TEM3P : Multiphysics Analysis Tool for Accelerator Applications

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Overview

- Advanced Computations Department
- Modern Accelerators and Multiphysics Problems
- TEM3P : Multiphysics Module in ACE3P Code Suite
- Applications
- Summary and Future Work

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Advanced Computations at SLAC & Collaborations

SLAC Team

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***Computational Scientists*:**

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Accelerator Collaborators

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Computational Science Collaborators (SciDAC 1 + 2: 2001-2012)

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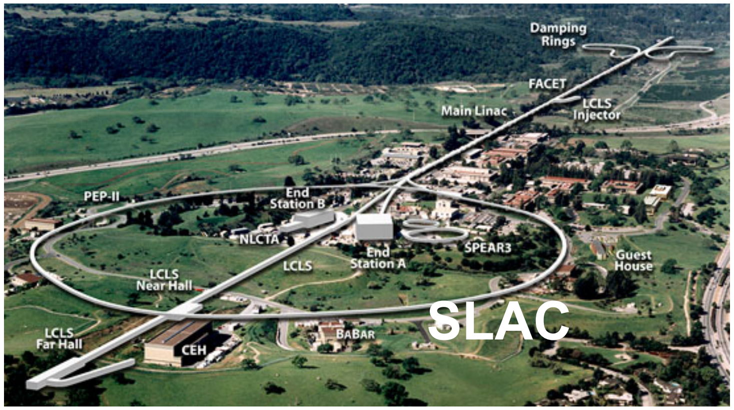
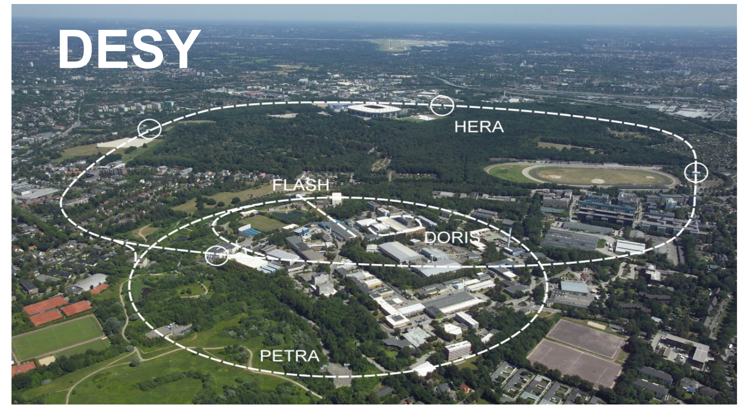
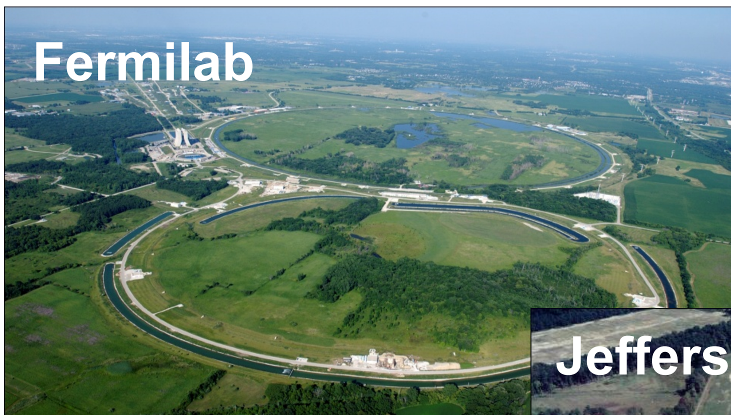
Particle Accelerator Facilities

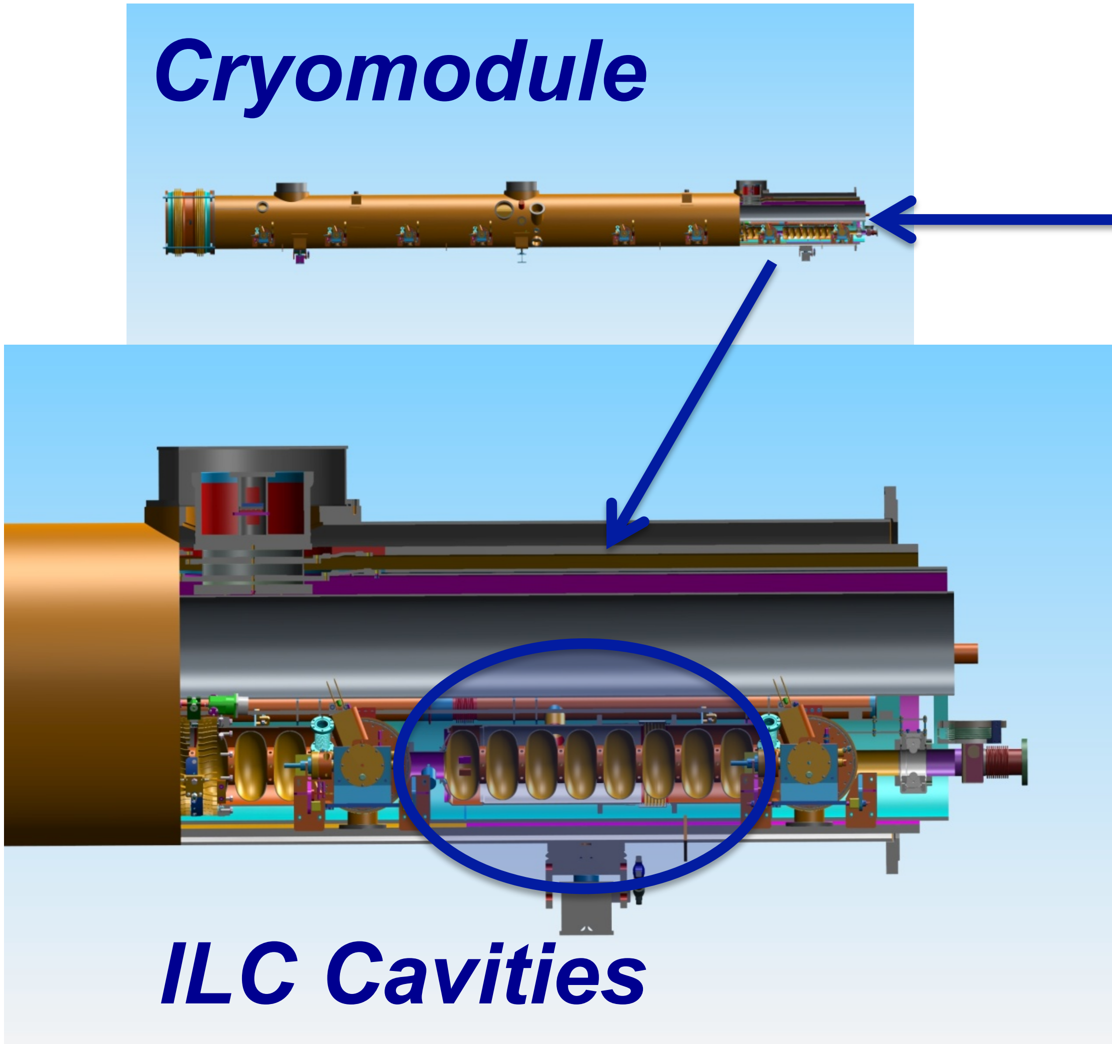


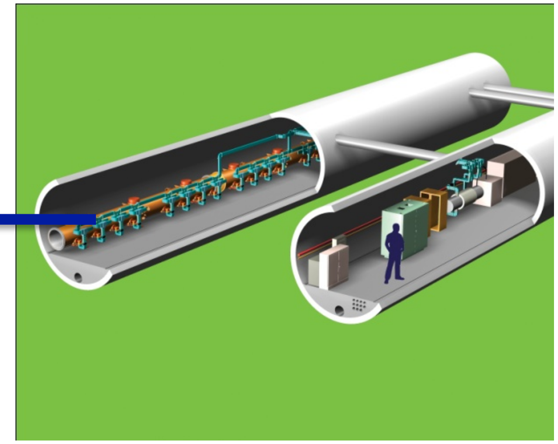




** Courtesy of SLAC, DESY, Fermilab, CERN, Jefferson Lab, International Linear Collider*

Superconducting Accelerator Cavity Module

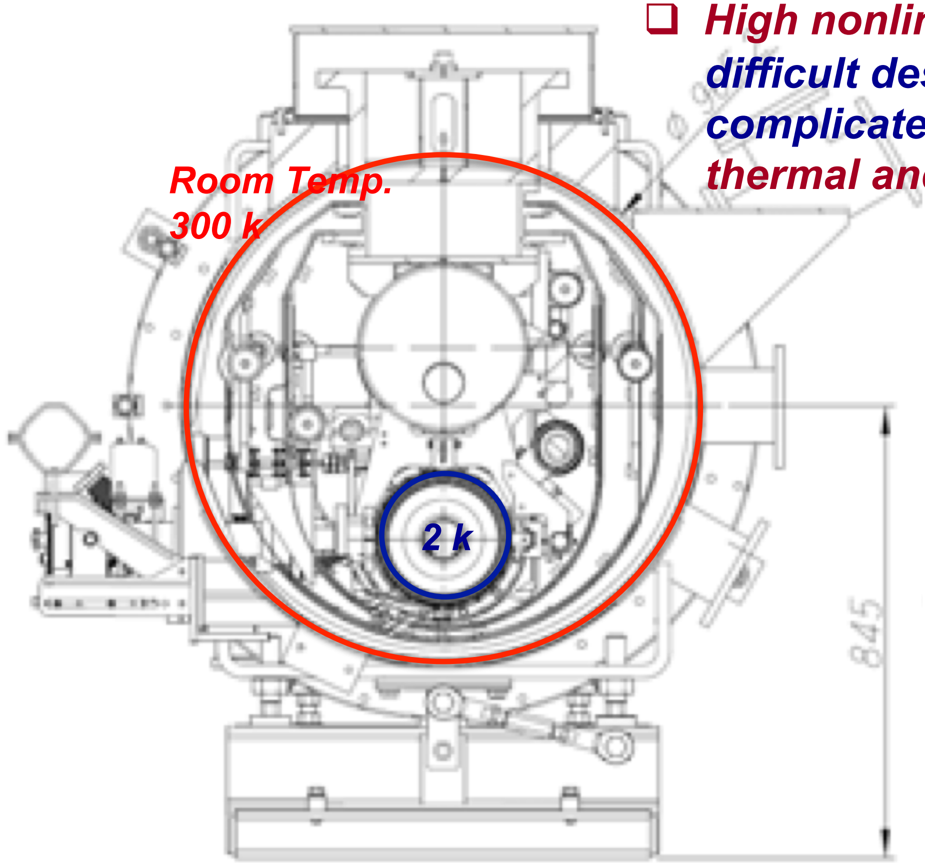


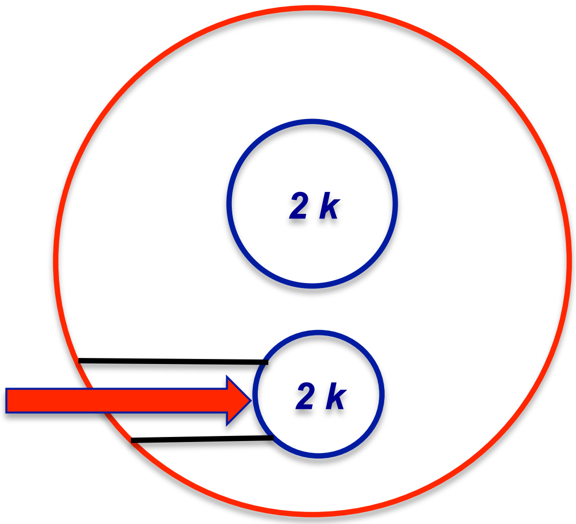


*** Courtesy of SLAC, DESY, Fermilab, CERN, International Linear Collider***

Thermal & Structural Problems

- ***Input Coupler introduces conduction heat transfer between 2 k and 300 k.***
- ***High nonlinearity of the material property poses difficult design challenges, due to the complicated interactions among electromagnetic, thermal and structural effects.***





**picture extracted from paper "S1-Global collaborative efforts 8-cavity-cryomodule : 2FNAL, 2 DESY and 4 KEK" by N. Ohuchi and et al.*

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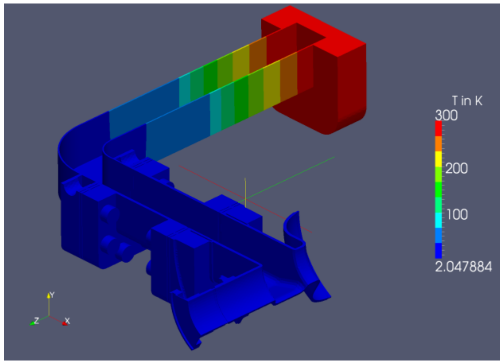
Multiphysics Analysis for Accelerator Cavity

- Thermal instability
  - An example of the sources
    - RF heating,
    - Highly nonlinear thermal conductivity and electrical resistivity of superconducting materials.
  - Results
    - $T > T_{critical}$
    - Superconductivity is lost.



- Structural deformation
  - Examples of the source
    - RF heating (thermal stress),
    - Large temperature differential (thermal stress),
    - Lorentz force detuning.
  - Results
    - Frequency shift (away from operating frequency),
    - Changes in EM field distribution,
    - Beam instability.
- Needs for fast, robust, and accurate multiphysics code

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Accelerator Modeling with EM Code Suite ACE3P

Meshing* - *CUBIT *for building CAD models and generating tetrahedral meshes*
http://cubit.sandia.gov

Modeling and Simulation – *SLAC's suite of conformal, higher-order, C++/MPI based parallel finite-element electromagnetic codes*
https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx

ACE3P (Advanced Computational Electromagnetics 3D Parallel)

Frequency Domain:	**Omega3P**	– **Eigensolver**
	S3P	– **S-Parameter**
Time Domain:	**T3P**	– **Wakefields and Transients**
Particle Tracking:	**Track3P**	– **Multipacting and Dark Current**
EM Particle-in-cell:	**Pic3P**	– **RF guns & klystrons**
Multi-physics:	**TEM3P**	– **EM, Thermal & Structural effects**

Postprocessing* - *ParaView *to visualize unstructured meshes & particle/field data*
http://www.paraview.org/

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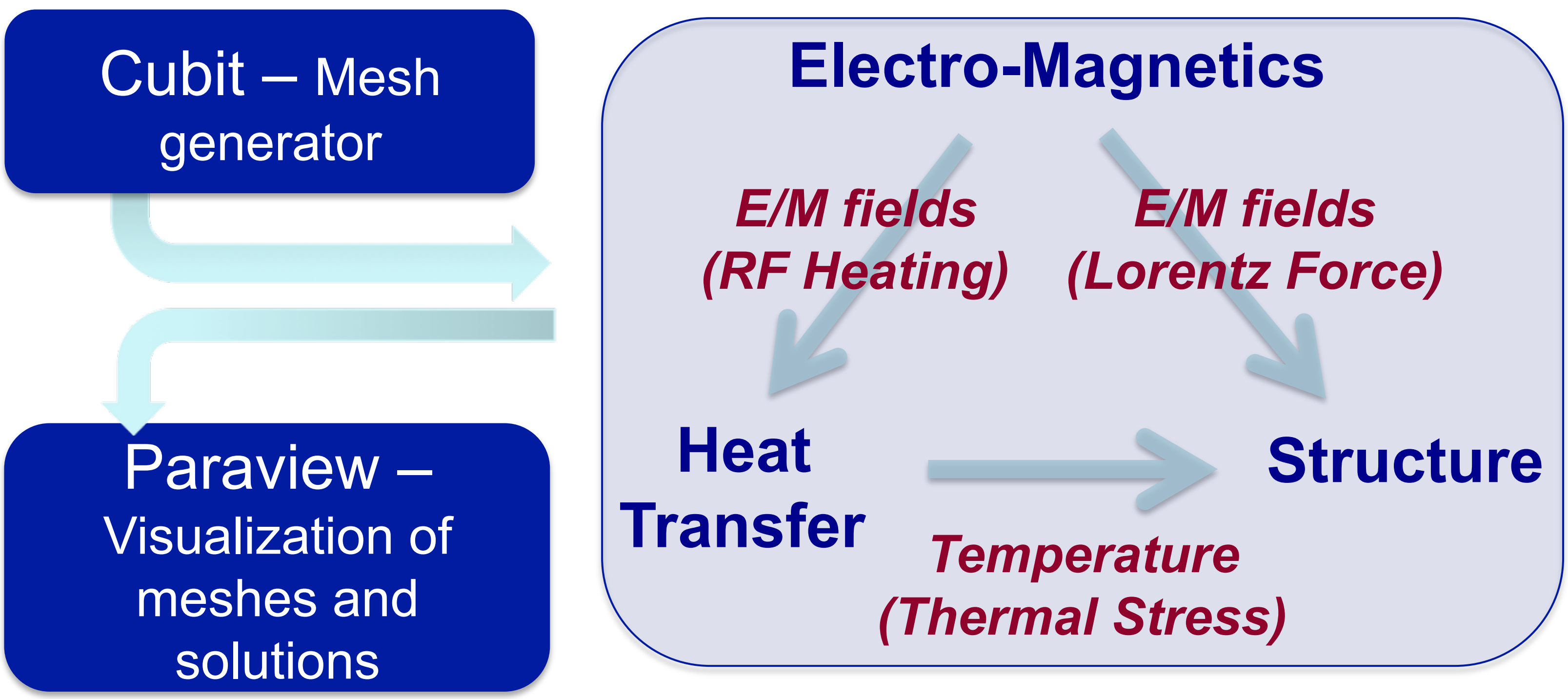
Multiphysics Code for Accelerator Cavity

- ***Successful operation of accelerators based on superconducting rf cavities depends heavily on the combined effects of thermal, structural, and electromagnetic interactions.***
- ***Parellel computatiom reduces cost and time of the design cycle.***
- ***Virtual prototyping of accelerator cavities on computers in a shared framework.***



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Governing Equations for Multiphysics Code

Omega3P

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \vec{E} \right) - k^2 \varepsilon \vec{E} = 0 \quad on \quad \Omega$$

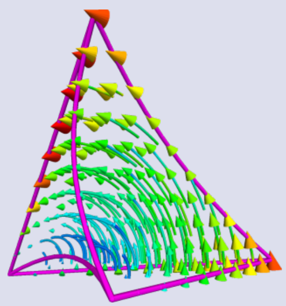
$$\vec{n} \times \vec{E} = 0 \quad on \quad \Gamma_E$$

$$\vec{n} \times \frac{1}{\mu} \nabla \times \vec{E} = 0 \quad on \quad \Gamma_M$$

$$Kx = k^2 Mx$$

$$Kij = \int_\Omega (\nabla \times N_i) \cdot \frac{1}{\mu} (\nabla \times N_j) d\Omega$$

$$Mij = \int_\Omega N_i \cdot \varepsilon N_j d\Omega$$



Using quadratic curved tetrahedral elements with higher-order vector basis functions

Tem3P

$$\nabla \cdot (k \nabla T) + Q = 0 \quad on \quad \Omega$$

$$T = T \quad on \quad \Gamma_D$$

$$[k \nabla T + q] n = 0 \quad on \quad \Gamma_N$$

Using nodal basis functions

$$\nabla \cdot \left[\mu \left(\nabla u + \nabla u^T \right) + \lambda (\nabla \cdot u) I - (3\lambda + 2\mu) \alpha \nabla T \right] = 0 \quad on \quad \Omega$$

$$u = \hat{u} \quad on \quad \Gamma_D$$

$$\bar{t} n = 0 \quad on \quad \Gamma_N$$

$$where \quad \mu = \frac{E}{2(1+v)}, \lambda = \frac{vE}{(1+v)(1-2v)}$$

For linear elasticity and isotropic material

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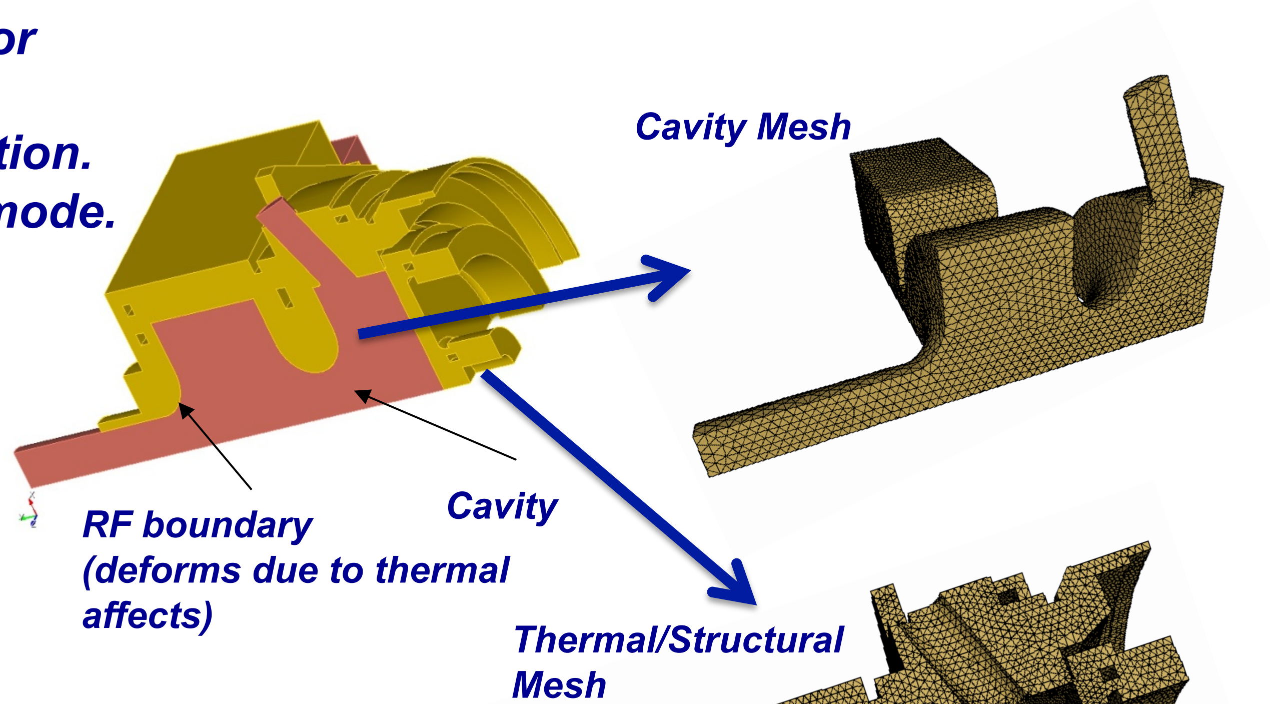
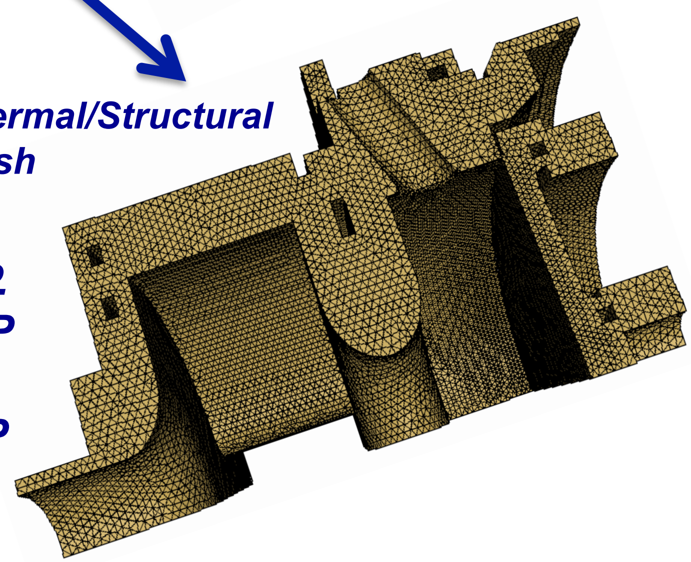
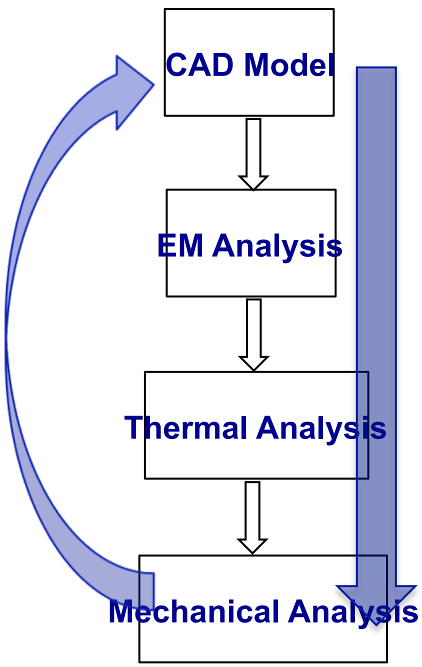
Virtual Prototyping of LCLS RF Gun

- ❑ ***Problem: High current or high voltage induces***
  - ❑ ***Structural deformation.***
  - ❑ ***Shift accelerating mode.***







- ❑ ***Analysis Steps :***
  - ❑ ***EM fields from Omega3P.***
  - ❑ ***Temperature from Tem3P (RF heating).***
  - ❑ ***Deformation from Tem3P (Thermal load).***

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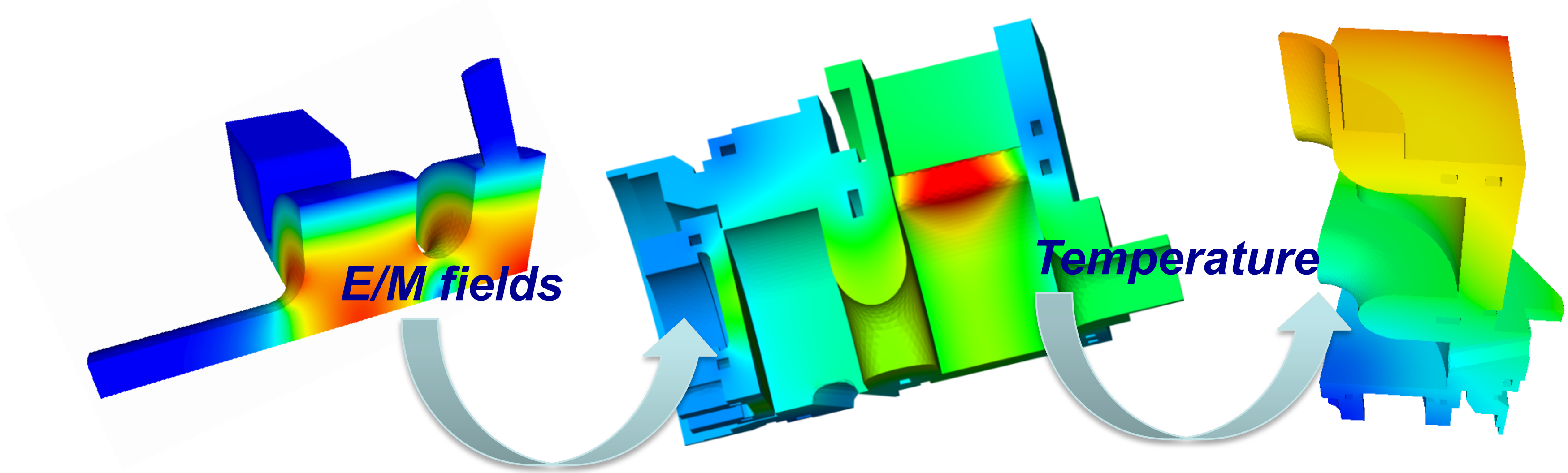
Linac Coherent Light Sources RF Gun

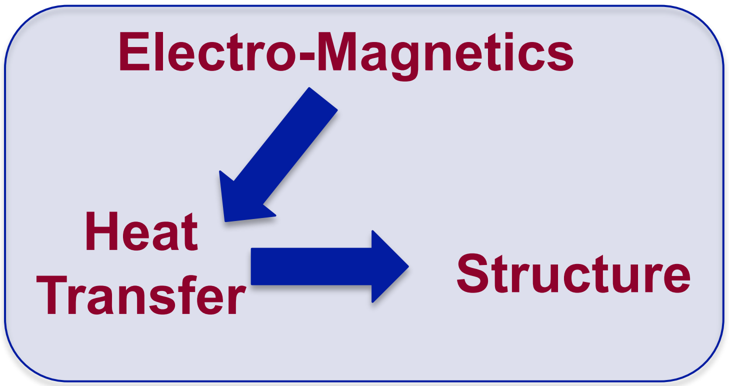
TEM3P Simulation of LCLS RF Gun

Benchmarked with Ansys

Operating mode : 2.856 GHz ***T_{max} = 49.82 C*** ***U_{max} = 3.699e-5 m***



- ***Identify frequency shift of 650 kHz caused by thermal drift in the accelerating frequency***
  - ***Water temperature is lowered to compensate for this shift***



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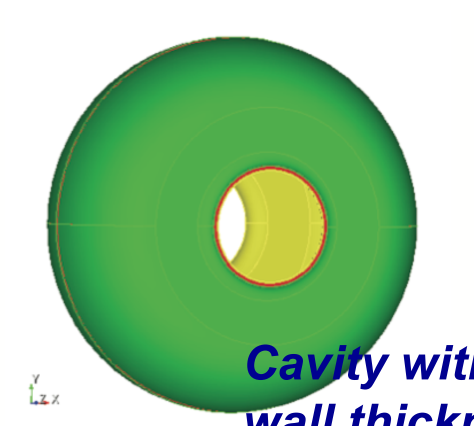
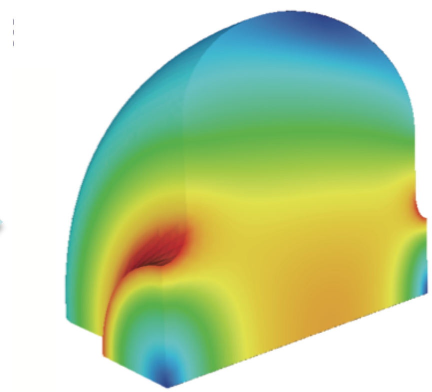
Lorentz Force Detuning of Ichiro Cavity

CAD Model



Cavity with 2.8 mm wall thickness

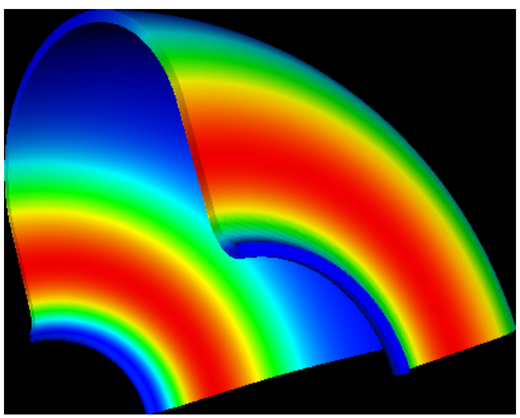
EM Analysis with Omega3P



Lorentz Force Calculation with Tem3P

$$P_L \propto \frac{1}{4}\left(\mu_0 H^2 - \varepsilon_0 E^2\right)$$

Structural deformation field



Electro-Magnetics

Heat Transfer

Structure

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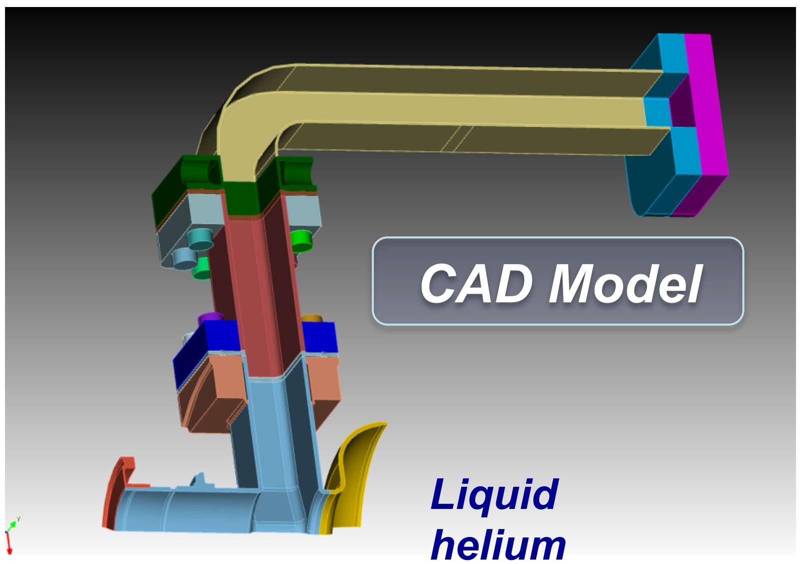
JLab HCCM HOM Coupler

- *Performance of next generation accelerators requires precise thermal and mechanical analyses along with accurate electromagnetic design.*
- *In the superconducting cavity study, high nonlinearity of material properties poses challenging problem.*



Jlab High Current Cryomodule Cavity Higher Order Mode Coupler

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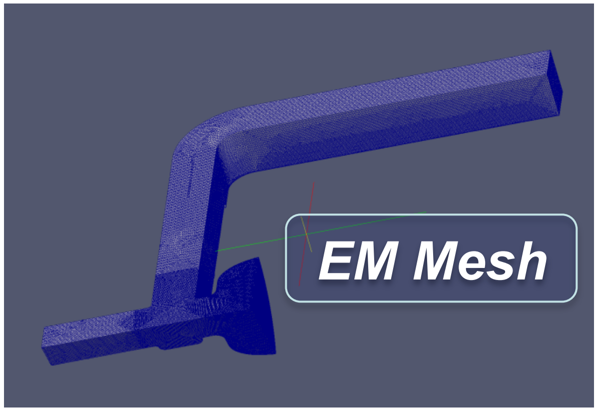
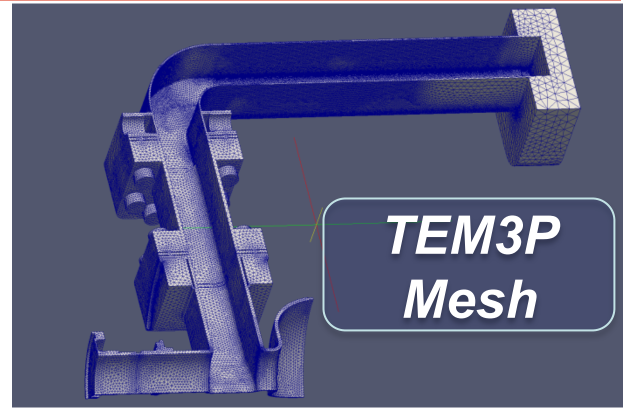
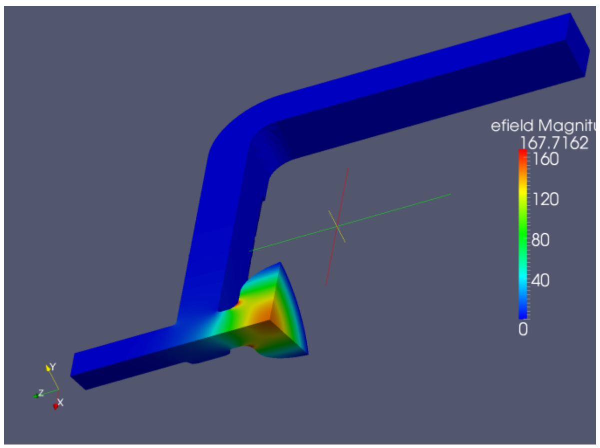
TEM3P Simulation of HCCM HOM Coupler

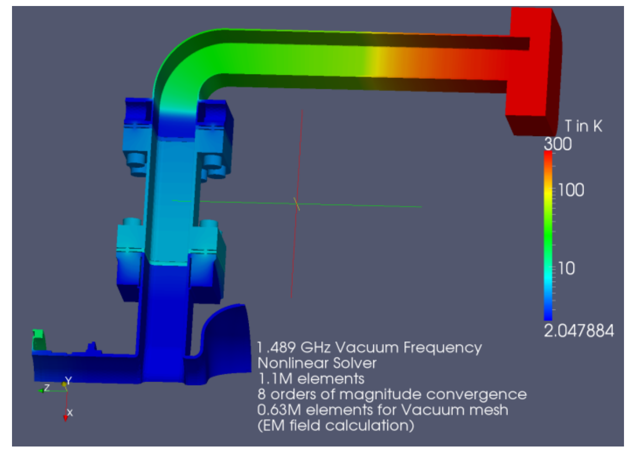


- ❑ ***Materials:***
  - ❑ ***Nb***
  - ❑ ***Nb-Ti***
  - ❑ ***AlMg***
  - ❑ ***Cu***
  - ❑ ***StainlessSteel***





Benchmarked with Ansys



- ❑ ***Successfully solved highly nonlinear thermal problem using multiphysics coupling.***
- ❑ ***Temperature spans from ~ 2 k to 300 k.***

Electro-Magnetics

Heat Transfer

Structure

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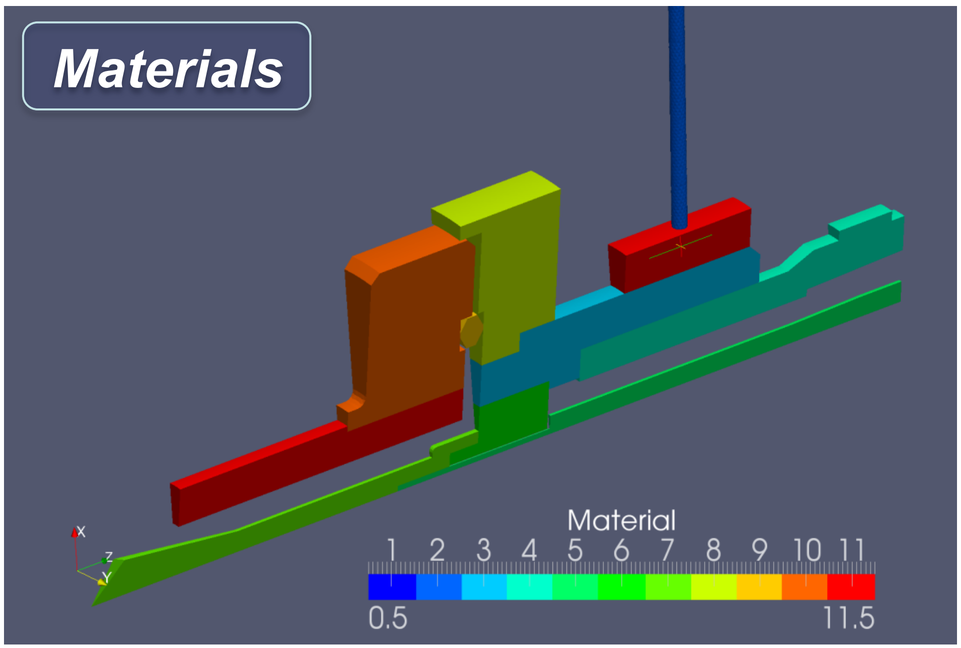
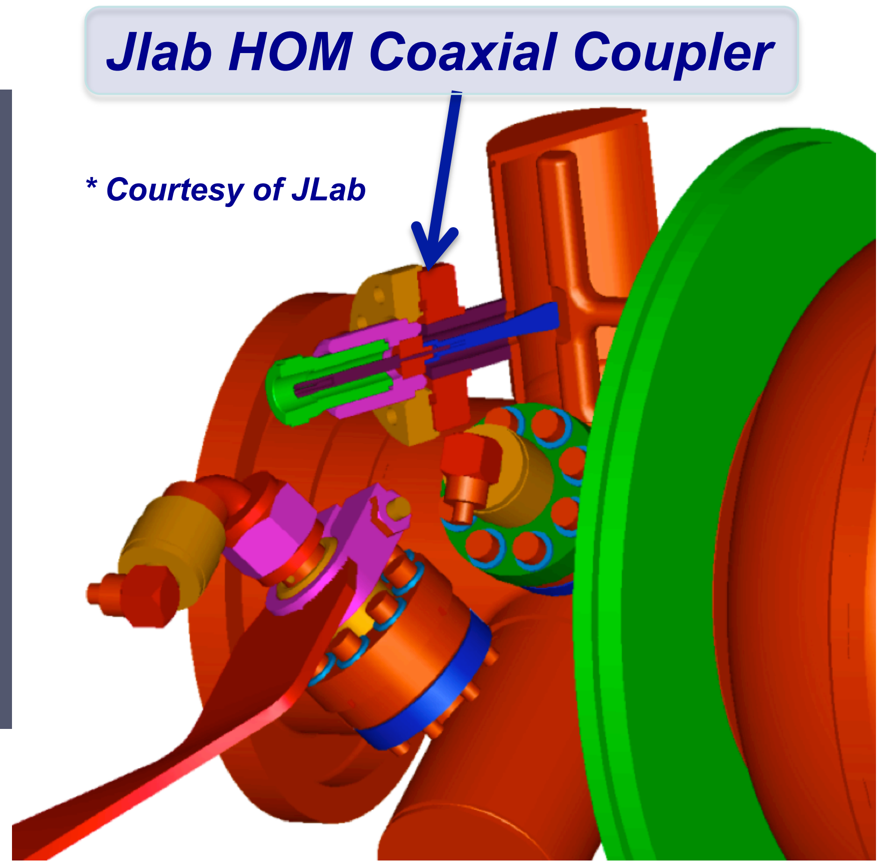
JLab HOM Coaxial Coupler

- Improves beam stability.
- Thermal impedance of HOM coupler causes instability in the superconducting cavity.
- Accurate thermal simulation desired.

- Input : 0.5 W RF power
- Boundary condtions:
  - Heat flux, Natural Convection, RF Heating, Fixed Temperature





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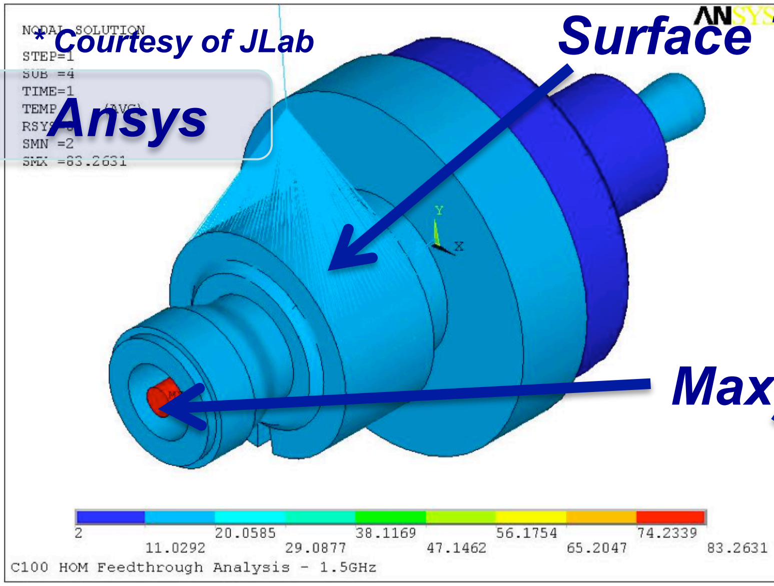
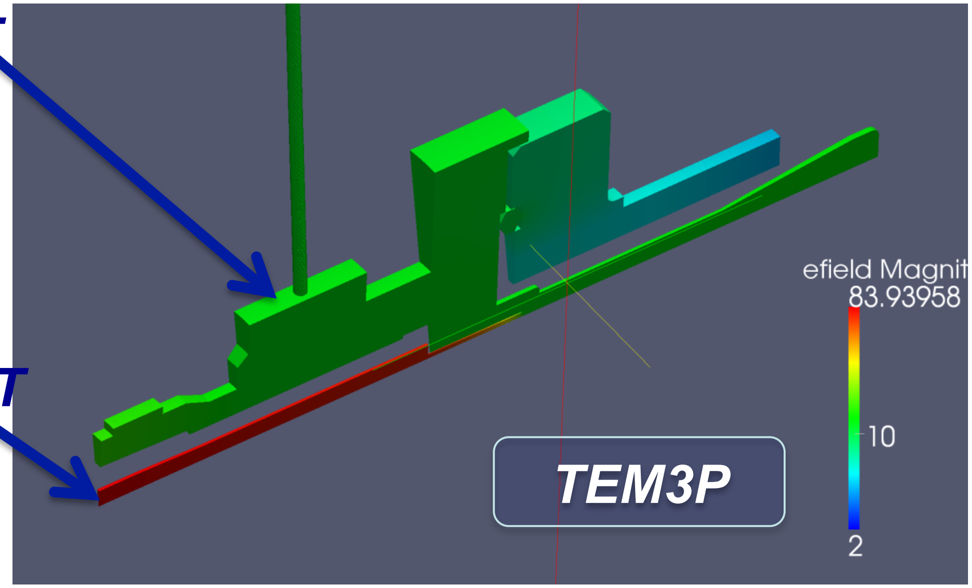
TEM3P Simulation of Coaxial Coupler





Temperature	Ansys	Tem3P	Test	Diff
Max (k)	*83.26*	*83.94*	*N/A*	*~ 0.8 %*
Surface (k)	*11.96*	*12.07*	*11.9*	*~ 1.4 %*

Successfully solved a highly nonlinear Multiphysics problem and matches very well with the test result.

Electro-Magnetics

Heat Transfer

Structure

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Summary and Future Work

- ***Summary***
  - ***Developed the parallel multiphysics code, TEM3P, for accelerator cavity simulation.***
  - ***Benchmarked with Ansys and applied to the real world applications in the accelerator cavity design.***
  - ***Robust parallel solvers in TEM3P enable simulations with fast turnaround time and hence allow virtual prototyping of cavity design on computers.***

- ***Future work***
  - ***Parallel scaling in computation and memory***
  - ***Temporal and spatial scaling.***

Questions ?