New ideas for axion like particle dark matter search

F. Caspers, K. Zioutas, M. Betz, 2012

In the context of finding suitable large magnets for RF and microwave axion search, the Tore supra ring had been proposed. This Tokamak which could probably be made available for DM search has a huge volume and a strong magnetic field (30000 liter and 4.5 Tesla). It appears on a first glance, as an interesting candidate for this kind of experiment. One can find a suitable microwave mode which meets the condition that the RF electric field is parallel to the magnetostatic field. The eigenfrequency field pattern and Q factor for this mode and a few adjacent ones are calculated the some field patterns shown graphically. The use of the torus type cavity is not restricted to the Tore Supra. It can in principle be applied to any torus type structure also scaled up toward smaller dimensions and higher frequencies. In the second part of the slide presentation some alternatives and other cavity magnet concepts are shown and discussed.

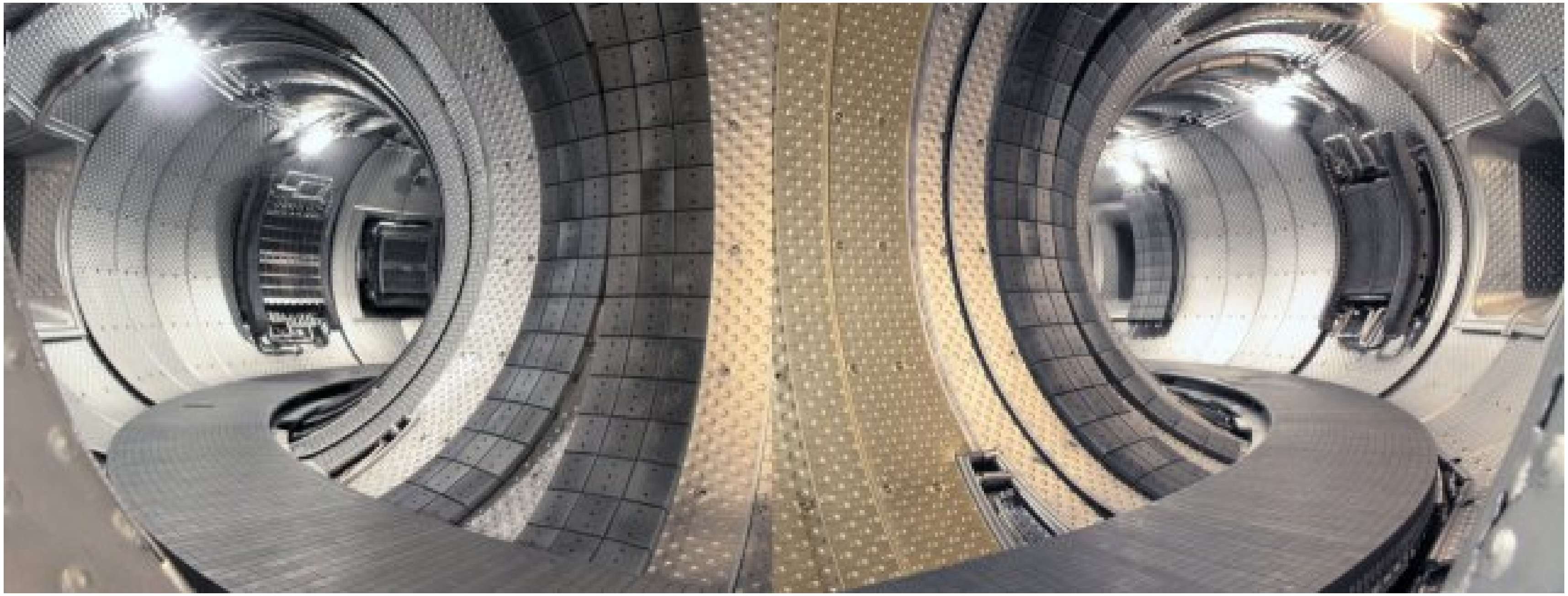
Tore Supra

- From wikipedia:
- Tore Supra is the only one of the largest tokamaks to have superconducting toroidal magnets, allowing the creation of a **strong permanent toroidal magnetic field**
- … it allows to test critical parts of equipment such as plasma facing wall components or superconducting magnets that will be used in its successor, ITER.

Tore Supra

- The machine might be available for axion search as its successor ITER becomes operational
- It is equipped with a big (V = 30 000 l) and strong magnet (B = 4.5 T)
- Large active volume for relic axion → photon conversion
- We use the Tore Supra chamber as a big microwave resonator

Tore Supra



Outer plasma diameter :	4.8 m
Inner plasma diameter:	1.6 m
Plasma volume	30.3 m^3
Toroidal magnetic field at the plasma centre :	**4.5 T**
Maximum magnetic field on the conductor :	9.0 T
Average diameter of a magnet coil :	2.60 m

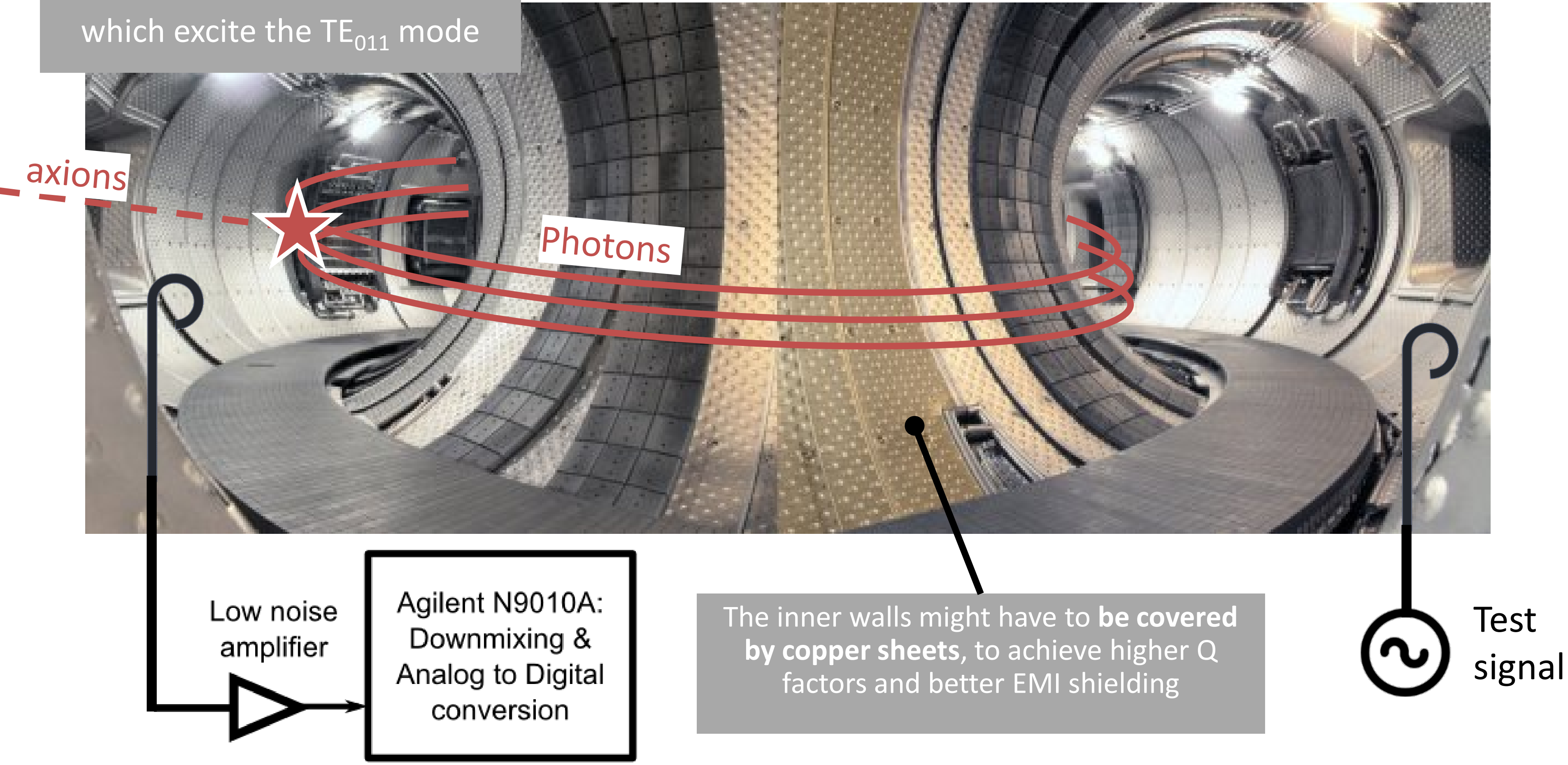
Dimension of NbTi superconductor :	2.8 x 5.6 mm^2
Total magnetic energy :	600 MJ
Plasma current :	1.7 MA
Potential duration of the discharge :	1000 s
Cooling power at 80 K :	40 kW
Cooling power at 4.5 K :	650 W
Cooling power at 1.75 K :	300 W

Data and picture from: http://www-fusion-magnetique.cea.fr

K. Zioutas, M. Betz, 2012

Tore Supra

The magnetic field converts axions to microwave photons, which excite the TE_{011} mode

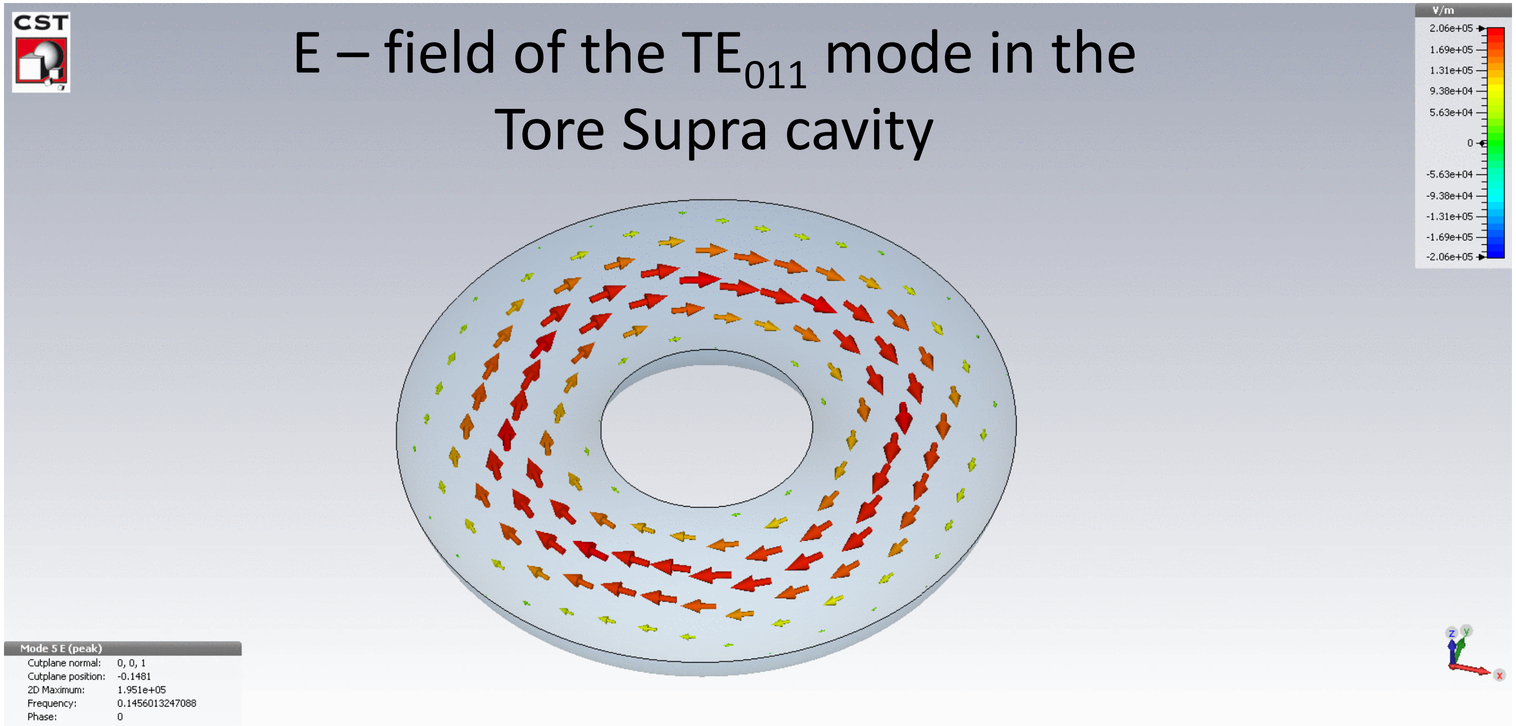


The inner walls might have to **be covered by copper sheets**, to achieve higher Q factors and better EMI shielding

The microwave signal is coupled out by a small antenna and amplified. A commercial spectrum analyzer can be used to detect the axion signal

A test signal might be necessary **to proof that the detector is working** and to determine resonant frequency over time

Preliminary simulation results



E – field of the TE_{011} mode in the Tore Supra cavity

Mode 5 E (peak)

Cutplane normal:	0, 0, 1
Cutplane position:	-0.1481
2D Maximum:	1.951e+05
Frequency:	0.1456013247088
Phase:	0

- Inner radius: 0.8 meter, outer radius: 2.4 meter
- $TE_{011} = H_{011}$ mode, **f= 145.601 MHz**
- → **Most sensitive to axions with**

  $m_a = 6 \cdot 10^{-7}$ eV

Wall material	Conductivity	Unloaded Q - factor
Stainless steel	9.8e+5 S/m	**19271**
Copper	5.8e+7 S/m	**148250**

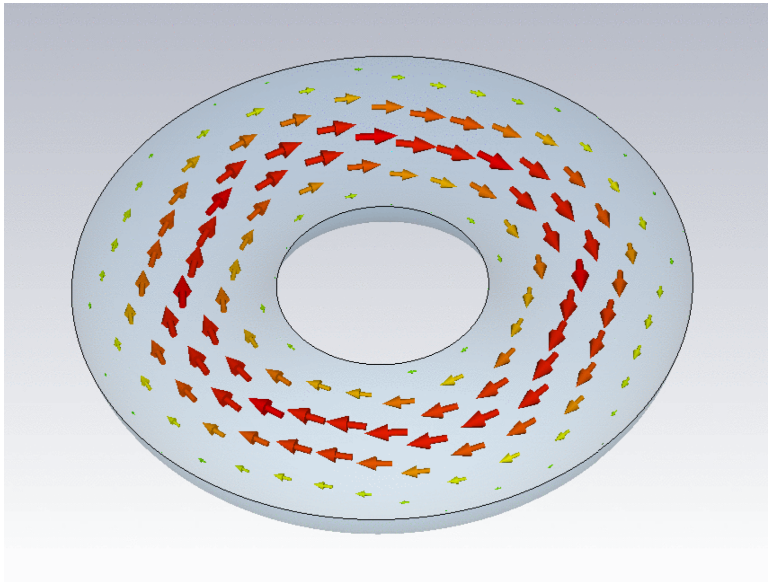
The relic axion overlap integral

- To see if the TE_{011} mode is sensitive to relic axions, we must evaluate its geometric form factor C
- Essentially: E-field must be **parallel** to the static magnetic field to couple to axions (dot product!)
- This is the case for Tore Supra

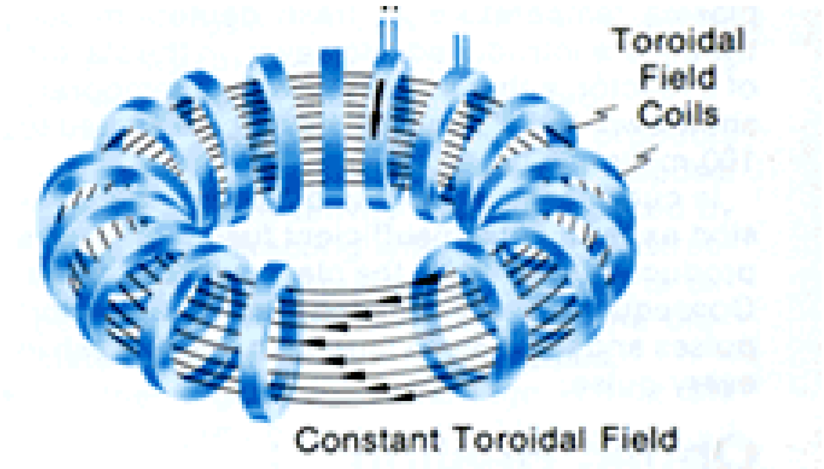
$$C = \frac{\left(\int dV\, \mathbf{E}_{\rm cav}(\mathbf{x}) \cdot \mathbf{B}_0(\mathbf{x})\right)^2}{V|\mathbf{B}_0|^2 \int dV\, \epsilon(\mathbf{x}) \mathbf{E}^2_{\rm cav}(\mathbf{x})},$$

$C \approx 0.39$ (from numerical calculation)

E – field of TE_{011} mode (E_{CAV})

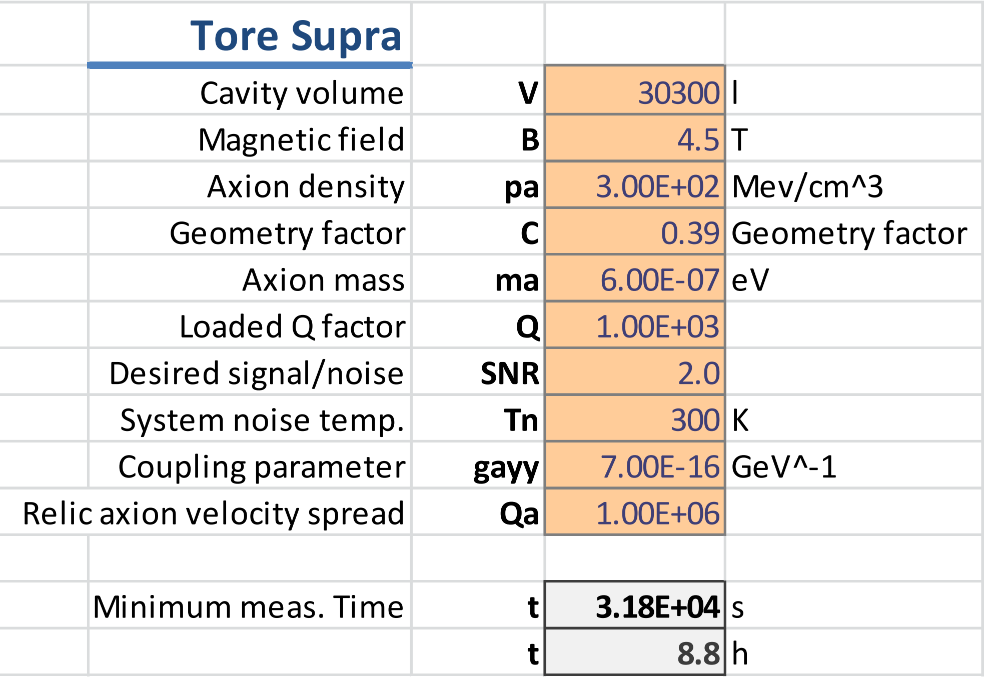


Static magnetic field of superconducting magnets (B_0)



P. Sikivie, Phys. Rev. D32, 2988 (1985), [Erratum-ibid.D36:974,1987].

Expected sensitivity

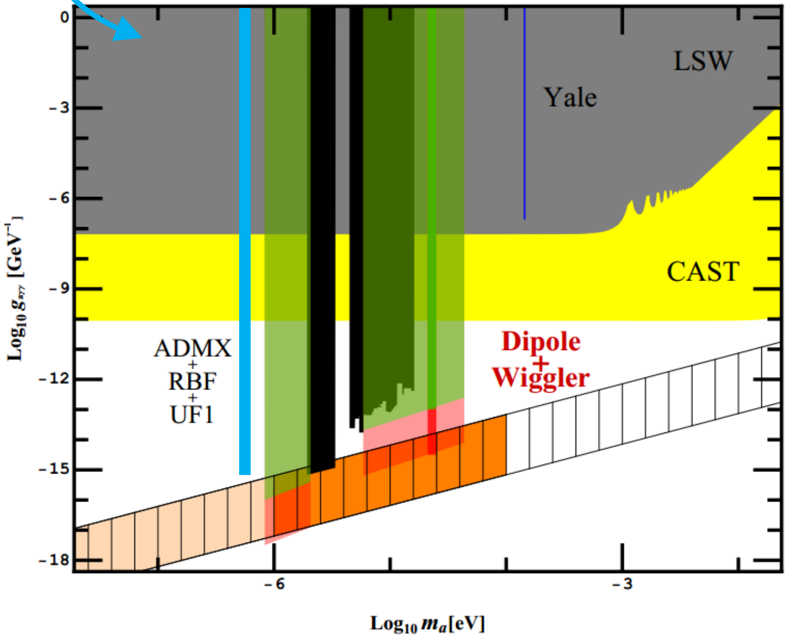


Tore Supra			
Cavity volume	**V**	30300	l
Magnetic field	**B**	4.5	T
Axion density	**pa**	3.00E+02	Mev/cm^3
Geometry factor	**C**	0.39	Geometry factor
Axion mass	**ma**	6.00E-07	eV
Loaded Q factor	**Q**	1.00E+03	
Desired signal/noise	**SNR**	2.0	
System noise temp.	**Tn**	300	K
Coupling parameter	**gayy**	7.00E-16	GeV^-1
Relic axion velocity spread	**Qa**	1.00E+06	
Minimum meas. Time	**t**	**3.18E+04**	s
	t	8.8	h

With the rather conservative parameters on the left (Q_L = 1000), we could reach

$g_{a\gamma\gamma} = 7\cdot10^{-16}$ GeV^{-1}

in a **9 h** measurement run



$$
\begin{aligned}
P_{\mathrm{out}} &= g_{a\gamma\gamma}^2 V B^2 \rho_a C \frac{1}{m_a} \min[Q, Q_a] \\
&= 1.1\times10^{-26}\mathrm{W}\,(g_{a\gamma\gamma}10^{15}\mathrm{GeV})^2 \left(\frac{C}{0.66}\right)\left(\frac{B}{5\mathrm{T}}\right)^2\left(\frac{V}{5\ell}\right) \\
&\quad\times\left(\frac{\rho_a}{300\mathrm{MeV/cm^3}}\right)\left(\frac{2.1\times10^{-5}\mathrm{eV}}{m_a}\right)\left(\frac{Q}{10^3}\right),
\end{aligned}
$$

Alternative magnets for haloscopes

Dipole magnets

Wiggler magnets

Toroidal magnets

O. Baker et al., Prospects for Searching Axion-like Particle Dark Matter with Dipole, Toroidal and Wiggler Magnets, [Phys. Rev. D 85, 035018 (2012)]

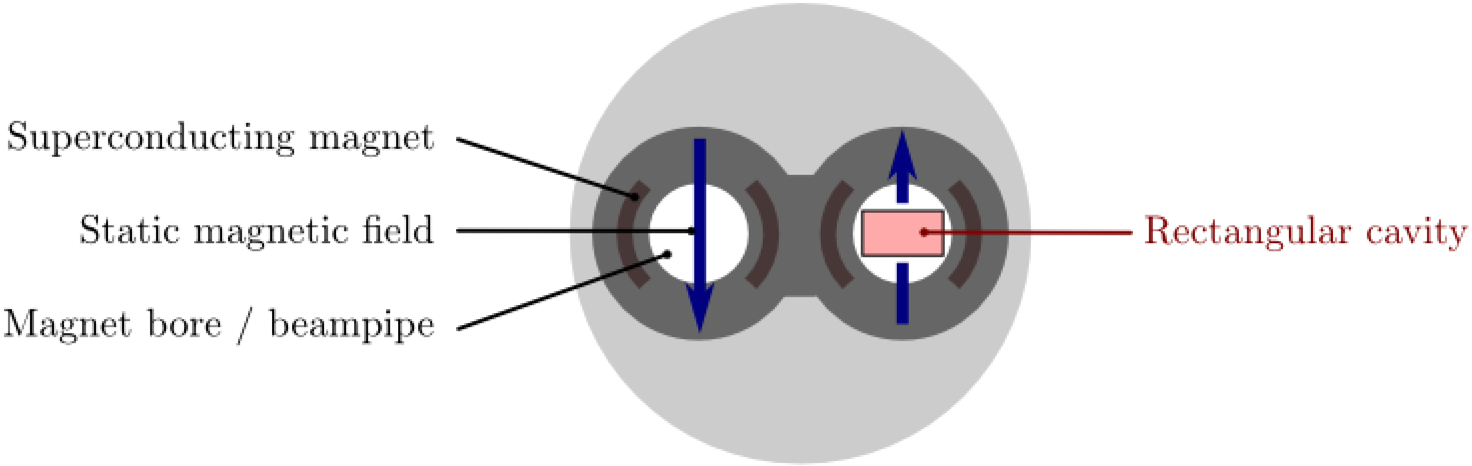
Pictures from: CERN, DESY, CERN

Alternative magnets for haloscopes

- Up to now all haloscope searches have used **solenoid** magnets to provide the magnetic field
- However, at accelerator and advanced light source facilities a range of magnets are available, that have not yet been exploited for their use in searches for ALP DM (axion like particle dark matter)
- In particular we have the typical **dipoles** used for the accelerator itself as well as **toroidal** magnets used in particle detectors
- In addition we have the **wiggler** magnets used for creating synchrotron and free electron laser light
- Can we use these magnets efficiently in haloscope searches for ALP DM?

Dipole magnets

- Accelerator dipoles offer strong fields (LHC: **9.5 T**) in a long region (**14 m**), with the magnetic field oriented perpendicular to the long direction
- A long and thin rectangular microwave cavity could be introduced in the magnet
- In this configuration, TE – modes couple to axions
  (The E-field is parallel to the static magn. field)

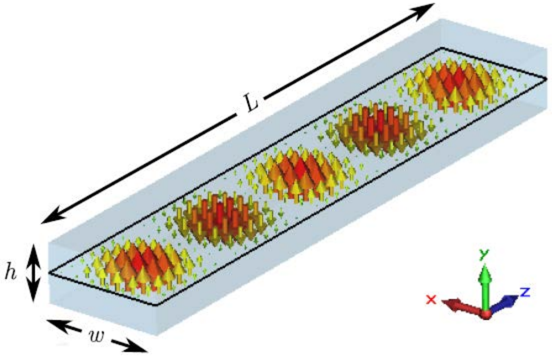


Dipole magnets

- The TE_{101} – mode couples strongest to axions (Geometry factor C = 0.66)

- In our example configuration it would be resonant at $f_{res} \approx 5$ GHz → **$m_a \approx 2.1 \cdot 10^{-5}$ eV**
  (assuming w = 30 mm, h = 20 mm, L = 8 m)

- But:
- If the aspect ratio L/w becomes this large, the modes in the cavity converge towards a **common resonant frequency**
- Two modes with similar resonant frequency will couple to each other and exchange energy.
  This energy is lost!



E-field of the TE_{105} mode in a rectangular cavity

Dipole magnets

- Higher order **modes limit the maximum length** of **one** cavity

  $L_{max} = 1.5$ m for Q = 1000

  $L_{max} = 6.7$ m for Q = 20000

- To solve this problem, we can:
  - Use **wiggler magnets** (next slide)
  - Use an **array of several cavities** with $L < L_{max}$

- Power is coupled out from each cavity and fed to an external power combiner (hybrid)

- Our results predict that only a few cavities are needed to fill a typical magnet, making this approach technically feasible

Wiggler magnets

- We get maximum coupling to axions, if the **TE_{10n}** mode is used, where ***n*** is the number of magnetic oscillations in the wiggler magnet

- An advantage of the wiggler conguration is that the mode spacing grows with ***n***. **The problem of overlapping modes is therefore somewhat reduced**

- Maximum length of **one** cavity in a wiggler magnet with 1 magnetic oscillation over 30 cm:

L_{max} = 4.7 m for Q = 1000

L_{max} = 14.1 m for Q = 3000

Dipole magnets: tuning

- To sweep over a range of values for the axion mass (m_a) tuning of the cavity is necessary
- This can be achieved by placing movable dielectric rods in the cavity
- The geometry depicted below provides 13 % adjustment range over m_a while keeping the geometric factor approx. constant

w	30 mm
h	20 mm
L	300 mm
D_w	4 mm
D_h	8 mm
D_i	0 - 10 mm

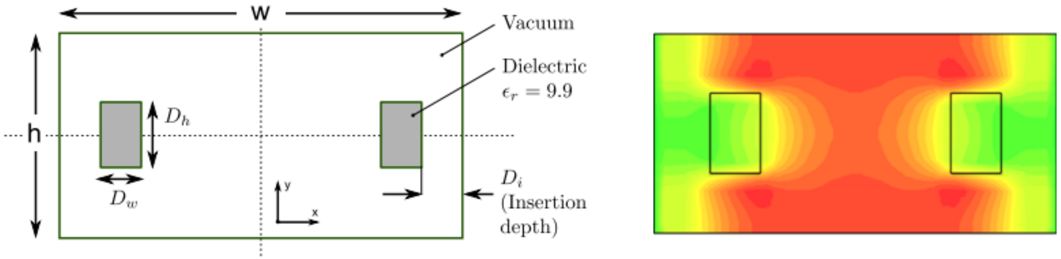
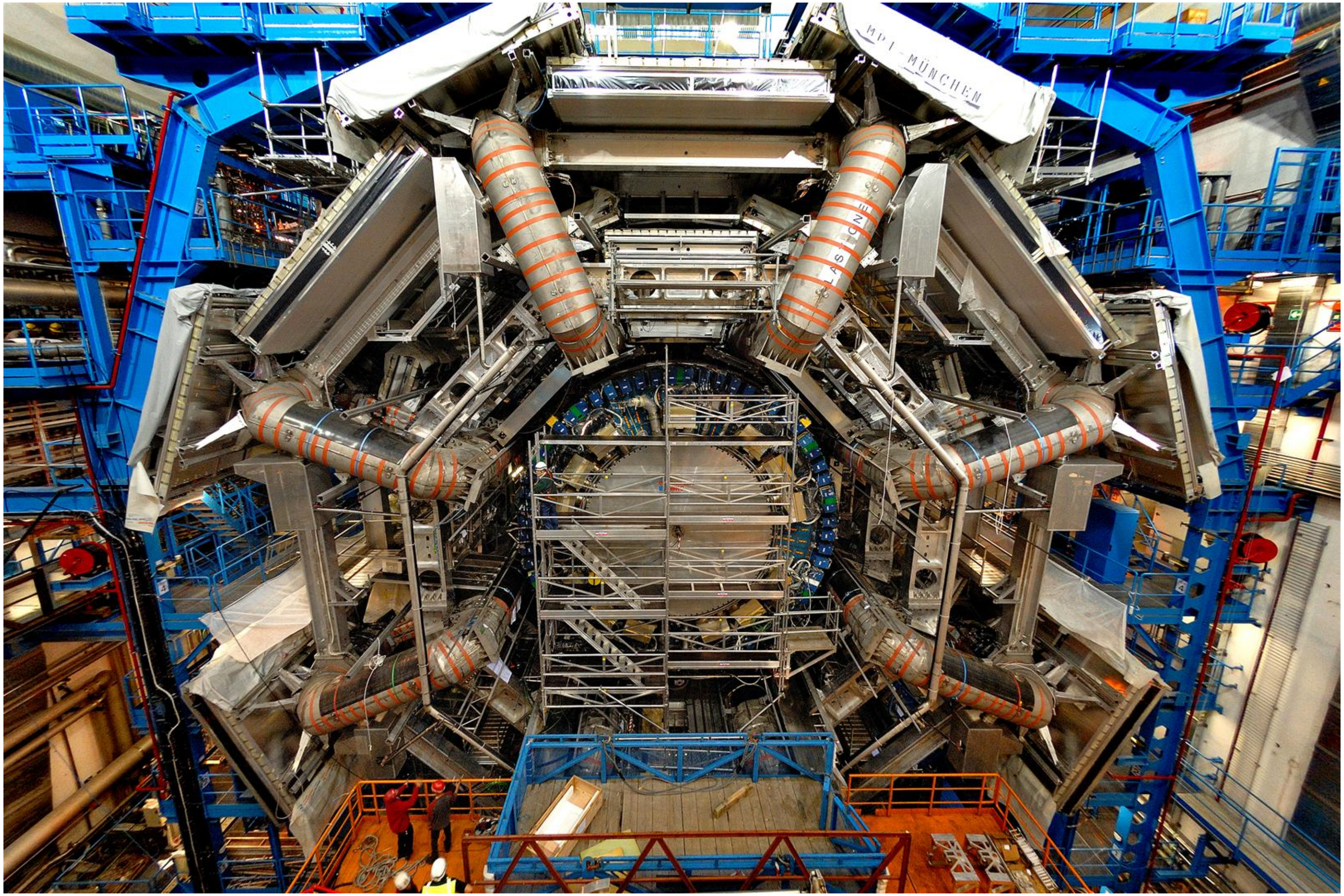


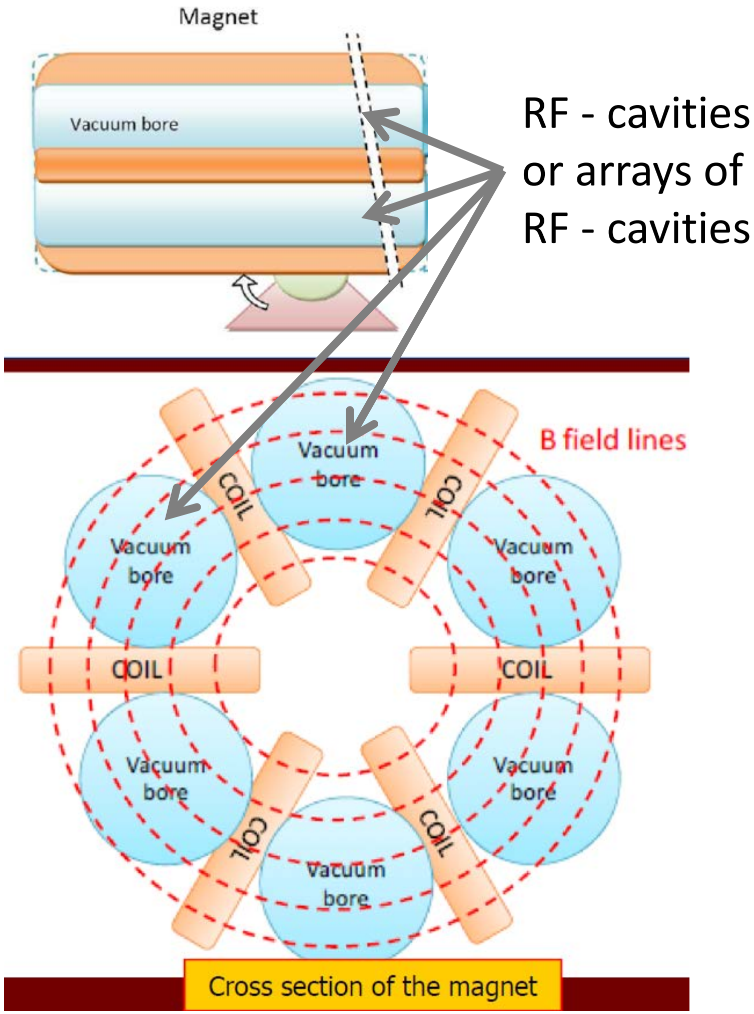
Figure 4: Cross section of the waveguide with dielectric tuning rods on each side. The relative electric field intensity in y-direction (parallel to the static magnetic field of the external magnet) is shown in color code (blue = negative, green = neutral, red = positive).

Toroidal magnets: Inspired by Atlas



RF cavities in toroidal magnets

- Currently used in particle physics detectors such as ATLAS
- In certain regions, these magnets provide transverse (to the long side) magnetic fields similar to dipole magnets
- **But the corresponding bore sizes are significantly larger!**
- The large volumes provide a significant advantage in sensitivity
- Either with single big cavities for low axion mass m_a or with an array of smaller cavities for larger axion masses



RF - cavities
or arrays of
RF - cavities