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Author
Lambertson, G.R.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

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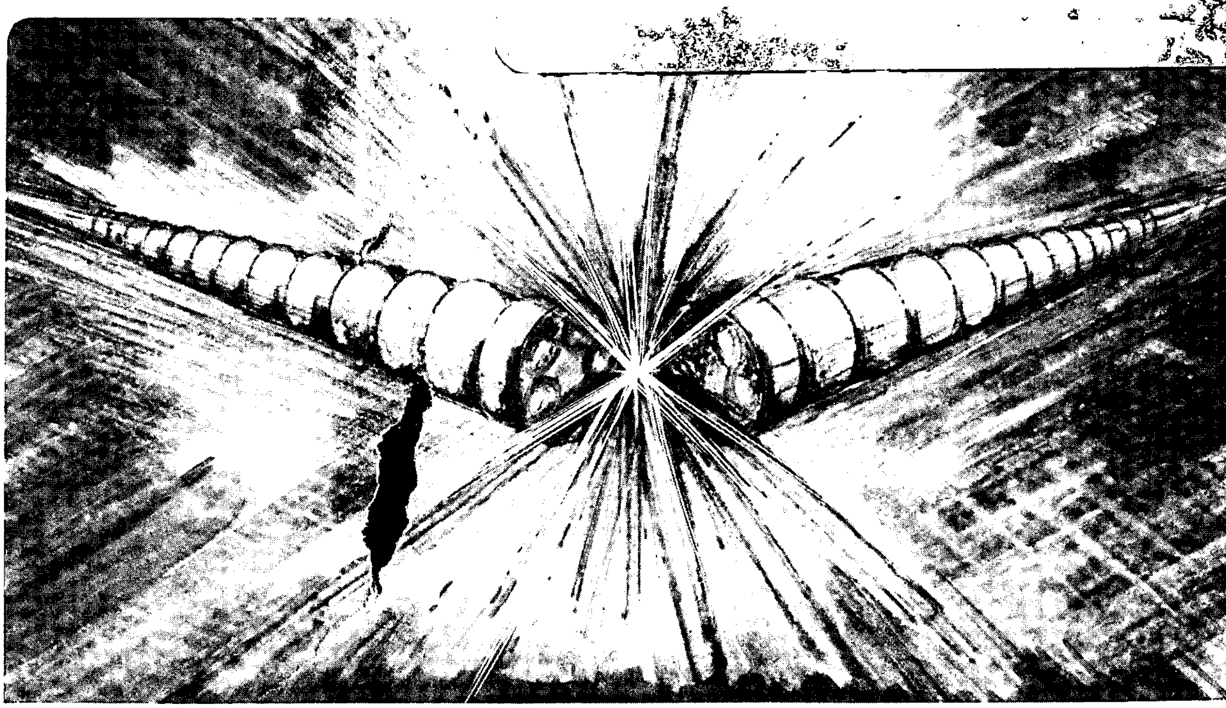

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Glen R. Lambertson

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Glen R. Lambertson
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract

Criteria for the design of feedback systems to suppress coherent beam instabilities are presented. These address starting amplitudes, diffusion from noise during damping or long storage, and choice of kicker. As a model for future accelerators, specifications of the proposed 20 TeV SSC are used to calculate parameters of systems to control expected instabilities. A scenario and hardware to stabilize the transverse mode-coupling instability is examined. The scale of the systems is large but not out of scale with the large ring.

Introduction

The use of feedback to control coherent responses in the synchrotron is at least as old as the first use of a phase loop to combat beam loading. There is now a long list of instabilities that are considered in designing an accelerator. Those that cannot be avoided with certainty are candidates for control through feedback. It is the intent of this study to review the stabilization problems that are likely to arise in a future hadron collider in order to reveal the scale and feasibility of constructing those feedback systems. Phase feedback through the rf cavity will not be included. General requirements for the systems will first be proposed, followed by numerical parameters based as an example on the 20 TeV SSC Reference Design A.(1)

Basic Functions

The driving electromagnetic force for coherent instability is expressed in terms of the product of the perturbation I or I_x times a beam coupling impedance $Z_\parallel$ or $Z_\perp$.(2) As an illustration, for transverse motion this is simply stated by

$$\ddot{x} + \omega_\beta^2 x = j \frac{\omega_o \beta c}{2\pi} \frac{e}{E} Z_\perp I x \quad .$$

Definitions of the impedances are

$$Z_\parallel = \frac{e}{I} \int_0^{2\pi R} \mathcal{E}_\parallel \, ds \quad \text{and} \quad Z_\perp = \frac{j}{\beta I x} \int_0^{2\pi R} (\mathcal{E} + v \times B)_\perp \, ds$$

in which the fields $\mathcal{E}$ and B arise in response to the passage of the beam. From these we can see that the change per turn in energy or in transverse momentum induced by the coupling impedance is, expressed as voltage,

$$\left.\frac{\Delta E}{e}\right|_z = Z_\parallel I \qquad \text{longitudinal per turn and}$$

$$\left.\frac{\Delta p_\perp c}{e}\right|_z = j \, \beta Z_\perp \, I x \quad \text{transverse per turn.}$$

To stabilize the beam, the feedback must add at least sufficient opposing kicks to cancel the component of these forces causing growth. Coherent instabilities expected in high energy proton rings have growth rates that are much slower than the orbital frequency f_0. In fact all expected modes in the SSC grow even more slowly than ω_s, the (angular) synchrotron frequency. This fortunate circumstance allows correction to be delayed by one turn after detection of a beam motion. An exception to the above would be the fast microwave instabilities but it appears possible to make these stable by providing a suitable large and smooth beam tube in combination with frequency spread.

Initial Damping Rate

For the foregoing reasons, stabilization alone would not be difficult. But it will also be the function of the systems to damp some initial oscillations and then to hold the stabilized beam without causing growth of emittances for its lifetime in the collider. During the damping stage, frequency spread in the beam will cause diffusion of the coherent amplitude, a, to produce growth in emittance, ϵ. Let

$$\text{transverse emittance } \epsilon_\perp = 6\gamma \; \sigma_x^2 / \bar{\beta} \quad \text{and}$$

$$\text{longitudinal emittance } \epsilon_\parallel = 2\pi^2 \, \sigma_\ell \, \sigma_p$$

where β is the average betatron function and σ_x, σ_ℓ, and σ_p are transverse, longitudinal and momentum rms amplitudes. Starting with an initial amplitude a_0, coherent damping will proceed according to

$$\frac{da^2}{dt} = -2Da^2 = -2(D_F - D_Z)a^2$$

assuming growth of the non-coherent σ^2 is not a large factor. Here the total damping rate D is a combination of that from the feedback system (F) and growth from coupling impedence (Z). For emittance growth I use the equation

$$\frac{d\sigma^2}{dt^2} \approx \frac{\Delta\omega_s^2}{4 \, \ell n \, 2} a^2$$

where $\Delta\omega_s$ is the FWHM spread of angular frequencies in the oscillating beam particles.

From these relations we can find that the growth in σ during damping is

$$\Delta\sigma^2 = \frac{a_o^2}{16 \, \ell n \, 2} \left(\frac{\Delta\omega}{D}\right)^2 \quad .$$

This should be limited to a small addition to the emittance, say < 0.1, which leads to a minimum damping rate

$$D > 0.94 \, \Delta\omega \, \frac{a_o}{\sigma} \, , \qquad (1)$$

$$\text{or} \qquad D_F > D_Z + 0.94 \, \Delta\omega \, \frac{a_o}{\sigma} \quad .$$

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If an instability is near threshold, $D_Z \sim \Delta\omega/3$, so we see that this requirement is of concern only if near threshold or if $a_0 >> \sigma$. For any quantitative studies, the starting amplitude must be specified. In order to proceed with the feedback characteristics, I shall adopt as a convenient reference an initial amplitude equal to the emittance amplitude σ. In an actual case, special rapid, but perhaps low-bandwidth, dampers may be needed to reduce specific large disturbances in the injected beam, after which the instability suppressors would operate.

Choice of Kicker

Costs, space needed, and noise problems are reduced by using the most appropriate, usually the most efficient, kicker structure. The kicker power may be written as

$$P = \frac{1}{2}\left(\frac{\Delta E}{e}\right)^2 \frac{1}{R_{\parallel} T^2} \quad \text{or} \quad P = \frac{1}{2}\left(\frac{\Delta P_{\perp} c}{e}\right)^2 \frac{1}{R_{\perp} T^2} \tag{2}$$

for the two types used, where $R_{\parallel}T^2$ or $R_{\perp}T^2$ is the kicker shunt impedance including transit-time factor T. For estimations in this paper I have used approximate values characteristic of each type structure as follows.

For octave bandwidth about wavelength λ, the stripline $\lambda/4$ loop pair, which as a quality factor $Q = \omega/\Delta\omega$ of unity, has

$$R_{\parallel}T^2 = 8\ Z_L g^2 \frac{\ell}{\lambda} \approx 400 \frac{\ell}{\lambda}\ \text{ohm}$$

and

$$R_{\perp}T^2 = 8\ Z_L g^2 \frac{\ell}{\lambda}\left(\frac{\lambda\!\!\!^{-}}{b}\right)^2 \approx 400 \frac{\ell}{\lambda}\left(\frac{\lambda\!\!\!^{-}}{b}\right)^2. \tag{3}$$

Here $(Z_L g^2)$ is a geometric factor, b is the beam tube radius, and ℓ is the overall length of a closely-spaced series of loop pairs.

Closely related to the stripline loop and the drift tube but capable of being made with a specified Q-value by adding resistance is the stripline plate, ~ $\lambda/4$ long and resonated at its center support on a ~ $\lambda/8$ stub line. (At low frequencies, an inductor may be used). For this type we have

$$R_{\parallel}T^2 = \frac{8}{\pi}(Z_L g^2)\frac{\ell}{\lambda}Q \approx 127\frac{\ell}{\lambda}Q$$

$$R_{\perp}T^2 = \frac{8}{\pi}(Z_L g^2)\frac{\ell}{\lambda}\left(\frac{\lambda\!\!\!^{-}}{b}\right)^2 Q \approx 127\ \frac{\ell}{\lambda}\left(\frac{\lambda\!\!\!^{-}}{b}\right)^2 Q$$

$$= 20.3\,\frac{\ell c}{b^2\Delta\omega}\ . \tag{4}$$

Cavity resonators with TM modes usually have larger transverse dimensions but can provide very-high Q-values and high power dissipation. For these,

$$R_{\parallel}T^2 \approx \mu_0 c\,\frac{4}{\pi}\,T^2\,\frac{\ell}{\lambda}\,Q \approx 380\,\frac{\ell}{\lambda}\,Q$$

$$R_{\perp}T^2 \approx \mu_0 c\,\frac{32}{25}\,T^2\,\frac{\ell}{\lambda}\,Q \approx 154\,\frac{\ell}{\lambda}\,Q \tag{5}$$

Certainly where power level is a concern, a large shunt impedance appears desirable, but other considerations enter. The kicker adds an increment of coupling impedance to that already present, and troublesome, in the ring. One can show that there is a minimum power solution, but for that condition, the kicker adds an impedance comparable to that being opposed by the feedback. It seems unreasonable to add such a large destabilizing impedance. Therefore, I shall adopt a criterion that the added impedance must be less than 20% of the ring impedance. The relations between RT^2 and Z are listed here with the 20% limits:

$$\Delta \mathrm{Re} Z_{\parallel} = R_{\parallel}T^2/2 < 0.2\ Z_{\parallel}$$

$$\Delta \mathrm{Re} Z_{\perp} = R_{\perp}T^2/2\lambda\!\!\!^{-} < 0.2\ Z_{\perp}\ . \tag{6}$$

These limits will be reached only for very strong feedback but there are some such transverse instabilities in the SSC design that might arise. For that reason, I write below the minimum power needed only to stabilize against $Z+\Delta Z$.

$$\min P_{\perp} = 2.5\left|\vec{Z}_{\perp} + \vec{Z}_k\right| (\beta I \sigma_x)^2/2\lambda\!\!\!^{-} \tag{7}$$

in which $|\vec{Z}_k| = 0.2|\vec{Z}_{\perp}|$.

Longitudinal coupled-bunch feedback

In common with many accelerators the SSC would need a phase-loop to remove instabilities driven by the r.f. cavities and lying within the response widths of the r.f. fundamental. The suppression of these dipoles disturbances has had a long history of development of systems involving high gain, moderate bandwidth, and r.f. noise suppression[3,4]. I shall not include that specialized problem in this review. But I will note that the combination in the SSC of high r.f. frequency (360 MHz) and low synchrotron frequency (~ 10 Hz) brings in more modes of coupled-bunch instabilities that would be addressed through the r.f. cavity response.

Parasitic cavity resonances above the fundamental are expected to drive a variety of coupled-bunch modes. With 9000 bunches, there are at most 9000 modes and a bandwidth of 15 MHz will be needed in feedback systems for dipole and for quadrupole motions. Each of these would require fast analog and digital processing and storage of 9000 individual bunch signals; fortunately, the digital hardware speed is just now available. The sextupole motion is marginally stable, but if present would require more sophistication to extract the sextupole component from other bunch deformations.

The instabilities will need suppression from injection through flattop. It is the initial damping at injection that determines the maximum, corrective kick to be provided. Using the criteria for 10% emittance growth during damping from an initial amplitude as equal to the normal rms emittance amplitude σ_ϕ or σ_E, I calculate for the dipole case a required kick per turn of $\Delta E/e$ = 530 KV and power of 440 kW. While not infeasible, these are large and impel me to assume that the r.f. phase loop will reduce the initial coherent motion to less than σ_ϕ before these higher-mode motions, with growth rates about 1 $\sec^{-1}$, need damping. Hence, I can specify $a_0 = 1/3\,\sigma_\phi$ and calculate a dramatic reduction of feedback strength.

Using parameters for the SSC listed in Tables I and II, calculation of the feedback parameters proceeds as follows. During initial damping, I shall not cancel the real frequency shift $\mathrm{Re}\Delta\omega$; after that the feedback strength D_F, with a shift in phase, would be able to cancel the full magnitude of $Z_{\parallel}$. D_F is obtained from equation (1) where $\Delta\omega_s \approx 3$ x Landau-damping-rate

$$D_F = D_Z + (0.94)(\Delta\omega)\frac{a_o}{\sigma} \qquad (8)$$

$$= (0.89) + (0.94)(5.34)/3 = 2.56\ \mathrm{sec}^{-1}.$$

For compactness, the kicker of cavities should operate at as high a frequency as possible and still couple well to the dipole motion. Choose f = 500 MHz. The shunt impedance for a kicker 10 m long is

$$R_{\parallel}T^2 = 380\ \frac{\ell}{\lambda}\ Q = (380)\ \frac{10}{0.6}\ \frac{500}{15} = 2.1 \times 10^5\ \Omega$$

This increases $Z_{\parallel}$ by 3.5%. The kick per turn using

$$\frac{da}{dt} = -D_F a = \frac{f_o}{2}\ \frac{\Delta E}{e} \quad \text{with } a = a_o = \frac{1}{3}\ \frac{\sigma_e}{e} \quad \text{is}$$

$$\frac{\Delta E}{e} = \frac{2}{3.3\mathrm{x}10^4}\ (2.56)\ \frac{1}{3}\ (1.5\mathrm{x}10^{-4})10^{12} = 77\ \mathrm{KV/turn}$$

$$\text{and } P = \frac{1}{2}\left(\frac{\Delta E}{e}\right)^2 R_{11}T^2 = \frac{1}{2}\ \frac{(77\mathrm{x}10^3)^2}{2.1\mathrm{x}10^5} = 14\ \mathrm{kW}.$$

A similar calculation for the quadrupole feedback, keeping arbitrarily the initial condition $a_o = \sigma_\phi/3$ gives the results in Table II. For this bunch motion, the amplitude a is a measure of the distortion of the phase ellipse and a/σ_ϕ is the peak-to-average bunch current variation. To couple most effectively to this motion, the feedback frequency should have $\lambda \sim \sigma_\ell$ giving 680 MHz and with that frequency the required kick is found from

$$\frac{\Delta E}{e} = \frac{4}{efo}\left(\frac{\sigma_E}{3}\right) D_F \quad .$$

Noting that this quadrupole feedback is considerably stronger than the dipole, one is reminded of the sensitivity of the numbers to the uncertain factors of initial amplitude and net growth rate.

In view of the considerable problems with noise in phase feedback systems, one must ask what demands arise from a specification that diffusion during a flattop of 24 hours duration (t_c) not exceed ~ 20% in emittance. The loop gain GB is not large; we find electronic gain $G = 2D_F/f_o$ = (2)(2.56)/3.3 x 10^4 = 1.5 x 10^{-3} and beam response B determined at ω_s by the frequency spread[4,5] is

$$B = \frac{\pi}{2}\ \frac{\omega}{\Delta\omega} = \frac{\pi}{2}\ \frac{1}{0.05} = 31.4.$$

In this case, the feedback does little to reduce noise from input circuits or power amplifier and the allowed output level $\Delta\phi^2$ is

$$\frac{d\sigma^2}{dt} = f_o\ \mathrm{x(noise}\ \Delta\phi^2) < 0.2\ \frac{\sigma_\phi^2}{t_c} \quad .$$

Expressed as equivalent input noise $\delta\phi^2$ this is

$$\text{input } \delta\phi \ < \frac{\sigma_\phi}{G}\sqrt{\frac{0.2}{f_o t_c}} = 9.0 \times 10^{-3}\ \text{radian.}$$

The output power amplifier will have a minimum noise level. The requirement for this expressed as a fraction of the maximum power level, max $\Delta\phi^2$ rms is

$$\frac{\text{noise } \Delta\phi^2}{\max\ \Delta\phi^2} < \frac{fo}{10\ D_F^2\ t_c}\ \frac{\sigma_\phi^2}{a_o^2} = 5.3 \times 10^{-3},\ \text{or } -23\ \text{dB.}$$

These noise limits for the dipole and quadrupole systems are listed in Table II.

Transverse coupled-bunch feedback

The dipole motion couples to the large peak in resistive-wall impedance at low frequencies. Of 9000 possible modes, probably not all will be excited, nevertheless for the present purpose a bandwidth of 15 MHz adequate to damp all modes is assumed. Following my adopted criteria, one arises at the parameters given in Table III, which shows that this is not a difficult stabilization problem. Instability is not expected at full energy. It suggests that if, as expected, not all modes grow, then with a more narrow bandwidth a combined injection damper and stabilizer could be designed. In this case the noise level of the stronger kicker must be watched. In any case a much greater transverse problem would arise if the coupled-mode instability were present.

Transverse coupled-mode feedback

This single-bunch instability has been seen in electron rings PETRA[6] and PEP[7] but not yet in proton rings. High peak bunch current and small aperture make it a possibility in the SSC. It is driven by the coupling of peak current to the broad-brand impedance from contributions by many discontinuities and devices in to otherwise smooth beam tube. At the estimated impedance of 50 MΩ/m the motion would be stable. But because of the upward uncertainty in this impedance, the serious limitation the instability would impose, and our lack of experience in stabilizing it in proton rings, I shall use for the purpose of this study $Z_{\parallel}$ = 200 MΩ/m.

Onset of the instability arises when the real frequency shifts of adjacent modes (dipole, quad, sext, etc) equal the mode separation ω_s. Some studies[8] have indicated a very limited increase in stability from feedback against the rigid-bunch dipole mode only. In the proton machine we can detect and operate on the higher modes also and that with some optimism is the rationale for stabilization.

The frequencies at which coupling is strongest for each mode are, for a gaussian bunch, given by [9]

$$f = nfo = \sqrt{m}\ fo/\sigma_\tau \equiv \sqrt{m}\ \frac{\beta c}{2\pi\sigma_\ell} \quad .$$

There frequencies are given in Table IV. The bandwidth needed at each is again 15 MHz. The dipole spectrum is wide giving one a range of frequencies, I shall use 100 MHz noting that a low frequency reduces the coupling impedance added by the kicker.

Expecting substantial powers need, it is of interest to calculate the minimum power using Eq. (7). These values are listed in Table IV along with the lengths of tuned-plate kickers required.

The dipole kicker is too long, the parameter values given in Table III have been based on a 20-meter dipole kicker. The power per meter of kicker for m = 1 and 2 may be unrealistic and a subject for a more detailed study.

As with the other transverse instability, this one also is active only at low energy and noise effects during long storage is not a factor. However, the beam must be stabilized for about an hour at low energy and during this time one wishes $\Delta\sigma^2 < 0.1\sigma^2$. Both a rapid damping rate $D_F = 164\ \text{sec}^{-1}$ and a low frequency spread $\Delta\omega/\omega \approx 10^{-6}$ make the loop gain high

$$GB = \left(\frac{2D_F}{f_o}\right)\left(\frac{\pi\ \omega}{2\Delta\omega}\right) = \frac{(2)(164)}{3.3\times10^3}\ \frac{\pi 10^6}{2}\ = 1.56\times10^5.$$

Hence the feedback will reduce the noise effects from input noise to

$$\frac{d\sigma}{dt}^2 = fo\ \frac{(\delta x)^2}{B^2}\ ,\ \text{desired less than}\ 0.1\ \frac{\sigma^2}{t_c}$$

giving the input noise limit

$$\frac{\delta x}{\sigma} < \sqrt{\frac{0.1}{f_o t_c}}\ \frac{\pi}{2}\ \frac{\omega}{\Delta\omega} = 143\quad .$$

Thus, input noise is no problem at all and similarly one finds no restriction on output power amplifier noise.

Conclusion

This overall review of feedback systems brings awareness of the individual nature of each instability problem when quantitative aspects are being estimated. Hardware problems are very sensitive to assumptions and criteria about starting conditions and emittance growth during damping. Predicted power levels in the range 10-to-100 KW seem in keeping with the size of a large accelerator but we have seen how the power in one example was reduced a factor of 30 by reducing starting amplitude a factor of 3. Also safety factors have been omitted in these studies in order not to obscure relationships. Noise appears to be a concern only in the longitudinal feedback systems. Attention is called for in the pickup and kicker designs to avoid degrading the stability of the beam by adding unnecessary and unused coupling responses.

Table I: SSC - A PARAMETERS

	Unit	Injection		Full Energy
Energy, E	TeV	1		20
Ave I	A		0.07	
Peak I_p	A		4.0	
Bunches M			9000	
Orbit f_o	Hz		3300	
Synch F_s	Hz	14		27
Bunch σ_ℓ	m		0.07	
rms σ_E/E	10^{-4}	1.5		0.5
Bunch $\epsilon_\ell = 2\pi^2\ \sigma_t\sigma_E$	eVs	0.66		4.4
rms $\epsilon_\perp = \gamma\sigma^2\ /\bar{\beta}$	10^{-6}m		1.0	
$\bar{\beta} = R/\nu$	m		150	

Table II: LONGITUDINAL FEEDBACK AT INJECTION

		Unit	Dipole $m = 1$	Quadrupole $m \pm 2$
	Z_{II}	MΩ	3	3
Damping	Landau	sec^{-1}	1.8	3.6
	Im $\Delta\omega$	sec^{-1}	-0.9	-0.9
	Re $\Delta\omega$	sec^{-1}	2.4	3.6
	Feedback, D_F	sec^{-1}.	2.56	4.24
	f	MHz	500.	680.
	Δf	MHz	15	15
	Initial Amplitude	σ_ϕ	0.33	0.33
	P	kW	14	121
	$\Delta E/e$	kV	80	264
	$R_{\parallel}T^2$	MΩ	0.21	2.9
	ℓ	m	10	10
Noise limit	input		0.9 millirad	0.01 peak/ave
	output			
	amplifier	dB	-23	-27

TABLE III: TRANSVERSE FEEDBACK AT INJECTION

			Coupled bunch	Coupled-mode, single bunch		
		Unit	dipole $m = 0$	dipole $m = 0$	quad. $m = 1$	sext. $m = 2$
	Z	MΩ/m	500	200*	200*	200*
Damp.	Landau	sec^{-1}	0.7	0.7	0.7	0.7
	$\lvert\Delta\omega\rvert_z$	sec^{-1}	-8.75	-164∇		
	Feedback	sec^{-1}	10.85	164	53	34.
	f	MHz	$\leq$ 500	100	680	970
	Δf	MHz	15 or	15^+	15^+	15^+
	P	kW	0.17	10	min 11	min 16
	$\Delta p_\perp c/e$	kV	17.2	330	380	380
	$R_\perp T^2$	MΩ	0.86	5.7	max 5.6	max 3.9
	ℓ	m	3	20	19.5	13.7

Systems have initial amplitude = σ and kickers of resonated $\lambda/4$ plates.

* Four times nominal goal
∇ Threshold is at ~ 88 sec^{-1}.

Table IV

mode (m)	dipole 0	quad. 1	2	3	4
frequency (GHz)	0 (100)	0.68	0.97	1.18	1.36
min P(kW)	1.6	11.	17		
kicker ℓ (m)	133	19.5	13.7		

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720