NON-INTERFERING BEAM DIAGNOSTIC DEVELOPMENTS

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Abstract

New high power proton and heavy ion LINAC projects are a big challenge for beam diagnostic developments. Due to the high inherent beam power mostly all destructive measurement techniques are not applicable. Thus a lot of beam diagnostic developments are under way from enhancements of well-known systems like current transformers to new designs for profile or bunch length measurements using e.g. the interaction of the high power beams with the residual gas in the LINACs. The latest progress in this field will be reviewed with descriptions of some remarkable solutions.

INTRODUCTION

The development of new high power proton/ion LINACs is still going on. The aims of such new accelerators are highest beam pulse or D.C. currents and highest brilliances. The demands for new beam diagnostic devices are as follows:

- As much as possible the devices shall work non-interfering to measure even beams of highest power which destroy every material put into the beam line.
- The length of diagnostics mechanics in beam direction shall be as small as possible to have nearly 100 % space for accelerating and focusing elements, which is necessary because of the high space charge forces.

All these parameters together are very challenging, but those developing beam diagnostic equipment can profit from the following trends in the industry:

- A huge market of remote controllable devices has grown, which can be used as parts of diagnostic systems without modifications.
- Digital data treatment methods and devices like FPGAs and DSPs have become cheap and their capabilities are growing fast.
- A special industry segment, the vision systems, shows these trends exemplarily. Digital cameras with fast speeds and/or high resolution are capable to send their image data without any loss directly digital to the user [1].

This overview will report about some examples following the above mentioned tendencies – the focus is glanced at the latest developments in the field of transformers, optical profile measurement devices and a nonintersecting bunch length measuring techniques.

NEW TRANSFORMER APPLICATIONS

BNL Developments for SNS

An interesting example for the use of digital data treatment in connection with a well-known transformer technique was developed by M. Kesselman et al. for the SNS facility [2]. The time structures of the beams range from sub-µs bunches to 1 ms long macro-pulses.

Figure 1: SNS transformer for the DTL section.

To realize only one current measurement device which is capable to observe these different beams with a rise time of about 1 ns and a droop of 0.1 %/ms is normally not possible: an extremely large and expensive core of a (passive) transformer would meet the low droop but not the necessary rise time. In addition, the required space for such a device is not given in a linac. An active-passive transformer would have the same problems, only the size would shrink. To meet both requirements a digital compensation scheme was developed to use a commercial available Fast Current Transformer [3], see Fig. 1 and 2.

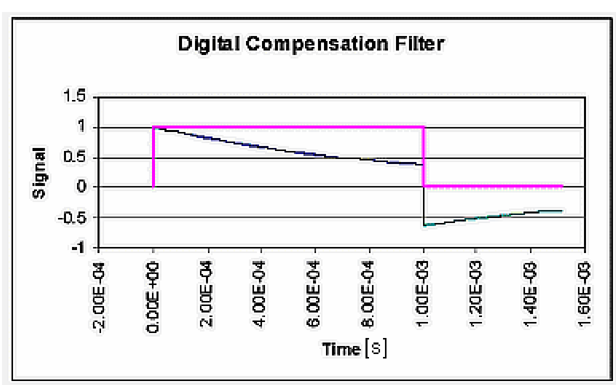

Figure 2: Compensation of an ideal exponentially decaying transformer output signal (blue drooping trace) with a 1ms time constant compensated by an IIR filter that introduces a 1s time constant instead of the 1ms time constant (squared-up magenta trace).

The reconstruction of the original current pulse is based on using an IIR (infinite impulse response) filter. The realization shows that the transformer time constant has to be known with high accuracy that could only be achieved by implementing an online calibration procedure [4]. The IIR filter can easily be realized in a field programmable

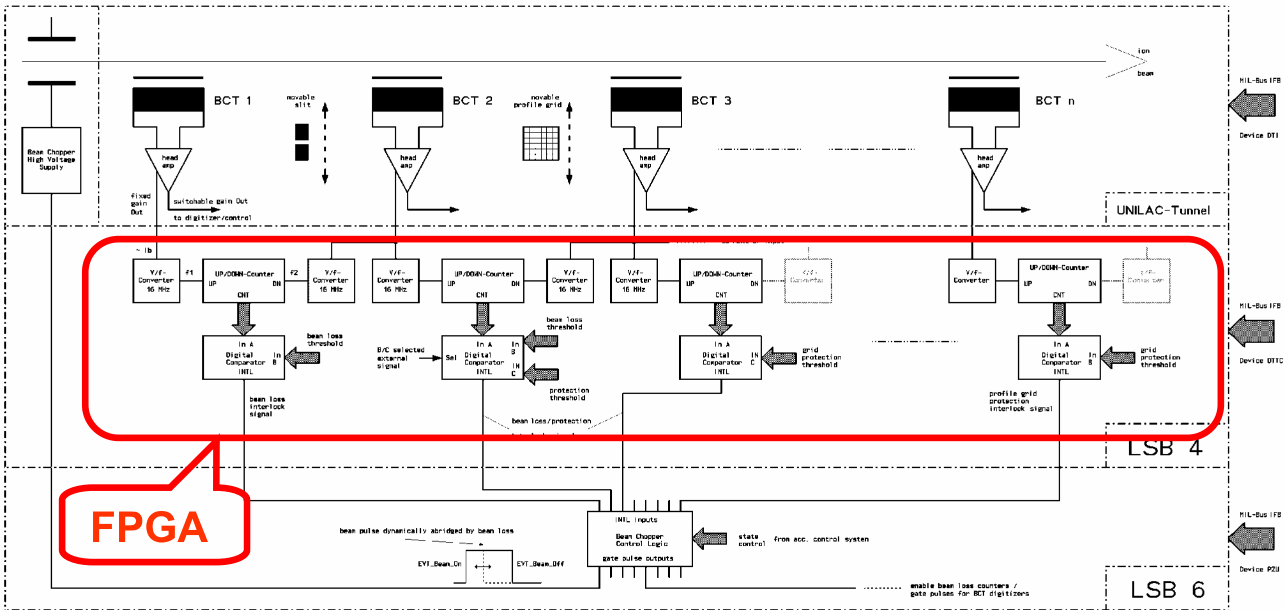

Figure 3: Scheme of the online transmission control electronics at GSI.

gate array (FPGA) or digital signal processor (DSP) and can run at real time if required. The present version is successfully running offline on a PC under LabVIEW.

GSI Transmission Control Electronics

A complex system was built up at GSI to protect the machine against destruction [5], see Fig 3. It consists of a couple of transformers along the LINAC and the transfer line to the following synchrotron each having a pre-amplifier directly attached and a high-dynamic voltage-to-frequency converter outside the tunnel, which is also used for the digitisation of the macro-pulse currents. The simple idea now is to use an up-down counter for each pair of consecutive transformers with a digital comparator which can handle several thresholds in parallel for multiple functions: transmission control (beam loss control), protection control for slits and SEM profile grids. The implementation of the electronics is done in FPGAs, working with a pulse repetition rate of 50 Hz. Protection and loss control are done online by actively chopping the beam on the low energy side. The digital approach has a very high dynamics and beam pulses from 10 µs to 8 ms can be handled without gain range switching. The reaction time of some µs is dominated by cable delays in the moment. Because the principles are simple and very reliable, no further machine destructions are observed after the installation.

TRANSVERSE PROFILE MEASUREMENTS USING BEAM INDUCED FLUORESCENCE

The profile of a proton or ion beam can be determined by observing the beam induced fluorescence (BIF) emitted by the residual gas molecules. In most cases N_2 dominates the residual gas composition. Due to the electronic stopping power the molecules are ionized. The fluorescence in the wavelength range 390 nm < λ < 470 nm is generated by a transition band to the N_2^+ electronic ground state, having a lifetime of about 60 ns [6]. The low amounts of photons have to be amplified using an image intensifier. This commercially available device consists of a photo cathode to transform the photons into electrons, which are than amplified by a spatial resolving MCP electron multiplier. It is followed by a phosphor screen to create again photons, which are finally monitored by a CCD camera.

Developments at LANL

During the 90ies first developments exploring the above mentioned technique were done at LANL by D. P. Sandoval, J.D. Gilpatrick et al [7,8]. Mostly commercial devices were used for the measurement set-up:

- CCD camera based on a Kodak DCS 420m chip
- DEP image intensifier, variable gain from 1 to 4000
- Lens system: Computar f/1.8, remote controlled
- N_2 gas injection system with Maxtek piezoelectric valve and a Balzers backpressure control system

Series of comparative measurements with a wire scanner (WS) were performed using the following beam conditions: a some MeV proton beam of 100 mA, 1 to 10 ms pulse length, 6 Hz repetition rate, 6-7 averages per picture, see an example in Fig. 4. The profile measurement data agree within < 10% with those of the wire scanner, while the BIF profiles show always a slight broadening, maybe caused by the movement of the ionized N_2^+-particles due to space charge effect in the lifetime (60 ns) of the excited state.

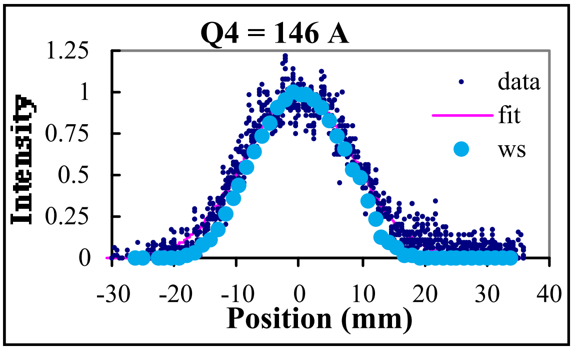

Figure 4: BIF example measurement at LANL in comparison with a measurement of a wire scanner (WS).

Investigations at Orsay

P. Ausset et al made intense investigations on the BIF method using a 95 keV, 100 mA proton beam in a low energy beam transport line between the ECR ion source and the following RFQ [9]. The measurement system was based on a set-up similar to LANL, but using an intensified 16 bit CCD camera instead. The measured profiles have the same geometrical shape for all gases (N_2, Ne, Ar, Kr, Xe in addition to the residual gas) at the same pressure, see Fig. 5 for a comparison.

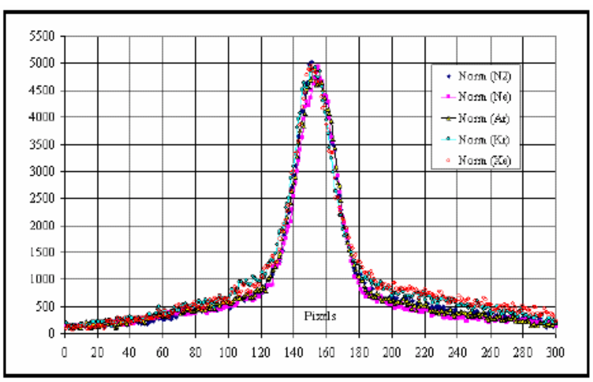

Figure 5: Normalised Profiles measured in the LEBT section of the IPHI project at Orsay.

BIF System Development at GSI

The GSI UNILAC is a pulsed heavy ion LINAC with a macro pulse length of about 100 µs to fill the proceeding synchrotron. The beam profile should be monitored within a single macro pulse. Therefore the use of a long integration time for an improved signal-to-noise ratio is impossible. Due to the low amount of emitted photons during the 100 µs integration time, a large amplification of 10^6 is required by using a double MCP inside the image intensifier [10]. The whole set-up is shown in Fig. 6. A raw image is displayed in Fig. 7 together with the transverse profile as yielded from the projection along the beam path [11]. Each of the light spots on the raw image is created by a single photon.

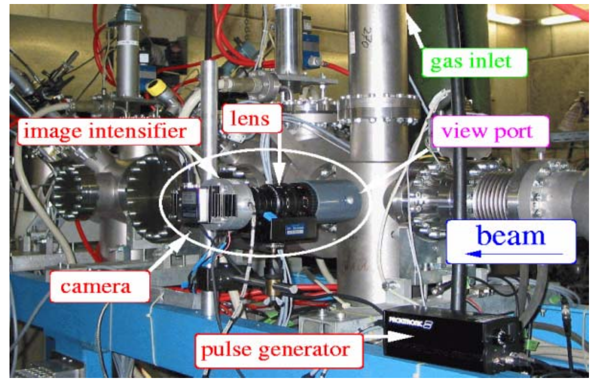

Figure 6: Measurement set-up in the experimental hall after the UNILAC at GSI.

Due to the statistical nature of the signal generation, the data quality can be enhanced by data binning of the individual projections or by summing up several images. The resolution of 300 µm/pixel is sufficient for the displayed parameters. A higher resolution can be reached by varying the distance between the beam pass and camera or by a proper choice of the optics, making this method very flexible. By using a regulated gas valve the pressure could be locally (within ~1 m) raised up to 10^{-4} mbar. No measurable influence on the ion beam delivered to the GSI synchrotron was detected. The correspondence of the measured profile to other methods is excellent.

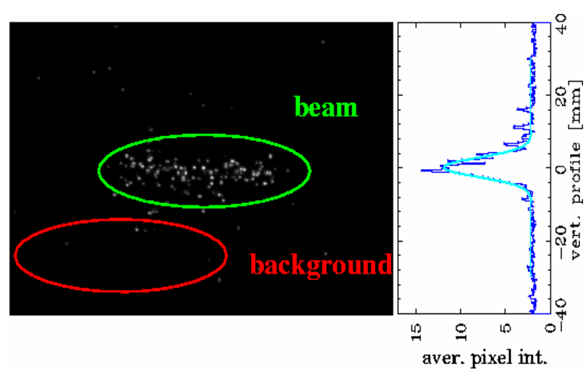

Figure 7: Image of a 200 µs U^{28+} beam with I=700 µA recorded during one UNILAC macro-pulse with a vacuum pressure of about 10^{-5}mbar. The two dimensional image from the intensifier (left) and the projection for the vertical beam profile (right) is shown.

An advanced application for the residual fluorescence measurement is the determination of a possible variation of the beam profile during the macro pulse, as shown in Fig. 8. The fast switching of the voltage between the photo cathode and the MCP within 100 ns can be used to restrict the exposure time. For the case of Fig. 8 one image of 40 µs exposure time is recorded and the measurement is repeated with 8 different trigger delays. This type of measurement is not possible with an intersecting SEM-grid due to the risk of wire melting by the large beam power.

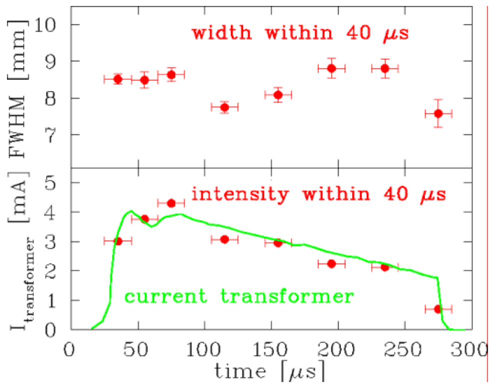

Figure 8: The measurement of the width variation during a macro pulse is shown. The lower graph shows the normalized image intensity together with the measured beam current.

At the GSI test set-up an 8 bit Basler 301f CCD camera with a maximum of 80 frames per second at 658 x 494 pixels was chosen. The CCD signals are directly digital-converted at the camera head and transferred using Firewire IEE1394a protocol [12]. Compared to an analog video link, no degradation of the signal due to long cables occurs. At the moment the Firewire bus standard allows a maximum data rate of 400 Mb/s which equals to 100 frames per second at VGA resolution. The variable bus architecture with up to 63 nodes is well suited for the distributed diagnostic installations in the various beam lines. The maximum cable length for electrical transmission is 20 m. For the long distances between the diagnostics and the control room fiber optic cables driven by opto-couplers are used.

The data are transferred to a Windows PC via a standard PCI interface. The analysing software is written in LabVIEW, serving as a modern software tool with embedded image processing macros. The Firewire driver from the commercial package IMAQ-Vision is used for data acquisition and analysis. It also allows controlling various camera functions like exposure time, electronic gain and triggering. With minor modifications, the same software can be installed on a recent available real-time platform with LabVIEW-RT as the basic operating system. The data acquisition and the first step of data analysis can than be treated locally. It is linked via standard Ethernet to a PC or workstation, where further analysis and archiving is performed.

LONGITUDINAL PROFILE MEASUREMENTS

The determination of the longitudinal density distribution of a bunched beam is an important issue because it is required for an optimal matching between different LINAC-modules as well as for the comparison with numerical calculations taking space charge effects into account. The bunch structure cannot be determined by capacitive pick-ups for non-relativistic beam velocities due to a faster propagation of the electric field. Thus, at most LINACs an intersecting method is used with the help of secondary electrons emitted from a wire crossing the beam [13,14]. The wire is biased with about -10 kV to pull the secondary electrons toward a slit outside the beam path. An rf-deflector follows, where the electrons are modulated in transverse direction by an electric rf-field. The deflection angle depends on their relative phases, i.e. the device transforms the time information into a spatial difference.

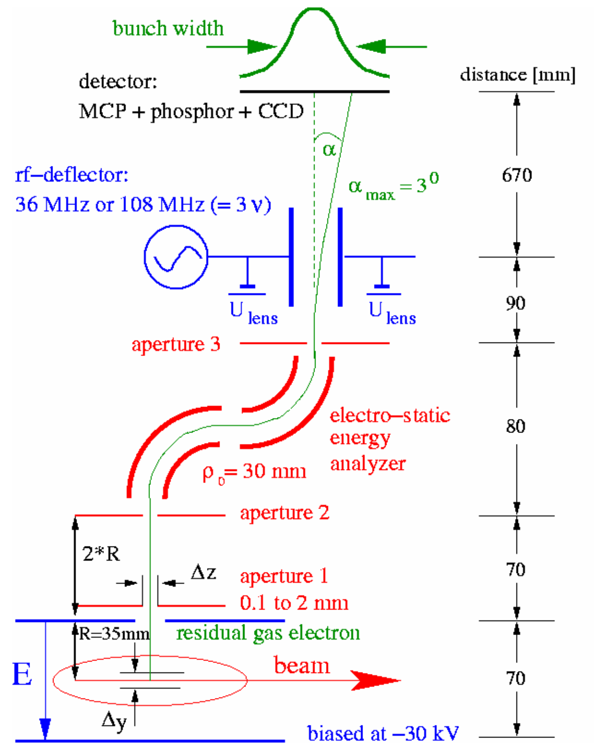

Figure 9: Schematic sketch of the GSI bunch shape monitor.

An adoption to a non-intersecting approach has recently tested at GSI [15]. Here the time spectroscopy of secondary electrons created by atomic collisions between the beam ions and the residual gas molecules is performed. In Fig. 9 the general principle is shown. The secondary electrons are accelerated by a homogeneous electrical field of 420 V/mm formed by 160 x 60 mm^2 electrodes outside of the beam pass, as usually used for residual gas profile monitors. To restrict the source region for the secondary electrons, an aperture system is used with remotely controlled opening. These apertures serve also as entrance and exit slits for an electro-static energy analyzer in a point-to-point focusing mode. In connection with the apertures, the source volume is only about 0.2 mm in ion beam direction and in the direction of the external E-field. This is comparable to the wire thickness in the standard wire application. The time-to-spatial transformation is performed with the same type rf-deflector as mentioned above [14]. We use either a device on the ground rf-frequency of 36 MHz or on the third harmonics of 108 MHz. The latter one offers a higher resolution, but the measurable bunch length is restricted to about a phase 20° of the ground rf, i.e. to about 1.5 ns.

The deflectors are built as λ/4 resonators and a power input of about 10 W is sufficient for the required transverse deflection. After a flight length of 670 mm the single electrons are amplified by a Chevron MCP-phosphor combination and monitored by a digital CCD camera.

Systematic test measurements with this new device were performed at 11.4 MeV/u for several ion beams. A typical raw image of the bunch as seen by the CCD camera is shown in Fig. 10. The deflection with a frequency of 108 MHz is displayed horizontally. The projection of the light intensity on this axis gives the bunch shape. This measurement proves the general functionality of this novel device, where short bunches of σ = 125 ps had been monitored. It is required to subtract a homogeneous distributed background. This is probably due to X-rays from secondary electrons accelerated by the electric field and hitting the stainless steel plate of the electric field box. A 5 mm thick steel shielding behind the energy analyzer will be installed in the near future to absorb these X-rays (maximum energy 30 keV), thus leading to a strong background reduction by a factor of at least 100. After this modification, a nearly background-free measurement is expected, which will allow single macro-pulse monitoring. The displayed measurement had been performed with a low current 60 μA Au^{25+} beam. If the amount of secondary electrons does not result in a sufficient statistics, the vacuum pressure can be raised by a regulated gas inlet system. It has been proved, that a local pressure bump up to 10^{-4} mbar in the transfer lines does not influence the beam properties. Due to the statistical nature, averaging also improves the signal-to-noise ratio leading to a large dynamic range.

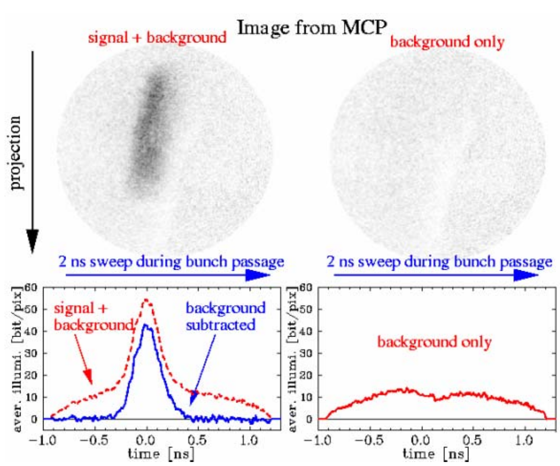

Figure 10: Typical image (inverted colour) from the MCP for a 60 μA Au^{25+} beam averaged over 16 macro-pulses with 1 ms. The background is displayed on the right.

The longitudinal emittance can be estimated by varying the voltage amplitude of a buncher cavity and measuring the bunch width. This corresponds to the quadruple variation for the transverse case. The orientation and absolute value of the emittance is yielded by fitting a parabola through the square of the bunch width. This is shown in Fig. 11. For a high current, 2 mA Ni^{14+} beam only 4 macro-pulses of 0.2 ms duration were averaged. Due to the nature of the fitting procedure, the error is relatively large, but it offers a simple method of emittance estimation.

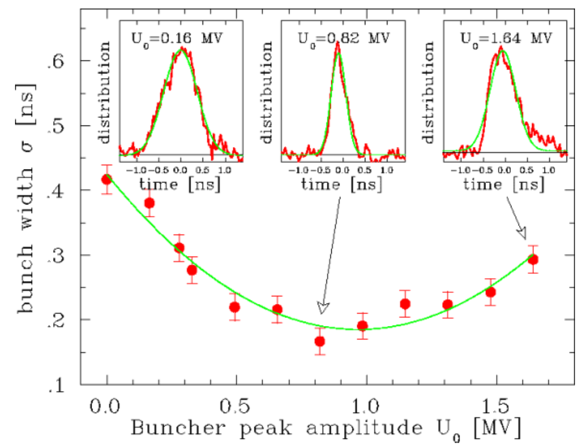

Figure 11: Measurement of the bunch width (one standard deviation) as a function of the buncher voltage 31 m upstream to the detector performed with a 2 mA Ni^{14+} beam.

The trajectories of the secondary electrons are influenced by the space charge of the high intensity beam. This influence is larger as for the wire based method, because in the latter case the electric field is much stronger close to the biased wire as compared to the homogeneous field of the non-interfering method. A numerical analysis is required to estimate the beam current and bunch length, where the electron trajectories are deformed significantly, resulting in a misleading signal reading. For the high current operation at the UNILAC, the influence is tolerable, as the calculations reported in [15] have shown.

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