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MANUFACTURING AND COMMISSIONING OF CYCLOTRONS IN A SERIES PRODUCTION AT VARIAN

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Abstract

On 16th of March 2019 Varian celebrated the 10th anniversary of first patient treatment in the Munich Proton Center.

Since the first cyclotron installation, 22 cyclotrons have successfully been manufactured, commissioned, and tested in Troisdorf production.

A better understanding of the cyclotron mechanisms and physics allowed for significant faster commissioning lead times without changing the hardware setup substantially.

Essential improvements in area of qualification of magnetic field configuration, RF conditioning, and beam commissioning are presented.

KEY PERFORMANCE INDICATORS

Varian's superconducting AC250 cyclotron delivers proton beams with a fixed energy of 250 MeV with beam currents of up to 800 nA. This compact cyclotron is a four-sector cyclotron operating at an RF frequency of approx. 72 MHz, which is the second harmonic of the orbital frequency, see [1] and [2] for more key parameters of the cyclotron.

During the last years, several improvements were introduced in the phase of production and factory commissioning of the cyclotron. This allowed an increased number of fully commissioned cyclotrons, which were tested and optimized to the medical specifications needed for clinical operation, especially with respect to extraction efficiency as well as beam shape and stability.

After the superconducting coil is cooled down to liquid helium temperature of 4.2 K the magnetic is excited for the first time followed by the field mapping process. By using a pre-shimmed cyclotron, i.e. omitting several shimming / field mapping iterations, the number of field maps could be reduced significantly. During the commissioning of the first cyclotrons, several iterations were performed, i.e. the magnetic field configuration was optimized incrementally by adjustments of the shimming pattern. Afterwards the magnetic field was mapped. Starting with cyclotron #7 (C7), the number of shimming iterations and corresponding field maps was gradually decreased towards a pre-shimming first time used with cyclotron #15, see Fig. 1. This means, that a default shimming pattern is used for each cyclotron and the magnetic field configuration is only verified via field mapping.

Although test criteria (e.g. extraction efficiency, max. beam intensity, and beam position stability) have simultaneously become more elaborate and strict over the past years, improvements of the test processes as well as hardware changes result in a significant reduction of needed working hours for RF and beam commissioning as well, see Fig. 2. Details of the improvements will be described in the following section.

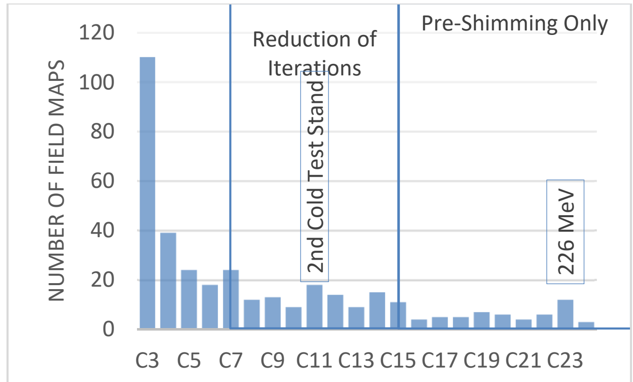

Figure 1: Number of collected field maps for different projects (indicated by C followed by integer).

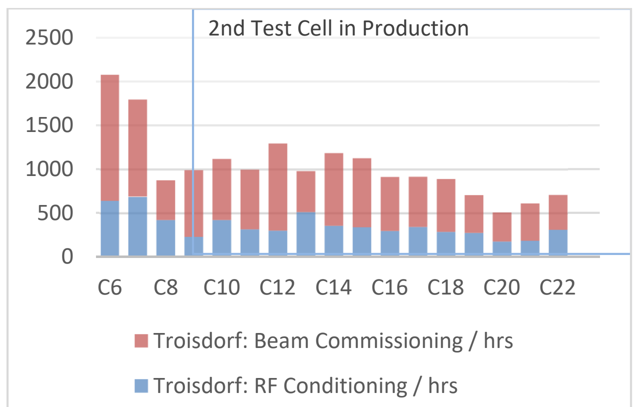

Figure 2: Used working hours for RF and beam commissioning in the Troisdorf cyclotron test cells.

IMPROVEMENTS

Several hardware changes were introduced with the goal to make commissioning processes faster, more reliable, and reproducible. During beam commissioning, a so-called foil irradiation is performed several times. After each beam characterization and optimization iteration, beam width and position are checked via the irradiation of radiation sensitive foils. These foils are attached to the entrance and exit of the extraction deflectors and focusing bars. Figure 3 shows a schematic overview of the cyclotron and the position of the different extraction elements.

Instead of pasting the foil pieces directly to the respective component, foil frames and holders were designed for easier and more reliable installation of the foils.

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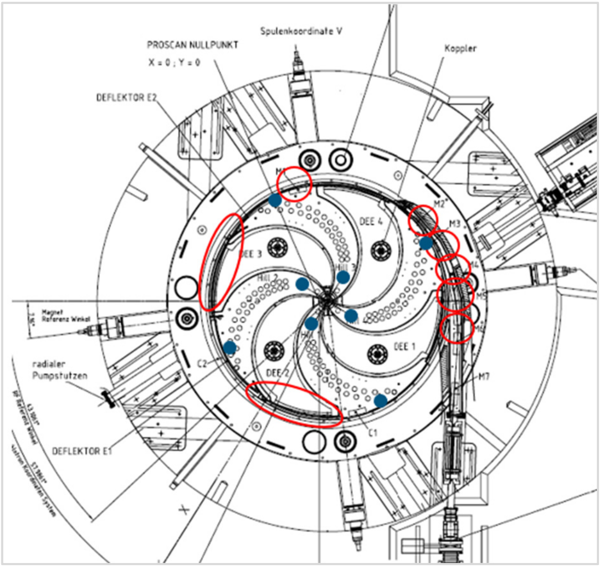

Figure 3: Sketch of cyclotron layout. The red circles depict the extraction element positions (see Fig. 5).

In addition, the design of the Dee Rims, which connect the RF cavity structure of both pole caps, has been changed. At the early stage of RF commissioning, the electrical field inside the cavity might not be well balanced yet. This may result in strong current flows at the four Dee Rims, causing their contact fingers to burn. After changing the design at this point, burned Dee Rim contact fingers only rarely occur. Figure 4 shows both Dee Rim designs, where the top one shows partly burned contact fingers. The bottom picture shows a new-designed Dee Rim which was in operation throughout RF and beam commissioning.

Besides hardware changes, processes throughout all phases of cyclotron commissioning have been reorganized to enhance effectivity and robustness of test procedures and results. This was possible especially by gathering data and experience from former cyclotron commissioning procedures. The first example is in the field of the field mapping and shimming process, see above. Regarding RF commissioning, a self-developed automatization tool is in operation. This tool was designed to support the cyclotron operator during RF and beam commissioning and is an extension to the current cyclotron control system. Together with the existing control system functions this tool is able to continue RF operation after an RF trip without any action needed from the operator. This in tool in principle allows a completely automatic RF commissioning in the sense of slowly ramping up RF power and self-adjusting the power level towards stable conditions. It has proven to significantly speed up the conditioning process, as it is now possible to run 24 hours a day, even when no cyclotron operator is present.

[1]The beam distribution and position is processed via Python by analysing a video with respect to a distribution of bright pixels.

Figure 4: Top: Dee Rim with old design of contact fingers. Starting from the edge of the Dee Rim, the contact fingers are melted due to high currents caused by disbalanced EM fields. Bottom: Dee Rim with new-designed contact fingers. No sign of deterioration is noticeable. Note, that this Dee Rim was installed during RF and beam commissioning.

Moreover, meanwhile the superconducting coil is prealigned before the cyclotron enters the test cell. The coil was previously aligned using foil irradiations in order to avoid a tilted coil and, thus, vertical oscillations of the proton beam while being extracted, see [3] for details. Nowadays, the forces of the coil support links are balanced in a way that the torsional moment is minimized as far as possible. This results in much less foil irradiations and, thus, faster beam commissioning. Figure 5 shows examples of irradiated foils before and after the coil was tilted. By optimizing the coil position beforehand, the first foil irradiations can be omitted.

On the other hand, the vertical position of the coil still needs to be optimized using a proton beam. For this purpose, so-called viewer probe is used. This basically consists of a CCD camera at the top of a lance, which can be moved radially inside the cyclotron to visualize vertical position and shape of the proton beam. By tracking the vertical position from the inner region up to the extraction channel, the vertical coil alignment can be evaluated. Data acquisition and evaluation of this process has recently been fully automatized using a self-developed blob[1] detection algorithm, see Fig. 6.

Beside imaging the beam, another important part of the cyclotron beam commissioning is the so-called characterization for different settings. For this purpose, various parameters (e.g. main coil current, electro-static beam steerers, or variable collimators) are scan whilst recording beam position, shape, and intensity.

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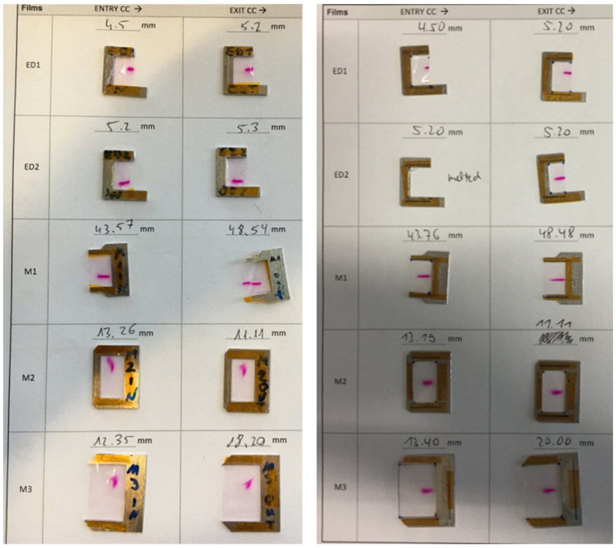

Figure 5: Examples of foil irradiations performed during beam commissioning. Left: vertical beam oscillations are visible along the beam path due to misaligned (tilted) coil. Right: coil pre-alignment eliminates oscillation and allow an straight beam path through the extraction.

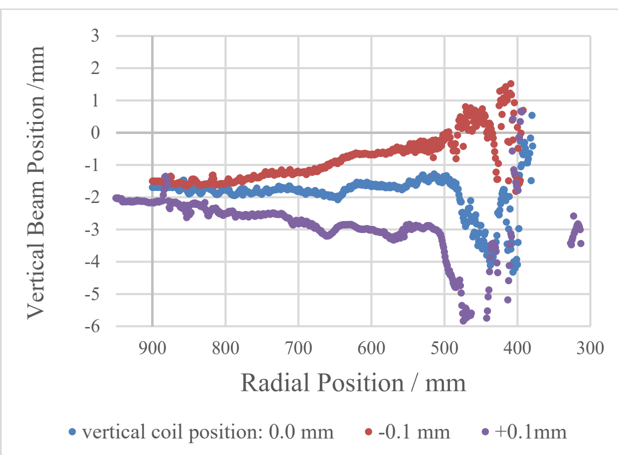

Figure 6: Vertical beam oscillation along cyclotron radius for 3 different vertical coil positions (please note: radial position axis is inverted, 360 mm corresponds to outermost radius/ extraction).

For this procedure, automatic routines were adapted to test cell commissioning, which are already used during clinical cyclotron operation on-site. This allows an improved data collection and comparability at different stages of beam commissioning as well as between different cyclotrons in the test cells.

CONCLUSION AND OUTLOOK

Several improvements of the cyclotron factory tests and commissioning process have been presented. This comprises hardware changes as well as an improvement of test processes to make the commissioning process faster, more reliable, and enhance the robustness of test results. For the future, further improvements are currently being planned. Among others, one very promising approach is to perform beam commissioning and optimization using pulsed RF instead of continuous wave operation. By doing so, beam commissioning would become independent of stable RF conditions at higher powers, where the actual RF conditioning is done automatically overnight. First test runs have successfully been carried out and show comparable results of measured beam properties.

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