CST STUDIO SUITE® PARTICLE DYNAMICS WORKSHOP SERIES

Simulations with EM Studio and Particle Studio



Agenda

- EM/PS Solver Overview
- Magnets
- Cavity Simulations
 - Eigenmodes & PostProcessing
- Wakefield Analysis
- Full Particle Dynamics

CST STUDIO SUITE® Solver Overview





RF Fields		
T	Transient	 broadband arbitrary time signals
E	Eigenmode	 strongly resonant structures narrow band cavities
Static Fiel	lds	
Es	E- Static	static electric problems
Ms	M- Static	static magnetic problems
Particle So	olvers	
Trk	Tracking	Solver for static simulations such as electron guns or mass spectrometer
Pic	Particle In Cell	Selfconsistent transient field and particle solver including full space charge effects
WAK	Wakefield	 Transient solver with special beam excitation (predefined fixed straight beam path)



Sources:

- Potentials on conductors (fixed or floating)
- Boundary potentials (fixed or floating)
- Homogeneous volume and surface charges
- Charges on PEC solids

Postprocessing:

- Capacitance matrix
- Force calculation

Additional features:

- Adaptive meshing
- Optimizer
- Open boundaries



Sources:

- Current paths
- Current coils
- Permanent magnets
- Homogeneous magnetic source fields
- Stationary current field

Postprocessing:

- Inductance matrix
- Torque and force calculation

Additional features :

- Adaptive meshing
- Optimizer
- Nonlinear materials
- Open boundaries

CST EMS Sources







Algorithm:

- 1. Calculate electro- and magnetostatic fields
- 2. Calculate force on charged particles
- 3. Move particles according to the previously calculated force Trajectory



$$\frac{d}{dt}(m\vec{v}) = q(\vec{E} + \vec{v} \times \vec{B}) \quad \text{Velocity update} \qquad m^{n+1}\vec{v}^{n+1} = m^n\vec{v}^n + q\Delta t \left(\vec{E}^{n+1/2} + \vec{v}^{n+1} \times \vec{B}^{n+1/2}\right)$$

$$\frac{d\vec{r}}{dt} = \vec{v} \quad \text{Position update} \qquad \vec{r}^{n+3/2} = \vec{r}^{n+1/2} + \Delta t \vec{v}^{n+1}$$
Leap Frog Scheme

Space Charge Effect





TRK Emission Models

1. Fixed Emission

Applicable for known beams Input: Current, Beam Voltage

- 2. Space Charge Limited Emission Necessary for Electron Guns Current(Voltage) according to Childs Law
- 3. Thermionic Emission Enhances Space Charge Limit Richardson Dushman Equation
- 4. Field Induced Emission Fowler-Nordheim Equation





Particle Interfaces

Particle Emission

- According to exported data of previous simulation
- According to ASCII files of known particle distributions

Advantage

- Splitting of large tracking simulations
- Speed up for collector simulation





Tracking/PIC simulation with import interface





Particle in Cell

Self consistent modeling of collisionfree plasma

Macro charge (e.g. $q=10^6 e^-$)



Relativistic equation of motion

$$\frac{\partial \vec{u}}{\partial t} = \frac{q}{m_0 c} \left(\vec{E} + \vec{v} \times \vec{B} \right)$$
$$\frac{\partial \vec{r}}{\partial t} = \vec{v} \qquad \vec{u} = \frac{\vec{p}}{m_0 c} = \frac{m(v)\vec{v}}{m_0 c} = \gamma \cdot \vec{\beta}$$

Current caused by particle motion acts as source in Maxwell's equations.

$$\operatorname{rot}\vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}; \quad \operatorname{div}\vec{J} = -\frac{\partial \rho}{\partial t}$$

A priori charge conserving algorithm.



Particle in Cell (PIC) Algorithm





PIC Emission Models

1. DC Emission



2. Emission of a series of Gaussian bunches

- 3. Field Emission according to Fowler Nordheim Equation
- 4. TRK/PIC interfaces for emitting the beam of a specific gun or for loading ASCII files of known particle distributions
- 5. Secondary electron emission
- 6. Explosive Emission







The Wakefield solver computes the wake potential:

$$\vec{W}(x,y,s) = \frac{1}{q_1} \int_{-\infty}^{\infty} \left(\vec{E}(x,y,z,t = \frac{s+z}{v}) + \vec{v} \times \vec{B}(x,y,z,t = \frac{s+z}{v}) \right) dz$$

$$\int_{x}^{y} \underbrace{\vec{v}_2 = \vec{v}}_{q_1} \underbrace{\vec{v}_1 = \vec{v}}_{vt - s} \underbrace{\vec{v}_1 = \vec{v}}_{vt - s} \underbrace{\vec{v}_2 = \vec{v}}_{vt - s} \underbrace{\vec{v}_1 = \vec{v}}_{ext} \underbrace{\vec{v}_1 = \vec{v}}_{Beam path} \underbrace{\vec{v}_1 = \vec{v}}_{Beam path}$$

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logitudinal Gaussian shape)

Magnets



Magnet Design



Quadrupole Magnet:

- → Source: Coils/Permanent Magnets
- \rightarrow 3D M-static run
- \rightarrow 2D M-static rotational/translational symmetry possible

Magnet Design





Results from M-Static:

- \rightarrow Quadrupole like B-Field
- \rightarrow Sinusoidal magnetic field along azimut
- \rightarrow Pole pieces quite saturated

LF-Thermal Coupling







Coupled Simulation:

- \rightarrow Import of LF losses into thermal solver
- \rightarrow Thermal stationary/transient run
- \rightarrow Automization of loop possible via SAM approach

Cavity Simulation



Cavity Construction



Automatic creation of a cavity part

 \rightarrow Transformation for multiples

Eigenmode Simulation



Crab cavity courtesy of Dr. Graeme Burt, Lancaster University

Solver	Advantage	Disadvantage	Mesh Type
AKS	fast	no losses	Hexahedral
JDM	robust	slow	Hexahedral
Default	robust, fast	-	Tetrahedral



Hexahedral mesh

Type:

Phase:

- \rightarrow no convergence
- Tetrahedral mesh
- \rightarrow convergence in < 2 min

Eigenmode Simulation



Crab cavity courtesy of Dr. Graeme Burt, Lancaster University

- $\rightarrow\,$ Automatic curved elements up to 3rd order applied
- $\rightarrow\,$ New TET mesh engine for improved mesh distribution





Q-Factor and Loss Calculation



Different Loss Mechanisms:

- \rightarrow Output power through a coupler (P_{out})
- \rightarrow Volume losses in lossy dielectrics (P_{volume})
- \rightarrow Surface losses due to finite metal conductivity (P_{surface})

Superposition for each mode to get Q



Volume and Surface Losses





On (Default): Losses via perturbation method \rightarrow less resources Off: Losses included in solver run \rightarrow needed if losses

change the field pattern

Q Loss and Q

Hield data. [Hode 1						•	Calculate
Material/Solid	Conductivity	Mue	Loss/W	Loss/%	Q		Specials
Cond. Enclosure	5.8000e+007	1	2.3342e+005	98.9	2.4520e+004	_	
PEC	5.8000e+007	1	4.1562e+000	0.00176	1.3771e+009		Export
component1:solid3	L		3.5993e-002	1.53e-005	1.5901e+011		Close
component1:solid3_1			4.1202e+000	0.00175	1.3891e+009		Help
Sum of Surface Losses			2.3342e+005	98.9	2.4519e+004		Theip
Volume Losses			2.5148e+003	1.07	2.2759e+006		
Sum			2.3594e+005		2.4258e+004		

Surface losses are always evaluated with Loss and Q post processing

Normalization to 1J

External Q





For lossless structures: Q_{external} = Q_{loaded}



External Q



Shunt Impedance, R over Q





Lorentz Force Density



Force Density: $P = \frac{1}{4} \left(\mu_0 H_s^2 - \epsilon_0 E_s^2 \right)$

Especially interesting for superconducting cavities



*) Picture from H. Gassot, Institut de Physique Nucléaire, Orsay, France Evaluated as post processing step

<u> Lorentz</u> Forces



Geometric Tolerances / Sensitivity





Design Mode	n par	ameter " Frequer	r_a" ncy	Derivative of	frequency
1	0.9	6461990	GHz	0.1799115 G	Hz/in
Design Mode	n par	ameter " Frequer	r_v" ncy	Derivative of	frequency
1	0.9	5461990	SHz	-0.5956404 (GHz/in

Strapped Magnetron Example

- $\rightarrow\,$ Face constraints applied to anode and vane radius
- \rightarrow Sensitivity of Eigenfrequency to (small) geometry changes in ONE 3D run

Simulating Detuning Effects



Wakefield Analysis



Wakefields









Results:

- \rightarrow Electromagnetic fields
- \rightarrow Wake Potential, Wake Impedance
- \rightarrow Postprocessing available for user defined sampling



Integration Methods







Direct:

- \rightarrow For β < 1 the only method

Indirect Testbeams:

- \rightarrow Integration along the gap
- $\rightarrow~$ Only for β = 1

Indirect Interfaces:

- $\rightarrow \mbox{ Direct integration in } \\ \mbox{ discontinuity }$
- \rightarrow Only for β = 1

Short Bunches



Total length:	1.30 m		
Max. transverse dimension:	0.12 m		
Beam width:	0.0001 m		
⇒ Frequency:	~60GHz		
⇒ Electrically Large!			

NSLS Storage Ring Impedance Budget:

- \rightarrow Possible with MPI
- \rightarrow Simulation Time: 5h 12min, 4 Nodes, 820 Millionen Mesh Cells

*A. Blednykh, S. Krinsky, J. Rose "Coupling Impedance of CESR- B RF Cavity for the NSLS-II Storage Ring", BNL-79152-2007-CP

Short Bunches



	Published	CST
Loss Factor	3.5 V/pC	3.4 V/pC
Kick Factor	25.4 V/pC/m	25 V/pC/m

NSLS Storage Ring Impedance Budget:

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Loss Consideration

abeling Name: loss (t=0end(0.1))	Automatic labeling	ОК	-	-	80502	
Type E-Field H-Field acurrent (TLM only) Surface current (TLM only) Power flow Current density Power loss density/SAR Electric energy density Magnetic energy density Farfield/RCS Field source	Specification Time Frequency Start time: Step width: Contemport Average rep. period: Contemport Step Start	Apply Cancel Help			55660 44723 36779 26834 17889 8945	

286.8 285.2 283.7 282.2 280.7 279.2 277.7 276.1 274.6

Time Integrated Volume Losses:

- \rightarrow 3D Information about the losses
- \rightarrow Coupling to thermal solver of MPS
- \rightarrow Averaged losses as source for thermal solver

Loss Consideration





Cavity courtesy of Diamond Light Source

Time Integrated Surface Losses:

- $\rightarrow~$ So far only per material
- \rightarrow Can be observed during simulation
- \rightarrow Heat source has to be applied in thermal solver

Special Wake-Solver Pa	Special Wake-Solver Parameters					
General Waveguide	daterial Solver					
Special settings						
Lossy metal model order:						
10						
Material monitor						
Frequency power losses (1D) Settings						
Time power losses for SI (1D)						
Time Power Losses for SI Monitor (1D)						
Start time:	1	ОК				
Step width:	0	Cancel				
End time:	9e-9	Help				
🔽 Average rep. period	0.0					



Loss Consideration





Cavity courtesy of Diamond Light Source

Time Integrated Surface Losses:

- \rightarrow So far only per material
- \rightarrow Can be observed during simulation
- \rightarrow Heat source has to be applied in thermal solver



P _{loss} via k (wake loss factor)	11.29 W
P _{loss} from monitor	11.41 W



Accuracy Consideration



С

Structure courtesy of DESY

Dispersion error:

- \rightarrow Important, if wake potential is small
- Improves with equidistant mesh \rightarrow
- \rightarrow Improves with "Transmission line" current injection

User Defined Bunch Shapes





Define Particle Beam						
Name:				ок		
ParticleBeam1				Cancel		
Beam properties				Help		
Shape:	signal1	•		Wakefields		
Velocity (beta):	1.0][Preview		
Charge:	1e-9	c				



Signal definition via excitation function:

- \rightarrow ASCII import and formulas can be used
- \rightarrow Allows Non-Gaussian shapes
- \rightarrow Allows bunch series

Full Particle Dynamics



PIC Simulation of Cavities





- \rightarrow Preloading of Eigenmode fields
- \rightarrow Choice of initial phase and scaling
- \rightarrow Low current applications: Disregard space charge
- \rightarrow GPU Support: Realistic RFQ \rightarrow Speed up of 4.876* and higher

* Kepler 20 Card vs. Intel E5530 2x 2.4GHz, 96GB RAM, 120k Particles, 1.36 Mio mesh cells

PIC Simulation of Cavities



Emittance definition:

$$\epsilon_{x,rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

Postprocessing Results:

- → PIC 2D monitor: projected & slice emittance
- → Phase space monitor: longitudinal emittance



C-Band Linear Accelerator







[1] Design, simulation and measurement conducted by M. Ruf, K. Thurn and L.-P. Schmidt at Chair for High Frequency Technology, University of Erlangen-Nuremberg

Data Exchange



Folder se	ettings
C:\tem	p\Temp\DE2\Trajectory Export
Sampling	ratio
Particle	:
Time:	1





File name:	position monitor 1.txt				
Save as type:	ASCII Files (*.txt)				
- Frame Selection -					
C sancin (



ASCII Export of:

- \rightarrow Trajectory (TRK)
- \rightarrow PIC 2D / PIC Position Monitor
- VBA Access of:
- \rightarrow Trajectory (TRK)
- \rightarrow PIC 2D Monitor

Multipaction Analysis



Time / ns

Single Run:

- \rightarrow Preloading of Eigenmode in PIC solver
- \rightarrow Preloading of initial particle cloud
- \rightarrow Observation of exponential particle increase
- \rightarrow Collision information available for TH analysis

Multipaction Analysis



Parametric Run:

- \rightarrow Reveals the power threshold
- $\rightarrow\,$ Automatic detection of exponential increase



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New Features 2016



Visualization



Standard 3D Viewer now used also for PIC plots



Visualization



Clamp mode Finding e.g. very slow particles... Special color inside/outside clamping range Hide out of range 2D/3D Plot 2D/3D Plot Normal: Free Clamp to Range Clamp to Range Normal: Free Position: 0 Min: 0.00266 Min: 0.00265897 Position: 0 uttina Reset Smart Cutting Reset Smart Plane Scaling Scaling Max: 224 $(\mathbf{+})$ Max: 5 Plane Scaling Scaling Color Ramp and Scaling ectional View Sectional View Color Ramp and Scaling e¥ 224 🔸 203 — 4.55 -183 -4.09 -163 -3.64 -142 -3.18 — 122 -2.73 -102 -2.27 -81.4 -1.82 -61 -1.37 -40.7 -0.911 20.4 -0.457 -0.00266 🕳 0.00266 -

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Keep Mesh

Multipaction Simulation

Parametersweep of input power

No change of geometry

Performance improvement if mesh is reused





MESH PROTECTION ACTIVE:

Since only parameters which does not influence the mesh are involved, mesh will not be deleted during this Parameter Sweep run.





Target Frequency for WG Port





Mode #51



- → Reduction of evaluated port modes
- → Absorption of unconsidered port modes
- → Reduction in total simulation time by factor 8.7

Target Frequency for WG Port



Mac	ros		Easier for the u no VBA define	user: finition	
Ru	n Macro		automatic s	setting of generalized port mode solve	er
	Calculate	×			
	Construct	×		Set Bort Target Cut Off Frequency	
	File	×			
	Materials	×			
	Parameters	×		Port Number:	
	Report and Graphics	×		Target Cut Off Frequency 0	
	Results	×		(in project units)	
	Solver	•	Check GPU Computing Setup		
	Wizard	►	Mesh	OK Cancel	
Edi	t Macro		Monitors and Probes		
	Open VBA Macro Editor		Ports •	Identical Wavequide Ports - Reuse Mode Calculation	
	Make VBA Macro	ľ	Sources 🔸	Set Port Target Cut Off Frequency	
	Import VBA Macro	1		· · ·	
	Edit / Move / Delete VBA Macro.				

Spatially Varying Material



- Axial varying losses for e.g. TWT can now be applied to one single material by space map based material
- Splitting in different object/materials is obsolete now



Spatially Varying Material





Eigen H-Field in Gun Iteration



article Trac	king		1			X	
Tracking : Meshing :	solver settings strategy:					Start	
Low Free	Low Frequency						
Particle s	Particle source:						
particle2	· •	Stor	e result d	ata in cach		· · · · · · · · · · · · · · · · · · ·	
Core its						Acceleration	
- Gun itera	tion					Specials	
Relative	accuracy:					Apply	
-30	d₿	Perf	orm gun i	teration		Close	
		Con:	sider mag	netic tield			
- Tracking f	fields					нер	
Active	Field	Factor	Freq.	Phase	*		
X	E-Static	1.0	0				
×	M-Static	1.0	0				
	Analytic	1.0	0				
	External	1.0	0				
					Ŧ		

Important for High Voltage guns (~500kV), where the Eigen H-Field has a focusing effect in contrast to the Eigen E-Field.

Otherwise beam expansion is overestimated.

External TET Field Import

Import External Fields	
External fields OK Image: Update local copies Mue: 1.0 Active Description Rel. Path Type Factor Frequency P: accelerator_cavity_eigenmu Image: Eigenmode Image: P: accelerator_cavity_eigenmu Image: Eig	A * * * * * *
Import Field from Project Add from File Add from Project Cancel	
Field Help	Predefined e-eigenmode field Cutplane name: Cross Section A 2D Maximum: 4.24e+06 Cutplane normal: 1, 0, 0 Cutplane position: 0
TET Fields can be loaded directly from	Interpretation 0.5521 Phase: 67.5 Scaling Factor: -0.0315678 + i -0.999502

 \rightarrow E-Static

- \rightarrow M-Static
- \rightarrow Eigenmode

External TET Field Import





Frequency Domain Solver successful

Pic

Import External Fields External fields OK Use local copies only Update local copies Mue: 1.0 Cancel Factor Frequency Phase Shift Active Description Rel. Path Type Signal Help 9.5 0.0 0.0 Constan X P: CSTD-104-2959_MWS X HFFD-MOR 1.0 Add from Project... Delete Add from File... Preview Import Field from Project Project OK CSTD-104-2959 MWS.cst • Cancel Field Help FD-MOR Tet [1]

Spectrogram



0K

Frequency vs. Time Behaviour for Non-linear Systems

Specify Action			
Fourier Transform	T	Resample with Nyquist rate before evaluation	Window function:
Fmin: Fmax: # of samples: Normalization: Result type:	0.3 8 [Auto, from length of input signal] 1 Magnitude (linear)	To single-sided spectrum	Window width in project units:
D Results Probes\E-Field\Prob	e Signals\E-field (2.11 0.0 3.2)(Y) [pic]		
Complex R field (2.11 0.0 3.2)(Y Complex R	e Im Mag MagdB Ph)(pic)_FT\t_center=2 e Im Mag MagdB Ph	Ţ	
Complex R	e 💿 Im 💿 Mag 💿 MagdB 💿 Ph	OK Cancel Help	

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Spectrogram



Frequency vs. Time Behaviour for Non-linear Systems



Frequency / GHz



- Performance Improvement
 - \rightarrow Faster resize
 - \rightarrow Faster plot option change





- More Flexibility
 - Abscissa and ordinate can be

chosen from: Position Normed Momentum

Position Normed Momentum Gamma Beta Velocity Energy

Define PIC Phas	e Space	e Monit	or		— ———————————————————————————————————
General Name:	pic ph	ase spa	ice monil	tor 1	ОК
Abscissa Type:	Positio	n		•	Help
Component:	© X	© Y	🔘 Z	Abs	
Ordinate Type:	Energ	y		•	
Component;	© X	O Y	🔘 Z	Abs	
Time settings					
Start time:	0.0				
Step width:	0.1				
End time:	0.0				



- More Flexibility
 - Abscissa and ordinate can be

chosen from: Position Normed Momentum

Normed Momentum Gamma Beta Velocity Energy

Special Case:

Equal Position and Velocity componente \rightarrow Evaluation of longitudinal Emittance

Define PIC Pha	se Space Monitor	—
General Name:	pic phase space monitor 1	ОК
Abscissa Type:	Position •	Cancel Help
Ordinate	X Y V ADS	
Type:	Velocity	
Type: Component: Time settings Start time:	Velocity ▼ ○ X Y Image: Constraint of the second sec	



- More Flexibility
 - Abscissa and ordinate can be

chosen from: Position

Normed Momentum Gamma Beta Velocity Energy

Special Case:

Equal Position and Velocity componente \rightarrow Evaluation of longitudinal Emittance





Emittance from PIC 2D Monitor



Projected as well as slice emittance

mplate Based Postprocessing	Evaluate PIC2D Monitors	
eneral Results	Name of Particle Monitor pic 2d monitor 1	-
Particles	Particle Propagation Direction	+x 🔻
Export 3D Trajectory Plot as Bitmap Export Particle Interfaces (TRK) ID Trajectory Plot (TRK)	Specify result value Type: Current	1
Evaluate PIC 2D Monitor	Current]
Load Particle Info	v-Projected Emittance v-Projected Emittance u-Slice Emittance v-Slice Emittance	Į
	x-max Position x-min Position y-max Position y-min Position z-max Position z-min Position	Ī
Settings Delete Duplicate Evaluate 🚹 🚺 Delete All Evaluate All	Number of Particles]
Abort Close Help		

Emittance from PIC 2D Monitor

Please note: Emittance implemented in TRK code & Template

$$\epsilon_{x,rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

Emittance often used by accelerator people

The normalised emittance is given by $\epsilon_{n,rms} = \beta \gamma \epsilon_{rms}$, where the two factors are the relativistic Lorentz factors. The normalisation is necessary to make beams with different energies comparable [6].

TET TRK Solver



Meshing strategy:		Mesh Ty	Mesh Type:			Diari
Low Fre	quency 💌	Tetrah	Tetrahedral 💌			Close
Particle s	ource:		Me	esh Setting	gs	Apply
particle1	_	🗌 🗖 Stor	e result d	ata in cach	ne	
						Optimizer
s un itera Relative	tion accuracy;					Par. Sweep.
-30	💌 dB	🗌 Perf	orm gun it	Acceleration		
			sider magi	netic held		Specials
iracking	fields					
Active	Field	Factor	Freq.	Phase		Help
×	E-Static	1.0	0			
	M-Static	1.0	0			
×	Analytic	1.0	0			
×		1.0	0			
X I I	External					

