

CW HEAVY ION ACCELERATOR WITH ADJUSTABLE ENERGY FOR MATERIAL SCIENCE*

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Abstract

The proposed eXtreme MATERIAL (XMAT) research facility at ANL's Advanced Photon Source (APS) combines medium-energy heavy-ion accelerator capability with the high-energy X-ray analysis to enable rapid in situ mesoscale bulk analysis of ion radiation damage in advanced materials and nuclear fuels. The XMAT facility requires a CW heavy-ion accelerator with adjustable beam energy in the range of 300 keV/u to 1.25 MeV/u. Such an accelerator has been developed and comprises of an ECR ion source, a normal conducting RFQ and four multi-gap quarter-wave resonators (QWRs) operating at 60 MHz. This paper presents the linac design and the multi-physics design of the RFQ and the QWRs. The design includes a beam transport system capable of focusing ions into a 20-micron diameter spot on the target.

INTRODUCTION

Many technological areas in our life benefit from using new materials. Materials and our ability to design and fabricate them are undergoing a dramatic revolution leading to improved costs, safety, efficiency, and reduced waste. Active development of nuclear energetics requires new materials to be used in nuclear reactors to increase their life time, enhance accident tolerance, improve burn-up operation, and enable advanced reactor designs. Material properties deteriorate due to micro-structural defects caused by protons and neutrons and can include bubbles, voids, precipitates, solute segregation, grain boundaries, helium cavities, amorphization etc. These can lead to consequences such as void swelling or cracking [1]

XMAT FACILITY

The traditional approach of performing neutron irradiation in test reactors, followed by post-irradiation testing and examination, is extremely time consuming as it takes years to reach the required dose. To expedite the required experimental time down to hours or days, a dedicated facility XMAT (Fig.1) is being developed at Argonne National Laboratory. Combining the capabilities of a heavy-ion linac and the brightest X-ray source in the western hemisphere—the Advanced Photon Source (APS), the facility will enable material scientists to:

- Accelerate heavy ions to energies about 1 MeV/u for sample irradiation. These energies correspond to those of fission products in nuclear reactors.

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- Deliver mixed beams with the same charge-to-mass ratio (e.g. $^{86}\text{Sr}^{15+}$ and $^{132}\text{Xe}^{23+}$) to model the simultaneous damage by fission fragments.
- Separate damage and interstitial effects since the ion energy deposition and implantation probability peaks are offset in distance [2]
- Provide $\sim 10\ \mu\text{m}$ beam penetration into samples to avoid surface effects, which otherwise interfere with real damage effects [3]
- Provide high damage doses ($\sim 25\ \text{dpa/hour}$) that will allow rapid material screening.
- Benefit from using high-energy, focusable X-rays to enable 3 dimensional meso-scale in situ study of radiation damage. Such experiments will allow observing and understanding the physics of radiation damage.

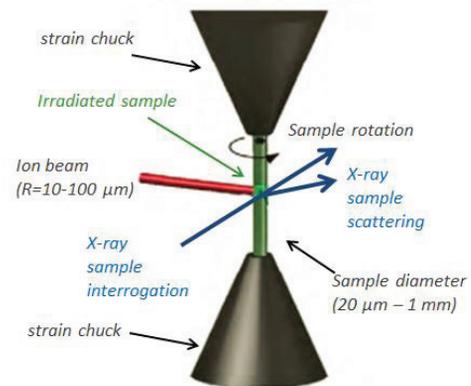


Figure 1: XMAT beamline scheme.

This paper presents the results of a pre-conceptual design and analysis of a continuous wave (CW) linear accelerator capable of delivering 1.2 MeV/u ion beams with mass-to-charge ratio of 5 and less.

HEAVY ION ACCELERATOR

The proposed heavy-ion linac design, presented in Figure 2, is capable of accelerating particles with $A/Q=5$ to 1184 keV/u (1200 keV/u for $^{238}\text{U}^{50+}$ ions). Heavy ions of any species from protons to uranium are extracted from an Electron-Cyclotron-Resonance (ECR) ion source and then delivered to a 4-meter RFQ where they are bunched and accelerated to 300 keV/u. The beam is then re-bunched in a 4-gap quarter wave resonator (QWR) and accelerated to the final energy in four normal conducting continuous wave (CW) multi-gap QWRs. Finally, the beam comes through a 100 micron slit and is focused into a 30 micron spot on the target using superconducting solenoids in the microbeam forming section.

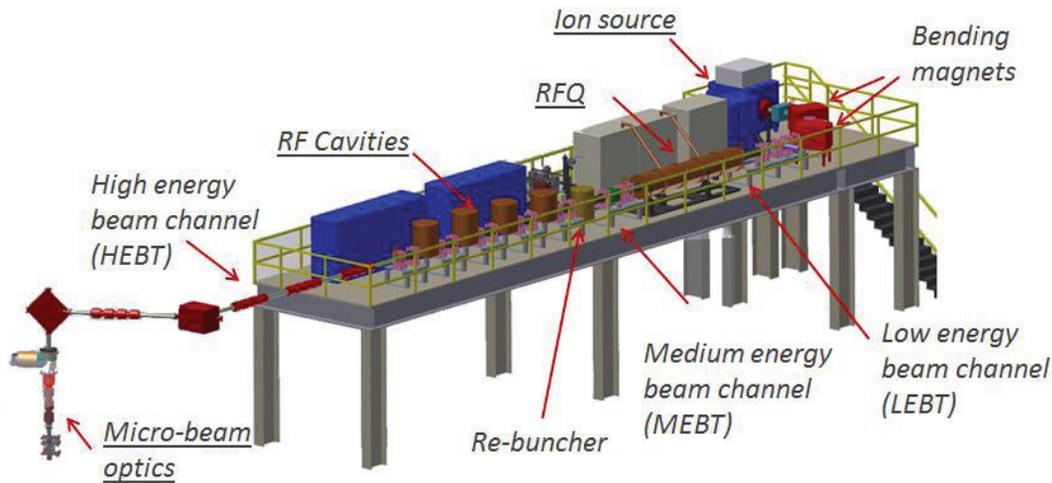


Figure 2: XMAT heavy ion linac.

Due to limited space at APS, the ion accelerator must be designed to be placed on the roof top. Each part of the linac will be discussed in details in the following sections

ION SOURCE

The recent success in ECR ion source development, in particular the VENUS ECR source in Lawrence Berkeley National Laboratory, has practically solved the problem of acquiring a reliable continuous ion beams with the required currents, species and charge states. Fig. 3. shows examples of beam currents achieved with the VENUS source [4]. In particular, it is possible to get 1.9 eμA beam of U⁵⁰⁺ ions, or 5 eμA of U⁴⁷⁺ ions. The latter allows relaxing of the requirements for the micro-beam focusing system down to a 30 micron diameter.

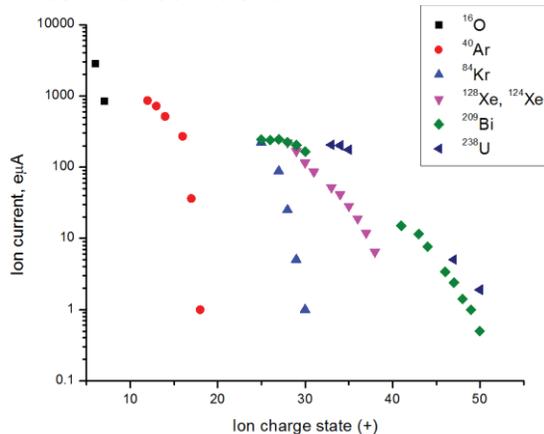


Figure 3: Ion currents achieved at VENUS.

Using a VENUS-like ECR source, which provides sufficient currents of heavy ions with high charge states, significantly reduces the overall cost of the accelerator by reducing required total voltage.

RFQ

The main requirements for the XMAT linac RFQ are as follows:

- Absolutely reliable CW operation for all species of heavy ions with mass-to-charge ratio of 5 and less;
- Formation of a beam with low longitudinal emittance.
- Moderate peak fields to avoid any possible breakdowns and avoid lengthy conditioning of the resonator. In particular, the peak electric field should be below 1.6 Kilpatrick unit;
- High particle transmission efficiency (~95%)
- No transverse rms emittance growth through the RFQ.

Table 1: RFQ main parameters

Parameter	Value
Frequency, MHz	60.625
Design A/q ratio	5
Input energy, keV/u	5.0
Output energy, keV/u	302.5
Transmission, %	>95
Inter-vane voltage, kV	70
Average radius, mm	7.2
Total length, m	4.04

The frequency of 60.625 MHz was chosen for the XMAT linac in order to use similar sub-systems as the current ATLAS facility and therefore, reduce the overall cost of the facility. Designing a conventional RFQ without a multi-harmonic buncher allows for high transmission through the RFQ of 95% for ²³⁸U⁵⁰⁺ ions at the price of relatively larger longitudinal beam emittance as compared to the ATLAS RFQ. Table 1 summarizes the parameters of the proposed RFQ.

Argonne National Laboratory has recently successfully designed, built and installed a 3.8m long 60.625 MHz RFQ as a part of the ATLAS Upgrade project [5]. This RFQ can accelerate heavy ions from 30 to 295 keV/u with 83% transmission efficiency. The latter is defined by an

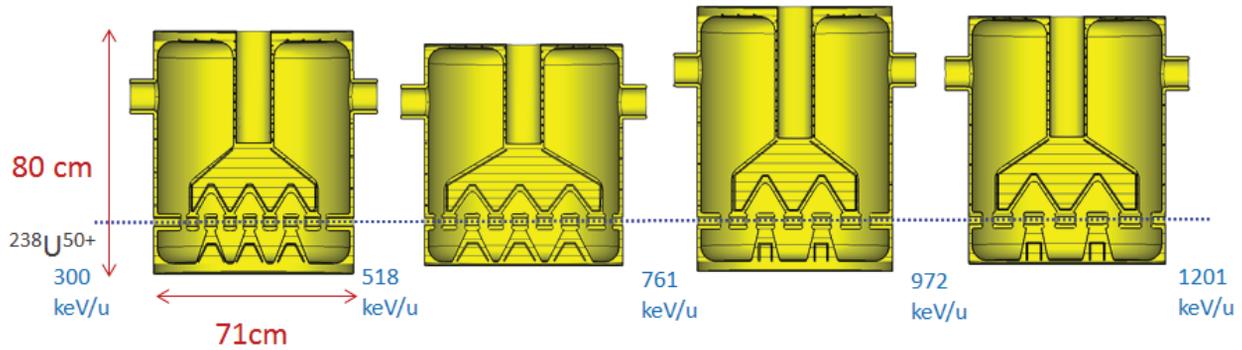


Figure 4: Accelerating cavities layout.

external multi-harmonic buncher. To maintain a high level of operational reliability, we recommend the development and fabrication of a new XMAT RFQ that would be based on the 4-vane ATLAS RFQ structure.

ACCELERATING CAVITIES

As follows from our studies, normal conducting accelerating structures are very efficient for CW acceleration of heavy ions up to ~ 1.5 MeV/u. Several examples of cost-efficient CW room temperature heavy-ion linacs with energies up to 1.5 MeV/u have been built recently. These are RILAC-2 for the rare isotope beam facility at RIKEN [6] and the ISAC injector at TRIUMF [7]. Comparing these two accelerators with the SC ATLAS Positive Ions Injector (PII) section [8], we can conclude that for given total voltage, the wall plug power for a NC linac is comparable to an equivalent SC linac, while the hardware and operational cost of a SC linac are higher. The latter is especially true for a stand alone accelerator as XMAT.

Four low-beta accelerating cavities are required to accelerate uranium ions from 0.3 MeV/u to 1.2 MeV/u. In this beam velocity range (2.5 – 5.0 % of the speed of light), multi-gap cavities are the most efficient. Figure 4 presents the schematic layout of the cavities designed for the XMAT linac. The beam is focused by quadrupole doublets with 60 T/m located between the cavities.

Electromagnetic Design

The electromagnetic design was performed using CST Microwave Studio [9]. The main considerations of cavity design were the following:

- An operation frequency of 60.625 MHz, the same as for the RFQ.
- The same cavity diameter for all cavities to facilitate the manufacturing
- Peak electric fields should be ≤ 1.5 Kilpatrick value
- Gap widths should be adjusted to make the field distribution uniform
- Drift tube lengths should be adjusted for synchronous acceleration
- The structure should be rigid and allow water cooling
- The cavity weight should be manageable

Figure 5 shows the surface electric field distribution in the first cavity, which is uniform around a drift-tube tips and has no “hot” spots. The magnetic field peaks at the narrow side of the rack, but that will not cause any problem since cooling channels will be placed near that region. The final parameters for each of the four cavities are summarized in Table 2

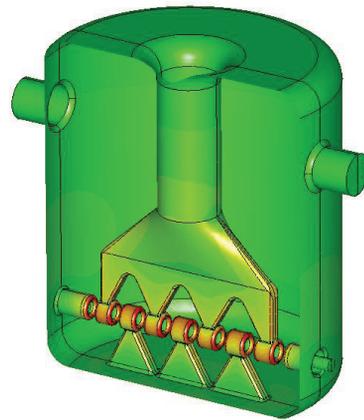


Figure 5: Electric field distribution in the first cavity.

Table 2: Accelerating Cavities Parameters

Parameter	Values			
Cavity #	1	2	3	4
Cavity diameter, cm	71	71	71	71
Number of gaps	8	8	6	6
Synchronous phase, deg	-30	-30	-25	-25
Design A/q ratio	5			
Energy gain, keV/u	218	243	211	229
Peak electric field, MV/m	13.8	13.9	13.8	13.9
RF losses, kW	10.3	14.2	13.2	16.2

Multiphysics Analysis

Since we are going to build a cavity prototype, a thorough multiphysics analysis of these cavities using CST Multiphysics Studio and ANSYS Multiphysics [10] was performed. We consider an all-copper cavity.

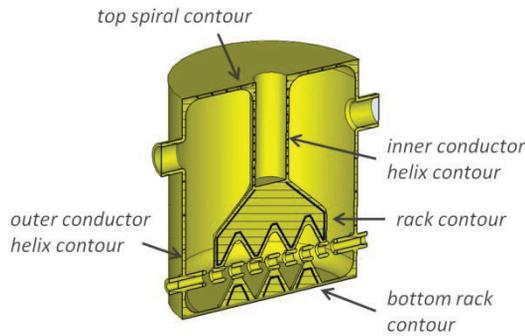


Figure 6: Cavity water cooling channels.

In order to remove the RF generated heat, we have designed a system of water cooling channels, as presented in Figure 6. There are five connected 2.5 mm-diameter contours with circulating water which reduce the temperature of the cavity to 5 °C above the room temperature, everywhere except the transition from the rack holding the drift tubes to the inner conductor as shown in Figure.7. Since the magnetic field peaks in this area, the temperature in this region is higher by ~11 degrees.

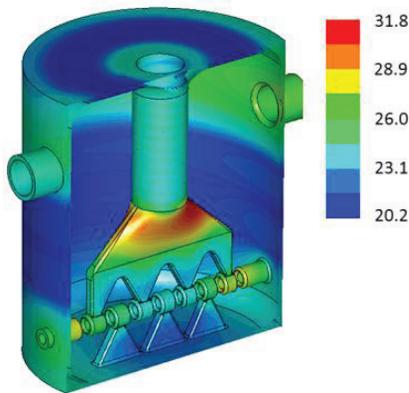


Figure 7: Temperature distribution in the cavity in °C.

Another important factor of the resonator design is its structural stability. There are two sources of mechanical stresses and deformations: temperature expands and the atmospheric pressure shrinks the cavity. By choosing the proper design of mechanical support, it is possible to reduce total stresses and deformations significantly. The deformations in the optimized cavity are presented in Figure 8. According to simulations, the optimal top and bottom plate thickness should be 3.8 cm. In this case the maximal stresses are 4.5 times lower than the copper yield stress.

Re-buncher

For XMAT, one room-temperature QWR will be used as a rebuncher after the RFQ. The geometry was optimized for a frequency of 60.625 MHz and $\beta_{opt} \sim 0.025$. The optimum beta value corresponds to a maximum voltage gain of 0.25 MV. A 4-gap QWR

structure was chosen over a 2-gap cavity in order to reduce the required RF power which is equal to 2.75 kW.

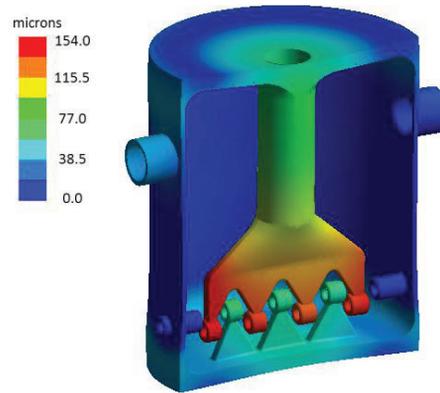


Figure 8: Cavity deformations (magnified).

Beam Dynamics

The following considerations were taken into account for the accelerator design:

- The possibility to adjust the output energy. This can be done by reducing the voltage or complete voltage turn off in the last active cavity
- The maximum voltage in the cavity is limited by the peak fields which should be less than 1.5 Kilpatrick for reliable operation
- Drift tube apertures of 3 cm were chosen as a compromise between the transverse acceptance and acceleration gradient
- The magnetic field in the focusing quadrupoles doesn't exceed 1.1 T

The TRACK code [11] has been used for the design study and beam dynamics simulations in the linac. Realistic EM fields from CST Microwave Studio were imported into TRACK for accurate simulations. The longitudinal bunching is performed using the re-bunching cavity after the RFQ. The calculated beam envelope along the structure is shown in Figure 9.

MICROBEAM SECTION

The final section of the beam-line is required to provide beam focusing to a 10-micron diameter spot. This is done in several steps. First, a symmetric round beam is formed in the HEBT with a beam diameter of 1 cm. Then, the beam passes through a 100-micron round collimator, so that its current is reduced by a factor 10^4 down to the required rate of 10^7 particles/sec. The micro-beam is then focused via two superconducting solenoids to the final diameter. The microbeam formation scheme is presented in Fig. 10.

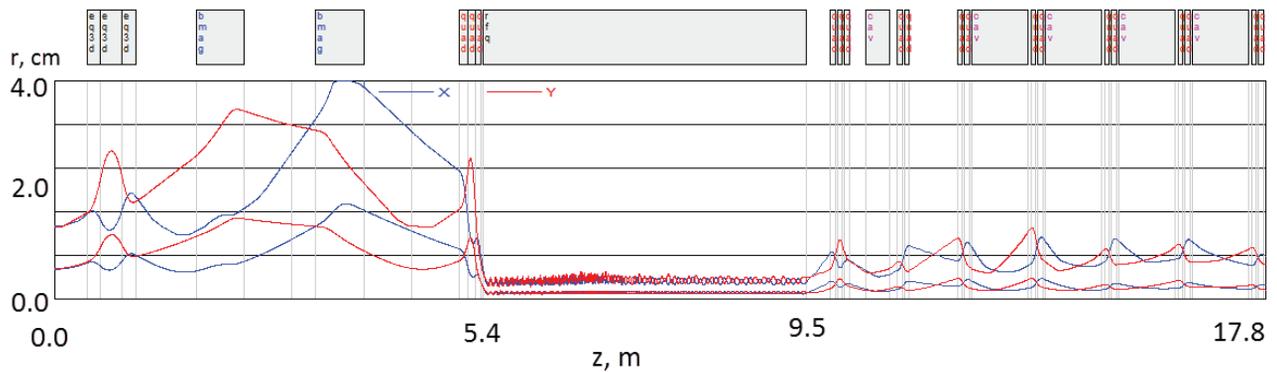


Figure 9: Beam envelope (x – red, y - blue) along the accelerator. The following notations are used: eq3d – electrostatic quadrupole, bmag – bending magnet, quad – magnetic quadrupole, cav – cavity.

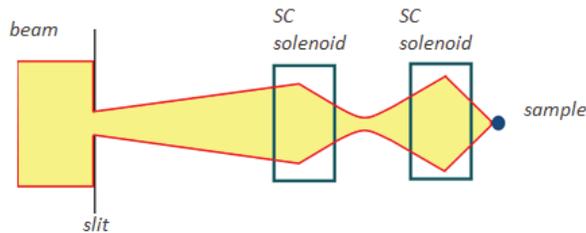


Figure 10: Microbunch forming system.

We have used the TRACK code to determine the optimal distances between the slits and solenoids and the solenoids field strengths. The realistic 3D magnetic field distribution of the PXIE SC solenoid [12] was used in the simulations. The optimal results were achieved by using two superconducting solenoid with 8.4 T and 10 T magnetic fields that allowed us to focus the beam to a 33-micron spot. The main limiting factors of the minimum achievable beam size are the transverse beam emittance and chromatic aberrations.

SUMMARY

A new unique radiation damage facility for material sciences combining a heavy-ion linac and high-energy X-rays has been designed and is planned to be built at Argonne National Laboratory. This facility will enable rapid in situ mesoscale analysis of the processes. The ion irradiator consists of an ECR ion source, an RFQ and four multi-gap QWR resonators. The ECR is an effective source providing the required currents for heavy ions with mass-to-charge ratios of 5 or less, which permits more efficient acceleration and thus a shorter linac. A room temperature linac is more cost and power efficient for the required energies and currents than a superconducting one. At the end of the linac, a microbeam formation section has been designed to focus the beam onto 10-100 micron samples. A full multiphysics design and analysis was performed for the accelerating structures, showing no significant heating or deformations. A prototype for the first accelerating cavity is ready to be built.

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