Measurement of the $B^0-\bar{B}^0$ oscillation frequency $\Delta m_d$ with the decays $B^0 \rightarrow D^-\pi^+$ and $B^0 \rightarrow J/\psi K^{*0}$

LHCb Collaboration

1. Introduction

The frequency $\Delta m_d$ of oscillations between $B^0$ mesons and $\bar{B}^0$ mesons also describes the mass difference $\Delta m_d$ between the physical eigenstates in the $B^0-\bar{B}^0$ system, and has been measured at LEP [1], the Tevatron [2,3], and the $B$ factories [4,5]. The current world average is $\Delta m_d = 0.507 \pm 0.004$ ps$^{-1}$ [6], whilst the best single measurement prior to this Letter is by the Belle experiment, $\Delta m_d = 0.511 \pm 0.005$ (stat) $\pm 0.006$ (syst) ps$^{-1}$ [5]. In this document the convention $h = c = 1$ is used for all units.

With increasing accuracy of the measurement of $\Delta m_d$, the counterpart of $\Delta m_d$ in the $B^0-\bar{B}^0$ system [7], a more precise knowledge of $\Delta m_d$ becomes important, as the ratio $\Delta m_d/\Delta m_s$ together with input from lattice QCD calculations [8,9] constrains the apex of the CKM unitarity triangle [10,11]. Therefore, the measurement of $\Delta m_d$ provides an important test of the Standard Model [12,13]. Furthermore, $\Delta m_d$ is an input parameter in the determination of $\sin 2\beta$ at LHCb [14].

This Letter presents a measurement of $\Delta m_d$, using a dataset corresponding to 1.0 fb$^{-1}$ of pp collisions at $\sqrt{s} = 7$ TeV, using the decay channels $B^0 \rightarrow D^-\pi^+$ ($D^- \rightarrow K^+\pi^+\pi^-\pi^0$) and $B^0 \rightarrow J/\psi K^{*0}$ ($J/\psi \rightarrow \mu^+\mu^-$, $K^{*0} \rightarrow K^+\pi^-$) and their charge conjugated modes.

For a measurement of $\Delta m_d$, the flavour of the $B^0$ meson at production and decay must be known. The flavour at decay is determined in both decay channels from the charge of the final state kaon; contributions from suppressed $B^0 \rightarrow D^+\pi^-$ amplitudes are negligible. The determination of the flavour at production is achieved by the flavour tagging algorithms which are described in more detail in Section 4.

The $B^0$ meson is defined as unmixed (mixed) if the production flavour is equal (not equal) to the flavour at decay. With this knowledge, the oscillation frequency $\Delta m_d$ of the $B^0$ meson can be determined using the time dependent mixing asymmetry

$$A_{\text{mix}}(t) = \frac{N_{\text{unmixed}}(t) - N_{\text{mixed}}(t)}{N_{\text{unmixed}}(t) + N_{\text{mixed}}(t)} = \cos(\Delta m_d t),$$

where $t$ is the $B^0$ decay time and $N_{\text{unmixed}}$ is the number of (un)mixed events.

2. Experimental setup and datasets

The LHCb detector [15] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV to 0.6% at 100 GeV, and an impact parameter (IP) resolution of 20 $\mu$m for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photons, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, an electromagnetic calorimeter and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction.

Events including $B^0 \rightarrow D^-\pi^+$ decays are required to have tracks with high transverse momentum $p_T$ to pass the hardware trigger. The software trigger requires a two-, three- or four-track secondary vertex with a large sum of the $p_T$ of the tracks, significant displacement from the associated primary vertex (PV), and at
least one track with $p_T > 1.7$ GeV and a large impact parameter with respect to that PV, and a good track fit. A multivariate algorithm is used for the identification of the secondary vertices [16].

Events in the decay $B^0 \to J/\psi K^{*0}$ are first required to pass a hardware trigger which selects a single muon with $p_T > 1.48$ GeV. In the subsequent software trigger [16], at least one of the final state particles is required to have $p_T > 0.8$ GeV and a large IP with respect to all PVs in the event. Finally, the tracks of two or more of the final state particles are required to form a vertex which is significantly displaced from the PVs in the event.

For the simulation studies, pp collisions are generated using PYTHIA 6.4 [17] with a specific LHCb configuration [18]. Decays of hadronic particles are described by EVTGEN [19] in which final state radiation is generated using PHOTOS [20]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [21,22] as described in Ref. [23].

3. Selection

The decay time $t$ of a $B^0$ candidate is evaluated from the measured momenta and from a vertex fit that constrains the $B^0$ candidate to originate from the associated PV [24], and using $t = \ell \cdot m(B^0)/p$, with the flight distance $\ell$. The associated PV is the primary vertex that is closest to the decaying $B^0$ meson. No mass constraints on the intermediate resonances are applied. For the calculation of the invariant mass $m$, no mass constraints are applied in the $B^0 \to D^- \pi^+$ channel, while the $J/\psi$ mass is constrained to the world average [6] in the analysis of the decay $B^0 \to J/\psi K^{*0}$.

All kaons, pions and muons are required to have large $p_T$ and well reconstructed tracks and vertices. In addition to this, particle identification is used to distinguish between pion, kaon and proton tracks.

The $B^0 \to D^- \pi^+$ selection requires that the $D^-$ reconstructed mass be in a range of $\pm 100$ MeV around the world average [6]. Furthermore, the $D^-$ decay vertex is required to be downstream of the PV associated to the $B^0$ candidate.

The sum of the $D^-$ and $\pi^+$ $p_T$ must be larger than 5 GeV. The $B^0$ candidate invariant mass must be in the interval $5000 < m(K^{*+}\pi^-\pi^+) < 5700$ MeV. Additionally, the cosine of the pointing angle between the $B^0$ momentum vector and the line segment between PV and secondary vertex is required to be larger than 0.999.

Candidates are classified by a boosted decision tree (BDT) [25, 26] with the AdaBoost algorithm [27]. The BDT is trained with $B^0 \to D^- \pi^+$ candidates with no particle ID criteria applied to the daughter pions and kaons. The cut on the BDT classifier is optimised in order to maximise the significance of the $B^0 \to D^- \pi^+$ signal. Several input variables are used: the IP significance, the flight distance perpendicular to the beam axis, the vertex quality of the $B^0$ and the $D^-$ candidate, the angle between the $B^0$ momentum and the line segment between PV and $B^0$ decay vertex, the angle between the $D^-$ momentum and the line segment between PV and the $D^-$ decay vertex, the angle between the $D^-$ momentum and the line segment between the $B^0$ decay vertex and $D^-$ decay vertex, the IP and $p_T$ of the $\pi^+$ track, and the angle between the $\pi^+$ momentum and the line segment between PV and $B^0$ decay vertex. Only $B^0$ candidates with a decay time $t > 0.3$ ps are accepted.

To suppress potential background from misidentified kaons in $D^- \to K^+ K^- \pi^-$ decays, all $D^-$ candidates are removed if they have a daughter pion candidate that might pass a loose kaon selection and are within a $\pm 25$ MeV mass window (the $D^-$ mass resolution is smaller than 10 MeV) around the $D^-$ mass when that pion is reconstructed under the kaon mass hypothesis.

Remaining background comes from $B^0 \to D^- \rho^+$ and $B^0 \to D^- \pi^+$ decays. In both cases the final state is similar to the signal, except for an additional neutral pion that is not reconstructed. This leads to two additional peaking components with invariant masses lower than those of the signal candidates. Therefore, for the measurement of $\Delta m_d$ only candidates with an invariant mass in the range $5200 < m < 5450$ MeV are used.

The $B^0 \to J/\psi K^{*0}$ selection requires that the $K^{*0}$ candidate has a $p_T > 2$ GeV and $826 < m(K^{*0}\pi^-) < 966$ MeV.

The unconstrained $\mu^+\mu^-$ invariant mass must be within $\pm 80$ MeV of the $J/\psi$ mass [6]. $B^0$ candidates are required to have a large IP with respect to other PVs in the event and the $B^0$ decay vertex must be significantly separated from the PV. Additionally, $B^0$ candidates are required to have a reconstructed decay time $t > 0.3$ ps and an invariant mass in the range $5230 < m(J/\psi K^{*0}\pi^-) < 5330$ MeV. To suppress potential background from misidentified $B^0 \to J/\psi K^{*0}$ decays, all candidates are removed for which the $K^{*0}\pi^-$ mass is within a $\pm 10$ MeV window around the nominal $\phi(1020)$ mass when computed under the kaon mass hypothesis for the pion. The resulting mass distributions for the two decay channels are shown in Fig. 1.

4. Flavour tagging

This analysis makes use of a combination of opposite side taggers and the same side pion tagger to determine the flavour of the $B^0$ meson at production. The opposite side taggers, which use
decay products of the b quark not belonging to the signal decay, are described in detail in Ref. [28].

The same pion tagger uses the charge of a pion that originates from the fragmentation process of the $B^0$ meson or from decays of charged excited B mesons. Pion tagging candidates are required to fulfil criteria on $p_T$ and particle identification, as well as their IP significance and the difference between the $B^0$ candidate mass and the combined mass of the $B^0$ candidate and the pion [29].

Depending on the tagging decision, a mixing state $q$ is assigned to each candidate, to distinguish the unmixed ($q = +1$) from the mixed ($q = -1$). Untagged events ($q = 0$) are not used in this analysis. The tag and its predicted wrong tag probability $\eta_q$ are evaluated for each event using a neural network calibrated and optimised on $B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow D^{*-} \mu^+ \nu_\mu$ events.

To take into account a possible difference in the overall tagging performance between the calibration channels and the decay channels used in this analysis, the corrected wrong tag probability $\omega$ assigned to each event is parametrised as a linear function of $\eta_q$ (the method is described and tested in Ref. [28])

$$\omega(\eta_q|p_0, p_1) = p_0 + p_1(\eta_q - \langle \eta_q \rangle),$$

(2)

where $p_0$ and $p_1$ are free parameters in the fit for $\Delta m_d$ described in Section 6. In this way, uncertainties due to the overall calibration of the tagging performance are absorbed in the statistical uncertainty on $\Delta m_d$ returned by the fit.

5. Decay time resolution and acceptance

The decay time resolution of the detector is around 0.05 ps [30]. This is small compared to the $B^0$ oscillation period of about 12 ps and does not have significant impact on the measurement of $\Delta m_d$. The resolution is accounted for by convolving a Gaussian function $G(t; \sigma_1)$, using a fixed width $\sigma_1 = 0.05$ ps, with the signal probability density function (PDF) from Eq. (5). Possible systematic uncertainties introduced by the resolution are discussed in Section 7.

Trigger, reconstruction and selection criteria introduce efficiency effects that depend on the decay time. While these effects cancel in the asymmetry of Eq. (1) for signal events, they can be important for event samples that include background. As will be shown in Section 6, the only relevant background in the $B^0$ signal region is combinatorial in nature. For this background the asymmetry $N_{q=1}^{bkg}(t) - N_{q=-1}^{bkg}(t)$ is expected to cancel to first order as $q$ has no physical meaning. Therefore,

$$A_{\text{mix}}(t) \propto \frac{(N_{q=1}^{\text{sig}}(t) + N_{q=-1}^{\text{bkg}}(t)) - (N_{q=1}^{\text{sig}}(t) + N_{q=-1}^{\text{bkg}}(t))}{(N_{q=1}^{\text{sig}}(t) + N_{q=1}^{\text{bkg}}(t)) + (N_{q=-1}^{\text{sig}}(t) + N_{q=-1}^{\text{bkg}}(t))} \times \frac{S(t)}{S(t) + B(t)} \cos(\Delta m_d t),$$

(3)

where $N_{q=1}^{\text{sig}}(t)$ denotes the number of unmixed or mixed signal (sig) and background (bkg) events, $S(t)$ and $B(t)$ denote the number of signal and background events as a function of the decay time. Thus, the shapes of $S(t)$ and $B(t)$ have to be known to account for the time dependent amplitude of the asymmetry function.

In the analysis of decays $B^0 \rightarrow J/\psi K^{*0}$, the decay time acceptance is determined from data, using a control sample of $B^0 \rightarrow J/\psi K^{*0}$ events that is collected without applying any of the decay time biasing selection criteria. The decay time acceptance is evaluated in bins of $t$ and is implemented in the fit described in Section 6.

In the decay $B^0 \rightarrow D^- \pi^+$ there is no control dataset that can be used to measure the decay time acceptance. From an analysis of simulated events, it is determined that the decay time acceptance can be described by the empirical function

$$\epsilon_{\text{acc}}(t|a_1, a_2) = \frac{1}{2} \left[ 1 + \cos\left(2\pi a_1 t + \frac{\pi}{2}\right) \right],$$

(4)

where the parameters $a_1$ and $a_2$ are both free in the maximum likelihood fit for $\Delta m_d$ described in Section 6.

6. Measurement of $\Delta m_d$

The value of $\Delta m_d$ is measured using a multi-dimensional extended maximum likelihood fit. The $B^0 \rightarrow D^- \pi^+$ data are described by a two component PDF in which one component describes the signal and the other describes the combinatorial background. The signal component consists of the sum of a Gaussian function and a Crystal Ball function [31] with a common mean for the mass distribution, multiplied by a function $P_{\text{sig}}^t$ to describe the decay time distribution,

$$P_{\text{sig}}^t(t, q; \tau, \Delta m_d, \omega, \sigma_1, a_1, a_2) \propto \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{(t-t_0)^2}{2\sigma_1^2}\right) \cdot G(t; \sigma_1) \cdot \epsilon_{\text{acc}}(t|a_1, a_2).$$

(5)

Here, $\epsilon(t)$ is the step function, while the $B^0$ lifetime $\tau$ is a free fit parameter and the average decay time resolution $\sigma_1$ is fixed. Other fit parameters are $a_1$ and $a_2$ from the decay time acceptance function $\epsilon_{\text{acc}}(t|a_1, a_2)$ described in Section 5, as well as the parameters $p_0$ and $p_1$ from the tagging calibration function $\omega(\eta_q|p_0, p_1)$ described in Section 4. Any $B^0/B^0$ production asymmetry cancels in the mixing asymmetry function, and is neglected in this analysis.

The combinatorial background component consists of an exponential PDF describing the mass distribution and the decay time PDF

$$P_{\text{bkg}}^t(t, q; \tau_{\text{bkg}}, \omega_{\text{bkg}}, \sigma_1) \propto \frac{1}{\sqrt{2\pi}\sigma_1} \exp\left(-\frac{t-t_0}{\tau_{\text{bkg}}} \right) \cdot G(t; \sigma_1) \cdot \epsilon_{\text{acc}}(t|a_1, a_2).$$

(6)

The PDF is similar to the signal decay time PDF with $\Delta m_d$ fixed to zero. The parameter $\omega_{\text{bkg}}$ allows the PDF to reflect a possible asymmetry in the number of events tagged with $q = \pm 1$ in the background. The effective lifetime $\tau_{\text{bkg}}$ of the long-lived background component is allowed to vary independently in the fit.

Possible backgrounds from misidentified or partially reconstructed decays are studied using mass templates determined from simulation. These are found to be negligible in the mass window $5200 < m(K^+\pi^-\pi^-\pi^+) < 5450$ MeV that is used in the fit (cf. Fig. 1).

In the $B^0 \rightarrow J/\psi K^{*0}$ analysis, the signal mass distribution is modelled by a double Gaussian function with a common mean and the decay time PDF is the same as described in Eq. (5), except for the decay time acceptance $\epsilon_{\text{acc}}(t|a_1, a_2)$ that is replaced by the acceptance histogram described in Section 5 and has no free parameters. The mass distribution of the combinatorial background in $B^0 \rightarrow J/\psi K^{*0}$ decays is also described by an exponential function. However, the decay time distribution includes a second component of shorter lifetime to account for prompt $J/\psi$ candidates passing the selection. The long-lived component is described by the same function as the combinatorial background in $B^0 \rightarrow D^- \pi^+$ decays as in Eq. (6), whereas the short-lived component is described by a simple exponential function. No other significant source of background is found.
The resulting values for $\Delta m_d$ are $0.5178 \pm 0.0061$ ps$^{-1}$ and $0.5096 \pm 0.0114$ ps$^{-1}$ in the $B^0 \to D^-\pi^+$ and $B^0 \to J/\psi K^0$ decay modes respectively. The fit yields $87724 \pm 321$ signal decays for $B^0 \to D^-\pi^+$ and $39\,148 \pm 316$ signal decays for $B^0 \to J/\psi K^0$. The fit projections onto the decay time distributions are displayed in Fig. 2 and the resulting asymmetries are shown in Fig. 3. No result for the $B^0$ lifetime is quoted, since it is affected by possible biases due to acceptance corrections. These acceptance effects do not influence the measurement of $\Delta m_d$.

7. Systematic uncertainties

As explained in Section 5, systematic effects due to the decay time resolution are expected to be small. This is tested using samples of simulated events that are generated with decay time distributions given by the result of the fit to data and convolved with the average measured decay time resolution of 0.05 ps. The event samples are then fitted with the PDF described in Section 6, with the decay time resolution parameter fixed either to zero or to $\sigma_t = 0.10$ ps. The maximum observed bias on $\Delta m_d$ of 0.0002 ps$^{-1}$ is assigned as systematic uncertainty. Systematic effects due to decay time acceptance are estimated in a similar study, generating samples of simulated events according to the nominal decay time acceptance functions described in Section 5. These samples are then fitted with the PDF described in Section 6, but neglecting the decay time acceptance function in the fit. The average observed shift of 0.0004 ps$^{-1}$ (0.0001 ps$^{-1}$) in $B^0 \to D^-\pi^+$ ($B^0 \to J/\psi K^0$) decays is taken as systematic uncertainty. The influence of event-by-event variation of the decay time resolution is found to be negligible.

In order to estimate systematic effects due to the parametrisation of the decay time PDFs for signal and background, an alternative parametrisation is derived with a data-driven method, using sWeights [32] from a fit to the mass distribution. The sWeighted decay time distributions for the signal and background components are then described by Gaussian kernel PDFs, which replace the exponential terms of the decay time PDF. This leads to a description of the data which is independent of a model for the decay time and its acceptance, that can be used to fit for $\Delta m_d$. The resulting shifts of 0.0037 ps$^{-1}$ (0.0022 ps$^{-1}$) in the decay $B^0 \to D^-\pi^+$ ($B^0 \to J/\psi K^0$) are taken as the systematic uncertainty due to the fit model.

Uncertainties in the geometric description of the detector lead to uncertainties in the measurement of flight distances and the momenta of final state particles. From alignment measurements on the vertex detector, the relative uncertainty on the length scale is known to be smaller than 0.1%. This uncertainty translates directly into a relative systematic uncertainty on $\Delta m_d$, yielding an absolute uncertainty of 0.0005 ps$^{-1}$.

From measurements of biases in the reconstructed $J/\psi$ mass in several run periods, the relative uncertainty on the uncalibrated momentum scale is measured to be smaller than 0.15%. This uncertainty, however, cancels to a large extent in the calculation of the $B^0$ decay time, as it affects both the reconstructed $B^0$ momentum and its reconstructed mass, which is dominated by the measured momenta of the final state particles. The remaining systematic uncertainty on the decay time is found to be an order of magnitude smaller than that due to the length scale and is neglected.

A summary of the systematic uncertainties can be found in Table 1. The systematic uncertainty on the combined $\Delta m_d$ result is calculated using a weighted average of the combined uncorrelated
Table 1  
 Systematic uncertainties on $\Delta m_d$ in $\text{ps}^{-1}$.

| Source                           | $B^0 \rightarrow J/\psi K^{*0}$ | $B^0 \rightarrow D^- \pi^+$ |
|----------------------------------|---------------------------------|----------------------------|
| Acceptance                       | 0.0001                          | 0.0004                     |
| Decay time resolution            | 0.0002                          | 0.0002                     |
| Fit model                        | 0.0022                          | 0.0037                     |
| Total uncorrelated               | 0.0022                          | 0.0037                     |
| Length scale                     | 0.0005                          | 0.0005                     |
| Total including correlated       | 0.0023                          | 0.0037                     |

The combined value for $\Delta m_d$ is calculated as the weighted average of the individual results taking correlated systematic uncertainties into account.

$$\Delta m_d = 0.5156 \pm 0.0051 \text{(stat.)} \pm 0.0033 \text{(syst.)} \text{ps}^{-1}.$$  

The relative uncertainty on $\Delta m_d$ is 1.2%, where it is around 0.6% for $\Delta m_s$ [7]. Thus, the uncertainty on the ratio $\Delta m_d/\Delta m_s$ is dominated by $\Delta m_d$. As the systematic uncertainties in the $\Delta m_d$ and $\Delta m_s$ measurements are small, the error on the ratio can be further improved with more data.

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13 Sezione INFN di Bari, Bari, Italy
14 Sezione INFN di Bologna, Bologna, Italy
15 Sezione INFN di Cagliari, Cagliari, Italy
16 Sezione INFN di Ferrara, Ferrara, Italy
17 Sezione INFN di Firenze, Firenze, Italy
18 Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
19 Sezione INFN di Genova, Genova, Italy
20 Sezione INFN di Milano Bicocca, Milano, Italy
21 Sezione INFN di Roma Tor Vergata, Roma, Italy
22 Sezione INFN di Roma Sapienza, Roma, Italy
23 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
24 ACH University of Science and Technology, Kraków, Poland
25 National Center for Nuclear Research (NCBJ), Warsaw, Poland
26 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
27 Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
28 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
29 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
30 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
31 Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
32 Institute for High Energy Physics (IHEP), Protvino, Russia
33 Universidade de São Paulo, São Paulo, Brazil
34 Universitat de Barcelona, Barcelona, Spain
35 European Organization for Nuclear Research (CERN), Geneva, Switzerland
36 Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
37 Physik-Institut, Universität Zürich, Zürich, Switzerland
38 National Research Centre Kurchatov, Moscow, Russia
39 H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
40 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
41 Department of Physics, University of Warwick, Coventry, United Kingdom
42 STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
43 School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
44 School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
45 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
46 Imperial College London, London, United Kingdom
47 Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
48 Department of Physics, University of Oxford, Oxford, United Kingdom
49 Syracuse University, Syracuse, NY, United States
50 Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil
51 Institut für Physik, Universität Rostock, Rostock, Germany

* Corresponding author.
E-mail address: tobias.brambach@tu-dortmund.de (T. Brambach).

1 ACH University of Science and Technology, Moscow, Russia.
2 Università di Bari, Bari, Italy.
3 Università di Bologna, Bologna, Italy.
4 Università di Cagliari, Cagliari, Italy.
5 Università di Ferrara, Ferrara, Italy.
6 Università di Firenze, Firenze, Italy.
7 Università di Urbino, Urbino, Italy.
8 Università di Modena e Reggio Emilia, Modena, Italy.
9 Università di Genova, Genova, Italy.
10 Università di Milano Bicocca, Milano, Italy.
11 Università di Roma Tor Vergata, Roma, Italy.
12 Università di Roma La Sapienza, Roma, Italy.
13 Università della Basilicata, Potenza, Italy.
14 LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
15 Hanoi University of Science, Hanoi, Viet Nam.
16 Massachusetts Institute of Technology, Cambridge, MA, United States.
17 Associated to: Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil.
18 Associated to: Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany.