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RF System and Related Multibunch Instabilities Issues for the ELFE at Hera Stretcher

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Introduction

The Nuclear Physics European Community has suggested to investigate the possibility of using the Desy Hera ring as a pulse stretcher for generating a continuous electron beam of 15-25 GeV [1]. For injection it is envisaged to use part of the TESLA collider linac. The basic parameters of Hera-e as stretcher ring are shown in Table I.

Table I

Ring length	63336 m	
RF frequency	433.33 MHz	
Harmonic number	9178	
Revolution time	21.13 μs	
Momentum compaction	6.5 x10^-4	
Horizontal tune	46.335	
Vertical tune	47.401	
Energy	15 GeV	25 GeV
Synchrotron tune	0.028	0.061
Energy loss/turn	7.4 MeV	57 MeV
Cavity voltage	12 MV	90 MV
Stored current	150 mA	150 mA
Hor. damping time	92,4 ms	20.1 ms
Vert. damping time	85.9 ms	18.6 ms
Long. damping time	41.4 ms	8.9 ms
Equilib hor. emittance	1.1x10^-8 m rad	3.2x10^-8 m rad
Equilib. energy spread	5.5x10^-4	8.5x10^-4
Equilib. bunch length	9.9 mm	7.7 mm

One of the most significant modifications necessary to convert the Hera-e ring into a pulse stretcher concerns the RF system. The design of this is determined by the overall voltage per turn, by the power to be supplied to the beam and by the effects of the interaction of the multibunch beam circulating in the ring.

The ring is supposed to be filled in 40 revolutions by a single train of bunches from part of the TESLA linac, which has an RF pulse duration of 0.8 ms., with a repetition rate of 10 Hz. The structure of the injection pulse is shown in Fig. 1.

There will be about 9000 bunches circulating in the ring, with an interbunch spacing of 2.3 ns. One must therefore consider with great care the issues of multibunch instabilities arising from the impedances of the RF cavities and of the vacuum chamber.

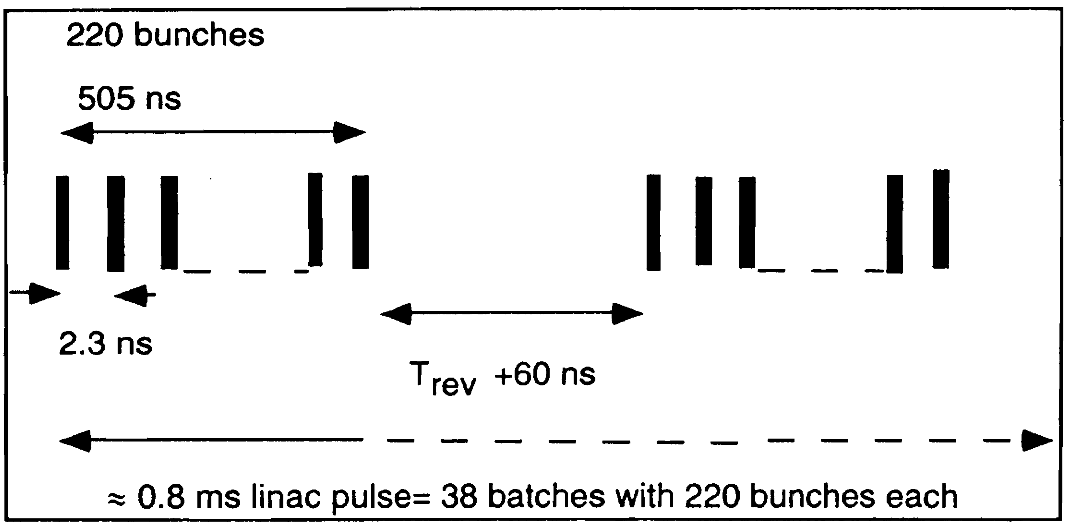

FIG. 1 - TESLA linac pulse used to fill the stretcher ring.

RF system

At 25 GeV the cavities have to supply 90 MV and 8.5 MW continuously to a beam of 150 mA. The choice of the frequency is a compromise between the physics request for a high duty cycle and the possibility of adapting existing klystrons to the required power level per unit in CW operation. Moreover, the interbunch time interval decreases with growing frequency and the implementation of bunch to bunch feedbacks becomes more difficult. The chosen frequency is 433.33 MHz, i.e. the 3rd subharmonic of the Tesla 1300 MHz. A frequency close to 500 MHz offers the advantage of exploiting already developed bunch to bunch feedback systems, which are, as it will be shown, necessary to counteract multibunch instabilities.

Various types of cavities have been considered, single cell or multicell, normal conducting (NC) or superconducting (SC). In order to make a comparison we have to set a limit of about 200 kW for the power that can be carried by each fundamental mode coupler. Both coaxial and waveguide couplers have been tested up to 300 kW in matched conditions, but in our case there will be relevant reflected power during part of the cycle as discussed later on. Because of this limit, multicell cavities have to be operated at much lower voltage than their capability and therefore are not competitive with single cells. Moreover, NC single cells supply about one third of the voltage that can be given by SC ones, and dissipate on their walls more power than is given to the beam. In Table II we show a comparison between the various solutions.

Table II

	NC multicell	SC multicell	SC -1 cell
Voltage/cavity	2.25 MV	2.25 MV	2.25 MV
N° of cavities	40	40	40
Power dissipated	4.2 MW	320 W@Q=10^9	2500 W

The choice falls therefore naturally on SC cavities and among these on single cell ones, which have the advantage of an easier HOM damping which is absolutely necessary to achieve stability against multibunch oscillations. In fact multicell cavities present trapped modes which are very difficult to extract.

In Table III are summarized the characteristics of the chosen RF system. One klystron supplies power to a group of four cavities. Each klystron will be separated from the load by a circulator capable of absorbing 400 kW reflected power when beam loading is absent. The power will be distributed to the cavities by magic tees or directional couplers in cascade.

Table III

Beam current	150 mA
Voltage / cavity	2.25 MV
Number of cavities	40
Power / cavity	210 kW
Cavities / klystron	4
Power / klystron	1 MW
Fundamental R/Q	100 Ω
Fundamental Qe	2.5x10^5

The coupling factor in matched condition is $Q_e \approx$ 2.5x10^5. It is known that, in order to avoid Robinson instability, one must either decrease the Q_e below the matched value, at the expense of extra power, or implement a feedback that stabilizes the cavity voltage. As cavities are powered in groups of four, only the vector sum of the voltages can be stabilized. This, however, together with a slightly lower Q_e than the matched one, should be sufficient to avoid the instability, which anyhow would regard only the initial current peak during the extraction cycle.

At injection, when beam current and power are maximum, the cavities should be detuned so as to compensate the beam loading, in order to minimize the reflected power. The required detuning is:

$$\Delta f / f_{RF} = \lfloor (R/Q) I \cos\phi \rfloor / (2V)$$

where ϕ is the synchronous phase angle, I is the beam current and V the cavity voltage. This detuning will be constant during the cycle, because the 100 ms cycle period is too short for a mechanical system to respond. This causes an enhancement of the reflected power with respect to the compensated value . The power required from the generator to keep a constant RF voltage is:

$$P_i = \frac{(V + IrQ_e \sin\phi)^2}{4rQ_e} + \frac{(V \tan\delta)^2}{4rQ_e}$$

with $\tan\delta = 2Q_e\,\Delta f/f_{RF}$; $r=R/Q$

Diagrams of incident and reflected power versus current, for constant cavity voltage, are shown in Fig. 2. As the cavities could have different voltages, the detuning should be optimized for each cavity by minimizing the reflected power at injection. The tuning system of each cavity will be designed so as to respond only to slow average variations of the cavity tune. For this purpose the maximum beam stored current should be kept for about 1 ms before the beginning of extraction to allow sampling of phase difference between incident wave and cavity voltage after transients have died out.

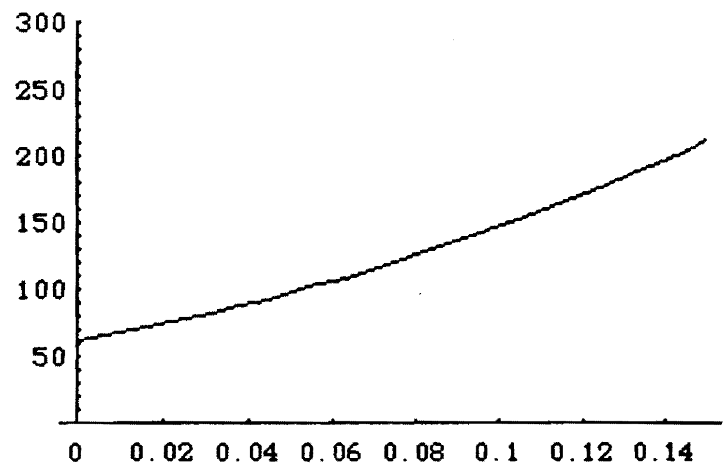

FIG. 2 – a) Power from generator (kW) vs. beam current (A).

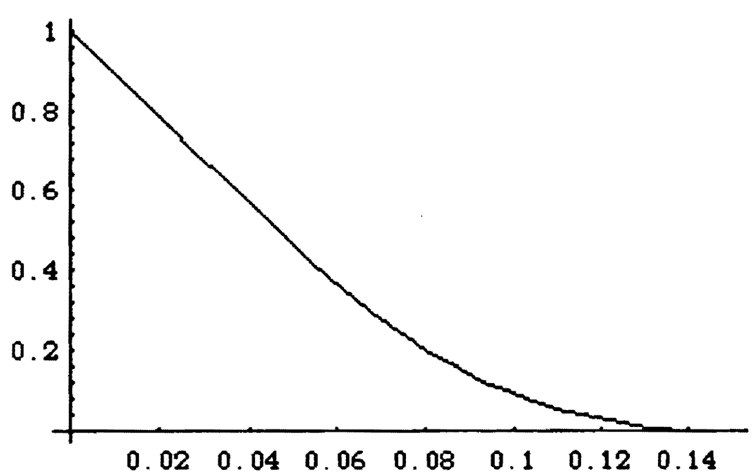

FIG. 2 – b) Reflected power ratio vs. beam current.

Operation at lower energies would be performed by reducing the number of active cavities (at 15 GeV a group of four would be sufficient). The other ones would be strongly detuned so as not to have beam interaction with the fundamental mode.

The loss factor is very low, of the order of 0.1 V/pC, which means that the beam loses about 5 W per cavity to HOMs. This makes it easier to absorb the power for mode damping.

In Fig. 3 we show a possible cavity grouping used to lower losses from tapers.

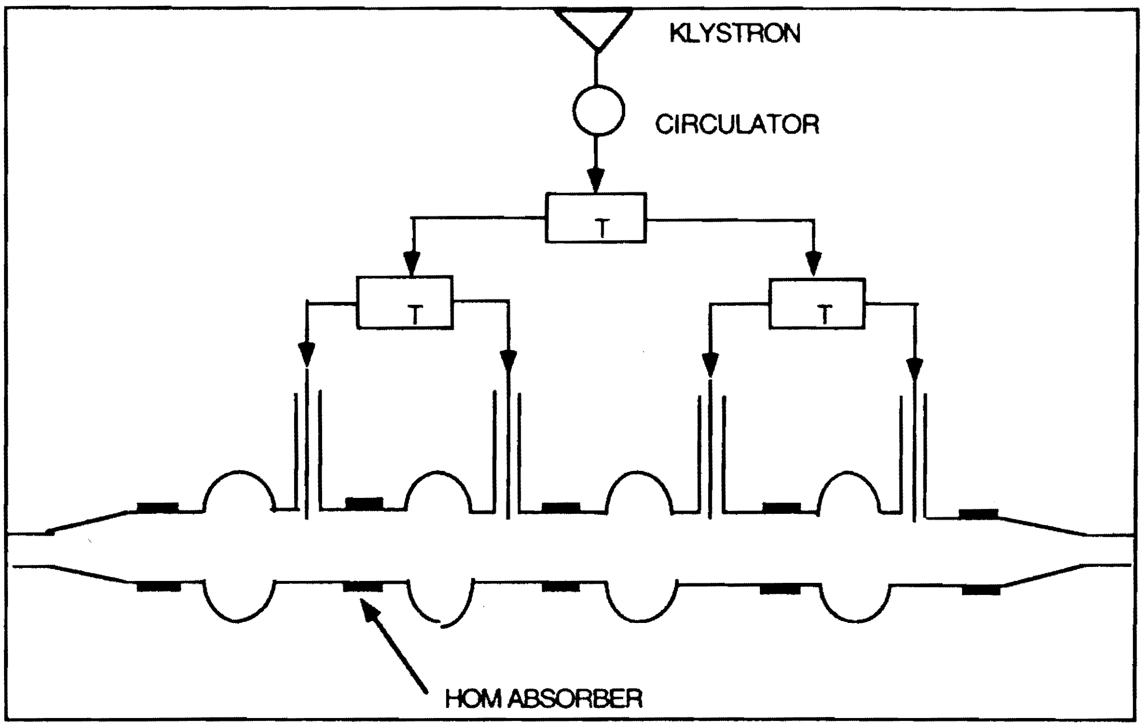

FIG. 3 – RF system module.

Cell Shape

The main requirements for designing the superconducting RF accelerating cavity are:

1) low electron field emission and surface power loss for maximizing the accelerating gradient;
2) low contents of higher order modes (HOMs) to provide easier control of the single bunch and multibunch instabilities.

Unfortunately, the two requirements are in contrast with each other. A lower value of beam pipe radius would be in favour of a higher accelerating gradient because it reduces the ratios of the maximum surface electric and magnetic field to the accelerating gradient, but it increases the longitudinal and transverse loss parameter and hence the broad band impedance.

Moreover, since the relevant coupling impedance R/Q scales approximately as r^{2m} where r is the particle distance from the axis and m depends on the mode configuration (longitudinal or transverse), a large beam tube should be preferred. Therefore, to fulfil the above requirements a compromise is required.

In this paper, the same design criteria used at the Cornell laboratory for the choice of the cavity shape were followed. In Fig.4 the cavity profile and the relative sizes are shown .

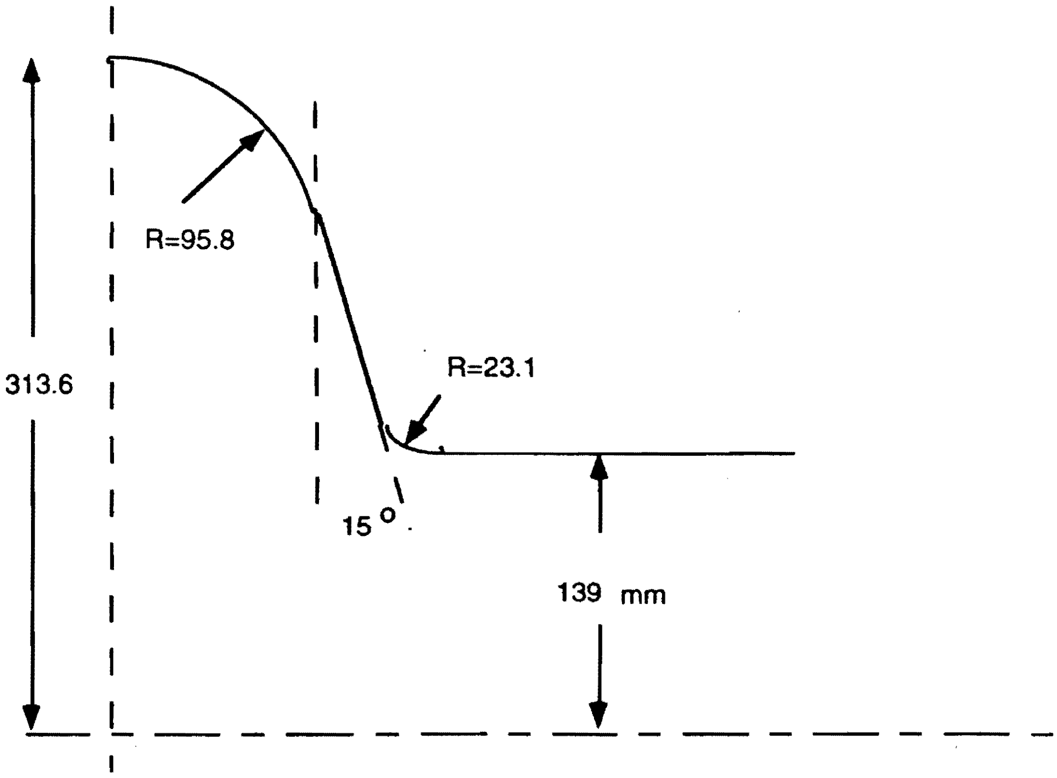

FIG. 4 – Cavity shape.

Table IV lists the properties of the fundamental mode TM_{010} as computed by OSCAR2D code.

Table IV

Frequency	433 MHz
R/Q	90 Ω
ko(found)	0.06 V/pC
Emax/Eacc	2.9
Hmax/Eacc	54 Oe/MV/m
Dissipation (Q=1*10^9,Eacc=2.75 MV/m)	84 W

The study of the HOMs has been carried out by means of the well-known code Urmel.

The geometry shown in Fig. 2 makes use of the concept of using a large beam tube to let the resonant modes in the region of the cavity propagate out via the beam pipe. Because of the low cut-off frequency values (825 MHz for TM and 632 MHz for TE modes), all longitudinal HOMs and most of transverse have significant fields outside the cell region and their R/Q is thereby reduced. Only the two lowest frequency transverse HOMs TM_{110} and TE_{111}, remain mostly trapped in the main cavity body.

In Table V the relevant RF parameters of the trapped modes are presented.

Table V

MODE	FREQUENCY (MHz)	R/Q * (Ω)
TM_{110}	587	11.4
TE_{111}	551	2.81

* Voltage integrated at 0.139 cm off axis

To confirm the reduction of HOMs effects on particle dynamics, we have run the TBCI and ABCI codes for monopolar and dipolar wakefields, by assuming the bunch length σ=1 cm. The total loss factor due to the overall effect of longitudinal modes on a particle travelling on the symmetry axis of the cavity, is found to be k_t = 0.165 V/pC and it is dominated by the fundamental mode, as expected and presented in Fig. 5.

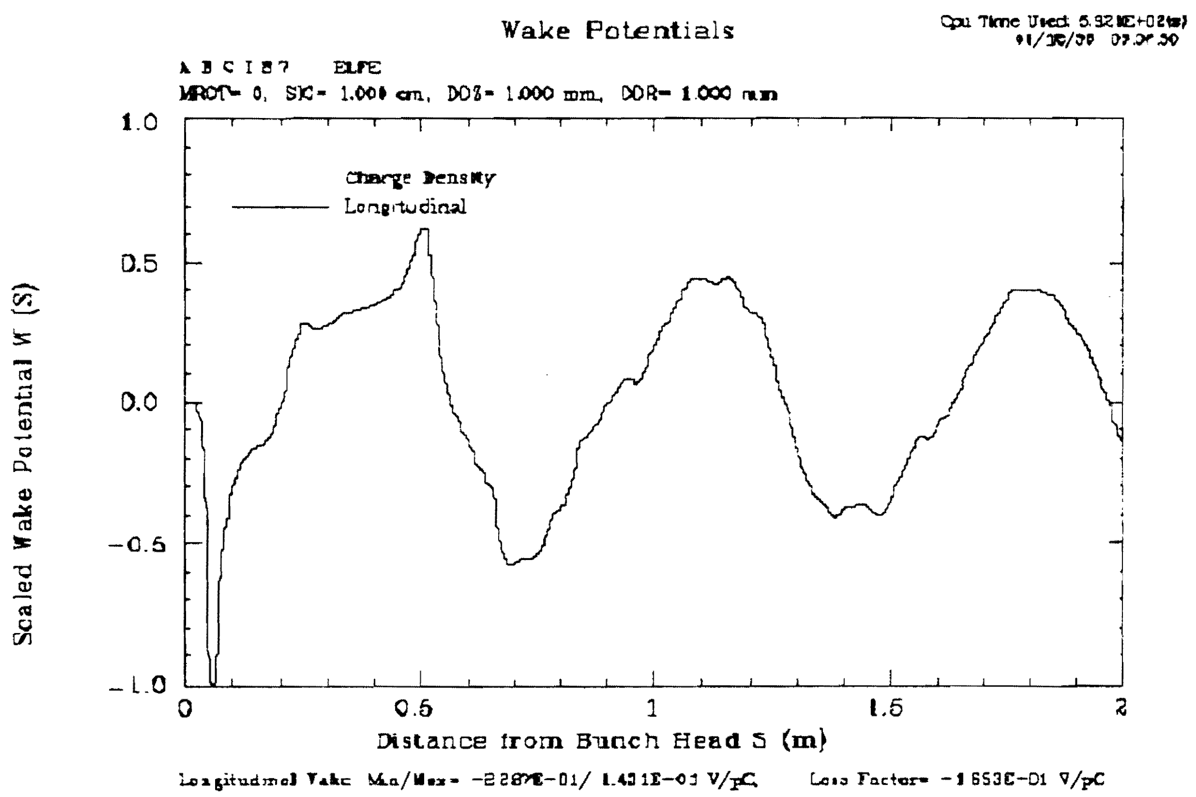

FIG. 5 - Longitudinal wake potential in a cell.

The increment of the value of the power loss factor with respect to the fundamental one (DK = k_t - k_0) is very low, of the order of 0.1 V/pC, which means that the beam loses 5 W per cavity to HOMs.

We also estimated the dipolar HOMs contribution on particle dynamics. The average transverse kick parameter k^, which is the equivalent of the loss factor for the dipole modes, as computed by TBCI code, is found to be k^= 0.23 V/(pCm). While the transverse kick due to the trapped modes TM_{110} and TE_{111}, is respectively k^= 0.13 V/(pCm) and k^= 0.03 V/(pCm). In this case the global wakefield is mostly dominated by the deflecting mode TM_{110} as it is presented in Fig 5 . To extract these trapped modes, the solution adopted by in the Cornell design [2] is to use a "fluted" beam pipe. Another solution, proposed by A. Mosnier [3], consists in a semi-closed structure with an enlargement of the beam tube after one of the irises.

The problem to be faced is the HOM damping technique. The Q values of the parasitic modes must be lowered drastically for avoiding both single and multibunch instabilities.

Several possibilities have been tested, like the use of absorbing materials which provide global damping for all HOMs. An optimum position for these absorbers may be found, without affecting the fundamental mode significantly.

Coupled-bunch collective effects

The high current and the large number of bunches in the ring make the coupled-bunch effects important. The consequent coherent instabilities are caused by the strong coupling between the beam and the parasitic HOM resonances of the RF cavity and of other resonating objects in the beam pipe. In the transverse case, harmful oscillations can be driven also by the resistive wall wake fields.

These instabilities can be partially suppressed by designing structures with a low shunt impedance; damping techniques of the HOMs recently developed can reduce the shunt impedance of the HOMs to few thousand of ohms. Another complementary possibility is to cure the instability by means of a feedback system. Besides, we should not forget to consider the Landau Damping, which can provide the required damping of those coupled-bunch modes on which a feedback is uneffective.

An exhaustive analysis of all these effects would require the knowledge of details in the machine and RF design not yet available at this stage. Therefore, for the moment we shall limit ourselves to the assessment of the harmfulness of the HOMs in relation to the radiation damping alone. In other word we will calculate the required shunt impedance such that the instability is damped by radiation effects. We further compute the rise time of the transverse instability due to a Copper vacuum chamber in case of zero chromaticity. The interaction with accelerating mode of the RF is not considered.

HOM Longitudinal Coherent Instability.

The analysis of the dynamics of k_b equispaced bunches interacting with the long range wake fields is performed by computing the coherent frequency shift predicted by Sacherer's theory.

The spectrum of the bunches executing "free" m-pole coherent longitudinal oscillations is given by lines at frequencies

$$\omega_p = (pk_b + n + m\nu_s)\omega_o$$

$$-\infty < p < +\infty \ , \ 0 \le n \le k_b - 1, \ p,n \text{ integers}$$

where n is the number of the relative mode of oscillation, ν_s is the synchrotron tune and ω_0 is the revolution frequency.

For the m=1 dipole mode, the shift of the coherent frequency ω_c is:

$$\Delta\omega_{c,n} = j\frac{\alpha_c I_b}{\omega_s (E/e)}(Z_n)_{effective}$$

where I_b is the beam current, α_c the momentum compaction.

For simplicity we consider the effect of a single HOM with longitudinal impedance:

$$Z(\omega) \ = \ \frac{R}{1 + jQ\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$

where R is the shunt impedance and Q the merit factor. The highest growth rate is obtained when the HOM resonant frequency coincides with an unstable sideband frequency. For a gaussian bunch with rms length σ_τ, we get:

$$\frac{1}{\tau} = \frac{\alpha_c I_b c R}{2(E_o/e)L_o\omega_s\sigma_\tau}G(x);$$

$$G(x) = \frac{2}{x}e^{-x^2}I_1(x^2); \; x = \omega\sigma_\tau$$

where $I_1(x)$ is the modified Bessel function and L_o the machine length. The function G(x) has a maximum at $\omega = 23.78\,\mathrm{GHz}$ (15 GeV) and at $\omega = 29.73\,\mathrm{GHz}$ (25 GeV). In table 6 we give, for such values of ω, the shunt impedance leading to a rise time comparable to the radiation damping time. In other words, the beam is stabilized by radiation damping if the shunt impedance of the HOMs does not exceed the values in the Table.

Table VI

Energy	15 GeV	25 GeV
$\tau_{radiation}$	41.4 ms	8.9 ms
R (max)	120 kΩ	1.5 MΩ

HOM Transverse Coherent Instability

The spectrum of the coherent transverse oscillations is given by lines at frequencies

$$\omega_p^{\mp} = (pk_b + n + \nu_{x,y} + m\nu_s)\omega_o$$

where $\nu_{x,y}$ is the transverse betatron tune. Analogously to the longitudinal case we consider a single transverse relative mode, (m = 0 is the lowest one). The perturbed frequency of the coherent oscillation mode is modified from the unperturbed value by a complex coherent frequency shift:

$$\Delta\omega_n^{\perp} = j\frac{I_b c^2}{2\nu_{x,y}\omega_o(E/e)L_o}\left(Z_n^{\perp}\right)_{effective}$$

We assume the beam coupled to a resonant transverse impedance:

$$Z_{\perp}(\omega) = \left(\frac{\omega_r}{c}\right)\frac{R_{\perp}^{Urmel}}{1 + jQ\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$

where $R_{\perp}^{Urmel}$ is the transverse shunt impedance per unit meter as given by the URMEL code. In the full coupling condition we get:

$$\frac{1}{\tau_o^{\perp}} = \frac{cI_b}{2\omega_\beta(E_o/e)L_o\sigma_\tau}R_{\perp}^{Urmel}G_{\perp}(x)$$

$$G_{\perp}(x) = xe^{-x^2}I_o(x^2); \; x = \omega_r\sigma_\tau$$

In this case the maximum value of $G_\perp(x)$ is obtained when ω=0. In Table VII we give a rounded value of the transverse impedance for which the beam is at the stability limit provided by the radiation damping, when ω=0.

Table VII

Energy	15 GeV	25 GeV
$\tau_{radiation}$	92.4 ms (x) 85.9 ms (y)	20.1 ms (x) 18.6 ms (y)
$R_\perp^{Urmel}$ (max)	2 MΩ/m	16 MΩ/m

Resistive Wall Transverse Coherent Instability.

This instability can be driven by the real part of the resistive wall impedance:

$$Z_\perp^{rw}(\omega) = (1+j)\frac{RZ_o}{b^3}\delta_o\sqrt{\frac{\omega_o}{\omega}}$$

where

$$\delta_o = \sqrt{\frac{2\rho R}{Z_o}}$$

and with ρ the resistivity of the vacuum chamber material, R the mean storage ring radius, b the radius of the ring vacuum pipe, Z_0 the free space impedance (=377 Ω).

If one of the lines in the bunch spectrum is very close to the origin in the negative frequency region, the resistive wall instability takes place since this line is associated with a very large negative resistance:

$$\mathrm{Re}\left[Z_\perp^{rw}\right] = -\frac{RZ_o\delta_o}{b^3}\sqrt{\frac{1}{\left|\mathrm{Fraq}\left(\nu_{x,y}\right) + m\nu_s\right|}}$$

The single line approximation works well for multibunch regime with a number of bunches k_b>>1. But we should expect that this approximation is not reliable when the chromaticity ξ>0. In fact by increasing ξ the bunch spectrum is moved to higher frequency region and the relative contribution of the line closest to the origin gets smaller while the contribution of other lines within the bunch spectrum grows. In this case we should take into account all these lines.

Here-under we give the results of a single line approximation at ξ=0 in the case of Copper chamber (ρ= 1.8*10^{-8} Ωm) with a vacuum chamber radius b = 2cm. With the betatron tunes given in Table I (i.e. Fraq(ν_x)= .665 and Fraq(ν_y)= .599), we get:

$$\mathrm{Re}\left[Z_\perp(\omega)\right] = \begin{cases} 18.1\ \mathrm{M\Omega/m}\ (x) \\ 19.1\ \mathrm{M\Omega/m}\ (y) \end{cases}$$

obtaining the rise times for the instability shown in Table VII. In this case the instability is much faster than the radiation damping time so that the use of a feedback system appears to be necessary.

Table VII

Energy	15 GeV	25 GeV
$\tau_{resistive\ wall}$	10.7 ms (x) 10.4 ms (y)	17.8 ms (x) 17.4 ms (y)

Feedback systems

Starting with longitudinal instabilities due to cavity monopole modes, tests on the cavities developed for the CESR luminosity upgrade have shown that such modes, having an R/Q < 10 Ω, can be damped to Q factors below 100 [9].

From the considerations of the previous chapters it results that the longitudinal instabilities, which mainly arise from the HOMs of the cavities, could be damped by synchrotron radiation alone. In the above evaluation, however, spurious impedances arising from bellows, kickers etc, have not been taken into account. On the real machine it could therefore result that an active feedback system should be added to complement the synchrotron radiation damping. The requirements on such a system are anyhow relaxed because it has to cope with only a fraction of the overall impedance.

The bunch by bunch approach is more attractive than the frequency domain one, since an a-priori knowledge of the endangered modes is not required. In this system each bunch is treated as an individual oscillator. The basic components are: a time gated phase detector, a bank of M parallel filters (M being the number of bunches) producing the correction kick signals, phase shifted by $\pi/2$, a broad band amplifier and a broad band kicker [4][5].With a number of bunches of the order of thousands the parallel filter approach is of difficult realization. Fortunately the electronic technology now available allows the realization of a mixed microwave-analog- digital system employing fast ($\geq$ 500 Msamples/sec) Analog to Digital and Digital to Analog converters and fast Digital Signal Processors as filters. A considerable R&D work on feedback systems for B factories has been carried on at SLAC [6] and KEK [7] for 1658 and 5000 bunches respectively.. The first complete system is now running at ALS, where stable operation at 400 mA in 328 bunches has been obtained [8].

The main advantage of such a system is that the same DSP can process several bunches, thus reducing the hardware complexity . Moreover the relatively low synchrotron frequency, with respect to revolution frequency, allows to reduce substantially the sampling rate.

All the above developments can be exploited directly for ELFE, as the inter-bunch interval, and the related Nyquist sampling bandwidth are certainly within the capabilities of systems above mentioned [6-8], already realized and in operation.

The transverse feedback system has to cope mainly with the RW instability. It is simpler than the longitudinal one because each bunch signal does not need a separate delay filter, as the $\pi/2$ phase shift is readily obtained by placing two pick-ups (for each plane) located $\approx$ 90 degrees apart in betatron phase and adding the corresponding signals with appropriate coefficients to provide the quadrature kicker signals, for arbitrary kicker location (see Fig. 6).

The main accelerator parameters relevant to the design of the transverse system and the resulting specifications are given in Table IX. In the following table only the vertical (y) direction is considered, which is more critical due to the lower chamber dimension, but similar considerations are valid for the horizontal direction.

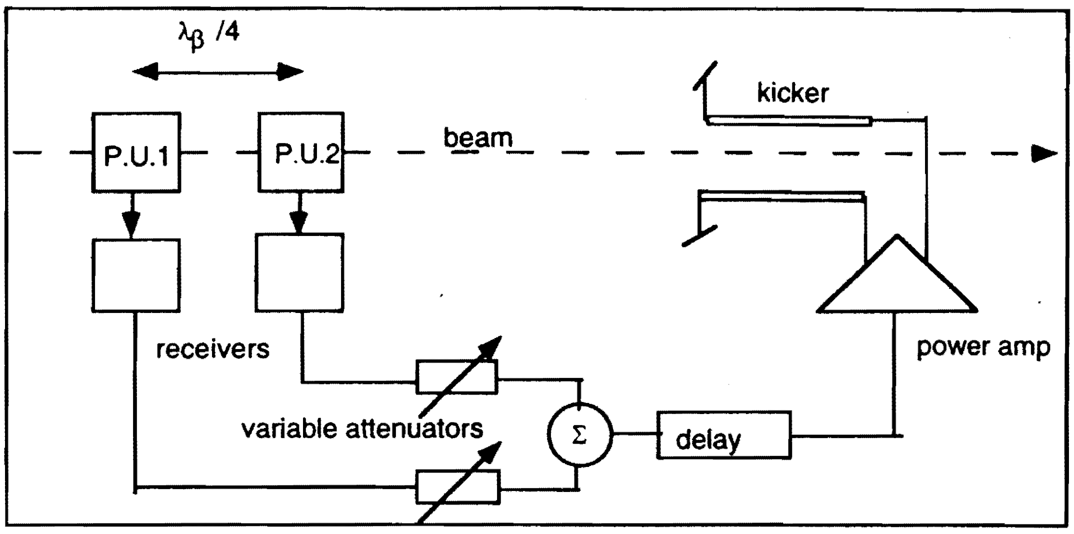

FIG. 6 - Transverse feedback sketch.

Table IX

Energy	15 GeV
Average current	150 mA
RF frequency	433.3 MHz
Orbit frequency	47.32 kHz
Bunch spacing	2.3 ns
Average β_y	20 m
Fractional tune	0.599
RW impedance	20 MΩ/m
Growth rate of m=0 mode	96 sec^{-1}
Feedback gain required	3 kV/mm
Electronics bandwidth	10 kHz - 250 MHz

The maximum available kick and the corresponding mode amplitude are determined by the available amplifier power and by the kicker impedance. Actually a power of 500 W with such a bandwidth is obtainable, eventually combining two amplifiers. With a kicker impedance of ~4 kΩ, which seems quite obtainable with 50 Ω stripline electrodes ~0.3 m long and large covering factor, one can obtain a 2 kV kick and a corresponding maximum mode amplitude of 0.6 mm. It must however be noticed that the feedback action takes place (in a nonlinear way) even with the amplifier clipping and therefore the correctable mode amplitude can be larger than this.

In order to exploit the maximum damping capability of the system one must anyhow take care that injection offsets are avoided and that the electronics design foresees cancellation of orbit drifts.

All the above specifications and the power and kicker data seem to be within the state of the art.

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