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A STRONG FOCUSSING RING, AS BEAM STRETCHER FOR SYNCHRO-CYCLOTRONS

by

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Abstract

The possibility of injecting the Synchro-Cyclotron extracted proton beam into a strong focussing ring called CYBEST, is investigated. It is seen that pion beams produced in internal targets of such a device show some advantages with respect to present Synchro-Cyclotron beams. More detailed studies are needed however for final judgement. CYBEST is realizable if a sufficiently fast extraction from the Synchro-Cyclotron could be obtained. The magnetic structure is simple but occupies a large area and the required aperture is also relatively large.

General Remarks

The production of secondaries in a Synchro-Cyclotron from an internal target suffers from a number of intrinsic limitations, such as:

a) bad optical properties of secondary beams, which have to traverse intense and variable magnetic fields;

b) fixed momenta of outgoing beams for a given target position and beam path;

c) positive pions produced in forward directions bent and lost toward the inside of the SC;

d) relatively poor target efficiency due to the small focussing forces;

e) effective duty cycle in general considerably lower than unity.

On the other hand the utilization of an external target in the extracted proton beam, together with the advantages of being in a field free region, has serious disadvantages especially for the yield of negative pions and the thickness of the target itself (long source, electron contamination at low energy).

In order to improve the performance of the SC as a physics tool, it has therefore been proposed (C. Rubbia) to study the possibility of injecting the extracted proton beam into a strong focussing ring acting as a beam stretcher, with targets placed, like in an AGS, in field free regions. One would have then the advantages of multitraversals (like for SC internal targets) and of good optics for particles of either sign.

In addition, the strong focussing properties of the ring would lead to higher target efficiencies which would compensate the loss of particles due to the extraction, while the effective duty cycle would be, at least theoretically, close to unity due to the natural debunching of the beam.

Finally, with such a device, secondaries of either sign and of any produced momentum would be available along any given beam path. In general, therefore, one could hope to obtain, under certain assumptions, better and more intense pion beams than with a SC.

The paper reviews the conditions under which the instrument would be feasible and tries to evaluate its possible advantages. It is shown that the latter depend on the values of certain parameters not all of which are exactly known to-date. Preliminary conclusions are however drawn on the basis of the best data available. Possible magnetic structures are also studied, merely to get an idea of the overall size.

For brevity in what follows the strong focussing ring is called CYBEST (CYclotron BEam STretcher).

One can note that the use of a strong focussing beam stretcher may be of some interest in connection with other accelerators (e.g. Linacs) in view of its advantages with regard to duty cycle and targeting.

1. Feasibility and Performance of CYBEST

The feasibility of CYBEST depends essentially upon the achievement of the fastest possible extraction from the SC. The required speed is far from being obtained at present in synchro-cyclotrons, but a certain development work is progressing on a new extraction scheme which shows some possibilities of approaching it, as will be seen later on.

It is therefore justified to try to evaluate the possible performance of the instrument, on the assumption that the required feature for extraction could be obtained.

The merit of CYBEST with respect to any

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given SC varies with the sign and energy of the secondaries considered. In the case of the CERN SC, one can distinguish the following cases :

1) negative pions,

2) positive pions of low energy (e.g. less than ~ 100 MeV),

3) positive pions of high energy (e.g. more than ~ 100 MeV).

1.1 Negative Pions

The highest yield of negative pions is obtained in the SC from internal targets. It is therefore appropriate to compare possible beams of negative pions from internal targets in the SC and in CYBEST.

The performance of CYBEST depends on many points :

1) ejection from the SC,

2) injection into CYBEST,

3) target efficiencies in the two devices,

4) acceptance and in general optical properties of secondary beams,

5) duty cycle.

From the point of view of total numbers of secondaries produced in the target, CYBEST is convenient if :

$$\eta_1 \eta_2 F_{i2} > F_{i1}, \qquad (1)$$

where η_1 = extraction efficiency from SC

η_2 = injection efficiency into CYBEST

F_{i1}= target efficiency in SC

F_{i2}= target efficiency in CYBEST

To get however the pion yield accepted by a secondary beam one has to introduce also an optical acceptance A different for the two cases:

$$\eta_1 \eta_2 F_{i2} A_2 > F_{i1} A_1 \qquad (2)$$

These various parameters can be assessed as follows.

1.1.1 Extraction Efficiency η_1

With the present extraction schemes (Le Couteur), CYBEST is hardly conceivable, mainly because of the too slow and inefficient extraction. Typical figures are :

Extraction time - ~ 200 μsec

Extraction efficiency - ~ 0.05

Such a long extraction time makes the injection into CYBEST practically impossible.

A certain work is going on however on a new extraction scheme[1], based on a kicker coil followed 3/4 λ downstream by an ironless magnetic channel. One sees the possibility of obtaining :

Extraction time - ~ 0.30 μsec

Extraction efficiency - ~ 0.40.

With such a fast extraction the injection into CYBEST becomes possible in one turn. Any slower extraction time would require multi-turn injection.

1.1.2 Injection Efficiency η_2

The requirements of such single-turn injection into CYBEST are the following :

Revolution time CYBEST = 0.30 μsec = ~ 5 x Revolution time SC

Circumference CYBEST = ~ 5 x Circumference SC

Kicker pulse length = 0.30 μsec

Kicker switching-off time <~ 0.030 μsec

Kicker repetition rate = 54 c/s

It seems possible to realize such a system, as mentioned in 3.1. η_2 would then be close to 90%.

A two or three turn injection is also possible, but in such a case η_2 would be smaller and the technical problem more complicated.

1.1.3 Target Efficiencies F_{i1} and F_{i2}

Target efficiencies in strong focussing machines have been studied by various authors, in particular by H.G. Hereward and al.[2], who have prepared a computer programme known to give results in good agreement with experience for the case of CERN PS. We have adapted the programme to CYBEST and carried out studies on Beryllium targets of various forms from which we can conclude that a $F_{i2} \approx 0.20$ can be expected.

For the SC, extensive computations as for strong focussing machines did not exist for our energy. A report by M. Barbier and al.[3] indicates for a Beryllium target a $F_{i1} = 0.07$ in the CERN SC. In order to be consistent with the procedure adopted for CYBEST, we have adapted the computer programme above to the SC. By this we obtain a $F_{i1} = 0.03$ (stochastic operation), which we retain for the comparison. It must be noted that in (2) what counts is the ratio of F_{i2} and F_{i1}, which stands a higher chance to be correct than the two values taken separately.

1.1.4 Acceptance and Optical Properties

The acceptance and in general the optical

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properties of secondary beams from internal targets in the SC and in CYBEST are obviously different. CYBEST is generally more favourable since :

a) the first focussing element can be put closer to the target;

b) sign and momentum of secondaries can be selected along a given beam path by acting only on the elements of the beam itself;

c) the target being essentially in a field free region, chromatic and non-linear aberrations are considerably reduced;

d) there is no lower limit in the energy of secondaries which can be obtained.

To express this quantitatively a number of specific cases should be treated in great details. For the moment we have compared some present SC beams with reasonable CYBEST beams. Gains of CYBEST vs. SC for optics range from 1.7 to 2.5 for π^- energies from 85 to 250 MeV.

1.1.5 Duty Cycle

Many experiments in which the background is produced by the accelerator and which rely on coincidence measurements are seriously affected by the duty cycle of the particle flux.

Background from accidental events normally depends on the ratio of the resolving time τ of the equipment to the duty cycle D. A gain in τ/D therefore represents a gain in signal to noise ratio which in certain respects is equivalent to an increase in effective beam.

In our case, we have :

D in present CERN SC (slow extraction) = 0.40

D in CYBEST (natural debunching) - Theoretical = ~ 1.00

1.1.6 Total CYBEST gain

Values given in the preceding paragraph lead to an overall gain from 4.1 to 6.0, as summarized under 1.4.

1.2 Positive Pions of Energy Lower than 100 MeV

For pions in this energy range, the highest yield is obtained at present from internal targets in the SC. The comparison is essentially the same as for negative pions apart from the fact that in the SC positive pions can be extracted from the machine only if they are produced in the backward direction. One can take this into account in assessing A_1. All other parameters remain the same. One has, for some practical cases, gains as high as 65 (see 1.4).

1.3 Positive Pions of Energy Higher than 100 MeV

With the CERN SC as an illustrative example, these pions can be obtained only from external targets in the extracted proton beam. In CYBEST they can be obtained of course also from internal targets. The usual comparison of the total numbers of secondaries in the range produced in the two cases makes CYBEST advantageous if :

$$\eta_1 \eta_2 F_{i2} > \eta_1' F_{e1} \qquad (3)$$

where η_1 = extraction efficiency from SC (very fast)

η_1' = extraction efficiency from SC (slow)

η_2 = injection efficiency in CYBEST

F_{i2} = target efficiency in CYBEST

F_{e1} = efficiency of the external target in the extracted proton beam

One can note that the two extraction efficiencies η_1 and η_1' are not equal since they refer to two different extraction methods. For injection into CYBEST one has to use the very fast method mentioned above which is also more efficient than the present slower method, used for the extracted beam striking directly an external target. In the present CERN SC $\eta_1' = 0.05$. F_{e1} depends on the actual thickness of the target. Studies conducted by Michaelis and al.[4,5] indicate that there is, for a given material, an optimal thickness from the point of view of pion yield, beyond which the flux of pions accepted by a given reasonable optical system goes down. Such a thickness usually corresponds to 1/4 interaction length, giving F_{e1} = ~ 0.15. CYBEST gains can be then 9.6.

To make the comparison more complete one can point out that in the above one has assumed the same reactions for pion production in the two cases, whereas in practice one could use a liquid hydrogen target in the external beam[6] and therefore profit from the reaction

$$p + p \rightarrow \pi^+ + d$$

which, especially around 600 MeV proton energy yields higher pion flux than other mechanism. This would tend to decrease the above gains.

1.4 Conclusions.

The following table summarizes the comparisons :

Particle	Energy (MeV)	Total gain ($\frac{CYBEST}{SC}$)
π^-	85	4.1
	105	4.8
	250	6.0
π^+	85	14.3
	105	65.0
π^+	>100	9.6

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In evaluating these gains, which are highest for positive pions, one should bear in mind that the comparison is made between an ideal machine, preliminarily assessed, and an actual synchro-cyclotron. More detailed studies may lead to a somewhat different picture. In addition to the yield, however, one has to take into account the various other facts mentioned above, namely

CYBEST vs. SC

a) either sign, variable energy secondary beams obtainable in any given beam path,

b) reduced aberrations,

c) absence of a lower limit in the energy of secondaries,

d) cleaner high energy π^+ beams

2. Magnetic Structure

As already mentioned, only an alternating gradient structure is capable of fulfilling the requirements and of showing the advantages outlined above. Theory and symbols follow Courant and Snyder[7].

2.1 Radius of Curvature.

If one wants to avoid correcting elements for the saturation effects, B_e (field on eq. orbit) should be :

$$B_e \leq 1.0 \text{ T}$$

With $\hat{p} = 1.24$ GeV/c and from $\hat{p} = 0.3\ \rho\ B_e$

$$\rho \geq 4.14 \text{ m}$$

2.2 Structure

In a low energy machine, where the fraction of the circumference occupied by straight-sections is relatively high, various structures can be considered. With the simplest one, the so called FODO, reasonable values of Q can only be obtained by rather high values of n/ρ. If this can be kept in convenient limits, such a structure is however rather economical in circumference and in cost and shows a good momentum compaction function (relatively high momentum spread accepted) but it may require correcting elements. With the FOLO structure, derived from FODO by replacing every D-magnet by a lens L_D and by making the F-magnets twice as long, one obtains the same Q-value as above with considerably smaller n/ρ in the F-magnet and reasonable characteristic of the L_D lens. The structure is however less economical both in circumference and in cost and has a worse momentum compaction function, whereas correcting elements might be avoided. In what follows, an example of FODO and one of FOLO are treated in some details but without any attempt of optimization. A low value of B_e (1.0 T) is used in both cases since a rather long circumference is needed for single turn injection and it is convenient to reduce or eliminate the correcting elements. Figs. 1 and 2 give the schematic layouts of the two machines, while Figs. 3 and 5 show the basic structure.

2.3 Long Straight-sections

At least two long straight-sections are needed, one for injection and the other for internal targets. In fact four would be more adequate : one for injection, two for targets and one for auxiliary equipment (e.g. kicker magnet for target sharing).

The relatively small value of $\bar{\beta}$ compared with a reasonable straight-section length (> 1m) calls for the adoption of a simple matched section following Collins[8]. Figs. 4 and 6 give the layout of the straight-sections for the examples considered.

2.4 Aperture

The useful field region inside the vacuum chamber must accommodate :

a) closed orbit displacements due to misalignments and imperfections of magnets,

b) amplitude of the betatron oscillations due to emittance of the injected beam and to errors in injection,

c) radial spread of the beam due to momentum spread.

Table 1 gives a summary of the aperture requirements for the chosen examples. From this point of view, FODO is more advantageous, especially horizontally, due to the better momentum compaction function.

In addition extra space is required for an efficient targeting. Studies are in progress but one can say already that one may need doubling the horizontal dimensions.

2.5 List of Parameters

Table 2 contains the most important parameters. It will be noticed that both the profile parameter n/ρ in magnets and the gradient G in lenses for the FOLO case are conservative and facilitate the design. It is felt that, for such a case, no correcting elements would be required. For FODO, n/ρ tends to be on the high side, increasing the difficulty of magnet design and requiring possibly correcting elements.

3. Technical Problems

It is not the purpose of this paper to treat in details the numerous technical problems involved. In what follows only two of them are mentioned, simply to complete the description of the device.

3.1 Injection

For single turn injection, the simplest scheme consists in the use of a full aperture kicker which should comply with the following specifications :

Pulse length at full aperture	: ~ 0.30 μ sec
Falling-off time	: < 0.03 μ sec
Total deviation strength	: ~ 40 mrad
Cycling time	: 54 c sec^{-1}

This seems realizable following a paper by Fischer[9].

3.2 Magnet Yoke and B = B(t)

In first approximation, the magnetic field B can be independent of time. In fact, for a flexible and efficient targeting, it is convenient to move the beam onto a stationary target by means of a slight variation of the magnetic field with time. One has :

$$\delta B_e(\rho + \delta\rho) = -B_e \,\delta\rho$$

$$\delta B_e = -\frac{\delta\rho}{\rho + \delta\rho} B_e \cong -\frac{\delta\rho}{\rho} B_e$$

with $B_e = 1.0$ T, $\rho = 4.14$ m and $\delta\rho = \mp 30$ mm., one has

$$\delta B_e = \pm 7.2 \times 10^{-3} \text{ T} = \pm 72 \text{ gauss}$$

Assuming that this field variation takes 16 msec and the return to normal field for the next cycle 2 msec, the eddy currents do not represent a problem if laminations 1-2 mm thick are used. The utilization of such laminations is also technically and economically convenient.

4. Conclusions

CYBEST is realizable if the required extraction time can be achieved. Its advantages, which appear to be of some value in the preliminary treatment of par. 1, can only be finally assessed by more extended studies. The required magnetic structure, although fairly simple, occupies a relatively large area, while no major technical problems, apart from the extraction from the SC, are anticipated. The aperture is also rather large. Finally similar devices may be of some interest in connection with other accelerators (e.g. linacs) in view of their advantages with regard to duty cycle and targeting.

Acknowledgements

The authors are indebted to Dr. E.G. Michaelis and Dr. C. Rubbia for many useful discussions and suggestions. They wish to thank Dr. W. Hardt and Dr. L. Resegotti for advice about the magnetic structure and Dr. E. Keil and Dr. P. Strolin for supplying the synchrotron programme. Thanks also to Dr. J. Ranft for information on target efficiency computations.

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TABLE 1 - Required semi-aperature*

	FOLO (mm)	FODO (mm)
Vertical half-aperture		
$\hat{Z}_{co}$ closed-orbit displacement	3.0	4.0
$\hat{Z}_b$ amplitude of betatron oscillations	15.0	12.7
	18.0	16.7
Radial half-aperture		
$\hat{X}_{ce}$ closed-orbit displacement	4.9	4.6
$\hat{X}_b$ amplitude of betatron oscillations	9.6	8.3
X_s momentum band (1%)	55.0	35.5
	69.5	48.4

* Without taking into account requirements for target operation.

TABLE 2 - List of parameters

	SYMBOL	FOLO	FODO	UNIT
Maximum momentum	p max	1,240	1,240	MeV/c
Peak field at equilibrium orbit	B_e	1.0	1.0	T
Magnetic radius	ρ	4.14	4.14	m
Average radius	R	9.90	8.50	m
Total Q value	Q(H) = Q(V)	4.25	4.25	
Number of normal periods	N	26	26	
Length of a normal period	Lp	2.10	1.60	m
Effective length of a magnet	L_m	1.00	0.50	m
Effective length of a lens	L_l	0.50	-	m
Length of normal straight-sections	L_{ss}	0.30	0.30	m
Profile parameter of magnet (F)	n/ρ	4.54	9.93	m^{-1}
Profile parameter of magnet (D)	n/ρ	-	10.20	m^{-1}
Gradient in L_D lens	G	9.20	-	T m^{-1}
Phase advance in normal period	μ	π/4	π/4	
Number of Collins insertions		2	4	
Total length of an insertion		4.02	3.21	m
Length of field-free section in centre		1.70	1.29	m
Phase advance in insertion		π/2	π/2	

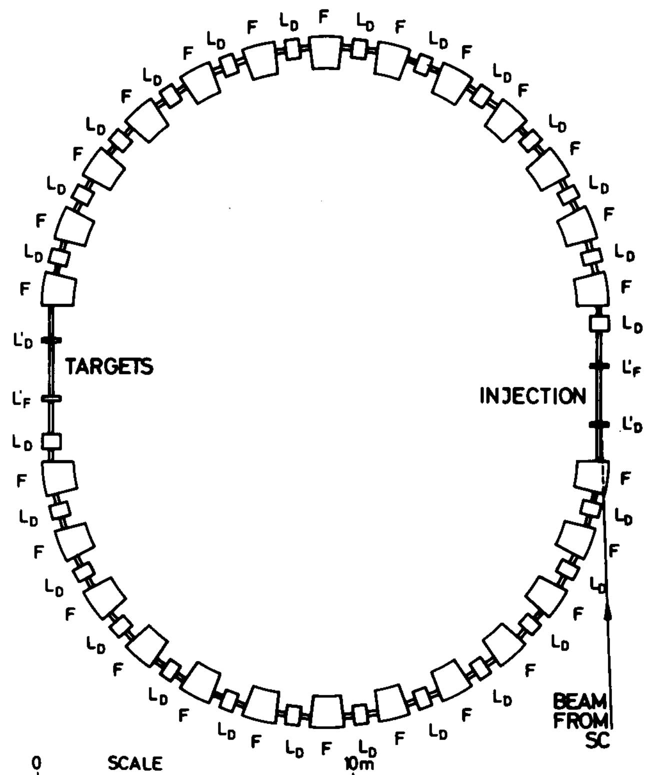


Fig. 1 : CYBEST FOLO Structure

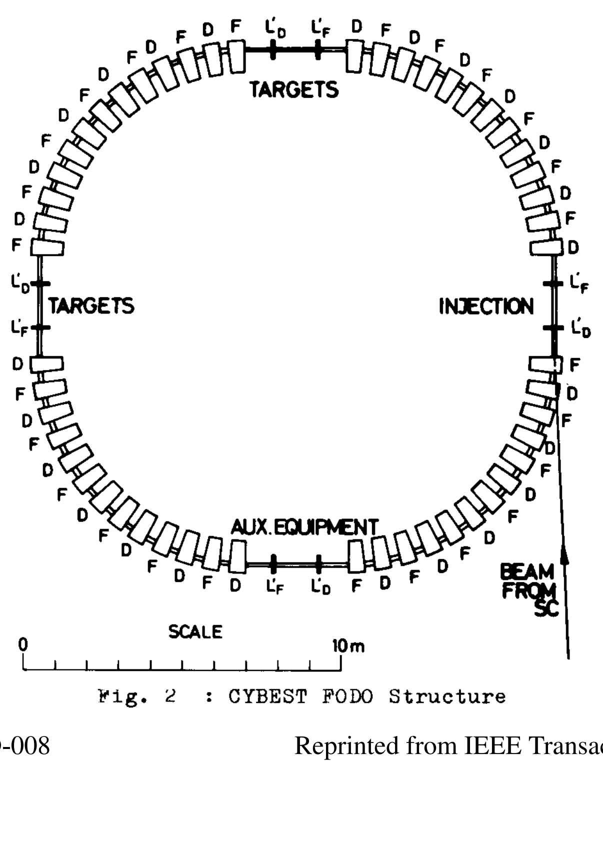
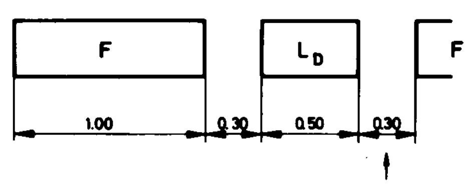


Fig. 2 : CYBEST FODO Structure



26 periods in total

2 periods with Collins straight-sections in place of ↑

Fig. 3 : Basic Structure - FOLO

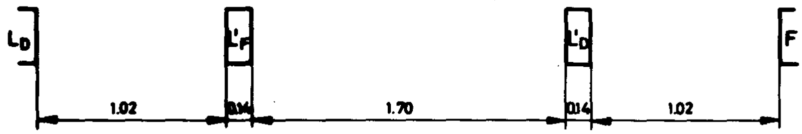


Fig. 4 : Layout of Collins Straight-Sections for FOLO

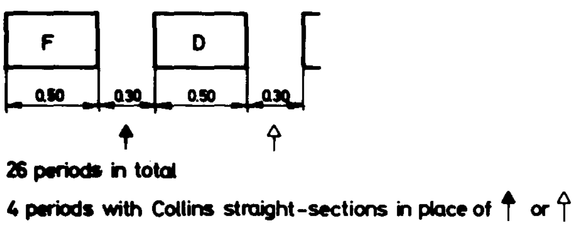


Fig. 5 : Basic Structure - FODO

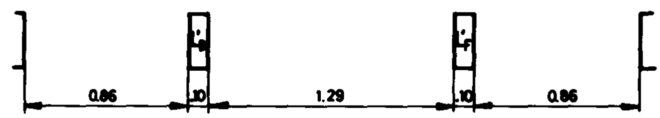


Fig. 6
Layout of Collins Straight-Sections for FODO

DISCUSSION

BLASER: How do you want to make the injection, single-turn injection, or how?

BRIANTI: Well, this depends on the achieved speed from the extraction. Since the circumference of this device is five times the maximum circumference of the cyclotron, we can extract five turns from the SC for a single turn. This is probably too fast, but I was not considering more than two-turn injection, two or three turns as the very maximum. The figures that you have seen were based on single turn.

RICHARDSON: Is there any engineered estimate on cost?

BRIANTI: Not really an engineered estimate. I think that if one has to make a new building, it is certainly in the region of two million dollars. Without a new building, it is not more than 1. 5.