DEE VOLTAGE CALIBRATION FOR THE ACCEL PROTON THERAPY CYCLOTRON

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Abstract

ACCEL Instruments GmbH has developed a superconducting cyclotron for the use in proton therapy systems. An essential step during the commissioning of the medical cyclotron is the calibration and balancing of the DEE voltages. Using a very compact and low cost X-ray detector the bremsstrahlung spectrum of stray electrons accelerated by the four RF cavities has been measured. To determine the peak voltage a regression analysis of the measured spectrum has been carried out using a non-linear multiple convolution model taking into account the energy gain of the stray electrons between the liner and the DEE, the bremsstrahlung spectrum integrated over angle as well as the attenuation effects caused by the liner and the limited detector resolution. The correlation between the model and the measurement was very good. A software tool enabling automatic spectrum acquisition and analysis capable of online determination of the DEE voltages has been developed in LabVIEW graphical programming environment. Careful balancing of the DEE voltages resulted in better beam focusing and a cyclotron extraction efficiency larger than 80%. The absolute acceleration voltage has been confirmed by turn-separation measurements.

INTRODUCTION

ACCEL Instruments GmbH is a leading supplier of accelerator equipment and systems for research, industry and healthcare. For application in the field of proton therapy ACCEL developed a new 250 MeV superconducting cyclotron in cooperation with the National Superconducting Cyclotron Laboratory in Michigan, USA [1]. The first two cyclotrons of this type have been commissioned successfully and are integrated in proton therapy facilities, one at the Paul Scherrer Institute (PSI) in Switzerland and one at the Rinecker Proton Therapy Center (RPTC) in Germany [2].

The RF system of the ACCEL superconducting cyclotron consists of four cavities or 'DEEs' that are operated in the second harmonic continuous wave mode. Each of the four DEEs is located in a 'valley' of the magnetic field shaping iron as shown in Fig 1. In this configuration the capacitive load on the RF system is minimised as well as the RF operating power. Each DEE has stems on both top and bottom so that top-to-bottom voltages inside the DEEs can be nulled by positioning of the shorting plates on upper and lower stems. Power from the RF amplifier is coupled to only one of eight stems; hence the RF system has a single 'driven' DEE. Of the remaining three DEEs one is galvanically coupled to the driven DEE in the central region and two satellite DEEs are coupled capacitively. The stems are used to tune the relative voltages between each of the four DEEs. The average voltage can be increased or decreased by setting the power of the RF amplifier.

The DEE voltages are balanced and calibrated during commissioning using the bremsstrahlung measurement. Balanced DEEs are a prerequisite for effective beam centering and high extraction efficiency.

PRINCIPLE OF MEASUREMENT

Electrons escaping from the surface of DEE and liner are accelerated in the RF field and emit a bremsstrahlung spectrum when hitting a metal surface. The endpoint energy of the spectrum is a measure of peak DEE voltage. In order to measure the spectrum a direct line of sight should exist between the X-ray detector and the DEE. For this purpose four penetrations through the cyclotron iron yoke in the magnetic 'valleys' are available at a radius of 300 mm. The very small (Ø14 mm) X-ray detector can be placed directly behind the liner outside of the vacuum as shown in Fig. 1.

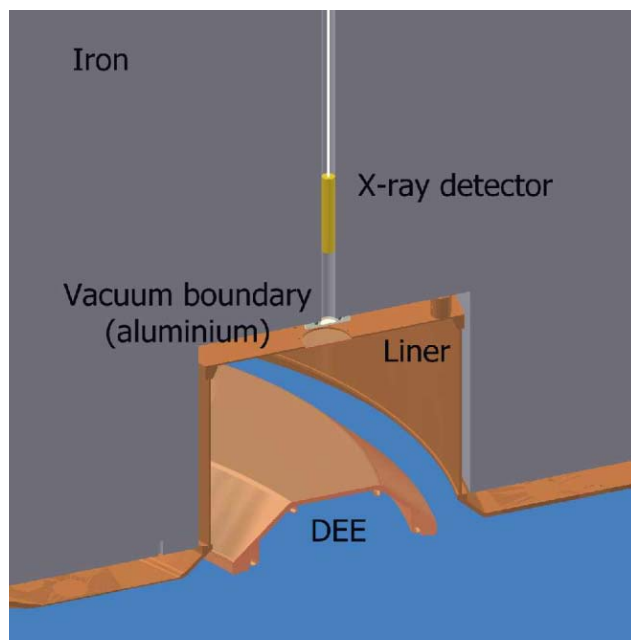

Fig. 1. Cross sectional view of the X-ray detector mounted behind the liner.

This enables a fast exchange of the detector and facilitates calibration. By retracting the detector further

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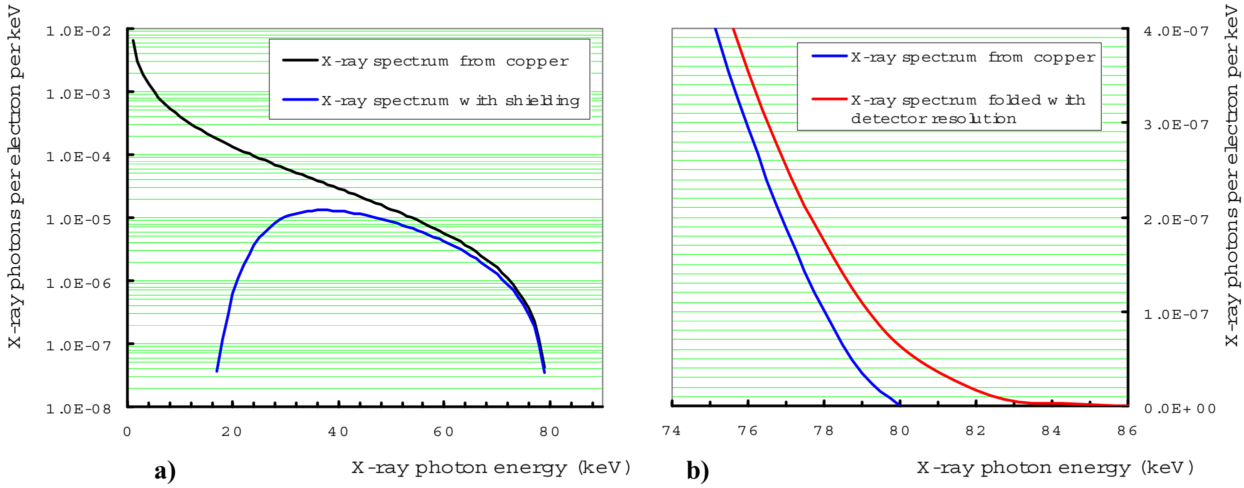

Fig. 2 a) Calculated x-ray spectrum for a DEE potential of 80 kV and the spectrum attenuated with 0.5 mm copper and 2 mm aluminium. b) Calculated x-rax spectrum after convolution with detector resolution.

from the liner the count rate can be reduced and the collimating effect of the iron is stronger. An additional advantage of the measurement setup is that only a single detector is needed to measure all four DEEs in a short time. The detector used is based on a 5x5x5 mm CdZnTe crystal operating at room temperature. The detector with integrated pre-amplifier is mounted in a cylindrical housing. The cost of the small detector size is a limited energy resolution compared with the much bigger Ge detectors. This is not problematic as long as the detector is carefully calibrated and the detector resolution is included in the regression analysis.

MODELING THE X-RAY SPECTRUM

Locating the endpoint energy of a measured spectrum can be troublesome because of statistical uncertainties, limited detector resolution and background noise. To improve the measurement of the endpoint the bremsstrahlung spectrum and detector characteristics are combined in a model and fitted to the measured data. An example of this approach is given by Oldeman [3]. Our model contains four components:

- Energy gain of electrons in the RF field

It is assumed that electrons start at the surface of the DEE and are accelerated towards the liner, following the magnetic field lines. By solving the equation of motion for the electron, the maximum energy gain as a function of DEE voltage and starting phase can be calculated [4]. Calculation shows that when the cyclotron is operated at 80 kV DEE voltage the electrons reach an energy of 77.76 eV or 97.2% of the maximum DEE potential.

- The bremsstrahlung spectrum

The electron energy as a function of starting phase is not the same as the energy distribution of the electrons reaching the liner. For simplicity the energy distribution is assumed to be sinusoidal. Then the integrated over-angle X-ray spectrum as a function of photon energy is calculated following the approach of Duke [5]. The shape of the bremsstrahlung spectrum is shown in Fig. 2a).

- Attenuation from liner and vacuum flange

The low energy photons are not of interest for the determination of the maximum energy and are attenuated by the 0.5 mm copper liner and a 2 mm aluminium vacuum flange. As can be seen in Fig. 2a) the high energy part of the spectrum is almost unaffected by the shielding.

- Detector resolution

The small size of the X-ray detector makes it possible to mount the detector close to the liner but comes at the cost of a low energy resolution. The FWHM of ~6 keV at 80 keV is included in the model with a convolution. The effect of the detector resolution on endpoint energy is shown in Fig. 2b).

SOFTWARE

Data fitting to the model via a regression analysis needed a software implementation that takes into account all of the above mentioned model components. All used integrations, convolutions and interpolations were coded in ANSI_C, always paying attention to accuracy requirements. Since the calculations are relatively time-consuming special care was taken on computation speed. Moreover, the user can reduce the number of points to be fitted in a spectrum and define the region of interest relevant for fitting. These features considerably speed up the whole process. On a standard PC the results are typically available after some seconds. The routines were then compiled to a library to enable the integration into a user-friendly LabVIEW-based interface [6]; a panel of the PicoSpec Gold Spectrum Viewer is shown in Fig. 3. This software is now used to control the detector and portable Multi-Channel Analyser (MCA) settings as well as to analyse the recorded spectra online and to continuously display the calculated DEE voltage.

RESULTS

The first spectra were measured with the detector mounted directly behind the aluminium flange, reducing the collimating effect of the iron to a minimum. This

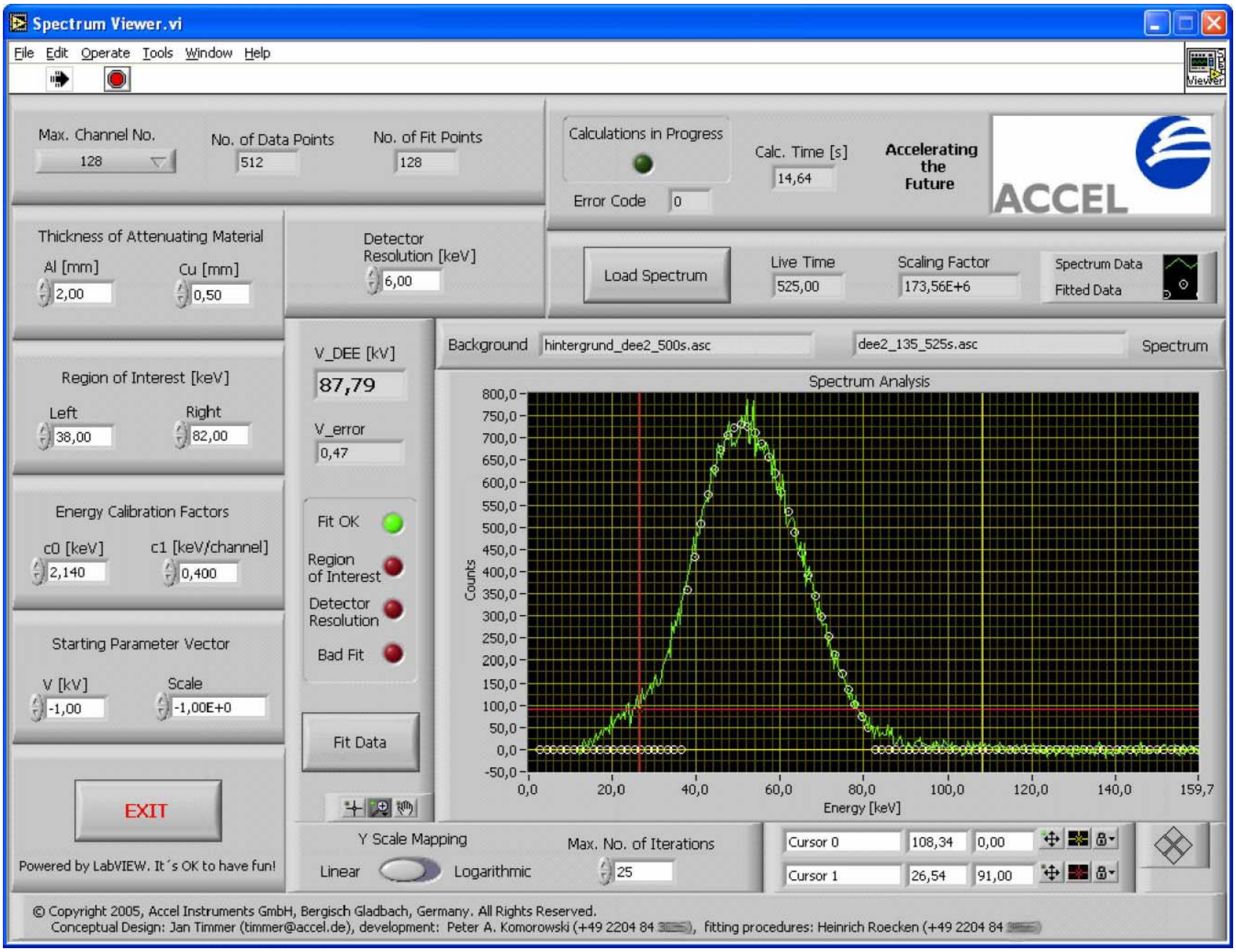

Fig. 3. PicoSpec Gold Spectrum Viewer. The measured spectrum is shown in green, the fitted spectrum (87.79 kV) is plotted with white circles.

resulted in a high count rate and a poor match between measured and fitted spectra, especially at the high energy flank. It was assumed that electrons from all four DEEs were seen and the detector was retracted to increase the collimating effect. At a distance of ~70 mm between detector and flange, the optimum between count rate and collimation was found. At this position a small deviation between measurements and model still exists at the high energy tail as can be seen in Fig. 3.

Then spectra were recorded at three different RF power levels for all four DEEs. The first set of measurements showed a spread in DEE potentials of 20 kV. In several measurement cycles this spread was reduced to ~2 kV as displayed in Fig. 4.

The results of the X-ray measurements were cross-checked by measuring turn separation with a shadow-finger current probe in the centre of the cyclotron. Turn separation is a measure for the average potential on the four DEEs and can only be used after balancing the DEE potentials. The measurement was done at an RF power of 120 kW and the result was compared with orbit tracking calculations. Fig. 5 shows good agreement between measurements and calculations, confirming the reliability

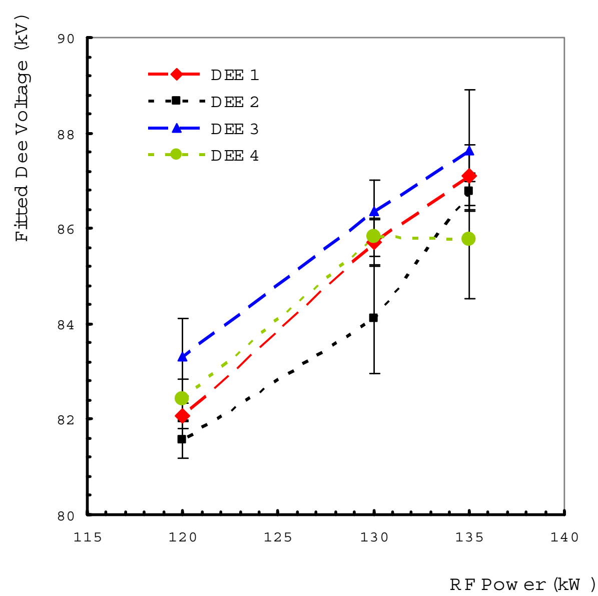

Fig. 4. Final set of DEE voltage measurements at different RF power levels showing a DEE potential spread of ~2 kV.

of the X-ray measurements. Another confirmation of the validity of the X-ray measurements comes from a beam profile measurement in the inner region of the cyclotron which is described by Baumgarten [7].

It must be stressed that an optimal DEE balance is not a goal in itself. Equally balanced DEEs improved the cyclotron stability, reducing the number of RF trips and eliminating damage to contact fingers. Small adjustments away from the equilibrium were made afterwards to optimise beam centering.

Overall, the portable measurement system consisting of detector, MCA and laptop with PicoSpec Gold software proved to be a reliable and indispensable diagnostic tool during the commissioning of the superconducting cyclotrons.

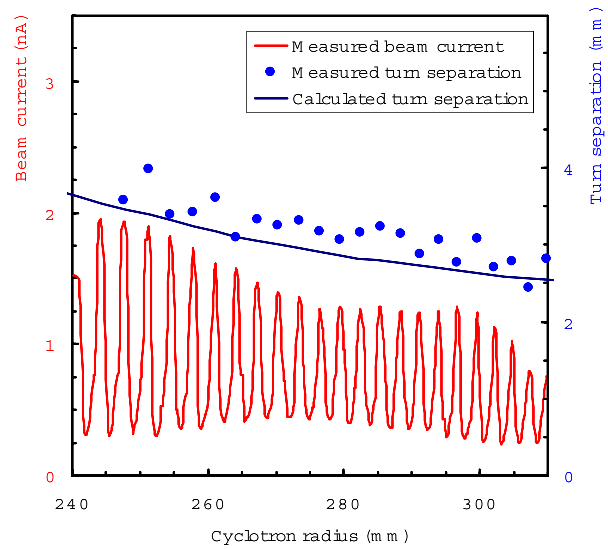

Fig. 5. Beam current trace showing individual turns at 120 kW RF power. The measured turn separation is in good agreement with the calculated turn separation.

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