DESIGN OF FRONT END FOR RF SYNCHRONIZED SHORT PULSE LASER ION SOURCE

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Abstract

An laser ion source which produces short pulse ion beam is under development. In this ion source, laser plasma is produced in an RF electric field and ions are extracted from the plasma before its expansion. The ion beach can be injected into RF acceleration bucket of RFQ. For this ion source, an accelerator front end was designed.

SHORT PULSE LASER ION SOURCE

Short pulse ion beams are promising candidate as a component of a high efficiency accelerator front end. In conventional ion source, the pulse length of the extracted ion beams are longer than the RF (Radio Frequency) period of the subsequent accelerator. Therefore, the ion beams must be bunched in the front end of the accelerator such as an RFQ (Radio Frequency Quadrupole). If the beam is already bunched at the extraction area of the ion source, the beam can be injected into accelerating RF phase and directly accelerated in RFQ. Then, the bunching section of the RFQ can be omitted and the accelerating efficiency of RFQ can be improved.

For production of initially-bunched beam, laser plasma induced by ultra-short pulse laser has a promising potential. With the focused short pulse laser in a few tenth of micro meter, the volume of the interaction region are small enough to produce bunched ions, and the ions in the plasma produced by the short pulse laser are supposed to have also short pulse structure. If the short pulse ions bunch can be produces in an RF electric field, the ions can be captured by the RF bucket and the bunch structure can be kept. Therefore, the production of short pulse ion bunch can be achieved and direct acceleration of the bunched ion beam in RFQ can be realized.

PLASMA PRODUCTION CONDITION

In this section, conditions to produce short pulse ion beam is discussed.

For the extraction the ions from the laser plasma, the thickness of plasma should be smaller than Debye length. The Debye length λ_D is defined as

$$\lambda_D = \sqrt{\frac{\epsilon_0 kT}{n_e e^2}} \tag{1}$$

where ϵ_0, k, T, n_e and e are the permittivity of vacuum, the Boltzmann constant, electron temperature, electron density, and elementary charge, respectively. The thickness of the plasma is the same order of the laser dimension at the focal point. In our test bench, the focal spot of laser can be controlled less than 50 μm. For the practical use of ion beam, peak current of extracted microbunch should be larger than 1 mA. To achieve this current, the number of protons per microbunch is larger than 10^7. From those condition, the temperature of plasma should be between 100 eV and 1 keV. The summery of the discussion is illustrated in Figure 1. The region colored by light green is the sufficient condition to produce short pulse ion bunch.

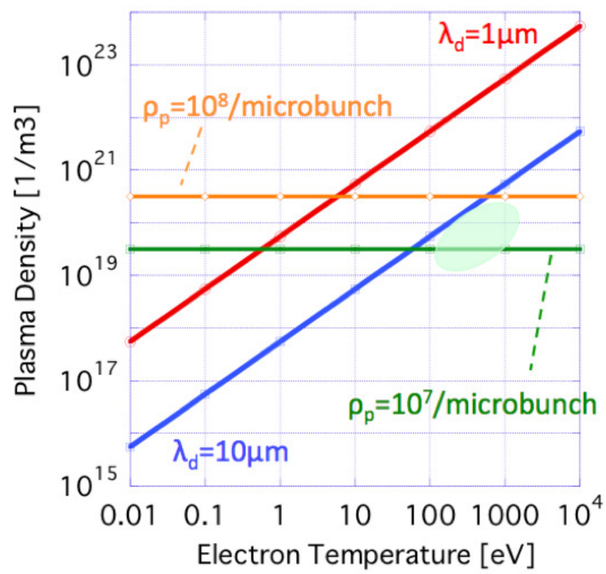

Figure 1: Condition of short pulse ion beam production. The region colored by light green is suitable for the production of short pulse ion beam.

Amplitude and frequency of applied electric field in the acceleration gap are also important. Figure 2 shows minimum amplitude of RF electric field in 1 mm acceleration gap to extract protons within half RF cycle. The minimum amplitude of the field is a function of RF frequency. For example, 5 MV/m of peak amplitude of the electric field is needed for 100 MHz RF field. There is also a limit of amplitude of electric field, known as Kilpatric criteria,

$$f[\text{MHz}] = 1.64(E[\text{MV/m}])^2 \exp\left(-\frac{8.5}{E[\text{MV/m}]}\right). \tag{2}$$

This relation is an indication of the amplitude of the electric field which can be applied without discharge. Combined this relation and the minimum electric field to extract protons discussed above, it is supposed that the frequency of the applied electric field should be less than 200 MHz to extract protons (see Figure 2).

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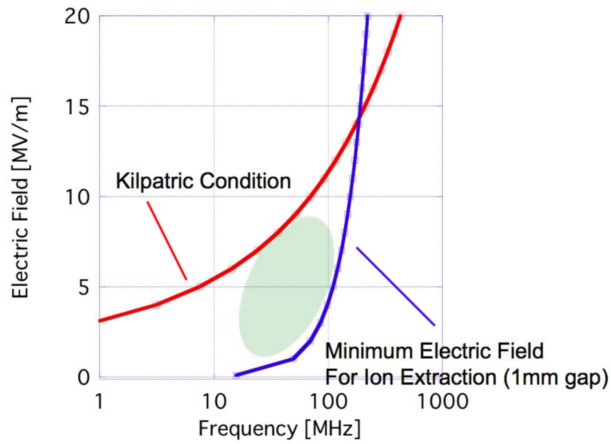

Figure 2: The relation between amplitude and frequency of the extraction electric field. The region colored by light green is suitable for the extraction of the ions

PROOF-OF-PRINCIPLE EXPERIMENT

To demonstrate the production of the short pulse ion beam with a short pulse laser and an RF electric field, a proof-of-principle experiment was carried out. In this experiment, H_2 gas was ionized by short pulse laser in an acceleration gap of RF resonator and the accelerated particle was observed by a current probe.

In this experiment, the pulse duration of the irradiated laser was 40-fs and the laser energy per pulse was tuned about 100 μJ. The laser pulse was focused to aspot with 11 μm diameter by an off-axis parabolic mirror and the Rayleigh length of laser at interaction point was measure about 1 mm. The estimated laser power density at the laser-gas interaction point was about 10^{15} W/cm^2. A 53 MHz RF resonator was fabricated for this experiment (see Figure 3). This resonator equipped with pulsed gas valve. The pulsed gas valve can be switched by piezo-electric valve and hydrogen gas can be produced into the laser-gas interaction point with 1 ms pulse duration. A electric field with 2 kV amplitude was applied in the laser-gas interaction point. Selecting the RF phase at the laser irradiation timing between 0 and 90 degree, bunched ions were observed by the current probe. The pulse length of the ions was about 3 ns and the current was up to 1 mA (corresponding to 10^7 protons per micro-bunch) [1].

CONCEPTUAL DESIGN OF FRONT END WITH SHORT PULSE LASER ION SOURCE

In the proof-of-principle experiment, production of a short pulse ion bunch was demonstrated. For injection into a RFQ, accelerated voltage of the ions should be larger than a few tenth of kilo-Volt. As discussed above, amplitude of the applied electric field in the ion source cell is limited as high as 10 MV/m, which corresponding to 10 keV energy of ions. Considering the fabrication of the RFQ, injection energy should be between 30 keV and 50 keV. To provide additional energy gain to injected ions, booster cell should be installed between the ion source and the RFQ. A schematic image of the front end is illustrated in Figure 4.

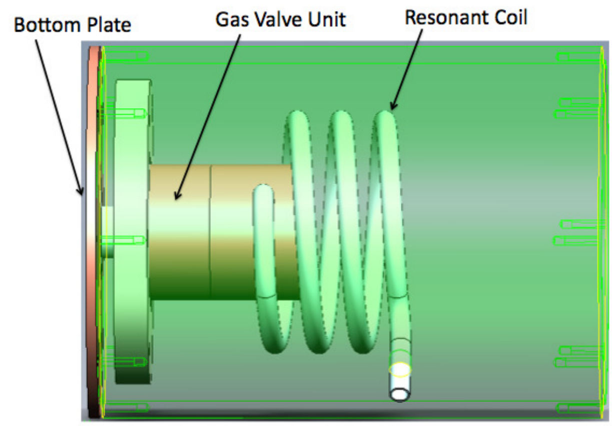

Figure 3: A image of the fabricated RF resonator for the proof-of-principle experiment.

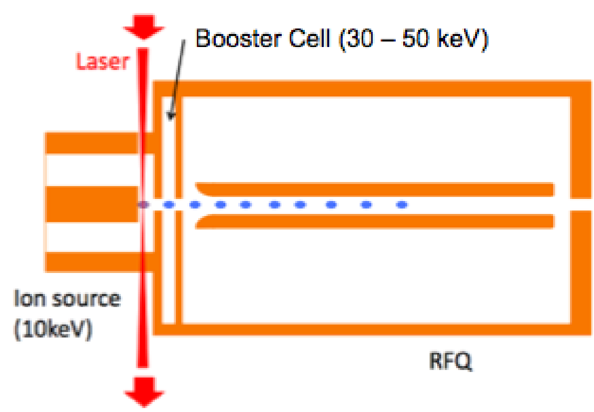

Figure 4: A conceptual image of the accelerator front end with the short pulse laser ion source.

RFQ PARAMETERS

In this study, energy of output protons from RFQ is chosen as 2.5 MeV for the application to compact neutron source. The frequency of the RFQ was set as 200 MHz, because solid state RF power source is available at this frequency. Considering the sparking problem, the inter-vane voltage and average bore of vanes (r_0) were chosen as 75 kV and 4 mm, respectively. Because the injected ions already have micro-bunch structure, bunching section in no longer needed. Then, the modulation parameter and synchronous phase can be set as constants. The determined parameters are summarized in Table 1.

Using the parameters in Table 1, the length of RFQ for 10 keV, 30 keV and 50 keV injection energy was calculated, respectively. The calculated results are shown in Table 2. The length of RFQ can be shorten because no bunching section is needed.

Table 1: Main Parameters of Designed RFQ

Particle	Proton
Frequency	200 MHz
Injection Energy	10 - 50 keV
Electrode Voltage	75 kV
Output Energy	2.5 MeV
Modulation Parameter	2.4
Synchronous Phase	-25 degree
r_0	4 mm

Table 2: Dependence of RFQ ength on on njection energy.

Ion Injection Energy	RFQ Length
10 keV	2.72 m
30 keV	2.62 m
50 keV	2.58 m

For more effective acceleration in RFQ, vane shapes should be optimized. Introducing higher order terms in addition to the two-term potential, a trapezoidal vane modulation shape with high acceleration gradient can be achieved [2]. Adopting 7-term potential for vane shape optimization, the accelerating efficiency can be enhanced by up to 15 % with less multipole components. Figure 5 is a example of the trapezoidal vane shape for high efficiency acceleration. With this new vane shape, total length of RFQ can be shortened less than 2.4 m. To confirm the beam acceleration performance in this front end, a bean simulation code is under development.

CONCLUSION

RF synchronized short pulse laser ion source is one of the candidate of a component of high efficiency accelerator front end. Irradiating short pulse laser to gas in RF electric field, initially bunched ions can be produced. Because of its short pulse duration, the ion bunch can be directly inject and accelerated by RFQ without the bunching process. A proof-of-principle experiment demonstrated the production of bunched ion beam. With the ion bunch, an accelerator

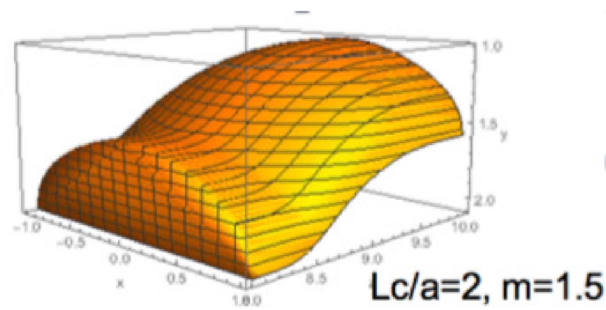

Figure 5: A trapezoidal vane shape for high efficiency acceleration.

front end and RFQ without bunching section was designed. Furthermore, trapezoidal vane shape for high efficiency acceleration can shorten the length of RFQ up to 15%.

ACKNOWLEDGEMENT

This work was supported by Grant-in-Aid for JSPS (Japan Society for the Promotion of Science) Fellows.

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