Development and testing of the gravitational wave antenna MiniGRAIL in its full-featured configuration

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Bibliography

[1] Hulse, R. A. The discovery of the binary pulsar. *Rev. Mod. Phys.* **66**, 699–710 (1994).

[2] Taylor, J. H. Binary pulsars and relativistic gravity. *Rev. Mod. Phys.* **66**, 711–719 (1994).

[3] Weber, J. Gravitational radiation. *Phys. Rev. Lett.* **18**(13), 498–501, Mar (1967).

[4] Weber, J. Gravitational radiation experiments. *Phys. Rev. Lett.* **24**(6), 276–279, Feb (1970).

[5] Sigg, D. and the LIGO collaboration. Proc. of the 5th Edoardo Amaldi Conf. on Gravitational Waves (Pisa, Italy 5-12 July 2003). *Class. Quantum Grav.* **21**, S409–S416 (2004).

[6] Acernese, F. et al. Proc. of the 5th Edoardo Amaldi Conf. on Gravitational Waves (Pisa, Italy 5-12 July 2003). *Class. Quantum Grav.* **21**, S385–S394 (2004).

[7] Willke, B. et al. proc. of the 5th edoardo amaldi conf. on gravitational waves (pisa, italy 5-12 july 2003). *Class. Quantum Grav.* **21**, S417–S423 (2004).

[8] Takahashi, R. and the TAMA collaboration. Proc. of the 5th Edoardo Amaldi Conf. on Gravitational Waves (Pisa, Italy 5-12 July 2003). *Class. Quantum Grav.* **21**, S403–S408 (2004).

[9] Conti, L. and the AURIGA collaboration. The AURIGA second scientific run and the dual detector of gravitational waves. *Nucl. Instrum. Methods* **A 518**, 236–239 (2004).

[10] Aguiar, O. D. et al. proc. of the 5th edoardo amaldi conf. on gravitational waves (pisa, italy 5-12 july 2003). *Class. Quantum Grav.* **21**, S457–S463 (2004).

[11] de Waard, A. et al. proc. of the 5th edoardo amaldi conf. on gravitational waves (pisa, italy 5-12 july 2003). *Class. Quantum Grav.* **21**, S465–S471 (2004).

[12] Coccia, E. Proc. of the International Conference on Gravitational Waves: Sources and Detectors, 201. World Scientific, Singapore (1996).

[13] Johnson, W. W. and Merkowitz, S. M. Truncated icosahedral gravitational wave antenna. *Phys. Rev. Lett.* **70**, 2367 (1993).

[14] Forward, R. L. Multidirectional, multipolarization antennas for scalar and tensor gravitational radiation. *Gen. Relat. Gravit.* **2**(2), 149 (1971).

[15] Jr, R. M. M., Magalhaes, N. S., Aguiar, O. D., and Frajuca, C. Response of spherical gravitational wave antenna modes to high-energy cosmic ray particles. *Class. Quantum Grav.* **19**(7), 1955 (2002).

[16] Maggiore, M. *Gravitational Waves: Theory and experiments.* Gravitational Waves. Oxford University Press, (2007).

[17] Hartle, J. *Gravity: An Introduction to Einstein's General Relativity.* Addison-Wesley, Boston, (2003).

[18] Thorne, K. S. Gravitational radiation. In *Three Hundred Years of Gravitation*, 330–458. S.W. Hawking and W. Israel, Cambridge University Press,Cambridge (1987).

[19] Merkowitz, S. M. *Truncated icosahedral gravitational wave antenna.* PhD thesis, Louisiana State University, Louisiana, USA, (1995).

[20] Merkowitz, S. M. and Johnson, W. W. Spherical gravitational wave antennas and the truncated icosahedral arrangement. *Phys. Rev. D* **51**, 2546 (1995).

[21] Merkowitz, S. M. Techniques for detecting gravitational waves with a spherical antenna. *Phys. Rev. D* **56**, 7513 (1997).

[22] Merkowitz, S. M. Solution to the inverse problem for a noisy spherical gravitational wave antenna. *Phys. Rev. D* **58**, 062002–1 (1998).

[23] Gottardi, L. Complete model of a spherical gravitational wave detector with capacitive transducers: Calibration and sensitivity optimization. *Phys. Rev. D* **75**(2), 022002, Jan (2007).

[24] Misner, C. W., Thorne, K. S., and Wheeler, J. *Gravitation.* W. H. Freeman, San Francisco, (1973).

[25] Gottardi, L. *Transducers and low noise two-stage SQUID amplifiers for the spherical gravitational wave antenna MiniGRAIL.* PhD thesis, Leiden University, (2004).

[26] Tesche, C. D. and Clarke, J. DC SQUID: Noise and optimization. *J. Low Temp. Phys.* **29**, 301 (1977).

[27] Lobo, J. A. and Serrano, M. A. *Europhys. Lett.* **35**, 253 (1996).

[28] Dubath, F., Extermann, J., and Gottardi, L. On the sensitivity of a hollow sphere as a multi-modal resonant gravitational wave detector. *Class. Quantum Grav.* **24**(9), 2231 (2007).

[29] Stevenson, T. R. Limits on the sensitivity of spherical gravitational wave detectors and on the accuracy of reconstructed signals. *Phys. Rev. D* **56**(2), 564–587, Jul (1997).

[30] Zhou, C. Z. and Michelson, P. F. Spherical resonant-mass gravitational wave detectors. *Phys. Rev. D* **51**, 2517 (1995).

[31] Costa, C. F. D. S. *Data Analysis Pipeline For The Spherical Gravitational Wave Antenna MiniGRAIL*. PhD thesis, University of Geneva, (2010).

[32] Foffa, S. and Sturani, R. The coherent detection method of gravitational wave bursts for spherical antennas. *Class. Quantum Grav.* **26**(10), 105013 (2009).

[33] Pro/ENGINEER, http://www.ptc.com/.

[34] MATLAB, http://www.mathworks.com/products/matlab/.

[35] de Waard, A. *Minigrail. The first spherical gravitational wave antenna*. PhD thesis, Leiden University, Leiden, The Netherlands, (2003).

[36] de Waard, A., Frossati, G., Zendri, J. P., Coccia, E., and Fafone, V. New technique to measure the mechanical quality factor of metals using spherical samples. *Physica B* **280**, 535 (2000).

[37] Gottardi, L., de Waard, A., and Frossati, G. Two-stage SQUID systems and transducers development for MiniGRAIL. *Class. Quantum Grav.* **21**, S1191–S1196 (2004).

[38] Frossati, G. et al. present status of miniGRAIL. In *Proceedings of the 10th Marcell Grossmann Meeting on General relativity*. Rio de Janeiro, Brazil (2003).

[39] Benzaim, Y. *Mechanical attenuation system for MiniGRAIL*. graduation thesis, Universiteit Leiden, unpublished, (2004).

[40] Foffa, S. and Sturani, R. Event trigger generator for resonant spherical detectors of gravitational waves. *Class. Quantum Grav.* **25**(18), 184036 (10pp) (2008).

[41] National Instruments LabView, http://www.ni.com/labview/.

[42] STAR Cryoelectronics, 25-A Bisbee Court,Santa Fe, NM 87508-1412.

[43] http://www.hisparc.nl.

[44] Josephson, B. D. Possible new effects in superconductive tunneling. *Phys. Lett.* **1**, 251–253 (1962).

[45] Chesca, B., Kleiner, R., and Koelle, D. Squid theory. In *The SQUID Handbook*. J. Clarke and A.I. Braginski Eds., Wiley-VCH,Weinheim, Germany.

[46] Ketchen, M. B. dc SQUIDs 1980: The state of the art. *IEEE Trans. Magn.* **17**, 387 (1981).

[47] Jin, I., Amar, A., Stevenson, T. R., Wellstood, F. C., Morse, A., and Johnson, W. W. A 35 $\hbar$ two-stage SQUID system for gravity wave detection. *IEEE Trans. Appl. Supercond.* **7**, 2742–2746 (1997).

[48] Podt, M. *Wideband low-noise integrated SQUID systems*. PhD thesis, University of Twente, Enschede, The Netherlands, (2003).

[49] Schreier, R. and Temes, G. *Understanding delta-sigma data converters*. IEEE Press, (2005).

[50] http://rsync.samba.org.

[51] Paik, H. J. Superconducting tunable-diaphragm transducer for sensitive acceleration measurements. *J. Appl. Phys.* **47**, 1168 (1976).

[52] Jaszczuk, W., ter Brake, H. J. M., Flokstra, J., Veldhuis, D., Stammis, R., and Rogalla, H. Bonding of a niobium wire to a niobium thin film. *Meas. Sci. Technol.* **2**(11), 1121–1122 (1991).

[53] IPHT Jena e.V., Department of Quantum Electronics, Postfach 100239, 07702 Jena, Germany.

[54] Leiden Cryogenics B.V., Galgewater 21, 2311 VZ Leiden, The Netherlands.

[55] Pleikies, J. *Strongly coupled, low noise DC-SQUID amplifiers*. PhD thesis, University of Twente, Enschede, (2009).

[56] Quantum Design, 11578 Sorrento Valley Road, Suite 30, San Diego, CA 92121.

[57] Pobell, F. *Matter and Methods at Low Temperatures*. Springer, Berlin, 3rd ed. edition, (2002).

[58] Kanskar, M. and Wybourne, M. N. Crossover between dissipative and nondissipative electron transport in metal wires. *Phys. Rev. Lett.* **73**(15), 2123–2126, Oct (1994).

[59] Zhong, Y. L. and Lin, J. J. Observation of a linear mean-free-path dependence of the electron-phonon scattering rate in thick AuPd films. *Phys. Rev. Lett.* **80**(3), 588–591, Jan (1998).

[60] Pleikies, J., Usenko, O., Stolz, R., Fritzsch, L., Frossati, G., and Flokstra, J. Hot-electron effect in PdAu thin-film resistors with attached cooling fins. *Supercond. Sci. Tech.* **22**(11), 114007 (2009).

[61] Frossati, G. *PhD Thesis.* PhD thesis, University of Grenoble, Grenoble, France, (1978).

[62] Buraschi, M. I., Pignatel, G. U., and Sanguinetti, S. Low-temperature conductivity behaviour of ion implanted silicon bolometers. *J. Phys.: Condens. Matter* **2**(50), 10011 (1990).

[63] Quaranta, O., Spathis, P., Beltram, F., and Giazotto, F. Cooling electrons from 1 to 0.4 k with v-based nanorefrigerators. *Appl. Phys. Lett.* **98**(3), 032501 (2011).

[64] Stevenson, T. R. and Haucke, H. J. Behavior of a dc squid tightly coupled to a high- Q resonant transducer. In *Proc. of the 1st Edoardo Amaldi Conf. on Gravitational Waves*, 390. World Scientific, Singapore (1995).

[65] Vinante, A. *Optimization of a two-stage dc SQUID for resonant gravitational wave detectors.* PhD thesis, University of Trento, Trento, Italy, (2002).

[66] Falferi, P., Bonaldi, M., Cerdonio, M., Vinante, A., Mezzena, R., Prodi, G. A., and Vitale, S. 27 $\hbar$ squid amplifier operating with high-q resonant input load. *Appl. Phys. Lett.* **88**(6), 062505 (2006).

[67] Baggio, L., Bignotto, M., Bonaldi, M., Cerdonio, M., Conti, L., Falferi, P., Liguori, N., Marin, A., Mezzena, R., Ortolan, A., Poggi, S., Prodi, G. A., Salemi, F., Soranzo, G., Taffarello, L., Vedovato, G., Vinante, A., Vitale, S., and Zendri, J. P. 3-mode detection for widening the bandwidth of resonant gravitational wave detectors. *Phys. Rev. Lett.* **94**(24), 241101, Jun (2005).

[68] Giffard, R. P. Ultimate sensitivity limit of a resonant gravitational wave antenna using a linear motion detector. *Phys. Rev. D* **14**, 2478 (1976).

[69] Baggio, L., Cerdonio, M., Ortolan, A., Vedovato, G., Taffarello, L., Zendri, J.-P., Bonaldi, M., Falferi, P., Martinucci, V., Mezzena, R., Prodi, G. A., and Vitale, S. χ^2 testing of optimal filters for gravitational wave signals: An experimental implementation. *Phys. Rev. D* **61**(10), 102001, Apr (2000).

[70] Bonifazi, P., Ferrari, V., Frasca, S., Pallottino, G. V., and Pizzella, G. Data Analysis Algorithms for gravitational wave experiments. *Il Nuovo Cimento* **1C-6**, 465 (1978).

[71] Michelson, P. F. and Taber, R. C. Sensitivity analysis of a resonant mass gravitational wave antenna with resonant transducer. *J. Appl. Phys.* **52**, 4313 (1981).

[72] Vinante, A. and the AURIGA Collaboration. Present performance and future upgrades of the auriga capacitive readout. *Class. Quantum Grav.* **23**(8), S103 (2006).

[73] Degen, C. L., Poggio, M., Mamin, H. J., Rettner, C. T., and Rugar, D. Nanoscale magnetic resonance imaging. *Proceedings of the National Academy of Sciences* **106**(5), 1313–1317 (2009).

[74] Kleckner, D., Pikovski, I., Jeffrey, E., Ament, L., Eliel, E., van den Brink, J., and Bouwmeester, D. Creating and verifying a quantum superposition in a micro-optomechanical system. *New J. Phys.* **10**(9), 095020 (2008).

[75] Mamin, H. J. and Rugar, D. Sub-attonewton force detection at millikelvin temperatures. *Appl. Phys. Lett.* **79**(20), 3358–3360 (2001).

[76] Stipe, B. C., Mamin, H. J., Stowe, T. D., Kenny, T. W., and Rugar, D. Noncontact friction and force fluctuations between closely spaced bodies. *Phys. Rev. Lett.* **87**(9), 096801, Aug (2001).

[77] Kuehn, S., Loring, R. F., and Marohn, J. A. Dielectric fluctuations and the origins of noncontact friction. *Phys. Rev. Lett.* **96**(15), 156103 (2006).

[78] Kuehn, S., Marohn, J. A., and Loring, R. F. Noncontact dielectric friction. *J. Phys. Chem. B* **110**(30), 14525–14528 (2006).

[79] LaHaye, M. D., Buu, O., Camarota, B., and Schwab, K. C. Approaching the quantum limit of a nanomechanical resonator. *Science* **304**(5667), 74–77 (2004).

[80] Regal, C. A., Teufel, J. D., and Lehnert, K. W. Measuring nanomechanical motion with a microwave cavity interferometer. *Nat. Phys.* **4**(7), 555–560, July (2008).

[81] Teufel, J., Donner, T., Castellanos-Beltran, M., Harlow, J., and Lehnert, K. Nanomechanical motion measured with an imprecision below that at the standard quantum limit. *Nat. Nanotechnol.* **4**(12), 820–823 (2009).

[82] Rocheleau, T., Ndukum, T., Macklin, C., Hertzberg, J., Clerk, A., and Schwab, K. Preparation and detection of a mechanical resonator near the ground state of motion. *Nature* **463**(7277), 72–75 (2009).

[83] Poggio, M., Jura, M., Degen, C., Topinka, M., Mamin, H., Goldhaber-Gordon, D., and Rugar, D. An off-board quantum point contact as a sensitive detector of cantilever motion. *Nat. Phys.* **4**(8), 635–638 (2008).

[84] Ciobanu, L., Seeber, D. A., and Pennington, C. H. 3d mr microscopy with resolution 3.7 μm by 3.3 μm by 3.3 μm. *Journal of Magnetic Resonance* **158**(1-2), 178 – 182 (2002).

[85] Tyszka, J. M., Fraser, S. E., and Jacobs, R. E. Magnetic resonance microscopy: recent advances and applications. *Curr. Opin. Biotech.* **16**(1), 93 – 99 (2005). Analytical biotechnology.

[86] Blank, A., Suhovoy, E., Halevy, R., Shtirberg, L., and Harneit, W. Esr imaging in solid phase down to sub-micron resolution: methodology and applications. *Phys. Chem. Chem. Phys.* **11**, 6689–6699 (2009).

[87] Rugar, D., Budakian, R., Mamin, H. J., and Chui, B. W. Single spin detection by magnetic resonance force microscopy. *Nature* **430**, 329–332, July (2004).

[88] Mamin, H. J., Budakian, R., Chui, B. W., and Rugar, D. Detection and manipulation of statistical polarization in small spin ensembles. *Phys. Rev. Lett.* **91**(20), 207604, Nov (2003).

[89] Gysin, U., Rast, S., Ruff, P., Meyer, E., Lee, D. W., Vettiger, P., and Gerber, C. Temperature dependence of the force sensitivity of silicon cantilevers. *Phys. Rev. B* **69**, 045403, Jan (2004).

[90] Uhlig, K. 3he/4he dilution refrigerator with pulse-tube refrigerator precooling. *Cryogenics* **42**(2), 73 – 77 (2002).

[91] Perisanu, S., Vincent, P., Ayari, A., Choueib, M., Purcell, S., Bechelany, M., and Cornu, D. High q factor for mechanical resonances of batch-fabricated sic nanowires. *Appl. Phys. Lett.* **90**, 043113 (2007).

[92] Chui, B., Hishinuma, Y., Budakian, R., Mamin, H., Kenny, T., and Rugar, D. Mass-loaded cantilevers with suppressed higher-order modes for magnetic resonance force microscopy. In *TRANSDUCERS, Solid-State Sensors, Actuators and Microsystems, 12th International Conference on, 2003*, volume 2, 1120–1123. IEEE, (2003).

[93] Heeres, E., Katan, A., van Es, M., Beker, A., Hesselberth, M., van Der Zalm, D., and Oosterkamp, T. A compact multipurpose nanomanipulator for use inside a scanning electron microscope. *Rev. Sci. Instrum.* **81**, 023704 (2010).

[94] Heemskerk, P. *Cantilever Displacement Detection with a SQUID.* graduation thesis, Universiteit Leiden, unpublished, (2009).

[95] Falferi, P., Bonaldi, M., Cerdonio, M., Mezzena, R., Prodi, G., Vinante, A., and Vitale, S. 10 [h-bar] superconducting quantum interference device amplifier for acoustic gravitational wave detectors. *Appl. Phys. Lett.* **93**(17), 172506–172506 (2008).

[96] Vijay, R., Devoret, M., and Siddiqi, I. Invited review article: The josephson bifurcation amplifier. *Rev. Sci. Instrum.* **80**, 111101 (2009).

[97] Nichol, J., Hemesath, E., Lauhon, L., and Budakian, R. Displacement detection of silicon nanowires by polarization-enhanced fiber-optic interferometry. *Appl. Phys. Lett.* **93**(19), 193110–193110 (2008).

[98] Schinkelshoek, L. graduation thesis, Universiteit Leiden, unpublished, (2011).

[99] Vinante, A., Wijts, G., Schinkelshoek, L., Usenko, O., and Oosterkamp, T. Magnetic resonance force microscopy of paramagnetic electron spins at millikelvin-temperatures. *Nat. Commun.* **2**, 572– (2011).