BEAM EXTRACTION FROM SYNCHROTRONS*

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Abstract

Nearly all synchrotrons have some means of extracting the circulating beam. A description of the various techniques and technological requirements for these beams are given along with the performance expected and achieved.

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The Proceedings of the previous Conferences of this series provide an interesting if not exhaustive chronicle of the development on external beams. Thus in 1956, while the AGS and CERN PS were still in the design stage, the only beam extraction work reported was the Piccioni scheme for the Cosmotron. Several papers on nonlinear resonances were reported but the authors were more concerned with keeping beams in machines rather than getting them out. In 1959, a modification of the Piccioni scheme to fit the AGS was described. More significantly, the fast kicker used to inject into the Stanford-Princeton storage rings described at that meeting was quickly copied for fast extraction from the big synchrotrons. The Cambridge group brought out the suggestion to use a beam instability to extract the beam. This suggestion eventually materialized in the form of their successful current strip ejection. 1961 saw little about ejection from synchrotrons but a paper by Teng covers a theoretical study of resonance extraction from the synchrocyclotron.

In 1963 at Dubna, the fast beams at Brookhaven and CERN were described. CERN reported tests on a prototype resonant extraction system and CEA reported their current strip ejection. In 1965 the CERN group described their completed slow ejection system. Slow ejection was also described for the Frascati electron synchrotron. By 1967 the Princeton-Penn accelerator had an operational resonant extraction scheme. The Conference that year also had an interesting theoretical paper by Kobayashi on resonant extraction. At Erevan two years ago there were several discussions of the performance of the CERN and AGS slow ejection systems. The CERN-Serpukhov collaboration described the fast extraction system being developed for the Serpukhov machine. Preliminary calculations on resonant extraction for that machine were also reported. Thus we see that ejection has been a significant topic at these Conferences. This simply reflects the fact that ejection has been a major concern of the operations staffs of the various laboratories.

What is the present status of ejection? First, consider fast ejection. The principle of fast ejection is quite simple. Between RF bunches, a magnet is switched on which deflects the beam behind a current septum. The septum magnet deflects the beam into the extraction channel which possibly includes some more magnets in the straight sections of the machine. The performance of such a beam is also simple to understand. If the fast kicker magnet is fast enough to switch completely between RF pulses, and if the amplitude is sufficient to move the beam cleanly past the septum, the efficiency should be 100% and the beam emittance should be exactly equal to that of the circulating beam. Of course, any tails on the beam spatial distribution will cause some loss in efficiency, but existing fast beams come very close to ideal performance. Although there are many details of hardware, by far the most crucial item is the fast kicker. A typical fast kicker is the one designed for the Serpukhov machine by the CERN-Serpukhov collaboration with full aperture of 10×14 cm^2, rise time of 150 ns, and 1000 G field.

Originally, the fast ejection concept was developed to provide external beams for physics experiments. Now some of the most elaborate extraction systems are those used to extract the beam from one machine for injection into another. The ejection systems from the CERN PS for injection into the ISR, at NAL from the booster to the main ring, and at CERN from the booster to the PS are good examples.

The principles of resonant extraction are somewhat more complicated. A variety of theoretical models have been devised to permit systematic analysis of the process. The method described by Kobayashi at the 1967 Conference is worthy of particular mention because of its simplicity and immediate physical insight. To illustrate this model, consider the case of a weak focusing lattice with a ν-value near one third and a single sextupole in the ring. The matrix for three revolutions ignoring the sextupole is simply

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} \cos 6\pi\nu & \sin 6\pi\nu \\ -\sin 6\pi\nu & \cos 6\pi\nu \end{bmatrix} \begin{bmatrix} x_o \\ x'_o \end{bmatrix} .$$

Let $6\pi\nu = 2\pi + \epsilon$, $\epsilon \ll 1$.

$$\begin{bmatrix} x \\ x' \end{bmatrix} \cong \begin{bmatrix} 1 & \epsilon \\ -\epsilon & 1 \end{bmatrix} \begin{bmatrix} x_o \\ x'_o \end{bmatrix} .$$

To $[x]$ we should add the contributions caused by the nonlinearities of the sextupole. To lowest order, these can be computed by assuming the ν-value is exactly 1/3. Thus for one revolution we form

$$\begin{bmatrix} x \\ x' \end{bmatrix} = \begin{bmatrix} \cos (2\pi/3) & \sin (2\pi/3) \\ -\sin (2\pi/3) & \cos (2\pi/3) \end{bmatrix} \begin{bmatrix} x_o \\ x'_o \end{bmatrix} ,$$

$$x = \cos \frac{2\pi}{3} x_o + \sin \frac{2\pi}{3} x'_o = -\frac{1}{2} x_o + \frac{\sqrt{3}}{2} x'_o .$$

*Work supported by the U.S. Atomic Energy Commission.

Then after the sextupole,

$$x' = \text{linear portion} + S\left(-\frac{1}{2}x_o + \frac{\sqrt{3}}{2}x_o'\right)^2 .$$

This term is then transformed to the final state using the matrix for two revolutions. Similarly, we transpose the initial vector around two revolutions, pass it through the sextupole, and transpose the answer through one revolution to the final state. Finally, we add the contribution from the sextupole after the third revolution. We simply add the three nonlinear contributions because we are only interested in the lowest order corrections. The total change (linear and nonlinear) in x and x′ is thus

$$\Delta x = \epsilon x_o' - \frac{\sqrt{3}}{2} S\left(-\frac{1}{2}x_o + \frac{\sqrt{3}}{2}x_o'\right)^2 + \frac{\sqrt{3}}{2} S\left(-\frac{1}{2}x_o - \frac{\sqrt{3}}{2}x_o'\right)^2$$

$$\Delta x' = -\epsilon x_o - \frac{1}{2} S\left(-\frac{1}{2}x_o + \frac{\sqrt{3}}{2}x_o'\right)^2 - \frac{1}{2} S\left(-\frac{1}{2}x_o - \frac{\sqrt{3}}{2}x_o'\right)^2 + S x_o^2 .$$

If we consider the time for three revolutions as the unit of time,

$$\Delta x = \frac{dx}{dt} = + \frac{\partial H}{\partial x'}$$

$$\Delta x' = \frac{dx'}{dt} = - \frac{\partial H}{\partial x} .$$

Thus the equations of motion can be derived from the Hamiltonian

$$H = \frac{\epsilon}{2}(x^2 + x'^2) + \frac{S}{4}(3xx'^2 - x^3) .$$

All properties of the system can be trivially derived from this function. In particular, when H has the value

$$\frac{\left(\frac{2}{3}\epsilon\right)^3}{S^2} ,$$

the equation factors into three straight lines

$$\left(\frac{S}{4}x + \frac{\epsilon}{6}\right)\left(\sqrt{3}\,x' + x - \frac{4\epsilon}{3S}\right)\left(\sqrt{3}\,x' - x + \frac{4\epsilon}{3S}\right) = 0$$

forming the separatrix between stable and unstable motion. The tedious but straightforward transformations required to use this method for realistic synchrotrons can be obtained from Kobayashi's paper.

The numerical methods using digital computers to study beam ejection are also interesting. The method most frequently used proceeds as follows. Assume a fixed point exists. Then near this fixed point,

$$\begin{bmatrix} x_f \\ x_f' \end{bmatrix} ,$$

the motion for three revolutions (or one revolution for integer extraction) is described by

$$\begin{bmatrix} x - x_f \\ x' - x_f' \end{bmatrix} = M \begin{bmatrix} x_o - x_f \\ x_o' - x_f' \end{bmatrix} .$$

If one has a computer program for tracing rays around the machine, then three points noncollinear in the (x,x′) phase plane traced around the machine three times (or one for integer extraction) to form three final points give rise to six equations which can be solved for the six unknowns, the elements of M and the coordinates of the fixed point. Because the motion is nonlinear, this only approximates the solution but a few iterations quickly converges to answers of sufficient accuracy.

The third-integral extraction scheme used at the Brookhaven AGS was designed completely numerically and, based on our experience with this technique, it is my opinion that this is one of those rare problems in which the computer technique brings just as much insight into the problem as would a purely theoretical model. It also has one distinct advantage. The solution for basic parameters of the system can incorporate without difficulty all features such as orbit bumps, other nonlinearities, fringing fields of the septum magnets, etc. without any increase in complexity of the problem.

Resonant extraction systems are now operating at several laboratories. Electron synchrotrons typically use a current strip to simultaneously serve as a septum magnet and a field perturbation to cause instability. These systems usually run at a half-integer resonance. Efficiencies of 70 to 80% are typical. The CERN PS has used an integer extraction system as part of their program for several years. A unique feature of this type of resonance extraction is the very large spiral pitch of two or more centimeters per turn which permits efficiencies of 75 to 85% even with a septum of 3 mm thickness. This efficiency has been improved in later developments using septum lenses and an electrostatic septum. The Brookhaven AGS uses a third-integer extraction system. This system uses two stages of septum magnets. The first septum has a thickness of 0.75 mm so that 80 to 85% efficiency is possible even with the spiral pitch of 0.8 to 1.0 cm per three turns. A very similar scheme has been studied for the Serpukhov machine. The resonant extraction scheme is also being exploited by weak-focusing machines. The $\nu = 2/3$ extraction at the Princeton-Penn machine is almost identical in principle to the AGS scheme.

Most groups with operating beams now believe they have satisfactory agreement between performance and analytical or numerical predictions. This permits us to proceed with the design of extraction systems for future machines with a great amount of confidence.

It is obvious that as soon as the efficiency reaches 80 or 90%, the efficiency itself is no longer the important parameter but the loss. An improvement from 90 to 99% would hardly be noticed by the experimenter but is an order of magnitude improvement to the life of radiation limited accelerator components. With resonant extraction systems, the single parameter most important to the loss is the septum thickness. A very significant suggestion by A. Maschke of NAL was to replace the first stage septum magnet by an electrostatic septum. This is largely motivated by the realization that conventional septum magnets have nearly reached the limit of technology. For example, in the 0.75 mm thick copper septum used at Brookhaven, the only cooling possible is at the edges. Because of the poor heat transfer, the current distribution and hence the fringing field changes significantly during the current pulse. This happens in a magnet with a field of only 1.4 kG with a pulse of only 400 ms. The kick strength routinely obtained in magnetic devices cannot be readily duplicated in electrostatic fields. However, one can design an extraction system such that the kick required in the first stage is modest so fields of $\sim$ 100 kV/cm are interesting. At kick strengths of this magnitude or less, it is clearly possible to make thinner foil or wire electrodes than current sheets of equivalent effectiveness. Once the septum is sufficiently thin another important advantage emerges. Particles that hit the septum probably scatter out of the septum before undergoing nuclear interaction. These particles either scatter into the extraction channel directly or back into the machine for later extraction. To emphasize this possibility, one should use as high Z material as possible. However, to keep the average linear density down, the septum should be constructed of fine wires with several diameters spacing. The deflecting field of such a device is not significantly different than that from parallel planes. The use of wires also improves the ability of the device to sustain high voltage, because the anode is now transparent to electrons or negative ions in any current discharge. Typical parameters are 25 to 50 μ diameter tungsten wires about 1 mm apart with a field of 100 keV/cm.

With such a very thin septum, some new possibilities are quite apparent. First, one really does not need resonant extraction. At NAL, efficiencies of about 99% are expected just using the scattering. Second, there is no real difference between fast and slow extraction; the scattering mode can work in whatever mode the beam is targeted on the wires. If the beam is moved across the septum in a few turns, the beam can be peeled out with low loss. This is the inverse of the multiturn injection used now at Brookhaven. Such a scheme is being developed at Brookhaven to replace the fast ejection system. It has several distinct advantages in flexibility for sharing beam among experiments and it should be an easier system to maintain. Finally, the very thin electrostatic septum answers a very definite need in the experimental area. It is frequently desirable to split a beam into two channels. The beam loss and background from the splitter septum can be a serious problem. The electrostatic septum is again the answer.

In conclusion, the extracted beams are now of major importance to our accelerator facilities. Improvements of these extraction systems can permit better experiments and can enhance the life and performance of the accelerator. Resonance extraction was a major step in this direction. The development of very thin septum devices is the next logical step with equally far reaching importance.

DISCUSSION

H. BRUCK : There has been discussion of using the Piccioni extraction scheme at very high energy, because the angular diffusion gets smaller with energy. How would you compare this system and resonant extraction at very high energy ?

M. BARTON : Even with existing weak focusing machines, the Piccioni scheme can always be improved, even to the point of being competitive with resonant extraction. At higher energy it could indeed again become attractive.

M. OLIVO : What is the diameter and material you plan to use for the septum ?

M. BARTON : We use tungsten wires of 50µ diameter with one millimeter spacing.

R. WIDEROE : How great will the extraction loss be with these 50µ tungsten wires ?

M. BARTON : We should be able to approach 99 % efficiency.

C. GERMAIN : What material for the cathode and what gap value have you used in your latest tests on an electrostatic septum at Brookhave ?

M. BARTON : I believe the cathode is stainless steel.

L. TENG : The cathode on the N.A.L. electrostatic septum is made of titanium with a special anodizing process.

T. KHOE : In the Proceedings of CERN Conference 1969 a paper by Symon and Laslett considers resonance extraction.

M. BARTON : Yes, I forgot to mention that paper.

T. KHOE : For an ideal linear circular machine with ideally one sextupole field, there is no unstable fixed point for $\nu x > 0.682$. This can also be shown by J. Moser's canonical transformation method.

H. REICH : Dr. Barton pointed out that it took some time to adopt resonant schemes for extraction from proton synchrotrons despite the fact that the beam dynamics had been developed (to keep the beam in the machine). I would also like to add "and although resonant extraction had been achieved from the Iowa synchrotron in 1955". It just shows how communication among accelerator people has improved since then !

H.A. GRUNDER : Would you please elaborate on your statement that with 0.2 % non-linearities, extraction at the AGS is not longer possible.

M. BARTON : A field deviation of a few times 10^{-3} from the ideal linear field prevents the extraction from working.

H.A. GRUNDER : But there must be a perturbation which is suitable for resonant extraction even in the presence of guide field non-linearities.

M. BARTON : The only suitable correction is to correct all magnets.

C. GERMAIN : I would like to point out the possibility of using a composite electrostatic septum in order to overcome the drawbacks of a wire array septum : the first part can be a section of wire array with a somewhat lower field in order to reduce the probability of breaking wires when sparks occur and still retain the advantages of the wire array for a reduced Coulomb scattering angle; the second part can be a thin foil septum withstanding the maximum operational voltage.

As regards the possible performance of electrostatic septa, may I refer to the paper in these proceedings in which we present the results obtained at CERN and just say that a working gradient of 120 to 150 kV/cm over a 10 mm gap seems possible, provided all necessary precautions are taken to protect the cathode against stray particles impinging at grazing incidence and triggering sparks.

J.H.B. MADSEN : Will the use of internal targets be maintained at the AGS ?

M. BARTON : The sharing of beam works best with a low percentage on the internal target. As long as the total radiation left in the machine is consistent with acceptable radiation levels, such sharing can be used.