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R&D PROGRESS OF ELECTRON CYCLOTRON RESONANCE ACCELERATOR*

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Abstract

Several attractive features of a novel electron Cyclotron Resonance Accelerator (eCRA) include: a compact robust room-temperature single-cell RF cavity as the accelerator structure; continuous ampere-level high current output without bunching; and a self-scanning accelerated energetic e-beam, obviating need for a separate beam scanner. Hence an eCRA can be highly compact and efficient to produce high power electron beams and x-ray beams. The applications of the eCRA includes the replacement of Cs-137 based dosimeter calibration systems, and the replacement of Co-60 based sterilization systems. The R&D progress of eCRA is reported here. A 2-MeV eCRA Demonstrator is under construction at BNL to validate the eCRA acceleration mechanism experimentally. A 5-MeV eCRA Upgrade with high beam power is in the design phase.

INTRODUCTION

Radioactive sources have been used in a variety of beneficial applications including sterilization of medical devices, irradiation to reduce the food-borne illnesses transmission, instrument calibration, National Security, et al [1]. However, radioactive sources pose both safety and security risks, if these sources are mishandled. Replacement technologies for radionuclide sources, using accelerator-based X-ray generators, are available or possible for most irradiation applications. To produce x-rays, high-energy accelerated electrons strike a heavy metal target and are rapidly decelerated, generating bremsstrahlung photons with a broad and continuous energy spectrum with all energies below the maximum energy (that of the electrons) and an average energy of about one-third of the maximum energy.

But to substitute Cobalt-60 irradiation directly, a high power accelerator capable of delivering a high power electron beam with energy not less than 5 MeV and with high RF-to-beam efficiency is desired. Our novel design of an eCRA-driven e-beam/X-ray generator system can provide a novel system to fulfil the needs of irradiation applications with compact size and high efficiency.

DESCRIPTION OF eCRA

The physical principle underlying eCRA [2] differs fundamentally from the principles underlying all other types of particle accelerators such as linacs or cyclotrons.

The eCRA concept uses a compact robust room temperature single-cell microwave cavity as the accelerator structure to produce a continuous, high current, un-bunched, self-scanning e-beam, with a projected RF-to-beam efficiency about 80%; and obviating the need for an active e-beam scanner [2, 3]. The theoretical and numerical analysis of eCRA can be found in Ref. [2]. Simulations have demonstrated that for electrons injected into a TE_{111} rotating-mode cylindrical cavity immersed in a strong axial magnetic field, high current beams with accompanying heavy beam loading experience acceleration to multi-MeV levels. The eCRA can continuously accelerate charged particles at arbitrary injection phases. With continuous injection of a beam during a full RF cycle, the output beam follows a circular (elliptical) path for circular (elliptical or linearly) polarized RF field. The sweeping beam intersection on a planar target perpendicular to the cavity axis constitutes self-scanning, which completes a full scanning path at a time scale of nanoseconds instead of milliseconds without using alternative current electromagnets.

EXPERIMENTAL EFFORTS OF eCRA DEMO

An eCRA-based e-beam accelerator, the BNL eCRA demonstrator (DEMO) [3], is under construction at BNL to validate the eCRA acceleration mechanism and beam manipulation and serve as a test bed for the x-ray generator design and its x-ray characteristics study. It is designed around some existing components including the S-band microwave waveguides and hybrids, solenoid magnets, iron flux cages and support frame, to significantly reduce the hardware costs. Yet the magnetic field strength is only about 0.25 T at the cavity region, limited by the specification of existing solenoids, hence it is expected to produce electron beams with beam energy about 2.0 MeV.

As shown in Fig. 1, the CST Particle Studio simulation of the eCRA validates that an 18 keV input electron beam with a radius of 5 mm and energy spread of 10% is accelerated to 2.0 MeV inside the eCRA. A thin titanium foil (25~100 micron in thickness) attached to a slotted copper plate is used as the cavity end wall and a beam window to allow the accelerated electron beam to transmit without much energy loss while blocking the microwave from leaking into the downstream beam pipe. However, the CST results can't reflect the reduction of beam energy due to the beam interception with the titanium foil and copper frame. Hence a GEANT4 based program G4beamline is used to simulate the beam-matter interaction approximately. As shown in the histogram of the

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transmitted beam energy in Fig. 2, the majority portion of the beam remains about 2 MeV, with less than 10% of the beam lost about 0.2 MeV after the interception with the copper frame at a large pitch angle. Note that the microwave field distribution is approximated as a circular polarized standing plane wave while experiencing difficulties to import the realistic time dependent rotating TE111 mode in this G4beamline model.

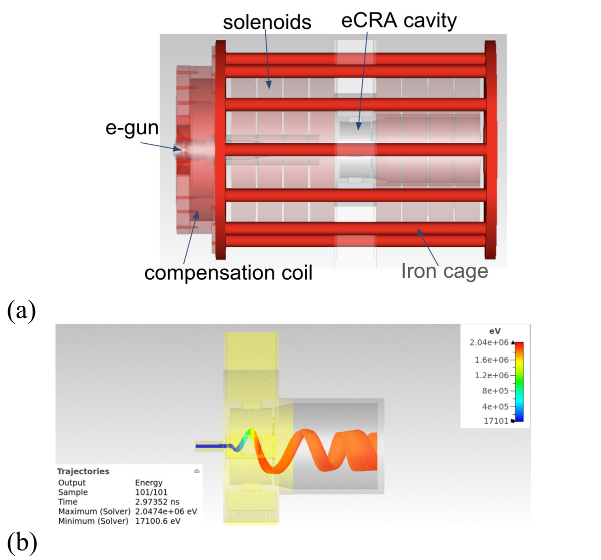

Figure 1: CST Particle Studio simulation of the eCRA. (a) The CST model, where the eCRA cavity is enclosed inside the iron cage with multiple solenoids. (b) The Particle Tracking result shows that an 18 keV input electron beam with a radius of 5 mm and energy spread of 10% is accelerated to 2.0 MeV.

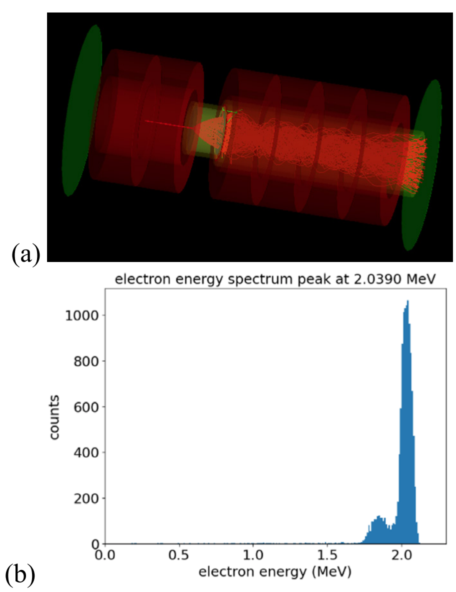

Figure 2: G4beamline simulation. (a) The model and particle traces, with red blocks indicating solenoids and red traces for electron beams. (b) the energy histogram of the transmitted electron.

Currently the components of the eCRA cavity have been manufactured as shown in Fig. 3, and are ready for the brazing procedure. But due to the supply chain issue, the vendor of the gridded thermionic electron gun beam has postponed the delivery significantly. The electron beam diagnostic setup is designed to use a YAG screen close to the eCRA exit, as shown in Fig. 4. A distinct donut-shape image on the YAG screen will be a clear indication of the accelerated electrons transmitted through the titanium foil as predicted by the simulation in Fig. 1b.

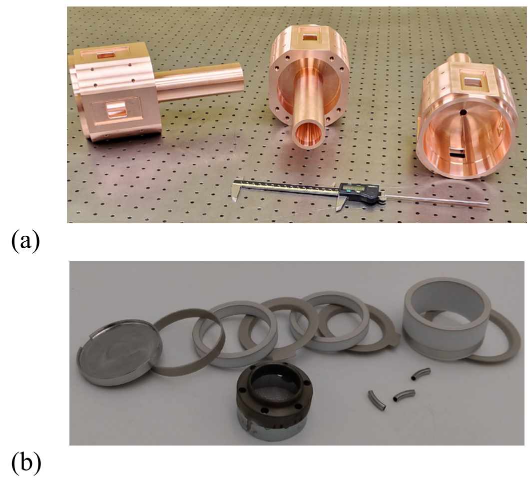

Figure 3: (a) The main body of the eCRA cavity before brazing the waveguide ports to it. (b) the components of the gridded thermionic electron gun for the eCRA.

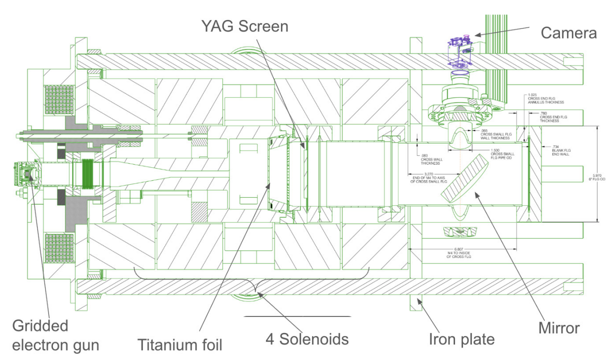

Figure 4: The engineering design of the eCRA beam diagnostic using YAG screen for beam imaging.

For the high-current, high efficiency performance for eCRA as described in this paper, the particle beams produced may not exhibit the low emittance values that are important for most discovery research. Rather, the beams could be useful for industrial applications where higher emittance and some energy spread can be tolerated, in favour of high beam power.

CONCEPTUAL DESIGN OF eCRA UPGRADE

The eCRA Upgrade [4], an upgraded version of the BNL eCRA DEMO, is parametrized to generate a 5 MeV, peak 1-to-5 A e-beam with a duty factor of 0.01%, for an average beam power of 0.5-to-2.5 kW, as a pilot project to demonstrate its capability to replace Cobalt-60 irradiation system, with its conceptual design shown in Fig. 5. This eCRA Upgrade will operate at S-band (2.856 GHz) using

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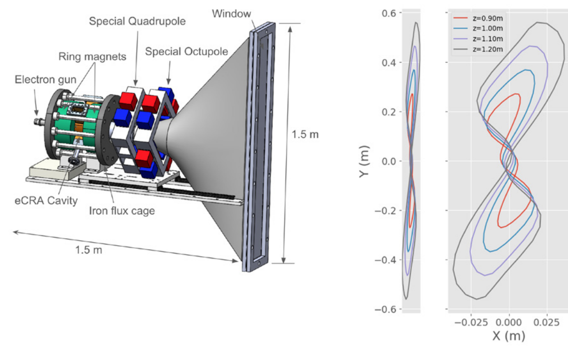
the same e-beam injector, RF source, RF power distribution network as in the DEMO.



(a) (b)

Figure 5: (a) Conceptual design of the eCRA Upgrade, with permanent magnet rings for eCRA, and a static beam transport to transform the beam profile using special quadrupole and octupole permanent magnets. (b) The trajectories of the electron beam projected on x-y planes at different longitudinal locations. The left subplot with identical scale in x and y directions indicates a large aspect ratio between the vertical and horizontal direction of the output beam.

In the design of eCRA Upgrade, the electromagnetic coils are replaced with ring permanent magnets and small trim coils to increase the magnetic field that surrounds the DEMO cavity by a factor of about 2.5, as this is predicted to allow an increase in the e-beam energy from about 2 to 5 MeV. Further, a new static beam transport system is designed to uniformly spread the e-beam into a narrow but tall profile for either electron or x-ray irradiation for sterilization, for example. Inspired by the design in Ref. [5], a coupling of a linear magnetic field (quadrupole magnetic field) and an octupole magnetic field can achieve large beam transverse spreading with good homogenization at the same time. Preliminary simulation using particle tracking, shown in Fig. 5b, indicates that the eCRA output beam can be spread out over the area of 120 cm $\times$ 8 cm at a location of 120 cm away from the cavity center with a large aspect ratio of 15:1 between vertical and horizontal directions. Unlike conventional AC-driven scanning magnets, the self-scanning of an eCRA beam goes through a whole irradiation path within a single RF cycle which is at the time scale of sub-nano seconds, instead of milliseconds. Together with high radiation flux and consistent motion of products on the conveyor system, the irradiation process is expected to be much more uniform on the products.

High-intensity electron beams and/or x-rays are particularly useful in industrial irradiation applications. To produce x-rays, high-energy accelerated electrons strike a high-Z metal target and are rapidly decelerated, generating bremsstrahlung photons with a broad and continuous energy spectrum with all energies below the maximum energy (that of the electrons) and an average energy of about one-third of the maximum energy. As a rough estimation, assuming an accelerated beam with energy of 5 MeV and an average beam current of 20 mA, for an average beam power of 100 kW, and taking the energy conversion efficiency from electron to x-ray of 8%, the radiation flux can reach 1 MCi, which is comparable to the irradiation capability of a large-scale industrial sterilization facility [6]. Those sterilization facilities may contain millions of curies of Co-60 (IAEA Category 1) to expose a wide variety of products to ionizing radiation, including medical devices, spices, and other foods.

CONCLUSION

The eCRA system offers a reliable, portable device capable of sustained operation to produce e-beam/X-ray for industrial and security applications cost-competitively, particularly for the replacement of Co-60 based sterilization systems. The eCRA R&D progress is reported here.

Acknowledgements

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