LINAC FOLLOWED BY AN ELECTRON COOLER TO PROVIDE A SHORT BUNCH PROTON BEAM*

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Abstract

A cell irradiation scheme with a short pulse duration combining an RF linac with a storage and cooler ring, S-LSR, has been proposed. By application of an electron beam cooling at S-LSR to the 7 MeV output proton beam from the linac, it is demonstrated that a short pulse beam bunch as ~3 ns duration can be provided with the use of a fast beam extraction for the proton beam intensity of ~3 x 10^7 per shot with the repetition rate up to 1 Hz.

INTRODUCTION

Recently, it is reported that laser produced proton beam with a rather higher peak intensity in a short duration can realize double strand breaking (DSB) of DNA of human cancer cells [1]. We want to investigate such a capability with more quantitative manner with a conventional RF accelerator by collaboration with researchers outside of ICR, for example, biologists in National Institute of Radiological Sciences (NIRS).

At ICR, Kyoto University, a proton linac consisting of an RFQ and a drift tube linac (DTL) of Alvarez type with the operation frequency of 433.3 MHz, has been operating since 1991[2,3], which had been mainly used for beam dynamics studies in the RF linac together with material irradiation before construction of an ion storage and cooler ring, S-LSR. After completion of S-LSR [4], the linac has been mainly utilized as its injector for the case of electron beam cooling of 7 MeV protons.

The time structure of the output beam from the linac is illustrated in Fig. 1[2]. The main parameters of the linac are listed up in Table 1[3]. Its macro pulse width is 50 μs with the maximum repetition rate of 180 Hz although the RF pulse width is designed to be 60 μs as is known from Fig. 1, because the RF filling time of the DTL is ~10 μs. due to a rather high quality factor of its cavity. As the microscopic structure of the RF has a periodicity with ~2

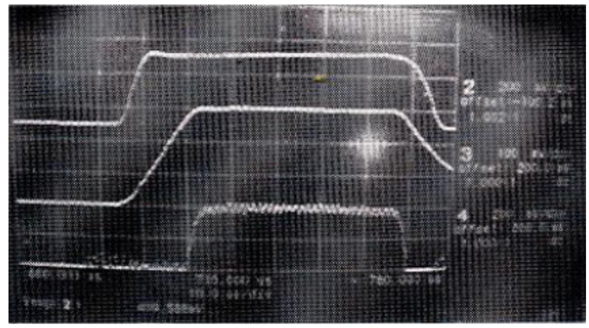

Figure 1: Observed signals of picked up RF power levels of the RFQ (top) and DTL (middle). The bottom signal is the output beam accelerated by the whole linac system. Time scale in abscissa is 10 μs/div.

ns, the output beam of the linac is considered to have a microscopic width well less than ~1ns. If one of them can be selected out, it can give a very short pulse proton beam, which might be usable as a timing pulse for measurement such as TOF measurement. It, however, requires very fast deflection elements, and is considered to be very difficult to realize for higher energy protons usable for cancer therapy.

Up to now, the time structure of our linac has been paid attention in order to attain longer possible pulse width so as to reduce the rate of accidental coincidence for the case of direct use for physics experiments. As the rising time of the output beam of our linac is rather long as ~10 μs, it is not possible to provide a short pulse beam as ~15 ns duration by direct delivery of the output beam of linac. In order to attain the similar or higher dose rate compared with the laser-produced proton beam keeping such a condition as not damage the nearby normal cells for the case of medical usage, we are proposing the scheme to cool down the output beam of the linac after injection into an ion storage ring, S-LSR. In the present paper, such a scheme and its attained results are presented.

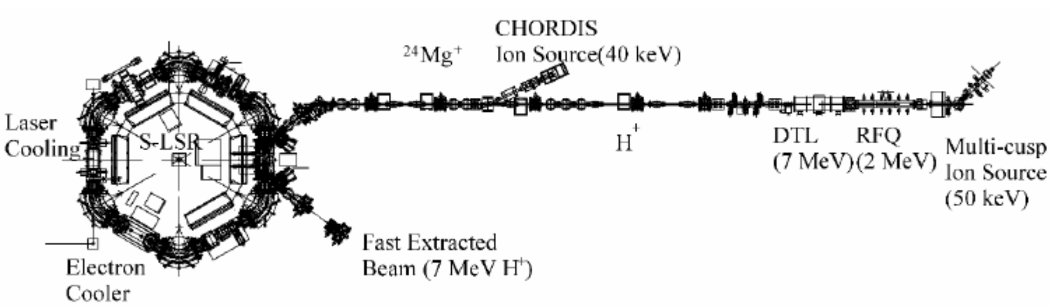

Figure 2: Layout of a combined system of a proton linac with an Ion Storage and cooler ring, S-LSR.

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Table 1: Parameters of Proton Linac at ICR, Kyoto University

Multicusp ion source	
ion species	H^+, H^-
extraction voltage	50 kV
RFQ linac (4-vane)	
vane length	2195 mm
characteristic bore radius	3.0 mm
minimum bore radius	2.0 mm
intervane voltage	80 kV (1.8 Kilpatrick limit)
output beam energy	2 MeV
transmission efficiency	95% (at 30 mA)
Alvarez linac	
tank length	1868 mm
number of drift tubes	28
Q magnet	NdB permanent mag.
maximum surface field	26 MV/m (1.3 Kilpatrick limit)
beam energy	7 McV
RF power source	
klystron	L-5773 (Litton)
output peak power	1.2 MW
frequency	433.3 MHz
Rep. Rate	Up to 180 Hz
duty factor	~1 % (maximum)

SCHEME OF CREATION OF SHORT PULSE PROTON BEAM

Required Condition of Irradiation

The beam irradiation condition by the laser-produced proton beam which showed the capability of DSB of DNA can be summarized in Table 2. Due to low LET, proton beam is considered to be inadequate for DSB of DNA in the cancer cell keeping the normal cells unaffected, which we want to check in more quantitative way. The condition in Table 2 is our tentative goal to be realized with the use of a conventional RF accelerator, except for the beam energy, for which, we utilize the output energy, 7 MeV, from our total linac system because of its merit of easiness of irradiation of the cells

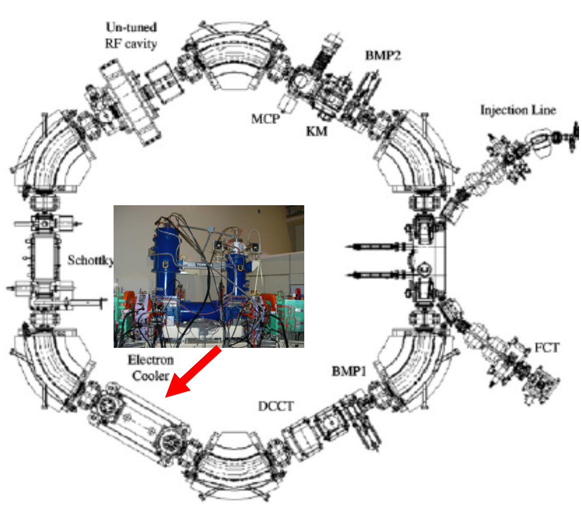

Figure 3: Layout of S-LSR [4]. The circumference and superperiodicity are 22.557 m and 6, respectively.

Table 2: Parameters of Laser-produced Proton Beam [1]

Beam Energy	0.8-2.4 MeV
Proton Number per shot	2.5±0.5 x 10^4
Irradiation Size	1 mm in diameter
Pulse Duration	15 ns
Repetition rate	1 Hz
Dose Rate per shot	0.1±0.02 Gy

through window keeping the cells in atmospheric condition. As is shown in the table, the dose rate is required to be controlled very precisely in order to be applied for medical irradiation. So our scheme is also required to have precise controllability.

Injector Linac

Our linac system consisting of an RFQ and DTL can provide the proton beam with 7 MeV up to 2 mA in peak intensity, which includes ~2 x 10^8 protons in 15 ns time interval. The direct use of this output, however, cannot match with our purpose because it is not so easy to select out the beam only in this time interval. The rising and falling time of the kicker magnet is longer than a few tens ns, which disable us to create such a short pulse as ~15 ns and, more seriously, precise control of the beam duration shot by shot is very difficult. It is inevitable to apply the further process to the linac output to create the needed time structure with good accuracy.

Accumulation and Cooling Scheme

In order to realize proton beam irradiation with short pulse duration covering the condition as given in Table 2, we are proposing such a system as injects and accumulates proton beam into a storage and cooler ring S-LSR and apply an electron beam cooling and a fast beam extraction [5]. The layout of the system is shown in Fig. 2.

S-LSR is a ring with the circumference and superperiodicity of 22.557 m and 6, respectively [4]. The output beam from the linac are guided by a dipole magnet and a septum magnet to the injection chamber and then overlapped with the closed orbit of S-LSR partially deformed to the outside direction in this area with the use of two bump magnets (BPM1, BPM2) set into the ring as shown in Fig. 3 [5]. After the start of beam injection, the

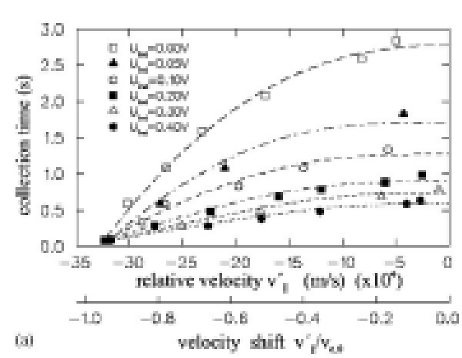

Figure 4: Electron cooling time for various sweeping time of relative velocity between proton and electron beams.

distorted orbit is gradually shifted back to the central position without excitation of the bump magnets in order to apply multi-turn injection into the horizontal transverse phase space.

The electron cooler with U shape as shown in Fig. 3 is installed into S-LSR. The cooling time of electron cooling can be made well shorter than 1 sec. by sweeping the relative velocity between proton and electron beams as shown in Fig. 4 [4] and irradiation with 1 Hz is capable. The horizontal beam size after electron beam cooling is measured to be small enough as shown in Fig. 5 [6]. The vertical beam size at equilibrium is considered to be the same order as the horizontal one because of the horizontal and vertical coupling due to solenoid magnetic field in the cooling region. So irradiation size smaller than 1 mm in diameter is well possible for the beam number between 10^4 and 10^8 although some scheme to shape to a larger size for lower intensities and special care for the damage to normal cells for the case of higher intensity are required.

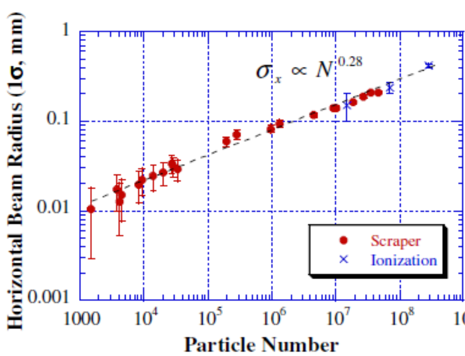

Figure 5: Horizontal beam radius as a function of the particle numbers with an electron current of 25 mA for cooling.

Fast Extraction of Short Bunch Beam

As an electrostatic pick up installed into S-LSR ring has the time resolution ~10 ns, it is not good enough to evaluate the bunch length for the present case. So as to evaluate the bunch length with better time resolution, we have applied a fast extraction to electron cooled proton beam and measured its length with the use of a Fast Current Transformer (FCT) with a time resolution less than 1 ns. For this measurement RF voltage of 800 V with the harmonic number of 2 has been utilized. As the revolution time of 7 MeV proton beam though S-LSR is 620 ns, the kicker magnet (KM) with the rise time and duration of 80 ns and 800 ns, respectively, can well kick out the two bunches of the circulation proton beam without any loss. The following two methods of short-bunch formation have been utilized.

Phase Rotation Method

RF voltage is applied to a coasting beam after sufficient momentum cooling by an electron beam cooling and then the beam start synchrotron oscillation in the longitudinal phase space. The bunch length becomes minimum after 90° rotation. So the timing of the KM is

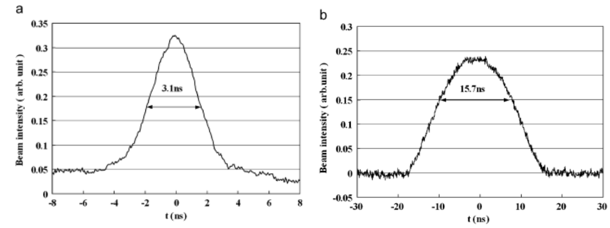

Figure 6: Measured bunch length of the electron cooled proton beam, by (a) Phase Rotation Method and (b) Bunching Method.

required to be carefully adjusted with the start of excitation of the RF voltage. The shortest bunch length of ~3 ns has been realized with this method for the circulating proton number of 1.4 x 10^8 (corresponding to the proton number of ~3 x 10^7 through the FCT for irradiation because of extraction efficiency of ~20 %) as shown in Fig. 6(a) [5].

Bunching Method

RF Field is applied continuously together with the electron beam cooling, which can compress the beam emittance in both longitudinal and transverse directions. The bunch length attained by this method for the beam intensity of 1.4 x 10^8 is measured to be 15.7 ns as shown in Fig. 6 (b) [5]. As the extraction efficiency of this method is ~100 %, the fast-extracted irradiation proton number is almost the same as the circulating proton number.

SUMMARY

Short pulse proton beam irradiation system with the use of conventional RF accelerator has been investigated. By combination of the RF linac consisting of RFQ and DTL with an ion accumulation and cooler ring, S-LSR, which has a facility of an electron beam cooling, the capability of irradiating the cell with a short pulse of the duration ~3ns and ~16 ns with the beam intensities up to 3 x 10^7 and 1.4 x10^8 per shot, respectively, has been demonstrated. As the beam intensity reduction keeping the short bunch length is considered to be easily realized, careful irradiation studies on dose rate dependence for both normal and cancer cells with the scheme presented here, is to be started from now on by the collaboration with the experts from outside institution such as NIRS.

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