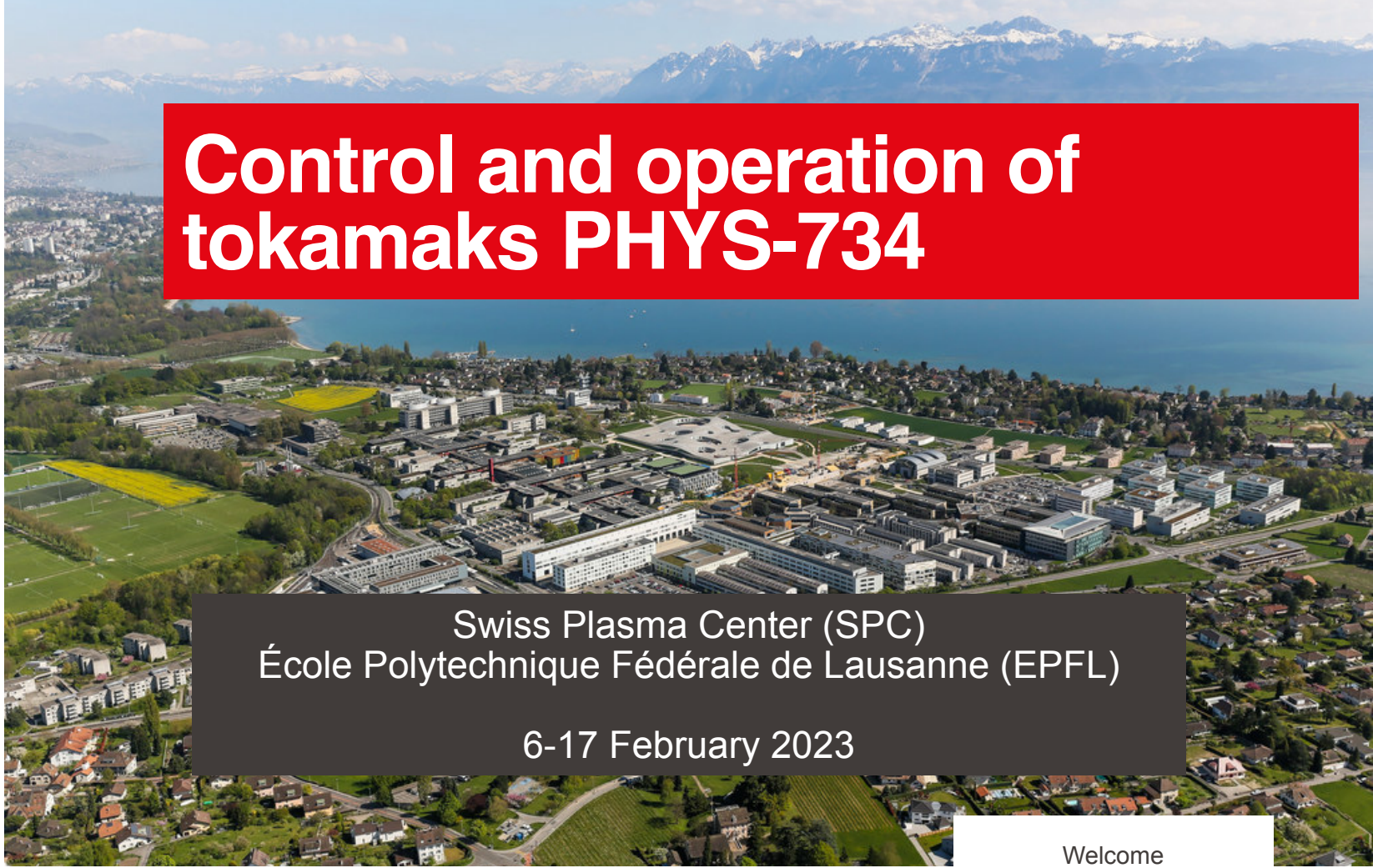
Control and operation of tokamaks PHYS-734



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

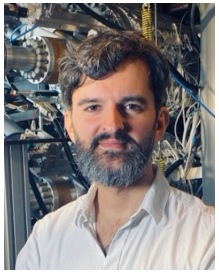
6-17 February 2023

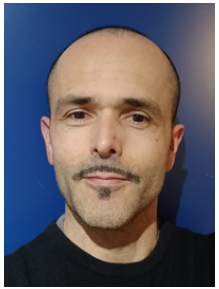
Welcome

SWISS PLASMA CENTER

Lecturers

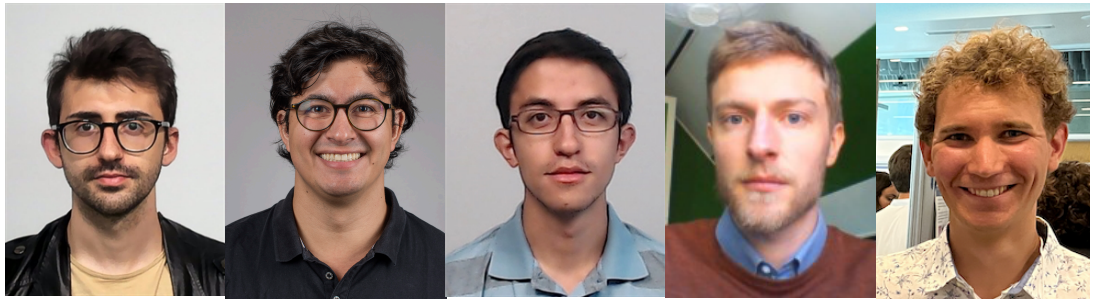
- Federico Felici
- Antoine Merle
- Cristian Galperti
- Holger Reimerdes
- Alessandro Pau





Teaching Assistants

- Francesco Pastore
- Daniel Biek
- Pedro Molina
- Reinart Coosemans
- Stefano Marchioni



- Cassandre Contré
- Michele Marin
- Antonia Frank
- Simon van Mulders
- Mengdi Kong

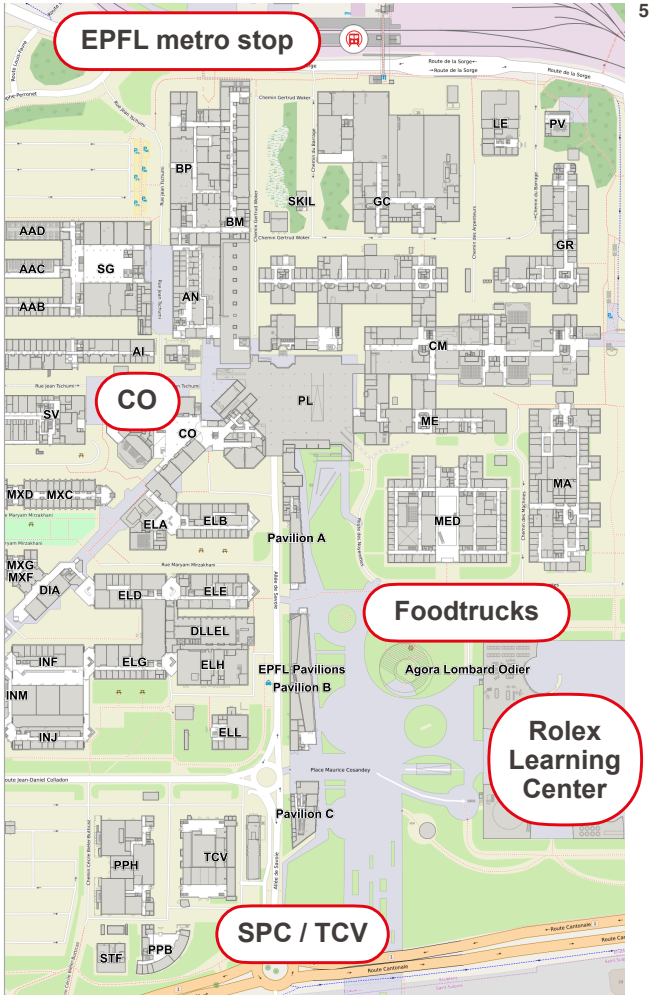
Course background

- **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
- **Now extended over 2 weeks.. with enhanced local and international participation!**

Logistics

- Room CO3 for lectures
- Rooms CO5 & CO6 for exercises

- We start at 9:00, most days, in CO3



Computing / Software for exercises

- **Exercises are in MATLAB**
- **Rooms CO5 and CO6 have workstations with Windows and MATLAB 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 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, 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 16th
- List of questions will be distributed
- Topics covered marked with * in course schedule
- 2ECTS = 28h lectures + 28h self-study

Course schedule - Week 1

(See Moodle for updates)

Monday 6.2.2023				
9:00-11:00	Lecture 0	General Intro & basic control recap	CO3	*
11:00-12:30	Lecture 1	Magnetic Control 1: Currents & Fields	CO3	*
13:30-15:15	Lecture 1	Magnetic Control 1: Currents & Fields	CO3	*
15:30-17:30	Exercise 1	Exercise 1: PF coil current control	CO5 & 6	*
Tuesday 7.2.2023				
9:00-10:45	Lecture 2	Magnetic control 2: Ip control	CO3	*
11:00-12:30	Lecture 2	Magnetic control 2: Mag. Measurements	CO3	*
13:30-15:30	Exercise 2	Exercises: Ip control / plasma reconstruction	CO5 & 6	*
16:00-17:45	Lecture 3	Magnetic control 3: RZ control	CO3	*
Wednesday 8.2.2023				
9:00-10:45	Lecture 3	Magnetic control 3: RZ control	CO3	*
11:00-12:30	Exercise 3	Exercises: R,Z control: Nyquist, loop gain tuning etc	CO5 & 6	*
13:30-15:45	Exercise 3	Exercises: R,Z control: Nyquist, loop gain tuning etc	CO5 & 6	*
16:00-17:45	Lecture 4	Magnetic control 4: Grad-Shafranov equations & Free boundary inverse solvers: MEQ suite of codes, FBT & LIUQE	CO3	*

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	CO3	*
13:30-15:30	Poster session	Mini poster session	CO hallway	
15:30-16:45	Lecture 6	Technology lecture	CO3	
17:00-18:30	Visit	TCV/SPC visit	TCV / PPH?	
19:00-?	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 7	Divertor heat flux control	CO3	
13:30-15:45	Exercise	Free time for exercises	CO3	
16:00-17:45	Exercise	Free time for exercises	CO3	

Course schedule - Week 2

(See Moodle for updates)

Monday 13.2.2023				
9:00-12:30	Lecture 8	Magnetic control 5: Free boundary evolution & contr	CO3	
13:30-17:30	Exercise 8	Free boundary evolution exercise	CO5 & 6	
Tuesday 14.2.2023				
9:00-10:15	Lecture 9	Kinetic control actuators & diagnostics, 0D kinetic co	CO3	*
10:30-12:30	Exercise 9	0D kinetic control exercise	CO5 & 6	*
13:30-17:30	Exercise	Free time for exercises	CO5 & 6	*
Wednesday 15.2.2023				
9:00-12:30	Lecture 10	1D proflie dynamics and control	CO3	*
11:30-12:30	Exercise 10	RAPTOR code and exercise introduction	CO3	*
13:30-17:30	Exercise 10	Profile evolution (RAPTOR) exercise	CO5 & 6	*

Course schedule - Week 2

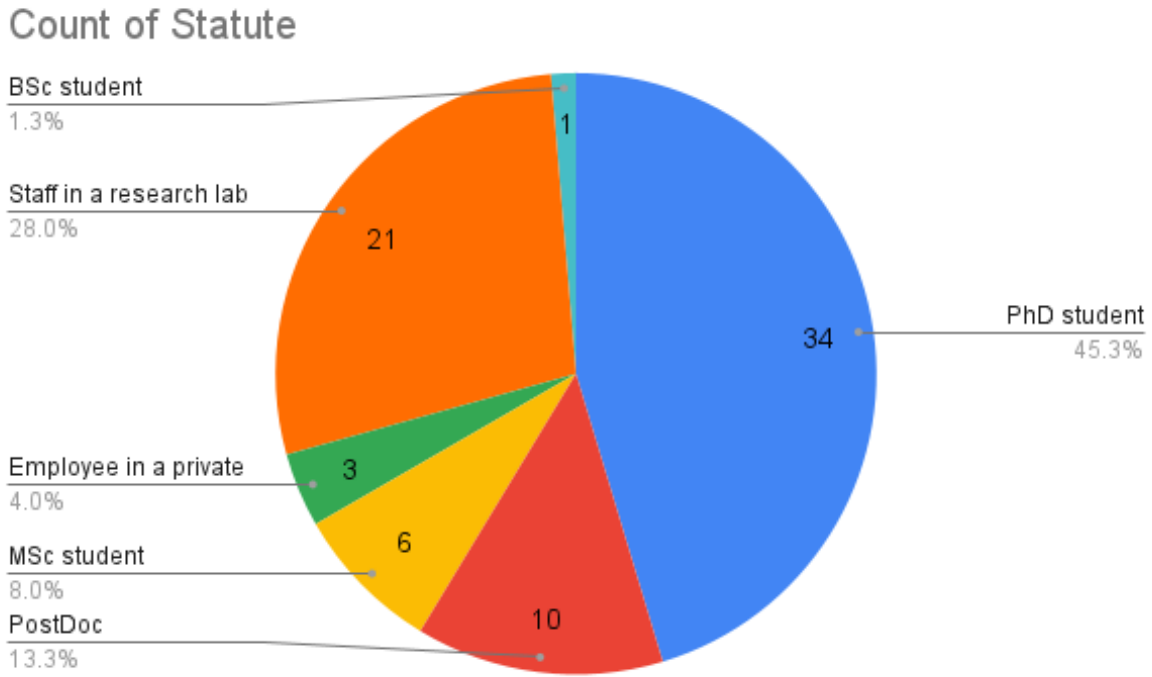
(See Moodle for updates)

Thursday 16.2.2023				
9:00-11:30	Lecture 11	Machine Learning for plasma control	CO3	
11:30-12:30	Lecture 11	Magnetic control of TCV through deep Reinforcement Learning	CO3	
13:30-15:00	Lecture 12	Emerging topics: supervisory control & actuator management, needs for ITER, etc	CO3	
15:00-16:00	Lecture 12	Dynamic pulse scheduling and disruption avoidance	CO3	
16:00-17:30	Exercise	Free time for exercises	CO5 & 6	
Friday 17.2.2023				
AM	Exercise	Free time for exercises | Oral Exams	CO5 & 6	
PM	Exercise	Free time for exercises | Oral Exams	CO5 & 6	

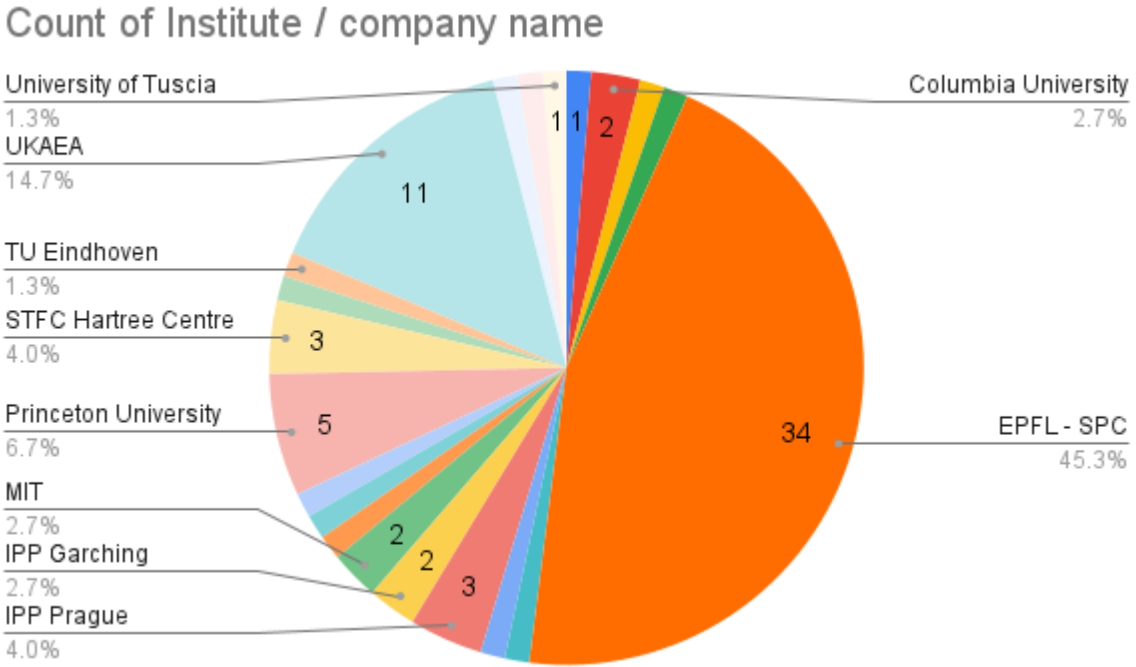
Events/activities

- **Poster session: Thursday 9th 13:30-15:30, CO second floor**
  - Responsible: Simon van Mulders
  - Please announce your poster title to Simon if you have not done so yet
- **TCV Tour: Thursday 9th 17:00-18:30**
  - Responsible: Cassandre Contré
  - Let Cassandre know if you will **NOT** join
- **Thursday dinner**
  - 19:30 Chalet Suisse, Lausanne (map)
  - Approximately 30CHF for main course (fondue, raclette, …)
  - Let us know your attendance after the coffee break
  - Responsible: Pedro Molina
- **Saturday snow activity**
  - Responsible: Antonia Frank & Pedro Molina

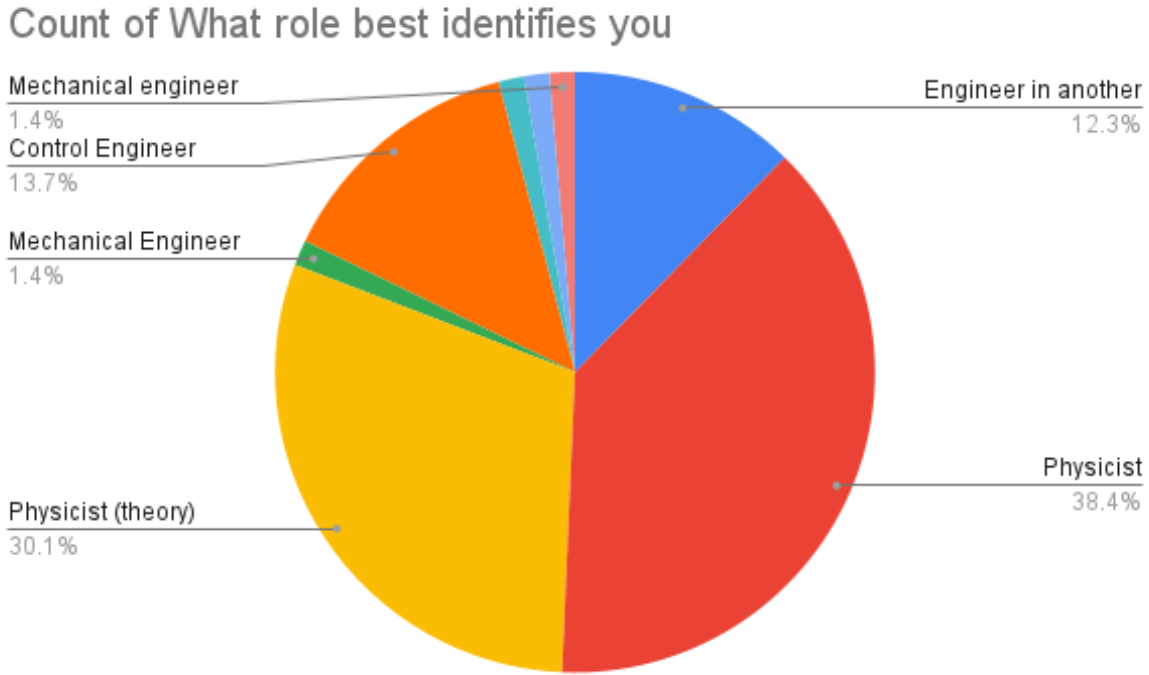
Who are you


Count of Statute
BSc student
1.3%
Staff in a research lab
28.0%
Employee in a private
4.0%
MSc student
8.0%
PostDoc
13.3%
PhD student
45.3%
1
21
3
6
10
34

Who are you


Count of Institute / company name
University of Tuscia
1.3%
UKAEA
14.7%
TU Eindhoven
1.3%
STFC Hartree Centre
4.0%
Princeton University
6.7%
MIT
2.7%
IPP Garching
2.7%
IPP Prague
4.0%
Columbia University
2.7%
EPFL - SPC
45.3%
1
1
2
11
3
5
2
2
3
34

Who are you


Count of What role best identifies you
Mechanical engineer
1.4%
Control Engineer
13.7%
Mechanical Engineer
1.4%
Physicist (theory)
30.1%
Engineer in another
12.3%
Physicist
38.4%

Final words before we start

- 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