Search for Relic Axions with the CAST Dipole magnet at CERN

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CAPP
Center for
Axion and Precision
Physics Research

CAPP

Center for Axion and Precision Physics Research at KAIST, Daejeon, South Korea

Korea
Advanced
Institute of
Science and
Technology

Established October 2013. Goal: ~ 60 people within the first 3-5 years

- 15 research fellows - 20 grad. Students - 10 junior/senior staff
- Visitor program - Engineers, Technicians

CAPP, April 2016

Outline

- Axion search motivation
- A common DM axion detection method
- Status of cold dark matter axion searches
- Search in a dipole magnetic field
- The CAST-CAPP/IBS Project at CERN

CAPP Program

Focus is on two key issues of contemporary physics:

- Nature of dark matter
    - ○ Comprehensive axion search program (~75%)
- Baryon asymmetry of the universe
    - ○ R&D towards a proton EDM measurement in a storage ring (~25%)

CAPP main goals in axion search

- Establish state of the art axion dark matter experimental program at KAIST

- R&D program to improve on all experimentally accessible parameters

- Promote/contribute-to international collaborations

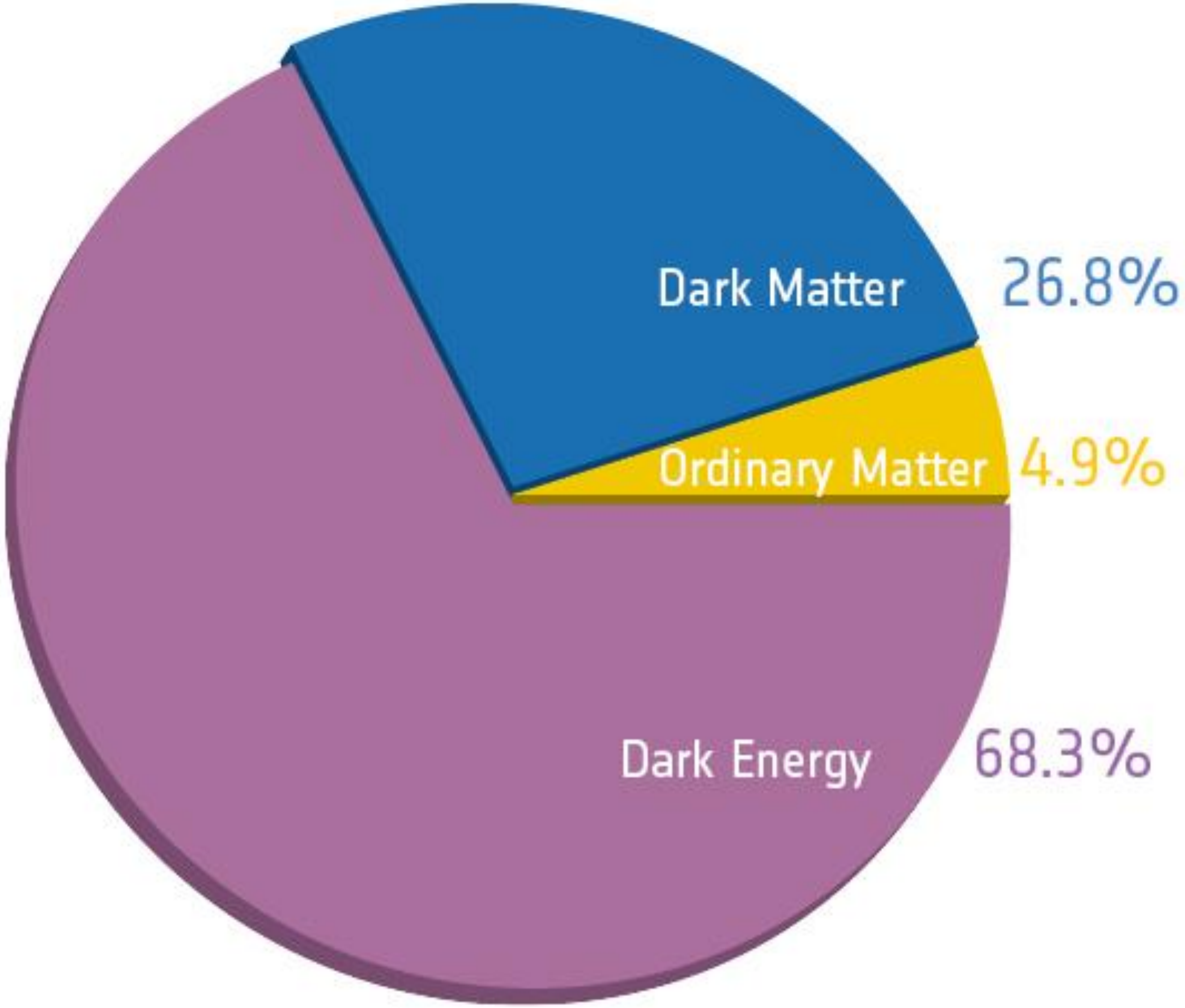
  CAPP is leading a new experiment (CAST-CAPP/IBS project), within the CERN Solar Axion Telescope (CAST) collaboration at CERN, to search for cold dark matter axions with rectangular cavities in the CAST dipole magnet

Axion search motivation

The axion is a good cold dark matter candidate if its mass is in the range $\approx (1 - 100)\ \mu$eV.

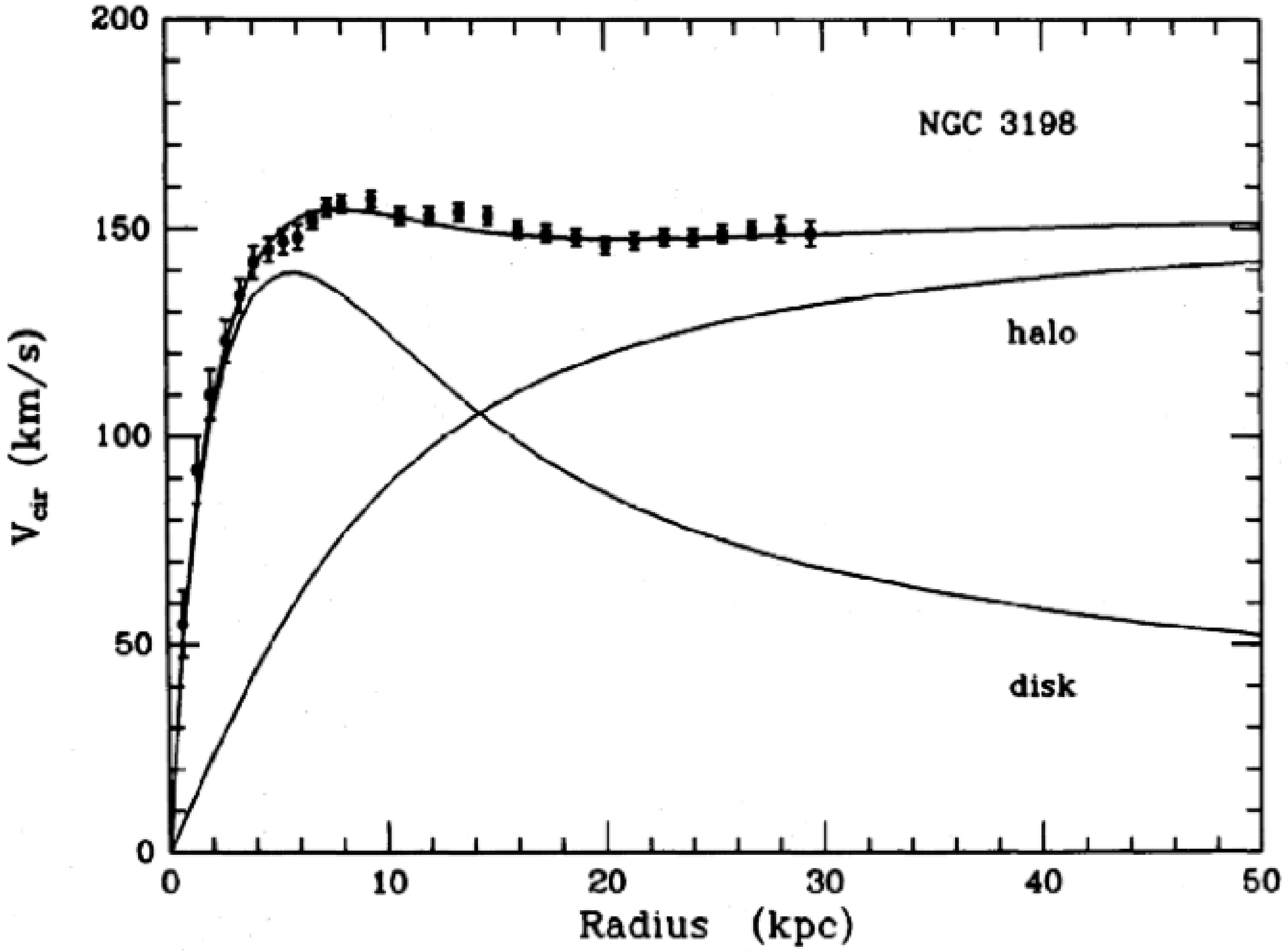
An axion discovery would solve the so called strong CP problem.

The composition of our universe



http://www.esa.int/spaceinimages/Images/2013/03/Planck_cosmic_recipe

Evidence for DM



Rotational curves in spiral galaxies.
At large distances from the center of galaxies, stars have higher than expected orbital velocities.

$$v = \left(\frac{G\,M(r)}{r}\right)^{1/2}$$

Circular orbit

F. Zwickey, Helv. Phys. Acta. 6, 110 (1933)

The strong CP problem

$$\mathcal{L}_{QCD} = \ldots + \theta \frac{\alpha_s}{8\pi} G\tilde{G} \longleftarrow$$

this term
violates CP

Measuring the EDM of a particle is a good test of CP violation

An estimate of the neutron EDM:

$$d_n \approx 3.6 \times 10^{-16}\ \theta\ \ e \cdot cm$$

M. Pospelov, A. Ritz, Ann. Phys. 318 (2005) 119.

Whereas the experiment sets a limit at

C. A. Baker, et al, hep-ex/0602020

$$d_n < 2.9 \times 10^{-26}\ e \cdot cm \longrightarrow \theta < 10^{-10}$$

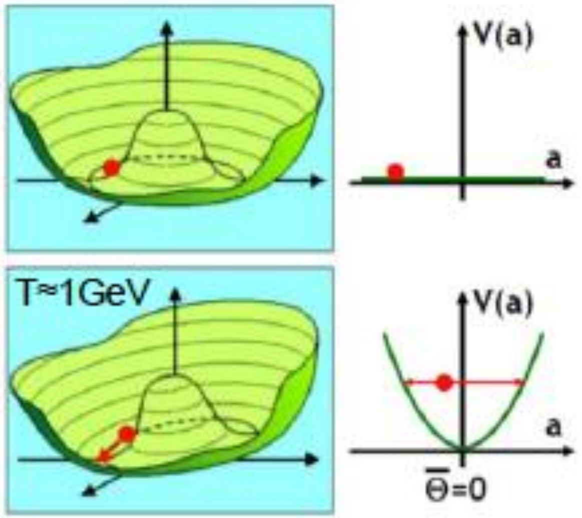
The measured value of the θ parameter is ~10 orders of magnitude smaller than QCD predictions

Solution to the strong CP problem

- Peccei-Quinn : θ_{QCD} is a dynamical variable (1977).
- Wilczek and Weinberg: axion particle (1977)
- J.E. Kim: Hadronic (invisible) axions (1979)

- Axions: pseudoscalars, similar to pions, but much lighter

$$m_a \approx 6 \times 10^{-6}\ \mathrm{eV}\ \frac{10^{12}\ \mathrm{GeV}}{f_a}$$



The link between axion and DM

- Dark matter density: 0.3-0.5 GeV/cm^3
- Axions in the 1-100 μeV range: 10^{12}-10^{14}/cm^3
    - Light axion would have condensed with the right density to be DM
- Lifetime ~ 7×10^{44}s (100μeV / m_a)^5 .
- Axions interact very weakly
- Kinetic energy ~$10^{-6}m_a$ ("cold") very narrow line in spectrum.

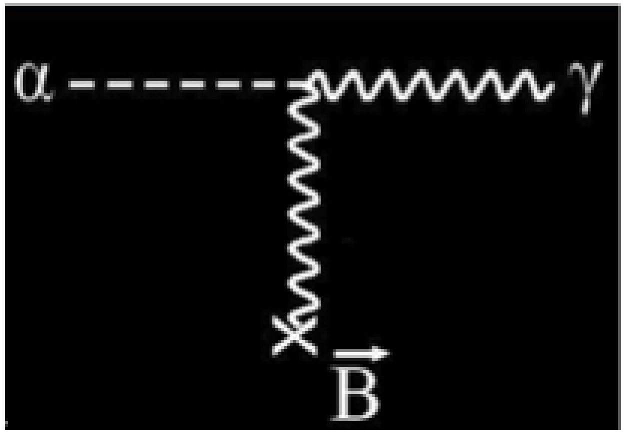
$\longrightarrow$ can be treated as a classical system.

Common detection method

Based on the axion coupling to two photons.

In the presence of a strong magnetic field the conversion probability is enhanced (similar to Primakoff (*) effect)

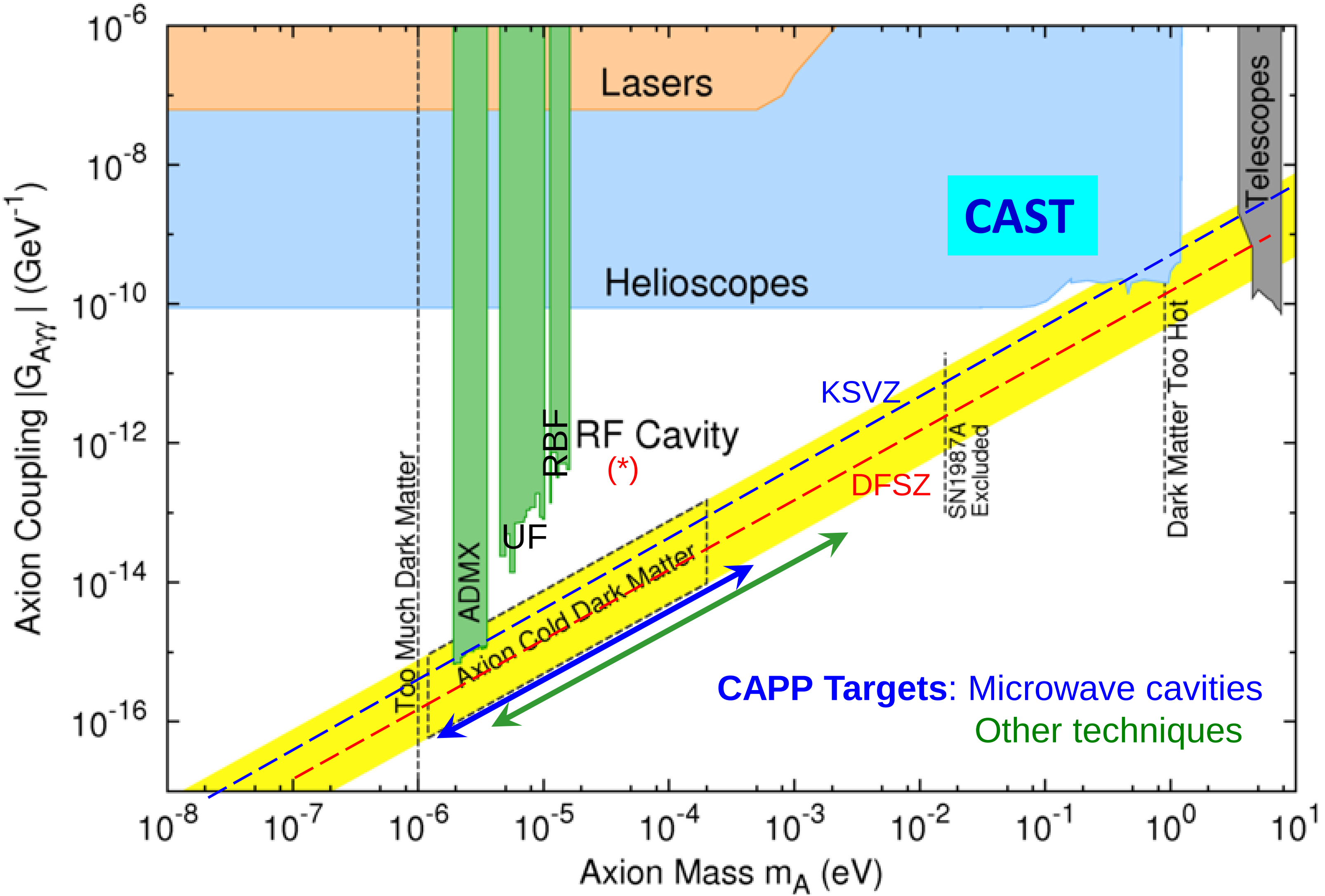
$$\mathcal{L} = -g_{a\gamma\gamma} a(t) \boldsymbol{E}(\boldsymbol{t}) \cdot \boldsymbol{B}$$



$g_{a\gamma\gamma}$	coupling constant
$a(t)$	axion field
B	provides a virtual photon enhancing the conversion probability
E(t)	electric field associated with the outgoing photon

(*) H. Primakoff, Phys. Rev. 81, 899 (1951)

Axion experments: two parameter searches



(*) One missing experiment. See later.

Axion detection with microwave cavities

Axion-to-photon conversion probability 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:

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

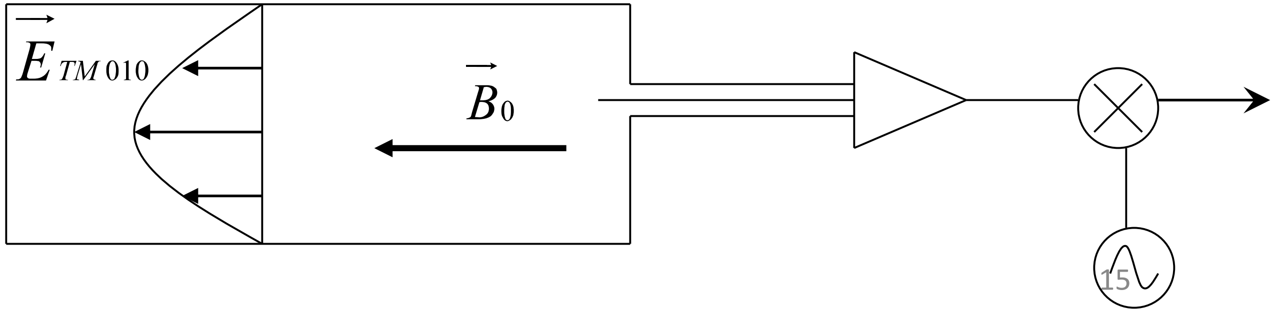
$$Q = 2\pi f \, \frac{\text{Stored Energy}}{\text{Power Loss}}$$

Quality factor

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

Geometry factor

→ Tunable cavities



(*) P. Sikivie, Phys. Rev. Lett. 51, 1415 (1983).

CAPP/IBS axion target plan

- Major improvement elements:
  - High field solenoid magnets, B: 9T→25T→40T
  - High volume magnets/cavities, V: 5*l*→50*l*
  - High quality factor of cavity, Q: $10^5 \rightarrow 10^6$
  - Low noise amplifiers, T_N: 2K→0.25K
  - Low physical temperature, T_{ph}: 1K→0.1K

Scanning rate improvement: 25×10^6

Improvement in coupling constant: 70

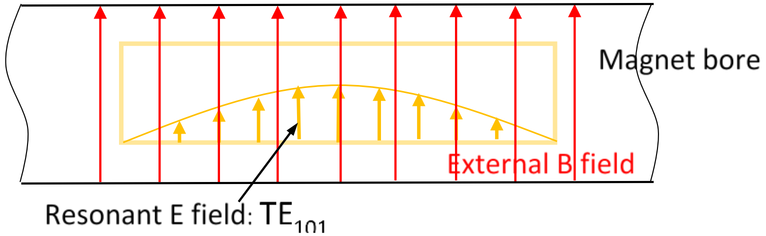
Axion dark matter in the mass range ~1μeV to 100μeV. Plan to either detect or exclude axions down to 10% of dark matter.

CAST-CAPP/IBS search: rectangular geometry (*)

First experiment using rectangular cavities in a dipole magnet

- Rectangular cavity resonant frequencies

$$f_{lmn} = \frac{c}{2\pi\sqrt{\mu_r \epsilon_r}} \sqrt{\left(\frac{l}{w}\right)^2 + \left(\frac{m}{h}\right)^2 + \left(\frac{n}{L}\right)^2}$$

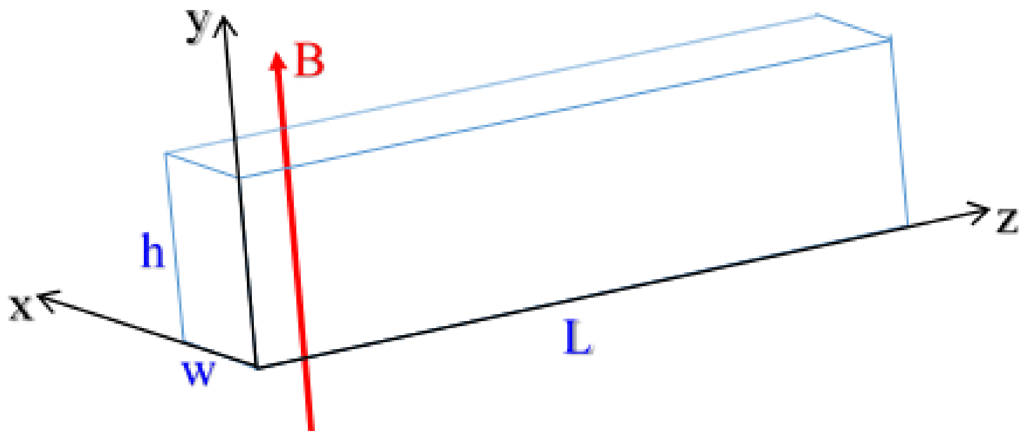


- Resonant E field aligned with the external B field: TE_{l0n} modes

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

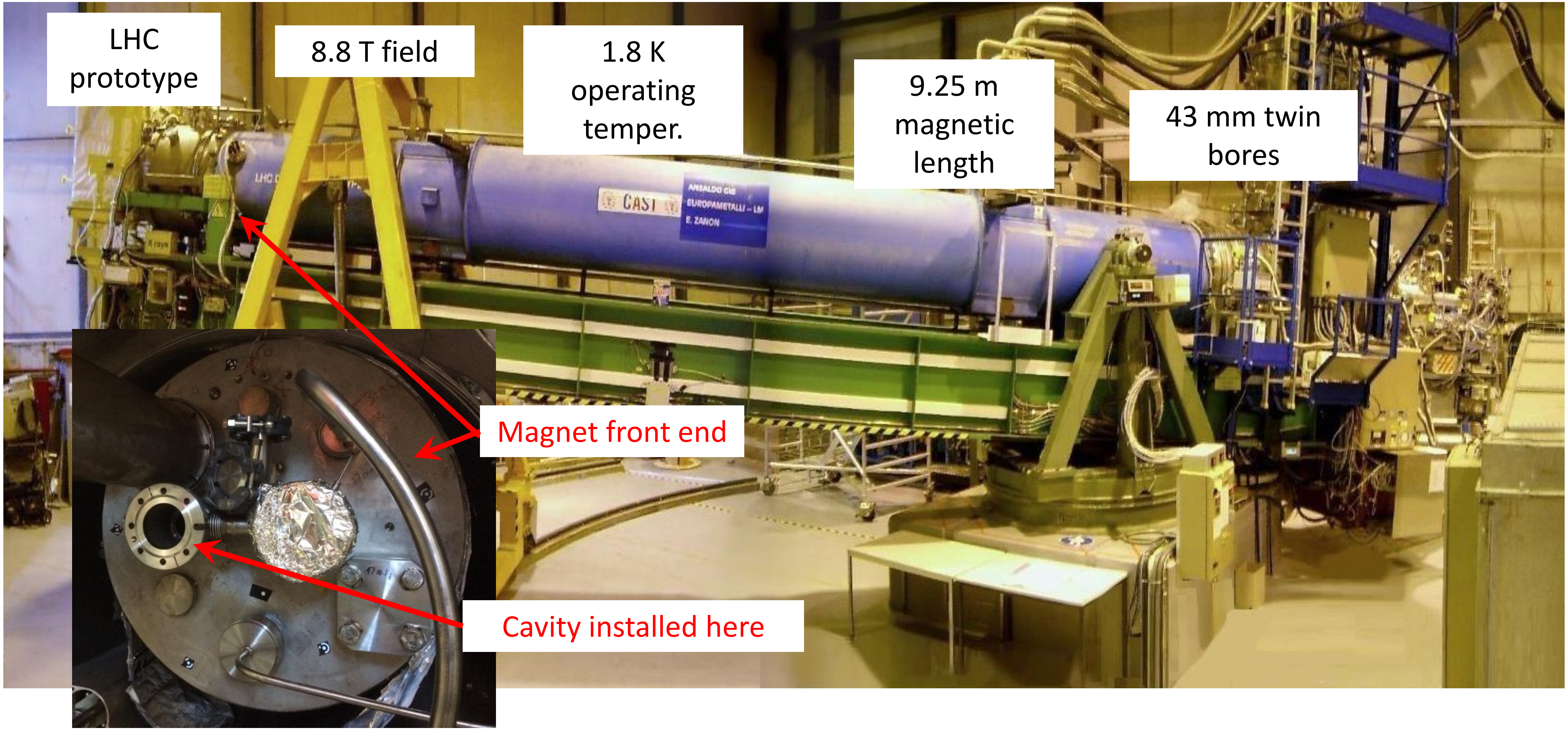
$$E_x = E_z = 0$$

.



(*) O. Baker et al., Phys. Rev. D85, 035018 (2012)

CAST-CAPP/IBS Search: The CAST Dipole Magnet



LHC prototype

8.8 T field

1.8 K operating temper.

9.25 m magnetic length

43 mm twin bores

Magnet front end

Cavity installed here

Resonant power

- $$P \;=\left(g_{a\gamma\gamma}\right)^{2}\rho_{a}\frac{1}{\boldsymbol{m_a}}B^{2}CV\,min[Q_c,Q_a]$$
  $$=\;1.6\;\times10^{-23}\mathrm{W}\;\times\left(g_{a\gamma\gamma}10^{14}\mathrm{GeV}\right)^{2}\left(\frac{\rho_a}{300\ \mathrm{MeV/cm^3}}\right)\left(\frac{2.4\times10^{-5}eV}{\boldsymbol{m_a}}\right)$$
  $$\times\left(\frac{B}{9\ \mathrm{T}}\right)^{2}\left(\frac{\boldsymbol{C}}{0.66}\right)\left(\frac{V}{5\ l}\right)\left(\frac{Q}{5\ \times10^{3}}\right)$$

- 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 ~ 5,000; critical coupling
  - Q_c loaded quality factor
  - Q_0 cavity quality factor

Time required for a single measurement (example)

$$\boxed{SNR = \frac{P}{K_B\, T}\sqrt{\frac{t}{b}}}$$

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

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 rate (example)

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

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

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

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

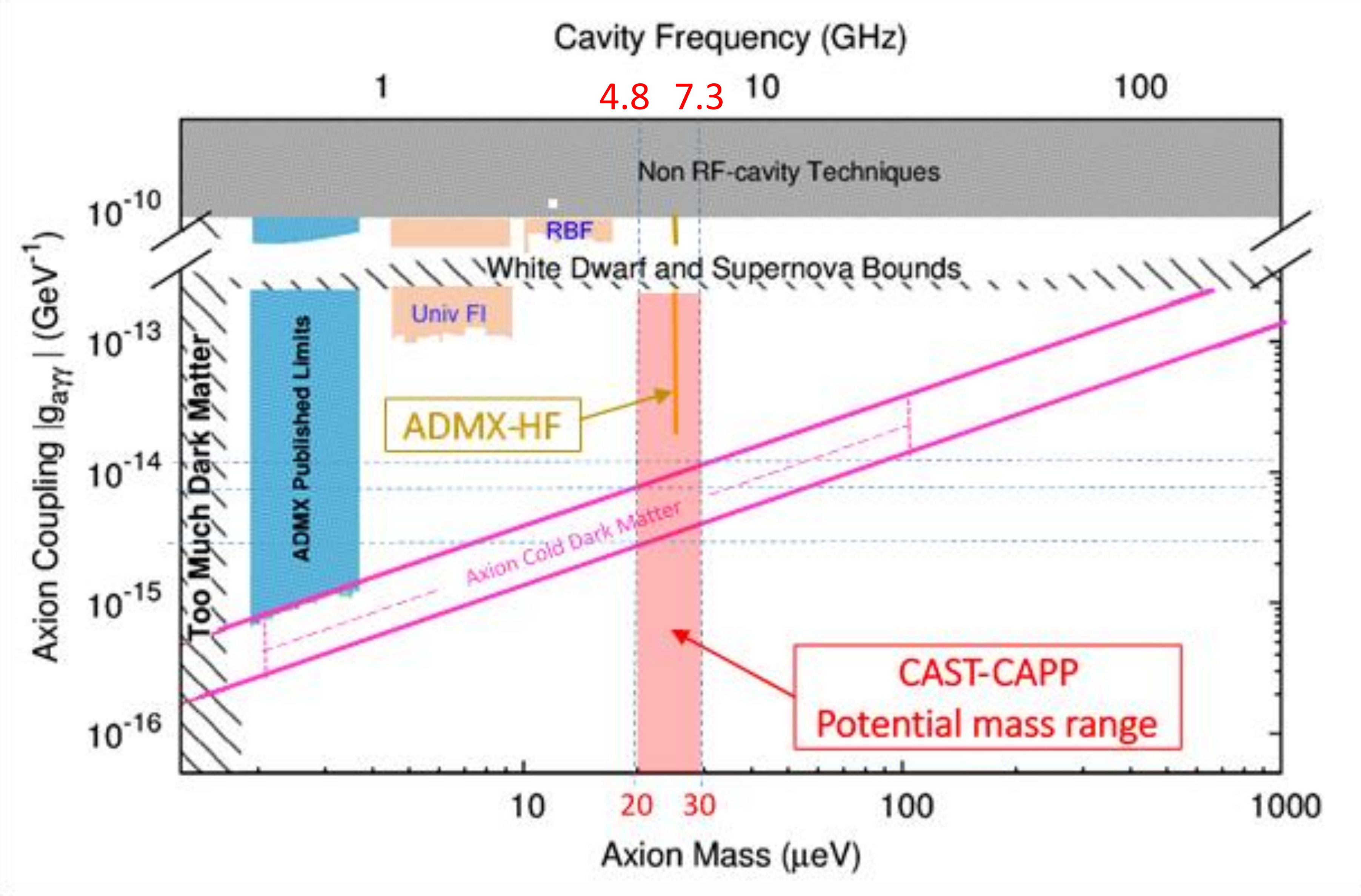
V = 5 liters

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

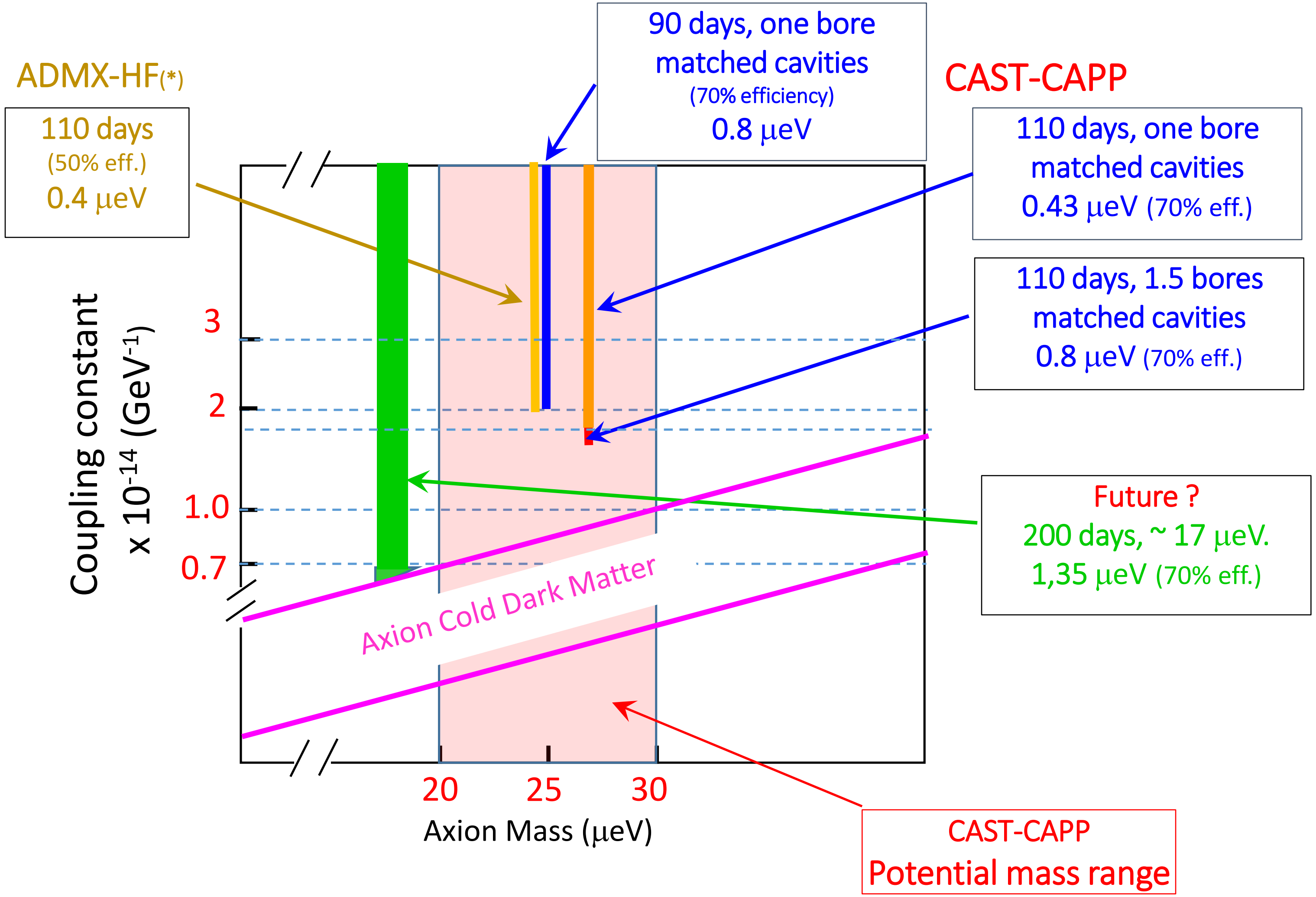
- Q_c loaded quality factor
- Q_0 cavity quality factor

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

Sensitivity



CAST-CAPP sensitivity

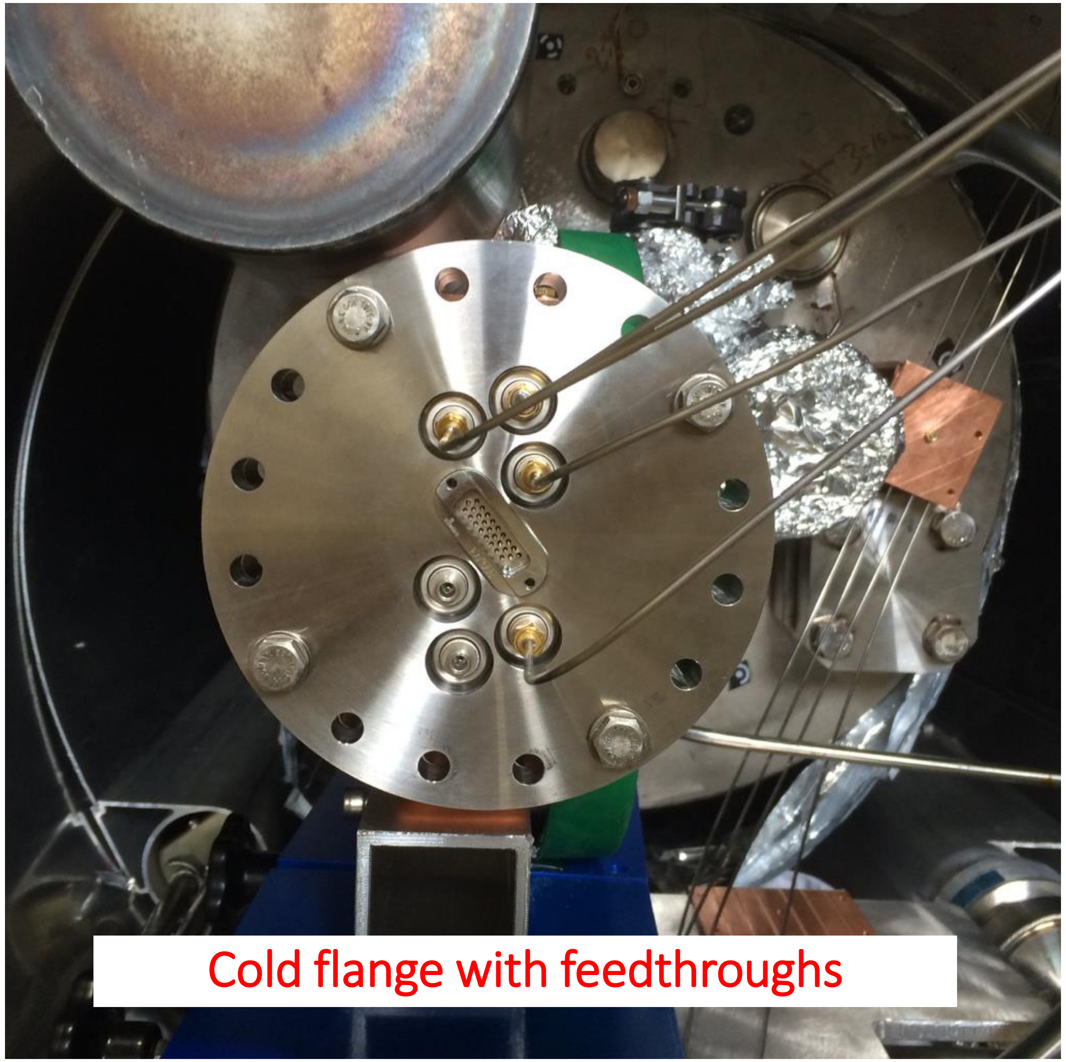


(*) arXiv:1610.02580v1 8 Oct 2016

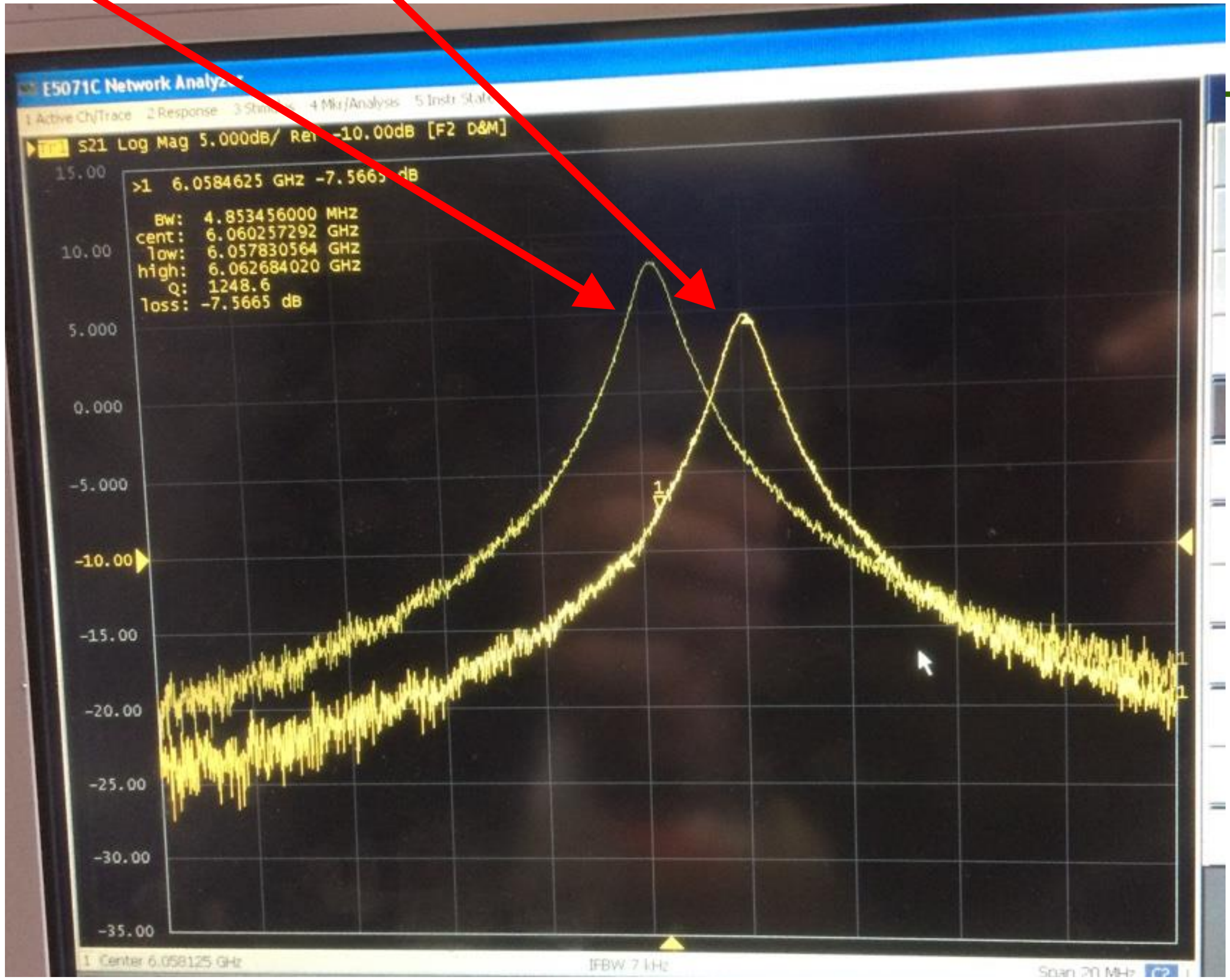
Status: One year since project started

- November 2015: Project start after CERN SPSC approval
- Jan-May 2016: cavity prep, integration with magnet, vessel design and construction, OK to install
- June 2016: cavity installation and testing
  - Resonance measured after installation, before and after start of vacuum pumping
  - Resonant frequency shifted up by ~ 1.8 MHz, roughly corresponding to the change in electrical permittivity of the medium, at room temperature.

Cavity resonance before and after vacuum pumping



Cold flange with feedthroughs



```
Tr1 S21 Log Mag 5.000dB/ Ref -10.00dB [F2 D&M]
>1  6.0584625 GHz -7.5665 dB

   BW:  4.853456000 MHz
 cent:  6.060257292 GHz
  low:  6.057830564 GHz
 high:  6.062684020 GHz
    Q:  1248.6
 loss: -7.5665 dB
```

```
1 Center 6.058125 GHz          IFBW 7 kHz          Span 20 MHz
```

Resonant frequency shifted up by ~ 1.8 MHz, corresponding to the change in electrical permittivity of the medium, at room temperature.

Status: One year since project started

- August/September 2016:
  - Magnet cold (1.8 K)
  - Fundamental resonant frequency re-measured: shifted up from to ~ 6.078 GHz → the cavity behaves as expected.
  - Magnet ramped to 13,000 A (operating field): no significant changes in the resonance
  - Quench tests:

    Magnet quenched from low and operating field (~ 9 T): Cavity unaffected.

    → cavity mechanically and electrically stable
- November 28: ~ 1 week data acquisition before magnet shut down

Cavity unchanged and stable before and after magnet quench

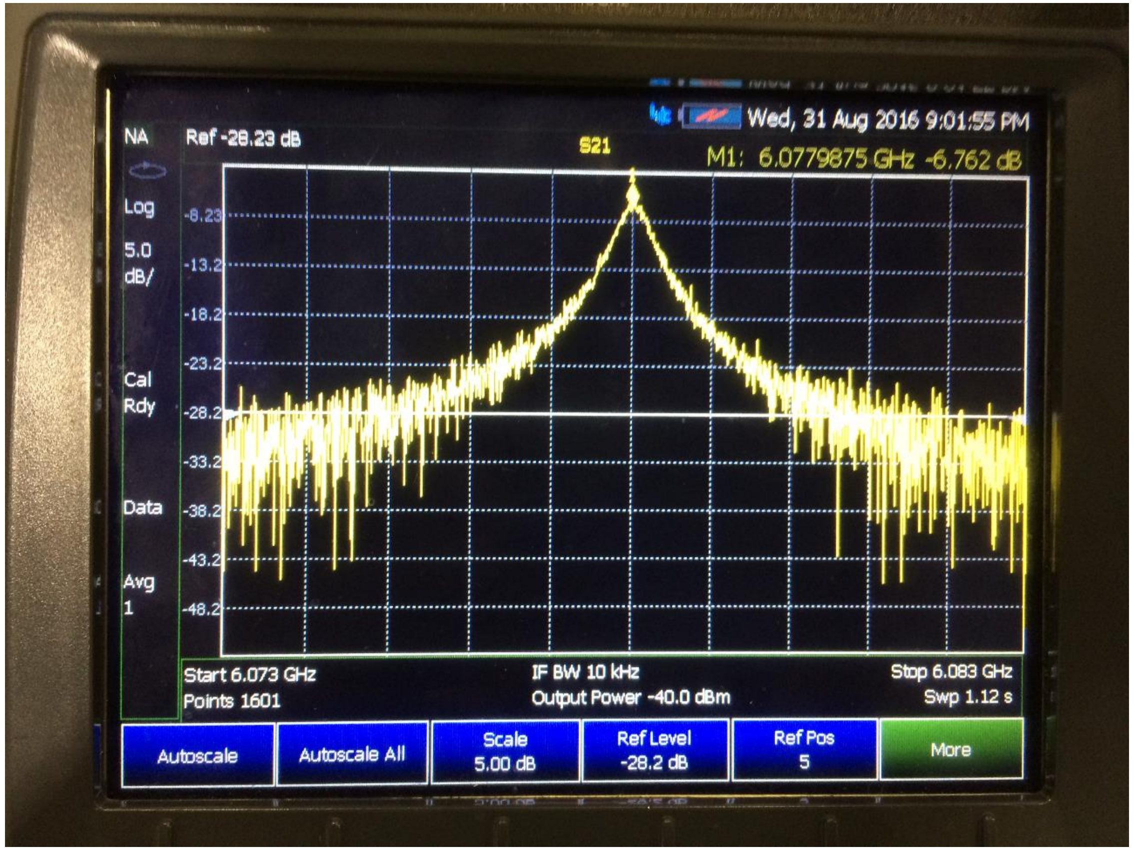
Center freq. = 6.078 GHz

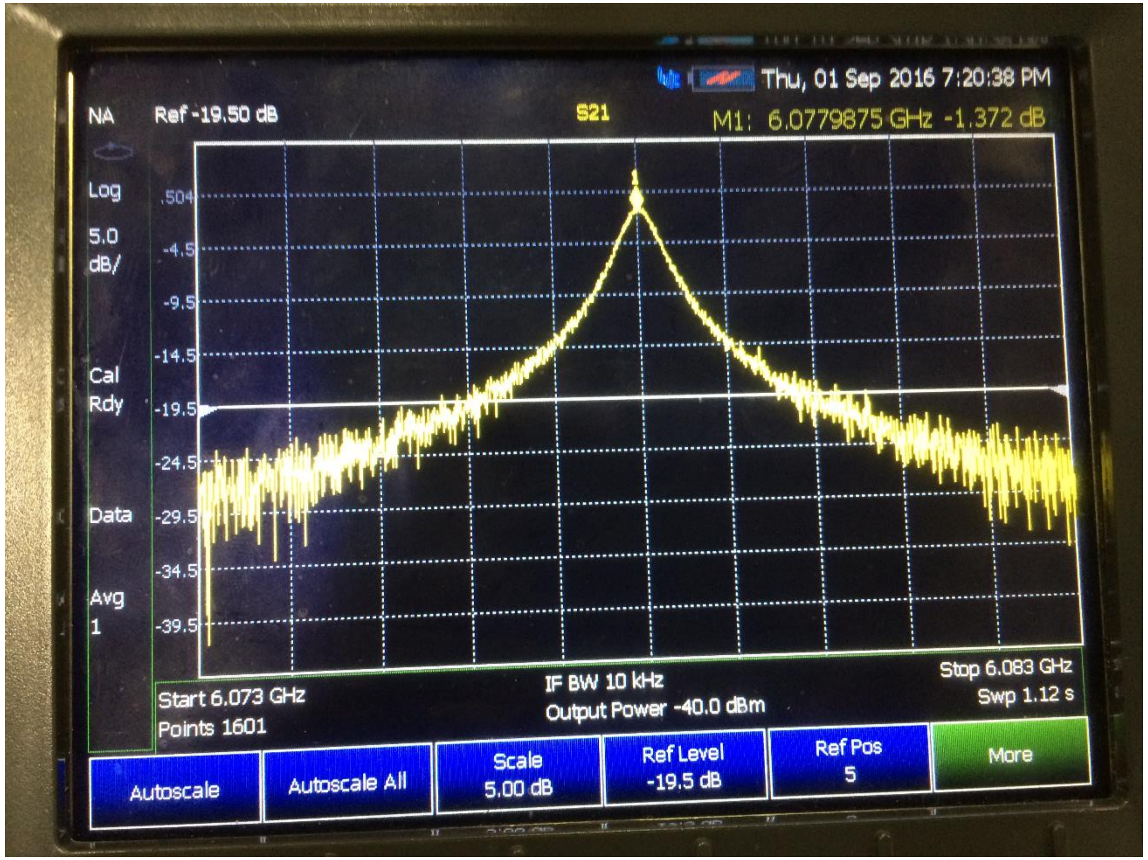
Magnet cold

Before magnet quench (full field)

After magnet quench

Amplitude





Resonant frequency
unchanged

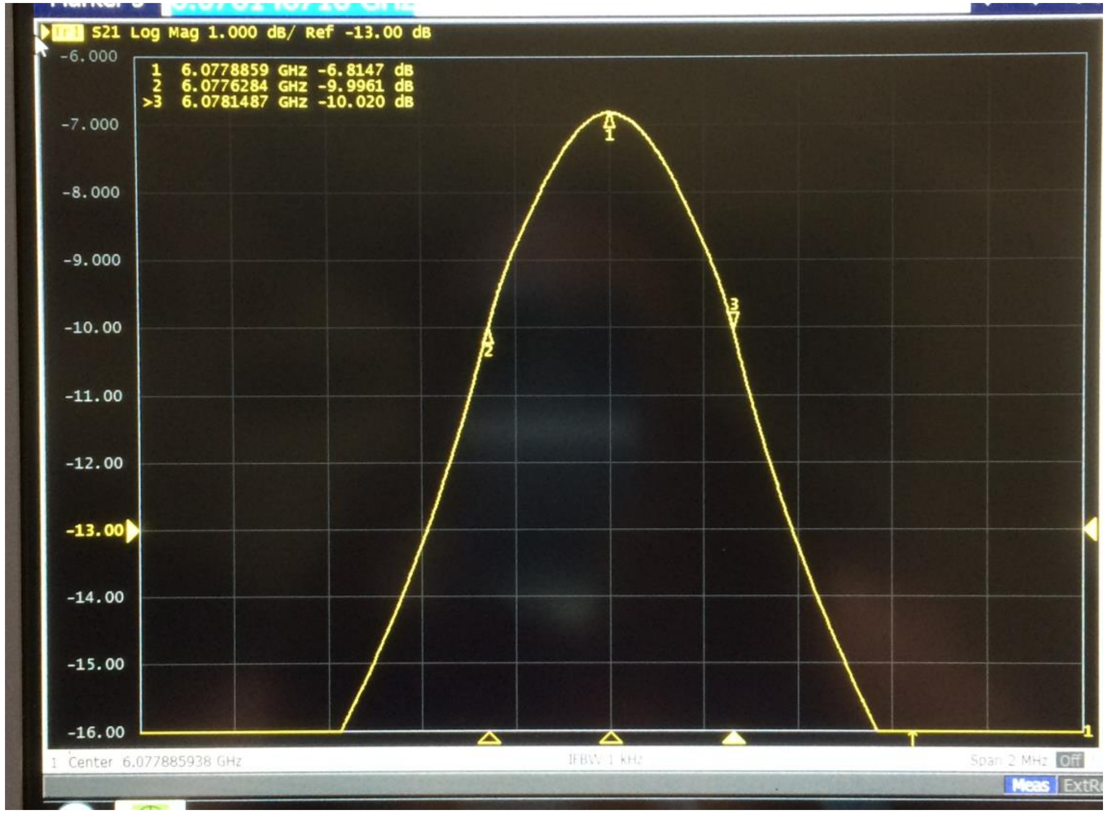
Frequency

A closer look at the resonance with and without the magnetic field

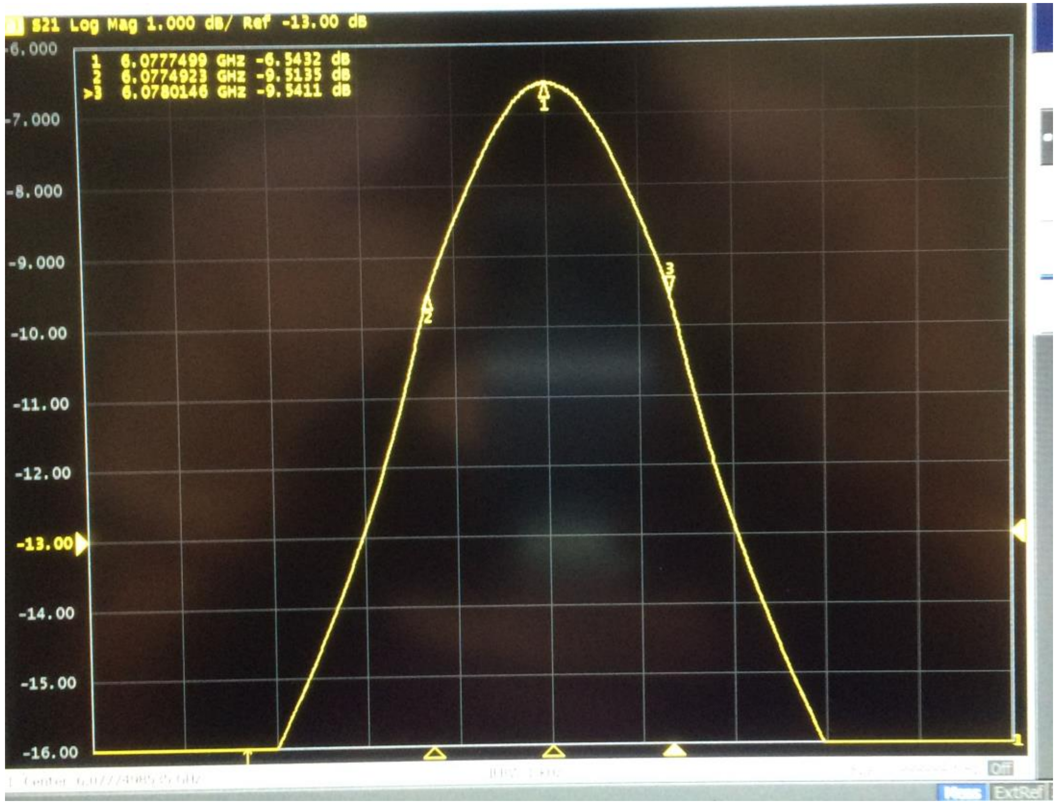
Center freq. = 6.078 GHz

Magnet cold

Magnet off



Magnet on



Amplitude

Frequency

Resonant frequency shifted by –136 KHz, 2 parts in 100,000.

Installed Cavity

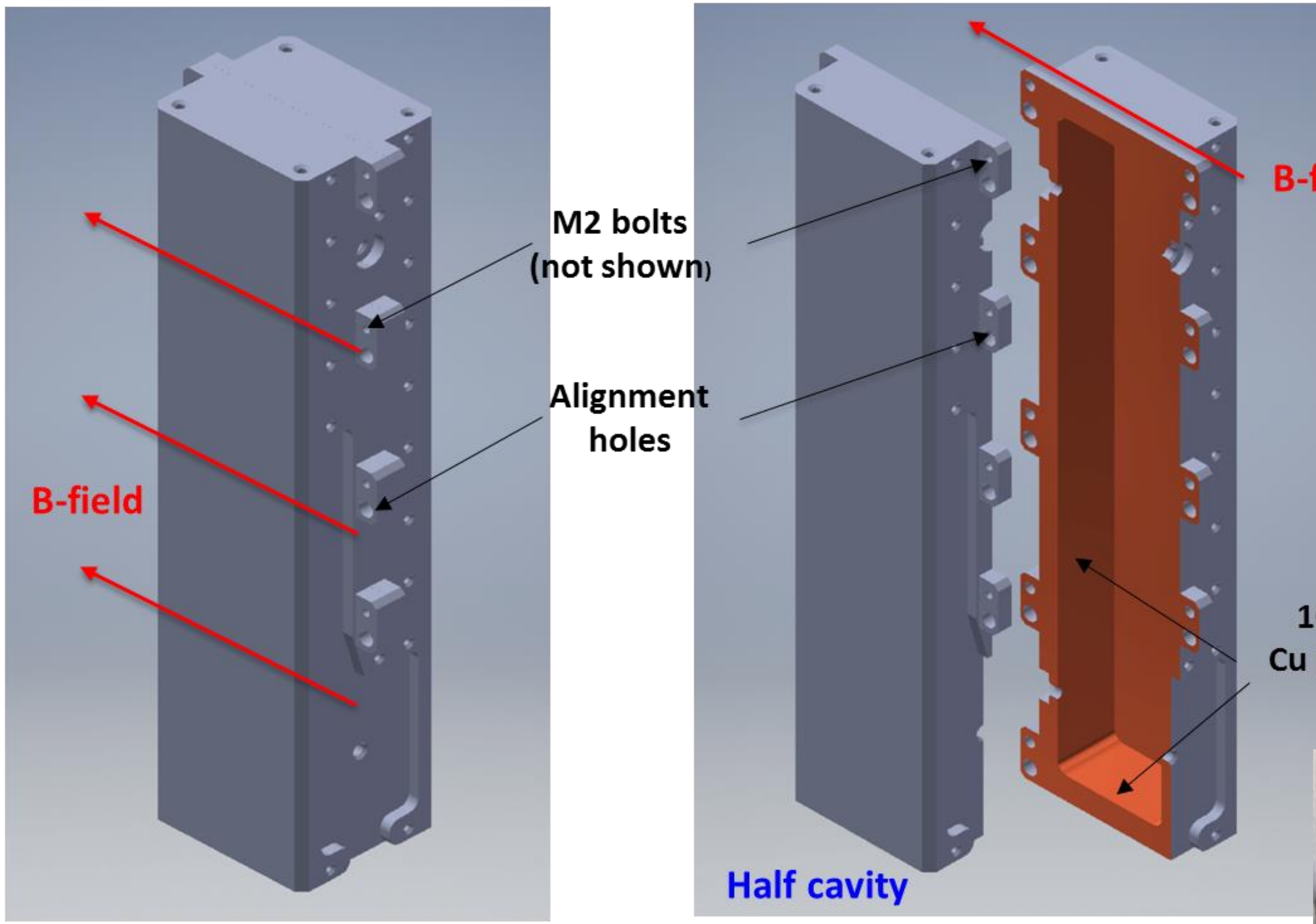
- Fundamental mode f ≅ 6.078 GHz (low-T)
- Q ≅ 10,000 (room-T)
- Dimensions: 138 mm X 25 mm X 23 mm.
- Material: stainless steel 10-micron thick electrodeposited copper layer
- Longitudinally split
- Magnetically coupled

Setup

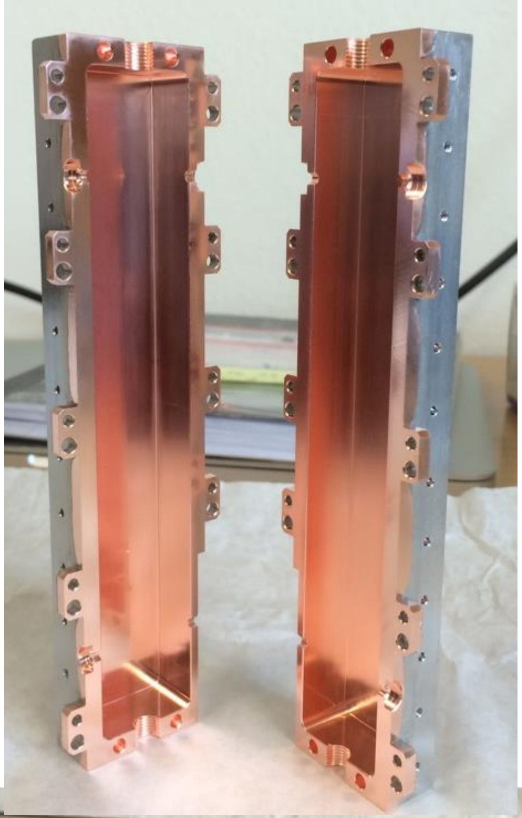
- Cavity signals to a cryogenic low noise HEMT amplifier outside of the cold bore, inside a vacuum vessel
- Two temperature sensors: one on cavity, one near the cryogenic amplifier
- Cavity temperature 3.8 K
- Amplifier temperature 2.5 K
- 2-axis Hall probe near the cavity; 3-axis Hall probe near the amplifier

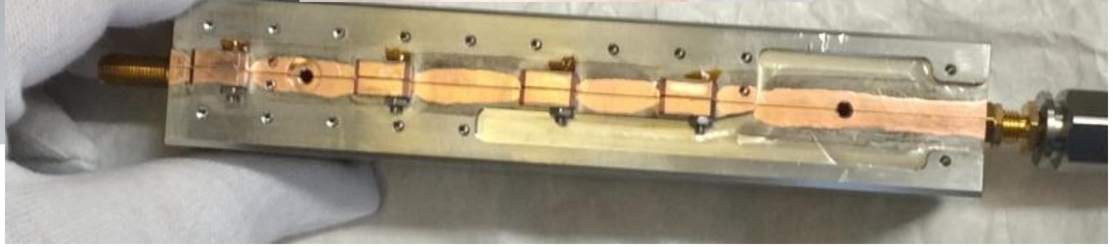
The RF cavity installed inside the bore

“Inspired” by LHC beam screen design and testing , but 7 times thinner copper plating

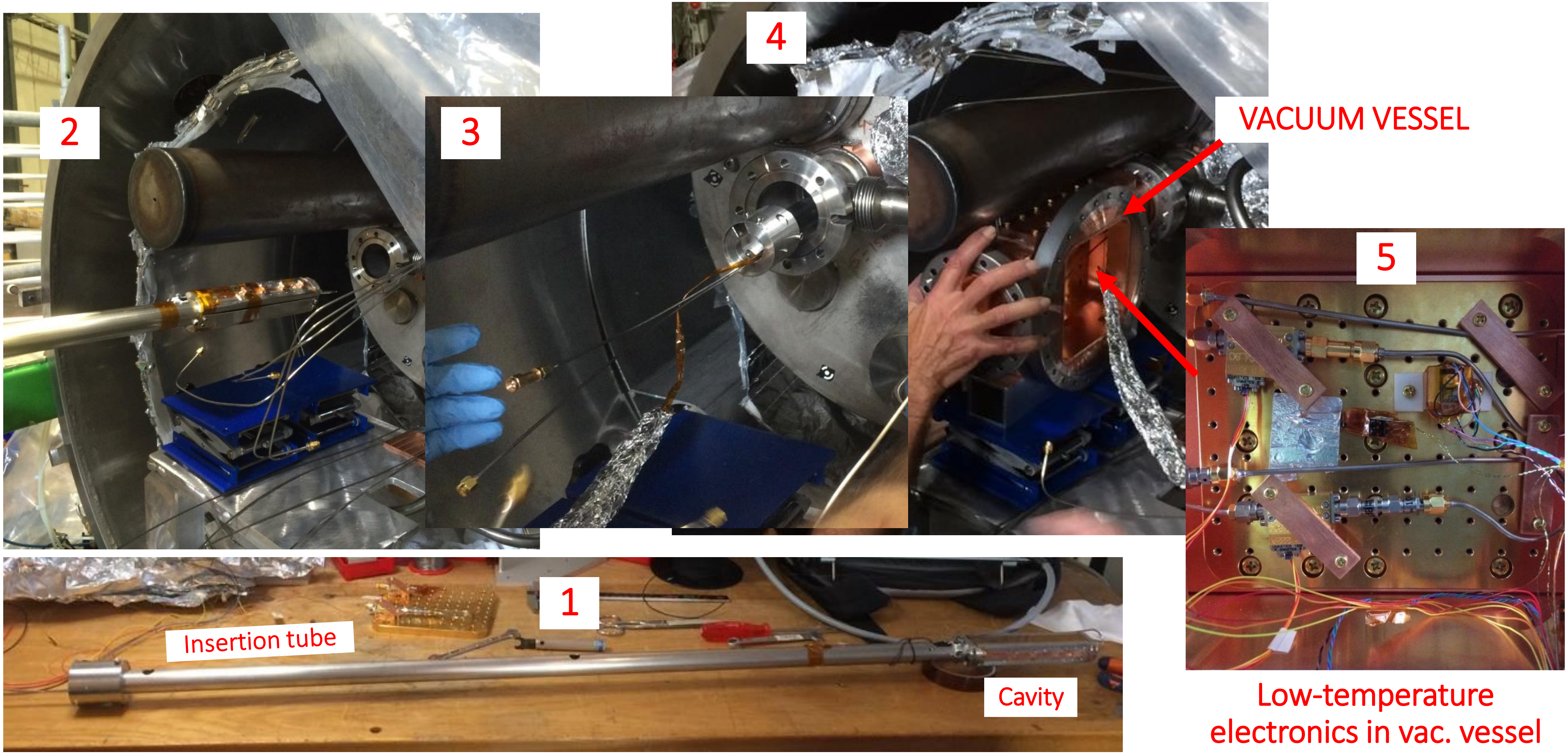


Assembled cavity



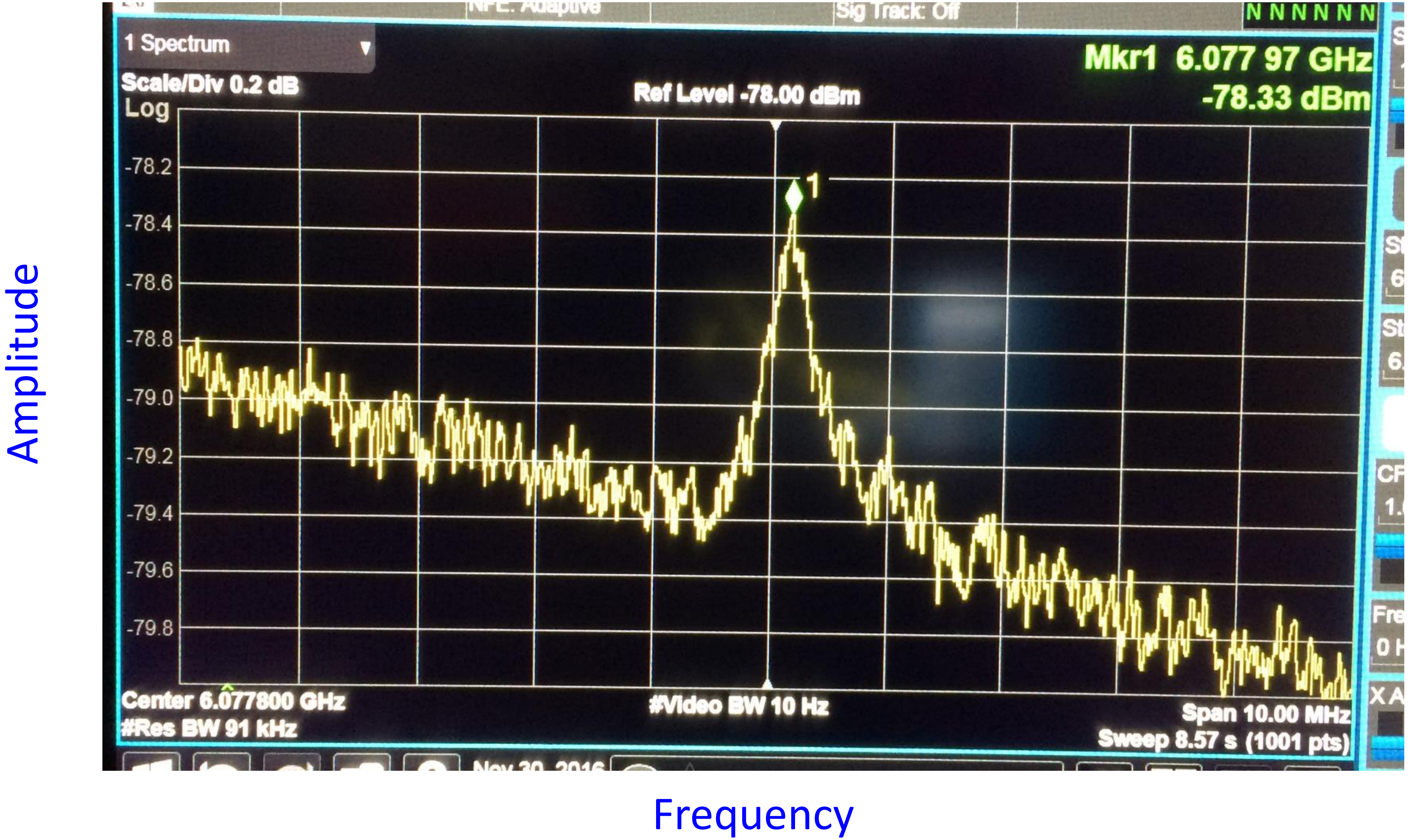


Installation

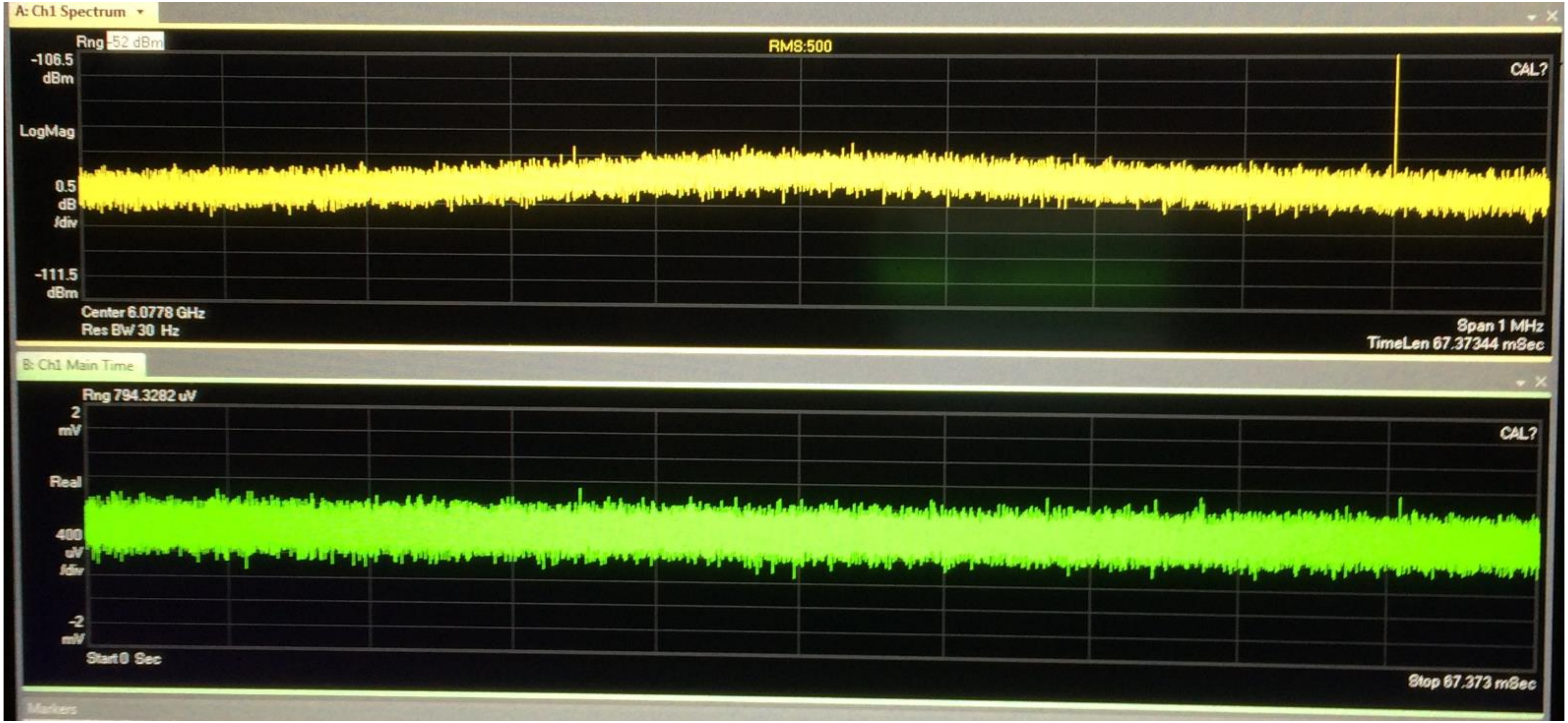


Low-temperature electronics in vac. vessel

A sample from recent data acquisition



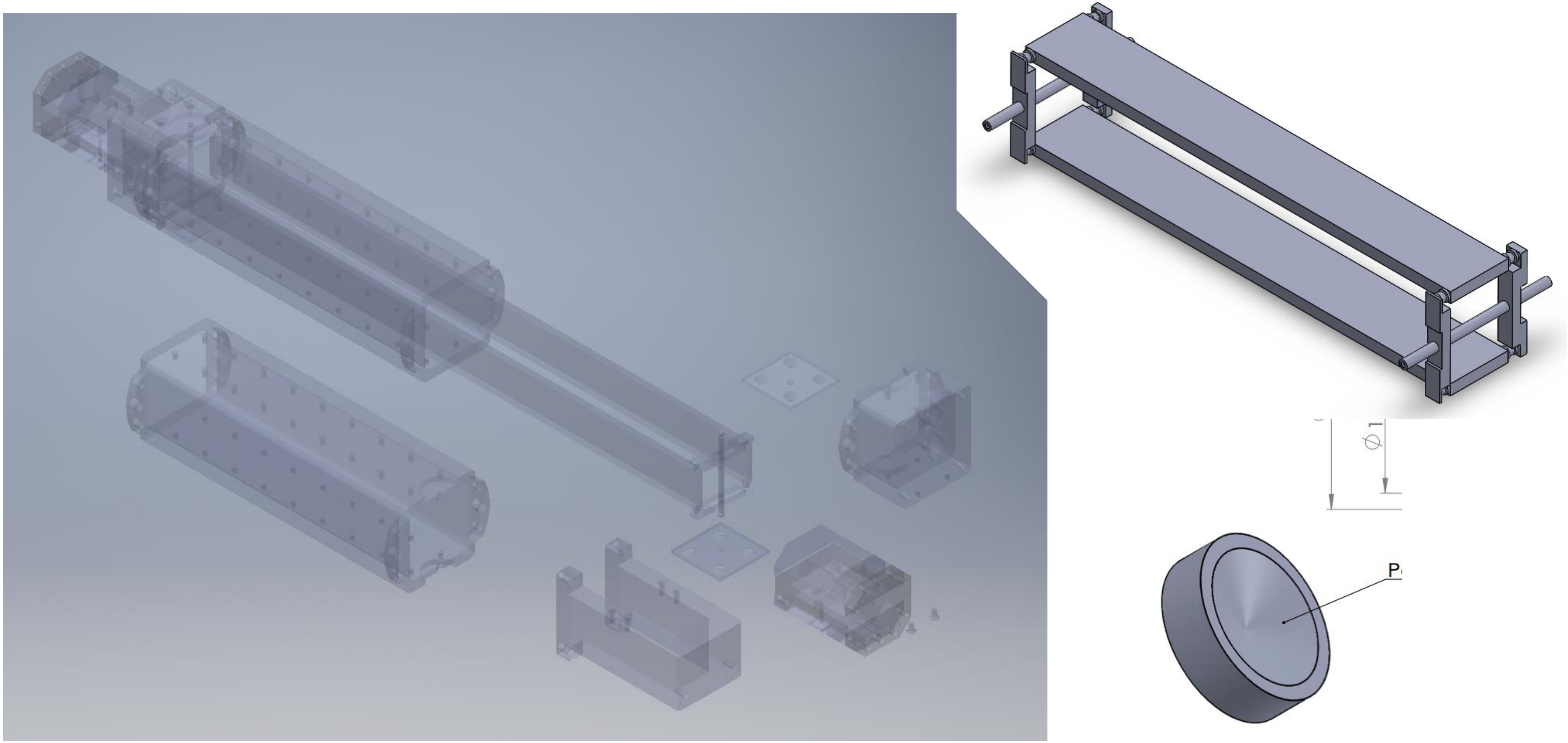
A sample from recent data acquisition



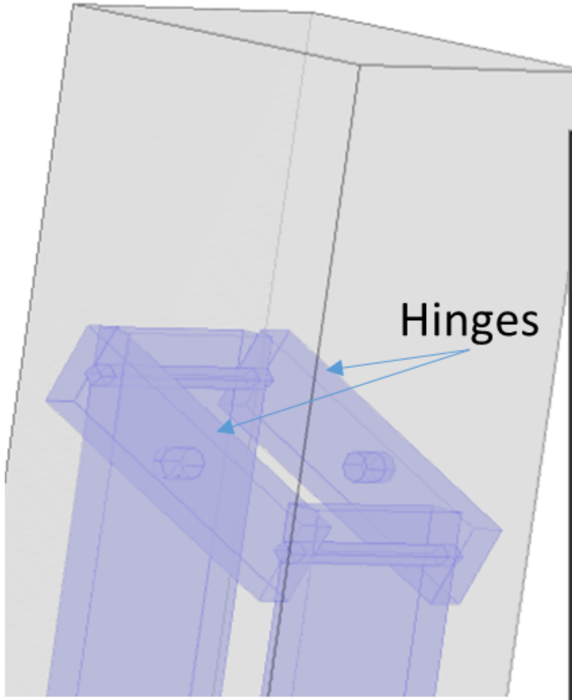
CAST-CAPP R&D

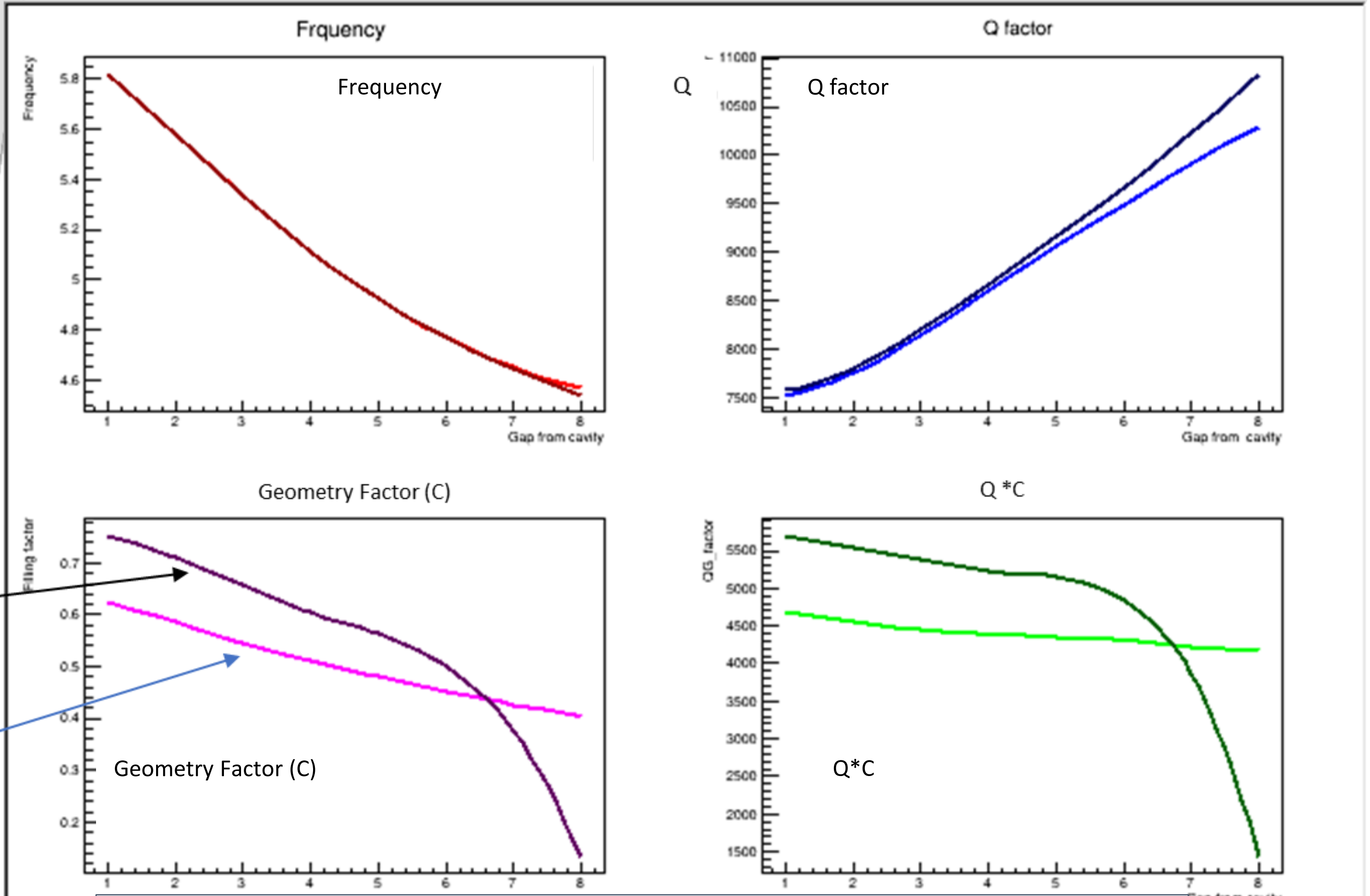
- Design and fabrication of longer rectangular cavities.
- Amplifiers in high magnetic fields.
- Cavity tuning and coupling for multi-cavity operation.
- Multi-cavity operation

Next: Cavity tuning with dielectric bars



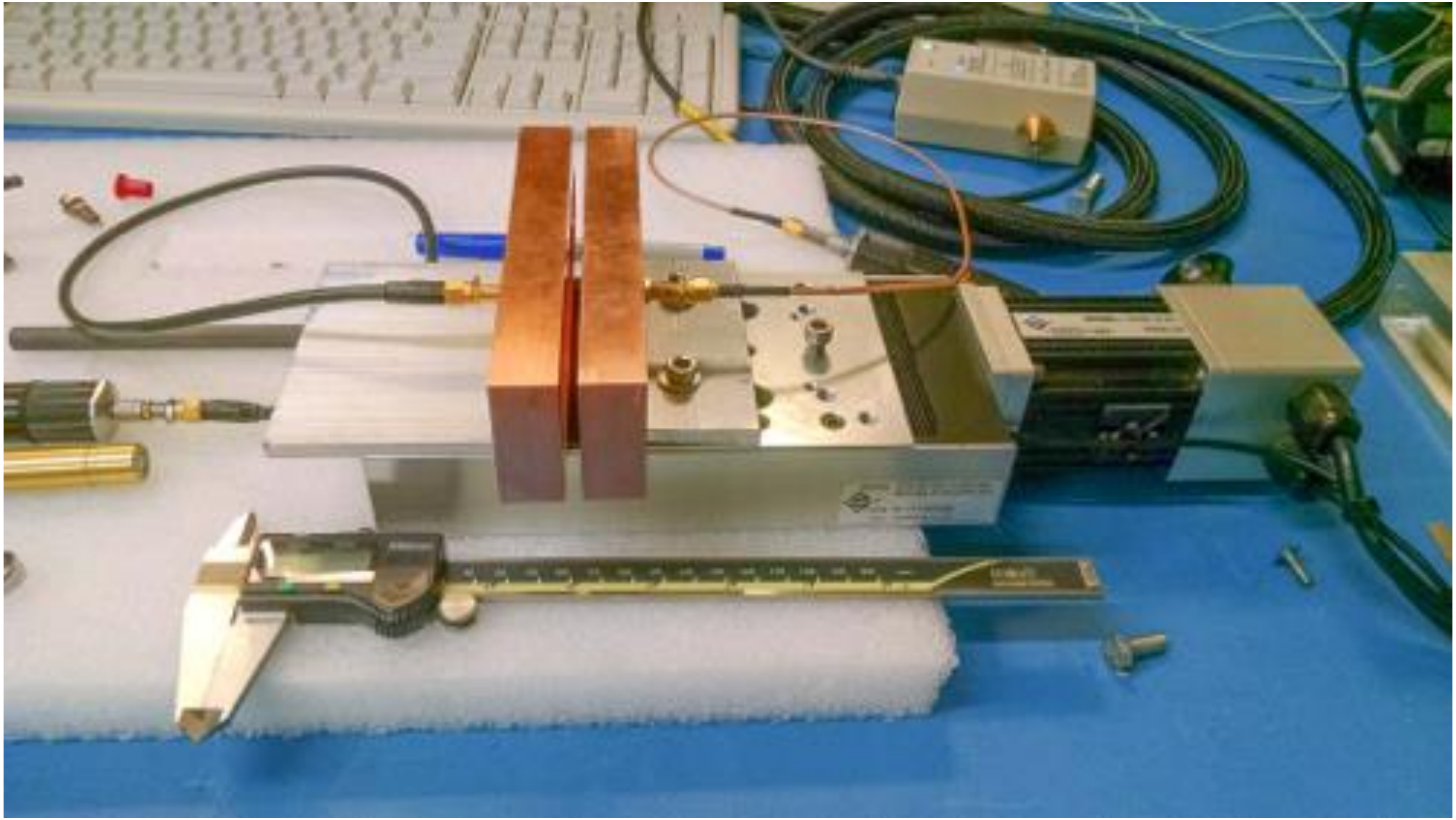
Cavity tuning with dielectric bars



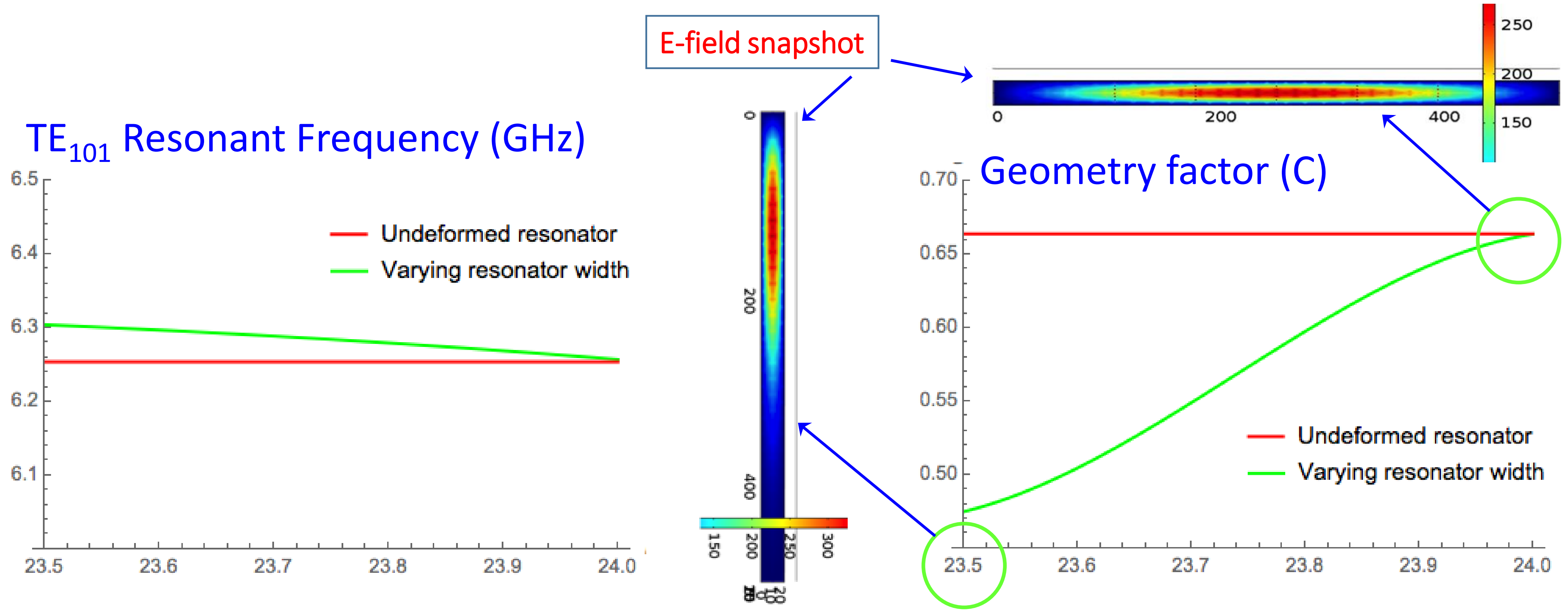


Horz. axes: bar insertion distance from longitudinal wall

Alternative tuning: Split cavity



Cavity engineering:
Mechanical tolerances vs. mode localization.
Cavity: 2.5cm X 2.4cm X 50cm



E-field snapshot

TE_{101} Resonant Frequency (GHz)

Geometry factor (C)

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

Summary:

- For the first time, a microwave cavity has been installed in a dipole magnet for axion search
- The cavity is stable inside the magnet, unaffected by quench forces
- We have taken a few days of data
- This feasibility study shows that an axion search experiment using the Sikivie technique is sustainable in a large dipole magnet
- We plan to move to multiple cavities for higher sensitivity