DIAGNOSTIC INSTRUMENTATION FOR MEDICAL ACCELERATOR FACILITIES

M. Schwickert, GSI, Darmstadt, Germany
A. Peters, Hit GmbH, Heidelberg, Germany

Abstract

A number of accelerator facilities are presently emerging for the medical treatment of tumor patients using proton and light ion-beams. Both, the development of relatively compact accelerators and extensive studies on ion-therapy carried out at various accelerator laboratories were prerequisites for the layout of dedicated medical accelerator facilities.

This paper focuses on the special demands for beam diagnostic devices during the commissioning and routine operation of a medical accelerator. The proton-therapy project PROSCAN at the Paul-Scherrer-Institute in Villigen/Switzerland exemplifies medical treatment in the frame of a research institute. As examples for dedicated ion-therapy projects the beam diagnostic layout is presented for the CNAO project (Centro Nazionale Adroterapia Oncologica) located in Pave/Italy and the HIT facility (Heidelberg Ion Therapy) in Heidelberg/ Germany. Beam diagnostic devices of HIT are illustrated and the underlying concept for the type and precision of the devices is explained. Additionally, measurement results of the HIT linac and synchrotron commissioning are presented.

MEDICAL ACCELERATOR FACILITIES

The basic physical concept of hadrontherapy is that charged hadrons deposit the maximum energy density at the very end of their range (Bragg peak). The penetration depth in matter, i.e. the position where the ion beam is applied, is determined by the kinetic energy of the particles. In order to penetrate 30 cm in the human body an ion energy of 250 MeV for protons is needed, and 430 MeV/u for carbon ions, respectively [1]. The reason for the use of carbon ions instead of protons is the increased energy deposition per unit track length (Linear Energy Transfer, LET) therefore resulting in increased radiation efficacy.The radio-biological motivation for hadron-therapy is that the ion energy is applied to destroy the DNA inside the tumor-cell nucleus. Single or double strand breaks of the DNA can be restored, but not for very high local doses producing clustered lesions [2]. Since 1997 the so-called rasterscan method has been successfully applied in the GSI pilot project [3]. By this method the tumor volume is painted with a pencil-ion beam using an active variation of the beam properties, i.e. energy, intensity and position. The beam energy is given by the synchrotron extraction energy. The beam intensity is monitored with ionization chambers, and the beam width is measured using fast multiwire proportional chambers, both placed in front of the patient.

Hospital based facilities for radiotherapy with carbon ions are up to now in operation only in Japan (HIMAC, HIBMC). Two European carbon facilities, CNAO in Pave (Italy) and HIT in Heidelberg (Germany) are presently under construction and are presented in more detail in the next paragraphs.

Protontherapy for deep-seated tumors is at the moment performed or in the planning phase at hospital based facilities in Switzerland, France, Italy, Germany, USA (5), Japan (2), China and Korea [5].

Whereas the PROSCAN project at the Paul-Scherrer-Institut represents a development of a medical treatment facility on the site of a research institute, HIT and CNAO are examples, where the know-how of a research institute has been successfully deployed to construct a medical accelerator facility as part of a hospital complex. From the European point of view the activities are now concentrated in the European Network for Light Ion Therapy (ENLIGHT++) [4].

GENERAL CONSIDERATIONS FOR BEAM DIAGNOSTICS

Beam diagnostics (BD) plays an important role especially in medical accelerator facilities, due to the fact, that in this case reliable beam production is a prerequisite for the availability of medical treatments. The layout of the beam diagnostics has to obey important characteristics, concerning the precision of the devices, their usability, as well as their operational availability.

The precision of the detectors has to fit the needs for troubleshooting and/or upgrades. In many cases an order of magnitude in precision resolves error states otherwise not detectable, like long-term drifts of power supplies, or 50Hz-noise on the beam transport system etc. Another important task that is more unique to beam production facilities is to put high priority on the usability of BD devices (e.g. the user interface has to be self-explanatory). Thirdly all specifications for the BD devices have to comply with every defined beam parameter and possibly beyond, in order to ensure their operational availability to the user.

Additional requirements, more related to the routine operation of the facility, are the reliability, maintainability, modularity and/or standardization of the BD components. Reliability of the devices is constituted by taking into account the error tolerance of the devices, redundant layouts (where possible) and intrinsically safe devices with interlock generation. In order to optimize the BD maintainability, e.g. offline test functions are important, as well as the availability of commercial parts on the hardware side. Additionally a modular hardware structure using standardized equipment allows for a fast substitution of erroneous components. In this context medical accelerator facilities have to be regarded as beam production machines with a well-defined parameter space in contrast to research institutes with a continuous upgrade situation.

THE PROSCAN PROJECT

The Paul-Scherrer Institute (PSI) in Villigen (Switzerland) is one of Europe's centres for proton-therapy research and has recently begun work with a new superconducting proton cyclotron COMET [5]. In 1984 the OPTIS proton therapy programme started in collaboration with the Lausanne University Eye clinic. PSI has experiences in the use of beam scanning techniques for the treatment of very large tumors. In 1996 Gantry 1 started, where the beam scanning technique has been adopted to perform radiation therapy with a scanned proton beam on a gantry [6]. Before the Proscan project Gantry 1 had used the proton beam from the large 590 MeV proton cyclotron for the treatment of deep-seated tumors with intensity modulated proton therapy (IMPT). In the past one of the main disadvantages has been that the cyclotron has shut down periods of about four months per year for service and upgrades. Therefore, in 2000 PSI decided to expand its radiotherapy activities into the PROSCAN project, a dedicated accelerator facility at PSI for proton therapy with a new Gantry 2 (cf. Figure 1).

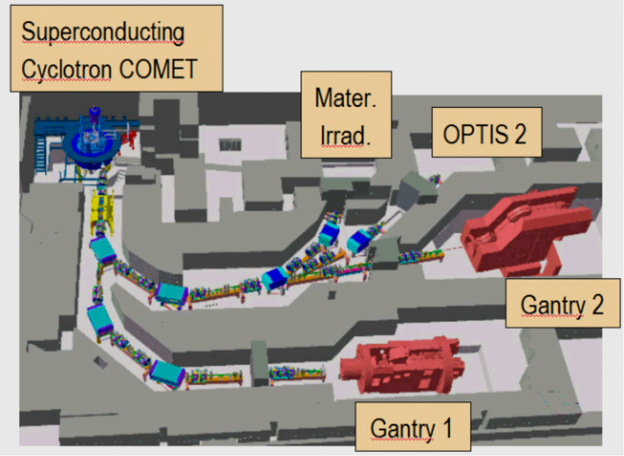

Figure 1 Beam line layout of PROSCAN (PSI)

The new cyclotron COMET was manufactured by ACCEL Instruments GmbH in close collaboration with PSI. Whereas Gantry 2 is still under construction, the superconducting cyclotron has been installed and the commissioning took place from 2005-2006. The first beam of the new cyclotron has been extracted in April 2005. The extraction efficiency has reached the design value of 80% in October 2005 and the first patient treatment using a proton beam from the new cyclotron took place in February 2007.

Proscan Beam Diagnostics

At the PROSCAN beam lines 37 "thick" (beam destructive) multi strip ionization chamber (MSIC) profile monitors can be inserted on demand for machine tuning purposes. In addition, 5 of 8 stoppers serve as Faraday cups. Continuous online measurements are provided by 6 „thin" current monitors (4 with added multi strip profile monitors), 4 beam position monitors, 22 halo monitors and 7 external loss monitors. Nearly all detectors are based on ionization chambers (IC) [7].

The "thick" MSICs consist of three successive metalized ceramic boards, divided by 4 mm wide air gaps. Whereas the outer boards provide the HV electrodes, the inner board has a thick-film coating of metalized strips in horizontal (front side, seen in beam direction) and vertical direction (other side). A high voltage of +0.6 kV is sufficient to suppress ion recombination to less than 10%. If a thick monitor is placed erroneously in the beam, the beam energy is degraded strongly and the beam is lost in the next dipole magnet.

The "thin" current monitors in front of the degrader and of the gantries are mounted fixed in the beam path as safety devices. Due to their small thickness excessive beam scattering is prevented. The devices in front of the degrader also include profile monitors (Figure 2). They consist of a stack of alternating high-voltage and measurement planes made from 6 μm titanium foils. The beam current is measured by a full foil, while two foils with 32 etched strips with 1mm pitch deliver the horizontal and vertical beam profiles. The IC monitor is immersed in nitrogen inside a box with 50 μm titanium entrance and exit windows. It is operated at a bias voltage of 2 kV in order to prevent recombination and to reduce the charge collection time.

In addition the same mechanical setup is placed directly in vacuum (without the detector box) and serves as a secondary emission monitor with a linear response even at the highest beam current densities.

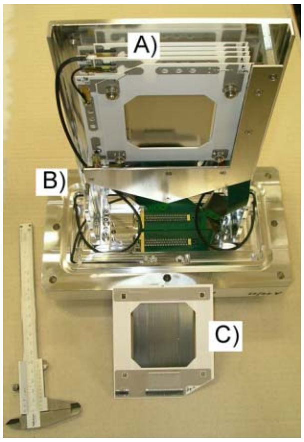

Figure 2 Thin current and profile monitor in front of the degrader A) stack of titanium foils for HV supply and measurements, B) flange and C) ceramic frame with multi-strip foil.

THE CNAO FACILITY

In 2001 the Italian Ministry of Health has created the CNAO Foundation (Centro Nazionale Adroterapia

Oncologica), consisting of five hospitals situated in Milan and Pave and the former TERA foundation [8]. Additionally the Italian National Institute of Nuclear Physics (INFN), the University and Polytechnic of Milan, and the University and Town of Pave now participate in CNAO. In 2002 the final design of the CNAO accelerator facility was settled [9].

The CNAO facillity will use light ion beams (proton, carbon) for tumor treatment and radiobiological research. The treatment will be performed in the end-stage of CNAO using 5 treatment rooms, 3 rooms with fixed beam and 2 rooms with gantries. In the first stage of CNAO 3 treatment rooms will be equipped with 3 horizontal and 1 vertical fixed beam setups (see Figure 3). The CNAO cancer therapy facility is presently under construction in Pave, 30 km south of Milan. The facility is located in close proximity to the San Matteo hospital, which offers a well-suited medical infrastructure for the new treamtent facility. The underground level of the building hosts the accelerator and the treatment rooms.

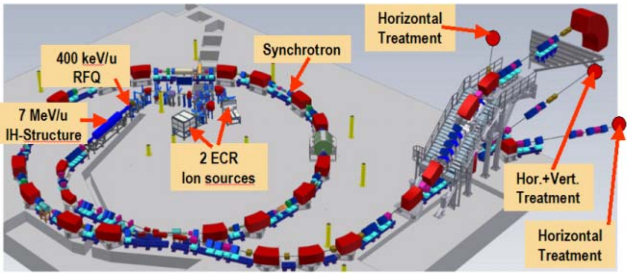

Figure 3 Layout of the CNAO facility

The accelerator part follows partly the concept of the Proton Ion Medical Machine Study (PIMMS) hosted at CERN [10]. In the frame of the collaboration with CNAO GSI is responsible for the layout, construction and delivery of the CNAO Linac. The Linac is composed of an RFQ and an IH-structure identical to the one designed for the HIT facility [11]. The RFQ accelerates particles from 8 keV/u to 400 keV/u and the IH further accelerates the ion beam 7 MeV/u. The CNAO synchrotron consists of two symmetric achromatic arcs connected by two dispersion free straights and has a circumference of approximately 78 m. The maximum energy of the ions is 400 MeV/u at a repition rate of 0.4 Hz. The synchrotron and high-energy part of the machine are engineered by CERN, INFN and LPSC/IN2P3. At present it is foreseen to begin the commissioning of the machine in fall 2007.

To facilitate the commissioning and integration of the Linac system into the CNAO facility an autonomous control system and all necessary BD devices were included into the GSI delivery. The GSI BD group manufactures, delivers and commissions diagnostic components for the Linac and MEBT (Medium Energy Beam Transfer) sections. For monitoring the beam profile at the entrance of the Linac and in the MEBT in total 7 profile grids will be installed. The ion current will be detected with 2 AC-transformers and 5 Faraday-Cups. Here GSI supplies the electronics for the Faraday-cups. In order to detect the beam energy using the time-of-flight method 4 phase probes are included in the delivery. A detailed description of the detectors is given in the next section since they are identical to the BD components produced for HIT. Also the foil stripper mounted on a stepping motor vacuum feed-through and a modular DAQ system is supplied in the frame of the GSI BD delivery.

Part of the BD equipment produced for CNAO was used in the test measurements at the RFQ-Testbench installed at GSI during October/November 2006.

HIT – HEIDELBERG ION THERAPY

Since 1997 more than 350 patients have been successfully treated in the GSI experimental cancer treatment program using the intensity controlled rasterscan method with carbon ions [3]. Based on the GSI pilot project it was decided to build a dedicated facility at the university hospital of Heidelberg for the treatment of about 1000 patients/year [12].

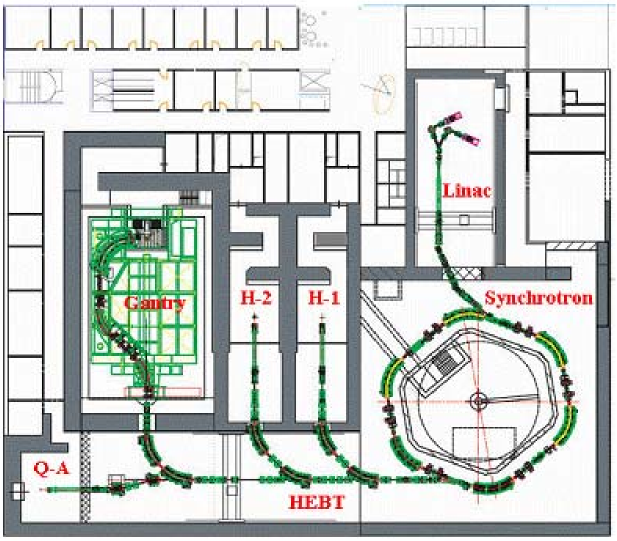

Figure 4 Layout of the HIT facility

All key parameters of the HIT facility are defined by the demands for radiotherapy. Two ECR ion sources allow for a relatively fast change of the ion species (p, He, C and O ions). Patient treatment is performed in 3 treatment areas, including the first heavy ion isocentric gantry.

The ion energy of 50-430 MeV/u is chosen such that the ion range in water is 20-300 mm. The synchrotron has an extraction time of 1-10s with 1E6 to 4E10 ions per spill and the beam diameter can be chosen from 4-10 mm FWHM. Figure 4 presents the layout of the first underground floor of the HIT facility housing the accelerator complex.

The two parallel ECR ion sources produce dc-beam currents of up to 1.2 mA for protons at 8 keV/u. The injector linac consists of an RFQ accelerating the ions to 400 keV/u in close connection to an IH-structure that accelerates the beam to the synchrotron injection energy of 7 MeV/u. A compact synchrotron with a circumference of 65 m further accelerates the ion beam. The beam is distributed to four target stations. Two stations have a fixed horizontal beam and the third treatment place is equipped with the isocentric gantry allowing 3D irradiations from all directions [13]. The gantry beam transport system (3 dipoles, 8 quadrupoles) has a weight of 140t and the total weight of the gantry adds up to 570t. The construction of the gantry structure and the integration of the components were performed by MT Aerospace. All treatment places are equipped with a magnetic scanner system for 3D volume conformal irradiations using the rasterscan method.

Commissioning of the HIT accelerator

In winter 2005/2006 the low energy beam transport system (LEBT) has been assembled in the new Linac hall and the commissioning of the ion sources started in April 2006. The LEBT, Linac and MEBT (medium energy beam transport) sections were mounted and commissioned successively in the period May-December 2006.

The commissioning of the LEBT and Linac sections was performed in three steps: 1) ion sources and LEBT, 2) 400 keV/u RFQ and 3) 7 MeV/u IH-structure. The measurements of all relevant beam parameters (beam intensity, profile, energy etc.) were performed using the HIT BD components [14, 15].

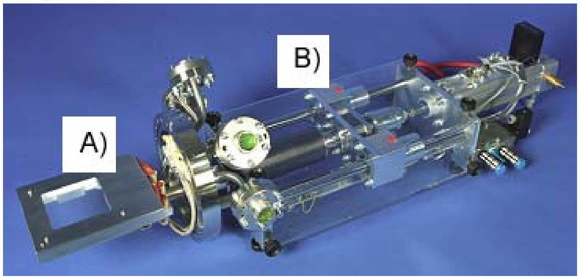

Figure 5 Profile grid (A) with pneumatic actuator (B)

During the commissioning of the LEBT section (May-June 2006) the dc beam of the two ion sources was measured using Faraday-cups and profile grids. The BD components in the two ion sources branches were especially designed to withstand the relatively high dc-beam power of up to 360 W at a very small penetration depth of approx. 100 nm. Water-cooled Faraday-cups were used for the detection of the beam current in the two source branches. The intersecting part of the device is made of a W/Cu sandwich structure with a circular shaped suppression electrode operated at 1 kV.

In each source branch a combination of horizontal slits and a Faraday-cup is installed at the exit of the spectrometer magnet for the acquisition of mass spectra. Profile grids were used for the alignment of the ion beam with the geometrical axis of the transport system and to tune the focussing elements. Figure 5 shows a standard profile grid with 64 wires per plane, both horizontal and vertical, and a spacing of the grid wires of 1.2 mm.

The main task of the Linac commissioning (Sept.-Dec. 2006) was to tune the RFQ to the design energy of 400 keV/u. For precise energy measurements a temporary setup at the RFQ exit was equipped with 3 phase probes for energy detection using the time-of-flight (TOF) method. The signals of the capacitive pickups are amplified by low-noise 60dB pre-amps and fed into fast 4 GSa/s digitizer boards for online display in the accelerator control system.

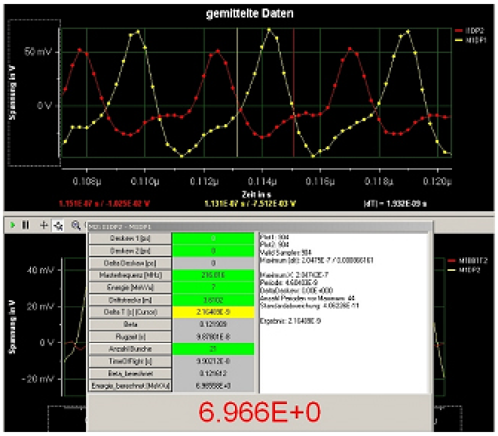

Figure 6 TOF-Energy measurement at the exit of the IH-DTL, top: signals of 2 successive phase probes, bottom: energy calculation using the cross-correlation of the phase probe signals (E=6.996 MeV/u)

Figure 6 shows an example measurement of two successive phase probes at the exit of the RFQ. The visible phase shift of the signals reflects the time-of-flight between the two probe positions. The graphical user interface allows displaying the beam energy online by calculating the cross-correlation of the two phase probe signals. To control the beam intensity in the linac section 3 AC-Transformers are installed and an online display of all 3 ACTs allows monitoring the beam transmission during routine operation of the Linac. By the end of 2006, the installation of the synchrotron and HEBT sections was finished and in February 2007 the first beam was injected into the HIT synchrotron. The synchrotron ring is equipped with two viewing screens, one screen is installed in period 1 (just before the re-entry into the injection septum) and a second viewing screen is installed in the extraction channel.

Figure 7 displays the image of the very first turn of a 7 MeV/u carbon ion beam in the HIT synchrotron.

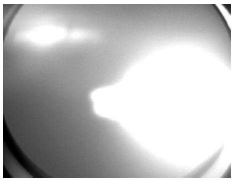

Figure 7 First circulating beam in the HIT synchrotron, detected with a viewing screen

The target of the viewing screens is coated with P43, a scintillating material optimized concerning low beam intensities and small optical decay times (1 ms), in order to preserve the time structure of the beam. To monitor the position of the circulating beam each of the 6 synchrotron periods is equipped with a shoe-box type beam position monitor (BPM). The pick-ups have been especially designed for the relatively low revolution frequency of 0.5-3 MHz of the HIT synchrotron. nd the plate signals are converted to position data using commercial log-ratio BPM electronics [16].

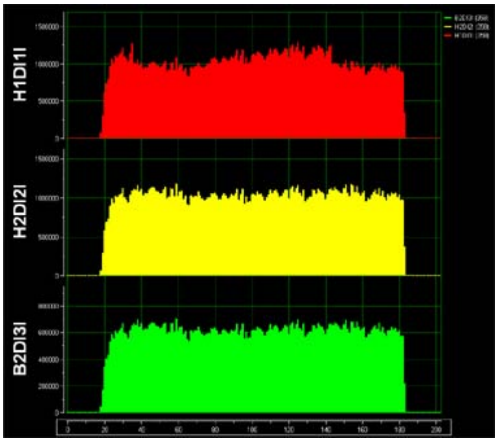

Figure 8 Spillstructure measured with 3 successive ionization chambers

As an example of HEBT diagnostics Figure 8 shows the signals of 3 successive ionization chambers for a 250 MeV/u carbon beam with an optimized flat spill structure The ionization chamber is part of a combined detector head consisting of a multi-wire proportional chamber (MWPC) on the front and the IC on the backside, both operated with Ar/CO_2 gas.

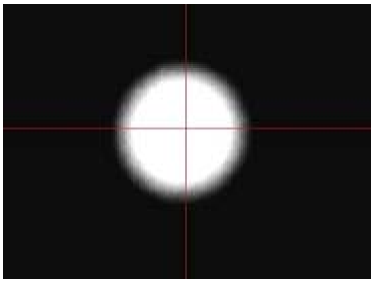

Figure 9 First beam at the Isocenter, measured with the isocenter-diagnostics device (beam diam.: 10 mm)

At the treatment places special viewing screens are used to verify the beam position and profile at the so-called iso-center, i.e. the point where the ion beam is applied to the patient. These isocenter-diagnostic devices consist of a 20x30mm viewing screen (P43), that is monitored using a double peltier-cooled high-resolution CCD camera [17]. The whole setup is mounted on air inside a metal housing to prevent the camera from outside stray light. The isocenter-diagnostics is fixed to the patient robot for the positioning of the scintillating screen.

In March 2007 the first beam was successfully transmitted to the target, represented by the isocenter diagnostics. Figure 9 shows the isocenter screen hit by a 430 MeV/u carbon ion beam.

SUMMARY AND OUTLOOK

It was shown, that hadrontherapy has developed from a research-center based niche medical application to a potentially standard technique. Three examples for medical treatment facilities have been presented, all in different project states. The PSI PROSCAN project has recently started patient treatment but is still located inside a research center. The CNAO facility is under construction and will serve as the major centre for hadrontherapy in Italy. Various examples of the HIT beam diagnostic measurements underlined the importance of BD during the commissioning phase. The facilities presented in this report open up the scenery for far more standardized hospital-based medical accelerators of the future.

ACKNOWLEDGEMENTS

I'm greatly indebted to my former colleague and present collaboration partner Andreas Peters, who has been responsible for the BD layout of HIT at the GSI therapy project, for his introduction to beam diagnostics and so many fruitful discussions. Rudolf Dölling is acknowledged for kindly providing information about the PROSCAN diagnostics. For the CNAO project I thank Sandro Rossi for the supplied data and Bernhard Schlitt and Andreas Reiter of the GSI-CNAO collaboration. Udo Weinrich and Dieter Wilms are thanked for the joint effort of the HIT commissioning team.

REFERENCES

[1] H. Stelzer, Nuclear Physics B Proc. Suppl. 61(3), 1998, 650.
[2] Y. Schweinfurth et al., GSI Scientific Report 2004, 2004, 274.
[3] G. Kraft et al. , Conf. Proc. EPAC1998, 1998, 212.
[4] http://ptcog.web.psi.ch/
[5] J.M. Schippers et al., Conf. Proc. Cyclotrons2004, 2004, 188.
[6] J.M. Schippers et al., Journal of Physics: Conference Series 41 (2006) 61.
[7] R. Dölling, this Conf. Proceedings.
[8] U. Amaldi and M. Silari, “The TERA Project and the Centre for Oncological Hadrontherapy”, Laboratori Nazionali dell'INFN, Frascati, 1995.
[9] S. Rossi, Conf. Proc. EPAC2006, 2006, 3631.
[10] L. Badano, S. Rossi et al., “Proton-Ion Medical Machine Study (PIMMS), Part I and II, CERN/PS 1999-010 DI and CERN/PS 2000-007 DR, Geneva.
[11] B. Schlitt et al., Conf. Proc. LINAC2006, 2006, 148.
[12] H.Eickhoff et al., Conf. Proc. EPAC2004, 2004, 290.
[13] U. Weinrich, Conf. Proc. EPAC2006, 2006, 963.
[14] A. Reiter et al., Conf. Proc. EPAC 2006, 2006, 1028.
[15] A. Peters and P. Forck, Conf. Proc. BIW 2000, 2000, 519.
[16] www.bergoz.com
[17] www.hamamatsu.com