ASTRA Manual extract

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Contents

6. Input namelists for *Astra*

6.1. The namelist NEWRUN

The namelist NEWRUN contains basic instructions for the tracking.

Parameter	Specification	Unit	Default Value
Head	Character*150		
	header line for protocol.		
RUN	Integer		1
	the RUN number is used as extension for all output files (see Table 3). It is automatically incremented if a LOOP is specified.		
LOOP	Logical		FALSE
	see chapter 4.9.		
NLoop	Integer		
	see chapter 4.9.		
Distribution	Character*150		
	name of the initial particle distribution, see chapters 2 and 3.		
ion_mass( )	Real*8 Array	eV/c^2	0.0
	the mass divided by the charge state of user defined particles. Negatively charged particles are defined by a negative value of the ion_mass parameter. Particle index 5 – 14 in the input distribution file refer to ion_mass(1) – (10). See also the corresponding *generator* definitions (7). Mass proportional results (energy and momenta) are normalized to the charge state!		
N_red	Integer		1
	if > 1 only every N_redth particle of the distribution is used. The charge of the particles is scaled accordingly.		
Xoff	Real*8	mm	0.0
	horizontal offset of the input distribution. Active if Xoff $\neq$ 0.0.		
Yoff	Real*8	mm	0.0
	vertical offset of the input distribution. Active if Yoff $\neq$ 0.0.		
xp	Real*8	rad	0.0
	horizontal trajectory angle, additive to input distribution.		
yp	Real*8	rad	0.0
	vertical trajectory angle, additive to input distribution.		
Zoff	Real*8	m	0.0
	longitudinal offset of the input distribution. Active if Zoff $\neq$ 0.0.		
Toff	Real*8	ns	0.0
	timing offset of the input distribution. Active if Toff $\neq$ 0.0.		
Xrms	Real*8	mm	-1.0
	horizontal rms beam size. Scaling is active if Xrms > 0.0.		

Yrms	Real*8	mm	-1.0
	vertical rms beam size. Scaling is active if Yrms > 0.0.		
XYrms	Real*8	mm	-1.0
	horizontal and vertical rms beam size. The parameter XYrms has priority over the parameters Xrms and Yrms.		
Zrms	Real*8	mm	-1.0
	rms bunch length. Scaling is active if Zrms > 0.0.		
Trms	Real*8	ns	-1.0
	emission time of the bunch. Scaling is active if Trms > 0.0.		
Tau	Real*8	ns	0.0
	exponential delay time of the emission. Active if Tau ≠ 0.0. Note that the delay time is random and might interfere with the quasi random nature of an input distribution.		
cor_px	Real*8	mrad	0.0
	correlated divergence of the bunch. Scaling is active if cor_px ≠ 0.0.		
cor_py	Real*8	mrad	0.0
	correlated divergence of the bunch. Scaling is active if cor_py ≠ 0.0.		
Qbunch	Real*8	nC	0.0
	bunch charge. Scaling is active if Qbunch ≠ 0.0.		
SRT_Q_Schottky	Real*8	$nC\cdot(m/MV)^{1/2}$	0.0
	variation of the bunch charge with the square root of the field on the cathode. Scaling is active if SRT_Q_Schottky ≠ 0.0.		
Q_Schottky	Real*8	nC·m/MV	0.0
	linear variation of the bunch charge with the field on the cathode. Scaling is active if Q_Schottky ≠ 0.0.		
debunch	Real*8		0.0
	'debunched' particles, i.e. particles with a distance to the bunch center exceeding debunch$\cdot\sigma_z$ are passivated, i.e. their status will be set to 0 or 1. Debunch is defined relative to the rms bunch length, hence it should not be used close to the cathode where σ_z can be zero. The procedure is active when debunch is ≠ 0.0		
Track_All	Logical		TRUE
	if false, only the reference particle will be tracked. The ref file contains the off-axis results in this case.		
Track_On_Axis	Logical		FALSE
	if true, the reference particle will be tracked only on axis. The ref file contains the on-axis results in this case.		
Auto_Phase	Logical		TRUE
	if true, the RF phases will be set relative to the phase with maximum energy gain.		

Phase_Scan	Logical		FALSE
	if true, the RF phases of the cavities will be scanned between 0 and 360 degree. Results are saved in the PScan file. The tracking between cavities will be done with the user-defined phases.		
check_ref_part	Logical		TRUE
	if true, the run will be interrupted if the reference particle is lost during the on- and off-axis reference particle tracking.		
L_rm_back	Logical		FALSE
	if true, particles are immediately discarded when they start to travel backwards. If false, backward traveling particles are only discarded when they pass the lower boundary Z_min. Note, that in some cases (phases) the particles can change the direction of motion several times, before hitting a boundary.		
Z_min	Real*8	m	
	lower boundary for discarding particles. If Z_min is not specified by the user it is automatically set by the program assuming that particles are supposed to travel in positive Z-direction.		
Z_Cathode	Real*8	m	
	position of the cathode for the calculation of the mirror charge. If Z_Cathode is not specified by the user it is automatically set by the program to the minimal particle position provided the bunch is emitted from a cathode.		
H_max	Real*8	ns	0.001
	maximum time step for the Runge-Kutta integration.		
H_min	Real*8	ns	0.0
	minimum time step for the Runge-Kutta integration and min. time step for the space charge calculation. During the emission process from a cathode the time step is forced to H_min. If zero H_min is set automatically based on the parameter N_min (namelist CHARGE) in accordance to Eq. (4.1).		
Max_step	Integer		100 000
	safety termination: after Max_step Runge_Kutta steps the run is terminated.		
Lmonitor	Logical		FALSE
	if true, the particle number and average position will be reported on every time step. For diagnostics only, slows down the calculation.		
Lprompt	Logical		TRUE
	only for Windows PC version. If true a pause statement is included at the end of the run to avoid vanishing of the window in case of an error.		

6.2. The namelist OUTPUT

In the namelist OUTPUT specifications for the generation of output are defined.

Parameter	Specification	Unit	Default Value
ZSTART	Real*8	m	0.0
	minimal z postion for the generation of output, tracking may start at z ≠ ZSTART according to the definition of the initial particle distribution.		
ZSTOP	Real*8	m	0.3
	tracking will stop when the bunch center passes ZSTOP.		
Zemit	Integer		100
	the interval ZSTOP-ZSTART is divided into Zemit subintervals. At the end of each subinterval output of line-typ is generated.		
Zphase	Integer		1
	the interval ZSTOP-ZSTART is divided into Zphase subintervals. At the end of each subinterval a complete particle distribution is saved. It is recommended to set Zemit = $n \cdot$ Zphase, $n \in \mathbb{N}$.		
Screen( )	Real*8 array	m	
	additional position for the generation of output.		
Scr_xrot( )	Real*8 array	rad	0.0
	rotation angle of the screen in the x-z plane. Active if Scr_xrot( ) ≠ 0.0 and only in combination with Local_emit. The angles are measured relative to the z-axis, i. e. the standard position corresponds to Scr_xrot( ) = π/2.		
Scr_yrot( )	Real*8 array	rad	0.0
	rotation angle of the screen in the y-z plane. Active if Scr_yrot( ) ≠ 0.0 and only in combination with Local_emit. The angles are measured relative to the z-axis, i. e. the standard position corresponds to Scr_yrot( ) = π/2.		
Step_width	Integer		0
	output generation based on time steps rather than on positions. Output is generated every Step_width · time step.		
Step_max	Integer		0
	terminates output based on Step_width. Run may continue if Max_step > Step_max.		
Lproject_emit	Logical		FALSE
	if true, the transverse particle positions of all particles will be projected into a common plane at the longitudinal bunch center position prior to the calculation of the emittance, spot size etc. See section 4.13.3.		
Local_emit	Logical		FALSE
	if true, the transverse particle positions of all particles will be recorded when passing the output position plane prior to the calculation of the emittance, spot size etc. The longitudinal particle coordinates in output files are recalculated based on times and velocities and are only approximate. Hence distributions saved with this option should not be used as input distributions for further tracking! The distance between subsequent output positions has to be larger than the bunch length, or they will be skipped. See section 4.13.3.		

Lmagnetized	Logical		FALSE
	if true, solenoid fields are neglected in the calculation of the beam emittance. See section 4.13.1.		
Lsub_rot	Logical		FALSE
	if true Lmagnetized will be set true and the angular momentum of the bunch is subtracted for the emittance calculation based on the actual x-py and y-px correlation of the bunch rather than by the canonical momentum. See section 4.13.1.		
Lsub_Larmor	Logical		FALSE
	if true a rotation of the transverse coordinate system induced by a solenoid will be taken into account. See section 4.13.2.		
Lsub_coup	Logical		FALSE
	if true a rotation angle of the transverse beam spot will be corrected before the emittance is calculated. See section 4.13.2.		
Rot_ang	Real*8	rad	0.0
	rotation angle for emittance calculation in connection with Lsub_coup. If no rotation angle is specified an optimized rotation angle will be taken. See section 4.13.2.		
Lsub_cor	Logical		FALSE
	if true the reduced emittance is calculated in addition to the standard emittance. See section 4.13.6.		
RefS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
EmitS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated. See section 4.13.		
C_EmitS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated. See section 4.13.5.		
C99_EmitS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated. See section 4.13.5.		
Tr_EmitS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated. See section 4.13.4.		
Sub_EmitS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated. See section 4.13.8.		
Cross_start	Real		0.0
	start point for detecting cross over particles (Sub_EmitS = False). See section 4.13.7.		

Cross_end	Real		0.0
	end point for detecting cross over particles (Sub_EmitS = False). See section 4.13.7.		
PhaseS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
T_PhaseS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
High_res	Logical		FALSE
	if true, particle distributions are saved with increased accuracy. See Table 4.		
Binary	Logical		FALSE
	if true, the particle distributions is saved in binary format.		
TrackS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
TcheckS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
SigmaS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
CathodeS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
LandFS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		
LarmorS	Logical		FALSE
	if true, output files according to Table 3 and Table 4 are generated.		

4.12. Data output and organization of output files

Output of the beam emittance and other statistical beam parameters is generated if 'EmitS = True'. For the calculation of statistical bunch parameters the distance ZStop-ZStart is divided into Zemit intervals. Note that the Runge-Kutta time step is adjusted, i.e. reduced if necessary, in order to interrupt the tracking close to the specified locations. (The beam position refers to the average longitudinal beam position.) This might lead to a reduction of each time step, i.e. to an increased accuracy of the calculation, if the intervals are shorter than the bunch motion in one time step. A warning is given in this case because the result of the calculation might depend on a parameter for the output generation if H_max is too big.

The complete particle distribution is saved at Zphase different locations if 'PhaseS = True'. The distance ZStop-ZStart is divided into Zphase intervals and the nearest location defined by means of Zemit is chosen. It is recommended to set Zemit = n·Zphase, $n \in \mathbb{N}$. Additional output positions can be specified by specifying screen locations (see chapter 6.2). The approximate longitudinal position of a saved particle distribution is indicated in the file name as a four digit number, which corresponds in general to the rounded beam position in cm. If necessary the units for the file name definition is changed (if the distance of the output positions is too small, or if the last output position is too big). If required the naming convention is changed to a relative position (i.e. output position minus start position) which is indicated by a warning message.

In some cases it is desirable to generate output based on time steps rather than on locations. For this purpose the switch T_PhaseS can be set true. A complete particle distribution is saved in time intervals defined by Step_width·H, where Step_width is a user defined integer number and H is the Runge-Kutta time step which is automatically adjusted (between H_min and H_max). In order to limit the generation of output with this option the parameter Step_max can be set to n·Step_width, where n is the number of particle distributions to be saved. The T_PhaseS option can be combined with the PhaseS option.

A log file is generated for each run. In the first section of the log file all namelists of the input deck containing user specified or default values of all possible parameters are stored. The output is generated in a system dependent format; hence this file can in general not be transformed to a different system without problems. While this section is somewhat difficult to read, the way the output is generated allows printout also in cases of serious errors. In the second part of the log file a listing of the names and z-locations or times of saved phase space distributions is stored which is required by the graphic program *postrpo.* The third column of the listing contains the solenoid field value at the location of the saved phase space distribution.

Astra produces output on different length scales, time scales or scales for the variation of a parameter, respectively. Table 3 lists generic file names, logical switches and the scale on which data are stored.

Table 4 lists the output file data structure, i.e. the parameters that can be found in the different files, their units and the format of the files. Note, that the generation of output increases the computation time, especially when it is created on short time scales like tcheck and track files. Hence no superfluous output should be generated when computation time is an issue.

generic name	logical switch	approx. scale
project.ref.run	RefS	Runge-Kutta time step H_{max}
project.track.run	TrackS	Runge-Kutta time step H
project.Cathode.run	CathodeS	Runge-Kutta time step H
project.Fields.run	automatic[1]	Runge-Kutta time step H
project.tcheck.run	TcheckS	Runge-Kutta time step H
project.Xemit.run project.Yemit.run project.Zemt.run	EmitS	(ZStop-ZStart)/Zemit[2]
project.Xemit2.run project.Yemit2.run	Lsub_cor	(ZStop-ZStart)/Zemit[2]
project.TRemit.run	TR_emitS	(ZStop-ZStart)/Zemit[2]
project.Cr_emit.run	Cross_start $\neq$ Cross_end	(ZStop-ZStart)/Zemit[2]
project.Sub_emit.run	Sub_EmitS	(ZStop-ZStart)/Zemit[2]
project.Cemit.run	C_EmitS	(ZStop-ZStart)/Zemit[2]
project.C99emit.run	C99_EmitS	(ZStop-ZStart)/Zemit[2]
project.Larmor.run	LarmorS	(ZStop-ZStart)/Zemit[2]
project.Sigma.run	SigmaS	(ZStop-ZStart)/Zemit[2]
project.Density.run	DensityS	(ZStop-ZStart)/Zemit[2]
project.zpos.run	PhaseS	(ZStop-ZStart)/Zphase, Screen & Wake positions
project.tstep.run	T_PhaseS	Step_width$\cdot$Runge-Kutta time step
project.Lost_Part.run	LClean_Stack	Runge-Kutta time step H
project.Log.run	PhaseS	Start of the run and (ZStop-ZStart)/Zphase and Screen positions or Step_width$\cdot$Runge-Kutta time step
project_E.Log.run	Log_Error	Start of the run
project.LandF.run	LandFS	(ZStop-ZStart)/Zphase and Screen positions
project.PScan.run	Phase_scan	1 degree of the RF phase of each cavity
project.Scan.run	LScan	(S_max-S_min)/S_numb
project.lab.run	LScan	
project.Error.run	ErrorS	run end

run = run number, zpos = z-position, tstep = time step

1 cavity fields are saved when beam loading or time depending field options are used.

2 output is generated in addition at Screen positions and Step_width$\cdot$Runge-Kutta time step.

Table 3: Generic file names, logical switches and scales for the data output with *Astra*.

Name	1	2	3	4	5	6	7	8	9	Format
ref	z m	t ns	pz MeV/c	dE/dz MeV/m	Larmor angle rad	x_{off} mm	y_{off} mm	px eV/c	py eV/c	1P,9E12.4 1P,9E20.12
track	seq. numb	stat. flag	z m	x mm	y mm	Ez V/m	Er, or Ex V/m	0.0, or Ey V/m		2I5,1P,6E12.4
Cathode	z m	t ns	long. sp. ch. field on cathode V/m	acc. field on cathode V/m	charge nC	min. grid position m	max grid position m	emission flag		1P,7E12.4,L3
Fields	z m	t ns	Cavity gradient (i) (i = 1…number of cavities N_C) MV/m							1P,N_CE12.4
tcheck	z m	t ns	${\frac{\sigma_{r0}}{\sigma_r}}^{nr(r)}$	${\frac{\sigma_{z0}}{\sigma_z}}^{nr(z)}$	${\frac{\gamma}{\gamma_0}}^{nr(\gamma)}$	${\frac{\sigma_{r0}}{\sigma_r}}^{nz(r)}$	${\frac{\sigma_{z0}\,\gamma_0}{\sigma_z\,\gamma}}^{nz(\gamma z)}$	scaling counter		1P,7E12.4,I10
Xemit	z m	t ns	x_{avr} mm	x_{rms} mm	x'_{rms} mrad	$\varepsilon_{x,norm}$ π mrad mm	$x\cdot x'_{avr}$ mrad			1P,7E12.4
Yemit	z m	t ns	y_{avr} mm	y_{rms} mm	y'_{rms} mrad	$\varepsilon_{y,norm}$ π mrad mm	$y\cdot y'_{avr}$ mrad			1P,7E12.4
Zemit	z m	t ns	E_{kin} Mev	z_{rms} mm	ΔE_{rms} kev	$\varepsilon_{z,norm}$ π keV mm	$z\cdot E'_{avr}$ keV			1P,7E12.4
Xemit2	z m	$K^x_{2,Z}$ π rad m	$K^x_{3,Z}$ π rad m	$\varepsilon^{reduced\ z}_{x,rms}$ π mrad mm	$K^x_{2,E}$ π rad m	$K^x_{3,E}$ π rad m	$\varepsilon^{reduced\ z\&E}_{x,rms}$ π mrad mm			1P,7E12.4
Yemit2	z m	$K^y_{2,Z}$ π rad m	$K^y_{3,Z}$ π rad m	$\varepsilon^{reduced\ z}_{y,rms}$ π mrad mm	$K^y_{2,E}$ π rad m	$K^y_{3,E}$ π rad m	$\varepsilon^{reduced\ z\&E}_{y,rms}$ π mrad mm			1P,7E12.4
TRemit	z m	t ns	$\varepsilon^{trace\ space}_{x,rms}$ π mrad mm	$\varepsilon^{trace\ space}_{y,rms}$ π mrad mm	$\varepsilon^{trace\ space}_{z,rms}$ π µm					1P,5E12.4
Cr_emit	z m	t ns	x_{rms} mm	y_{rms} mm	$\varepsilon_{x,rms}$ π mrad mm	$\varepsilon_{y,rms}$ π mrad mm	rest charge nC	cross over charge nC		1P,8E12.4
Sub_emit	z m	t ns	x_{rms} mm	y_{rms} mm	$\varepsilon_{x,rms}$ π mrad mm	$\varepsilon_{y,rms}$ π mrad mm	charge of sub-ensemble nC	active rest charge nC		1P,8E12.4

Cemit	z m	$\varepsilon_{x,norm}$, Cx_95, Cx_90, Cx_80 π mrad mm			$\varepsilon_{x,norm}$, Cy_95, Cy_90, Cy_80 π mrad mm			$\varepsilon_{x,norm}$, Cz_95, Cz_90, Cz_80 π keV mm		1P,13E12.4
C99emit	z m	$\varepsilon_{x,norm}$, Cx_99.99, Cx_99.9, Cx_99 π mrad mm			$\varepsilon_{x,norm}$, Cy_99.99, Cy_99.9, Cy_99 π mrad mm			$\varepsilon_{x,norm}$, Cz_99.99, Cz_99.9, Cz_99 π keV mm		1P,13E12.4
Larmor	z m	t ns	avr. Larmor angle rad	rms Larmor angle rad						1P,4E12.4
Sigma	z m	E_{kin} Mev	sig $_{i,j}$ (i = 1..6, j = i..6)							1P,23E14.6
Density	z m	t ns	Number of particles (i), Particle density (i) (i = 1..5)							1P,12E12.4
zpos[1]										1P,8E12.4,2I4
tstep[1]										1P,8E20.12,2I4
Lost_Part[1]										binary
Log	file name	z m	Bz T							A50,2D12.4
LandF	z m	Npart[2]	Q nC	number of lost particles[3]	deposited energy[3] J	tot. energy exchange with fields[3] J				1P,6E12.4
PScan	phase deg	E_{kin} MeV	compression factor	β / β_0						1P,4E12.4
Scan	Scan_ para	z m	FOM(1) – FOM(10)							1P,12E17.8
lab	Label for scan and error plots: X-axis, Y-axis, title									A80
Error	Run #	z m	FOM(1) – FOM(10)							1P,12E17.8

1 zpos = z-position, tstep = time step; zpos, tstep and Lost_Part files have the same structure as input distribution files, the format depends on user settings.

2 Npart = number of active particles.

3 within the previous z-interval.

Table 4: Data structure of output files.

2. Definition of the initial particle distribution

Rather than generating the initial particle distribution internally, the tracking program *Astra* reads the initial particle coordinates from a file. This file may be generated by the program *generator* or by a user written program. However, also any output distribution of the *Astra* code, which has not been generated with the Local_emit = T option, can be used as input distribution, thus supporting the piecewise tracking of a long beam line. In order to be compatible with the graphic program *postpro* the input distribution file name should end with the extension '.ini' or with '.zpos.run', where zpos is a four digit number specifying the longitudinal beam position and run is a three digit number specifying the run number (see chapter 5.6). Table 1 lists the structure of particle distribution files. The Fortran format depends on user settings and is: 1P,8E12.4, 2I4 (default) or 1P,8E20.12,2I4 if High_res = T or binary if binary = T. The same settings are valid for *generator* and *Astra*.

	1	2	3	4	5	6	7	8	9	10
Parameter	x	y	z	px	py	pz	clock	macro charge	particle index	status flag
Unit	m	m	m	eV/c	eV/c	eV/c	ns	nC		

Table 1: Structure of particle distribution files.

The first line of the file defines the coordinates of the reference particle in absolute coordinates. It is recommended to refer it to the bunch center. **Longitudinal particle coordinates, i.e. z, pz and t are given relative to the reference particle.** (If the reference particle is lost the average position of the particle position will be saved with status flag = -99. Coordinates are relative to the average position in this case.) If the particles shall be emitted from a cathode they have to be generated with the same longitudinal position, e.g. z = 0.0 and with an appropriate spread in time, i.e. clock values in nanoseconds. In addition the status flag has to be set accordingly (see Table 2).

The macro charge of the particle is given in nano Coulomb. It is possible to specify each particle with a different charge; the emittance calculation will be done with the appropriate weighting.

The particle index specifies the kind of particle to be tracked:

Index 1 refers to electrons,
2 to positrons,
3 to protons and
4 to hydrogen ions.

Index 5 – 14 refer to particles with user defined ratio of mass to charge state. The sign of the charge specified in the column 8 is not relevant. It is possible to mix different kinds of particles as an initial particle distribution.

The status flag contains information of the particle status as listed in Table 2. Particles with a negative status flag are either lost by some mechanism or not yet started. (The output files list the coordinates of all particles even of those that have been lost. The order of the particles does not change; hence it is easily possible to follow the development of individual particles.) Passive particles are tracked as normal particles but they are not taken into account in the calculation of the beam emittance etc. and they are not taken into account when the space charge field is calculated. They will, however, be tracked taken the action of the space charge field onto them into account. They are typically used to cut off beam tails or halo particles. The trajectories of 'probe particles' and the space charge fields acting onto these particles will be found in an output file for later analysis.

Status flag	Comment	Status
-99[1]	average position of distribution	will not be tracked
-95	ref. particle only; Z_0 > ZStop	lost
-94	ref. particle only; more than Max_Step steps	lost
-92[2]	probe rejected by space charge at the cathode	lost
-91[2]	rejected by space charge at the cathode	lost
-90	probe particle before Z_{min}	lost
-89	particle before Z_{min}	lost
-86[3]	probe particle traveling backwards	lost
-85[3]	particle traveling backwards	lost
-31	particle discarded by user	lost
-30	particle preliminary discarded by user	lost
-22	probe secondary electron, lost on aperture	lost
-21	secondary electron, lost on aperture	lost
-20	passive probe particle, lost on aperture	lost
-19	passive particle, lost on aperture	lost
-17	trajectory probe particle, lost on aperture	lost
-15	standard particle, lost on aperture	lost
-6	passive probe particle, at the cathode	not yet started
-5	passive particle, at the cathode	not yet started
-4	secondary particle	not yet started
-3	trajectory probe particle at the cathode	not yet started
-1	standard particle, at the cathode	not yet started
0	passive probe particle	tracking[4]
1	passive particle	tracking[4]
3	trajectory probe particle	tracking
4	cross over particle[5]	tracking
5	standard particle	tracking
6, 9…33	probe secondary electrons of generation 1, 2…10 or higher	tracking
8, 11...35	secondary electrons of generation 1, 2…10 or higher	tracking

1 if the reference particle is lost the average position of the distribution will be saved with index -99

2 only if Schottky parametrs are specified.

3 only active, if L_rm_back = T is set.

4 passive particles are not taken into account for the set-up of the space charge grid, the calculation of space charge fields and for the calculation of internal beam parameters. If the 2D space charge routine is active the particles are still tracked under the influence of space charge fields, while in case of the 3D routines the space charge field is zero for these particles.

5 only if cross_start ≠ cross_end. See section 4.13.7.

Table 2: Definition of important status flags.

6.10. The namelist SOLENOID

The namelist SOLENOID allows to include arbitrary solenoid fields by means of tables, which may be generated by analytical calculations, measurements or numerical codes. The table has to contain the z-position (column1 in m) and the corresponding longitudinal on-axis magnetic field amplitude (column 2 arb. units) in a free format. The transverse field components are calculated from the derivatives of the on-axis field; see Appendix (chapter 8). The polynomial expansion extends to 1^{st} order or, with S_higher_order = True, to 3^{rd} order. A smoothing procedure can be applied to suppress numerical noise by setting S_smooth( ) = n, $n \in \mathbb{N}$.

Parameter	Specification	Unit	Default Value
LOOP	Logical		FALSE
	see chapter 4.9.		
LBfield	Logical		FALSE
	if false, all solenoid fields are turned off.		
File_Bfield( )	Character*150 array		
	user specified file name.		
S_noscale( )	Logical		FALSE
	if true, the solenoid field will not be scaled, but the file values will be taken as field values in T .		
S_smooth( )	Integer array		0
	controls the number of iterations of a soft, iterative procedure for smoothing field tables. Since the transverse field components are based on derivatives of the field table and can be noisy if the table is not precise, smoothing is recommended. Use fieldplot to check that the longitudinal field component remains basically unchanged and that the transverse components get smooth.		
S_higher_order( )	Logical array		TRUE
	if true, the field expansion extends to 3^{rd} order, if false the field expansion extends only to 1^{st} order. If true stronger smoothing of the field might be required.		
MaxB( )	Real*8 array	T	0.0
	maximum field value of the solenoid field. The field is scaled to this value.		
S_pos( )	Real*8 array	m	0.0
	shifts the longitudinal solenoid position. S_pos is added to the position defined in File_Bfield( ).		
S_xoff( )	Real*8 array	m	0.0
	horizontal offset of the solenoid.		
S_yoff( )	Real*8 array	m	0.0
	vertical offset of the solenoid.		

S_xrot( )	Real*8 array	rad	0.0
	rotation angle of the solenoid in the x-z plane, i.e. around the y-axis.		
S_yrot( )	Real*8 array	rad	0.0
	rotation angle of the solenoid in the y-z plane, i.e. around the x-axis.		

7. Input namelist for *generator*

7.1. The namelist INPUT

Parameter	Specification	Unit	Default Value
FNAME	Character*150		rfgun.ini
	file name for initial particle distribution; recommended extensions are .ini or .zpos.run, respectively.		
Add	Logical		FALSE
	if true the input list has to be specified N_add times and N_add different distributions will be added.		
N_add	Integer		0
	number of distributions to be added.		
Ipart	Integer		100
	number of particles to be generated.		
Species	Character*80		Electrons
	species of particles to be generated. Valid are: **el**ectrons, **po**sitrons, **pr**otons **hy**drogen. The key word **ion** allows to generate particles with user defined ratio of mass to charge state. In addition to the keyword ion a number between 1 and 10 has to be specified, e.g. ‘ion 1’. The number is used as index in the ion_mass specification. The parameter ion_mass needs to be specified in generator and again in the namelist NEWRUN of *Astra*. To adopt the graphics program *postpro* additional specifications in the Plot_steering.par file are optional (see chapter 5.6).		
ion_mass( )	Real*8 Array	eV/c^2	0.0
	the mass divided by the charge state of user defined particles. The index number corresponds to the number specified together with the keyword ions in the Species definition. Negatively charged particles are defined by a negative value of the ion_mass parameter. Ion_mass(1) – (10) is mapped onto particle index 5 – 14 in the saved particle distribution file.		
Probe	Logical		TRUE
	if true, 6 probe particles are generated at locations: (0.5σx, 0.5σz), (1.0σx, 1.0σz), (1.5σx, 1.5σz), (0.5σy, -0.5σz), (1.0σy, -1.0σz), (1.5σy, -1.5σz).		
Passive	Logical		FALSE
	if true only passive particles will be generated.		
Noise_reduc	Logical		TRUE
	if true, particle coordinates are generated quasi-randomly following a Hammersley sequence.		
Cathode	Logical		TRUE
	if true the particles will be generated with a time spread rather than with a spread in the longitudinal position, i.e. sig_z, Lz and rz are set to zero and sig_clock, Lt and rt have to be specified. See chapter 7.2 to chapter 7.4. Status flags will be set accordingly.		
R_Cathode	Real*8	m	0.0
	radius in case of a curved, i.e. non planar cathode. Active if R_cathode is not zero. See section 7.5.2.		

High_res	Logical		FALSE
	if true, the particle distribution is saved with increased accuracy. See Table 4.		
Binary	Logical		FALSE
	if true, the particle distributions is saved in binary format.		
Q_total	Real*8	nC	1.0
	total charge of the particles. The total charge is equally distributed on the Npart particles. (*Astra* would allow also particles with varying macro charge in one distribution.)		
Type	Character*80		standard
	defines the type of the distribution. Valid are **standard** and **ring**.		
Rad	Real*8	mm	0.0
	radius of ring type distributions.		
Tau	Real*8	ns	0.0
	exponential delay time of the emission. Active if Tau $\neq$ 0.0. The delay is added to any distribution in time, i.e. to any distribution starting at the cathode. Note that the delay time is random and might interfere with the quasi random nature of an input distribution.		
Ref_zpos	Real*8	m	0.0
	z position of the reference particle, i.e the longitudinal bunch position.		
Ref_clock	Real*8	ns	0.0
	initial clock value of the reference particle, can in general be set to zero.		
Ref_Ekin	Real*8	MeV	0.0
	initial kinetic energy of the reference particle.		
Dist_z	Character*80		uniform
	specifies the longitudinal particle distribution. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
sig_z	Real*8	mm	0.0
	rms value of the bunch length.		
C_sig_z	Real*8		0.0
	cuts off a Gaussian longitudinal distribution at C_sig_z times sig_z. Active if $\neq$ 0.0.		
Lz	Real*8	mm	0.0
	length of the bunch.		
rz	Real*8	mm	0.0
	rising of the bunch distribution; only for plateau distribution.		
sig_clock	Real*8	ns	1.0D-3
	rms value of the emission time, i.e. the bunch length if generated from a cathode.		

C_sig_clock	Real*8		0.0
	cuts off a Gaussian longitudinal distribution at C_sig_clock times sig_clock. Active if $\neq$ 0.0.		
Lt	Real*8	ns	0.0
	length of the bunch; only for plateau distribution.		
rt	Real*8	ns	0.0
	rise time of the bunch; only for plateau distribution.		
Dist_pz	Character*80		uniform
	specifies the longitudinal energy and momentum distribution, respectively. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
sig_Ekin	Real*8	keV	0.0
	rms value of the energy spread.		
C_sig_Ekin	Real*8		100.0
	cuts off a Gaussian energy and momentum distribution at C_sig_Ekin times sig_Ekin. Active if $\neq$ 0.0.		
LE	Real*8	keV	0.0
	width of the energy distribution.		
rE	Real*8	keV	0.0
	rising of the energy distribution, only for plateau distribution.		
emit_z	Real*8	π keV mm	0.0
	longitudinal particle emittance. Can be specified instead of the energy spread. If an energy spread and an emittance is specified the energy spread has priority.		
cor_Ekin	Real*8	keV	0.0
	correlated energy spread.		
E_photon	Real*8	eV	0.0
	photon energy for Fermi-Dirac distribution.		
phi_eff	Real*8	eV	0.0
	effective work function for Fermi-Dirac distribution.		
Dist_x	Character*80		Gaussian
	specifies the transverse particle distribution in the horizontal direction. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
sig_x	Real*8	mm	1.0
	rms bunch size in the horizontal direction. Also the vertical bunch size if Dist_x = radial.		
C_sig_x	Real*8		0.0
	cuts off a Gaussian horizontal distribution at C_sig_x times sig_x. Active if $\neq$ 0.0.		
Lx	Real*8	mm	0.0
	width of the horizontal particle distribution.		
rx	Real*8	mm	0.0
	rising of the horizontal particle distribution; only for plateau distribution.		

x_off	Real*8	mm	0.0
	horizontal offset of the particle distribution.		
Disp_x	Real*8	m	0.0
	horizontal dispersion; a horizontal offset is added to all particles according to: $x = x + Disp\_x \frac{\Delta P}{P}$; increases the calculated bunch emittance.		
Dist_px	Character*80		Gaussian
	specifies the transverse momentum distribution in the horizontal direction. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
Nemit_x	Real*8	π mrad mm	0.0
	normalized transverse emittance in the horizontal direction. Can be specified instead of a transverse momentum spread. If a momentum spread and an emittance is specified the emittance has priority. Also the normalized vertical emittance if Dist_px = radial.		
sig_px	Real*8	eV/c	0.0
	rms value of the horizontal momentum distribution.		
C_sig_px	Real*8		100.0
	cuts off the horizontal momentum distribution at C_sig_px times sig_px.		
Lpx	Real*8	eV/c	0.0
	width of the horizontal momentum distribution; only for plateau distribution.		
rpx	Real*8	eV/c	0.0
	rising of the horizontal momentum distribution; only for plateau distribution.		
cor_px	Real*8	mrad	0.0
	correlated beam divergence in the horizontal direction $= -\frac{\alpha}{\beta[m]} x_{rms}[mm]$. For extreme settings of cor_px the correlated beam divergence cannot be set correctly and the beam energy will be increased by *generator*. A warning will be given in this case.		
Dist_y	Character*80		Gaussian
	specifies the transverse particle distribution in the vertical direction. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
sig_y	Real*8	mm	1.0
	rms bunch size in the vertical direction. Not significant if Dist_x = radial.		
C_sig_y	Real*8		0.0
	cuts off a Gaussian vertical distribution at C_sig_y times sig_py. Active if $\neq$ 0.0.		
Ly	Real*8	mm	0.0
	width of the vertical particle distribution.		
ry	Real*8	mm	0.0
	rising of the vertical particle distribution; only for plateau distribution.		

y_off	Real*8	mm	0.0
	the vertical offset of the particle distribution.		
Disp_y	Real*8	m	0.0
	vertical dispersion; a vertical offset is added to all particles according to: $y = y + Disp\_y \frac{\Delta P}{P}$; increases the calculated bunch emittance.		
Dist_py	Character*80		Gaussian
	specifies the transverse momentum distribution in the vertical direction. For valid keywords and related parameters see chapter 7.2 to chapter 7.4.		
Nemit_y	Real*8	π mrad mm	0.0
	normalized transverse emittance in the vertical direction. Can be specified instead of a transverse momentum spread. If a momentum spread and an emittance is specified the emittance has priority. Not significant if Dist_px = radial.		
sig_py	Real*8	eV/c	0.0
	rms value of the horizontal momentum distribution.		
C_sig_py	Real*8		0.0
	cuts off a Gaussian vertical momentum distribution at C_sig_py times sig_py. Active if ≠ 0.0.		
Lpy	Real*8	eV/c	0.0
	width of the vertical momentum distribution; only for plateau distribution.		
rpy	Real*8	eV/c	0.0
	rising of the vertical momentum distribution; only for plateau distribution.		
cor_py	Real*8	mrad	0.0
	correlated beam divergence in the vertical direction $= -\frac{\alpha}{\beta[m]} y_{rms}[mm]$. For extreme settings of cor_py the correlated beam divergence cannot be set correctly and the beam energy will be increased by *generator*. A warning will be given in this case.		

7.2. 1D distributions

7.2.1 uniform distribution

Definition and basic relations

$$f(x) = \frac{1}{FWHM} \qquad \text{for } |x| \le \frac{FWHM}{2}$$

$$0 \qquad \text{elsewhere}$$

rms value $\sigma = \frac{FWHM}{2\sqrt{3}}$

Generator specifications

Dimension	**Key word**	**Parameter** *FWHM* or σ	**unit**
temporal[1]	Dist_z = '**u**niform'	Lt or sig_clock	ns
longitudinal[2] z	Dist_z = '**u**niform'	Lz or sig_z	mm
longitudinal E_{kin}	Dist_pz = '**u**niform'	LE or sig_Ekin or emit_z	keV or keVmm
transverse x	Dist_x = '**u**niform'	Lx or sig_x	mm
transverse y	Dist_y = '**u**niform'	Ly or sig_y	mm
transverse p_x	Dist_px = '**u**niform'	Lpx or sig_px or Nemit_x	eV/c or mrad mm
transverse p_y	Dist_py = '**u**niform'	Lpy or sig_py or Nemit_y	eV/c or mrad mm

[1] active if Cathode = TRUE, [2] active if Cathode = FALSE

7.2.2 plateau distribution

Definition and basic relations

$$f(x) = \frac{1}{L}\frac{1}{1+\exp\left(\frac{2}{rt}\left(2|x|-L\right)\right)} \qquad rt \le \frac{L}{2}$$

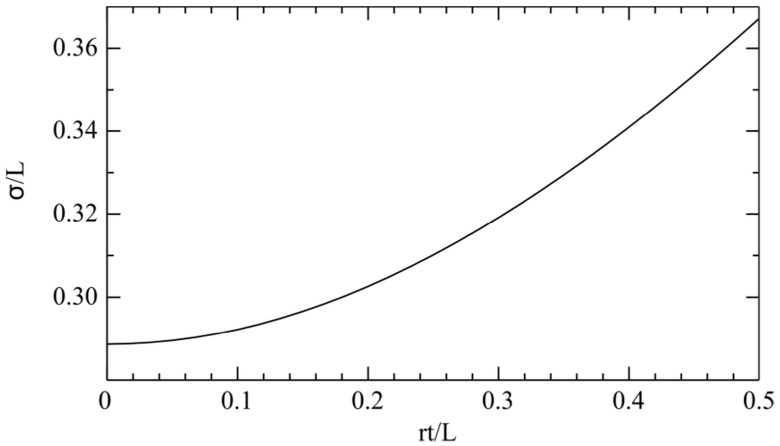
Definition of *rt*:
rt is defined by a straight line with a slope *A* given by:

$$A = \frac{d}{dx} f(x)\Big|_{\pm\frac{L}{2}}$$

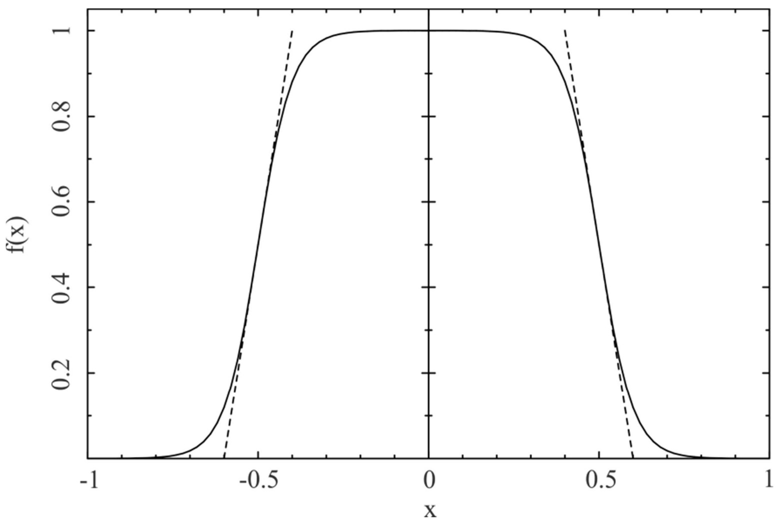
Within *rt* the straight line inclines form 0 to the plateau value of the distribution.

FWHM value FWHM = L

rms value $\frac{L}{2\sqrt{3}} \le \sigma \le \frac{L}{2.8} \qquad rt \le \frac{L}{2}$



Relation of rms value and rise time



Example: Plateau distribution with *L* = 1 and *rt* = 0.2. Straight lines according to the definition of *rt*.

Generator specifications

Dimension	Key word	Parameter *L*, *rt*	unit
temporal[1]	Dist_z = '**p**lateau'	Lt, rt	ns
longitudinal[2] z	Dist_z = '**p**lateau'	Lz, rz	mm
longitudinal E_{kin}	Dist_pz = '**p**lateau'	LE, rE	keV
transverse x	Dist_x = '**p**lateau'	Lx, rx	mm
transverse y	Dist_y = '**p**lateau'	Ly, ry	mm
transverse p_x	Dist_px = '**p**lateau'	Lpx, rpx	eV/c
transverse p_y	Dist_py = '**p**lateau'	Lpy, rpy	eV/c

[1] active if Cathode = TRUE, [2] active if Cathode = FALSE

7.2.3 inverted parabola (longitudinal)

Definition and basic relations

The inverted parabola distribution produces linear longitudinal space charge fields. It corresponds to the projection of a uniformly filled ellipsoid onto the z-axis.

$$f(z) = \frac{3}{4z_{\max}}\left(1-\frac{z^2}{z_{\max}^2}\right) \qquad |z| \le z_{\max}$$

FWHM value $\quad FWHM = \sqrt{2}z_{\max}$

rms value $\quad \sigma_z = \frac{z_{\max}}{\sqrt{5}}$

Generator specifications:

Dimension	**Key word**	**Parameter σ**	**unit**
temporal[1]	Dist_z = '**inverted**'	sig_clock	ns
longitudinal[2] z	Dist_z ='**inverted**'	sig_z	mm

7.2.4 Gaussian distribution

Definition and basic relations

$$f(x) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left(-\frac{1}{2}\frac{x^2}{\sigma^2}\right)$$

FWHM value $\quad FWHM = 2\sqrt{-2\ln(0.5)} = 2.35\sigma$

Generator specifications:

Dimension	**Key word**	**Parameter σ**	**unit**
temporal[1]	Dist_z = '**g**auss'	sig_clock	ns
longitudinal[2] z	Dist_z ='**g**auss'	sig_z	mm
longitudinal E_{kin}	Dist_pz = '**g**auss'	sig_Ekin or emit_z	keV or keVmm
transverse x	Dist_x = '**g**auss'	sig_x	mm
transverse y	Dist_y = '**g**auss'	sig_y	mm
transverse p_x	Dist_px = '**g**auss'	sig_px or Nemit_x	eV/c or mrad mm
transverse p_y	Dist_py = '**g**auss	sig_py or Nemit_y	eV/c or mrad mm

[1] active if Cathode = TRUE, [2] active if Cathode = FALSE

7.2.5 truncated Gaussian distribution

Definition and basic relations

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma_{inp}} \exp\left(-\frac{1}{2} \frac{x^2}{\sigma_{inp}^2} \right) \qquad \text{for } |x| \le C_{Cut}\sigma_{inp}$$

relation between σ_{inp} and rms value of the truncated distribution σ_{out}

$$\frac{C_{Cut}\sigma_{inp}}{\sqrt{3}} \le \sigma_{out} \le \sigma_{inp}$$

Note that the cut produces a rectangular structure. Compare with the 2D-Gaussian distribution 7.3.2.

Generator specifications

Dimension	**Key word**	**Parameter** σ_{inp}, C_{Cut}	**unit**
temporal[1]	Dist_z = '**g**auss'	sig_clock, C_sig_clock	ns, dim. less
longitudinal[2] z	Dist_z = '**g**auss'	sig_z, C_sig_z	mm, dim. less
longitudinal E_{kin}	Dist_pz = '**g**auss'	sig_Ekin or emit_z, C_sig_Ekin	keV or keVmm, dim. less
transverse x	Dist_x = '**g**auss'	sig_x, C_sig_x	mm, dim. less
transverse y	Dist_y = '**g**auss'	sig_y, C_sig_y	mm, dim. less
transverse p_x	Dist_px = '**g**auss'	sig_px or Nemit_x, C_sig_px	eV/c or mrad mm, dim. less
transverse p_y	Dist_py = '**g**auss'	sig_py or Nemit_y, C_sig_py	eV/c or mrad mm, dim. less

[1] active if Cathode = TRUE, [2] active if Cathode = FALSE

7.3. 2D distributions

7.3.1 radial uniform distribution

Definition and basic relations

$$f(x,y) = \frac{1}{\pi r^2} \qquad \text{for} \quad x^2 + y^2 \le r^2$$

$$0 \qquad \text{elsewhere}$$

The projection onto the x-axis (eqv. y-axis) is a half ellipse

$$f(x) = 2\int_0^{y_m} f(x,y)\, dy = \frac{2\sqrt{r^2 - x^2}}{\pi r^2} \qquad |x| \le r$$

with the following properties:

FWHM value FWHM = $\sqrt{3}\, r$

rms value $\sigma = \frac{r}{2}$

Generator specifications

Dimension	**Key word**	**Parameter** r or σ	**unit**
transverse x, y	Dist_x = '**r**adial uniform'	Lx or sig_x	mm
transverse p_x, p_y	Dist_px = '**r**adial uniform'	Lpx or sig_px or Nemit_x	eV/c or mrad mm

7.3.2 (truncated) 2D-Gaussian distribution

Equivalent to distributions 7.2.4 and 7.2.5 but with $f(y) = f(x)$. The cut will produce a circular structure.

Generator specifications

Dimension	**Key word**	**Parameter** σ_{inp}, C_{Cut}	**unit**
transverse x, y	Dist_x = '**2**D-Gaussian’	sig_x, C_sig_x	mm, dim. less
transverse p_x, p_y	Dist_px = '**2**D-Gaussian’	sig_px or Nemit_x, C_sig_px	eV/c or mrad mm, dim. less

7.4. 3D distributions

7.4.1 isotropic momentum distribution

Definition and basic relations

A distribution with isotropic emission angles into a half sphere. The following relations hold:

$$p_x^2 + p_y^2 + p_z^2 = P^2 = E_{kin}^2 + 2E_{kin}$$

rms value $\sigma p_x = \sigma p_y = \dfrac{P}{\sqrt{3}}$

$$\sigma p_z = \frac{P}{2\sqrt{3}}$$

mean value $p_{z,mean} = \dfrac{P}{2}$

normalized transverse emittances[1]:

$$\varepsilon_{x,y} = \sigma_{x,y} \frac{1}{\sqrt{3}} \sqrt{\frac{2E_{kin}}{m_0 c^2}}$$

Generator specifications

Dimension	**Key word**	**Parameter E_{kin}**	**unit**
p_x, p_y, p_z	Dist_pz = '**i**sotropic'	LE	keV

7.4.2 photo emission from a Fermi-Dirac distribution

Definition and basic relations

A distribution describing the photo emission from a metallic cathode at room temperature according to ref. [2]. The random generator works only as true random generator, the noise reduction option is hence switched off, if selected in the input deck. As input parameters the effective work function Φ_{eff} , i.e. including a possible reduction due to the Schottky effect, and the photon energy E_{phot} need to be given. The following relations hold:

rms value $\sigma p_x = \sigma p_y = \sqrt{\dfrac{E_{phot} - \phi_{eff}}{3 m_0 c^2}}$

mean Energy $\bar{E}_{kin} = \dfrac{2}{3}\left(E_{phot} - \phi_{eff}\right)$

Energy spread $\sigma_{Ekin} = \dfrac{1}{3\sqrt{2}}\left(E_{phot} - \phi_{eff}\right)$

normalized transverse emittances:

$$\varepsilon_{x,y} = \sigma_{x,y}\sqrt{\frac{E_{phot} - \phi_{eff}}{3 m_0 c^2}}$$

Generator specifications

Dimension	**Key word**	**Parameter** Φ_{eff} , E_{phot}	**units**
p_x, p_y, p_z	Dist_pz = '**FD_300**'	phi_eff, E_photon	eV

7.4.3 uniformly filled ellipsoid

Definition and basic relations

$$f(x,y,z) = \frac{3}{4\pi Lx\, Ly\, Lz} \qquad \text{for} \quad \frac{x^2}{L_x{}^2} + \frac{y^2}{L_y{}^2} + \frac{z^2}{L_z{}^2} \le 1$$

$$0 \qquad \text{elsewhere}$$

the projection onto the z-axis (eqiv. x- and y-axis) is an inverted parabola:

$$f(z) = 4\int_0^{Lx}\int_0^{Ly} f(x,y,z)\,dx\,dy = \frac{3}{4Lz}\left[1 - \frac{z^2}{Lz^2}\right] \qquad |z| \le Lz$$

with the following properties:

FWHM value FWHM$_z$ = $\sqrt{2}\; Lz$

rms value $\sigma_z = \frac{Lz}{\sqrt{5}}$

Generator specifications

Dimension	**Key word**	**Parameter** $L_{x,y,z}$ or $\sigma_{x,y,z}$	**unit**
temporal[1]	Dist_z = '**u**niform **e**llipsoid'	Lt or sig_clock	ns
longitudinal[2] z	Dist_z = '**u**niform **e**llipsoid'	Lz or sig_z	mm
transverse x	Dist_z = '**u**niform **e**llipsoid'	Lx or sig_x	mm
transverse y	Dist_z = '**u**niform **e**llipsoid'	Ly or sig_y	mm

[1] active if Cathode = TRUE, [2] active if Cathode = FALSE

7.5. Miscellaneous options

7.5.1 ring type distributions

If Type = 'Ring' is specified any standard transverse distribution is offset by a radius specified with parameter Rad and uniformly distributed on a circle. Thus a circular charge distribution is generated. The cross section of the ring can vary from x to y depending on the setting of transverse parameters.

7.5.2 emission from a curved cathode

In order to start a distribution from a curved cathode the radius of the cathode can be specified with the parameter R_cathode. For this option photo emission is assumed, hence the longitudinal starting position and the starting time are modified according to the cathode radius. All other parameters remain unchanged.

References

[1] K. Floettmann 'Note on the thermal emittance of electrons emitted by Cesium Telluride photo cathodes' TESLA-FEL Report 1997-01. http://flash.desy.de/sites/site_vuvfel/content/e403/e1642/e839/e829/infoboxContent830/fel1997-01.pdf

[2] D. Dowell, J. Schmerge 'Quantum efficiency and thermal emittance of metal cathodes' PRST-AB 12,074201, 2009. http://prst-ab.aps.org/pdf/PRSTAB/v12/i7/e074201