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THE DESIGN AND PERFORMANCE OF THE BEAM DIAGNOSTIC SYSTEM OF THE NAC SEPARATED-SECTOR CYCLOTRON

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Summary. The design, manufacture and installation of most of the beam diagnostic components for the k=200 MeV separated-sector cyclotron (SSC) have been completed and the system has been used extensively under operating conditions during the past year. The layout, specific design characteristics and the performance of the system are discussed. Emphasis is placed on the design requirements imposed by variable-energy multi-particle beams, beam intensities from a few nA to 100 µA and beam powers up to 10 kW.

Introduction

The first proton beams have been injected, accelerated and extracted from the SSC during the past year.[1,2] The beam diagnostic system proved to be an indispensable tool during this commissioning phase.

The basic design of the SSC with a narrow gap of only 30 mm within the vacuum chamber in the sector magnets, and the fact that the two rf resonators each occupy one complete valley, confine the diagnostic equipment for the SSC mainly to the two valley vacuum chambers. Special attention had to be given to the fact that the SSC must deliver a variety of beams (from protons to heavy ions with a 10:1 energy range), beam pulse lengths and beam intensities. The beam diagnostic system must thus cater for:

(i) minimum injected and maximum extracted beam energies ranging typically from 0.8 MeV to 200 MeV for protons, respectively;
(ii) various beam penetration depths, e.g. up to 130 mm for 200 MeV protons in graphite;
(iii) beam intensities ranging from a few nA (for heavy ions) up to 100 µA (for protons); and
(iv) beam powers up to 2 kW for 200 MeV protons and 10 kW for 100 MeV protons, confined to beam diameters of a few mm.

Layout and diagnostic equipment

The layout of the beam diagnostic system is illustrated in Fig. 1. As it is impractical to install more than 2 long probes, we opted for a solution

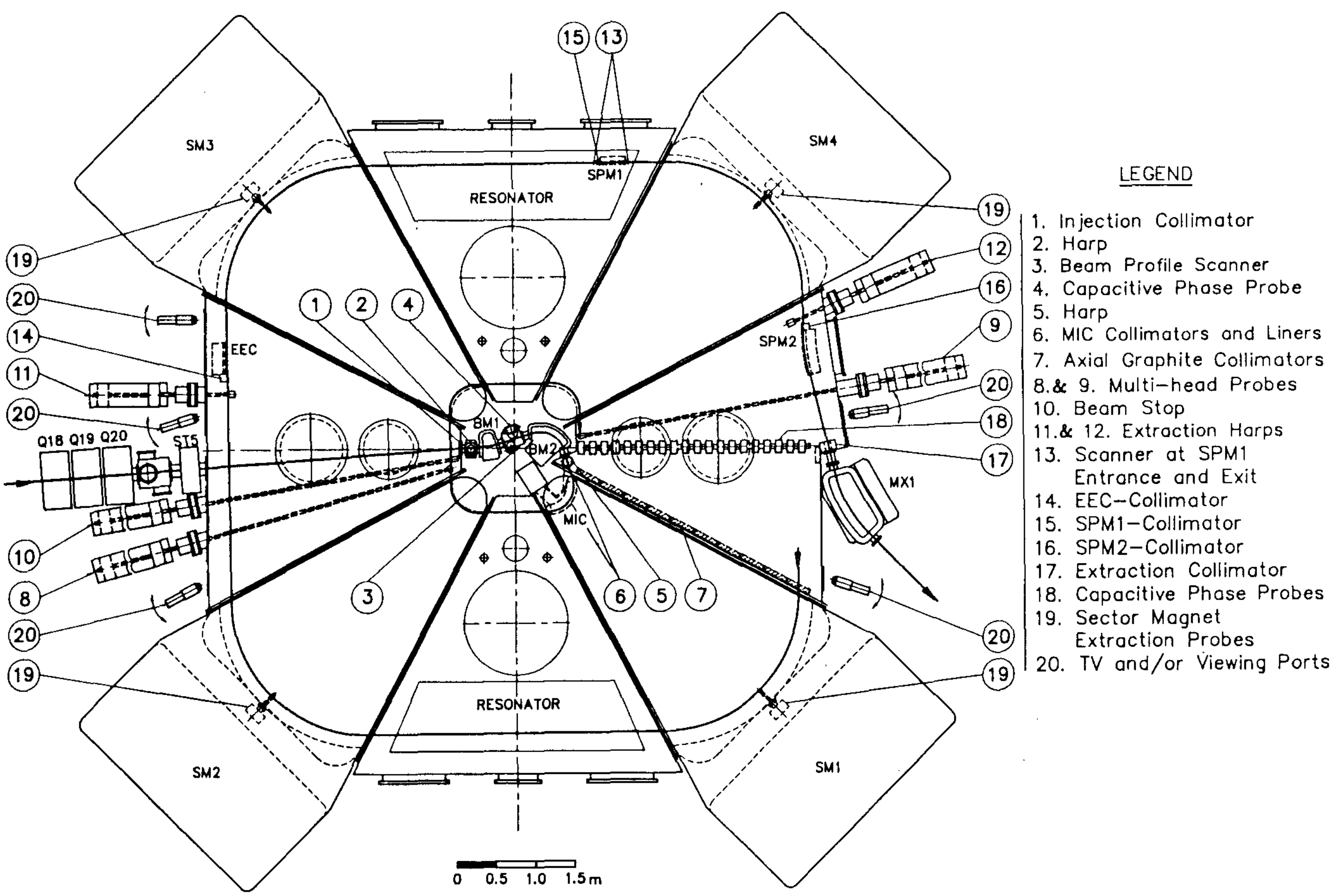

Fig. 1 The layout of the beam diagnostic system of the SSC.

with a more complex mechanical design whereby various types of diagnostic heads can be mounted onto these probes.

Central region beam diagnostics

Two harps, a beam profile scanner and a capacitive phase probe have been installed amongst the two bending magnets, BM1 and BM2, and the magnetic inflection channel (MIC), see Fig. 1, to facilitate the beam injection. The harp and scanner data are acquired for on-line display on a graphics terminal in the control room. The capacitive phase probe aids in determining the injection phase and time-structure of the beam (especially with buncher operation).

The multi-head probes (MHP)

Two such identical probes are installed in opposite valleys (Figs. 2 and 3). Each probe can cover the whole acceleration range and can be driven into a parking chamber, which can be isolated from the valley vacuum chamber with a valve. Special trolleys on rails carry the heavy shaft (with the various heads) both inside and outside the vacuum chamber; alignment has to be carried out over a total length of 8 m. Data acquisition is carried out with probe speeds up to 40 mm/s. Any one of the following four probe heads, mounted on a water-cooled copper base at the end of the shaft,can be rotated into the beam plane (Fig. 4):

(i) The 3-finger differential head, which should stop the beam completely, is used for low beam energies with typical penetration depths of 2 mm in copper, i.e. up to 35 MeV protons. The radial and axial beam distribution and beam centering near injection are monitored with the 3 tantalum fingers protruding from behind the copper head by 0.5 mm.

(ii) The tomography head, which consists of three 0.1 mm spring-tensioned tungsten wires at 45° to each other [3], is used to analyse the beam shape (cross-section), the axial and radial intensity distribution and beam centering, mainly at high beam energies.

(iii) The 4-finger head consists of four 0.1 mm thick tantalum plates with different heights, to establish the axial (as well as radial) beam distribution, mainly at high energies.

(iv) The capacitive phase probe consists of two copper pick-up plates symmetrically spaced about the median plane, to determine the beam phase, the bunch-length, the time-structure and to ensure isochronous acceleration (with the aid of trim-coil re-adjustments). This probe head serves as an intermediate solution until the main set of 20 phase probes is operational.

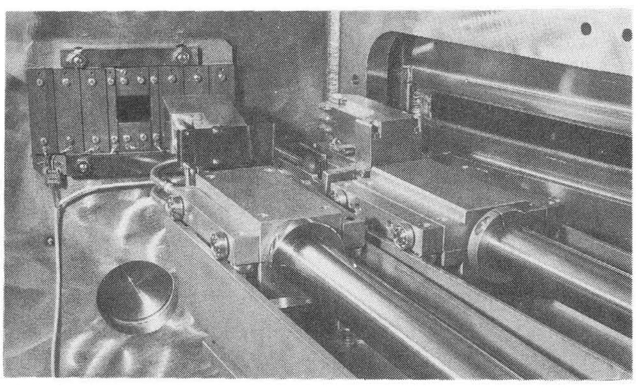

Fig. 2 The injection valley vacuum chamber with the multi-head probe (right) and beam stop (left) driven in fully. The injected beam enters the central region via the injection collimator (far left).

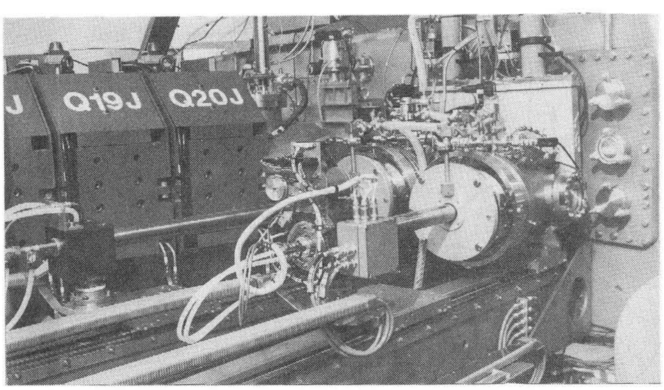

Fig. 3 The support and drive mechanism of the multi-head probe (right) and beam stop (centre) with the last section of the transfer beamline (left).

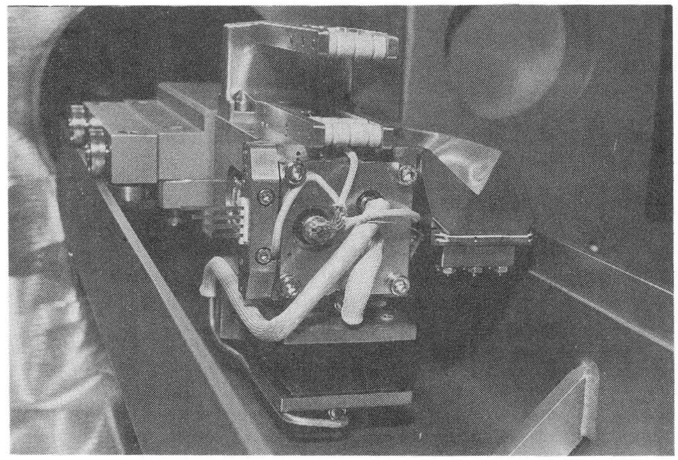

Fig. 4 The multi-head probe with the 4 different probe heads. Clockwise from the top (i.e. the median plane) are: the tomography head, the 3-finger differential head, the capacitive phase probe and the 4-finger head.

The different probe heads are interchangeable and any new probe head design could easily be accommodated on the copper base. Except for the 3-finger differential head, which is to be used for low beam energies up to 2 kW, all the other heads (with their supporting copper forks) can operate with beam powers up to 10 kW. A typical orbit pattern measured with one of the tomography probe wires over the whole acceleration range is illustrated in Fig. 5.

The beam stop

The beam stop can intercept the beam at any radius over the whole acceleration range. It is often used in conjunction with the MHPs to intercept the beam at a larger radius to avoid unnecessary activation while optimizing the machine and to act as a beam dump if the beam is not extracted. The total beam current intercepted can be measured. A tantalum plate on the outermost edge of the copper head protects the head from the low energy beam injected through the valley vacuum chamber to avoid any confusion during beam injection (see Fig. 2). The water-cooled copper head can stop all beams and dissipate all beam powers deposited at various penetration depths, i.e. up to 10 kW. The head is long enough to intercept the beam even for orbit separations

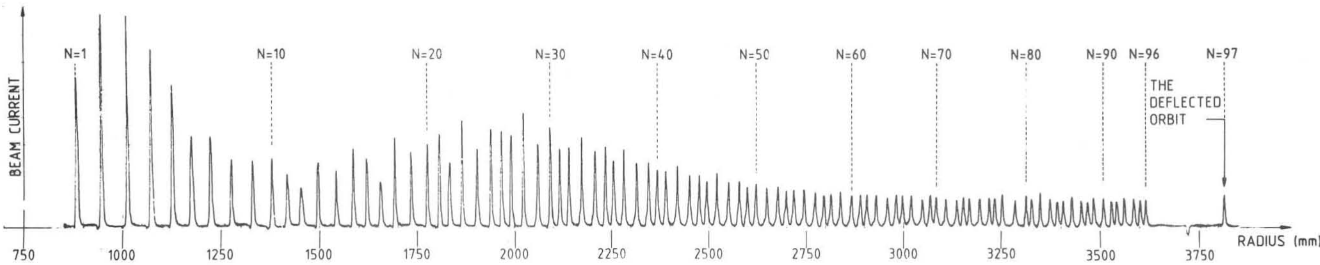

Fig. 5 The orbit pattern of a proton beam accelerated in the SSC from 3.15 to 66 MeV, as measured with the vertical wire of the tomography head over the whole radial range. The extracted beam is visible on the far right.

of up to 130 mm at injection as can be expected for some heavy ion beams with only 32 revolutions. The support and driving mechanism of the beam stop is identical to that of the multi-head probes, except that the head is not rotatable.

The axial graphite collimators

These large collimators extend over the whole radial range (see Fig. 1) and limit the axial beam aperture to 26 mm. The upper and lower halves each consist of 10 separately insulated and symmetrically spaced graphite blocks from which intercepted beam currents can be measured (Fig. 6). The collimator thicknesses increase from 20 mm at injection to 185 mm at extraction. The blocks are indirectly water-cooled and insulated by hard-anodized aluminium strips. Graphite was preferred to copper for reduced activation and simplified cooling and construction.

The extraction harps

Two identical extraction probes have been manufactured and are to be installed during the next shut-down; one in front of the electrostatic extraction channel and the other in front of the second septum magnet to scan the last few orbits near the extraction radius to optimize beam extraction. Both probes consist of a harp with 48 spring-tensioned 0.1 mm tungsten wires, spaced at 1 mm intervals, and 9 horizontal tantalum blades mounted on an aluminium fork (Fig. 7), to determine the horizontal and vertical beam distributions respectively. The harps are multiplexed and serviced with a microprocessor controlled beam current measurement and data acquisition system for display of the beam profile at the control console.

The scanner on the first septum magnet (SPM1)

A beam profile scanner is mounted on the extraction magnet SPM1 (Fig. 8), and installed inside the inner delta of the west resonator. Two tantalum blades (0.5 mm thick) scan the beam alternately at the entrance

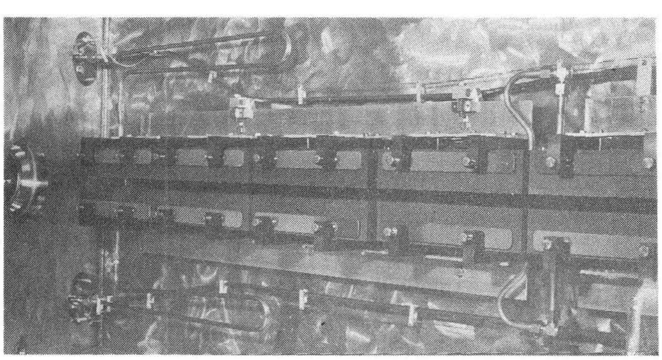

Fig. 6 The axial graphite collimators mounted symmetrically about the median plane against the side wall of a valley vacuum chamber. Only the outer 5 of the 10 collimator pairs is visible.

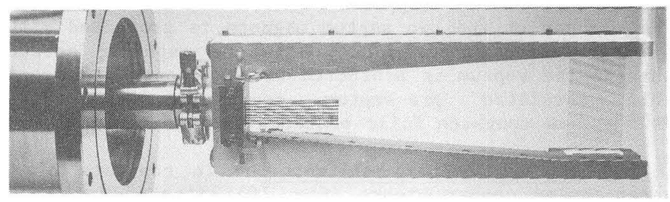

Fig. 7 The extraction harp with 48 vertical wires at the tip of the fork and 9 horizontal tantalum blades (see text).

and exit of SPM1 to establish the optimum position of the SPM1 septum relative to the orbits, as shown in Fig. 9. The drive consists of an indirectly water-cooled dc vacuum motor with tachogenerator and potentiometer.

Collimators and liners

Various low-energy and high-energy collimators have been installed. Extensive three-dimensional cooling calculations have been carried out to optimize the water-cooling duct configuration, especially for the high-energy beams with varying penetration depths (and Bragg peaks) and beam diameters.

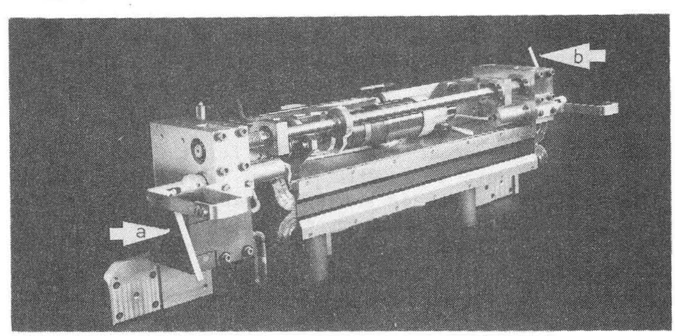

Fig. 8 The beam profile scanner mounted on top of the first septum magnet (inside the inner delta of a resonator) with scanning tantalum blades at the entrance (a) and the exit (b). The entrance is protected by a copper collimator.

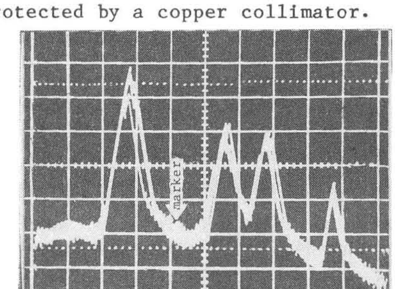

Fig. 9 Orbit structure at the entrance to SPM1 as measured with the scanner mounted on this magnet. The deflected orbit lies to the left of the marker - indicating the centre of the septum - whereas the previous orbits lie to the right.

The injection collimator: A collimator, made up of 10 insulated graphite sections installed in front of the port leading to the central region (see Fig. 2), has proved very useful in finding the injected beam.

The MIC collimator and liners: The MIC entrance is protected with 4 water-cooled copper collimators. Eight water-cooled copper liner sections, insulated for beam current measurement, protect the MIC coil and frame inside and outside the channel.

Extraction component collimators and liners: Each of the three extraction components is protected with a water-cooled copper collimator at its entrance.[2] The air-gap of the two septum magnets is protected with a water-cooled copper duct, while the magnetic screen outside the septum is protected with a copper liner. A thin insulated pre-septum consisting of three 0.05 × 7 mm tungsten foils protects the EEC septum.[2]

The extraction collimator: It consists of 4 water-cooled copper blocks (Fig. 10) situated in front of the port through which the beam is finally deflected out of the SSC.

The phase probes

The design for a set of twenty stationary capacitive phase probes along the extraction valley vacuum chamber centre-line is in progress. The proposed pick-up head design has been tested to our satisfaction under operating conditions with the phase probe on the MHP. Identical phase probes are to be installed with 50 × 50 mm pick-up plates.

The sector magnet extraction probes

The design of 4 identical probes to scan the last few orbits along the hill centre-line (near extraction) is in progress. These probes are to be used for beam centering studies. The beam intensity distribution is to be measured with a 0.1 mm tungsten wire in the 30 mm sector magnet vacuum chamber gap.

The beam current measurement system

All beam current measurements for the SSC, except for scanners, are made with linear current amplifiers with a switched 8-decade range. A maximum error of less than 10% was demonstrated on the most sensitive range, i.e. 100 pA full-scale reading. Each amplifier has an over-current alarm facility, a low-pass filter, an analogue output and automatic offset correction and range selection. The 32 amplifiers (housed in 16 screened modules) in a cardframe are serviced by one high speed ADC via a multiplexer and a common bus system. The ADC is linked via an optically isolated bus to the slave of an industrial microcontroller, which performs real-time multi-tasking with software residing in an EPROM. This self-contained subsystem is housed in one cardframe. It receives control information from and supplies data to a microprocessor via the industrial microcontroller master (with its high speed serial communication link). This master is daisy-chained to a further 3 such subsystems. A terminal provides local control via the microprocessor, which is linked via CAMAC to the control computer.

The system is divided into 4 subsystems: 2 cardframes for the 64 static current masurements, and 2 cardframes for the 24 dynamic measurements which may be carried out during probe movement. The latter is to be extended to 32 measurements when the sector magnet extraction probes are implemented. Static current measurements are made continuously with the micro-controller slave. During dynamic current measurements the shaft-encoder synchronization electronics of a preselected probe provides an interrupt to the microcontroller slave for every 0.5 mm movement, thus initiating a measurement of the specified channels. This provides synchronization between probe position and current measurement. One parallel data bus had to be provided directly between each of the microcontroller slaves and the CAMAC mailbox to account for the high data transfer rate required. Software has also been implemented to display these data on a high resolution graphics screen at the control desk.

The beam phase measurement system

The central beam phase measurement system is based on numerous capacitive phase probes along the beamlines and in the SSC, multiplexed to a double-heterodyne system, which makes use of the mixing technique across the 5 to 27 MHz frequency band of the rf system.[4] Measurements can be referenced to the phase of the rf at the injector, the buncher or the SSC. The second-harmonic rf component present in the beam pulse signal from a phase probe is extracted and mixed with the rf reference signal (after frequency doubling) first to a fixed intermediate frequency (IF) of 9 MHz and then to a second IF of 1.5 kHz at which phase is measured.

Performance tests were carried out and the phase response was assessed over 0° to 360° and a 100 dB dynamic range, down to the -127 dBm level of the second-harmonic component of the beam pulse signal as expected for 1 nA beams.[4] Beam pulse harmonics up to 750 MHz were simulated with a spectrum generator. The measured phase is invariant with signal level over the 100 dB dynamic range to within 0.5°. The phase response (measured against calibrated coaxial air-lines) is linear to within 0.5° over the extremes of level and rf frequency. Beam phase measurements carried out under operating conditions with the capacitive phase probe on the MHP have shown that phase can be resolved to <1°. The system is now placed under direct control of a microprocessor linked to CAMAC.

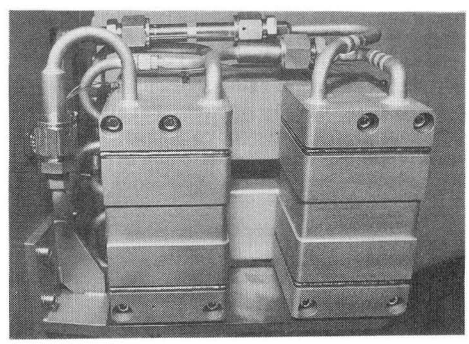

Fig. 10 Front view of the extraction collimator mounted in front of the extraction port.

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