BEAM INTENSITY MODULATION CAPABILITIES OF VARIAN'S PROBEAM® ISOCHRONOUS CYCLOTRON

S. Busold*, H. Röcken, Varian Medical Systems Particle Therapy GmbH, Troisdorf, Germany

Abstract

Varian's ProBeam® 250 MeV superconducting proton cyclotron is an isochronous cyclotron for radiological applications using pencil beam scanning mode and provides continuous beam (at its fundamental frequency of 72 MHz). In its clinical operation mode, up to 800 nA of proton beam are specified and routinely extracted. Even more can be extracted in technical mode. The cold cathode Penning ion source provides enough protons to reach this current, and a layer-to-layer intensity modulation of the scanned beam is realized with an internal electrostatic deflector, which is used to vary the extracted beam current between maximum and zero. However, for research applications there is sometimes the request for higher flexibility, in particular for higher possible beam intensities and faster beam intensity modulation. In order to explore capabilities of the machine for such research modes, experimental investigations have been performed: Pulsed beams with repetition rates of up to 2 kHz and variable pulse lengths down to 4 µs as well as peak currents during pulse of up to 30 µA are in the accessible range with only changes at power supply level.

STANDARD OPERATION MODE

The ProBeam cyclotron delivers up to 800 nA proton beam in clinical operation. Protons are generated in the internal cold cathode Penning ion source, which is running continuously and allows varying the beam current via setting of the internal discharge current. The relation between both is found to be linear in the typically used internal discharge range (80 to 280 mA). The source parameters typically need adjustment only once at the start of each treatment day, and in general need little tuning along cathode life time to compensate for the normal wear of these parts.

Fast beam intensity modulations during treatment are possible via an internal electrostatic deflector. This deflector is designed for switching frequencies up to 2 kHz and switching times from one stable deflection level to another within less than 100 µs. This time scale for precise switching is determined by ringing, which is caused by the electrical properties of the voltage supply line from power supply to cyclotron. Beam blocking voltage level, however, can be exceeded permanently within only 3 µs.

MODIFICATIONS

Generation of high intensity proton beams for experimental operation is possible via modifications on power supply level and considering the general constraint that the average extracted proton current should not exceed approx. 1 µA for machine safety reasons.

From this follows directly: A pulsed beam operation is necessary to limit the average current. In particular, a pulsed operation of the ion source supports this operation mode by allowing much higher short term internal discharge currents (thus extracted beam currents), that would not be stable in continuous operation mode of the source. In the following section, such a pulsed mode of the ProBeam's ion source is characterized.

Change to Pulsed Ion Source Mode

An additional electrical module (one standard 19" rack slot) was installed at the ion source power supply. It basically consists of a capacitor which is constantly charged by the power supply, and a wave form generator controlled high voltage switch, as well as means for current and voltage diagnostics. An extensive parameter scan has been performed at a dedicated ion source test stand [1] at *Paul Scherrer Institut* (PSI) and the dependencies on pulse rate, duty, applied discharge voltage, and hydrogen gas pressure within the source have been evaluated. Although absolute numbers for the extracted beam at this test stand and extracted beam at the cyclotron may not be compared directly, the general scaling behaviour might well be. Results are shown in Figure 1 and Figure 2. Due to the source operation at the test stand at lower magnetic field (approx. 1 T) higher internal source pressures and lower internal discharge currents are used compared to the ProBeam cyclotron.

Several general characteristics could be observed and are in accordance to the expectations in this operation mode:

- Stable operation at much higher peak discharge currents during pulses compared to continuous mode is possible.
- Towards high duty factors the behaviour approaches the continuous mode.
- Shortest pulse lengths result in highest average currents during pulse.
- Higher voltage leads to higher currents.
- Lower H_2 gas pressure is also beneficial for higher currents.

*contact: simon.busold@varian.com

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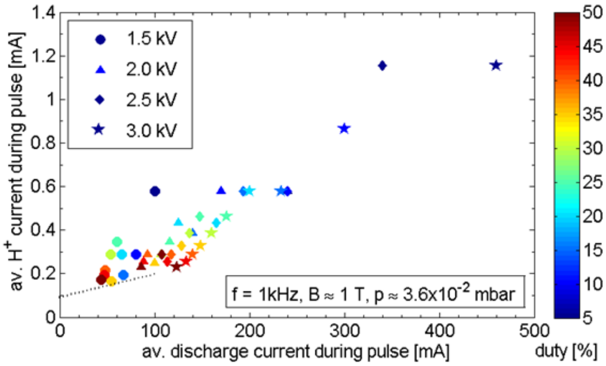

Figure 1: Average extracted proton current during pulses at 3.6x10^{-2} mbar hydrogen gas pressure within source. Dashed line indicates standard continuous source operation (duty = 100%).

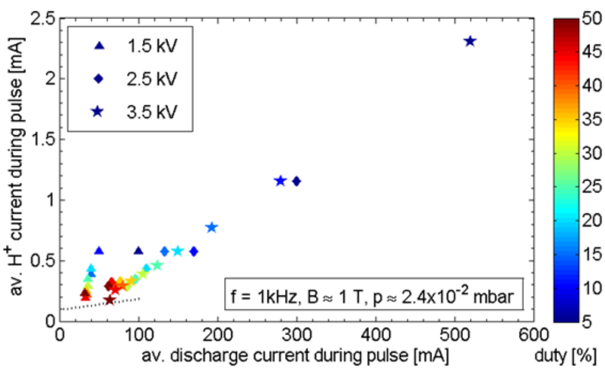

Figure 2: Average extracted proton current during pulses at 2.4x10^{-2} mbar hydrogen gas pressure within source. Dashed line indicates standard continuous source operation (duty = 100%).

Compared to continuous mode, the average proton current during pulse could be increased by a factor x10 to x20 at 1 kHz pulse repetition rate, 5% duty, 3.5 kV applied high voltage, 2.4x10^{-2} mbar hydrogen gas pressure and a magnetic field of 1 T in the test stand. Peak currents of the extracted protons could not be measured directly in the experimental setup, but can be estimated by analyzing the discharge current characteristic and making the reasonable assumption that the extracted current is proportional to the discharge current.

At switching, the discharge current rises quickly (approx. 4 µs) from zero to a maximum value (depending on applied voltage) and then exponentially decreases (half life approx. 10 µs) towards a constant value, see Figure 3. In the case of 3.5 kV applied voltage a peak discharge current of approx. 2 A was measured. The observed behaviour is independent from repetition rate and duty, and the increased average current towards lowest pulse lengths can completely be attributed to this initial effect of quick discharge current rise after switching and consecutive exponential decay to a DC equivalent level. Considering only the 10 µs around the maximum discharge current, a current increase of at least a factor x30 as compared to continuous operation can be calculated. Additionally, a clear scaling with applied discharge high voltage was observed, giving potential for easy further increase of peak currents.

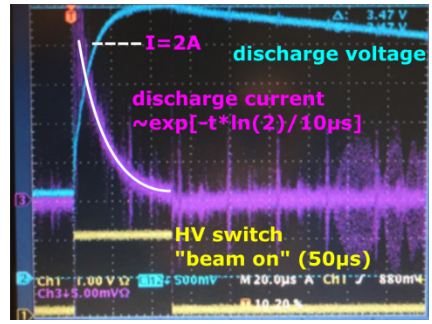

Figure 3: Discharge characteristic (current and voltage) for pulsed operation with 1 kHz repetition rate and 5% duty at 3.5 kV applied voltage.

In order to produce clean short and high intensity proton bunches, the cyclotron's internal deflector might be used to cut out part of the pulsed beam from the ion source. A brief overview is given in the following section.

Modification of the Electrostatic Deflector System

The cyclotron's internal electrostatic deflector can be used to modulate the beam intensity even on µs time scale if the voltage supply cable is matched to suppress ringing.

Calculations show that the system can produce proton pulses down to 4 µs pulse length. Experimentally this has been demonstrated at PSI on an appropriately modified system. Figure 4 shows the picture of such a 4 µs short proton bunch, measured with a fast scintillator and photo diode system connected to an oscilloscope.

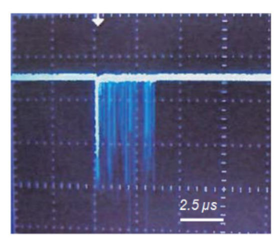

Figure 4: Approx. 4 µs short proton pulse, detected at PSI via a fast scintillator and photo diode (courtesy of J. M. Schippers *et al.*).

CONCLUSION AND DISCUSSION

For research and experimental modes we have introduced a pulsed proton beam delivery mode for the ProBeam cyclotron via moderate modifications at power supply level. Pulsing the ion source and optimizing the internal electrostatic deflector system gives access to pulsed beams (≤2 kHz) with short pulse lengths (≥4 µs) and high peak intensities.

The pulsed mode operation of the ion source was successfully demonstrated at a dedicated test stand at PSI and

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a peak current increase of at least a factor x30 was achieved. Thus, scaling from 1 µA extracted current in continuous mode at the ProBeam cyclotron, an increase to ≥30 µA average current during several µs short beam pulses is possible.

Space charge influences are not to be expected for these currents yet. Furthermore, beam loading is also not expected to be an issue, as the maximum beam power at 30 µA proton current would be 7.5 kW and thus only 6.5% of the total radiofrequency power input into the resonator. Regulation of this influence is possible with the machine's control system.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. Busold *et al.*, "Recent ion source developments for Varian's ProBeam cyclotron", presented at Cyclotrons'16, Zurich, Switzerland, September 2016, paper THP06, this conference.

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