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PARTICLE TRACKING USING ELEGANT FOR THE BENDING ARC IN ERLP.

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Abstract

Elegant has been used to track electron bunches round a proposed 180 degree TBA bending arc for the 4GLS prototype ERLP. The final bunch parameters (transverse emittance, average energy) are given for bunches which cover the range of likely bunch parameters. Energy loss is small. Emittance blow up is only significant (>20%) for the shortest bunches considered. There is no evidence for the microbunching instability caused by CSR.

In case compression has to be carried out after the arc, an addenda gives the results of tracking bunches of 0.5psec rms. Again no microbunching is apparent, energy loss is small (of the order of 0.2%), but there is significant (>50%) emittance blow-up .

1. DESCRIPTION OF THE ARC

The arc consists of a single TBA cell, with the magnets of roughly equal strengths. Two pairs of quadrupoles are located between the bending arcs to obtain the isochronous condition [1] and a pair of quadrupoles is placed either end of the cell to make the cell optically stable. The final choice of cell out of the possible solutions was governed by finding the cell with the lowest beta values. This was accomplished using a mathematica code written by Hywel Owen.

Length (m)	element	angle	Strength 50MeV / 25MeV
0.4	drift		
0.3	quad		4.0
0.4	drift		
0.3	quad		-4.0
0.4	drift		
0.5	dipole	1.04927	0.3497 T / 0.1749 T
0.84025	drift		
0.3	quad		6.0
0.56973	drift		
0.3	quad		-2.8
0.4	drift		
0.5	dipole	1.04305	0.3477 T / 0.1739 T

Table 1. Cell elements. The cell is symmetric about the second dipole.

2. BUNCH PARAMETERS

The arc is designed to transport 35 MeV electrons. The effect of CSR is expected to increase with increasing charge density (ie decreasing bunch length and emittance), and decreasing energy spread. Two limiting case were tracked, one using the minimum reasonable bunch size equivalent to a FWHM of 2psec, (rms value of 0.85ps), an energy spread of 0.02% rms and normalised emittance of 1mm mrad, and one derived from the parameters for the ERLP FEL as given in [2]. For the FEL, a bunch length of <0.6psec rms is required; assuming a compression of a factor 5 in a chicane between the arc and the FEL yields a bunch length of 3psec (rms) in the arc. The normalised emittance was 5 mm mrad, and the energy spread 0.1%. In all cases a charge of 80 pC is used. The values of the beta parameters at the start of the arc are $\beta_x = 7.97$ and $\beta_y = 2.26$, obtained from matching in Elegant. A few bunches with intermediate parameters were also tracked.

3. RESULTS

3.1 Energy loss within bunch and bunch length variation.

Table 2 shows the energy and length of the bunch at the end of the arc. Note that the sigma values are taken from the Elegant output file of the final parameters, and are the rms values of the whole distribution, not slice values.

σ (de) initial	σ (z) initial (μm)	ε_n (mm mrad)	σ (de) final	σ (z) final (μm)	Average γ final	Energy loss	No of particles
				50MeV			
0.1%	900	5	0.101%	900.09	97.781	0.02%	50K
0.1%	900	5	0.101%	900.10	97.781	0.02%	200K
0.02%	254	5	0.045%	254.72	97.72	0.08%	200K
0.02%	506	1	0.032%	508	97.76	0.04%	50K
0.02%	254	1	0.059%	255	97.704	0.10%	50K
0.02%	254	1	0.059%	255	97.705	0.10%	400K
				25MeV			
0.1%	900	5	0.102%	900.09	48.881	0.04%	200K
0.05%	900	5	0.055%	900.02	48.881	0.04%	200K
0.02%	255	1	0.101%	256.9	48.809	0.19%	200K

Table 2. Energy and length parameters of the bunch.

The energy loss through the arc due to CSR is roughly independent of electron energy, the greatest fractional loss being 0.2% for the high density bunch at 25MeV. The elongation of the bunch is negligible in all cases looked at. Figure 1 shows the momentum distribution through the bunch at the start of the arc and the end, for the worst case at 50MeV. The maximum to minimum energy difference in the bunch is about 0.25% for this case. For the equivalent 25MeV case, the energy variation across the bunch is about 0.4%.

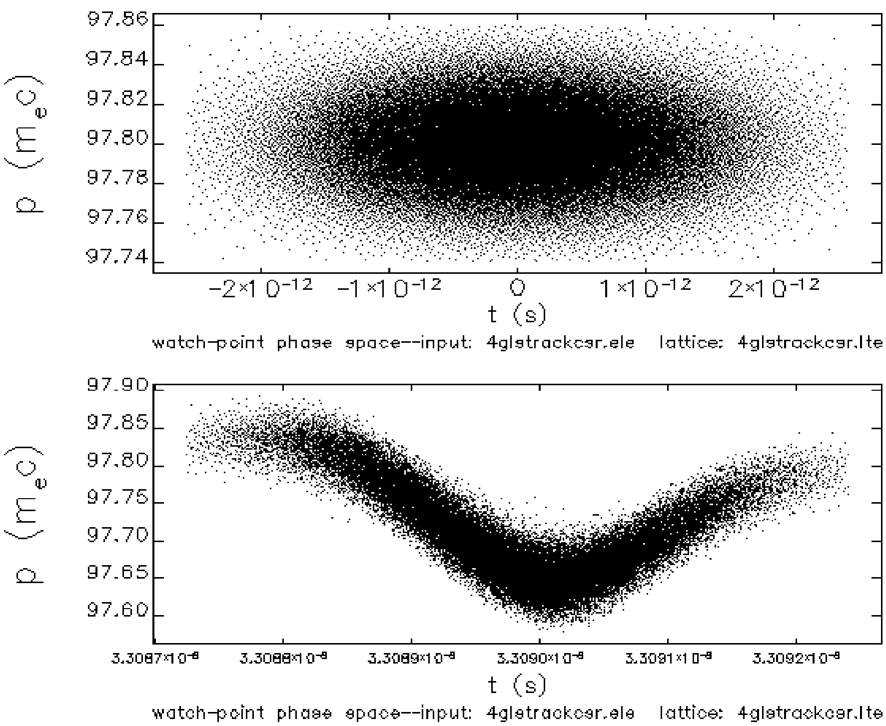

Figure 1. Momentum distribution along the bunch at the start at end of the arc for case of 50 MeV, 0.02% energy spread, 1 mm mrad normalised emittance and for the 254 µm bunch.

3.2 Emittance blow up

Table 3 gives the final emittance values for the bunches. Note that there is no change to the vertical emittance. Significant blow up of the horizontal emittance occurs for the 254 µm bunches. The increase is caused mainly by an increase in angular spread, as can be seen from Figure 2 and Figure 3 where the distribution of x against x' is shown for both energies at the beginning and end of the arc for the 254 µm bunches with 0.02% energy spread and normalised emittance of 1mm mrad. The emittance blow up is greater for the lower energy bunch. Figure 4 shows a similar figure for the 254 µm bunch, normalised emittance of 5 mm mrad and 50MeV.

σ (de)	σ (z) um	ε_n (x) initial (mm mrad)	σ(x) final (µm)	σ(x') final (µrad)	ε_n (x) final (mm mrad)	ε_n(y) final (mm mrad)	No of particles
				50 MeV			
0.1%	900	5	624	81.0	5.05	5	50K
0.1%	900	5	624	80.9	5.05	5	200K
0.02%	254	5	581	110.7	**6.4**	5	200K
0.02%	506	1	277.75	41.3	1.15	1	50K
0.02%	254	1	315.6	79.9	**2.52**	1	50K
0.02%	254	1	313.3	79.6	**2.49**	1	400K
				25MeV			
0.1%	900	5	871	117	5.0		200K
0.05%	900	5	875	117	5.006		200K
0.02%	254	1	532	162	**4.2**		200K

Table 3. Emittance values for the bunches.

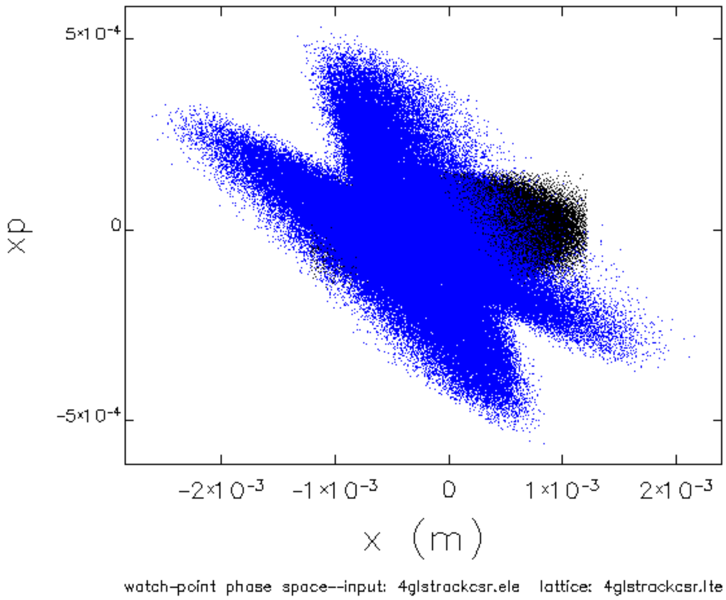

Figure 2. Distribution of x against x' for the 25 MeV 254 μm bunch, 1 mm mrad normalised emittance and 0.02% energy spread. Black - at the start of the arc, blue - at the end of the arc.

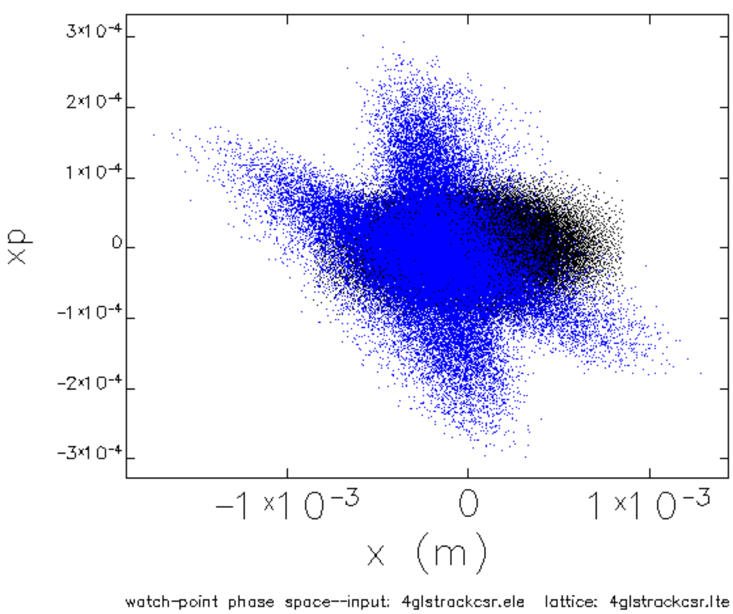

Figure 3. Distribution of x against x' for the 50 MeV 254 μm bunch, 1 mm mrad normalised emittance and 0.02% energy spread. Black - at the start of the arc, blue - at the end of the arc.

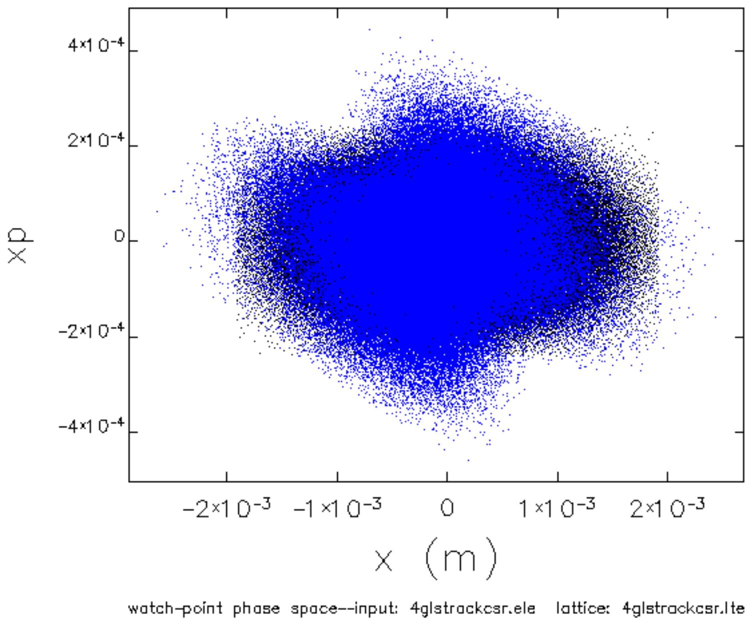

Figure 4. Distribution of x against x' for the 50 MeV 254 μm bunch, 5 mm mrad normalised emittance and 0.02% energy spread. Black - at the start of the arc, blue - at the end of the arc.

3.3 Micro-bunching.

Micro-bunching is predicted to be worst for the lowest energy spread and highest electron density [3]. The results of tracking for the 4GLS arc showed this trend. However, there is some concern that the microbunching could be the result of a numerical instability in the code and it does appear to decrease with increasing number of macroparticles. Whether it is eventually all smoothed out for a large enough calculation still needs to be investigated. However, for the lower charged ERLP bunches, microbunching does not appear to be a problem. Figure 5 and Figure 6 show the linear density for the case at 50 MeV expected to be most susceptible to micro-bunching, with 400,000 and 200,000 particle simulations. Figure 7 and Figure 8 show the linear density in the least susceptible case, for 50,000 and 200,000 particle simulations respectively. It appears that the roughness in the profile depends on the number of particles and is independent of the bunch properties.

As a final check on the micro-bunching istability due to CSR, one ought to track a bunch with an initial density fluctuation to see if this grows due to the micro-bunching instability.

4. SUMMARY

For ERLP, microbunching due to CSR does not appear to be a problem. The absolute energy loss due to CSR is independent of electron energy for the cases studied, and at worst the fractional loss is 0.2% of the bunch energy (for the case of the 'dense' 25MeV bunch). The energy variation along the bunch is less than 0.4%. The bunches are not significantly lengthened and transverse emittance blow-up is greater than 15% only for the 2psec FWHM bunches (not for 4psec or 7psec bunches). For the 2psec bunches, the emittance blow up is worse for the lower energy, being a factor 4.2 as opposed to 2.5 for the 50 MeV case.

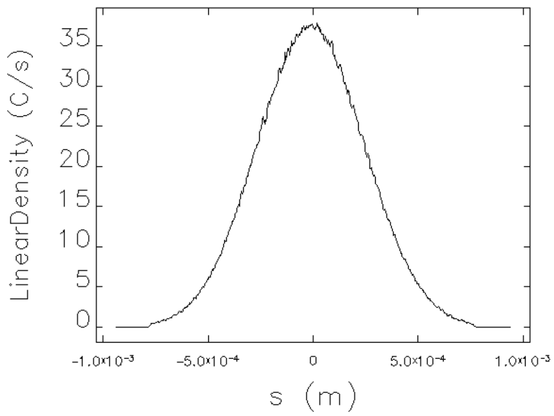

Figure 5. Linear density at end of arc for a 50 MeV 254 µm bunch with energy spread of 0.02% and normalised emittance of 1 mm mrad. 400,000 macroparticles.

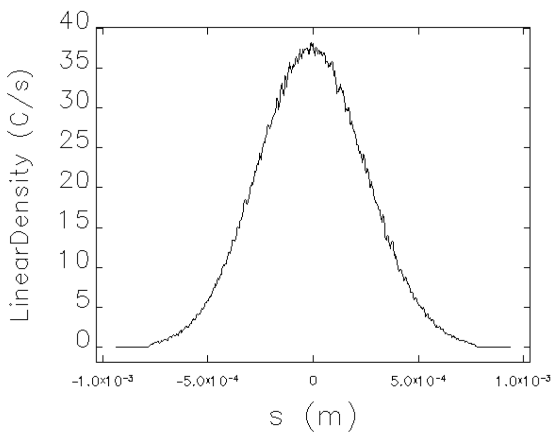

Figure 6 Linear density at end of arc for a 50 MeV 254 µm bunch with energy spread of 0.02% and normalised emittance of 1 mm mrad. 200,000 macroparticles.

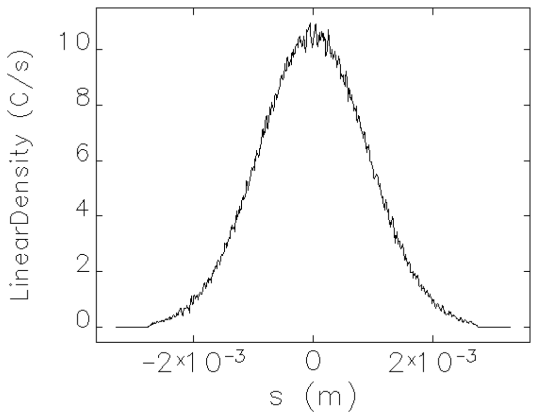

Figure 7. Linear density at end of arc for a 50 MeV 900 μm bunch with energy spread of 0.1% and normalised emittance of 5 mm mrad. 50,000 macroparticles

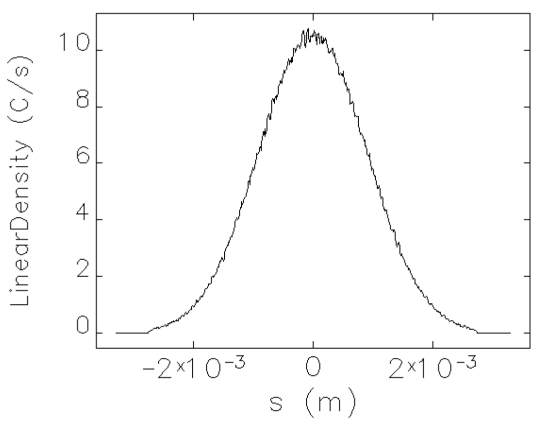

Figure 8. Linear density at end of arc for a 50 MeV 900 μm bunch with energy spread of 0.1% and normalised emittance of 5 mm mrad. 200,000 macroparticles

References.

1. d'Amico, E.T. and Guignard, G., CERN SL/95-120 (AP)/CLIC Note No.292 (1995)
2. Thompson, N., 4GLS report erlp-ofel-rpt-0001
3. Stupakov, G. and Heifets, S., *Phys. Rev. ST Accel. Beams* **5**, 054402 (2002)

5. ADDENDUM - 0.5 PSEC BUNCHES

In the case of a reverse operation of the compression system, compression will have to be carried out in the arc or prior to the arc. In this case, much denser bunches will be travelling round at least part of the arc. To investigate the possible disruption caused by CSR, bunches with 0.5psec rms have been tracked, and the results for energy loss and emittance blow up are displayed in Table 4 and Table 5 respectively. It can be seen that the energy loss is about 0.2%. The induced energy change along the bunch varies from 0.5% for the 25MeV case, to 0.3% for the 5 mm mrad emittance bunches at 35MeV. The emittance is increased by about 50% for cases with $\varepsilon_n = 5$ and by nearly an order of magnitude in the case of $\varepsilon_n = 1$. It may seem surprising that the final emittance for the $\varepsilon_n = 1$ bunch has increased to greater than that for the $\varepsilon_n = 5$ bunch. However, as the bunches are far from perfect gaussian shapes, the estimate of final emittance from the product of the rms values for the x and x' distributions is inaccurate and should be treated with caution. Also factors such as the increased energy distribution for the $\varepsilon_n = 1$ may also play a role in the transverse spread of the bunch. The final x and x' distributions for the case of $\varepsilon_n = 1$ are given in Figure 9.

σ (de) initial	σ (z) initial (μm)	ε_n (mm mrad)	σ (de) final	σ (z) final (μm)	Average γ final	Energy loss
			35 MeV			
0.1%	150	5	0.12%	152.51	68.385	0.17%
0.02%	150	5	0.08%	152.09	68.384	0.17%
0.02%	150	1	0.12%	156.6	68.336	0.24%
			25MeV			
0.1%	150	5	0.14%	153.1	48.794	0.22%

Table 4. Effect of CSR on energy and bunch length of 0.5psec bunches

σ (de)	σ (z) um	ε_n (x) initial (mm mrad)	σ(x) final (μm)	σ(x') final (μrad)	ε_n (x) final (mm mrad)
			35 MeV		
0.1%	150	5	664.5	163	7.4
0.02%	150	5	662	165	7.5
0.02%	150	1	631	213	9.2
			25 MeV		
0.1%	150	5	777	194	7.4

Table 5. Effect of CSR on emittance for 0.5psec bunches.

The linear density distributions are given (Figure 11 and Figure 12) for the $\varepsilon_n = 5$, 25MeV case and for the $\varepsilon_n = 1$, 35MeV case which his the largest CSR in the above examples. There is no evidence of micro-bunching in the plot of linear density. In the small emittance case, the length profile is 'sharpened'. The energy variation along the bunch is given for the small emittance case in Figure 12.

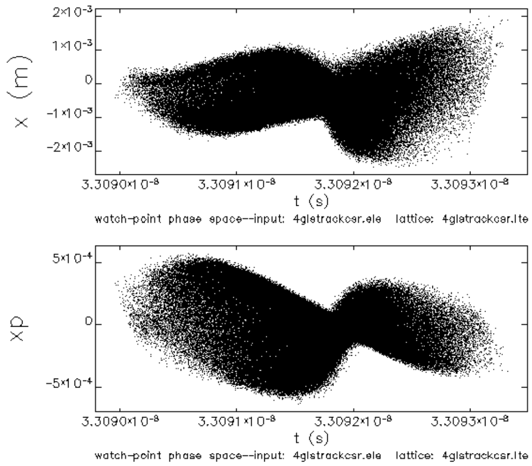

Figure 9. Final distributions for x and x' for the 35MeV, ε_n =1 bunch, energy spread of 0.02%

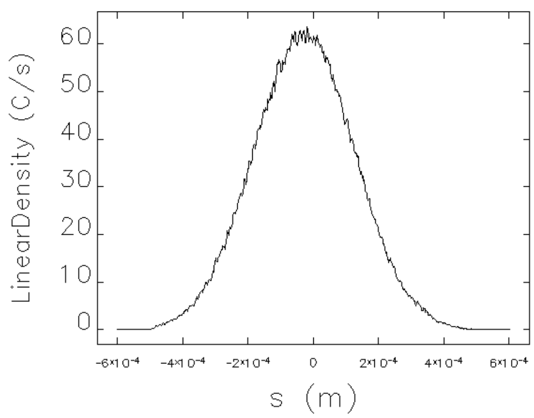

Figure 10. Linear density at end of arc for a 25 MeV 150 μm bunch with energy spread of 0.1% and normalised emittance of 5 mm mrad. 200,000 macroparticles

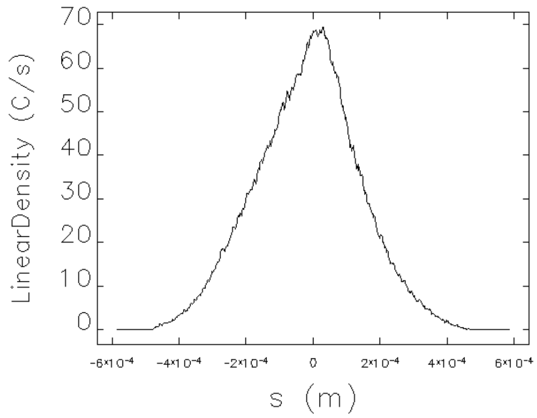

Figure 11 Linear density at end of arc for a 35 MeV 150 µm bunch with energy spread of 0.02% and normalised emittance of 1 mm mrad. 200,000 macroparticles

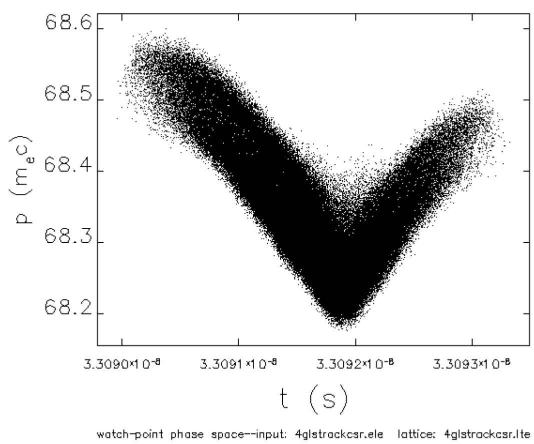

Figure 12 Momentum distribution along the bunch at the end of the arc for case of 35 MeV, 0.02% energy spread, 1 mm mrad normalised emittance and for the 150 µm bunch.