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RF BEAM SWEEPER FOR PURIFYING IN-FLIGHT PRODUCED RARE ISOTOPE BEAMS AT ATLAS FACILITY*

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Abstract

RadiaBeam is developing an RF beam sweeper for purifying in-flight produced rare isotope beams at the ATLAS facility of Argonne National Laboratory. The device will operate in two frequency regimes – 6 MHz and 12 MHz – each providing a 150 kV deflecting voltage, which doubles the capabilities of the existing ATLAS sweeper. In this paper, we present the design of a high-voltage RF sweeper and discuss the electromagnetic, beam dynamics, and solid-state power source for this device.

INTRODUCTION

The Argonne Tandem Linac Accelerator System (ATLAS) is the national user facility, providing stable and radioactive low-energy heavy ion beams. The latter have supported multiple astrophysics experiments for about two decades [1]. One way of producing Radioactive Ion Beams (RIB) at ATLAS is the in-flight method, providing access to more than 100 short-lived isotopes in the mass range up to A~60 [2]. During this process, the primary beam traverses the production target. Its energy is degraded, and the beam acquires a long low-energy tail from the multiple-scattering processes in the target material. These tails can easily dominate the low-intensity RIB beams of interest.

To handle the large divergence and energy spread of the in-flight produced beam, an in-flight radioactive beam separator (AIRIS) was recently commissioned to enhance the radioactive beam capabilities of the ATLAS facility [3]. This system, shown in Fig. 1 (top), consists of a production target placed at the end of ATLAS followed by a two-step ion separator. The first step is a magnetic achromat while the second consists of an RF sweeper or chopper [4,5].

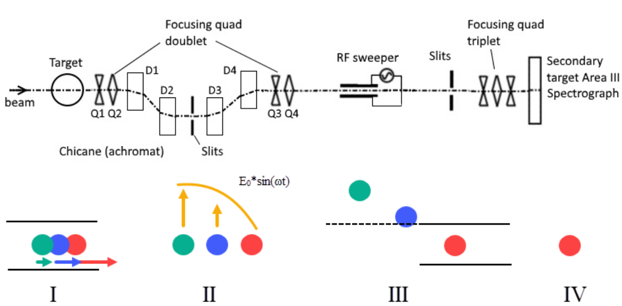

Figure 1: Layout of the ATLAS in-flight RIB facility (top) and the scheme of rare isotope RF separation (bottom).

The RF sweeper provides contaminant beam reduction through velocity differences: a time difference eventually develops between the two beam components due to the velocity difference and results in a varying deflection in the time-dependent electric deflecting field (see Fig. 1) [6]. For many cases of interest at ATLAS, the currently existing sweeper, operating at an ATLAS sub-harmonic of 6 MHz with a maximum voltage of 55 kV, was sufficient for a clean separation with 1-meter-long sweeper plates and a 10 cm gap. However, there are still many other beams that require at least twice as high voltage.

One class of experiments that could benefit from a higher-voltage separator would be those beams produced in fusion evaporation, such as the (^{3}He, n) reaction used for production of ^{22}Mg from ^{20}Ne and ^{44}Ti from ^{42}Ca. These beams are also wanted at low energy (< 5 MeV/u). Another class of experiments could be the beams that are created with (d, p) for A>30. Here, the issue is the primary beam charge states, so, it would be helpful to have a larger kick of these beams, which are typically requested at more like 10 MeV/u, as the fully stripped primary beam is close in energy to the beam of interest. For lower energy beams ~ 5 MeV/u, 6 MHz would be better because of the flight time. Hence a new RF sweeper design that includes 12 MHz high voltage for fast beams > 10 MeV/u, and 6 MHz with moderately high voltage for low energy beams ~5 MeV/u is needed.

In order to enable these experiments, RadiaBeam is developing the RF sweeper capable to operate at both 6 MHz and 12 MHz frequencies with about triple the voltage of the existing ATLAS sweeper. We have completely revised the electrical and engineering design of the original sweeper to allow operation at 150 kV.

In this paper, we present the electromagnetic design of the high voltage RF sweeper, beam dynamics, the conceptual engineering design, and the design of the solid-state RF power supply to feed the system.

ELECTROMAGNETIC DESIGN

We designed a structure capable to operate at both 6 MHz and 12 MHz frequency. The maximum operation voltage in both regimes is up to 150 kV. The design relies on the idea of establishing resonance between the capacitor (electrodes) and variable inductance (coil). We decided to use a sliding contact (switch) that electrically divides two coils in series. Figure 2 shows the circuit diagram of the device and its 3D model in CST Microwave Studio.

The operation principle of the sliding switch is the following: the switch is disconnected to enable the 6 MHz mode in which the two coils are in series, and when the

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switch is connected it creates a short circuit at the end of Coil 1, enabling the 12 MHz mode.

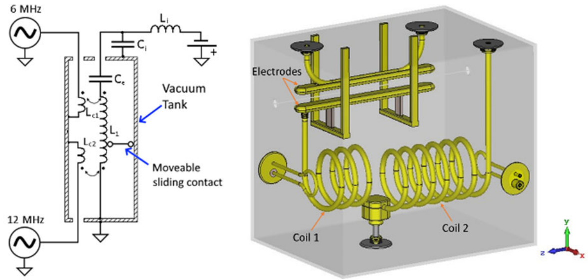

Figure 2: Schematics of dual frequency RF sweeper (left) and its 3D model (right).

We tuned the cavity to the required frequencies by adjusting the number of periods and the diameter of the coils. Coil 1 is comprised of three periods, and Coil 2 of six, the diameter of the coils is ~35 cm. The electrodes are 1 m long with 75 mm gap, its shape has been optimized to reduce the peak fields on the edges (see Fig. 3). We have performed a preliminary thermal analysis of the structure considering a water flow rate of 10 L/min at 30°C in the cooling channels, which are further described in the following section. Table 1 contains the main RF parameters for both regimes.

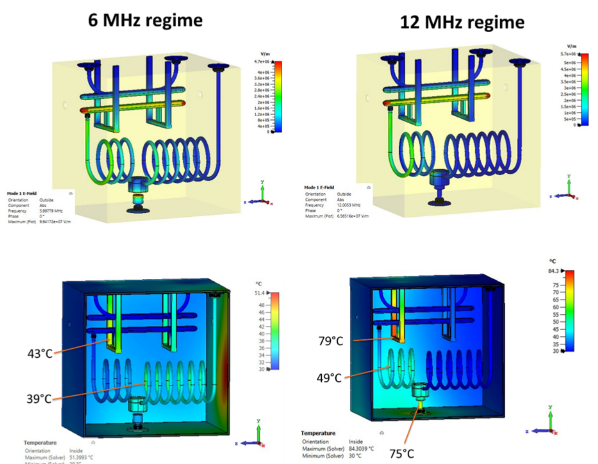

Figure 3: The surface electric fields in the sweeper (top) and the thermal maps (bottom) for 6 MHz and 12 MHz regimes normalized to 1 J.

Table 1: RF Parameters of the Sweeper

Frequency regime	6 MHz	12 MHz
Q-factor	4000	5000
RF power @150 kV, kW	8.8	10.3
Peak E-field (E_p), MV/m	5.9	5.6
$E_p/E_{Kilpatrick}$	1.3	1.2
Number of coil loops	9	3
Max. temperature, °C	44	80

Additionally, we designed two RF couplers to excite the modes (Fig. 2). The loop next to Coil 1 is the RF feed for the 12 MHz regime, and the loop next to Coil 2 feeds the 6 MHz regime. Both couplers are slightly over-coupled with the resonant structure to account for mechanical tolerances.

We performed beam dynamics simulations in the old sweeper using the TRACK code [7]. In particular, we simulated ^{50}Ca beam, obtained from ^{48}Ca at 10 MeV/u with a two-neutron pickup. Figure 4 demonstrates that the ^{48}Ca primary beam core & tail are eliminated by AIRIS/Raisor, while ^{49}Ca contaminant is reduced but not completely eliminated. With a higher voltage in the new sweeper, we could potentially remove the remaining contaminants.

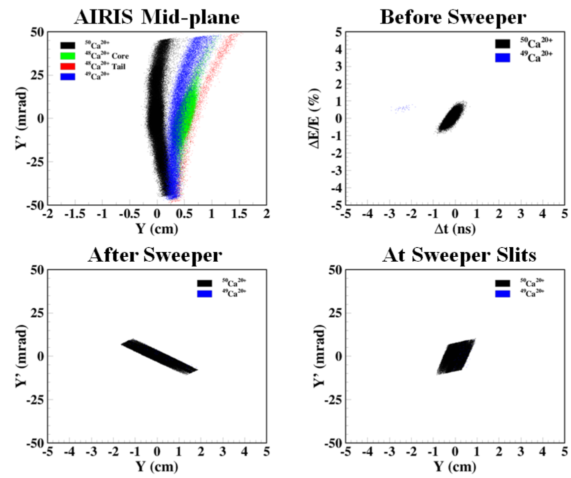

Figure 4: Test Case of ^{50}Ca RIB from ^{48}Ca primary at 10 MeV/u.

Then, we performed a series of beam dynamics simulations of the with different frequencies (6 MHz and 12 MHz) and voltages. In these simulations we found that for lower energy beams ~5 MeV/u, which corresponds to 10% the speed of light, it requires 33 ns to cross the 1 meter-long sweeper. At 12 MHz, the period of oscillations is 83 ns, so the beam spends 40% of the period in the sweeper and can be partly deflected. This indicates that for low-energy beams 6 MHz is a better fit and it doesn't require significant high voltage.

ENGINEERING DESIGN

The engineering design of the RF sweeper (Fig. 5) accounts for RF specifications, manufacturability, structural stability under vacuum, and assembly tolerancing allowances. A drop-in design approach was chosen for the system to improve the chamber's hermeticity by minimizing the number of lids. Additionally, attaching most of the components to a lid will allow for ease of access for levelling and repairing. Vacuum will be sealed using a Viton O-ring, and an additional canted spring contact will be added to make the inner lid an electrical ground surface as well.

The RF couplers will be attached through copper flanges with a pair of seals for vacuum and grounding. The flanges include features for rotational adjustment to allow some control over the amount of inductive flux going into the coils. Water cooling is applied on both electrode plates, coils, and couplers. We have chosen a tube-in-tube cooling approach for the coils and the couplers. The electrode plate

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connected to the coils will include channels milled into it to allow for cooling throughout its mass.

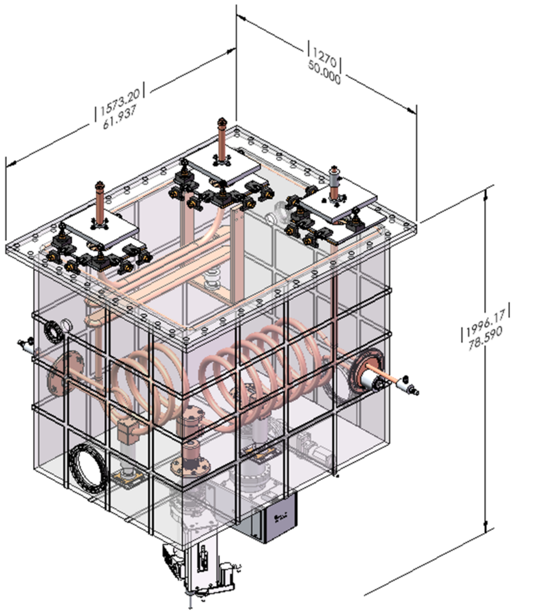

Figure 5: Engineering design of the RF sweeper with overall dimensions in millimeters (in brackets) and inches.

RF POWER SUPPLY

We are developing a solid-state class-E RF power source with two channels (6 MHz and 12 MHz) both with a controlled output power of up to 16 kW CW to enable a large range of deflection voltages in the sweeper. The source consists of 8 modules with 2 kW output power each and 8-way power combiner.

We designed a module capable of providing 1 kW CW power at 12 MHz based on IXYS 102N06A RF MOSFET to verify the operation of the Class-E topology in a solid-state amplifier. The idea behind class-E is to reduce or eliminate the effects that various capacitances within the MOSFET have on efficiency and operation at high frequencies. The 1 kW module diagram is shown in Fig. 6. The gate driver (DEIC420) is a CMOS high-speed high current gate driver specifically designed to drive MOSFETs in Class D and E for RF applications at up to 45 MHz. We built the module and performed RF power tests at RadiaBeam. The results shown in Fig. 7 indicate an average efficiency of the module of 84% over 300-970 W output power range.

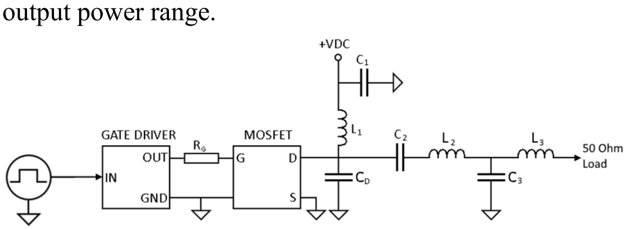

Figure 6: RF circuitry of the Class-E 1 kW module.

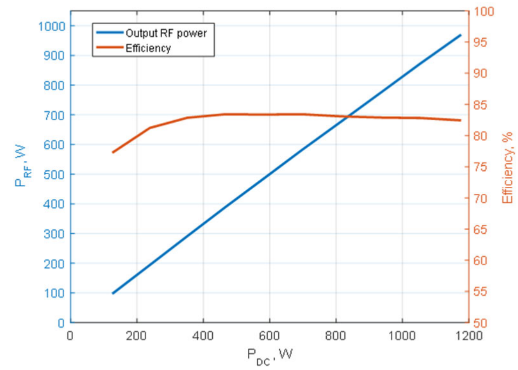

Figure 7: Measured output RF power and efficiency vs. DC power for the 1 kW module.

Then, we upgraded the 1kW circuit for 2 kW CW power for both 6 and 12 MHz channels. The 2 kW modules (Fig. 8) are also based on a class-E push-push up amplifier, consisting of a pair of MOSFET switches, a transformer for combining the two outputs with 180° phase, and a matching circuit that has two functions: converting the output impedance of the transistors to a load resistance of 50 Ohms and obtaining a sinusoidal output signal. The amplifier also contains a control circuit that converts the input sine wave to a square wave and provides with a 180° phase shift between the two stages. Additionally, the amplifier uses an RF choke coil and blocking capacitors to minimize AC signal noise.

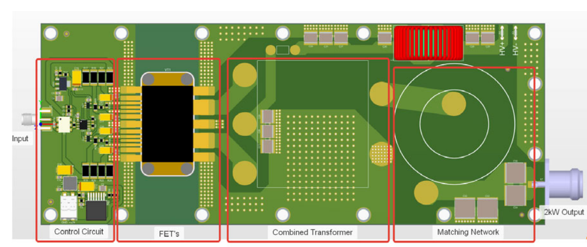

Figure 8: Amplifier pallet design of the 2-kW module.

We are currently in the process of assembling the modules and designing the power combiners in order to reach the required output power level.

SUMMARY

We have designed a high-voltage RF beam sweeper for the ATLAS facility. The device incorporates a sliding switch to allow operation at two frequencies: 12 MHz and 6 MHz. Thermal analysis has been performed to ensure the manufacturability of the device. In addition, we are developing an in-house solid-state RF generator to provide the required power level for the two frequency regimes.

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