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Development of irradiation capabilities to address the challenges of the nuclear industry

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ABSTRACT

With the announcement of the U.K. new nuclear build and the requirement to decommission old facilities, researchers require bespoke facilities to undertake experiments to inform decision making. This paper describes development of The University of Manchester's Dalton Cumbrian Facility, a custom built research environment which incorporates a 5 MV tandem ion accelerator as well as a self-shielded ^{60}Co irradiator. The ion accelerator allows the investigation into the radiolytic consequences of various charged particles, including protons, alpha particles and a variety of heavier (metal and nonmetal) ions, while the ^{60}Co irradiator allows the effects of gamma radiation to be studied. Some examples of work carried out at the facility are presented to demonstrate how this equipment can improve our mechanistic understanding of various aspects of the deleterious effects of radiation in the nuclear industry. These examples include applications in waste storage and reprocessing as well as geological storage and novel surveying techniques. The outlook for future research is also discussed.

1. Introduction

Pioneering research in nuclear science at the University of Manchester dates back to Rutherford's famous gold foil experiments [1] and has continued with significant contributions in atomic physics – both experiment [2–10] and theory [11–13] – as well as in radiobiology [14–17] and the nuclear energy industry [18–23]. In 1954 the first nuclear reactor to produce electricity was commissioned at Sellafield in Cumbria and since then the U.K. nuclear industry has grown, new builds are planned, old plants must be decommissioned and radioactive waste materials must be treated and disposed. The Sellafield site now represents perhaps the greatest hazard within Europe [24].

In 2005 the Dalton Nuclear Institute was founded by The University of Manchester to expand expertise in nuclear science and engineering. In 2013, the Institute opened the Dalton Cumbrian Facility (DCF), located near Whitehaven in Cumbria and proximal to the Sellafield site, to enhance knowledge and technology transfer between academia and the nuclear industry. Focus areas include decontamination and decommissioning, nuclear waste management and storage, new build plant and both existing and new materials which are relevant to the new nuclear build.

The DCF capabilities include a 5 MV NEC 15SDH-4 Pelletron tandem ion accelerator and a Foss Therapy Services Model 812 ^{60}Co gamma irradiator as well as an array of analytical interrogation equipment to characterise any changes as a result of irradiation. This equipment includes a Bruker Vertex 70 FT-IR with RamII Raman attachment, an FEI Quanta 250 FEG ESEM incorporating EBSD, EDX and WDX, an Agilent 1260 HPLC, a Thermo Scientific DIONEX ICS-2100 ion chromatography machine, a Micrometrics TriStar II 3020 BET analyser, an Analytik Jena Multi N/C 2100 S total C/N analyser and an Agilent 7890B gas chromatograph with TCD, μECD and FID detectors set-up with switching valves to prevent damage to the machine from substances such as nitric acid. Here we present a description of both the accelerator set-up and the gamma irradiator. In addition we provide some current applications of the equipment as well as the outlook for future work.

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2. Irradiation facilities

2.1. The ion accelerator

A major component of the DCF infrastructure is the 5 MV NEC 15SDH-4 Pelletron tandem accelerator for inducing radiation damage and conducting radiation chemistry experiments [25–29] (Fig. 1). The accelerator is equipped with two ion sources: a high current Toroidal Volume Ion Source (TORVIS) [30–31] providing up to 10 MeV H^+ at 100 μA and up to 15 MeV He^{2+} at 15 μA; and a low current Source of Negative Ions by Caesium Spluttering (SNICS) providing partially and fully stripped heavy (metal and non-metal) ions. At present, we have cathodes for C, O, V, Cr, Fe, Ni, Cu, Zr and W for the SNICS source, but ease of change of the cathode means that we can exchange the SNICS ion type for virtually any heavy ion type.

Six beamlines are available, three of which are in one concrete walled target room and are designated for radiation chemistry studies at relatively low beam currents of typically 10 nA or less. Another three, incorporating raster scanners for uniform beam illumination over large sample areas – typically 1–2 cm across, are contained in a second target room and are used for radiation damage experiments at much higher currents, employing up to a maximum of 100 μA of protons. The exact build of the assembly at the end of the beamline varies depending on the nature of the experiment. Example beamlines for radiation chemistry and materials damage are described below.

2.1.1. Radiation chemistry beamlines

Radiation chemical studies use a targeting system attached to the end of a dedicated beamline similar to the apparatus in Fig. 2 developed by LaVerne and Schuler [32]. This targeting assembly employs a circular beam collimator producing a charged particle flux over the area of 0.38 cm^2 at the exit window. The exit window is made of 3.6 mg/cm^2 thick titanium foil. High vacuum of about 10^{-6} Torr is maintained inside the beamline during experiments.

During irradiation a collimated ion beam passes through the electron suppression zone, where the backscattered electron current (I_{BS}) is magnetically confined, collected and measured. The beam current (I_B), which corresponds to the charged particles deposited into an irradiated sample, is collected from the sample cell and the exit window.

The irradiation sample cell is typically made of glass with a thin mica window for ion beam exposure. Liquid solutions under study are vigorously mixed during irradiation to achieve homogenous irradiation of the solution as well as distribution of the produced radiolytic products.

2.1.2. Materials damage beamlines

A custom-made rig for in-vacuum irradiation of solid materials, capable of being mounted to the end of any of the accelerator's beamlines, has been developed (Fig. 3). Samples up to 5 by 25 by 50 mm can be mounted on the copper block. Its thermal mass allows for passive temperature control and there is instrumentation for thermal and beam current monitoring. Further development of a thermal control rig is in progress. It is complementary to an end station developed by Was and co-workers [33] for irradiation in vacuo. Alternatively a non-vacuum rig is available for in-air irradiation of samples up to 4 by 4 cm, of any depth.

2.2. Foss therapy services model 812 ^{60}Co irradiator

Details of the Foss Therapy Services Model 812 Cobalt 60 self-shielded irradiator are provided in Fig. 4. Sources are Russian model GIK-7M-4 capsules each with an initial activity of 2500 Ci. These are evenly distributed along the length of the source rod with each rod containing up to three capsules. Reloading is required every 5.2 years to maintain the desired irradiation ability. With fresh capsules in each assembly the maximum capability of the irradiator is 22.5 kCi (680 Gy/min).

Currently, two rods are loaded to produce an initial total activity of 15 kCi. Depending on the distance from the source rods this results in an absorbed dose ranging from over 400 Gy/min to approximately 4 Gy/min and can be reduced to 0.06 Gy/min with attenuation and only a single rod raised. This system provides the facility with the flexibility to investigate a range of dose rates, from rates characteristic of spent fuel right down to background levels of radiation.

3. Case studies

Researchers work closely with industry to investigate a range of problems of specific interest to the U.K. nuclear industry. Examples include the radiolysis of systems used for spent fuel reprocessing and the effect of ionising radiation on geological formations and electrical components. In addition, useful work such as calibration of charge collection dosimetry on the beamlines is also carried out and novel studies in fields of interest outside the nuclear industry, such as conductive polymers, are performed.

3.1. Radiation damage during geological storage

The DCF plays an important role in researching the implications of deep geological disposal of radioactive waste. A detailed understanding of the response of mineral phases to the radiation fields

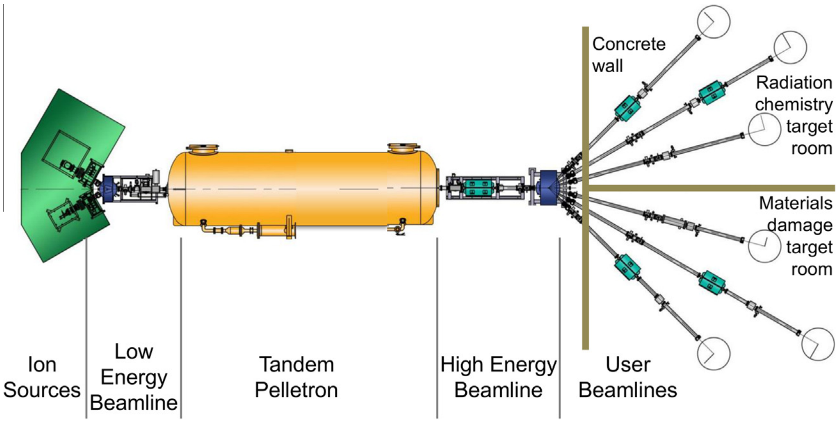

Fig. 1. Layout of the Pelletron at the Dalton Cumbrian Facility.