A study of the regenerative extraction system in the CERN synchrocyclotron

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ABSTRACT

A study of the present regenerative extraction system is briefly reviewed and a proposal is given for improvements yielding an increase in extraction efficiency from the present 5% to a theoretical maximum of 85%. Possible means of obtaining beams of high and low duty cycle have also been studied and are briefly discussed.

1. INTRODUCTION

The high intensity ($\geqslant 10\,\mu$ A) expected in the improved synchrocyclotron raises strong demands for a more efficient extraction than the present (5%). As a first step towards an improved system the present extractor was simulated on a computer to get a detailed knowledge of its behaviour as regards reasons for beam loss, energy spread, etc. Based on the results obtained the second step has been to study desirable modifications. This paper gives a brief account of the results of the calculations and also of studies on a device providing for slow or fast extraction and beam stretching on internal targets.

2. GENERAL

The extraction system of the CERN synchrocyclotron is of non-linear conventional configuration with an iron magnetic channel placed 54° before the regenerator. The regenerator lies at 225 cm radius which in the actual magnetic field corresponds to about 590 MeV average extracted particle energy with a spread of 3–4 MeV *FWHM.* The maximum radial and axial betatron amplitudes at normal settings of the machine have been measured to be 10 cm and 1·5 cm, respectively.

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3. SOME RESULTS OF STUDIES ON THE PRESENT SYSTEM

3.1. *Radial motion*

Fig. 1 shows a radial phase plot at the channel entrance of a sample of median plane particles of different betatron amplitude, phase and acceleration history. The acceptance area of the channel is marked in the figure. Each band corresponds to a certain radial amplitude as indicated. The unfavourably large final turn separation of 4–5 cm, given by the projection of each particle band on to the r-axis, indicates that the regenerator is too strong.

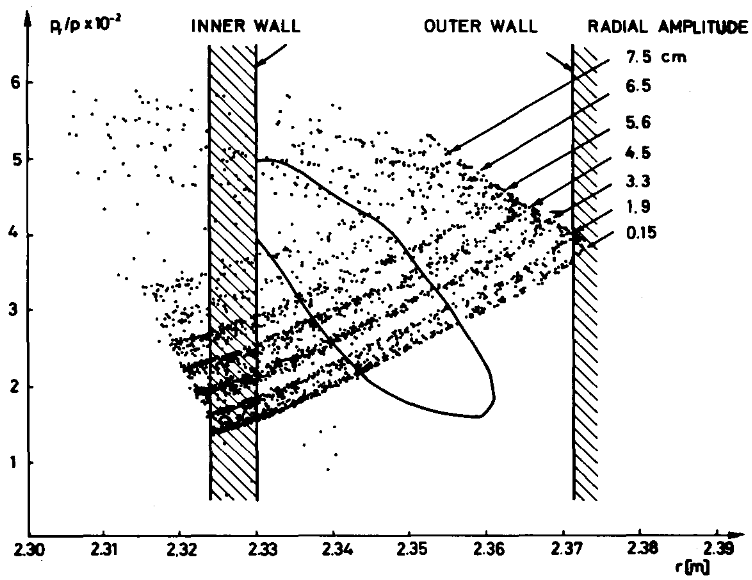

Fig. 1. Radial phase plot at magnetic channel entrance with acceptance area and channel walls indicated

3.2. *Axial motion*

The perturbation on the axial particle motion from the stray field of the channel is demonstrated in Fig. 2, showing an axial phase ellipse of initially ½ cm amplitude on the last three turns. At the last passage before entering the channel (in particular the first section) the protons see a strong field gradient of the order of -1000 G/cm over about 15°, which causes a considerable axial overfocusing. This is shown by the strongly squeezed final phase ellipse. The effect which becomes worse for larger radial amplitudes accounts for most of the beam loss in our cyclotron and is probably relevant for others having the same configuration.

3.3. *Extraction probability*

Following the idea of A. C. Paul[1] the extraction probability for a particle having betatron amplitudes A_r and A_z has been calculated and is given graphically in Fig. 3.

The efficiency for median plane particles lies around 20% and decreases rapidly with increasing betatron amplitudes. Using these curves and the measured amplitude distributions an extraction efficiency of 3% has been calculated.

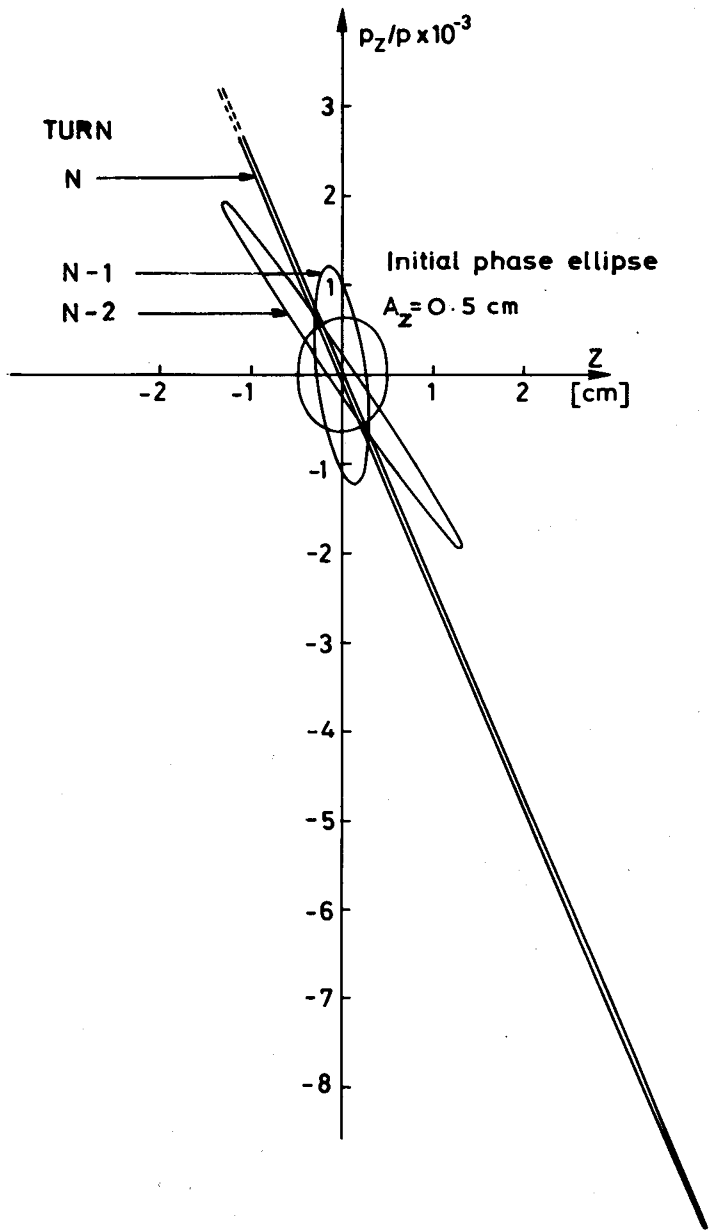

Fig. 2. Axial phase plot at channel entrance showing the evolution of a phase ellipse of 1 cm amplitude on the last three turns

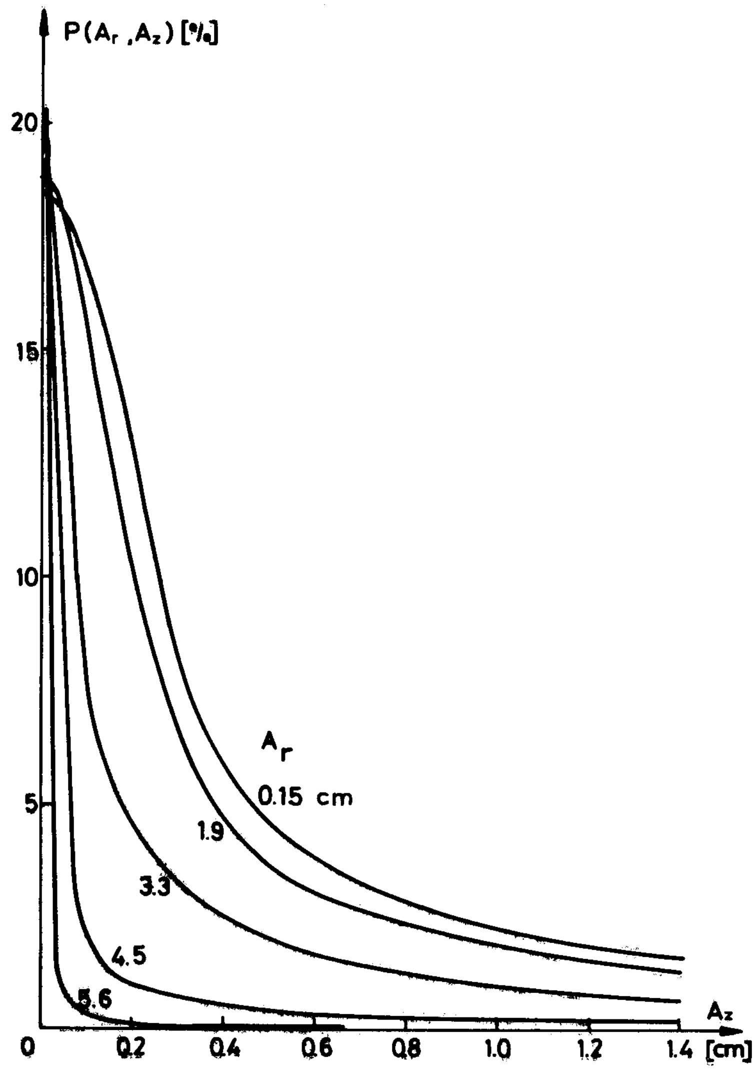

Fig. 3. Extraction probability (P) vs axial amplitude (A_z) for a sample of radial amplitudes

3.4. *Energy distribution in the extracted beam*

The energy E_u at which radial instability occurs is shown in Fig. 4 vs initial radial amplitude (full curve). Weighting the amplitude dependent extraction probability with the betatron amplitude distributions yields at this stage of extraction ($E = E_u$) a primary energy distribution D_u which is independent of accelerating voltage. For particle beams with a wide spread of radial amplitudes, D_u gives the dominant contribution to the final energy distribution D_f.

The second, normally less important contribution to D_f arises from the greatly different excess energy gain δE picked up by the particles after radial instability has occurred. The energy gain differs because the number of turns n needed to complete extraction ($10 \lesssim n \lesssim 70$) as well as the electrical phase φ ($0 \leqslant \varphi \leqslant 90°$) varies considerably. δE can be written explicitly $\delta E = N V_m \cos\varphi$ and shows a roughly gaussian distribution $D_{\delta E}$ between the limits

$$0 \lesssim \delta E \lesssim n_{\max} V_m \tag{1}$$

where V_m means maximum energy gain per turn. Since $n_{\max}$ is practically independent of radial amplitude and voltage, except at very small values, the width of $D_{\delta E}$ from (1) is roughly proportional to V_m and is, as an example, 0·7 MeV (*FWHM*) for V_m = 50 keV. A moderate acceleration voltage consequently reduces the contribution to D_f from $D_{\delta E}$. The average final energy $\langle E_f \rangle = E_u(A_r) + \langle \delta E \rangle$ versus radial amplitude is shown in Fig. 4 (dashed curve).

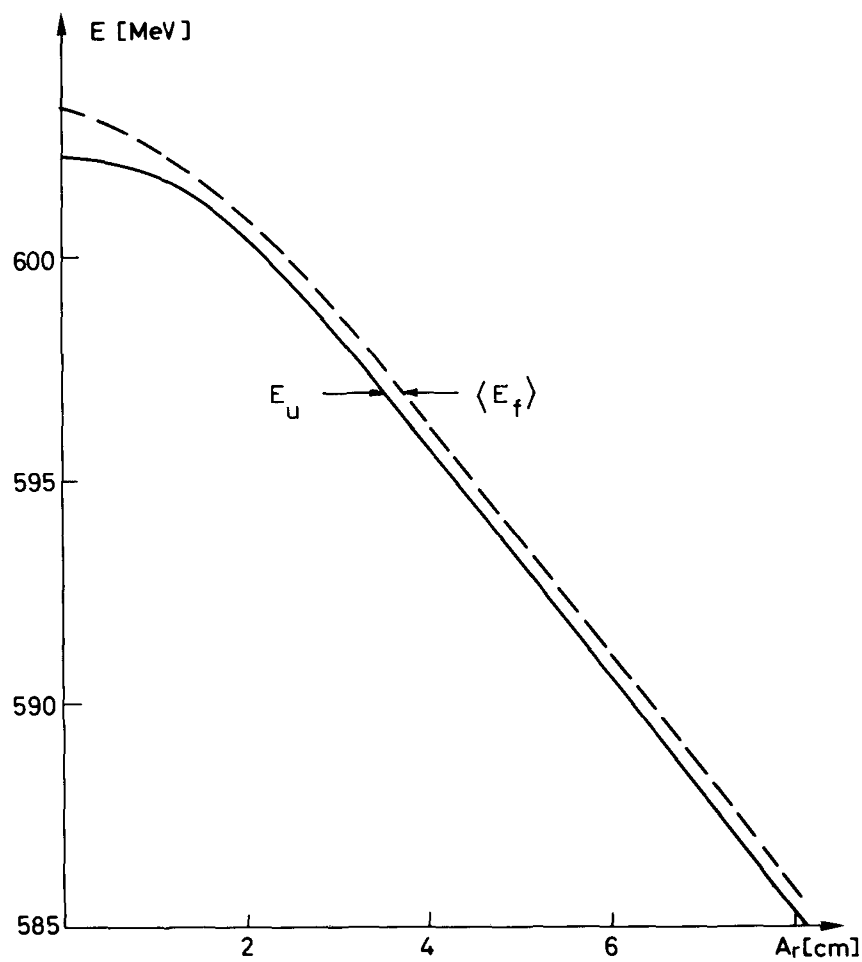

Fig. 4. Particle energy at radial instability (E_u) and average final energy ($\langle E_f \rangle$) versus radial amplitude (A_r)

3.5. *Energy-time relation in the extracted beam*

The final energy (dashed band) and the intensity distribution in the extracted beam pulse are shown as functions of time in Fig. 5. Since the slope of the band is roughly equal to dE_s/dt (E_s = synchronous energy) the time-dependent average final energy E_{av} at time t is

$$E_{ay}(t) \cong E_{\text{mean}} + (t - t_1)\, dE_s/dt \tag{2}$$

where E_{mean} is the time-independent mean extracted energy. Hence, to each time $t = t_0$ in the beam pulse there corresponds an average energy given by (2) with a maximum uncertainty ΔE_t as is suggested in the figure.

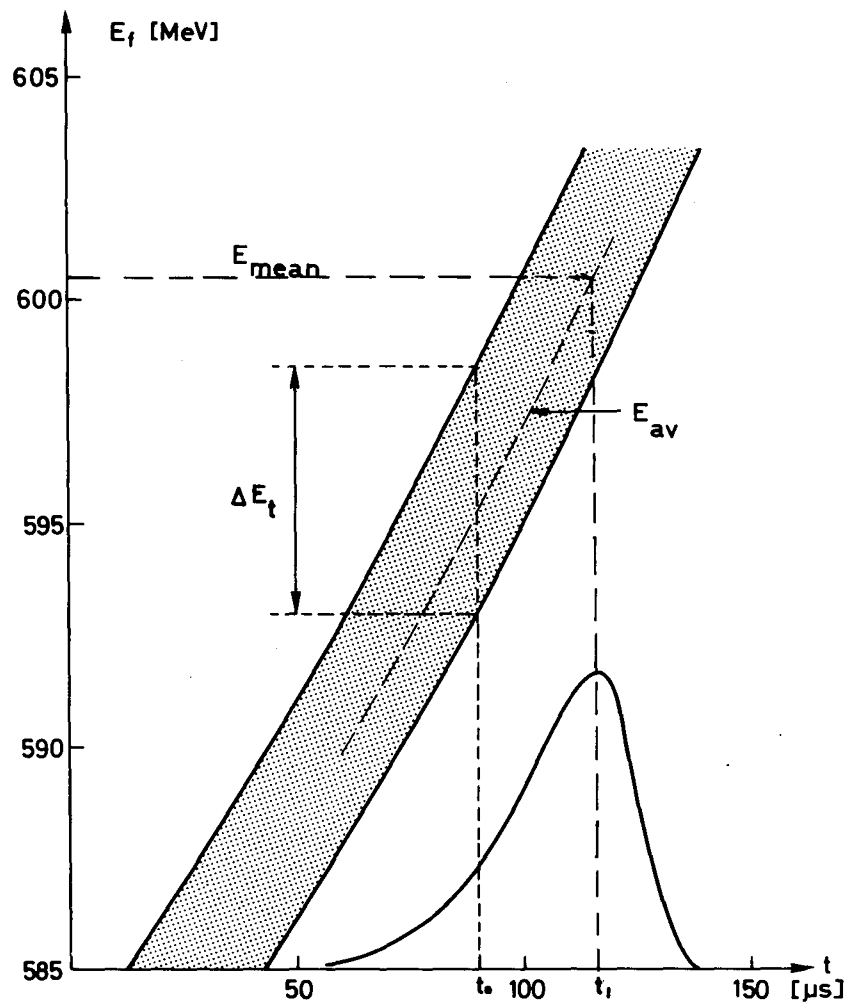

Fig. 5. Final extracted particle energy (E_f) (dashed band) and intensity distribution in arbitrary units (full curve) versus time

ΔE_t depends on the size of the synchrotron bucket which is given by the voltage and frequency-time programme. Fig. 6 shows as an example ΔE_t versus cos φ_s for three different values of V_m; 1, 10 and 50 keV/turn. In order to minimise ΔE_t one should choose a low voltage and a value of cos φ_s close to one.

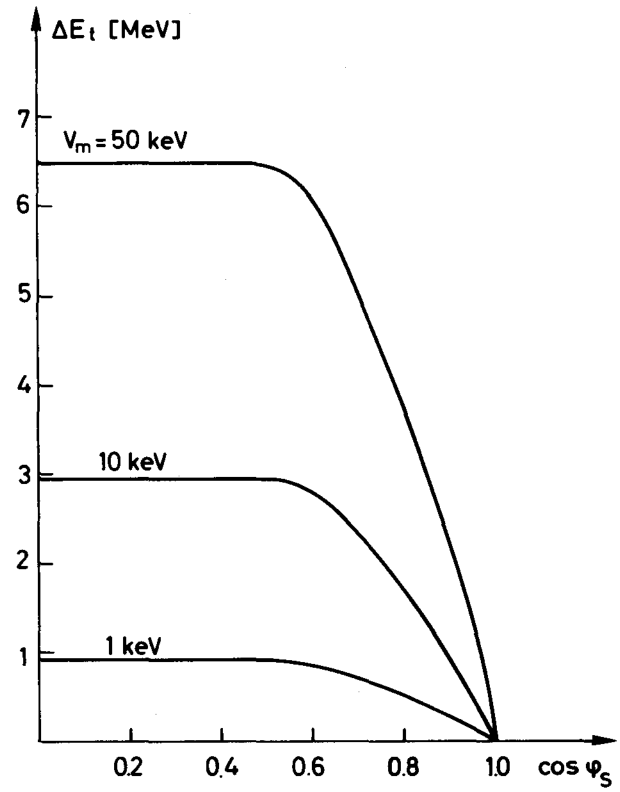

Fig. 6. Time-correlated energy uncertainty ΔE_t *vs cos* φ_s *for some different maximum energy gains/turn,* V_m

4. RESULTS OF STUDIES ON IMPROVEMENTS

4.1. *Extraction efficiency*

Having an extraction channel with a septum of width d at a radius r_{sept} and a regenerator which together with the fringe field gives a turn separation $\Delta r(r)$ the extraction efficiency ϵ can be written

$$\epsilon = 1 - d/\Delta r(r_{sept}),\ \Delta r \geqslant d \tag{3}$$

It is then assumed that r_{sept} is chosen to let the beam enter before the Walkinshaw resonance sets in and causes axial losses and that the radial and axial emittances can be transmitted without losses through the channel. Moreover, Δr is assumed to be independent of radial amplitude which is justified as long as the amplitude band is narrow (say $A_r < 2$ cm).

4.2. *Regenerator field*

According to (3) a large value of Δr is favourable for optimisation of ϵ. However, in order to avoid deterioration of the beam quality due to non-linearities in the channel and fringe fields $\Delta r \approx$ 2–2·5 cm has been considered a reasonable upper limit. A regenerator field ΔB meeting that requirement is shown in Fig. 7 together with its associated Δr-function. The regenerator extends over 10° of azimuth. The axial blow-up F due to the influence of the Walkinshaw resonance ($\nu_r = 2\nu_z$) is also given in Fig. 7 versus particle radius. F is defined as the ratio between the maximum projected z-value of a traced axial phase ellipse at radius r and its initial amplitude. The resonance is seen to set in very rapidly at $r \cong$ 2·34 m.

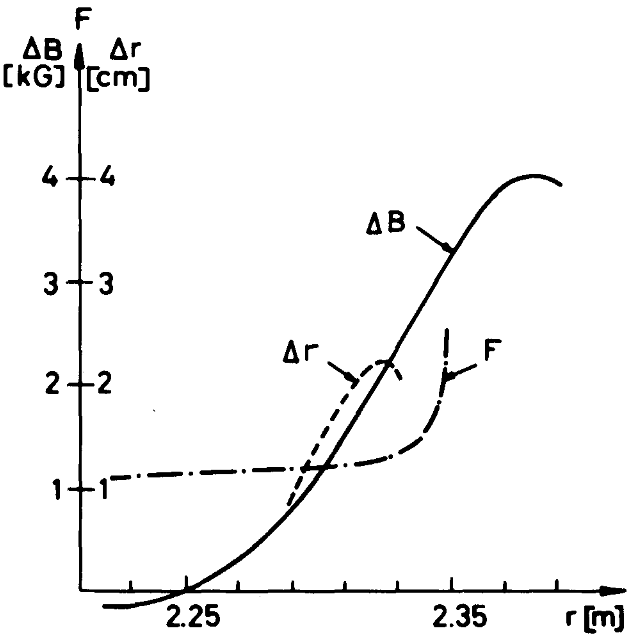

Fig. 7. Regenerator field Δ B, *turn separation* Δ r *and axial blow-up factor* F *versus radius*

4.3. *Magnetic channel*

From Section 3.2. and Eqn (3) it is concluded that one should look for a thin-septum channel with minimum gradient distortion outside the septum. An improved version of a 2 kG, 86 kW electromagnetic channel of coaxial type, initially proposed by M. Morpurgo,[2] has been developed by A. Susini[3] to form the entrance section of the magnetic channel. A radial cross-section of the electromagnetic channel, which will be curved and 80 cm long, is shown in Fig. 8. The copper septum is 2·5 mm thick and carries 12 000 A. The possibility of casting the channel in cement is being studied. The remaining part of the channel will be of conventional iron type.

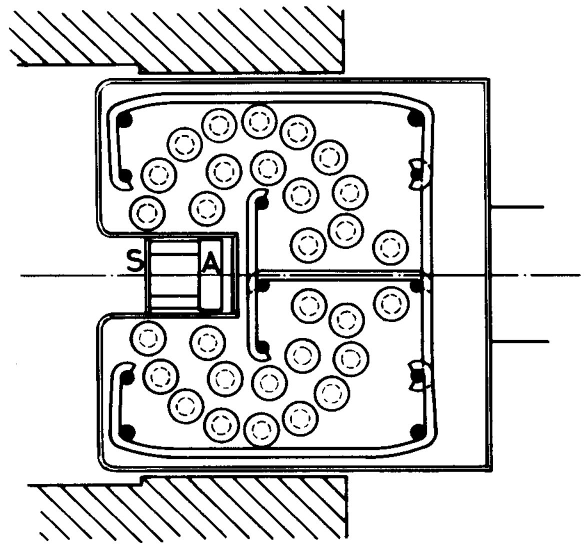

Fig. 8. Cross-section of electromagnetic channel showing conductor configuration with septum (S) and antiseptum (A). The channel aperature is 4·0 x 3·5 cm^2

4.4. *Expected performance*

The calculations of the figures given below are based on the assumption that A_r and A_z are less than 1 cm as suggested from model measurements.[4] Estimating the effective septum thickness to be 3·5 mm, putting Δr = 2·3 cm and assuming the conditions of validity of (2) to hold, one obtains an efficiency of 85%. The energy spread in the extracted beam will be about 1·0 MeV *FWHM* when extracting at full dee voltage (V_m = 54 keV/turn) and only about 0·5 MeV when using an auxiliary acceleration electrode (cee) on low voltage. The radial and axial emittances of the extracted beam are expected to be less than 15 and 25 mm mrad, respectively.

5. LONG AND SHORT BURST

Means of varying the duty-cycle of the extracted beam have been studied. A time varying magnetic field bump of about 200 G maximum field over 15° produced by a coaxial coil, is foreseen and will yield a maximum duty cycle of 85% and an energy spread less than 3 MeV in the extracted beam.[5] The same perturbation produced rapidly will give a fast extracted beam of about 1 μs pulse length.

A secondary acceleration system (cee) capturing the stacked beam adiabatically into a stationary bucket and operating in a single sweep mode is proposed.[6] The cee will produce an extracted beam of high resolution (0·5 MeV) and with a duty cycle of 10–15%.

A space saving design incorporating the coil within the cee has been proposed.[7]

6. ACKNOWLEDGEMENTS

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