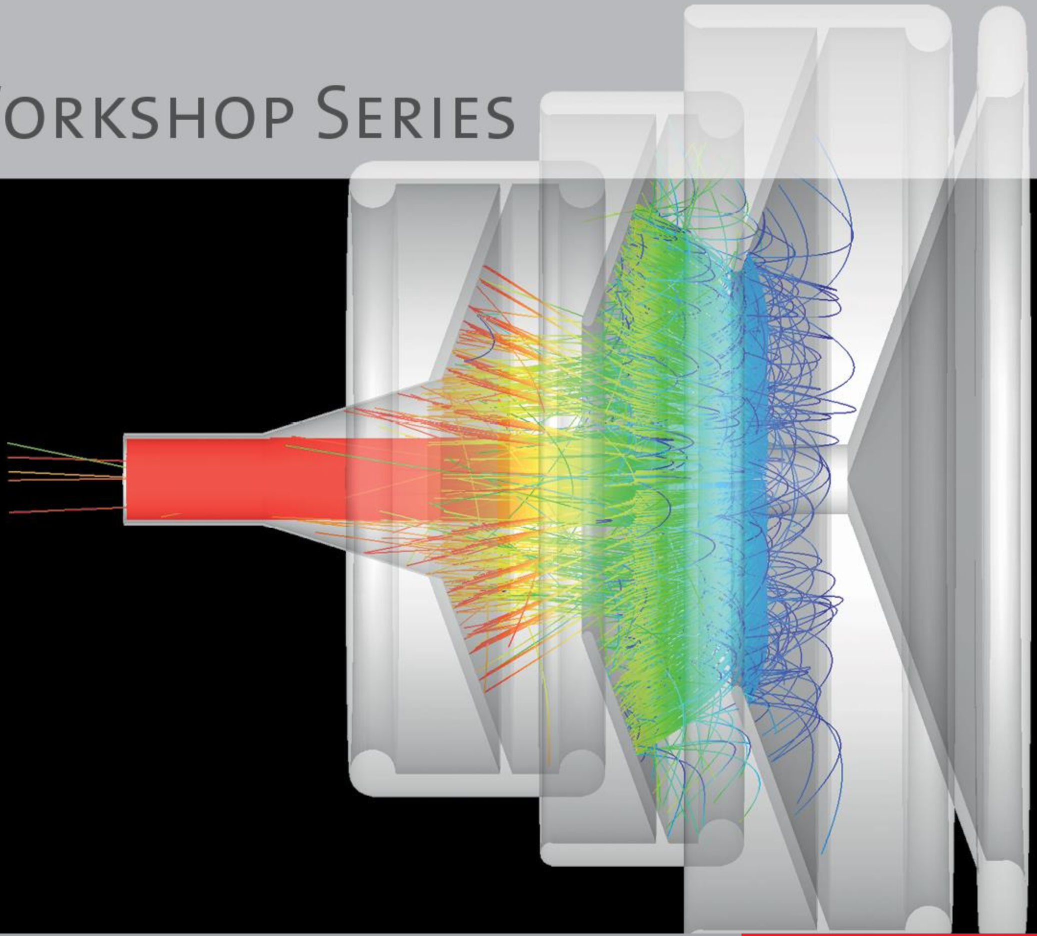
CST STUDIO SUITE®

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 Fields	
Es E- Static	▪ static electric problems
Ms M- Static	▪ static magnetic problems
Particle Solvers	
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)

Electrostatics

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

Magnetostatics

Sources:

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

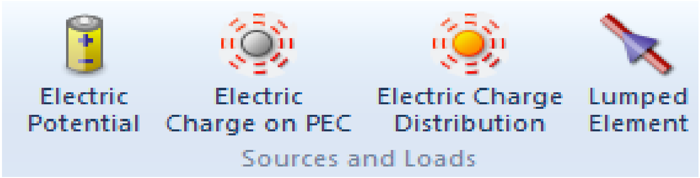
Postprocessing:

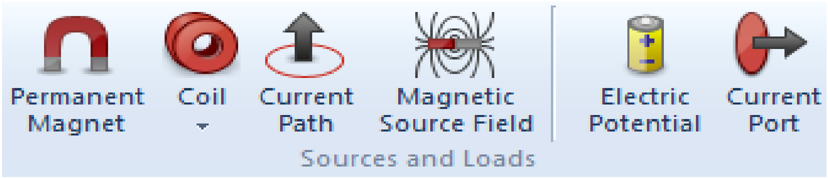
- Inductance matrix
- Torque and force calculation

Additional features :

- Adaptive meshing
- Optimizer
- Nonlinear materials
- Open boundaries

CST EMS Sources

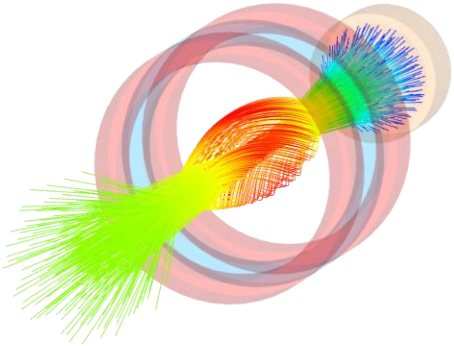




Tracking Solver

Algorithm:

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



$$\frac{d}{dt}(m\vec{v}) = q(\vec{E} + \vec{v} \times \vec{B})$$

Velocity update

$$m^{n+1}\vec{v}^{n+1} = m^{n}\vec{v}^{n} + q\Delta t\left(\vec{E}^{n+1/2} + \vec{v}^{n+1} \times \vec{B}^{n+1/2}\right)$$

$$\frac{d\vec{r}}{dt} = \vec{v}$$

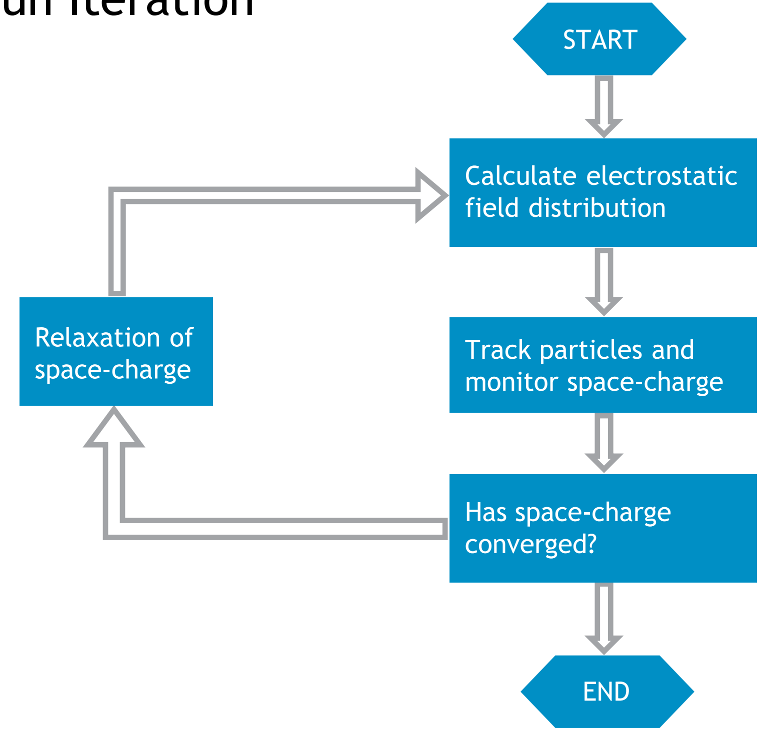
Position update

$$\vec{r}^{\,n+3/2} = \vec{r}^{\,n+1/2} + \Delta t \vec{v}^{\,n+1}$$

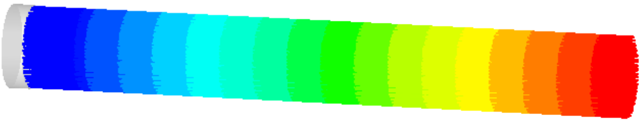
Leap Frog Scheme

Space Charge Effect

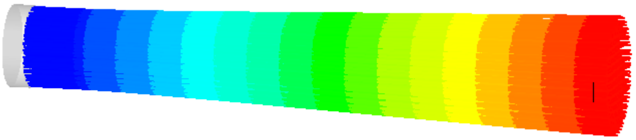
Gun Iteration



Without Gun Iteration:



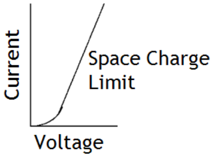
With Gun Iteration:



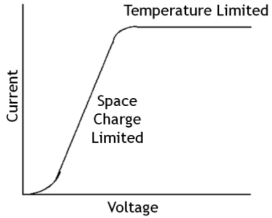
TRK Emission Models

1. Fixed Emission
   Applicable for known beams
   Input: Current, Beam Voltage

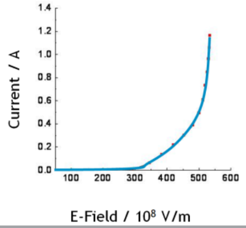
2. Space Charge Limited Emission
   Necessary for Electron Guns
   Current(Voltage) according to Childs Law



3. Thermionic Emission
   Enhances Space Charge Limit
   Richardson Dushman Equation



4. Field Induced Emission
   Fowler-Nordheim Equation



Particle Interfaces

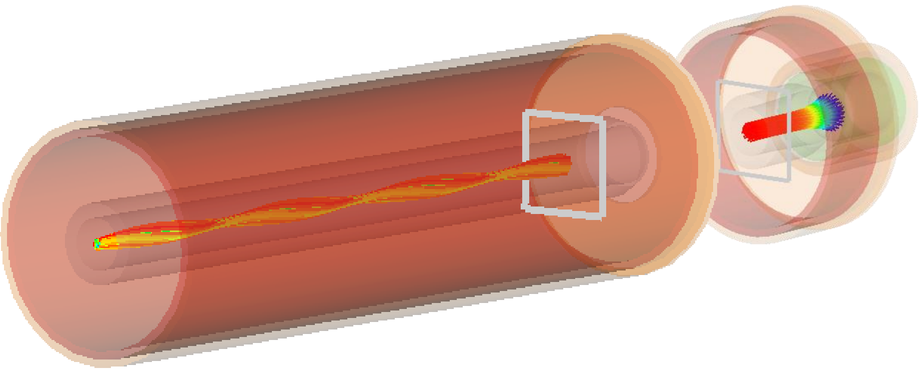
Particle Emission

- 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

Gun simulation with export interface

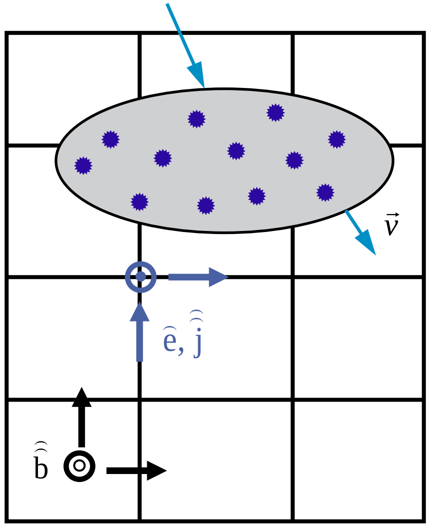


Tracking/PIC simulation with import interface

Particle in Cell

Self consistent modeling
of collisionfree plasma

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



Relativistic equation of motion

$$\frac{\partial \vec{u}}{\partial t} = \frac{q}{m_0 c}\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

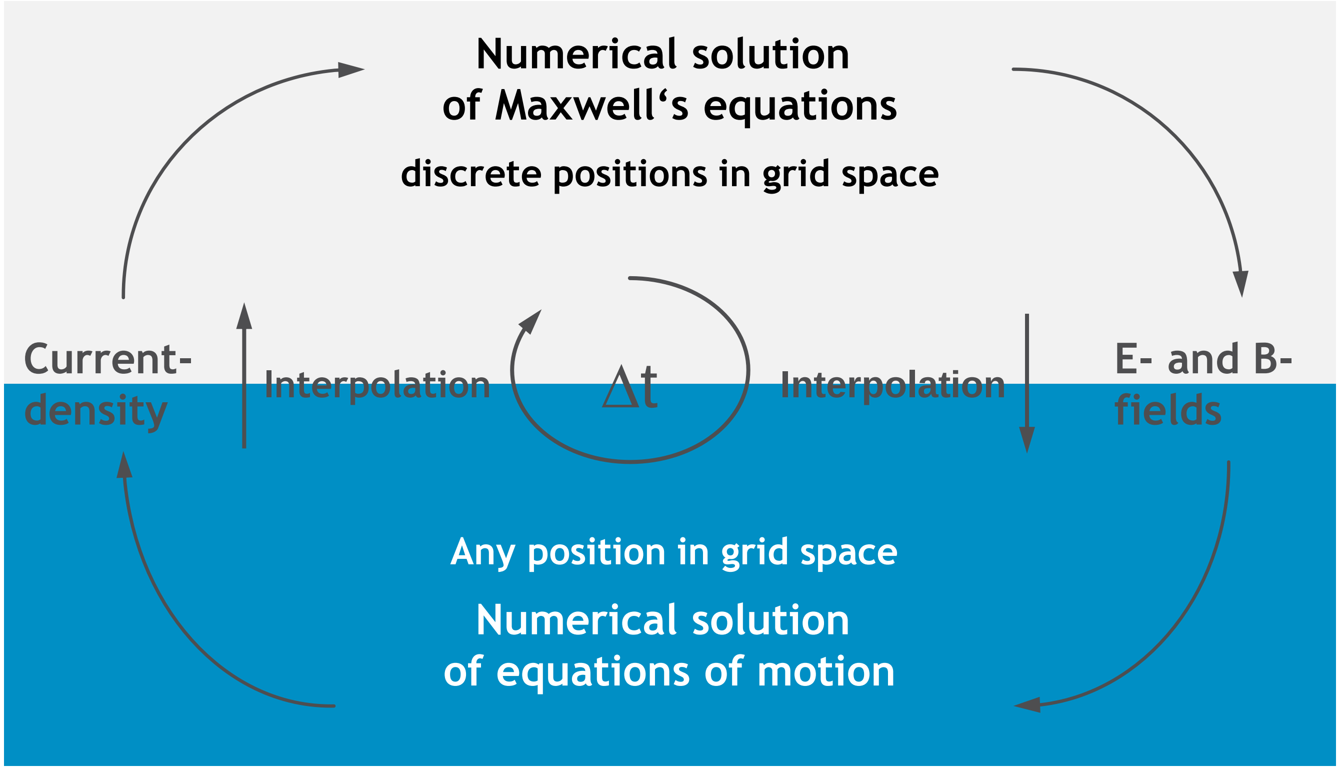
$$\frac{\partial \vec{r}}{\partial t} = \vec{v} \qquad \vec{u} = \frac{\vec{p}}{m_0\, c} = \frac{m(v)\,\vec{v}}{m_0\, c} = \gamma \cdot \vec{\beta}$$

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

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

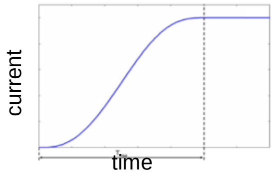
A priori charge conserving algorithm.

Particle in Cell (PIC) Algorithm

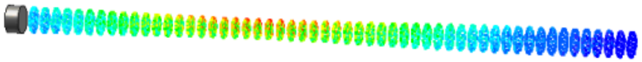


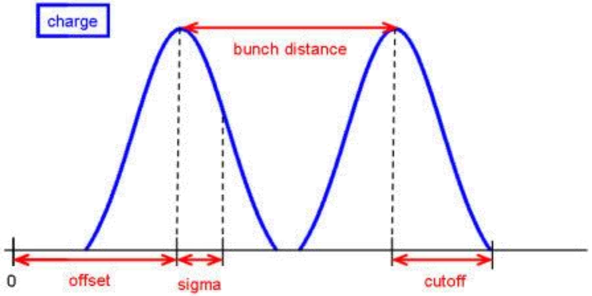
PIC Emission Models

1. DC Emission

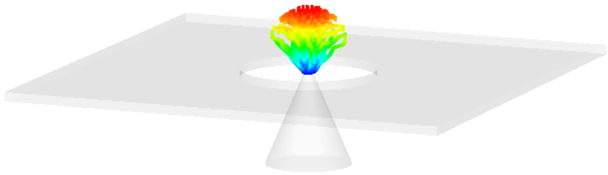


2. Emission of a series of Gaussian bunches





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

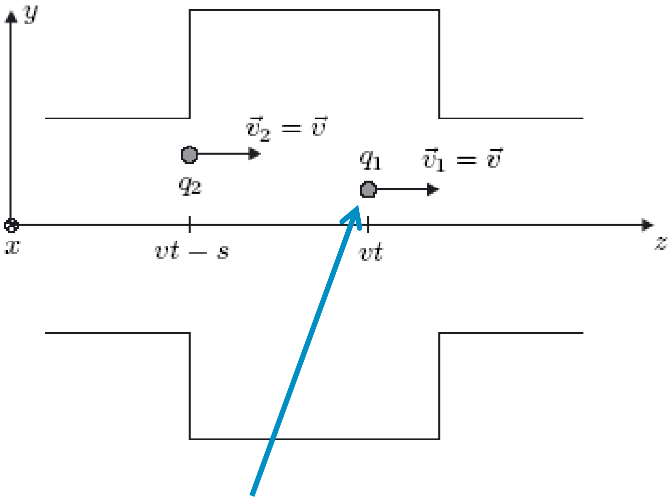
5. Secondary electron emission

6. Explosive Emission

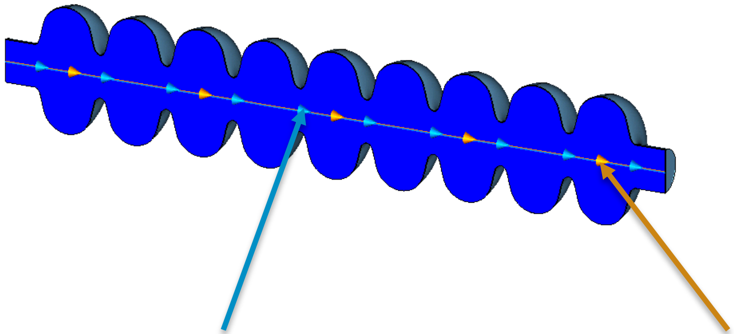
Wakefield Solver

The Wakefield solver computes the wake potential:

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



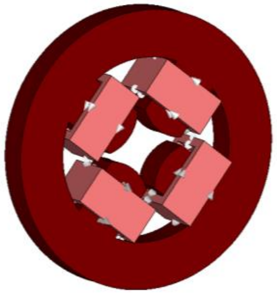
Excitation (pencil beam with logitudinal Gaussian shape)



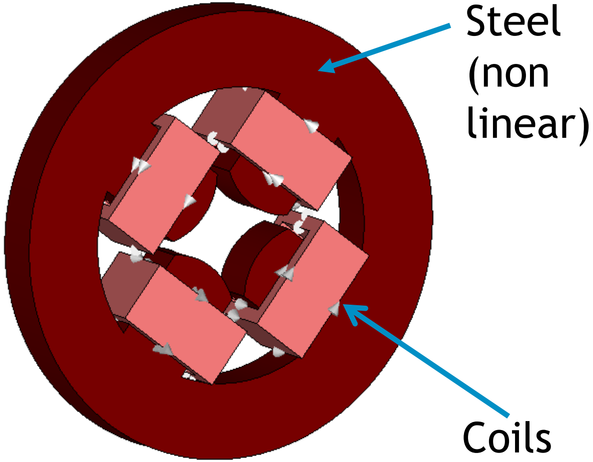
Beam path

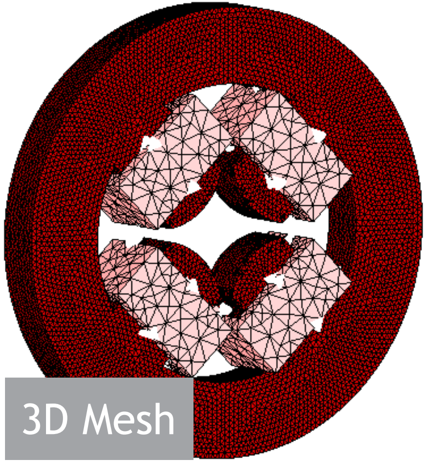
Integration path

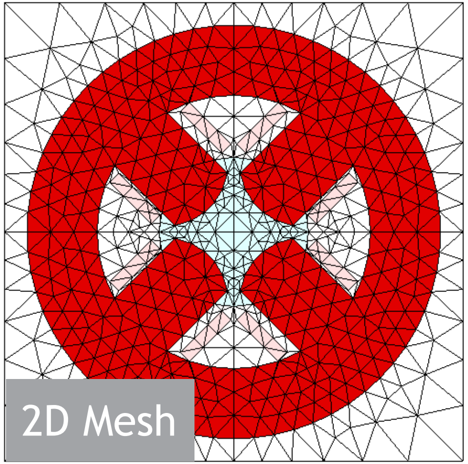
Magnets



Magnet Design







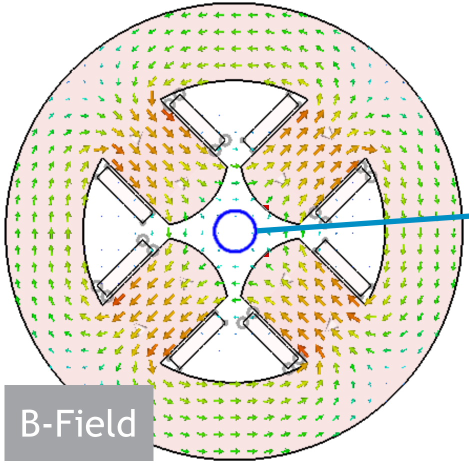
Quadrupole Magnet:

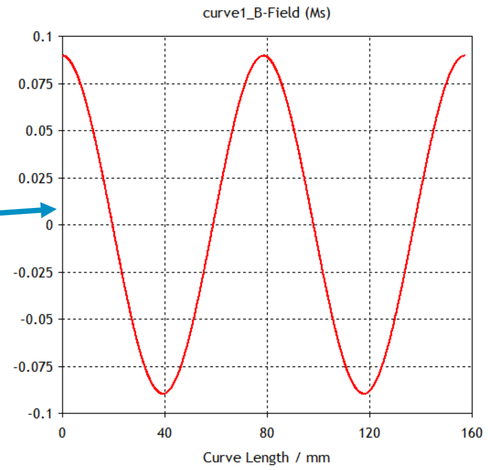
→ Source: Coils/Permanent Magnets

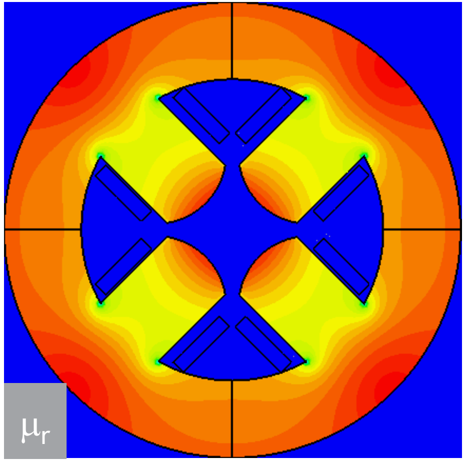
→ 3D M-static run

→ 2D M-static rotational/translational symmetry possible

Magnet Design

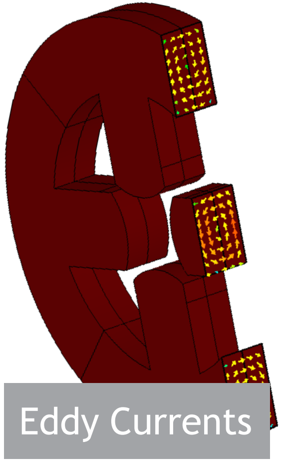


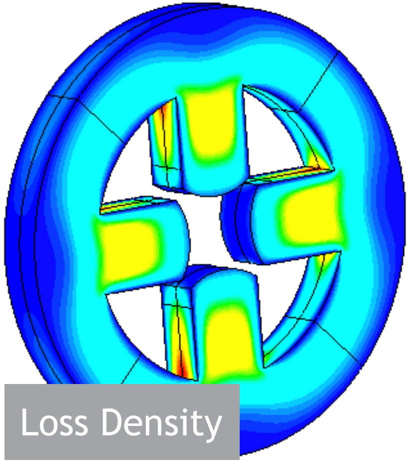


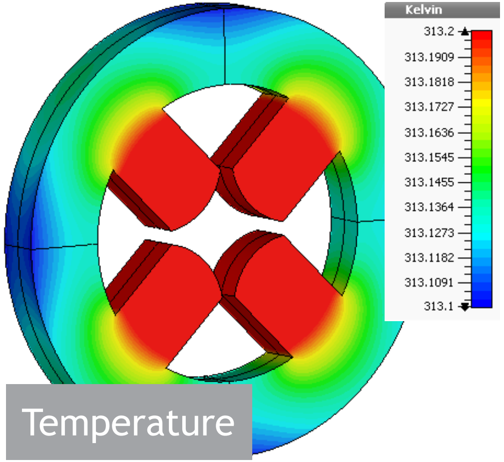


Results from M-Static:
→ Quadrupole like B-Field
→ Sinusoidal magnetic field along azimut
→ Pole pieces quite saturated

LF-Thermal Coupling







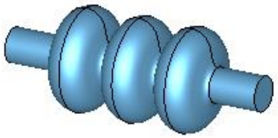
Coupled Simulation:

→ Import of LF losses into thermal solver

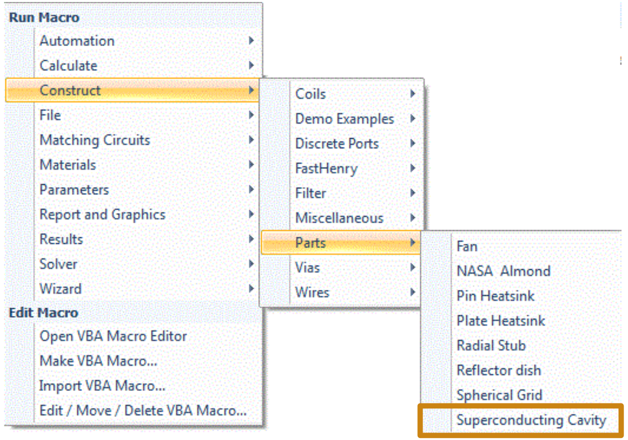
→ Thermal stationary/transient run

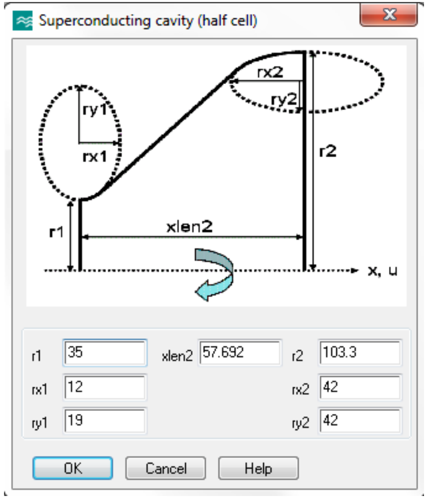
→ Automization of loop possible via SAM approach

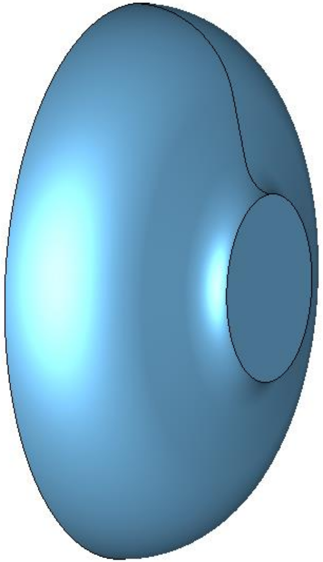
Cavity Simulation



Cavity Construction

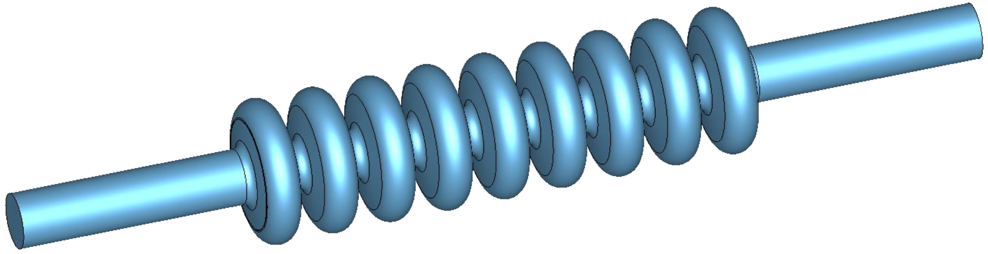




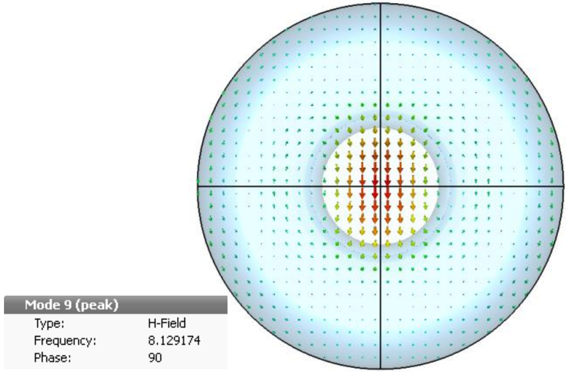


Automatic creation of a cavity part
→ Transformation for multiples

Eigenmode Simulation



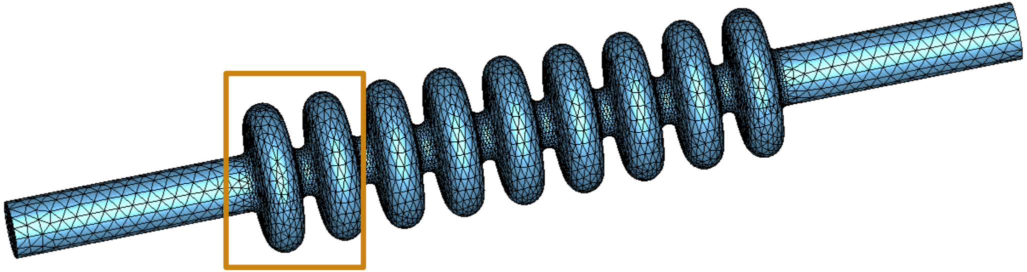
Crab cavity courtesy of
Dr. Graeme Burt, Lancaster University



Hexahedral mesh
→ no convergence
Tetrahedral mesh
→ convergence in < 2 min

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

Eigenmode Simulation



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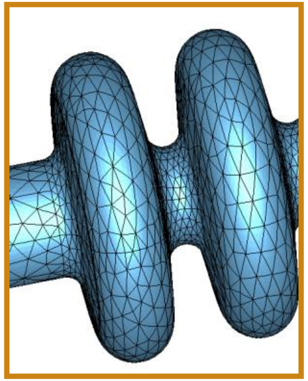
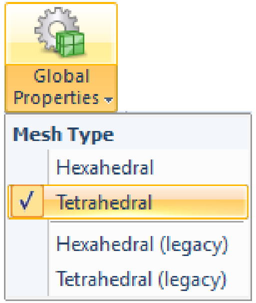
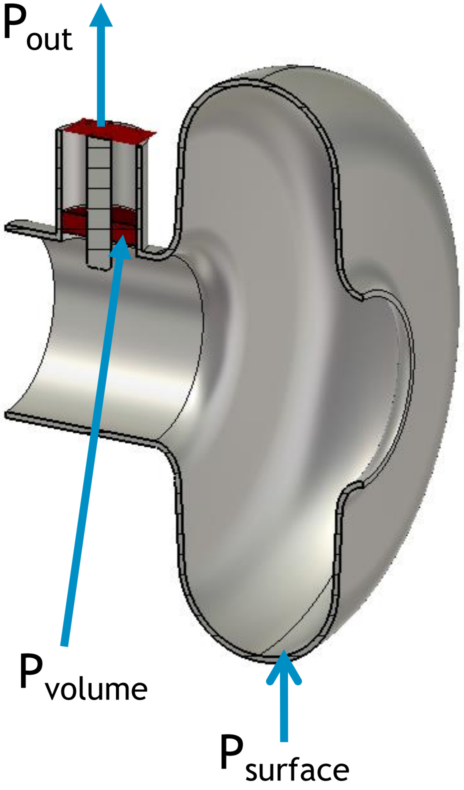


→ Automatic curved elements up to 3rd order applied
→ New TET mesh engine for improved mesh distribution



Q-Factor and Loss Calculation



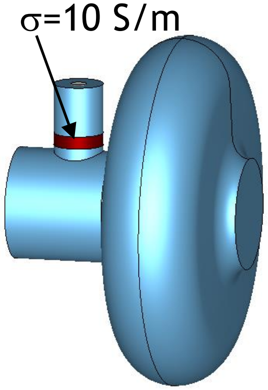
Different Loss Mechanisms:

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

Superposition for each mode to get Q

$$\frac{1}{Q_{\mathrm{loaded}_n}} = \frac{P_{\mathrm{volume}} + P_{\mathrm{surface}} + P_{\mathrm{out}}}{\omega \cdot W} = \frac{1}{Q_{\mathrm{volume}}} + \frac{1}{Q_{\mathrm{surface}}} + \frac{1}{Q_{\mathrm{external}}}$$

Volume and Surface Losses



Q-factor calculation

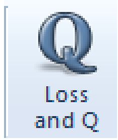
☐ Calculate external Q-factor

☐ Consider losses in postprocessing only

Eigenmode solver results:

Mode	Frequency	Accuracy	
1	0.9136223 GHz	4.515e-007	Q = 1.238e+006

On (Default):
Losses via perturbation method → less resources
Off:
Losses included in solver run → needed if losses change the field pattern



Q-Factor Calculation

H-Field data: Mode 1

Material/Solid	Conductivity	Mue	Loss/W	Loss/%	Q
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
component1:solid3			3.5993e-002	1.53e-005	1.5901e+011
component1:solid3_1			4.1202e+000	0.00175	1.3891e+009
Sum of Surface Losses			2.3342e+005	98.9	2.4519e+004
Volume Losses			2.5148e+003	1.07	2.2759e+006
Sum			2.3594e+005		2.4258e+004

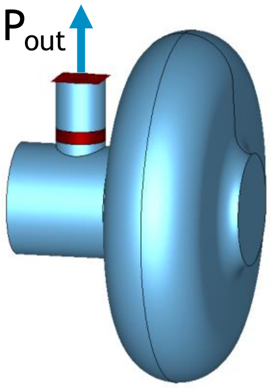
Calculate | Specials... | Export... | Close | Help

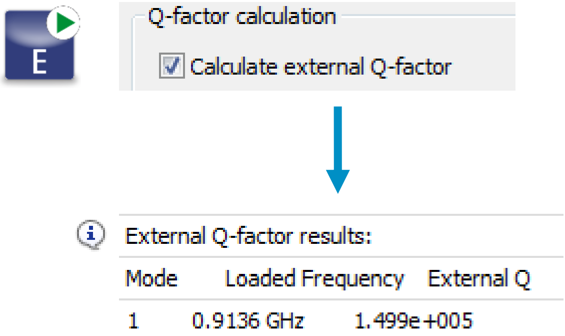
Modify... | Modify All... | Hide / Unhide | Hide/Unh. All

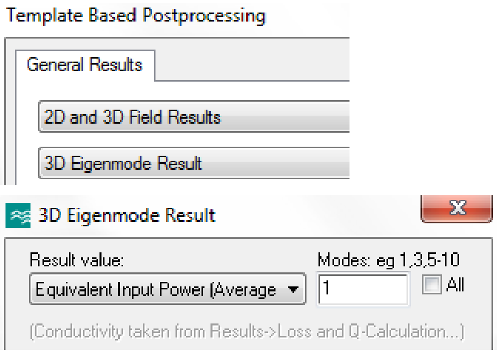
Surface losses are always evaluated with Loss and Q post processing

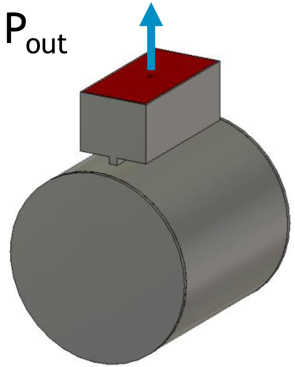
Normalization to 1J

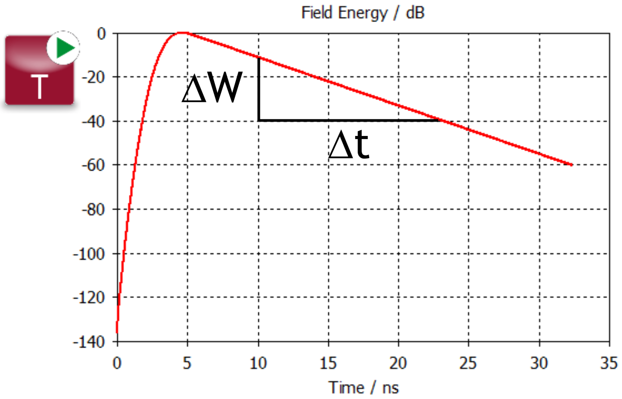
External Q











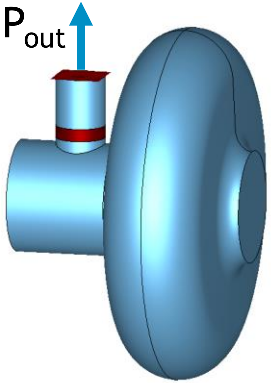
For lossless structures:

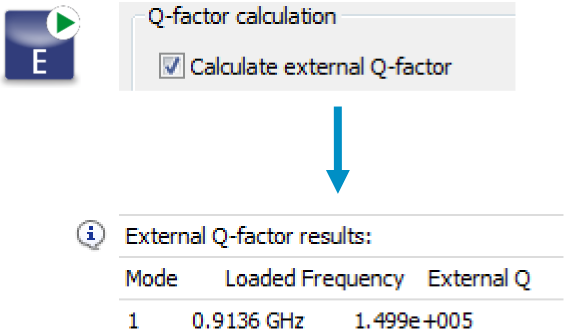
$Q_{external} = Q_{loaded}$

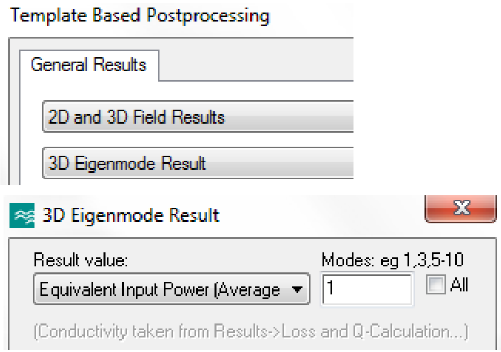
$$\tau = -10 \frac{1}{\frac{\Delta W}{\Delta t}} \frac{1}{\ln(10)}$$

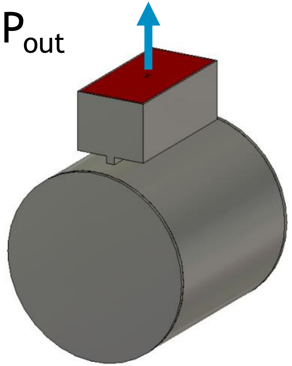
$$Q_{loaded} = \tau \cdot \omega_0$$

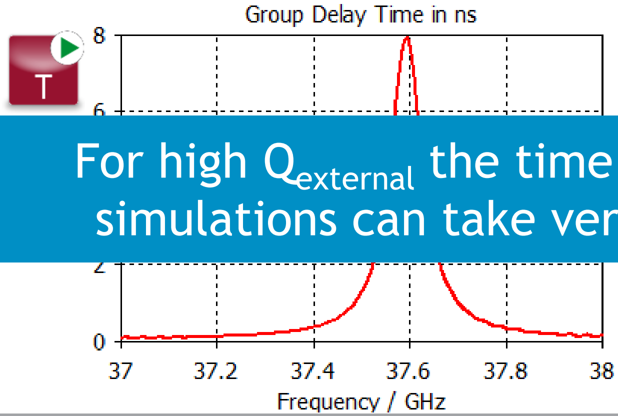
External Q







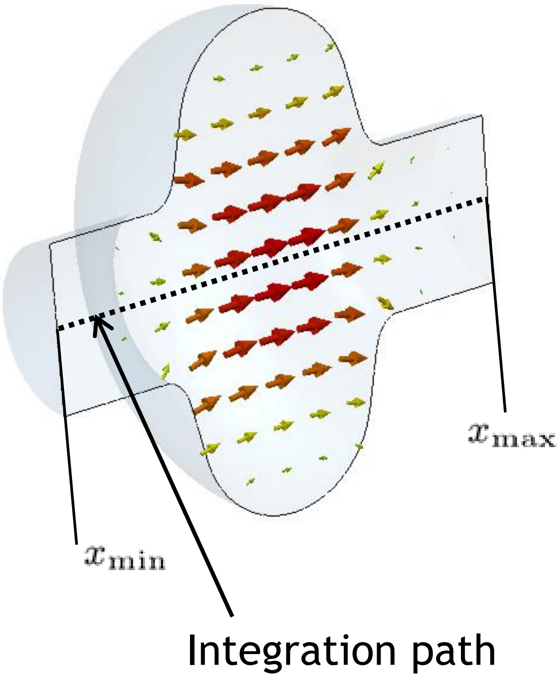




For high $Q_{external}$ the time domain simulations can take very long.

$$Q_{ext.} = \frac{\omega_0 \Gamma_{D1}}{4}$$

Shunt Impedance, R over Q



Shunt Impedance:

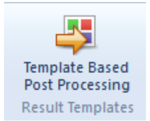
$$R_n := \frac{|\underline{U}_n|^2}{P_{\mathrm{loss}_n}} \qquad \underline{U}_n := \int_{x_{\mathrm{min}}}^{x_{\mathrm{max}}} E_x(x) \cdot e^{j\frac{\omega_n x}{\beta \cdot c_0}} \, \mathrm{d}x$$

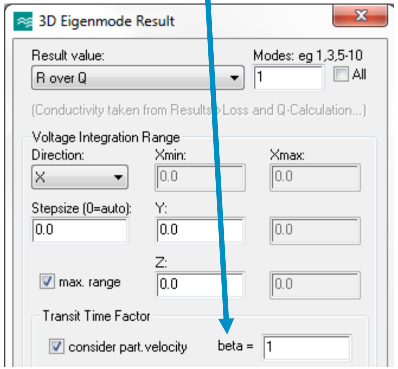
R over Q:

$$\frac{R_n}{Q_n} = \frac{|\underline{U}_n|^2}{\omega_n \cdot W_n}$$

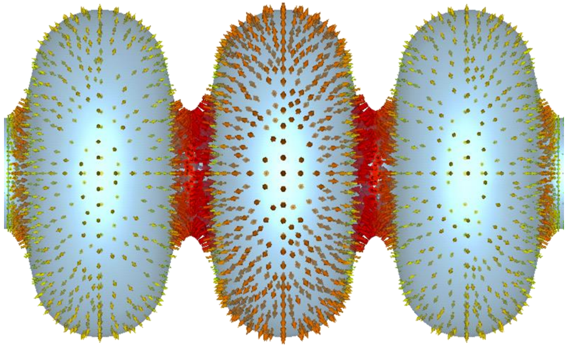
ω_n = frequency of mode n
W_n = stored energy of mode n

Integration including particle velocity in post processing





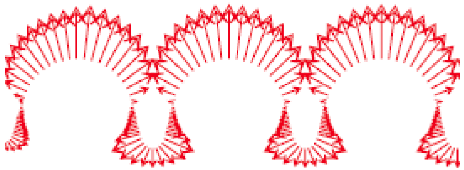
Lorentz Force Density



Force Density:

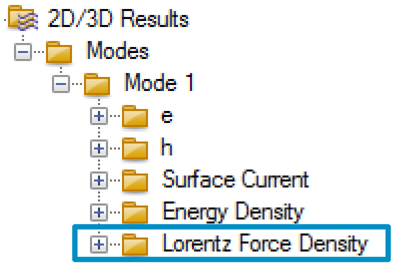
$$P = \frac{1}{4}\left(\mu_0 {H_s}^2 - \epsilon_0 {E_s}^2\right)$$

Especially interesting for superconducting cavities

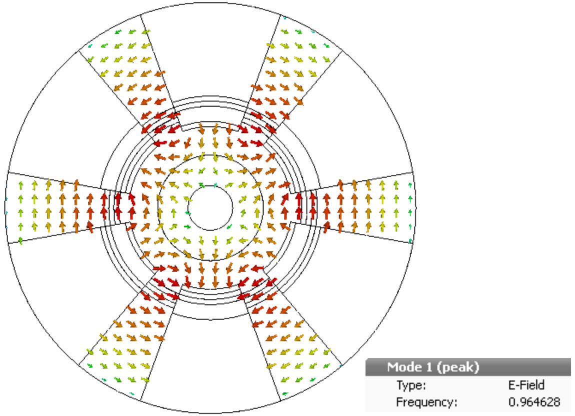


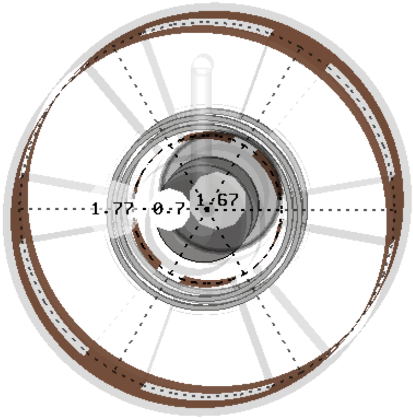
*) Picture from H. Gassot, Institut de Physique Nucléaire, Orsay, France

Evaluated as post processing step



Geometric Tolerances / Sensitivity





Sensitivity analysis results:

Design parameter "r_a"

Mode	Frequency	Derivative of frequency
1	0.9646199 GHz	0.1799115 GHz/in

Design parameter "r_v"

Mode	Frequency	Derivative of frequency
1	0.9646199 GHz	-0.5956404 GHz/in

$$f_{res}(p + \Delta p) = f_{res}(p) + \frac{\partial f}{\partial p}\Delta p$$

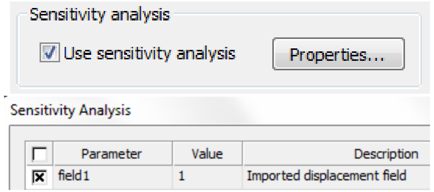
Strapped Magnetron Example

→ Face constraints applied to anode and vane radius

→ Sensitivity of Eigenfrequency to (small) geometry changes in ONE 3D run

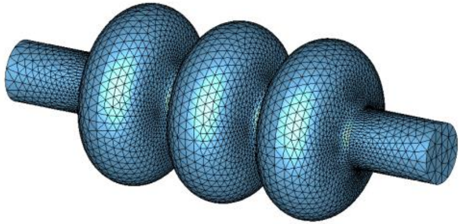
Simulating Detuning Effects

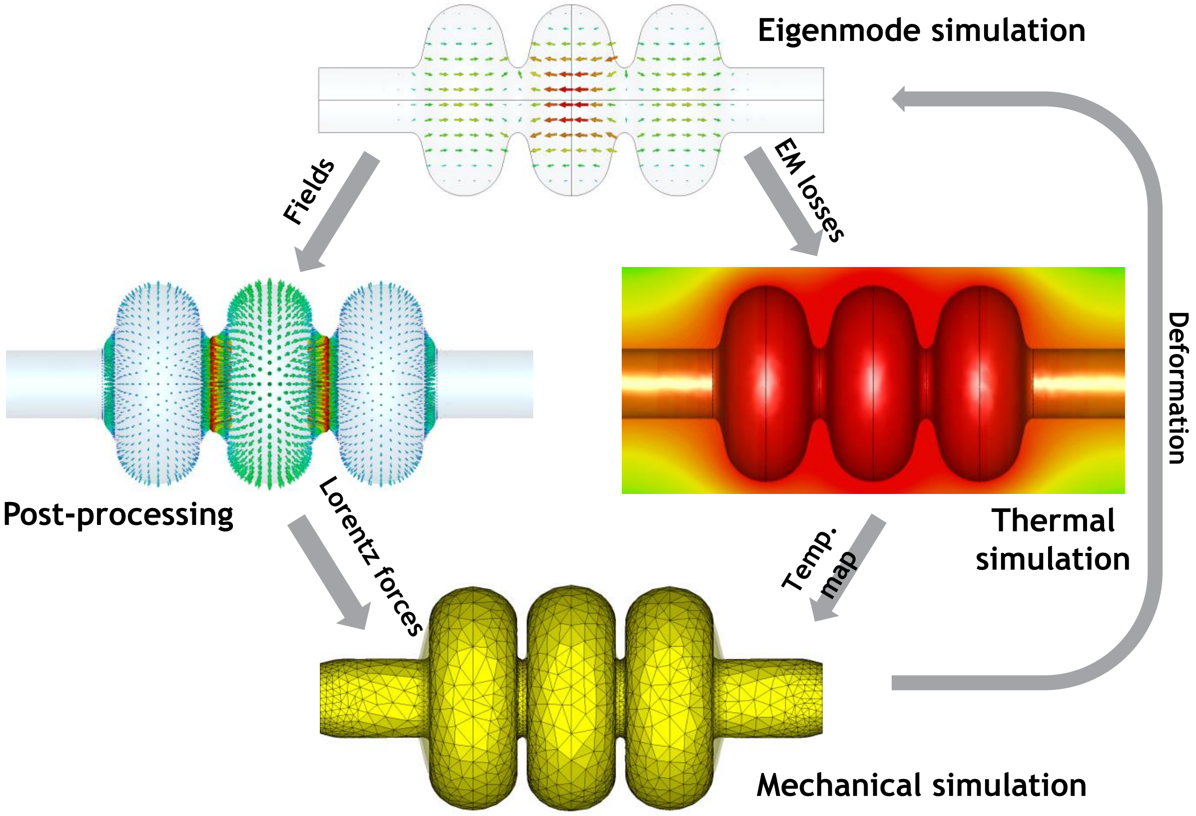
Simulating Detuning Effects



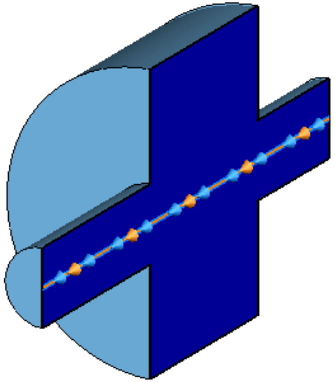
$$\Rightarrow f_{initial}, \Delta f, f_{deformed}$$

All solvers available on tetrahedral mesh

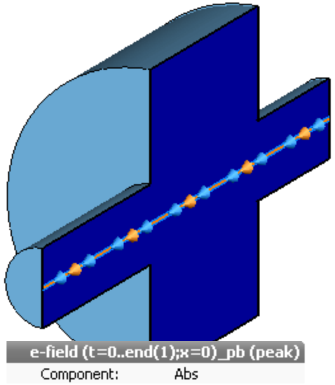


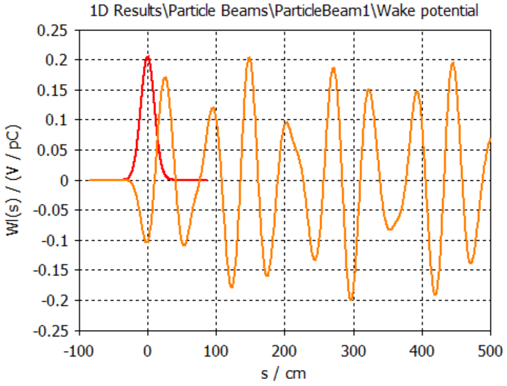


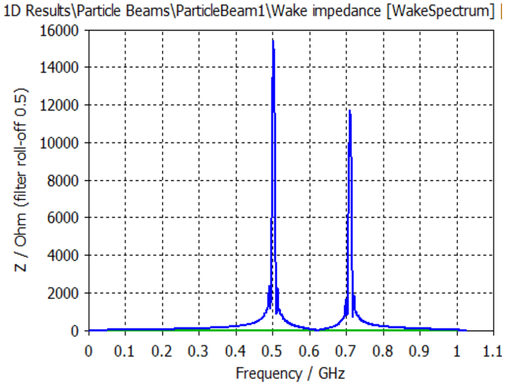
Wakefield Analysis



Wakefields





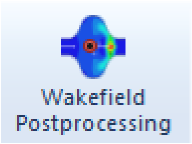


Results:

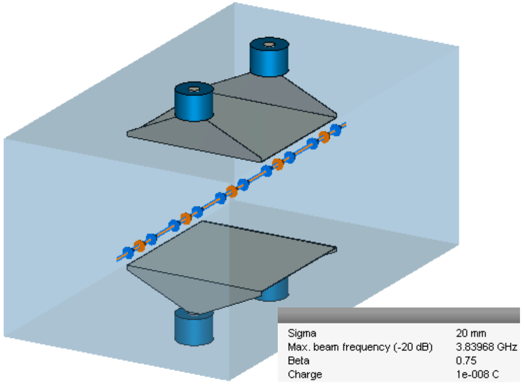
→ Electromagnetic fields

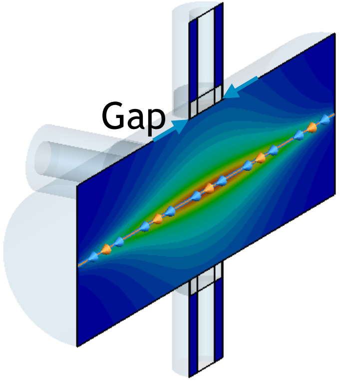
→ Wake Potential, Wake Impedance

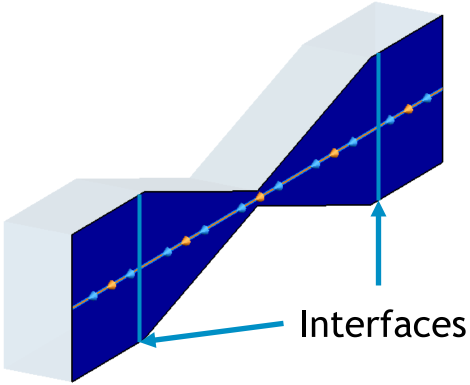
→ Postprocessing available for user defined sampling



Integration Methods







Direct:

→ Integration along beam path

→ For $\beta < 1$ the only method

Indirect Testbeams:

→ Integration along the gap

→ Only for $\beta = 1$

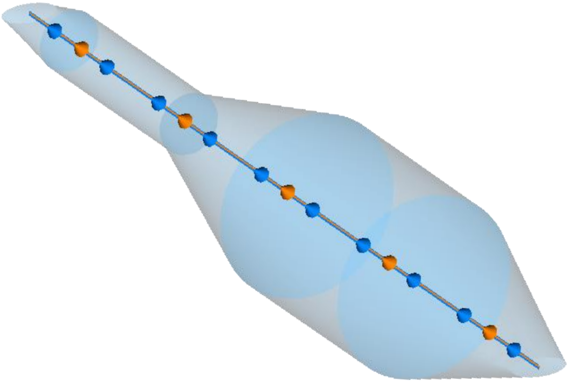
Indirect Interfaces:

→ Direct integration in discontinuity

→ Tube considered on the interfaces

→ Only for $\beta = 1$

Short Bunches



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

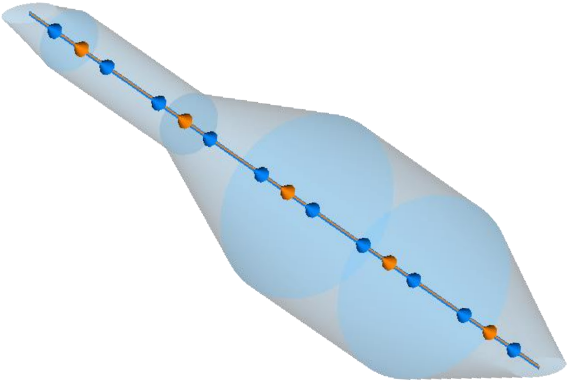
NSLS Storage Ring Impedance Budget:

→ Possible with MPI

→ 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

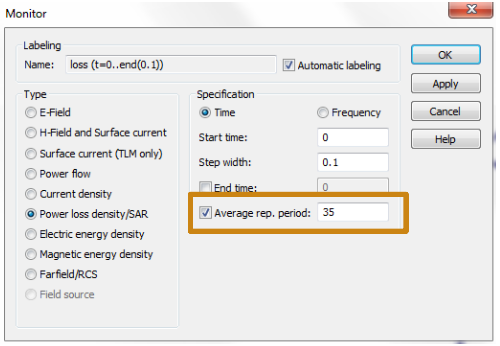
NSLS Storage Ring Impedance Budget:

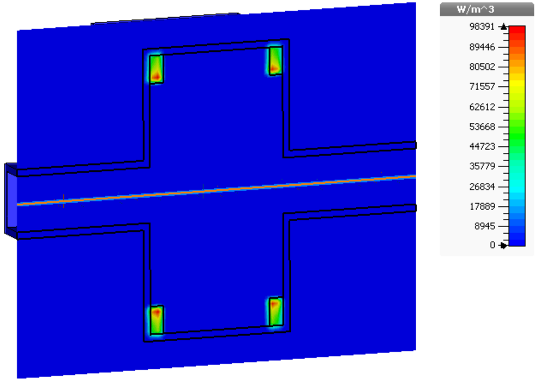
→ Possible with MPI

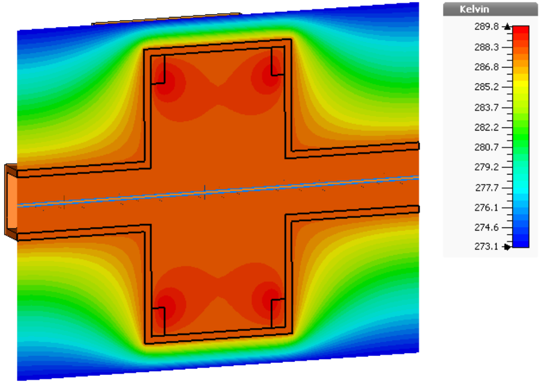
→ Simulation Time: 5h 12min, 4 Nodes, 820 Millionen Mesh Cells

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

Loss Consideration







Cavity courtesy of CERN

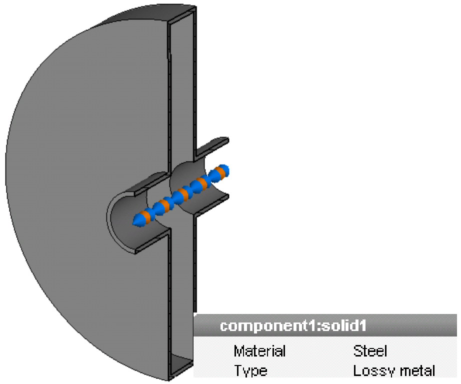
Time Integrated Volume Losses:

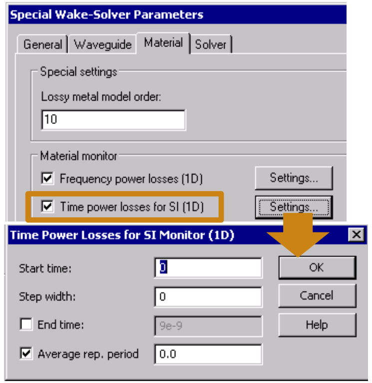
→ 3D Information about the losses

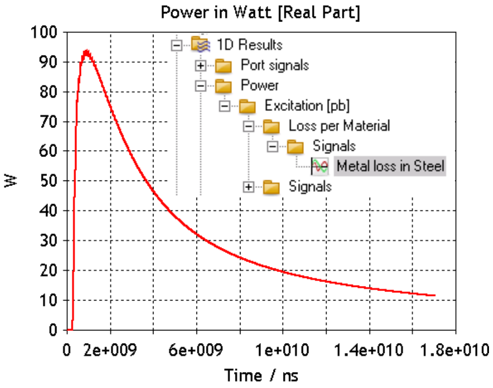
→ Coupling to thermal solver of MPS

→ Averaged losses as source for thermal solver

Loss Consideration







Cavity courtesy of
Diamond Light Source

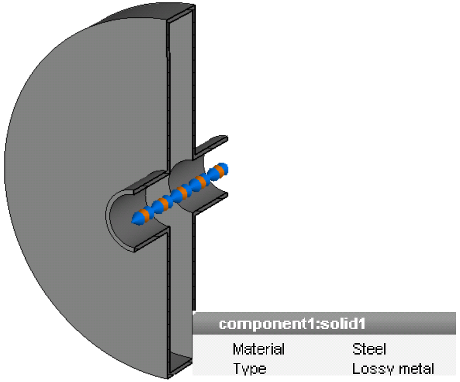
Time Integrated Surface Losses:

→ So far only per material

→ Can be observed during simulation

→ Heat source has to be applied in thermal solver

Loss Consideration

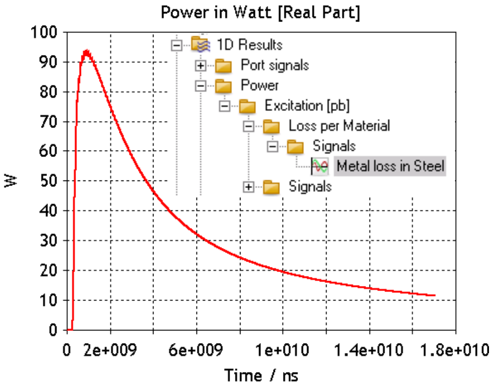


Cavity courtesy of
Diamond Light Source

Energy balance:

$$\Delta W = q^2 k$$

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



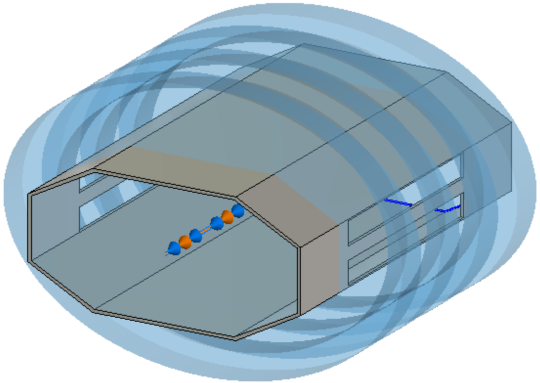
Time Integrated Surface Losses:

→ So far only per material

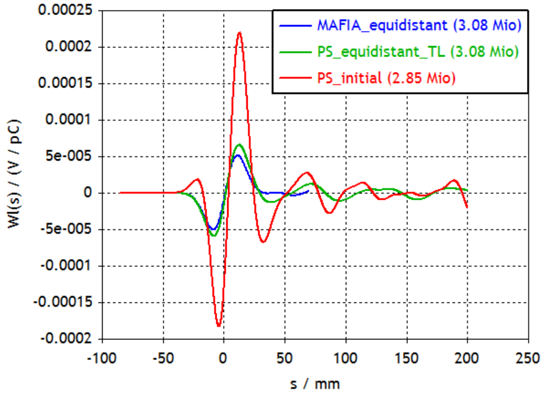
→ Can be observed during simulation

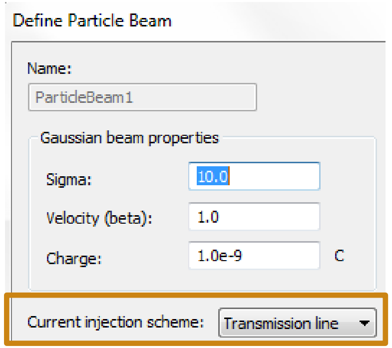
→ Heat source has to be applied in thermal solver

Accuracy Consideration



Structure courtesy of DESY





Dispersion error:

→ Important, if wake potential is small

→ Improves with equidistant mesh

→ Improves with "Transmission line" current injection

User Defined Bunch Shapes

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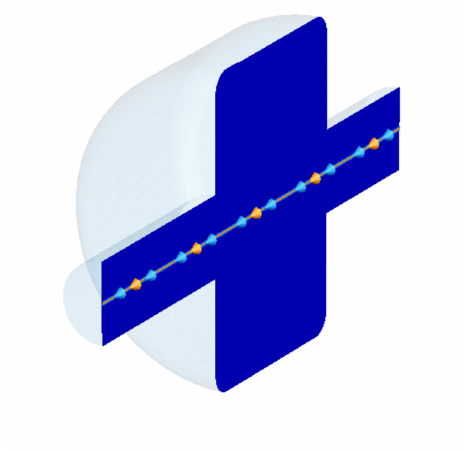
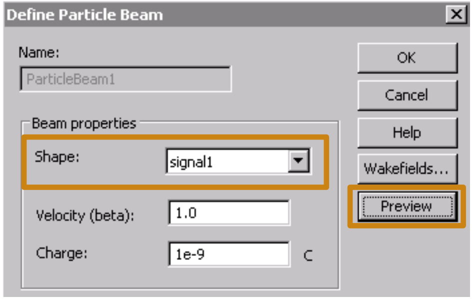
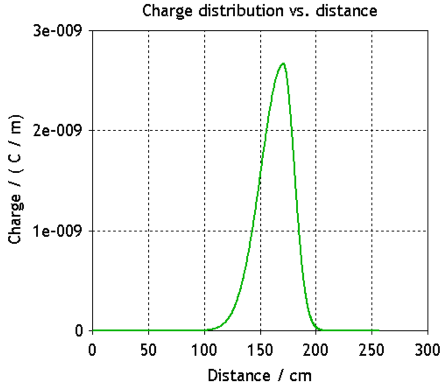
New Feature 2015

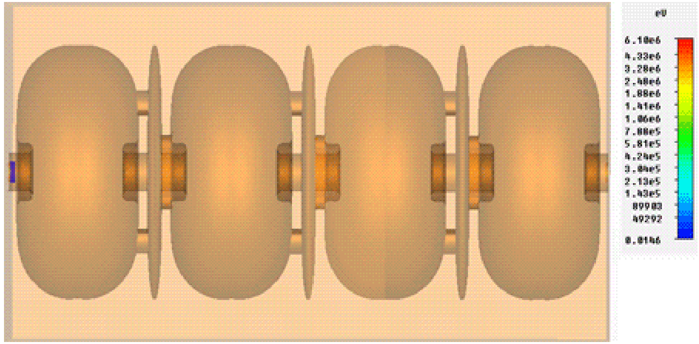




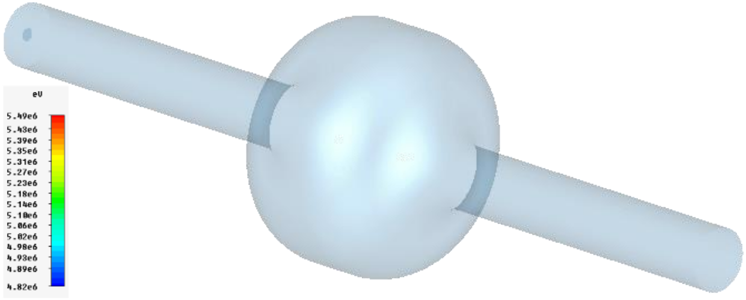


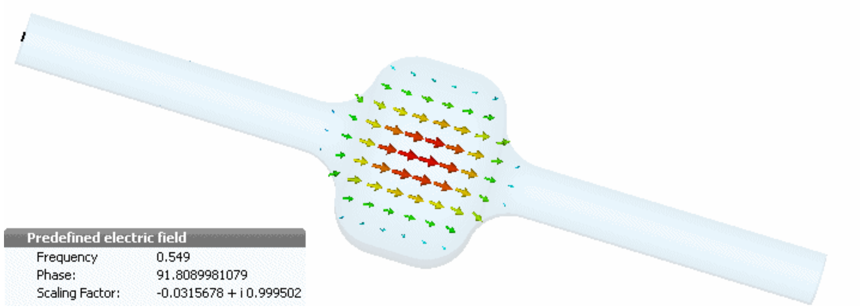
Signal definition via excitation function:
→ ASCII import and formulas can be used
→ Allows Non-Gaussian shapes
→ Allows bunch series

Full Particle Dynamics



PIC Simulation of Cavities

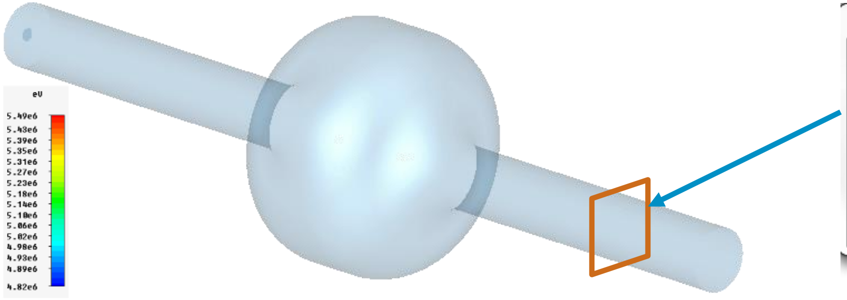


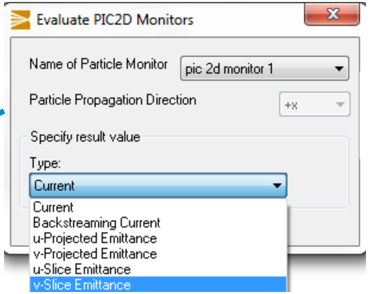


- → Preloading of Eigenmode fields
- → Choice of initial phase and scaling
- → Low current applications: Disregard space charge
- → GPU Support: Realistic RFQ → Speed up of 4.876* and higher

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

PIC Simulation of Cavities





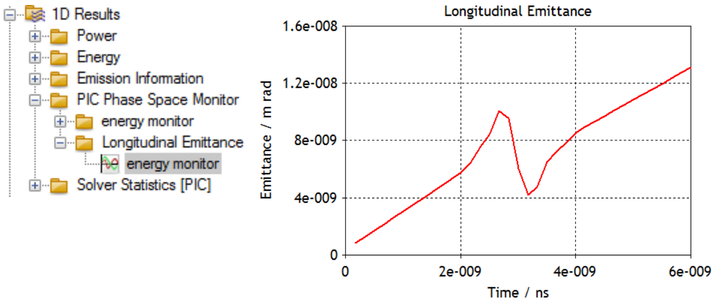
Emittance definition:

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

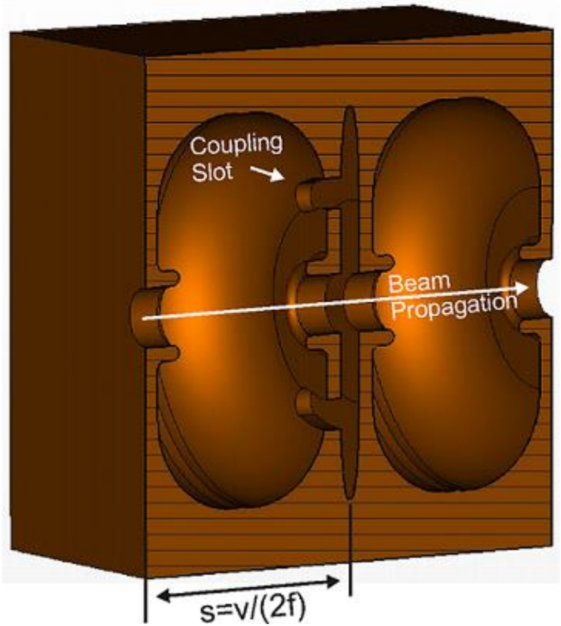
Postprocessing Results:

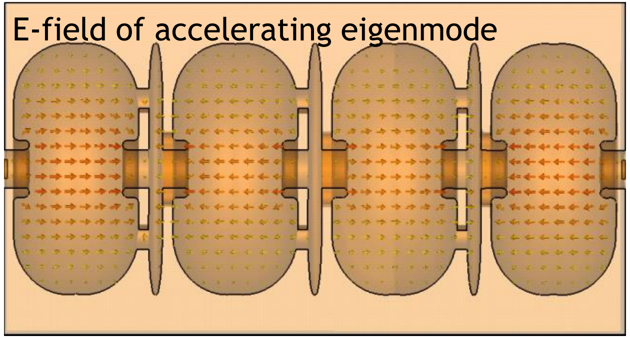
→ PIC 2D monitor: projected & slice emittance

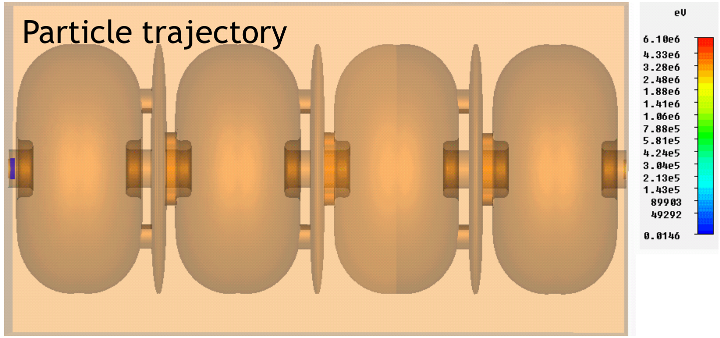
→ Phase space monitor: longitudinal emittance



C-Band Linear Accelerator

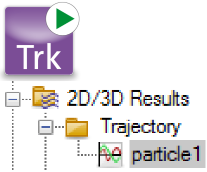


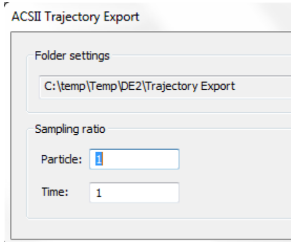


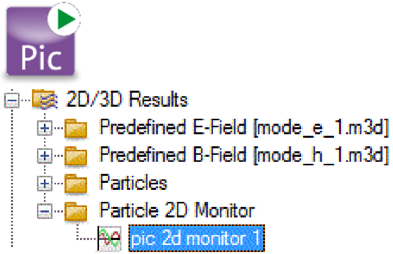


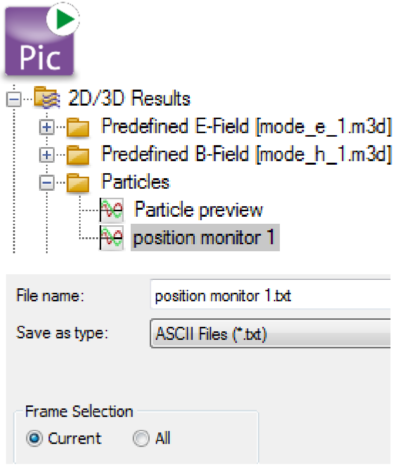
[1] Design, simulation and measurement conducted by M. Ruf, K. Thurn and L.-P. Schmidt at Chair for High Frequency Technology, University of Erlangen-Nuremberg

Data Exchange









ASCII Export of:

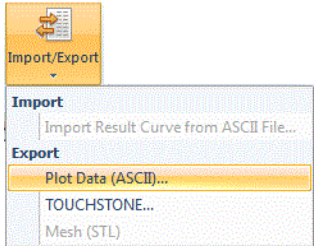
→ Trajectory (TRK)

→ PIC 2D / PIC Position Monitor

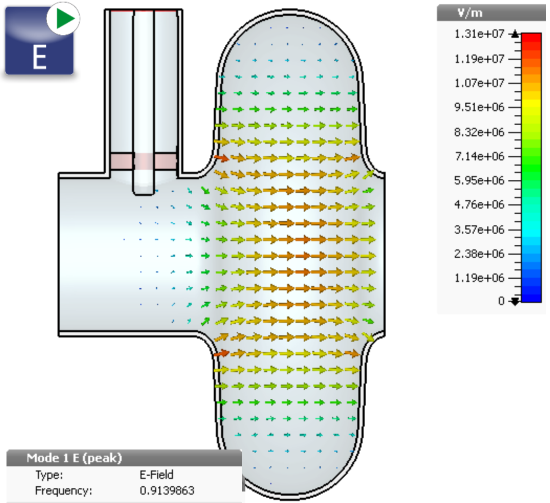
VBA Access of:

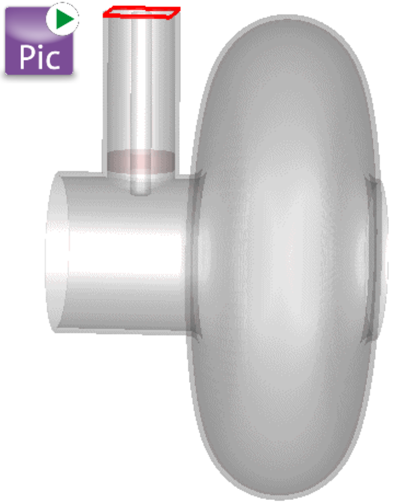
→ Trajectory (TRK)

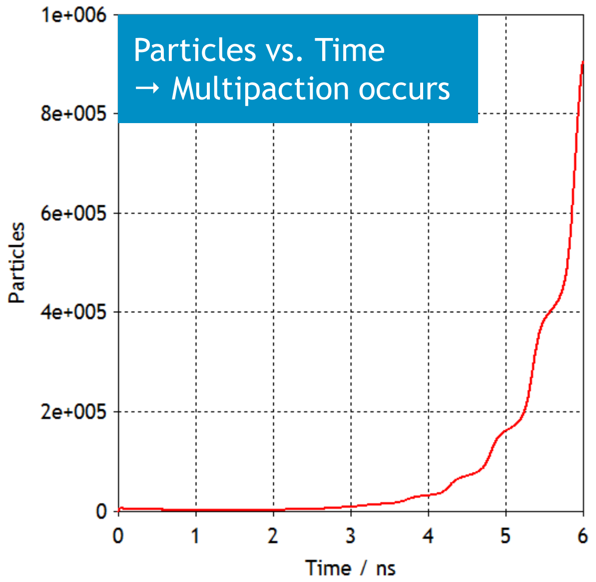
→ PIC 2D Monitor



Multipaction Analysis







Single Run:

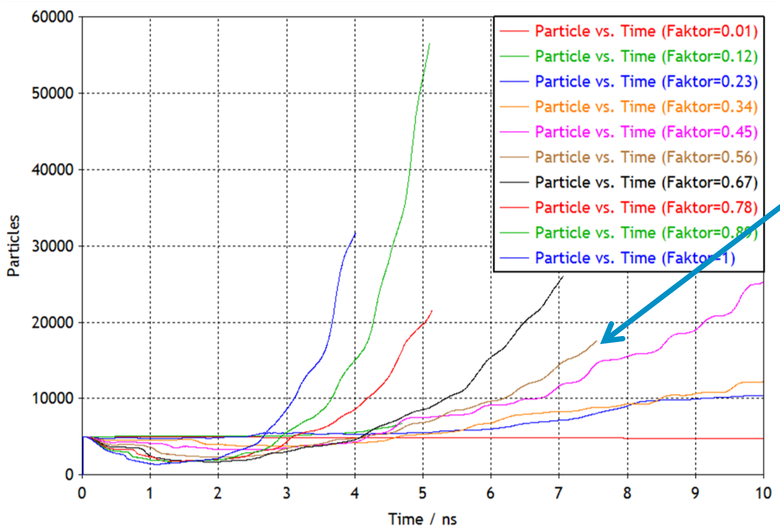
→ Preloading of Eigenmode in PIC solver

→ Preloading of initial particle cloud

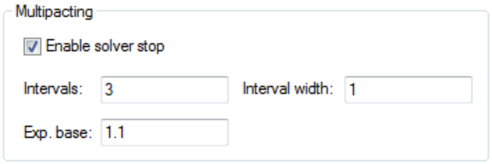
→ Observation of exponential particle increase

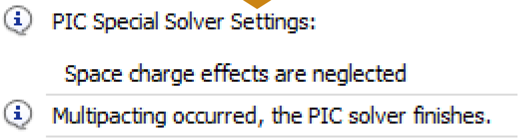
→ Collision information available for TH analysis

Multipaction Analysis



Automatic Solver Stopp

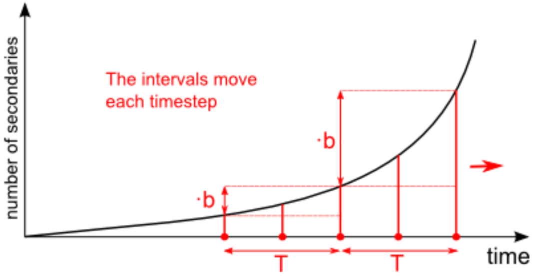




Parametric Run:

→ Reveals the power threshold

→ Automatic detection of exponential increase



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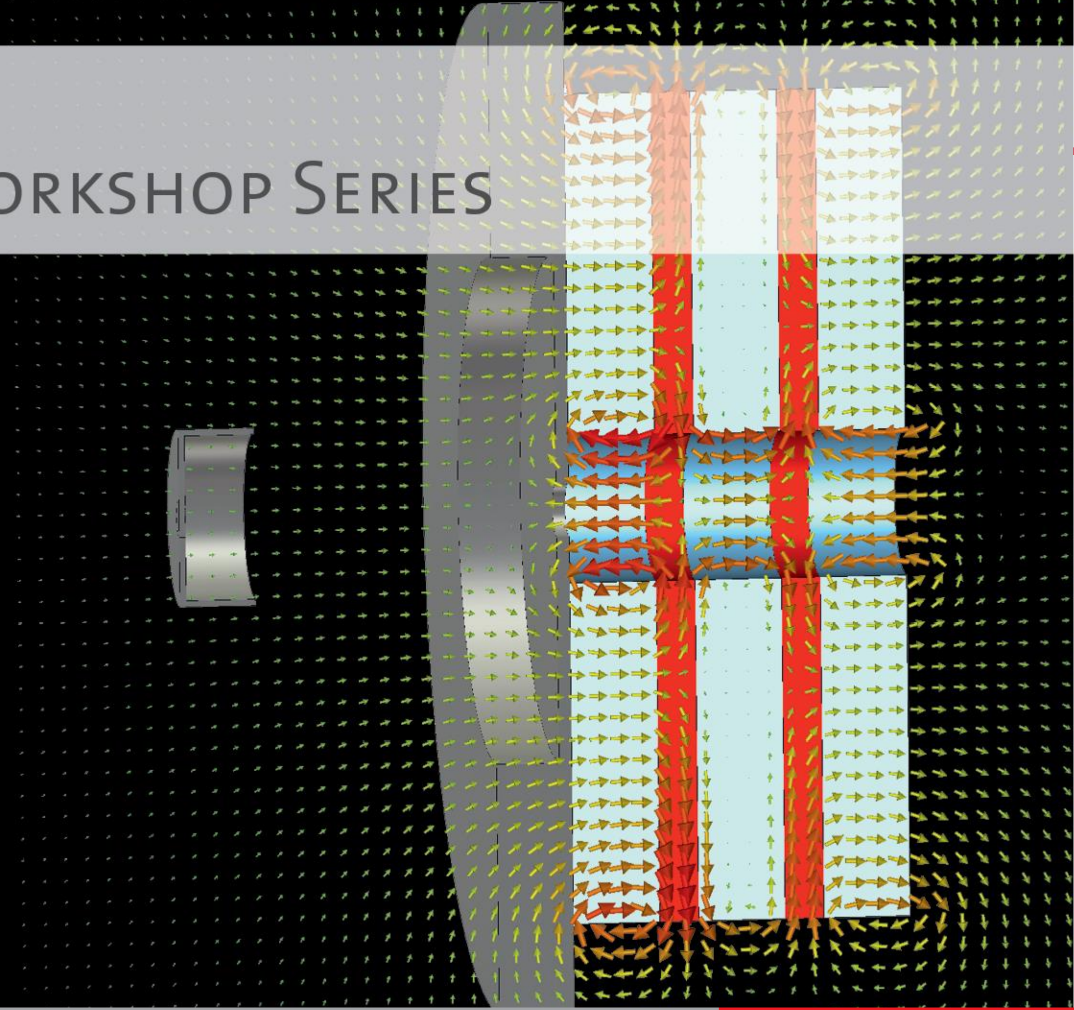
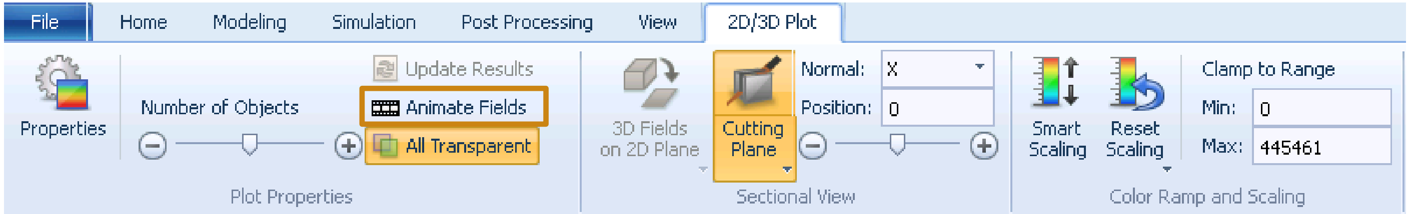
Particle Dynamics Workshop Series

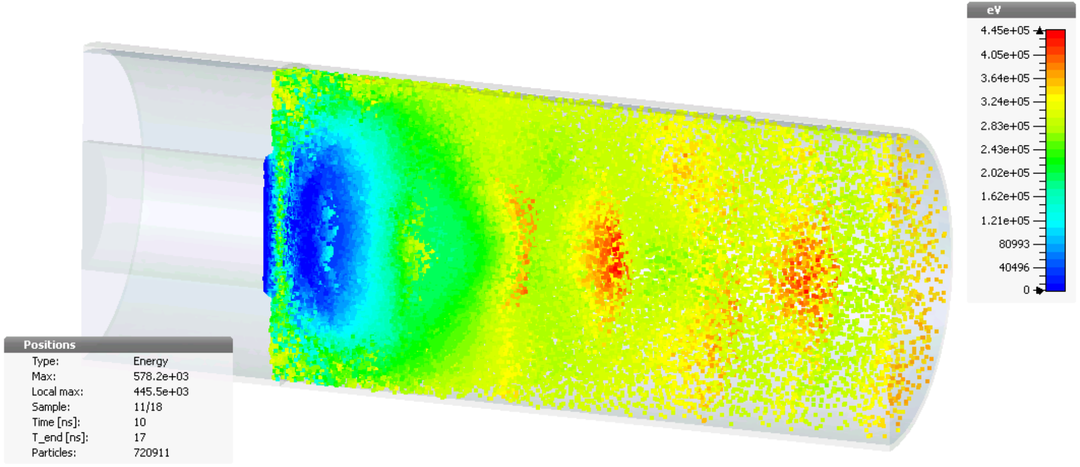


New Features 2016

Visualization

- Standard 3D Viewer now used also for PIC plots



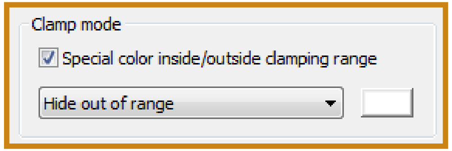


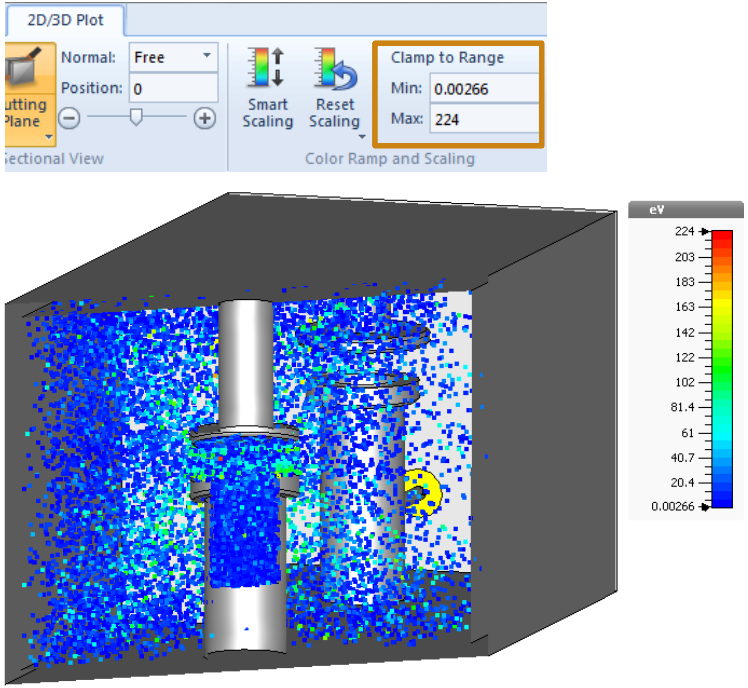
Ribbon can now be used!

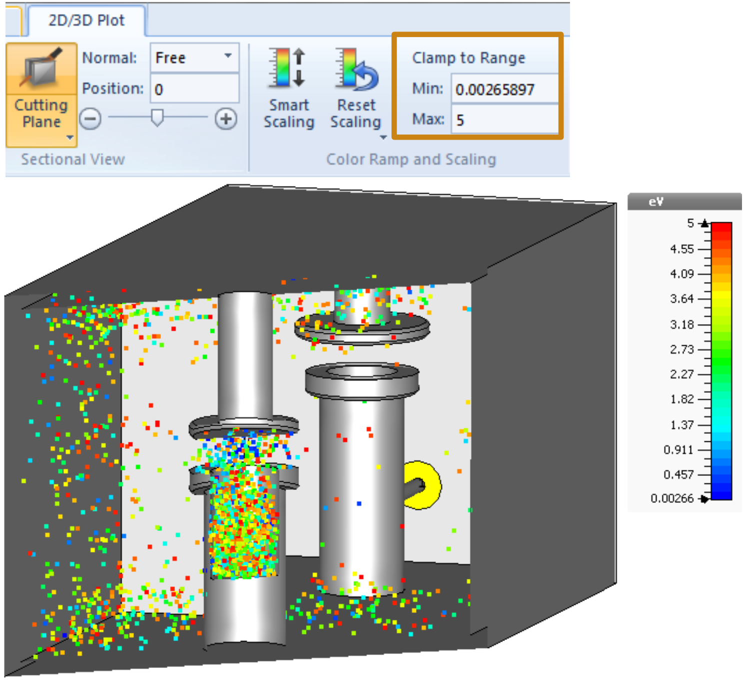
Save Video Macro works as well.

Visualization

- Finding e.g. very slow particles…



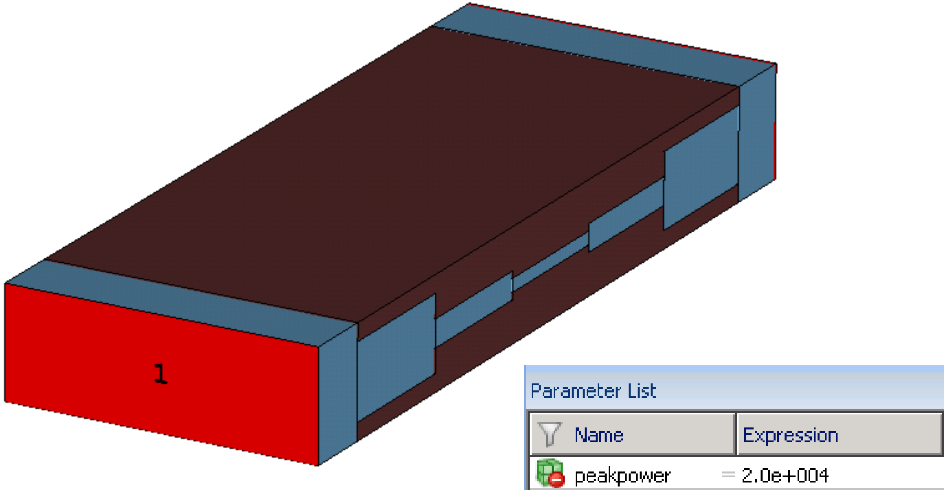




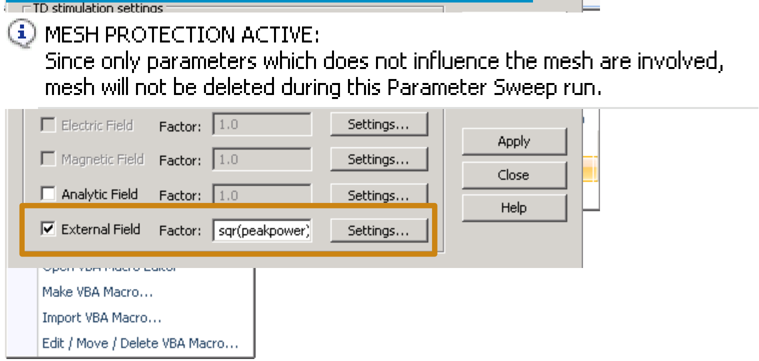
Keep Mesh

Multipaction Simulation

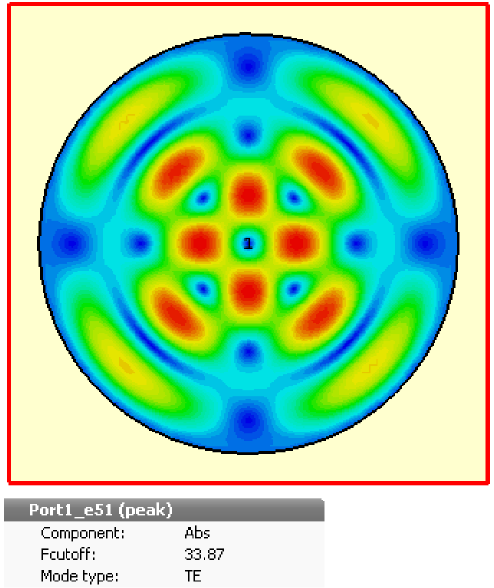
- Parametersweep of input power
- No change of geometry
- Performance improvement if mesh is reused



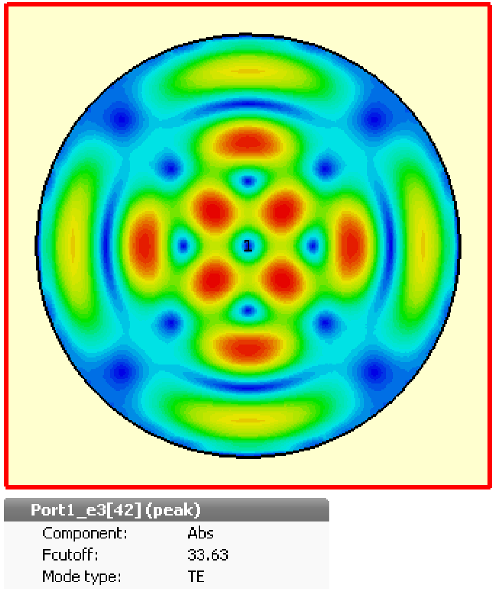
For small example:
2m 9s instead of 3m 6s



Target Frequency for WG Port



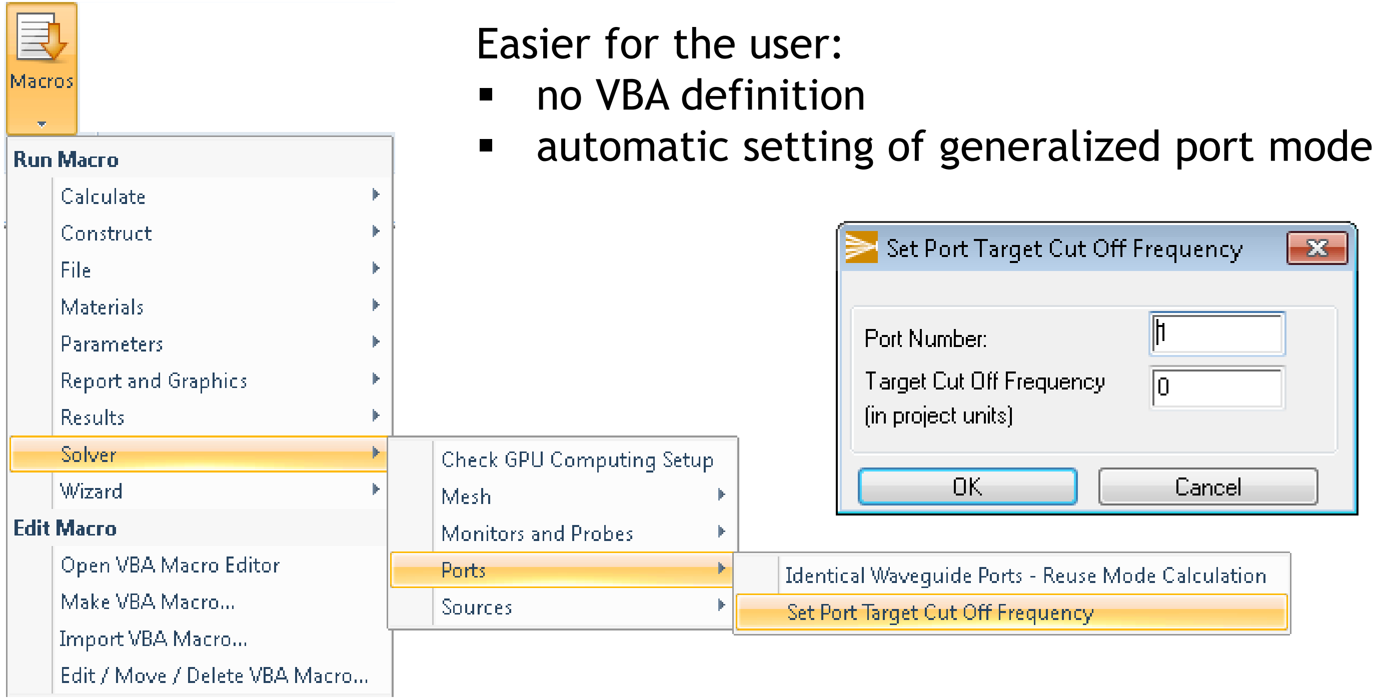
Mode #51



Mode #3

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

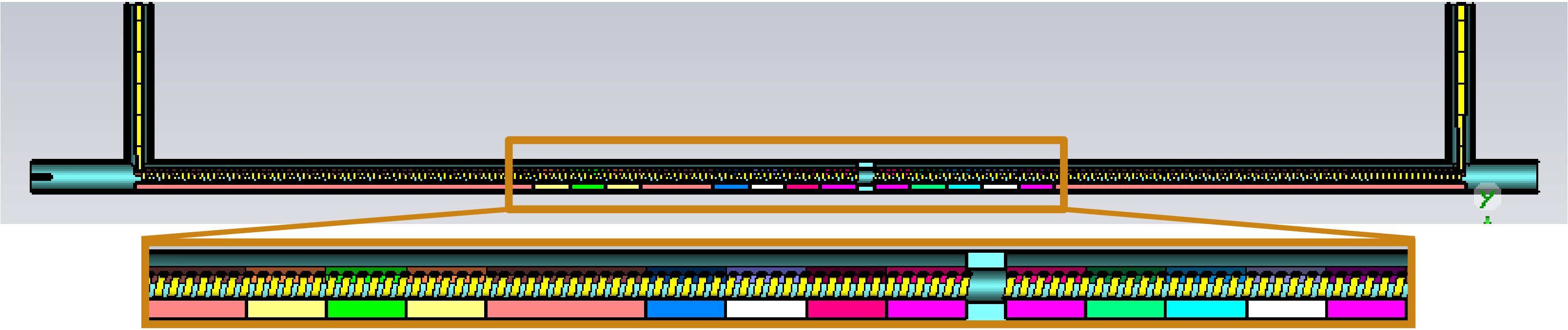
Target Frequency for WG Port



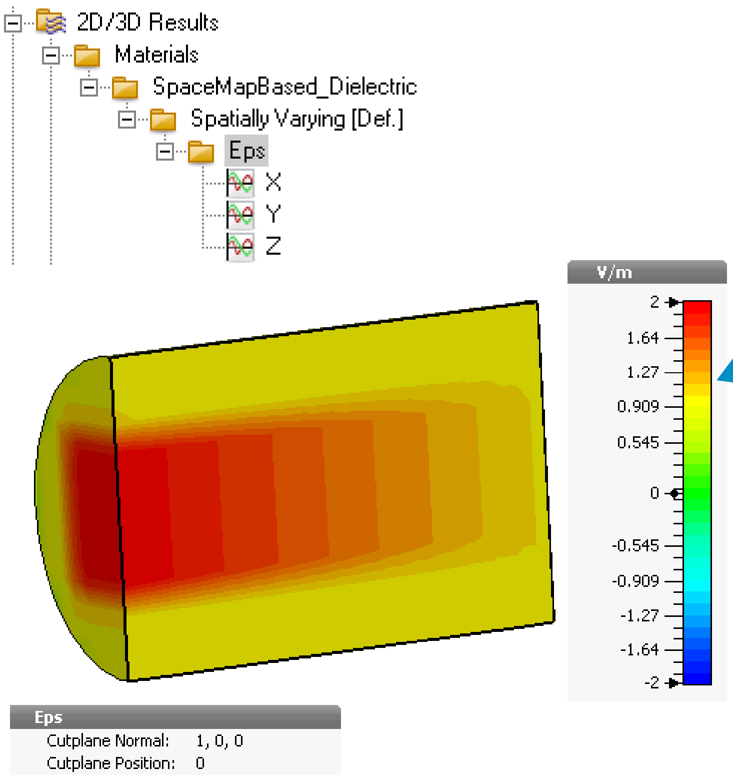
Easier for the user:
- no VBA definition
- automatic setting of generalized port mode solver

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



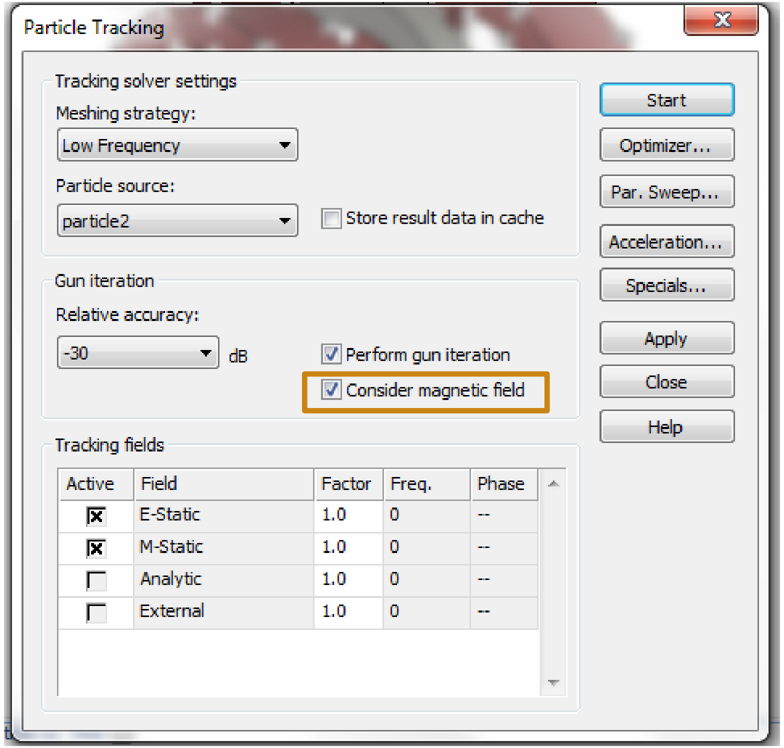
Loaded from Textfile via VBA

MaterialMap_eps - Notepad

File Edit Format View Help

```
# CST material field file
# Format: FixedGrid
# Version: 20150107

# LengthUnit: mm

# SamplePoint x:
0.0 15.0

# SamplePoint y:
0.0 15.0

# SamplePoint z:
20.0 100.0

# Symmetry x: true
# Symmetry y: true

# Data section:

1 1
1 1

2 2
2 2
```

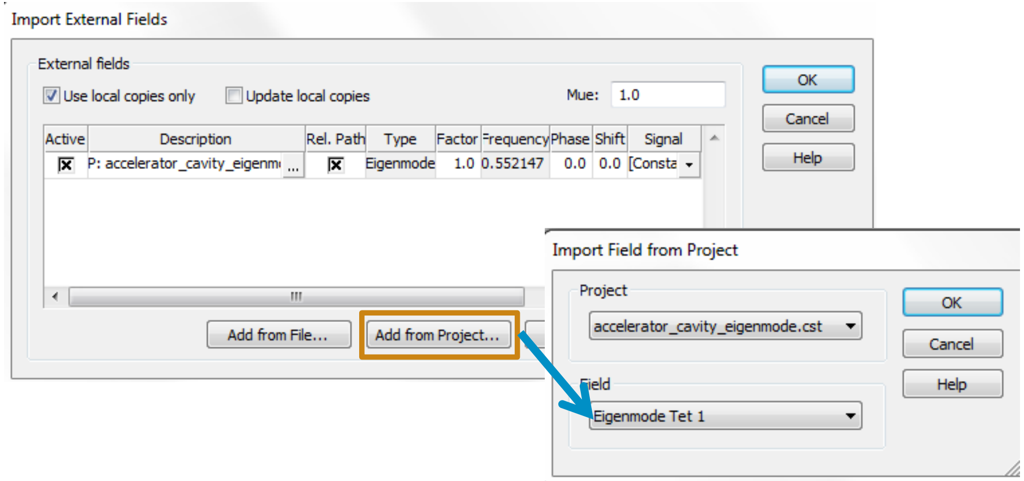
Eigen H-Field in Gun Iteration

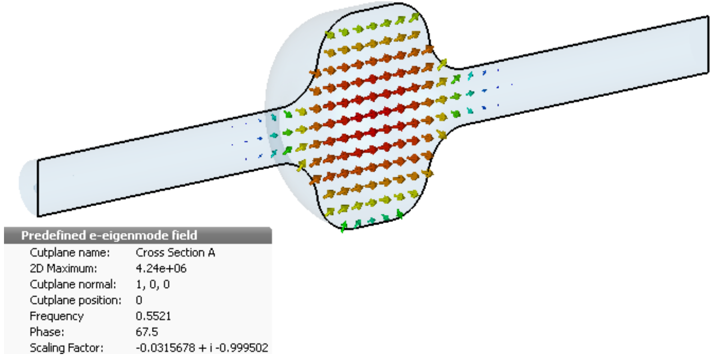


Important for High Voltage guns (~500kV), where the Eigen H-Field has a focusing effect in contrast to the Eigen E-Field.

Otherwise beam expansion is overestimated.

External TET Field Import





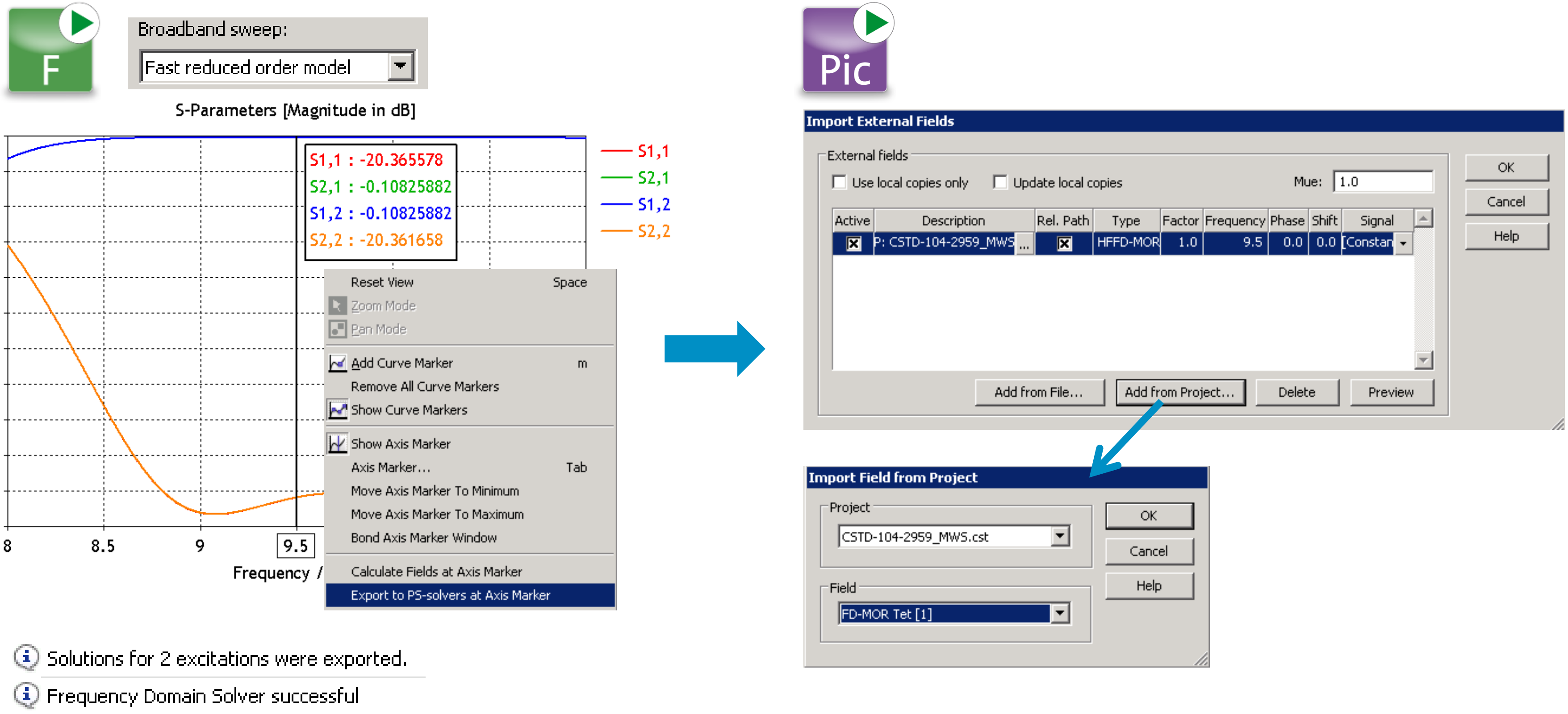
TET Fields can be loaded directly from

→ E-Static

→ M-Static

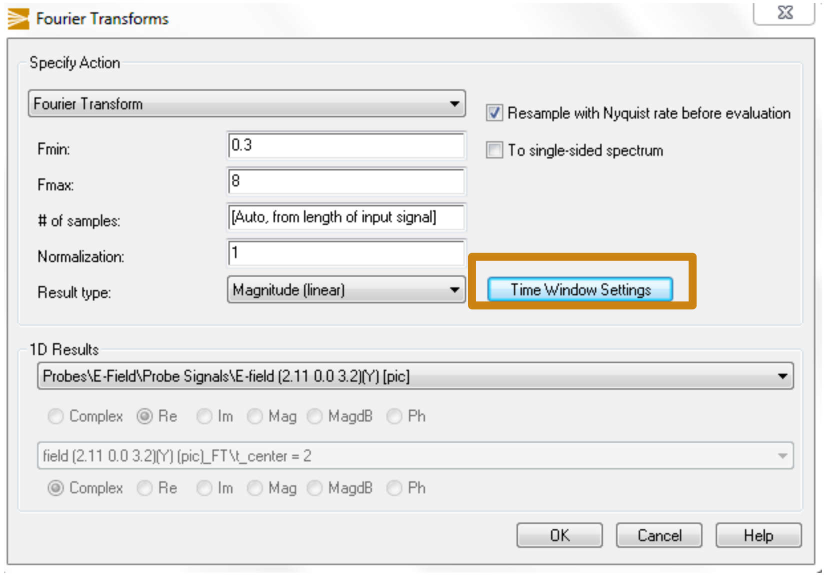
→ Eigenmode

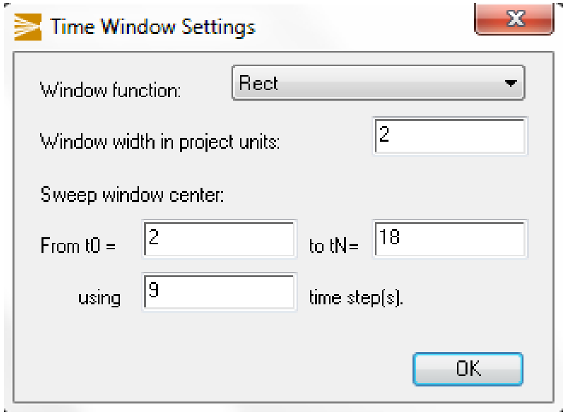
External TET Field Import



Spectrogram

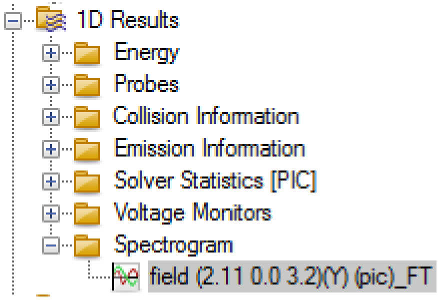
Frequency vs. Time Behaviour for Non-linear Systems

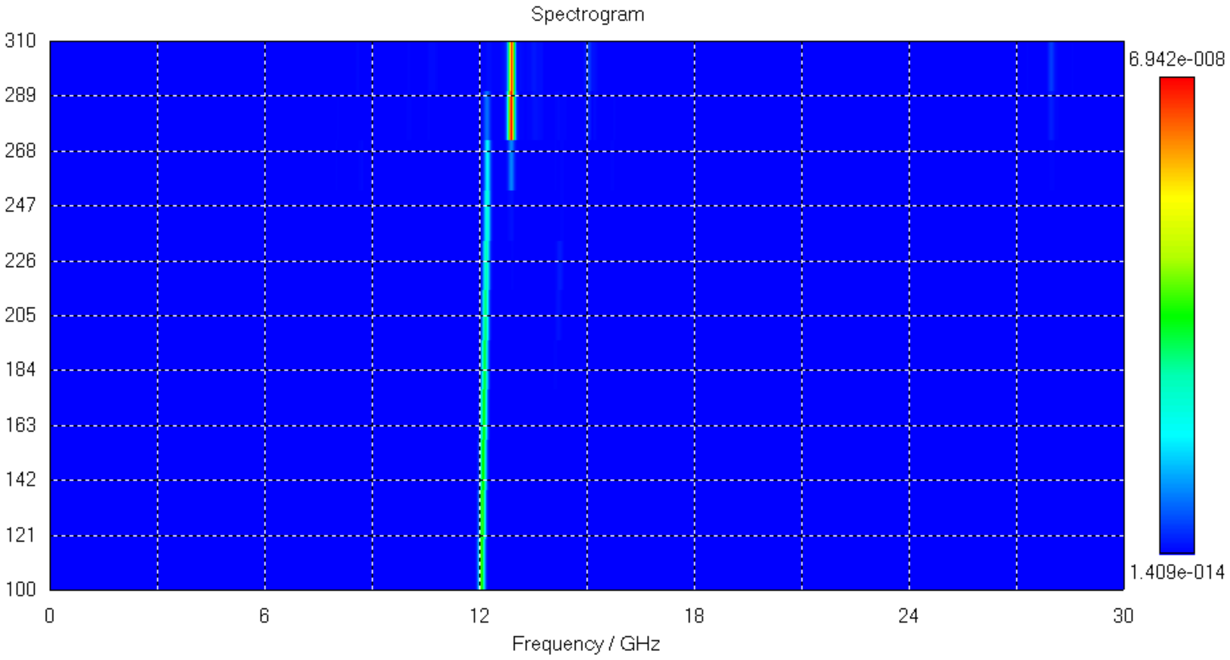




Spectrogram

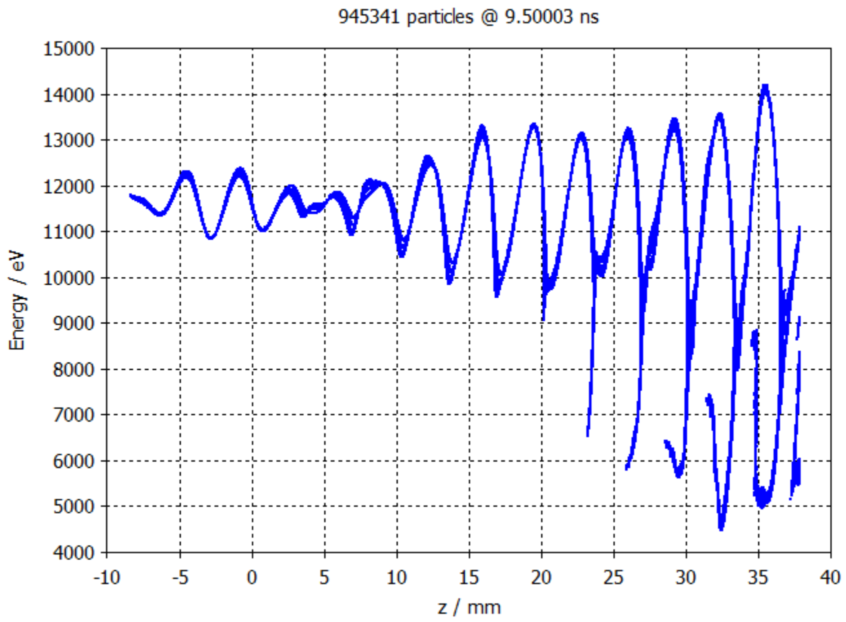
Frequency vs. Time Behaviour for Non-linear Systems





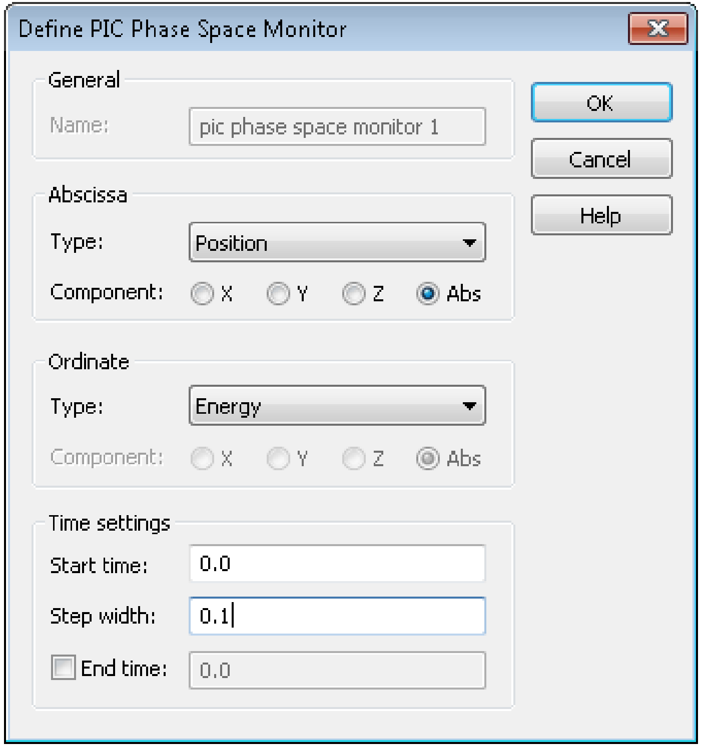
Phase Space Monitor

- Performance Improvement
  - → Faster resize
  - → Faster plot option change



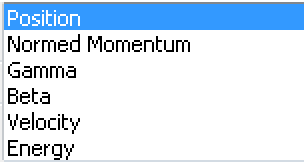
Phase Space Monitor

- More Flexibility
  - Abscissa and ordinate can be chosen from:
    - Position
    - Normed Momentum
    - Gamma
    - Beta
    - Velocity
    - Energy



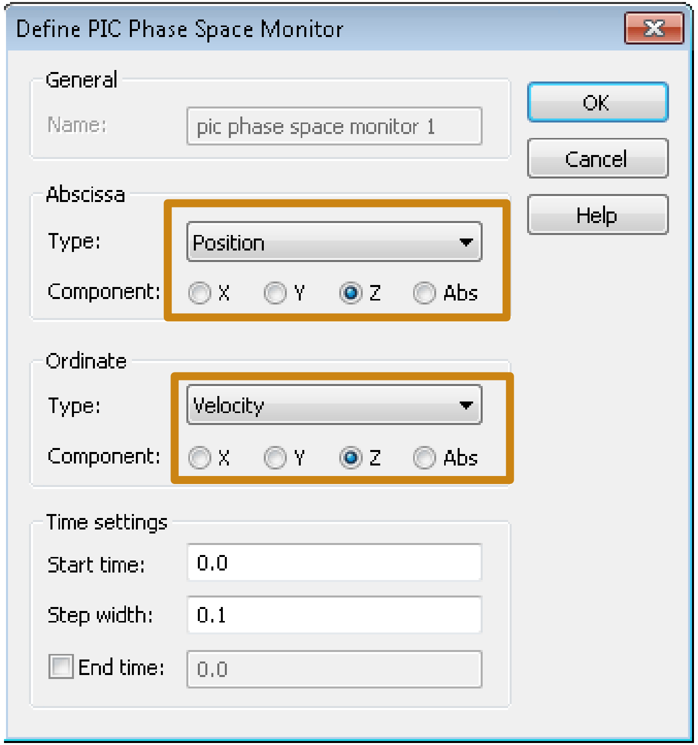
Phase Space Monitor

- More Flexibility
  - Abscissa and ordinate can be chosen from:



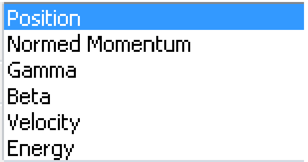
  - Special Case:

    Equal Position and Velocity componente → Evaluation of longitudinal Emittance



Phase Space Monitor

- More Flexibility
  - Abscissa and ordinate can be chosen from:



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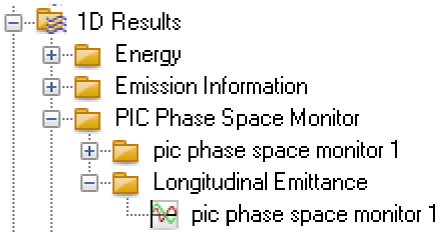
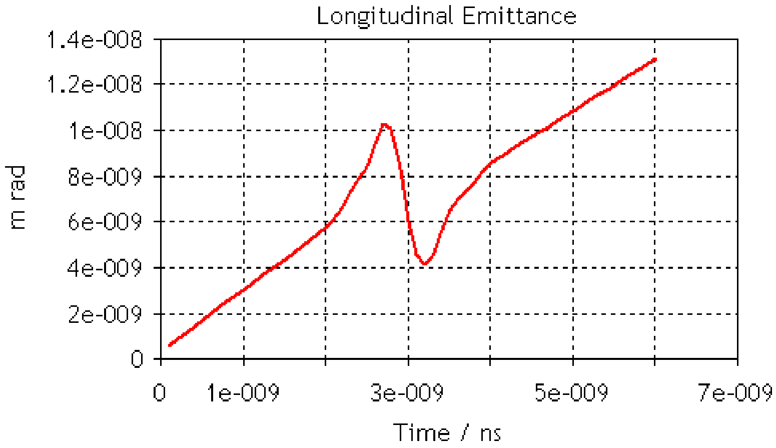
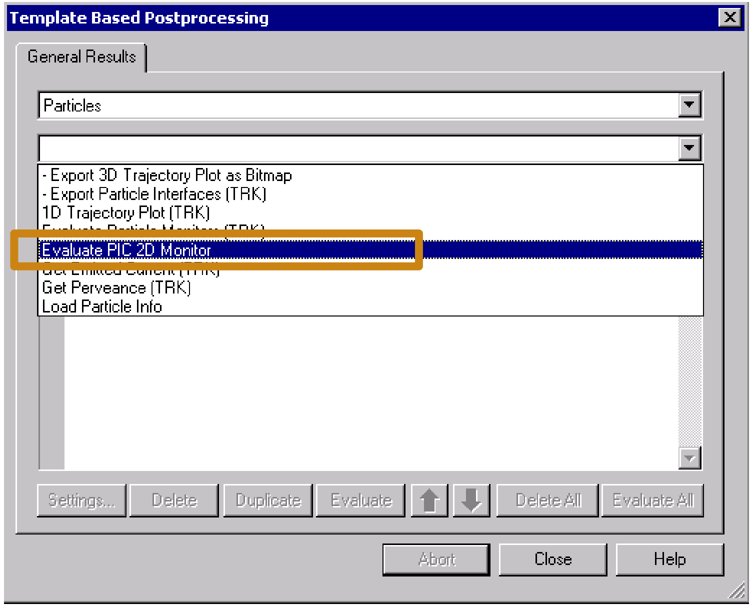
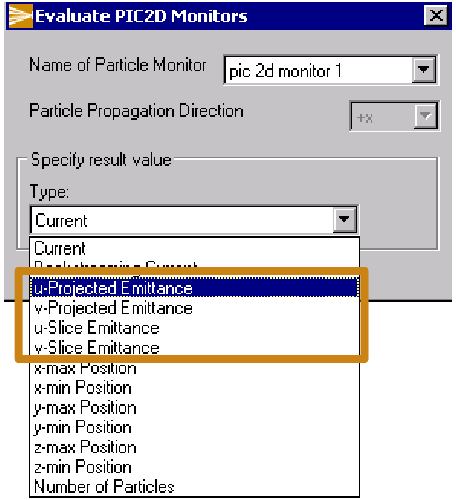




Emittance from PIC 2D Monitor

- Projected as well as slice emittance





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