REVIEW OF BEAM DIAGNOSTICS IN ION LINACS

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Abstract

High quality beam diagnostics have been found to be useful for rapid commissioning and good operation of ion linacs, especially for linacs containing many separate rf cavities. Our group, at the INR, has been working on the development and practical use of several beam diagnostic tools. As such, we have been engaged in beam measurements on operating ion linacs in close collaborations with several laboratories: CERN, DESY, Fermilab, GSI, KEK, SSC and TRIUMF. Experience with commissioning these new beam diagnostic devices, their use for beam measurements, and studies of the machine performance will be discussed. In particular, a description of the new tools for time-of-flight (TOF) and bunch shape measurements, and the results of beam studies using them will be reported.

The purpose of the paper is not to review all types of beam diagnostic devices to be used in ion linacs, but to familiarize the reader with several modern techniques for the measurement of ion beam parameters.

1 BUNCH SHAPE MONITORS

A device, allowing the measurement of the bunch shape (or phase spectrum) of the proton beam with high precision has been developed and built for the first time at INR [1]. The principle of operation (see fig. 1) is based on the analysis of secondary electrons produced by a primary beam hitting a 0.1 mm diameter tungsten wire (position 1 in fig. 1), to which a potential of -10 kV is applied. In a BSM the longitudinal distribution of charge of the analyzed beam is coherently transformed into a spatial distribution of low energy secondary electrons through transverse rf modulation. The temporal distribution of the secondary electrons follows the distribution of the beam being measured with a time delay <5 ps. The historical view of the BSM development is elsewhere [2].

A number of modified BSMs has been built recently with additional functional abilities. The Bunch Length and Velocity Detector (BLVD) provides a measurement of the average beam velocity as well as the bunch shape [3,4]. The traditional BSM can be modernized to measure longitudinal and transverse distributions of beam bunches including two component H^+ and H^- beams [5]. A further modification of the monitor is a 3D-BSM - a detector, which allows the measurement of the charge density distribution in a 3-dimensional space [6]. A fairly high level of mechanical design has been demonstrated during the development of BSM for the installation on the inter-tank space between the Alvarez tanks of the DESY 50 MeV Linac. The detector, called IT-BSM, fits onto the existing 2 ports on the cylindrical surface of the inter-tank space [7].

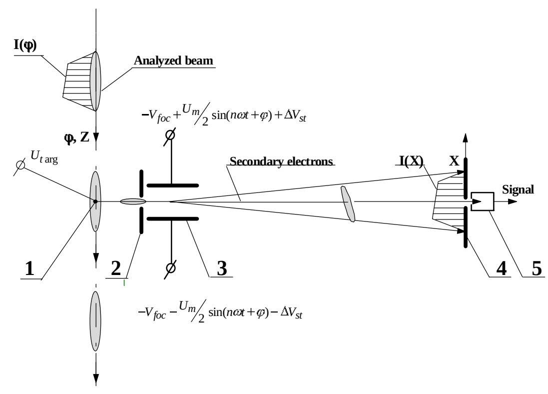

Figure 1: Principle of operation of the BSM. 1 – target, 2 – input collimator, 3 – rf deflector and electrostatic lens, 4 – output collimator, 5 – secondary electron multiplier (SEM).

BSMs have found applications in a number of accelerators [1-10]. Four BLVDs have been developed, designed and built at the INR for the meson factory linac (INR), CERN heavy ion linac [4], DESY H^- linac [7] and KEK H^- RFQ [9]. The 3D-BSM operates routinely in CERN proton linac [6]. IT-BSMs are installed at the DESY 50 MeV H^- linac. Similar IT-BSMs are being manufactured for the CERN proton linac.

1.1 Bunch Length and Velocity Detector

TOF methods have been used to measure the average velocity of beams with an rf bunch structure. Either two monitors installed a known distance apart [11] or a single movable one [12] can be used for this purpose. A BSM can be used as a movable detector [3]. When moving the BSM in a longitudinal direction one can observe a change in the bunch phase shape location by a value $\Delta\varphi_0=2\pi d/\beta\lambda$, where β is the relative velocity of the beam, λ is the wavelength of the deflector rf field and d is the distance of the monitor displacement. By measuring $\Delta\varphi_0$ and d one can find the beam velocity. For a high β it is expedient to use a higher harmonic for the deflecting field. The BLVD for the DESY Linac operates at the fourth harmonic f=810.24 MHz. For 50 MeV protons the value of the detector translation, $\beta\lambda/2$, is 60 mm. Fig. 2 shows the curves obtained during the energy measurement output of the 50 MeV DESY linac. The phase positions of the centers of the bunches measured before and after the detector translation are practically the same and the energy found experimentally $W_{exp}=50.04$ MeV is practically equal to $W_{design}=50.00$ MeV.

The BLVDs provide energy measurements with an accuracy of about 0.15%.

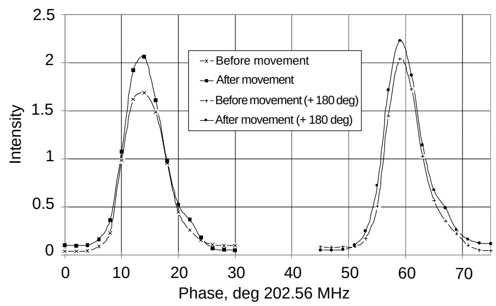

Figure 2: Bunch shapes during energy measurement.

1.2 Detectors to measure a three dimensional density distribution

In order to measure the 3-dimensional density distribution of a bunch, the following modifications of the BSM have been done: the target (pos. 1 in fig.1) is moved across the beam horizontally; the secondary electron beam is collimated by slit which is moved vertically and finally the electron beam is analyzed as in a standard BSM. Owing to the high strength of the electric field near the target, the electrons move practically horizontally and their vertical co-ordinates at the plane of the horizontal slit correspond to a short vertical section of the target wire determined by the position of the slit. Spatial distribution of the electrons after the passage through the rf deflector and drift space is measured with the 30 channel electron collector.

1.3 Phase resolution and sensitivity of BSM

The main parameter of the BSM is its phase resolution which depends upon a number of factors [1,2]. A resolution of 1° for frequencies up to 400 MHz can be achieved. The sensitivity of the BSM becomes important during the measurement of a low intensity beam or a longitudinal halo of a relatively high intensity beam. Normally electron multipliers are used in BSMs to detect secondary electrons. Typical values of the maximum gain of the multipliers for different types of the devices are ~10^5-10^8 and can be adjusted over three to four orders of magnitude by varying the HV. The multipliers can detect individual electrons so, as a matter of principle, by increasing the duration of the measurements it is possible to measure longitudinal parameters of extremely low intensity beams. Practically, the sensitivity is limited in any specific case. The minimum peak beam current we have made measurements by BSM was about 1 μA.

1.4 H^- beam measurements with a BSM

BSMs now operate with proton, H^- and lead ion beams. There are specific features of the BSM operation for each of these three types of ions. Particularly, for all type of ions there is a small fraction of high energy electrons (delta-electrons) but the number of such electrons compared to secondary ones is negligible and there is no real influence on operation of the bunch shape monitors. As for negative hydrogen ion beams, the electrons detached from the ions in a target can perturb the results of the measurements. An experimental study of the influence of detached electrons has been carried out during the commissioning of the DESY BSMs and KEK BLVD. In fig. 3 the bunch shape of the 30 MeV H^- beam is shown. The right bump in the figure is caused by the influence of the detached electrons. The secondary electrons can be separated from the detached electrons using a simple spectrometer located on the path of electrons to the electron beam detector [10].

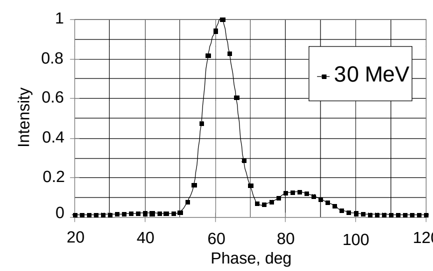

Figure 3: Bunch shape of 30 MeV H^- beam.

Further studies of the H^- beam have been made on the KEK 3 MeV RFQ with the help of a BLVD. In order to avoid the contribution of the detached electrons a 1 μm aluminum foil has been installed upstream of the BLVD wire target. The passage of the H^- beam through the foil produces a proton beam without any change of the longitudinal charge distribution. In order to measure the bunch shape in a wide dynamic range the measurements have been done with different gains of the SEM tube using the calibration curve. The longitudinal density distributions for H^- and proton beams are similar except for the halo region. Fig. 4 shows the particle fraction with respect to the phase extension for H^- and proton bunches. The proton beam contains much less particles in the halo, but still has a long tail. The

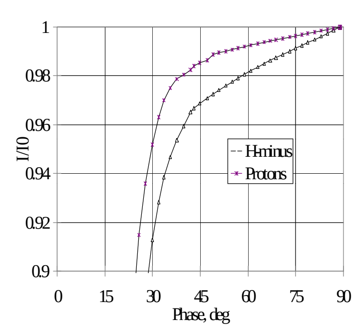

Figure 4: Particle fraction as a function of phase half-width for H– and proton

background for the proton beam is connected with a systematic error due to the electron beam interaction with the edge of collimator (pos. 2 in fig. 1) [9].

2 TRANSVERSE PARTICLE DENSITY MEASUREMENT

The use of high intensity beams for the irradiation of targets near the melting temperature requires control of the transverse beam density. The measurement of the profiles is not enough. As was mentioned the 3D-BSM could measure the density in three-dimensional space and the particle distribution on the transverse cross-section can be obtained by the integration along the longitudinal coordinate. However, the 3D-BSM has relatively small transverse aperture ~10x10 mm^2. For the measurement of the transverse particle density distribution a detector has been developed [13]. The electrons are produced due to the interaction of primary beam with the thin wire which is under negative potential. The electrons move on orbit in uniform magnetic field applied perpendicularly to the beam pipe axis. The secondary electrons are focused by electrostatic lenses in the vertical plane and by the magnetic field in the horizontal plane. The electron density distribution in the horizontal direction is transformed without distortion to the collector which is the multi-channel plate and located outside of beam pipe. The density distribution in the vertical direction is obtained with the help of wire movement along the vertical coordinate. The detector is installed in the 750 keV injection line of the MMF linac and an example of a beam density distribution is shown in fig. 5.

Another type of the particle transverse density measuring device is a residual gas monitor which is used on many accelerators. In Atomic Energy Institute, Moscow, this type of monitor has been modernized by adding an electrostatic analyzer which gives the possibility to observe on-line the density distribution of the particles [14]. The ions created in the residual gas are accelerated by the applied electric field and are collected by the multi-channel plate. The electrons at the exit of the multi-channel plate produce an image on the phosphor. After extraction from the beam pipe the trajectory of the residual ions is governed by the 45° electrostatic bend. Therefore the image on the phosphor directly corresponds to the density distribution of the primary beam. The use of ions, not electrons, allows one to deal with the signals with very low noise. The image from the phosphor is viewed by a CCD camera and is digitized. The residual ion beam current is directly proportional to the stopping power $d\varepsilon/dx$. The minimum collector current density which can be measured with good signal/noise ratio is ~10^{-16} A/mm^2. For example, for a 600 MeV proton beam with cross-section ~25 mm^2 the minimum peak current which can be observed by a residual gas detector at vacuum pressure of 10^{-6} torr is ~0.7 μA.

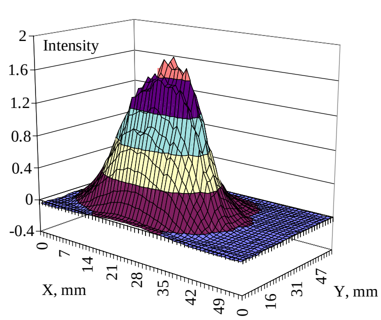

Figure 5: Transverse density distribution on 750 keV injection line of the MMF linac.

This type of monitor can be applied for all type of ions in wide energy range from several keV/n to hundreds of MeV/n. The range of beam current being studied is from nanoamps to hundreds of milliamps. The spatial resolution, whether one uses electrons or the ions, is limited, as space charge perturbs the trajectory of the collecting particles. This can be greatly improved upon applying high extraction voltages and a focusing magnetic field in the same direction.

3 WIRE-SCANNERS, HARPS

The wire scanners and harps are applied in all type of linacs. The use of wire-scanners is preferable for many reasons, but the harps are best for quick measurements in one beam shot. The spatial resolution of wire-scanners can reach a micrometer and with fast electronics, bunches can be observed individually. Their great sensitivity followed by the multi-gain amplifier allows the study of halos [15].

Carbon or SiC wires with a diameter > 0.002" are mostly used for high intensity beam diagnostics up to 1 mA average current for a 800 MeV beam. The wire scanners and harps must satisfy the following main specifications: 1) Multiple scattering of the primary must be small; 2) High vacuum; 3) Must not be destroyed by thermal expansion; 4) Must not melt; 5) Must be strong enough to withstand shock waves due to sudden vacuum failures; 6) Cooling is by radiation – the emissivity should be high; 7) The thermionic emission must be a small fraction of the secondary emission current. There are additional features in the design of scanners and harps for heavy ion [16].

4 TIME-OF-FLIGHT MEASUREMENTS

In a multi-cavity rf linac the measurements of relative as well as absolute energy is required. For this purpose TOF measurements are widely used [11]. The beam energy is calculated through the beam velocity. The TOF device includes a phase monitor and signal processing circuit. As a phase monitor coupling loop, capacitative pickup [16], wall current monitor [17], directional coupler [18] and rf resonators [19-21] have been used. The latter provides most sensitive measurements, a phase monitor capable to measure 1nA beam current has been reported [20,21].

In rf linacs the TOF is calculated through the measurements of phase difference. For relative measurements it is enough to observe the phase difference between the induced signals. However to obtain the absolute beam energy the calibration is required. For calibration purposes two detectors must be excited by an external rf in phase. The relative velocity of bunched beam is calculated as $\beta = \frac{L}{\lambda}\frac{1}{n + \Delta\varphi / 2\pi}$, where L is the distance between the monitors, $\Delta\varphi$ is the phase difference of the induced signals with wavelength λ, n is determined as a integer of $L/\beta_0\lambda$. The latter means that the beam velocity β_0 must be known roughly. The rough value of the absolute velocity β_0 can be found, for example, using one more phase probe [16] located closer to the other in order to have $n=0$. If a chopper exists in the linac one can produce single bunch mode for the measurement goals [17].

The precision of the velocity measurements is found as $\frac{\delta\beta}{\beta} = \frac{\delta L}{L} + \frac{\delta(\Delta\varphi)}{2\pi n + \Delta\varphi}$. By the selection of long enough distance the first term can be made negligibly small. An accuracy of phase measurement depends on processing circuit. Careful design of phase detectors can provide a precision of ~1° at a frequency of ~1 GHz. TOF measurements can be applied for beams with kinetic energy close to the rest energy of the particle. Relative energy measurements can be performed with resolution as low as $6\cdot10^{-5}$ [21], for absolute measurements the precision is $\sim10^{-3}$.

5 EMITTANCE MEASUREMENT

Conventional slit-collector measurements give detailed information about the emittance which may be neither elliptical nor symmetrical. They may be extended up to perhaps 200 MeV before multiple scattering in the slit ruins the profile resolution. Several methods have been reported in which the emittance is assumed to be elliptical (see references in [16]). For low energy beams <10 MeV/n the conventional method of the emittance measurement has been modified by using a phosphor screen instead of the particle collector. The beam image after the slit or pepper-pot is directly digitized by a CCD camera connected to a personal computer. This technique produces emittance during single shot and is successfully used for proton [22] or heavy ion beams [23,24].

New opportunities are being discovered for H^- beam diagnostics because of the simplicity of H^- beam neutralization by the laser beam [25]. H^0 transverse emittances are measured downstream of an H^- beam bending. To measure the longitudinal emittance the detached electron beam is analyzed.

5.1 Emittance measurement of 50 MeV H^- Beam

As an example, we describe a technique to measure the emittance in all 3 planes at the output of the DESY 50 MeV H^- linac. At the output of the linac the ellipse in the longitudinal phase space is assumed as a canonical shape. Then the longitudinal emittance is determined as a multiplication of the momentum spread and phase width. The longitudinal phase distribution has been measured with the help of a BLVD located close to the exit of the last tank. The momentum spread is measured by magnet spectrometer which operates on-line owing to a target converting H^- to protons. Owing to a narrow target (28 μm wire) and unit transformation of the transverse emittance from the target to the "momentum" harp location, the effect of the transverse emittance on the momentum measurement resolution is negligible. The horizontal profile determined by the harp well corresponds to the beam momentum distribution with a conversion ratio $\Delta p/p$ = 0.0526·x, where $\Delta p/p$ is in [%] and x is in [mm]. The spatial resolution of the "momentum" harp has been improved by sweeping the beam center at the harp position by the setting of several values of the bending magnetic field. Energy spread and phase spectrum measured at the signal level of 98% result in an emittance value of 2104 π·keV·deg, which is 5.05 times larger than the rms value.

For fast measurement of the transverse emittance on there is a procedure of the emittance restoration based on three profiles measured by the harps [26]. To improve the spatial resolution of the harps we have measured the beam profiles by sweeping the beam position on the harps. To produce a beam center deviation the steering magnets located upstream of the harps have been calibrated. The rms value of the density distribution has been calculated from 20-30 measurements on each harp. Emittance calculation has been done by using the least squares method. Table 1 shows rms emittance in all 3 planes.

5.2 Emittance measurement of 50 MeV Proton Beam

The proton Linac at CERN serves as an injector to the booster and operates with a peak current up to 170 mA in routine operation. For the emittance measurement during one shot in all 3 planes special equipment has been developed [27]. The transverse emittances are measured by the help of two kicker magnets for the sweeping of the beam position on the slit. Downstream of the slit a quadrupole doublet allows the adjustment of the resolution on the collector. Longitudinal measurement equipment contains two 54.3° bending magnets to provide the spectrometer function, rf cavity located downstream of the first spectrometer and slit. The rf cavity tuned to the linac frequency works as a rotating lens in the longitudinal phase space transforming the phase dispersion into an energy dispersion which is analyzed by the second spectrometer magnet. After the installation of the 3D-BSM 90 cm behind the last Alvarez tank, the measurements of both transverse and longitudinal rms emittances became available. The measurement of the transverse rms emittance with the help of the 3D-BSM is performed by several (more than 3) settings of the quadrupole gradients and taking measurements for the calculation of rms radius. In table 2 the rms emittance data for a 170 mA proton beam is listed. The measurements performed by direct measurement of the emittance area in the phase space and by the help of 3D-BSM are consistent. The longitudinal rms emittance is determined as a multiplication of rms phase width by the rms energy spread from the spectrometer measurement.

Table 1: 50 MeV Beam Emittance

Lab	DESY	CERN,
H, normalized, π·mm·mrad	2.1	4.5
V, normalized, π·mm·mrad	1.8	4.1
L, π·deg·keV	417	780

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7 REFERENCES

[1] A.V. Feschenko and P.N. Ostroumov. Bunch Shape Monitor and Its Application for an Ion Linac Tuning. Proc. of the 1986 Linac Conf., Stanford, June 2-6, pp. 323.

[2] A.V. Feschenko. Bunch Shape Monitors Using Low Energy Secondary Electron Emission. AIP Conf. Proc. 281, Proc. of the BIW, Berkeley, 1992, p.185.

[3] P.N. Ostroumov. Average Velocity Measurement of Accelerated Beam by Means of an Upgraded Bunch Length Detector. INR Preprint-812/93, May 1993.

[4] Yu.V. Bylinsky et al. Bunch Length and Velocity Detector and Its Application in the CERN Heavy Ion Linac. Proc. of the EPAC-94, London, 1994, p. 1702.

[5] A.V. Feschenko et al. A Detector to Measure Longitudinal and Transverse Distribution of a Two Component Ion Beam. Proceedings of the EPAC 92, Berlin, 1992, p.1073.

[6] A.V. Feschenko et al. A Three Dimensional Bunch Shape Monitor for the CERN Proton LINAC, Proc. of the 1996 Linac Conf., Geneva, 1996, p. 193.

[7] V.V. Feschenko at al. Bunch Shape Monitors For The DESY H^- Linac, Proceedings of PAC97, Vancouver, Canada, 1997. To be published.

[8] E.S. McCrory et al. Use of an INR-Style Bunch Length Detector in the Fermilab Linac. Proc. of the Linac-92, Ottawa, 1992, p. 662.

[9] A.V. Feschenko et al. Bunch Length and Velocity Measurement of the JHP-RFQ Beam with INR BLVD. This Proceedings.

[10] J.M. Hurd et al. Bunch Shape Monitor for SSCL Linac. Proc. of the 1993 PAC, Washington, 1993, p. 2426.

[11] Linear Ion Accelerators. Ed. by B.P. Murin, V.2, Atomizdat, 1978 (in Russian).

[12] A.V. Feschenko et al. Precise Energy Measurement of the Continuous Proton Beam. Proc. of the 1989 IEEE Particle Acc. Conf., Chicago, 1989, p. 1409.

[13] A.M. Tron and Vasilev. Secondary Electron Monitor of Beam's Two-Dimwnsional Transverse Current Density Distribution. EPAC-92, p.1124.

[14] V.G. Mikhailov et al. Muli-parameter Ionization Detectors for Measurement of Accelerated Particle Beams. PTE, 1995, No 6., p. 39.

[15] O.R. Sander et al. Recent Improvement in Beam Diagnostic Instrumentation. IEEE Trans., Vol. NS-26, No. 3, June 1979, p. 3417.

[16] P. Strehl. Ion Beam Diagnsotics. In "Handbook of Ion Sources", CRC Press, 1995, p. 385.

[17] M.B. Popovic et al. Time-of-Flight Measurements of Absolute Beam Energy in the Fermilab Linac", Proc. of the 1993 PAC, p.1689.

[18] J.D. Gilpatrick et al. Noninterceptive Beam Energy Measurements in Line D of the Los Alamos Meson Physics Facility. ibid, p. 485.

[19] A.V. Feschenko and P.N. Ostroumov. Velocity Measurement by Means of Mechanical Movement of a Detector. AIP Conf. Proc. 333. Proc. of the 1994 BIW, Vancouver, p. 478.

[20] J.M. Bogaty and B.E. Clifft. A Low-Cost Non-Intercepting Beam Current and Phase Monitor for Heavy Ions. Proc. of the 1995 PAC, p. 2625.

[21] P.N. Ostroumov et al. A very Sensitive Non-Intercepting Beam Average Velocity Monitoring System for the TRIUMF 300-keV Injection Line. AIP Conf. Proc. 390. Proceedings of the BIW, Argon, Illinois, p. 557.

[22] T. Shirai et al. One Year Operation of the 7 MeV Proton Linac. Proc. Of the 1993 PAC. p. 1697.

[23] M. Bourgeois et al. High Charge State Ion Beam Production from Laser Ion Source. Proc. of the 1996 Linac Conf., Geneva, 1996, p. 378.

[24] M. Domke et al. A Single Shot Emittance Measuring System for Intense Heavy Ion Beams. Proc. of 3rd European Workshop on Beam Diagnsotics and Instr. for Part. Accel. (DIPAC97). Frascati, Italy, 1997.

[25] W.B. Cottingame et al. Proc. of PAC85, IEEE Trans. Nucl. Scin. NS-32 (5) (1985), p. 1871.

[26] L. Criegee. Emittance measurement for Linac III. PLIN - Note 88-04, 1988.

[27] P. Tetu. New Linac Three Phase Planes Pulsed Emittance Measuremnt. Proc. of the 1979 Linac Conf., p.309.