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LIGHTHOUSE - A SUPERCONDUCTING LINAC FOR PRODUCING MEDICAL ISOTOPES

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Abstract

The medical isotope ^{99}Mo is used for diagnosing several 10 million patients every year. Up to now, it is produced from highly enriched Uranium (HEU) using high-flux neutron reactors. The Institute for Radio Elements (IRE), Belgium has projected the design of a high-power superconducting linac for producing ^{99}Mo without use of nuclear fission as part of their SMART project. The LightHouse accelerator consists of a photo gun and seven superconducting radiofrequency (SRF) modules, a beam splitter, and target illumination optics. It will deliver two electron beams of 75 MeV and 1.5 MW each.

The photo gun and the SRF modules are based on the CBETA design of Cornell University. Photocathodes are prepared and transferred in situ. We report on the design principles and the Beam Test Facility operating since April 2022.

DESCRIPTION OF PROJECT

Radioisotopes are used in nuclear medicine to detect numerous diseases for example by spectroscopic imaging. In case of cancer, it is predominantly used to determine how much the disease has spread to identify to best possible treatment. The metastable isotope ^{99m}Tc is applied to patients in more than 80% of the diagnostic treatments. IRE [1] is one of the world's leading suppliers of its parent isotope ^{99}Mo.

The large majority of ^{99}Mo production is based on purification of fission products produced in nuclear research reactors from enriched Uranium. The risk of proliferation, aging reactors, and long-lived nuclear waste are reasons to switch to an alternative production process. Within the SMART project (Source of MedicAl RadioisoTopes) [2], IRE is developing a ^{99}Mo production facility based on accelerator technology in partnership with ASML [3]. In this approach, a ^{100}Mo target is illuminated with an electron beam. The electrons are stopped in the ^{100}Mo target, producing bremsstrahlung. A (γ, n) reaction will then knock out one neutron from the Mo-nucleus, yielding the radioisotope ^{99}Mo.

Currently, the project is in the design and prototyping phase, which is going to be completed in 2024 with a decision of IRE's board on the realization of the project. Manufacturing and construction are scheduled to be completed by 2026, to be followed by installation and commissioning until 2029. After one year of pilot production, the high-volume production is envisioned to start in 2030.

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Within this project, RI Research Instruments (RI) [4] takes the responsibility for the design, fabrication, installation, and commissioning of the full accelerator. This includes the photocathode production and laser systems, the cryogenic plant and RF amplifiers, the machine protection system, the accelerator control system, and the beam transport and beam scanning onto the target.

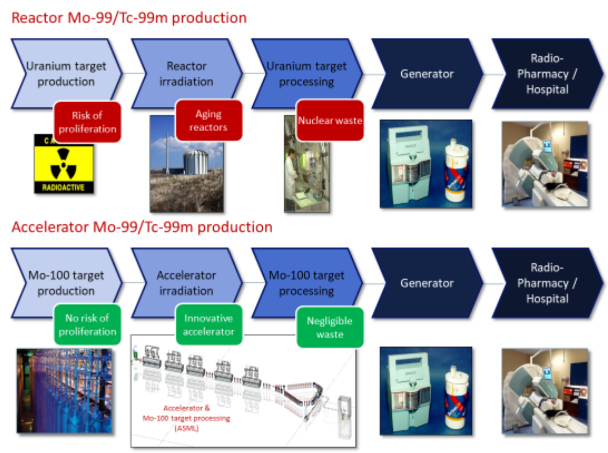

Figure 1: Innovative production of Mo-99 from accelerator irradiation compared to traditional production in a nuclear reactor from Uranium targets. Courtesyof IRE.

DESIGN PRINCIPLES

The new production site is planned to take over the full volume of ^{99}Mo production for IRE. The required beam power is 3 MW, with an electron beam energy of 75 MeV and a beam current of 40 mA at 1.3 GHz continuous wave (CW). The large average beam power calls for the use of SRF technology.

To reach the desired specific activity of ^{99}Mo, a two-sided irradiation is mandatory. This results in a superior depth profile of heat load and specific activity inside the target. The two-sided irradiation is realized by splitting the electron beam in two after acceleration to full energy.

Injectors

Relying on a single production facility also puts high demands on the uptime of the accelerator. This is implemented by providing two fully equipped parallel injectors allowing for rapid switching. As they will be placed in separate rooms, it will also be possible to maintain one injector while the rest of the accelerator is running in full production mode with the other injector.

A 3D model of the LightHouse accelerator is shown in Fig. 2. The photo-gun operates at 350 keV and the SRF module with five two-cell cavities accelerates the beam to

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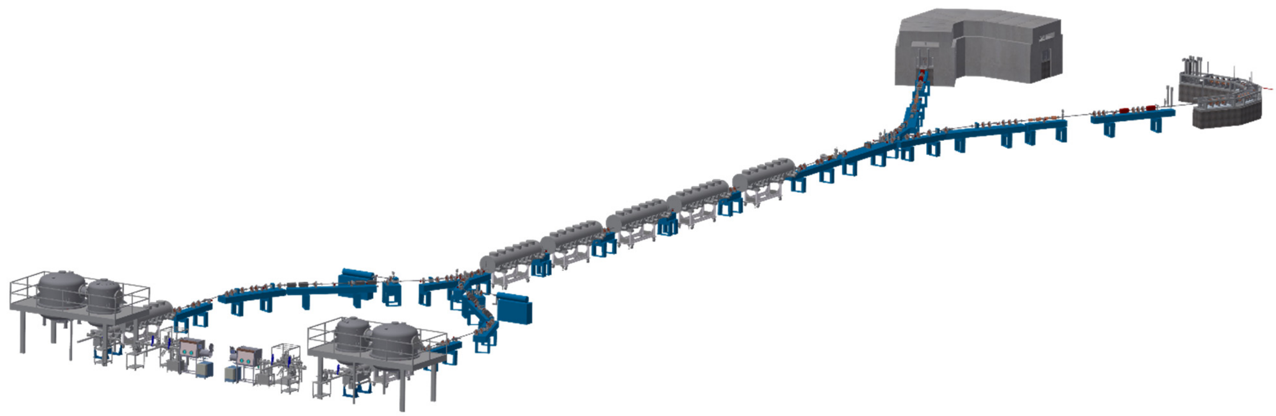

Figure 2: 3D Model of the LightHouse accelerator. Two parallel injectors (left) will increase the availability of the system. The electron beam will be split at 75 MeV into two arcs to illuminate the target (top right, details not shown) from both sides simultaneously. The last part of the beamline will be designed to tolerate the high radiation background from the target. The shielding is only shown for the left arc but would be applied for both sides.

12.5 MeV. Gunand SRF module are based on the CBETA injector design by Cornell University [5]. Photo cathodes are prepared in situ using thermal evaporators and crucibles large enough for depositing a large number of photocathodes. They are transported by a transfer system to the gun located within the same vacuum system. This will ensure ideal conditions for the photocathodes and maintain a high quantum efficiency (QE). Production and transport will be fully automated.

Linac and Beam Splitter

In the main linac, the e-beam is accelerated to 75 MeV with five identical copies of the injector cryomodule. The facility thus comprises seven cryomodules in total. Each cavity is powered by a solid-state amplifier with up to 130 kW of power. The RF amplifiers are built using gallium nitride transistors and have proven a plug to RF efficiency of 62%. The fundamental power couplers (two per cavity) are designed to handle up to 80 kW each and are currently put to testing.

Beam splitting will be done resonantly with a normal conducting 650 MHz transverse deflecting cavity (TDC) and static magnetic optics. This leads to two beams with 650 MHz repetition rate each, avoiding any beam pauses, which would otherwise lead to thermal cycling of the target.

Beam Scanner and Radiation Hard Arcs

Additional TDCs will scan the beam and generate a specific pattern that optimizes the heat load and the specific activity of the target. Arcs with imaging properties will transport the beam pattern up to the target.

Due to the two-sided irradiation, a significant amount of scattered radiation will leak from the target and its primary shielding upstream into the beamline of the opposing e-beam. This requires a radiation hard design of beamline components e.g., magnets are expected to receive up to 100 MGy in their lifetime. Build-in redundancy and quick access to critical components through a shielded service level above the beamline will ensure a minimum downtime in case of repairs. Replacement of beamline sections is facilitated by the use of pillow seals that allow for disconnecting the highly activated beam tubes without the need to manually connect vacuum flanges or other activated components.

The arcs will also host a differential pumping system, ensuring good beamline vacuum levels, since no vacuum window can be used towards the target due to the high beam power.

Machine Protection System

To prevent damage to the accelerator caused by beam loss or non-compliant machine settings, a Machine Protection System (MPS) hase been designed. Its key feature is a reaction time from detector to stopping the beam in below 1 µs realized by a simple and fast gate logic, which sets output permits as a function of binary, active-high input signals. The MPS also controls and verifies the beam's duty cycle and average beam power and is scalability to accommodate several hundrets of input signals. A prototype of the MPS has successfully demonstrated these performance requirements.

PROTOTYPES

Prototypes of key accelerator components have been built and are currently being tested at RI. This includes one full RF amplifier rated to 130 kW, four 1.3 GHz fundamental power couplers including an RF test stand, the 650 MHz splitter TDC, various electron beam diagnostics including electronics, a prototype of the MPS, and, foremost, the Beam Test Facility (BTF).

Beam Test Facility

The BTF hosts the 350 keV electron source including a high-voltage (HV) power supply, laser system, photocathode production, a beamline with solenoids, beam diagnostics, a bending magnet, and beam dump. The MPS prototype controls beam patterns and can be used for interlock

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processing. This represents the complete setup of the electron source of the LightHouse accelerator plus a diagnostic beamline but excluding the buncher cavity. Photographs and a schematic overview of the BTF are shown in Fig. 3.

The main goal of the BTF is to show a photo cathode operational lifetime of more than 24 hours at 40 mA beam current and 350 keV. Furthermore, this installation enables us to study the interplay between various sub-systems, like automated preparation, transfer, and insertion of photocathodes into the gun or a feedback loop on the laser power to continuously compensate for degrading QE while keeping the electron beam current stable at 40 mA. With the BTF, our team is also gaining relevant experience with operating the systems in preparation for the ambitious commissioning schedule of the LightHouse accelerator.

In April 2022, we reached a major milestone at the BTF showing electron beam operation for the first time. In that run, beam operation was still limited to 120 keV and low duty cycle, given that the HV power supply was operated without insulation gas and that the beam dump for full beam power was not yet installed.

In the meantime, various upgrades have been implemented, which will allow us to reach the full specification of the electron source within 2022.

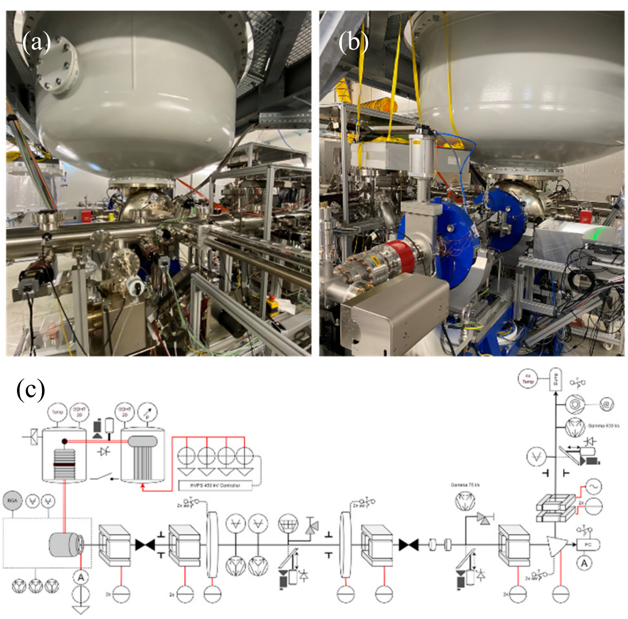

Figure 3: (a) Photograph of the BTF from behind the gun, also showing a part of the photocathode production and transfer system, (b) photograph of the BTF from the beamline side with two solenoid magnets and beam current monitors, (c) schematic overview of the BTF and its components.

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