# A High Intensity Radiation Effects Facility

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**Abstract** The facility of the Michigan Ion Beam Laboratory at the University of Michigan has been upgraded to conduct high intensity radiation effects studies on materials. This upgrade is necessary to pursue higher radiation damage levels than the studies previously conducted. To achieve this capability a new volume ion source was installed which can produce several times more $H^-$ current than the previous duoplasmatron. We will describe the objectives of the research and the facility as well as applications to a variety of radiation damage problems.

## Introduction

The need for basic information regarding the microstructural effects of neutrons in components of aging light water reactors motivated the creation of the facility described in [1] (fig.1).

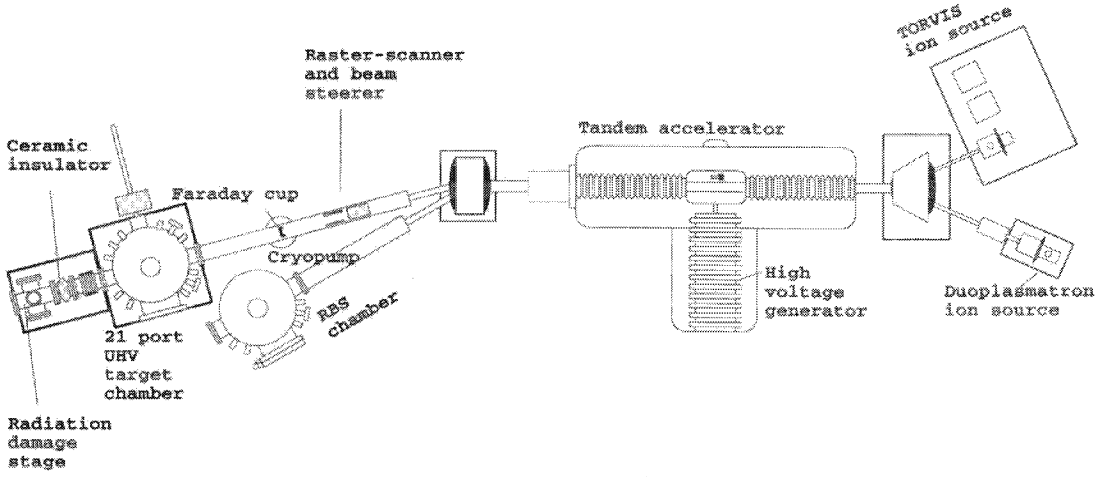


Fig.1 A schematic of the tandem accelerator and associated beam lines. The proton irradiation stage is located at the end of the leftmost beam line

Although it would seem preferable to study samples exposed to neutrons in-core, factors such as time, accessibility and expense make the search for alternatives attractive. If ion irradiation can generate microstructures comparable to those of interest, the radiation damage caused by neutrons can be studied in a more controlled and safer environment. The success of this approach has been demonstrated in a variety of studies [4-9] in which samples of stainless steel were irradiated for long periods of time with high intensity beams of protons at controlled temperatures. Doses of about 1 dpa (displacement per atom) were achieved in periods of about 40 hours with beam densities of about 10 $\mu A/cm^2$. Since the continuing interest in this work would require higher doses, it became apparent that the existing setup would be insufficient to carry out the irradiations in reasonable time periods due to frequent interruptions for equipment maintenance and personnel fatigue. A search was therefore initiated for an ion source that could provide larger intensities in order to replace the existing duoplasmatron source.

## Ion sources

Due to transmission losses through the accelerator and the need to overscan the samples to assure beam uniformity it is necessary to have up to 60 μA of $H^-$ extracted from the ion source in order to achieve a 40 μA

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of high-energy beam. This current is above the specifications for comfortable operation of the duoplasmatron ion source although intensities of up to 90 μA $H^-$ were sometimes achieved. Long periods of adjustments were required together with frequent alignments and cleaning of internal components. Due to unrepeatable behavior of the source as it is pushed to operate above its specifications, it was sometimes necessary to allow for periods of up to 1 week to achieve a good intensity beam before an irradiation could begin. During this time the source had to be dismantled several times for alignments and filament coating also would need to be redone until a satisfactory source could be built. Once optimized it could maintain the beam through the current irradiation but it's other applications, such as providing $He^+$ for surface analysis, would require further maintenance and dismantling.

After many consultations, we concluded that a practical replacement would be the TORVIS (TORoidal Volume Ion Source). Built commercially by National Electrostatics Corporation (Middleton, WI) it is a DC version of the source that was initially developed at Brookhaven National Laboratories by Pelec and Alessi [3]. The axial region of the source is separated from the outer region by a conical magnetic dipole field. This field prevents fast electrons from destroying the $H^-$ ions that are formed in the axial region by the dissociative attachment of excited $H_2$ with slow electrons (fig.2).

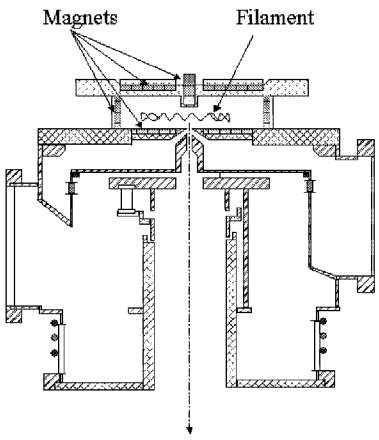


Fig.2 The TORVIS source. The plasma chamber containing the filament and surrounded by magnets is on top, followed by the extractor and lens assembly. The two side ports connect to high-speed turbomolecular pumps.

To control and monitor the parameters of the source such as gas pressure, filament current, arc current, etc. a software control program was developed. It is based on National Instruments Corp. (NI), Labview and controls the source parameters via serial ports. The interface between the computer and the source is an electronic device called an I/Oplexer. Three of these are used, which contain different analog and digital input/output modules. This setting allows the computer to be electrically isolated from the power supplies, which are on a high voltage platform. The Graphical User Interface is easy to understand and the source parameters can be logged into a file for future reference. The TORVIS source has proven to be extremely reliable requiring very low maintenance. We can easily obtain about 300 μA at the entrance of the accelerator, and in excess of 150 μA at the high-energy side. The only limitation on using very high currents is the power supply for the high voltage generator of the accelerator, which limits the total load to about 1 mA.

## Description and capabilities

The irradiations are conducted at the Michigan Ion Beam Laboratory at the University of Michigan. This facility houses a 1.7 MV tandem accelerator built by General Ionex Corp. in which the high voltage is generated by a rectifier stack. Due to continuous use at high voltages, the oscillator tubes of the original push-pull circuit, which provides the high voltage radio frequency, needed frequent replacement at considerable expense and difficulty with unacceptable disruptions to the research programs. Due to this, the circuit was replaced by a solid-state power supply built by Accelerator Systems Inc., Atkinson NH. This has ensured continuous and reliable operation for long periods.

Presently there are 3 ion sources, a duoplasmatron which can provide about 1μA of $He^-$, 50 μA $H^-$, a sputter source with a capability of producing negative ions of heavier elements and the newly installed TORVIS with a capability of producing up to 400 μA of $H^-$. The latter has replaced the duoplasmatron in its function of generating $H^-$ beam. Depending on the charge state of the ion emerging from the gas stripper situated at the high voltage terminal, beams up to 5 MeV can be obtained. For protons, the maximum energy is 3.4 MeV. Irradiations have been conducted with beams of energy as low as 500 keV with adequate transmission through the accelerator tube. A raster-scanning system allows targets up to 5 cm. in diameter with the present beam line configuration. The beam quality is monitored and adjusted via a profile monitor manufactured by National Electrostatics Corp. Samples are mounted on a stage inside an electrically isolated chamber and maintained under high vacuum in the range low $10^{-7}$ - $10^{-9}$ torr. Temperature control is achieved by mounting the samples on a copper block with a liquid metal (indium or tin) coupling to facilitate heat conduction between the samples and the stage (fig.3).

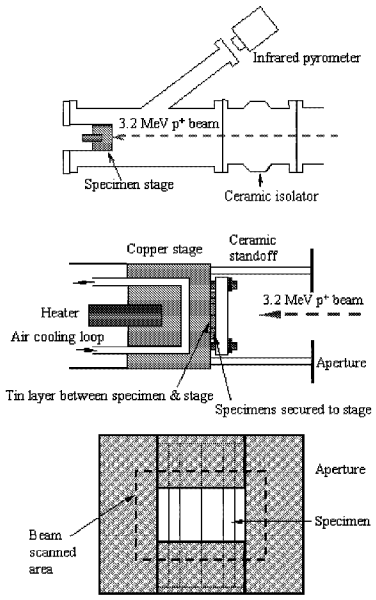


Fig. 3. Schematic of the irradiation stage for high intensity radiation studies. The middle drawing shows details of the specimen stage with the cooling loop and heater. At the bottom a detail of the aperture system for uniformity control.

The nominal surface temperature can be controlled to within +/- 5 $^0$ C of the desired goal temperature, which can range between 50$^0$ C and 500$^0$C. Higher sample temperatures (> 600$^0$ C) can be achieved by using a nickel stage identical in design to the copper stage and the same mounting procedures. Simultaneously heating the stage from the rear with an electric heater cartridge inserted into a cavity in the back of the stage and cooling the stage with air or water maintains the temperature during irradiation. With a power density of about 40 W/cm$^2$, a temperature difference of 20 - 100$^0$ C between the front of the samples and the back of the stage is typical during irradiation at any temperature. The sample temperature is monitored using an infrared pyrometer that can be remotely controlled to scan the irradiated region. Thermocouples, which are connected to each individual sample, are continuously monitored from a data acquisition program written in Labview. These are also used to calibrate the pyrometer via emissivity adjustment prior to applying the proton beam. The incident beam is focused down to a spot approximately 3 mm in diameter and then raster-scanned across the samples. About half of the total beam is scanned onto a 4-aperture system that completely surrounds the samples. The apertures, which are not cooled, including mounting screws, are completely constructed of tantalum, in order to withstand the temperature increase. They are directly supported on the stage by ceramic standoffs. Electrical feedthroughs carry the currents to the computer where balancing the current on each of these by adjustment of horizontal and vertical steering ensures uniform irradiation.

The computer monitors the irradiation process by reading the current on the samples and on the four apertures surrounding them. The thermocouples are connected to a specialized card from National Instruments Corp. (NI) for temperature monitoring, and then sent to the computer via a data acquisition card. This card also monitors the current on the apertures, stage and the signal coming from the pyrometer. A digital counter input is attached to the digitized output of a current integrator connected to the stage. An analog output is used to send a signal to an audible alarm that can be triggered when certain conditions are not met. The main data acquisition screen displays information about all the parameters of interest, which is simultaneously saved to a file for future reference. Both the computer that controls the source and the one that controls the data acquisition process are connected via a local computer network. The next goal would be to remotely access, control and view the parameters of both computers. Labview is a versatile language that allows this to be accomplished and we are in the process of implementing this capability. In view of the high current capabilities of the new ion source we expect that what used to be a 40 h irradiation to have about 1 dpa would take about 12h.

## Results

The validity of the approach taken to simulate neutron damage by high-energy protons is demonstrated in comparison irradiations of 316 stainless steel with neutrons and protons. Figures 4 and 5 show grain boundary composition profiles, and the increase in yield strength due to neutron and proton irradiation of the same heats of material. Neutron irradiations were conducted at 274°C and dose rates around 5 x 10$^{-8}$ dpa/s in the Barseback reactor in Sweden, and proton irradiations were conducted in MIBL at 360°C and at a dose rate of 7 x 10$^{-6}$ dpa/s. As shown in Fig. 4, the composition profiles of Ni, Cr and Si for the respective irradiations are nearly identical in magnitude and spatial extent and capture the complicated "W" shaped chromium profile at the grain boundary. The same is true in Fig. 5 where the hardening of the alloy as a function of dose falls on nearly the same curve. Similar agreement occurs for microstructure and IASCC susceptibility. Figures 6 –8 provide examples of the range of irradiation capabilities that are accessible in the MIBL damage facility. Figure 6 shows the variation in grain boundary chromium content in one iron-base and two nickel-base austenitic alloys following proton irradiation to 0.5 dpa. Note that the irradiation temperature spans from 200°C to 600°C. Some

experiments have also been conducted as high as 700°C. Figure 7 shows an example of a low temperature irradiation of an austenitic 304 stainless steel. All irradiations were done at 50°C and samples were then annealed at temperatures up to 500°C to remove the radiation damage, resulting in softening of the alloy. Irradiations with the new source have been conducted up to doses of 10 dpa and experiments are being planned with doses that exceed this value. However, the versatility of the source allows for extremely low dose irradiations as shown in Figure 8 for model reactor pressure vessel alloy (Fe-0.9Cu-1.0Mn) irradiated to doses as low as 0.001 dpa (10,000x lower than for austenitic alloys). Results show that the hardening obtained with proton irradiation is in excellent agreement with that obtained with neutron or electron irradiation. These results serve to show the wide range of applicability of the radiation damage facility (in temperature, dose, dose rate and target alloy) and the success in using proton irradiation to study neutron irradiation effects.

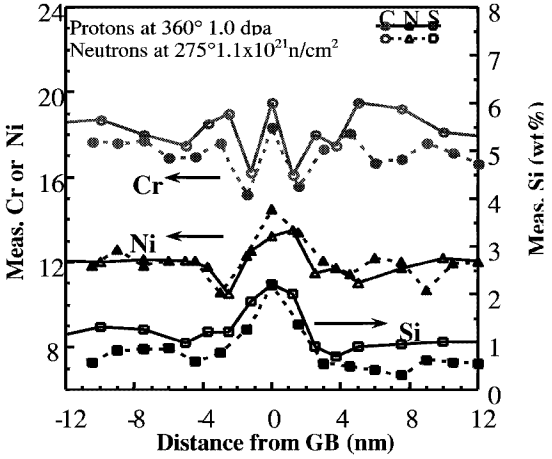


Figure 4: Comparison of Cr, Ni, and Si segregation profiles for proton and neutron irradiation of CP 316 SS to 1.0 dpa Ref 7.

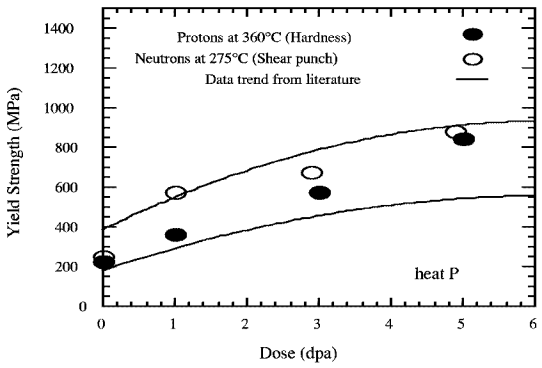


Figure 5: Change in yield stress under proton and neutron irradiation for the same heat of 316SS

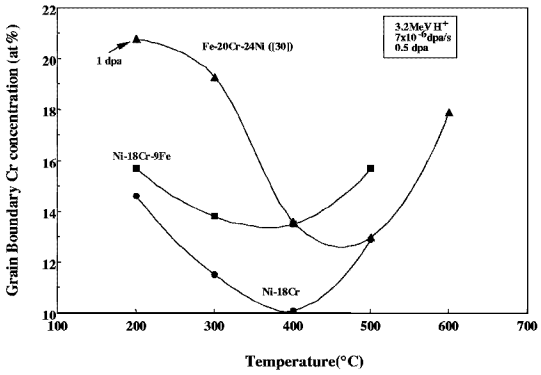


Figure 6: Measured grain boundary Cr concentration as a function of irradiation temperature for Ni-18Cr, Ni-18Cr-9Fe, and Fe-20Cr-24Ni irradiated with 3.2 MeV protons to 0.5 dpa. Ref. 8

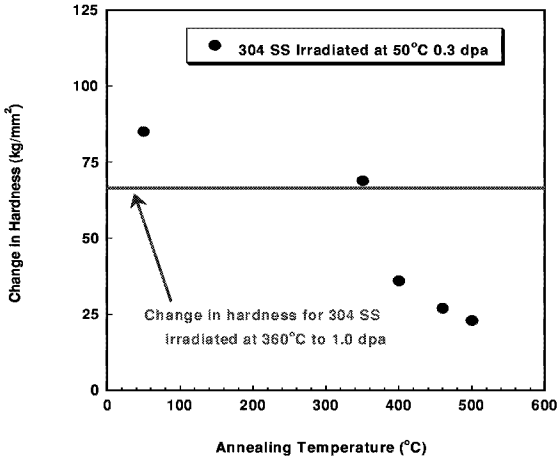


Figure 7: Results of microhardness for post-irradiation annealing of 304 SS irradiated at 50° C to 0.3 dpa. Annealing times were 0.5 hours except at 350° C where the annealing time was 3.5 hours. Ref. 9.

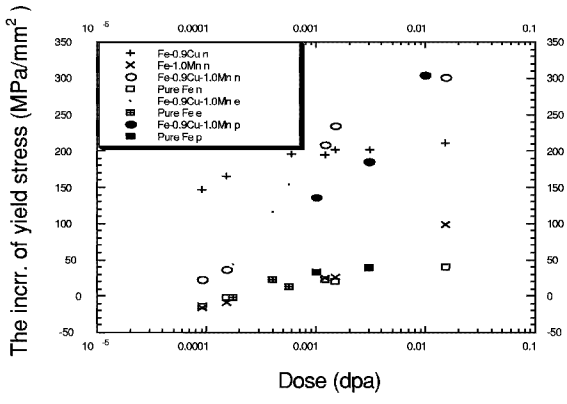


Figure 8: Comparison of yield strength increment on some model alloys versus dose for neutron, proton and electron studies (n, p, e respectively). Ref. 5 for n,e, Ref. 6 for p.

## Summary

The upgraded facility of the Michigan Ion Beam Laboratory for Surface Modification and Analysis at the University of Michigan offers the capability of radiation damage studies using protons at high or low dose rates under practical time scales with precise temperature control in a computer controlled and monitored experiment. The commercial availability of the TORVIS ion source has been instrumental in this achievement.

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