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SLOW EXTRACTION AT THE SSC

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Resonant slow extraction at the SSC will permit fixed-target operation. Stochastic extraction appears to be a promising technique for achieving spill times of the order of 1000 s. However, systematic sextupole error fields in the SSC dipoles must be reduced a factor of twenty from the design values; otherwise the extraction process will be perturbed or suppressed. In addition, good regulation of the SSC power supplies is essential for smooth extraction over the spill period.

Introduction

This paper is an outgrowth of the work performed by my group at the recent Snowmass workshop on the fixed-target option for the SSC.[1] Previous work by Zisman[2] and Bodek et al.[3] has concluded that resonant extraction was indeed possible within a "good field" region of ±1 cm radially if the spill length did not exceed 200 s (duty factor of 17% for 200-s ramps and 650-s fill) and if a considerable effort was made to maintain magnet regulation to a few parts in 10^6. In this study we have performed a simple modelling of the extraction process. We also carry out an approximate calculation of the "good field" region and have investigated both stochastic extraction and the SSC power supplies.

Resonant Slow Extraction

For the machine we assume that of the reference design study RDS A.[4] This design has a circumference of 90.48 km and superperiodicity three. There are three utility insertions. The electrostatic septum would be located in the center of one utility insertion where β_x = 1500 m, and be followed by an iron septum in, e.g., the following half cell without bending magnets. The nominal tune of the SSC is $97^{3/4}$ and it can be easily moved down to slightly above $97^{2/3}$ for third-integer resonant extraction. Thus the extraction would take place using the $3\nu_x = 293$ resonance. The calculation of extraction dynamics is straightforward[5]—we create a 293nd harmonic sextupole by locating sextupoles at, for example, the centers of the HF quads in the arcs where β_x = 330 m. The strength is given by

$$S = \sum \left(\frac{B''\ell_s}{2}\right)_i \cos(293\phi_i + 3\theta) \ , \qquad (1)$$

where the sum is over the sextupoles of length ℓ_s, $B'' = d^2B/dx^2$, and $\phi = \int ds/(\nu\beta)$. For S = 35000 T/m we obtain a maximum size of ±9 mm in the arcs, and a step size of 6 mm at the wire septum (x_s = 1 cm). If the wire thickness is 0.1 mm, then the extraction efficiency should be near 97.5%. For a beam with normalized emittance $\varepsilon_n = 10\pi$ mm-mrad, particles at the periphery of the phase-space triangle will just start to extract at a tune $\nu_x = 97^{2/3} + 0.0024$. As the tune is moved closer to $97^{2/3}$, then the stable region is decreased.

For the modelling of the extraction process we position a thin sextupole of negative polarity at a horizontal betatron phase 2π·16.2222 and a partner of positive polarity at phase 2π·47.7777. These locations are in two successive long bend arcs. The strength $B''\ell_s/(2B\rho)$ was chosen to be 0.3 m^{-2}. Thus no zeroth harmonic contributions are generated which could interfere with the chromaticity correction. These sextupole placements result in a value $\theta = -30^\circ$. The tune of the machine was chosen to be 97.6692 ($97^{2/3}$ + 0.0025). Figure 1 shows the x-x′ phase space at the electrostatic septum. The points represent the trajectories of two particles whose starting coordinates are x = 0.866 mm, and x = 0.5 mm, respectively, with x′ = 0. The outer particle corresponds to a normalized emittance of ~ 10π mm-mr, and is unstable; it would be extracted by jumping the septum at $x = x_s$ = 1.0 cm. Fits to the data of Fig. 1 do show that the step size is ~ 6 mm at x_s = 1 cm and we can expect an extraction efficiency of ~ 97.5% in this case. The efficiency can be raised by increasing the sextupole strengths and/or increasing the septum position x_s.

The "Good Field" Region for Slow Extraction

Now, if there are systematic error fields present in the SSC magnets, the extraction process can be perturbed or even suppressed. The systematic errors generate amplitude- and momentum-dependent tune shifts—during the extraction process these effects can cause (i) a reduction in step size and extraction efficiency, (ii) curving of the separatrix, (iii) possibly retrapping, and (iv) emittance blowup. Random errors due to errors in coil placement can, e.g., interfere with the extraction harmonic. Likewise, random horizontal fields near the coils of bending magnets can increase the vertical emittance during the extraction process. The "good field" region can be defined somewhat arbitrarily as the radial aperture in which the tune shifts are less than ±0.001. The "good field" region is actually obtained indirectly by calculating the expected tune shifts that arise from systematic multipole errors in the SSC dipoles of the Reference Design Study A.[4] A simple procedure developed for the CERN SPS and used for the SSC[6] suggests that a ±1-cm "good field" aperture is possible at 20 TeV, providing that the systematic sextupole b_2 coefficient is reduced by a factor of 20. For the design A dipoles this means b_2 should be reduced from 7×10^{-4} to 0.35×10^{-4}. In addition, the random sextupole component Δb_2 should be less than 5×10^{-4}.

Stability of Power Supplies

The extraction time t_e must be long enough to ensure a reasonable duty factor. For 1000-s ramps (both up and down) and a 675-s fill time, the duty factor d.f. = $t_e/(t_e + 2675)$. For example, with t_e = 200 s we find d.f. = 7% and with t_e = 2000 s we find d.f. = 43%. We remark that the beam should possess a tune spread $\Delta\nu$ to facilitate smoother extraction; this can be introduced via a positive chromaticity $\Delta\nu/\nu = \xi\Delta p/p$. However, power-supply ripple causes severe modulation of the extracted beam.[2] For a maximum 100% modulation of the extracted beam the ripple r in $\Delta p/p$ space should be less than $(\Delta p/p)/(t_e\omega)$ where ω represents the dominant ripple frequency ($\omega = 2\pi \times 60$ Hz).[7] For t_e = 200 s and $\Delta p/p = 10^{-4}$ we obtain $r < 1.3 \times 10^{-9}$. Another analysis has been performed of the SSC power supplies to estimate quantitatively the maximum ripple that can be tolerated for a 200-s flat top (t_e): it is found that the current ripple requirements are 2 ppm for the main circuit, 10 ppm for correction quadrupoles, and 250 ppm for the correction dipoles.[8] These requirements assume that a bevy of compensation schemes are also implemented.

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Stochastic Extraction

In view of the severe ripple requirements, we have investigated stochastic extraction schemes; such techniques produce prolonged spills of 1000 s at LEAR.[9] This technique uses rf noise to diffuse small fluxes of beam rapidly into the resonance region and significantly eases the ripple requirements.[7] For the example above, the ripple requirements are of the order of $r < 10^{-6}$, which is 1000 times easier. The improvement factor over the conventional is most conveniently expressed by an inequality

$$I > \frac{2}{\pi}\left(t_e \omega\right)^{1/2} \quad (2)$$

which varies over the extraction process. The corresponding ripple $r < (D/\omega)^{1/2}$, where D is a time dependent diffusion coefficient in $\Delta p/p$ space. The required value is

$$D(t) = \left(\frac{2\Delta p/p}{\pi}\right)^2 \frac{1}{t_e - t} \quad (3)$$

where t is the elapsed spill time. The diffusion is generated by an rf noise voltage via

$$D = \frac{1}{2\Delta f}\left(\frac{V}{B\rho C}\right)^2 \quad (4)$$

where Δf is the noise bandwidth, V is the rms noise voltage and C is the machine circumference. Typical noise voltages needed are of the order of 20 MV at 360 MHz. A more thorough discussion of stochastic extraction for the SSC is given by Marriner.[10] It appears that sustained spills of 2000 s would be possible using stochastic extraction. However, the conventional stochastic extraction used at LEAR and described above is for a coasting beam. For the SSC we have the added complication of synchrotron radiation--for reference design A the beam loses 122 keV/turn (or 400 MeV/s). One possible cure would be to ramp down the machine as the extraction proceeds (E ~ 19.6 TeV after ~1000 s). Another complication is a possible need for an abort gap in the beam; perhaps a "barrier bucket" can be implemented. Marriner[10] discusses an "Unconventional Stochastic Extraction" technique to handle the problem of synchrotron radiation energy loss during extraction. In this case (1) the tune of the machine is held fixed, (2) the beam is held in stationary buckets whose heights are gradually reduced, and (3) particles spilling out of the buckets lose energy to synchrotron radiation and move toward the extraction resonance by virtue of a positive non-zero chromaticity. A band of rf noise is applied prior to extraction to smooth out the ripple, as discussed above.

Conclusions

We believe that slow resonant extraction is a viable option at the SSC. Reasonable duty factor can be experienced with stochastic extraction techniques. Further detailed studies of tracking, synchrotron radiation energy loss, stochastic extraction, etc., should be undertaken if, in fact, user interest is sufficient to justify this option.

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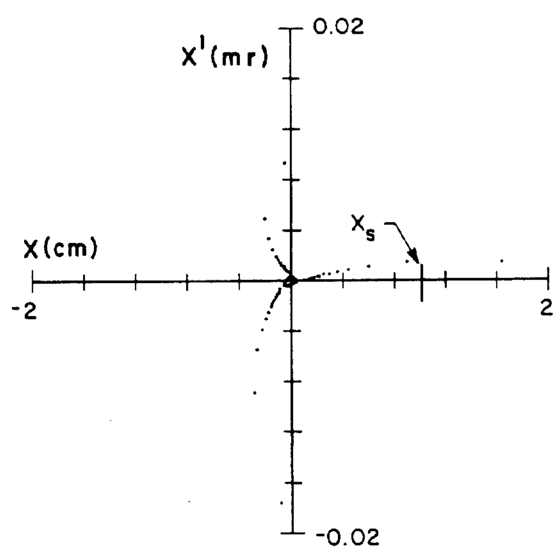

Fig. 1. x-x′ phase spaces at the septum location for two particles starting with x = 0.866 mm, and x = 0.5 mm; the starting x′ = 0 in both cases.