INTERNSHIP REPORT

École Polytechnique Fédérale de Lausanne

IQM Quantum Computers

Design and Simulation of Superconducting Quantum Circuits

Supervisor:

Dr. Caspar Ockeloen-Korppi

Prof. Daniele Mari

Candidate:

Daniele Cucurachi

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Chapter 1

Introduction

Quantum Computers bring the promise to solve various problems which are beyond the capabilities of computers based on classical physics [1]. In the last decades several quantum algorithms showing a clear quantum advantage have been discovered, leading physicists and engineers to imagine a novel type of computers. This formidable technological challenge is what many research laboratories and quantum companies are facing today.
In the last few years we observed an exponential growth in the number of companies developing commercial quantum technologies products, in parallel with the birth of university study programs entirely focused on quantum science and technology [2]. The quantum industry is developing quickly, sustained by major funding, and is going to become a trillion dollar industry within a few decades [3].

1.1 IQM Quantum Computers

IQM Quantum Computers is the European leader in superconducting quantum computing.

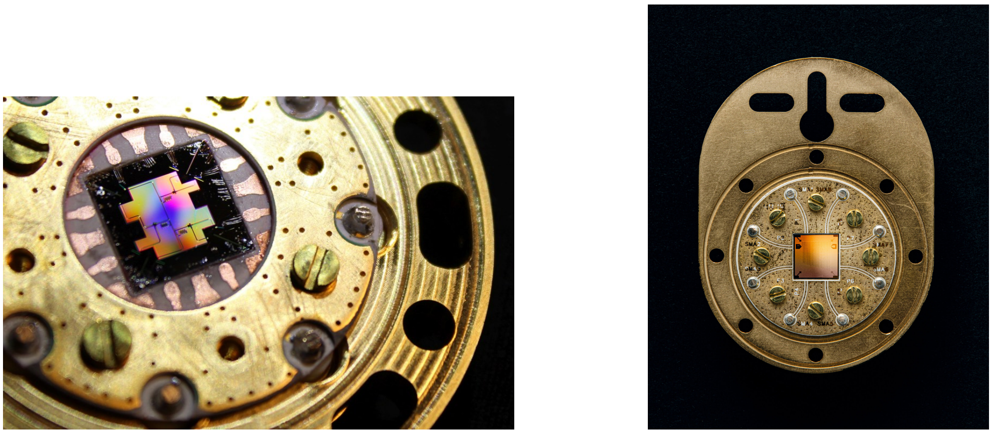


Figure 1.1: IQM chips on PCB [4]

Headquartered in Espoo (Finland), IQM has offices in Munich (Germany) and Paris

(France). With more than 180 employees, IQM has one of the largest industrial team of quantum experts and it is active in quantum computing research with over 700 scientific publications about quantum hardware [5], applications [6] and control electronics [7] and almost 30000 citations.

Source: [4]

Figure 1.2: IQM's fabrication facility

IQM Quantum Computers delivers on-premises quantum computers for research laboratories, supercomputing centers and industrial customers and provides complete access to its hardware.

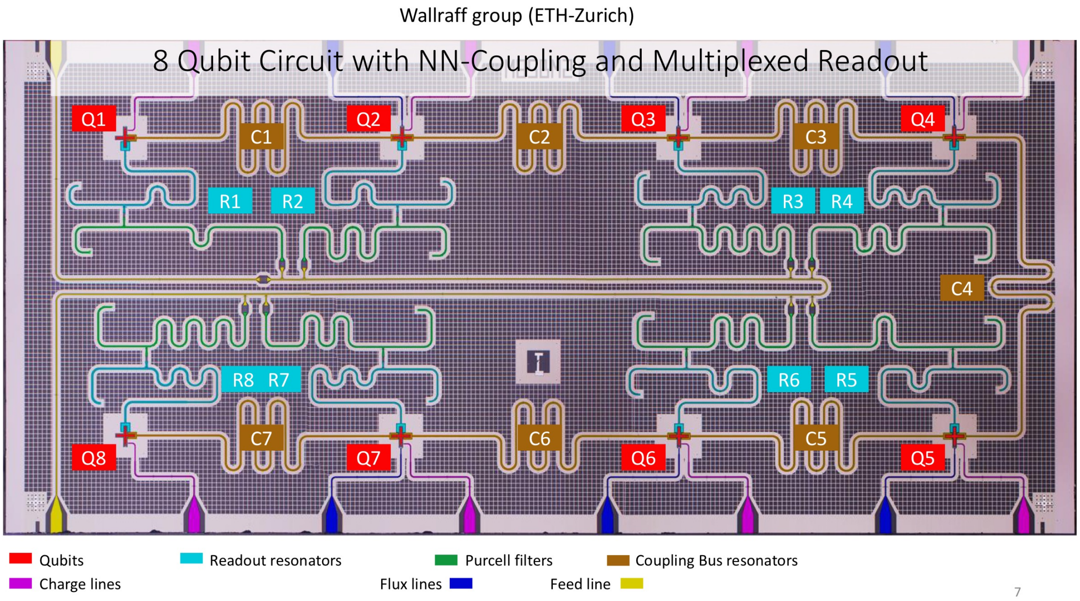
Source: [4]

Figure 1.3: IQM's Quantum Computers design

IQM aims to reach quantum advantage through a unique application-specific co-design approach. The co-design strategy consists in optimizing the hardware in order to efficiently run specific algorithms that solve relevant problems: IQM is building application-specific quantum computers by implementing increasing levels of specialization at the hardware level.

1.2 Superconducting Quantum Circuits

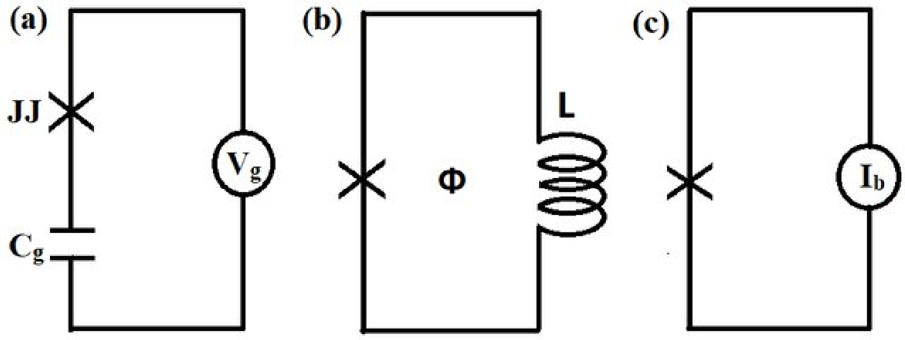
Superconducting quantum circuits are solid state electrical integrated circuits made of superconducting materials like Aluminum or Niobium. They are one of the most promising platforms for building quantum processors [8]. Figure 1.4 shows a superconducting chip where the fundamental elements are marked in different colours.



Source: [9]

Figure 1.4: Quantum processing unit designed and fabricated at Quantum Device Lab (A. Wallraff group, ETH Zurich). The fundamental elements are marked in different colours.

The core of superconducting quantum circuits are superconducting qubits: anharmonic oscillators made of superconducting circuit elements. Superconducting qubits are usually divided into three categories [10]: charge qubits, flux qubits, and phase qubits (see Figure 1.5).
Derived from these three archetypes, a multitude of superconducting qubit types have been studied in paste decades, such as Fluxonium qubits, Transmon-type qubits, C-shunt flux qubit, hybrid qubits, and others.
Superconducting circuits are one of the most popular platforms for quantum computing for many different reasons [11, 9]:



Source: [10]

Figure 1.5: Superconducting qubit circuit diagrams: (a) Charge qubit, (b) Flux qubit, (c) Phase qubit. Where Vg bias voltage, Ig bias current, L inductance, Cg capacitance, ϕ flux, JJ Josephson junction.

- High designability: superconducting quantum circuits can be designed using software tools like KQCircuits, parameters such as capacitance and inductance values can be easily tuned by changing the geometry of the circuit elements. Some properties can be also controlled in situ, like qubits frequencies by means of a SQUID and a fluxline.

- Well developed fabrication techniques: these devices are fabricated using techniques from semiconducting industry (e-beam lithography, evaporation, ...) which have been improved and refined for decades.

- Ultra-low noise: ultra-low temperatures offer an optimal environment to preserve quantum information.

- Easy coupling: in superconducting quantum circuits, qubits can be easily coupled by inductance or capacitance. Advanced circuit architectures allow to control the coupling in situ [12].

- Easy control and readout: several techniques, compatible with standard microwave instrumentation, have been developed for the operation and measurement of superconducting qubits.

1.3 Internship Goal

The internship goal, as stated in the employment contract and internship agreement, is the following:

> *"The main objective of the training is to obtain the knowledge and competences in the physics of superconducting quantum devices as well as the instrumentation and software used in the context, and related characterization and benchmarking methodologies. The content of the training is expected to be useful for the candidate for the purposes of working within the quantum industry. Furthermore, the content is expected to be useful in academic studies and research up to PhD level."*

In particular, as part of the DAS Team (Design and Simulation Team), my work was focused on the development of software tools for automating the design and simulation of superconducting circuits.
The design and simulation of superconducting quantum circuits constitutes the core of IQM Quantum Computers work, a company whose focus is mainly on the hardware side of quantum computing. It is a difficult and time consuming process involving several repetitive tasks and increasing levels of complexity. This is why the future of superconducting quantum hardware design is automation.
In the past, the majority of university research groups, laboratories and quantum companies have been designing their devices "by hand". Such approach becomes more and more inefficient and error prone as the number of qubits increases together with the complexity of the chip. It is not a viable options since the ultimate goal is scaling up. Software tools for quantum circuits design and simulation, like the ones developed by IQM, will be essential to reach the quantum advantage by providing scalable solutions for QPUs (Quantum Processing Units) development for the quantum computers of tomorrow.

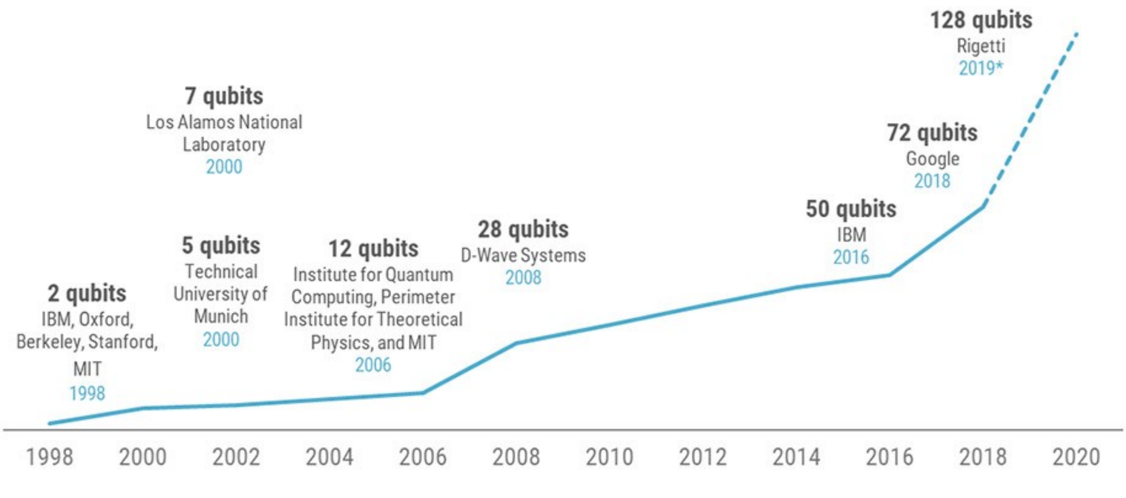


Figure 1.6: Scaling in the number of qubits in the last twenty years [13]

Chapter 2

Results and Contributions

At IQM I contributed to the development of *KQCircuits*, an open source Python library for automating the design and simulation of superconducting quantum circuits. I also contributed to the development of other IQM's private libraries. In the following section I am going to present the results of my work during the 6-months internship. However, the pictures reported here are part of *KQCircuits* only, since it is an open source project accessible to anyone. My contributions to the other IQM's projects cannot be reported in details as they are company private libraries.

2.1 KQCircuits

KQCircuits is an open source software tool for automating the design of superconducting quantum circuits which provides a scalable solution for the future of superconducting quantum computing [14, 4].

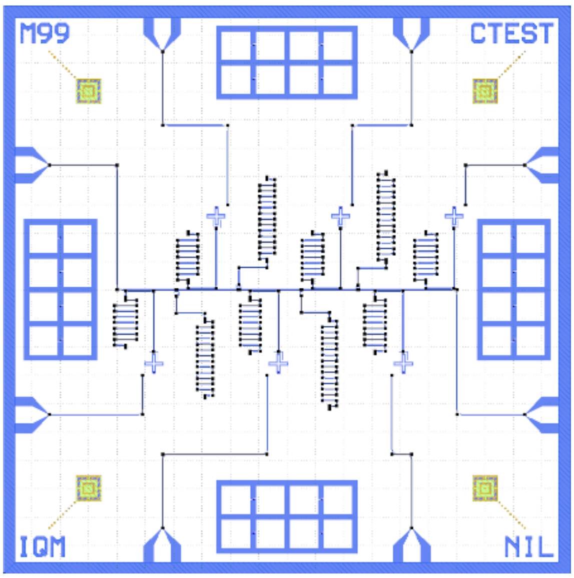


Figure 2.1: Example of QPU designed with *KQCircuits* [14]

In general, QPUs (Quantum Processing Units) design is a complex process that requires several tools:

- FEM (Finite Element Method) simulations
- MW (Microwave) netlist modeling
- Hamiltonian calculations
- Geometry building

KQCircuits is a geometry building tool that aims to automatize and speed up the QPU design process. It also allows to easily interface the device design with FEM simulation softwares like ANSYS and Sonnet (see KLayout, ANSYS and Sonnet).

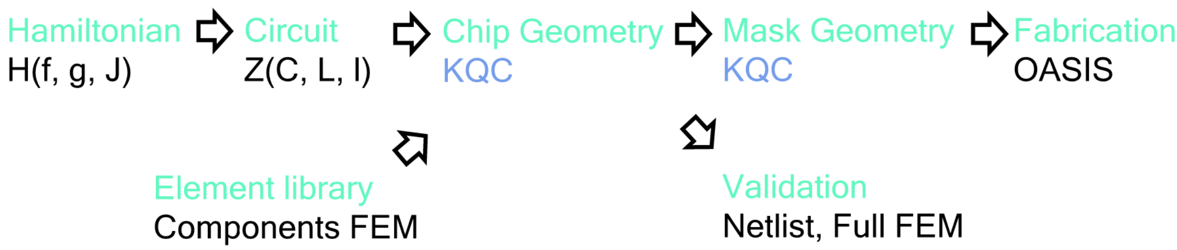


Figure 2.2: QPUs (Quantum Processing Units) design workflow [14].

Supported by *KLayout* (see KLayout, ANSYS and Sonnet), *KQCircuits* generates multi-layer 2-dimensional-geometries which represents the fundamental elements of a quantum processing unit. These elements are parametrized geometrical objects that can be easily customized. *KQCircuits* also provide the user with possibility to define new elements and assemble them with existing ones in order to create a complete quantum processing unit design. Together with quantum circuits fundamental elements, several chip templates are available: not only QPUs but also EBL patterns and optical masks for quantum circuits fabrication. Scripts for exporting chips and masks files in the standard format used for the actual devices fabrication are also available in the library.

2.1.1 KLayout, ANSYS and Sonnet

In this subsection I am going to briefly present the softwares that supports *KQCircuits* in the design and simulation process of quantum circuits.

KLayout: *KQCircuits* uses the *KLayout* API. KLayout is a GDS file editor: it allows to visualize, edit and modify GDS and OASIS files (standard file formats used for micro and nanofabrication), or even create them from scratch.

FEM Simulation Softwares: ANSYS HFSS (High Frequency Simulation Softwares) and Sonnet are widely used FEM (Finite Element Method) simulation softwares. These softwares analyze the electromagnetic performances of a given device.

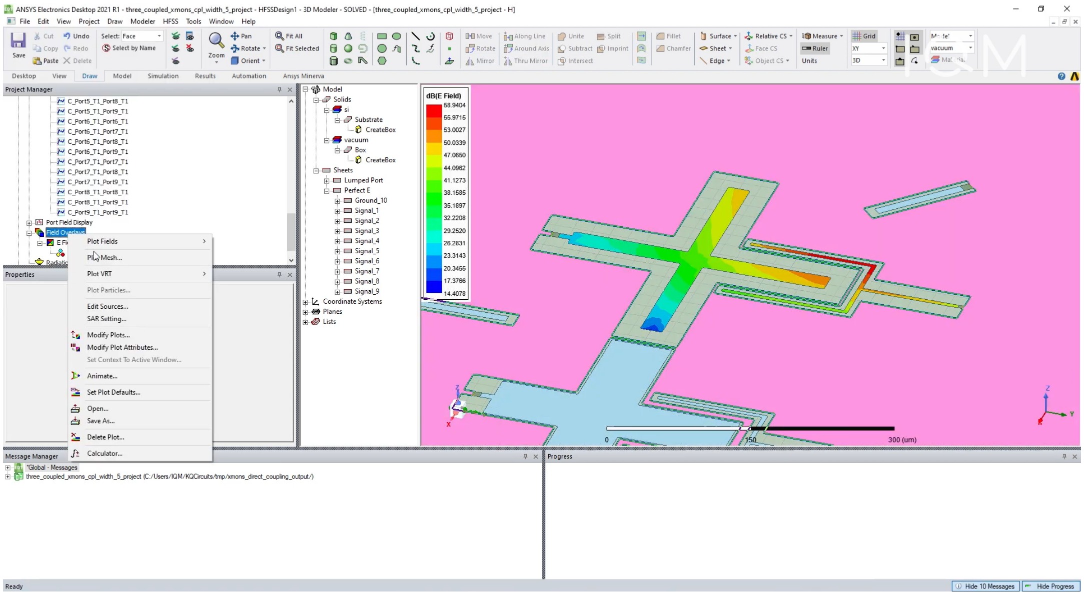


Figure 2.3: ANSYS HFSS simulation of an Xmon qubit [4]

2.2 Contributions

In the following, a list of my contributions to *KQCircuts* and other IQM's projects is reported.

2.2.1 KQCircuits Contributions

- **SQUIDs reference points:** added SQUIDs reference points in qubits and chips' testarrays.

- **Updated SQUIDs test structures in several chips:** added PCell parameters for better control over test structures design in several chips. Implemented:

  - possibility to choose the loop area for every test structure individually
  - possibility to enable or disable step increment in SQUIDs junction width through the definition of a starting value and a step increment value

  Added also boolean PCell parameters in "Junction Test 2" chip to choose whether to create the connection arms and the SQUID device or only the connection arms. This allows to delete SQUID devices while keeping the same exact chip geometry instead of deleting both the devices and the arms connecting them to the pads.

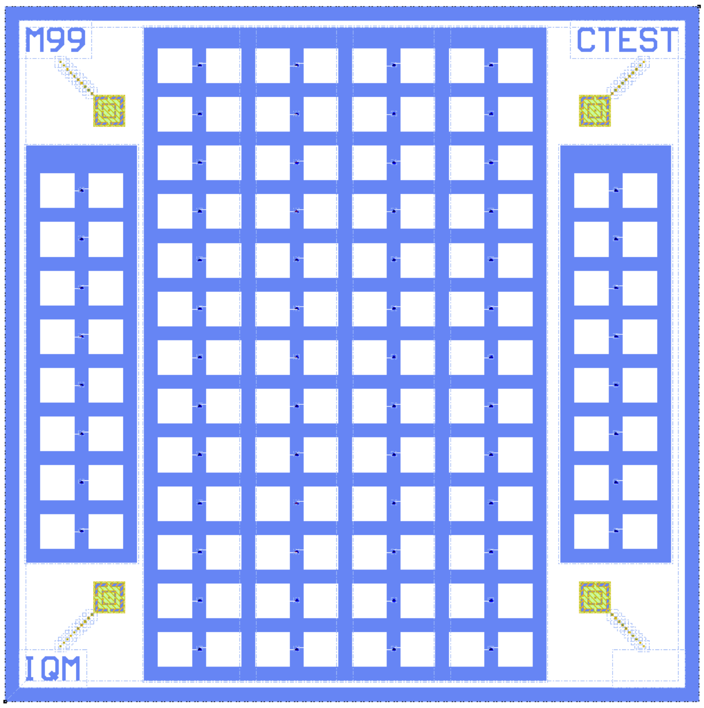


Figure 2.4: Junction Test 2 chip [14]

- **Lithography Test chip and alignment cross markers:** updated Lithography Test chip as requested by the fabrication team and coded a new marker (alignment cross marker).

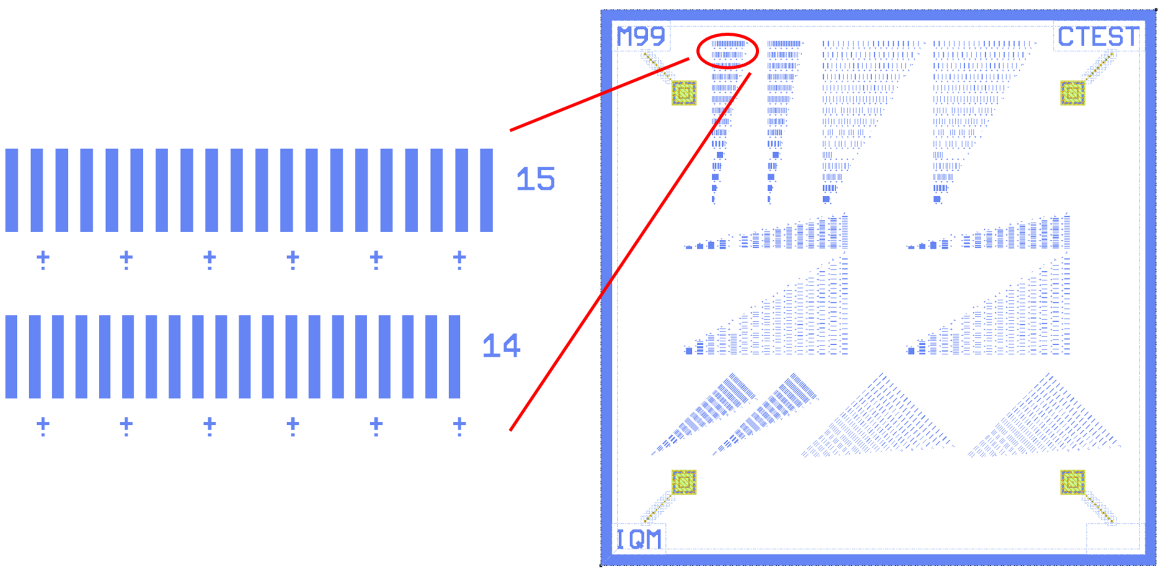


Figure 2.5: Lithography chip detail: test structures and alignment cross markers [14]

- **"Manhattan" SQUIDs:** added "Manhattan" SQUIDs with proper mirroring (all the SQUIDs fingers point towards the same direction to facilitate fabrication process) to qubits and couplers in six chips. In addition, I added several PCell parameters for SQUIDs design so that it's possible to modify SQUIDs design directly from the chips.

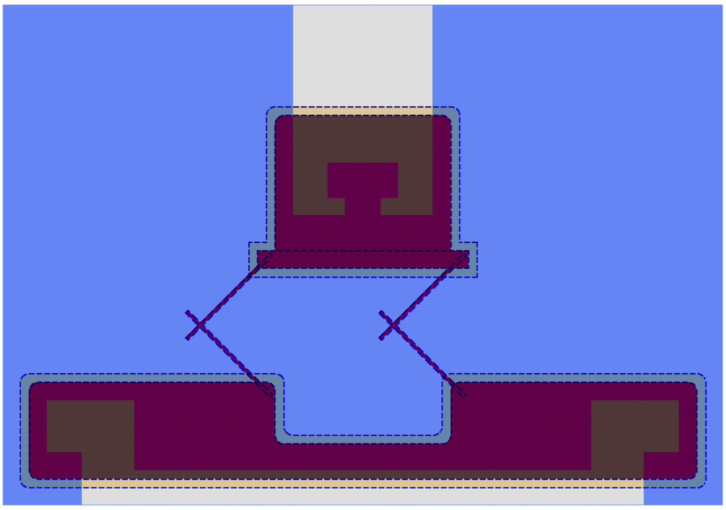


Figure 2.6: Manhattan SQUID design [14]

- **Demo chip's fluxline waveguides:** re-routed Demo chip's fluxlines in order to avoid connections at the wrong angles which would cause gaps in the geometry.

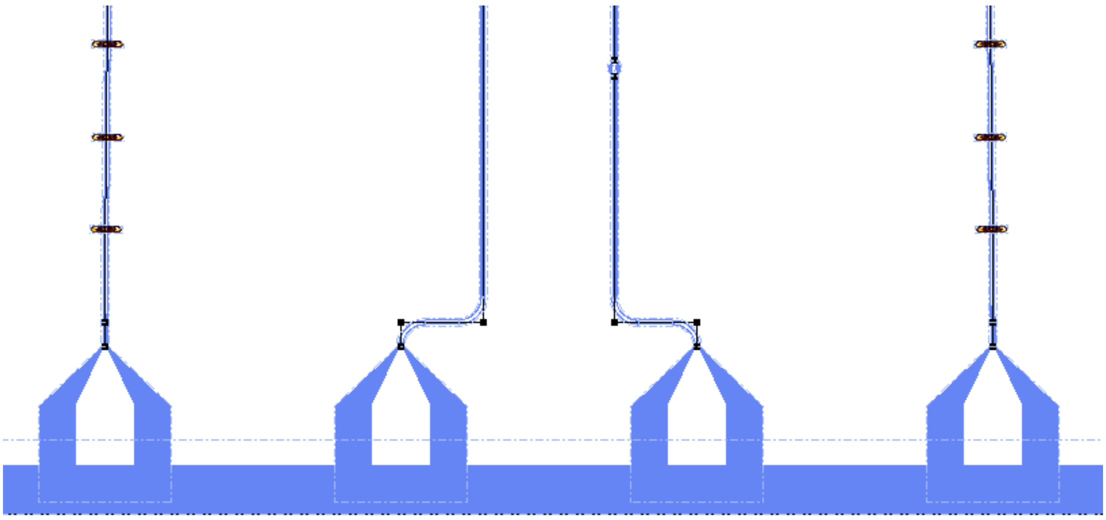


Figure 2.7: Demo chip's launchers and lines [14]

2.2.2 Contributions to other IQM's projects

- **Launchers names:** Updated launchers' names in all chips, refactored related functions.
- **Fabrication Mask:** coded a mask for chips fabrication, together with a new tailored mask layout and two new markers for measuring alignment accuracy.
- **Test structures update:** Updated test structures in five chips implementing several fabrication team requests.
- **New "Manhattan" SQUID version:** coded a new "Manhattan" SQUID version. Refactored existing SQUIDs geometries.
- **Fabrication Test Mask:** coded a mask for chip fabrication tests, together with a new tailored mask layout (not used for the mask in the end) and a new structure for film testing.
- **Test structures connection to ground:** coded test structure connections to ground bumps in order to avoid test pads resonance overlapping with actual qubits resonance during measurements. Updated test structures in several chips such that these connection do not overlap with the chips' lines or other chip's elements.
- **Refactored chip's parameters:** removed useless parameters imported from "squid" class, fixed test structures parameters and added new parameters for better design control from the GUI (Graphical User Interface) in *KLayout*.
- **EBL-Lithography Test chip:** coded a new EBL Test chip requested by the fabrication team. The chip contains alignment markers and several copies of a new EBL test structure I coded.
- **GUI-based routing:** implemented a graphical user interface based routing protocol that allows to easily route fluxlines and drivelines in complex chips. Routing the lines in complex chips is a time consuming task. Since all the elements in *KQCircuits* are code generated, routing a line means coding one by one all the nodes defining the line's path inside the chip. Every line has to be coded such that overlapping with chip's elements or other lines is avoided. The routing protocol I developed allows to route manually drivelines and fluxlines directly from graphical user interface in *KLayout* while visualizing the chip's geometry. This brings a speed up which is fundamental for large chips with many lines. Once all the lines have been routed, a macro is used to print out python code generating them. The code can be then copied and pasted into the chip's script.
- **Second Fabrication Mask:** in progress

- **Quality Factor chip parameters calculations:** updated notebook for Quality Factor chip parameters calculations with the prospect of validating the netlist model by comparing calculated parameters with measured ones.
- **Quality Factor chips analysis:** carried out a systematic study of Quality Factor chip samples and found inconsistencies in the resonator's resonant frequencies. I first collected and analyzed the data (creating a Python notebook for data visualization and fitting), than I investigated possible explanations (overetching simulations, impedance mismatching simulations, requested chips direct analysis to fabrication team, ...).

2.3 Conclusions

The design and simulation of superconducting quantum circuits at IQM Quantum Computers opens and validates new paths and ideas starting the “loop” of R&D work by giving birth to new devices designs with different levels of maturity. It constitutes the core of a company that works mainly on the hardware side of quantum computing.
As member of the DAS Team (Design and Simulation Team), I have been able to apply the technical and scientific knowledge acquired during my studies. I joined a highly talented and motivated team and I had the chance to demonstrate my professional independence as a consistent part of my work during the internship has been carried out independently. Thanks to a great work environment I managed to integrate into the team and the professional context very easily and I have acquired new technical skills and knowledge by working alongside experienced scientists. I made several relevant contributions to various IQM’s projects in the contest of superconducting circuits design and simulation and this work experience gave me an insight into the QPU (Quantum Processing Units) design process.
Improving QPU design tools is essential to the advancement of the technology. With *KQCircuits*, IQM Quantum Computers aims to provide the world wide quantum community with an open and intuitive framework to design and simulate quantum circuits. The development of a community-driven platform to accelerate the progress is an important step for the future of quantum computing.

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