ACE3P time-domain codes applied to CLIC

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SciDAC Scientific Discovery through Advanced Computing

SciDAC Finite Element Electromagnetics

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Parallel Finite Element EM code suite **ACE3P**

SLAC has developed the conformal, higher-order, C++/MPI-based parallel EM code suite ACE3P for high-fidelity modeling of large, complex accelerator structures.

ACE3P: Parallel Finite Element EM Code Suite

(Advanced Computational Electromagnetics, 3D, Parallel)

	ACE3P Modules	– Accelerator Physics Application
Frequency Domain:	Omega3P	– Eigensolver (nonlinear, damping)
	S3P	– S-Parameter
Time Domain:	T3P	– Transients & Wakefields
	Pic3P	– EM Particle-In-Cell (self-consistent)
Particle Tracking:	Track3P	– Dark Current and Multipacting
	Gun3P	– Space-Charge Beam Optics
Multi-Physics:	TEM3P	– EM-Thermal-Mechanical

Visualization: ParaView – Meshes, Fields and Particles

Funded by SciDAC1 (2001-2006) and continuing under SciDAC2 (in black)
Under development for ComPASS (2007-2011) (in blue)

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ACE3P Finite Element EM Time-Domain

Combine Ampere's and Faraday's laws

$$\nabla \times \nabla \times \vec{E} + \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu\sigma_{eff} \frac{\partial \vec{E}}{\partial t} = -\mu \frac{\partial \vec{J}}{\partial t}$$

$$\sigma_{eff} = \omega\varepsilon_0\varepsilon_i$$

T3P and Pic3P: full-wave EM from first principles

Unconditionally stable time integration*

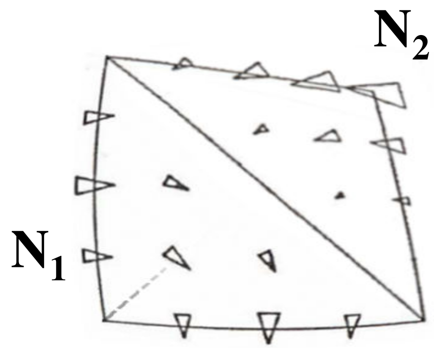
Solve linear system at every time step:

Ax=b

ACE3P Finite Element Method:

Curved tetrahedral finite elements with higher-order vector basis functions $\mathbf{N_i}$:

$$\mathbf{E}(\mathbf{x}, t) = \sum_i e_i(t) \cdot \mathbf{N_i}(\mathbf{x})$$



For order *p*=2: 20 different $\mathbf{N_i}$'s
For order *p*=6: 216 different $\mathbf{N_i}$'s

*__Navsariwala & Gedney__, *An unconditionally stable parallel finite element time domain algorithm*, Antennas and Propagation, **1996**

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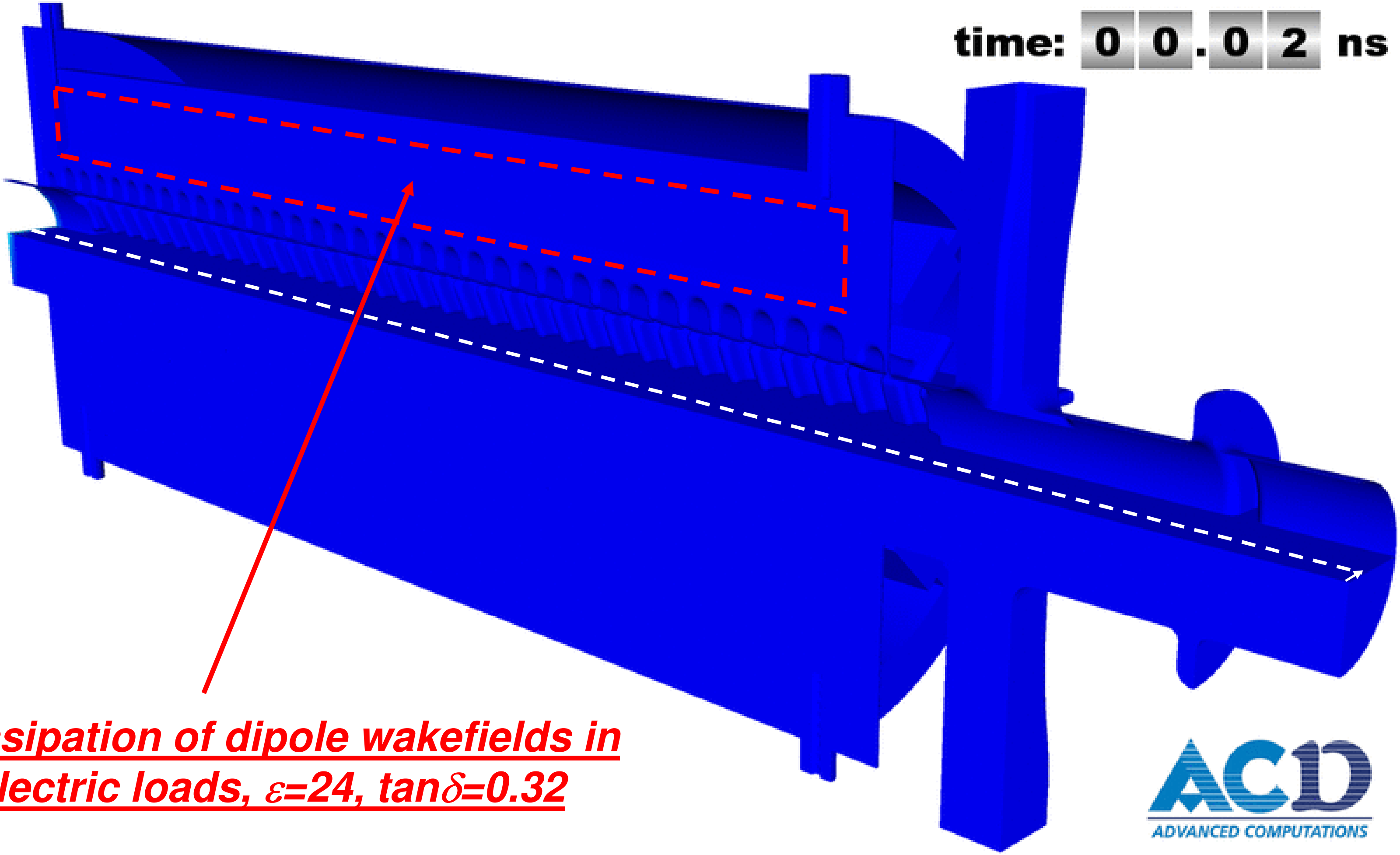
Previous work: PETS wakefield damping…



Dissipation of dipole wakefields in dielectric loads, ε=24, tanδ=0.32

ACD ADVANCED COMPUTATIONS

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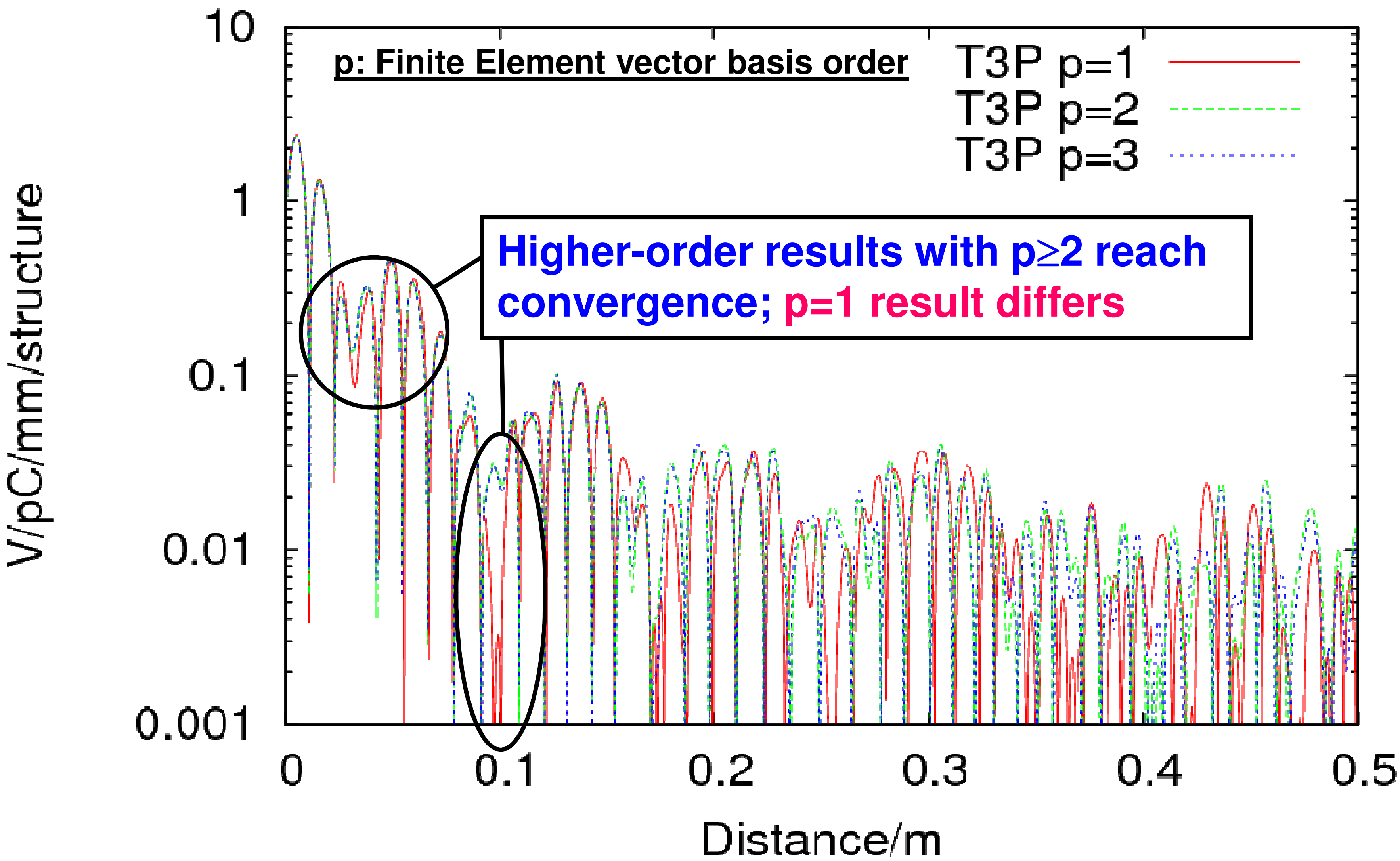
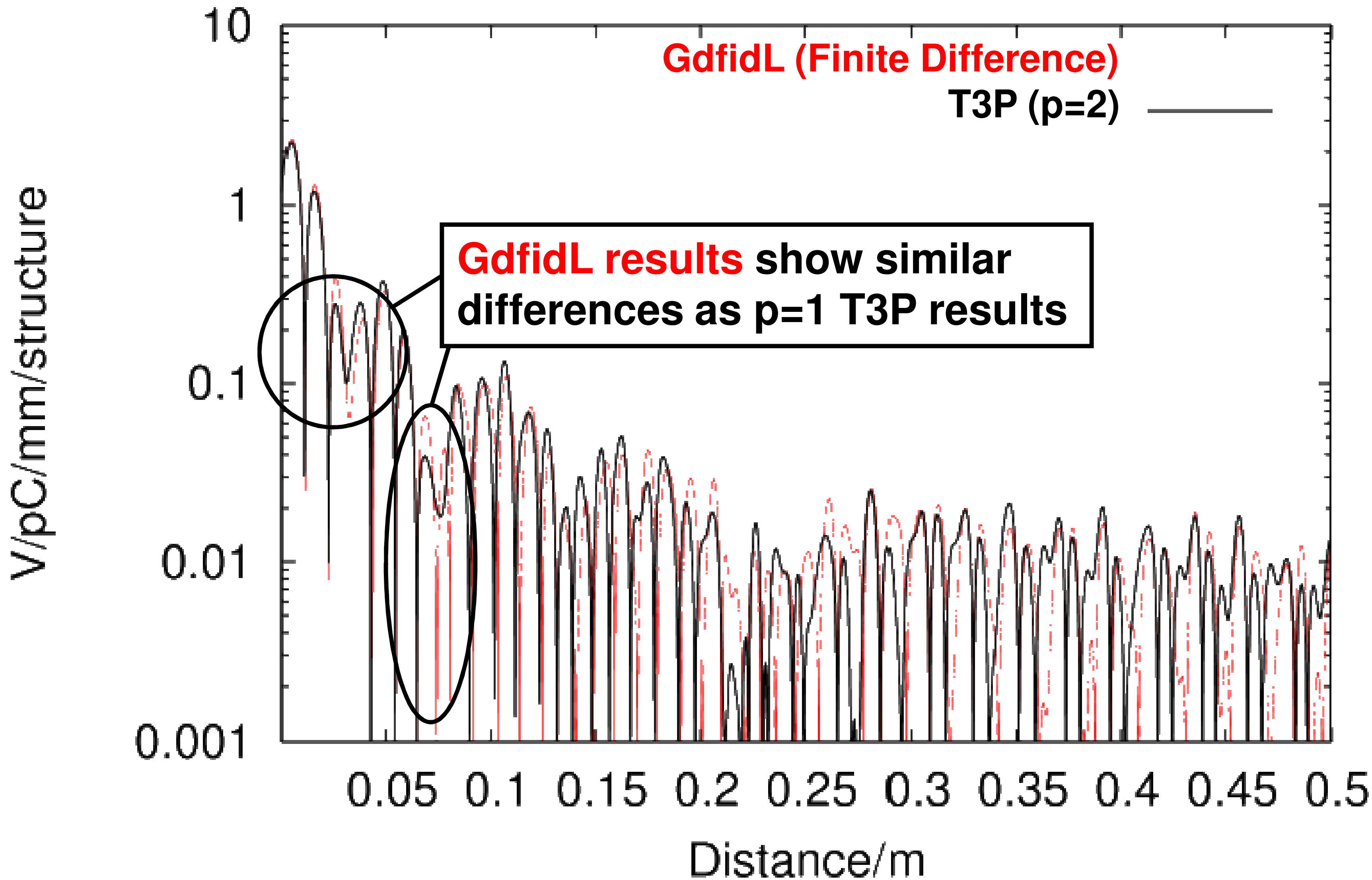
… PETS wakefield convergence …

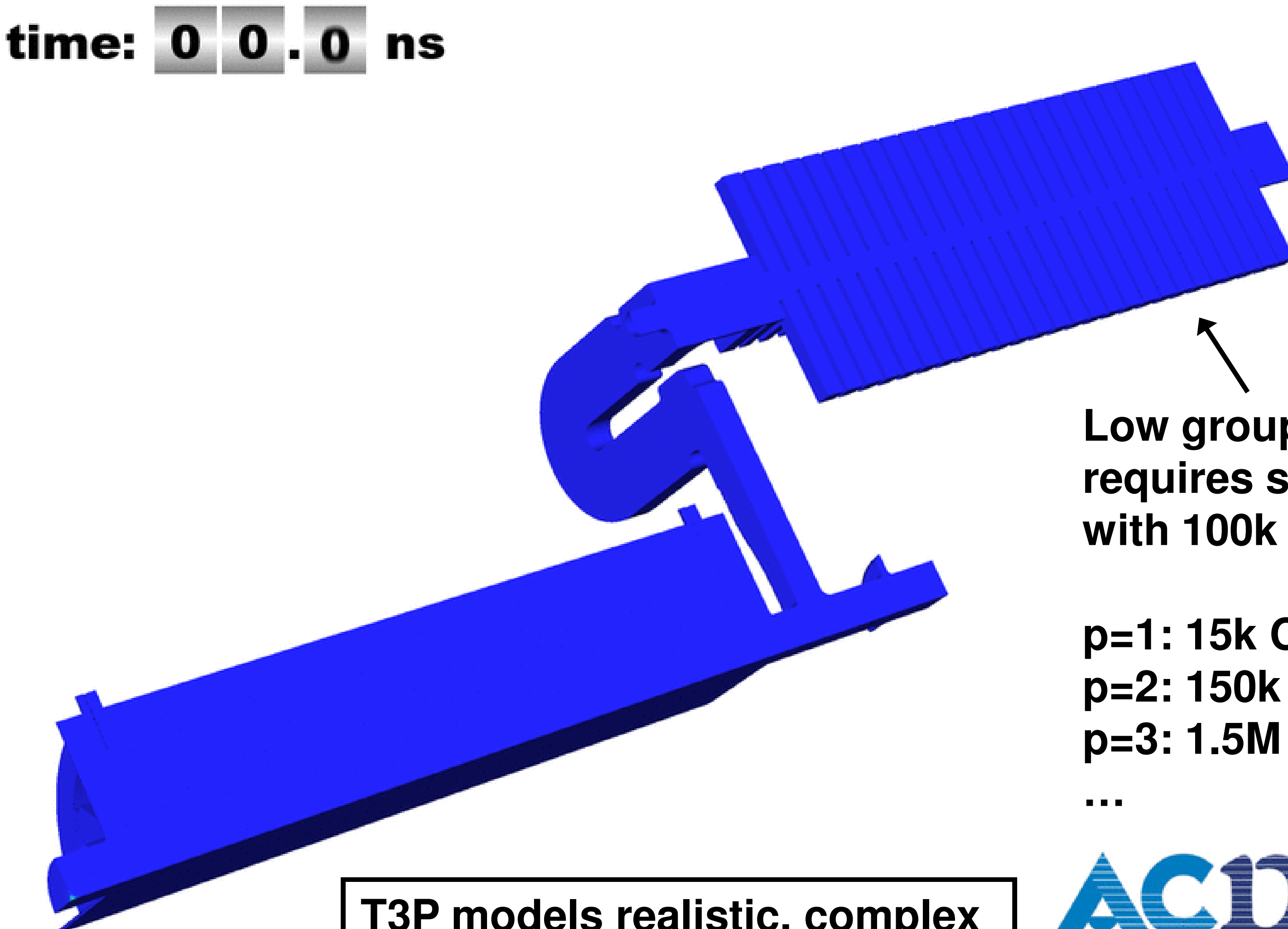


… Benchmarking: T3P vs. GdfidL …



Slightly simplified geometry - GdfidL results by I. Syratchev

… and Simulation of RF power transfer

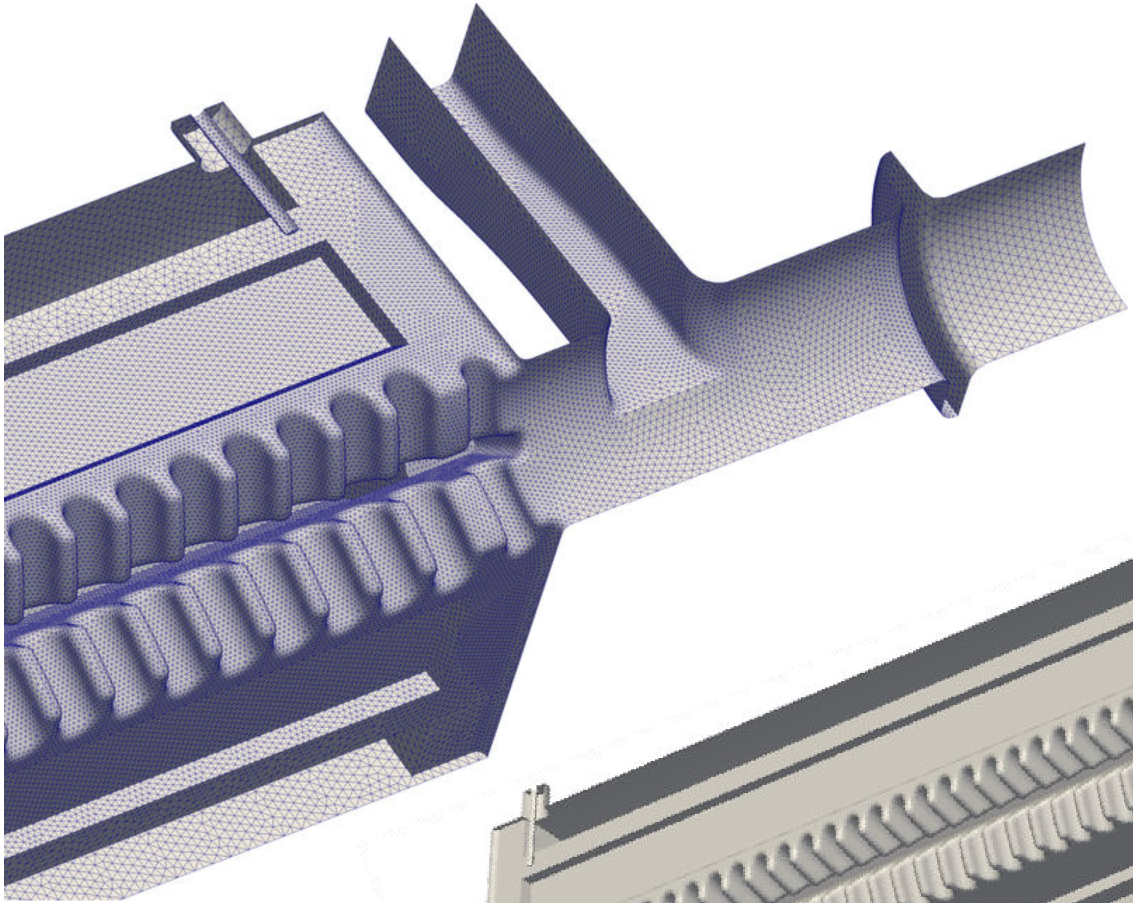


Low group velocity requires simulations with 100k time steps

p=1: 15k CPU hours
p=2: 150k CPU hours
p=3: 1.5M CPU hours
…

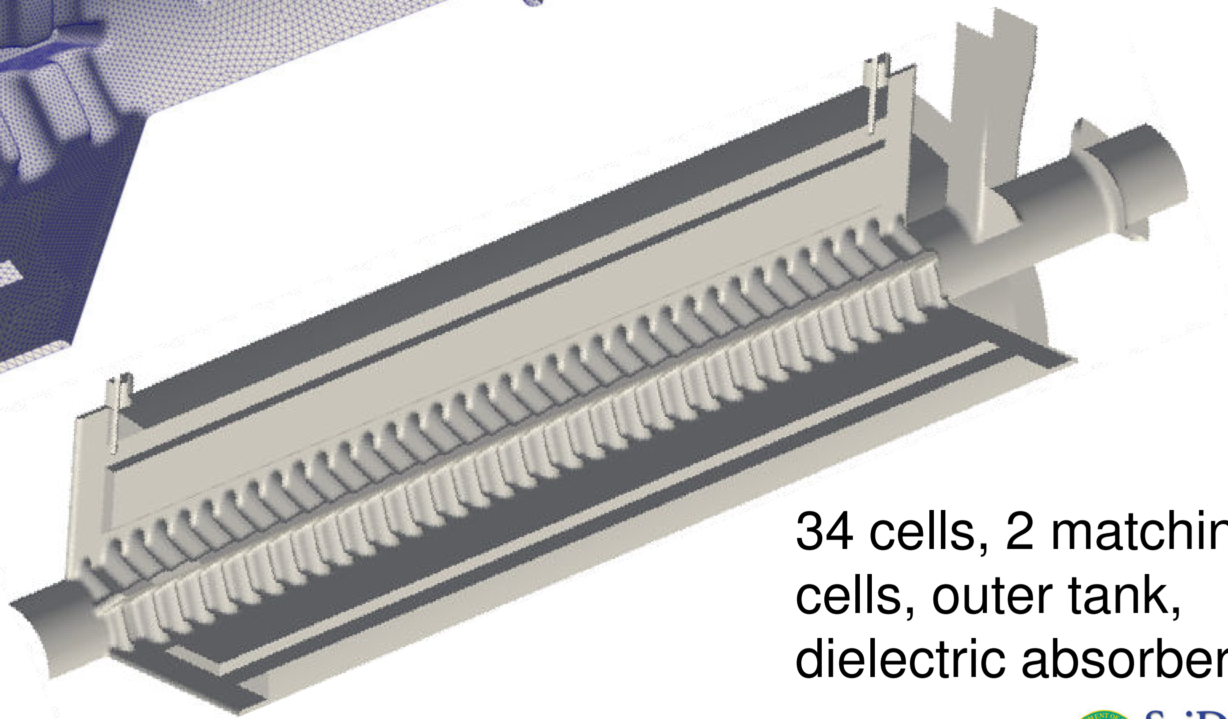
T3P models realistic, complex accelerator structures with unprecedented accuracy

Now… PETS power extraction study



Unstructured conformal (curved) mesh model of a quarter structure, 0.5 mm mesh size on iris:

3.7M tetrahedral elements



34 cells, 2 matching cells, outer tank, dielectric absorbers

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solid model courtesy CERN

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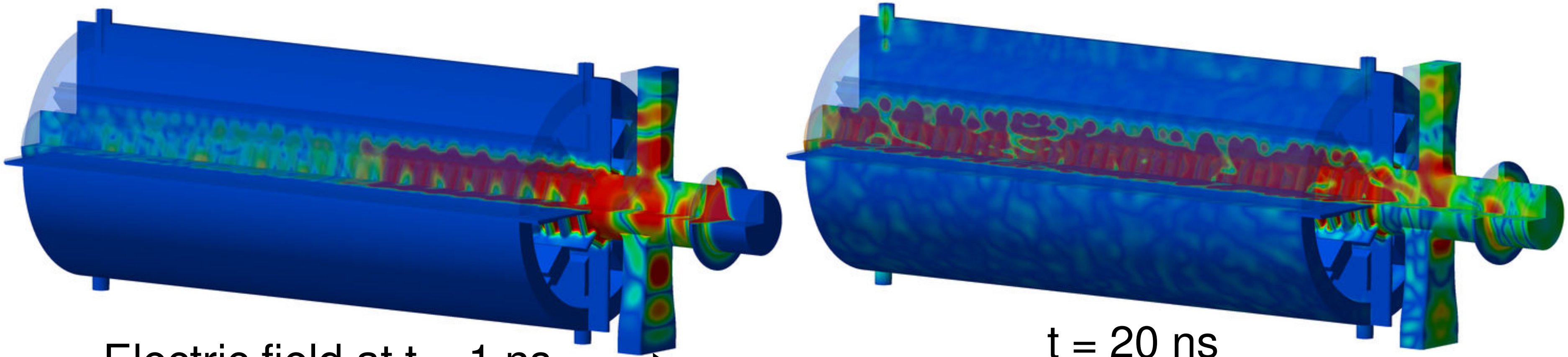
T3P - Single drive bunch in PETS

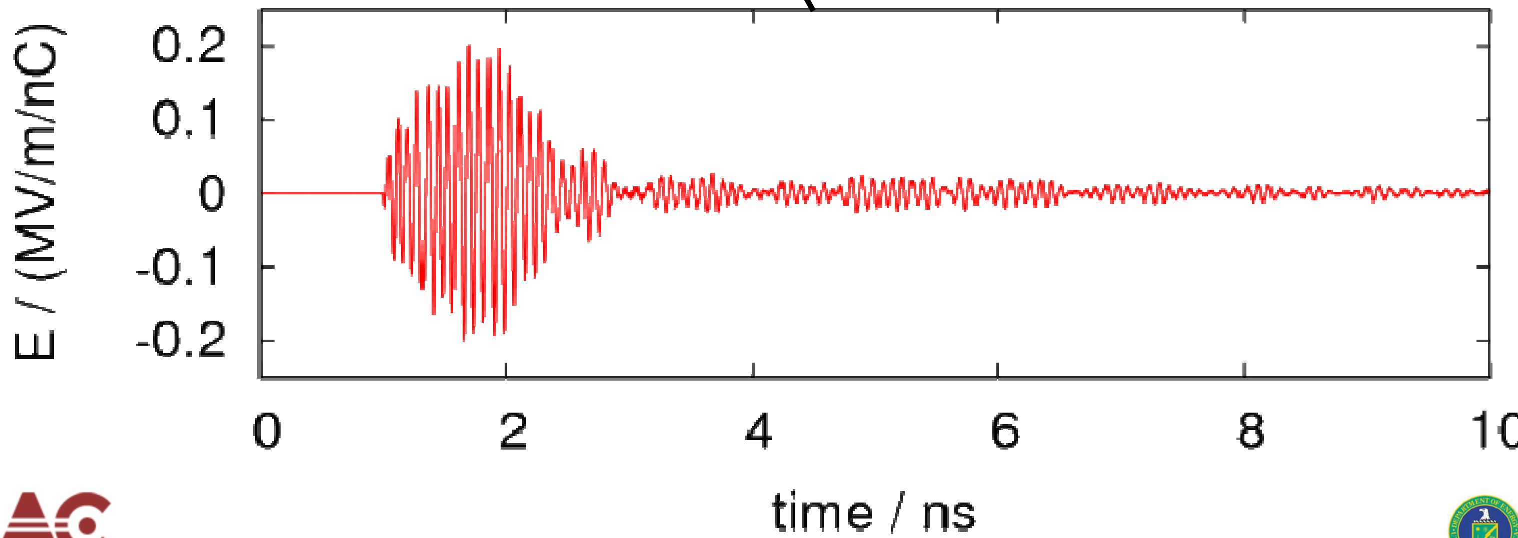


Electric field at t = 1 ns

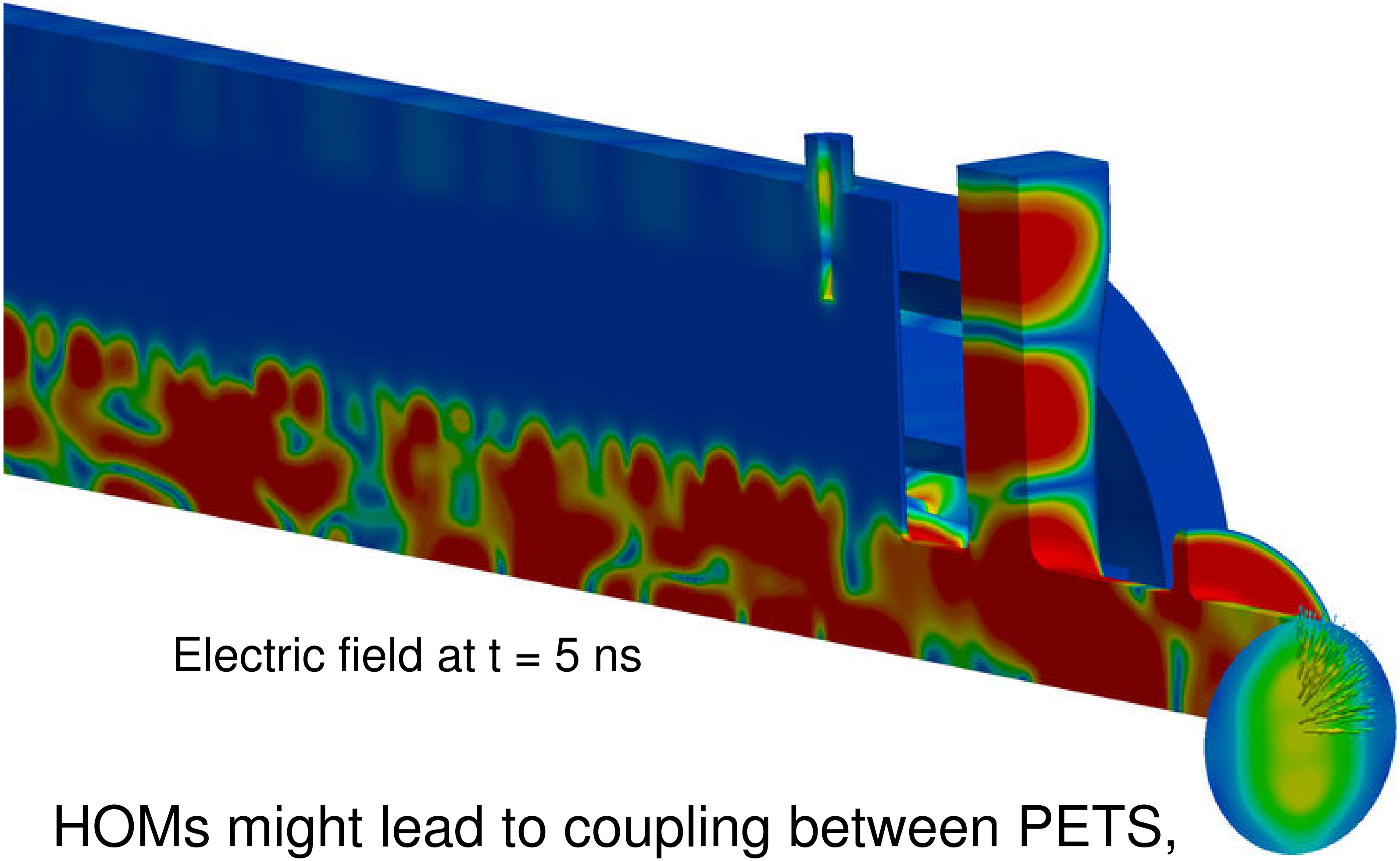
t = 20 ns
(renormalized scale)

E_{max} at PETS output port

σ_z=2 mm



T3P – HOMs in PETS (single drive bunch)

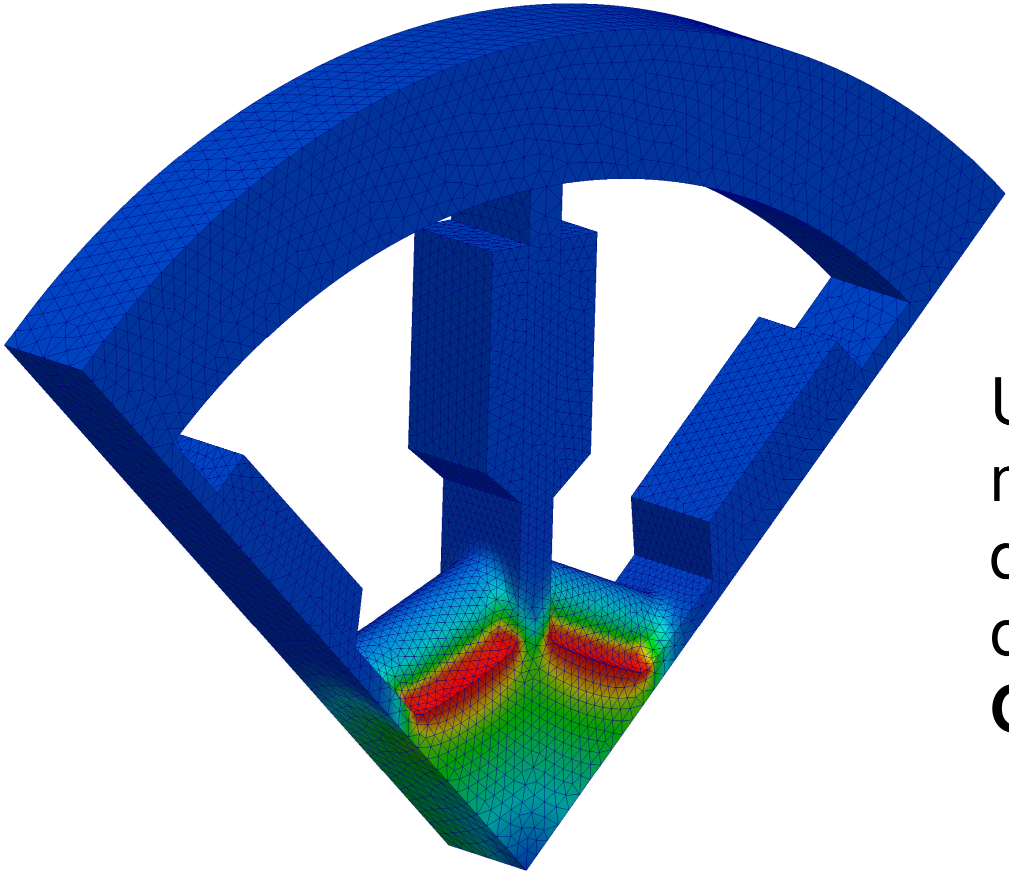


Electric field at t = 5 ns

HOMs might lead to coupling between PETS, requires further study.

PETS single cell RF frequency calculation

To model multiple drive bunches, need to know proper bunch spacing, given by RF frequency.



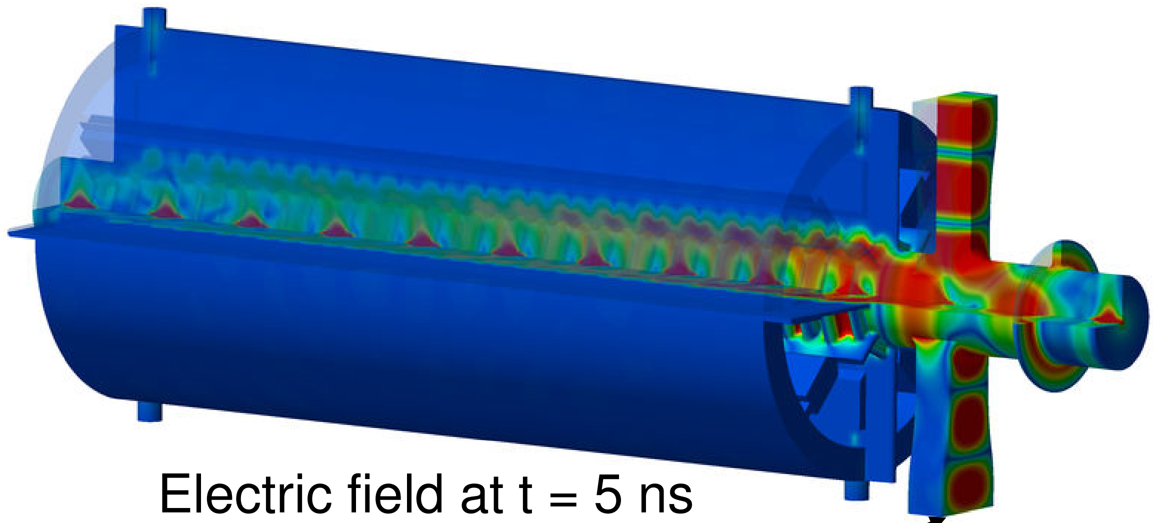
100k elements, p=2

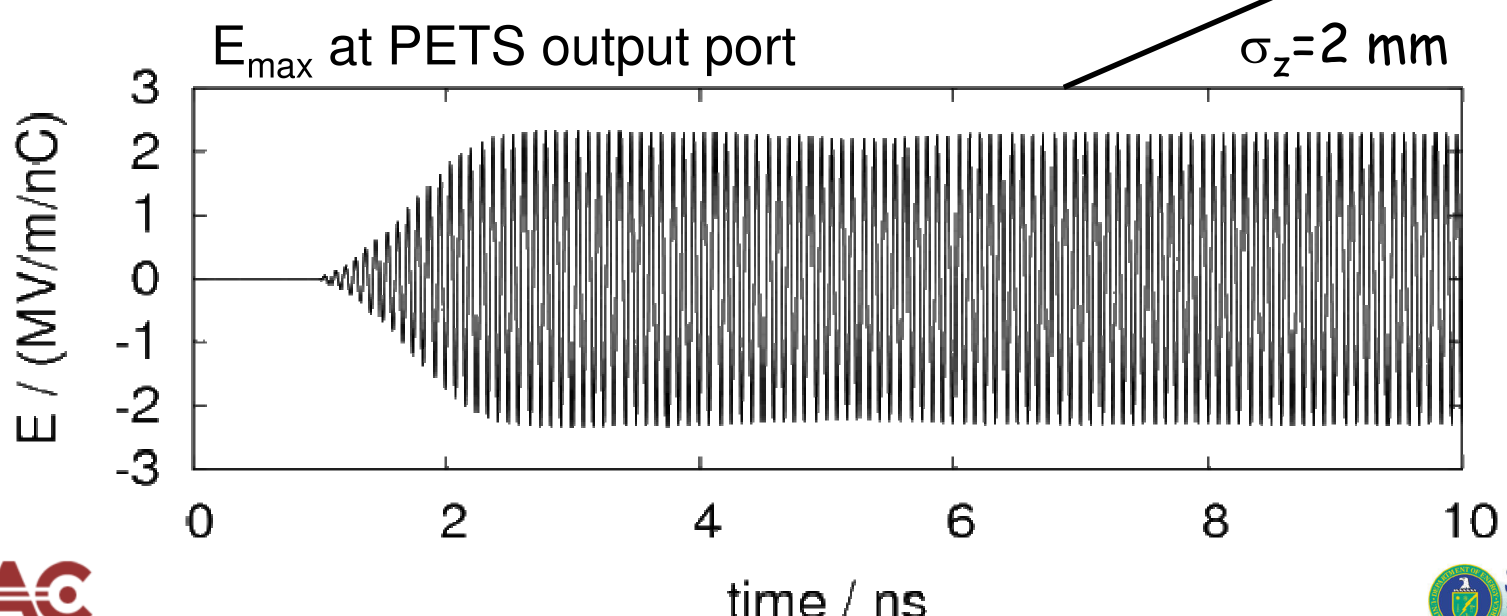
Using the same mesh model as for T3P time-domain calculations, obtain RF frequency with **Omega3P**:

f=11.9822(2) GHz

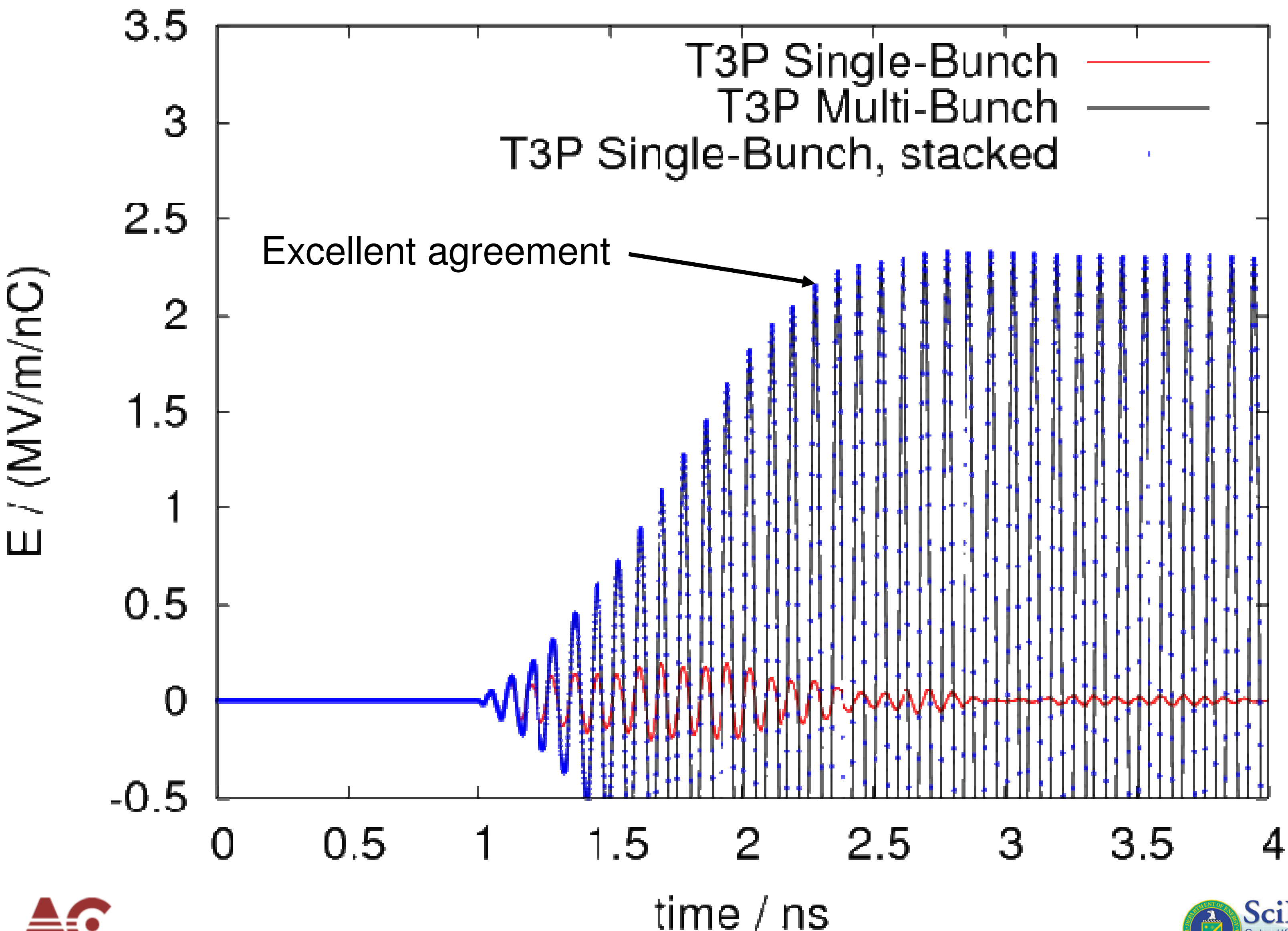
T3P - Multiple drive bunches in PETS

T3P simulation using one bunch per RF bucket:



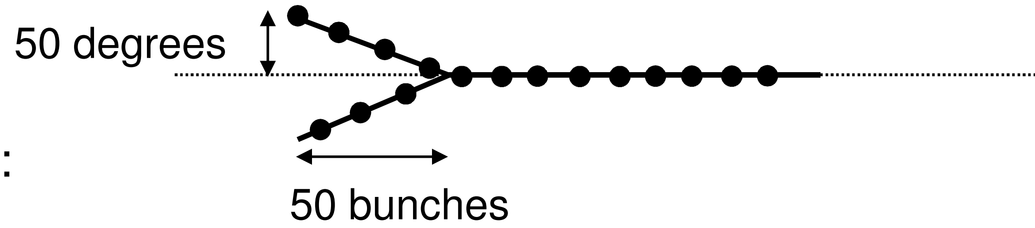


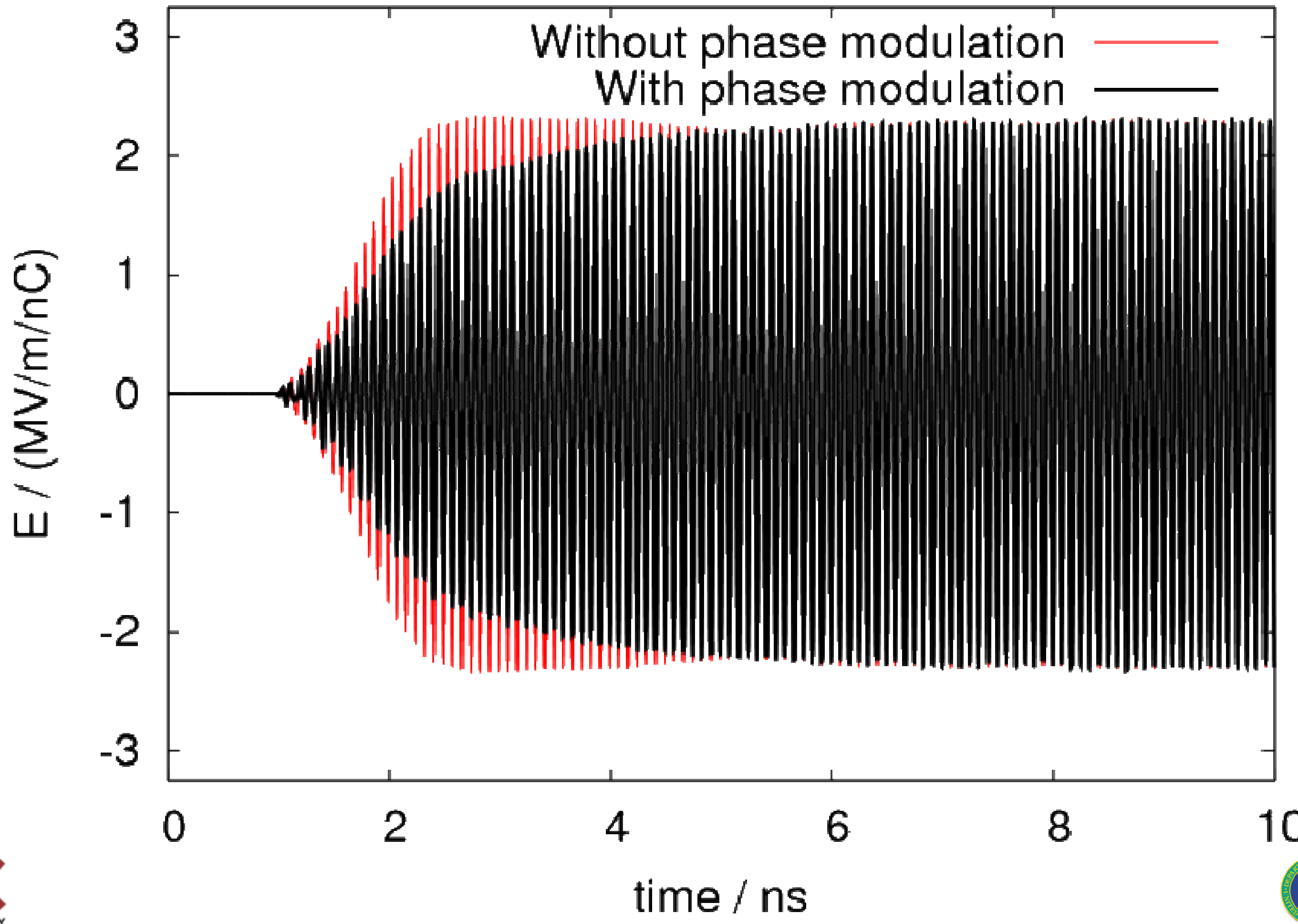
Multi-bunch simulation vs. stacking



RF pulse formation

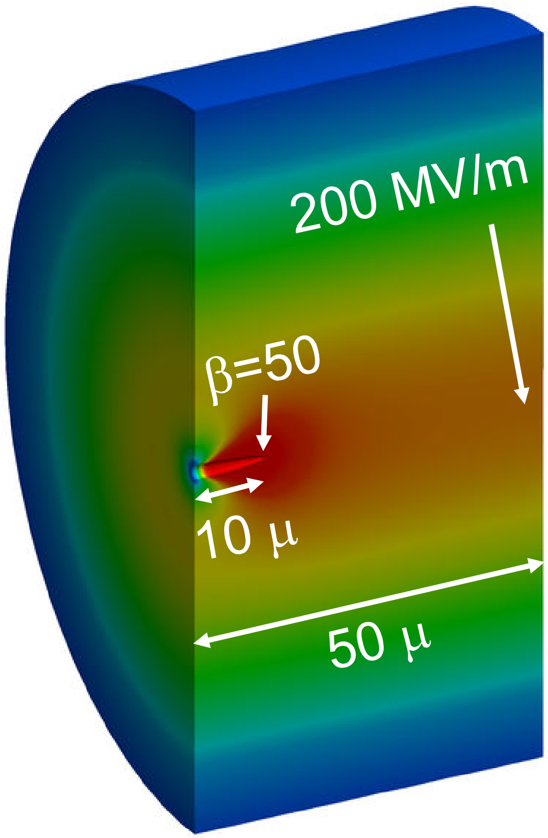
Phase modulation:
Ramping of drive bunch injection phase offsets, e.g.:





Pic3P: Dark current field emitter modeling

Aim: Use PIC code Pic3P to self-consistently model field emission process to help understand dark current emission and heating.



Enhanced surface RF fields calculated with **Omega3P**

Simulation parameters and assumptions:

- Ellipsoidal copper tip, half-axes 10μ x 1μ x 1μ (β=50)
- Surface fields obtained from eigenmode calculation
- Emission from tip surface, depends on local field strength (RF + space charge)

Fowler-Nordheim predicts emission of Q=0.67 pC from such a tip during one RF cycle, without space-charge effects. A PIC simulation is used to estimate the actually emitted charge.

1) Push (macro-)particles $$\frac{d\mathbf{p}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

2) Deposit charges $$\mathbf{J}(\mathbf{x}, t) = \sum_i q_i \cdot \delta(\mathbf{x} - \mathbf{x}_i(t)) \cdot \mathbf{v}_i(t)$$

3) Calculate EM space-charge fields

4) Emit particles using **Fowler-Nordheim** field emission **in RF *and* space charge fields**

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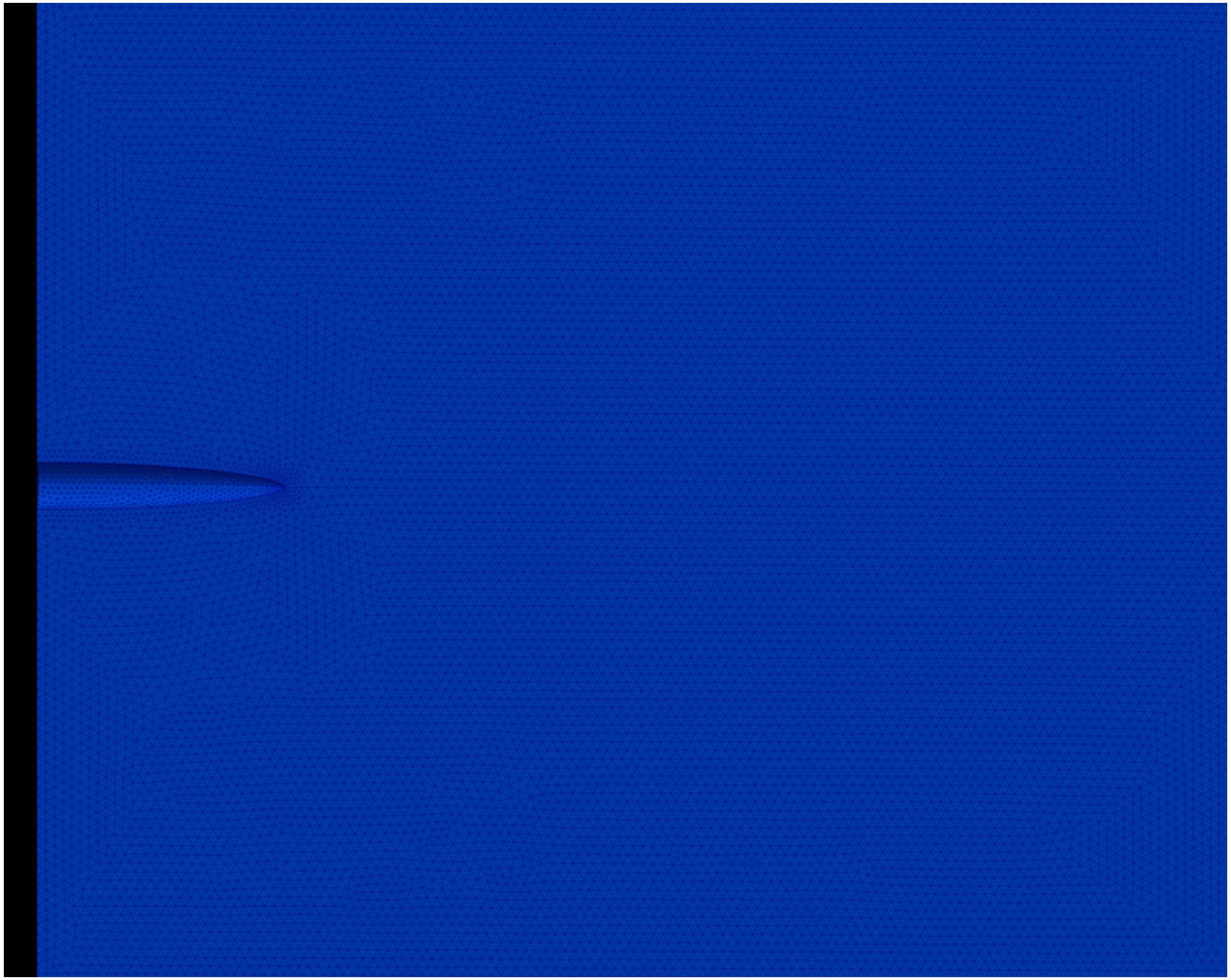
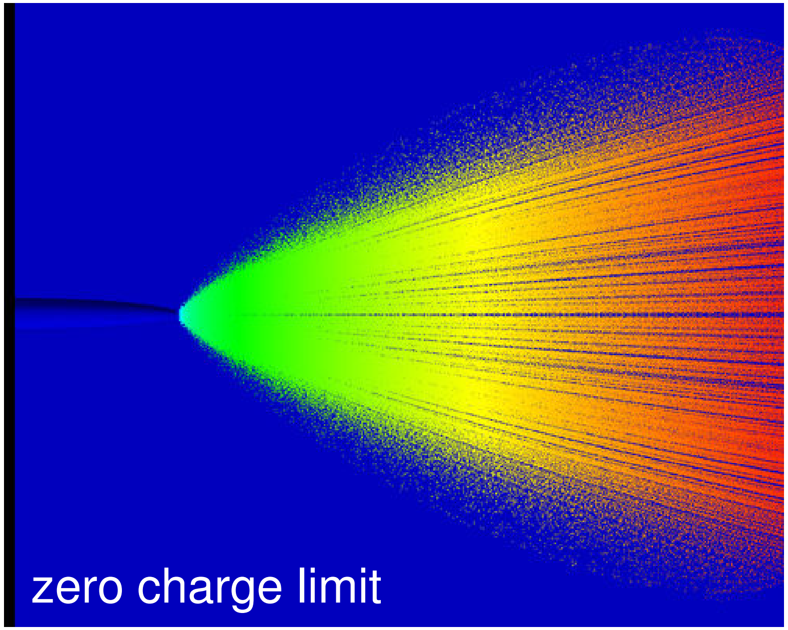
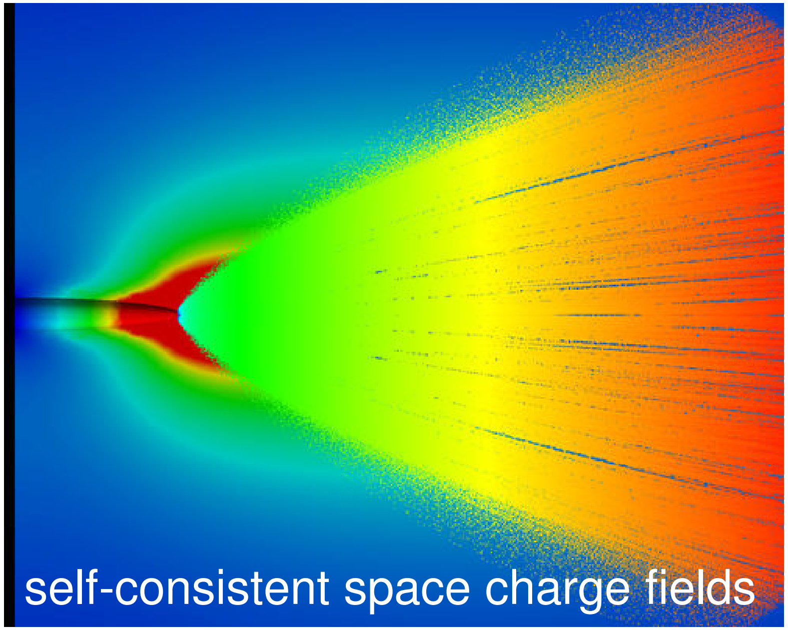
Pic3P: Self-consistent field emission



Pic3P simulation of field emission, including space-charge effects.
Parameters indicated on previous slide.
Particles colored by momentum, only space-charge fields shown.

Pic3P: Space-charge effect in field emission





For the simulated 10-degree window around the RF peak, Fowler-Nordheim without space-charge predicts Q=0.14 pC, but PIC simulation shows only Q=0.06 pC emitted charge.

Observed space-charge limitation of emission by a factor of ~ 2.
Estimated emitted average current for full RF cycle from this tip: ~ 5 mA

work in progress

Summary and Outlook

- **SLAC's Advanced Computations Department** has developed the **parallel Finite Element ACE3P code suite** for high-fidelity electromagnetic modeling of complex accelerator structures, using conformal unstructured meshes and higher-order field representation.
- **T3P** was applied to model the RF power generation in the PETS.
- **Pic3P** was applied to model self-consistent dark current field emission.

Future work may include (we welcome suggestions!)**:**

- Pulse formation and dispersive effects in accelerating structure
- Wakefield damping in accelerating structure
- Coupling between PETS and accelerating structure
- Calculation of trapped modes between PETS
- Further dark current field emission and heating studies

We acknowledge our SciDAC and CERN collaborators

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