

Matching the Cold AGS Snake to the AGS Lattice

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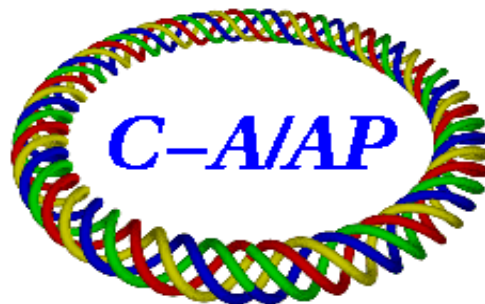
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1 Introduction

Ernest Courant proposed and worked out a solution of matching of the cold snake to the AGS lattice using four quadrupoles [1]. The present report is a remake of his work, using a realistic “Bleser” lattice for the AGS and a set of transfer matrices for the snake at different energies. The snake model was described in a previous CAP note [2]. Our purpose is to specify the value of the excitation of the four added quadrupoles and of the AGS tune quadrupoles in preparation of the commissioning of the snake. Two of the four quadrupoles will be obtained by additional currents in two of the already existing tune quadrupoles; two extra quadrupoles will be fabricated.

The four matching quads will be located in A17, A19, B1 and B3 in the AGS, as shown in Fig. 1. QCA17 and QCB3 will be obtained by extra windings on the tune quads, QHFH and QHFV at the same locations. Space is very tight in the AGS, so the total length of the new fabricated quadrupoles at A19 and B1 is limited to 0.35 m, see Figs. 2,3,4,5. Note that at the present time the gap at A19 is occupied by an octupole. As a reference, the length of the existing tune quads is 0.39088 m (15.4 in).

2 MAD procedure

1. Match bare insertion. (*MAD* commands in Italics.)
 - Use *MAD8*
 - Use Bleser AGS lattice (*e.g.* /home/luccio/MAD/AGS/T-Snake/lattice/ags.lat).
 - Start with bare machine (no snake), called AGS (*use*, period=A20DUM, super=12). This is the insert line with no snake.
 - With *cell* find the tune quad currents XQH and XQV that produce a given tune, say $Q_x=8.78$, $Q_y=8.90$ in the whole machine, or $Q_x/12$, $Q_y/12$ in the period.
 - Save twiss functions (*savebeta*) at both ends of line.
2. Match insertion with snake
 - Insert snake represented by a matrix in MAD format. Matrices calculated with *Snig* at different beam energies are stored in /home/luccio/MAD/AGS/T-Snake/TMaps/
 - See first what happens doing nothing.
 - Do insertion match using the four matching quads. (*use* period=A20SNK0 and *match* line=A20DUM). I.e. match the line with snake to the line previously tuned with no snake
 - *vary* KCA17, KCA19, KCB1, KCB3.
 - Constraints at the end of line are the ones previously saved - we want the rest of the lattice to look like before the snake was inserted.

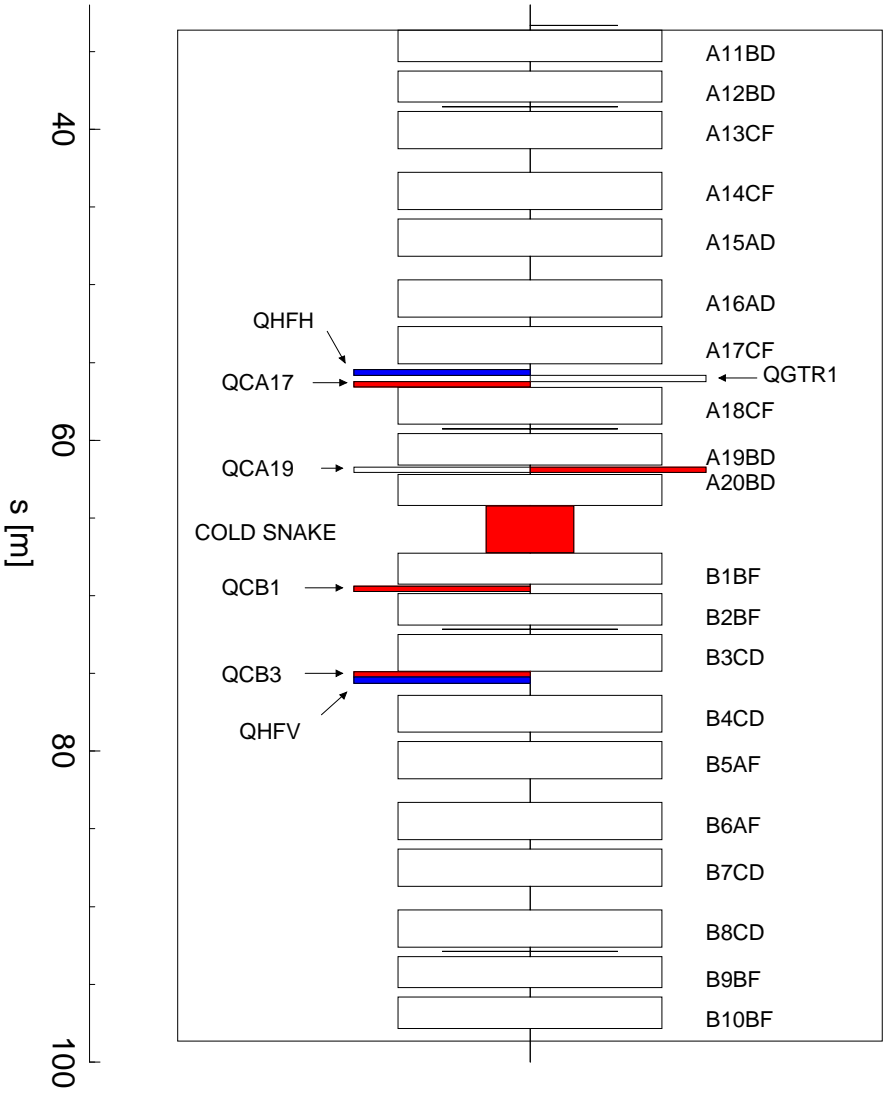


Figure 1: Cold Snake insert in the AGS

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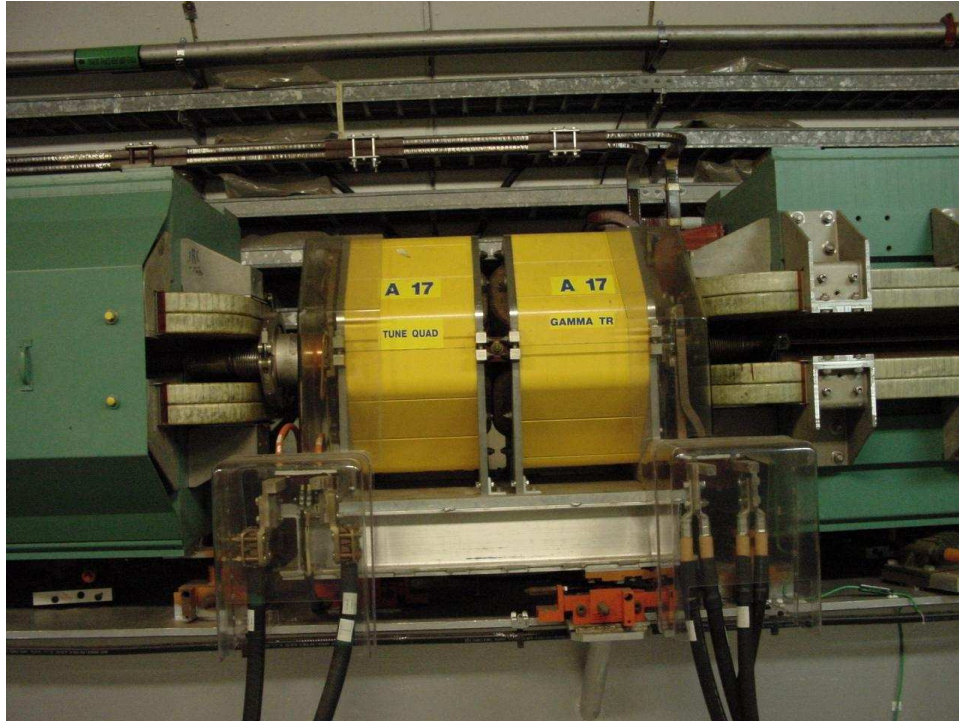


Figure 2: AGS: gap at A17

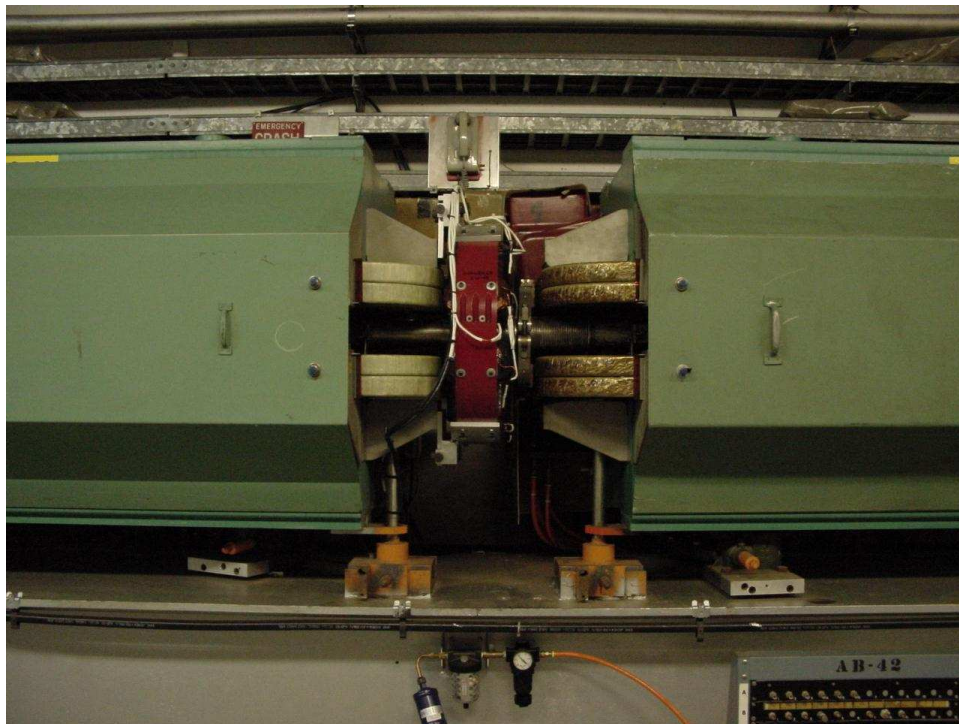


Figure 3: AGS: gap at A19

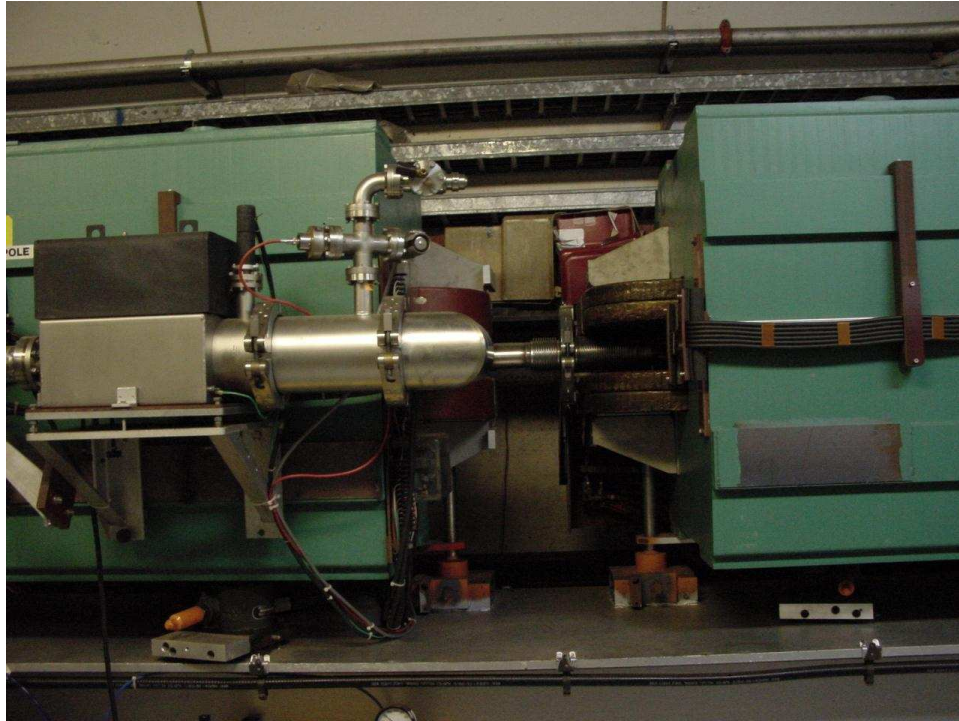


Figure 4: AGS: gap at B1

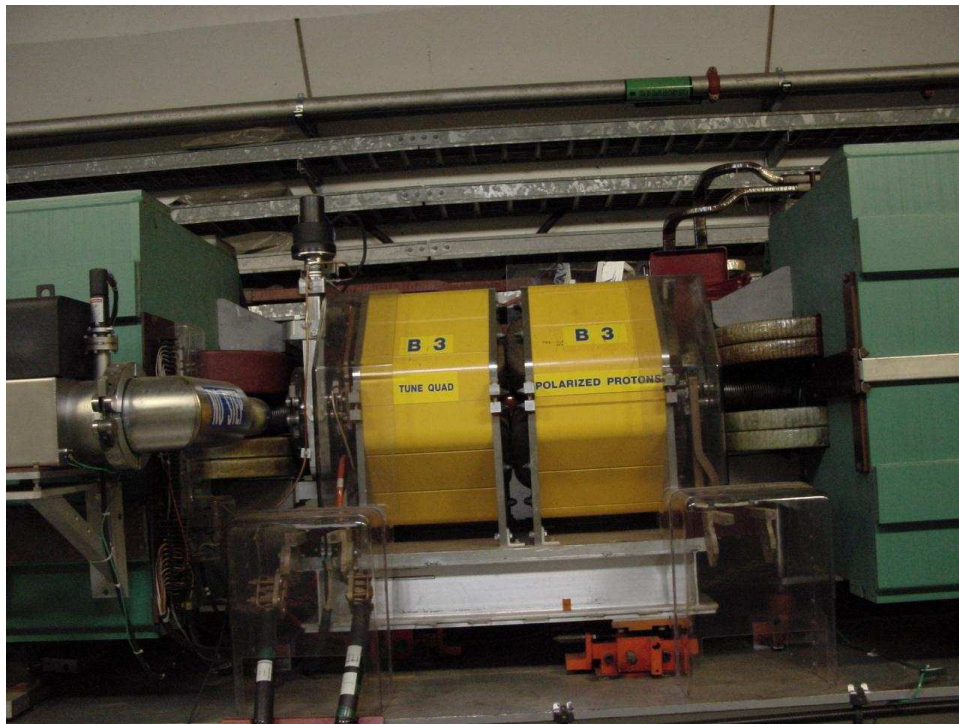


Figure 5: AGS: gap at B3

3. Retune

- *use*, AGS-SA, i.e. the whole machine containing the snake.
- Varying tune quads, with constraints for the maximum beta values outside the snake insertion. Betas may go crazy inside, but they must remain limited in the rest of the ring.

3 Snake Transfer Maps

4×4 transverse transfer linear maps have been described in [2]. The snake, which is represented in the *MAD* model as a 3 m long matrix, becomes more and more transparent with increasing beam energy: see plots of the individual matrix elements as a function of energy in Fig. 6.

Among the matrix elements, important are the $R(2,1)$, giving the horizontal focusing of the snake, and $R(4,3)$ that gives the vertical focusing, respectively. They are shown again in Fig. 7. It is important to realize that these focusing elements scale with energy almost exactly as the reciprocal of the beam rigidity $B\rho$ squared, as expected, because the orbit amplitude in the helical snake grows linearly with the energy, but the transverse magnetic field on the orbit scales with the square of the orbit displacement [2].

4 At injection: $\gamma = 2.5$

At injection, at the lowest end of energy, matching the cold snake to the AGS lattice using the four matching quadrupoles proves particularly challenging, since both snake focusing and coupling are the highest. Following the *MAD* matching procedure described above, we found a good solution for the realistic AGS 'Bleser' lattice, similar to what had been obtained by E.Courant on an idealized lattice. Since the real AGS is not too linear due to hysteresis in the magnets, with the non linearities represented in the model after work by Bleser, Auerbach, Tanaka and Luccio, the scaling of this low energy solution to higher energies proved an interesting task. Matching can only be achieved at the expense of a high value of the β envelope function.

The good solution matches the insertion containing the snake to the rest of the AGS, keeping the β functions unchanged, with respect to the bare AGS *i.e.* with no snake, everywhere but in the snake section. We will show the AGS β later, together with the same obtained at higher energies.

5 Matching and retuning at higher energies

In the following, for each energy in unit of γ we will give calculated values of quadrupole K [$1/m^2$], or currents X [A], and gradients G [T/m], where

$$G = K \cdot B\rho, \quad K = -\frac{1}{B\rho} \frac{\partial B}{\partial r} = \frac{B}{B\rho L}, \quad B = \frac{\partial B}{\partial r} = cX + \text{higher order terms}$$

Case 0: We first attempted to obtain matching conditions at increasing energies, up to AGS extraction: $\gamma = 26$, using the same procedure than at injection, with the algorithms provided by the *MAD* program. The experience was very frustrating and inconclusive, because we could indeed find a solution at each individual energy, but these solutions did not yield monotonically decreasing curves for the matching quadrupole strength according what physical good sense would suggest. The problem was caused by the fact that the parameter space explored has 8 dimensions: 2 initial setting of the betatron values to initialize the matching, 4 values of the strength of the matching quadrupoles, and 2 values for the AGS tune quadrupoles. All parameters were very sensitive to the outcome. Results were found smooth and monotonic above a value of $\gamma = 5$, but noisy and unreliable in the region between the good solution at injection and this energy. Here, we only show the orbit in these *MAD* matched cases. Fig. 8 shows that there are clean

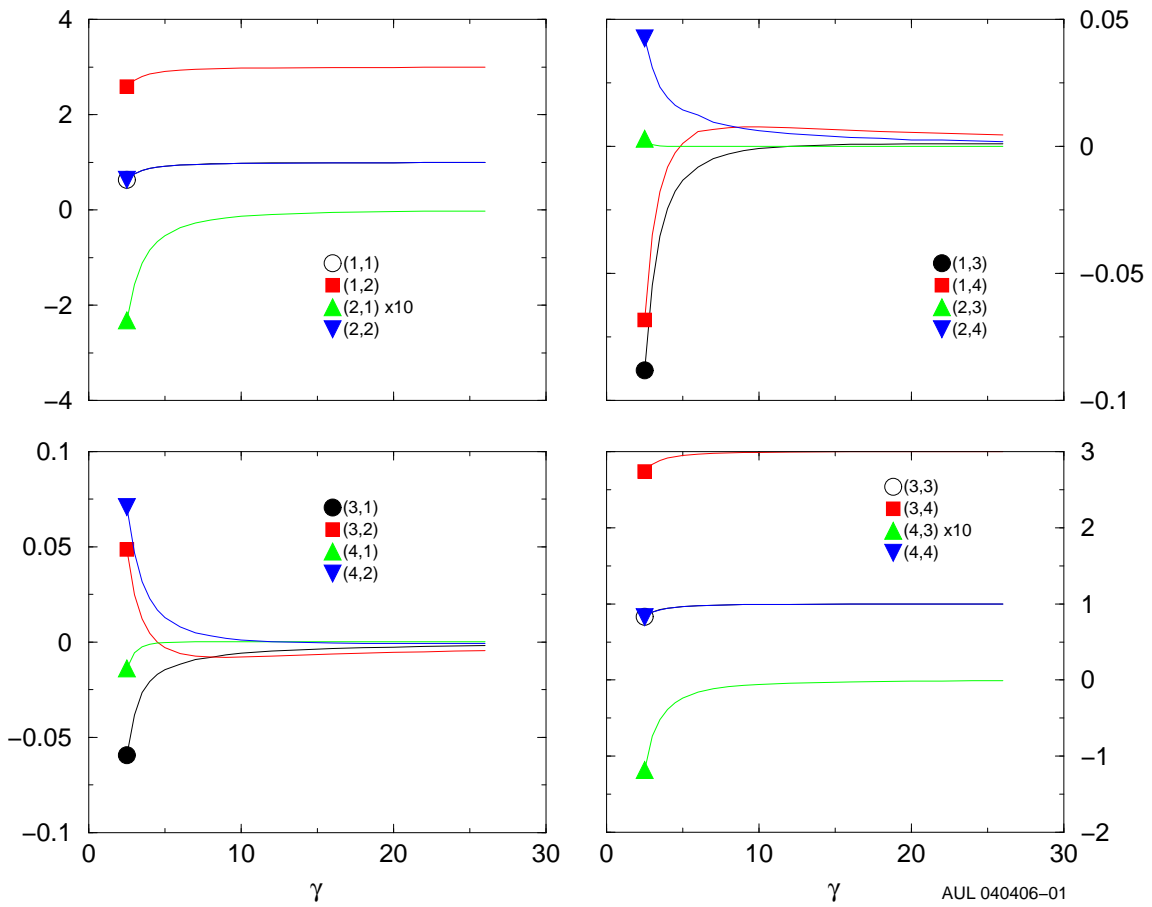
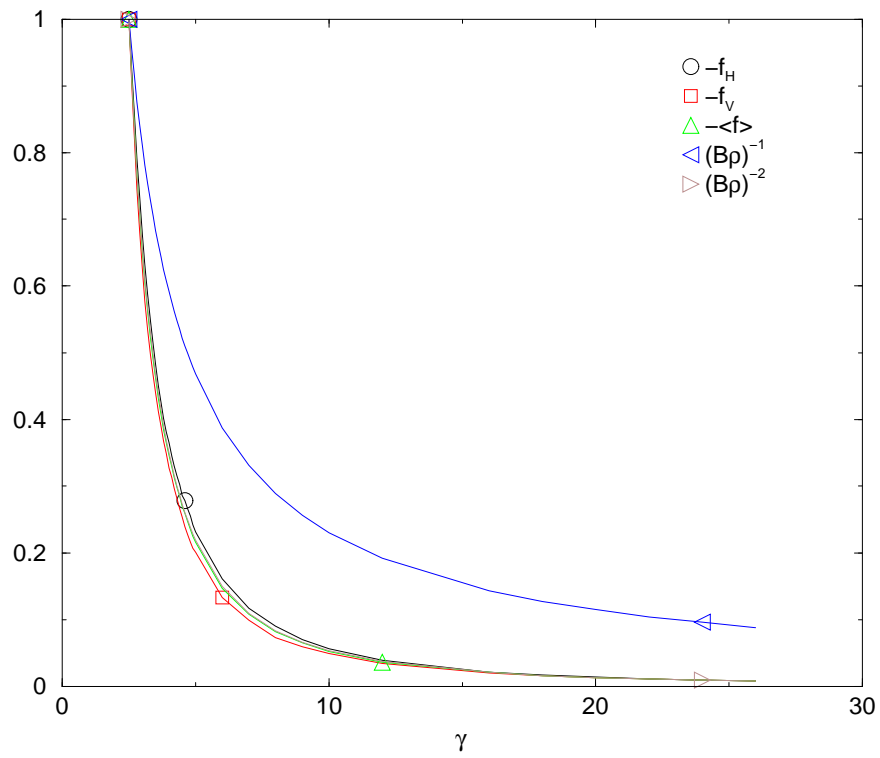


Figure 6: Elements of the transport matrix of the Snake. The upper left plot shows the elements for horizontal transfer, and the lower right plot for vertical transfer, respectively. The other two diagrams are for coupling elements.



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Figure 7: Focusing elements of the transport matrix of the Snake vs. beam energy. They scale as $1/(B\rho)^2$.

orbits outside the insertion not perturbed with what is obtained w/o the snake. We don't show the corresponding matching quadrupole currents, because they are of no practical use.

Case 1: Using the solution found at injection as a solid base, consistent results were found instead by simply scaling the matching quadrupole strengths K like the focusing elements in the transfer matrices of Fig. 7

$$K = K_0 \frac{(B\rho)_{inj}^2}{(B\rho)^2},$$

A first run was done by starting from a stable value of the betatron tune $\nu_x = 8.60$ and $\nu_y = 8.90$, for the AGS with the snake inserted. The high value of the vertical tune was dictated by a desire to have it as close as possible to the integer for spin preservation (in a window of tune to avoid a snake resonance). The starting was the good case referred to above. Then, we proceeded scaling down the matching quads as said, and retuning at each step to obtain the “magic” value $\nu_y = 8.96$. The horizontal value of the betatron tune was left free. The purpose was to find the values of ν_x vs. energy that the lattice liked most. Fit of these values with some analytical expression could suggest how to proceed further. Results of this run are shown in Figs. 9, 10, 11, 12, and 13.

The figures show the following:

- A continuous acceptable solution is found at all energies. The matching quadrupoles fade away at high energy, where the snake has very little residual focusing.
- Rematching in order to obtain a high value of the vertical betatron tune requires large currents (the AGS tune quads power supply is rated for 700 A maximum current, so we are within the limits).
- A Best fit of the horizontal tune found by the *MAD* matching algorithm is an inverse-energy square law

$$\nu_x \approx 8.54457 + 1.85346/\gamma^2. \quad (1)$$

- At low energy the beam is wide in vertical. At high energy the beam is wider in the horizontal direction. The two trends exchange roles at about $\gamma = 5$, where we found difficulties when trying to obtain an optimum match. The cause is complex, because is due to the interplay of the focusing properties of the bare lattice, almost constant over the entire energy range and the focusing of the helical snake that decreases with energy.

Case 2: Using the “natural” trend of the vertical tune of Case 1, we run a Case 2, that used the same values of the matching quadrupoles vs. energy, but where we searched for a rematch with ν_y still kept at a value of 8.96, but with ν_x made to follow the fit of Eq.(1). Results are shown in Figs. 14, 15, 16, and 17. For this case we still obtain a noisy value of the orbit amplitude at low energy. Tables 1 and 2 give numerical values for this case

Case 3: Can we keep a low constant value of ν_x along the acceleration? a value of 8.60, combined with 8.96 for the vertical proved impossible. A value $\nu_x = 8.64$ did converge (Case 3), for $\gamma > 4$, but fell in a region of instability below. Results for the tune, the maximum beta, and the corresponding values of tune quads parameters are shown in Figs. 18, 19, 20, and 21, respectively.

The complete beta wave and dispersion for 4 chosen energies for Case 2 are shown in Figs. 22 and 23

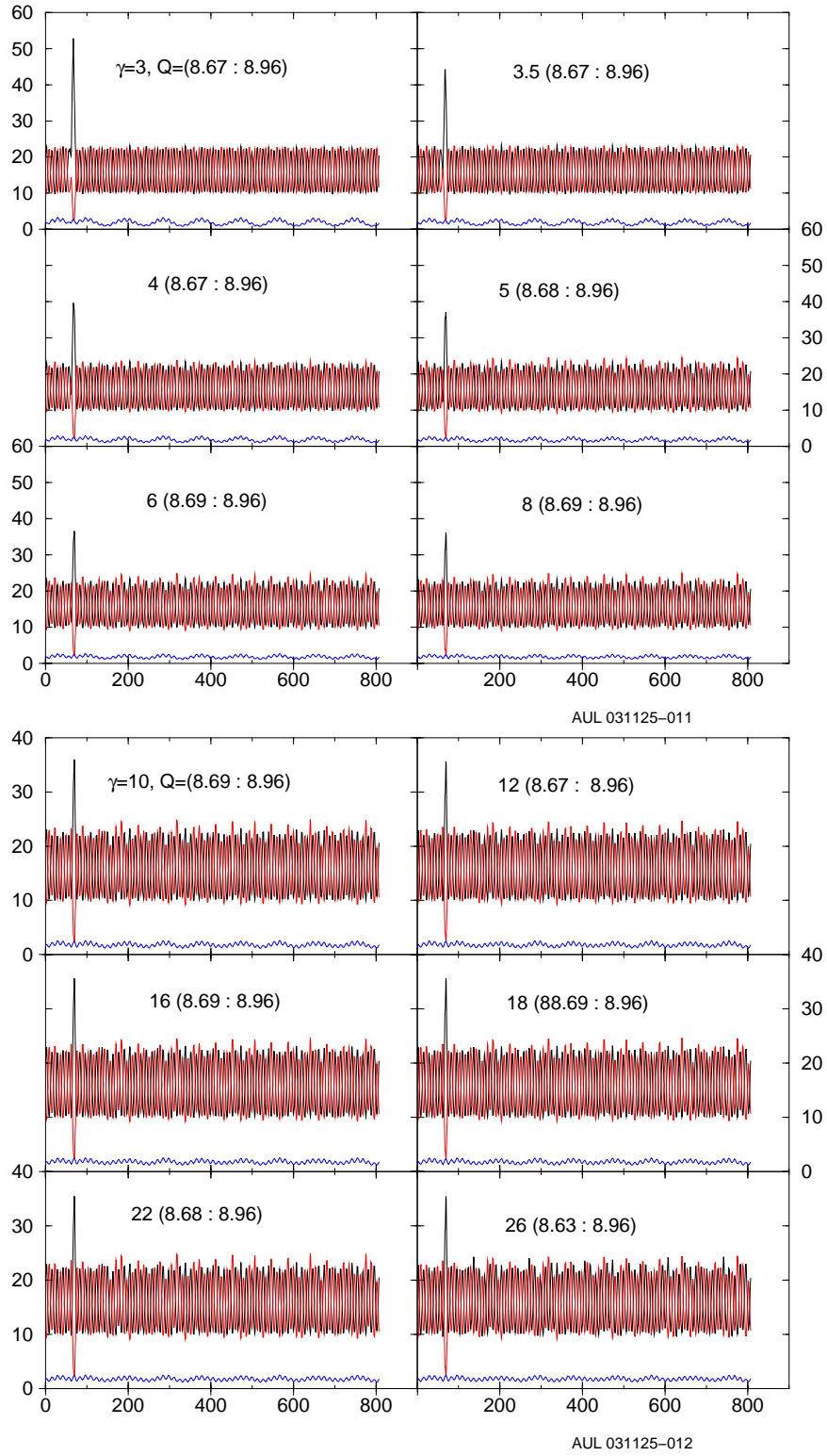
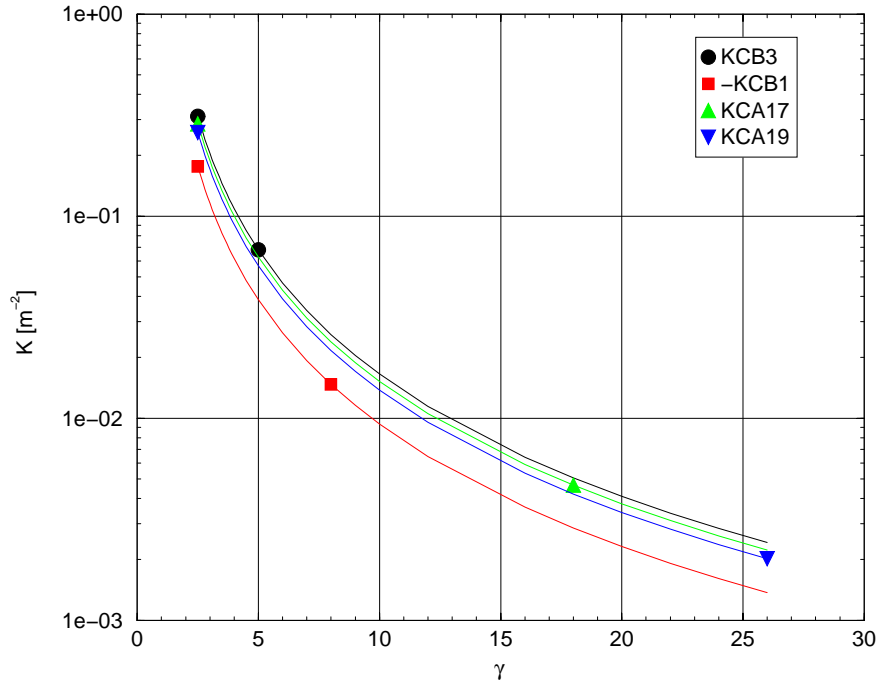
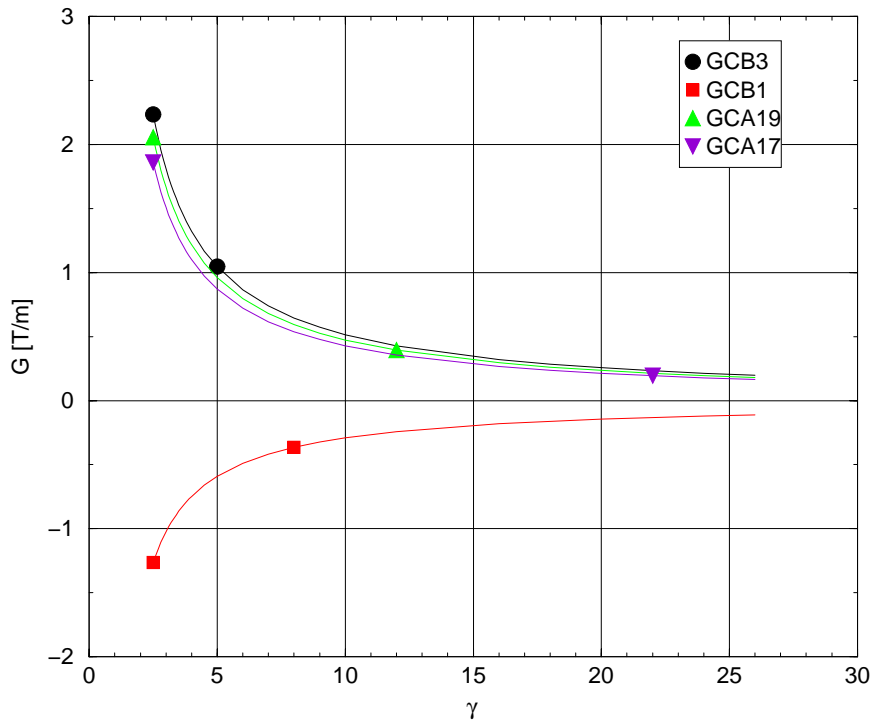


Figure 8: Bleser lattice: γ from 1.5 to 26. MAD optimization of matching



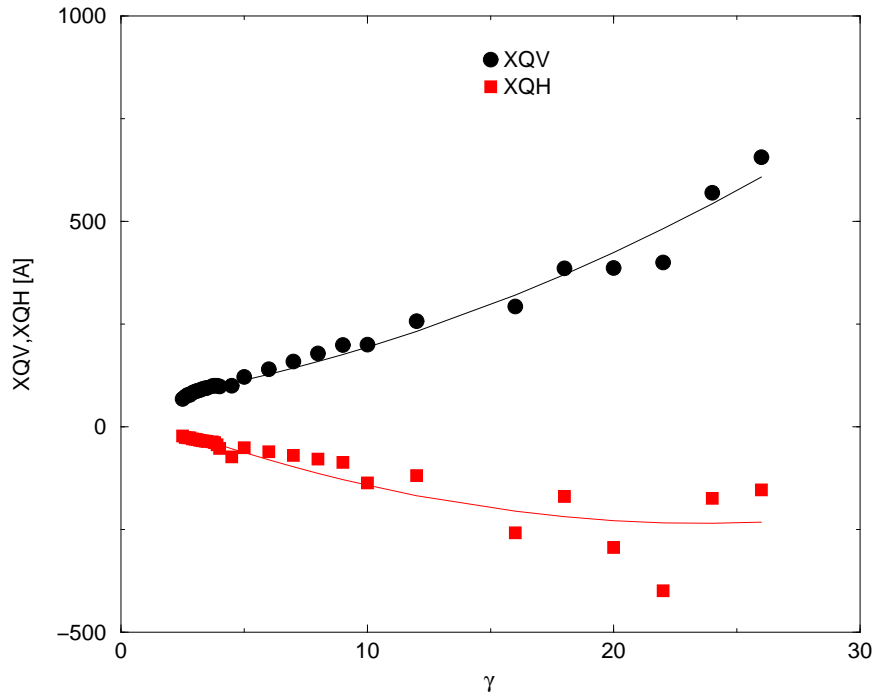
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Figure 9: K parameter of the matching quadrupoles as a function of energy. The inverse- $(B\rho)^2$ law is assumed.



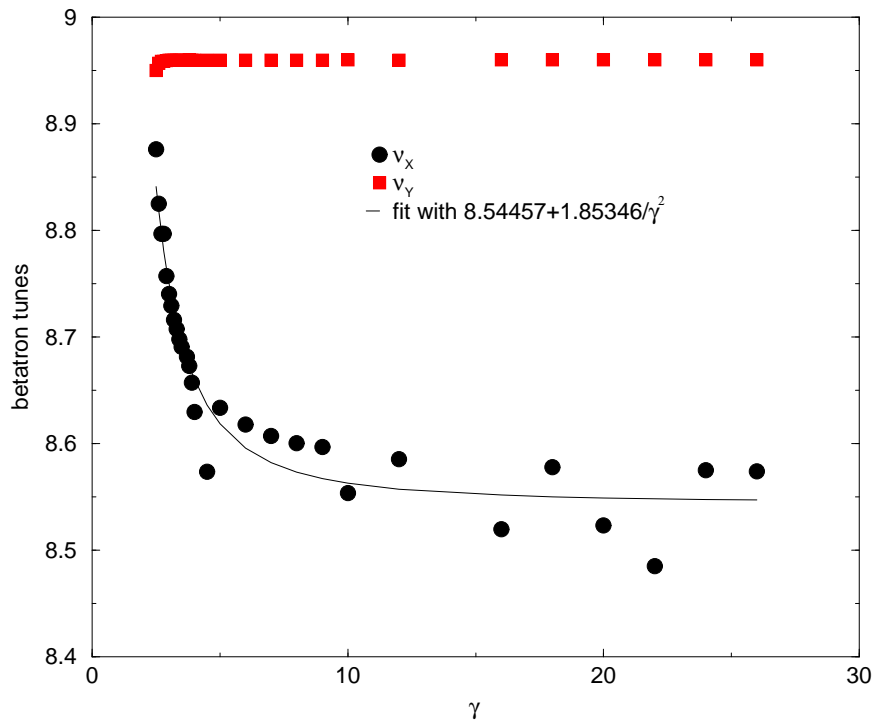
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Figure 10: Gradient of the matching quadrupoles.



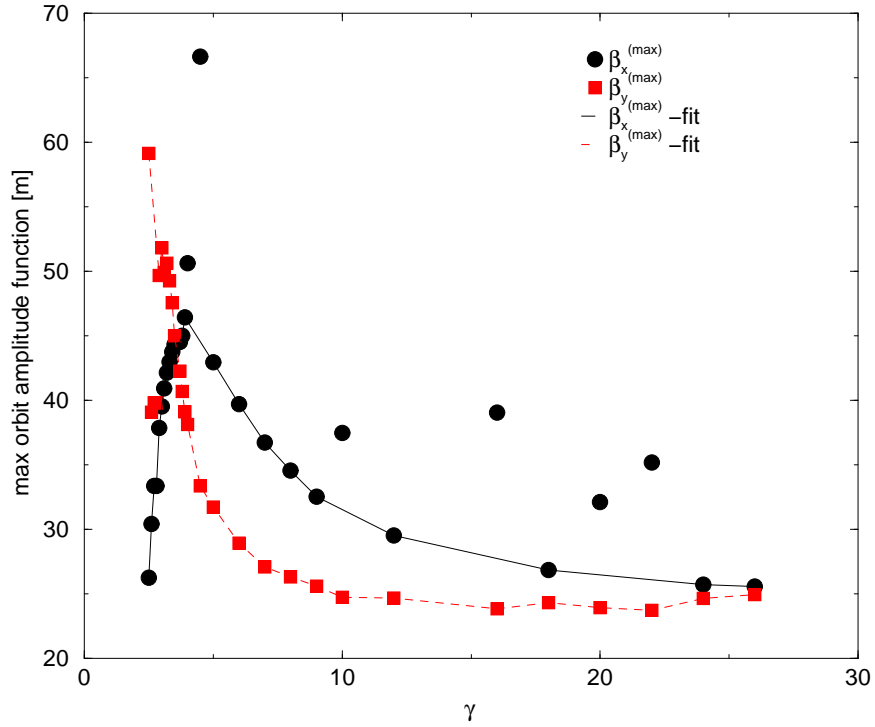
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Figure 11: Case 1. Current in the tune quadrupoles [A].



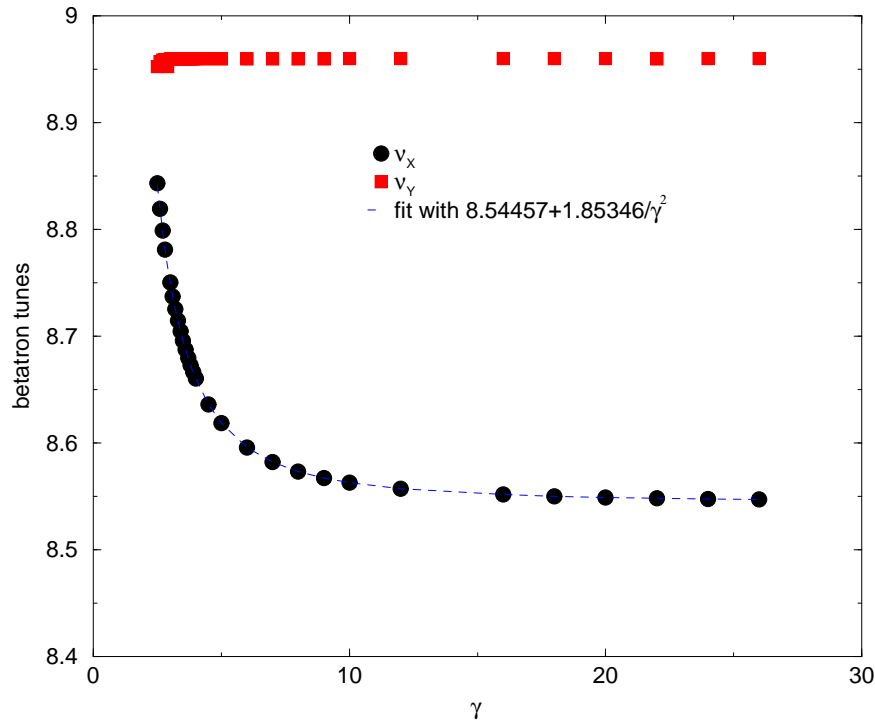
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Figure 12: Case 1: Betatron tunes. Retune is done to obtain $\nu_y = 8.96$. ν_x is left free.



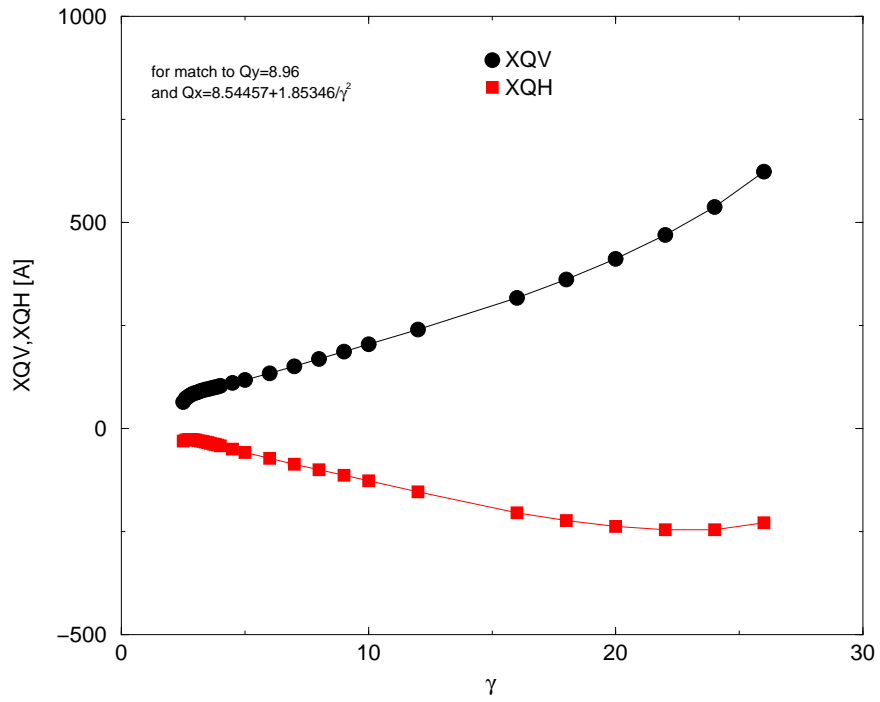
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Figure 13: Case1: Maximum value of the beam amplitude function β after matching and retuning.



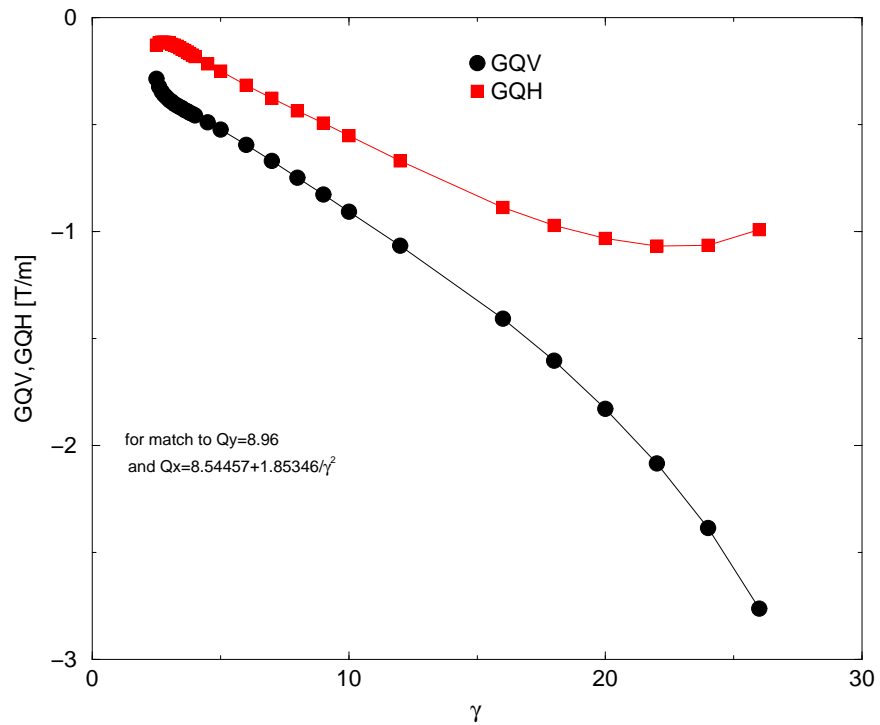
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Figure 14: Case 2. Betatron tunes after rematch.



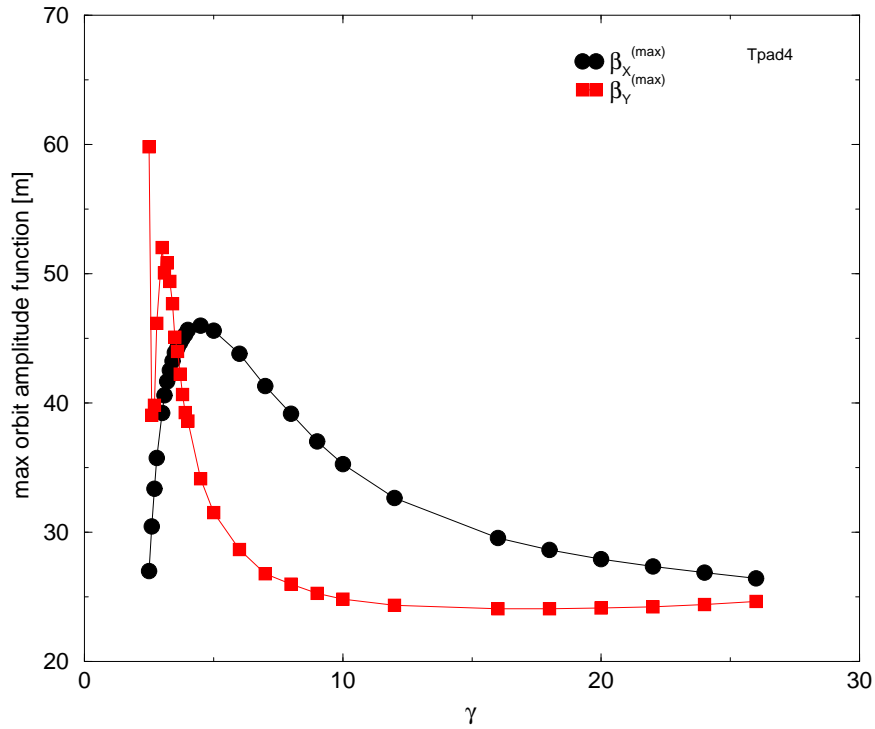
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Figure 15: Case 2. Current in the tune quadrupoles.



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Figure 16: Case 2. gradients in the tune quadrupoles.



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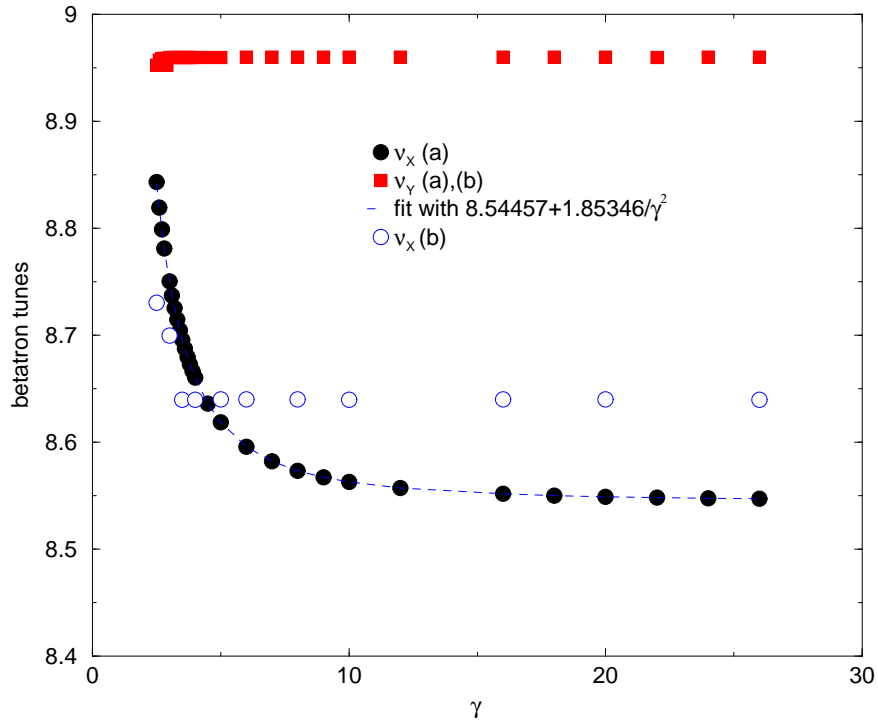
Figure 17: Case 2. Maximum beta.

Table 1: Case 2: Quadrupole strengths to match snake to AGS lattice

γ	KCB3	KCB1	KCA19	KCA17	GCB3	GCB1	GCA19	GCA17
2.5	0.3114602 -	0.1761206	0.2864219	0.2593226	2.2335215	-1.2629838	2.0539690	1.8596362
3.0	0.2043954 -	0.1155790	0.1879641	0.1701802	1.8093592	-1.0231338	1.6639051	1.5064775
3.5	0.1453479 -	0.0821895	0.1336634	0.1210170	1.5257856 -	0.8627822	1.4031280	1.2703734
4.0	0.1090109 -	0.0616421	0.1002475	0.0907628	1.3213691 -	0.7471913	1.2151445	1.1001756
4.5	0.0849435 -	0.0480328	0.0781149	0.0707242	1.1664185 -	0.6595718	1.0726503	0.9711633
5.0	0.0681318 -	0.0385263	0.0626547	0.0567267	1.0446340 -	0.5907066	0.9606560	0.8697652
6.0	0.0467189 -	0.0264180	0.0429632	0.0388983	0.8650391 -	0.4891515	0.7954988	0.7202340
7.0	0.0340659 -	0.0192631	0.0313273	0.0283633	0.7386678 -	0.4176926	0.6792864	0.6150168
8.0	0.0259549 -	0.0146767	0.0238684	0.0216101	0.6447621 -	0.3645920	0.5929298	0.5368307
9.0	0.0204395 -	0.0115579	0.0187964	0.0170180	0.5721696 -	0.3235433	0.5261730	0.4763900
10.	0.0165168 -	0.0093397	0.0151890	0.0137519	0.5143422 -	0.2908438	0.4729943	0.4282427
12.	0.0114347 -	0.0064659	0.0105154	0.952057	0.4279586 -	0.2419966	0.3935550	0.3563195
16.	0.0064124 -	0.0036260	0.0058969	0.0053389	0.3204790 -	0.1812205	0.2947158	0.2668317
18.	0.0050624 -	0.0028626	0.0046554	0.0042149	0.2847531 -	0.1610186	0.2618618	0.2370862
20.	0.0040981 -	0.0023173	0.0037687	0.0034121	0.2562024 -	0.1448741	0.2356064	0.2133149
22.	0.0033854 -	0.0019143	0.0031132	0.0028187	0.2328607 -	0.1316751	0.2141410	0.1938804
24.	0.0028437 -	0.0016080	0.0026151	0.0023677	0.2134203 -	0.1206822	0.1962635	0.1776943
26.	0.0024224 -	0.0013698	0.0022277	0.0020169	0.1969780 -	0.1113847	0.1811430	0.1640045

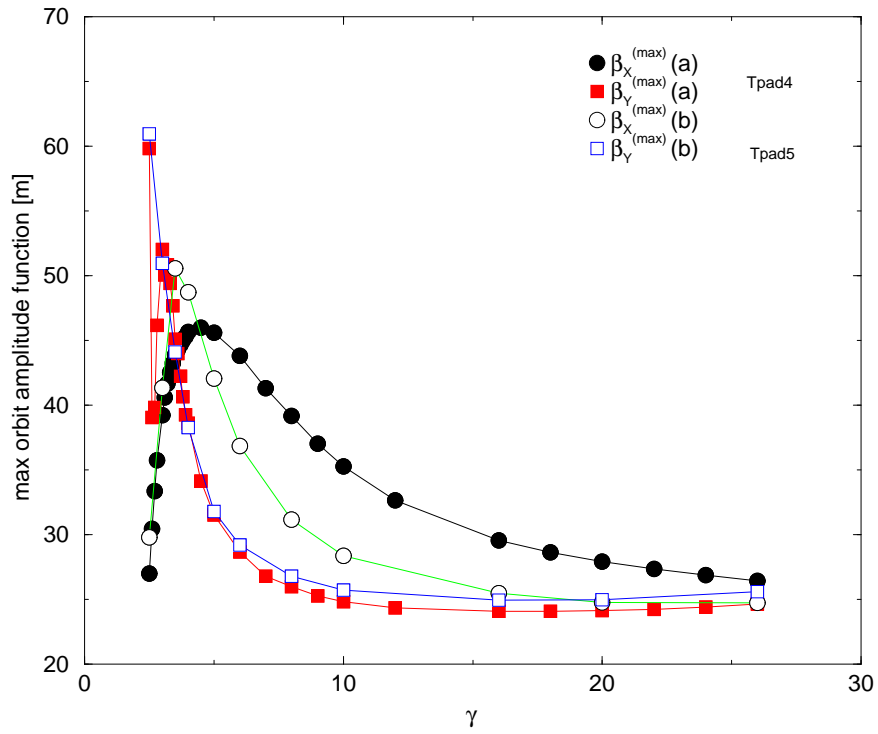
Table 2: Case 2: Tune quadrupole strengths to retune AGS lattice. Eq.(1)

γ	XQV	XQV	GQV	GQH	Q _x	Q _y	β_x^{max}	β_y^{max}
2.5	64.08840	-30.60576	-0.2870466	-0.1299278	8.843231	8.952803	26.997752	59.824393
3.0	86.53432	-28.19026	-0.3862544	-0.1193275	8.750545	8.959682	39.250029	52.042858
3.5	95.28881	-34.80679	-0.4249795	-0.1483590	8.695878	8.959925	43.925902	45.116546
4.0	102.75767	-42.63781	-0.4580305	-0.1826991	8.660413	8.959974	45.674643	38.601271
4.5	110.02215	-50.60077	-0.4901880	-0.2175951	8.636100	8.959989	45.991600	34.149593
5.0	117.62807	-58.38337	-0.5238678	-0.2516783	8.618709	8.959994	45.621745	31.535574
6.0	133.82942	-73.17413	-0.5956438	-0.3163912	8.596056	8.959998	43.837995	28.676076
7.0	150.66591	-87.11228	-0.6702787	-0.3772988	8.582397	8.959999	41.325345	26.812699
8.0	168.44222	-100.67960	-0.7491229	-0.4365156	8.573531	8.959999	39.171065	26.007628
9.0	186.20909	-113.99635	-0.8279628	-0.4945713	8.567453	8.959999	37.028425	25.283354
10.	204.11551	-127.38189	-0.9074532	-0.5528604	8.563105	8.960000	35.275679	24.849346
12.	240.08177	-154.38257	-1.0671842	-0.6702406	8.557441	8.960000	32.669800	24.372170
16.	316.64004	-204.51250	-1.4073205	-0.8875331	8.551810	8.960000	29.575014	24.087135
18.	361.01844	-224.06799	-1.6044666	-0.9721115	8.550291	8.960000	28.631608	24.102803
20.	411.52746	-238.29043	-1.8287671	-1.0335751	8.549204	8.960002	27.930254	24.155958
22.	469.15718	-246.38287	-2.0845574	-1.0685328	8.548354	8.959956	27.353523	24.254967
24.	537.06423	-245.56874	-2.3857901	-1.0650163	8.547788	8.960002	26.881445	24.408383
26.	622.42157	-228.62447	-2.7642171	-0.9918067	8.547272	8.960021	26.458312	24.645137



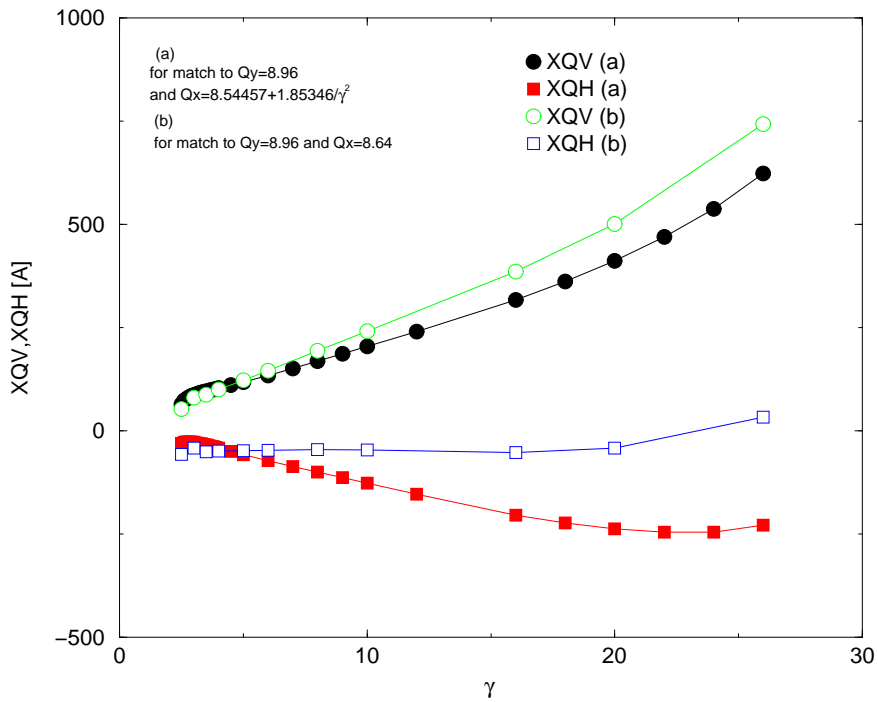
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Figure 18: Case 3. Betatron tunes after rematch, compared with Case 2.



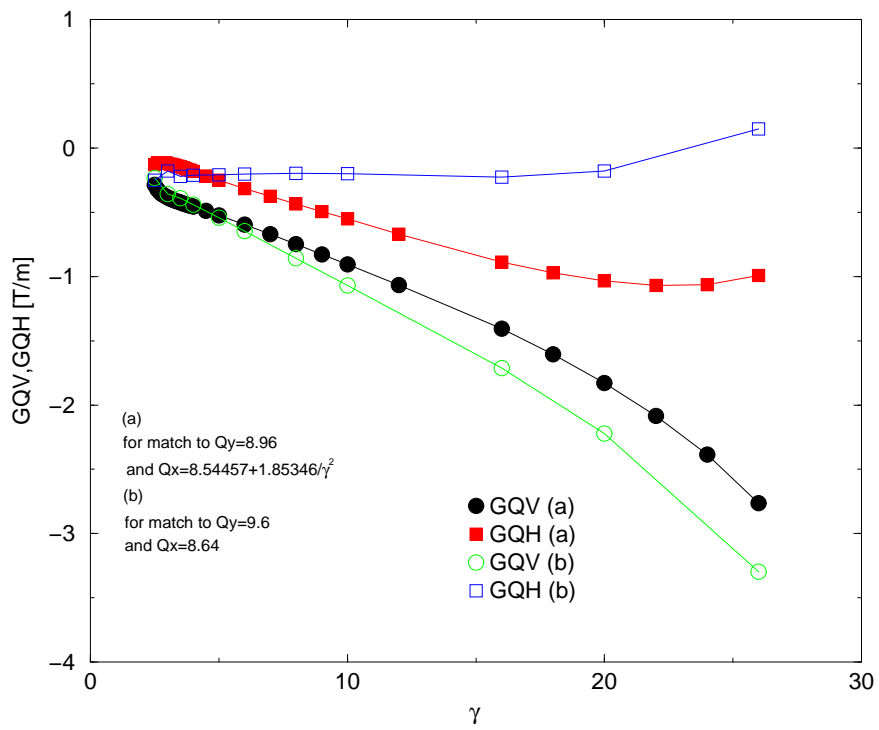
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Figure 19: Case 3. Maximum beta. Compared with Case 2.



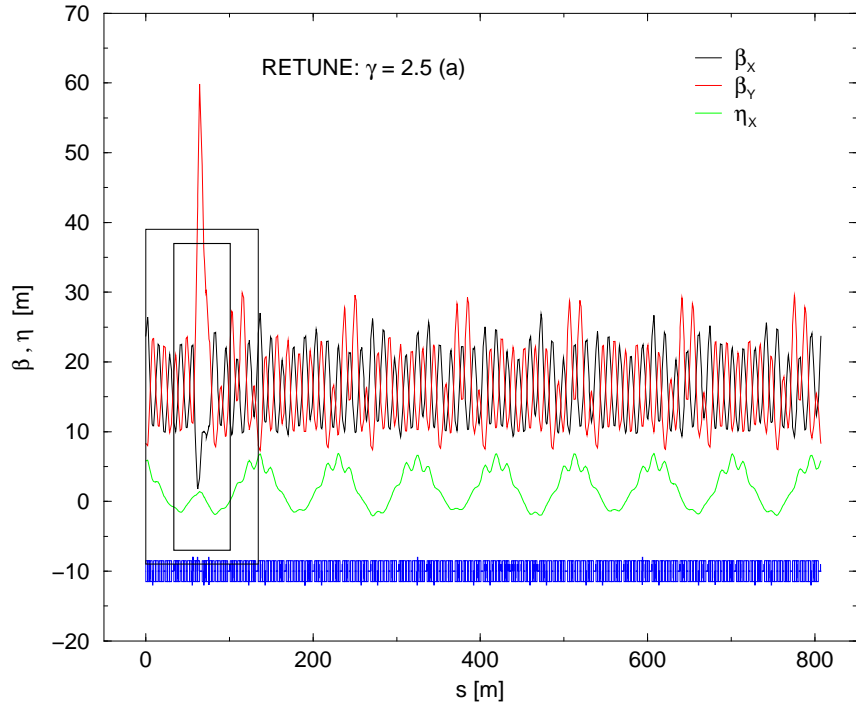
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Figure 20: Case 3. Current in the tune quadrupoles. Compared with Case 2.

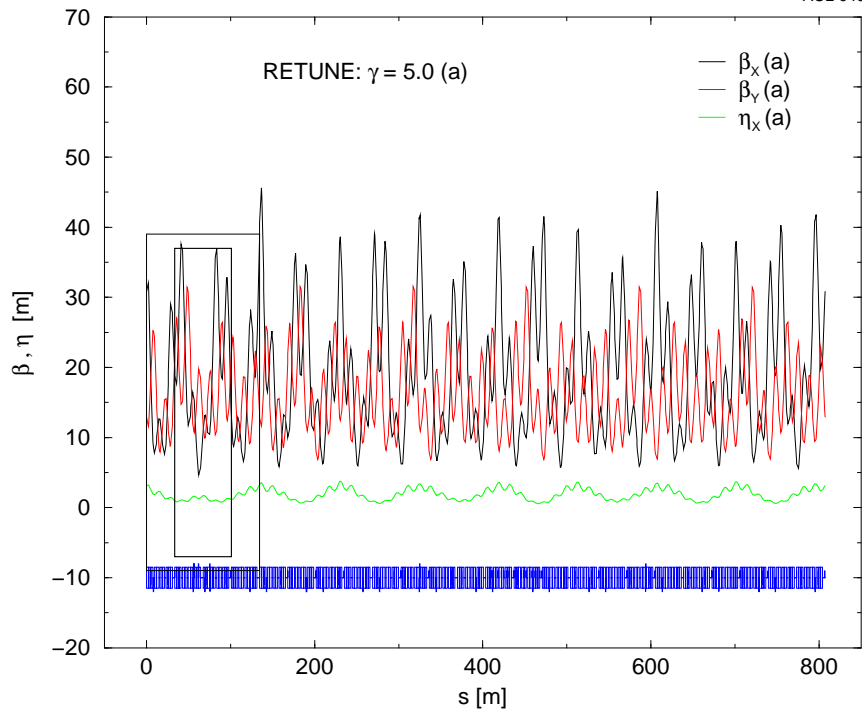


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Figure 21: Case 3. gradients in the tune quadrupoles. Compared with Case 2.

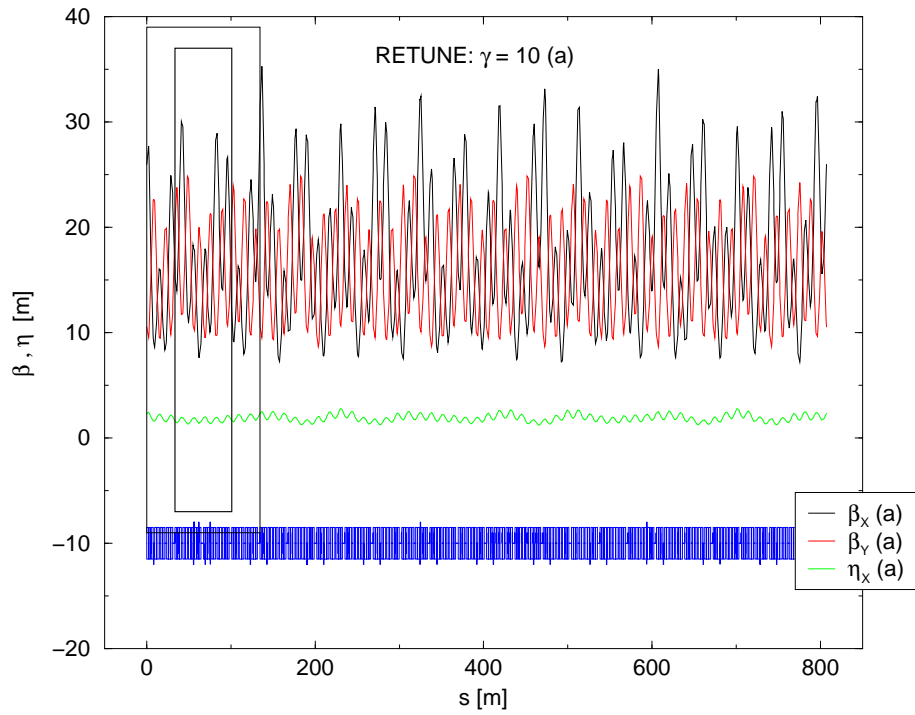


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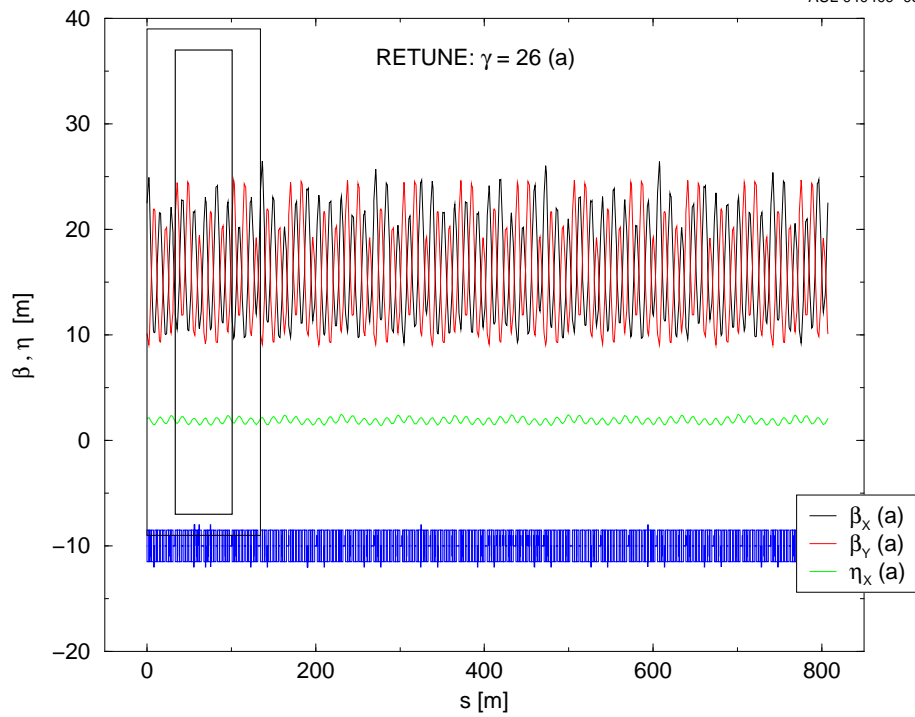


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Figure 22: Case 2. Beta wave and dispersion at two chosen energies.

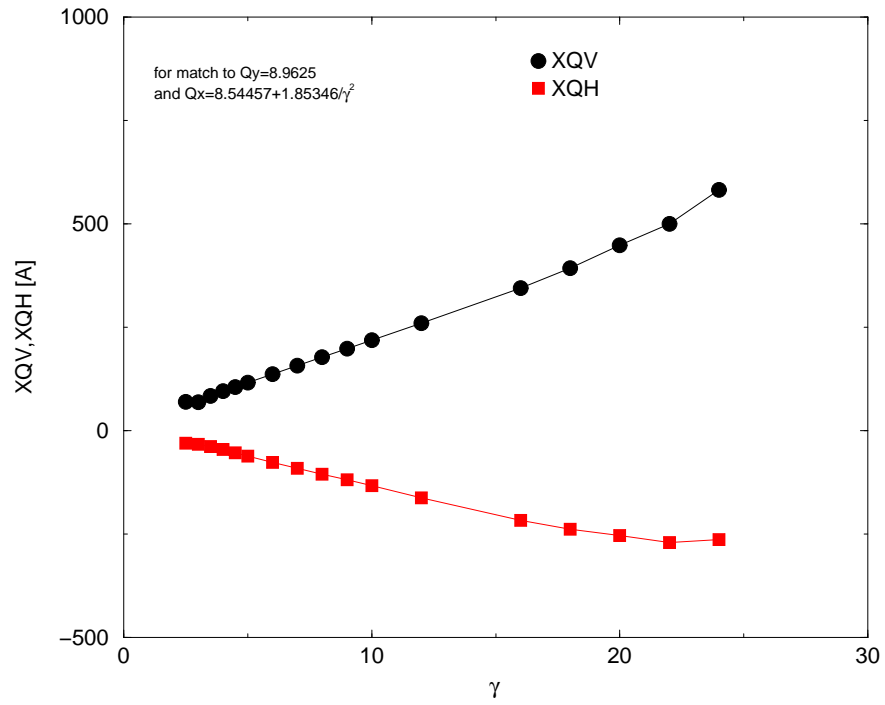


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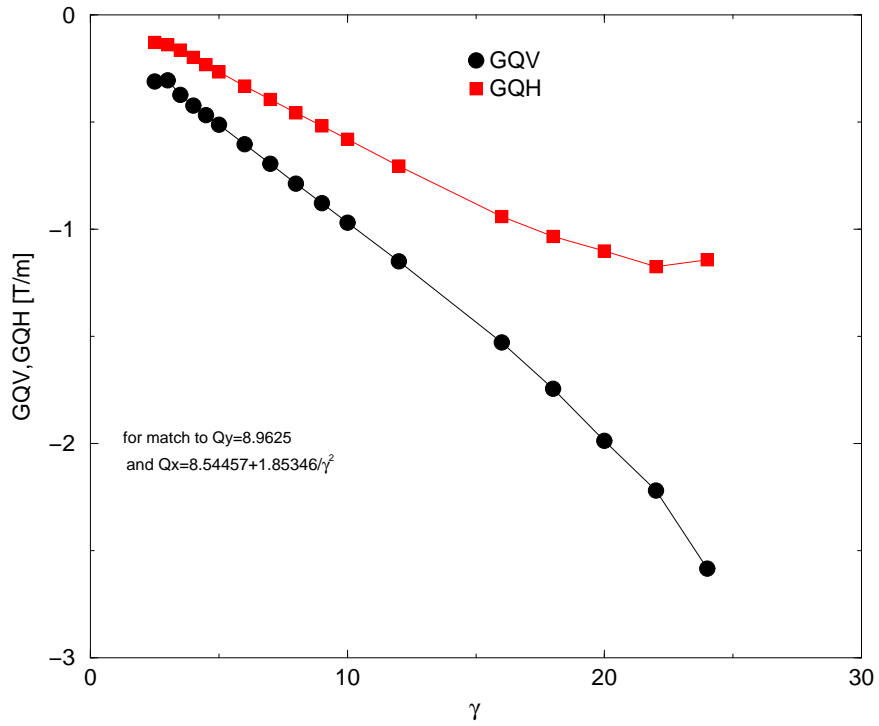
Figure 23: Case 2. Beta wave and dispersion at two chosen energies.



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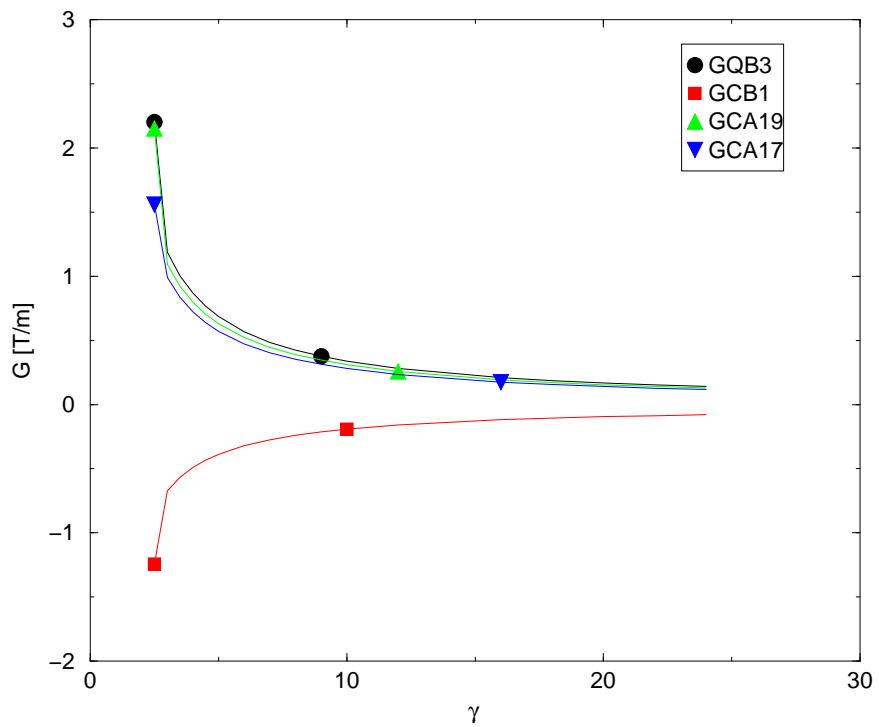
Figure 24: Case 4: current in the tune quadrupoles.

Case 4 Matching quadrupole A17 is lumped with tune quad QH, and B3 with QV, respectively. Retune to obtain $\nu_y = 8.9625$.



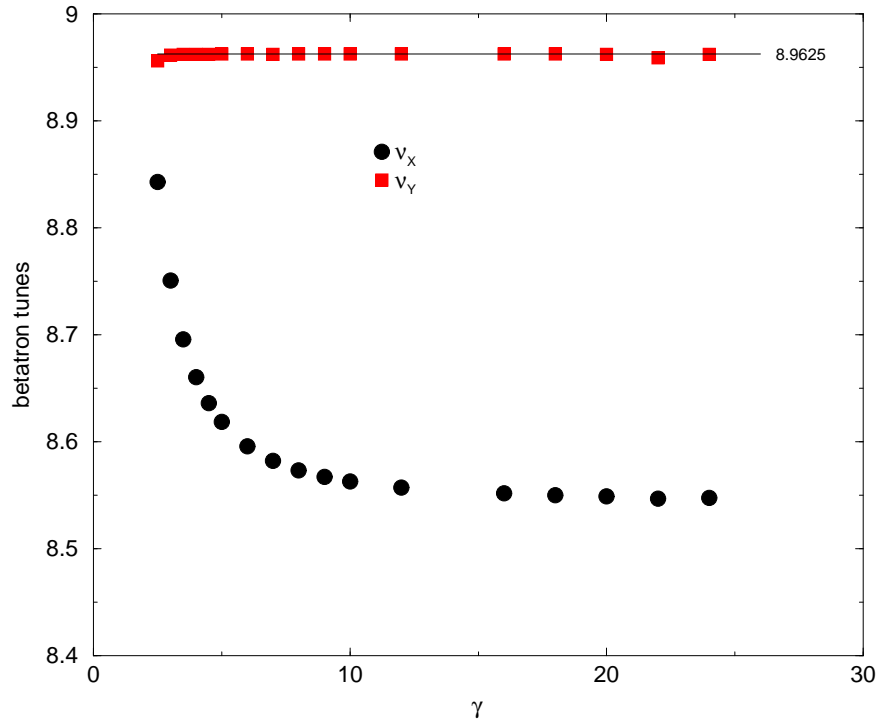
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Figure 25: Case 4; gradients in the tune quadrupoles.



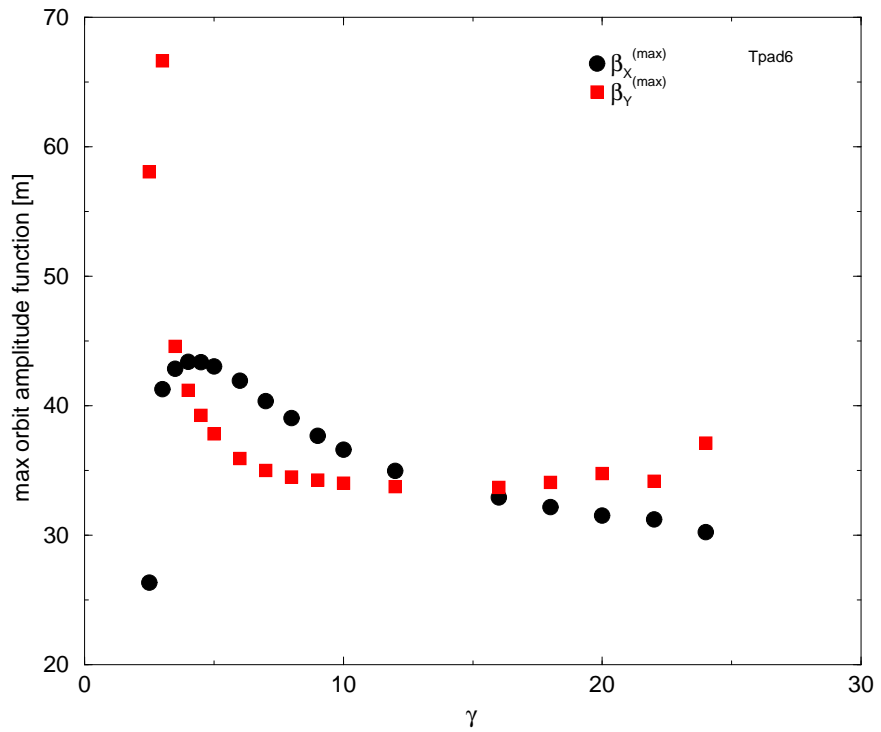
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Figure 26: Case 4: gradient of the matching quadrupoles. QCA17 is lumped with QH and QCB3 with QV, respectively.



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Figure 27: Case 4: betatron tunes after rematch.



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Figure 28: Case 4: maximum beta.

Table 3: Case 4: Matching quadrupole strengths.

γ	GCB3	GCB1	GCA19	GCA17
2.5	2.2023105	-1.2429583	2.1513402	1.5579697
3.0	1.1873906	-0.6714310	1.0919365	0.9886248
3.5	1.0012957	-0.5662003	0.9208017	0.8336814
4.0	0.8671475	-0.4903439	0.7974377	0.7219895
4.5	0.765461	-0.4328436	0.7039260	0.6373253
5.0	0.6855403	-0.3876509	0.6304298	0.5707828
6.0	0.5676813	-0.3210054	0.5220455	0.4726530
7.0	0.4847502	-0.2741105	0.4457812	0.4036044
8.0	0.4231246	-0.2392633	0.3891097	0.3522948
9.0	0.3754858	-0.2123251	0.3453006	0.3126306
10.	0.3375367	-0.1908661	0.3104022	0.2810340
12.	0.2808475	-0.1588102	0.2582702	0.2338344
16.	0.2103141	-0.1189258	0.1934070	0.1751081
18.	0.1868690	-0.1056684	0.1718466	0.1555877
20.	0.1681326	-0.0950736	0.1546165	0.1399877
22.	0.1528146	-0.0864117	0.1405299	0.1272339
24.	0.1400569	-0.0791976	0.1287978	0.1166118

Table 4: Case 4: Tune quadrupole and tune after RETUNE.

γ	XQV	XQH	GQV	GQH	ν_x	ν_y	β_x	β_y
2.5	69.50638	-30.51519	-0.3109822	-0.1295304	8.842867	8.956203	26.362331	58.077715
3.0	68.45034	-33.05269	-0.3063162	-0.1406640	8.750745	8.961549	41.307977	66.648328
3.5	83.75624	-38.69407	-0.3739693	-0.1654080	8.695918	8.962372	42.886177	44.586139
4.0	94.99565	-46.33294	-0.4236824	-0.1988951	8.660426	8.962479	43.419881	41.204526
4.5	105.18205	-54.25947	-0.4687613	-0.2336208	8.636105	8.962499	43.370263	39.281710
5.0	115.38584	-62.03082	-0.5139379	-0.2676442	8.618712	8.962502	43.063738	37.829604
6.0	135.96795	-76.98028	-0.6051213	-0.3330307	8.596057	8.962500	41.958611	35.948805
7.0	156.31732	-91.35123	-0.6953402	-0.3958078	8.582420	8.962445	40.358093	35.011962
8.0	177.31752	-105.4806	-0.7885025	-0.4574541	8.573531	8.962500	39.077189	34.497822
9.0	197.89848	-119.5168	-0.8798514	-0.5186190	8.567491	8.962515	37.700742	34.273267
10.	218.35955	-133.8103	-0.9707036	-0.5808307	8.563105	8.962500	36.607276	34.031845
12.	259.07449	-162.7503	-1.1515578	-0.7065663	8.557442	8.962500	34.979993	33.775256
16.	344.25203	-217.00616	-1.5299898	-0.9415787	8.551810	8.962500	32.932564	33.716489
18.	392.83004	-238.45247	-1.7457474	-1.0342752	8.550291	8.962500	32.187046	34.095397
20.	447.58488	-254.32295	-1.9888253	-1.1028244	8.549204	8.962497	31.533243	34.785932
22.	499.99999	-271.37590	-2.2213962	-1.1764553	8.546819	8.958973	31.234811	34.189181
24.	581.88058	-263.89028	-2.5845079	-1.1441361	8.547788	8.962497	30.265418	37.119023

6 Conclusions

Matching of the Warm Snake to the AGS lattice using four “Courant” quadrupoles is possible. For the quadrupoles there is no much space available, therefore they will present a severe challenge to the Engineers. A perfect match, *i.e.* one that will leave the optics in the part of the lattice outside the section containing the snake is also possible in theory, but it is not desirable because the corresponding currents in the matching quadrupoles do not vary according to smooth curves vs. energy. A reasonable matching is obtain by letting the curves decrease with beam energy following a $(B\rho)^{-2}$ function.

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