

EXPERIENCE OF CYCLOTRON OPERATION WITH BEAM SHARING AT TSL

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Abstract

Following a reorientation in 2005/2006, the focus of activities at TSL was shifted from nuclear physics to proton therapy and radiation testing with protons and neutrons. In order to use the beam as efficient as possible beam sharing is employed. The paper describes the development of a range of control system utilities, for example switching of the beam between users by the principal user instead of being controlled via a cyclotron operator.

INTRODUCTION

The Gustaf Werner cyclotron, completed in the early 1950s as a fixed-energy 185 MeV proton synchrocyclotron was converted during the eighties to a variable-energy multi-purpose sector-focused cyclotron and has been since then in use for a wide range of applications. An interesting feature of the accelerator is that it is operated both as an isochronous cyclotron and as a synchrocyclotron.

The principal users are now the proton therapy facility of the Academic Hospital, Uppsala, as well as accelerated testing of electronics at the neutron and proton irradiation facilities. Other applications are detector development and calibrations, as well as nuclear data measurements. Heavy ion beams are produced mainly for biomedical research [1].

THE GUSTAF WERNER CYCLOTRON

With a k -value of 192, non-relativistic ions can be accelerated up to an energy of $192 \times Q^2/zA$ MeV, whereas the maximum energy for protons is limited to 180 MeV. In the isochronous cyclotron mode proton energies between 25 and 100 MeV can be delivered, whereas the synchrocyclotron mode is employed for proton beams with energies between 100 and 180 MeV. In this mode beam stretching is often used to provide a beam (macroscopic) duty factor of about 15%. This is achieved by reducing the df/dt and the accelerating voltage during extraction. More details may be found in [2, 3].

Heavy ion beams are mostly utilized for the biomedical research program where the most frequently used beams are fully stripped ^{12}C and ^{14}N with a highest achievable energy of 40 MeV/nucleon. The ECR ion source is of an

older generation and was upgraded in 2002 in collaboration with JYFL [4], which resulted in a significant improvement of the performance of the source.

IRRADIATION FACILITIES

Proton Therapy

The average number of radiation fractions given per treatment week for 2009 was 28. This includes mainly treatments of intracranial tumors and cancer of the prostate [5]. Prostate cancer patients are treated with protons in combination with photons. Treatments of eye melanomas have been given but occur less regularly depending on the need. Experience indicates that the technical design of the switching procedure functions well.

Facilities in the Blue Hall

There are three irradiation facilities in the Blue Hall: ANITA, QMN, and the proton facility.

The ANITA facility (Atmospheric-like Neutrons from thick TARget) provides a neutron beam with atmospheric-like spectrum ("white", "spallation", cosmic-ray induced neutrons), primarily for studies and testing of electronic components and systems for neutron-induced single-event effects (SEE), which cause one of the major reliability concerns in semiconductor electronic components and systems [6], [7]. The proton beam is guided to a tungsten target, which fully stops the incident protons. The resulting neutron beam is formed geometrically by a collimator aperture. A modular design of the aperture allows the user to select the size of the neutron beam spot between 1 and 120 cm. The highest neutron flux is available at the Standard User Position (SUP), located 250 cm downstream of the production target. The energy-integrated neutron flux above 10 MeV amounts to $\approx 10^6 \text{ cm}^{-2}\cdot\text{s}^{-1}$ for "the standard ANITA neutron field", defined as the field at the SUP for the standard incident proton beam current of 200 nA on the production target. The user can choose lower flux at any time, down to $\approx 200 \text{ cm}^{-2}\cdot\text{s}^{-1}$ at the SUP and further down to $\approx 5 \text{ cm}^{-2}\cdot\text{s}^{-1}$ at the downstream end of the beam path. At a given position, the available range of immediate flux variation amounts to a factor of at least 150, which is achieved by altering the repetition frequency of the beam macropulses. All mentioned features are fully compatible with the beam sharing mode. Further details can be found in Ref. [8], [9].

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The Quasi-Monoenergetic Neutron (QMN) facility shares the beam line with the ANITA facility and uses the ${}^7\text{Li}(p,n)$ reaction for neutron production. The energy of the peak neutrons is selectable in the 20–175 MeV range. The flux of high-energy peak neutrons amounts to $3 \cdot 10^4 - 3 \cdot 10^5 \text{ cm}^{-2} \cdot \text{s}^{-1}$ at the SUP, dependent on energy. In addition to SEE testing and studies (see the previous section), the QMN facility is employed for nuclear data measurements and detector calibrations. Further details can be found in Ref. [9], [10].

The accelerated proton beam, with the energy selectable in the range 20-180 MeV, can be guided to another beam line in the Blue Hall. Most of applications (testing for SEE and total ionisation dose effects, detector development and calibrations) utilize broad uniform proton fields, obtained by scattering of the primary beam on a tantalum foil. The produced scattered proton beam of Gaussian shape is geometrically limited using a set of graphite collimators. The diameter of the resulting beam spot can be chosen in the range 0.4-20 cm. The highest available proton flux amounts to $5 \cdot 10^7 - 5 \cdot 10^9 \text{ cm}^{-2} \cdot \text{s}^{-1}$ for the scattered beam and to $10^{11} - 10^{12} \text{ cm}^{-2} \cdot \text{s}^{-1}$ for the unscattered one, dependent on the proton energy. The proton flux is controllable within a range of ≈ 10 orders of magnitude. Further details can be found in Ref. [9].

BEAM SHARING TECHNIQUES

Due to the predominant use of beam time by proton therapy since 2005/2006, it became crucial to develop a method that could allow other users access to the beam in parallel with therapy treatments. While practised at TSL in specific situations during the last 10 to 15 years, beam sharing's possibilities were considered from a new perspective realizing that it is the only workable solution that would allow the laboratory to continue offering proton and neutron irradiation services for non-therapy users from industry and science, as well as to develop new irradiation facilities, as e.g. ANITA (see the respective section). A second motivation for exploring a new beam sharing approach, is related to the fact that reduced manpower motivated an operatorless control room solution.

A suitable beam sharing technique was therefore developed in 2006, which enables the beam to be switched between different irradiation areas by the principal user, instead of being controlled via the cyclotron operator. This enables a more efficient use of beam time and manpower. The duty of being operator is still assigned to one of the cyclotron personnel. The installation of mobile telephone repeaters throughout the facility enables users to contact the "operator" (who may be performing other duties), should the need arise.

The control system group at TSL developed a range of features that help the users to evaluate the beam quality.

Beam Sharing Scenario

During a run in the beam sharing mode, the beam is made available alternately for proton therapy, as the

primary user, and for one of the irradiation facilities (IF) in the Blue Hall, as the secondary user.

Before the beam sharing can be operated by users, it has to be set up by the cyclotron operator. This procedure is usually performed on Mondays and the resulting settings are used during the following week. Depending on the beam characteristics requested by the primary and secondary users, the following decisions are made:

- Selection of parameters that will be changed when switching the beam between the users.
- Choice of the delay time between requesting and granting the beam switching.
- Setting up alarm limits for the beam current.

After the beam switching is set up and all necessary quality assurance measurements are done, the control of the beam switching can be handed over to the therapy staff. From this moment on the cyclotron operator does not need to be in the control room, provided the operational status is normal. If the beam characteristics deviate from the preset range, the programs run by the primary and/or secondary users send alarm message(s) to the operator's mobile telephone.

Therapy, as the primary user, has full and exclusive control over the switching of the beam from the irradiation facility to the therapy area and vice versa. The switching of the beam is done using a dedicated program available only to the therapy staff and the cyclotron operators. The sequence for switching from the irradiation facility to therapy consists of the following steps:

- The therapy operator initializes the beam switch after selecting the number of irradiation fields and possibly adjusting the expected duration of the therapy beamtime slot.
- A voice message is sent to the cyclotron and IF control rooms to inform about the scheduled beam switching.
- After the preset delay, the beam is switched to the therapy area.
- After passing the beam current check, the beam is available for the therapy.

Switching the beam from therapy to IF includes the following actions:

- The therapy operator initializes the beam switch after selecting the expected time the beam will be available at the irradiation facility.
- The switching is performed.
- After passing the beam current check, the beam is available at the IF with a voice message sent informing that the beam is available for the specified expected time.
- If the secondary user has enabled the beam, it is put on target, otherwise the beam is turned off. The secondary user may turn on the beam again at any time.

Features Available for Users

The sets of available features are different for the therapy and IF users. The therapy operator controls the beam switching process and can monitor the beam

parameters (beam current, beam shape and position on viewers, beam position and angle using two multisector ionization chambers). The therapy operator also controls the access to the therapy room and the total dose delivered to the patient. The therapy staff is responsible for the dose control and patients' safety.

After the specified number of irradiation fields is completed, the therapy operator is reminded by the program to switch the beam back to the secondary user.

IF users have limited access to the control system via the Automated Workplace (AWP) with a simple graphical user interface, where the following features are available:

- Control of access to the irradiation facility area.
- Enabling/disabling the beam.
- Monitoring the beam current and other parameters.
- Monitoring the expected remaining duration of the beam slot for therapy or IF.
- Viewing the status of the beam switching (i.e. showing which beam line the beam is directed to).
- Viewing graphical plots of the beam current or particle beam flux density, as well as the event log.

In addition, the AWP allows the user to preprogram an irradiation so that it is automatically terminated after accumulation of a preset particle fluence on the user's object or device under test. This application makes use of real-time readings coming from one of calibrated proton or neutron monitors.

SCHEDULE AND USERS OF THE BEAM

A typical operation schedule has a four-week cycle, as detailed in Table 1.

Table 1: Available time slots with 180 MeV beams.

Week #	Time slots			
	07-09	09-18	18-22	22-07
1	Trim/QA	PT [+ IF]	-	-
2	Trim/QA	PT + IF	IF	-
3	Trim/QA	PT + IF	IF	-
4	Trim/QA	PT + IF	IF	IF

Abbreviations: PT = Proton Therapy, IF = Irradiation Facilities in the Blue Hall, QA = Quality Assurance. "PT + IF" indicates slots in the beam sharing mode.

The average share of the beam time available for IF in the beam sharing mode (between 09:00 and 18:00) amounts to $\approx 70\%$, or ≈ 6 hours. In weeks 2, 3 and 4 (see Table 1), IF users may continue running even after 18:00 in the single-user mode.

In addition, there are 3-4 weeks per year when the cyclotron can be run in a mode dedicated to the needs of a specific user, thus not necessarily using 180 MeV protons. Beams of heavy ions can be delivered, as well as protons with energy below 180 MeV (down to about 25 MeV).

The beam usage statistics for 2008 and 2009 shows a 36% increase for proton therapy and a 6% increase for the irradiation facilities.

ONGOING DEVELOPMENTS

A new diagnostic system is under development, which includes replacing the existing Vidicon-camera system with solid-state cameras.

The following developments are in progress at the irradiation facilities in the Blue Hall:

- A variable energy degrader, which would allow us to offer proton beams with controllable energy without re-tuning the cyclotron.
- Interactive user control of the beam intensity, compatible with the beam sharing mode.
- A shed for shielding of user's out-of-beam equipment from thermal and epithermal neutrons.

CONCLUSIONS (AND OUTLOOK)

The accelerator and irradiation facilities are continually developed and rebuilt according to users' demands.

Beam sharing between proton therapy and alternative radiation facilities has proven to function reliably and safely.

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