16th November 2010

OSQAR Status Report*

Progress in the Photon Regeneration Experiment

***Abstract** - The status of the OSQAR experiments is presented highlighting the progress achieved in 2010. For the photon regeneration part, three experimental runs have been performed after thorough preparatory phases in the CERN SM18 test hall. For the first time, this experiment has been successfully conducted with two aligned LHC dipoles and the expected sensitivity was achieved for the search of light scalar and pseudoscalar particles. Concerning the measurement of the Vacuum Magnetic Birefringence (VMB), dedicated studies to integrate within a LHC dipole the newly developed ultra-fine ellipsometry techniques have been performed in collaborating Institutes.*

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1. Introduction

Particle/astroparticle physics is not restricted to the high energy frontier. Many extensions of the Standard Model, in particular those based on supergravity or superstrings, predict not only massive particles like WIMPS (weakly interacting massive particles), but also weakly interacting sub-eV particles (WISPs). Whereas the former ones can be searched for at TeV colliders such as the LHC, signature of WISPs seems most likely to be detected in low energy experiments based on lasers, microwave cavities, strong electromagnetic fields or torsion balances (for a recent review of the scientific cases see [1]). The OSQAR proposal is at the forefront of this emerging low energy frontier of particle/astroparticle physics. It combines the simultaneous use of high magnetic fields with laser beams in two distinct experiments. In the first one, the photon regeneration effect is looked for as a light shining through the wall, whereas in the second one, ultra-fine magnetic birefringence of the vacuum is aimed to be measured for the first time [2]. In 2010, OSQAR activities were pursued at CERN as well as in collaborating institutes. This status report will highlight the progress achieved in both of these experiments following the newly revised program [3].

* P. Pugnat, G. Deferne, M. Finger, M. Finger Jr, M. Král, M. Schott and A. Siemko on the behalf of the OSQAR collaboration for Optical Search of QED vacuum magnetic birefringence, Axion & photon Regeneration. The members of the OSQAR collaboration are listed at the end of this document. Co-spokespersons : Pierre.Pugnat@lncmi.cnrs.fr and Krzysztof.Meissner@fuw.edu.pl

2. The Photon Regeneration Experiment: Preparatory phases, experimental runs & results

2.1. Reminder : Principle of the Photon Regeneration experiment

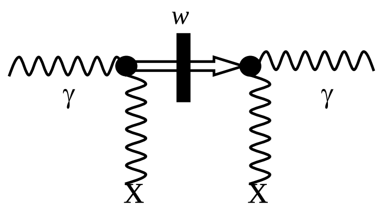


Fig.1. Photon regeneration principle

The photon regeneration experiment was proposed by K. van Bibber et al. [4] to detect light neutral scalar and pseudoscalar particles such as the axion that couple weakly to matter (WISPs). The basic ingredient comes from the coupling of the WISPs to two photons allowing their conversion to real photons in the presence of a magnetic field [5]. The conversion probability of WISP ↔ photon in vacuum is given as a function of the diphoton coupling constant $g_{w\gamma\gamma}$ by [5]:

$$P_{\gamma\leftrightarrow w} = \frac{1}{4}(g_{w\gamma\gamma}BL)^2\left(\frac{2}{qL}\sin\frac{qL}{2}\right)^2 \quad (1)$$

with $\hbar = c = 1$, $q = |k_\gamma - k_w|$ the momentum transfer, B and L the magnetic field and magnetic length respectively. If a photon beam propagating in the transverse magnetic field is intercepted by an optical barrier, all photons not converted into WISPs will be absorbed whereas on the other side of the barrier, the reverse process will allow the light shining through the wall (Fig.1) with a photon flux given by :

$$\frac{dN_\gamma}{dt} = \frac{P}{\omega}\eta\, P_{\gamma\leftrightarrow w}{}^2 \quad (2)$$

where P is the optical power, ω the photon energy and η the efficiency of the detector. Formula (2) shows that the regenerated photon flux scale as $(BL)^4$ highlighting the importance to use high field magnets. It can also be emphasized that when the magnetic field is switched off, the conversion of photon to paraphoton can be looked for [2].

2.2. OSQAR boundaries & constraints

2.2.1. Safety

Operating a class-IV laser in the SM18 experimental hall cannot be performed without a strict respect and control of the safety procedures. No exception can be tolerated especially because this hall is also an official itinerary for visitors. A safety audit has been conducted on March 8th and some recommendations have been asked to be implemented [6] such as improvements of the operating procedures as well as additional shields for the laser beam around the optical absorber (Fig. 1). The latter is made by a refractive brick mounted on a XY table and can be removed easily for the alignment operation performed at the minimum optical power of the laser. The water connection to the laser cooling system should also be modified to improve the SM18 hall access and the installation of a dedicated demineralised water circuit is well underway.

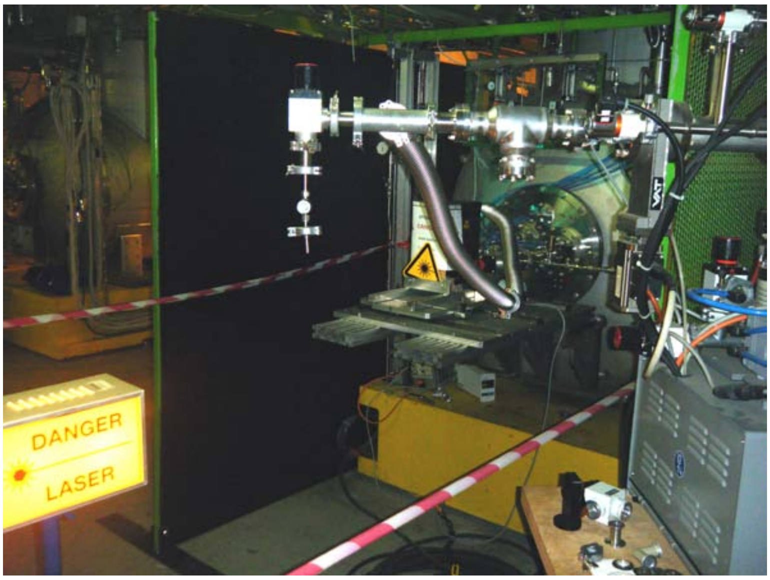


Fig. 2. Optical absorber and protection shields at the exit of the first magnet. The pumping group is also visible on the right side.

2.2.2. Cryogenics : shutdown and the sharing of the cryogenic cooling capacity

SM18 hall is a unique infrastructure, which allows testing long superconducting magnets on horizontal benches. It was specially developed for the LHC and is still in use to test spare LHC magnets [7]. From March 15th to June 9th the cryogenic infrastructure of the SM18 hall was shut down for the annual maintenance. This has prevented the operation of both OSQAR superconducting magnets. For the remaining period, the magnet test activities at SM18 and the limitation of the cooling capacity of the cryogenics, which was not available as expected, have constrained the OSQAR operation with both magnets at 1.9 K to a cumulative time not exceeding 3 full weeks (see Table 1). Some uncontrolled interruptions of experimental runs have been experienced coming from the water cooling of the magnet power cables or from the cryogenics. *The total duration of OSQAR experimental runs was much less than the 6 weeks requested for 2010* [3].

Period	OSQAR configuration	Data acquisition runs
22 - 25 February	Photon Regeneration - 2 LHC dipoles temporary used/available - 18 W Ar+ laser with linear polarization // B	- Cumulative time integration of ► 0.83 h for scalar search ► 0.67 h for paraphoton search
19 June - 7 July	- 1 LHC dipole temporary used/available - 14 W Ar+ laser (new one provided by ESPCI-Paris)	- Background study & and long term stability runs
19 - 27 August	Photon Regeneration - 2 LHC dipoles temporary used/available - 14 W Ar+ laser (new one provided by ESPCI-Paris) with linear polarization ⊥ B	- Cumulative time integration of ► 85 h for pseudo-scalar search ► 18.5 h for scalar search ► 72 h for background

Table 1. Overview of the OSQAR experimental runs in 2010.

2.2.3. Laser breakdown and its replacement

The first measurement campaign was stopped due to a breakdown of the 18 W Ar+ laser. The postmortem diagnosis has revealed that the plasma tube is out of order. A new 14 W Ar+ laser was provided by the ESPCI-Paris (Ecole Supérieure de Physique & de Chimie Industrielles de la ville de Paris), installed and put in operation hereafter. This new laser, Coherent Innova 400-15, has required the installation of a new power line 400 V/125 A. At present and for both remaining experimental runs shown in Table 1, the maximum optical power was limited to 7 Watt because of an abnormally high pressure of the plasma in the sealed tube. This could be due to outgassing effect as the laser was not used since quite a long time and dedicated actions to improve the situation are ongoing.

2.3. Preparatory phases

Following the unexpected circumstances in 2009, two new spare LHC dipoles have been assigned to OSQAR [8]. Both of them were installed on the test benches B1 and E2 (Fig. 3) and aligned with a Laser Tracker LTD 500 from Leica. They were cold tested before being used in routine operation to provide a magnetic field of 9 T over 14.3 m. Magnet apertures was pumped typically down to 10^{-6}-10^{-7} mbar using two turbomolecular pumping groups.

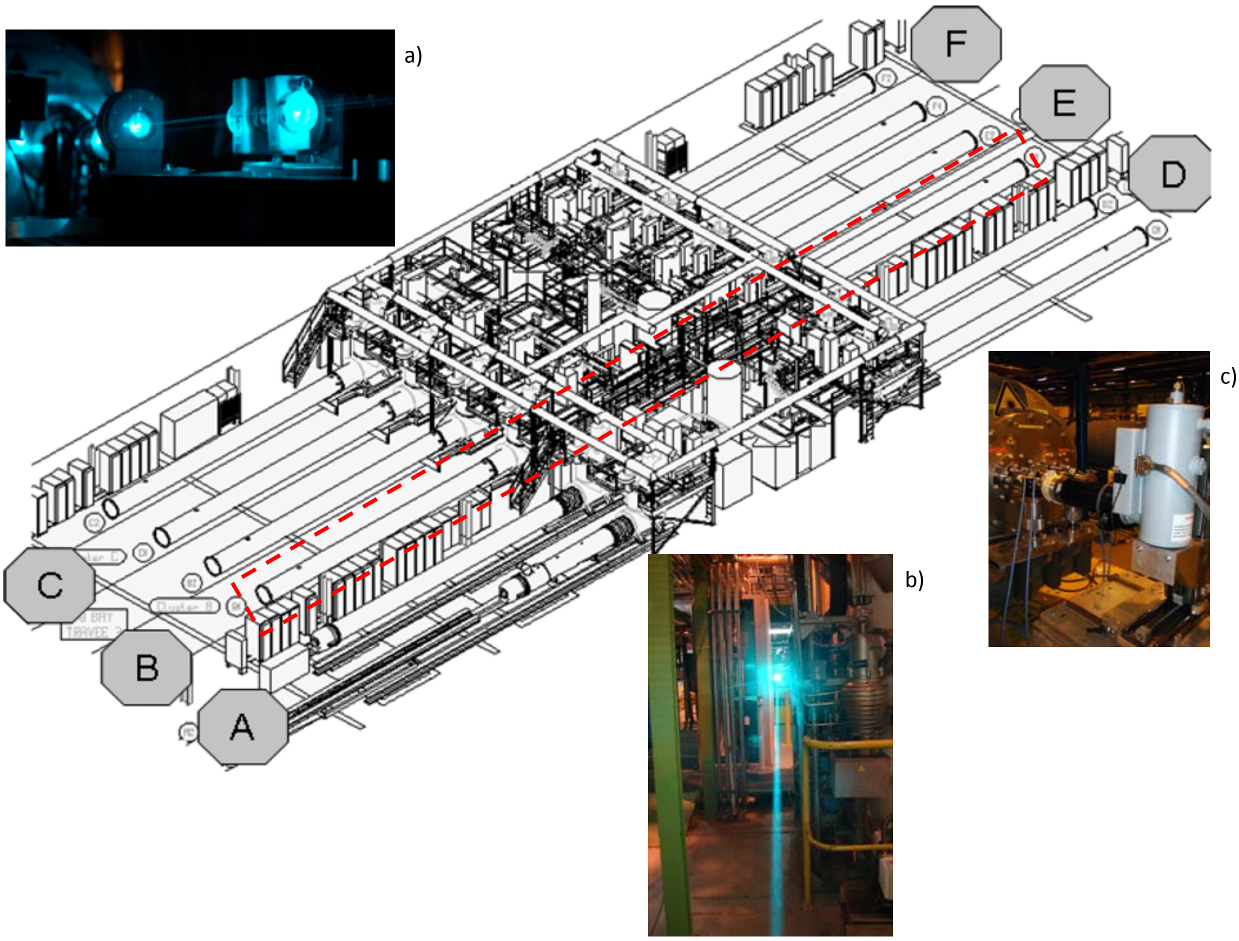
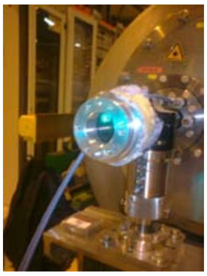


Fig. 3. Layout of the LHC superconducting magnet test plant consisting of 12 test benches grouped in 6 clusters (A to F). The total length between the entrance and the exit of the OSQAR dipoles highlighted by the red dashed line is about 53 m. a) Laser beam at the first magnet entrance in B1; b) Laser beam propagating between magnets installed on B1 and E2 benches; c) LN_2 cooled CCD detector at the second magnet exit.

To reduce the laser divergence a dedicated beam expander telescope was specially developed (Fig. 3a). By combining converging and diverging lenses, the optical Gaussian beam with a waist equal to 0,7085 mm at the level of the output coupler, was shaped to obtain a spot size not exceeding 6 mm of diameter at 53 m (Fig. 4b). To minimize spherical aberrations, lenses were mounted with planar surfaces face-to-face (Fig. 4a) and thermal effects on lenses were minimized by developing proper supports. At the exit of the second magnet, an optical lens was installed (Fig. 4c) to focus the laser beam on the CCD detector and obtain a full width half maximum for the intensity of 0,478 mm.

A procedure to align the laser beam inside the aperture of both dipoles to reach the CCD detector has been developed and long term stability runs have been performed. As the result of the activities in the SM18 hall, the laser beam alignment can be lost. This was observed after the transportation around OSQAR benches of heavy loads such as magnets and periodic checks have been implemented during experimental runs interrupting the data acquisition.


a)


b)


c)

Fig. 4. a) Principle of the beam expander telescope developed for OSQAR with a fine tunable distance between both lenses. b) The laser beam at the exit of the second magnet. c) Focus lens at the exit of the second magnet aperture just in front of the CCD (not shown).

2.4. Experimental runs

A typical experimental run starts and ends with the beam alignment using absorptive filters to reduce the laser intensity below the saturation level of the LN2 cooled CCD detector from Princeton Instruments. In its 1D mode the CCD can be seen as an array of 1100 pixels of 5 mm height densely packed over a length of 27 mm. The quantum efficiency of the detector is equal to 50 ± 2 % for the Ar+ laser wavelengths and the number of dark counts per pixel is lower than 0.1 cts/mn.

The laser beam has a well defined linear polarization parallel to the magnetic field. This configuration is suitable for the search of pseudoscalar/axion particles. For scalar particle, a $\lambda/2$ wave plate oriented at 45° is inserted at the laser exit to align the polarization perpendicular to the magnetic field.

2.5. Results and analysis

Data acquired during 2010 runs are undergoing detailed analysis. First, signals coming from cosmic rays have to be removed. Problems linked to the stability of the background of the CCD make the global analysis based on the overall cumulative data recording difficult. The combined analysis taking into account all experimental data instead of proceeding to rejections is under study.

At present, the first analysis was performed for the best recorded data regarding the search of WISPs. The preliminary results from two selected data sets of Run II corresponding to a time integration of 12.7 h at 6.5 W and 7.37 h at 6.7 W for pseudoscalar and scalar particle respectively, are presented in Fig.5. Results from OSQAR Run I, already reported [3], and from the ALPs collaboration [9] are also shown, the latter being the present reference result.

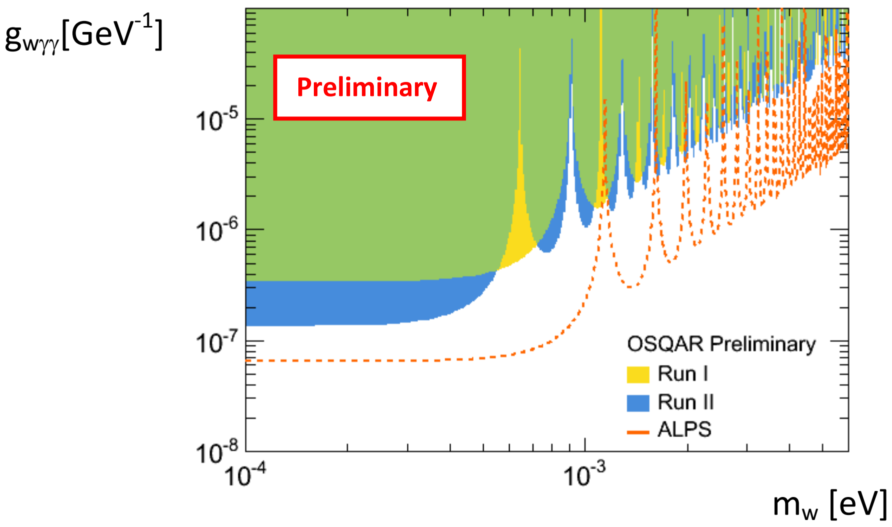


Fig. 5. Preliminary results of Run II for the exclusion limits of pseudoscalar and scalar particle search, which are very similar. *Reminder : Yellow + Blue = Green*

2.6. Objectives for 2011 and 2012

Two main hypotheses have been considered to improve the discovery potential of the OSQAR photon regeneration experiment during 2011 and 2012 runs. The first one concerns the increase of the optical power by a factor of at least 50 using an extended laser cavity. The second hypothesis requires the use of a new state-of-the-art CCD detector, which will allow a reduction of the background by a factor of 50. An increase of the quantum efficiency of the CCD by a factor of about 2 is also foreseen and was not considered for the expected exclusion limits given in Fig.6.

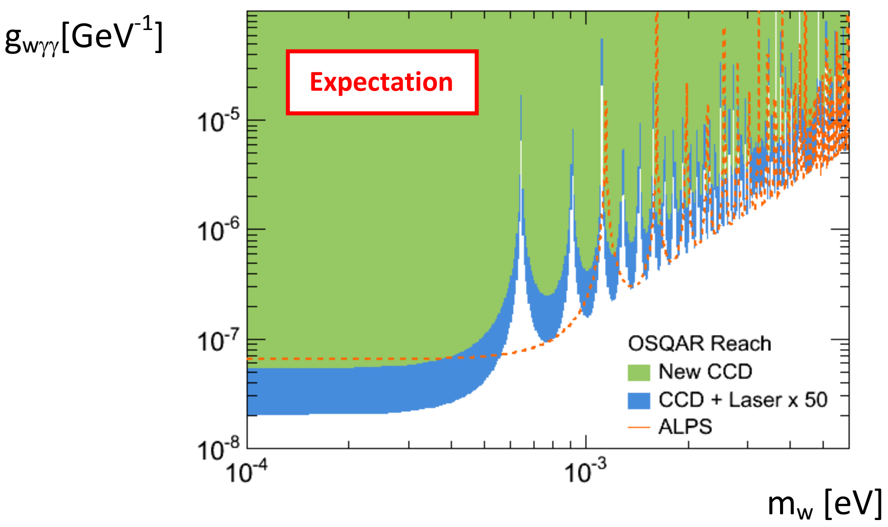


Fig. 6. Expected exclusion limits for pseudoscalar and scalar particle search from OSQAR.

3. Towards the VMB Measurement

One of the main objectives of OSQAR is to measure for the first time ever the ultra-fine Vacuum Magnetic Birefringence (VMB) predicted by the QED [3]. An optical scheme has been proposed [10], validated and subsequently improved [11], [12]. An update to the OSQAR proposal for the VMB measurement is in preparation.

4. Conclusions, Perspectives & Requirements

As a summary, the discovery potential of the OSQAR photon regeneration experiment has significantly been improved in 2010 by the simultaneous use of 2 LHC dipoles, each of them providing 9 T over 14.3 m. The sensitivity obtained for pseudoscalar/axion and scalar search reached the foreseen target [3] and is only surpassed by the new results recently published by the ALPs experiment at DESY [9] (see Fig. 5 & 6). Unexpected circumstances, *i.e.* the laser breakdown and the less than expected availability of the cryogenic cooling capacity, have prevented to further increase the sensitivity. This latter problem has affected the foreseen operation time of both OSQAR superconducting magnets. The OSQAR collaboration expects an improvement in 2011 in this respect. Among other problems encountered and which can also be solved, it can be mentioned:

- an improvement of the magnet operation efficiency over long time periods without interruptions,
- a thorough optimization of the cryogenic cooling capacity shared between the various activities in the SM18 test hall.

The last point has already received a dedicated attention after the appointment by the TE department of a coordinator for the SM18 activities. Still better situation can be expected for the OSQAR runs in 2011. Obviously the OSQAR collaboration is willing to participate in common efforts to the above mentioned points.

For 2011, the request from the OSQAR collaboration concerns the possibility to use both allocated test benches and dipoles at 1.9 K with the required cryogenic cooling capacity together with dedicated resources. **The required run durations at cold conditions are at least: 1 period of 2 weeks and 4 periods of 1 week each.** This will allow completing the revised program [3] with as main objectives for the photon regeneration experiment:

- to increase the optical power of the laser and to develop a resonant cavity,
- to improve the signal to noise ratio by at least one order of magnitude by using a new CCD with less read-out noise, less dark current, higher quantum efficiency and also by optimizing the beam focusing on the CCD.

Concerning the possibility **to get the funding for a new CCD, a discussion with the CERN directorate is expected to converge towards a positive issue.** It should be emphasized that the CCD detector used so far for the photon regeneration experiment starts to be obsolete and moreover has to be shared with another research team in Grenoble. This brings an additional constraint difficult to afford by the OSQAR collaboration. The new CCD will allow to fully exploit the unique opportunity brought by LHC magnets and to realize a photon regeneration experiment with an unprecedented sensitivity. By assuming the same sensitivity for the photon detection as the one reached by the ALPs collaboration [9], the exclusion limit for the diphoton coupling constant to scalar and pseudoscalar particles can be expected to be improved significantly with the foreseen runs of the OSQAR experiment in 2011 and 2012 (Fig. 6).

Concerning the measurement of the Vacuum Magnetic Birefringence predicted by the QED, a first prototype of a rotating optical cavity can be expected to be produced by the end of 2011 or in 2012 as a function of the support coming from funding agencies.

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OSQAR Participation to International & National Conferences in 2010

15-17 January, *Axion 2010*, Gainesville, University of Florida; http://www.phys.ufl.edu/research/Axions2010/

15-19 March, *Verhandlungen*, Bonn 2010, DE; http://www.dpg-verhandlungen.de/year/2010/conference/bonn/part/t/session/54/contribution/2/

14-18 June, *Advanced Photons and Science Evolution 2010*, Osaka Japan; http://www.yamadazaidan.jp/ys/apse2010/

5-9 July, AXION-WIMP 2010, *The 6th Patras Workshop on Axions, WIMPs and WISPs*, Zurich University, CH; http://axion-wimp.desy.de/

18-24 July, SPIN-Praha-2010, *Symmetries and Spin*, Institute for Advanced Studies, Charles University, Prague, CZ; http://theor.jinr.ru/~praha/2010/

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► *26 Members from 11 Institutes (CERN, Cz, Fr & Po)*

CERN, Geneva, Switzerland

G. Deferne, P. Pugnat (now at LNCMI-Grenoble/CNRS), M. Schott & A. Siemko

Charles University in Prague, Faculty of Mathematics & Physics, Prague, Czech Republic

M. Finger Jr., M. Finger, M. Slunecka

Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic

J. Hošek, M. Kràl, K. Macuchova, J. Zicha

Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Prague, Czech Republic

M. Virius

ISI, ASCR, Brno, Czech Republic

A. Srnka

IMEP/LAHC - INPG, 38016 Grenoble Cédex-1, France

L. Duvillaret, G. Vitrant, J.M. Duchamp

IN, CNRS – UJF & INPG, BP 166, 38042 Grenoble Cédex-9, France

B. Barbara, R. Ballou

LASIM, UCB Lyon1 & CNRS, 69622 Villeurbannes, France

M. Durand, J. Morville

LSP, UJF & CNRS, 38402 Saint-Martin d'Hères, France

R. Jost, S. Kassi, D. Romanini

Technical University in Liberec, Liberec, Czech Republic

M. Šulc

Warsaw University, Physics Department, Poland

A. Hryczuk, K. A. Meissner