IF YOU CAN'T STAND THE HEAT

Strictly speaking, the SMART project is not Big Science, but the collaboration of over 25 research institutes and high-tech companies working on a revolutionary technology for the production of radioisotope ^{99}Mo is definitely impressive. The technology comprises a large electron accelerator and huge irradiation and extraction facilities. At the heart of the system is a matchbox-sized target that is irradiated by a 3-MW electron beam. Alongside the radiative load on the target and exposure unit, the heat load on the target is among the key challenges of the SMART project. Demcon is developing an 'exotic' solution: cooling with liquid sodium.

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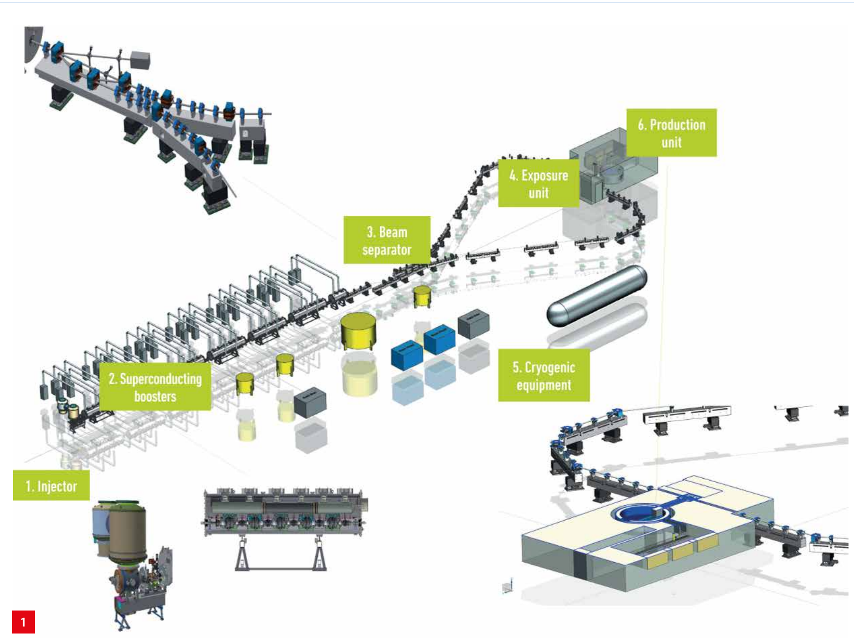
Introduction

In the past decades, driven by Moore's Law, ASML investigated several options for short-wavelength light sources for its lithography systems, ultimately leading to EUV. One of the alternative options that was discarded along the way was a free-electron laser, the origin of which was a high-energy electron beam. In 2015, ASML realised that this option could be adapted to produce the radio-isotope molybdenum-99 (^{99}Mo).

ASML decided to continue development of this so-called LightHouse principle externally. To that end, they engaged in a partnership with IRE (Institute of Radio Elements), headquartered in Fleurus (Belgium). IRE, world leader in the production of radioisotopes used for diagnosis and therapy, is one of the producers of ^{99}Mo, the most widely used radioisotope for diagnosis in nuclear medicine.



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The LightHouse concept. Electrons are injected (1) into the accelerator that is provided with superconducting boosters (2). The electron beam is accelerated to 75 MeV and then split into two beams (3) that irradiate a target from both sides in the exposure unit (4). The superconducting boosters are cooled with cryogenic equipment (5), while the target is cooled with liquid sodium (not shown). In the production (harvesting) unit (6), the intended product, ^{99}Mo, is harvested from the target after irradiation. (Source: SMART)

The ^{99}Mo isotope is produced in a nuclear reactor by irradiating enriched uranium. Worldwide, IRE is the largest of four suppliers of medical radioisotopes. It does not operate a reactor of its own, but relies on several reactors in Europe. The ^{99}Mo produced there is extracted by IRE and then supplied to hospitals. When the ^{99}Mo arrives in the hospital, it has partly decayed into the short-lived technetium-99m, the element that is administered to patients before a scan is made.

Production in a nuclear reactor is not a sustainable model. The reactors that are used currently for this purpose are nearing their end-of-life, which makes operation unreliable and hence jeopardises the reliability of supply, as no buffer stock can be created due to the rapid decay of ^{99}Mo. In addition, the uranium used in these reactors poses huge safety and waste problems.

LightHouse concept

In the LightHouse concept (Figure 1), ^{99}Mo is produced by irradiating the non-radioactive ^{100}Mo with an intense electron beam. Compared to nuclear production, this alternative is, in principle, reliable and cheaper, requires no radioactive uranium and produces hardly any waste. In addition, the technique is capable of producing quantities comparable to those produced by a nuclear reactor. Electron accelerators are already used to produce small quantities of low-specific-activity ^{99}Mo, but this does not meet the specifications for large-scale production of ^{99}Mo for nuclear medicine. That requires a superconducting, high-power linear electron accelerator. The electron beam it produces is split into two to expose a target composed of ^{100}Mo-enriched molybdenum from both sides, to achieve a relatively uniform activation profile. The high-energy electrons are stopped in the target, which produces *Bremsstrahlung* (high-energy gamma rays) that transforms the ^{100}Mo into ^{99}Mo. After irradiation, the ^{99}Mo is harvested from the target.

The LightHouse concept poses big physical and technical challenges. Therefore, financially supported by the Belgian authorities, IRE, with the technical support of ASML, integrated the LightHouse technology in the SMART project (Source of MedicAl RadioisoTopes), in which over 25 research institutes and high-tech companies participate. The various production components of the future LightHouse facility are developed by specialists. Research Instruments, based in Bergisch Gladbach (Germany), is an expert in the field of particle accelerators, while Demcon is developing the exposure unit, including the target, and the harvesting unit.

Target design

Cooling

One of the major project assignments was awarded to Demcon: developing a target that could survive the 3-MW heat load caused by the electrons. This is indeed a challenge, because the target is the size of a matchbox (the reason for this size will be explained below). The heat load, equivalent to the heat produced by three Formula-1 cars, requires massive cooling. Since only a small part of the power is used to create the ^{99}Mo, 2 MW of heat is generated in the target and 1 MW is lost in adjacent components of the exposure unit. Hence, both need to be cooled very efficiently. For cooling, liquid sodium was selected as the coolant, because sodium has a relatively low melting point and a high specific heat capacity. However, it is flammable and chemically aggressive, which makes it difficult to handle.

Modular

The design of the target is modular, based on the irradiation and harvesting procedures; each time highly irradiated parts (modules) of the target are harvested, the medium irradiated parts are rearranged within the target and fresh ^{100}Mo-containing parts are added. For confidentiality reasons, no further details can be shared.

Simulation

Extensive simulations were performed to verify the concept and investigate whether the target and the surrounding structures could survive the irradiation and the liquid sodium cooling. Experiments were conducted with a sodium-cooling test circuit to verify the simulations, and a 1:1,000 version of the SMART factory was built. Particular simulation problems included calculating the local heat load in the target and the complex target geometry, which led to high flow velocities and extreme pressure differences.

Materials

Material selection for the structural parts around the target was another issue. Insufficient data were available for the extreme heat and irradiation conditions; hence feasibility studies were performed with the most critical parts. For the target material itself there was no choice: it had to be ^{100}Mo. Unfortunately, little information was available. Concerning radiation damage, both embrittlement and swelling (components getting bigger, which is highly undesirable in complex machinery) are a problem. To gain insight into these matters, a visit was paid to the European Spallation Source, the Big Science facility based in Sweden that operates the world's most powerful neutron source.

Size

Determining the optimum target size was a trade-off between power density and the competition between ^{99}Mo activation and decay. A low power density is preferred to keep the accelerator and target manageable, while on the other hand a high electron current density is needed to achieve sufficient activation. The cross-section of the target was optimised to an area just under 10 cm^2 and its depth is related to the penetration depth of electrons in this specific target, which is in the order of centimeters. Hence, the 'matchbox'. If the target is too small, it will cook and evaporate under the heat load. If it is made larger, the yield will be lower, given the beam energy and current.

Exposure unit

The exposure unit is housed in a vacuum vessel. The target is surrounded by components designed to extract the 1 MW that is not absorbed by the target. A so-called power dump acting as a first layer around the target absorbs the high-energy radiation, while concrete shielding outside the vacuum vessel protects humans and machines against the 'low'-energy scattered radiation and the produced neutrons. As the extreme conditions will undoubtedly lead to damage, easy replacement of parts was one of the demands.

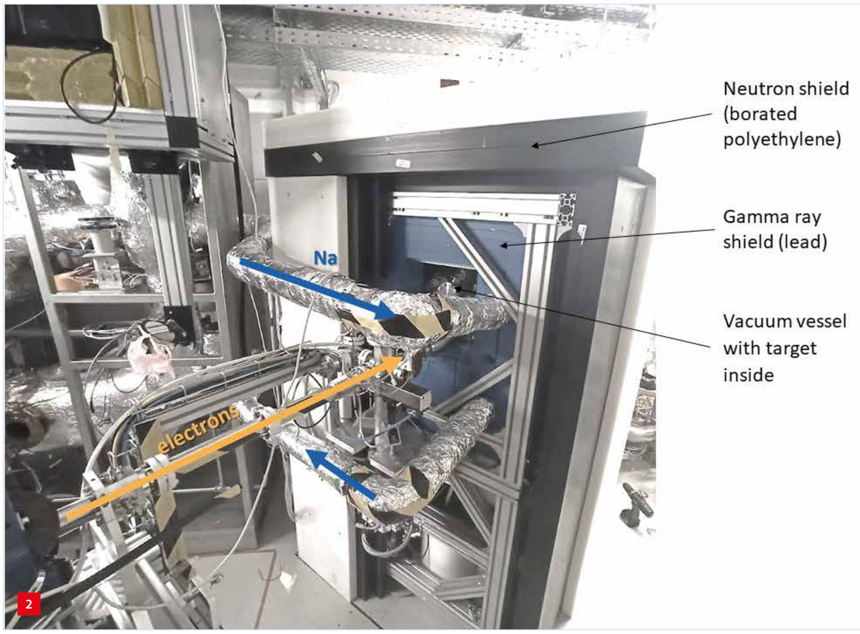
Harvesting unit

Demcon also elaborated the design of the harvesting unit, where the ^{99}Mo is extracted from the exposure unit and harvested, and substantiated this with analysis of test set-ups and tests on specific parts. Here, the radiation intensity is orders of magnitude lower, but components such as motors and sensors are highly sensitive to radiation damage. Therefore, the biggest design challenge was the 24/7 long-term reliability of the SMART factory.

A fast extraction procedure was required to minimise the loss of activated material due to natural decay. After irradiation for 23 h, extraction should be performed within 1 h. Accuracy for target positioning is in the range of 0.1 mm, which is relatively very precise, as the manipulation unit has a size in the order of several meters. Manipulation is fully automated; only the chemical processing of the harvested parts is performed manually, by an operator using a telemanipulator.

Outlook

Using the 1:1,000 miniature version of the SMART exposure unit (Figure 2), running with full power density, the first short-run test (several seconds) was done this year. This is proof of the thermal feasibility of the cooling concept. Later this year, Demcon plans a long exposure run to validate the structural integrity of the target including the long-term effects of exposure to radiation and liquid metal, after which development & engineering will be completed next year. In 2028, the revolutionary nuclear medicine production technology is scheduled to hit the market.



The 1:1,000 miniature version of the SMART exposure cell. It was installed at the ELBE electron accelerator at HZDR Dresden-Rossendorf (one of Germany's Big Science facilities). Power density, Na cooling and target materials are representative of the SMART target.