PULSED RF ACCELERATOR OF ELECTRONS WITH BEAM RECIRCULATION*

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Abstract

We discuss the project of upgrading existent 20 MeV L-band electron linac at Argonne National Laboratory aimed at electron energy increasing. It is shown that the proposed beam recirlculation will provide an electron beam with a pulse current 0.5 A and energy of particles 45 MeV on the accelerator output. Problems of stability of recirculating beam are discussed.

INTRODUCTION

The L-band linac of the Argonne National Laboratory Chemistry Division has been put into operation in 1969 [1]. At the present time the injector part of the linac consists of a triode 135 kV electron gun, 12th- and 6th-subharmonic prebunchers, a single-cavity prebuncher, five-cell traveling-wave prebuncher and a traveling-wave buncher. The later three elements are operating at the linac fundamental frequency of 1300.7 MHz. The main acceleration of particles is performed in the two tapered accelerating traveling-wave sections. The shunt impedance of the section is 40 MOhm/m, the beam loading factor is 1.93 MeV/A. The linac delivers relativistic electron beams in multi-bunch pulses with duration from $4\cdot10^{-9}$ to $5\cdot10^{-6}$ s or in single bunch mode with typical pulse duration of $3\cdot10^{-8}$ s. Electron energy at the linac exit reaches 22 MeV for single bunch mode. At a pulse beam current of 2.0 A energy of electrons does not exceeds 15 MeV in a long-pulse mode.

There is the interest in linac upgrade to increase electron energy to 40 – 45 MeV in the long-pulse mode for photonuclear radioisotope production. Pulse beam power should not be less than 20 MW to prowide sufisient average beam power. Single bunch mode of linac opretion have to be preserved. It is necessary to achieve upgrade without significant changes to the existing RF system and be able to fit into existing room.

In present work we consider one of possible approaches for the linac upgrading that is development of the linac with electron beam recirculation using the existing accelerating sections (including the third section operating now in the bunch compression system).

Upgraded linac will operate with about 0.5 A pulse current that will provide enough high beam loading. To study influence of transients on beam recirculation it was necessary to develop corresponding simulation techniques.

Another critical problem at such high pulse beam currents is beam blow-up (BBU). Therefore it was essential to elaborate simulation technique to research BBU at beam recirculation.

To simulate particle dynamics taking into account beam recirculation we developed codes that were based on two different approaches. First of them represents disk loaded waveguide (DLW) as a chain of coupled cavities (CCC). Self consistent beam dynamics is simulated both in the band of fundamental mode and in the band of the first dipole mode taking into account influence of waveguide couplers [2]. To provide simulation of beam dynamics in recirculator the code was upgraded by adding beam recirculating module. The second approach of self-consistent beam dynamics simulation in linacs consisting of standing wave (SW) and trawling wave (TW) structures was based on technique [3]. The technique only applicable to study slow varying phenomena with narrow frequency spectrum in working pass band of RF linacs. SUPERFISH group of codes [4] and technique [5] were used to evaluate parameters of axially symmetrical SW and TW structures. The PARMELA [6] code was used to simulate particle motion and to evaluate data needed to solve equation of field excitation. Technique [3] was upgraded by adding an algorithm to merge injected and recirculated beams as well as to evaluate parameters of recirculated beam.

CHOICE OF ACCELERATOR CONFIGURATION

A preliminary analysis has shown that configuration with the multiple passing of beam through accelerating sections is rather challenging because of problems, caused by considerable beam loading and pulsed character of beam. Therefore we limited ourselves to only double passage of the beam through accelerating sections. Preliminary simulation of beam dynamics with upgraded CCC model has shown that configuration with single pass acceleration in first section with double beam passage through the second and third section is preferred due to the higher BBU threshold current.

Multiple variants of recirculator arcs were simulated using the programs TRANSPORT [7] and MADX [8]. We have accepted arcs based on the dipole magnet with an angle of rotation close to 90° as being the most compact. The ring is a four-magnet racetrack with two long gaps, for accelerating sections and quadruple magnets. Due to the chosen ring structure one of two long gaps should have the nonzero first-order dispersion. Two accelerating sections were placed in the achromatic

*Work supported by STCU project #P228

dispersion-free gap and two triplets of quadruple lenses were placed on the opposite chromatic gap that provides necessary conditions of ring operation. Due to such versatile ring arrangement the working points can be easy adjusted. The ring structure without an output device is shown in Fig. 1 where 1 is the first accelerating section, 2 are elements of an injection chicane, 3 and 4 are the second and the third accelerating sections, 5 is 12° dipole magnet, 6 and 9 are 102° dipole magnets, 7 are quadruples lenses, 8 are 90° bending magnets.

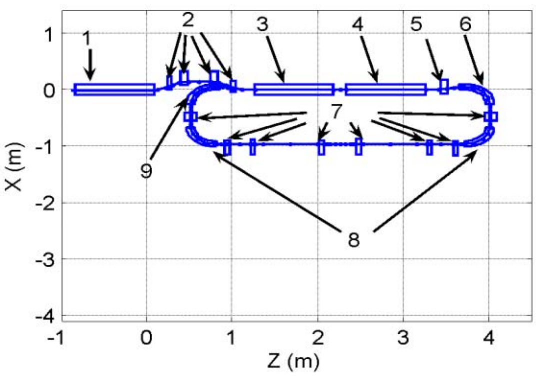

Figure 1: Structure of a recirculator.

After the first passage the electron beam should get into the accelerating section in the corresponding phase. For this purpose we provide a possibility to change the ring orbit length by changing the length of short straight section of the ring. The adjustment range is near 13 cm that exceeds the half wavelength λ of accelerating field in the sections. The angle of rotation equal to 102° is necessary to provide merging of the beam coming from first section and the recirculating beam. This merging is reached in the last magnet of the chicane. For the ring symmetry the right arc (see Fig. 1) and the left arc are similar. The beam extraction (not shown in the figure) is carried out from the 102° magnet of right arc 6. Isochronous motion of particles is reached by two quadruple lenses in the short gaps between the magnets which form the negative first-order dispersion at the orbit segments in magnets 8. There are no focusing magnets on the straight segment with accelerating sections. The beam focusing is accomplished via the nonuniform field in the magnets of arcs.

One of the complicated procedures is the matching of the injected beam with the ring optics. For simulation and optimization of the particle motion from the output of the first accelerating section through the chicane, two accelerating sections and recirculator magnetic system, taking into account the acceleration, a polymorphic code of the MADX program was used.

The amplitude functions for the beam single-pass throughout the ring taking into account the acceleration with the achromatic injection system are shown in Fig. 2. The energy of the reference orbit of the chicane is 10 MeV, and the ring is 27 MeV.

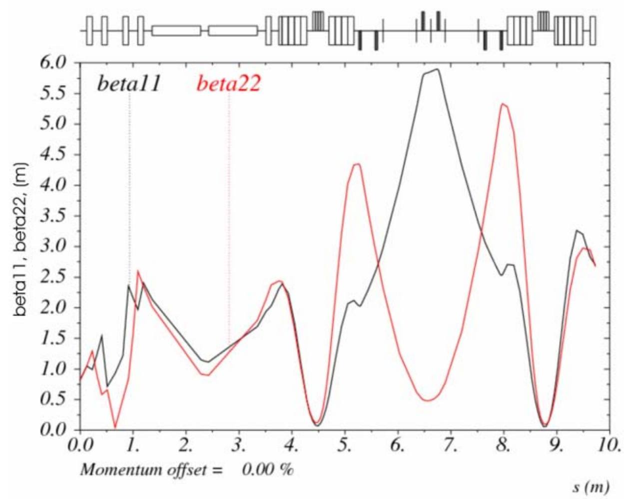

Figure 2: Amplitude functions.

After the second pass through the accelerating structures the beam gets into the bending magnet 6 (see Fig. 1) inside of the equilibrium orbit at an angle directed outwards to it. Then beam trajectory crosses the magnet and goes out of the ring. To return beam on the axis of the accelerating sections it is necessary to use at list two additional magnets. At the moment beam trajectory is calculated in the approach of ideal rectangular field distribution in the magnet 6. More correct calculations taking into account focusing properties of the magnet fringing field can be carried out on the magnetic field map that will be obtained for actual magnets.

We have simulated the unsteady particle dynamics in the recirculator with the use of the modernized technique [3]. The coordinates of particles moving through the magnetic system comprised of dipole magnets with nonuniform field was calculated using transport matrices. After fitting the phases of accelerating field in sections to get a maximal acceleration we have carried out a search for the steady-state regime. It was reached by fitting both the temporary position of the beam current pulse relatively to the rf pulses feeding the sections as well as amplitudes of accelerating field in the sections It is necessary to note if change of output power of klystrons is more than ±2% the operation becomes unstable. The simulation results are presented below. Fig. 3 shows the beam pulses in the critical points of the recirculator. In steady state regime during the first pass through the ring the beam loses the 1/6th of the current injected from the first section while no current losses occur during the second pass. The energy spectra of particles at the third section output are shown in Fig. 4.

The CCC model was used to investigate the dependence of the BBU starting current I_{th} on the ring length in the case of a real transmission matrix of the magnetic system. The results are shown in Fig. 5. L_0 corresponds to the ring circumference equal to 37λ. It is seen that the starting current values for the vertical $I_{th,y}$ and horizontal $I_{th,x}$ polarizations are close to each other and can be made above the recirculator operating current by adjusting the orbit length. Analysis of the longitudinal motion shows that at the level of I_{th} about 1 A the energy gain decrease caused by disturbance of the optimum phasing does not exceed 4%.

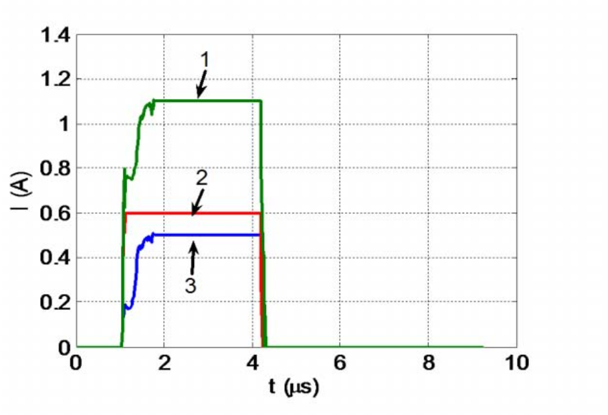

Figure 3: Current pulses: 1 – current at the third section output, 2 – current at the first section output, 3 – current of particles that passed through the ring magnetic system.

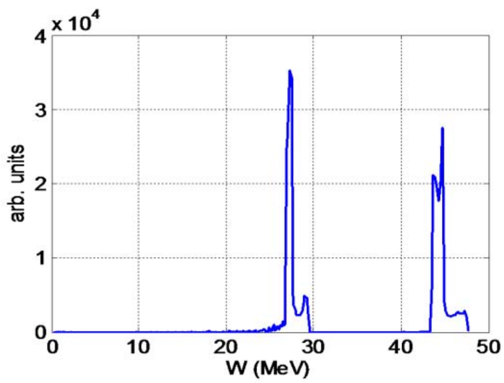

Figure 4: Energy spectrum at the third section output.

Recirculator parameters are given in Table 1.

The setting accuracy of recirculator elements by coordinates is ±0.1 mm, of main bending magnets by the angle – ±0.5 mrad, of all the rest elements – ±1 mrad.

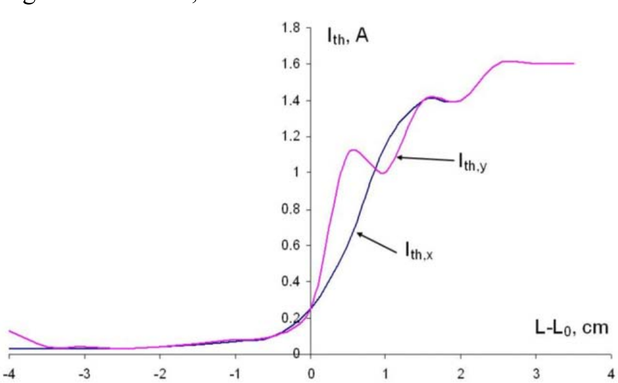

Figure 5: The transverse instability starting current I_{th} versus the ring length.

Table 1: Recirculator parameters

Frequencies of betatron oscillations Q_x, Q_y	~1.5, ~1.5
Number of main dipole magnets	4
Number of quadrupoles	8
Orbit length, m	8.528
Energy at the input, MeV	10
Peak rf power of sections respectively, MW	13,16,16
Current at the input, A	0.6
Energy after the first pass, MeV	27.4
Current after the first pass, A	0.5
Energy after the second pass. MeV	44.7
Current after the second pass, A	0.5

CONCLUSION

The structure of a recirculator is developed that makes possible to increase the particle energy of the Argonne linear electron accelerator up to 45 MeV at a beam pulse current of 0.5A. The results show that at this pulse current the stable particle acceleration can be achieved.

To modernize the linac it is necessary to design and to build nine magnets and eight quadruples together with equipment for their support and alignment. RF system has to be upgraded to TV 2022D klystron to provide enough rf power for accelerating sections.

Exact design of ring output device can be obtained after manufacturing the main ring magnets.

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