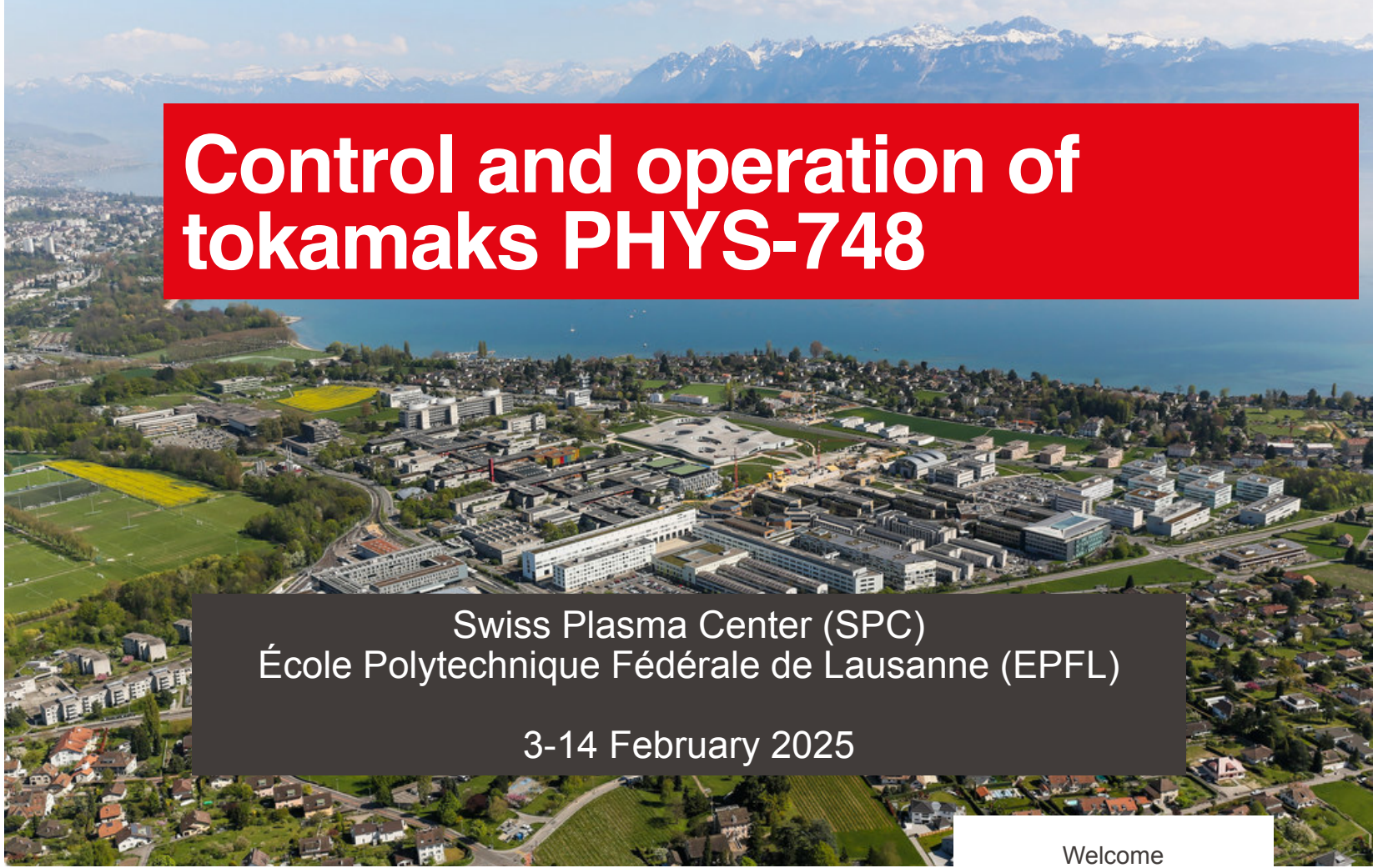
Control and operation of tokamaks PHYS-748



Swiss Plasma Center (SPC)
École Polytechnique Fédérale de Lausanne (EPFL)

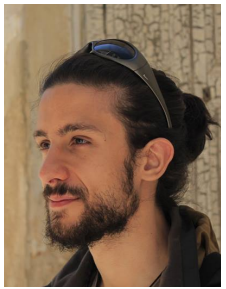
3-14 February 2025

Welcome

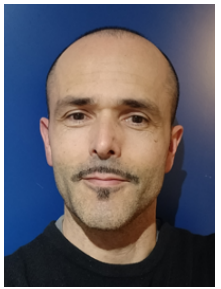
SWISS PLASMA CENTER

Lecturers

- **Federico Felici** (Guest lecturer)
  Previously at EPFL-SPC, now Google DeepMind
- **Adriano Mele** (EPFL-SPC)
- **Antoine Merle** (EPFL-SPC)
- **Cristian Galperti** (EPFL-SPC)
- **Holger Reimerdes** (EPFL-SPC)
- **Alessandro Pau** (EPFL-SPC)





Teaching Assistants

- Francesco Pastore
- Jean-Pierre Svantner
- Pedro Molina
- Reinart Coosemans
- Guillaume Van Parys
- Sara Dubbioso
- Cassandre Contré
- Michele Marin
- Antonia Frank
- Lili Édes
- Cosmas Heiss
- Francesco Carpanese
- Yoeri Poels
- Cristina Venturini

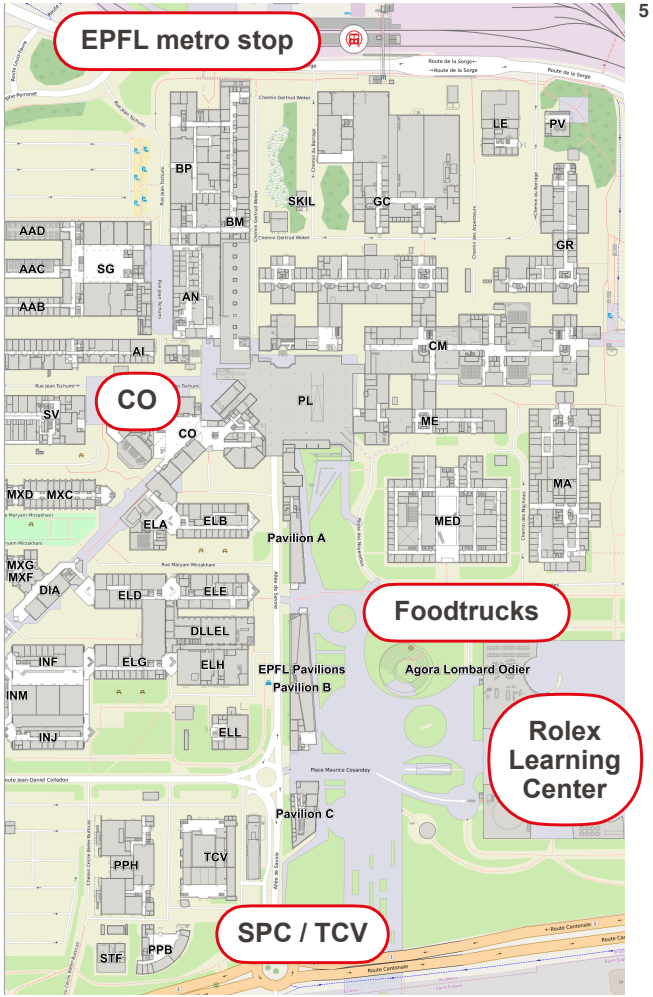
Course background

- **Early versions of this course taught at TU Eindhoven 2014-2017 as MSc course**
- **Merged with SPC Doctoral school course (2018)**
  - First taught by J. Lister, then J-M. Moret
- **Originally taught every 2 years, lasting 1 week**
  - Following diagnostics course the previous week
  - Considered too intense…
- **Since 2023 extended over 2 weeks.. with enhanced local and international participation!**
  - 2025 novelty: 3 instead of 2 ECTS for those seeking credits

Logistics

- Room CO2 for lectures
- Rooms CO4, CO5 & CO6 for exercises

- We start at 9:00, most days, in CO2



SWISS PLASMA CENTER

Computing / Software for exercises

- **Exercises in the first week are in MATLAB**
- **Some exercises in the second week are use Python**
- **Rooms CO4,5,6 have workstations with Windows and MATLAB + Python 3.12 (JupyterLab) installed.**
  - Download exercise from Moodle
  - Software packages needed for the exercises also on Moodle
- **Accounts:**
  - Those with EPFL accounts will have a network drive space
  - External participants need to either
    - use the same post
    - move their data around by other means when switching posts (USB keys, cloud repositories…)
  - EPFL participants with accounts on LAC can do the exercises there (ask us)

Learning objectives

- **Get insight in plasma and tokamak physics processes and why they require (or benefit from) control**
  - Learn how a tokamak ‘works’ in practice.
- **Gain understanding of control-oriented models for tokamak magnetic and kinetic control, and their role in controller design.**
  - Derive ‘simple’ models for various tokamak processes
  - Use models of TCV to design simple controllers.
- **Understand the different phases of a tokamak discharge, and the control problems & solutions for each phase.**
- **Become aware of various components of tokamak control systems**
  - Controllers, state estimation, event detection…
- **Be aware of control technology issues and related limitations.**
- **Promote links between:**
  plasma physics - tokamak technology - control engineering

Course overview

- **Part 0 - Recap/quick run-through of (linear) control theory**
- **Part I - Axisymmetric magnetic equilibrium control**
  - Basic electromagnetic modeling of toroidal currents in conductors
  - Plasma current and position estimation and control
  - Magnetic equilibrium, equilibrium (re)construction
  - Free-boundary equilibrium evolution, pulse planning, shape control
- **Part II - Kinetic control**
  - Control of temperature, density and plasma current profiles in 0D and 1D
  - Diagnostics & actuators for kinetic control
- **Part III - Further topics & trends**
  - Operational limits from MHD, MHD control
  - Power exhaust issues & control
  - Supervisory control, actuator management and off-normal event handling
  - Control technology
  - Machine Learning for tokamak plasma control

Exam

- Oral exam on Friday 14th (maybe spill over to following week)
- List of questions will be distributed
- Topics covered marked with * in course schedule
- 3 ECTS = 84h: 40h lectures + 44h self-study

Course schedule - Week 1

(See Moodle for updates)

Monday 3.2.2023				
9:00-11:00	Lecture 0	General Intro & basic control recap	CO2	*
11:00-12:30	Lecture 1	Magnetic Control 1: Currents & Fields	CO2	*
13:30-15:15	Lecture 1	Magnetic Control 1: Currents & Fields	CO2	*
15:30-17:30	Exercise 1	Exercise 1: PF coil current control	CO5 & 6	*
Tuesday 4.2.2023				
9:00-10:45	Lecture 2	Magnetic control 2: Ip control	CO2	*
11:00-12:30	Lecture 2	Magnetic control 2: Mag. Measurements	CO2	*
13:30-15:30	Exercise 2	Exercises: Ip control / plasma reconstruction	CO5 & 6	*
16:00-17:45	Lecture 3	Magnetic control 3: RZ control	CO2	*
Wednesday 5.2.2023				
9:00-10:45	Lecture 3	Magnetic control 3: RZ control	CO2	*
11:00-12:30	Exercise 3	Exercises: R,Z control: Nyquist, loop gain tuning etc	CO5 & 6	*
13:30-15:30	Exercise 3	Exercises: R,Z control: Nyquist, loop gain tuning etc	CO5 & 6	*
15:30-17:45	Lecture 4	Magnetic control 4: Grad-Shafranov equations & Free boundary inverse solvers: MEQ suite of codes, FBT & LIUQE	CO2	*

Course schedule - Week 1

(See Moodle for updates)

Thursday 9.2.2023				
9:00-11:00	Exercise 4	Equilibrium code exercises: FBT & LIUQE	CO5 & 6	*
11:00-12:30	Lecture 5	MHD limits and MHD control	CO2	*
13:30-15:30	Lecture 6	Technology lecture	CO2	
15:30-16:45	Poster session	Mini poster session	CO hallway	
17:00-18:30	Visit	TCV/SPC visit	TCV / PPH?	
19:30-?	Social event	Social event: Dinner Chalet Suisse		
Friday 10.2.2023				
9:00-10:30	Exercise	Free time for exercises	CO5 & 6	
10:30-12:30	Lecture 6	0D Kinetic control, actuators, diagnostics	CO2	
13:30-15:45	Lecture 7	Divertor heat flux control	CO2	
16:00-17:45	Exercise	Free time for exercises	CO2	

Course schedule - Week 2

(See Moodle for updates)

Monday 10.2.2023				
9:00-10:30	Lecture 8	Magnetic control 5: Free boundary evolution & contr	CO2	
10:45-12:30	Lecture 8b	Shape control		
13:45-15:00	Lecture 8b	Shape control		
15:00-17:30	Exercise	Free boundary evolution exercise	CO5 & 6	
Tuesday 11.2.2023				
9:00-10:15	Lecture 9	1D proflie dynamics and control	CO2	*
11:30-12:30	Exercise	RAPTOR code and exercise introduction	CO5 & 6	*
13:30-15:30	Exercise	Free time for exercises	CO5 & 6	*
15:45-17:30	Lecture 10	Emerging topics: supervisory control & actuator management, needs for ITER, etc		
Wednesday 12.2.2023				
9:00-12:30	Lecture 11a	Machine Learning for plasma control	CO2	*
11:30-12:30	Lecture 11b	Magnetic control of TCV through deep Reinforcement Learning	CO2	*
13:30-15:30	Exercises	Exercises on ML for control	CO5 & 6	*

Course schedule - Week 2

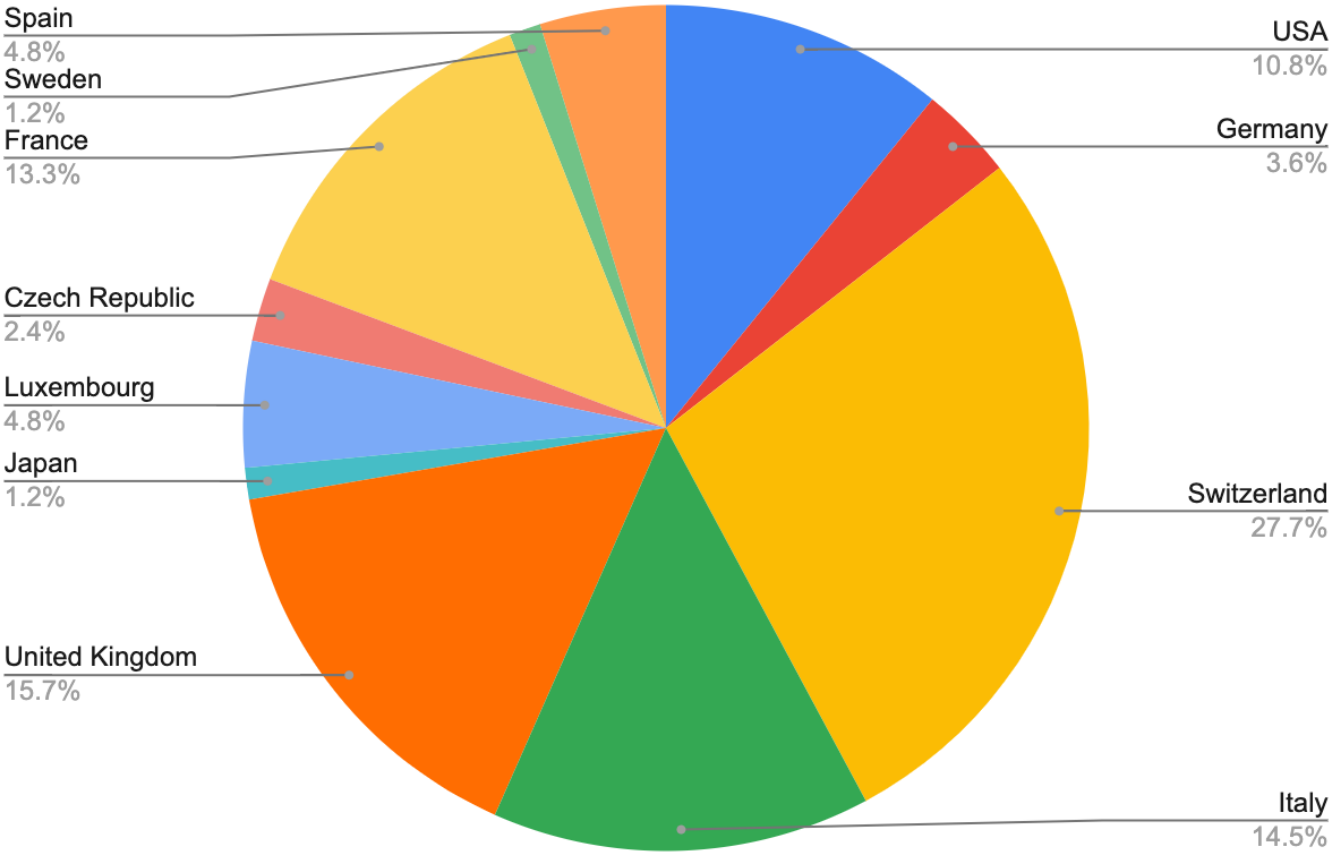
(See Moodle for updates)

Thursday 13.2.2023				
9:00-17:30	Exercises	Free time for exercises and self-study	CO3	
Friday 14.2.2023				
AM	Exercise	Free time for exercises | Oral Exams	CO5 & 6	
PM	Exercise	Free time for exercises | Oral Exams	CO5 & 6	

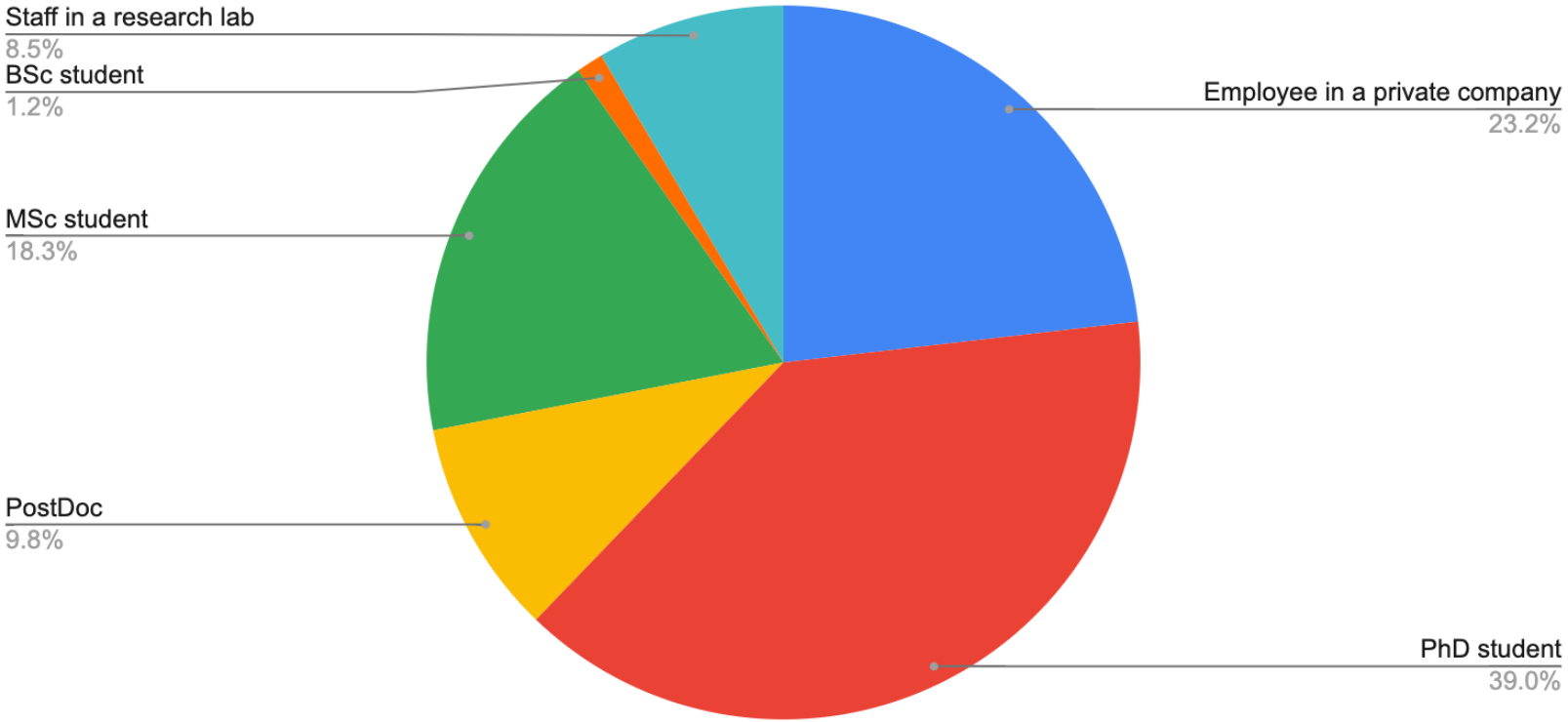
Events/activities

- **Poster session: Thursday 6th 15:30-18:00, CO lobby**
  - Responsible: Sara Dubbioso
  - Please announce your poster title to Sara if you have not done so yet
- **TCV Tour: Thursday 6th 17:00-18:30**
  - Responsible: Cassandre Contré
  - Let Cassandre know if you will **NOT** join
- **Thursday dinner**
  - 19:30 Chalet Suisse, Lausanne (map)
  - Approximately 50CHF, choice of 3 menus
  - Let us know your attendance today
  - Responsible: Pedro Molina
- **Saturday snow activity**
  - Responsible: Reinart Coosemans & Pedro Molina

Who is here?


Spain
4.8%
Sweden
1.2%
France
13.3%
Czech Republic
2.4%
Luxembourg
4.8%
Japan
1.2%
United Kingdom
15.7%
USA
10.8%
Germany
3.6%
Switzerland
27.7%
Italy
14.5%

Who is here?


Staff in a research lab
8.5%
BSc student
1.2%
MSc student
18.3%
PostDoc
9.8%
Employee in a private company
23.2%
PhD student
39.0%

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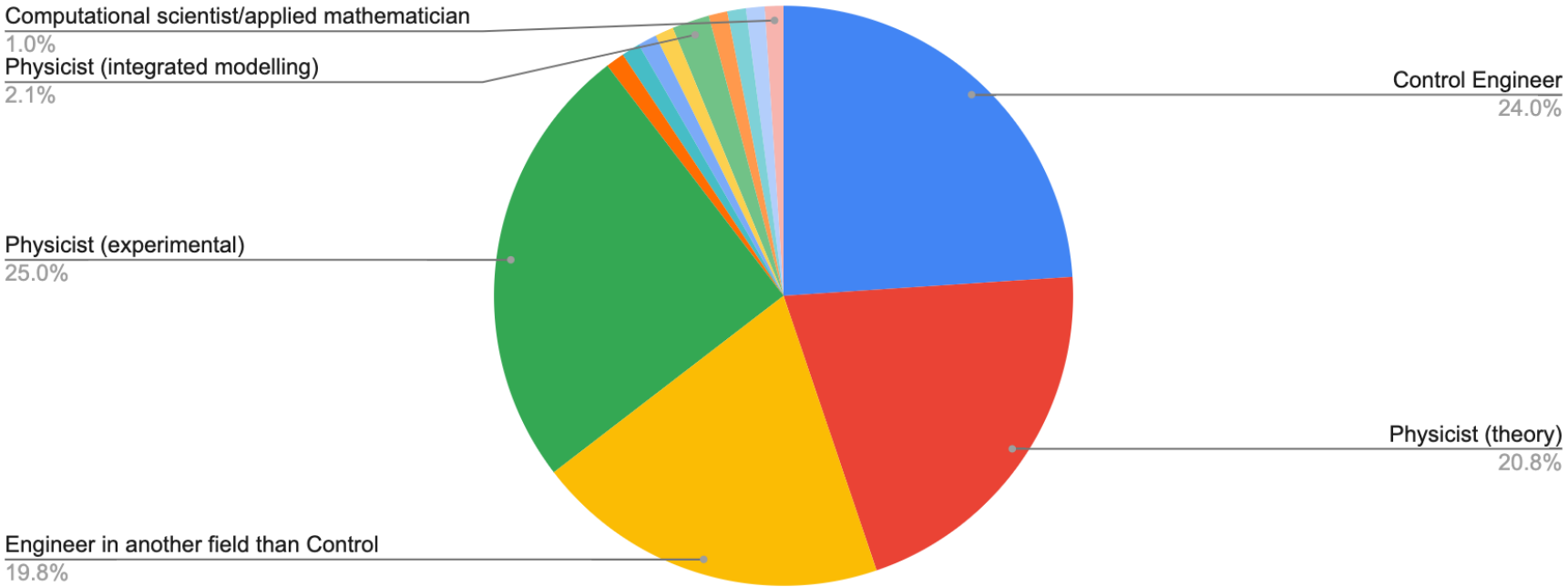
Computational scientist/applied mathematician
1.0%
Physicist (integrated modelling)
2.1%
Control Engineer
24.0%
Physicist (experimental)
25.0%
Physicist (theory)
20.8%
Engineer in another field than Control
19.8%

Who is here?

Final words before we start

- Diverse backgrounds - diverse knowledge sources and knowledge gaps
- Follow what you can - there’s something to take away for everyone
- Pair up with someone with a different skillset - help each other
- Ask questions
- Have fun