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DESIGN OF MULTI-MW RAPID CYCLING SYNCHROTRON FOR ACCELERATOR DRIVEN TRANSMUTATION SYSTEM *

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Abstract

For the practical application of Accelerator Driven System (ADS) that reduces the harmfulness of radioactive waste by nuclear transmutation, we are studying the development of a compact accelerator using a synchrotron as an accelerator capable of supplying a stable proton beam to a nuclear reactor. In this research, we aim to realize high efficiency and high reliability ring by adopting an alternating high temperature superconducting magnet and a high repetition synchrotron applying resonant beam extraction. In this paper, we report the fundamental design of the rapid cycling synchrotron.

INTRODUCTION

Treatment of spent fuel generated after nuclear reactor operation is a challenge to be solved globally. To reduce the amount of high-level radioactive waste, partitioning and transmutation of minor actinides (MA) has been studied for decades [1]. One of the promising transmutation technology is Accelerator Driven transmutation System (ADS). The ADS consists of a high-intensity proton accelerator, a spallation target and a subcritical reactor core where the MAs are loaded [2].

One of the inherent issues to operate ADS is beam-trip problem. When beam trips occur, the temperature of the reactor may fluctuate. This temperature fluctuation can cause thermal fatigue in ADS components, and reduce the lifetime of the system. The beam trip frequency of the superconducting linac for driving the ADS was estimated based on the operation data of the existing accelerator and the estimation result was compared with the allowable beam trip frequency calculated from the thermal analysis [3]. From the result of this study, it was shown that the beam trip frequency, especially for longer beam trip (> 5 minutes), is necessary to reduce down to about 1/35 of that for the existing accelerator facilities.

According to the statistics in Ref. [3], the most dominant cause of the longer beam trip is trouble of RF systems. Based on this result, the ADS so far has assumed the use of linear accelerators as high intensity accelerators, but this choice can be a serious problem. Since the linear accelerators consist of large number of RF systems, it seems to be difficult to reduce the total number of down time having the longer duration. To overcome this problem, circular accelerators can be promising candidates for ADS drivers. In the case of using a circular accelerator, the number of high frequency power supplies would be smaller than that of a linear accelerator, so it is possible to construct a system with a low possibility of beam stop. On the other hand, for use of the circular machines in the ADS, it is a problem that the circular accelerators ha lower beam current that can be generated per unit than the linear accelerator and the power consumption of the bending magnets is large. The problem of the lower current can be effectively increased by improving the output current per ring and parallelizing the accelerator system, and the power consumption of the electromagnet can be suppressed by the superconducting technology.

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RAPID CYCLING SYNCHROTRON FOR ADS

As discussed in the previous section, circular accelerators have the advantage of having less number of RF system in accelerator complex, and may be suitable for the use as ADS proton drivers. Among the various kind of circular accelerators, such as cyclotron, synchrotron and FFAG synchrotron, we have chosen Rapid Cycling Synchrotron (RCS). Although the RCS has fast ramping magnets and its operation is complicated, it can provide high energy (above 1 GeV) proton beam and the high power beam acceleration has already been realized. The beam energy above 1 GeV is important for the mitigation of the heat deposition into the beam window material, since the energy loss of high energy proton beam in material has minimum value around a few GeV region of projectile beam energy [4]. The 1-MW beam acceleration has been achieved with 3 GeV RCS successfully [5], in J-PARC [6]. If the RCS with larger repetition rate, such as 100 Hz, is developed, available beam power can be increased to milti-MW per single RCS ring. By using several such RCS accelerators in parallel and merging the beam from the accelerators, it is possible to sufficiently satisfy the beam power required for the ADS.

BASIC PARAMETER OF THE RCS

In this research, an RCS is designed for an ADS proton driver. As the prototype of the driver machine, beam power was set to The beam power was set to 1.5 MW. Although this value is insufficient for practical use in the full-scale ADS, it is larger than the present high-power accelerators and sufficient for proof-of-principle experiments with smaller-scale ADS reactors.

The prototype RCS design parameters are summarized in Table 1. Proton beam is injected with 100 MeV energy and accelerating up to 1.5 GeV. The injection energy was chosen

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Table 1: Fundamental Parameters of the Designed RCS

Parameter	Value
Injection energy	100 MeV
Extraction Energy	1.5 GeV
Output Beam Power	1.5 MW
Repetition Rate	100 Hz
Acceleration Time	< 5 ms
harmonic number	1

so that an injector linac can be shorted and required number of RF systems would be small. And the final energy of 1.5 GeV has advantage to mitigating the energy deposition at beam window of the subcritical core. In order to achieve the 1.5 MW output beam power, averaged accelerated beam current is 1 mA. This current value is expected to be realized by increasing the repetition frequency to 100 Hz. In order to achieve such a high repetition rate, the duration of beam acceleration should be less than 5 ms including beam injection time (see Fig. 1). This fast acceleration requires sophisticated accelerator design with shorter ring circumference and high voltage accelerating structures. In addition, it is also necessary to develop functions to meet the energy efficiency and high reliability requirement demanded by the ADS system. These functions are described below.

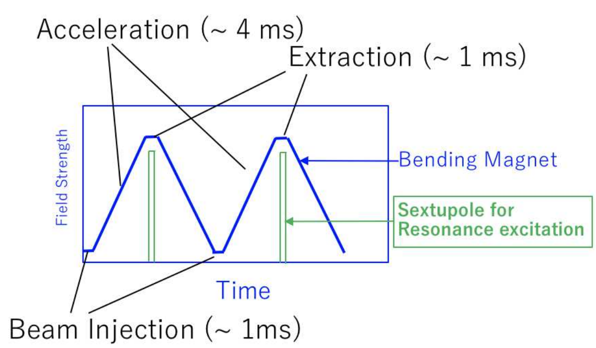

Figure 1: Image of RCS operation in time for high-repetition beam acceleration.

Bending Magnets with AC Superconducting Coil

To achieve the sufficient work of the ADS cycle, the beam acceleration efficiency in energy should be large. One of the criteria on the beam acceleration energy efficiency considering power selling of surplus electric power is 30%.

The dominant power consuming device in the RCS is bending magnet of the ring. In order to reduce the power consumption in the coil of bending magnet, application of superconducting technology is proposed. Since the field in RCS magnet is ramping up and down in 100 Hz, the superconducting coil is operating in AC mode. If high-temperature superconducting material such as REBCO, high efficiency and fast cycle magnets would be realized. Although the high-temperature superconducting material consume power due to AC loss caused by self-magnetic field, the AC loss would be reduced by optimizing the coil geometry [7].

Resonant Beam Extraction

Beam extraction systems in the RCS are one of the most complicated part in the machine complex. Although kicker magnets are usually utilized for the beam extraction system, the power supply for the kicker magnets consists of high-voltage switches. The high voltage switch may suffer from troubles such as dielectric breakdown and may cause the beam trip. In order to reduce the beam trip rate, more reliable extraction system is desired. Therefore, we propose extraction system with betatron resonance. This scheme is similar to the so-called slow beam extraction, but the system proposed in this research has a relatively short operation time of 1 ms (see also FIg. 1).

Utilizing the resonant beam extraction, peak current of the extracted beam would be lowered. Therefore, the beam shock of the beam injection in subcritical core can be suppressed. Since the RCS proposed in this study is operating at 100 Hz acceleration cycle, beam extraction duration should be up to 1 ms.

With the resonant beam extraction, beam loss at the beam extraction system, especially at septum magnets becomes a matter of concern. The reduction of the beam loss is one of the most important issues to suppress machine activation. In order to avoid the beam loss, application of the mass-less septum is proposed.

LATTICE DESIGN

The lattice design of the RCS was performed under the design philosophy that the machine circumference should be minimized. The super-periodicity of the lattice was set to 4-fold to have the space to distribute enough RF systems to achieve high-repetition rate beam acceleration.

The lattice designs at conceptual design stage are utilizing two scheme; combined function lattice and separated function lattice. The lattice parameters for both lattice are shown in Table. 2. The betatron tune for both lattice was set to $(\nu_x, \nu_y) = (3.67, 2.74)$. The betatron tune for the horizontal direction was set to near resonance, ($\nu_x \sim 11/3$), for the resonant beam extraction. The compensated chromaticity in horizontal direction was set to finite value to control the resonant condition at the beam extraction phase.

As a result of beam simulation with chromaticity compensated lattice, the combined function has larger dynamic aperture than the separated function lattice. This feature of the large dynamic aperture can be advantage in beam tuning for the resonant beam extraction. However, for practical beam operations, combined function lattice has less flexibility than separated function lattice. Therefore, both lattice have advantages and disadvantages, and will be studied both lattice design in future research.

In order to confirm the beam acceleration in 100 Hz acceleration cycle, RF pattern for beam acceleration in the

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Table 2: Designed Lattice Parameters

Parameter	Combined Function	Separated Function
symmetry	4	4
maximum flux density in bending magnets [T]	1.40	1.47
curvature radius [m]	5.36	5.09
circumference [m]	68.9	107.2
number of bending magnets	32	16
bending angle per magnet [degree]	11.25	22.5
length of a bending magnet [m]	1.053	2.000
number of long straight sectin	4	8
length of long straight sectin [m]	6.00	5.00
momentum compaction factor	0.09	0.08
chromaticity after compensation	(-1.25, 0)	(-0.63,0)

designed lattice was designed, respectively. Utilizing the accelerating cavity loaded magnetic alloy cores, the beam accelerating voltage up to 200/400 kV per turn would be achieve, for the combined/separated function lattice. With such a high voltage accelerating structures, beam acceleration including adiabatic capture can be done in the time shorter the 5 ms. Without the adiabatic capture, more fast beam acceleration or more low voltage operation of beam accelerating structure can be realized.

Detailed operation methods such as whether to use charge exchange injection and beam structure from the injector are not decided at the present moment, but the optimal operation pattern will be studied.

CONCLUSION

In order to construct reliable nuclear transmutation system, a Rapid Cycling Synchrotron was proposed for ADS proton driver. Increasing the repetition rate of acceleration up to 100 Hz, multi-MW beam power would be achieved. As the prototype of the machine, design of an RCS with 1.5 MW beam power is carrying out. In order to achieve the requirement for ADS drivers in terms of energy efficiency and reliability, application of AC superconducting technology and beam extraction with betatron resonance.

The RCS lattice was designed with combined function magnets and separated function magnets, respectively. The lattice with these magnets have advantages and disadvantages, so it is difficult to declare which one is better so far. In the near future we will design more detailed accelerator system.

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