Fast Determination of Spurious Oscillations in an Entire Klystron Tube with ACE3P

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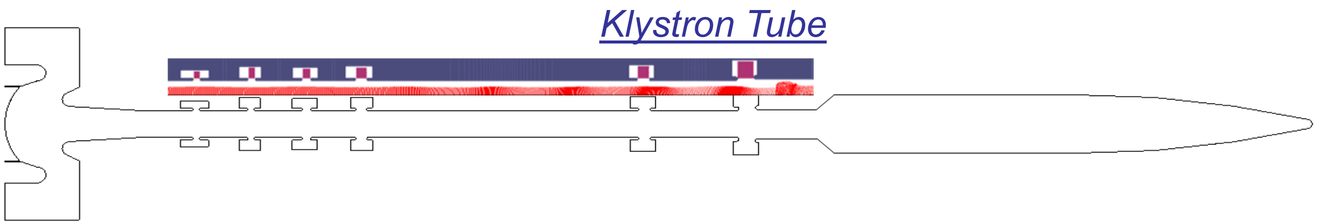
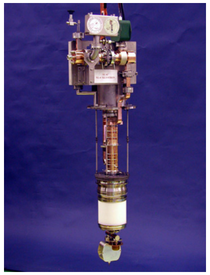
Overview

- **Klystron Oscillations**
- Numerical Approach
- Ongoing Effort

Spurious Oscillation in Klystron R&D





- Klystrons are essential power sources that drive RF accelerators
- They are expensive and complex devices that take time and effort to develop and produce
- Spurious oscillations are the cause of many klystron failures
- Ideally it would be more cost effective to catch potentially unstable modes in the design stage before fabrication and testing take place to reduce the number of prototypes to be built
- This would require an analysis of all possible modes that the klystron can support and their interactions with the electron beam
- It is desirable to have an fast, efficient and reliable simulation procedure with support from by the necessary numerical tools to determine if any of them is stable or not.

Oscillations in High-Power Klystrons

- Klystron oscillations can occur without the RF drive signal at (from grow noise) at frequencies other than the drive frequency
- They are not affected by variations in the operating parameters, such as the focusing magnetic etc.
- These high-Q resonances have been detected in the pulse transformer tank in the gun region, and also in the input and output couplers, etc.
- Such spurious oscillations are undesirable since the electron beam couples to these modes as well as the desired signal frequency.
- If the amplitude of the spurious oscillation becomes very large the main output signal may suffer from amplitude and phase instability leading to pulse shortening or decrease in efficiency.

Klystron R&D at SLAC

Tube first hot tested (best knowledge)

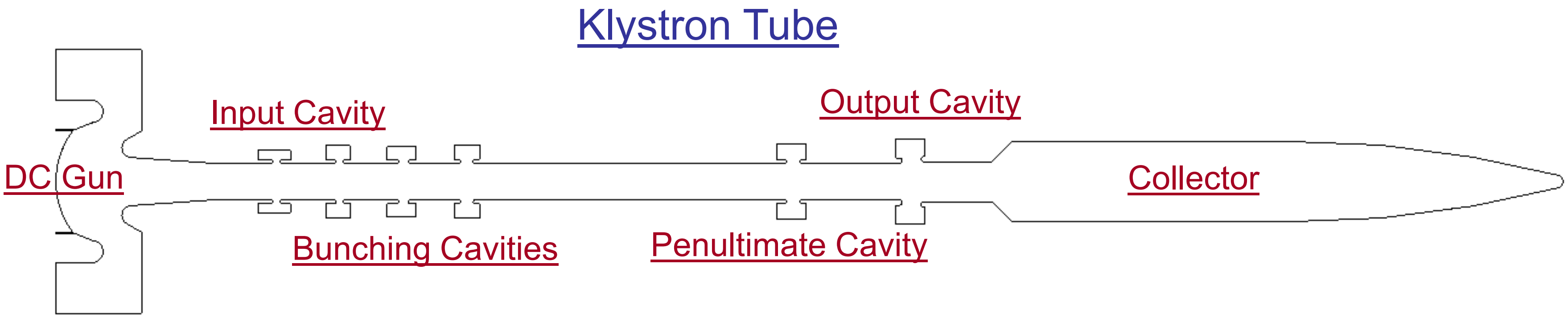
- S-band 5045 *(1985 – Preceded by XK5 1964)*
- SLAC/DESY S-Band *(1994)*

- B-Factory klystron *(1995)*

- XL4 & XL5 *(1995, 2010 respectively)*
- XP3-PPM focused *(1996)*
- XC8 *(1991)*

- W-Band-Sheet Beam *(2005)*
- L-Band-Sheet Beam *(2010 – **under development**)*

SLAC Klystrons with Oscillation Problems



- S-band 5045 - *?*
- SLAC/DESY S-Band – *Gun -1.365 GHz* (analysis)

- B-Factory klystron

- XL4 & XL5
- XP-PPM focused – *Gun - 2.860 GHz* (analysis)
- XC8 – *Output Cavity - 8.5 GHz* (analysis)

- W-Band-Sheet Beam - *?*
- L-Band-Sheet Beam – *(prediction by simulation possible?)*

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SciDAC Scientific Discovery through Advanced Computing

Overview

- Klystron Oscillations
- **Numerical Approach**
- Ongoing Effort

Previous Numerical Efforts

1995

SPURIOUS OSCILLATIONS IN HIGH POWER KLYSTRONS

B. Krietenstein, THD, Darmstadt, Germany,
K. Ko, and T. Lee, Stanford Linear Accelerator Center, Stanford University, Stanford, Calif
U. Becker and T. Weiland, THD, Darmstadt, Germany
M. Dohlus, DESY, Hamburg, Germany

1996

Simulation of Oscillations in High Power Klystrons

U. Becker, B. Krietenstein, T. Weiland; TH Darmstadt; Germany
M. Dohlus; DESY; Hamburg; Germany
K. Ko; SLAC; Stanford; California

PIC simulation not needed - Particle tracking sufficient

2005

CALCULATION OF BEAM-LOADED Q IN HIGH-POWER KLYSTRONS*J. DeFord and B. Held, Simulation Technology & Applied Research, Inc., Mequon, WI ,

K. Ko and V. Ivanov, SLAC, Menlo Park, CA 94025, U.S.A.

Criteria for Oscillation - Beam Loading

- The criteria that determine whether a mode will oscillate is that its **beam loading be <u>negative</u>**, and that the power it extracts from the beam <u>exceeds</u> its losses to external loading and wall dissipation

Power Transferred (P) / (2 x pi x freq x Stored Energy (U))

$= \quad 1/Q_b \quad + \quad 1/Q_e \quad + \quad 1/Q_0$

Beam Loading External Loss Wall Loss

$= \quad 1/Q_{TOTAL}$

$< \quad 0$

Computing Q_b, Q_e and Q_0

- **Q_b** – Under the DC fields **(EGUN)** and RF field **(Omega3P)**,

  (1) track particles over a RF period through the cavity and sum up the energies of all particles with no RF field
  -> U_{beam}

  (2) repeat (1) but adding a specified RF field
  -> $U_{beam + mode}$

  $Q_b = 2 \times pi \times U_{mode} / (U_{beam + mode} - U_{beam})$

  - *negative if beam loses energy to the RF mode*

- **Q_e** – solving the complex eigenvalue problem (**Omega3P**)

- **Q_o** – computed by perturbation theory **(Omega3P)**

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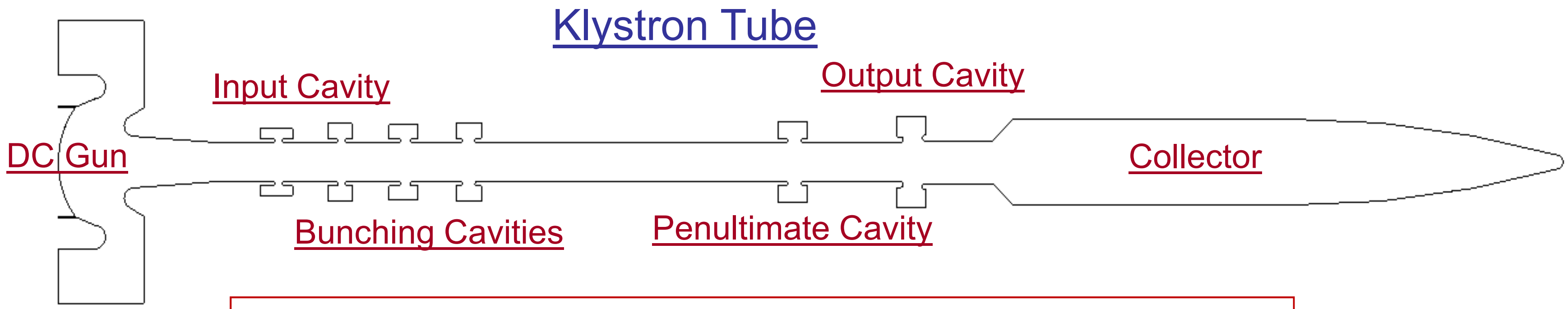
Simulation Codes for Klystron Oscillation



$1/Q_b$	+	$1/Q_e$	+	$1/Q_o$
Beam Loading		External Loss		Wall loss

For cylindrical tubes, calculations **are mostly 2D**

- DC Gun – ***EGUN***, *CST, Michelle, GUN3P*
- DC B Field – ***Poisson***, *CST*
- Beam Loading – ***Track3P***, *CST*
- RF Fields **(3D)** – ***Omega3P***, *CST*

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SciDAC Scientific Discovery through Advanced Computing

ACE3P Code Suite

- SLAC's suite of conformal, high-order, C++/MPI based finite-element *massively parallel* electromagnetic codes
- A unique capability for high-fidelity and high-accuracy accelerator simulation and modeling with its six application modules

ACE3P (Advanced Computational Electromagnetics 3P)

Frequency Domain:	***Omega3P***	***– Eigensolver (damping)***
	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**

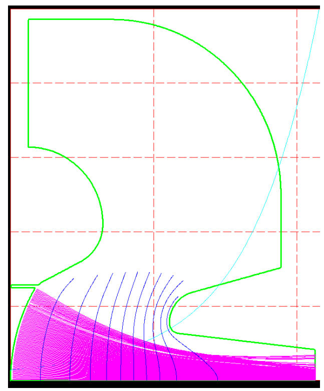
https://slacportal.slac.stanford.edu/sites/ard_public/bpd/acd/Pages/Default.aspx

Track3P Results for Qb

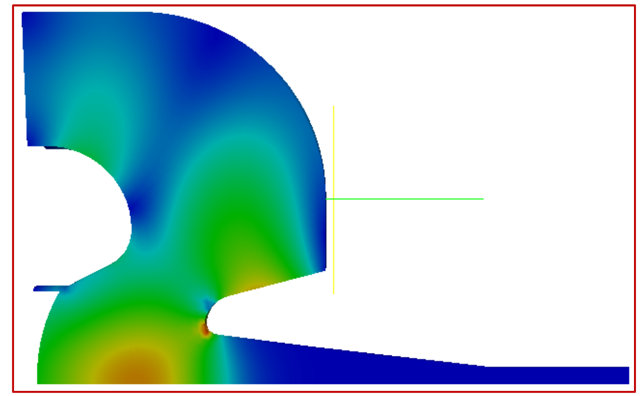
XP3 Gun - 490kV, 257A

Field	Energy (kev)
DC	**4.687451e+05**
DC + 2%.RF	4.658704e+05
DC + 4% RF	4.638590e+05
DC + 6% RF	4.632107e+05
DC + 8% RF	4.645737e+05
DC +10% RF	4.658177e+05

Energy Gain is negative



EGUN

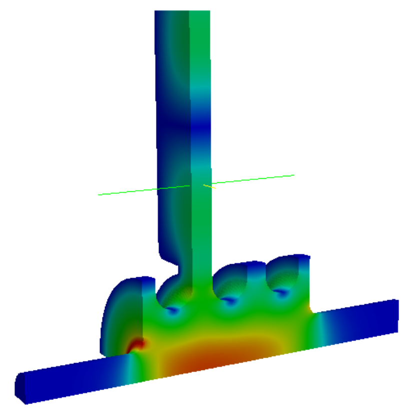


Omega3P - 2.71 GHz
Expt - 2.86 GHz

XC8 Output Cavity - 450kV, 517A

Field	Energy (kev)
DC	**4.500000e+05**
DC + 2% RF	4.499581e+05
DC + 4% RF	4.498144e+05
DC + 6% RF	4.496028e+05
DC + 8% RF	4.492976e+05
DC + 10% RF	4.489080e+05

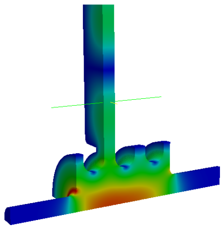
Energy Gain is negative



Omega3P – 8.49 GHz
Expt - 8.50 GHz

Omega3P Calculation of Qe

- Most computationally intensive effort is solving the complex eigenvalue problem in **3D t**o find Qe of the cavity



- **Omega3P** for the XC8 output cavity with

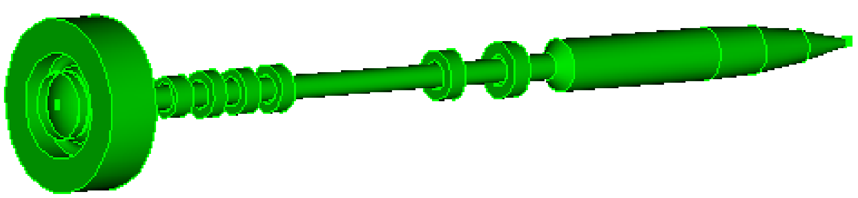
  Mesh size 1.5mm, <u>total mesh element19K</u>, DOF=116310, 2nd order basis function

  On **HOPPER** – computes **4 modes, 4GB memory, 21sec** wall clock time

- **HOPPER** is DOE's <u>Cray XE6 supercomputer at NERSC:</u>

  1 node (24 CPU – 4 CPUs with 6 cores each and **32 GB memory**)

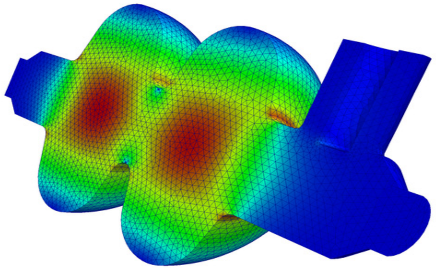
  6384 nodes, 153,216 compute cores, **217 TB of memory** and 2PB of disk

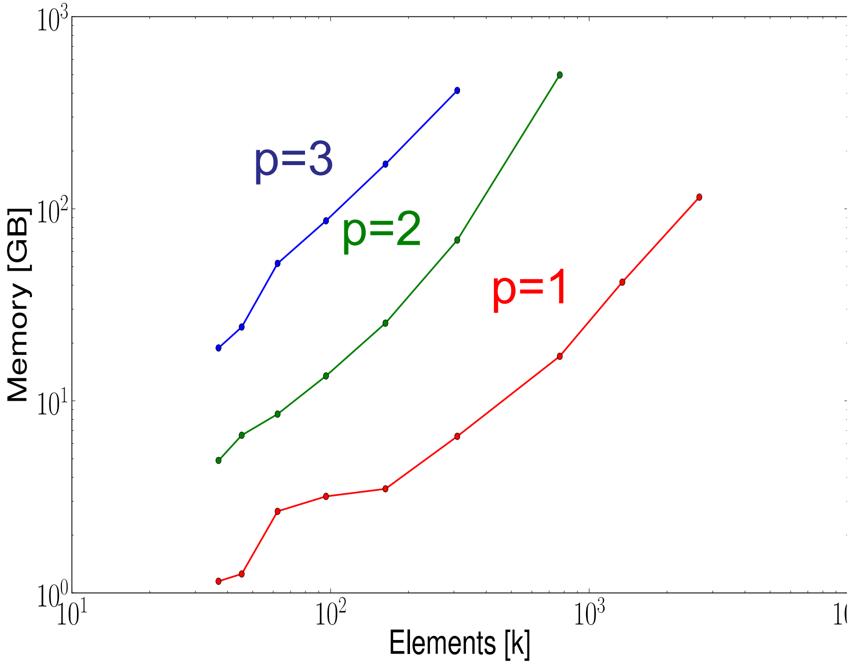


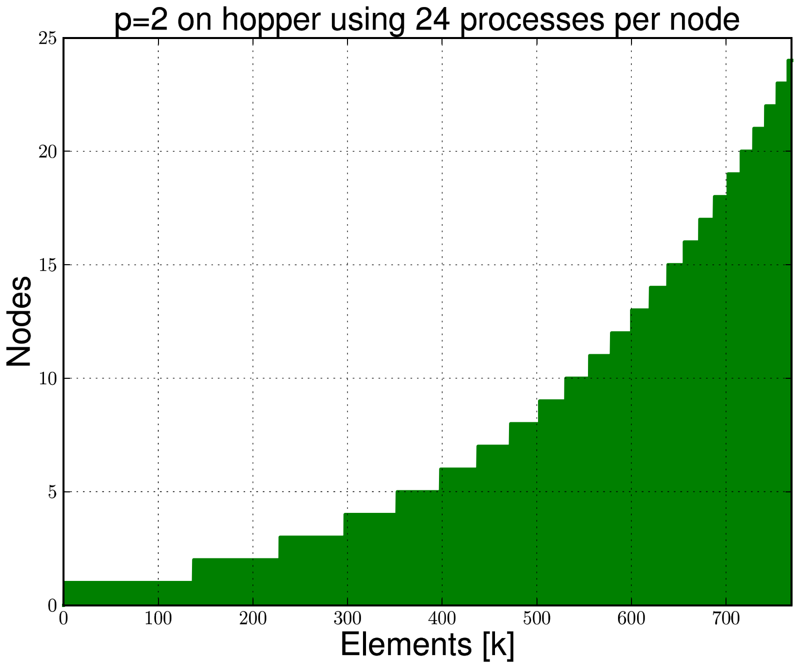
- Using High Performance Computing (HPC) resources, it is entirely **practical** *to find all the modes in a klystron tube in a matter of hours if not days!*

Omega3P Parallel Performance

Real lossless cavity
For complex (lossy) case, multiply by 1.5







Fast Determination of Oscillations in Klystron Tube

Enabling advances:

- Computing Q_b - Tracking is sufficient and PIC not needed
- Finding Q_e – HPC can provide memory and speed
- *Minimize klystron engineer involvement*
  - focus on modes with high Q_e and negative Q_b

Goal is to go from analysis to prediction

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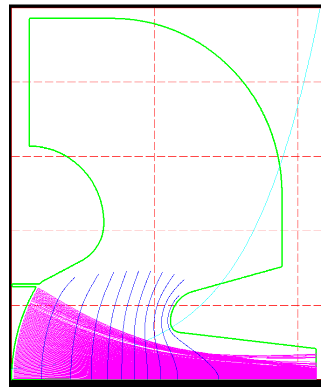
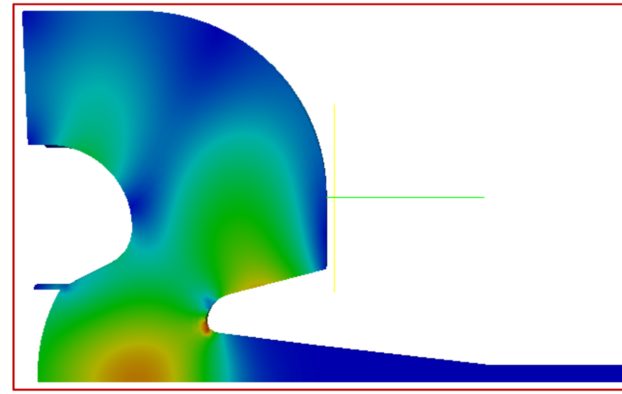


EGUN

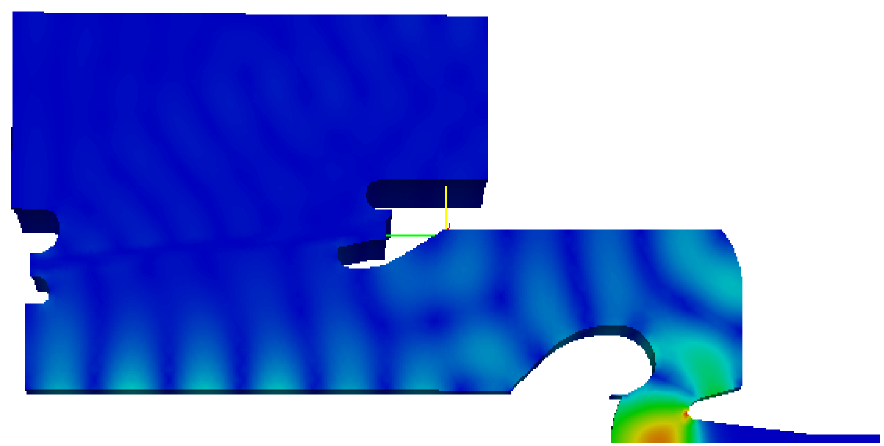


Omega3P - 2.71 GHz

Measurement	**Omega3P**
2.860 GHz	2.816 GHz

Qe:

Qb:



SLAC XC8 Output Cavity

XC8 Output Cavity - 450kV, 517A

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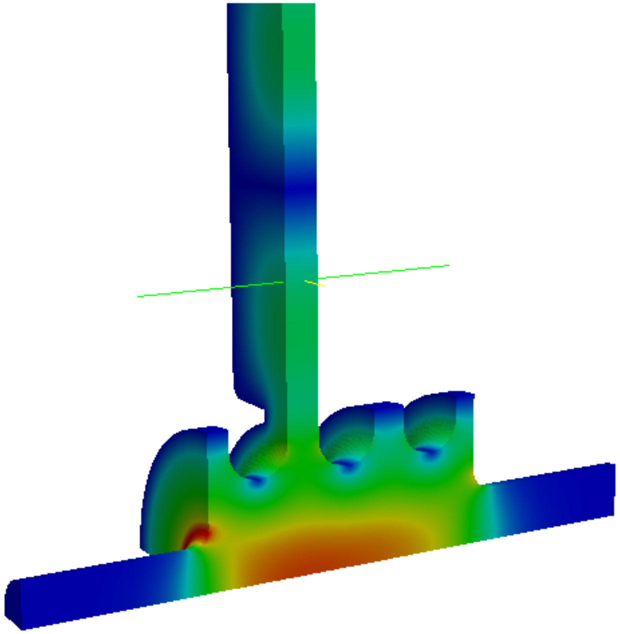
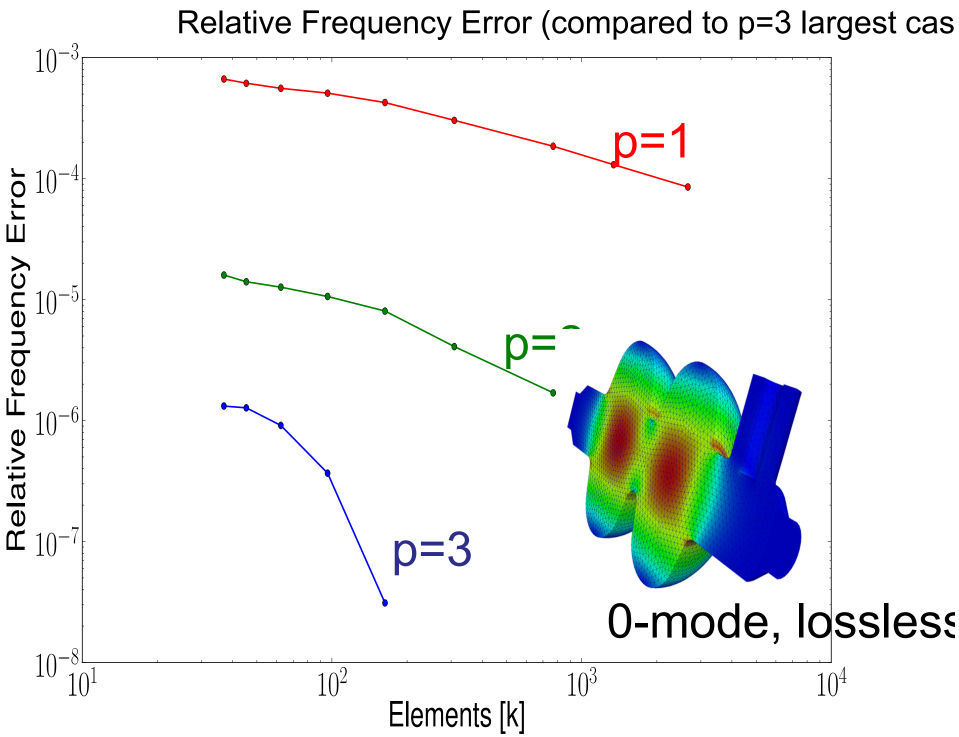
Measurement **Omega3P**

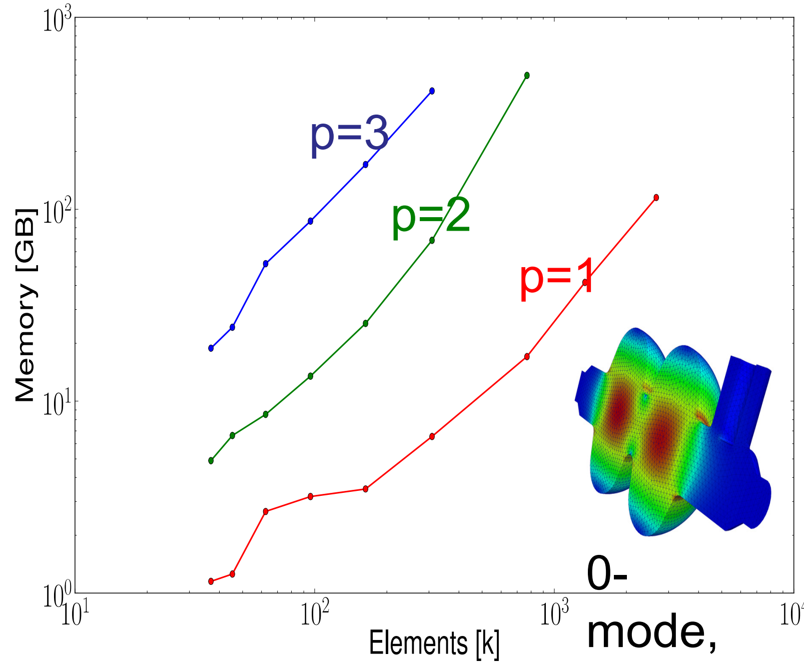
8.49 GHz



Qe: 814 (Omega3P) 798 (HFSS)
Qb: 750 (Superfish)
Qe: 6139 (Omega3P)

Solution Convergence of Omega3P





0-mode, lossless