# QUALITY IMPROVEMENT OF LASER-PRODUCED PROTONS BY PHASE ROTATION AND ITS POSSIBLE EXTENSION TO HIGH ENERGIES*

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*Abstract*

Energy spread compression scheme for laser-produced ions by phase rotation with the use of an RF electric field synchronized to the pulse laser has been proved in principle for rather lower energies up to ~2 MeV. Its extension to higher energy around 200 MeV has been investigated with multi-gap structure assuming higher frequency of L-Band (~1.3 GHz). RF defocusing effect worried about at lower energy was found to be manageable at such a higher energy if the laser-produced-protons are well treated just after production at the target

## INTRODUCTION

Based on recent rapid development of high-power short-pulse laser with the use of Chirped Pulse Amplification, laser-produced ion beam has been proposed to be utilized as an injection beam of a medical synchrotron for cancer therapy replacing the RF linac as shown in Fig.1 [1]. For that purpose, however, the characteristics of laser-produced ion beam are not well suited. The energy spread of the laser-produced ion beam has been almost 100 % without a rather sophisticated treatment of the production target [2] or additional radial focusing scheme [3], which seems not to be suitable for operation by a tolerable repetition (~1 Hz) with good reproducibility as is required from medical use.

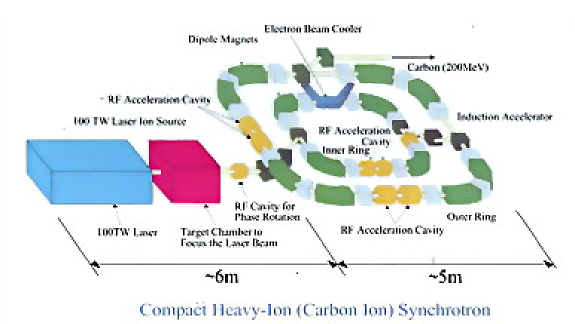


Figure 1: Layout of a medical synchrotron for cancer therapy replacing an injector linac by laser-produced ion beam.

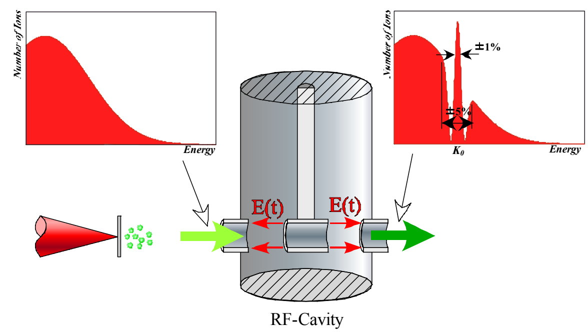


Figure 2: Illustration of the phase rotation principle.

In order to manage such a situation, a phase rotation scheme of the laser-produced ion beam with the use of an RF electric field synchronized to the pulse laser has been proposed [1]. In Fig.2, a basic concept of the phase rotation of phase rotation is illustrated. Utilizing the phase difference caused by the speed difference among ions with different energies, faster and slower ions are decelerated and accelerated, respectively in order to be put together into a central peak. Such an idea of energy spread compression of laser-produced ions by phase rotation has already been experimentally demonstrated with use of a rather smaller peak power (~10 TW) pulse laser, J-LITEX [4, 5]. Recent experiments with use of higher peak power (~100TW) laser, J-KAREN, has extended the energy of laser-produced proton up to ~4 MeV and also given us the information on the radial focusing/defocusing of such protons by the RF electric field created with the phase rotation cavity [6]. In the present paper, capability of multi-gap structure cavity for phase rotation has been considered for the case of

Table 1: Main Parameters of the Two Gap Resonator

| | | |
|---|---|---|
| Structure | | λ/4 with 2 gaps |
| RF Frequency | | 80.6MHz (83.7MHz) |
| Applied Power | | <30kW |
| Dimension | Outer Conductor | ID200mm×~1100mm |
| | Inner Conductor | ϕ40 mm×~700 mm |
| | Drift Tube | ID50×100mm |
| | Gap | 20mm |
| RF Tuner | | Cover ~250 kHz |
| Water Cooling | | Keep Temperature with in 0.5° |

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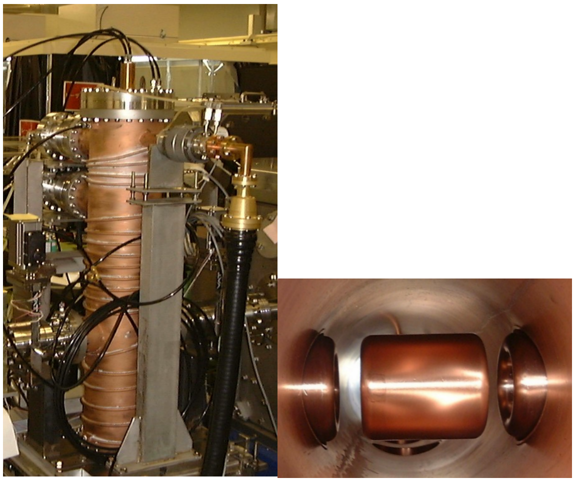

Figure 3: Fabricated two gap resonator for phase rotation of an injection beam for synchrotron with lower energy (~2 MeV).

extension to the higher energy (~200 MeV) applicable to cancer therapy directly. In the process, not only energy compression, but also radial oscillation amplitude is taken into account.

## PHASE ROTATION FOR INJECTION BEAM

For the scheme to utilize the laser-induced proton beam as the injection beam of a synchrotron to replace an injector linac, a two gap resonator with quarter wave-length as shown in Fig. 3 has been fabricated [4]. The main parameters of the cavity are listed up in table 1. The cavity is designed to enable phase rotation of the ion beam with the kinetic energy of up to 2 MeV/u for such ions as $^{12}C^{6+}$ with a charge to mass ratio of 1/2 [1].

### *Creation of Energy Peak*

The first phase rotation experiment with the use of J-KAREN has been performed with the set up as shown in Fig. 4. Due to the limited available time of J-KAREN, the energy spectrum of the laser-produced protons has been measured by their time of flight between production target and TOF detector, which, however, has been found to give a correct spectrum only for the case of without phase rotation, because due to energy change by the electric field of phase rotation cavity, time of flight of proton does not uniquely corresponds to its energy. So as to obtain correct energy spectrum of phase

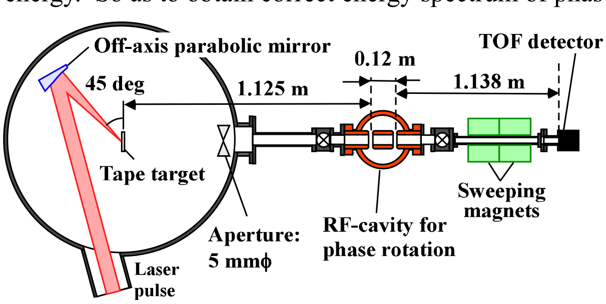


Figure 4: Experimental setup of proton-beam production and its phase rotation with the use of J-KAREN.

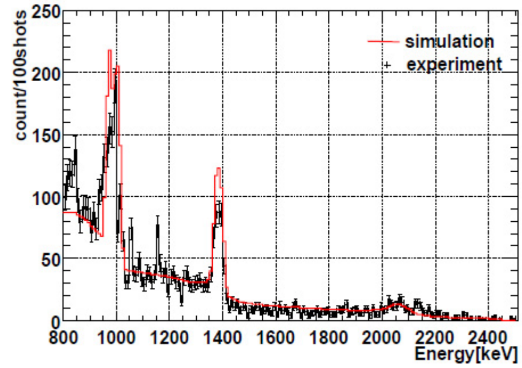


Figure 5: Energy spectrum of phase rotated laser-produced proton beam detected by a Thomson parabola. Clear peak creation has been observed at ~1.0MeV and ~1.4 MeV.

rotated protons, the next experiment with J-KAREN was performed by replacing TOF detector in Fig. 4 by a Thomson Parabola using CR39, which can give us correct energy information of detected protons. In Fig. 5, clear energy peaks formed by phase rotation are shown around 1.0 and 1.4 MeV [5]. It is shown that these peak positions coincide with the ones expected from simulation, which also coincide with the ones observed by the TOF method [6].

### *Radial Focusing Effect*

Through the experiments of phase rotation of proton beam produced by J-KAREN utilizing a two gap cavity above mentioned, radial focusing and defocusing effects as shown in Fig. 6 is observed Images of the mesh set 387 mm downstream from the production target were observed by CR39 detectors set at the positions 0.491 m down stream from the second gap of the phase rotation cavity (1.736 m downstream from the target). With

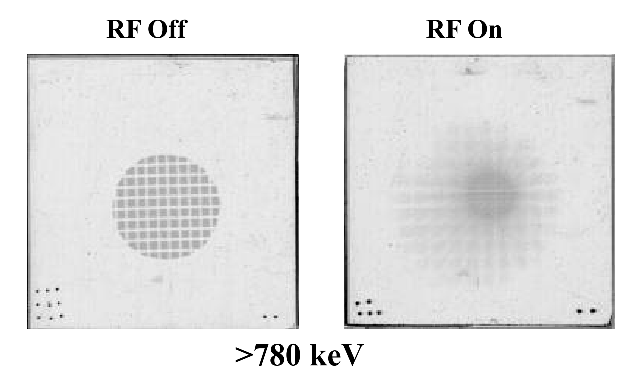


Figure 6: Observed radial focusing/defocusing effects on laser-produced protons by the electric fields of the phase rotation cavity located 1.125 m down stream from the production target. Images of the mesh set 387 mm downstream from the production target observed by CR39 detectors at the positions 1.736 m are shown for both cases with and without RF voltage of the phase rotation cavity.

application of phase rotation voltage, focusing and defocusing effects in radial motion are observed corresponding to various phases applied for protons with various energies. This is considered to be due to curved structure of the applied electric field at the phase rotation cavity, which results in the radial components of the electric field.

## MULTI-GAP STRUICTURE FOR HIGHER ENERGIES

The scheme to utilize the laser-produced protons by application of phase rotation and electron beam cooling as an injection beam of a synchrotron for cancer therapy [1] has been proved in principle up to now [4,5]. It, however, is considered a little bit complex compared with a scheme to produce directly a beam with the desired energy for cancer therapy by laser ion production and the latter scheme is eagerly pursuit although the energy attained with direct production by laser-plasma interaction is rather limited (~ 4 MeV) at the moment.

Even for proton beam, the desired energy for cancer therapy is rather high as >180 MeV for human body treatment and ~70 MeV for eye treatment. Extension of the energy of laser-produced ion has been under elaborate investigation all over the world to respond the urgent needs for wide spread use of effective cancer therapy. In addition to the increase of the attained ion energy, improvement of the characteristics of the laser-produced ion with good energy resolution and good reproducibility is one of the most important items to be investigated. For such a purpose, we have proposed to extend our previous two gap resonator to a multi-gap structure in order to increase the applicable energy to higher value without causing spark problem at the RF cavity. Expecting rapid increase of laser-produced protons, we have investigated the capability of applying the phase rotation scheme to laser-produced ions with such a higher energy (~200 MeV) as can directly be applied for cancer therapy.

### *Selection of RF Frequency*

As the RF frequency of the two gap resonator for phase rotation, we have adopted the same frequency as the source laser (~ 80 MHz) [4]. As the sparking limit of the RF electric field is proportional to square root of the frequency, it is preferable to select as high frequency as possible from this point of view, which, however, needs to be compromised with the practical aspects of hardware construction. Considering the easiness of synchronization between the RF electric field and the pulse laser together with the above requirement, we have selected the frequency of the integral (16 times) multiples of the source frequency of the pulse laser, [80.6 MHz (83.7 MHz)], in the L-Band [1290 MHz (1339 MHz)].

### *Multi-Gap Structure*

For the reference design of phase rotation of laser-produced proton to be directly applicable for cancer therapy, its energy is assumed at 200 MeV. In case we want to collect protons in the energy region of ±5% of this energy, maximum needed energy correction at a single passage through the resonator is 10 MeV. It seems to be well applicable by 12 cell resonator considering the so-called “Kilpatric limit” [7]. For the frequency ~1.3 GHz, the distance between the centres of adjacent two gaps is to be 130 mm if 200 MeV proton is assumed to pass through with the same phase. The energy compression is expected for the passage with the phase where the RF voltage is increasing, while the RF defocusing is anticipated with this phase. So as to suppress this radial defocusing, a scheme to utilize alternating phases at successive gaps has been proposed for lower energy [6]. Such radial focusing/defocusing effect, however, was found to be less dominant at the higher energy as -200 MeV from the computer simulation and it is considered to be manageable if enough focusing action has been applied before phase rotation. So it is possible to utilize every gap with the phase to compress the energy spread. Thus, the length of the phase rotation multi-gap cavity is expected to be around 1.5 m, which seems to be well compact for real medical applications.

## SUMMARY

With the use of multi-gap cavity with the frequency of L-Band (~1.3 GHz), energy peak creation by phase rotation is also expected for higher energy as ~200 MeV.

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