ELECTRON LINAC CONCEPTS FOR THE PRODUCTION OF MOLYBDENUM 99

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Abstract

The medical isotope Molybdenum-99 is presently used for 80-85% of all nuclear medicine procedures and is produced by irradiating highly enriched uranium U-235 targets in nuclear reactors. It has been proposed [1] that an electron linac be used for the production of ^{99}Mo via photo-fission of a natural uranium target. The nominal linac parameters are 50 MeV electron energy, 100 mA beam current and 100% duty factor. This paper describes two possible superconducting RF accelerator design concepts based on the frequencies of 704 MHz and 1.3 GHz. We present design parameters, efficiency and reliability estimates, and comparisons between the two options. Finally, we describe how the proposed e-linac project at TRIUMF can be used for proof-of-principle demonstration and critical validation tests of the accelerator-based production of ^{99}Mo

INTRODUCTION

Presently, 80-85% of all nuclear medicine procedures use a medical isotope known as Technetium-99, which is prepared from a parent radioactive atom, Molybdenum-99 (^{99}Mo). There are about 40 million such procedures worldwide per year, of which 20 million are performed in North America and about 1.5 million of those in Canada. In late 2007, N. America experienced a critical shortage of the medical isotope over a period of several weeks due to an extended shutdown of AECL's NRU reactor. With this as a backdrop (with support from the Ministry of Natural Resources Canada) TRIUMF, the University of British Columbia, and Advanced Applied Physics Solutions Inc. assembled a task force of experts to explore the feasibility of using accelerator-driven photo-fission to generate sufficient quantities of ^{99}Mo to supply a significant fraction of the North American demand.

The four main commercial producers of ^{99}Mo in the world use nuclear reactors with highly enriched uranium (HEU) targets. The reactors produce neutrons which in turn stimulate fission of U-235, producing a 6% yield of ^{99}Mo. In comparison, the proposed photo-fission accelerator approach would produce high-energy photons to split natural uranium U-238 with the same fractional production of ^{99}Mo as produced by neutrons (around 6%). Because the ^{99}Mo fractional fission yields from each technique are almost identical, the specific activity of the final ^{99}Mo-99 product should be identical. The probability of neutron-fission versus that of photo-fission, however, is favoured by a factor of nearly 3,000 and thus a high flux of photons is needed to equal the production rate from neutrons, everything else being equal. The large flux demands a high-current electron linac as the source of bremsstrahlung photons. Based on the production of sufficient 6-day Curies to satisfy the clinical demand for ^{99}Mo in Canada, it is estimated that 5 MW of electron beam power at 100% duty factor is required. The nominal e-linac parameters are 50 MeV electron energy and 100 mA beam current.

SRF Technology Options

The adoption of superconducting radio frequency (SRF) accelerating structures for the electron linac provides a cost effective approach to a MW-class fission driver because of the intrinsic power efficiency, compactness and high accelerating gradient they offer. Based on presently available technology, there is a choice of frequencies of the accelerating structures ranging from 500 MHz to 1.3 GHz. Two possible frequencies, 704 MHz and 1.3 GHz, were chosen to illustrate technically feasible conceptual designs. However, based on a preliminary analysis, the lower frequency option will probably result in lower capital cost. The operations costs are similar, as they are dominated by the high-power microwave generators driving the structures.

704 MHz OPTION

Brookhaven National Laboratory (BNL) is constructing a 20 MeV R&D Energy Recovery Linac (ERL) facility [2,5] based on SRF 5-cell cavities operating at 704 MHz, and designed to accelerate up to 0.5 A of average current. A single 1 MW CW klystron with a 2 MW IGBT power supply will power the 2.5 MeV SRF injector cavity. The 500 kW input couplers for this injector are presently under construction and will be tested in a conditioning box at BNL in 2009. The 5-cell SRF linac cavity has been successfully tested in the vertical test facility at Jefferson Laboratory demonstrating a quality factor in excess of 10^{10} at an accelerating gradient of 10 MV/m. Because the cavity design has been developed for high current applications, its longitudinal loss factor is exceedingly small (less than 1 V/pC) resulting in relatively low power dissipation in the higher order modes. Based on the availability and demonstrated performance of these components, a 5 MW photo-fission driver for the production of ^{99}Mo can be configured as follows: a thermionic injector can be used to supply 100 mA average current at a bunch repetition rate of 704 MHz and charge per bunch of 140 pC. The main accelerator (see Fig. 1) consists of a single cryomodule housing five 5-cell cavities, each providing an energy gain of approximately 10 MeV. For 100 mA of average current, the required RF power per cavity is 1 MW, supplied by a 1 MW klystron via two 500 kW input couplers. As the IGBT technology is scalable, it is expected that a single power supply can

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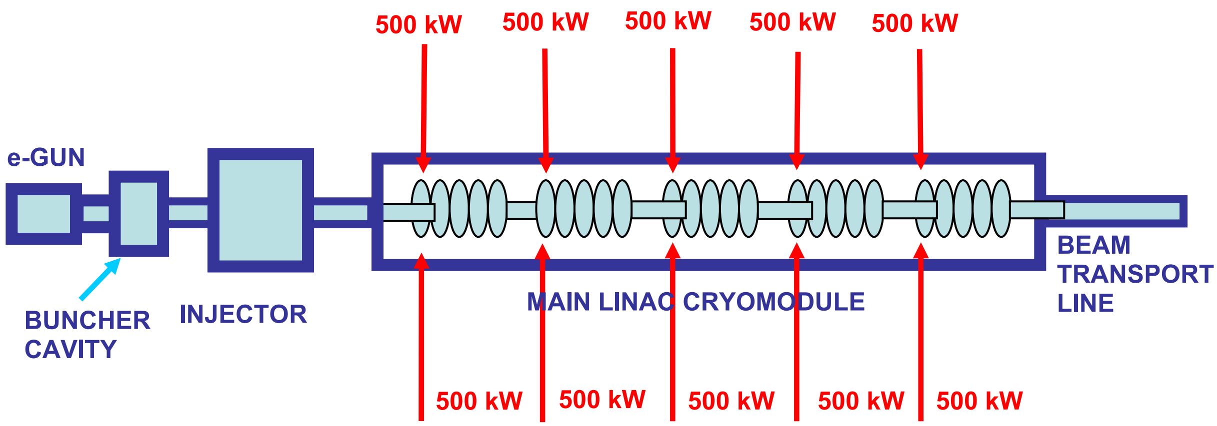

Figure 1: Schematic layout of 5 MW electron linac based on 704MHz SRF technology.

be used for several klystrons, although the exact number needs to be confirmed with the manufacturer. The wall-plug to beam efficiency for this design concept has been estimated to be in excess of 40%, dominated by the klystron efficiency at 60%. The total wall plug power consumption is about 12 MW, assuming 2K operation of the cryogenic plant. The frequency choice of 704 MHz in principle allows the option of 4K cryogenic operation. There are several advantages to this option including ease and robustness of operation, reduced system complexity, and lower operating and capital costs. For an industrial-scale application, such as the production of ^{99}Mo, this option should be explored. The estimated capital cost of the accelerator, including ancillaries and conventional services, is M$55.

1.3 GHz OPTION

There exists at Cornell University a 1.3 GHz Injector Linac[3] designed to provide ½-MW beam power. This linac is built from building blocks composed of a 100 kW klystron, two 50 kW input couplers and a 2-cell RF cavity driven at up to 10 MV/m gradient. The five SRF cavities are housed in a single cryostat. The energy gain is 1 MeV per cavity at 100 mA. The high-power coupler and klystron designs were demonstrated in 2007. This linac has been undergoing systems integration tests since May 2008 and beam tests[6] are anticipated starting December 2008. To first order, this design is directly scalable: 50 cavities driven by 50 klystrons (see Fig. 2) provide the desired 5 MW electron beam power. The cavities would be divided between five cryostats with focusing elements between. Simple scaling of the equipment cost for the ½-MW machine leads to a rough estimate of M$150 for the 5 MW version. However, the R&D cost is eliminated and some economy of scale should result from large-scale production. A cost around M$125 could be expected for the machine with ancillaries and conventional services.

The coaxial-type input couplers, and to a lesser extent the klystrons, form a bottle neck in the design. ERL prototypes at 1.3 GHz presently under development around the world drives the development of high power couplers and klystrons for their injectors. For example, the Japanese ERL program [4,7] is performing R&D on 170 kW couplers and 340 kW c.w. klystrons. Thus it is safe to assume that doubled power handling will be demonstrated in the near future. Doubling the power would allow the number of high-power RF building blocks to be halved: 25 cavities and 200 kW beam power per cavity. The multi-purpose input coupler design could be simplified, consistent with its narrower purpose in the fission driver application, and additional means of cooling introduced. These measures might reduce the machine cost by one third, to roughly M$80.

Reliability

Accelerators used for research have availabilities greater than 80% (notable exceptions are the new lights sources: for instance, the Advanced Photon source at Argonne operates with better than 95% availability), but the causes of downtime are broadly distributed and often involve activities related to research and development. Reliability analysis of accelerator components would identify areas where redundancy would increase accelerator reliability. Because the accelerator can be easily turned off and restarted, downtime events would likely have significantly less impact than that for a reactor.

COMPTON BACKSCATTERING

There is an alternate accelerator approach to ^{99}Mo production that promises to reduce substantially the operating costs of the facility substantially, but which requires significantly more R&D. This technique uses uranium photo-fission from quasi-monochromatic gamma-rays produced by Compton backscattering of laser photons from relativistic electrons.

Compton backscattering has been applied for the generation of high energy gamma-rays for a long time. Low energy photons colliding head-on with high energy electrons with relativistic factor γ create a pencil-like beam of gamma rays in the direction of the initial electron beam, and with energy up-shifted by $4\gamma^2$. The wavelength of the backscattered radiation depends on the angle θ between the incident electrons and the gamma rays:

$$\lambda_\gamma = \lambda_L\left(1+\gamma^2\theta^2\right) \qquad (1)$$

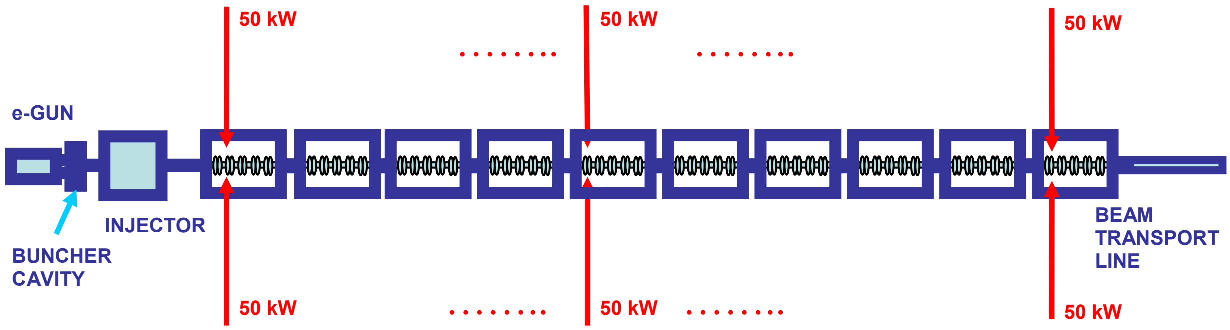

Figure 2: Schematic layout of 5 MW electron linac based on 1.3 GHz SRF technology.

For gamma rays with maximum energy of 14 MeV, the required electron beam energy is 485 MeV for a laser wavelength of 330 nm . To generate significant gamma-ray flux a short pulse laser operating with very high average power is required. The concept used here assumes that an optical enhancement cavity with Q of 1000 is driven by a 5kW average power laser to generate 5MW intracavity laser power colliding with the electron beam Assuming the performance of the MIT high average power laser [8], a 5 MW laser beam, at 330 nm wave-length, can be focused to a 3 µm spot size. For a bunch repetition rate of 100 MHz and 10 mA average electron beam current, the possible gamma flux from the Compton source is $N_\gamma \sim 9.3 \times 10^{15}$ gamma rays per second. Because the induced energy spread on the electron beam is below 3% one may recover most of the electron beam energy, and thus substantially increase the overall efficiency of the system.

Compton Source Concept

A possible accelerator concept would employ a DC photoinjector delivering 10 mA average current at 1.3 GHz and 80 pC per bunch, followed by a room-temperature buncher cavity, and a SRF 5 MeV injector. The beam is then injected into the main linac which comprises one cryomodule with 8 cavities operating at 20 MV/m, for a single-pass energy gain of 160 MeV. A three-pass recirculation system will result in final beam energy of 485 MeV. The laser-beam interaction takes place during the last recirculation, gamma rays will be generated, and the spent electron beam is sent back through the linac for three passes, 180^0 out of phase for deceleration and energy recovery. The beam is dumped at the final energy of 5 MeV. A rough estimate of the total wall plug power consumption of this facility is 800 kW, more than an order of magnitude below the concept of brehmsstralung-induced photons. It should be noted that several free electron laser groups around the world have reported [9] the production of MeV-scale gamma rays via Compton backscattering inside a free electron laser optical cavity.

CONCLUSION

The photo-fission accelerator technique has several key advantages: (1) The targets can be natural or depleted uranium, which (like LEU targets being developed for reactors) eliminates concerns about shipping and handling HEU, obviating questions of security and non-proliferation; (2) The accelerator can be turned on and off at will; (3) At end-of-life, an accelerator is comparatively inexpensive to decommission as major components are less prone to become radioactive over time than occurs in the high neutron environment of an operating reactor; and (4) The technology promises to be scalable. On the down side, an accelerator-based production facility would require substantially more electrical power than a reactor-based facility.

A 5 MW photo-fission driver is certainly feasible based on available technology. The frequency choice of 704 MHz has several advantages:

- this frequency lies in the television broadcast and the klystron design is less specialist than at 1.3 GHz;
- the structures have larger apertures which is beneficial to wakefield generation and halo losses;
- input couplers can operate at significantly greater power levels than at higher frequencies, resulting in simpler design (fewer components, therefore lower capital costs and higher availability); and
- cryoplant operation at 4K is a possibility that needs to be studied.

High machine reliability and availability are important for this application, and can be achieved. However, this requirement should be integrated in the initial design stages. The construction can take up to 3-4 years.

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