Haloscope Axion Searches with the CAST Dipole Magnet

The CAST-CAPP/IBS DETECTOR

Lino Miceli

IBS Center for Axion and Precision Physics Research (CAPP)

Korea Advanced Institute of Science and Technology (KAIST)

Daejeon, South Korea

11th PATRAS Workshop on Axions, WIMPs and WISPs

22-26 June 2015

University of Zaragoza, Spain

The IBS Center for Axion and Precision Physics Research (KAIST, Daejeon, South Korea)

Started at the end of 2013.

Director: Prof. Yannis K. Semertzidis.

Currently: ~ 30 people, including 13 Research fellows.

Goal: 50-60 people by 2018.

- 15 Research Fellows
- 20 Graduate students
- 10 Junior/senior staff
- Visitor program
- Engineers and technicians

The CAPP Program

Focuses on two key issues of contemporary physics:

1. The nature of dark matter
   - Investigated through an extensive axion search program constituting the main CAPP effort

[2. The origin of the matter anti-matter asymmetry of our universe (proton EDM)]

Axion Search Motivation

The axion arises as a consequence of the Peccei-Quinn solution to the strong CP problem (the measured upper limit of CP violation in strong interaction is ~10 orders of magnitude smaller than predictions)

The axion is a good cold dark matter candidate if its mass is in the range 1 μeV and 100 μeV

CAPP Axion Search Main Goals

- Establish state of the art axion dark matter experimental program at KAIST (in progress)
- R&D program to improve on all experimentally accessible parameters in microwave searches (in progress)
- Significantly contribute to main experimental efforts internationally. Two initiatives among others:
  - ✓Collaboration with ADMX (work in progress)
  - ✓Joined the CERN Axion Solar Telescope (CAST) collaboration
    - CAPP will lead a new experimental effort, part of the CAST program: axion search with rectangular cavities in the CAST dipole magnet.

CAPP Axion Search Main Method

Based on the axion coupling to two photons in the presence of a strong magnetic field

$$\mathcal{L} \sim g_{a\gamma\gamma} a(t) \boldsymbol{E}(\boldsymbol{t}) \cdot \boldsymbol{B}$$

$g_{a\gamma\gamma}$ coupling constant

$a(t)$ axion field

B provides a virtual photon enhancing the conversion probability

E(t) electric field associated with the outgoing photon

Detection Technique

CAPP Center for Axion and Precision Physics Research

Haloscope: axion-to-photon conversion probability is further enhanced in a microwave cavity that resonates to the frequency of the axion mass (Sikivie).

On-resonance axion conversion power in a microwave cavity

$$P \approx g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) \boldsymbol{B^2 \cdot Q \cdot V \cdot C}$$

$$Q = 2\pi f \frac{\text{Stored Energy}}{\text{Power Loss}}$$ Quality factor

$$C = \frac{1}{B_0^2 V} \frac{\left|\int \boldsymbol{B} \cdot \boldsymbol{E} d^3x\right|^2}{\int \boldsymbol{E} \cdot \boldsymbol{E} d^3x}$$ Geometry factor

The cavity needs to be tunable

Background

PHYSICAL REVIEW D **85,** 035018 (2012)

Prospects for searching axionlike particle dark matter with dipole, toroidal, and wiggler magnets

Oliver K. Baker,[1] Michael Betz,[2] Fritz Caspers,[2] Joerg Jaeckel,[3] Axel Lindner,[4] Andreas Ringwald,[4]
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[7]*University of Patras, Patras, Greece*

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In this work, we consider searches for dark matter made of axions or axionlike particles using resonant radio frequency cavities inserted into dipole magnets from particle accelerators, wiggler magnets developed for accelerator based advanced light sources, and toroidal magnets similar to those used in particle-physics detectors. We investigate the expected sensitivity of such axionlike-particle dark-matter detectors and discuss the engineering aspects of building and tuning them. Brief mention is also made of even stronger field magnets which are becoming available due to improvements in magnetic technology. It is concluded that new experiments utilizing already-existing magnets could greatly enlarge the mass region in searches for axionlike dark matter particles.

CAST-CAPP/IBS Search

First experiment using (tunable) rectangular cavities in a dipole magnet

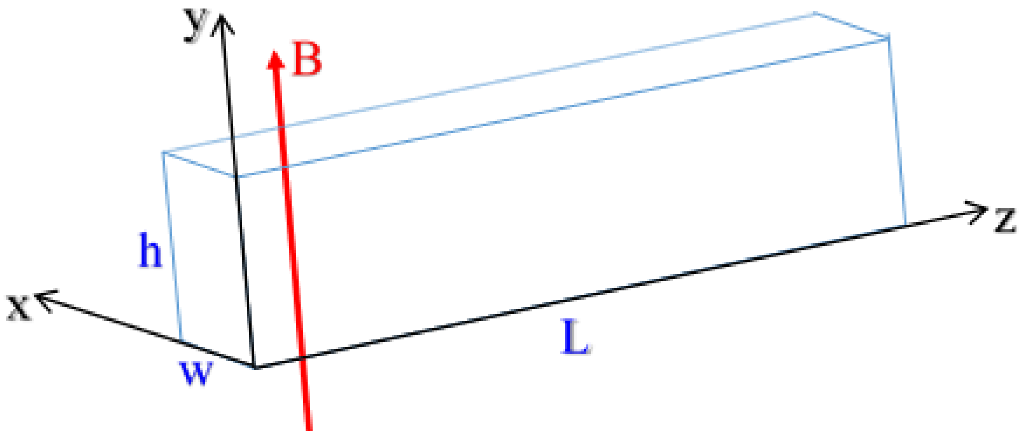
- Rectangular cavity resonant frequencies

$$f_{lmn} \sim \sqrt{\left(\frac{l}{w}\right)^2 + \left(\frac{m}{h}\right)^2 + \left(\frac{n}{L}\right)^2}$$

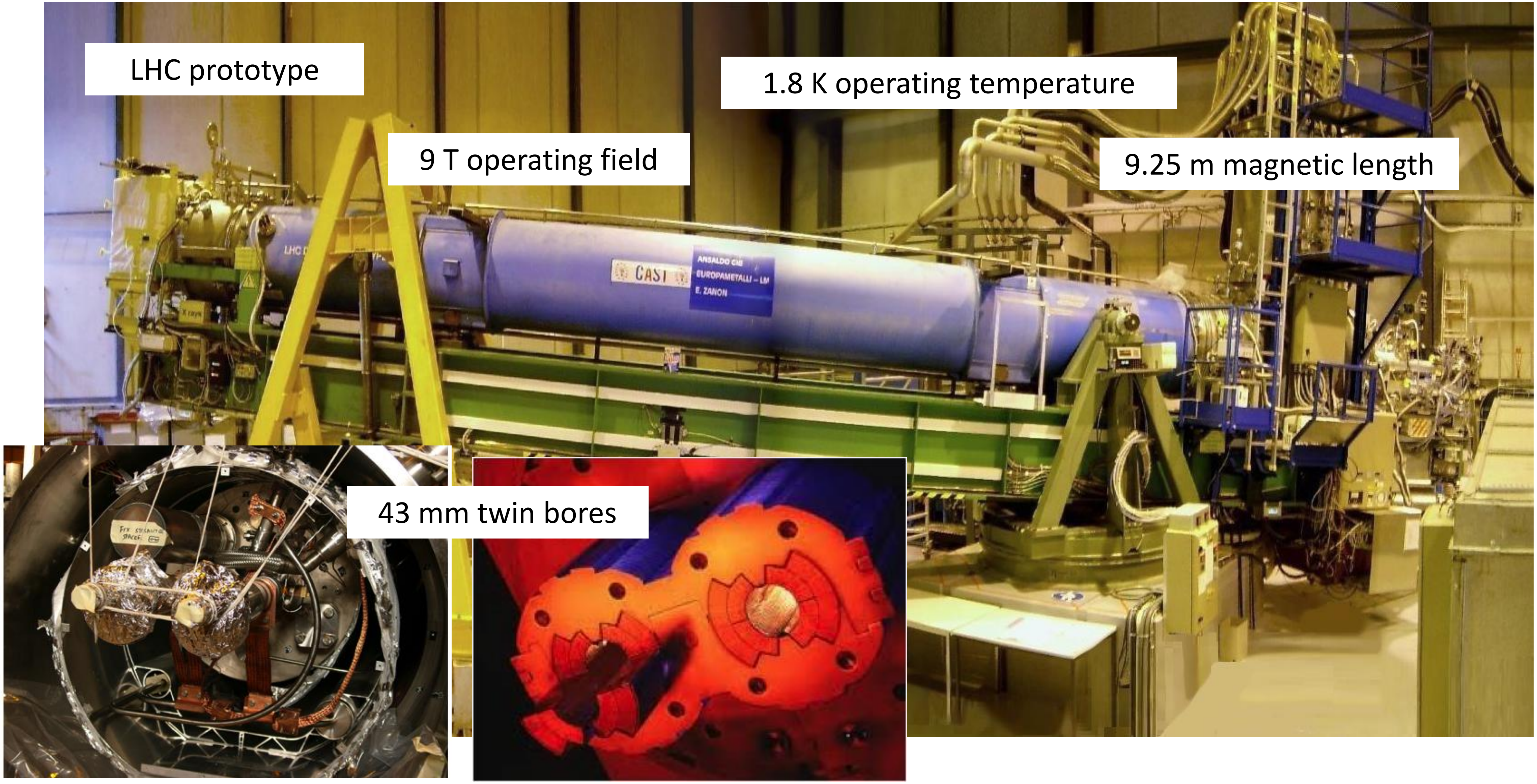
- Resonant E field aligned with the external B field: TE_{l0n} modes

$$E_y \sim \sin\left(\frac{l\pi}{h} x\right) \sin\left(\frac{n\pi}{L} z\right)$$

$$E_x = E_z = 0$$



CAST-CAPP/IBS Search: The CAST Dipole Magnet



LHC prototype

9 T operating field

1.8 K operating temperature

9.25 m magnetic length

43 mm twin bores

Experiment sensitivity example: cavity of 2.5 cm X 2.4 cm cross section

Sensitivity estimates are preliminary, assuming several cavities can be phase-locked together

- Resonant power

- $P = (g_{a\gamma\gamma})^2 \rho_a \frac{1}{\boldsymbol{m_a}} B^2 CV\, min[Q_c, Q_a]$

$$= 1.6 \times 10^{-25}\mathrm{W} \times (g_{a\gamma\gamma} 10^{15}\mathrm{GeV})^2 \left(\frac{\rho_a}{300\ \mathrm{MeV/cm^3}}\right)\left(\frac{2.4\times10^{-5} eV}{\boldsymbol{m_a}}\right) \times \left(\frac{B}{9\ \mathrm{T}}\right)^2 \left(\frac{\boldsymbol{C}}{0.66}\right)\left(\frac{V}{5\ l}\right)\left(\frac{Q}{5\times10^3}\right)$$

- m_a = 24 μeV (f = 5.8 GHz)
- B = 9 T , CAST magnet
- V = 5 liters
- Q = $min[Q_c, Q_a] = Q_0/2 \sim 5{,}000$; critical coupling
  - Q_c loaded quality factor
  - Q_0 cavity quality factor

Time required for a single measurement

$$t \;=\; 9\times10^{9}s\left(\frac{SNR}{4}\right)^{2}\left(\frac{T}{3.8\ \mathrm{K}}\right)^{2}\left(\frac{C}{0.66}\right)^{-2}\left(\frac{B}{9\ \mathrm{T}}\right)^{-4}\left(\frac{V}{5\ l}\right)^{-2}$$
$$\times\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^{-4}\left(\frac{\rho_a}{300\ MeV/cm^3}\right)^{-2}\left(\frac{2.4\times10^{-5}eV}{m_a}\right)^{-3}$$
$$\times\left(\frac{Q}{5\times10^{3}}\right)^{-2}\left(\frac{10^{6}}{Q_a}\right)\ \sim 10\ \text{days at}\ g_{a\gamma\gamma} = 10^{-14}\mathrm{GeV}^{-1}$$

m_a = 24 μeV (f = 5.8 GHz) ; B = 9 T , CAST magnet

V = 5 liters

Q = min[Q_c,Q_a] = Q_0/2 ~ 5,000; critical coupling

Q_c loaded quality factor

Q_0 cavity quality factor

T = System Temperature = physical temperature + receiver&amplifier-chain equivalent noise temperature. Commercial HEMT amplifiers.

Scanning speed example

$$\frac{df}{dt} = \frac{f}{Q}\frac{1}{t} \sim \frac{3.4\ KHz}{year}\left(g_{a\gamma\gamma}10^{15}\mathrm{GeV}\right)^4\left(\frac{5.8\ \mathrm{GHz}}{f}\right)^2\left(\frac{4}{SNR}\right)^2\left(\frac{3.8\ \mathrm{K}}{T}\right)^2$$

$$\times\left(\frac{B}{9\ \mathrm{T}}\right)^4\left(\frac{C}{0.66}\right)^2\left(\frac{V}{5\ l}\right)^2\left(\frac{Q}{5\times10^3}\right)$$

$$\sim\ 90\ \mathrm{MHz}\ /\mathrm{year}\ \ at\ g_{a\gamma\gamma}\ 10^{-14}\mathrm{GeV}^{-1}$$

m_a = 24 μeV (f = 5.8 GHz) ; B = 9 T , CAST magnet;

V = 5 liters

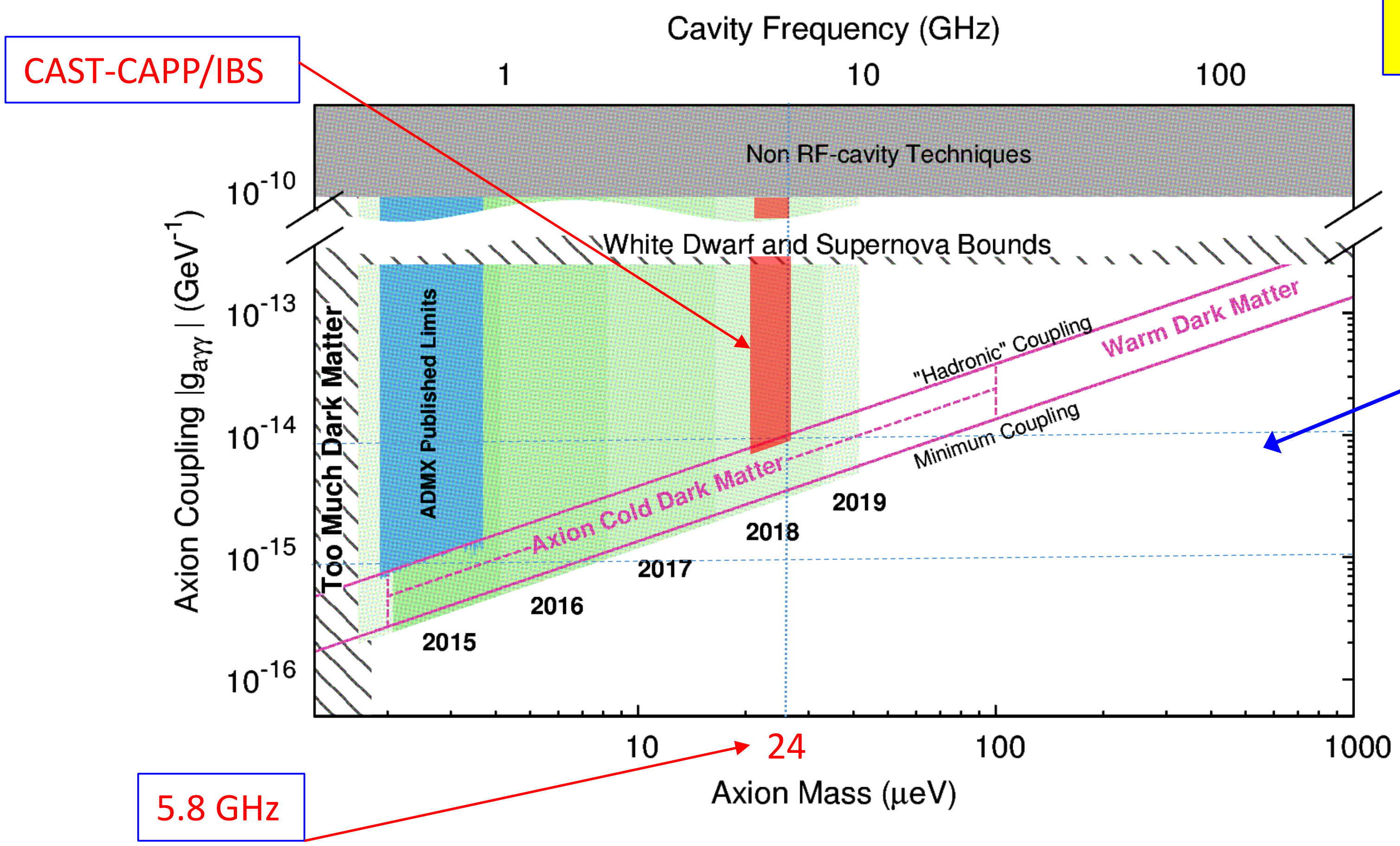
Q = min[Q_c,Q_a] = Q_0/2 ~ 5,000; critical coupling

- Q_c loaded quality factor
- Q_0 cavity quality factor

T : System Temperature = physical temperature + receiver&amplifier-chain equivalent noise temperature.

ADMX Plan and CAST-CAPP/IBS Experiment Sensitivity

Preliminary estimate



Gray Rybka
Multidark Joint Focus
Program on
WIMPs and Axions.
Daejeon, ROK
October 2014.

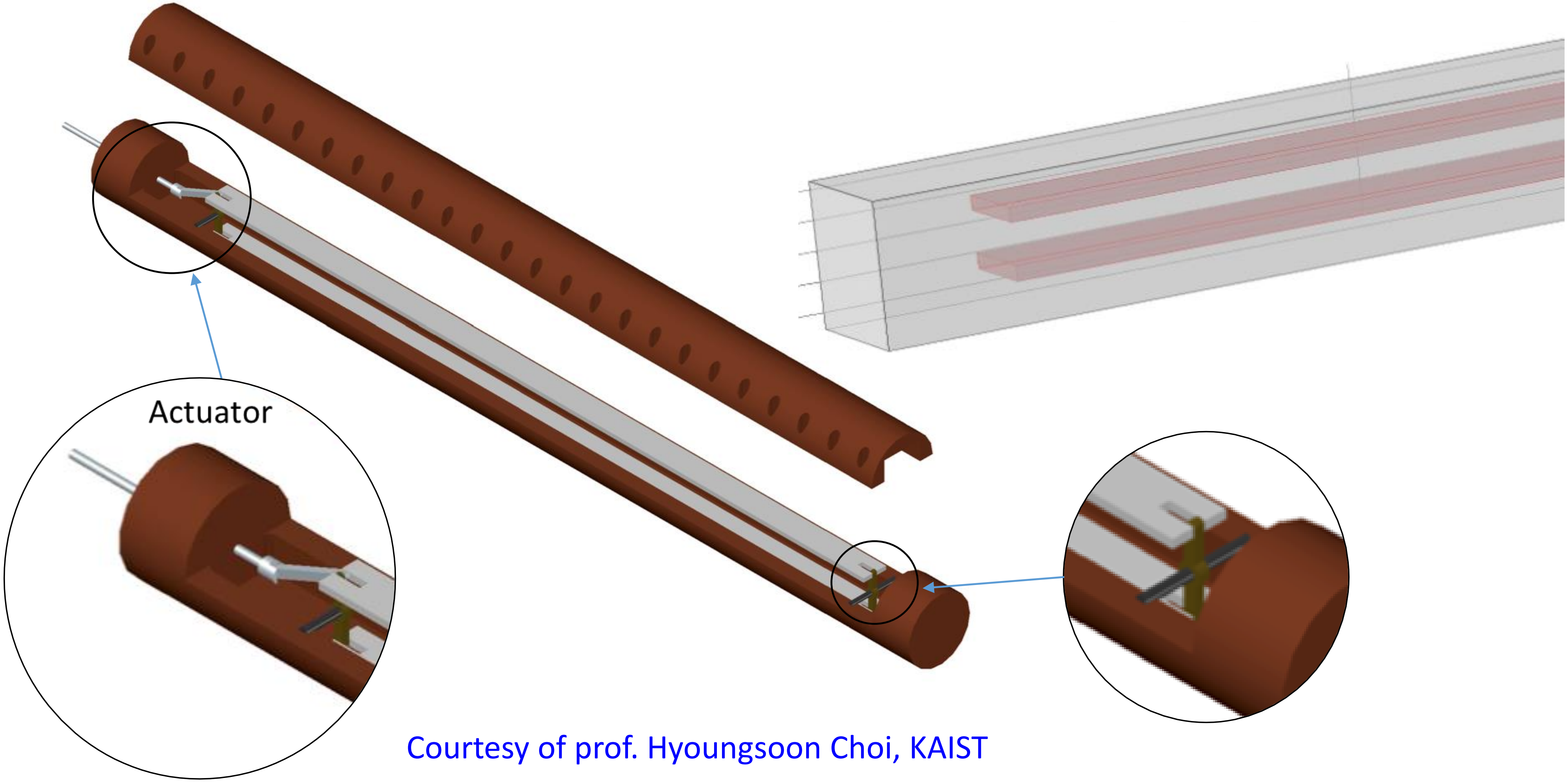
ADMX Gen-2 program: green and blue regions.

CAST-CAPP/IBS: Cavity engineering and first stage experiment

Tuning
Quality factor
Mechanical tolerances (→ mode localization)
Mode separation

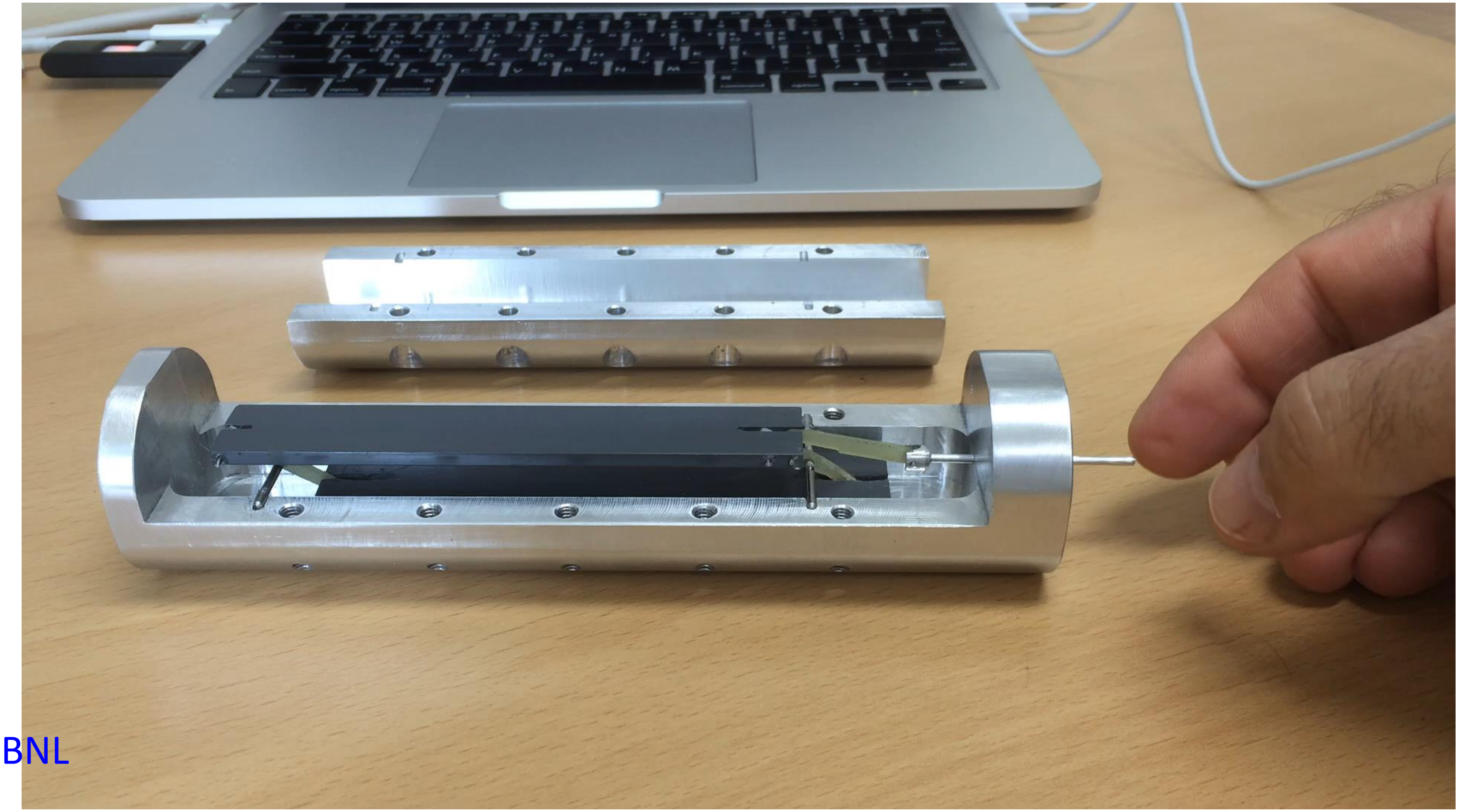
A first stage, exploratory experiment will run on a short cavities (~ 50 cm).
Cavities, including electronics setup, acquisition, and control,
can be tested at the CAPP in a cryo-cooler (thanks Dr. Yonuk Chong).

Engineering concept of a possible tuning solution (2.5cm X 2.4cm X 50cm prototype cavity) with dielectric tuning bars.



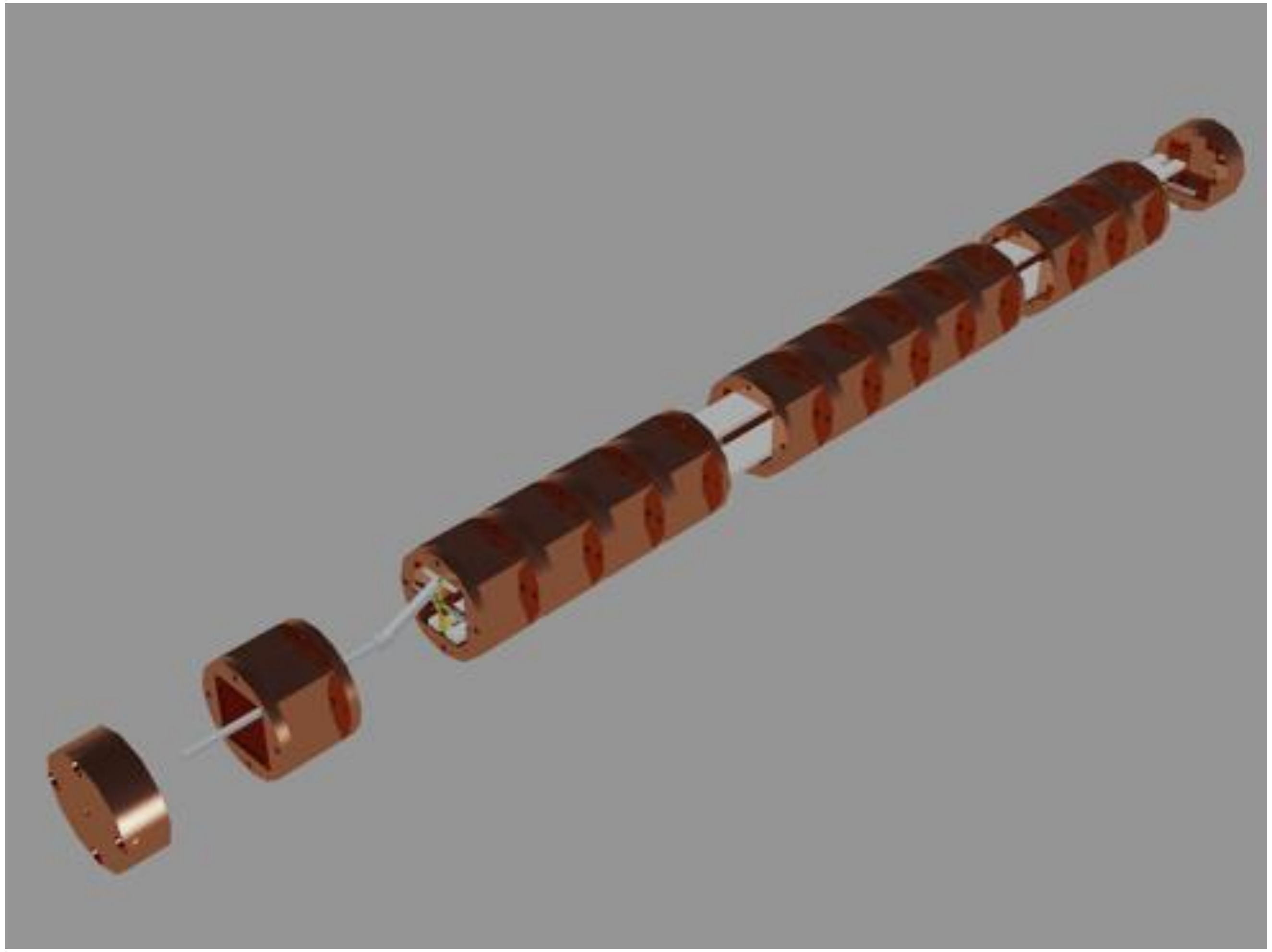
Courtesy of prof. Hyoungsoon Choi, KAIST

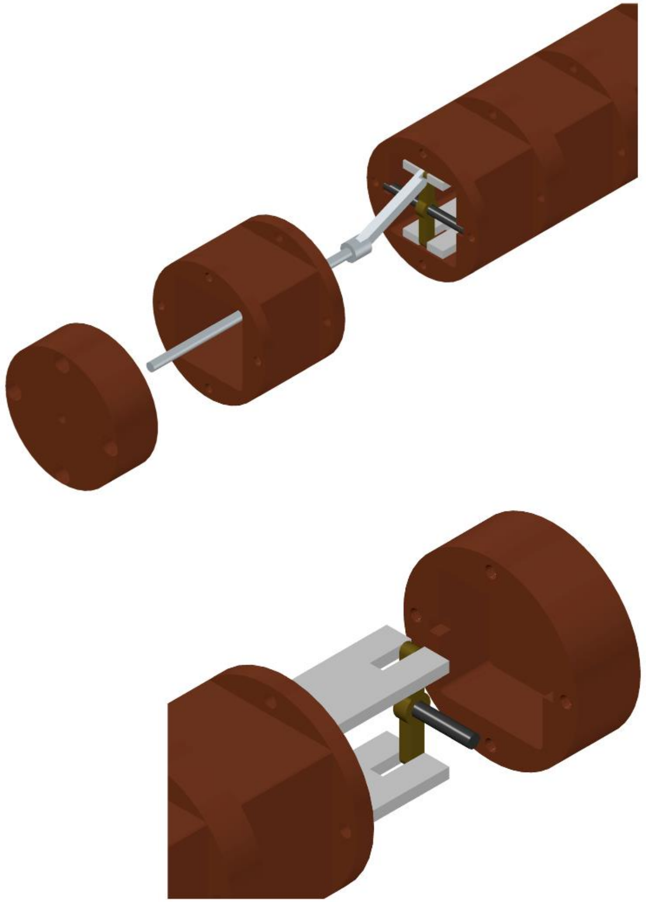
Rectangular Cavity Tuning Concept



Built by
Frank Lincoln, BNL

Sectioned rectangular cavity (2.5cm X 2.4cm X 50cm prototype cavity) with dielectric tuning bars.





Courtesy of prof. Hyoungsoon Choi, KAIST

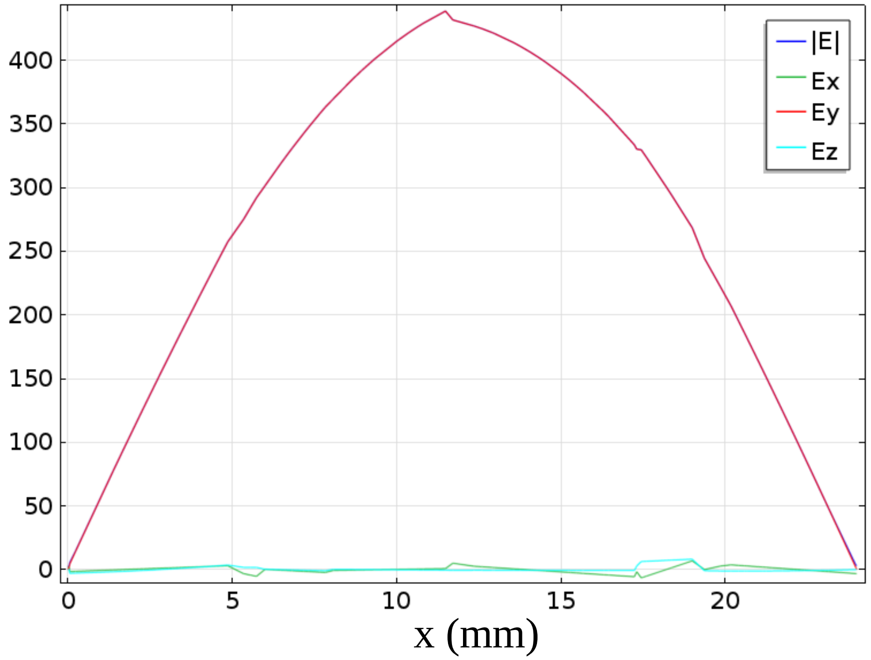
Preliminary modeling: 2.5cm X 2.4cm X 50cm cavity

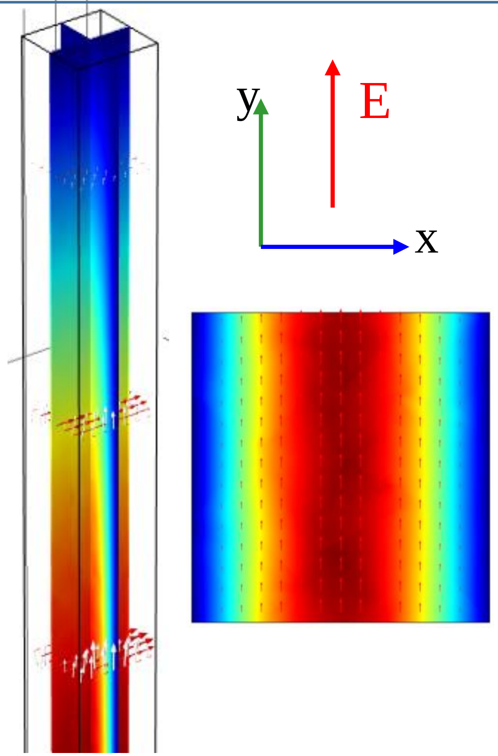
TE_{101} , f = 6.25 GHz, hollow cavity (no tuning).

Arbitrary vertical axes units

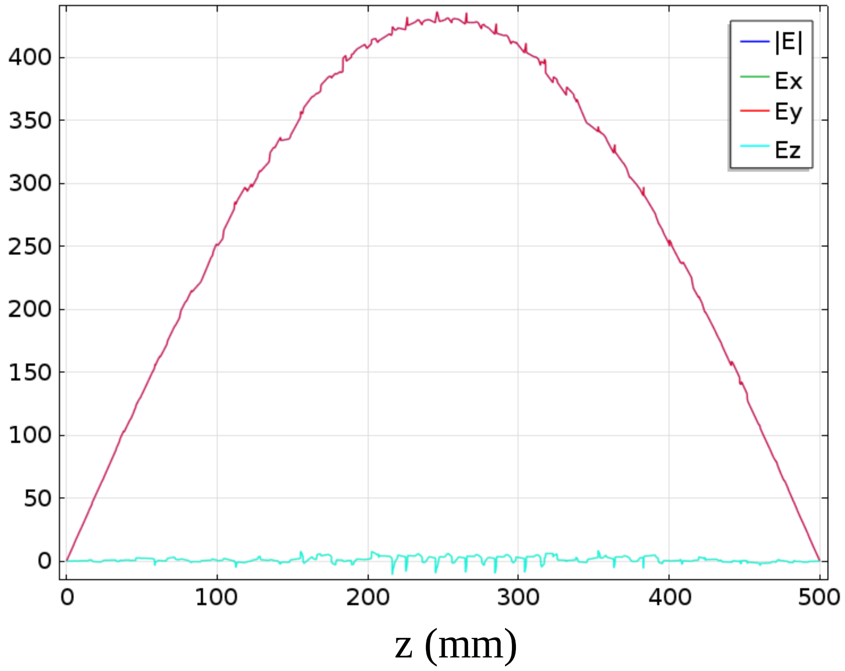
E-field snapshot: 3D and XY section
highest field in red color

E-field along x at the cavity z-center





E-field along longitudinal cavity axis



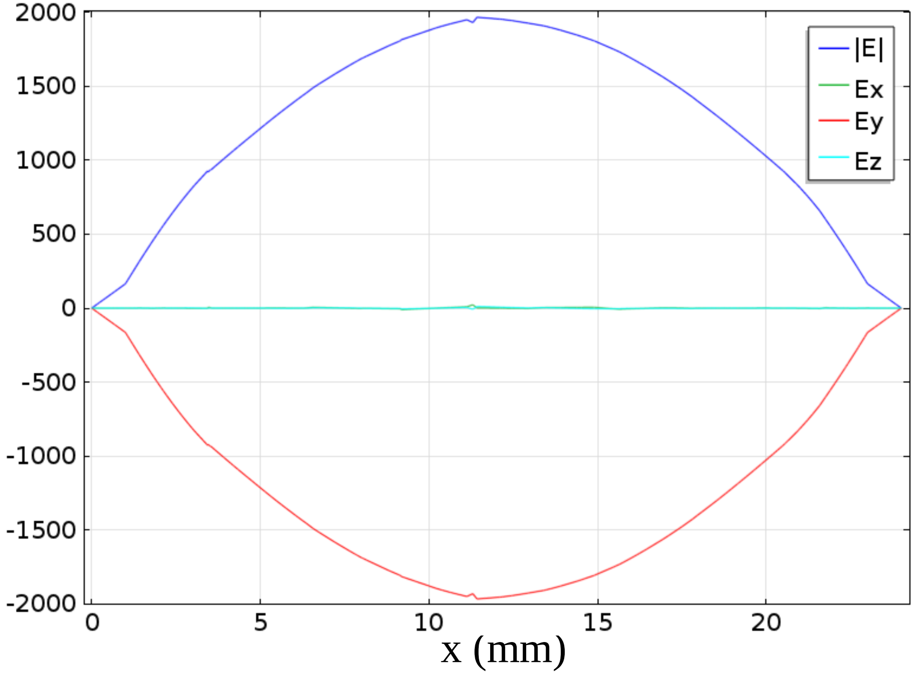
Preliminary modeling: 2.5cm X 2.4cm X 50cm cavity with diel. tuning bars

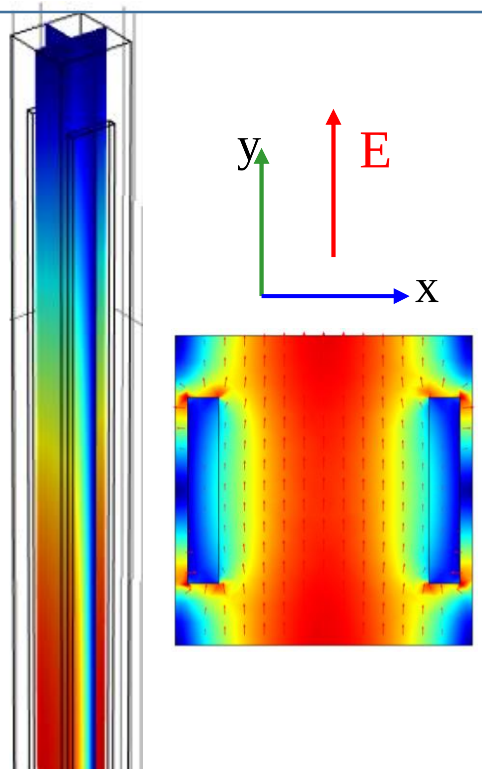
‘TE_{101} ‘, f = 5.83 GHz, bar insertion distance 1 mm.

Arbitrary vertical axes units

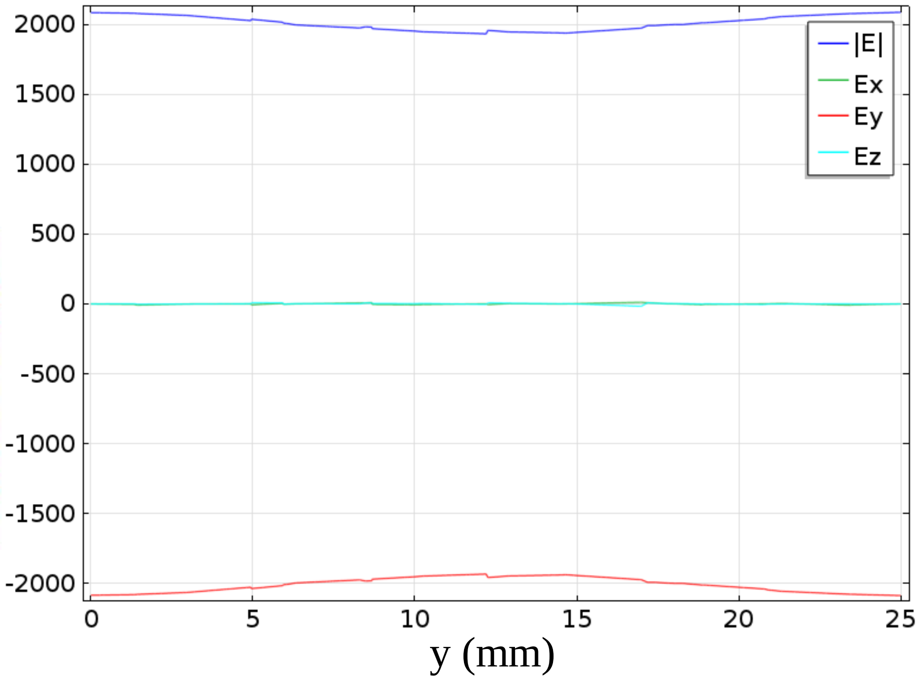
E-field snapshot: 3D and XY section
highest field in red color

E-field along x at the cavity z-center





E-field along y at the cavity center



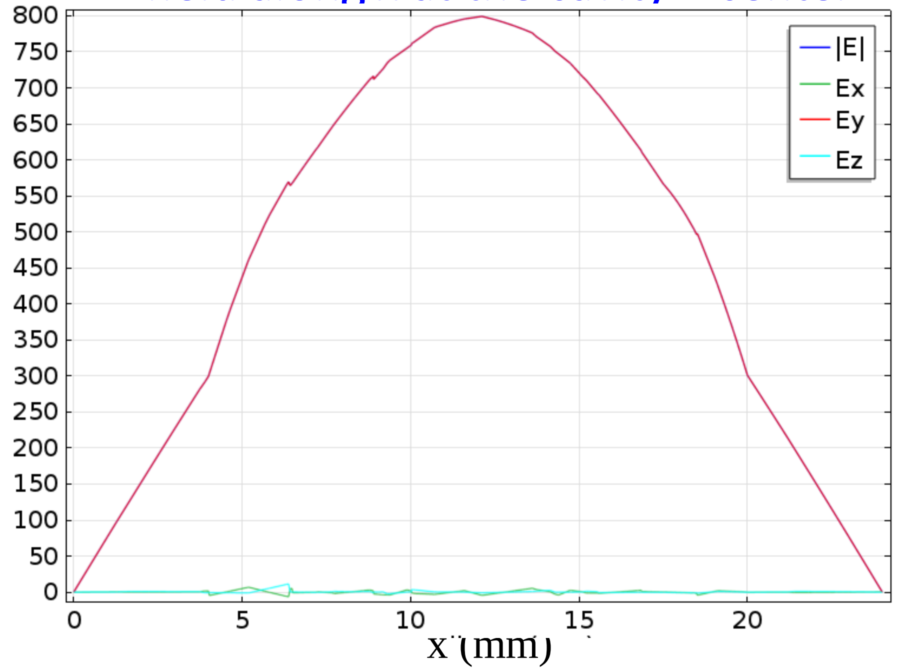
Preliminary Modeling: 2.5cm X 2.4cm X 50cm cavity with diel. tuning bars

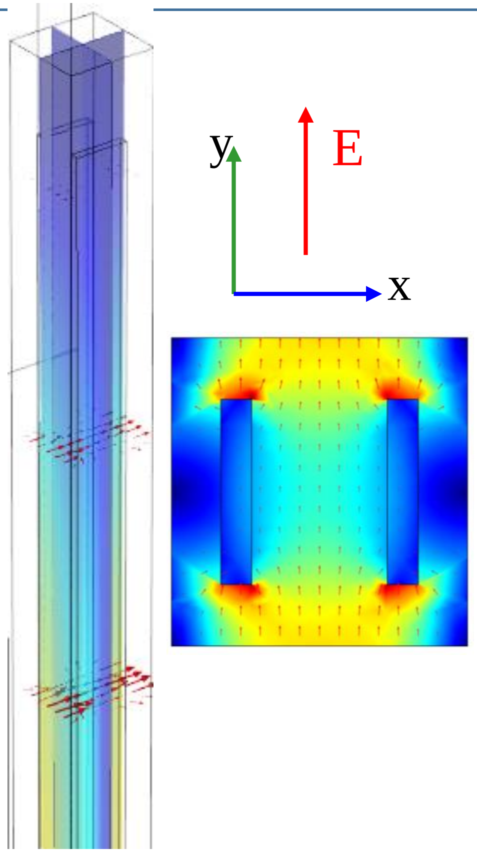
'TE_{101} ', f = 5.13 GHz, bars penetration distance 4 mm.

Arbitrary vertical axes units

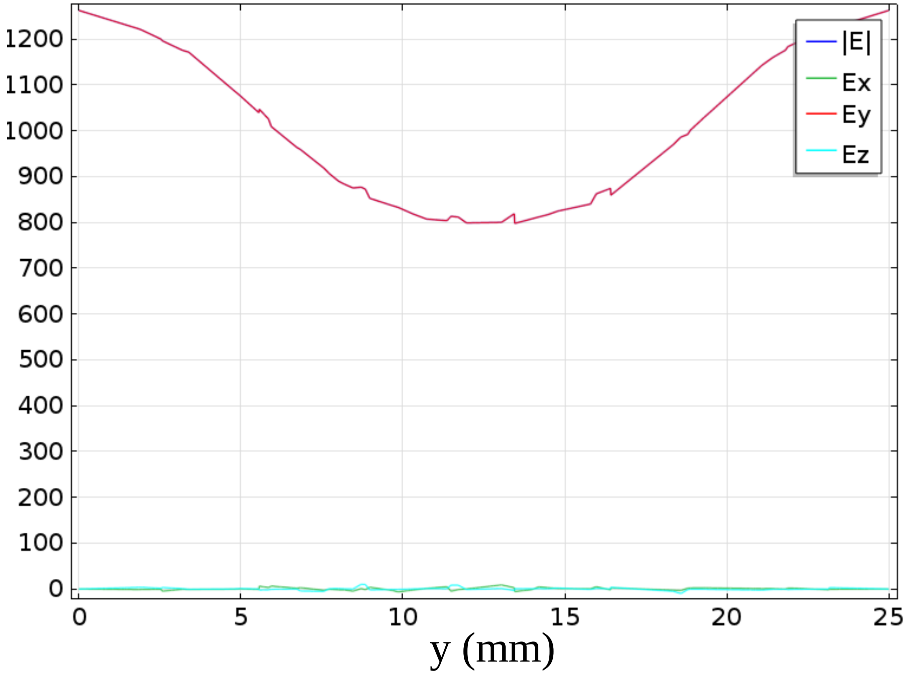
E-field snapshot: 3D and XY section
highest field in red color

E-field along x at the cavity z-center





E-field along y at the cavity z-center

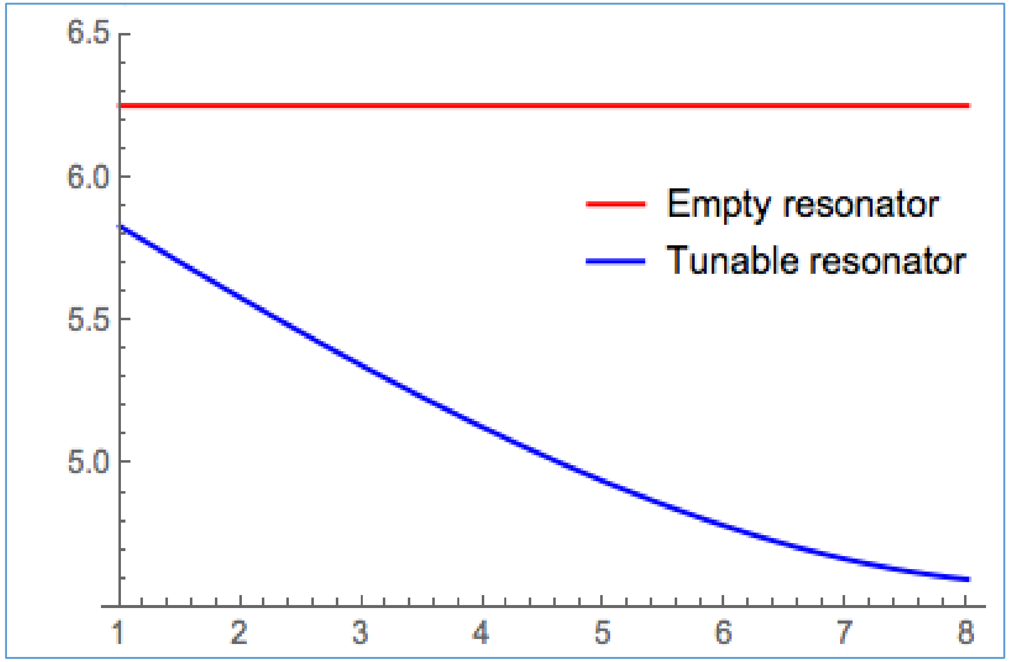


Preliminary modeling: 2.5cm X 2.4cm X 50cm cavity with diel. tuning bars

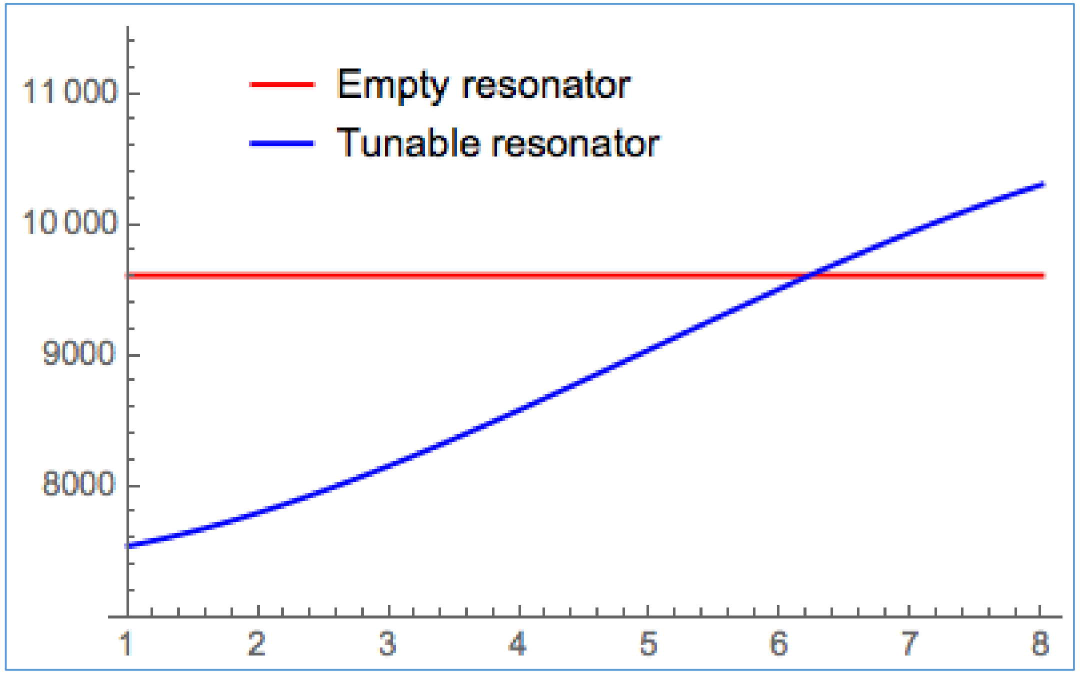
Horizontal axis: bar insertion distance (mm) from cavity walls

Cavity Tunability

TE_{101} Resonant Frequency (GHz)



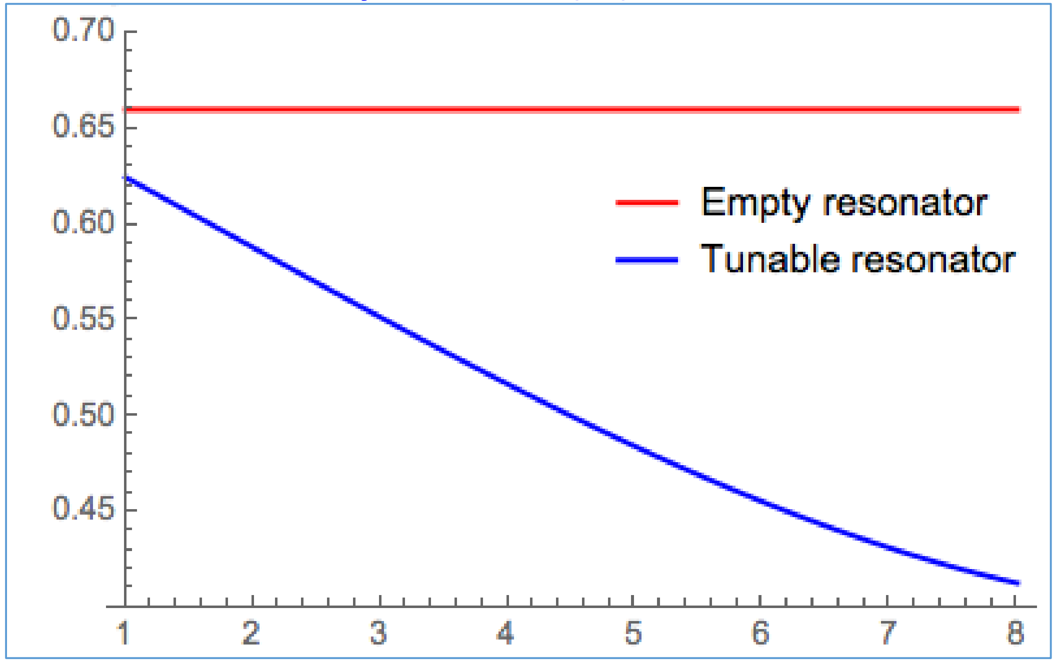
Quality factor (Q)



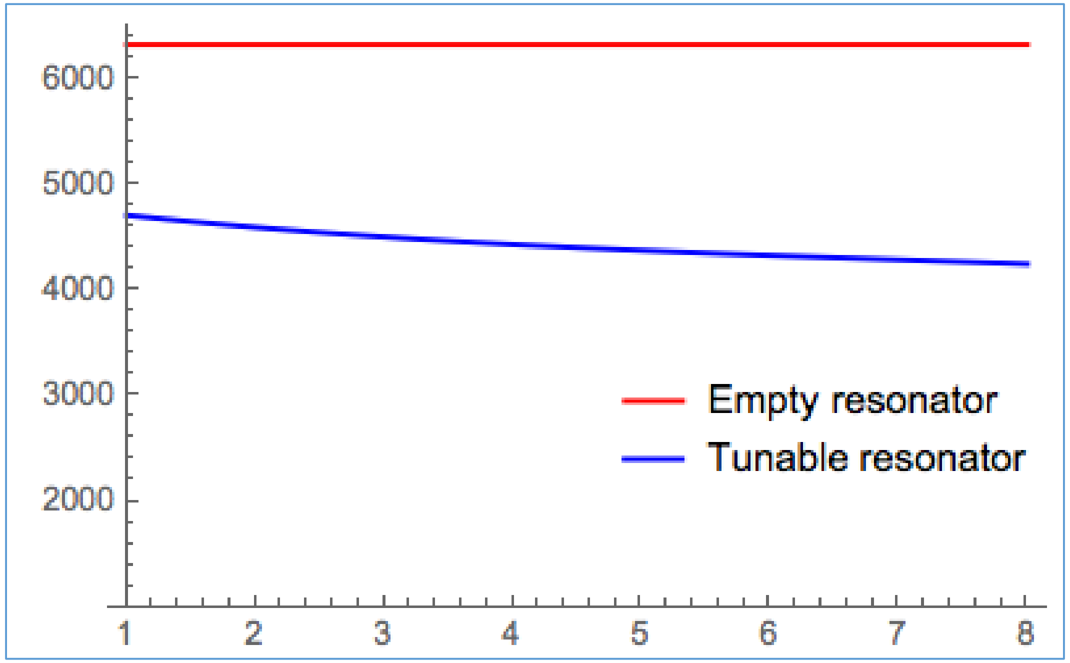
Preliminary modeling: 2.5cm X 2.4cm X 10cm cavity with diel. tuning bars

Horizontal axis: bars insertion distance (mm) from cavity walls

Geometry factor (C)

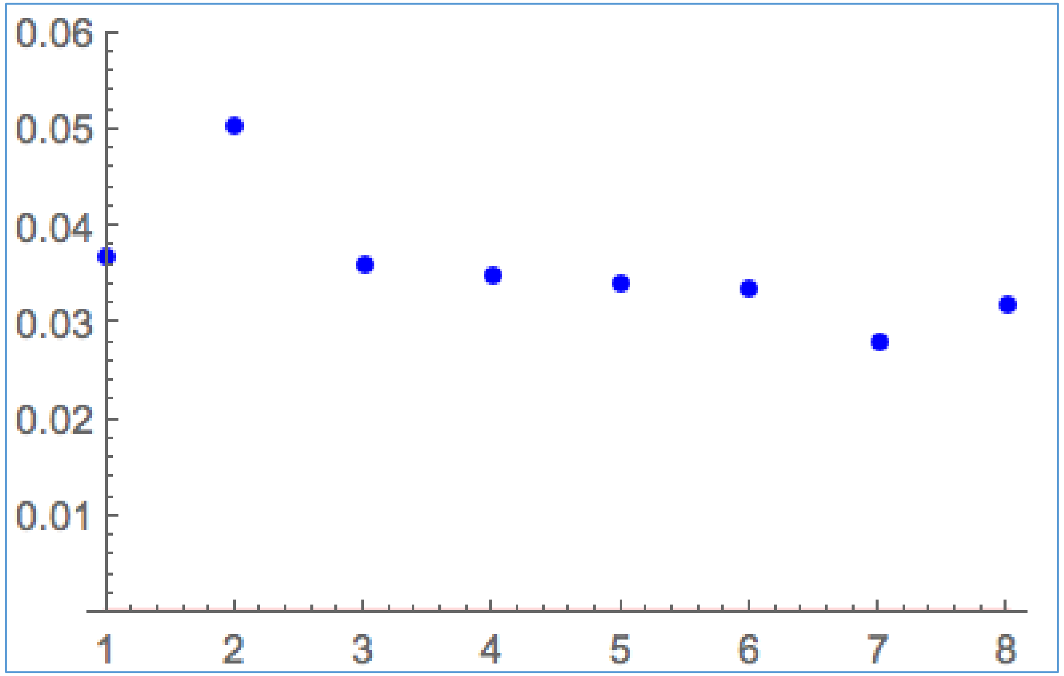


Q*C



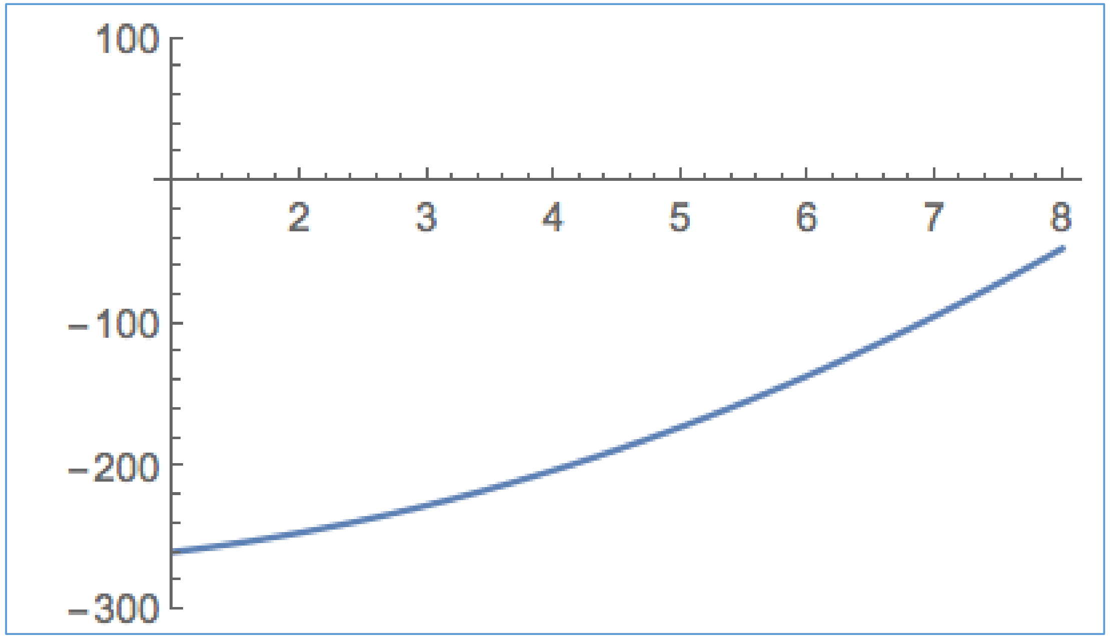
Preliminary modeling: 2.5cm X 2.4cm X 50cm cavity with diel. tuning bars

Mode separation (Q=10^4)



Tuning bar insertion distance (Δx)

Tuning Sensitivity: $\Delta f/\Delta x$ (MHz/mm)

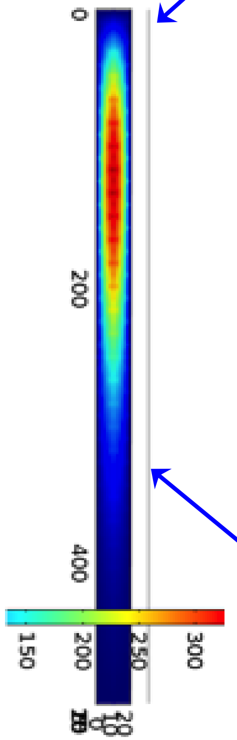


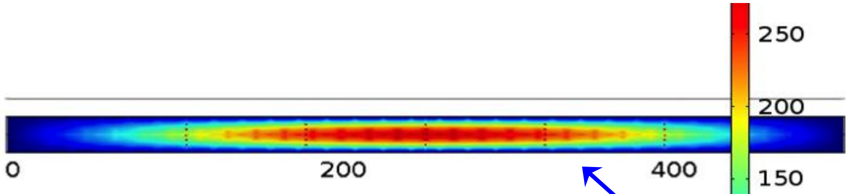
Tuning bar insertion distance (Δx)

Mechanical Tolerances vs. Mode Localization in 2.5cm X 2.4cm X 50cm cavity

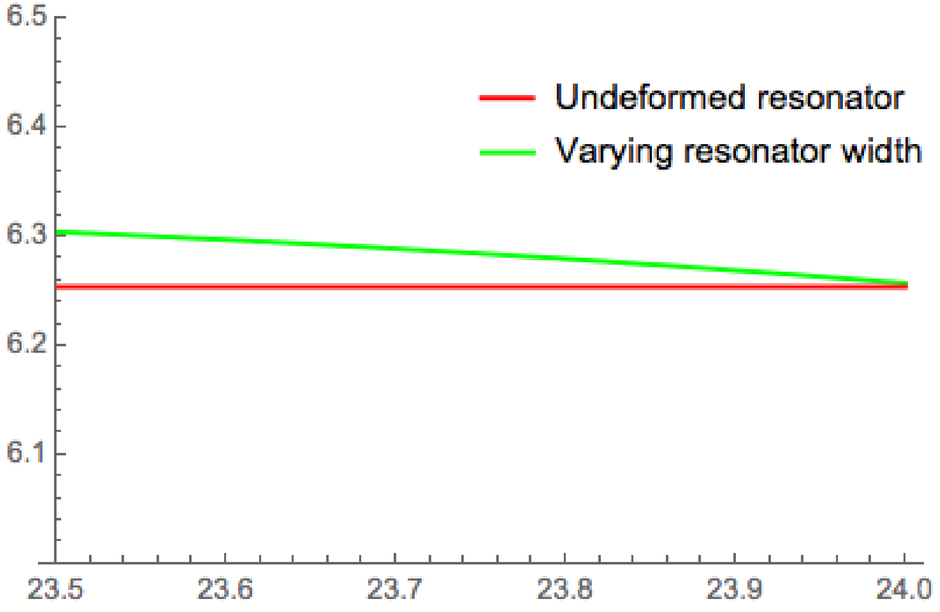
Horizontal axis: varying resonator width on one side (mm)

E-field snapshot

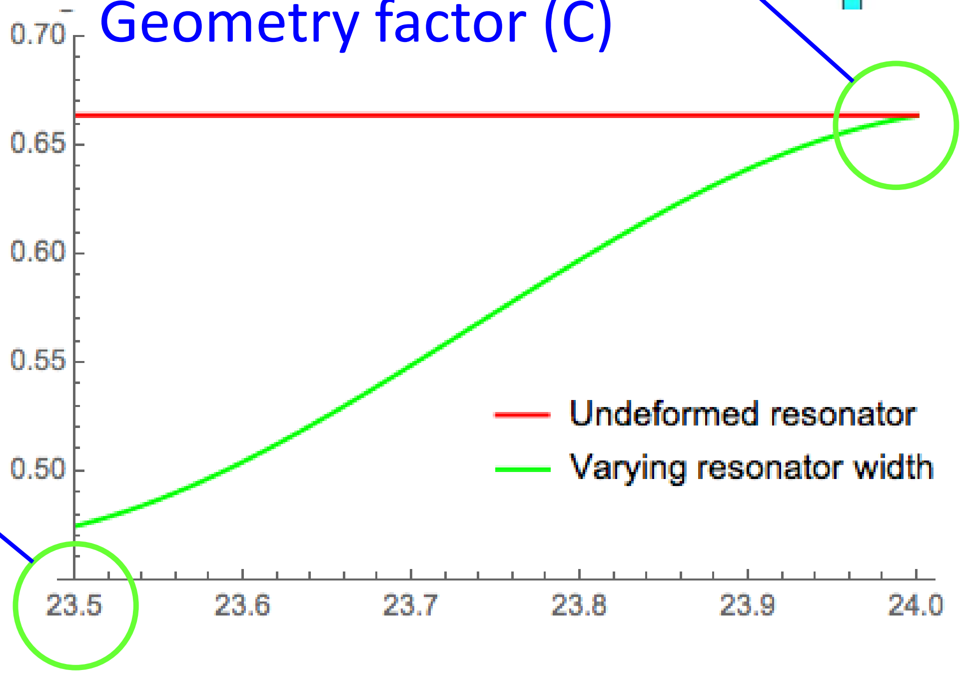




TE_{101} Resonant Frequency (GHz)



Geometry factor (C)



Outlook

- 2015
  - Prepare and test two, 50 cm long cavities
- 2016: insert two, ~ 50 long cavity in a single bore
  - Initial search with one 0.5 m long cavity
  - Study of HEMT amplifier response in high magnetic field
  - Explore phase matching two cavities
- 2017
  - …. ?

Contributors to the CAST-CAPP/IBS experiment

- IBS Center for Axion and Precision Physics Research (CAPP)
  - Yannis Semertzidis — CAPP Director
  - Beom-Ki Yeo — Simulations with OPERA, hardware
  - Miran Kim — Simulations with COMSOL, hardware
  - Others from CAPP: — Woohyun Chung, ByeongRok Ko, MyeongJae Lee, Soohyung Lee, Harry Themann, Sungwoo Yun
- CERN
  - CAST collaborators — CAST Magnet (special thank to Martyn Davenport)
  - Walter Wuensch — Cavity development
- Brookhaven National Laboratory (BNL)
  - Joseph M. Brennan — Signal processing, multiple cavity phase matching
  - Frank Lincoln — Mechanical Engineering
- Korea Advanced Institute of Science and Technology (KAIST)
  - Hyoungsoon Choi — Low Temperatures
  - Jhinhwan Lee — Tuning optimization, Q enhancement
- Korea Research Institute of Standard and Science (KRISS)
  - Yong-Ho Lee — Low noise amplifiers
  - Yonuk Chong — Low noise amplifiers, cavity tests at low temperatures