses we use the time delay method. Phasing of the sections 2 through 5 was performed by beam inducing method. Phasing of the injector and the first section was aimed on obtaining more particles in high energy region at maintaining good efficiency of the section. Reference energy of the chicane (23.8 MeV) and collimator transverse position were chosen in such way to cut particles below energy of a left edge of the distribution shown in Fig. 3. Particles with position left from particles with maximal energy, are compressed while the rest of particles are decompressed after the chicane. So, totally phase length of cut part of bunches almost does not change and is about of 70°. At the same time a core of bunches is enough dense (see Table 1). It is necessary to note that at phasing of the sections with beam induced method we place the core of bunches at wave crest. In this situation "tail" of bunches has lower energy gain and at the linac exit minimal energy of particles is about 70 MeV (including influence of transients).

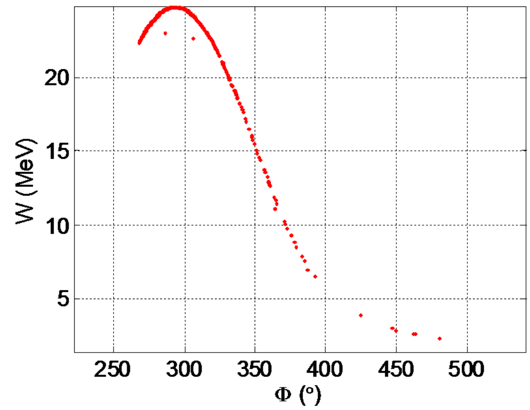

Figure 3: Steady state phase-energy distribution of particles at the exit of the first section.

Table 1: Beam Parameters

Beam parameter	1 section	Linac exit	Target
Current, A	0.711	0.650	0.613
Average energy, MeV	24.8	120.6	121.6
Energy spread (70% of particles), %	16	4.6	3.5
Phase length (70% of particles), degree	20.8	6.6	6.0
Normalized emittance $\varepsilon_{n\ rms\ x,y}$, mm·mrad	12, 12	67, 39	301, 35

Influence of energy spread and transients on transportation of beam to the target one can see in Table 1 and Fig. 4 – Fig. 5. Low energy particles get lost so average energy after the bend is some higher.

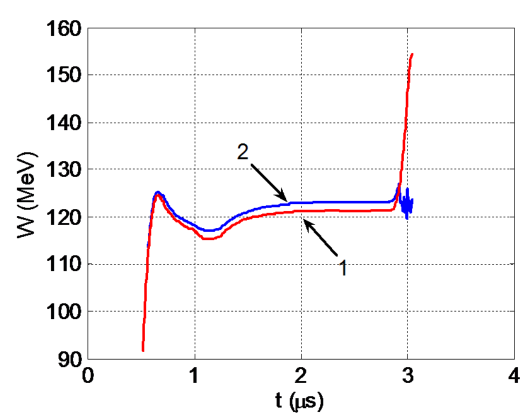

Figure 4: Average beam energy within current pulse at the linac exit (1) and after the bend (2).

Between the exit of the first section and the target beam loss is 14% including 6% losses in the bend. To get 100 kW power on the target it is necessary to have duty factor of 0.134% (or 600 pps at 2.3 µs pulse duration). At this duty factor the main losses are in the bend (5 kW) and in chicane (about 1.5 KW).

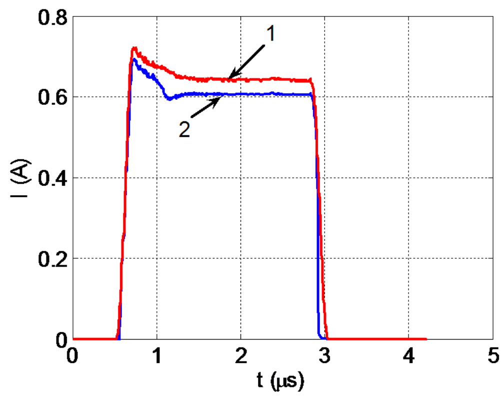

Figure 5: Beam current at the linac exit (1) and after the bend (2).

Energy characteristic of beam on the target is shown in Fig. 6. Overall energy spread is about 12%.

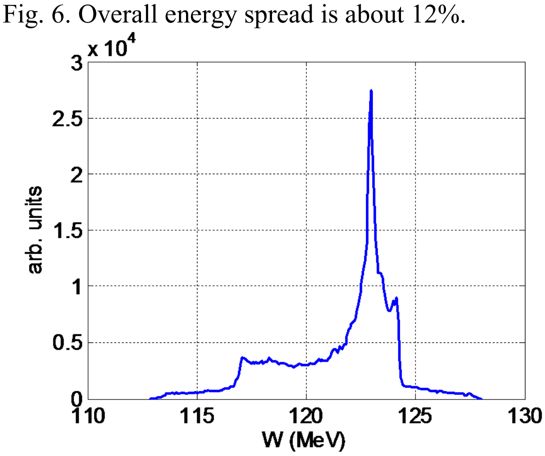

Figure 6: Energy spread on the target for the whole current pulse.

DISCUSSION

Although it seems that particle losses are not too high they can cause problems with radiation safety because of high energy neutron generation. Therefore filtration of such particles at energies below the threshold of photonuclear reactions is very helpful. We considered several variants to change an initial part of the linac. One of them is using short KUT type section [4] and the injector [5]. At RF power supply 1 MW and 8 MW of the injector and the section respectively this scheme provides 0.61 A beam current at energy of 8 MeV after the chicane (see Fig. 7). In steady state regime 12.5% of particles are lost in the chicane (85 mA). Phase length of bunches after filtration is 31° (99% of particles) and transversal emittance in a plane of deflection becomes even lower because filtration of harmful particles. It allows beam transportation through the linac and the bend without appreciable losses.

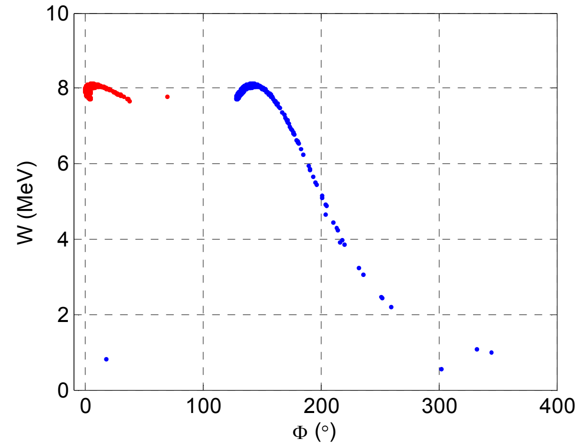

Figure 7: Phase-energy distribution before (blue dots) and after (red dots) the chicane.

We also simulated particle filtering with RF deflector. For this purpose we applied to particles phase dependent transversal momentum with amplitude that was of 5% from average longitudinal momentum. For the case just mentioned above a 20 mm collimator with aperture 10 mm installed at distance of 120 mm provides about the same current and phase length of bunches. Because of initial bunches are longitudinally non symmetrical, after filtration bunches have nonzero average transversal momentum in a plane of deflection and about five time increase of transversal emittance. So this method needs more study.

SUMMARY

At design of high power electron linacs for nuclear physics research it is necessary to take care about filtration of intra-bunch energy spread at energies below the threshold of photonuclear reactions.

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