A guides' guide to the synchro-cyclotron Visit Point

Francesco La Torre, Bernard Pellequer and Marco Silari

1. The SC Visit Point

You access the accelerator hall via a new entrance to building 300, which is a "timeline" taking visitors back in time from today to 1954. The walls of the hall are made of concrete 4 to 5 m thick. To enter the hall you traverse a 4 m think shielding wall (this section of the wall was originally made of concrete blocks 80 cm x 80 cm x 80 cm, the rest is solid concrete). The hall is about square with a surface area of approximately 300 m^2. The visit area is defined by the metallic floor and confined by the glass barriers. The original floor is seen outside the visitor path. The section of the floor close to the entrance has been removed so that visitors can see the entire accelerator. The section of the wall on the left of the entrance is in fact a sliding door, which was driven by the large motor attached to the door. There is a second sliding door, not accessible to visitors and not visible, behind the grid that you see on the left side of the accelerator when you are in front of it. There is a 50 t overhead crane on the roof.

Around the hall there are old objects that were part of the synchro-cyclotron installation or date to that time. On the wall on the right path of the entrance you see large tools that were used to tighten the bolts of the magnet pieces. At the end of the path you see two control units that were driving two mobile shields. All around (on the walls and on the two tables on the left path) you see other objects of the time such as loudspeakers, telephones, an oscilloscope, a mechanical computer, a typewriter.

Before or after running the 12 minute documentary, you can take time to provide visitors with additional explanations. In the following you find information that will help you to explain the visitors about the accelerator and its past history, and answer their questions (such as: What is the weight of the machine? Which was the RF frequency? How long did the particles take to get accelerated?). The Appendix gives you more detailed information if you are interested to learn more.

If there are questions on the **documentary** itself, explain that the video is about the synchro-cyclotron and not about the history of CERN. Only about 1.5 minutes are devoted to summarise the pre-history of CERN, which does not allow to making justice to every big contribution by other countries e.g. those that lost the competition for the location (e.g. Denmark, Netherlands, France), or to the particular role finally played by Switzerland.

Radiation protection: the SC visitors' path is classified as non-designated area, as the radiation dose rates are well below 2.5 uSv/h, the limit of a non-designated area of low occupancy. Therefore there are no specific requirements with respect to radiation protection and the guides do not need to wear personal or electronic dosimeters. The part of the SC hall behind the glass barriers remains Supervised Radiation Area and the related radiation protection requirements apply. This is why radiation warning panels are placed on both sides of the accelerator past the glass doors.

The weak remnant radiation comes from induced radioactivity in the accelerator components and in the walls due to the beam losses that occurred during the entire operational life of the SC (see table of cyclotron parameters in Appendix C). For your information, the dose rate goes from background level at the entrance and on the side of the SC close to it, and goes up to slightly above 1 μSv/h at the end of the hall, in front of the SC extraction system.

2. Cyclotron

A cyclotron consists of a flat accelerating chamber, housing two or more hollow electrodes called "dees", as in the first cyclotrons (and in the SC) they were D-shaped. A radiofrequency voltage is applied between the electrodes, so that there is an alternating electric field in the gap, but no field inside the dees. The vacuum chamber is placed between the pole expansions of a large electro-magnet, which produces a constant and almost uniform magnetic field perpendicular to the plane of the dees, and makes the particles travel on circular orbits. The cyclotron is intrinsically isochronous: as the particles gain energy they travel faster but progressively jump on larger orbits and thus have to travel a longer path, returning to the acceleration gap always in phase with the RF system. Figure 1 shows the original cyclotron concept. See Appendix for a more detailed description of the operating principle.

3. Synchro-cyclotron

The synchro-cyclotron is a variant of the “classical” cyclotron, designed to overcome the energy limit of the latter. In a synchro-cyclotron the frequency of the RF system is decreased gradually to remain synchronous with the revolution frequency of the particle as the particle becomes relativistic, so that much higher energies can be reached. Accurate tuning of the frequency modulation creates higher particle stability and the particle losses in each orbit are reduced. On the whole the construction of the synchro-cyclotron is similar to the cyclotron except for the modulated frequency of the RF supply.

4. CERN 600 MeV synchro-cyclotron

The 600-MeV proton synchro-cyclotron (SC) was the first accelerator designed and built at CERN. The SC energy was suggested by Enrico Fermi. The design of the machine started in 1953, before CERN came into existence. Building and construction for the machine began in 1954. The machine started operation in August 1957 and the experimental program in April 1958. A picture of the CERN synchro-cyclotron in its first year of operation is shown in Figure 2. Apart from an interruption to undergo a major upgrade in the early 1970s (which included the installation of a new axial ion source replacing the original radial source, a new radiofrequency system, new magnet coils and a new vacuum chamber), the accelerator had been in operation for 33 years until it was shutdown in 1990, providing a wealth of physics results with experiments with proton, neutron, muon and pion beams. Just to mention one thing, the first bubble chamber used at CERN was operated at the SC. The synchro-cyclotron after the improvement programme (SC2) and as is seen today is shown in Figure 3.

The SC initially served two experimental rooms located on both sides of the accelerator hall: the proton hall and the neutron hall. Experiments were done both with protons and with secondary particles (pions, muons and neutrons). Protons were extracted from the accelerator and delivered via beam transfer lines to the proton hall. You see the first part of the transfer line with the first focussing quadrupoles on the left side of the accelerator. An internal target was used for producing secondary particles, located on the other side of the accelerator with respect to the extraction system. In 1964 the ISOLDE facility was approved, a new underground experimental hall was built and experiments started in 1967. ISOLDE was transferred to its present location at the PS Booster when the SC was shut down.

The milestones in the SC history are listed in the Appendix.

5. Main accelerator parameters

The synchro-cyclotron was designed by an international group under the direction of Professor C.J. Bakker. The machine came into operation in August 1957, and since then it delivered a 600 MeV proton beam with an intensity that went progressively up from 0.3 μA to 1 μA. After the improvement program, the new intensity aimed at 10 μA, with a new and more efficient regenerative beam extraction system. The extraction efficiency increased from about 5% (a very low value compared with present standards!) to 70%.

The intensity improvement was mainly due to the use of a new type of ion source and to the increase of the repetition rate from 55 to 360 Hz. This latter increase resulted from the use of a rotating capacitor (ROTCO) for generating the frequency swing of the RF system, instead of the tuning-fork system used previously. At the same time, the energy gain per turn went from 3 keV to 20 keV. In the ROTCO the swing in radiofrequency from 30 MHz to 16.8 MHz at extraction was obtained by the change in capacity when the rotor blades, three rows with 16 teeth each, passed four rows of peculiarly shaped stator blades. It was a very complex system: two were built that could be exchanged for repair. The one installed is the second unit (ROTCO 2). The ROTCO was pulled back on rails (a section of which can still be seen) and picked up by the overhead crane.

The maximum magnetic field that can be produced between the poles of a large room-temperature electromagnet is about 2 T. This field can be reduced progressively to 1.8 T with increasing distance between the poles to achieve focussing of the beam. Such a field guides and focus 600 MeV protons on a maximum orbit of 2.25 m radius.

Surrounding each pole piece is a magnet coil made up of 9 double pancakes wound from hollow aluminium conductor through which cooling water flowed. These double pancakes, all identical, comprising 37 turns, were operated at a current of 1850 A. The conductor is of rectangular cross section bore through which the cooling water flowed.

See Appendix for more details on the accelerator parameters.

6. Main physics results

The main particle physics results achieved at the SC are: the first observation of the electron decay of the pion, which proved an important prediction of the weak interaction theory; the first precision measurement of the muon anomalous magnet moment; the first exact measurement of the decay rate of the positive pion into a positron, neutrino and neutral pion; the muon capture in hydrogen. A more detailed of the most important experimental results list is given in the Appendix.

7. Building

The building housing the synchro-cyclotron rises up on three levels: the large hall at the street level housing the upper half of the accelerator with the extraction beam lines; the underground level -1 that accommodates the bottom part of the machine; the underground level -2 housing the axial support of the ion source and the hydraulic bearings of the two moving shielding walls. A schematic view of the SC ground level with the proton and neutron experimental rooms is shown in Figure 4.

The two experimental rooms were decommissioned within a few years after shutdown and were converted into office space for the ALICE collaboration. The SC hall has been refurbished in 2012/13 and officially inaugurated, in the presence of the CERN Council, as EPS (European Physical Society) historic site and new CERN visit point on 19 June 2014.

FIGURES

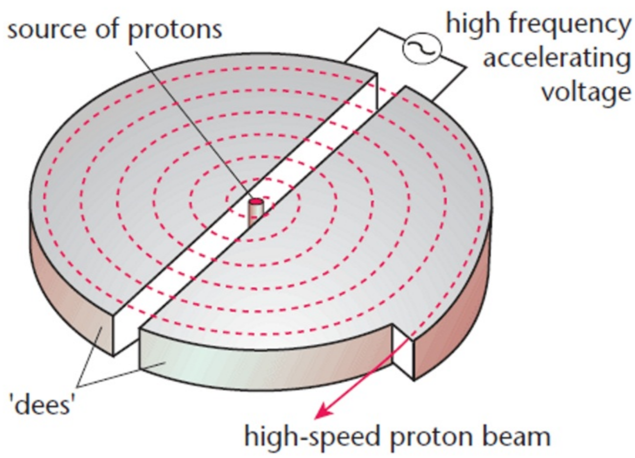

Figure 1. Schematic diagram illustrating the operation of the classical cyclotron; the magnetic field (not shown) is perpendicular to the plane of drawing.

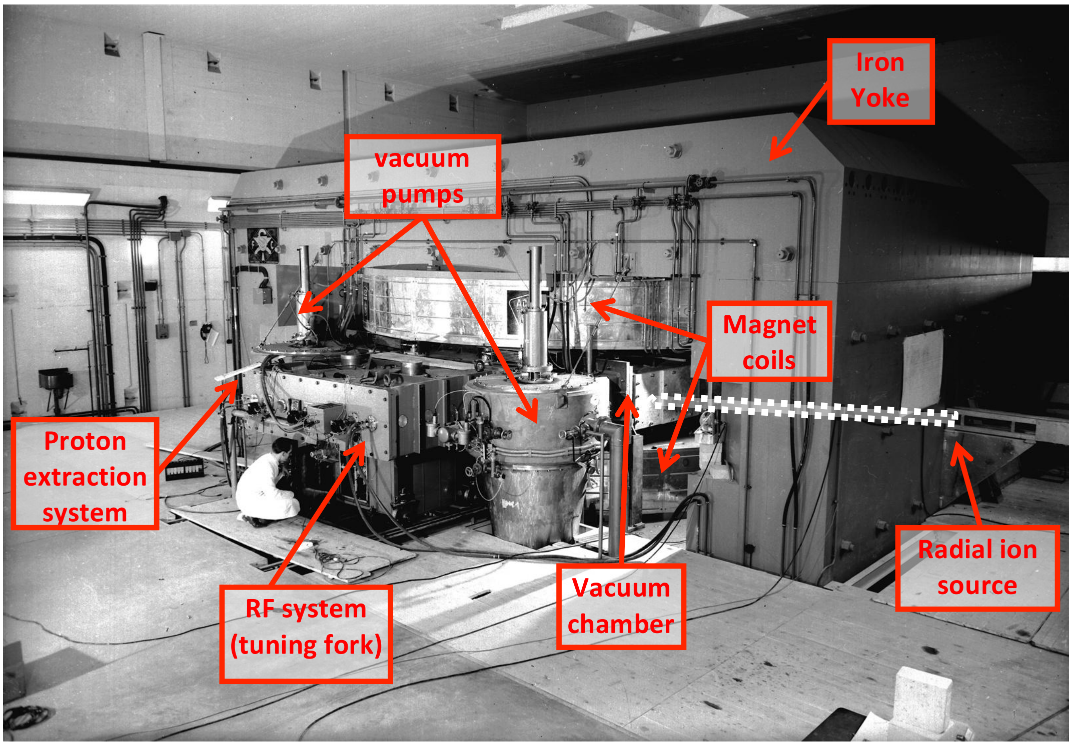

Figure 2. The CERN synchro-cyclotron in 1957 (SC1).

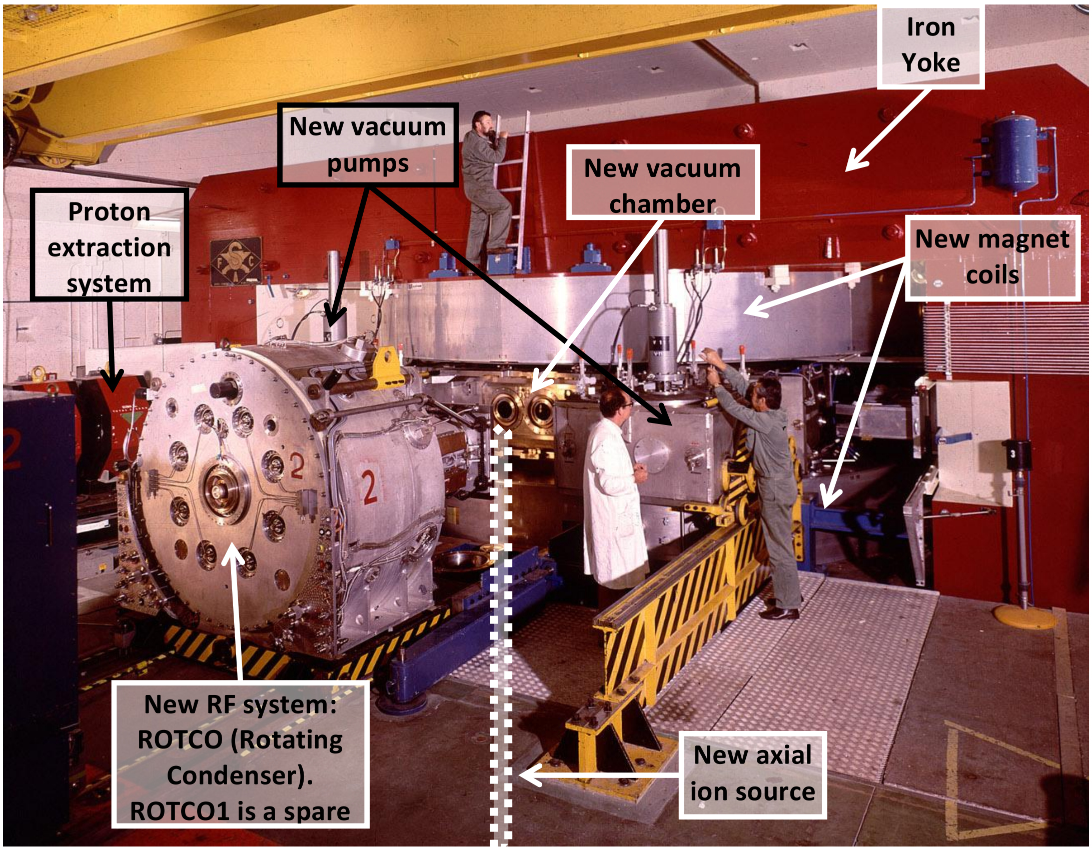

Figure 3. The synchro-cyclotron after the improvement programme (SC2) as it can be seen today.

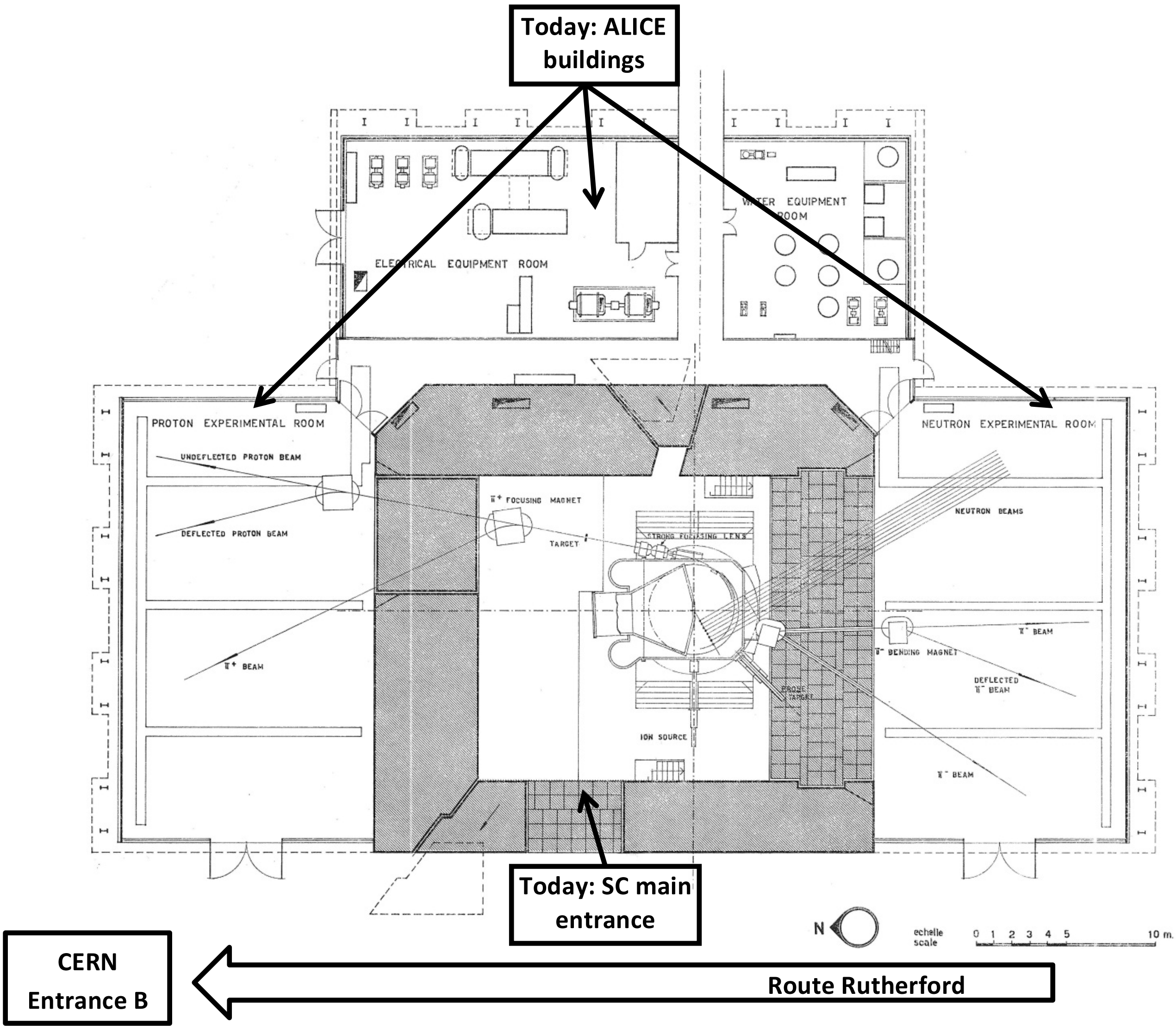

Figure 4. Schematic view of the SC ground level and its experimental rooms.

APPENDIX – IF YOU WANT TO KNOW MORE…

A. Cyclotron operating principles

The accelerated ions moving in a constant uniform magnetic field, perpendicular to the initial velocity, are subject only to the Lorentz force $\mathbf{F}_L = q\mathbf{v} \times \mathbf{B}$, where q and $\mathbf{v}$ are the charge and the velocity of the particle and $\mathbf{B}$ is the magnetic field induction. The charged particles experience a force transverse to their motion as well as to the direction of the magnetic field, the intensity of which is proportional to the velocity of the (non-relativistic) particle and to the field

$$F = qvB \tag{1}$$

Hence the centripetal force which the particles experience is given by

$$\frac{mv^2}{R} = qvB \tag{2}$$

If the magnet produces a strong enough uniform field, the particle moving perpendicular to the field follow a circular path of constant radius R

$$R = \frac{mv}{qB} \tag{3}$$

The time T required travelling one orbit of radius R with constant velocity v is

$$T = \frac{2\pi R}{v} = \frac{2\pi m}{qB} \tag{4}$$

The revolution frequency for a non-relativistic particle, also called "cyclotron frequency" is then given by

$$f = \frac{1}{T} = \frac{qB}{2\pi m} \tag{5}$$

In a conventional cyclotron, the cyclotron frequency is usually around 10 MHz for an RF power of around 100 kW. The accelerated particles are emitted from an ion source located in the centre of the machine, between the two polar expansions of the magnet. Starting from the source, the particles travel in circular orbits bent by the magnetic field. As their path passes through the gap between the two dees (Figure 1) they are accelerated by the RF electric field. While travelling inside the electrodes they are screened from the electric field and are only subjected to the magnetic field. While the ions travel inside the electrode the RF polarity reverses, so when half a turn later they return to the gap between the dees they find again the right electric field. Therefore, the particles are repeatedly accelerated each time they cross the gap. The orbital radius is initially small and as the particles accelerate, they spiral out to progressively larger radii. The cyclotron is intrinsically an isochronous accelerator: as the particles gain energy they travel faster but jump on larger orbits as the magnetic field is constant, and return to the acceleration gap always in phase with the RF system. The particles are then moved out of the magnetic field and extracted from the cyclotron. If the particles are extracted at a radius R_f, from expression (3)

$$R_f = \frac{mv_f}{qB} \tag{6}$$

where v_f is the velocity of the particle at extraction. In a non-relativistic cyclotron the final energy of the particle at extraction is then given by

$$E_f = \frac{1}{2} m v_f^2 = \frac{\left(qR_f B\right)^2}{2m} \tag{7}$$

The final energy is inversely proportional to the mass of the particle and directly proportional to the square of the radius at extraction and to the square of the magnetic field. High energies require high magnetic fields or large orbital radii, which require increasing the diameter of the pole expansions, and therefore size, weight and cost of the magnet.

Moreover, the condition for the validity of the classical approximation for the cyclotron frequency given by equation (5), limits the maximum energy to a few percent of the rest energy of the particles. In its original design with a flat pole, a classical cyclotron can typically reach a maximum energy of around 20 MeV. Higher energies (up to hundreds MeV) are achieved in cyclotrons of more sophisticated design, adopting more complex magnet pole shapes or in a synchro-cyclotron.

B. Synchro-cyclotron

The orbital or cyclotron frequency of a relativistic particle is given by

$$f_R = \frac{qB}{2\gamma\pi m_0} \tag{8}$$

where m_0 is the invariant rest mass of the particle and γ is the relativistic factor given by

$$\gamma = 1/(1-\beta^2)^{1/2} \tag{9}$$

and $\beta = v/c$ is the ratio between the velocity of the particle v and the velocity of light c. The relativistic increase of the mass, as the particles approach a fraction of the velocity of light, causes the revolution frequency of the particles to decrease so that they lose the isochronism with the RF frequency, finally fall out of resonance with the accelerating voltage and are no longer accelerated and eventually decelerated.

In a synchro-cyclotron the frequency of the RF system decreases during acceleration to remain in phase with the revolution frequency of the particles. The downside is that the particles are no longer distributed along the whole spiral trajectory as in a cyclotron, but they may only be accelerated in short pulses, because the RF can only "pick up" a bunch at the time from the ion source and has to guide it through the entire acceleration process until extraction. The bunches leave the source at a rate equal to the rate of the frequency modulation and so the beam produced by the machine is pulsed at the same rate, leading to a large reduction of the average beam intensity with respect to the cyclotron. On the other hand, an important advantage offered by the synchro-cyclotron is that since the orbit stability is greater, the particles are accelerated over a much greater number of turns and thus it is possible to use a much lower accelerating voltage.

C. Main parameters of CERN synchro-cyclotron

The table lists the SC performance before (SC1) and after (SC2) the improvement programme, along with some mechanical parameters

Machine parameters	SC1	SC2
Proton kinetic energy (MeV)	600	600
Internal proton beam (μA)	1.5 (~ 6 x 10^{12} protons per seconds)	7 (~ 6 x 10^{13} protons per seconds)
Extracted proton beam (μA)	0.07 (~ 4.4 x 10^{11} protons per seconds)	7 (~ 4.4x 10^{13} protons per seconds)
Extraction efficiency (%)	5	50 to 70
Energy spread (FWHM) (MeV)	5	0.5
Acceleration time (ms)	8.5	1.3
Average energy gain per turn (keV)	3	30
Number of revolutions	2×10^5	3×10^4
Repetition rate (Hz)	55	360
Protons per pulse	1.2 x 10^{11}	1.3 x 10^{11}
RF frequency swing	30.6 – 16.6 MHz	30.4 – 16.6 MHz

Magnet	Peak magnetic field	1.94 T
	Total weight	2500 t
	Pole diameter	5 m
Coils	Diameter	7.2 m
	Weight of each coil	60 t
	Weight of the aluminium of each coil	27 t
RF system	Weight of ROTCO	9 t
Vacuum system	Residual pressure	5 x 10^{-7} torr

D. Milestones in the SC history

1954: excavation works of the SC building

1957: 1st August, the SC produces its first beam at fully energy

1958: April, start of the experimental program

1965 – 1967: commissioning of an Isotope Separator on-line Detector, the ISOLDE underground experimental area. A vast range of short-lived nuclei became available for study at this facility, which attracted hundreds of nuclear physicists to participate in the experimental programme. The SC was adapted to provide beams for ISOLDE, and it received its first beam in October 1967.

June 1973 to September 1974: Improvement Programme: long shutdown for a major upgrade of the SC with the aim of increasing its mean beam intensity and improving the efficiency at which the circulation beam could be extracted from the machine. New coils, vacuum chamber, RF system and new axial ion source were installed.

1974: "New" machine called SC2 commissioned, energy reaches 604 MeV on 1st October and ten times higher beam intensity (10 μA at design value, although it has never reached more than 4.3 μA)

1976: first runs with $^{3}He^{2+}$, $^{12}C^{4+}$ (1979), $^{16}O^{6+}$,$^{14}N^{5+}$ and $^{20}Ne^{6+}$ (1980) ions

1990: 17th December, end of operation

E. SC main achievements

Particle Physics

1960: first observation of the electron decay of the pion (which proved an important prediction of the weak interaction theory) $\pi^{+} \rightarrow e^{+}\,\nu$

1960 – 1961: first precision measurement of the muon anomalous magnet moment (g -2)

1962: first observation of the decay $\pi^{+} \rightarrow \pi^{0}\ e^{+}\,\nu$ (the first exact measurement of the decay rate of the positive pion into a positron, neutrino and neutral pion)

1963: Measurements of the e^{+} helicity from μ^{+} decay

1967: Muon capture in hydrogen (the most accurate measurement of the capture rate of muons in liquid and gaseous hydrogen)

Exotic atoms

- measurement of the muonic X-rays (muonic atoms) (1961)
- investigation of nuclear structure: distribution of nuclear charges and magnetic moments
- electromagnetic interaction between the muon and the nucleus

Pion – nuclear interactions

- Pionic atoms: strong interaction effect (1974)
- Basic πN data: pion – nucleus elastic scattering
- Pion double – charge exchange
- Pion production and absorption

Condensed matter physics

- μSR-experiments (Muon Spin Rotation)

Nuclear physics at ISOLDE

- Spallation, fission, fragmentation reactions with production of radioactive species (exotic nuclei)
- Studies on nuclear masses, nuclear shapes, exotic decays

Optical spectroscopy of radioactive atoms at ISOLDE

- RADOP (Radioactive Detection of Optical Pump): discovery of shape staggering and shape coexistence in the Hg region
- Rabi apparatus for the measurement of spins and magnetic moments
- LIOP (Laser induced optical pumping)
- Collinear laser spectroscopy
- RIMS (Resonance ionization mass spectroscopy)