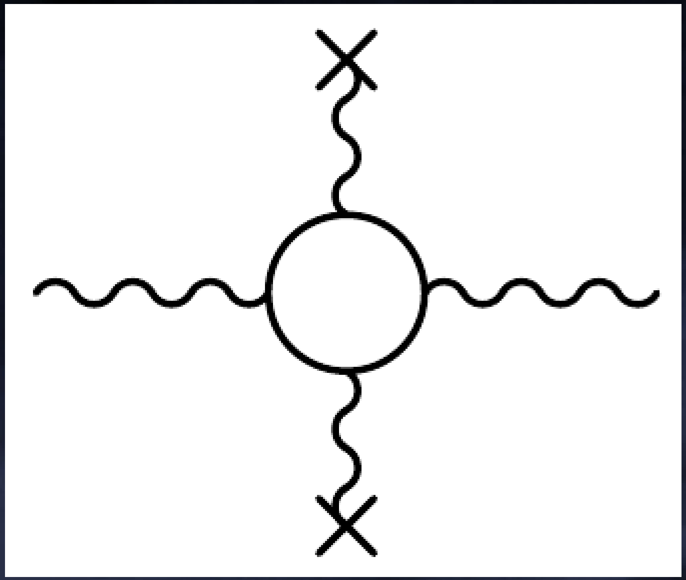
No signal yet: The elusive birefringence of the vacuum, and whether gravitational wave detectors may help



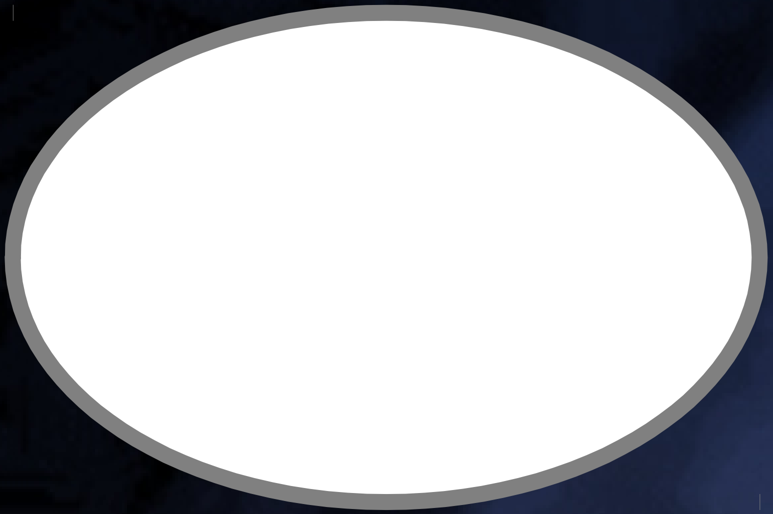
Hartmut Grote
AEI Hannover
CaJAGWR,
Caltech

24. Feb. 2015

Horror Vacui?

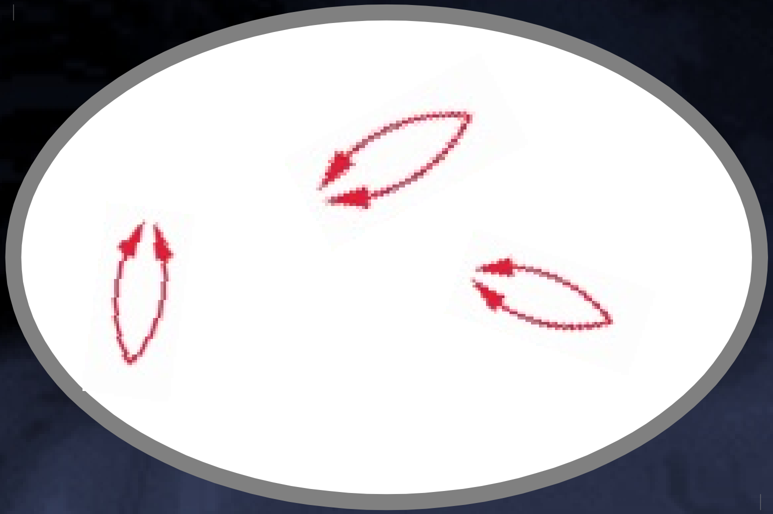
Otto Von Guerrike 1654/1656

Vacuum



The **physical vacuum**:

What is left when all that can be removed has been removed (J.C. Maxwell)



The quantum vacuum

Heisenberg:

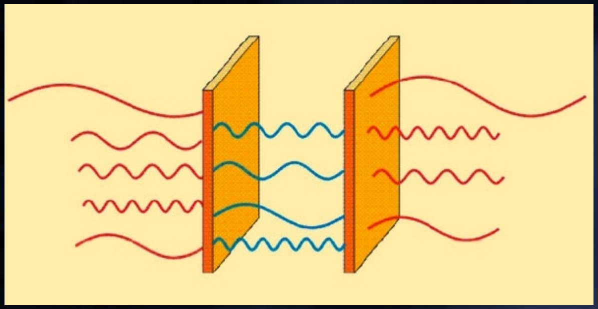
$$\Delta E \Delta t \approx \hbar$$

Non-zero ground state of EM field, and virtual particles

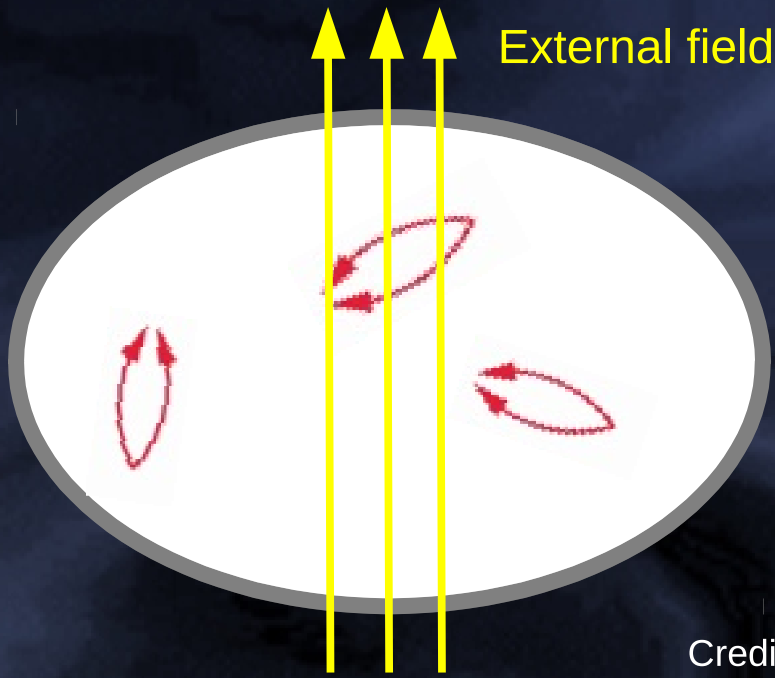
Credit:
G. Ruoso

The quantum vacuum

Examples that can be associated:
-Lamb shift
-Anomalous magnetic moment of e and μ
-Casimir force (though other interpretations exist)



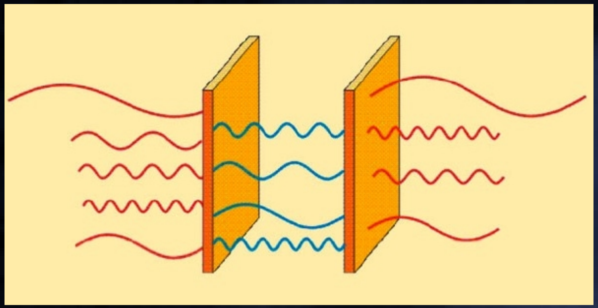
Here:
-Properties of the quantum vacuum in the presence of an external field



Credit:
G. Ruoso

The quantum vacuum

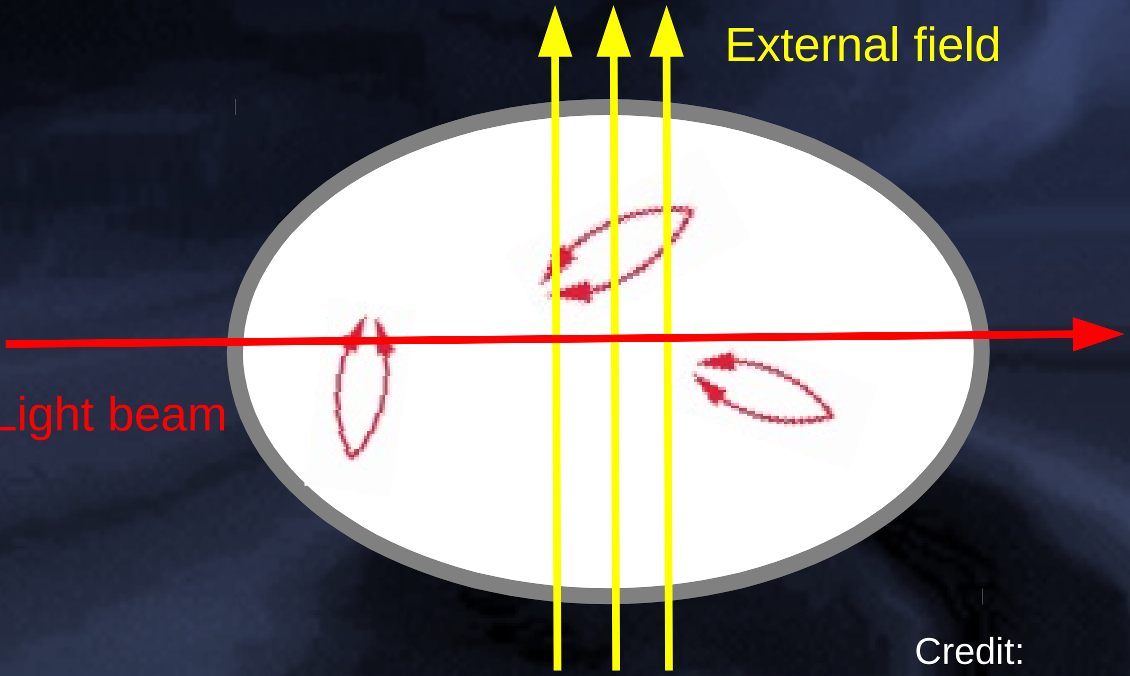
Examples:
-Lamb shift
-Anomalous magnetic moment of e and μ
-Casimir force



Here:
-Properties of the quantum vacuum in the presence of an external field

-Study with light

$\Delta n > 0$?



Credit:
G. Ruoso

Morley and Miller (1898)

PART II.

EXPERIMENTS ON THE VELOCITY OF LIGHT IN A MAGNETIC FIELD.[1]

BY EDWARD W. MORLEY AND DAYTON C. MILLER.

Phys. Rev. 7, Vol. 5, 283

Light source: Bunsen burner
colored with sodium
Light polarized with Nicol prism

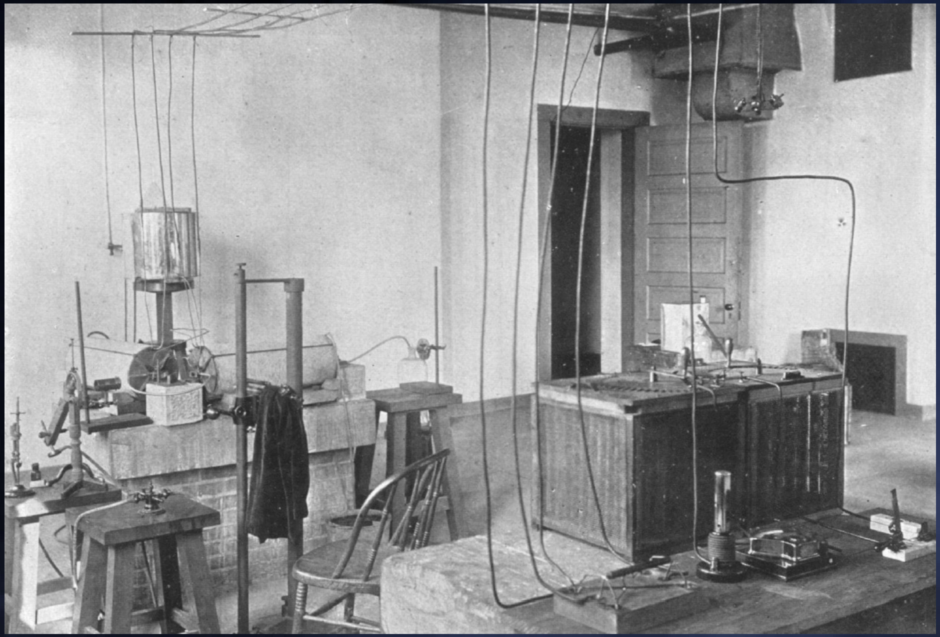
Magnetic field solenoidal B = 0.165 T

NOT IN VACUUM

Faraday rotation + change of velocity

Looking at fringes by eye, sensitivity:

Δ n ~ 10-8



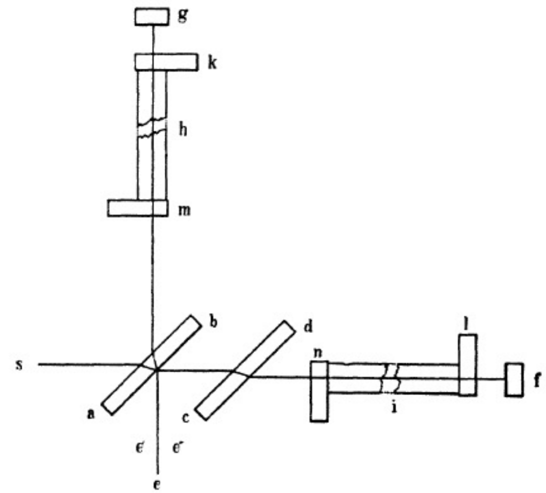


Fig. 1. Diagram, showing arrangement of optical parts.

Credit:
G. Ruoso

Watson - 1929

Motivated by the search for a **photon magnetic moment**

The Effect of a Transverse Magnetic Field on the Propagation of Light in vacuo

William H. Watson

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 125, No. 797 (Sep. 2, 1929), 345-351.

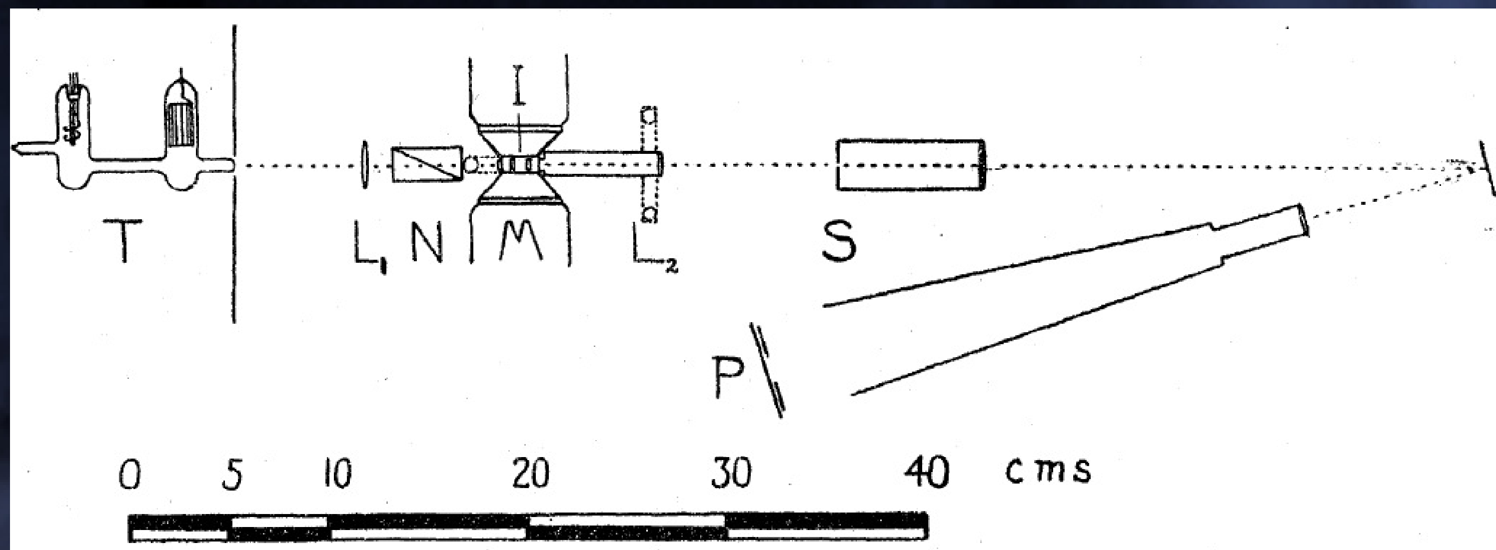


Fig. 1.

No effect measured: Δn < 4 10-7 T-1

Credit:
G. Ruoso

Consequences of Dirac's Theory of the Positron

W. Heisenberg and H. Euler in Leipzig[1]

22. December 1935

Abstract

According to Dirac's theory of the positron, an electromagnetic field tends to create pairs of particles which leads to a change of Maxwell's equations in the vacuum. These changes are calculated in the special case that no real electrons or positrons are present and the field varies little over a Compton wavelength. The resulting effective Lagrangian of the field reads:

$$\mathfrak{L} = \frac{1}{2}(\mathfrak{E}^2 - \mathfrak{B}^2) + \frac{e^2}{\hbar c}\int_0^\infty e^{-\eta}\frac{d\eta}{\eta^3}\left\{ i\eta^2(\mathfrak{E}\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)+\text{conj.}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2i(\mathfrak{E}\mathfrak{B})}\right)-\text{conj.}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}$$

$\mathfrak{E}, \mathfrak{B}$ field strengths

$|\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar} = \frac{1}{137}\frac{e}{(e^2/mc^2)^2} =$ critical field strengths

The expansion terms in small fields (compared to $\mathfrak{E}$) describe light-light scattering. The simplest term is already known from perturbation theory. For large fields, the equations derived here differ strongly from Maxwell's equations. Our equations will be compared to those proposed by Born.

$$L = L_{em} + L_{HE} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] + \ldots$$

QED Prediction

- Light slows down in vacuum in the presence of a magnetic field (perpendicular to the direction of light propagation) .

$$\Delta n_{\parallel} = 9.3 * 10^{-24} * B^2 [1/T^2]$$

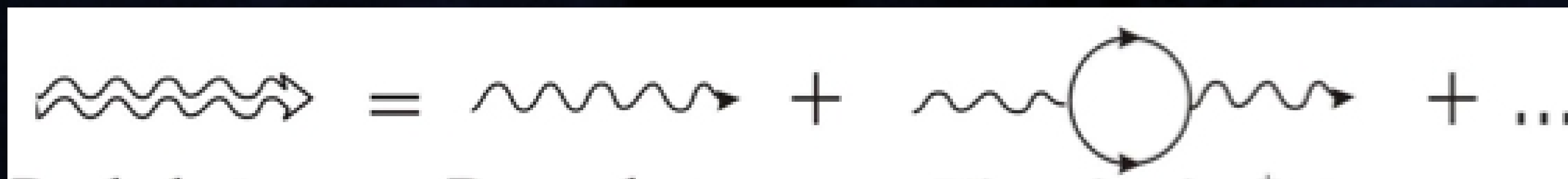
$$\Delta n_{\perp} = 5.3 * 10^{-24} * B^2 [1/T^2]$$

Vacuum is birefringent:

$$\Delta n_{\parallel - \perp} = 4 * 10^{-24} * B^2 [1/T^2]$$

Light propagation in QED

Without external field



= c

Real photon propagation

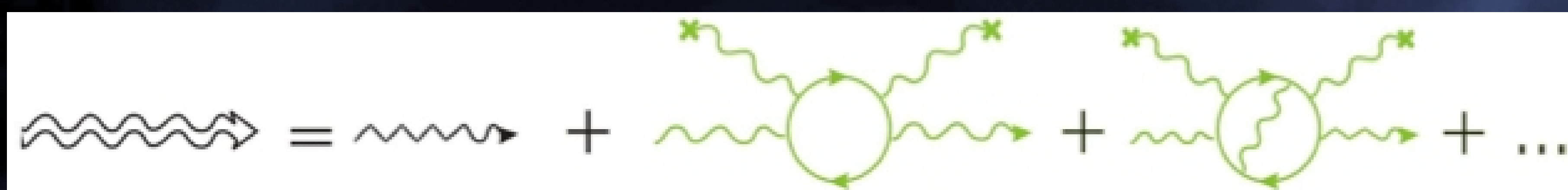
Bare photon propagation

Virtual pairs interaction

External B,E

External B,E

With external field



Real photon propagation

Bare photon propagation

Virtual pairs interaction

Higher order corrections

c depends on external field!

Credit:
G. Ruoso

Eur. Phys. J. D (2013) 67: 58
DOI: 10.1140/epjd/e2013-30578-7

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

The quantum vacuum as the origin of the speed of light

Marcel Urban[1], François Couchot[1], Xavier Sarazin[1,a], and Arache Djannati-Atai[2]

[1] LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
[2] APC, Université Paris Diderot, CNRS/IN2P3, Paris, France

Received 17 September 2012 / Received in final form 16 January 2013
Published online 21 March 2013 –

Abstract. We show that the vacuum permeability μ_0 and permittivity ϵ_0 may originate from the magnetization and the polarization of continuously appearing and disappearing fermion pairs. We then show that if we simply model the propagation of the photon in vacuum as a series of transient captures within these ephemeral pairs, we can derive a finite photon velocity. Requiring that this velocity is equal to the speed of light constrains our model of vacuum. Within this approach, the propagation of a photon is a statistical process at scales much larger than the Planck scale. Therefore we expect its time of flight to fluctuate. We propose an experimental test of this prediction.

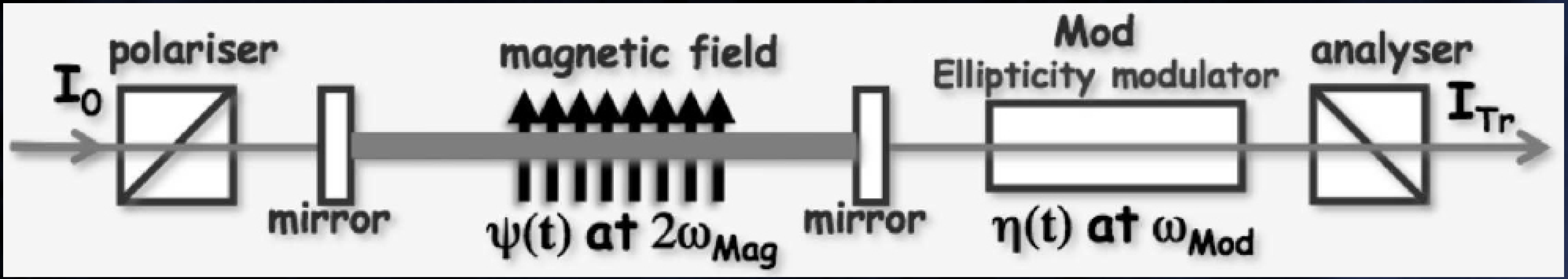
ε_0 and μ_0 may be consequences of ephemeral (virtual) particles,
...and so may c !

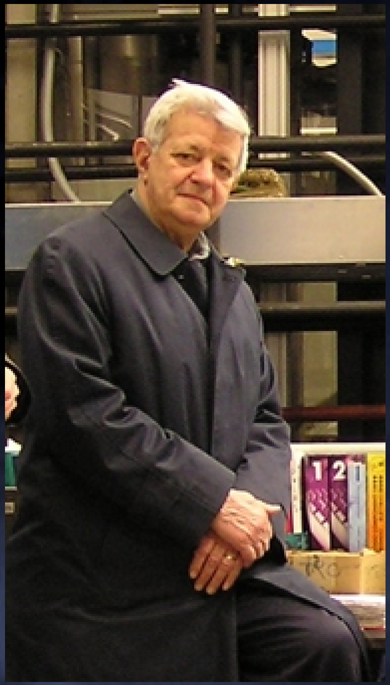
QED

- Not tested much in weak field, low energy limit

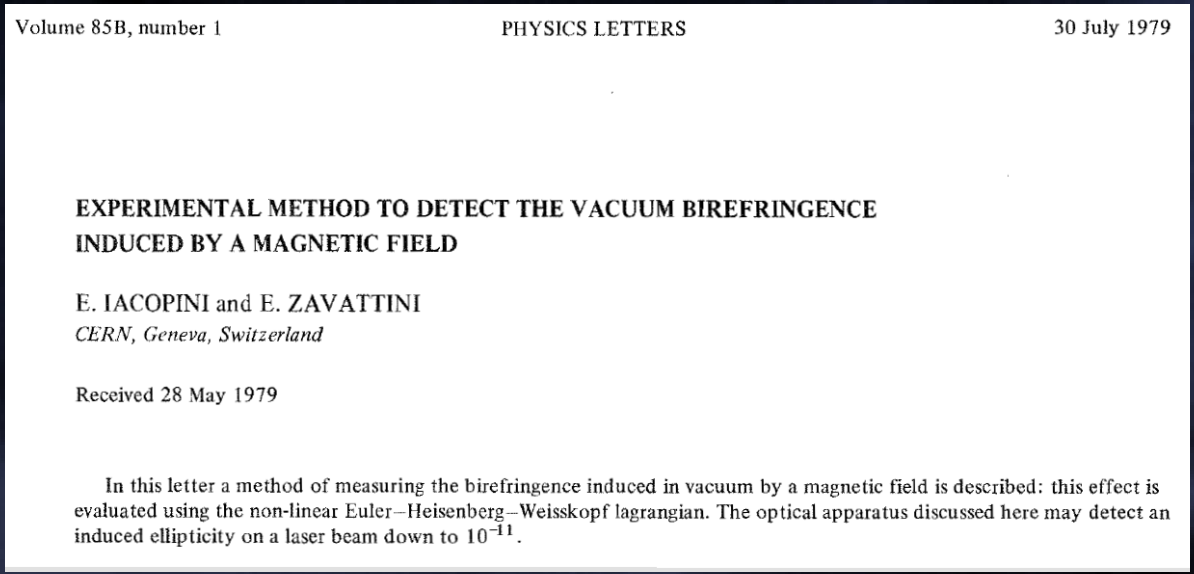
But some people try hard...

Ellipsometer Method





Emilio Zavattini
(1927 -2007)



Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

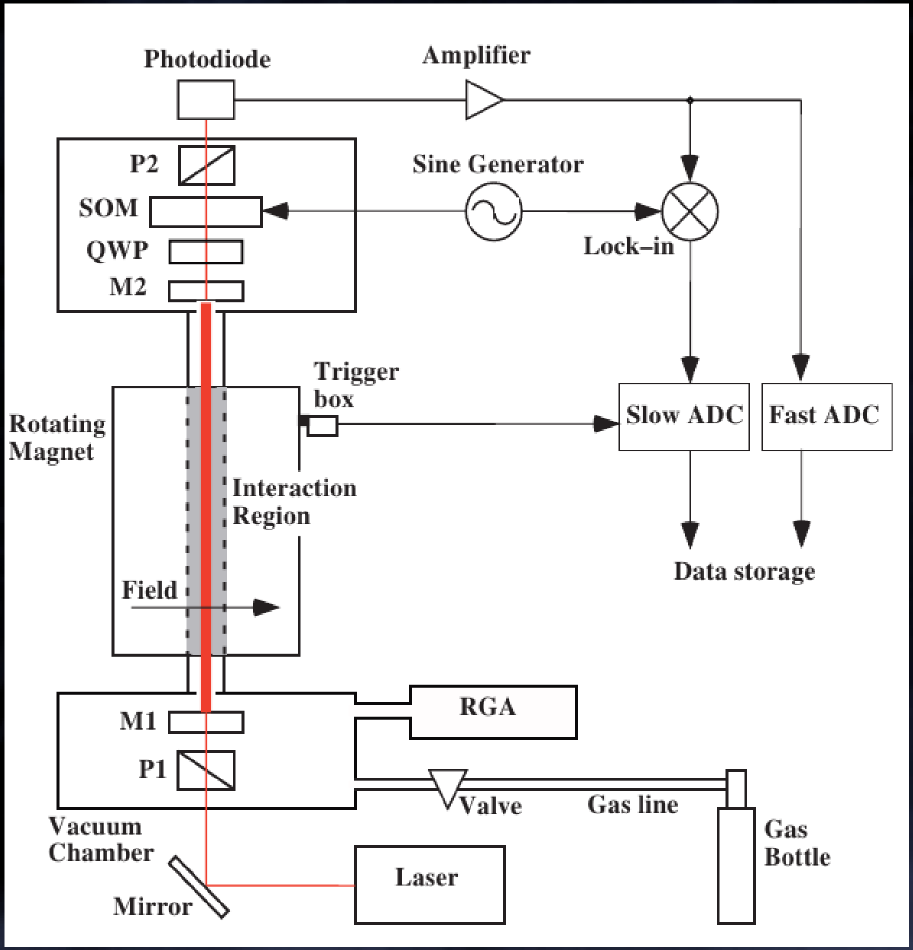
E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

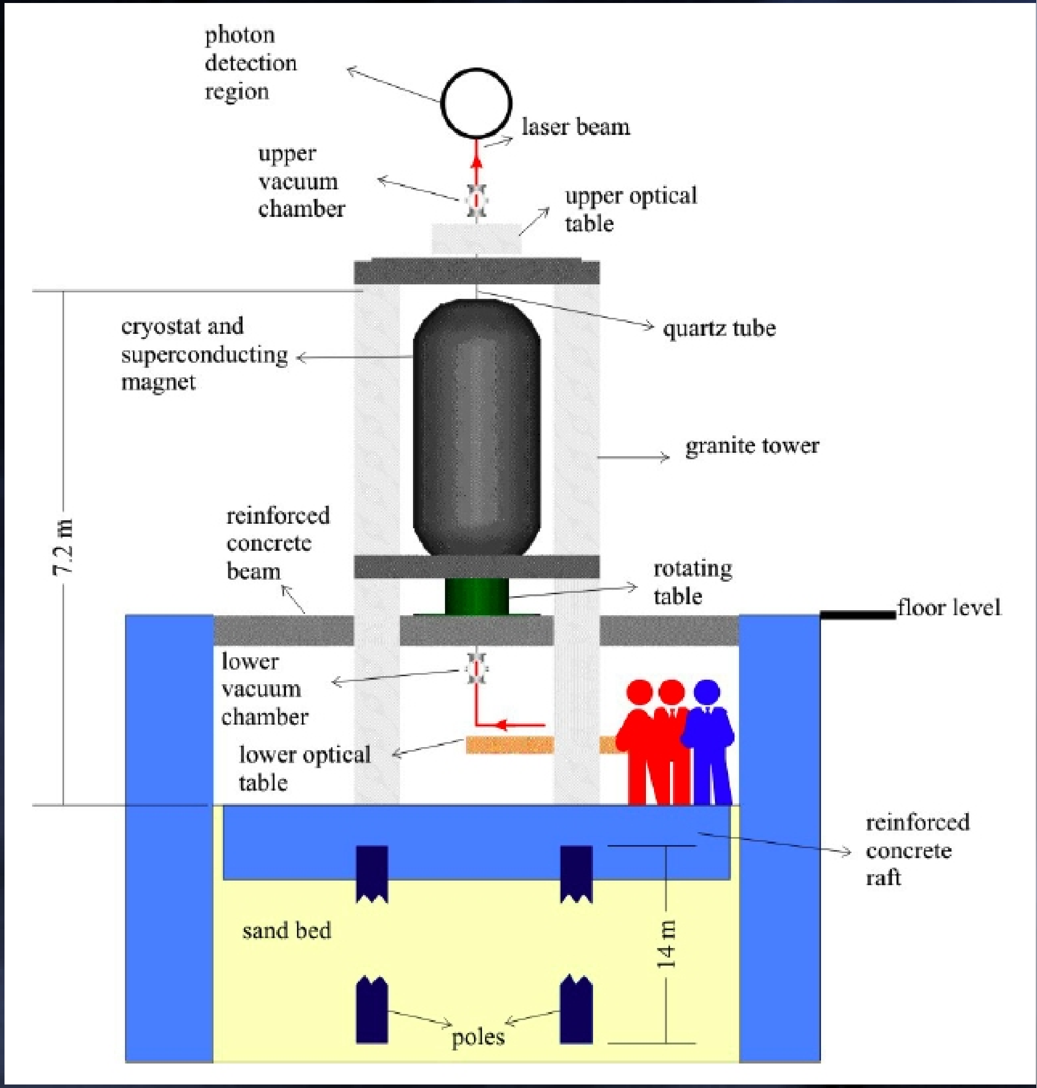
Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

Absolute phase shift is hard to measure, study anisotropic
Changes of refractive index instead. (birefringence, dichroism)

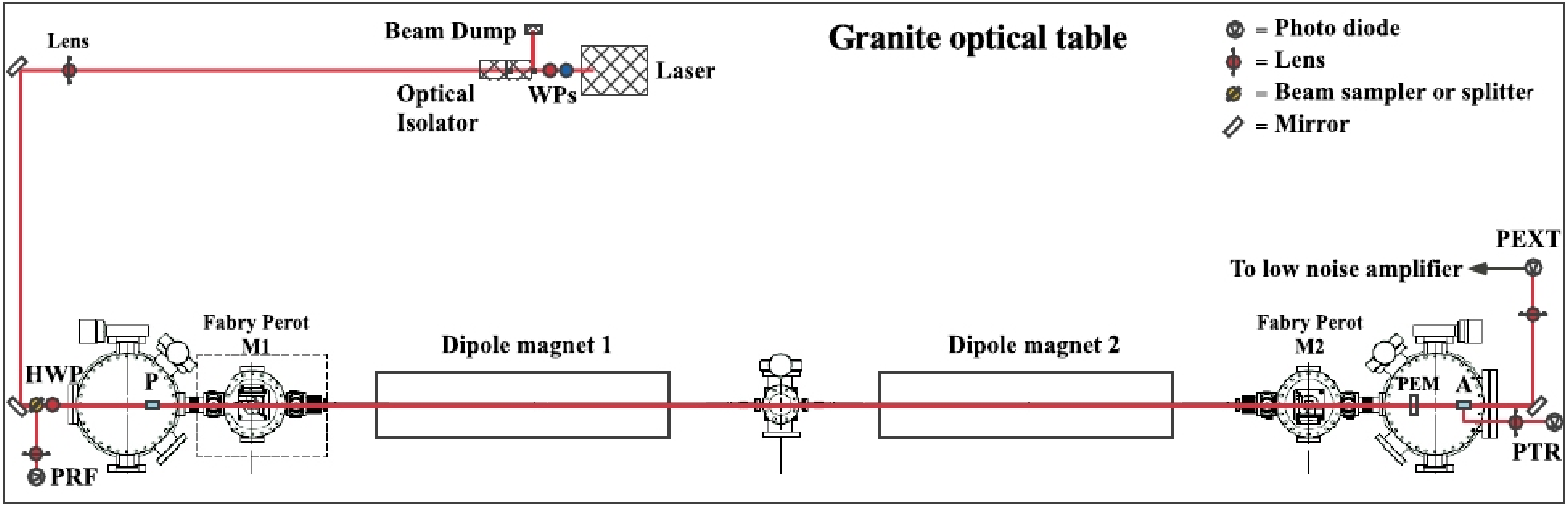
PVLAS Legnaro (1992-2008)

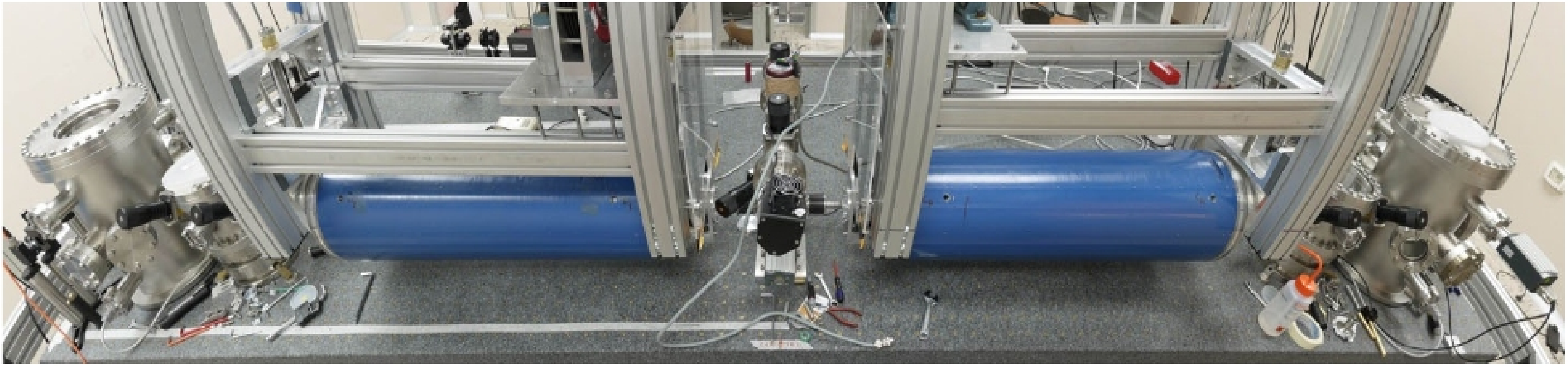




Factor 5000 away from QED prediction

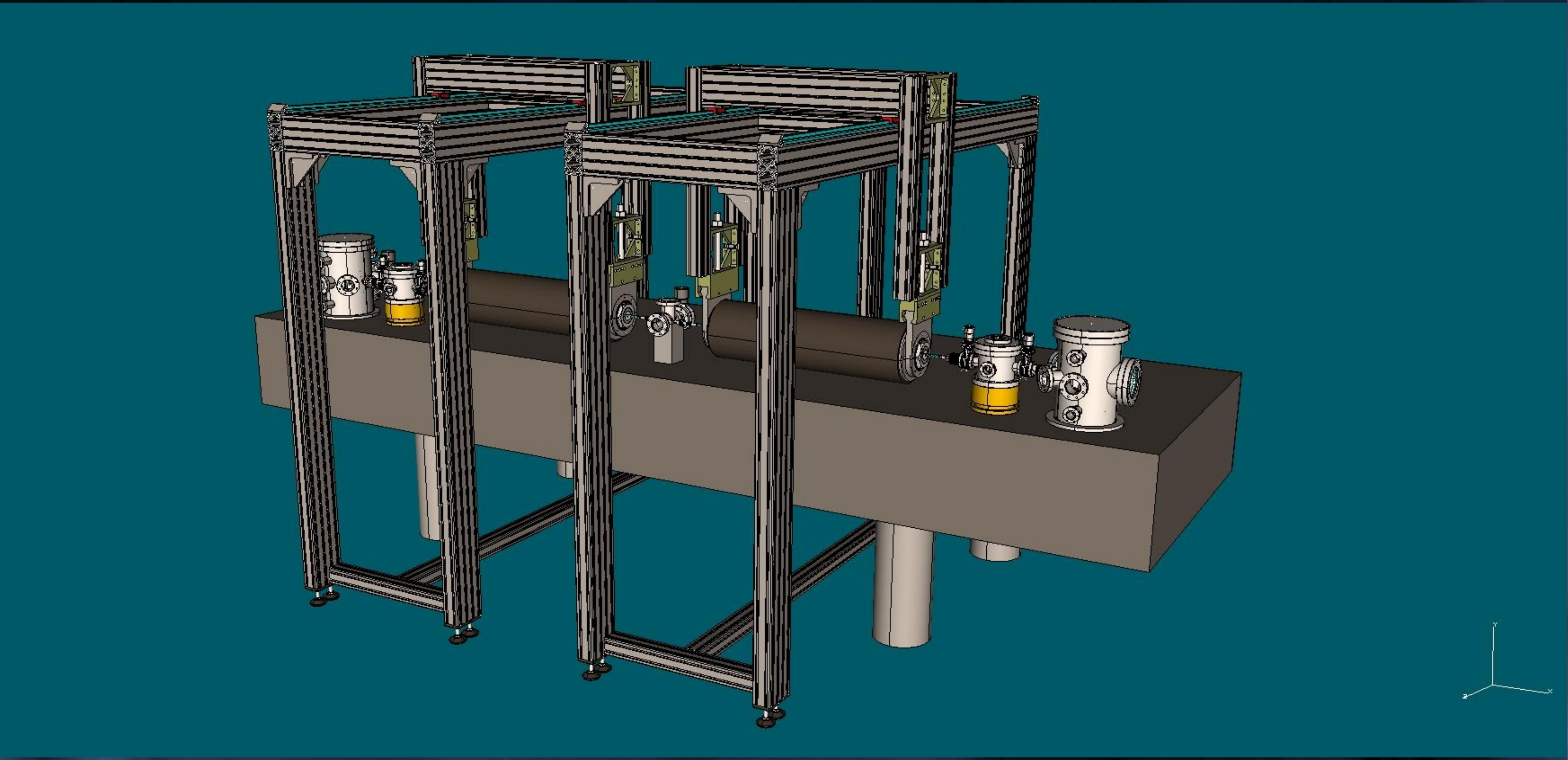
New PVLAS layout (Ferrara)





Finesse 700 000

Isolated optics table



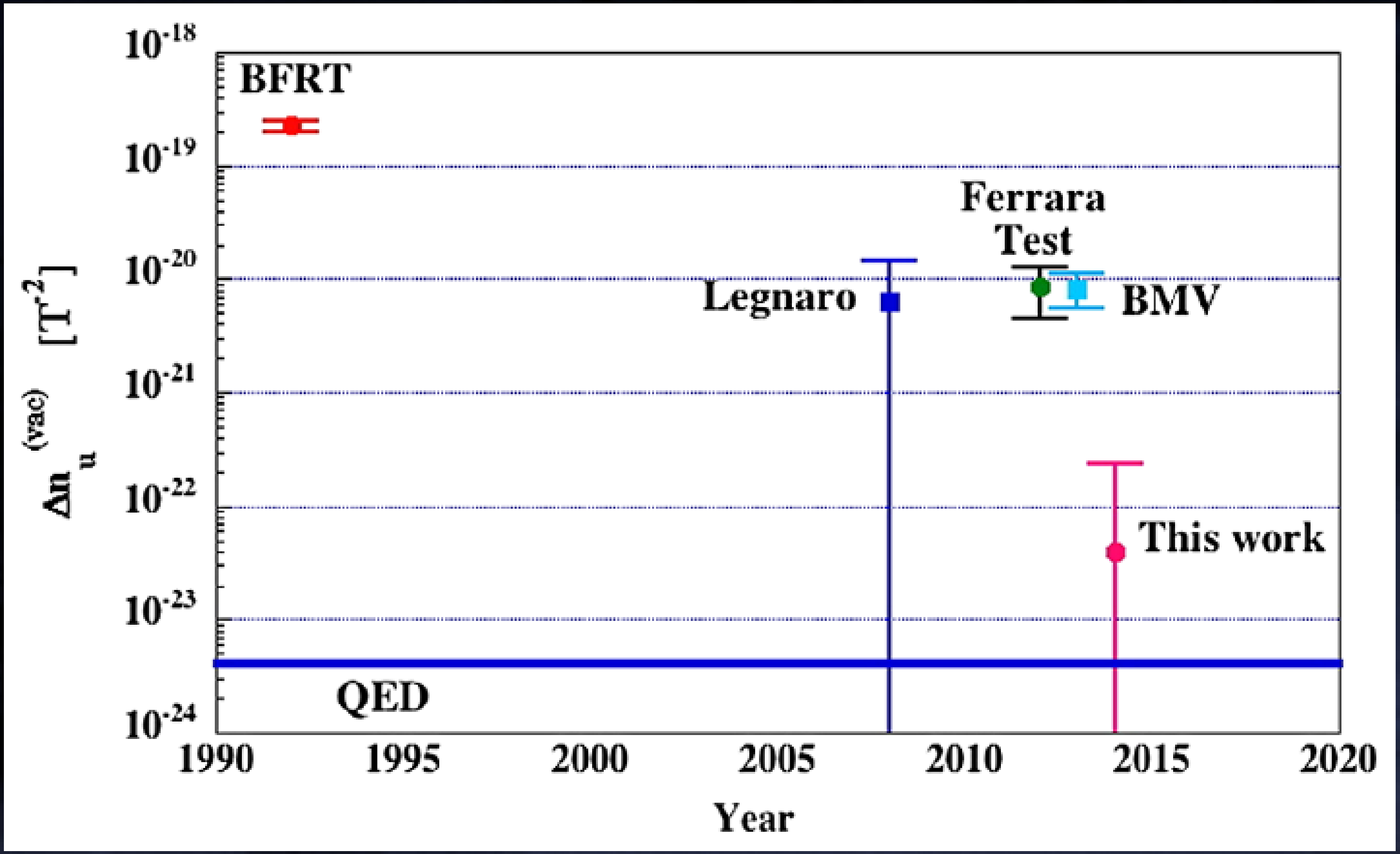
Credit:
G. Ruoso

3.75 Hz spinning...

Guido Zavattini

Baffles

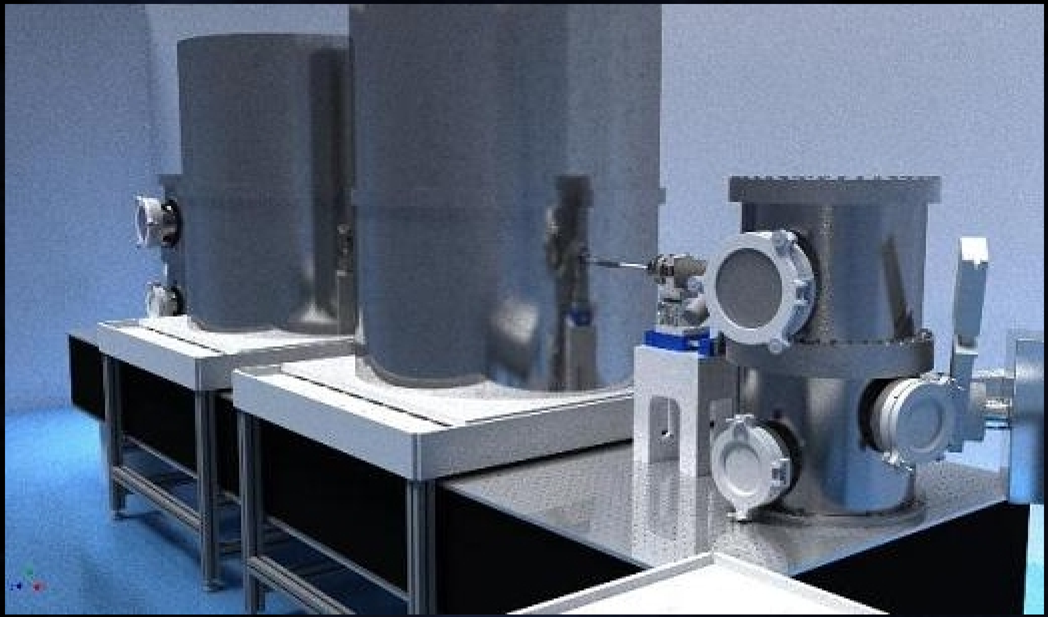
PVLAS: recent progress

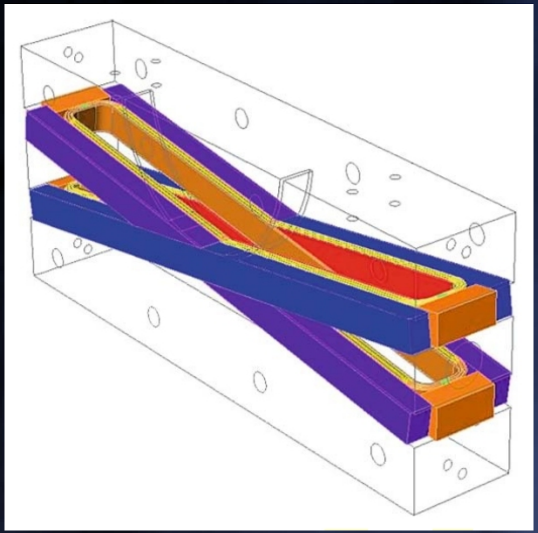


Limited by currently unexplained noise:
One suspect: birefringence of mirror coatings

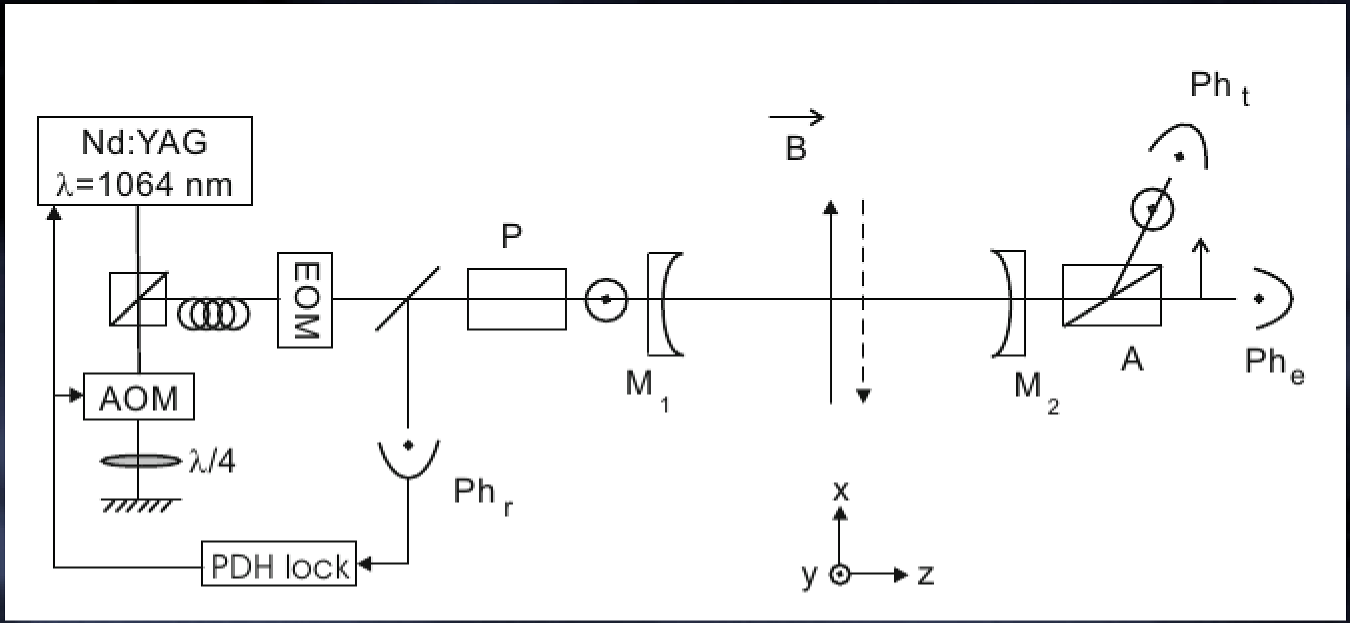
BMV: temporal B-field modulation with pulsed magnets

BMV, new setup (Jan. 2015)





X-coil



PVLAS, BMV, and others

- Measure *polarization variation* of laser beam induced by a varying magnetic field. The B-field variation can be spatial (PVLAS) or temporal (BMV).
- Typical problem: Bi-refringence of mirror optics ?
- Best upper limit today by PVLAS collab.: factor 10-50 away from QED prediction (new PVLAS Exp., improved factor ~100 in 2014)

Field modulation vs. measurement technique

	Rotate B-field	Modulate strength of B-field
Measure polarization	PVLAS, others	BMV
Measure phase	GW detectors?	GW detectors? (Get refractive indices for par. and perp. direction independently! → More implications for particle physics)

Connection to particle physics

- Milli charged particles:
  Hypothetical particles with mass < m(e),
  ->virtual pairs at lower energy, would show up as ellipticity in addition to QED prediction
- Axions: Effective absorption of photons (due to coupling to axions) would show up as dichroism (linear polarization rotation)

1979: Proposal to use Laser Interferometers

PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri
Institute of Physical Sciences of the University and Sezione dell'I.N.F.N.,20133 Milano, Italy
(Received 21 April 1978; revised manuscript received 9 November 1978)

Laser interferometry combined with present-day electronic techniques now make it possible to test nonlinear-electrodynamics predictions in the weak-field limit, up to a sensitivity of 10^{-23} in the relative variation of the velocity of light. The significance of such tests in regard to QED predictions is noted.

I. INTRODUCTION

In the past, nonlinear equations for electromagnetism have often been proposed, on the basis of theoretical motivations of a widely varying nature. Such proposed nonlinearities are either intrinsic or represent the interaction with other fields such as, for instance, the effects of vacuum polarization deriving from the interaction of the electromagnetic field with the electronic field. However, as far as experimental confirmation is concerned, there is a nearly total lack of direct information because the theoretically anticipated nonlinearities are exceedingly small.

The purpose of the present paper is to suggest that the progress in instrumentation and experimental techniques in recent years now makes it

equations predicted by QED should be o
some testable case. For clarity, we pr
report the procedure followed rather th
stating the resulting figures.

The equations of electromagnetism m
the inclusion of nonlinear terms read[1]

$$\nabla\times\vec{E}+\frac{1}{c}\dot{\vec{B}}=0,\quad \nabla\times\vec{H}-\frac{1}{c}\dot{\vec{D}}=0,$$

$$\nabla\cdot\vec{B}=0,\quad \nabla\cdot\vec{D}=0,$$

$$\vec{D}=\vec{E}+\gamma[\alpha(E^2-B^2)\vec{E}+\beta(\vec{B}\cdot\vec{E})\vec{B}],$$

$$\vec{H}=\vec{B}+\gamma[\alpha(E^2-B^2)\vec{B}-\beta(\vec{B}\cdot\vec{E})\vec{E}],$$

where all symbols conform to common
the coefficients α,β,γ have the followin
QED:

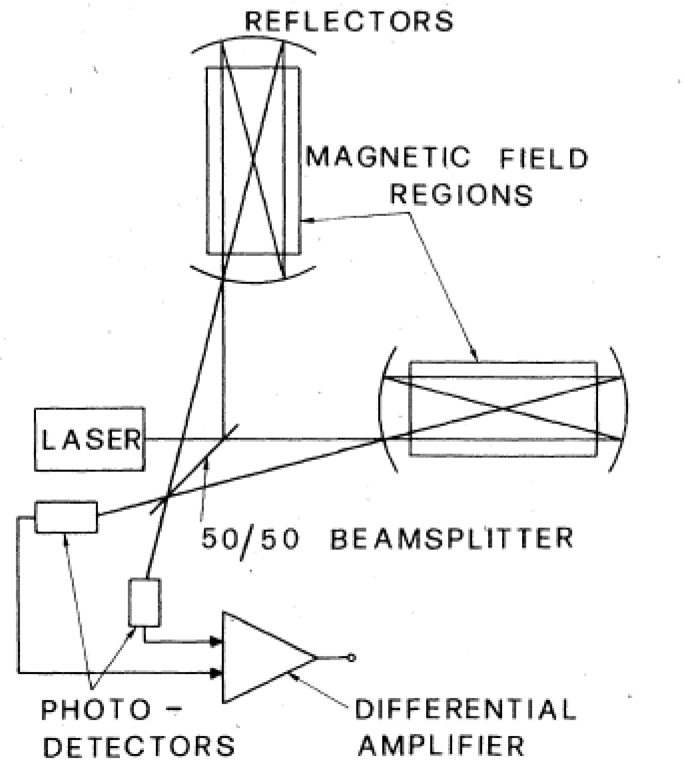


FIG. 1. Sketch of laser interferometer with magnetic field perturbation.

2002: Proposal to use GW detectors.

hep-ph/0204207
NIKHEF/2002-001

Exploring the QED vacuum with laser interferometers

Daniël Boer[1] and Jan-Willem van Holten[1,2]

[1] *Division of Physics and Astronomy, Vrije Universiteit, De Boelelaan 1081 NL-1081 HV Amsterdam, The Netherlands*

[2] *NIKHEF, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands*

February 1, 2008

It is demonstrated that the nonlinear, and as yet unobserved, QED effect of slowing down light by application of a strong magnetic field may be observable with large laser interferometers like for instance LIGO or GEO600.

12.20.Fv, 07.60.Ly, 41.20.Jb, 42.25.Lc, 41.25.Bs, 95.75.Kk

-too optimistic in assuming possible increase in sensitivity with increasing cavity Finesse
-neglecting possible integration of signal over time

2009: Virgo / Electro-Magnets

Eur. Phys. J. C (2009) 62: 459–466
DOI 10.1140/epjc/s10052-009-1079-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Probing for new physics and detecting non-linear vacuum QED effects using gravitational wave interferometer antennas

Guido Zavattini[1,a], **Encrico Calloni**[2]

[1] INFN, Sezione di Ferrara and Dipartimento di Fisica, Università di Ferrara, Polo Scientifico, Via Saragat 1, Blocco C, 44100 Ferrara, Italy
[2] INFN, Sezione di Napoli and Dipartimento di Scienze Fisiche, Università "Federico II", Mostra d'Oltremare, Pad. 19, 80125, Naples, Italy

Received: 28 April 2009 / Published online: 27 June 2009

-pointing out new physics potential

2009: LIGO/GEO Pulsed Magnets

epl A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

July 2009

EPL, **87** (2009) 21002 www.epljournal.org

doi: 10.1209/0295-5075/87/21002

Interferometry of light propagation in pulsed fields

B. DÖBRICH[a] and H. GIES

Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena
Max-Wien-Platz 1, D-07743 Jena, Germany, EU

received 16 April 2009; accepted in final form 30 June 2009
published online 28 July 2009

PACS 12.20.Fv – Quantum electrodynamics: Experimental tests
PACS 14.80.-j – Other particles (including hypothetical)

Abstract – We investigate the use of ground-based gravitational-wave interferometers for studies of the strong-field domain of QED. Interferometric measurements of phase velocity shifts induced by quantum fluctuations in magnetic fields can become a sensitive probe for nonlinear self-interactions among macroscopic electromagnetic fields. We identify pulsed magnets as a suitable strong-field source, since their pulse frequency can be matched perfectly with the domain of highest sensitivity of gravitational-wave interferometers. If these interferometers reach their future sensitivity goals, not only strong-field QED phenomena can be discovered but also further parameter space of hypothetical hidden-sector particles will be accessible.

-assumes aperture of O~cm

2015: Feasibility / Magnet design

PHYSICAL REVIEW D **91,** 022002 (2015)

On the possibility of vacuum QED measurements with gravitational wave detectors

H. Grote*

Max-Planck-Institut für Gravitationsphysik (Albert Einstein Institut) und Leibniz Universität Hannover, Callinstrasse 38, 30167 Hannover, Germany

(Received 17 September 2014; published 7 January 2015)

Quantum electrodynamics (QED) comprises virtual particle production and thus gives rise to a refractive index of the vacuum larger than unity in the presence of a magnetic field. This predicted effect has not been measured to date, even after considerable effort of a number of experiments. It has been proposed by other authors to possibly use gravitational wave detectors for such vacuum QED measurements, and we give this proposal some new consideration in this paper. In particular, we look at possible source field magnet designs and further constraints on the implementation at a gravitational wave detector. We conclude that such an experiment seems to be feasible with permanent magnets, yet still challenging in its implementation.

DOI: 10.1103/PhysRevD.91.022002 PACS numbers: 04.80.Nn, 42.50.Xa, 95.55.Ym, 95.75.Kk

I. INTRODUCTION

Corrections to the Maxwell equations that emerge from the quantum properties of the vacuum have been proposed many decades ago; see, e.g., [1]. Quantum electrodynamics

All of the ongoing experiments make use of the difference $\Delta n_{\parallel-\perp}$ of the predicted refractive index changes for different angles of the magnetic field with respect to the polarization direction of the light; i.e., they attempt to

Integration time for sinusoidal signal

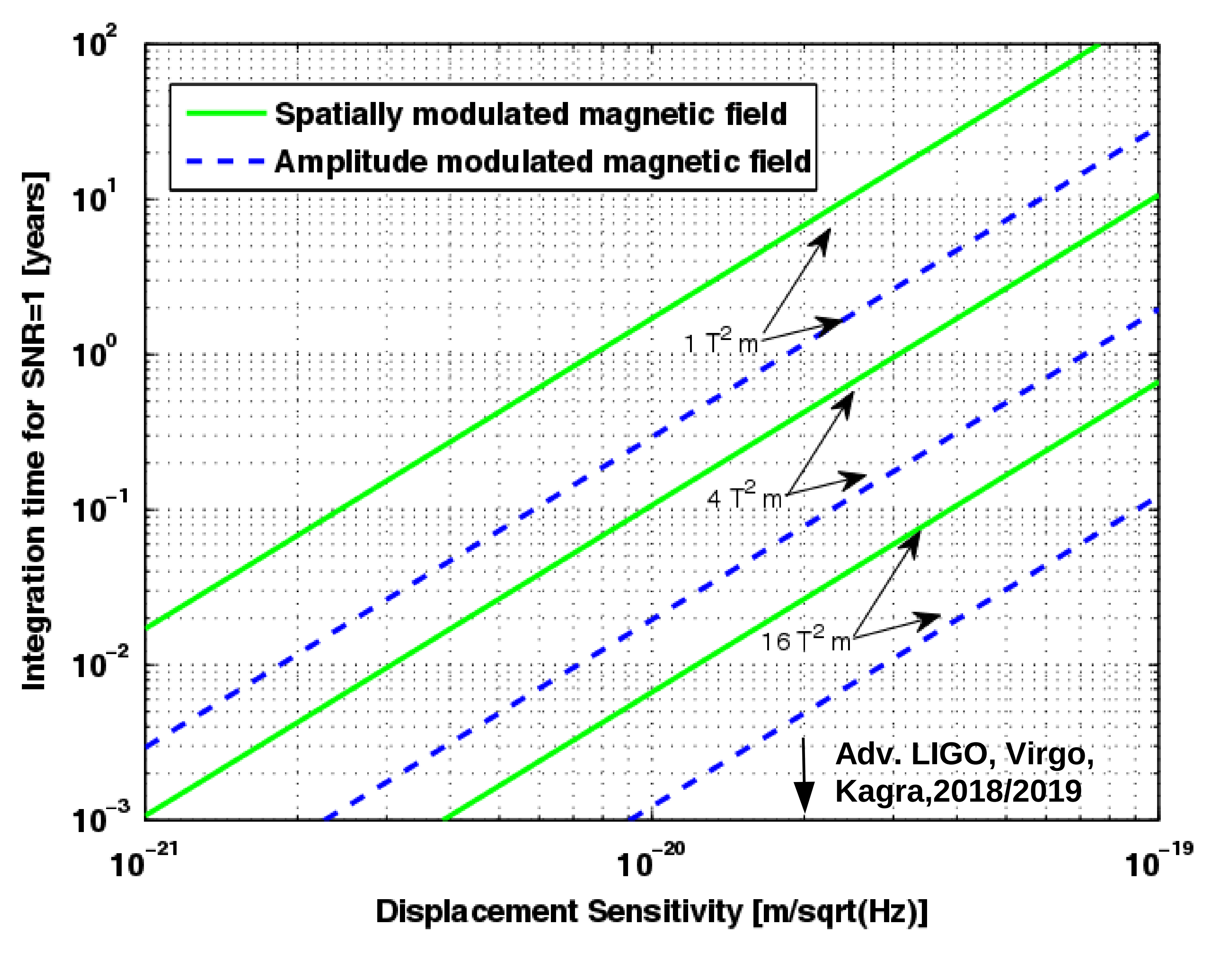
$$t_{SNR=1} = \left(\frac{\tilde{n}(f)}{S_{RMS,\parallel}} \right)^2$$

Displacement noise
Ampl. spectral density

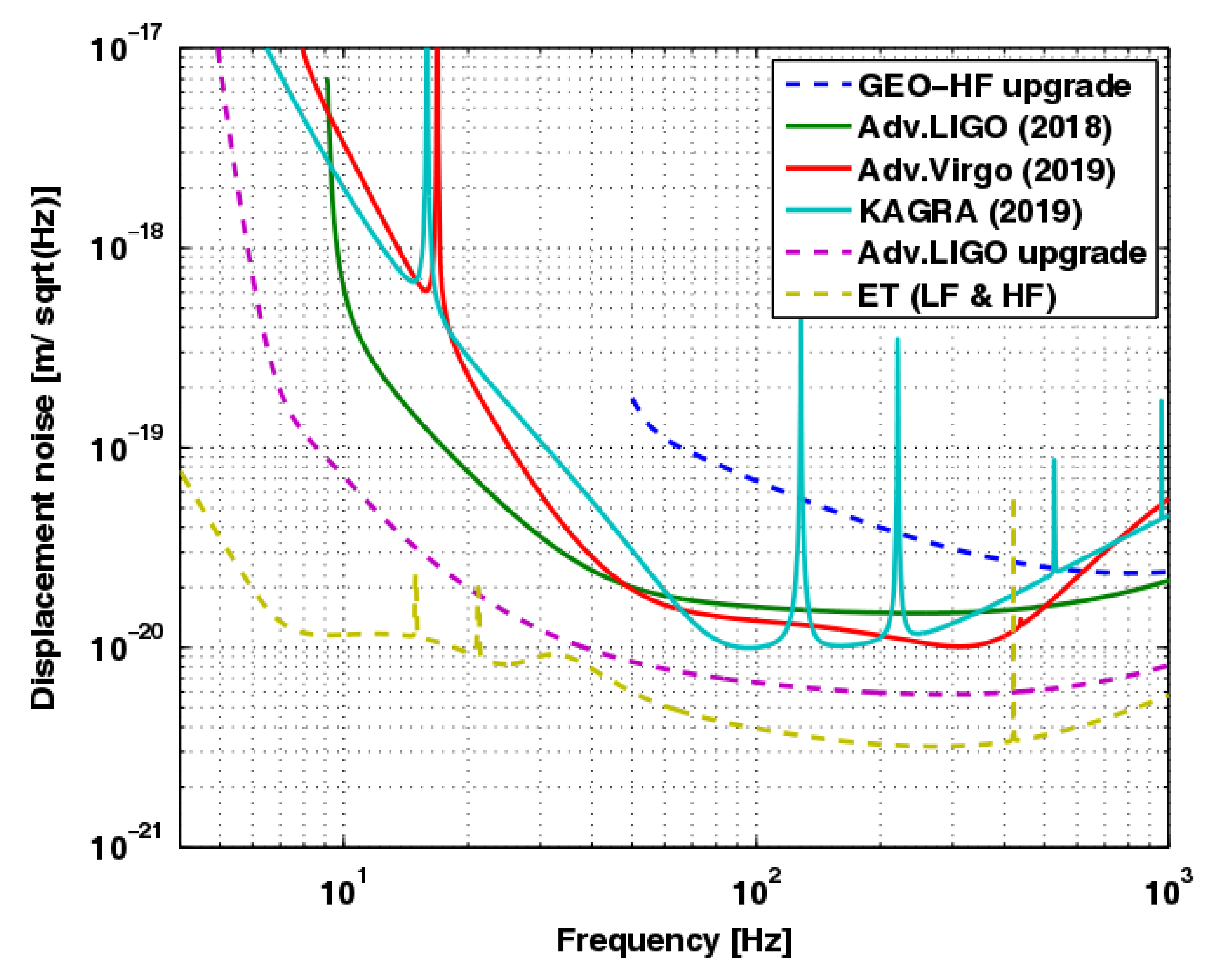
Displacement signal

$$S_{\parallel} = \Delta n_{\parallel} \times D = 9.3 \times 10^{-24} \times B^2 [\frac{1}{T^2}] \times D$$

Measurement time as function of displacement sensitivity

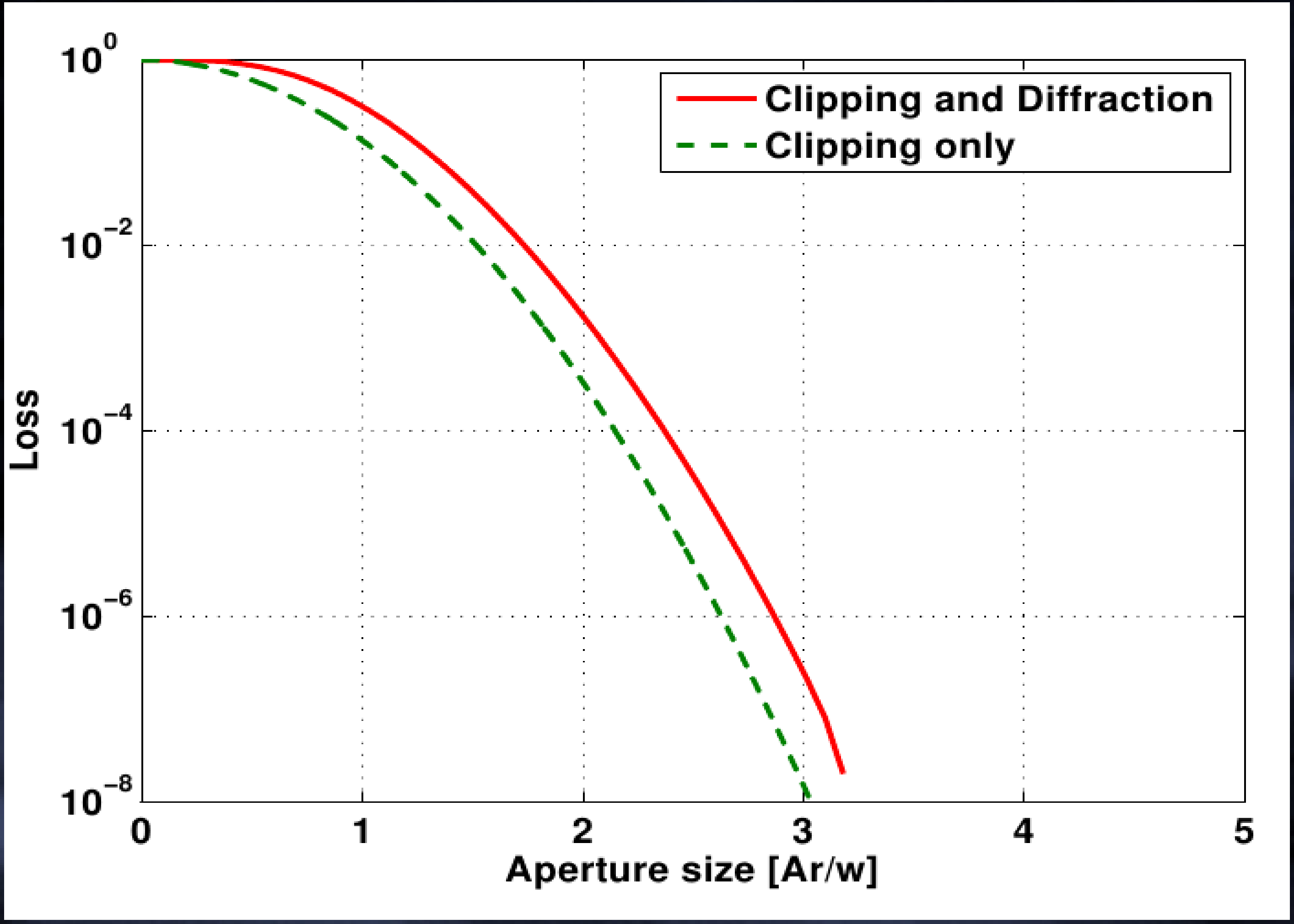


Displacement Sensitivities



Here: Is it feasible? And with what kind of magnet?

- IFO aspect: smallest acceptable aperture: ~3 times beam size (< 1ppm loss)



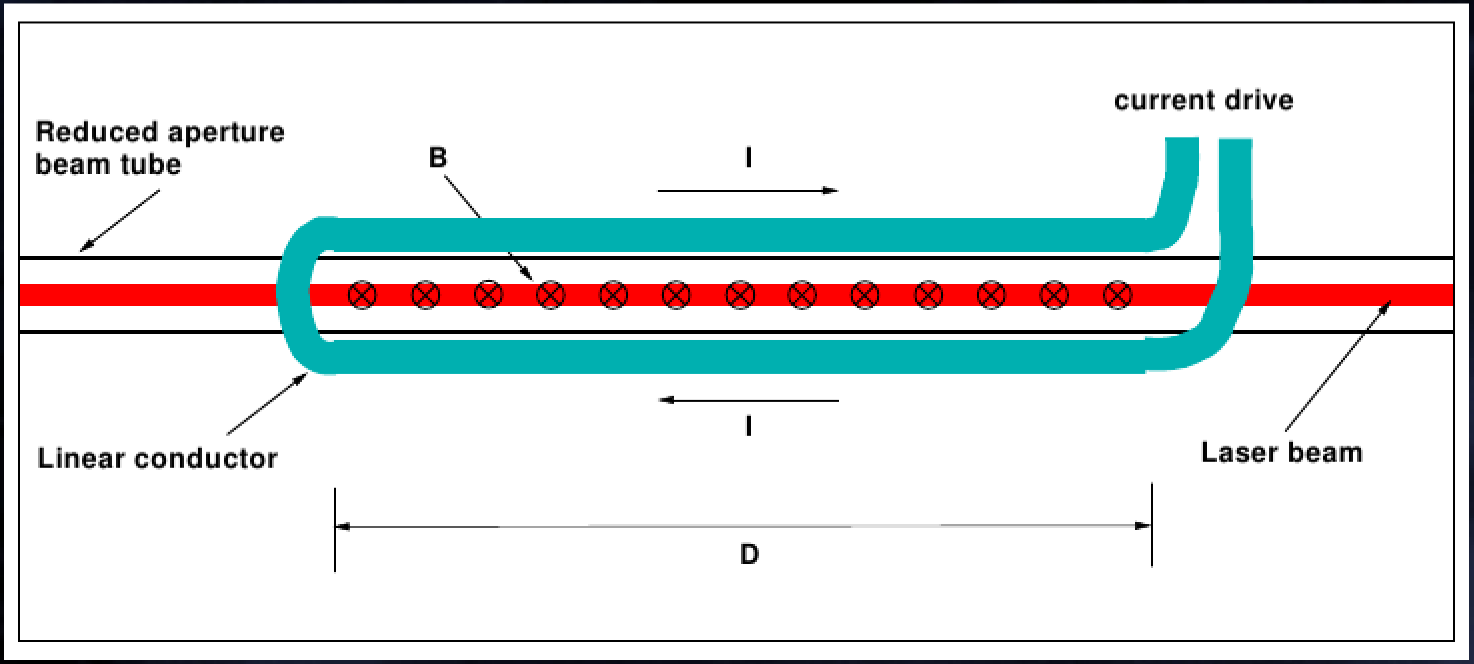
Energy in magnetic field:

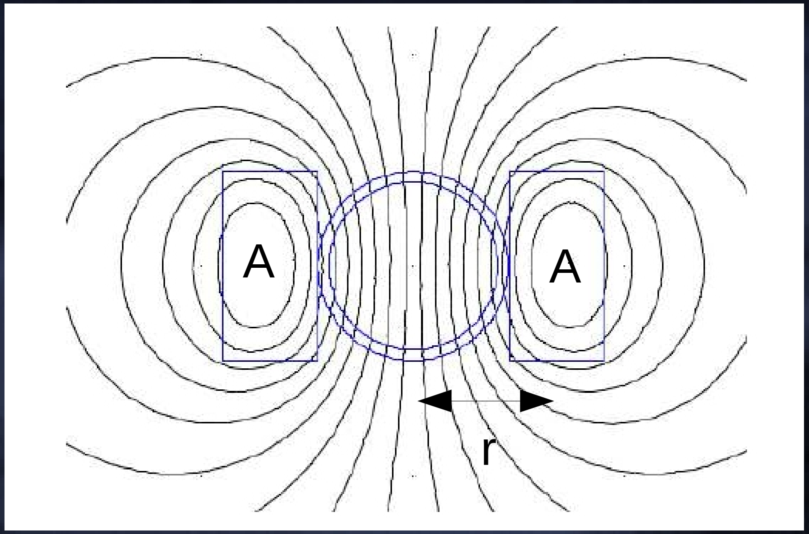
$$W = \frac{\pi}{2\mu_0} B^2 D r^2$$

Some IFO beam sizes

Interfero-meter	Beam radius at waist	Minimal aperture radius (3 x waist radius)	Realistic aperture radius, including vacuum tube
GEO (no arm cavities)	9 mm	27 mm	**40 mm**
Virgo	10 mm	30 mm	**45 mm**
LIGO	12 mm	36 mm	**55 mm**
KAGRA	16 mm	48 mm	**70 mm**
ET-LF	29 mm	87 mm	**130 mm**

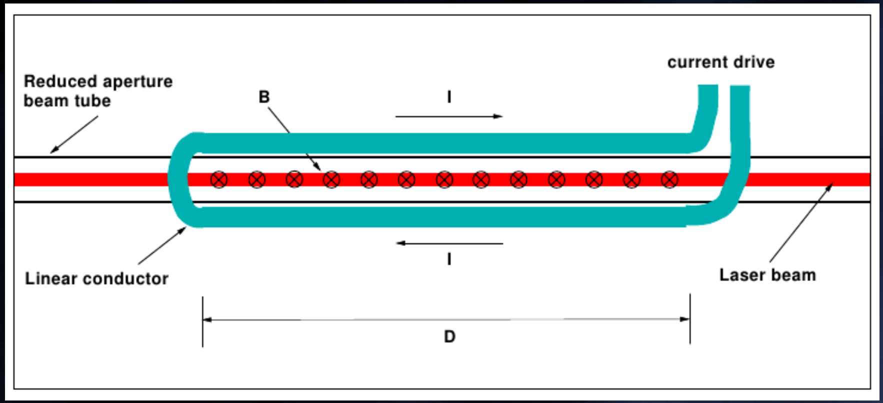
Linear magnet





Simple scaling law:
B^2 D ~ P A / r^2

Continuous operation of a linear magnet



For B^2 D = 1 T^2 m:
(r=55mm, A~r^2)

P = 300 kW (thermal dissipation only)
Pr = 2.5 MW (reactive power, f=25 Hz)
1 MW with ferro-magnetic material surrounding the conductor

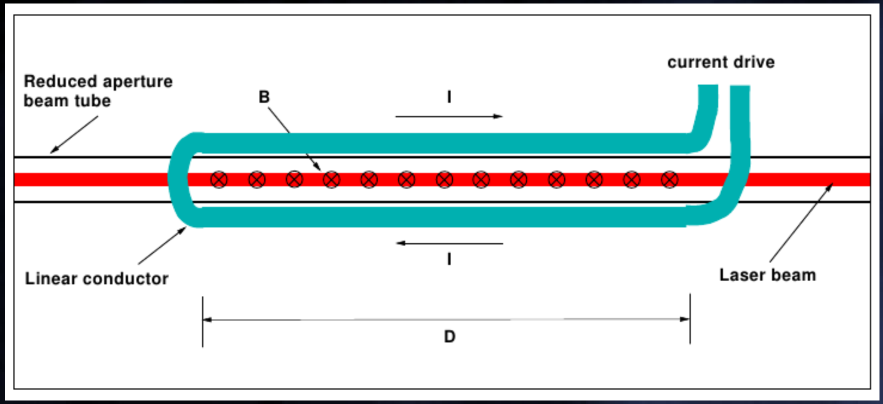
Electricity:
1 year * 1 MW = 8.76 M kWh ~ 2 M €

Intermittent operation of a magnet

$$t_{SNR=1} \sim \left(\frac{\tilde{n}(f)}{P}\right)^2$$

$$P = P_p \times \eta_p$$

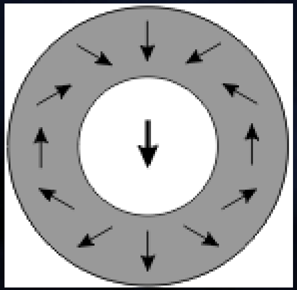
$$t_{SNR=1} \sim \eta_p \times \left(\frac{\tilde{n}(f)}{P}\right)^2$$



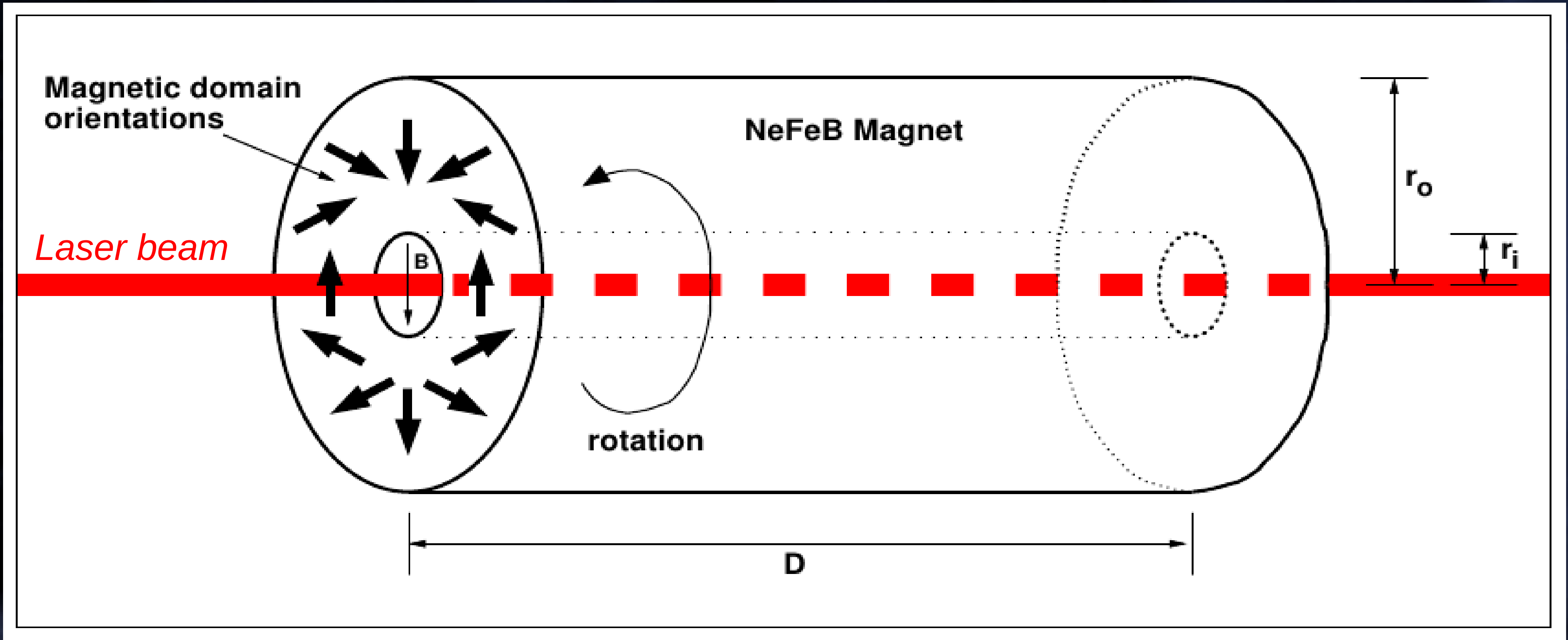
P = 20 kW (average power)
P = 100 MW (pulse power, 10ms pulse length)
E = 1 MJ, 240g TNT
1 pulse every 50 s.
600000 pulses for SNR=1 (1 year)

Magnet Aspects

- Electro-magnets: very difficult due to high energy in B-field. Perhaps better with new alloys and lower frequencies. Very large dissipation.
- Pulsed magnets: Limited lifetime seems the main problem. Large apertures do not exist yet. (see 'X-coil' for BMV, long development time)
- Permanent magnets: Field energy does not have to be shifted around...



Magnet as Halbach Cylinder



$$B = Br * \ln(ro/ri)$$

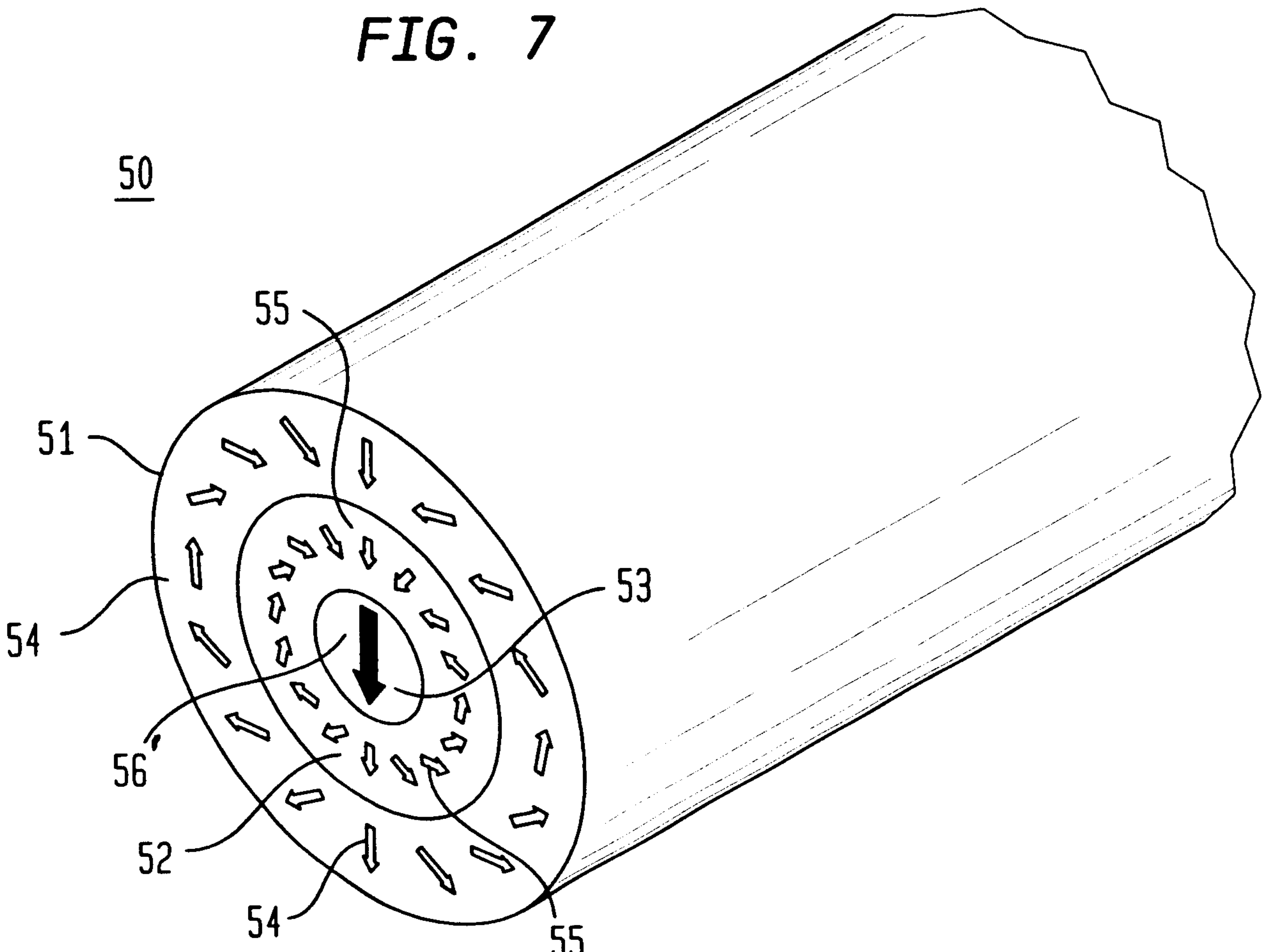
Br ~ 1.3T for NeFeB

Example: B = 1.0T for ro=121mm, ri=55mm → m=328kg for D=1.2m

NeFeB: 150$ / kg → 50k$ / Magnet

Nested Halbach cylinders for ampl. Modulated B field

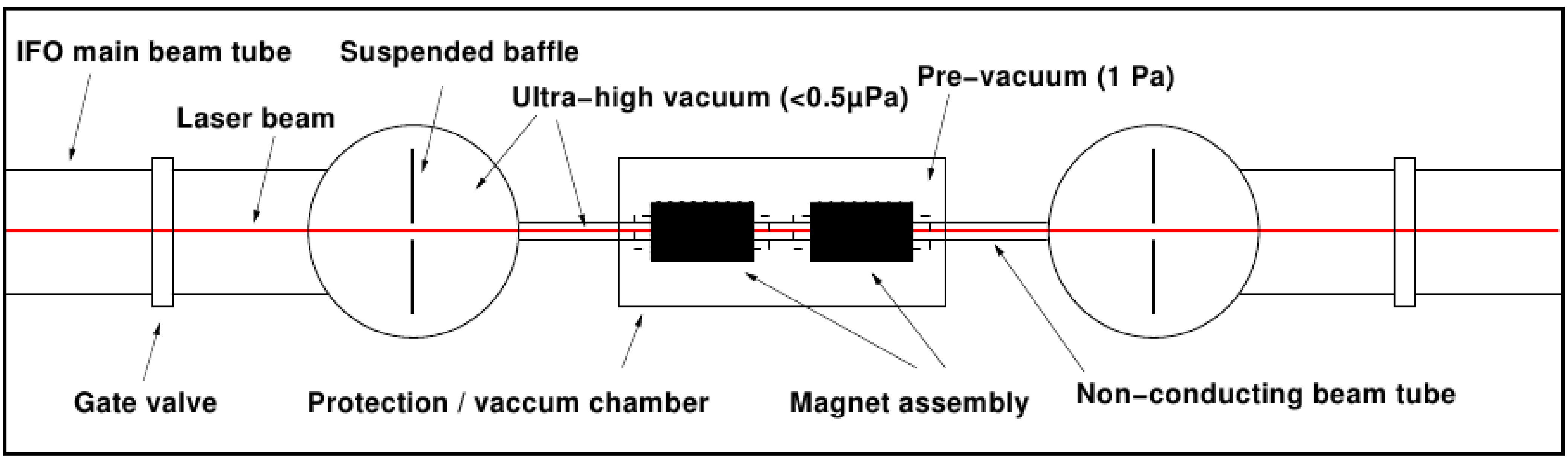
FIG. 7



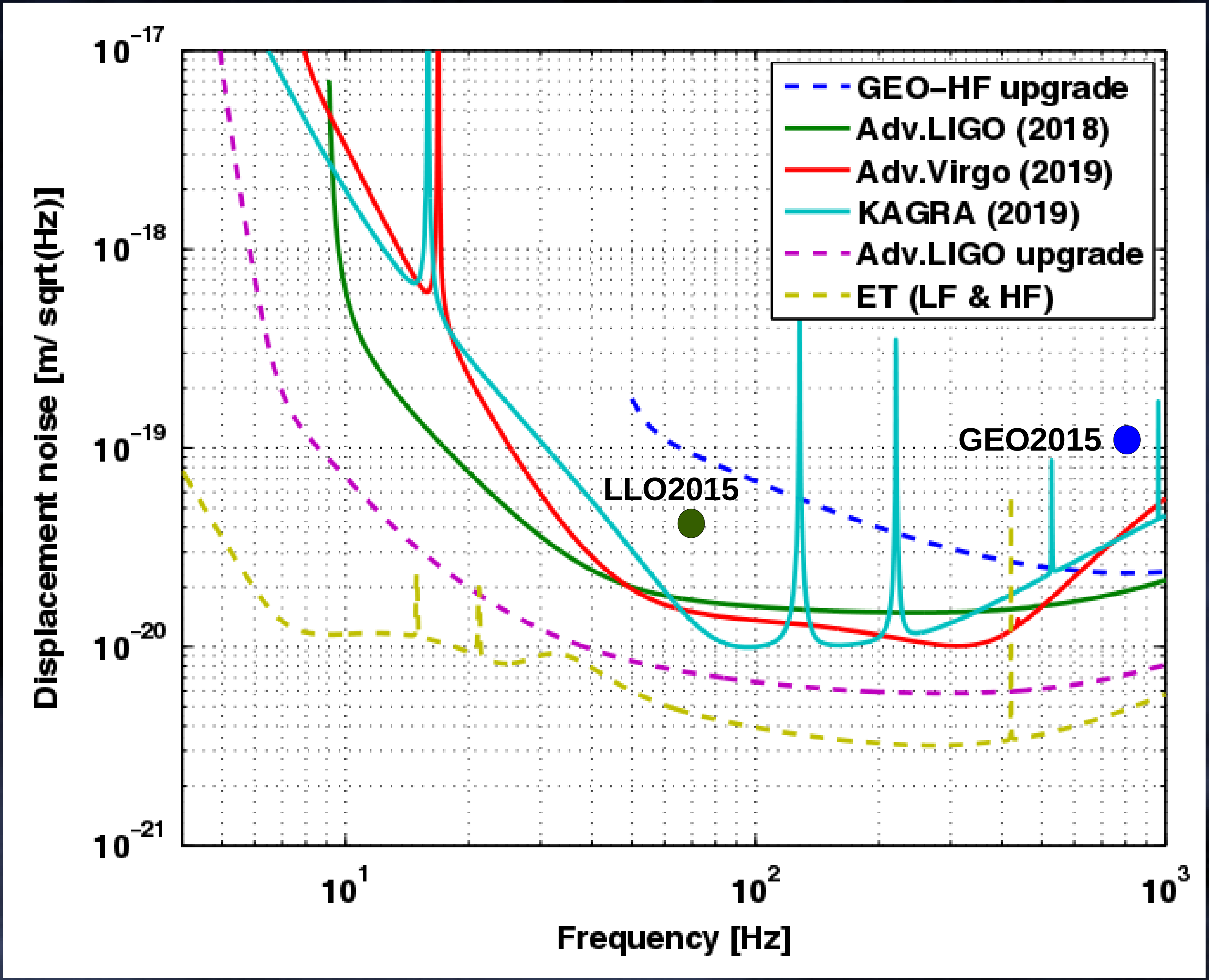
Advanced QED measurement !

IFO assembly with valves and baffles

- Chamber for baffle suspension at entry to small-aperture tube



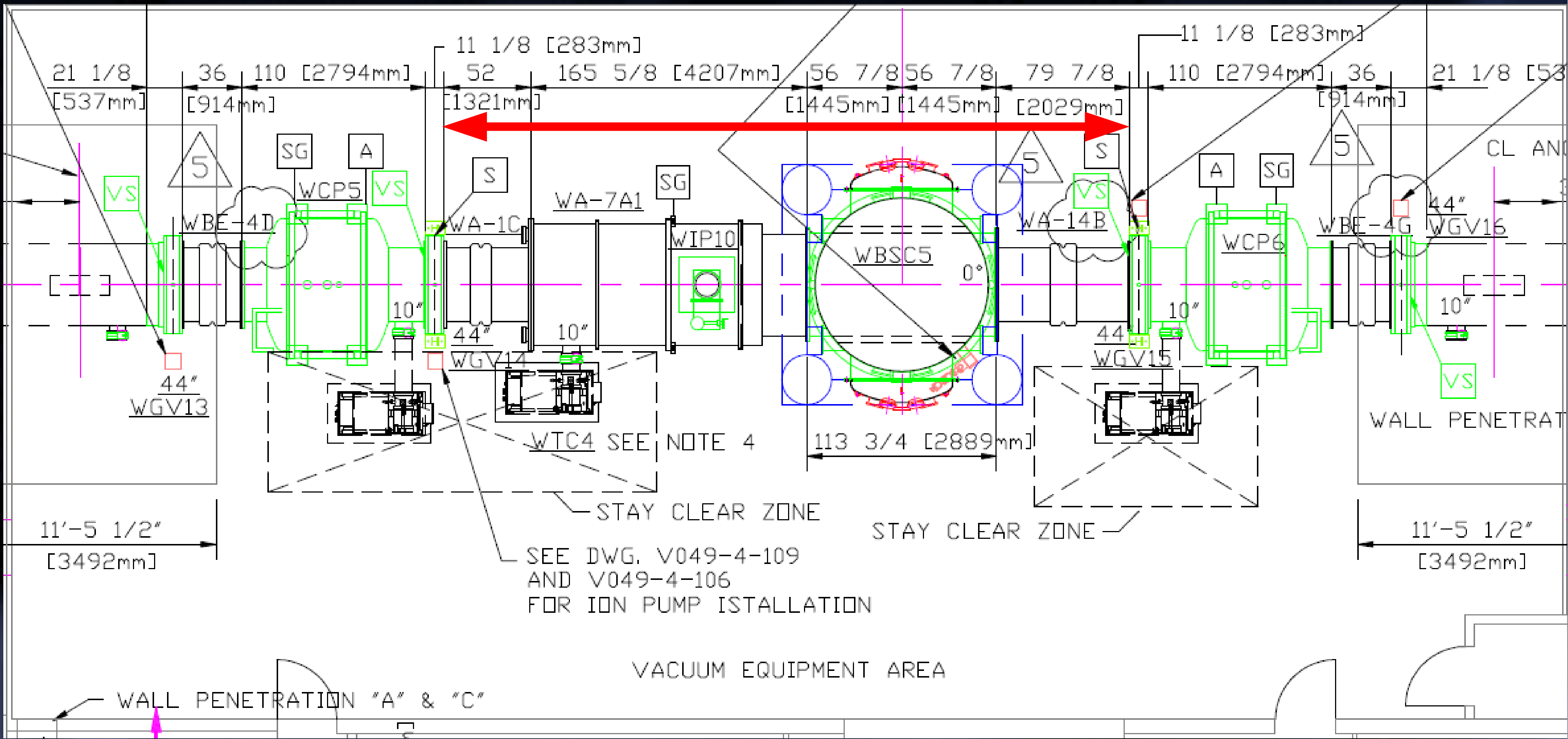
Where?



Low displacement noise hard to reach with small beams

LIGO Hanford:
Only facility with mid-tube gate valves

~10m space



e.g: install during A+ 2. upgrade phase, or Voyager upgrade...

A QED calibrator ?

- Magnetic field excitation stable over years, can be determined to sub-% level
- Only need magnetic excitation and QED prediction (and good vacuum)
- Long integration time:
  3% accuracy for ET-HF after 1 year

Conclusion

- VAC QED at GW-IFO:
  Different method (phase lag signal rather than polarization shift signal)
- Maybe ambitious, yet still looks feasible
- Quasi-parasitic addition to existing facility
- Permanent magnets seem to be an option for now