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ASTOR, CONCEPT OF A COMBINED ACCELERATION AND STORAGE RING FOR THE PRODUCTION OF INTENSE PULSED OR CONTINUOUS BEAMS OF NEUTRINOS, PIONS, MUONS, KAONS AND NEUTRONS

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Summary

A new concept for a high intensity accelerator for 2 GeV protons using the continuous 590 MeV beam from the present ring cyclotron has been worked out at SIN. To suppress the cosmic background in neutrino experiments a pulsed beam with high peak current and low duty cycle is required. Using the so called phase expansion effect[1,2] one can combine the acceleration and storage effect in a single isochronous cyclotron ASTOR. With the help of several RF cavities, positioned at different radii it is possible to operate ASTOR either in a pulsed mode at 1500 Hz or in a continuous mode. The anticipated beam powers are .8 MW and 4 MW respectively. The ASTOR concept is also applicable in a possible kaon factory design, acting as an interface between the SIN ring cyclotron and a 50 Hz synchrotron for 15 to 20 GeV protons.

Introduction

In the ASTOR concept a proton beam is first accelerated and then stored before being extracted with a kicker. This storing process can be accomplished with phase expansion[1,2], where the magnetic RF field is used to introduce a phase dependent shift in the revolution frequency: That is, the whole cyclotron acts as an adiabatic debuncher. The equations for the energy E and the phase Φ as a function of turn number n are obtained from the Hamiltonian H :

$$H = q\left[U_1(r)\ \sin\Phi - \frac{1}{k}\,U_k(r)\ \sin k\Phi\right] = \text{const.} \tag{1}$$

$$\frac{dE}{dn} = \frac{\partial H}{\partial \Phi} = q\left[U_1(r)\ \cos\Phi - U_k(r)\ \cos k\Phi\right]$$

$$\frac{d\Phi}{dn} = -\frac{\partial H}{\partial E} = -q\,\frac{dr}{dE}\left[\frac{dU_1(r)}{dr}\ \sin\Phi - \frac{1}{k}\,\frac{dU_k}{dr}\ \sin k\Phi\right]$$

where $q\,U_k(r)$ = peak energy gain per turn from the kth harmonic.
Liouville's theorem limits the maximum number of turns N_s which can be stacked in the phase space (energy, RF-phase). This leads to a kind of "ASTOR-equation" :

$$N_s = a\,\frac{\Delta\Phi_f}{\Delta\Phi_i}\,\frac{\Delta E_f}{E_{Gi}} \tag{2}$$

$\Delta\Phi_i$ = RF phase width at injection
$\Delta\Phi_f$ = RF phase width at extraction ($<360^0$)
a = filling factor (<1)
ΔE_f = total energy spread of extracted beam
E_{Gi} = energy gain per turn at injection

Equation (2) shows that the energy gain at injection should be as low as possible in order to obtain a high stacking efficiency.
With precessional injection one can clear the injection septum even with a relatively low energy gain. The ideal would be H^--injection with stripping, a method which has been investigated for the TRIUMF kaon factory project[3].

A schematic layout of ASTOR is shown in fig.1. With the use of several RF cavities, positioned at different radii as shown in fig.2, it is possible to operate ASTOR in the following two modes :

1. Continuous mode:
   Acceleration of a continuous (CW) 590 MeV proton beam to its final energy (like a conventional cyclotron).

2. Pulsed mode:
   Acceleration plus storage of the proton beam at the final energy and extraction as a single short pulse with a fast kicker.

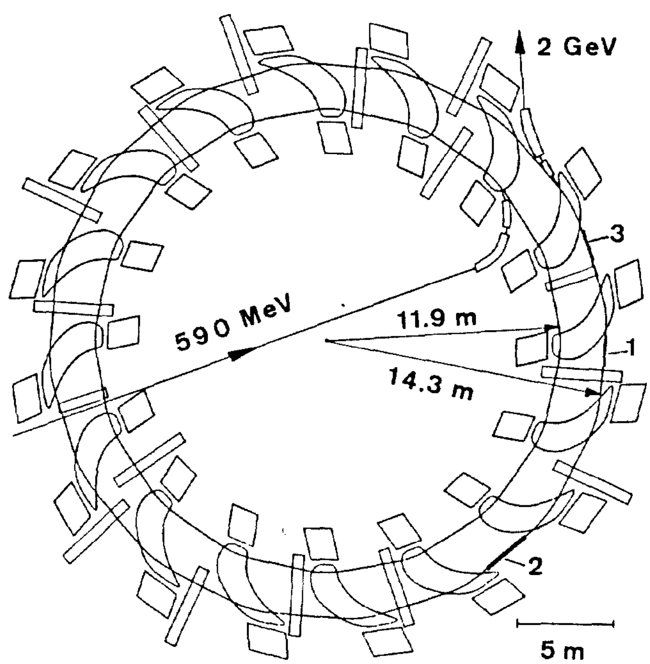

Figure 1: Layout of ASTOR , a .59 - 2 GeV isochronous cyclotron. The ring consists of 16 sector magnets, 14 RF cavities of 50 Mhz and 2 flat top cavities of 100 Mhz. In the continuous mode the beam is extracted with an electrostatic septum (1), while in the pulsed mode the beam is deflected vertically by a fast kicker (2) into a magnetic channel (3).

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Reference design for a 2 GeV ASTOR

For the original design[4] a reference energy of 2 GeV was chosen; this is a balance between the increase of neutrino flux and the maximum proton energy for an economic single stage ASTOR using conventional magnets. If superconducting magnets are used the energy could be raised to the 3 to 4 GeV region.

Fig.3 shows how about 500 turns can be stacked in the extraction region of this 2 GeV ASTOR. The initial phase width and energy gain are taken as 10° and 1.5 MeV. From the final energy spread of 39 MeV we can calculate with eq.(2) that more than 50 % of the available phase space could be filled by the stacking process. The calculation of fig.3 did not include longitudinal space charge forces. Since an isochronous cyclotron is always on transition the additional higher harmonic cavities are essential for the compensation of these longitudinal forces[5].
The stacked beam has horizontal and vertical widths of 30 & 8 mm. It is thus advantageous to extract the beam vertically. The requirements for the fast kicker operating at 1.5 kHz are very similar to the kicker presently under construction for the LAMPF storage ring[6]. In order to avoid beam losses one has to create both an azimuthal and a radial beam void. Since ASTOR operates on the 16th harmonic one can eliminate e.g. 3 out of the 16 micro pulses (50 MHz) at the 860 keV preinjector. This allows a 60 ns rise time for the kicker.
To create the radial void, the 590 MeV beam is switched at 1.5 kHz between ASTOR and the present 590 MeV targets in a 1:3 ratio. This gives an average current of .4 mA with a 2 mA beam anticipated from the new injector[7].

Table 1 shows some key parameters for ASTOR.

Table 1: Reference design for ASTOR .

Energy interval	.59 - 2 GeV
Radius interval	11.90 - 14.35 m
Number of sector magnets	16
Total magnet weight	6000 t
Max. magnetic field	2 T
Max. spiral angle	60°
Horizontal focusing frequency	1.7 - 3.9
Vertical focusing frequency	.7 - .8
Harmonic of acceleration	16
Cavities 50 MHz ,600 kV	6+6+2
Cavities 100 MHz ,600 kV (flat top)	2
Continuous beam mode :	
Average current <I>	2 mA
Orbit separation at extraction	>2.5 mm
Pulsed beam mode :	
Average current <I>	.4 mA
Number of stacked turns	500
Protons per pulse	1.5*10**12
Pulse length of extracted beam	260 ns
Peak current	1 A
Repetition frequency	1500 Hz
Field strength of kicker	.02 T*m
Duty cycle	5*10**-4
Phase width of injected beam	10°
Momentum spread of extracted beam	±.7 %

There are some aspects which need to be looked at more closely in this design:
- Inclusion of longitudinal space charge forces in equations (1).
- Beam loading of the RF cavities by a pulsed high intensity beam.
- Life time of kicker components with kHz repetition rates (10**8 kicks per day!)

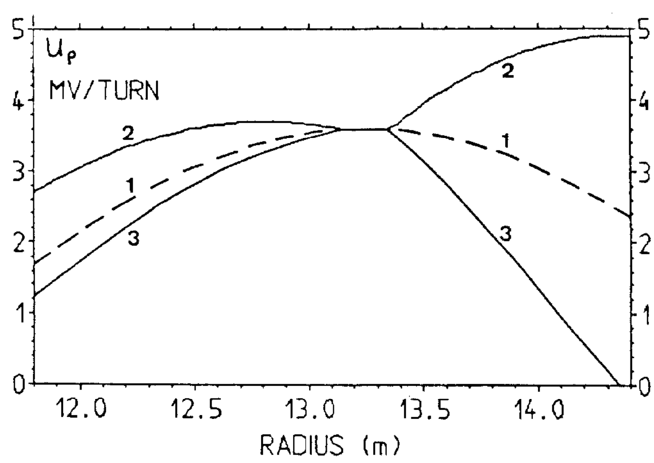

Figure 2: Peak voltage per turn as a function of radius in ASTOR. All 50 Mhz cavities have a cosine-like radial voltage distribution with a maximum voltage of 600 kV. The cavities are partitioned into three groups with different radial positions. The six main cavities provide the general acceleration (curve 1). Additional cavities around the injection and extraction region enhance the acceleration voltage (continuous mode, curve 2) or decrease the acceleration voltage (pulsed mode, curve 3) .

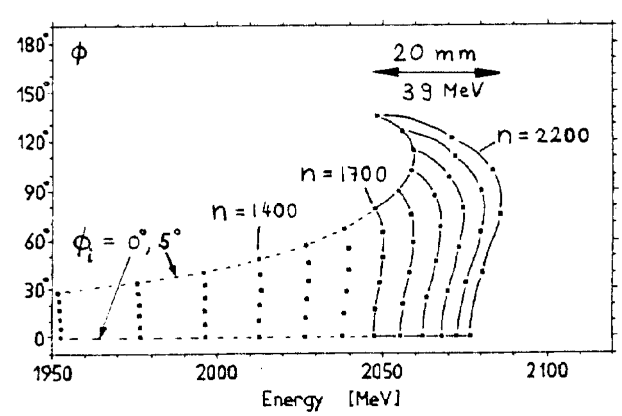

Figure 3: Energy-phase diagram for ASTOR, detail of extraction region. Energy and phase is plotted as a function of turn number n in steps of 100 turns. Shown are 6 particles with initial phases of 0°- 5° at 590 MeV. This corresponds to a phase width of 10°, since curves with negative phases are not plotted due to symmetry reasons. After 1700-2200 revolutions 500 turns are stacked in an interval of 39 MeV corresponding to a radial interval of 20 mm. These stacked particles can be extracted with a fast kicker as a single pulse.

Due to its flexibility as a very intense source of pulsed or continuous protons a 2 GeV ASTOR could support many different experimental activities :

- Neutrino experiments in the few hundred MeV region with high fluxes unattainable so far.
- The production of pions increases strongly between .59 and 2 GeV, leading to corresponding increase in the rate of stopped muons.
- To feed a spallation neutron source. The flux of the presently planned neutron source could be increased significantly in the continuous mode. In the pulsed mode the 1500 Hz repetition frequency could help to reduce the background. Reducing the repetion rate to 150 Hz e.g., gives good time of flight resolution for thermal neutrons. This would still represent a respectable pulsed neutron source, despite the corresponding decrease in average intensity to about 40 µa. The 150 Hz mode intensity could be increased with a dedicated accumulator, e.g. using the betatron phase space stacking method of Khoe and Lari[8].
- For the production of kaons the proton energy of 2 GeV is marginal, but the 100 % duty cycle and the large current of 2 ma could make some low energy (500 MeV/c) experiments possible. The large pion contamination can be reduced with time of flight techniques using the 50 MHz beam structure. But for most kaon experiments the energy of the primary proton beam has to be increased to several GeV.

ASTOR as an Interface to a synchrotron.

The most economic way to reach high energies as well as high intensities is with a fast cycling synchrotron. Cyclotrons although able to produce high average currents, have problems at high energies to achieve enough turn separation for extraction as well as sufficient vertical focusing (requiring spiral angles approaching 90°).
The ASTOR concept offers itself as a potential interface between our 590 MeV cyclotron and a 15 to 20 GeV synchrotron with e.g. 50 Hz repetition rate: Firstly matching the 50 MHz CW-beam to the repetition rate of the synchrotron and secondly, providing a higher injection energy leading to reduced space charge forces as well as a modest 5% frequency swing for the RF-system.

In ASTOR both the RF parameters and the magnetic field are fixed , hence the repetition rate for the ASTOR pulses is only dictated by the kicker and can be of the order of 1 kHz.

The 20 GeV accelerator could be based on three rings, an ACCUMULATOR, a SYNCHROTRON and a STRETCHER, placed inside the same 110 m radius tunnel (similar to the kaon factory design of TRIUMF[3,9]). The accumulator has a fixed magnetic field for 2 GeV protons and parks the 250 ns long pulses from ASTOR along its circumference. After 20 ms the accumulator is filled and all the protons transferred in a single turn to the synchrotron, where they are accelerated to their final energy. For high duty cycle beams the protons could be transferred to the third ring, a stretcher (with a fixed magnetic field) from which the beam is slowly extracted over the next cycle of 20 ms.

Such a 2 GeV ASTOR and 50 Hz synchrotron combined could deliver about 50 µA or 6*10**12 protons per pulse given a 1 mA CW-beam from the 590 MeV cyclotron. This intensity estimate includes the following considerations:

- Since the momentum spread has an influence on the cost of the synchrotron, put a limit of 1% on the total momentum spread of the beam from ASTOR, and also restrict the phase width to less than 200°. This then gives a RF bucket filling of less than 50% . These restrictions reduce the stackable turns N_s to 250 compared with 500 for the reference ASTOR design.
- Since the accumulator radius is more than 7 times larger than the final radius of ASTOR, and two pulses could be stacked at the same azimuth in betatron phase space, using e.g. the half integer resonance of ref.8, one can park 2*7 = 14 ASTOR pulses in the accumulator. The repetition frequency for the ASTOR kicker has thus to be 14*50 = 700 Hz.

If one succeeds in stacking four turns in the betatron phase space, e.g. using a third order resonance, then the repetition frequency for the synchrotron can be reduced to 25 Hz, with a corresponding reduction in RF and magnet costs.

Two options are presently under investigation which would make the ASTOR interface much less expensive, but would lead to somewhat lower intensities. A first, and rather bold option is to convert our 590 MeV cyclotron into an ASTOR device. The second option is to reduce the final energy of ASTOR to, say, 800 MeV. Both the 2 GeV and the 800 MeV ASTOR interface have the advantage, that practically the full 590 MeV beam remains simultaneously available for intermediate energy physics as well as for the spallation neutron source.

Acknowledgments

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