Adaptation of a Synchrotron Control System for Heavy Ion Tumor Therapy

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Abstract

At GSI, a tumor treatment facility is being established to demonstrate the therapeutical effectiveness of an improved irradiation method with light ions. This program imposes strict and challenging demands on the operation of the accelerators and hence the control system. These requirements and the means to satisfy them are described.

I. Tumor Therapy

A. *Status of Tumor Therapy in Germany*

Every year, about 350,000 people out of the 80 million population of Germany develop tumors. 200,000 of them undergo some form of radiation therapy in the course of their disease, often in combination with surgery, or with chemotherapy.

Irradiation with electromagnetic beams is the most common method. In the statistics of successful treatment, about 45% of all cases, radiation therapy is second with 12%, behind surgery (22%). Another 6% of successful cases result from a combination of radiation with surgery. Some tumors, on the other hand, cannot be attacked by surgery, because they are inoperable in general or have developed in or close to risky tissue, e. g. eyes, spinal cord or parts of the brain. Some types of tumor are resistent to electromagnetic radiation [1].

In Germany, about 70,000 patients per year could profit from improved radiation therapy.

B. *Irradiation with Heavy Particles*

For tumor treatment, light ions (e. g. carbon) have some advantages over electromagnetic radiation, leptons, and mesons. Gamma rays exchange energy with tissue in an exponential function of the penetration depth. This is a problem for tumors deep inside the body. Healthy tissue in front of and behind the tumor is heavily irradiated at the same time.

Protons and heavier ions lose the greater part of their energy at the end of their trajectories, in the Bragg-peak. The penetration depth is a well-known function of energy and tissue density. The tissue behind the end of the trajectory remains largely unaffected and the tissue in the entrance channel in front of the tumor experiences relatively low damage compared to treatment with electromagnetic beams. The damaging effects, double breaks of the DNA-strands (single breaks repair themselves), scale more than linearly with the energy loss per volume, again in favor of low damage in the entrance channel. A treatment split up into about 20 fractions on consecutive days gives the tissue with low damage time to recover while the irreversible damage level in the tumor volume accumulates.

Charged particles can be guided very precisely, and heavy ones do not straggle much. With significant improvements in tumor localization techniques, ion therapy is promising for high-precision treatment.

C. *Intensity-Controlled Raster Scan*

Particle irradiation is presently used for tumor therapy. The operating proton- (e. g. Loma Linda) and ion- (e. g. HIMAC, Chiba) treatment facilities work with fixed beam energies and without lateral beam deflection. The matching of dose deposition to the individual tumor geometry is achieved mainly by passive elements: sophisticated mechanical masks in front of the patient. The penetration depth of the projectiles is adjusted by the amount of solid material passed by the beam before it reaches the patient. Energy spread and emittance growth inherent with this technique are limiting factors for irradiation precision.

These limitations can be avoided by using an ‘active’ irradiation technique [2]: A thin “pencil beam” of well-defined energy is scanned over the irradiation volume. The penetration depth of the beam is adjusted by beam energy variation. Every energy step corresponds to a slice of tumor tissue in which the energy loss peaks. The lateral control of the beam is achieved by two scanner magnets in front of the patient. The ‘hot’ beam spot, some cubic millimeters, is precisely controlled in three dimensions (fig. 1).

A constant scanning velocity would require beams of constant intensity to generate a homogeneous dose distribution. To cope with intensity fluctuations in real beams, the intensity is measured on-line. This intensity measurement is used to control the scanner: the beam spot is shifted to the next position when a predetermined number of ions has been counted. Drop-outs in the beam will simply prolong the irradiation time for the actual volume element.

When the irradiation of one layer is completed, the beam is aborted, and the irradiation is continued with the next beam energy. A treatment session starts with the furthermost tumor layer. All layers — except the most distal one — have to be irradiated inhomogeneously in order to compensate for the effects of beams which have penetrated to irradiate the more distal layers.

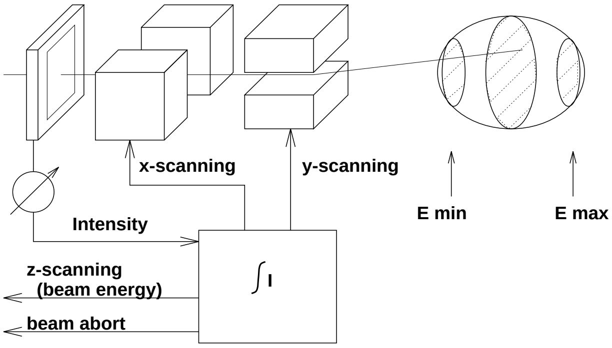

Figure. 1. Intensity Controlled Raster Scan

D. Tumor Therapy at GSI

GSI is a facility for physics research rather than for applications. The linear accelerator Unilac, the synchrotron SIS and the experimental storage ring ESR can handle all ions from Helium to Uranium. For therapy, the synchrotron is oversized in energy by a factor of 4. But presently GSI is the only facility in Europe which can provide all the tools needed for the intensity-controlled raster scan in therapy.

A project has been established to develop a raster scan with novel intensity control for practical use. To verify the usability of the raster scan, and to prove the effectiveness of the therapy, a five year program will start in fall '96, during which about 70 patients will be treated at GSI every year. A long tradition in biophysics research supports the therapy program.

II. Requirements

A. Responsibility of Accelerator and Therapy Staff

The accelerator and therapy facility are under control of different departments:

Operation of the therapy facility is done locally by medical staff. Their responsibility is to handle the treatment plans, to operate the raster scan, to guarantee patient safety and to request the appropriate beams. Sophisticated on-line beam diagnostics are provided to verify the correctness of the beam parameters. In case of intolerable deviations to the treatment plan, the beam is aborted and the irradiation is stopped.

The accelerator staff is responsible for delivering the beams for therapy with an operational reliability as high as possible. The accelerator provides two different means to abort the beam in less than 1 msec, both activated by the scanner control equipment.

B. Accelerator Operation for Therapy

The accelerator has to produce beams of different energies to scan the tumor depth.

The scanner should always operate close to its maximum speed to minimize the irradiation time. Corresponding to the need for inhomogeneous irradiation, beams of different intensities have to be provided. To adapt to different tumor sizes, the beam spot has to be adjustable. All other beam parameters will be fixed. The requirements for accelerator operation are:

- Ion species: $^{12}C^{6+}$ only
- Energy **E**: 80 – 430 MeV/u (20 – 300 mm penetration depth), 255 fixed levels ($\Delta z < 1$mm),

one patient: up to 64 energies

- Intensity **I**: $1{\cdot}10^6 - 1{\cdot}10^8$ ions / spill, 15 fixed levels
- Spot size (focus) **F**: 4 – 10 mm, 7 fixed levels
- Irradiation time for one patient: 5 min maximum
- Preparation time for a patient: 30 min
- Fast beam abort (less than 1 msec)

In order to achieve high operational reliability of the accelerator, the following requirements are laid down for therapy:

- Use only proven and validated settings.
- Protect settings from loss and accidental modification.
- Automatic operation, controlled by scanning equipment.
- Inhibit operator's access during irradiation.
- Avoid networking for settings; provide all therapy beams in stand-by on a pulse-to-pulse request basis.

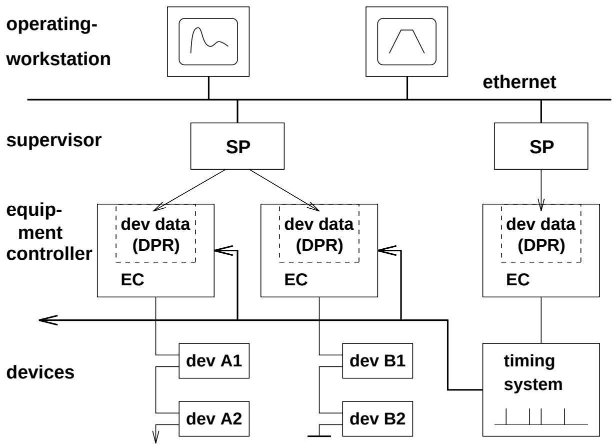

Figure. 2. Control System Architecture

The accelerator can easily provide the appropriate beam properties. But the modes of operation have to be upgraded to meet the requirements for therapy. The main modifications to upgrade the accelerator for therapy are to be made in the control system.

III. The Control System Architecture to Start From

The control system architecture (fig. 2, [3]) corresponds to the so-called 'standard model'. All real-time capability results from actions of the real-time software modules on the **E**quipment **C**ontrolers (ECs), started by the timing system. Communication with the operation level is done by **D**ual **P**orted **R**AM (DPR) on the ECs, the supervisor processors directly read and write the EC data. The real-time software modules run exclusively with data stored in DPRs. No component, hardware or software, from the EC upward is involved in a real-time process.

The DPRs are divided into 16 segments, representing the presently supported '**V**irtual **A**ccelerators' (VA). A VA is defined as a complete dataset stored in the DPRs necessary to execute an accelerator cycle. The operations software provides data for the DPRs to create a VA. The timing system makes the VA become 'real', i. e. to execute the datasets, allowing real-time execution of any sequence of VAs.

IV. Upgrade for Therapy

The present controls architecture and its real-time capabilities have met all demands to run the accelerators for the past five years. It is neither desirable nor possible within the given time frame to change it in its basic features. Extensions must be designed as add-ons to the given structure, and are mainly restricted to the equipment control assemblies. The operations software has to remain virtually unchanged. Adaptation of the device control software should be as simple as possible.

A. Substructuring of Virtual Accelerators

Pulse-to-pulse switching of the accelerator settings by sequencing different VAs is used routinely during operation of the accelerators, showing that the hardware is reproducible and allows the required therapy beam parameter variation. But the number of VAs is presetly limited to 16, which is insufficient for generation of the therapy beams. The concept of VAs has to be extended, allowing the implementation of enhanced flexibility.

One of the VAs (#15) will be used exclusively for therapy. It will be executed differently from pulse to pulse, representing the settings for therapy, labeled by **E**nergy, **I**ntensity, **F**ocus (**E**, **I**, **F**). Therapy data are stored not in the DPR but on the ECs to allow real-time access. The central timing system announces which of the therapy cycles is to be executed next. Then the data for this cycle are copied to the data area of #15 VA of the DPR (fig. 3). After copying, all device-specific software on the ECs can operate as at present, without any modification.

To store therapy data, we provide flash-EPROM for the ECs to protect against data loss. Special programming sequences, exclusively executed by the ECs, are needed to store data. This sets a high barrier against unwanted data modifications from the console level. New datasets first have to be supplied in the data area of #15 VA and then, after validation, explicitly copied to the therapy memory.

The full range of variable parameters **E**, **I**, **F** results in 26,775 different beams. Luckily, any single device depends only on subsets, in worst case on **E**×**F**. According to the device type any dependency of **E**, **I**, **F** can be configured, limited only by the available memory.

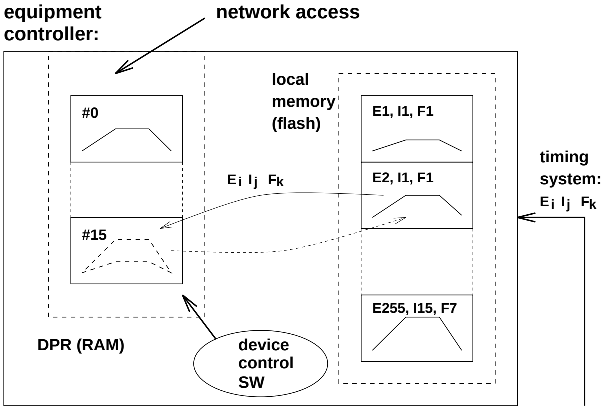

Figure. 3. Substructured virtual accelerators

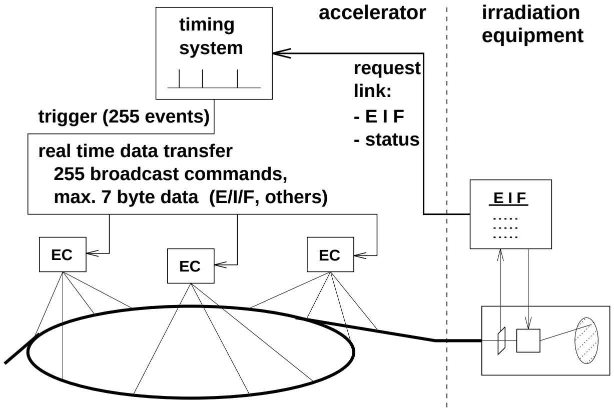

Figure. 4. Request Mechanism

B. EC Memory Upgrade

To store therapy data, about 100 ECs have been equipped with additional flash memory. Previously, EPROM used for the device-control software has been located on a piggy-back. The existing ECs can be re-used by replacing this memory piggy-back by a new one providing 2 MByte of RAM and 2 MByte of flash EPROM. Besides the storage of the EC's program code, it provides sufficient memory for therapy data for the majority of devices.

For devices with big data sets the memory can be doubled to 4 MByte of RAM and 4 MByte of flash EPROM, again allowing re-use of the costly processor part.

C. Timing System

To make the above-described procedures possible, the functionality of the timing system must be extended.

The timing system is the only system-wide interconnection with real-time performance. It can distribute 255 different time marks to all ECs to start real-time software modules at precisely set instants (Δt < $\pm 2\mu$sec).

Which beam is to be produced next is determined by the scanning control. Only at the end of each accelerator cycle can the decision be made whether the same beam is requested once more, or the next parameter set is to be executed. To provide the beam parameter information for the ECs in real-time, there is no other means in the GSI control system but the timing system. It is connected to the scanning control by a dedicated hardware link to receive, in addition to some status information, the request for the next therapy beam (fig. 4).

To distribute the beam parameter information (**E**, **I**, **F**) to all ECs, the timing system has been extended with data transport capability. In addition to the time marks, it allows broadcasting of 255 different commands, each with up to 7 Bytes of data. This can be used for real-time command execution on all devices, of which the most important is the delivery of **E**, **I**, **F**.

D. Device Control Software

At present, 45 different types of devices are supported, each of them requiring individual control software. About 20 have to be upgraded for therapy operation.

As far as possible, modifications are done in the system software, common for all devices. This includes data transfer on the timing bus and handling of flash EPROMs. A set of general copy routines is provided, allowing the copying of data between any kind of memory, either RAM or flash EPROM.

Considering device characteristics, device specific software has to be upgraded too. Based on widely-used programming standards, extensions could be written in a general way. Using include files, identical source code is used for all device-specific software. Only a short declaration section is needed, defining basic constants and types to adapt to the peculiarities of device types.

E. Data Supply

Because of the high number of datasets needed for therapy, manual tuning of the machines would be prohibitive. To derive data automatically, a model of the accelerator will be used, allowing calculation of all device data from high-level machine parameters such as ion charge and mass, energy, tune and focusing type.

Data for all therapy beams and all devices are calculated and sent to the devices in dedicated setup sessions. The data are validated with beam to assure correctness and then sealed in the EC's flash memory. Correct operation of the machine will be checked prior to the patient's irradiation. New data supply is expected to be necessary only after modifications to the accelerators or when the modeling of the machine is improved.

F. Accelerator Operation

The preparation time for one patient will be about 30 min, while the actual irradiation time will be less than 5 min. Reserving the accelerators for therapy during the patient's preparation time would result in wasting valuable beam time. The preparation time should be usable for physics experiments. Therapy and physics experiments require different ways of using the accelerators.

For therapy, only tested and approved data and courses can be used. Operation is fully automated; all operator interaction will be disabled during patient irradiation. The only possible human action is abortion of the irradiation by the medical staff.

Physics operation, on the other hand, requires fast and flexible reaction to the various experimental needs. The operations staff has to have full access to all devices to adjust the machines to changed conditions.

To fulfill the conflicting requirements for physics and therapy, the operational mode has to be switched. Switching is initiated by the therapy staff and can interrupt any physics program at the end of a machine cycle.

The command for switching is transferred to the central timing system by the request link. The central timing system then

- disables the execution of all physics cycles (VA #0 – #14),
- sends a lock command via the timing bus to all devices which from then on will reject all operator access,
- sends a command via the timing bus to all devices to verify therapy settings for non-pulsed properties, i. e. cups have to be out of the beam and slits have to be set to predefined values,
- enables the execution of the therapy cycle (VA #15).

Only then can the patient irradiation start: the scanner control requests beams and triggers the beam abort after complete irradiation of one tumor slice.

After irradiation of one patient is finished, the accelerator is switched back to physics operation. The central timing system disables execution of the therapy cycle, enables the execution of the physics cycles and revokes the locking of the devices to allow full access to the operators again. The interrupted physics program will continue automatically.

V. Conclusion and Outlook

With the measures described above, we are sure we can cope with the strict demands of the therapy program in terms of patient security, treatment speed, and treatment precision. Special emphasis is placed on minimizing the patient's stress level. This is why we did not compromise in improving operational reliability and treatment speed.

We hope that the program will be a success in terms of patient healing. If successful, the building of dedicated hospital-based irradiation facilities will be considered. Only with dedicated irradiation facilities can the high demand for treatment be met. For control system designers, it would be a real challenge to design from scratch a turn-key, fail-safe, and fool-proof control system for medical applications.

VI. Acknowledgements

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