THE BEAM DIAGNOSTIC SYSTEM FOR THE TRANSFER BEAMLINE AT THE NAC

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Summary

The beam diagnostic system for the transfer beamline between the injector cyclotron with a k-value of 8 and the separated-sector cyclotron (k = 200) has reached the stage where all the mechanical and electronic systems have been acquired and are presently being installed. The lay-out of the beam diagnostic system, the specific requirements and design parameters of the various mechanical and electrical components as well as their application to the measurement of particular beam properties are discussed.

1. Introduction

The low-energy transfer beamline between the solid-pole injector cyclotron SPC1 and the separated-sector cyclotron (SSC) has to transport all the light-ion beams delivered by SPC1 with variable energy (10:1 energy range) and intensity. Provision has also been made in the design of the beam diagnostic components to accommodate the requirements of the heavy-ion beams from a second injector cyclotron (SPC2). Minimum beam intensities of a few nA are envisaged for some heavy ions. The most stringent energy and beam power requirements are for a maximum proton energy of 8 MeV at 10 µA and for 4 MeV protons (being accelerated by the SSC to 100 MeV) up to 100 µA, needed for isotope production. The maximum specified beam power is thus limited to 400 W, which implies that with the use of a material such as tantalum for the interception of the beam, no water-cooling is necessary for any of these components for the expected beam sizes.

Apart from transporting the beam from the injector cyclotron to the SSC, the transfer beamline also has the important function of matching the six-dimensional phase space of the beam delivered by SPC1 to the acceptance of the SSC. The beam diagnostic system will thus, apart from its normal functions of recording and monitoring all the beam properties and diagnosing any problems which may occur with the beam, also play an indispensable role in setting up and tuning the beamline in the shortest possible time. Rapid energy and particle changes are of particular importance at the NAC for the efficient operation of this multi-disciplinary accelerator facility. In order to accomplish this a well-equipped beam diagnostic system is essential.

2. Layout

The layout of the beam diagnostic system for the transfer beamline between SPC1 and SSC is illustrated in figure 1. Most of the diagnostic equipment is mounted onto two standard types of diagnostic chambers (except for two special types due to local requirements in the beamline). The diagnostic components can thus easily be mounted either directly onto the chamber flanges for fixed installation or they can be mounted onto standard drives such as compressed-air actuators for in-out movement or onto precision high-vacuum feedthroughs with stepping-motors for accurate positioning. This system

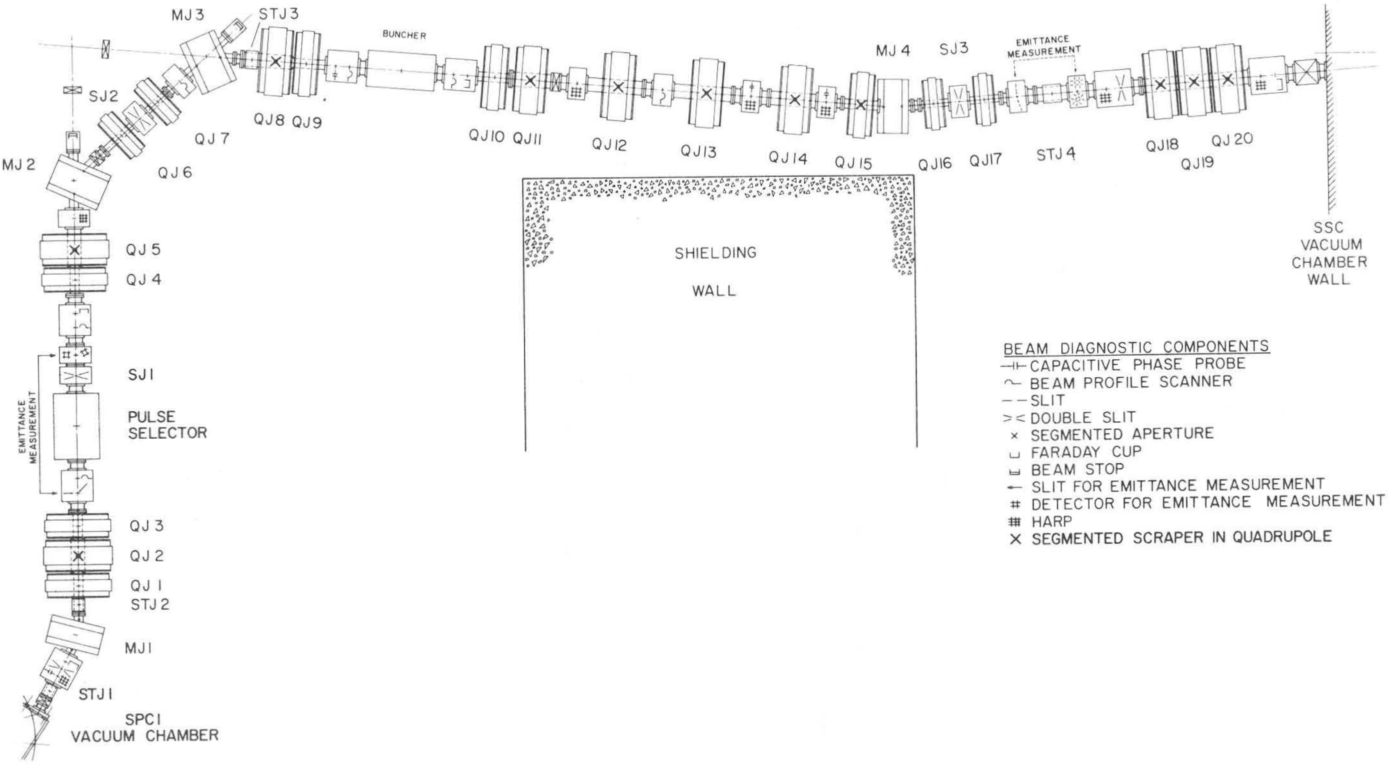

Fig. 1: The layout of the beam diagnostic system for the low-energy transfer beamline between SPC1 and SSC.

has the advantage that:

(i) it is very modular with inherent flexibility;
(ii) the diagnostic equipment can be mounted and demounted without having to be concerned with the alignment;
(iii) it is very compact because each component does not require its own vacuum enclosure; and
(iv) ports for vacuum pumps and vacuum equipment are provided on the chambers.

The different functions of the various sections of the beamline as well as the optical beam properties and the physical constraints were taken into consideration when the layout was made. A dominant characteristic of this beamline is the large beam size (up to 100 mm diameter), which requires large diagnostic equipment and mounting flanges.

The following diagnostic components are mounted onto a special chamber immediately after SPC1:

(i) a capacitive phase probe for beam energy measurement with the time-of-flight method as well as for phase measurement of the extracted beam with respect to the RF system;
(ii) a harp for beam profile and position measurement;
(iii) a double slit to collimate the beam and for momentum selection; and
(iv) a Faraday cup to measure the total beam current and to intercept the beam while optimising the cyclotron performance.

An emittance-measurement system is installed after the first quadrupole triplet. At the double waist, a double slit SJ1 is inserted. Two beam profile scanners on either side of this slit system will aid in focusing the beam to a waist at SJ1. A Faraday cup in front of QJ4 will intercept the beam while these measurements and set-up procedures are made.

In the achromat (QJ4 to QJ9):

(i) a harp in front of MJ2 and a beam profile scanner in front of MJ3 will monitor the beam profile at these locations as well as the beam alignment in the preceding straight sections;
(ii) a double slit at the waist between QJ6 and QJ7 will collimate the beam and can also be used to cut out off-momentum particles; and
(iii) the two beam-stops behind MJ2 and MJ3 can be used as beam dumps while setting up sections of the beamline.

The buncher phase can be optimised with a capacitive phase probe in front of the buncher. A beam waist will be formed at the buncher centre with the aid of beam profile scanners on either side of the buncher. A Faraday cup will intercept the beam during optimisation of the achromat and the buncher phase.

After the buncher the achromatic beam is shaped with the quadrupoles QJ10 to QJ15 (with independent x and y adjustment) for beam injection independent of the dispersion matching introduced by MJ4. Beam profile scanners and harps are located where possible between these quadrupoles to monitor the large beam envelope fluctuations. The beam energy will be measured with the first capacitive phase probe immediately after SPC1 and the two capacitive phase probes in front of QJ14 and QJ15.[1] Bunch length information can also be extracted with these capacitive phase probes and the capacitive phase probe in the central region of the SSC;[2] the effect of the buncher can thus be optimised.

A double slit is also located at the double waist between the doublet QJ16 and QJ17 to limit the beam to the desired dimensions. Provision is made for the installation of an emittance-measurement system in the drift length between QJ17 and QJ18. For financial reasons no second emittance-measurement system was acquired; however the set of emittance slits and detectors mentioned earlier can also be mounted here and linked to the same electronics. In front of QJ18 a harp is located to monitor the large beam diameters (up to 100 mm) while a slit system will collimate this beam if necessary.

Before the beam enters the valley vacuum chamber the beam profile and alignment will be measured with a harp, while a Faraday cup can intercept the beam during optimisation of the entire beamline optics. It can also be used to measure the total beam current to determine the efficiency of the injection beamline and the transmission through the SSC.

Segmented scrapers are installed inside the vacuum pipe at various quadrupole positions, where the beam reaches its maximum dimensions, to detect unacceptably large beam sizes. Beam-loss monitors will be installed along the beamline at a later stage to set alarms when unacceptable levels are detected.

The beamline vacuum is divided into three sections and except for the first Faraday cup the remaining three Faraday cups have been placed as close as possible in front of the vacuum valves to enable the beamline to be operated in modular sections.

Beam profile scanners as well as harps will measure the beam profile in this beamline. The criterion is that harps will be installed at large beam diameters (i.e. ≥30 mm) whereas beam profile scanners will monitor the smaller beam sizes. Scanners are preferred because of their power-handling capability.

3. The Beam Diagnostic Components

3.1 Beam Diagnostic Chambers

The diagnostic chambers are fitted with CF 150 flanges for mounting beam diagnostic equipment. Special attention was given to keeping the chambers as short as possible; for this reason the CF 150 entrance and exit flanges are not stub-mounted. Each chamber is provided with alignment pads onto which alignment equipment can be mounted to adjust the chamber accurately. Allowance has been made for rotation of the standard types of chamber in steps of 45° to allow each to be mounted with the desired flange orientation, using rotatable flanges on the beam pipes. CF 35 flanges are provided for vacuum test equipment and current feedthroughs if required. The vacuum pumping system is also mounted on the CF 150 ports.

3.2 Pneumatic Actuators

These actuators are for "in-out" movement of diagnostic components like harps, Faraday cups and capacitive phase probes. The latter probe requires an actuator which differs from that of the others because of the complex coaxial high-vacuum feedthrough. However, the harps and Faraday cups are mounted on a standard adapter at the end of a shaft, which is driven by a compressed-air cylinder with a stroke of 120 mm.

3.3 Harps

The harp is used for the measurement of the intensity distribution of beams in the two transverse directions. It can be reproducibly mounted onto the shaft of a pneumatic actuator. The harp consists of two

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arrays (perpendicular to each other) of 47 spring-tensioned 0.1 mm diameter tungsten-rhenium wires mounted on an insulating frame. An odd number of wires ensures that the centre wire lies on the beam axis; this is useful for display and alignment purposes. The wire spacing is 1 mm over the central 20 mm and then increases to 2 and then to 3 mm at the edges. A tantalum screen with an aperture of 86 mm is mounted in front for protection.

The Harp Electronics. Due to the large number of harp wires and the sensitivity of the current measurement it was proposed that only one electronic system be acquired for all the harps in the injection beamline and to multiplex between harps. Only in this way was a reasonable price per channel achieved. With this multiplexer, fast switching (i.e. 25 Hz) between any two harps is possible, so that the beam profile distribution of any two harps can be monitored and displayed simultaneously. Eight harps can be served with the electronic system. Each wire is linked via the multiplexer to the signal processing and control electronics containing current-to-voltage converters with range-selection and integrators. The 94 output signals are digitised with an ADC and then stored in two RAM's (one for the x- and one for the y-direction), where they can be read via CAMAC directly into the computer. The information is to be displayed with a graphics display system on the control console; with such a system the different wire spacings of the harp can easily be taken into account. An analogue output for test measurements or for oscilloscope display is also available. The harp and amplifier range selection are specified via CAMAC. The harp wires are monitored with a photo-diode to avoid overheating. These signals are available to the computer and are also used as independent hard-wired interrupt alarm signals. Opto-isolation is done in CAMAC.

3.4 Faraday Cups

Faraday cups can be inserted in the beamline with pneumatic actuators to intercept and stop the beam and to measure the total beam current accurately. It consists of an uncooled conical 2 mm thick tantalum cup insulated from a stainless steel support. A negative voltage can be applied to a cylindrical bias-electrode in front of the cup to reflect secondary electrons back into the cup for accurate current measurement. A tantalum screen defines the entrance aperture, which has a diameter of 65 mm. The beam falling onto this screen can also be measured. The maximum acceptable beam power-density is 2.5 kW/cm^2.

3.5 Capacitive Phase Probes

The beam pulse induces a signal in a capacitive phase probe as it travels through it. Information on the time-structure of the beam pulse as well as the beam phase with respect to the RF accelerating system can be obtained from this signal. The buncher phase can be adjusted and with the time-of-flight method the beam energy can be accurately determined. The capacitive phase probe consists of an inner and an outer stainless steel cylinder, constructed as a 50 Ω termination, and a segmented copper aperture at both ends for fine tuning of the impedance. The inner cylinder has an aperture of 60 mm and a length of 45 mm. The probe dimensions are specially optimized for our beam dimensions and characteristics to ensure that an optimum signal is induced.[2] This probe can either be mounted onto a CF 150 flange for fixed installation in the beamline, or it can be mounted onto a pneumatic actuator. A 1.5 mm thick tantalum screen in front of the probe serves as protection for larger beam sizes. Any beam falling onto this screen is continuously measured and monitored by alarm circuitry. The beam measurement electronics is described in reference 3.

3.6 Double Linear High-vacuum Feedthroughs

This high-vacuum feedthrough provides independent linear movement of two elements inside a diagnostic chamber, as is for example required for the accurate positioning of slit jaws. Both feedthroughs are mounted on one CF 150 flange, which in turn can be mounted onto any diagnostic port of the diagnostic chambers. Each feedthrough is driven by a stepping motor driving a ball-screw via a timing belt. One stepping motor step corresponds to 0.025 mm. Membrane bellows provide the vacuum seal over the stroke of 60 mm. An encoder is mounted for position measurement. The drive is also fitted with a magnetic brake and limit switches.

3.7 Slit Systems

The slit system consists basically of two jaws mounted on and driven by the double linear high-vacuum feedthrough described above. The uncooled jaws are made of 1.5 mm thick 60 mm x 80 mm tantalum plates, which are mounted onto the feedthrough with stainless steel forks. (The dimension of 60 mm is in the direction of motion). Each jaw can be driven 15 mm beyond the beamline axis. The jaws are electrically insulated to measure the beam current intercepted. The pair of slit jaws is protected with an insulated limit switch to prevent the two jaws from being driven against each other. Each jaw will be able to withstand a maximum beam power density of 2 kW/cm^2, and will be able to intercept at least the specified 400 W maximum beam power.

3.8 Beam Profile Scanners

The beam profile scanner is used for the measurement of the intensity-distribution of a beam in both the horizontal and vertical directions. The scanner basically consists of a 1 mm diameter helical tantalum scanning wire driven at both ends to avoid deformation. The intensity profile is obtained by directly measuring the current from the tantalum wire via a sliding contact. The noise performance of the scanner has been reduced to $\leq \pm$ 300 pA. The wire is driven by a DC motor (at 750 r/min) via a magnetic coupling across the vacuum enclosure. The wire position is detected with a rotary potentiometer on the shaft. The entrance aperture is limited to 60 mm for mechanical reasons. The scanner is mounted with a CF 150 flange (at 45^{o} to the vertical axis) on one of the ports on the diagnostic chambers. The option of retracting the scanner head was waived for financial reasons; however, the scanning wire is parked outside the beam when not in use.

The Scanner Electronics. A multiplexer is used so that one electronic system can serve up to eight scanners. Any two scanners out of a possible 8 can be monitored simultaneously. For the display of a beam profile, the beam current and the voltage from the endless rotary potentiometer are fed into two separate multiplexers. The current signal is amplified with a variable-gain amplifier with an analogue output to the y-channel of an oscilloscope and to a CAMAC-interface module. The signal for the wire position is first fed into a comparator and further signal-processing electronics before it is supplied to the same CAMAC-interface module or to the x-channel input of the oscilloscope for the horizontal sweep. Markers can also be placed on the profile trace via the z-input of the oscilloscope to indicate the relative beam position. The motor control and driver for the DC motor form part of the electronic system. The CAMAC-interface module includes electronics for range selection, a 10-bit ADC, a RAM for data storage and electronics to control the whole reading procedure as well as storage and output of data. It also allows the computer to select scanners and to switch the motors on and off.

3.9 Beam Stops

Each beam stop will be mounted at the end of a beamline with a CF 150 flange. It stops the beam, and the total beam current can be measured accurately because it is designed on the principle of a Faraday cup. The uncooled cup itself is of 2 mm thick tantalum. A 90 mm long cylindrical electrode (in front of the cup) with a negative bias voltage is used for secondary electron suppression. The entrance aperture of the 1.5 mm thick tantalum sputtering screen, from which beam current can also be measured, is 80 mm in diameter.

3.10 Segmented Scrapers

Segmented scrapers are installed inside the 152 mm diameter vacuum pipe at various quadrupole positions, where the beam reaches its maximum dimensions. Each segmented scraper consists of four 90^o segments which are individually insulated and 200 mm long. An alarm is given if the beam hits one of the segments. The segments are kept in position by an outer supporting ring which fits into the vacuum pipe: tolerances are taken up by springs. The radial thickness was kept to a minimum in order not to reduce the aperture available for the beam by too much.

3.11 The Emittance-measurement System (EMS)

Owing to the large beam sizes the slit and the detector are mounted onto independent linear vacuum feedthroughs which are mounted on two standard diagnostic chambers some distance apart to give sufficient measurement resolution. Each emittance-measurement system consists of two identical sets for the horizontal and vertical planes; however, only one electronic system serves both planes.

The linear vacuum feedthroughs carry a stepping motor driving a ball-screw such that one stepping motor step results in a linear displacement of 0.025 mm. An encoder is used for position measurement. A magnetic brake is fitted. The total stroke of 105 mm is achieved with bellows. The 0.1 mm wide slit is located in an uncooled 1.5 mm thick, 80 mm x 110 mm tantalum plate. The maximum beam diameter that can be scanned is 40 mm and the slit itself can be driven 25 mm beyond the beamline axis. The detector consists of an array of 29 tungsten-rhenium wires (with 0.1 mm diameter) and spaced at 1 mm intervals and carried by a C-shaped holder.

Electronics for the EMS. The signal-processing electronics contains 30 amplifiers, 29 for the harp-wires, and 1 for the slit current (which is typically a factor 100 larger than that from the wires) for normalisation. Eight amplifier ranges are provided, the lowest range corresponding to 100 pA full scale (i.e. 5 V output). The amplifiers are followed by 30 integrators which feed a 32:1 analogue multiplexer followed by an ADC. The stepping motor controller and driver also monitors the encoder positions. The whole emittance-measurement control system is CAMAC-based and controlled by a microprocessor linked to a CAMAC crate via an auxilliary crate controller.

3.12 Beam Current Measurement Electronics

Logarithmic current amplifiers were selected for beam current measurements from Faraday cups, beam stops, slit jaws, segmented scrapers and various screens. In the laboratory an accuracy of 1%-of-reading was demonstrated from 5 pA to 1 mA. Eighty such amplifiers are managed by a local microprocessor unit (MPU) and connected by CAMAC to the control computer. The local MPU will take care of rapid anti-logging and data buffering as well as calibration of all log amplifiers and monitoring of alarm levels.

3.13 Pneumatic Actuator and Stepping Motor Drivers

The pneumatic actuator control electronics consists of numerous plug-in modules, each of which controls the motion of an actuator. Alarm signals can be received by this module either from the computer control system via CAMAC or directly via a hard-wire link from the safety interlock system. Similarly, status and alarm signals are sent out to the computer control system and the safety interlock system.

Stepping motor drivers have been built, which also monitor the accurate position measurement of the encoders as well as the status of the limit switches. The magnetic brake to lock the drive is also controlled by this module.

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