Adapting numerical simulation results for coherent synchrotron radiation and space charge effects

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Abstract

At PITZ, beam dynamics are studied with the aim of producing and characterising a small transverse emittance electron beam which is fired from a radio frequency (RF) gun. Particles fired from the RF gun are subsequently tracked in 3D numerical simulations along the beamline. A new component for plasma wakefield acceleration (PWA) experiments, a bunch compressor, is currently being studied and will be added later if simulations show it is feasible for the PITZ beam parameters. There are space charge fields to account for throughout, and in the bunch compressor, coherent synchrotron radiation effects would come from the beam and dipole. Two different programs must be used to take these fields into account - ASTRA for space charge and CSRtrack for coherent synchrotron radiation. Each program is unable to read the output of the other, and so conversion programs must be written which will allow them to do so.

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1 Introduction

The Photo Injector Test Facility at Zeuthen (PITZ) was made primarily to optimize sources of high brightness electron beams for free electron lasers. An example of this is the upcoming European XFEL which will begin operations in 2017. The aim is to produce intense electron beams with a small transverse and longitudinal emittance [1]. In a free electron laser, low emittance is vital as it means the beam will be small and will result in a higher brightness, with more photons concentrated on a spot. Third generation synchrotron light sources have smaller demands towards the beam quality wheareas FELs impose strict demands. Beam dynamics are studied for different machine settings depending on different parameters. Essentially this involves inputting settings to see how the machine processes it.

One of the goals of PITZ is self modulation within a bunch in plasma wakefield accelerator experiments. Another goal, which is part of this project, is to study the possibilities to reach a high transformer ratio. This ratio is usually limited to 2 for collinear wakefield acceleration. In a wakefield accelerator there is a leading drive bunch which enters first and possesses a high charge. This is usually followed by the low charged, trailing witness bunch. The drive bunch is used to accelerate the witness bunch. This means that the transformer ratio is:

$$R = \frac{E_+}{E_-}$$

where E_+ is the maximum energy gain of the witness bunch (peak accelerating field behind the bunch) and E_- is the maximum energy loss of the drive bunch (peak decelerating field within the bunch) [2].

So for the witness beam to accelerate to a high energy, the transformer ratio should be as large as possible. Some methods of attaining a transformer ratio greater than 2 are the use of gaussian ramped charge bunches or triangular drive bunches (see section 3). For example, at PITZ the use of gaussian-shaped ramped bunches is expected to aid in reaching a transformer ratio of 8.

To achieve a high transformer ratio, there must be a high peak current, I_{peak}. Furthermore, the spacing must be well-defined between the peaks of the bunch. A well-defined bunch spacing means that the distance between each peak is identical. An example bunch can be seen in Fig. 3.2. To explore the possibilities of decreasing the longitudinal bunch size σ_z in the bunch compressor, simulations with CSRtrack can be used. The bunch must be compressed by a factor of 4 to attain the target ratio.

2 Project brief

Figure 2.1 shows a schematic of the PITZ apparatus. Electrons are emitted from the RF gun cavity (a) on the far right. The beam has a maximal energy of around 7 MeV after it leaves the gun. The booster cavity (b) enables the beam to be accelerated to approximately 25 MeV. The proposed bunch compressor will be positioned at (c), and will compress the bunch by a factor of 4 before it continues to the plasma chamber (d) where plasma wakefield acceleration takes place.

There are two different programs used to track particles both in and after they leave the RF gun. ASTRA (see section 3) is used from the gun to the bunch compressor. CSRtrack (see section 4) is used in the bunch compressor, and ASTRA is used once again from the bunch compressor to the plasma chamber.

The main problem is that the output file made by ASTRA is not fully compatible with the CSRtrack program, needing alterations to charge, and neither is CSRtrack's output compatible with ASTRA. The different formats of each output can be seen in Appendix A. So in order to be able to follow the particles as they move along the different parts of the linac (linear accelerator), the outputs must be made compatible. The primary aim of this project was to write conversion programs such that the output files should be interchangeable from different formats, and also to be able to verify the results.

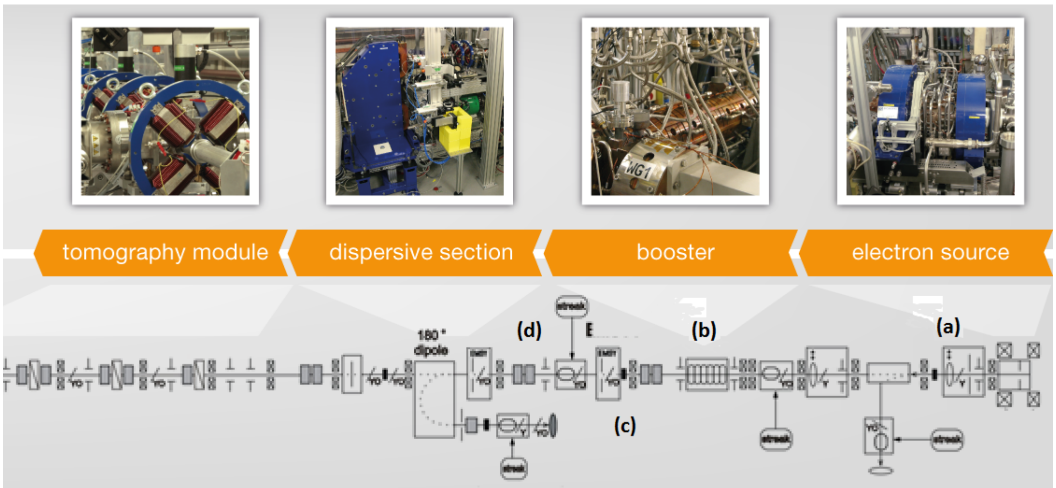

Figure 2.1: Schematic of the PITZ apparatus. This is an older schematic, and the linac will be altered slightly depending on whether the bunch compressor will prove to be feasible. If this is the case, the compressor will be placed at position (c) and the plasma chamber will be moved to position (d), with the surrounding components being shifted slightly.

3 ASTRA

A Space-Charge Tracking Algorithm (ASTRA) [3] is used to track the particles both inside and after they exit the gun. This program reads the initial particle coordinates from a file which is produced by a generator program, and then proceeds to track the particles through external fields that can be defined by the user. The space charge field of the particle cloud is taken into account. It uses the numerical analysis method RK4 (fourth-order Runge-Kutta integration) to track the particles [4].

The ASTRA program was explored in some detail, and tests were run to see what sort of output was produced when certain vital parameters such as solenoid field and transverse rms bunch size were altered. This was so that the ASTRA data could be compared to that produced by CSRtrack and so check that the conversion programs worked.

There were two main laser distributions explored in this project. Firstly, a flat-top, plateau distribution was used. Each pulse is either flat-top or Gaussian. The flat-top singlet illustrated in Fig. 3.1 has considerable noise, but demonstrates the basic profile. To attain a better plateau at least 200,000 particles should be taken into account in the ASTRA generator. In this case about 10,000 particles were considered for time purposes, as ASTRA takes several hours to process.

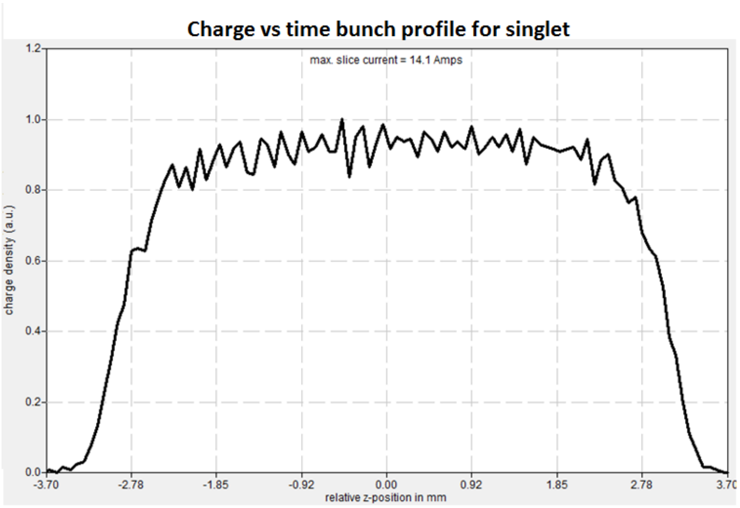

Figure 3.1: Flat-top plateau bunch profile for a laser pulse singlet.

The second distribution was a modulated one, composed of five sub-pulses corresponding to a ramped charge profile. Each individual pulse in the bunch takes a Gaussian shape, which is shown in Fig. 3.2. In a plasma wakefield accelerator, the leftmost bunch enters the plasma chamber first, each successive peak having a higher current than the previous. The distance between each peak should be identical to have a well-defined bunch spacing.

The following experiments were all conducted using a flat-top distribution. One experiment was to find the conditions for optimum brightness at the position z=5.277 m. The values of the parameters Lt (length of bunch for plateau distribution) and σ_{xy} (transverse rms bunch size in horizontal (x) and vertical (y) directions) were

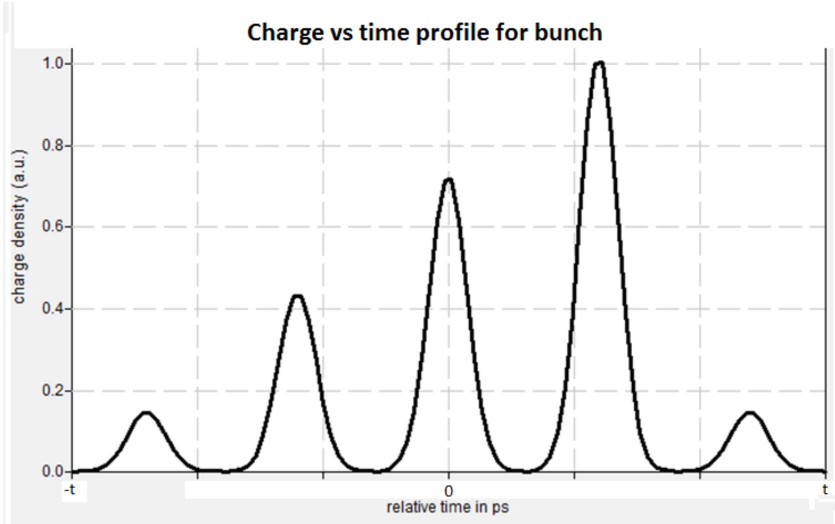

Figure 3.2: Bunch profile for a laser pulse 5-plot.

altered from their defaults of 25.0 ps and 0.29 mm respectively. The charge was kept at a constant Q = 250 pC. A range of 16 < Lt < 26 ps and $0.1 < \sigma_{xy} < 0.5$ mm was used, and it was assumed that the local brightness would change in the various combinations of Lt and σ_{xy}. The equation used to calculate peak brightness was

$$B = \frac{I_{peak}}{\epsilon_x \epsilon_y}$$

where I_{peak} is the peak current, and ϵ_x and ϵ_y are the emittances along the transverse plane.

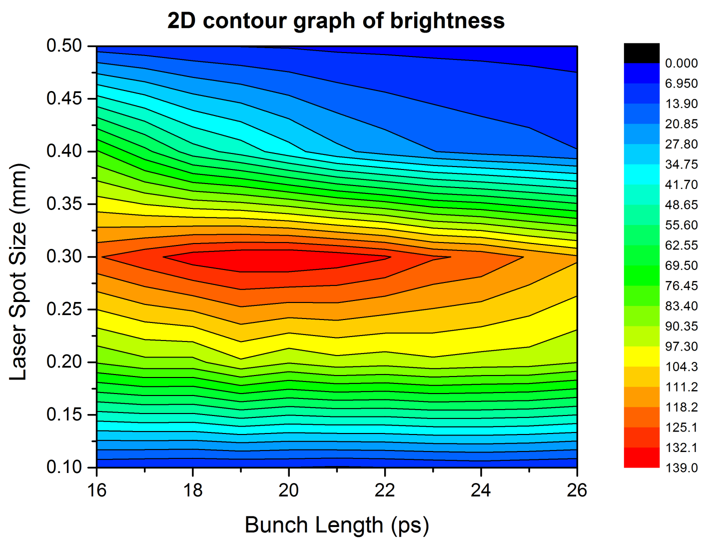

Figure 3.3: 2D contour map of brightness for a range of bunch length and transverse rms bunch size.

Figure 3.3 shows that brightness is at a maximum when the rms bunch size is at 0.3 mm and the bunch length is in the region of 16 to 23 ps. In an attempt to optimise the brightness further, the value of the bunch length was kept at a constant value while the solenoid current was altered. The bunch length used in this case was 16 ps. The current ranged 365 < I < 405 A and transverse rms bunch size was once again ranged from $0.1 < \sigma_{xy} < 0.5$ mm. In Fig. 3.4 the brightness has been further optimised to a maximum of 143.5 A/mm^2, for a solenoid current of 387 A and a transverse rms bunch size of 0.3 mm. To continue finding an optimum brightness, the bunch length can be altered to a new constant value over the aforementioned range of current and transverse rms bunch size. This is useful for finding which parameters need to be altered to get the maximum possible brightness, as a high brightness beam is important in free electron lasers.

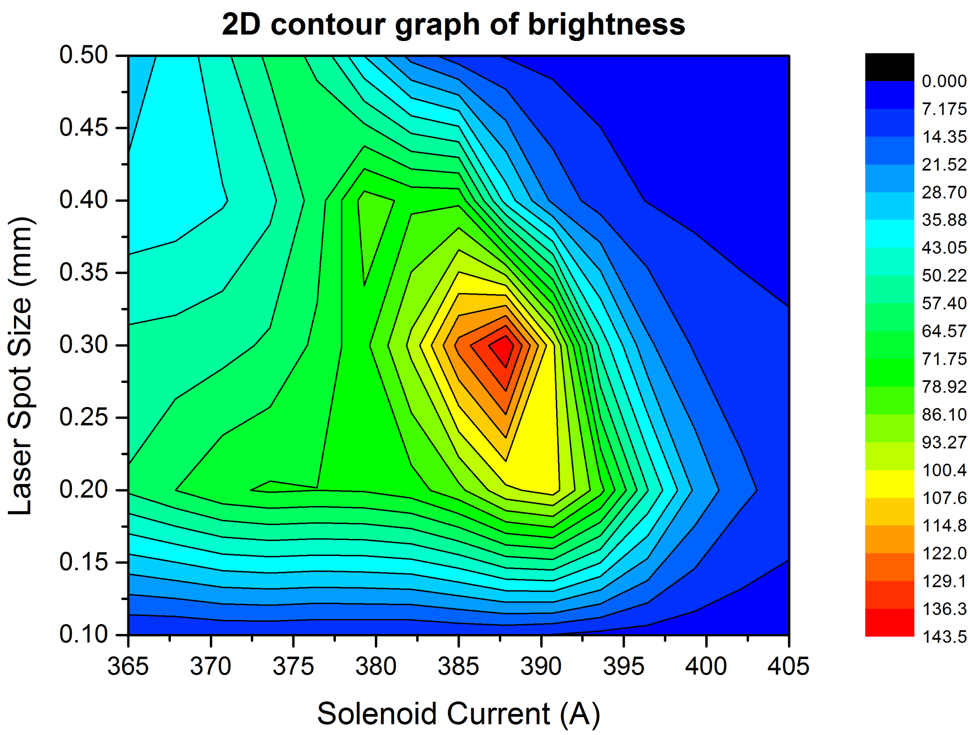

Figure 3.4: 2D contour map of brightness for a range of solenoid current and transverse rms bunch size.

Another experiment was to alter the magnetic field inside the solenoid to see the effects upon the transverse phase space. The magnetic field was set to a default value of -0.226522 T which is akin to a solenoid current of 385 A. The value of magnetic field B_z was altered around this value over the current range of 365 to 405 A. Figure 3.5 shows how the phase space changes around the default value of 385 A (b). If the current is decreased (a) then the transverse phase space has a declining slope in the positive current direction and an inclining slope (c) if the current is increased.

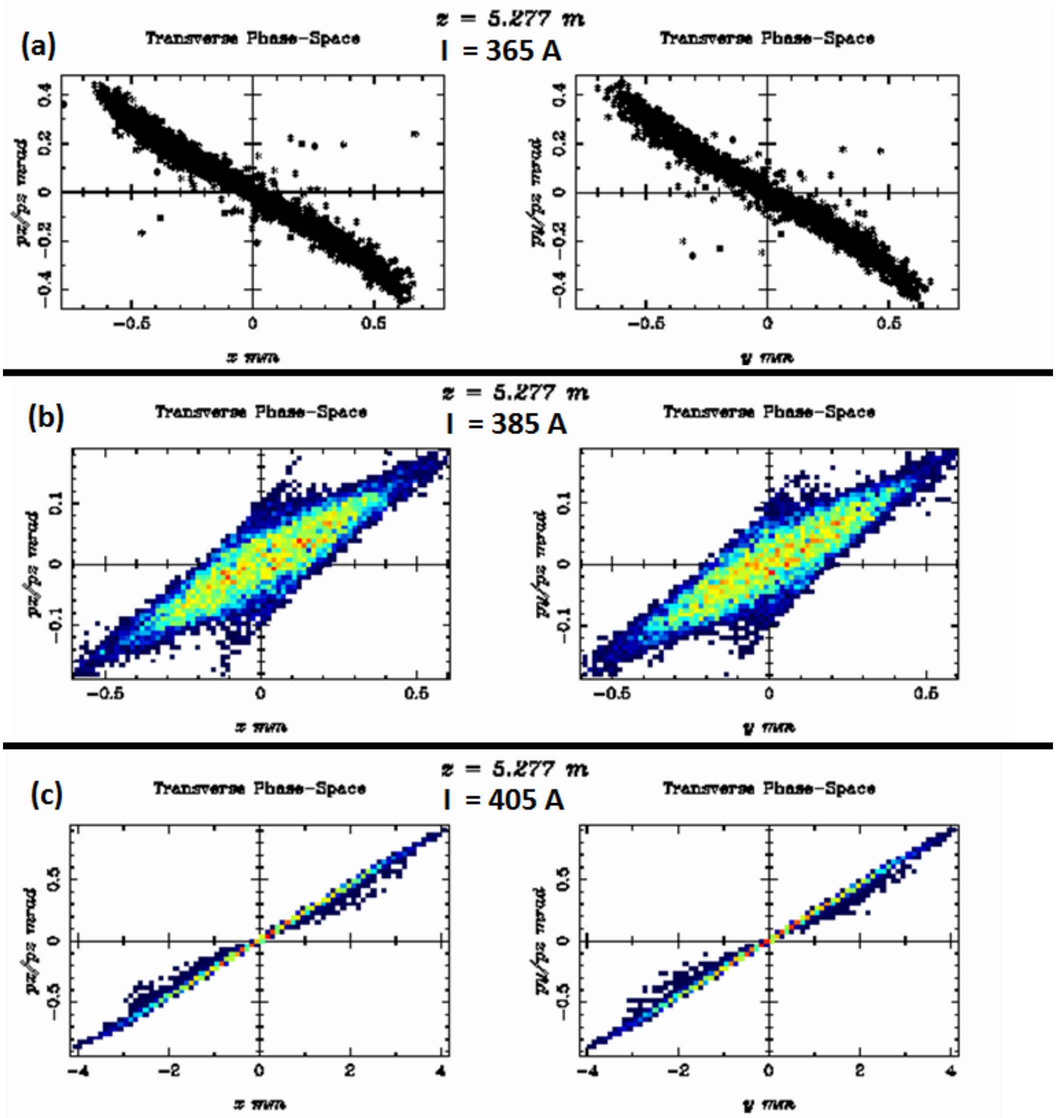

Figure 3.5: Transverse phase space for a solenoid current range of 365 to 405 A.

4 CSRtrack

CSRtrack (Coherent Synchrotron Radiation tracker) [5] tracks the particles as they pass through the bunch compressor. The program tracks particle ensembles through beamlines with arbitrary geometry. Coherent synchrotron radiation fields and intra-bunch fields can both be taken into account in the 3D field calculations. These are similar to space charge fields on straight trajectories, but on curved trajectories they cannot be cleanly separated from radiative fields. Particles are tracked through a magnetic lattice in absolute coordinates using a self-consistent algorithm [6].

5 Converting between ASTRA and CSRtrack

Before the bunch compressor, the program ASTRA2CSR is used, which takes an ASTRA output file and converts it into one of the two utilized formats recognizable by CSRtrack. After the bunch compressor, CSR2ASTRA is used.

The conversion program ASTRA2CSR changes the number of columns in the output, along with their values. It duplicates macroparticles, so for a charge N times larger than CSRtrack's q_0, there will be N identical lines. The program will also edit the longitudinal value of the reference particle (a test particle centred on zero) to leave $z_{ref} = 0$ m. The program CSR2ASTRA does the reverse conversion. The conversion process is illustrated in Fig. 5.1.

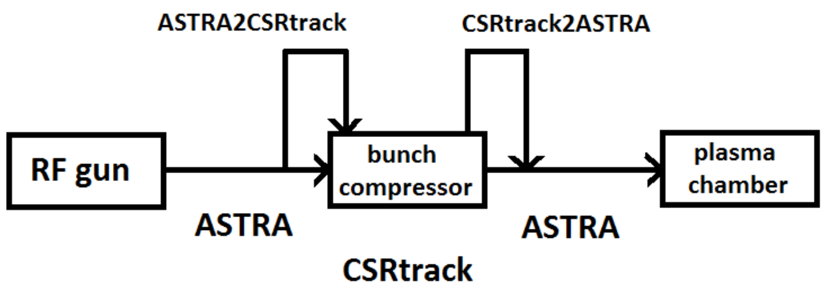

Figure 5.1: Conversion points for ASTRA and CSRtrack.

It is necessary to switch between ASTRA and CSRtrack as the programs include different factors in the calculation. ASTRA deals with space charge whereas CSRtrack accounts for coherent synchrotron radiation. It is not known at present which effect is stronger, so instead of using a single program all the way through, neither program can be discounted. The file format for ASTRA is ten columns filled with various parameters which are shown in Table A.1 in Appendix A.

CSRtrack has three different formats. Two of them, fmt1 and fmt3 have been looked at for this project. They are shown in Table A.2 and Table A.3 in Appendix A. By comparing the formats in the tables it is evident that neither program outputs are compatible with each other, hence the need for a program which can convert one output into a format that is recognizable by the other program.

The results of the two conversion programs were compared to see if they matched. Important parameters such as longitudinal rms bunch size, momentum spread, and emittance were checked. For a successful conversion, the error in the parameters from ASTRA to CSRtrack should be very small - approximately zero. Large errors may indicate a problem in the conversion. For example, the error calculation for longitudinal bunch size would be the following:

$$\frac{\sigma_{z,ASTRA} - \sigma_{z,CSR}}{\sigma_{z,ASTRA}} \approx 0$$

Table 5.1 shows the error between ASTRA and CSRtrack fmt1 for various parameters, while Table 5.2 refers to CSRtrack fmt3. The input file was for a pulse with five bunches at a charge of 10 pC. The percentage error is small ($< 2\%$) for each value taken into consideration, which indicates that there are no problems in the conversion.

	CSRtrack fmt1	**ASTRA**	**% Error**
I_{peak}	4.096 A	4.106 A	0.244
σ_z	1.46000 mm	1.46322 mm	0.22055
p_z	23.301 MeV/c	23.301 MeV/c	0.000
Q	-0.05 nC	-0.05 nC	0.00
δp_z	0.0101	0.0102	0.9900
ϵ_x	4.18E-06 m mrad	4.24E-06 m mrad	1.44
ϵ_y	2.51E-07 m mrad	2.54E-07 m mrad	1.20

Table 5.1: The errors in peak current, bunch size, momentum, charge, relative momentum spread, x- emittance and y- emittance for the conversion from CSRtrack fmt1 to ASTRA.

	CSRtrack fmt3	**ASTRA**	**% Error**
I_{peak}	4.096 A	4.106 A	0.244
σ_z	1.46000 mm	1.46322 mm	0.22055
p_z	23.309 MeV/c	23.309 MeV/c	0.000
Q	-0.05 nC	-0.05 nC	0.00
δp_z	0.01010	0.01024	0.9900
ϵ_x	4.24E-06 m mrad	4.21E-06 m mrad	0.71
ϵ_y	2.54E-07 m mrad	2.57E-07 m mrad	1.18

Table 5.2: The errors in peak current, longitudinal bunch size, momentum, charge, relative momentum spread, x- emittance and y- emittance for the conversion from CSRtrack fmt3 to ASTRA.

A direct comparison with ASTRA and CSRtrack output is not possible as between the two points of comparison, the beam passes through four dipole magnets, which affects the beam parameters. Different graphing software must be used to analyse the two sets of values. Phase Space Viewer in MATLAB was used for the original CSRtrack values, while an analysis code based on ROOT was used for the converted ASTRA file. From these results it can be seen that the converted values are in good agreement with the original values, and so the conversion was successful. This can be inferred from the shape of the graphs in Fig. 5.2 and Fig. 5.3. The basic shape is the same for the graphs, and so are the primary values such as peak current and momentum spread.

Figure 5.2 shows relative momentum spread against position for both the CSRtrack file and the ASTRA file. Despite the necessity for different graphing software, the relative energy/momentum spread is the same for both the original and the converted values. The current profiles in Fig. 5.3 are also identical for both CSRtrack and ASTRA. CSRtrack's fmt1 was also plotted and gives identical graphs for both the original and the converted file. This means that the conversion for both CSRtrack formats was successful.

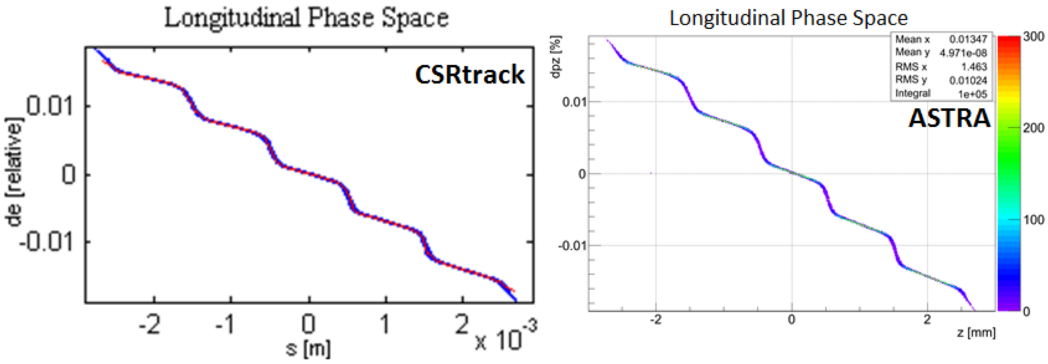

Figure 5.2: Longitudinal energy/momentum spread for original (left - CSRtrack fmt3) and converted (right - ASTRA). The two graphs are identical.

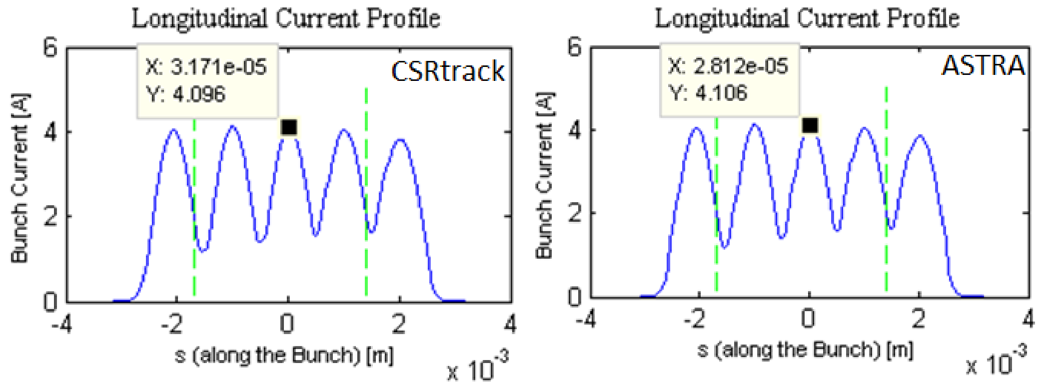

Figure 5.3: Current bunch profile for original (left - CSRtrack fmt3) and converted (right - ASTRA). They both have similar peak values.

6 Conclusions

The aim of the project was to write a series of conversion programs that would enable ASTRA output to be changed into a format that could be input into CSRtrack, and vice versa. This was the case for two different CSRtrack formats, fmt1 and fmt3, which can be compared to the ASTRA format in the Appendix A. The code was tested using numerous output files to see if the file had the same values after it had been converted twice. It was also checked with graphs such as Fig. 5.2 and Fig. 5.3 to see if the profile was the same after conversion. The numerical values of several important parameters such as longitudinal bunch size, emittance and momentum spread were compared in Table 5.1 and Table 5.2 to see if they were the same before and after conversion. The code was successful in all checks. Some future improvements to the code could be made to speed it up. It currently takes approximately ten minutes to convert a file containing 500,000 particles, mainly because it erases the lines which contain charge duplicates. If it were to skip the duplicates instead of erasing them, it should be considerably faster.

A Appendix

Column	1	2	3	4	5	6	7	8	9	10
Parameter	x	y	z	px	py	pz	cl	charge	id	flag
Unit	m	m	m	eV/c	eV/c	eV/c	ns	nC		

Table A.1: *The output format of ASTRA, where x, y and z are the particle coordinates, px, py and pz are the particle momentum in each direction, cl is the time the particle was at each position, id is the particle index, and flag refers to the status flag which tells whether the particle is standard, probe, or lost.*

1	2	3	4	5	6	7
t	0	0	0	0	0	0
z_r	x_r	y_r	pz_r	px_r	py_r	q_r
δz_i	δx_i	δy_i	δpz_i	δpx_i	δpy_i	q_i

Table A.2: *The output format of CSRtrack fmt1, where x, y and z are the particle coordinates, px, py and pz are the respective particle momentum, and q is the charge. In the first row, t refers to the time of the distribution. The second row refers to the reference particle. From the third row onward, the values are the difference in position and momentum relative to the reference particle.*

1	2	3	4	5	6	7	8	9	10	11	12
t	γ_r	0	0	0	0	0	σ_s	σ_r	σ_z	0	0
h_r	h'_r	v_r	v'_r	0	δe_r	q_r	$f_{s,r}$	$f_{h,r}$	$f_{v,r}$	$L_{s,r}$	$L_{t,r}$
h_i	h'_i	v_i	v'_i	s_i	δe_i	q_i	$f_{s,i}$	$f_{h,i}$	$f_{v,i}$	$L_{s,i}$	$L_{t,i}$

Table A.3: *CSRtrack fmt3 output, where the first row consists of the time t, and the Lorentz factor γ_r of the reference particle. The second row refers to the reference particle. The third row onwards are all of the other particles. H is the x position, h' is the slope in the horizontal direction, v is the y position, v' is the slope in the vertical position, s is the z position, δe is the relative energy deviation corresponding to reference momentum, q is the charge, $f_{s,h,v}$ are the force components in each direction, and L_s and L_t are the source and test flags respectively.*

Acknowledgements

I would like to thank Galina Asova and Martin Khojoyan for their guidance throughout this project.

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