BEAM EXTRACTION SYSTEM OF THE SYNCHROPHASOTRON

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Introduction

The creation of a beam extraction system of the Synchrophasotron (SPT)[1] began in the seventies. The high efficiency of the extraction system met the usual requirements - receiving an intense beam and lowering the induced radiation of accelerator parts. But besides that we had to have high efficiency because the radiation around the SPT had to be reduced as there is no biological shield and experiments with internal beam was limited to 10^{11}ppp. The alternative of an intricate and high cost radiation shield was to extract the beam with an efficiency of more than 90% and to transport it into the external experimental halls with suitable beam stoppers, which allowed the accelerator beam intensity to be increased at least by a factor of ten.

A large transverse size of the SPT vacuum chamber permitted the extraction system to be constructed with such a high coefficient of extraction, in principle, without great complications. On the other hand, such a large volume of the magnetic field complicates considerably its stabilization at a level of $10^{-6}\div10^{-7}$ which is necessary for uniform beam extraction. As the power consumption of the SPT magnet during a flat top exceeds 10 MW, the problem of suppression of guide field ripples to the above level has not been solved completely until now.

The development of the beam extraction system can be divided into three steps:

a) slow extraction[2] in the direction of the Big experimental hall SEB1 (Fig.1) intended mainly for operation at high energies,

b) extraction, conditionally called fast (≈600μs), in the direction of the Small experimental hall[3];

c) slow extraction in this direction for operation at intermediate energies (0.2÷0.5 GeV/nucleon), the construction of which is being continued.

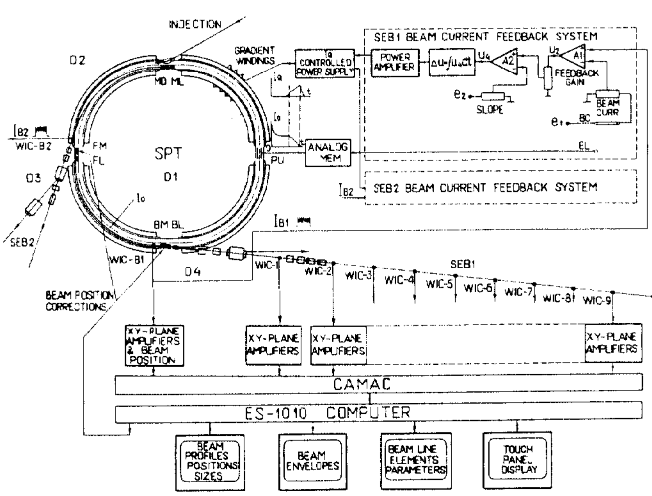

Fig.1. Block-diagram of the synchrophasotron extraction system.

During an accelerating cycle the system permits one to eject the beam in these two directions independently for any energies, intensities and durations. In these three operating modes a common resonance excitation device is used at a frequency of $Q_x = 2/3$. Resonance conditions are created by means of pole-face windings. The second sextupole harmonic is excited by a current with alternating polarity in even and odd quadrants. The radial current distribution in 8 conductors ensures nearly a parabolic form of magnetic field nonlinearity. A similar system of the pole-face windings is used to change a field gradient in the operating region of the accelerator chamber to excite the beam to resonance. Before reaching the guide flat-top, a sextupole perturbation is induced at a beam fixed radial position. The perturbation amplitude is determined by a required horizontal beam size at the septum-magnet entrance. Changing the current I_Q in the gradient windings, the field index is reduced from n=0.67 to n=0.624, and the frequency of horizontal betatron oscillations is shifted to the resonance region. The phase trajectories of particles at the azimuths of the straight section centers are shown in Fig.2.

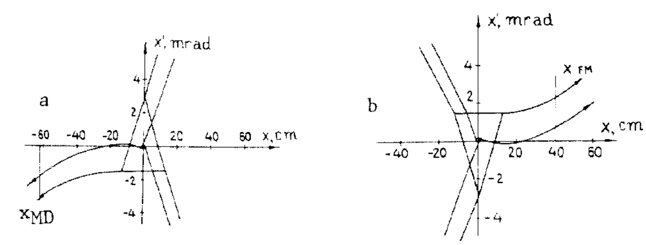

Fig.2. Phase diagram of particles at resonance: a) 1st and 3rd straight sections. b) 2nd and 4th straight sections.

The First Direction of the External Beam (SEB1)

The beam extraction in the first direction is performed by means of a two-stage scheme. Phase trajectories have been oriented in accordance with the position of the first bending stage in an external part of the second straight section. The first bending stage is plunged. It consists of a septum-magnet FM (the aperture is 220x65 mm^2 and the length 1.7 m) and a horizontal focusing Panofsky "semi-lens" FL with a neutral pole (the aperture is 220x72 mm^2 and the length 1 m). They form the beam at the entrance of the second immobile stage, BM and BL, located in the third straight section.

To rise the extraction efficiency and to decrease nonlinear distortions of the beam when transporting it inside the accelerator, the bending angle in the first stage has to be minimized. Therefore the second stage is placed close to the operation region of the accelerated beam at R_0+700 mm (this region of the SPT is ±630 mm). This permits one also to decrease the magnetic field in the first septum magnet to 0.25T and its septum thickness to 2 mm. Besides, the beam is transported to a "good field" area almost over the whole second quadrant. The operation of the lens with an intermediate crossover in the horizontal plane compensates significantly the influence of nonlinearities on the beam when it passes through the fringing field at the end of the second quadrant (Fig.3).

At the entrance of the first bending stage the angle of the beam decreases by 1.2 mrad during the extraction. This change is compensated by a linear increase of the current in the septum magnet. For more exact stabilization of the beam position a feedback circuit controlled by an ES-1010 computer is introduced into the septum magnet power supply.

A beam bending angle of about 105 mrad in the second stage allows one to avoid considerable nonlinearities of the fringing field at the beginning of the third

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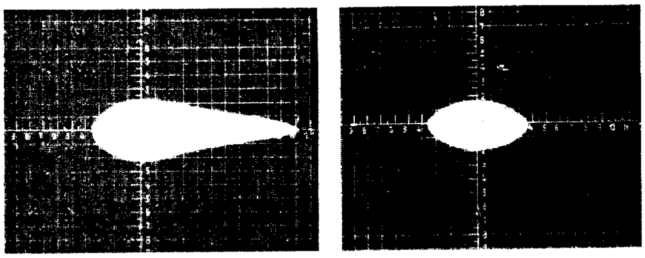

Fig.3. Beam at the entrance of the second inner stage: a) the beam is focussed; b) the beam is focussed with a preliminary crossover (scale in cm).

quadrant and to keep the phase area of the beam with insignificant distortions at the entrance of the external transport system (Fig.4).

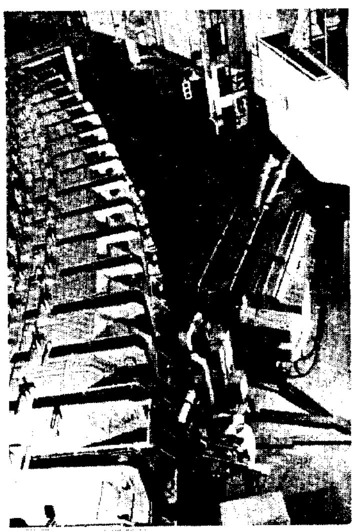

Fig.4. Head part of the first extraction channel.

The extraction efficiency in the first direction was measured after the realization of the system by the method[4] based on detecting secondary particle fluxes around the accelerator for two modes of its operation: the extraction system is on (L_{on}) and off (L_{off}). The extraction coefficient determined by the dependence $E_f = 1 - L_{on}/L_{off}$ was equal to 0.94. Similar measurements have been recently made again by means of dosimetric detectors registering radiation fluxes around the SPT. The estimations obtained which are more rough in this case because of a smaller number of detectors employed (Table 1) are in good agreement with the measurements carried out previously.

Table 1. Evaluation of the SEB1 Efficiency

	Detectors (Fig.1)			
	D1	D2	D3	D4
Readings of the detectors with extraction, L_{on}	2015	12	8	11
Readings of the detectors with no extraction, L_{off}	15198	243	104	148
Ratio of detector readings (coefficient of losses, L_{on}/L_{off})	0.13	0.04	0.077	0.074
Average coefficient of losses	0.08			
Extraction coefficient	0.92			

The Second Direction of the External Beam (SEB2)

The extraction system in the second direction has only one internal bending stage because there is no place for two bending stages in the straight sections (Fig.1). The extraction is of low efficiency, but this makes it possible to increase the number of experiments performed simultaneously during one cycle which do not need a high intensity. The bending stage consists of a horizontal-focusing lens ML and a septum-magnet MD placed in the first straight section at R_0- 600 mm. The magnetic field area outside this radius is not suitable for acceleration, but it permits one to implement one passage of particles under resonance conditions and their entry into the magnet gap to 150 mm. Therefore this stage is made as a fixed one. The beam bent outside intersects the first quadrant crossing the strong horizontal defocusing fringing field at the end of this quadrant. By means of the lens the horizontal size of the beam is decreased by a factor of some times (up to 120 mm) permitting its further transportation.

Until recently this extraction channel has been used only to radiate bubble chambers. This is the reason why the bending system had a small aperture and low power consumption (it was supplied with a short-pulse current). The spill duration in this mode is determined by the rate of current growth in the resonance gradient windings. If this rate is equal to 20 A/ms, the duration reduces to 600μs.

Recently the magnet and the lens of the SEB2 were changed for new ones having an extended aperture and power permitting an extraction time of 1s to be achieved. As the bending angle in the direction of the septum is very large (43 mrad), it is impossible to obtain the extraction efficiency higher than 60%.

Figure 5 shows the beam at the exit of the SPI chamber at the end of the first quadrant.

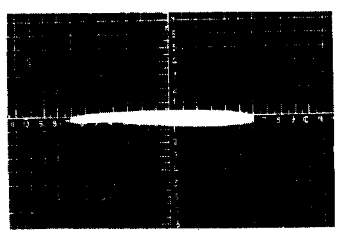

Fig.5. Beam in the second channel at the SPI exit (scale in cm).

Diagnostics and Control

A feedback circuit is used to dose and stabilize the slow extraction beam. In this circuit a signal proportional to the value of the external beam current I_B is compared with the reference voltage e_1 (Fig.1). Since the beam current is proportional to the derivative of frequency betatron oscillations dQ/dt, the difference of these signals is integrated and controls the current in the gradient windings. For expanding a dynamic range of the feedback circuit, an initial linear slope is introduced into the current of the gradient windings.

The value of the extracted beam current is controlled by a reference voltage from 10^{-3} up to the full circulating beam.

The feedback loop makes the extraction current more homogeneous and somewhat reduces low frequency pulsations (Fig.6).

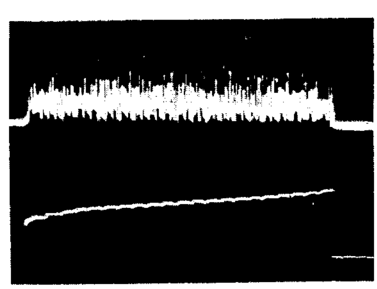

Fig.6. Extracted beam at a 450 ms spill (upper trace). Low trace is the current of the gradient windings controlled by the feedback loop.

If the pick-up (PU) signal I_0 is used as a reference, the beam spill duration is stabilized by the feedback.

The system based on an EC-1040 computer is used for tuning and maintaining the extraction conditions. One of the main functions is to monitor parameters of the extracted beam.

Wire two-coordinate (30x30 wires, 190x190 mm^2) ionization chambers (WIC) are used as profile monitors consuming an $Ar+CO_2$ gaseous mixture (Fig.7).

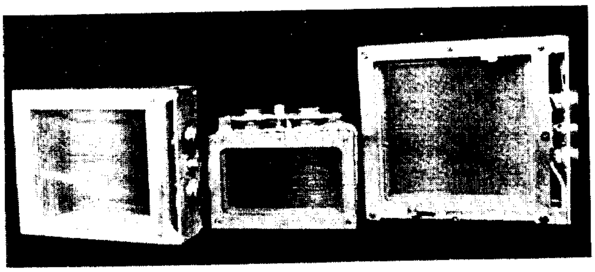

Fig.7. Multiwire ionization current chambers as a beam profile monitor.

The signal electrodes are spaced 2,4 or 6 mm apart (according to the beam size at the observed points of the transport line).

The operation over a wide range of intensities from 10^6 up to 10^{12}ppp is achieved by variations of the coefficient of gas amplification and the sensitivity of electronic current-to-voltage converters.

The converters are controlled by the computer through an analog multiplexer.

Nine WIC placed along the transport line are used to monitor space characteristics of the extracted beam up to 15 times during the extraction time. This allows one to know the evolution of the beam parameters during the extraction at each observed point of the transport line (Fig.8).

The method of measuring extracted beam emittance characteristics of the extracted beam is based on the assumption that the emittance diagram has an elliptical shape. Initial data for the real time program calculating these characteristics are: guide magnetic field induction during the beam extraction, current in the lenses of the beam transport line and beam dimensions at three points along the external beam line (at points of the WIC1,2,4 location). Values of $\pm 2\sigma$ are taken as a beam size corresponding to 95% of beam particles in phase ellipses.

The values of beam emittance measured for a guide accelerator field of 1.07T are $E_x = 25\,\pi$ mm·mrad and $E_y = 40\,\pi$ mm·mrad. Based on the phase ellipse parameters α, β, γ measured in an initial part of the beam line, operating calculations of beam envelopes along the whole beam line are carried out.

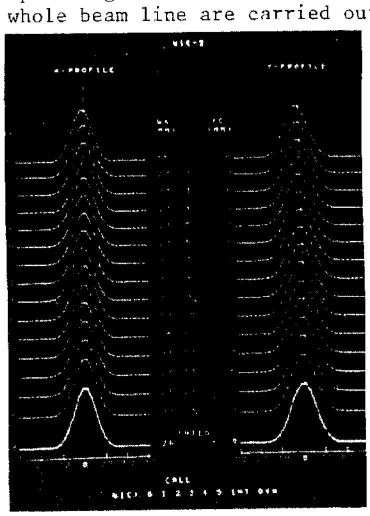

Fig.8. Profile beam evaluation during extraction.

Use of the Beams

In the Big experimental hall (Fig.9) a "fir-tree" structure of channels is used. Four channels begin from the target F4(1V,2V,7V and 8V), two channels from F5 (3V and 4V) and from F6(5V and 6V). The choice of such a scheme was due to the possibility of simultaneous and independent operation of these

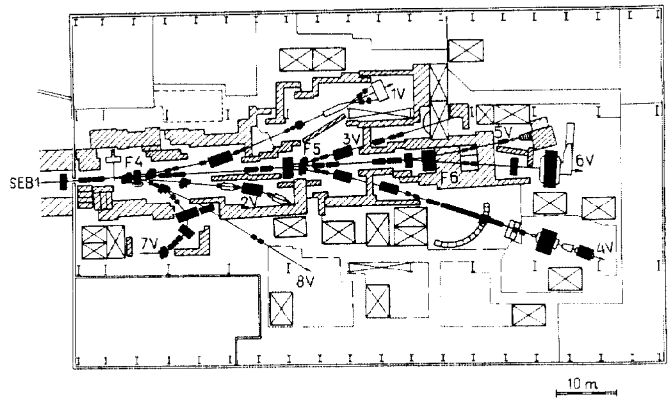

Fig.9. Layout of the beam channels in the Big hall.

channels. Secondary particles and their momentum can be selected in each channel. At the end of the hall a beam stopper is mounted which is used to damp the beam intensity up to 10^{12}ppp.

Now the ejected beams (from protons to silicon) are transported to twelve experimental installations[5] which are used to study relativistic nuclear physics.

In 1985 the accelerator should operate 3700 hours (2500 h on nuclei and 1150 h on protons).

Improvement in the vacuum chamber of the Synchrophasotron by means of cryogenic pumping, planned at the end of this year, should reduce the pressure in the ring approximately by a factor of ten. This will permit one to move the accelerated nuclei to the middle of the Mendeleev periodic table and to rize the beam intensity of neon, magnesium, silicon and so on.

Acknowledgement

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Table 2. Main Parameters of the SPT Extraction System

Resonance	$Q_x = 2/3$
Change of n	0.67-0.624
Energy range	
protons	0.65-8.8 GeV
nuclei	0.2-4.0 GeV/amu
Spill duration	600μs-0.6 s
Resonance control	pole windings
The first direction	
Efficiency	0.94
External beam emittance	
horizontal	25 π mm·mrad
vertical	40 π mm·mrad
Number of inner stages	2
First stage	
working position	R_0+350 mm
bending angle	9.8-11 mrad
Second stage	
working position	R_0+700 mm
bending angle	105 mrad
The second direction	
Efficiency	0.6
External beam emittance	
horizontal	30 π mm·mrad
vertical	45 π mm·mrad
Working position of the septum	R_0-600 mm
Bending angle	43-41.8 mrad

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