Simulation for choice of RF phase and RF jitters in the main linac

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1. Parameter of the linac

Parameters for 'CMS energy 1TeV case B' in the table 'Pre-ISG2 Parameters' are used except a/λ (=O. 18). Beta function is 7 m at 10 GeV and scales as square root of beam energy. Nominal normalized emittance is 3x10^{-8}.

2. Choice of RF phase

Let us define energy-z correlation as follows,

$$\delta E / E \equiv \frac{1}{E\sigma_z q} \int E(z) z \rho(z) dz \qquad (1)$$

where σ_z is the bunch length, z the longitudinal coordinate, $\rho(z)$ the charge density at z, $E(z)$ average energy at z.

We simulated six cases : (a) Constant phase, (b) Change phases once at 150 GeV, (c) Change phases twice at 150 GeV and 250 GeV, (d) twice at 150 GeV and 300 GeV, (e) twice at 150 GeV and 350 GeV, (f) twice at 150 GeV and 400 GeV. In all cases, phases are chosen to make the energy-z correlation at the end of linac zero, or the energy spread minimum. The phase in the case (a) is decided by this constraint as 15.4" (off crest angle of the bunch center). For the other cases, 'over head voltage', Voh, was a parameter to decide the phases.

Voh = (Total RF voltage)/(Total RF voltage in the case (a)) -1 (2)

Cases of Voh=O, 1, 3 and 5 % were simulated (Voh=O means the case (a)).

Energy spread (r.m.s.) along the linac are shown in the figure 1 for all simulated cases.

Energy-z correlation are shown in the figure 2 for the all cases except (a) which has almost zero energy-z correlation.

Energy-z correlation for the auto phasing condition is approximately constant along the linac and a rough estimation gives

$$\delta E / E(\text{auto phasing}) \approx eq\beta^2 W_T(2\sigma_z)/4E \approx 0.044 \qquad (3)$$

This is much bigger than that in the Voh=5% cases. To make such big energy slope, big over head voltage is needed and probably will not realistic.

Results of simulation

Emittance dilution are simulated for injection errors, vibration of quadrupole magnets and misalignment of quadrupole magnets with orbit correction.

We take ‘effective emittance’ as a measure of beam quality to look effects of jitters or fast errors which will not be corrected and emittance to look effects of fixed or slowly changing errors which will be corrected.

$$\varepsilon_{eff} \equiv \sqrt{<y^2><y'^2> - <yy'>^2} \qquad (4)$$

$$\varepsilon \equiv \sqrt{<(y-<y>)^2><(y'-<y'>)^2> - (<yy'> - <y><y'>)^2} \qquad (5)$$

where < > means the average of all particles.

Figure 3 shows averaged effective emittance dilution due to injection jitters. The offset and the angle of the injected beam were randomly set as gaussian with sigma of 0.5 of the beam size. Except for the injection error, linac was assumed to be perfect. The averages over 200 random seeds are shown.

Figure 4 shows averaged effective emittance dilution due to transverse vibration of quadrupole magnets. The transverse offset of quads were randomly set as gaussian with sigma of 10 nm. Except for the injection error, linac was assumed to be perfect. The averages over 200 random seeds are shown.

Figure 5 shows averaged effective emittance dilution due to transverse misalignment of quadrupole magnets with orbit correction. Simple one-to-one orbit correction was assumed. There were steering magnets and BPMs at all quadrupoles. Only BPMs at focusing quads were used and the beam is steered to make the BPM readings zero. The transverse offset of quads were randomly set as gaussian with sigma of 2 micron. The BPMs also have random transverse offset with sigma of 2 micron with respect to the quads’ center. Resolution of the BPMs was 1 micron. Accelerating structures were aligned perfectly w.r.t. the beam. The averages over 100 random seeds are shown.

It is obvious that energy-z correlation should be large, it means large over head voltage, to suppress emittance dilution caused by injection error and quads’ vibration. On the other hand, large energy spread makes dispersive effects large which is shown as emittance dilution caused by quads’ misalignment with orbit correction. Of cause, considering the efficiency, too large over head voltage should be avoided. As conclusion, the phases should be decided as a result of some compromise.

For further simulations we pick up the four cases Voh=O, Voh= I % phases change at 150 GeV and 250 GeV, Voh=3% phases change at 150 GeV and 300 GeV and Voh=5% case phases change at 150 GeV and 350 GeV.

3. RF jitter

Simulations with jitter of RF amplitude and phase have been done for the four cases of the phase choice. In the simulations, considering DLDS scheme, one RF unit consists of 12 accelerating structures and each unit has the same error of amplitude and phase with Gaussian distributions. All RF units have the same r. m. s. of the errors and no correlation was considered between different units.

Beam energy

Here, we looked final beam energy and energy spread with the error of RF.

Amplitude jitter causes pulse to pulse fluctuation of the beam energy (average of particles in one pulse). Assuming independent errors, the r.m.s. of the relative error of the beam energy can be estimated simply as

$$\sigma_{\langle E\rangle}/E = \sigma_{amp}/\sqrt{N_{RF}} \qquad (1)$$

where σ_{amp} is the r.m.s. of the relative amplitude jitter of each unit and N_{RF} the number of RF units. Figure 6 shows the results of simulations with 200 random seeds, r.m.s. of the relative energy error vs. r.m.s. of the amplitude jitter which are consistent with the equation (1) where N_{RF} = 399. Average of changes of energy spread in one pulse were less than le-6 in the simulations of any cases.

Phase jitter causes pulse to pulse fluctuation of the beam energy and also reduces the mean beam energy. Results of simulations with 200 random seeds are shown in figure 7 and 8. Figure 7 shows the average of the relative beam energy vs. r.m.s. of the phase jitter. Error bars in the figure 7 represent the fluctuations of the beam energy which are shown in figure 8 more clearly. Average of the energy reduction does not depend on the choice of the phases though the fluctuations become a little large for the case of the large over head voltage.

Transverse motion

Energy error along the linac induced by errors of RF amplitude and phase may affect transverse motions of the beam. When there are misalignment of magnets and/or orbit errors, pulse to pule energy difference will cause pulse to pule orbit difference due to dispersive effect.

As initial conditions, we set random misalignment of quads and calculated strength of steering magnets for one-to-one orbit corrections without RF errors. The misalignment and the setting of the magnets were saved and used in simulations with RF errors. The misalignment of the quads were assumed to be gaussian with sigma=2 micron, truncated 3-sigma. BPMs were also misaligned with respect to the quads with sigma=2 micron, truncated 3-sigma. BPM resolution was sigma=1 micron.

Figure 9 shows relative 'effective emittance' vs. r.m.s. of amplitude jitter for four cases of the phase choice. Figure 10 shows relative 'effective emittance' vs. r.m.s. of phase jitter. In both figures, each point represents average of 200 random seeds for jitters in one initial condition (one misalignment-orbit correction set). The same initial condition was used in the same case of the phase choice.

Because the results are statistically poor, simulations were done for 50 different initial conditions and 50 different RF errors for each initial condition (50 linacs, 50 pulses for each linac) only in the case of Voh=3%. Figure 11 shows relative ‘effective emittance’ increase vs. r.m.s. of amplitude jitter and Figure 12 shows relative ‘effective emittance’ increase vs. r.m.s. of phase jitter. In these two figures, average and r.m.s. of the additional increase of the effective emittance due to jitters are shown.

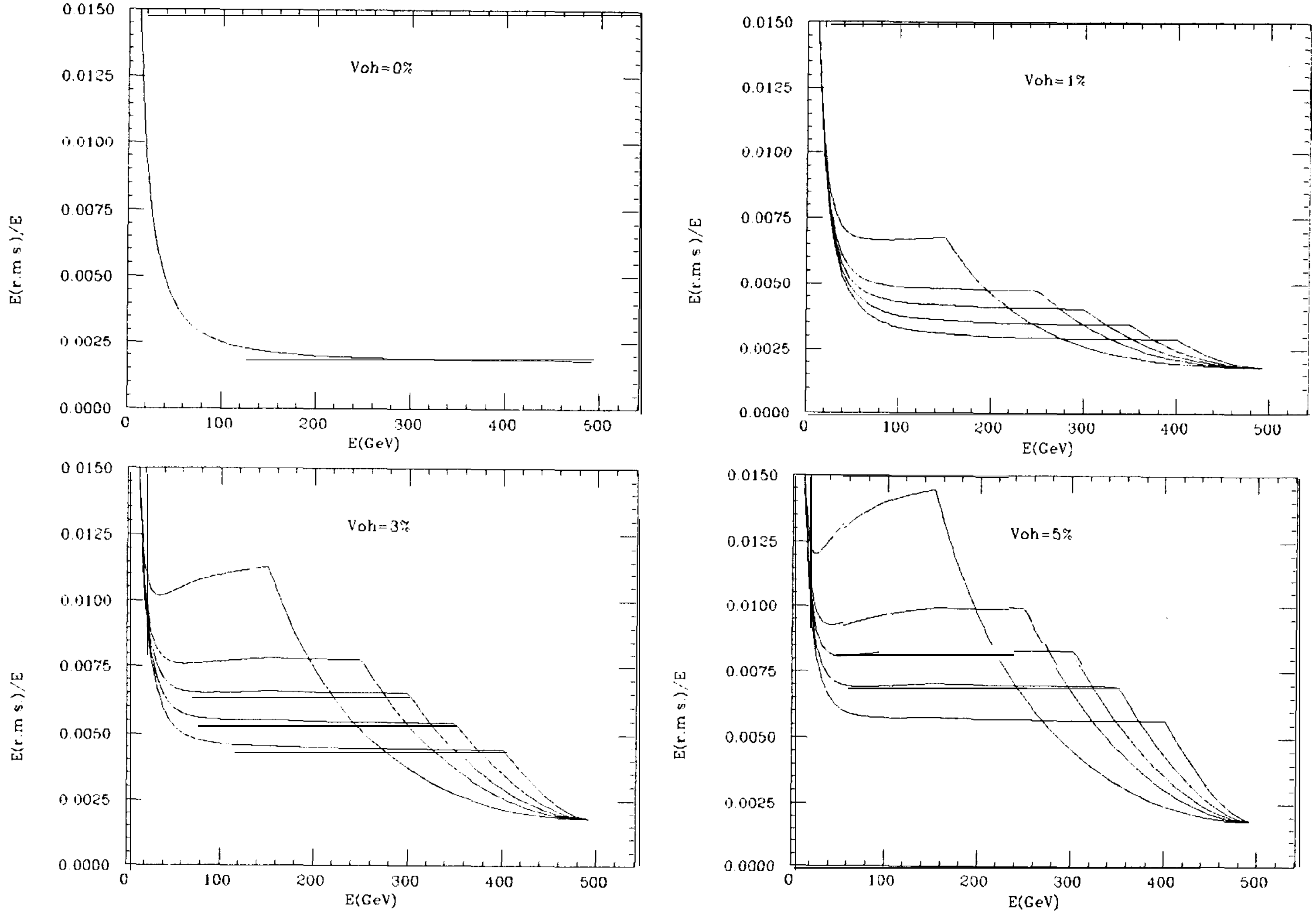

Fig. 1, Energy spread (r.m.s.) along the linac.

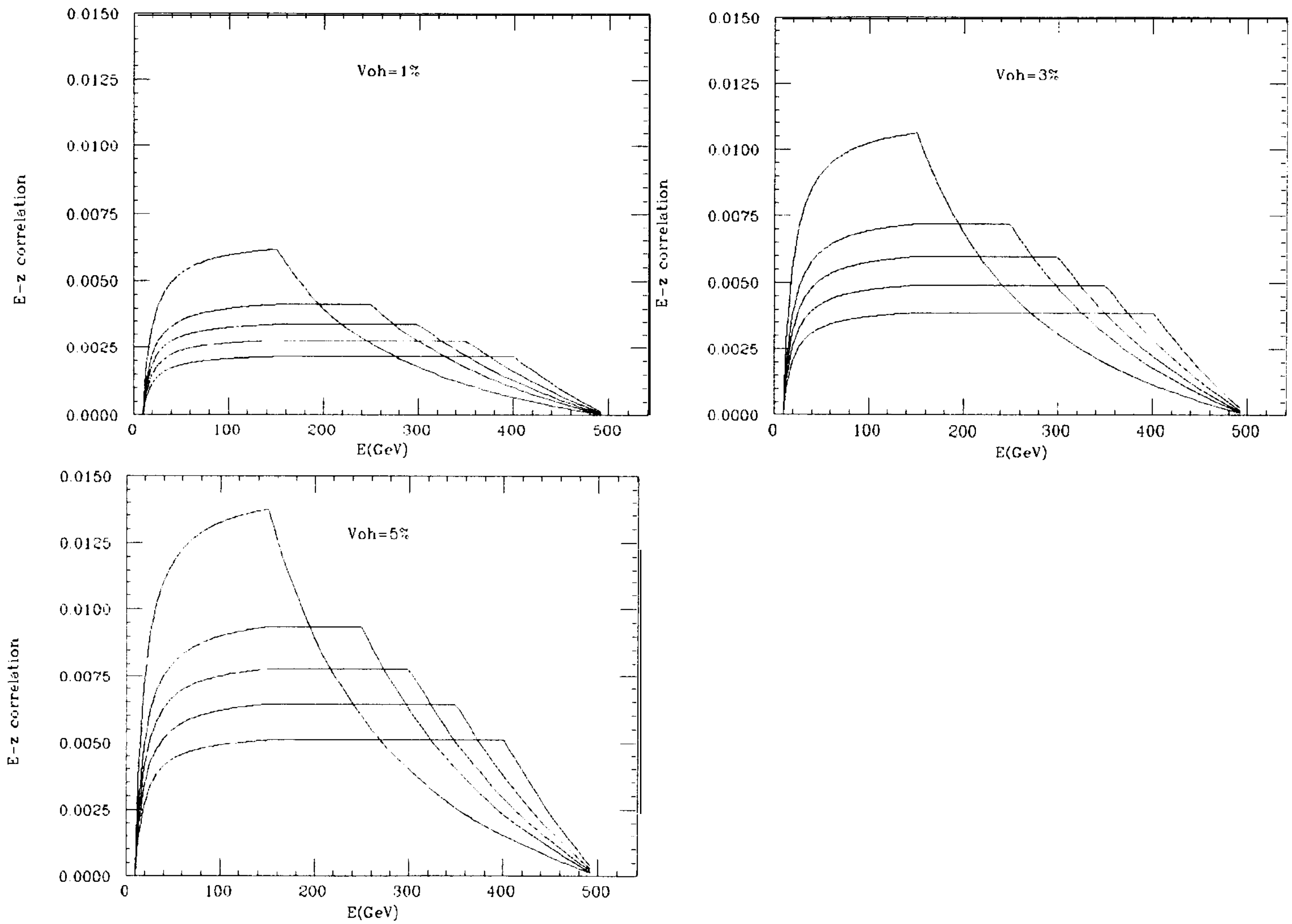

Fig. 2, Energy-z correlation along the linac.

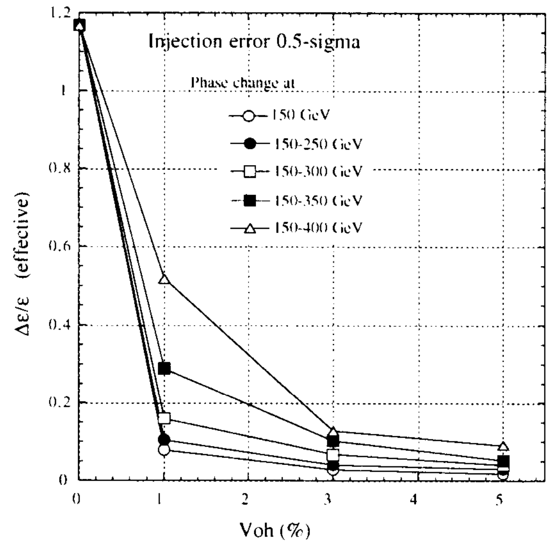

Fig. 3, Average effective emittance dilution due to injection jitters.

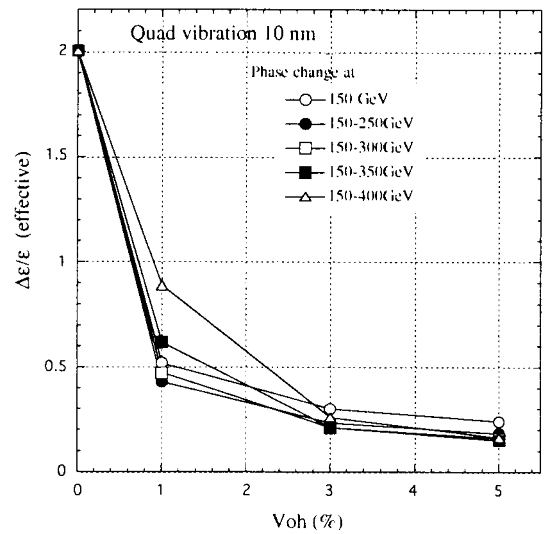

Fig. 4, Average effective emittance dilution due to transverse vibration of quadrupole magnets.

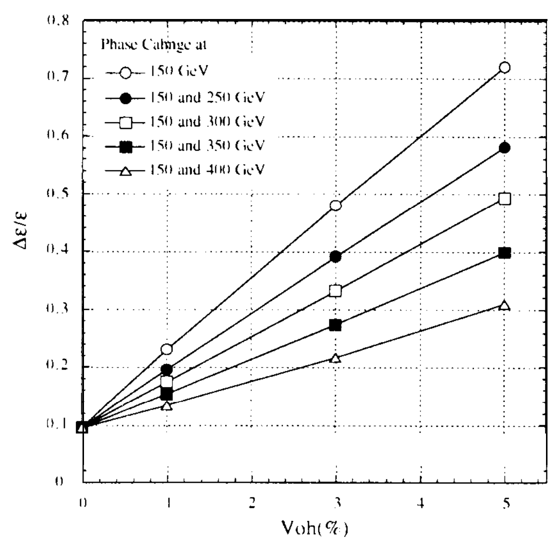

Fig. 5, Average emittance dilution due to misalignment of quadrupole magnets with orbit correction.

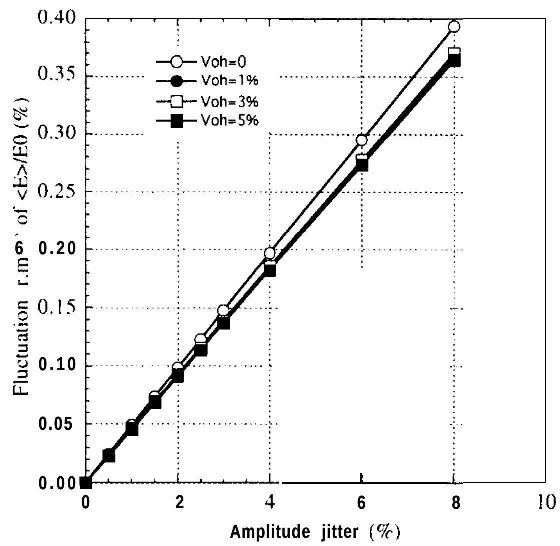

Figure 6, r.m.s. of the relative energy error vs. r.m.s. of the amplitude jitter, simulation with 200 random seeds.

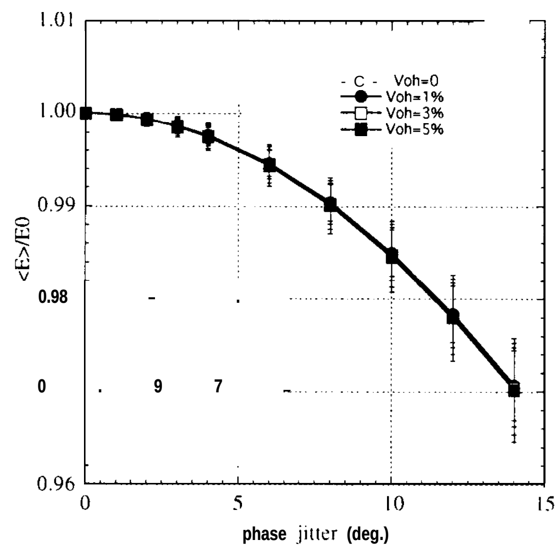

Figure 7, Average of the relative beam energy vs. r.m.s. of the phase jitter. Error bars represent the fluctuations of the beam energy.

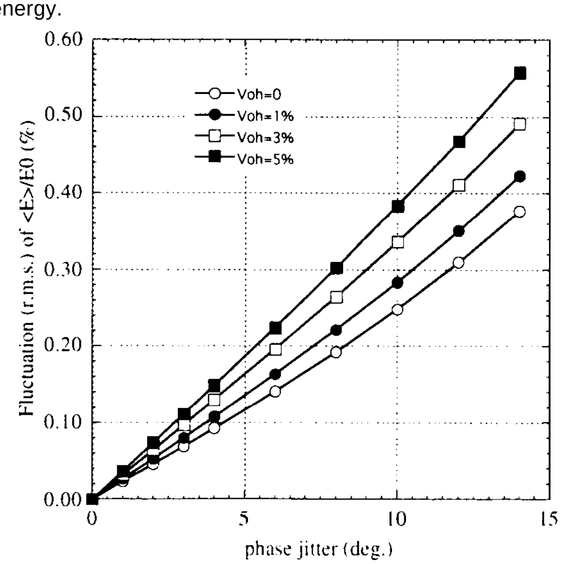

Figure 8, Fluctuations of the beam energy vs. r.m.s. of the phase jitter.

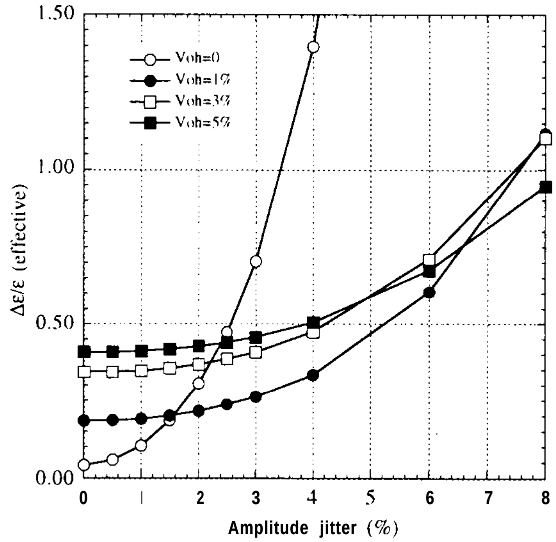

Figure 9, Relative 'effective emittance' vs. r.m.s. of amplitude jitter. Each point represents average of 200 random seeds for jitters in one initial condition

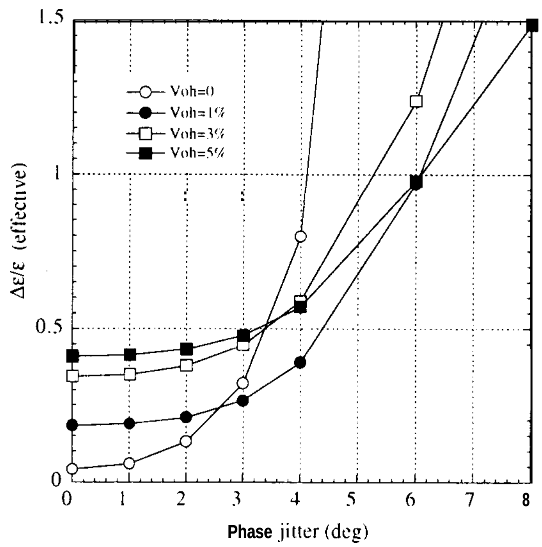

Figure IO, Relative 'effective emittance' vs. r.m.s. of phase jitter. Each point represents average of 200 random seeds for jitters in one initial condition

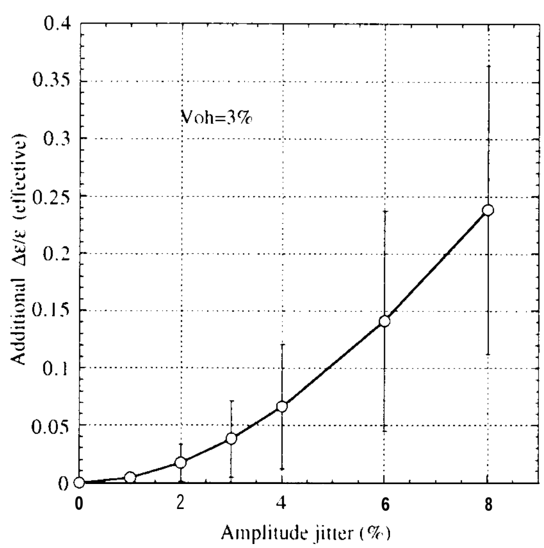

Figure 11, Relative 'effective emittancc' increase vs. r.m.s. of amplitude jitter. Average and r.m.s. of the additional increase of the effective emittancc due to jitters arc shown.

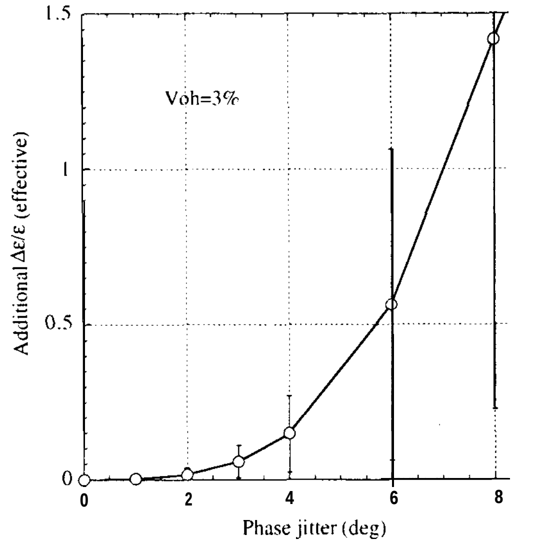

Figure 12. Relative 'effective emittancc' increase vs. r.m.s. of phase jitter. Average and r.m.s. of the additional increase of the effective emittance due to jitters are shown.