The Advanced Virgo+ status

Journal of Physics: Conference Series **2429** (2023) 012039 doi:10.1088/1742-6596/2429/1/012039

The Advanced Virgo+ status

F Acernese[1,2], M Agathos[3], A Ain[4], S Albanesi[5,6], C Alléné[7], A Allocca[8,2], A Amato[9,10], M Andia[11], T Andrade[12], N Andres[7], M Andrés-Carcasona[13], T Andrić[14], S Ansoldi[15,16], S Antier[17], T Apostolatos[18], E Z Appavuravther[19,20], M Arène[21], N Arnaud[11,22], M Assiduo[23,24], S Assis de Souza Melo[22], P Astone[25], F Aubin[24], S Babak[21], F Badaracco[26], S Bagnasco[6], J Baird[21], T Baka[27], G Ballardin[22], G Baltus[28], B Banerjee[14], P Barneo[12,29], F Barone[30,2], M Barsuglia[21], D Barta[31], A Basti[32,4], M Bawaj[33,19], M Bazzan[34,35], F Beirnaert[36], M Bejger[37], V Benedetto[38], M Berbel[39], S Bernuzzi[3], D Bersanetti[40], A Bertolini[10], U Bhardwaj[41,10], A Bianchi[10,42], M Bilicki[43], S Bini[44,45], M Bischi[23,24], M Bitossi[22,4], M-A Bizouard[17], F Bobba[46,47], M Boër[17], G Bogaert[17], G . Boileau[48,17], M Boldrini[49,25], L D Bonavena[34], R Bondarescu[12], F Bondu[50], R Bonnand[7], V Boschi[4], V Boudart[28], Y Bouffanais[34,35], A Bozzi[22], C Bradaschia[4], M Braglia[51], M Branchesi[14,52], M Breschi[3], T Briant[53], A Brillet[17], J Brooks[22], G Bruno[26], F Bucci[24], O Bulashenko[12,29], T Bulik[54], H J Bulten[10], R Buscicchio[55,56], D Buskulic[7], C Buy[57], G Cabras[15,16], R Cabrita[26], G Cagnoli[58], E Calloni[8,2], M Canepa[59,40], G Caneva[13], M Cannavacciuolo[46], E Capocasa[21], G Carapella[46,47], F Carbognani[22], M Carpinelli[55,60,22], G Carullo[32,4], J Casanueva Diaz[22], C Casentini[61,62], S Caudill[10,27], R Cavalieri[22], G Cella[4], P Cerdá-Durán[63], E Cesarini[62], W Chaibi[17], P Chanial[22,21], E Chassande-Mottin[21], S Chaty[21], P Chessa[32,4], F Chiadini[64,47], G Chiarini[35], R Chierici[65], A Chincarini[40], M L Chiofalo[32,4], A Chiummo[22], N Christensen[17], G Ciani[34,35], P Ciecielag[37], M Cieślar[37], M Cifaldi[61,62], R Ciolfi[66,35], S Clesse[67], F Cleva[17], E Coccia[14,52], E Codazzo[14], P-F Cohadon[53], A Colombo[55,56], M Colpi[55,56], L Conti[35], I Cordero-Carrión[68], S Corezzi[33,19], S Cortese[22], J-P Coulon[17], J-F Coupechoux[65], M Croquette[53], J R Cudell[28], E Cuoco[22,69,4], M Curyło[54], P Dabadie[58], T Dal Canton[11], S Dall'Osso[25], G Dálya[36], B D'Angelo[59,40], S Danilishin[9,10], S D'Antonio[62], V Dattilo[22], M Davier[11], J Degallaix[73], M De Laurentis[8,2], S Deléglise[53], F De Lillo[26], D Dell'Aquila[70,60], W Del Pozzo[32,4], F De Matteis[61,62], A Depasse[26], R De Pietri[71,72], R De Rosa[8,2], C De Rossi[22], R De Simone[64], L Di Fiore[2], C Di Giorgio[46,47], F Di Giovanni[63], M Di Giovanni[14], T Di Girolamo[8,2], D Diksha[10,9], A Di Lieto[32,4], A Di Michele[33], S Di Pace[49,25], I Di Palma[49,25], F Di Renzo[22,4],

L D'Onofrio[8,2], T Dooney[27], O Dorosh[74], M Drago[49,25], J-G Ducoin[75,21], U Dupletsa[14], O Durante[46,47], D D'Urso[70,60], P-A Duverne[11], L Errico[8,2], D Estevez[76], F Fabrizi[23,24], F Faedi[24], V Fafone[61,62,14], G Favaro[34], M Fays[28], E Fenyvesi[31,77], I Ferrante[32,4], F Fidecaro[32,4], P Figura[54], A Fiori[4,32], I Fiori[22], R Fittipaldi[78,47], V Fiumara[79,47], R Flaminio[7,80], J A Font[63,81], S Frasca[49,25], F Frasconi[4], A Freise[10,42], O Freitas[82], G G Fronzé[6], B Gadre[27], R Gamba[3], B Garaventa[40,59], J Garcia-Bellido[51], J Gargiulo [22], F Garufi[8,2], C Gasbarra[61,62], G Gemme[40], A Gennai[4], Archisman Ghosh[36], L Giacoppo[49,25], P Giri[4,32], F Gissi[38], S Gkaitatzis[22], F Glotin[11], B Goncharov[14], M Gosselin[22], R Gouaty[7], A Grado[83,2], M Granata[73], V Granata[46], G Greco[19], G Grignani[33,19], A Grimaldi[44,45], D Guerra[63], D Guetta[25], G M Guidi[23,24], F Gulminelli[84,85], Y Guo[10], P Gupta[10,27], N Gutierrez[73], L Haegel[21], O Halim[16], O Hannuksela[27,10], T Harder[17], K Haris[10,27], T Harmark[86], J Harms[14,52], B Haskell[37], A Heidmann[53], H Heitmann[17], P Hello[11], G Hemming[22], E Hennes[10], J-S Hennig[9,10], M Hennig[9,10], S Hild[9,10], D Hofman[73], N A Holland[10,42], V Hui[7], G A Iandolo[9], B Idzkowski[54], A Iess[69,4], G Iorio[34], P Iosif[87], T Jacqmin[53], P-E Jacquet[53], J Janquart[27,10], K Janssens[48,17], S Jaraba[51], P Jaranowski[88], P Jasal[12], V Juste[76], C Kalaghatgi[27,10,89], C Karathanasis[13], S Katsanevas[22], F Kéfélian[17], G Koekoek[10,9], S Koley[14], M Kolstein[13], S L Kranzhoff[9,10], A Królak[90,74], P Kuijer[10], S Kuroyanagi[51], P Lagabbe[7], D Laghi[57], M Lalleman[48], A Lamberts[17,91], A La Rana[25], I La Rosa[7], A Lartaux-Vollard[11], C Lazzaro[34,35], P Leaci[49,25], A Lemaître[92], M Lenti[24,93], E Leonova[41], N Leroy[11], N Letendre[7], M Lethuillier[65], K Leyde[21], F Linde[89,10], L London[41], A Longo[94], M Lopez Portilla[27], M Lorenzini[61,62], V Loriette[95], G Losurdo[4], D Lumaca[61,62], A Macquet[13,17], C Magazzù[4], R Maggiore[10,42], M Magnozzi[40,59], E Majorana[49,25], N Man[17], V Mangano[49,25], M Mantovani[22], M Mapelli[34,35], F Marchesoni[20,19,96], D Marín Pina[12,29,97], F Marion[7], A Marquina[68], S Marsat[57], F Martelli[23,24], M Martinez[13], V Martinez[58], A Masserot[7], M Mastrodicasa[25], S Mastrogiovanni[17], Q Meijer[27], A Menendez-Vazquez[13], L Mereni[73], M Merzougui[17], A Miani[44,45], C Michel[73], A Miller[26], B Miller[41,10], E Milotti[98,16], Y Minenkov[62], Ll. M Mir[13], M Miravet-Tenés[63], A L Mitchell[10,42], C Mondal[84], M Montani[23,24], F Morawski[37], G Morras[51], B Mours[76], C M Mow-Lowry[10,42], F Muciaccia[49,25], Suvodip Mukherjee[41], A Nagar[6,99], V Napolano[22], I Nardecchia[61,62], H Narola[27], L Naticchioni[25], J Neilson[38,47], S Nesseris[51], C Nguyen[21], G Nieradka[37], S Nissanke[41,10], E Nitoglia[65], F Nocera[22], J Novak[100,101,102,103], J F Nuño Siles[51], M Oertel[100,101,102,104,103], G Oganesyan[14,52], R Oliveri[100,101,102], M Orselli[19,33], C Palomba[25], P T H Pang[10,27], F Pannarale[49,25], F Paoletti[4], A Paoli[22], A Paolone[25,105], G Pappas[87], A Parisi[4,69], D Pascucci[36], A Pasqualetti[22], R Passaquieti[32,4], D Passuello[4], B Patricelli[32,4], R Pedurand[47], R Pegna[4,32], M Pegoraro[35], A Perego[44,45], A Pereira[58], C Périgois[66], A Perreca[44,45], S Perriès[65],

J W Perry[10,42], D Pesios[87], C Petrillo[33], K S Phukon[10,89], O J Piccinni[25,13], M Pichot[17], M Piendibene[32,4], F Piergiovanni[23,24], L Pierini[49,25], G Pierra[65], V Pierro[38,47], G Pillant[22], M Pillas[11], F Pilo[4], L Pinard[73], I M Pinto[38,47,106,8], M Pinto[22], K Piotrzkowski[26], A Placidi[19,33], E Placidi[49,25], W Plastino[107,94], R Poggiani[32,4], E Polini[7], E Porcelli[10], J Portell[12,29,97], E K Porter[21], R Poulton[22], M Pracchia[7], T Pradier[76], M Principe[38,106,47], G A Prodi[108,45], P Prosposito[61,62], A Puecher[10,27], M Punturo[19], F Puosi[4,32], P Puppo[25], G Raaijmakers[41,10], N Radulesco[17], P Rapagnani[49,25], M Razzano[32,4], T Regimbau[7], L Rei[40], P Rettegno[5,6], B Revenu[21,109], A Reza[10], A S Rezaei[25,49], F Ricci[49,25], S Rinaldi[32,4], F Robinet[11], A Rocchi[62], L Rolland[7], M Romanelli[50], R Romano[1,2], A Romero[13], S Ronchini[14,52], L Rosa[2,8], D Rosińska[54], S Roy[27], D Rozza[70,60], P Ruggi[22], E Ruiz Morales[51], P Saffarieh[10,42], O S Salafia[55,56,110], L Salconi[22], F Salemi[44,45], M Sallé[10], A Samajdar[56], N Sanchis-Gual[111,63], A Sanuy[12], A Sasli[87], P Sassi[19,33], B Sassolas[73], S Sayah[73], S Schmidt[27], M Seglar-Arroyo[7], D Sentenac[22], V Sequino[8,2], G Servignat[101], Y Setyawati[27], N S Shcheblanov[112,92], M Sieniawska[26], L Silenzi[19,20], N Singh[54], A Singha[9,10], V Sipala[70,60], J Soldateschi[93,113,24], V Sordini[65], F Sorrentino[40], N Sorrentino[32,4], R Soulard[17], V Spagnuolo[9,10], M Spera[34,35], P Spinicelli[22], C Stachie[17], D A Steer[21], J Steinlechner[9,10], S Steinlechner[9,10], N Stergioulas[87], G Stratta[114,25], M Suchenek[37], A Sur[37], J Suresh[26], B L Swinkels[10], A Syx[76], P Szewczyk[54], M Tacca[10], N Tamanini[57], A J Tanasijczuk[26], E N Tapia San Martín[10], C Taranto[61], M Tonelli[32,4], A Torres-Forné[63], I Tosta e Melo[60], E Tournefier[7], A Trapananti[20,19], F Travasso[20,19], J Trenado[12], M C Tringali[22], L Troiano[115,47], A Trovato[16,98], L Trozzo[2], K W Tsang[10,116,27], K Turbang[117,48], M Turconi[17], C Turski[36], H Ubach[12,29], A Utina[9,10], M Valentini[44,45], S Vallero[6], N van Bakel[10], M van Beuzekom[10], M van Dael[10,118], J F J van den Brand[9,42,10], C Van Den Broeck[27,10], M van der Sluys[10,27], A Van de Walle[11], J van Dongen[10,42], H van Haevermaet[48], J V van Heijningen[26], Z van Ranst[9], N van Remortel[48], M Vardaro[89,10], M Vasúth[31], G Vedovato[35], P Verdier[65], D Verkindt[7], P Verma[74], F Vetrano[23], A Viceré[23,24], J-Y Vinet[17], S Viret[65], A Virtuoso[98,16], H Vocca[33,19], R C Walet[10], M Was[7], N Yadav[37], A Zadrożny[74], T Zelenova[22], and J-P Zendri[35]

[1]Dipartimento di Farmacia, Università di Salerno, I-84084 Fisciano, Salerno, Italy
[2]INFN, Sezione di Napoli, I-80126 Napoli, Italy
[3]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
[4]INFN, Sezione di Pisa, I-56127 Pisa, Italy
[5]Dipartimento di Fisica, Università degli Studi di Torino, I-10125 Torino, Italy
[6]INFN Sezione di Torino, I-10125 Torino, Italy
[7]Univ. Savoie Mont Blanc, CNRS, Laboratoire d'Annecy de Physique des Particules - IN2P3, F-74000 Annecy, France
[8]Università di Napoli "Federico II", I-80126 Napoli, Italy
[9]Maastricht University, 6200 MD Maastricht, Netherlands
[10]Nikhef, 1098 XG Amsterdam, Netherlands

[11]Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France
[12]Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès, 1, 08028 Barcelona, Spain
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, and ICREA, E-08193 Barcelona, Spain
[14]Gran Sasso Science Institute (GSSI), I-67100 L'Aquila, Italy
[15]Dipartimento di Scienze Matematiche, Informatiche e Fisiche, Università di Udine, I-33100 Udine, Italy
[16]INFN, Sezione di Trieste, I-34127 Trieste, Italy
[17]Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Artemis, F-06304 Nice, France
[18]Department of Physics, National and Kapodistrian University of Athens, 15771 Ilissia, Greece
[19]INFN, Sezione di Perugia, I-06123 Perugia, Italy
[20]Università di Camerino, I-62032 Camerino, Italy
[21]Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[22]European Gravitational Observatory (EGO), I-56021 Cascina, Pisa, Italy
[23]Università degli Studi di Urbino "Carlo Bo", I-61029 Urbino, Italy
[24]INFN, Sezione di Firenze, I-50019 Sesto Fiorentino, Firenze, Italy
[25]INFN, Sezione di Roma, I-00185 Roma, Italy
[26]Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[27]Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University, 3584 CC Utrecht, Netherlands
[28]Université de Liège, B-4000 Liège, Belgium
[29]Departament de Física Quàntica i Astrofísica (FQA), Universitat de Barcelona (UB), c. Martí i Franqués, 1, 08028 Barcelona, Spain
[30]Dipartimento di Medicina, Chirurgia e Odontoiatria "Scuola Medica Salernitana", Università di Salerno, I-84081 Baronissi, Salerno, Italy
[31]Wigner RCP, RMKI, H-1121 Budapest, Hungary
[32]Università di Pisa, I-56127 Pisa, Italy
[33]Università di Perugia, I-06123 Perugia, Italy
[34]Università di Padova, Dipartimento di Fisica e Astronomia, I-35131 Padova, Italy
[35]INFN, Sezione di Padova, I-35131 Padova, Italy
[36]Universiteit Gent, B-9000 Gent, Belgium
[37]Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, 00-716, Warsaw, Poland
[38]Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
[39]Departamento de Matemáticas, Universitat Autònoma de Barcelona, 08193 Bellaterra (Barcelona), Spain
[40]INFN, Sezione di Genova, I-16146 Genova, Italy
[41]GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands
[42]Department of Physics and Astronomy, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, Netherlands
[43]Center for Theoretical Physics, Polish Academy of Sciences, 02-668, Warsaw, Poland
[44]Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
[45]INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
[46]Dipartimento di Fisica "E.R. Caianiello", Università di Salerno, I-84084 Fisciano, Salerno, Italy
[47]INFN, Sezione di Napoli, Gruppo Collegato di Salerno, I-80126 Napoli, Italy
[48]Universiteit Antwerpen, 2000 Antwerpen, Belgium
[49]Università di Roma "La Sapienza", I-00185 Roma, Italy
[50]Univ Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France
[51]Instituto de Fisica Teorica UAM-CSIC, Universidad Autonoma de Madrid, 28049 Madrid, Spain
[52]INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
[53]Laboratoire Kastler Brossel, Sorbonne Université, CNRS, ENS-Université PSL, Collège de France, F-75005 Paris, France
[54]Astronomical Observatory Warsaw University, 00-478 Warsaw, Poland

[55]Università degli Studi di Milano-Bicocca, I-20126 Milano, Italy
[56]INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
[57]L2IT, Laboratoire des 2 Infinis - Toulouse, Université de Toulouse, CNRS/IN2P3, UPS, F-31062 Toulouse Cedex 9, France
[58]Université de Lyon, Université Claude Bernard Lyon 1, CNRS, Institut Lumière Matière, F-69622 Villeurbanne, France
[59]Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
[60]INFN, Laboratori Nazionali del Sud, I-95125 Catania, Italy
[61]Università di Roma Tor Vergata, I-00133 Roma, Italy
[62]INFN, Sezione di Roma Tor Vergata, I-00133 Roma, Italy
[63]Departamento de Astronomía y Astrofísica, Universitat de València, E-46100 Burjassot, València, Spain
[64]Dipartimento di Ingegneria Industriale (DIIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
[65]Université Lyon, Université Claude Bernard Lyon 1, CNRS, IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
[66]INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
[67]Université libre de Bruxelles, 1050 Bruxelles, Belgium
[68]Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
[69]Scuola Normale Superiore, I-56126 Pisa, Italy
[70]Università degli Studi di Sassari, I-07100 Sassari, Italy
[71]Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
[72]INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
[73]Université Lyon, Université Claude Bernard Lyon 1, CNRS, Laboratoire des Matériaux Avancés (LMA), IP2I Lyon / IN2P3, UMR 5822, F-69622 Villeurbanne, France
[74]National Center for Nuclear Research, 05-400 Świerk-Otwock, Poland
[75]Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 75014 Paris, France
[76]Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[77]Institute for Nuclear Research, H-4026 Debrecen, Hungary
[78]CNR-SPIN, I-84084 Fisciano, Salerno, Italy
[79]Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
[80]Gravitational Wave Science Project, National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan
[81]Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
[82]Centro de Física das Universidades do Minho e do Porto, Universidade do Minho, PT-4710-057 Braga, Portugal
[83]INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
[84]Université de Normandie, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen, F-14000 Caen, France
[85]Laboratoire de Physique Corpusculaire Caen, 6 boulevard du maréchal Juin, F-14050 Caen, France
[86]Niels Bohr Institute, Copenhagen University, 2100 København, Denmark
[87]Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
[88]University of Białystok, 15-424 Białystok, Poland
[89]Institute for High-Energy Physics, University of Amsterdam, 1098 XH Amsterdam, Netherlands
[90]Institute of Mathematics, Polish Academy of Sciences, 00656 Warsaw, Poland
[91]Université Côte d'Azur, Observatoire Côte d'Azur, CNRS, Lagrange, F-06304 Nice, France
[92]NAVIER, École des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France
[93]Università di Firenze, Sesto Fiorentino I-50019, Italy
[94]INFN, Sezione di Roma Tre, I-00146 Roma, Italy
[95]ESPCI, CNRS, F-75005 Paris, France
[96]School of Physics Science and Engineering, Tongji University, Shanghai 200092, China
[97]Institut d'Estudis Espacials de Catalunya, c. Gran Capità, 2-4, 08034 Barcelona, Spain
[98]Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy
[99]Institut des Hautes Etudes Scientifiques, F-91440 Bures-sur-Yvette, France
[100]Centre national de la recherche scientifique, 75016 Paris, France

[101]Laboratoire Univers et Théories, Observatoire de Paris, 92190 Meudon, France
[102]Observatoire de Paris, 75014 Paris, France
[103]Université PSL, 75006 Paris, France
[104]Université de Paris, 75006 Paris, France
[105]Consiglio Nazionale delle Ricerche - Istituto dei Sistemi Complessi, I-00185 Roma, Italy
[106]Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", I-00184 Roma, Italy
[107]Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, I-00146 Roma, Italy
[108]Università di Trento, Dipartimento di Matematica, I-38123 Povo, Trento, Italy
[109]Subatech, CNRS/IN2P3 - Institut Mines-Telecom Atlantique - Université de Nantes, 4 rue Alfred Kastler BP 20722 44307 Nantes C'EDEX 03, France
[110]INAF, Osservatorio Astronomico di Brera sede di Merate, I-23807 Merate, Lecco, Italy
[111]Departamento de Matemática da Universidade de Aveiro and Centre for Research and Development in Mathematics and Applications, 3810-183 Aveiro, Portugal
[112]Laboratoire MSME, Cité Descartes, 5 Boulevard Descartes, Champs-sur-Marne, 77454 Marne-la-Vallée Cedex 2, France
[113]INAF, Osservatorio Astrofisico di Arcetri, I-50125 Firenze, Italy
[114]Istituto di Astrofisica e Planetologia Spaziali di Roma, 00133 Roma, Italy
[115]Dipartimento di Scienze Aziendali - Management and Innovation Systems (DISA-MIS), Università di Salerno, I-84084 Fisciano, Salerno, Italy
[116]Van Swinderen Institute for Particle Physics and Gravity, University of Groningen, 9747 AG Groningen, Netherlands
[117]Vrije Universiteit Brussel, 1050 Brussel, Belgium
[118]Eindhoven University of Technology, 5600 MB Eindhoven, Netherlands

E-mail: maddalena.mantovani@ego-gw.it

Abstract.
The gravitational wave detector Advanced Virgo+ is currently in the commissioning phase in view of the fourth Observing Run (O4).
The major upgrades with respect to the Advanced Virgo configuration are the implementation of an additional recycling cavity, the Signal Recycling cavity (SRC), at the output of the interferometer to broaden the sensitivity band and the Frequency Dependent Squeezing (FDS) to reduce quantum noise at all frequencies.
The main difference of the Advanced Virgo + detector with respect to the LIGO detectors is the presence of marginally stable recycling cavities, with respect to the stable recycling cavities present in the LIGO detectors, which increases the difficulties in controlling the interferometer in presence of defects (both thermal and cold defects).
This work will focus on the interferometer commissioning, highlighting the control challenges to maintain the detector in the working point which maximizes the sensitivity and the duty cycle for scientific data taking.

1. Introduction
The Advanced Virgo detector is a long scale enhanced Michelson interferometer located in Italy, close to Pisa, with the aim of detecting gravitational waves from astronomical sources. The Advanced Virgo interferometer has detected, together with the LIGO interferometers located in the USA [1], an impressive collection of gravitational wave emissions in the last observation runs O2 and O3.
Indeed, during the O2 observation run, just after the joining of the Advanced Virgo detector to the gravitational wave network, the first triple coincidence was observed (GW170817,[2]). During the last observation run (O3), which lasted about one year of data taking from April 2019 to March 2020, about 80 gravitational waves were detected.
After the O3 observation run the Advanced Virgo detector has been upgraded to the Advanced Virgo+ configuration to further improve the sensitivity and join the foreseen O4 run, together

with the LIGO and Kagra detectors, which will start in March 2023.
The major upgrades with respect to the Advanced Virgo detector are:

- Increase of the input power
- Implementation of the Frequency Dependent Squeezing (FDS)
- Addition of the Signal Recycling cavity (SRC).

All the aforementioned upgrades are meant to improve the detector sensitivity, but lead to an increase of complexity in the commissioning of the detector.
The increase of input power will improve the quantum noise at high frequency (shot-noise), but it will also lead to an increase of thermal aberration and radiation pressure effects. The implementation of the FDS will improve the broad-band sensitivity but it requires the installation and commissioning of a completely new hardware system [3]. The addition of the SRC will enhance the detector response to the gravitational wave signal. However it will require to control an additional degree of freedom (both in the longitudinal and angular directions) forcing to completely re-design the lock acquisition scheme and the steady state control scheme. The paper will focus on the commissioning of the Advanced Virgo+ detector upgrades, while the status of the FDS will be detailed in [4].

2. Advanced Virgo+ upgrades

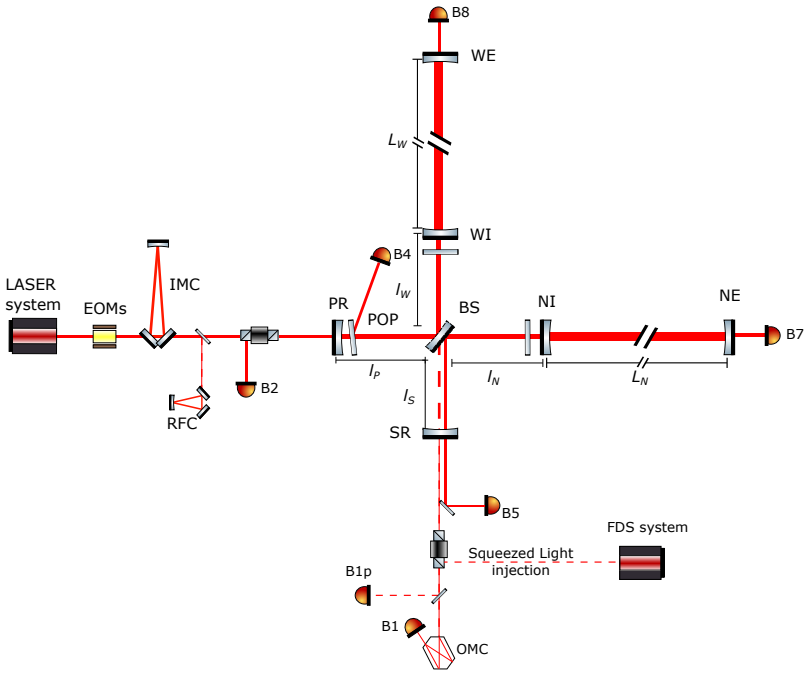

Figure 1. Optical scheme of Advanced Virgo+ in which the main optical components are shown and the main output ports are detailed (B_{XX}). Moreover the Injection system, including the Input Mode Cleaner cavity (IMC) is shown, as well as the Detection system, including the Output Mode Cleaner cavity (OMC). Moreover the FDS system injection point is shown.

The Advanced Virgo+ detector scheme is shown in Figure 1. The input beam is generated by a system of master/slave lasers with a current output power of 33 W after having passed through a 144 m long triangular cavity (Input Mode cleaner, IMC). The main beam is split at the beam splitter mirror (BS) into two beams which are injected into the two orthogonal

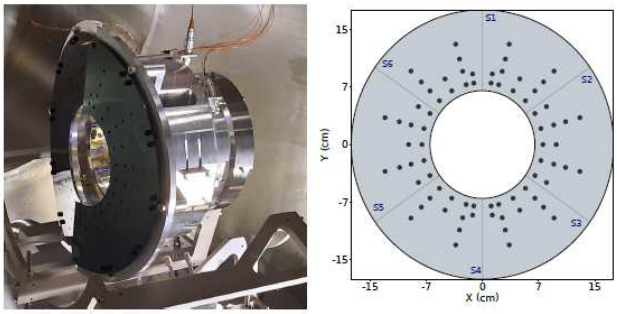

Figure 2. *left* Picture of the instrumented baffle installed in front of MC mirror. *right* Scheme of the embedded diodes on the baffle.

Figure 3. View of the filter cavity for the Frequency Dependent Squeezing.

Fabry-Perot arm cavities (North and West arms), to enhance the phase shift produced by the optical path length variation of the beam caused by a gravitational wave.
The power circulating is enhanced by the Power Recycling, while the SR cavity enhances the response of the detector versus the gravitational wave signal (detected on the dark port B1, see Figure 1). The installation of Advanced Virgo+ has been successfully completed in December 2020.

The major upgrades are the improvement of the injection system, the installation of the Frequency Dependent Squeezing (FDS) and the installation of the SR mirror at the output of the interferometer.
The injection system has been upgraded in order to allow an injected power to the interferometer of 40 W maximum (as a reference the injected power in O3 was 23 W). Moreover the MC mirror payload mechanics has been modified in order to fix controllability issues in the pitch direction, and stray light monitoring has been implemented using a baffle with embedded sensors, see Figure 2 [5].
The baseline design of AdV + involves injecting a Frequency-Dependent Squeezed vacuum field (FDS) in the interferometer (ITF) anti-symmetric port. This should lead to a decrease in the quantum noise contribution over the entire detection bandwidth. The selected method to realize FDS [6] is by exploiting the dispersion in reflection of a frequency independent squeezed (FIS) beam [7] by a detuned 285 meters long filter cavity (FC). The installation of the filter cavity including the 5 additional optical benches (two of which are suspended and operating in vacuum) used for the FC control and FDS injection [8] was completed in March 2021. Afterwards the commissioning phase of the FDS source started. Currently the rotation of the squeezing ellipse at about 20 Hz has been demonstrated with a FC lock accuracy down to 1 Hz and a level of round trip losses lower than 31 ppm in the best condition. These values together with the estimate of the optical propagation losses of 5-6 % and the squeezing ellipse angular jitter of 20 mrad are compliant with the first phase of the project. The second phase of the project, the injection of FDS into the interferometer, has just begun. The FDS cavity external view is shown in Figure 3.
Last but not least, the SR mirror has been added at the dark port of the interferometer. This upgrade is the one that improves the most the target sensitivity but also the one that requires the largest commissioning time since it strongly modifies the optomechanical response of the detector.

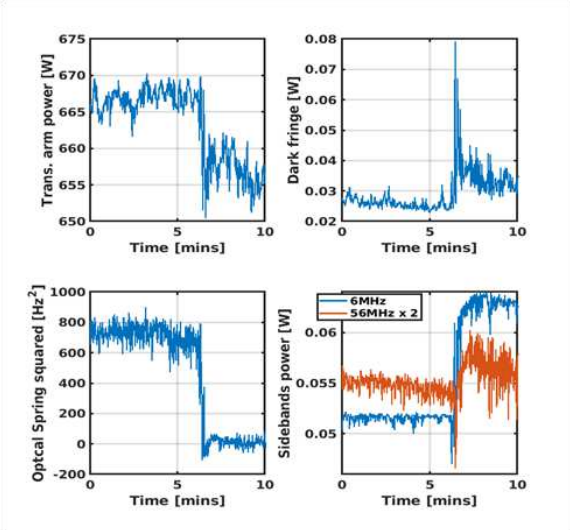

Figure 4. Example of sudden change of state in the detector working point. The change of state is visible in the powers detected in the various ports of the detectors.

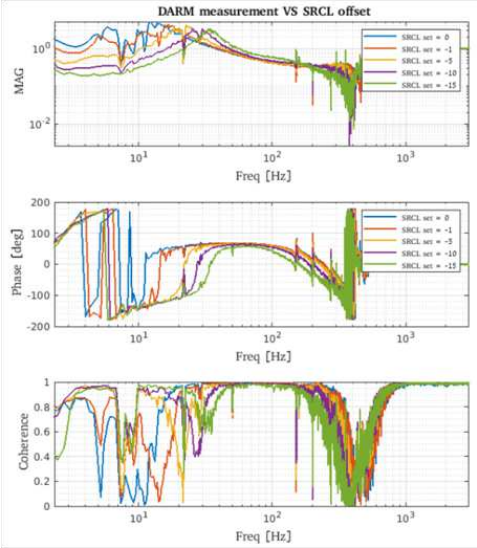

Figure 5. Example of detector response with respect to the SRC working point. It is visible that the structure at low frequency is largely changing the frequency of the peak from 15 Hz to 40 Hz, creating control instabilities.

3. Advanced Virgo+ commissioning phase

After the installation phase, the commissioning of the detector has started in January 2020. As already mentioned, the main part of the commissioning has been devoted to the control of the new optical configuration, including the process which brings the main optical components from the un-controlled state to the precise microscopic positions, called lock acquisition. The set of precise microscopic positions, called working point, is chosen in order to fulfill the resonance conditions of the optical cavities to provide the best sensitivity of the detector.

The control is done based on the Pound-Drever-Hall technique [9], for longitudinal control, and on the Ward technique [10], for the angular control, by adding phase modulations to the main beam (carrier). The phase modulations at 6.27 MHz, 56.44 MHz and 8.36 MHz are realized using Electro-Optic Modulators (EOMs, see Figure 1). The resonance conditions for the modulation sidebands and the Carrier fields, which define the longitudinal working point, are:

- Carrier resonant in the long arm cavities and in the PRC
- 8 MHz sidebands not resonant in any cavity
- 6 MHz sidebands resonant in the PR cavity
- 56 MHz sidebands resonant in the PR and SR cavities

Moreover the differential short Michelson degree of freedom (called MICH, equivalent to $l_n - l_w$) has to be kept in destructive interference.
Due to the addition of the SRC the lock acquisition has been strongly changed with respect to the one developed and implemented for the Advanced Virgo detector [11]. The lock acquisition strategy is generally based on the principle of controlling at first simple configurations and then increase the complexity of the system in semi-adiabatic steps. The lock acquisition developed

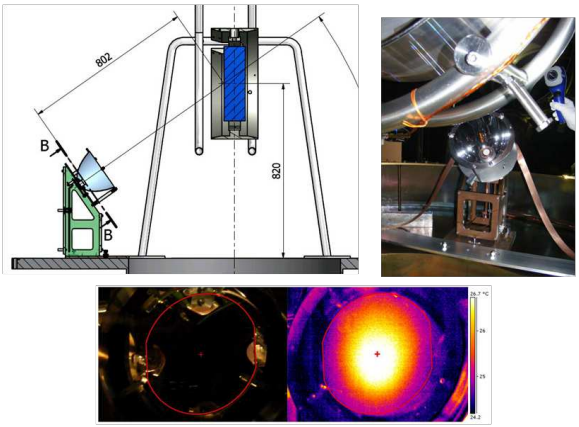

Figure 6. **top left** Technical drawing of the CHRoCC installation. **top right** Picture of the CHRoCC installed in the PR tower **bottom** Picture of the heating profile using, on the right, a thermal camera.

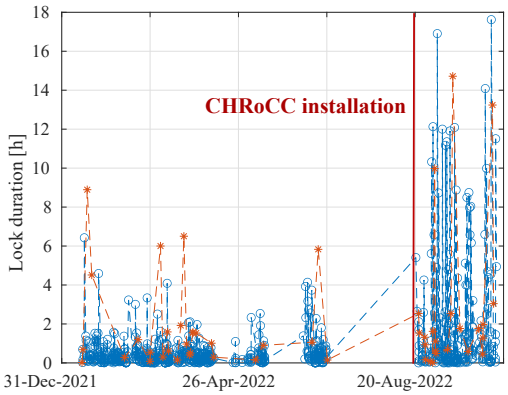

Figure 7. Distribution of the lock duration in hours since the beginning of the commissioning of the detector in the final working point (the red starred locks are the one manually ended). The red line show the start of the locking activities after the installation and pre-commissioning of the CHRoCC.

in Advanced Virgo+ is based on the lock procedure implemented in LIGO which implies the use of auxiliary lasers to disentangle the long arm degrees of freedom from the central area ones, [12] [13] [14] [15].
The first lock at the final working point, described above, with an input power of 33 W has been achieved on December 2021, but the lock showed strong instabilities and un-expected modifications in the detector response. An example of instability is shown in Figure 4, where is visible a sudden change of state in the longitudinal working point which causes lock loss, the so called *jumps*. The other un-expected effect is the strong modification in the opto-mechanical response of the detector. Figure 5 shows an example of the detector response versus the longitudinal position of the SR cavity (SRC set point).
These observations led to strong efforts in simulation studies to understand the origin of the instabilities. The outcomes of the studies proved that a possible cause of the issues was linked to aberrations in the optical configurations. It has to be noted that similar effects have been observed also in LIGO, but with a much lower impact [16]. This can be linked to the fact that Advanced Virgo+, in contrast to the LIGO design, has marginally stable recycling cavities.
The stability of a cavity is a very important characteristic, which depends only on the cavity geometry, and it determines the capability of a cavity to clean and suppress the transverse modes (High Order Modes [17]) generated by optical aberrations. This means that the Advanced Virgo+ detector is much more affected by cold and thermal aberrations with respect to the LIGO detector.
The most affecting parameter has been found to be the PR mirror radius of curvature (RoC) [18], and indeed in the initial optical configuration we had a PR RoC mistuned by 40m (it was pre-tuned to be compliant the thermal configuration of the PRC in case of 125 W of input power) making the PRC unstable. Unfortunately the actuator that was meant to tune the RoC could not be used due to installation problems. This issue has been overcome by adding an additional thermal actuator, called CHRoCC (Central Heating Radius of Curvature Correction, developed in 2013 for initial Virgo [19]). This actuator, visible in Figure 6, has been installed in July 2022

and its working principle is to shine black body radiation to the pick-off plate (POP) placed in front of the PR mirror, see Figure 1, to create a converging lens and to stabilize the PR cavity [20]. After the installation and the pre-commissioning of the actuator the lock stability has been strongly improved.
Figure 7 shows the lock duration distribution from the start of the final working point commissioning (after the complete lock acquisition has been implemented). Moreover it has to be noted that the lock duration distribution is dominated by un-attended operations during nights, since during day time the commissioning activities affect the locking stability.
After the lock losses issue has been mitigated, currently the detector is in the phase of optimizing of the global working point, which includes the tuning of the angular loops and the thermal actuators, to optimize the detector response and achieve good sensitivity for scientific data taking. This phase consists also in the noise hunting campaign to mitigate the technical noise sources and their couplings to the sensitivity.

4. Conclusions

The Advanced Virgo+ detector has successfully concluded the installation phase in 2021 and it is currently in the commissioning phase. The lock acquisition has been completed in December 2021 and a better lock robustness has been achieved after the installation of the CHRoCC actuator. The Advanced Virgo+ commissioning is now entering in the phase of fine tuning of the global working point and in the sensitivity improvement, through a campaign of reduction of technical noise and their coupling to the gravitational wave signal which is called *noise hunting phase*.

References

[1] Aasi J et al. (LIGO Scientific Collaboration) 2015 Class. Quant. Grav. 32 074001
[2] Abbott B et al. (LIGO Scientific Collaboration, Virgo Collaboration) 2017 Phys. Rev. Lett. 119
[3] Jean-Pierre Zendri, Jean-Francois Cohadon, Fulvio Ricci et al. 'Advanced Virgo Squeezer Technical Design Report' LVK internal note, https://tds.virgo-gw.eu/ql/?c=11140, VIR-0411C-15
[4] The Virgo Collaboration 'Status of Quantum Noise Reduction system in AdV+' proceeding for CRIS 22
[5] O. Ballester,et. al. 'Measurement of the Stray Light in the Advanced Virgo Input Mode Cleaner Cavity using an instrumented baffle' https://tds.virgo-gw.eu/ql/?c=17398, LVC internal note VIR-1149A-21
[6] H.J.Kimble, Y. Levin Y, A.B.Matsko, K.S.Thorne , S.P. Vyatchanin, Phys Rev D 65 022002 (2001)
[7] M Mehmet and H Vahlbruch, Class. Quantum Grav. 36 015014 (2019)
[8] The Virgo Collaboration, 'Advanced Virgo Plus Phase I Design Report', Virgo-Technical Documentation System, Report No. VIR-0596A-19 (2019) https://tds.virgo-gw.eu/ql/?c=14430
[9] Drever, R.W.P.; Hall, J.L.; Kowalski, F.V.; Hough, J.; Ford, G.M.; Munley, A.J.; Ward, H. 'Laser Phase and Frequency Stabilization 510 Using an Optical Resonator'. Applied Physics B 1983, 31, 97–105. https://doi.org/10.1007/BF00702605.
[10] Morrison, E.; Meers, B.J.; Robertson, D.I.; Ward, H. Automatic Alignment of Optical Interferometers. Applied Optics 1994, 33, 5041. https://doi.org/10.1364/AO.33.005041.
[11] F. Acernese, et al., 'The variable finesse locking technique, Class'. Quantum Gravity 23 (2006) S85–S89
[12] De Rossi, C.; Brooks, J.; Casanueva Diaz, J.; Chiummo, A.; Genin, E.; Gosselin, M.; Leroy, N.; Mantovani, M.; Montanari, B.; Nocera, F.; Pillant, G. Development of a Frequency Tunable Green Laser Source for Advanced Virgo+ Gravitational Waves Detector. Galaxies 2020, 8, 87. https://doi.org/10.3390/galaxies8040087
[13] Staley, A.; Martynov, D.; Abbott, R.; Adhikari, R.X.; Arai, K.; Ballmer, S.; Barsotti, L.; Brooks, A.F.; DeRosa, R.T.; Dwyer, S.; et al. 'Achieving Resonance in the Advanced LIGO Gravitational-Wave Interferometer'. Classical and Quantum Gravity 2014, 31, 245010. https://doi.org/10.1088/0264-9381/31/24/245010.
[14] Casanueva Diaz, J.; Leroy, N. 'Auxiliary Laser System: Study of the Lock Acquisition Strategy'. Technical report, Virgo Collaboration, 2019. VIR-0327B-19 https://tds.virgo-gw.eu/ql/?c=14154
[15] D. Bersanetti, M. Boldrini, J. Casanueva Diaz, A. Freise, R. Maggiore, M. Mantovani, M. Valentini 'Simulations for the locking and alignment strategy of the DRMI configuration of the Advanced Virgo+ detector', submitted to Galaxies MPDI

[16] Recording of LIGO-Virgo commissioning meeting, 4 March 2022, https://dcc.ligo.org/G2200312
[17] A.E. Siegman, 'Lasers', University Science Books, Mill Valley, 1986.
[18] A. C. Green, A. Bianchi, D. D. Brown, A. Freise, R. Maggiore, J. Perry, M. Salle 'Finesse 3 modelling to support AdV+ commissioning to O4: Understanding the DARM Spring (September LVK Talk)' VIR-0875A-22 https://tds.virgo-gw.eu/ql/?c=18521
[19] T Accadia et al 2013 Class. Quantum Grav. 30 055017
[20] A.Chiummo, A. Rocchi, S. Melo, C. De Rossi, E. Capocasa, R. Cavalieri, V. Dattilo, F. Gherardini, J. Degallaix, M. Mantovani, M. Tringali, R. Macchia for the CHRoCC team 'TCS: CHRoCC motivation, preparation and commissioning @VW' Virgo internal document VIR-0696A-22 https://tds.virgo-gw.eu/ql/?c=18342