A CONCEPTUAL DESIGN OF FFA RING FOR SUPER HEAVY ELEMENT PRODUCTION ADOPTING THE ERIT MECHANISM.

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Abstract

Production of super heavy elements of which atomic number is larger than 118 can provide new prospects in the field of nuclear physics. Extremely low production rate of these elements makes the experiments time consuming. This difficulty can be solved by using the energy recovery internal target, so-called ERIT, because the number of interactions can be increased as a circulating beam hits the target located in the ERIT ring. Here, we present a conceptual design of the FFA ring for super heavy element production adopting the ERIT mechanism.

INTRODUCTION

At the Institute for Integrated Radiation and Nuclear Science, Kyoto University (KURNS), basic experimental studies on the ADS, which stands for accelerator driven system, started in 2009 using a one of research reactors Kyoto University Critical Assembly (KUCA) [1]. In these studies, the KUCA was operated in the sub-critical mode and FFA accelerators was used as a proton driver.

In early 2009, we demonstrated the feasibility of ADS in the Uranium loaded sub-critical core under thermal system, hitting the tungsten target with proton beams of which energy is 100 MeV to generate the spallation neutron) [2]. In the next year, ADS experiments with Thorium loaded core were performed. For the next decade, experiments were conducted at this facility with a variety of core configurations. Finally, in 2019, phenomena of transmutations of MAs such as 237Np and 241Am in the ADS was confirmed using this facility [3]. As almost all the originally planned ADS experiments have been completed, several reuse plans of the main ring of FFA facility at KURNS is now under consideration: one is a pion production ring aiming for producing decay muons for various purposes and the other is a experimental apparatus for super heavy element production adopting the ERIT mechanism. As the former was already presented in the IPAC 2019 [4], we present the conceptual design of an FFA ERIT ring for a super heavy elements in this report.

SUPER HEAVY ELEMENT PRODUCING ERIT

One of the options of the KURNS FFA main ring reuse plan is modification aiming for producing super heavy elements of which mass number is 119 or more. Possible processes of producing super heavy elements are described by equations below.

$$^{51}_{23}\mathrm{V} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}_{119}\mathrm{Xx} \tag{1}$$

$$^{54}_{24}\mathrm{Cr} + {}^{243}_{95}\mathrm{Am} \rightarrow {}_{119}\mathrm{Xx} \tag{2}$$

$$^{54}_{24}\mathrm{Cr} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}_{120}\mathrm{Xx} \tag{3}$$

$$^{55}_{25}\mathrm{Mn} + {}^{243}_{95}\mathrm{Am} \rightarrow {}_{120}\mathrm{Xx} \tag{4}$$

Prior to these real super heavy element searches, a test run will be performed such as

$$^{48}_{20}\mathrm{Ca} + {}^{238}_{92}\mathrm{U} \rightarrow {}^{286}_{112}\mathrm{Cn}. \tag{5}$$

Extremely low production rate of these elements makes the experiments time consuming. Conventional way of the production, separation and detection of super heavy elements is shown in Fig. 1. In this setup, the primary beam hits the target only once. The new method introduced here, on the other hand, places the target in a ring with an ERIT mechanism [5] shown in Fig. 2 and aims to improve the production rate by repeatedly hitting the target with the circulating beam. Here, we present a conceptual design of the FFA ring for this purpose.

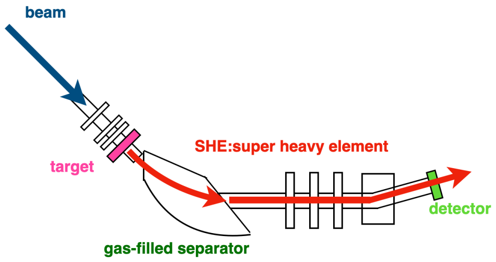

Figure 1: Conventional method of super heavy element production, separation and detection.

Emittance growth by hitting the target

To check the emittance growth, we performed beam simulations assuming the production target is 200 μg/cm^2 thick UO$_2$. The transverse(horizontal) emittance(normalized) growth is shown in Fig. 3. The effect of the ionization cooling works to suppress the emittance growth at most 120 πmm mrad. However, this cooling does not effect in the longitudinal direction. The growth of momentum spread can be suppressed by using a wedge target with the wedge factor η_w, which is is defined as

$$\eta_\mathrm{w} = \frac{D}{\rho}\frac{\partial \rho}{\partial R}, \tag{6}$$

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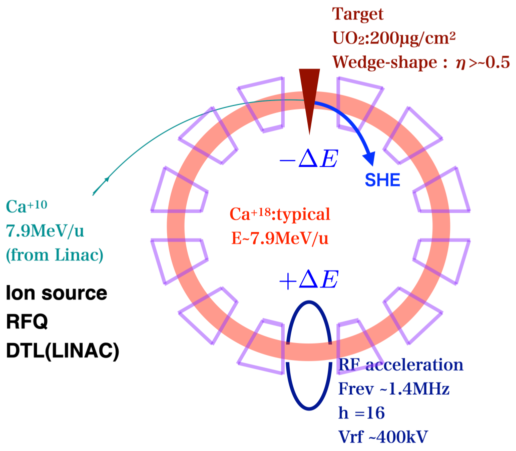

Figure 2: Schematic configuration of an ERIT system for producing super heavy elements.

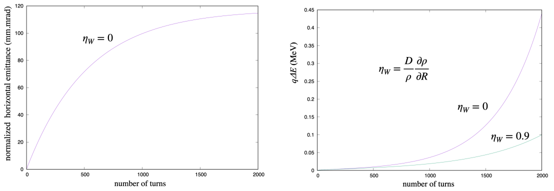

Figure 3: Beam simulation results of the growth of the horizontal emittance(left) and the momentum spread(right).

where D is a dispersion function and ρ is the density of the target. We expect over 100 turns can contribute to SHE producing process. In these simulations, the following parameters were used: the rf frequency of 1.4 MHz, the rf voltage of 400 kV and the harmonic number of 16.

Multi-charge state beam behavior in the ERIT scheme

It can be seen from the above discussion that in ERIT for super heavy element production, there is no significant increase of beam emittance in both longitudinal and transverse directions. However, the charge state transition as the primary beam passes through the target causes a transverse beam emittance growth which must be resolved.

Figure 4 shows closed orbits for 5 different charge state beams:$q = +16, +17, +18, +19$ and $+20$. Closed orbitals in different charge states are separated from each other by a considerable amount. Therefore, the amplitude of a particle in the beam is changed every transition of its charge state as passing through the target. Successive changes of the horizontal amplitude cause a rapid emittance growth. However, if the dispersion function and its derivative are zero at the target, the emittance growth can be suppressed. Beam tracking simulation was performed taking into account of this process with the stationary charge state distribution shown in Fig. 5. The result of tracking simulation with the lattice where $D \sim 0, D' \sim 0$ at the target for this process is shown in Fig. 6. To realize the dispersion free lattice, horizontal

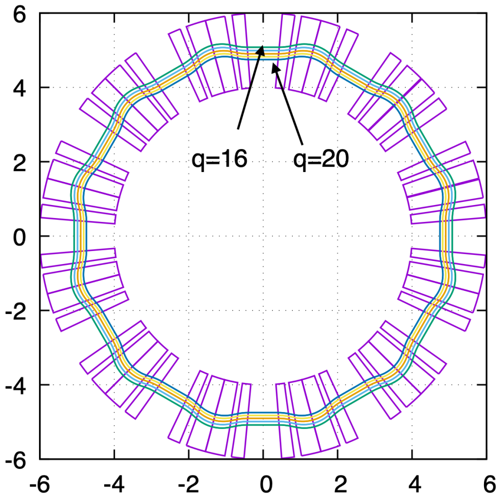

Figure 4: Closed orbits calculated for 5 different charge states:q = 16, 17, 18, 19, 20.

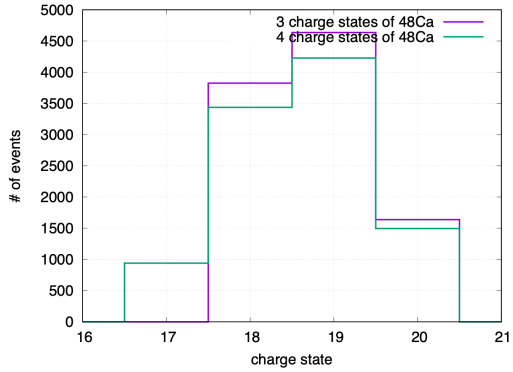

Figure 5: Stationary distribution of the charge state of the circulating $^{48}_{20}$Ca beam.

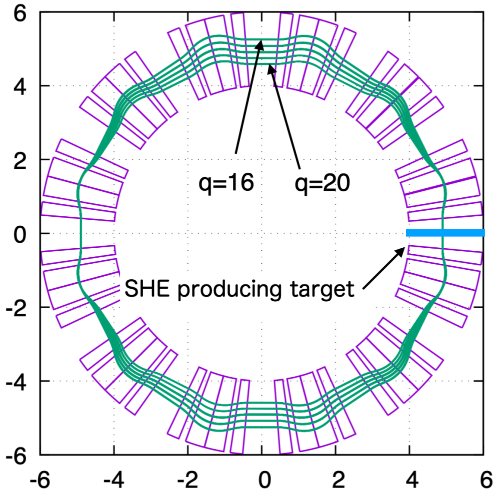

Figure 6: Beam tracking results with charge state transition by hitting the target.

tune was set close to $Q_x \sim 2.0$.

Figure 7 shows the survival ratio of the beam particles as functions of number of turns simulated with 1000 macro particles for different horizontal tunes, whose initial unnormalized emittance are 100 πµm rad in both horizontal and vertical directions. Beam sizes increase as shown in Fig. 8 and 9. To avoid harmful resonances, the horizontal tune needs to be off $Q_x = 2$. Numbers of turns survived were calculated by the particle tracking with initial amplitude zero varying the horizontal tune(Fig. 10). Transverse emittance growth is caused not only by closed orbit transition but also by the distortion of ellipse in the phase space. This is because the beam with the different charge has a different tune.

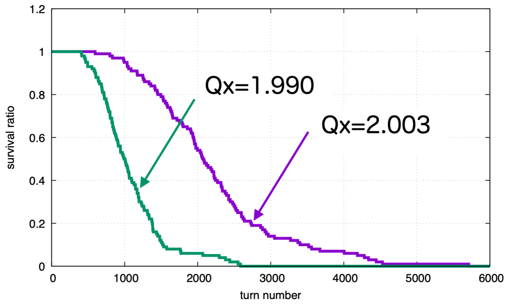

Figure 7: Survival ratio of the beam particle as a functions of number of turns simulated with 1000 macro particles for different horizontal tunes.

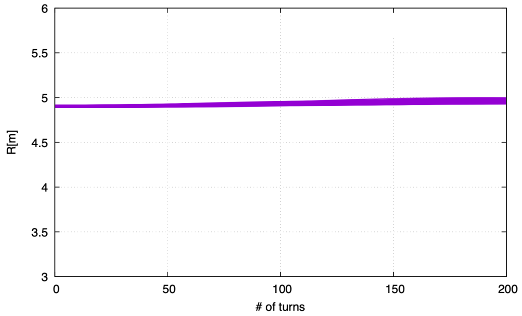

Figure 8: Horizontal beam size as a function of turn number.

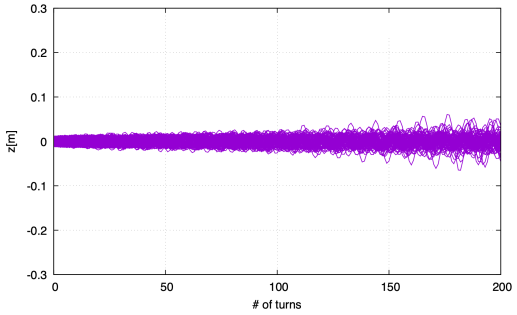

Figure 9: Vertical beam size as a function of turn number.

From the above discussion, it can be summarized that the transverse emittance growth can be avoided if the lattice satisfies the following conditions:

1. The dispersion and its derivative are zero at the target position.
2. Horizontal and vertical chromaticities are zero to higher orders.

Scaling FFA ring can satisfy them.

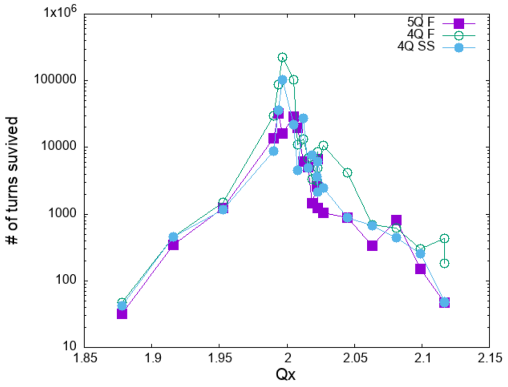

Figure 10: Beam simulation results of the growth of the horizontal emittance and the momentum spread.

SUMMARY

The scheme of FFA ERIT can increase the production rate of the super heavy elements. Beam emittance growth due to the charge state transition can be avoided by a zero-chromatic and dispersion free FFA lattice.

REFERENCES

[1] Y. Ishi *et al.*, "Present Status and Future of FFAGs at KURRI and the First ADSR Experiment", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper TUOCRA03, p. 1327–1329.

[2] C. H. Pyeon *et al.*, "First Injection of Spallation Neutrons Generated by High-Energy Protons into the Kyoto University Critical Assembly" *J. Nucl. Sci. Technol.*, vol. 46, no. 12, pp. 1091-1093, Aug. 2009. `doi:10.1080/18811248.2009.9711620`

[3] C. H. Pyeon *et al.*, "First nuclear transmutation of ^{237}Np and ^{241}Am by accelerator-driven system at Kyoto University Critical Assembly" *J. Nucl. Sci. Technol.*, vol. 56, no. 8, pp. 684-689, May 2019. `doi:10.1080/00223131.2019.1618406`

[4] K. Suga *et al.*, "Remodeling of 150 MeV FFAG Main Ring at KURNS TO Pion Production Ring" *Proc. of IPAC2019*, Melbourne, Australia, 2019. `https://doi.org/10.18429/JACoW-IPAC2019-MOPRB021`

[5] Y. Mori, *Nucl. Inst. Meth.*, A, vol. 536, p. 591(2006)