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SET-UP FOR ELECTRON COOLING EXPERIMENTS

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Abstract

A description is given of a set-up for studying electron cooling: the NAP-M proton storage ring for energies up to 150 MeV.

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To carry out experiments on electron cooling [1] a proton storage ring has been constructed at the Institute of Nuclear Physics (Siberian Division of the USSR Academy of Sciences), referred to as model NAP [2], with the following design parameters:

Accelerated particle energy	Up to 150 MeV
Injection energy	1.5 MeV
Curvature radius	3 m
Length of straight sections	7.1 m
Betatron oscillation frequency	Q_Z - 1.4
	1.2
Factor of spatial packing of the orbits	α - 0.8
Transition energy	110 MeV
Deflection magnet aperture	Δz - 7 cm
	Δr - 10 cm
Guide field stability	$\Delta B/B$ - 1.10^{-4}
Number of straight sections	4
Number of magnets	4
Accelerating voltage frequency	
At injection	0.36 MHz
At energy of 65 MeV	2.23 MHz
Accelerating voltage	10 V

The design work on the set-up and the production of individual assemblies were started in November 1971. In September 1973 operation commenced with a circulating beam. Up to April 1974, research was conducted into the proton beam and the storage ring's characteristics, and the final touches were put to the rf-system and computer control system. In May 1974 work commenced with two beams.

The magnetic system of the accelerator contains four deflection magnets with a zero gradient and edge focusing (with a geometric angle of cut-off tg θ = 0.579) and eight correction elements located at the ends of the straight sections. The magnets are of the non-laminated type, made from Armco iron and have a O-shaped profile.

The magnet supply is provided by a dc generator with a stabilizing system providing a field stability not worse than 1×10^{-4} in the operating range of 0.5 - 6 kA. At the same time, the stabilization system serves to control the magnetic field (by means of a reference voltage).

The correcting elements contain dipole, quadrupole and sextupole windings. The quadrupole windings are used for tuning the betatron oscillation frequencies to within $\pm$ 0.05 throughout the whole variation range of the guide field. The dipole magnets produce correcting fields up to 100 G, and h - z orbit correction can thus be achieved. Apart from the correcting elements at the injection energy there are coils for orbit correction, which provide a means of varying the guide field independently in the quadrants to within $\pm 10^{-3}$.

One of the straight sections contains the electron beam set-up described in /3/:

Length of cooling section	1 m
Electron energy	Up to 100 KeV
Electron current	up to 1 A
Relative transverse electron velocity	$\leqslant 5 \times 10^{-3}$
Energy stability	1×10^{-4}
Accompanying longitudinal magnetic field	1 kG

The set-up provides for the recovery of electron energy, so that the power used by the high-voltage sources is not greater than 2 kW. Shaping of a beam with small transverse electron velocities is achieved by means of a 3-electrode gun inserted in the longitudinal magnetic field /4/. The system of correcting coils provides a means for controlling the position of the electron beam in the cooling section, which is necessary for accurate impingement of both beams.

The proton injector used is a pulsed electrostatic accelerator with an energy of up to 1.5 MeV: τ = 4 microseconds, I = 1 mA. Single turn injection is used, and the particles are fed in vertically with an angle of 3°30' by means of a pulsed electrostatic inflector.

The bakeable vacuum chamber is made of stainless steel. Its design is such that chamber bake-out can be effected without dismantling the magnets. The heating temperature is up to 300° C. The vacuum is produced by 10 magnetic-discharge pumps with an output of 300 ℓ /sec and sorption pumps with titanium sputtering providing a vacuum in the main part of the storage ring of 5×10^{-11} torr. The injector accelerating tube, which is characterized by a pressure of the order of 10^{-6} torr, is connected to the storage ring by a channel in which differential pumping takes place, thus bringing the pressure down by four orders of magnitude.

The vacuum in the electron beam installation is provided by two magnetic-discharge pumps with an output of 150 and 300 ℓ /sec and two sorption pumps. In addition, there are magnetic-discharge pumps distributed along the electron-optical track, operating in the installation's own field. Unfortunately, if the electron beam is switched on when the distributed pumps are operating, it has been found that there is a rapid decay of the proton beam /5/. Consequently the experiments for electron cooling had to be carried out when the distributed pumps were switched off. When there is no electron beam and the distributed pumps are switched off, the pressure at the meeting region is of the order of $1 - 2 \times 10^{-8}$ torr. Injection of the electron beam leads to deterioration of the vacuum at the meeting region by an order of magnitude which determines a mean value of the vacuum around the ring of 2×10^{-9} torr.

The accelerating system of the storage ring consists of a master oscillator, a power amplifier and a cavity. A block diagram of the rf-system is shown in figure 2. The controlling element for varying linearly the oscillator's frequency is a Hall effect detector $B(t)$. To compensate for the delay of this signal in the control circuits use is made of the voltage from a coil $\dot{B}(t)$. Precise tuning of the frequency is carried out by means of the beam coordinate. The feedback circuit through the differential pick-up electrode contains an integrating amplifier and suppresses the "errors" in the coordinate by k $\simeq$ 16000 times at a zero frequency and by k $\simeq$ 40 times at frequencies of 1 - 50 Hz. Rapid phase frequency tuning is obtained by a second feed-back circuit through an integral pick-up electrode. Use of the feed-back lowers the requirements imposed on the background level and on the stability of the magnetic field and of the rf-system by k times. The feed-back system operates satisfactorily at currents of more than 30 microamperes at the injection energy.

The operational cycle is controlled by an "Odra-1304" computer. The operational cycle has the following appearance. Protons are injected into a rising magnetic field. The moment of injection is synchronized by the level of the field from a YaMR detector with an accuracy of $\Delta B / B \leqslant 10^{-4}$. The pattern of current rise in the magnets and correcting elements is controlled by the computer and is determined by a tabulation previously inserted in the operating memory of the machine. When the field levels out into a plateau, the rf-frequency is switched off, the longitudinal magnetic field is switched on as well as the fast (electron) heating of the beam cathode in the electron beam installation; the cooling process then begins. During this time the computer is used for processing the experimental results.

Normally, the time required for accelerating to an energy of the order of 100 MeV is about 30 seconds, the field rise time increasing twice as energy is acquired by the proton. The initial rate of the rise - 150 G/sec - is apparently limited by the lagging of the field behind the current owing to induction processes in the iron. Measurements have shown that the lag varies with the derivative of the field in accordance with $\Delta B(G) \simeq 4 \times 10^{-2} \dot{B}(G/sec)$.

The beam position is controlled by ten aperture probes and by eight pick-up stations. The aperture probes are used simultaneously for observing the dimensions and position of the beam during the first revolution; for this, they are equipped with plates coated with a luminescent material. Observation is effected from a distance by television cameras. The pick-up stations are connected by the general electronic system for data processing and the orbit profile is displayed on an oscillograph screen.

For measuring the transverse dimensions of the accelerated (cooled) beam, a particle decay method is used. The radial dimension is measured by an aperture probe which intersects with the proton beam, and the protons scattered on its edge are recorded by a scintillation counter at the other end of the section (/5/ figure 4). The vertical dimension is measured by an aperture probe with a scintillation counter which intersects the proton beam vertically. The signal from the counter provides an estimate of the dimensions and position of the beam's centre of gravity. The method has now been improved: a device is being produced which enables intersection of the beam by a 1-micron diameter quartz filament at a speed of approximately 7 m/sec.

The cooling process is accompanied by the formation of neutral atoms of hydrogen as a result of proton and electron re-combination in the interacting beams. These atoms (neutral) which have the energy of protons, are ejected through a special window in the vacuum chamber (wall thickness 0.2 mm) and recorded by a telescope with scintillation and Geiger counters. This method is used for adjusting the cooling rate /5/. For measuring the spatial distribution of the neutrals the Geiger counters are replaced by proportional counters.

The proton current is measured in several ways: by a Rogowski loop, an integral pick-up electrode, a magnetometer and also by spilling the beam on to a probe plate.

The parameters of the magnetic system were investigated by the behaviour of the beam in the storage ring. Measurement of the betatron frequencies with the well-known method of resonance build-up provided the following values at the optimum life-time $Q_h = 1.3$, $Q_x = 1.23$; the measurements $(\partial h / \partial \omega s)$ and $(\partial \omega s / \partial B)_E$ enabled a determination of the value $\alpha = 0.8$, which corresponds with the transition energy of 110 MeV. The coupling of radial and vertical betatron oscillations proved to be unexpectedly high.

The following values were obtained: proton beam life-time (when rf-system was switched off): up to 7 seconds at the injection energy, and up to 600 seconds at an energy of 65 MeV; proton current: up to 120 micro-amperes (3×10^8 particles), which opens up the way for experiments on electron cooling.

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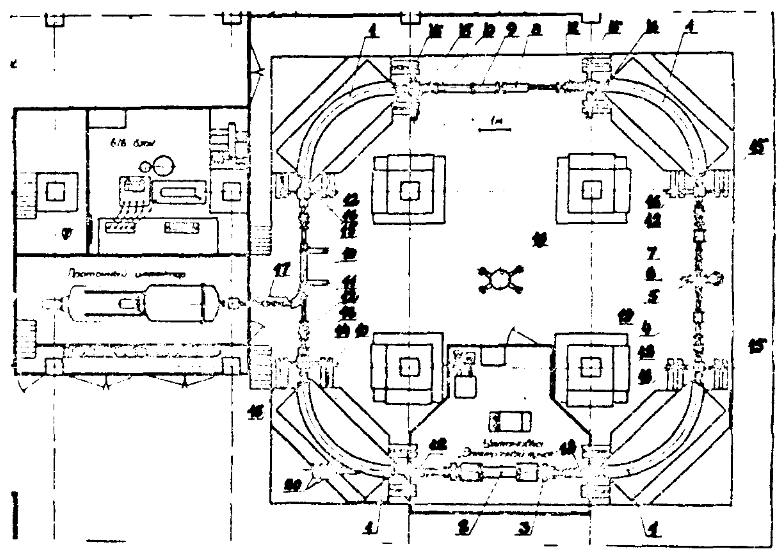
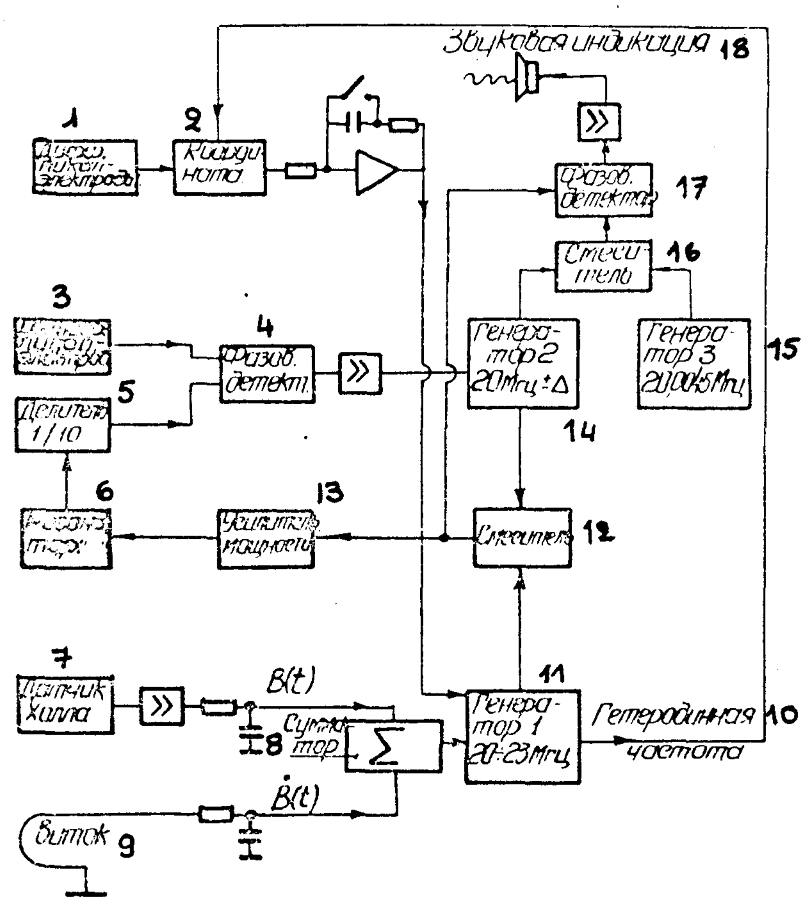


Fig. 1. Layout of NAP-M proton storage ring.

1. Magnets
2. Electron beam installation
3. Correcting magnet
4. Probe with scintillation counter
5. Magnesium jet
6. Vacuum valves
7. Magnetometer
8. Cavity
9. Deflector
10. Inflector
11. Inlet magnet
12. Pick-up station
13. Octupole lens
14. Quadrupole lens
15. Television camera
16. Aperture probe
17. Injection channel
18. Rogowski loop
19. Geodetic mark
20. Neutral counters



<u>Fig. 2</u>. Block diagram of the rf-system

1. Differential pick-up electrode
2. Coordinate
3. Integral pick-up electrode
4. Phase detector
5. Divider 1/10
6. Resonator
7. Hall effect detector
8. Summator
9. Coil
10. Heterodyne frequency
11. Oscillator 1 20-23 MHz
12. Mixer
13. Power amplifier
14. Oscillator 2 20 MHz $\pm \Delta$
15. Oscillator 20,0045 MHz
16. Mixer
17. Phase detector
18. Acoustic signal