HIGH POWER CYCLOTRON COMPLEX FOR NEUTRON PRODUCTION

Yury Alenitsky, Alim Glazov, Galina Karamysheva, Sergey Kostromin, Eugene Samsonov, Sergey Dolya, Leonid Onischenko, Sergey Vorozhtsov, Nikolay Zaplatin
Dzhelepov Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, 141980, Str. Joliot-Curie, 6, Dubna, Russia

Abstract

Opportunities are considered for production of accelerated proton beams with power as high as 8-10 MW, using the cyclotron method of acceleration. In PSI, a high current cyclotron complex unique in the world, a proton beam with average power of 2 MW is obtained, and technical opportunities for beam production with power more than 2 MW are considered now. It is planned to achieve a beam current of more than 3 mA in 2012. The PSI cyclotron facility consists of an 800 keV preinjector, 72 MeV cyclotron injector, and the 590 MeV ring cyclotron.

Now the cyclotron seems to be the cheapest accelerator for production of proton beams with energy up to 10 MW. There are some proposals to create such complexes; all of them have common properties. A full cycle of acceleration consists of three stages: high-voltage injection with bunching of continuous beam, then preliminary acceleration in a four-sector cyclotron, and acceleration up to the maximal energy (500-800 MeV) in a ring cyclotron with six or more sectors. At the first stage of acceleration, instead of injection by high voltage, one can use a few cyclotrons in parallel, with injection in the subsequent cascade of beam for intensity [1, 2, 3].

ELECTRON MODEL OF RING ISOCHRONOUS CYCLOTRON

In the Department of New Accelerators at the Laboratory of Nuclear Problems, Joint Institute for Nuclear Research (LNP JINR), high intensity projects began in the first 60 years of the last century. One of the first works [4] now offers a cyclotron with a high intensity proton beam for neutron production.

To study the beam dynamics at a high density of accelerating particles, the effects of space charge, and the influence of magnetic rigidity on the amount of accelerated current, in 1964 the Laboratory began design and construction of the ring cyclotron electron model with strong focusing. Use of the electron model has allowed modelling of the proton accelerator's entire energy range in a rather small installation.

The magnetic field of the model provides isochronous movement of accelerated particles, with field changes from 14 G up to 25 G in the radius range 180-1010 mm. It is formed through 13 pairs of concentric current coils. The axial focusing field is created by the special variation current coils, which forms eight spiral variations of the magnetic field. In this field the axial oscillation frequency Q_z can be changed in the range 1.1 - 1.45. The general view of the model is shown in Figure 1; its design is described in detail elsewhere [5].

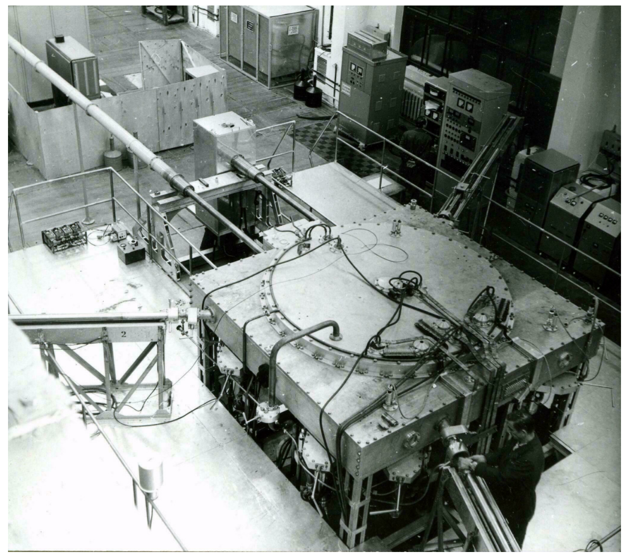

Figure 1: Electron model of the ring isochronous cyclotron (general view).

In the beginning of 1968 the model construction was completed. The electron beam was accelerated to a final energy E=409 keV with intensity 600 μA [6]. The density of the accelerated particles approached the space charge limit. It was experimentally shown that increasing the accelerating voltage and the frequency of the axial oscillations increases the beam current. For the beam size of Δ r, Δz = 5 mm, beam intensity was 0.6 mA.

These results from the electron model imply that for protons injected at 12 MeV, a proton beam current of 24 mA can be reached, and held at Δr, Δ z = 5 mm. This intensity increase, and other technical tasks, required highly effective extraction; intensity losses should not exceed 10^{-3}-10^{-4}.

Cyclotron beam extraction methods based on excitation of coherent free oscillations have been known for 70 years, but resulted in beam losses in the chamber of the accelerator of several percent and more; this is unacceptable when accelerating a beam of some MW.

Searching for mechanisms that could solve this problem resulted in discovery of the closed orbit expansion effect (COEE), which is due to changing the form of a magnetic field of the sector structure. COEE was experimentally confirmed [6] in 1974 on the electron model of the ring cyclotron. The research showed that, for special magnetic field variations at the

fax:+7-09621-66666, corresponding author e-mail address: alen@nusun.jinr.ru

extraction radius, the separation between the orbits of accelerating particles can be increased by up to few cm (in the usual isochronous field this separation is no more than a few mm). However, in experiments on the electron model, it was not possible to achieve complete separation of orbits, so the efficiency of the beam extraction was only 95%.

MODEL OF MAGNETIC SYSTEM RING CYCLOTRON (1:5) (SUPERCYCLOTRON)

These achievements over the last 70 years have enabled the building of a model of the magnetic system of a sector isochronous cyclotron with proton energies of 800 MeV – the *supercyclotron* [7]. Figure 2 shows the stand of this model of the magnetic system, consisting of two sector magnets and a system for field measurement.

Research on the supercyclotron magnetic system using models at different scales has proved the ability to form a magnetic field that combines conditions for strong focusing and isochronism at the full range of radia.

Briefly we shall consider the conditions for achieving COEE. By definition, the factor of the orbit expansion of the cyclic accelerator looks like:

$$\alpha = P/r * dr/dP.$$

Actually the length of an orbit in a cyclotron with a varying field differs from the length of a circle with radius r. It can be expressed as $P=eBr\Lambda$, where Λ reflects the increase of the particle orbit length in connection with variation of a magnetic field. After some transformations it is possible to rewrite that equation as:

$$\alpha = (1+n+r / \Lambda * d\Lambda /dr)^{-}.$$

Further, it is possible to show that the separation between orbits can be made large enough so that

$$n+r /\Lambda * d\Lambda /dr = -1,$$

or in a simplified variant,

$$\Lambda = 1 + (3/2+n+m) * \varepsilon^2/2N^2,$$

where $m=r /\varepsilon * d\varepsilon /dr$.

Thus to adjust COEE it is possible to change the average field or its variation derivative. Research on this question was carried out on an example of the magnetic system of the supercyclotron. With the help of model experiments and numerical calculations, the parameters of the beam extraction system elements were chosen on the basis of COEE.

The right half of the plan of the supercyclotron is shown in Figure 3; three of the four resonators are shown. The scale is shown on an axis of the resonator; the radius r from the center to the wall of the chamber is slightly more than 800 cm.

The magnetic system consists of eight sector C-shape magnets (two magnets were modeled at 1:5 scale). The system of corrective and rejecting magnets that creates a magnetic field for COEE is shown. The numerical calculations of proton beam dynamics were carried out for final emittances $\varepsilon_r = 2\pi$ mm*mrad and $\varepsilon_z = 8\pi$ mm*mrad. From calculations it follows that in created field at an energy gain of 2 MeV/turn growth occur of the orbits separation up to several centimeters during several turns almost without distortion of the emitanse size. That allows to establish in the specified place rejecting septum and to extract the beam lost-free.

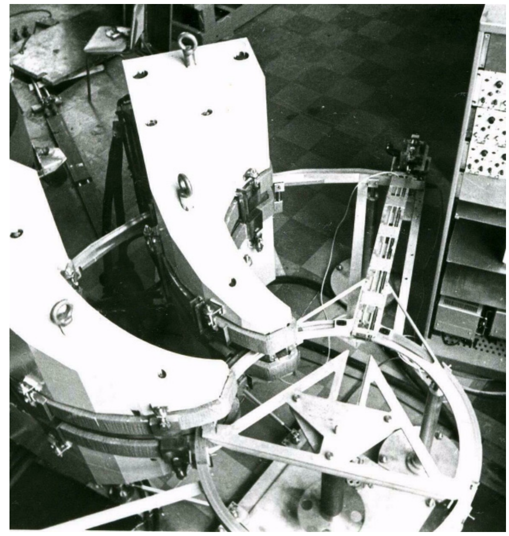

Figure 2: The stand of the supercyclotron magnetic system model (at 1/5 scale).

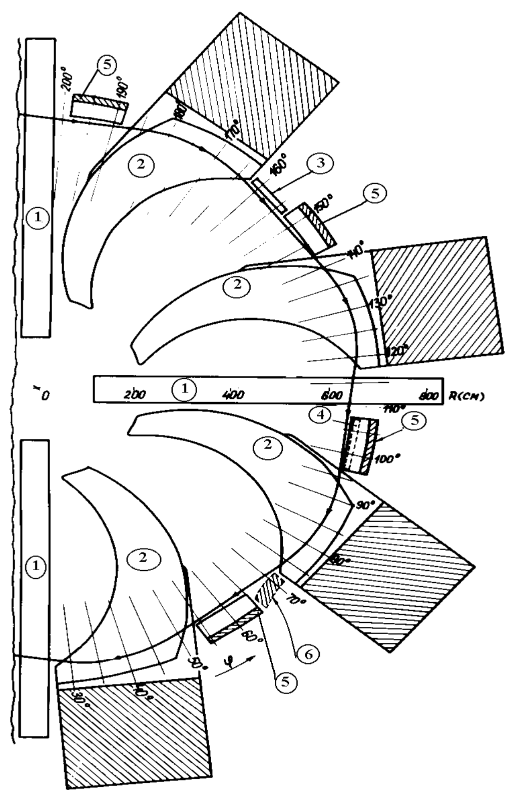

Figure 3: The plan of the supercyclotron includes 1 – resonators; 2—sector magnets; and 3,4,5,6—elements of the system of extraction.

Those calculations were carried out at the end of the last century, when PC performance was not sufficient for additionally accounting for space charge. New computer facilities with multiprocessor PCs should considerably increase the number of particles in a bunch that we can model. That will give more exact results.

CONCLUSION

Analyzing the different ways to increase intensity of the accelerated proton beam using cyclotrons has pointed to some research directions that can be explored with modern computing facilities:

The acceleration of heavier particles (deutrons or $H2^{+)}$ at a given space charge would double the number of hadrons delivered to a target for generation of neutrons. Such proposals are stated in [8-10].

The most realistic such project for neutron physics or control of a nuclear reactor, consists of three steps [10, 11]. The first step is initial acceleration to 5-15 MeV with four-sector cyclotrons. The second step is acceleration to 70-100 MeV with the same type of cyclotron. The third step uses an eight-sector cyclotron with a final beam energy of 600 - 800 MeV. The final energy should be chosen in view of necessity of 100 % extraction; for that it is necessary to achieve complete separation of orbits at the final radius.

REFERENCES

[1] "Working material status of the accelerator-driven systems (ADS)," IAEA, Vienna, Austria, 1996.

[2] A.M.Kozodaev, N.V.Lazarev, V.Shvedov, Accelerator – driven electronuclear systems. PEPAN Letters No. 3 (2004) 120.

[3] R.L. Sheffield, "Utilization of accelerators for transmutation and energy production," in Proceedings of HB 2010, PSI, ICFL, Paul Scherrer Insititute, CH-5232 Villigen, Switzerland.

[4] V.P.Dzhelepov, V.P.Dmitrievskiy et al., "High current accelerators of particles for high energy meson- factory," Successes of Physical Sciences, 85 (April 1965).

[5] A.T.Vasilenko et al., JINR 9-4512, Dubna, 1968.

[6] V.P.Dmitrievskiy et al.m JINR 9-83-290, Dubna, 1983.

[7] A.F.Glazov et al., Proceed. of conf. of accel. (Dubna,1976), vol 1,p. 23; Science, 1977.

[8] L.Calabretta, D.Rifuggiato et al., "A Superconducting Ring Cyclotron to Deliver High Intensity Proton Beams**,**" in Proceedings of EPAC 2000, Vienna, Austria.

[9] Yu. Alenitsky, JINR P9-2002-224, Dubna, 2002.

[10] N.Fietier and P.Mandrilon, "A Three – Stage Cyclotron for Driving the Energy Amplifier," CERN/AT/95-03(ET).

[11] L. Calabretta, M.M. Maggiore, and L.A.C. Piazza, "A Multi MegaWatt Cyclotron Complex to Search for CP Violation in the Neutrino Sector," in Proceedings of Cyclotron 2010.