

Qibocal: an open-source framework for calibration of self-hosted quantum devices

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Calibration of quantum devices is fundamental to successfully deploy quantum algorithms on current available quantum hardware. We present Qibocal, an open-source software library to perform calibration and characterization of superconducting quantum devices within the Qibo framework. Qibocal completes the Qibo middleware framework by providing all necessary tools to easily (re)calibrate self-hosted quantum platforms. After presenting the layout and the features of the library, we give an overview on some of the protocols implemented to perform single and two-qubit gates calibration. Finally, we present applications involving recalibration and monitoring of superconducting platforms.

I. INTRODUCTION

Recent developments in quantum technologies have demonstrated promising applications of quantum algorithms on hardware [1]. However, a major challenge preventing larger applications is the noise affecting current quantum systems, which reduces their fidelity. In fact, the error correction mechanisms [2, 3] required for the advent of fault-tolerant devices demand an error threshold far lower than what can currently be achieved by large-scale quantum systems.

To achieve and maintain current state-of-the-art fidelities, characterization and calibration software has become as crucial as well-designed and fabricated quantum hardware. Furthermore, maintaining accurate calibration of such devices requires a significant daily time investment. The noise affecting current devices results in shifts [4] in optimal parameter configurations, which must be addressed and corrected through appropriate recalibration experiments [5].

Current cloud providers of quantum hardware, including IBM Quantum [6], provide limited access to the code necessary for deploying quantum algorithms, lacking details about the software responsible for calibration. Recently,

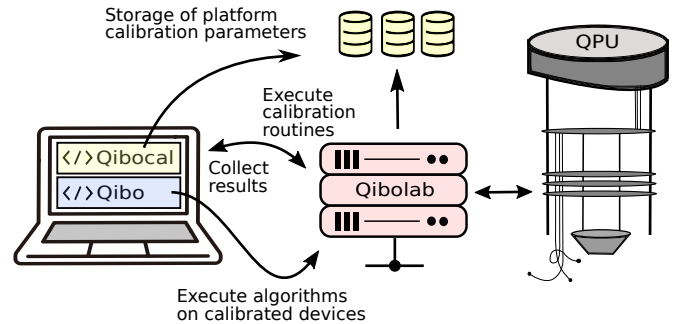


FIG. 1. Schematic representation of Qibocal's role in the hybrid-quantum operating system proposed within the Qibo framework.

several libraries [7–9] related to specific control electronics have begun offering open-source software dedicated to calibration and characterization. These protocols are designed for a particular brand of control electronics, making the translation of experiments between different instruments non-trivial.

To make software for controlling self-hosted devices widely accessible, we recently introduced Qibolab [10, 11] as a submodule of Qibo [12–15], an open-source middle-

ware framework for quantum computing. This module includes primitives for managing the experimental setups required for quantum computing. With Qibolab, both low level experiments and Qibo circuits can be executed on self-hosted quantum devices, which are increasingly becoming available for in-house use in research institutions.

Control over instruments alone is insufficient for successfully deploying quantum algorithms on hardware. Proper calibration and characterization of the entire system must be performed. For superconducting qubits, this involves performing a series of experiments designed to optimize the microwave pulses that implement native gates and measurements. Qibocal, which is based on both Qibo and Qibolab, was developed to ease the deployment of such calibration protocols on superconducting devices.

However, Qibocal is more than just a collection of experiments; its deep integration with Qibolab allows for the automation of the deployment and monitoring of quantum processors. Additionally, Qibocal offers the necessary syntax to seamlessly combine calibration protocols, enabling experimentalists to create custom *calibration programs*. While it is possible to define recalibration schemes using a direct acyclic graph (DAG) [5], specific applications can benefit from a more comprehensive dependency scheme including, for example, optimization loops.

In Fig. 1, we show schematically the role of Qibocal within the Qibo framework.

The paper is organized as follows. In Sect. II we present a detailed overview of the Qibocal library as of version 0.1.0. Sect. III lists some of the characterization and calibration protocols available in the library. In Sect. IV we showcase the capabilities of the library by presenting applications using Qibo. Finally, in Sect. V we draw our conclusions and describe future developments.

II. TECHNICAL SPECIFICATION

A. Software design

Qibocal is the software layer within the Qibo [12] framework which is responsible for characterizing and calibrating a quantum processor controlled through Qibolab [10].

At its core level, Qibocal includes several *protocols* which correspond to single experiments aimed at extracting or fine-tuning physical parameters relevant for the characterization and the calibration of superconducting quantum devices. On top of this, the library provides all necessary features to easily launch protocols, retrieve and share results. Qibocal also takes care of storing all parameters and setting an updated quantum processing units (QPU) configuration.

Among the operations needed to have a fully functional quantum computer, we could consider three differ-

ent types of experiments. Firstly, characterization experiments, which aim at extracting individual parameters of the system's model. Secondly, calibration experiments, which are mostly fine-tuning experiments to optimize specific parameters of the pulses used. Finally, we might also consider more generic experiments that cannot be fully classified as either calibration or characterization experiments such as validation experiments. Other than this last option, we are going to refer to any experiment of the two previous types as a *protocol*, for simplicity.

A protocol is represented in Qibocal by a *Routine* class and it aims at being a representation of a generic experiment that can be performed on a quantum computer. Such experiments usually involve two steps: *data acquisition* and *data processing*. In this context *data acquisition* refers to a generic measurement on a quantum device, ranging from low level experiments involving basic pulse sequences or circuit executions to more complex ones. *data processing* instead refers to any computation which is carried over after the measurement, i.e. when quantum hardware is no longer necessary. We can notice that it is not always trivial to separate the acquisition and processing in a complex procedure, since the latter part might affect the former. However, an advanced experiment can be conceived as composed by smaller entities, and protocols are intended to be the atomic operations.

Moreover, a few additional steps are optionally available: whenever the user is satisfied with the outcome, it is possible to *generate* an updated platform configuration, according to the results obtained. Furthermore, it is possible to visualize and report both the data and the post-processing analysis through tables and plots. All these steps are illustrated in Fig. 2.

We discuss briefly all the classes which are involved in the definition of a *Routine* object.

The external input to a *Routine* is represented by its *Parameters*, that are consumed by the *data acquisition* step. An example of such parameters could be sweeping ranges for spectroscopy experiments, selecting on which qubits the protocol will be executed, and even non-protocol-specific configuration parameters including the number of shots to be executed, and the relaxation time in between different measurements.

The raw data produced by the acquisition are stored in a *Data* class. By default, the acquired data will be stored in binary files for fast loading and dumping (mainly in a NumPy-specific format), while additional parameters are stored as JSON files. Nevertheless, Qibocal offers the flexibility to store and load data in any generic Python-friendly format as long as the user provides the corresponding methods for loading and dumping.

The information extracted from the acquired *Data* by the post-processing analysis is then collected in the

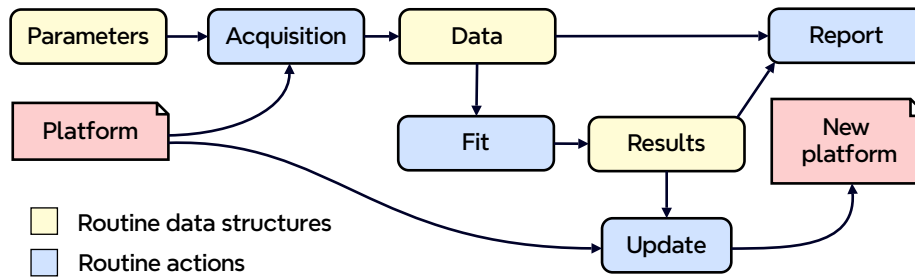


FIG. 2. Dependence scheme for a Qibocal Routine.

Results. These items are intended to be quite shallow, including only few parameters which summarize the outcome of that particular protocol. Finally, those results are used to update the quantum computer configurations, according to the newly calibrated parameters found.

1. Command line execution

Qibocal provides a simplified way to launch protocols through a command line interface (CLI), which is summarized in Fig. 3. All protocol-related information before execution, which basically consists of the `Parameters` and the QPU configurations, are serialized into a YAML file which we call *experiment runcard*. The `Runcard` is then deserialized by an `Executor` which takes care of instantiating a task which is associated to a specific `Routine`. After a task has been dispatched, the `Executor` stores all data obtained from acquisition and post-processing. The `Executor` also takes care of updating the QPU.

Through the CLI it is possible to run experiments with both acquisition and data processing using `qq run`, or the two steps can be performed separately using `qq acquire` or `qq fit` respectively.

Inside an *experiment runcard* it is possible to include more than one experiment, which will be executed sequentially. In this case, the QPU is updated immediately after each protocol, which means that the subsequent experiments will be performed with a `Platform` that contains the parameters calibrated by the previous experiment. This approach is intended to be employed mostly for monitoring application as well as short recalibration programs. We are going to address how to handle non-sequential schemes in Sect. II A 2

2. A calibration program

Often, the need occurs to perform ad-hoc measurements, which involve several protocols following specific schemes of dependencies which go beyond sequential ex-

ecution. This is also the case of a complex and scalable calibration workflow, which possibly targets a full-chip calibration.

To support this use case, graphs have often been used [5]. In particular, directed acyclic graphs (DAG) have been considered an optimal tool to represent a general calibration process. The reason why DAG are so convenient is that there is a clear way to implement their execution, as they define dependency relations, that could be resolved in a clear and possibly optimized way (e.g. exploiting its topological sorting).

However, not all types of execution can be represented by a DAG, but only those for which the execution process is fully known ahead of time. This purposefully prevents cyclic dependencies [5], approximating them with their unwrapping in layers of precision, but also any other runtime conditional (which lies at the foundation of a loop, but also of any Turing-complete execution).

Also notice that, in typical scenarios, the sequence of relevant operations in an initial phase is well-known, and pretty standard across different chips. This aspect as well hints the relevance of the representation as an *executed* program. Instead, during late refinements, it may be not as simple to clearly decouple different parameters, and the exact strategy could become more diverse. Thus, pushing the execution towards runtime allows for greater flexibility.

Indeed, Qibocal is designed to provide this flexibility and naturalness for the execution process, embedding the execution specification in the most common high-level representation: a programming language.

This is achieved by mapping the atomic operation, i.e. the protocol, to a callable function, the computation primitive of a procedural programming language. The exact meaning of this function may depend on the state of the calibration executor, which is responsible of supervising the whole process. The behavior is exactly the one depicted in Fig. 2, but the various protocol stages can be considered optional, or applied at a later stage: the latter option is the case of the report generation, while the first also includes acquisition, since a script can also process previously acquired data.

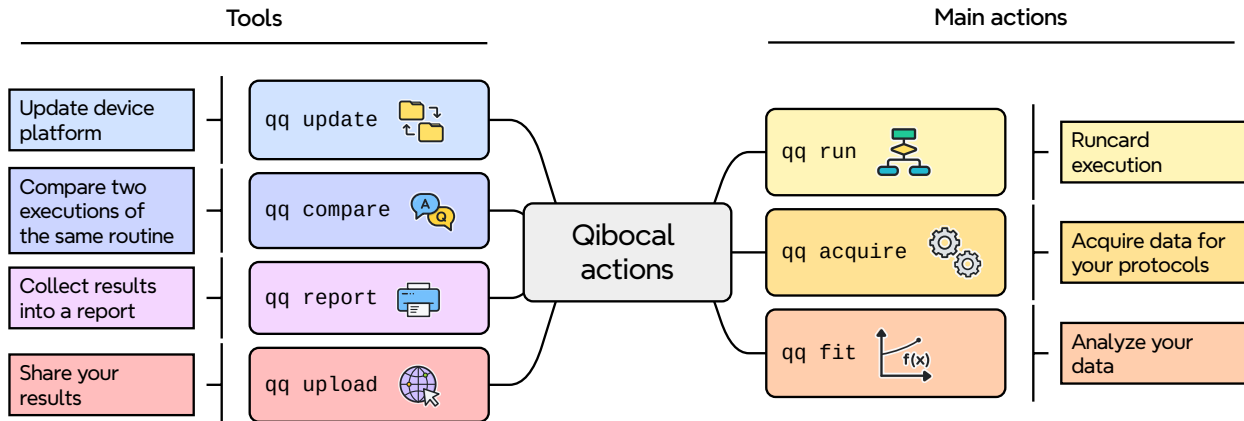


FIG. 3. Qibocal CLI.

Currently, this is made available in Python, where the executor is realized as an instance, and the protocols are mapped to its methods, which accepts parameters as input and return the post-processing results as the method's output. Additional executor's operations are supplied beyond the protocols, that creates the embedded domain specific language (eDSL) made available to the Qibocal's script user. Examples of them are the connection/disconnection process and the results serialization.

Despite the current choice of Python, related to the Qibocal implementation language, it is possible to expose the protocols in any other language, just binding the current library (which could be implemented as a simple wrapper of Python calls, but it is not yet done, and consequently not tested - delegating this development to the broader and ongoing effort for Qibo languages' interoperability). Beyond making the operations flexible and the specification process simpler, leveraging the programming languages' expressivity, it enhances the integration process with other tools, as the result of many protocols can be processed together with the aid of external libraries in the middle of the calibration workflow, and even directly integrate with further tools (monitoring, data provider, etc.).

The protocols are still distinguished by the possibility of tuning the exact acquisition experiment, as the sequence of pulses that should be played during the experiment and their exact timing. This is only available within a protocol, and constitutes a unit of computation. It is often associated to a typical post-processing, which is then convenient to keep together, but it could also be replaced (though it is often more convenient to realize any further processing on top of it). And similarly for the related update and report.

Even though the flexibility described above might lessen

the need of a wide range of protocols due to this possibility of moving the post-processing at a different level, it also accommodates potential extensions of the protocols, in addition to those provided by Qibocal itself. These new protocols just need to be registered and included in the executor object, for them to be available to the executor at runtime.

The exact executor and protocol API is still evolving, but a typical Qibocal script would look like:

```
def recurse(executor, par):
    output = executor.protocol_inner(..., par=
par)
    if condition(output):
        return output
    return recurse(executor, output.some_par)

executor = Executor(...)
executor.connect()

output_a = executor.protocol_a(...)
output_rec = recurse(executor, ...)
...

executor.disconnect()
executor.save()
```

B. Tools

Qibocal provides a series of tools aimed at facilitating the deployment of protocols.

At the end of a program launched through the CLI, a web page is produced with a comprehensive summary of all protocols launched. All the content shown is fully customizable by the user through the report function, which

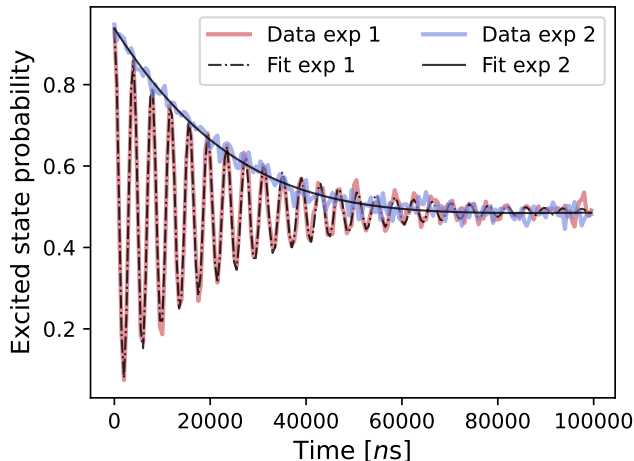


FIG. 4. Comparison between two Ramsey experiments executed using the command `qq compare` in `Qibocal`. In blue we present a first run of the experiment. The presence of oscillations is an indication of the fact that the frequency of the drive pulse is not aligned with the qubit frequency. In red we run the same experiment after correcting the qubit frequency.

is part of the `Routine` interface shown in Fig. 2. Any protocol is expected to generate a list of plots and tables, which will then be collected in the final report. At the same time, for more advanced users, we also provide a mechanism to pass directly HTML strings to have the possibility to completely customize the output for a specific experiment.

All reports produced are easily shareable by uploading them to a dedicated server. Such functionality is accessible by CLI using the command `qq upload`. We plan to also expose it directly when running custom protocols. Although we are aware that moving to a proper database system should be the standard choice, we find that the current simplified solution meets our needs.

We also offer the possibility to graphically compare two reports using the CLI command `qq compare`, which produces a combined HTML report where plots and tables are combined. This allows the user to quickly compare two different experiment runs, which is particularly valuable to assess any changes in the experimental setup. An example of this functionality is shown in Fig. 4.

Finally, although `Qibocal` is able to produce the updated `Qibolab` platform configuration after launching an experiment, the actual replacement of the old configuration in the installed location is performed as a separate stage using the `qq update` commands.

III. CALIBRATION PROTOCOLS

The code base introduced in the previous section can be harnessed to deploy calibration protocols developed using

`Qibolab` primitives. In this library, we include an extensive suite of calibration protocols, not only as useful tools for the calibration of superconducting qubit devices, but also as a starting point for developing new, personalized routines.

In this section we highlight some of the `Qibocal` features, describing a few of the available routines. To this purpose, we introduce them by following a standard, basic, calibration procedure [17].

A. Single qubit calibration

The first step towards fully controlling a qubit is the calibration of single qubit gates. More precisely, single qubit R_X gates together with R_Z rotations are sufficient to access any single qubit rotation [18]. Although R_Z rotations can be performed in several ways [19], the most effective method consists in a virtual implementation [20] based on shifting the phase of subsequent pulses during circuit compilation. For this reason, R_X rotations and measurement gates are the targets for single qubit calibration.

To assess the resonator and qubit frequencies of an unknown device, `Qibocal` provides ad hoc protocols for single and two-tone spectroscopies. For resonators of a 2D notch variety we provide fits [21] not to only retrieve parameters like the frequency of the resonator, but also quality factors and impedance mismatches. A Lorentzian fit is provided for other resonator types and for quick qubit recalibration schemes, where we expect to probe the resonator in a narrow frequency range. The frequency of the qubit can be extracted with a two-tone spectroscopy by fitting the transmitted signal with a Lorentzian fit. Moreover, the protocol controls the amplitude of the tone driving the qubit, allowing the same routine to probe higher energy transitions such as two photon transitions between the ground state and the second excited state.

Next is the calibration of a coherent π -pulse, a complete rotation from state $|0\rangle$ to $|1\rangle$. This task requires the calibration of the amplitude and the duration of a microwave pulse, and it is usually achieved through Rabi experiments [18], several versions of which can be found in `Qibocal`. Standard experiments to extract parameters related to the relaxation time T_1 and coherence times T_2^* and T_2^{Echo} are also provided. `Qibocal` also offers protocols to fine-tune drive pulse parameters, such as Ramsey experiments for correcting the frequency of the drive pulse or sequences aimed at amplifying the error on the amplitude of the drive pulse, which we refer to as *flipping* [22].

Thanks to `Qibolab`, these protocols, and in general most calibration routines in `Qibocal`, support the acquisition of not only the integrated and demodulated read-out signal, i.e., for each shot we extract the in-phase and quadrature components (IQ-plane), but also single-shot

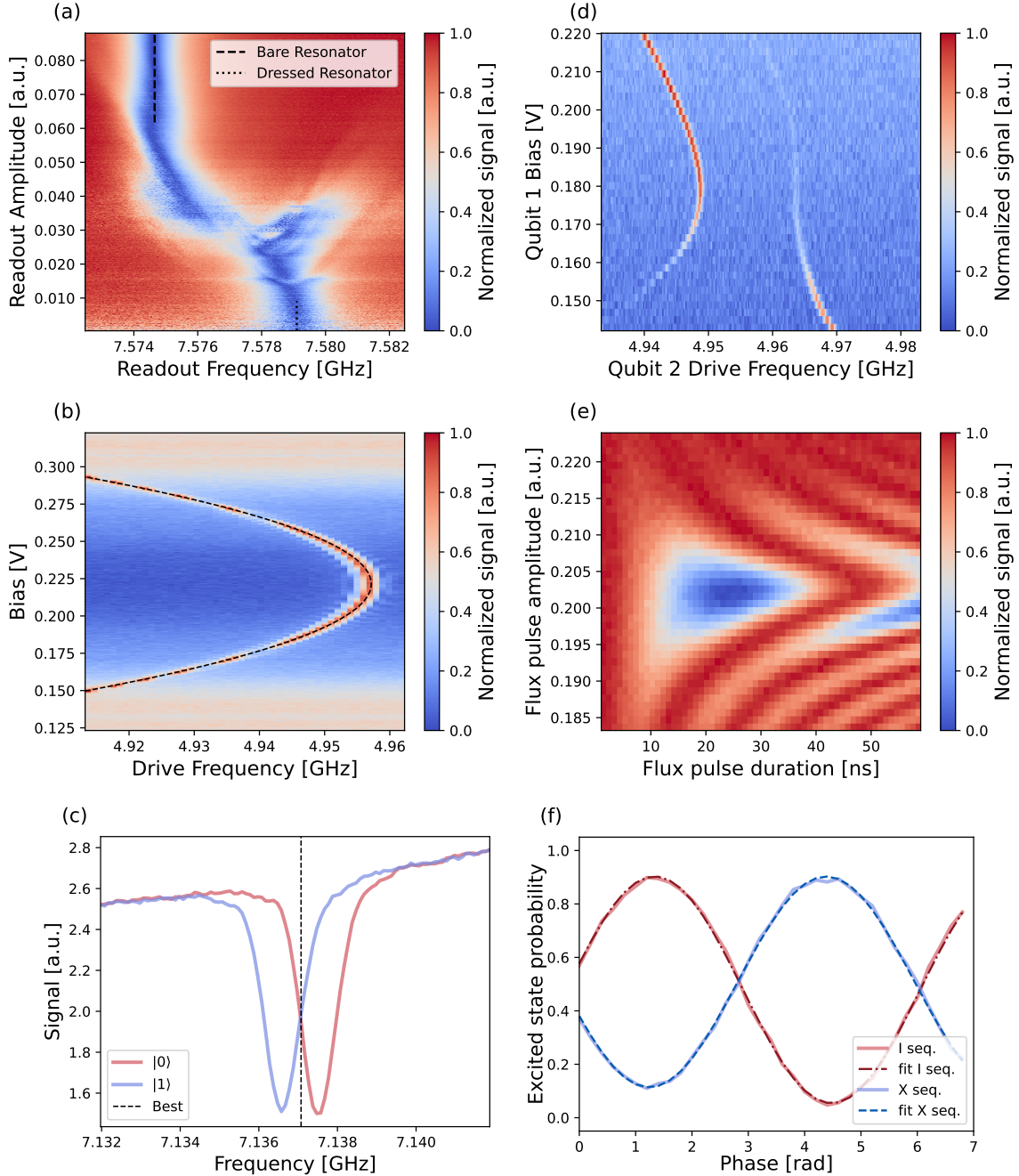


FIG. 5. Gallery of six Qibocal protocols. (a) Measurement of bare and dressed resonator frequency. (b) Qubit frequency measured as a function of the external bias line. The dashed line shows the expected frequency. (c) Transmission coefficient for different readout frequencies for a qubit prepared in state $|0\rangle$ (red) or $|1\rangle$ (blue). The dashed black line corresponds to the readout frequency which maximizes the separation between the two states. (d) Avoided crossing measured between two qubits. (e) Chevron pattern observed during the calibration of a CZ gate. (f) Correction of dynamical single-qubit phases after the application of a flux pulse implementing a CZ gate [16].

readout, from which we can easily retrieve probabilities.

This second mode needs to be calibrated first, and Qibocal offers several tools to help maximize single-shot readout fidelity. Standard single-shot classification is available, aimed at providing the parameters required for au-

tomatic discrimination within typical control electronics. Furthermore, Qibocal is able to train different machine learning models to classify states in the IQ-plane and offers different metrics to choose from [23].

After running all protocols listed above, the user should

be able to have a first calibration of single qubit gates, however, better results can be achieved by running more complex experiments. As the literature suggests [24], and Qibocal includes, calibration of the DRAG pulse will modify the envelope of R_x pulse rotations reducing leakage, and finding the readout frequency that maximizes the distance of the signals generated by the ground and the excited state in the IQ plane.

B. Two qubit gates calibration

Qibocal includes the necessary tools to extend the calibration to two-qubit gates. Various calibration schemes have been explored in the literature [19], but currently Qibocal supports the calibration of two qubit interactions based on flux tunable qubits [25], including chips with tunable couplers [26, 27]. The standard procedure consists in sending a flux pulse through a dedicated line to the qubit, which shifts its resonant frequency close to the one of a neighboring qubit, allowing for a swap or controlled-phase interaction depending on the initial state preparation [18]. The inclusion of couplers has been proven useful to reduce the ZZ coupling [28]. However, such architecture requires dedicated experiments to calibrate the couplers to switch on and off the interaction between the qubits.

For flux tunable calibration, Qibocal has specific routines to identify the interaction points for the iSWAP and CZ gates. Fig. 5b shows an example of qubit flux spectroscopy; after performing the fit we are able to extract the qubit-flux dependency (for more details see Sec. IV A) and find the operational flux point. In fact, if we move the flux point of the first qubit in order to be in resonance with the second one we can observe the typical avoided crossing shown in Fig. 5d. Once we have found the two-qubit interaction point, we can execute a Chevron-like experiment. By sweeping the flux pulse amplitude and the flux pulse duration, we can assess the pulse parameters required for a controlled two-qubit interaction. Such protocols exhibit a Chevron-like plot routine [18] as reported in Fig. 5e. This illustrates Qibocal's ability to fit and recognize parameters within two-dimensional data.

To further fine-tune the degree of interaction and calibrate a specific two-qubit gate, Qibocal provides additional routines to extract the correct conditional rotation. It also takes into account additional parameters such as remnant dynamical single qubit phases, as in Fig. 5f, and leakage to non-computational states [16].

Regarding two-qubit gates with couplers, we have implemented specific protocols to find the operational point of the couplers, i.e., where the qubits' interaction is active. To achieve the calibration, we sweep the amplitude of a flux pulse applied to the coupler and the duration of the qubit flux pulse to tune the two-qubit gate's pulse sequences.

C. Qubit benchmarking

Within the Qibocal library, complex benchmarking techniques are available to properly gauge the result of a calibration suite. Including benchmarking capabilities in the workflow of Qibocal is crucial, as they provide the relevant figures of merit that the calibration should achieve.

These protocols benefit from the structure already available within Qibocal, where the data acquisition step in an experiment can be decoupled from its post-processing. Not only this simplifies the routine construction, but it allows Qibocal to post-process a unique data acquisition with distinct protocols. Moreover, these benchmarking protocols can be interleaved within a calibration suite to properly track the improvement of fitted parameters, and their output used as cost functions within an optimization loop.

Tomographies on different levels are also available as Qibocal routines. While useful outside the context of calibration, they are an invaluable tool to certify the correctness of the calibration parameters and extract more information from the resulting quantum states and processes.

D. Experiments

The Qibocal tools designed for calibration protocols can also be used on more complex experiments. Moreover, the visualization and reporting that Qibocal provides, as well as its structured acquisition and fitting features can be readily adapted to fit any measurement.

Qibocal also provides two experiments to quantify the entanglement of the system. One experiment performs CHSH inequalities [30] over a range of measurement settings to assert the entanglement generated by two-qubit gates in the system. The other experiment goes further, and performs three qubit Mermin inequalities [31] to determine the ability of the system to produce multi-partite entanglement. Their purpose is twofold. They verify the calibrated parameters in a complete end-to-end application, and they serve as models for the connection of experiments through the Qibocal pipeline.

Any measurement, regardless of its complexity, when coded within the Qibo and Qibolab framework can be included in a calibration stack. This way, by interconnecting calibration and experiments, Qibocal can automatically perform calibration protocols to improve the results of the experiment immediately before said experiment is executed.

E. Automatic recalibration

This combination of protocols can be used as a tool for recalibration. Qibocal is able to feed the calibrated

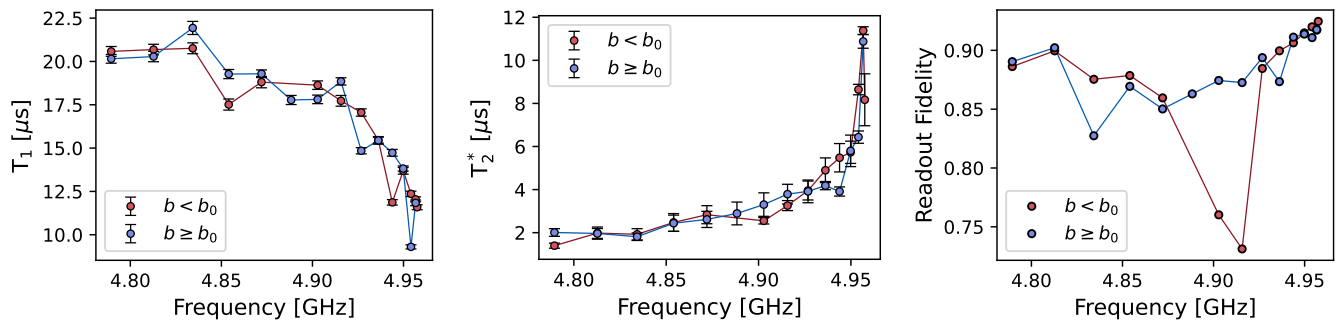


FIG. 6. Measurements of T_1 , T_2^* and readout fidelity as the qubit is operated at different frequencies. The blue curve indicates that the detuning is induced by increasing the flux, while the red curve corresponds to the case where we are decreasing flux. For each point we follow the recalibration procedure described in Sect. IV A. The behavior seen for T_1 measurements is consistent with the increase of the qubit’s Purcell protection (see [29] for a systematic study about the spontaneous emission of Transmon qubits).

parameters from one routine to the next, either sequentially or through non-trivial connections. The flexibility offered through the calibration program API presented in Sect. II A 2 allows for the creation of custom calibration schemes, including the possibility to deviate from a default pipeline based on the outcome of the previous experiments. Launching protocols directly through Python also enables the possibility to code ad-hoc stopping conditions based on specific threshold values. The verification tools available, such as tests designed to ensure the reliability of the fitted parameters, can turn this process into an automatic recalibration procedure.

IV. QIBOCAL IN ACTION

A. Coherence at different bias points

As an example of how Qibocal can be used to write custom experiments involving several protocols we compute the value of T_1 , T_2^* and readout fidelity for a qubit biased at different flux points. Although such experiment could be performed in a simpler way [32] for the purpose of showcasing the library capabilities we have recalibrated the qubit at each flux point. Before the experiment, we characterize how the qubit frequency changes with the flux by running a qubit flux spectroscopy where we fit the data with the standard approximation for those qubits, see Eq. 1 in [33] for example.

Our calibration procedure for each flux point involves the following steps:

1. update the qubit frequency according to the approximation used to fit the data;
2. execute the Rabi experiment to recalibrate the drive pulse amplitude;
3. execute the single-shot classification to run routines in single-shot readout acquisition mode;

4. execute the Ramsey experiment to fine-tune the drive frequency;
5. repeat the single-shot classification to fine-tune the readout;
6. measure T_1 , T_2^* and readout fidelity.

This experiment has been performed on a qubit built by QuantWare and controlled using a Quantum Machines [34] cluster through Qibolab. The results are displayed in Fig. 6. We can observe that the qubit exhibits a reasonably good T_1 value at the sweetspot of around $10 \mu\text{s}$; roughly at 150 MHz we can observe T_1 values reaching up to $20 \mu\text{s}$. T_2^* peaks at the sweetspot and deteriorates as we increase the detuning, as expected. Additionally, the readout fidelity reaches its maximum at the sweetspot.

B. Pulse optimization with randomized benchmarking

A common technique in the control of quantum devices is the optimization of pulse shapes based on high-level performance metrics. A simple example of the more general approach of *quantum optimal control* [35], is to search for pulse parameters maximizing the gate fidelities obtained from randomized benchmarking experiments [36] as the objective function [37, 38]. Qibocal is a flexible tool in the development and benchmarking of such techniques. As a basic example, we implement a gradient-free Nelder-Mead optimization loop for the $\frac{\pi}{2}$ -pulse using Qibocal’s Clifford randomized benchmarking routine and the device parameter update mechanisms. Fig. 7 shows the improvement in the randomized benchmarking decay parameter with the number of Nelder-Mead steps proposing values for the pulse amplitude and DRAG parameter of the pulse.

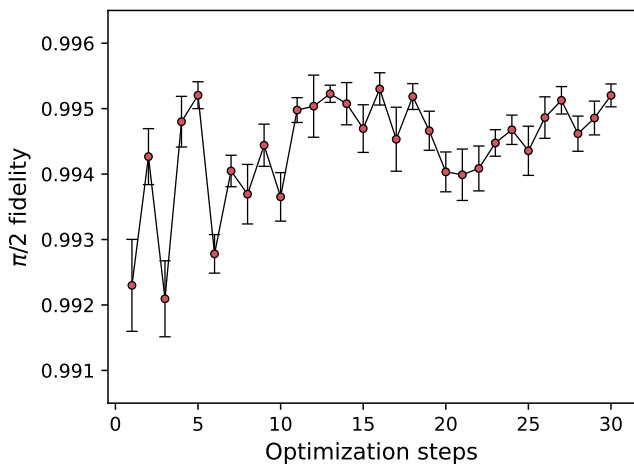


FIG. 7. The $\pi/2$ -pulse fidelity extracted from randomized benchmarking (RB) is used as the objective function of a Nelder-Mead optimization of the $\pi/2$ -pulse amplitude and DRAG parameter. The resulting $\pi/2$ -pulse fidelity after each step in the optimization is shown. The optimization results in an increase in fidelity with few evaluations of the cost function.

C. Re-calibration after changes in flux background

Changes in the system and environment parameters, e.g. the flux background, can require frequent re-calibration of super-conducting qubit. Such workflows for such re-calibration protocol can be combined from Qibocal routines. As example, we perform multiple re-calibrating of $\pi/2$ pulse using the following steps:

1. Ramsey spectroscopy for fine-tuning the drive frequency;
2. single-shot classification for fine-tuning the readout;
3. Rabi experiment to re-calibrate drive pulse amplitude;
4. single-shot classification for fine-tuning the readout.

We use a standard Clifford randomized benchmarking experiment to monitor the $\pi/2$ -pulse fidelity. To simulate a controlled drift of the qubit frequency we change the flux background by sending a bias to the flux line of the connected qubit. Fig. 8 shows a time line of the fidelities when applying different biases before and after re-calibration.

D. Monitoring qubit calibration

Qibocal can be used in monitoring tools, such as Grafana [39]. In this specific case Docker containers were used, in order to ensure the easiest portability of such tools. In particular, a Grafana Docker container was set up, automatically configuring the layout of the dashboard, with the possibility to also install third-party plugins. Monitor-

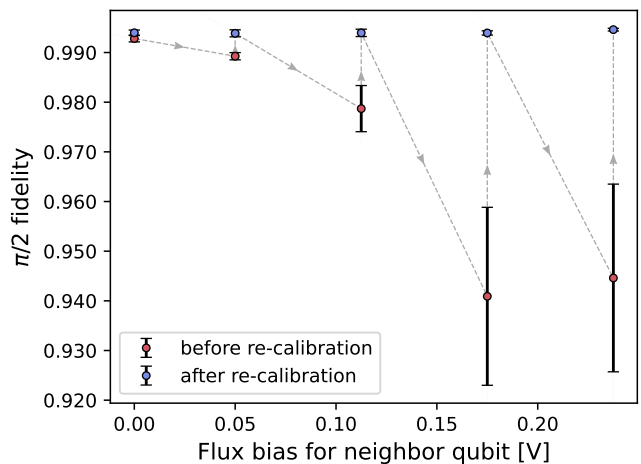


FIG. 8. Re-calibration of a qubit's $\pi/2$ -pulse after (controlled) changes of its flux background. Applied voltage to flux line of neighbouring qubit and randomized benchmarking $\pi/2$ -fidelity before (red) and after (blue) re-calibration against time. The gray dashed arrows describes how the calibration changes over time. Flux bias is relative to the qubit's calibrated sweetspot.

ing containers can be deployed at regular time intervals, measuring several qubit metrics. In the example of Fig. 9, T_1 , T_2^* and readout fidelity from one qubit were monitored every thirty minutes, with all measurements saved in a dedicated container running PostgreSQL [40]. More complex workflows can be set up, including simultaneously monitoring multiple qubits and recalibrating the chip if any metrics fall below a certain threshold. Additionally, the modular structure of Docker containers allows for more containers, to measure QPU usage or cryostat temperature.

V. OUTLOOK

In this paper we introduced Qibocal, an open-source software library for calibration and characterization of superconducting quantum devices. Qibocal is based on Qibo, a full-stack software framework which provides a simple interface to define circuit-based quantum algorithms via custom backends, *i.e.* dedicated plugin software libraries which deploy algorithms on specific hardware.

The release of Qibocal increases the usability of Qibo as a quantum middleware framework by providing specialized tools to (re)calibrate self-hosted quantum devices thanks to the seamless integration with Qibolab platform and instruments configuration. Qibocal aims to kickstart the software standardization of calibration protocols for quantum devices by reducing code redundancy between research groups and laboratories operating self-hosted quantum hardware platforms.

We described the software components and tools imple-

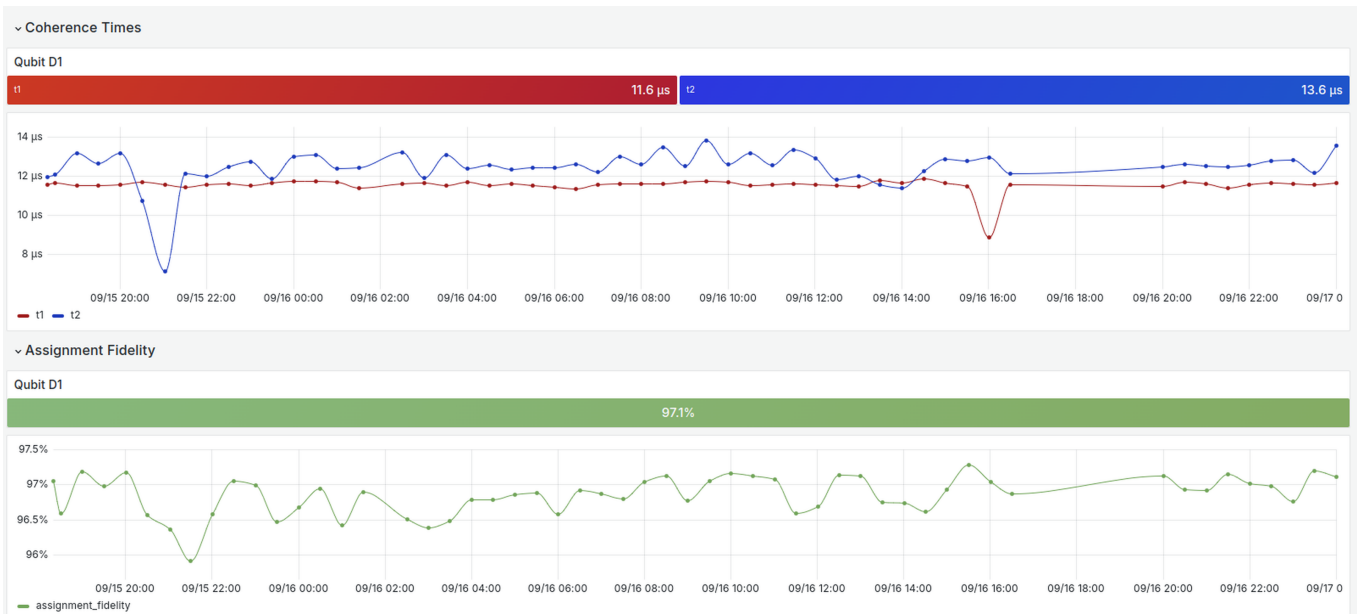


FIG. 9. Monitoring of coherence times and readout fidelity using Qibocal.

mented in release 0.1.0, with a focus on the protocols required for the calibration and characterization of single- and multi-qubit superconducting devices. Furthermore, we presented three examples of applications using Qibocal that demonstrated the utility of this library for quantum technology research: coherence at different bias points, calibration stability against noise and monitoring qubit calibration.

In future releases of Qibocal, we intend to extend its capabilities by defining custom and efficient calibration protocols for multi-qubit devices with a larger number of qubits. Indeed, thanks to the modularity of the library, we have the possibility to adapt and scale the API for large-scale systems. Although in the current release of Qibocal there are calibration experiments for two-qubit gates involving CZ or iSWAP, we are working to add new experiments to support also architectures with CNOT as a native gate, implemented through cross resonance [41]. Nevertheless, we have focused on superconducting chips due to their availability in our affiliated institution labs, however the software library can be extended to new quantum platforms and technologies supported by Qibolab, so we foresee the future possibility to deploying Qibocal in experiments based on trapped ions, neutral atoms and photonics among others. We plan to have access to this and other quantum hardware technologies in the next years through research collaborations and extend Qibo accordingly. We believe that with the release of Qibocal, Qibo becomes an even more unique and useful tool for the quantum computing community, reducing the software development effort for researchers in simulation, hardware control and calibration.

The code implementing the Qibocal module is available at:

<https://github.com/qiboteam/qibocal>.

All the data used in this manuscript are available at [42]:

<https://github.com/qiboteam/qibocal-paper-data>.

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