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An isochronous optics for EPA

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1 Introduction

An experiment using very short electron bunches in the EPA ring requires the orbit length to be independent of momentum and betatron amplitudes. The modification of the ring optics should be obtained preferably using the existing machine components, as the machine will return to normal lepton production immediately after the test. Equally, beam envelopes and trajectories in the injection area should change as little as possible.

This note presents the results of the beam optics calculations carried out to prepare the experiment.

2 Modification of α

The derivative of the orbit length w.r.t. $\Delta p/p$ is equal to the ring circumference C multiplied by the *momentum compaction* factor α. The latter depends on the value of the dispersion function in the bending magnets. If the dispersion is modified using a set of N quadrupoles the change of α is given [1] by

$$C\,\Delta\alpha \;=\; -\sum_{i=1}^{N} \Delta K_i\; L_i\; D_i\; D_i^* \tag{1}$$

with :

ΔK_i the normalized gradient increment of quadrupole i
L_i the length of quadrupole number i

D_i the *unperturbed* dispersion at quadrupole i
D_i^* the *modified* dispersion at quadrupole i

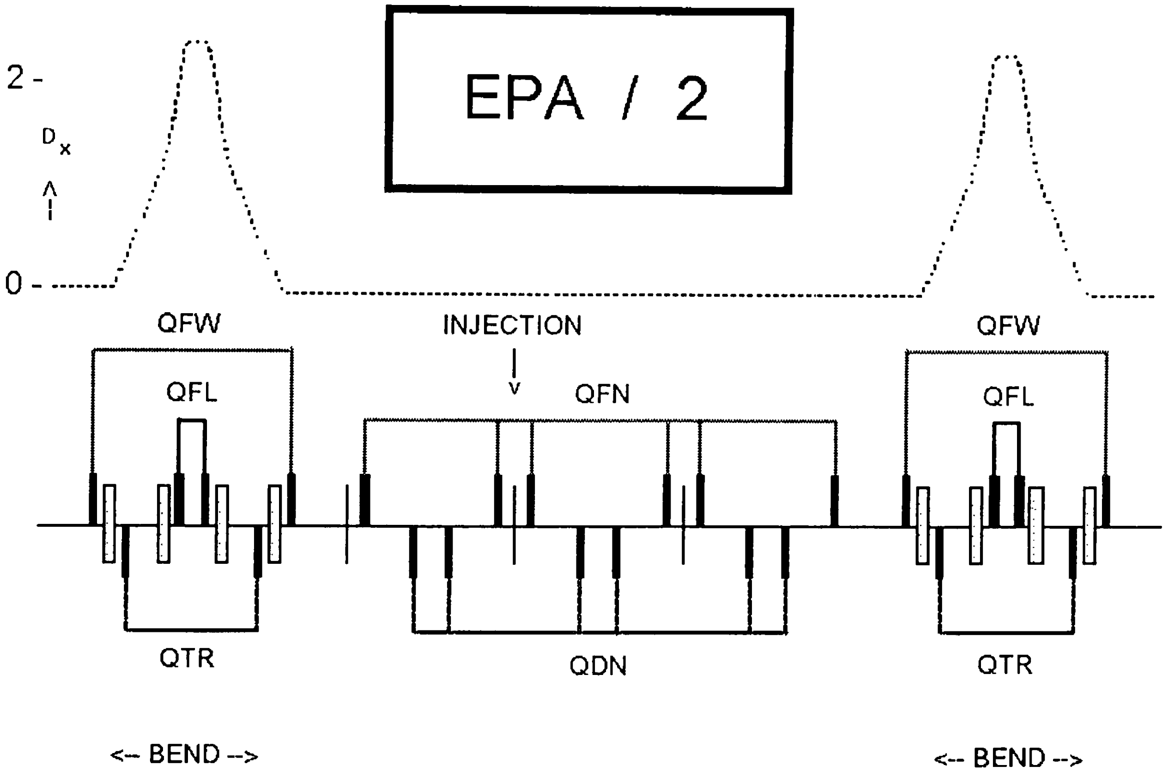

Figure 1: Layout of the quadrupole families and the dispersion function with the nominal optics in one half of the EPA ring

For *small* gradient increments the higher order terms in ΔK may be neglected and a crude estimation of the α change can be made using the dispersion values of the *nominal* machine only:

$$C\,\Delta\alpha \;\approx\; -\sum_{i=1}^{N} \Delta K_i\; L_i\; D_i^2 \tag{2}$$

This shows why the quadrupole families QFN and QDN have little effect, as at these locations D is zero in the nominal optics (see fig. 1). The QFI quadrupoles are not shown in this figure, they are assumed to belong to the QFN family and to have the same strength. The main contribution is made by QFL ($D \;\approx\; 2\ m$). QTR and QFW may be used to control the tunes, leaving the QFN and QDN families unchanged in order to perturb the injection conditions as little as possible.

The nominal and modified dispersion functions have been calculated with the MAD program (figure 2). The gradient settings for both cases are listed in table 1. A summary of the MAD results is printed in figure 9. The maximum β values (26 and 37 m) are larger than in the nominal machine ($\beta_x \approx \beta_y \approx 15\ m$).

In the machine experiment it will be useful to be able to fine tune the value of α by *manual* adjustment of one single family (QFL, see table 2).

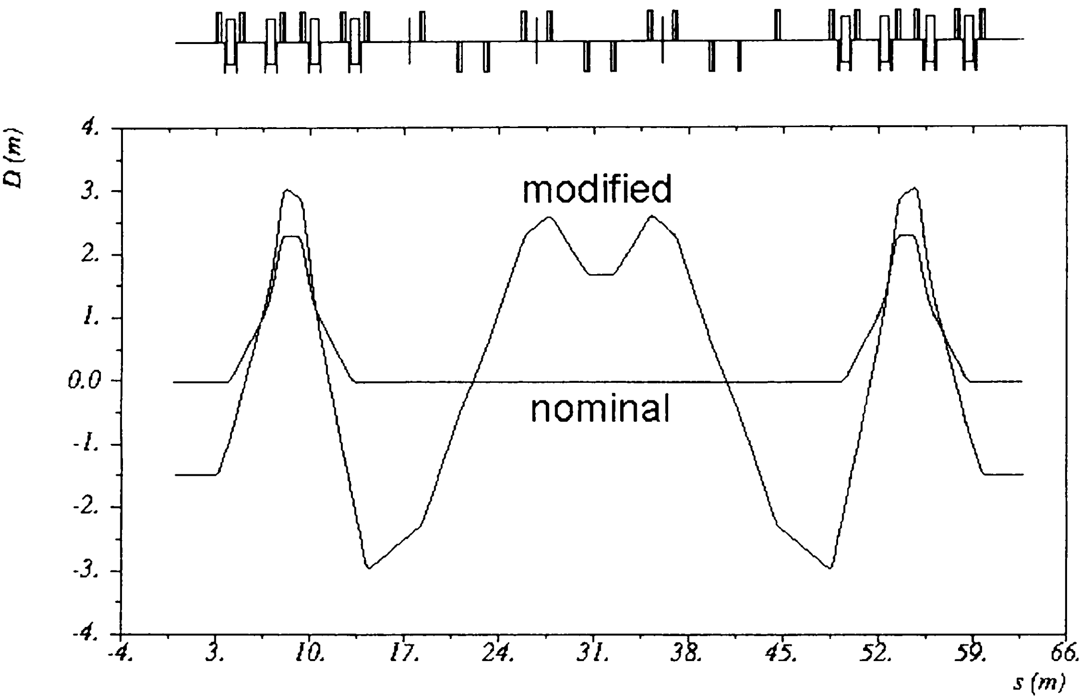

Figure 2: Dispersion functions with nominal ($\alpha = 0.03$) and modified ($\alpha = 0$) optics

3 The sensitivity of α to $\Delta p/p$ and betatron amplitudes

By adjusting the chromaticities to values close to zero the variations of α with $\Delta p/p$ could be minimized in the MAD calculation. To this end both chromaticities were first set to zero. Then the orbit length variations across the $\Delta p/p$ range between -.005 and +.005 were minimized by fine tuning the F sextupole current (XNH), yielding $Q'_x = -0.8$ and $Q'_y = +0.7$. The optimum sextupole settings are included (XNH and XNV) in table 1. The maximum length variation in this momentum range could thus be kept below 30 μm (fig. 3).

The residual length variation is of third order in $\Delta p/p$. Simulations show that by adding octupoles in EPA the variation might be further reduced to less than 1 μm.

An additional advantage of cancelling the length variations was discovered when tracking was done for particles with *finite* betatron emittances. Provisional tracking results show that this procedure made the trajectory lengths equally insensitive to the *betatron* amplitudes. Confirmation and explanation of this observation will require further study.

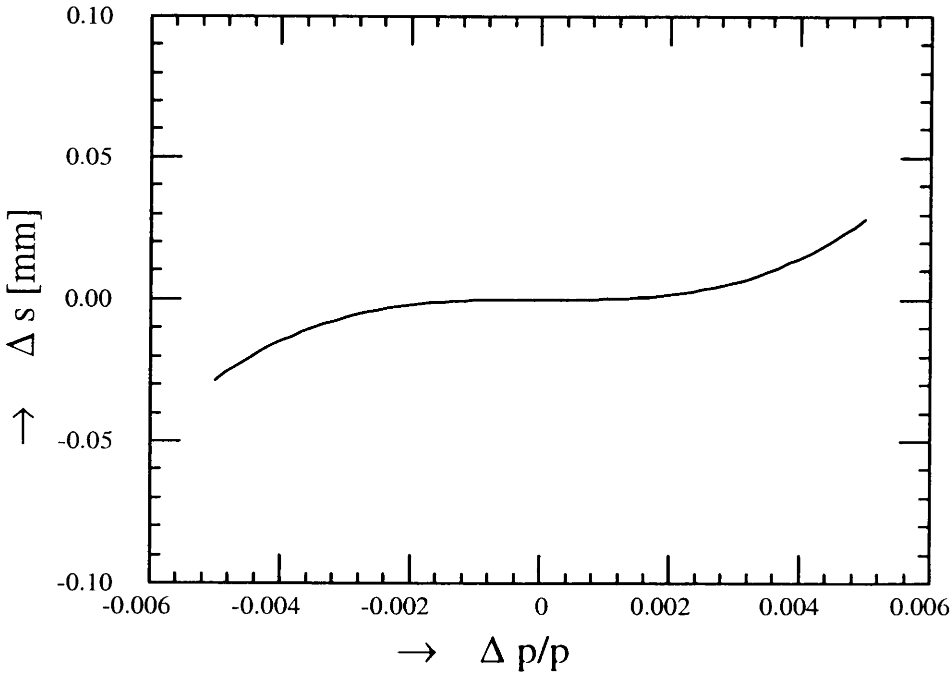

Figure 3: orbit length vs. momentum

4 Evolution of the bunch length

Particles were tracked without r.f. voltage, with initial conditions $\sigma_e = 2.5\ 10^{-3}$ and $\sigma_t = 7.5\ ps$. After 1000 turns the bunch length increases to $\sigma_t = 141\ ps$ (fig. 4) for particles with zero initial betatron amplitude.

The calculation of the exact contribution of the betatron amplitudes, although probably small as mentioned above, requires a more sophisticated description of the EPA bending magnet. The bunch length simulation was done with the combined function bending magnet model currently used for EPA in MAD, which has a *finite* magnetic length and may thus be used to calculate path length differences. On the other hand, this model is not sufficiently symplectic to allow tracking of transverse motion over 1000 turns and a *zero length* bend had to be used for this case. More work is required to build a model which allows simultaneous tracking in both transverse and longitudinal planes.

5 Adjustment of the revolution frequency

A $+0.2\ mrad$ kick in both bumpers BSW12 and BSW91 produces an orbit length increase of $1\ mm$ ($\approx 8\ ppm$) at the expense of an orbit distortion of only $3.4\ mm$. This may be useful in future tests where an adjustment of the revolution frequency is required.

Family	Normalized Gradient $[m^{-2}]$ or $[m^{-3}]$		Current $[A]$		
	Nominal	$\alpha = 0$	Nominal	$\alpha = 0$	I^{max}
QFN	0.5659220	0.565922	33.5360	33.5360	55
QFI	0.5335500	0.533550	28.7832	28.7832	46
QDN	-0.5689250	-0.568925	-33.7140	-33.7140	55
QFW	1.1104300	1.180000	51.5717	54.8027	95
QTR	-0.0521899	0.280000	-3.0927	16.5926	20
QFL	1.3803500	1.610630	74.4651	86.8879	118
XNH	8.4380000	5.511000	28.4171	18.5597	91
XNV	-6.1390000	-12.866000	-20.6747	-43.3296	91
HI.QFD1	2.0250000	2.127000	94.0471	98.7843	130
HI.QFD2	2.3700000	2.381000	110.0699	110.5808	130

Table 1: Quadrupole and sextupole settings with the nominal and with the $\alpha = 0$ optics

6 Injection and envelopes

The optics in the injection area is left *locally* unchanged, as the QFN and QFD settings are not modified. This ensures that the injection bump remains closed.

The optics of the injection line is not sufficiently flexible with the present configuration of the quadrupole families. Therefore a larger betatron mismatch than usual will have to be accepted in the test.

The first-turn beam envelopes at 1 σ are shown in figures 5 and 6. Multi-turn beam envelopes are presented in figures 7 and 8. The first-turn envelopes are globally larger with the modified optics, which may result in a smaller injection efficiency. The multi-turn envelopes with the modified optics are larger only in the long straight sections, but not in the injection kickers and septa.

QFL Current [A]	α [10^{-3}]
89.9	-12.0
88.9	-7.8
87.9	-3.8
86.9	0.0
85.9	3.5
84.9	6.8
83.9	10.0

Table 2: Fine tuning of α using one single quadrupole family

7 Conclusions

The above presented calculations show that EPA can be made isochronous across the momentum range of the incoming bunches. The 0th, 1st, 2d and 3d derivatives of the orbit length w.r.t. $\Delta p/p$ can be cancelled using respectively:

- bumpers BSW12 + 91
- quadrupoles QFL + QTR + QFW,
- sextupole XNH
- an octupole family, if this were available

The results obtained in simulation may be summarized as follows:

- $\alpha = 0$ can be obtained by adjusting 3 existing quadrupole families which do not change the injection conditions
- manual fine tuning of α is possible by adjusting the setting of *one single family* (QFL)
- tuning the HOR chromaticity (≈ -0.8) using the F sextupole family allows to keep α small in the entire $\Delta p/p$ range -.005 to +.005
- the residual orbit length variations are smaller than 0.030 mm
- the resulting bunch length increase is of the order of 140 ps after 1000 turns

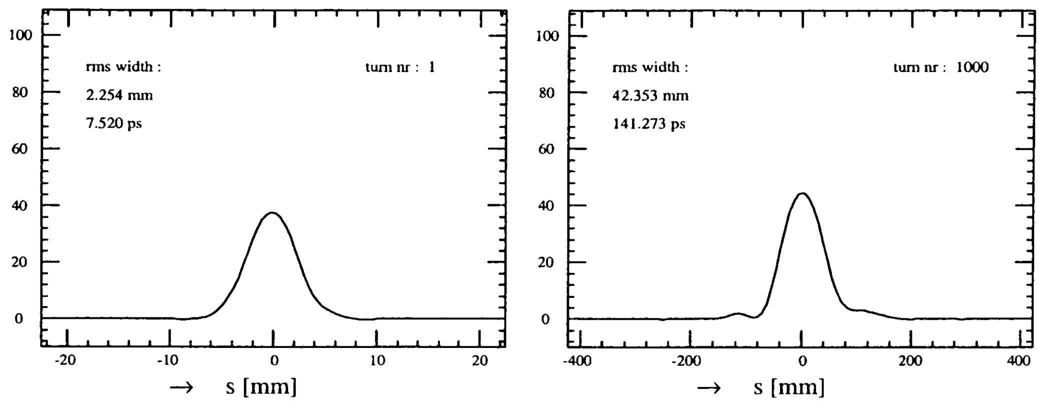

Figure 4: bunch shape at injection (left) and after 1000 turns (right)

Provisional simulation results suggest that with these settings the path length becomes equally independent of the *betatron* amplitudes. Further studies are required to confirm and explain this observation.

References

[1] T. Risselada, in *Proceedings of the Fifth General Accelerator Physics Course,* CERN 94-01, 1994, Vol. I, p.313

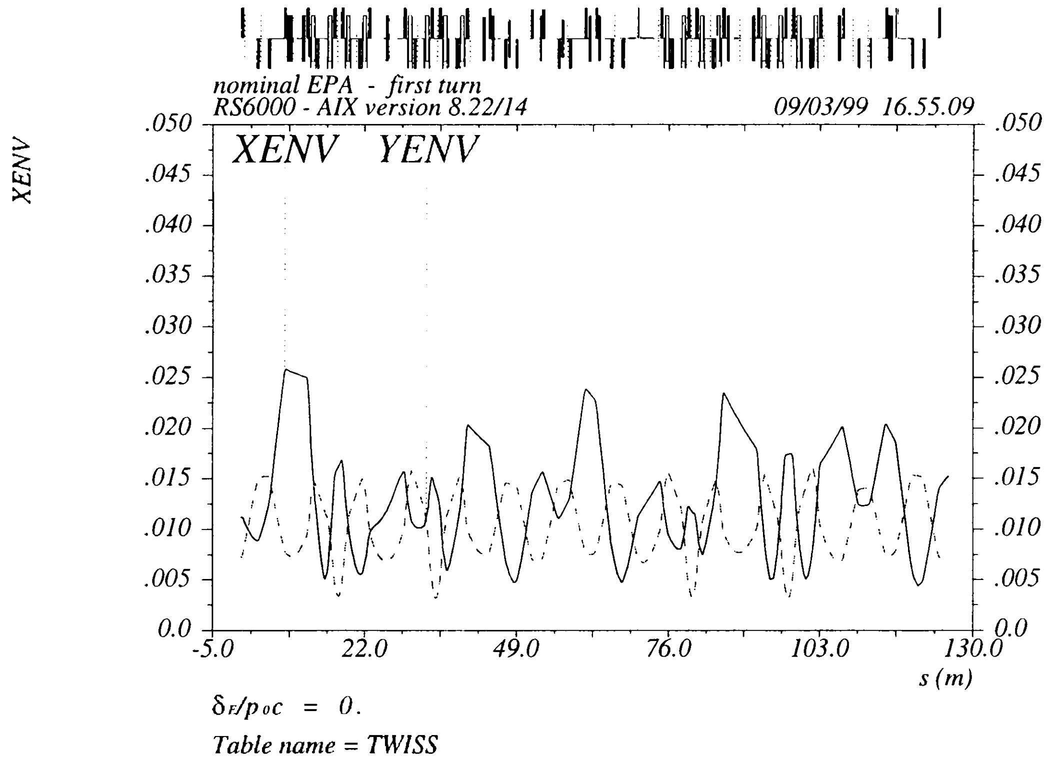

Figure 5: H and V first-turn envelopes at 1 σ with the nominal optics

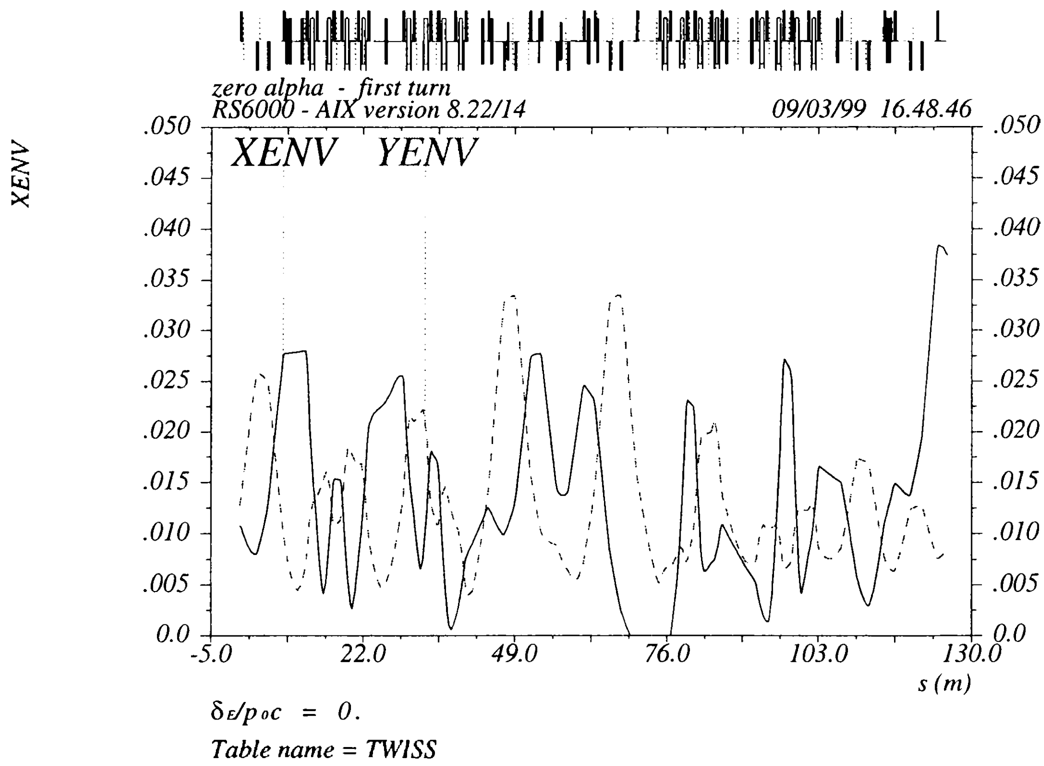

Figure 6: H and V first-turn envelopes at 1 σ with the modified optics

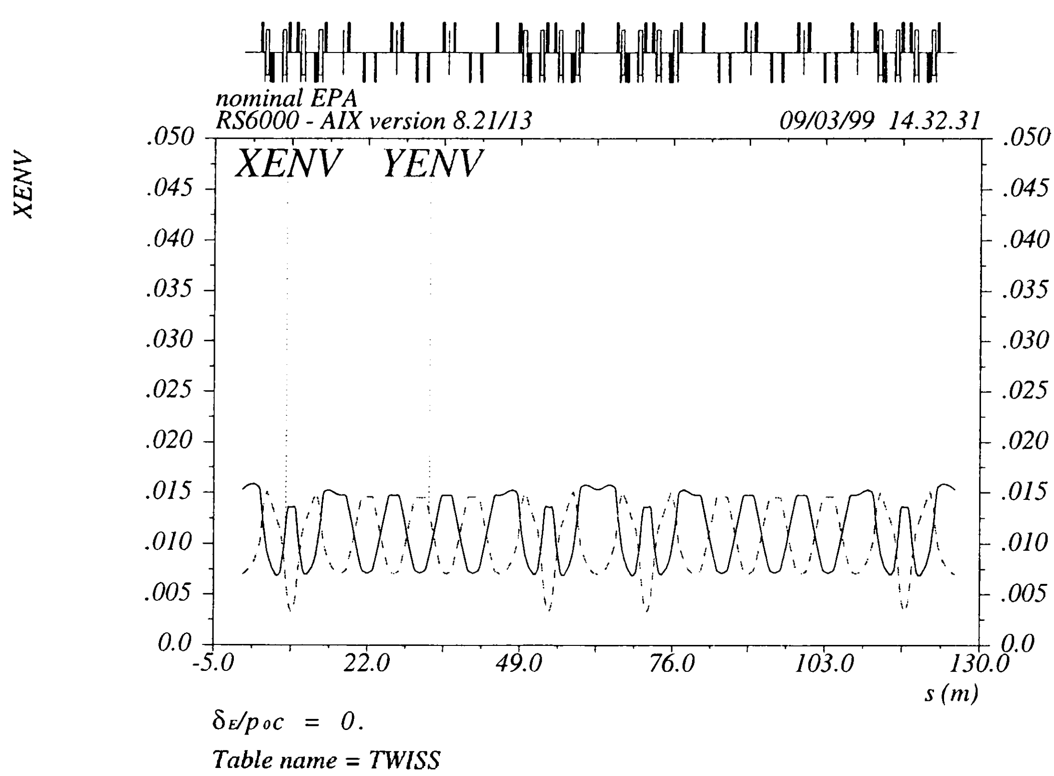

Figure 7: H and V multi-turn envelopes at 1 σ with the nominal optics

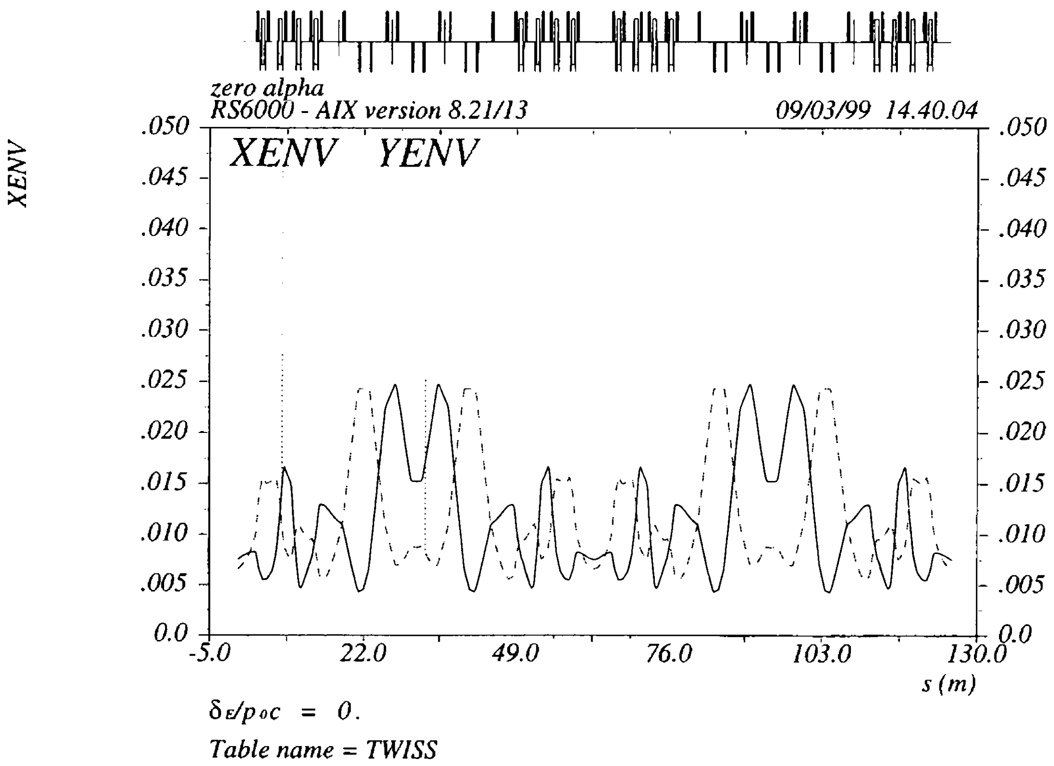

Figure 8: H and V multi-turn envelopes at 1 σ with the modified optics

EPA with alpha = 0 — "MAD" Version: 8.22/14 — Run: 15/03/99 15.57.57

Linear lattice functions. TWISS — line: EPA — range: #S/#E

Delta(p)/p: .000000 — symm: F — super: 1 — page 1

	ELEMENT SEQUENCE		I		HORIZONTAL						I		VERTICAL				
pos. no.	element name	occ. no.	dist [m]	betax [m]	alfax [1]	mux [2pi]	x(co) [mm]	px(co) [.001]	Dx [m]	Dpx [1]	betay [m]	alfay [1]	muy [2pi]	y(co) [mm]	py(co) [.001]	Dy [m]	Dpy [1]
begin	EPA	1	.000	7.992	.000	.000	.000	.000	-1.489	.000	2.738	.000	.000	.000	.000	.000	.000
2	SMH00D	1	.208	7.997	-.026	.004	.000	.000	-1.489	.000	2.754	-.076	.012	.000	.000	.000	.000
26	UMA03U	1	5.439	1.668	.466	.173	.000	.000	.228	.819	14.298	-.294	.165	.000	.000	.000	.000
52	UMA05U	1	8.906	4.273	.488	.415	.000	.000	2.925	-.143	3.875	.467	.234	.000	.000	.000	.000
97	UMA11U	1	14.748	25.182	1.271	.829	.000	.000	-2.911	.180	2.000	.085	.438	.000	.000	.000	.000
103	KFI11U	1	17.137	19.700	1.023	.847	.000	.000	-2.482	.180	4.469	-1.119	.586	.000	.000	.000	.000
105	KFI11D	1	17.380	19.209	.998	.848	.000	.000	-2.438	.180	5.042	-1.241	.594	.000	.000	.000	.000
114	BSW12U	1	18.763	13.417	3.831	.861	.000	.000	-1.963	.636	11.230	-4.004	.625	.000	.000	.000	.000
116	BSW12D	1	18.931	12.167	3.635	.863	.000	.000	-1.856	.636	12.613	-4.258	.627	.000	.000	.000	.000
126	UMA13U	1	22.553	1.522	-.403	1.097	.000	.000	.278	.527	37.018	-.018	.649	.000	.000	.000	.000
154	UMA23U	1	31.943	7.704	-.069	1.297	.000	.000	1.669	.000	4.816	-.107	.914	.000	.000	.000	.000
163	KFI31U	1	35.918	19.700	1.023	1.347	.000	.000	2.482	-.180	4.470	-1.116	1.086	.000	.000	.000	.000
165	KFI31D	1	36.161	19.209	.998	1.348	.000	.000	2.438	-.180	5.042	-1.238	1.094	.000	.000	.000	.000
174	BSW32U	1	37.544	13.417	3.831	1.361	.000	.000	1.963	-.636	11.218	-3.998	1.125	.000	.000	.000	.000
176	BSW32D	1	37.712	12.167	3.635	1.363	.000	.000	1.856	-.636	12.600	-4.251	1.127	.000	.000	.000	.000
182	UMA33U	1	40.273	1.527	.407	1.474	.000	.000	.281	-.527	36.955	.013	1.145	.000	.000	.000	.000
191	UMA41U	1	48.078	25.167	-1.271	1.742	.000	.000	-2.910	-.180	2.007	-.078	1.355	.000	.000	.000	.000
236	UMA45U	1	53.920	4.267	-.487	2.156	.000	.000	2.924	.143	3.847	-.463	1.560	.000	.000	.000	.000
262	UMA47U	1	57.387	1.662	-.462	2.398	.000	.000	.233	-.819	14.262	.289	1.629	.000	.000	.000	.000
290	UMA49U	1	62.656	7.996	.022	2.568	.000	.000	-1.489	.000	2.765	.064	1.784	.000	.000	.000	.000
306	BHZ52	1	67.192	3.222	1.054	2.669	.000	.000	-.649	.823	15.361	.729	1.947	.000	.000	.000	.000
318	UMA53U	1	68.270	1.668	.466	2.744	.000	.000	.228	.819	14.259	-.288	1.959	.000	.000	.000	.000
329	BHZ54	1	70.172	2.920	-1.547	2.930	.000	.000	2.032	1.582	11.066	5.610	1.980	.000	.000	.000	.000
344	UMA55U	1	71.737	4.273	.488	2.986	.000	.000	2.925	-.143	3.853	.465	2.027	.000	.000	.000	.000
389	UMA61U	1	77.579	25.182	1.271	3.401	.000	.000	-2.911	.180	2.008	.081	2.233	.000	.000	.000	.000
402	UMA62U	1	82.762	6.064	2.467	3.453	.000	.000	-1.220	.636	22.628	-5.764	2.430	.000	.000	.000	.000
408	UMA63U	1	85.385	1.522	-.403	3.668	.000	.000	.278	.527	36.955	-.012	2.443	.000	.000	.000	.000
417	BSW71U	1	89.099	18.421	-.956	3.791	.000	.000	2.366	.180	6.122	1.441	2.483	.000	.000	.000	.000
419	BSW71D	1	89.267	18.744	-.973	3.792	.000	.000	2.396	.180	5.653	1.357	2.487	.000	.000	.000	.000
421	KFI71U	1	89.685	19.577	-1.017	3.796	.000	.000	2.471	.180	4.605	1.146	2.500	.000	.000	.000	.000
423	KFI71D	1	89.928	20.078	-1.042	3.798	.000	.000	2.515	.180	4.078	1.024	2.509	.000	.000	.000	.000
432	UMA73U	1	93.714	7.705	.070	3.846	.000	.000	1.669	.000	4.817	.108	2.674	.000	.000	.000	.000
454	UMA83U	1	103.105	1.527	.407	4.046	.000	.000	.281	-.527	37.018	.018	2.939	.000	.000	.000	.000
463	BSW91U	1	107.881	18.421	-.956	4.291	.000	.000	-2.366	-.180	6.124	1.444	2.983	.000	.000	.000	.000
465	BSW91D	1	108.048	18.744	-.973	4.292	.000	.000	-2.396	-.180	5.655	1.360	2.987	.000	.000	.000	.000
467	KFI91U	1	108.467	19.577	-1.017	4.296	.000	.000	-2.471	-.180	4.605	1.149	3.000	.000	.000	.000	.000
469	KFI91D	1	108.710	20.078	-1.042	4.298	.000	.000	-2.515	-.180	4.076	1.026	3.009	.000	.000	.000	.000
475	UMA91U	1	110.910	25.167	-1.271	4.313	.000	.000	-2.910	-.180	1.999	-.082	3.149	.000	.000	.000	.000
522	UMA95U	1	116.752	4.267	-.487	4.728	.000	.000	2.924	.143	3.869	-.465	3.354	.000	.000	.000	.000
548	UMA97U	1	120.219	1.662	-.462	4.969	.000	.000	.233	-.819	14.302	.295	3.423	.000	.000	.000	.000
572	SMH00U	1	125.664	7.992	.000	5.143	.000	.000	-1.489	.000	2.738	.000	3.588	.000	.000	.000	.000
end	EPA	1	125.664	7.992	.000	5.143	.000	.000	-1.489	.000	2.738	.000	3.588	.000	.000	.000	.000

total length =	125.663600	Qx =	5.142822	Qy =	3.588022
delta(s) =	.000000 mm	Qx' =	-0.847816	Qy' =	0.978095
alfa =	-.580218E-09	betax(max) =	26.074515	betay(max) =	37.031352
		Dx(max) =	3.033247	Dy(max) =	.000000
		Dx(r.m.s.) =	1.864613	Dy(r.m.s.) =	.000000
		xco(max) =	.000000	yco(max) =	.000000
		xco(r.m.s.) =	.000000	yco(r.m.s.) =	.000000

Figure 9: MAD output for EPA with $\alpha = 0$