Ingeniería Eléctrica y temas afines

Superconductivity in Power Systems Engineering

Frederic Trillaud
Institute of Engineering
National Autonomous
University of Mexico

08/02/21

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- Low Temperature Superconductors (LTS)
- High Temperature Superconductors (HTS)
- Superconductivity: basic property
- Critical surface
- Applications in Power Systems Engineering (PSE)
- A couple of videos: application and potential issue
- REBCO technology (commercial tape)
- Modelling in PSE
- Current projects and status
- Conclusion
- “Posgrado en Ingeniería de la UNAM”

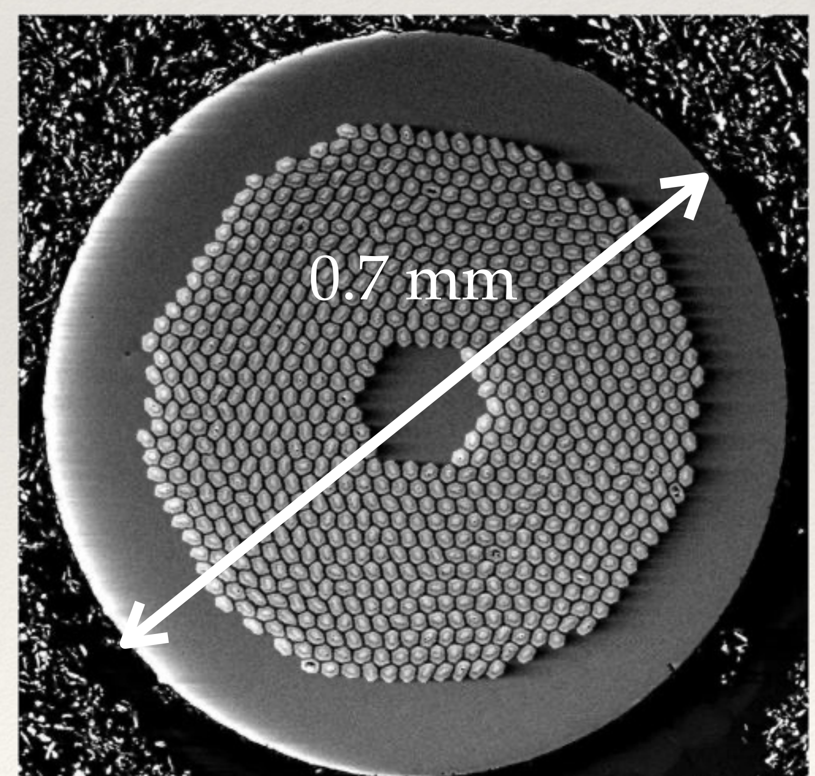
Low Temperature Superconductors (LTS)

- Discovered in the 60s
- “Low temperature” -> operated in liquid helium (boiling point: 4.2 K or -269°C)
- NbTi: the first and most superconductor used in actual applications (very manuable)
- Nb_3Sn: next generation(?) with better characteristics (heat treatment required and brittle)

NbTi

Luvata: https://www.luvata.com/products/superconductors

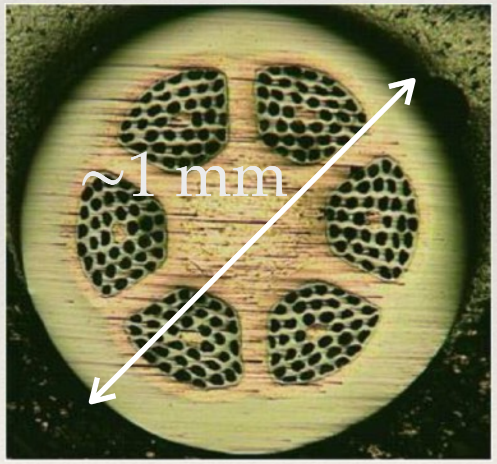
Nb_3Sn



http://www.hypertechresearch.com/nb3sn%20wire.htm

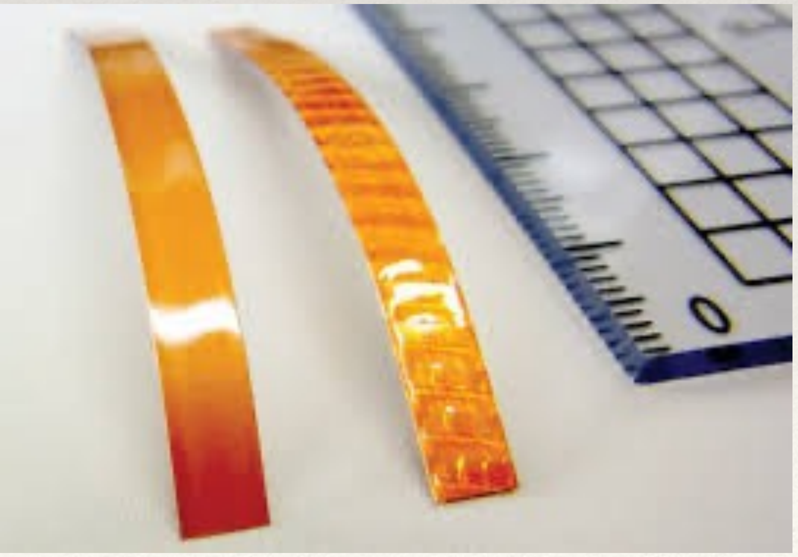
High Temperature Superconductor (HTS)

- Discovered in the 80s (BSCCO and YBCO), in 2001 for MgB_2
- "High temperature" -> operated above 10 K using liquid hydrogen (LH at 20 K) or liquid nitrogen (LN2 at 77.3 K)
- Family of BSCCO (Bi2223 and Bi2212): the most used, very sturdy (tapes and wires)
- REBCO, GdBCO or YBCO: trendy due to its high current density, but fragile technology
- MgB_2: in development, promising to be the cheapest technology. Very similar to Nb_3Sn technology



http://www.hypertechresearch.com/mgb2%20wire.htm

https://sumitomoelectric.com



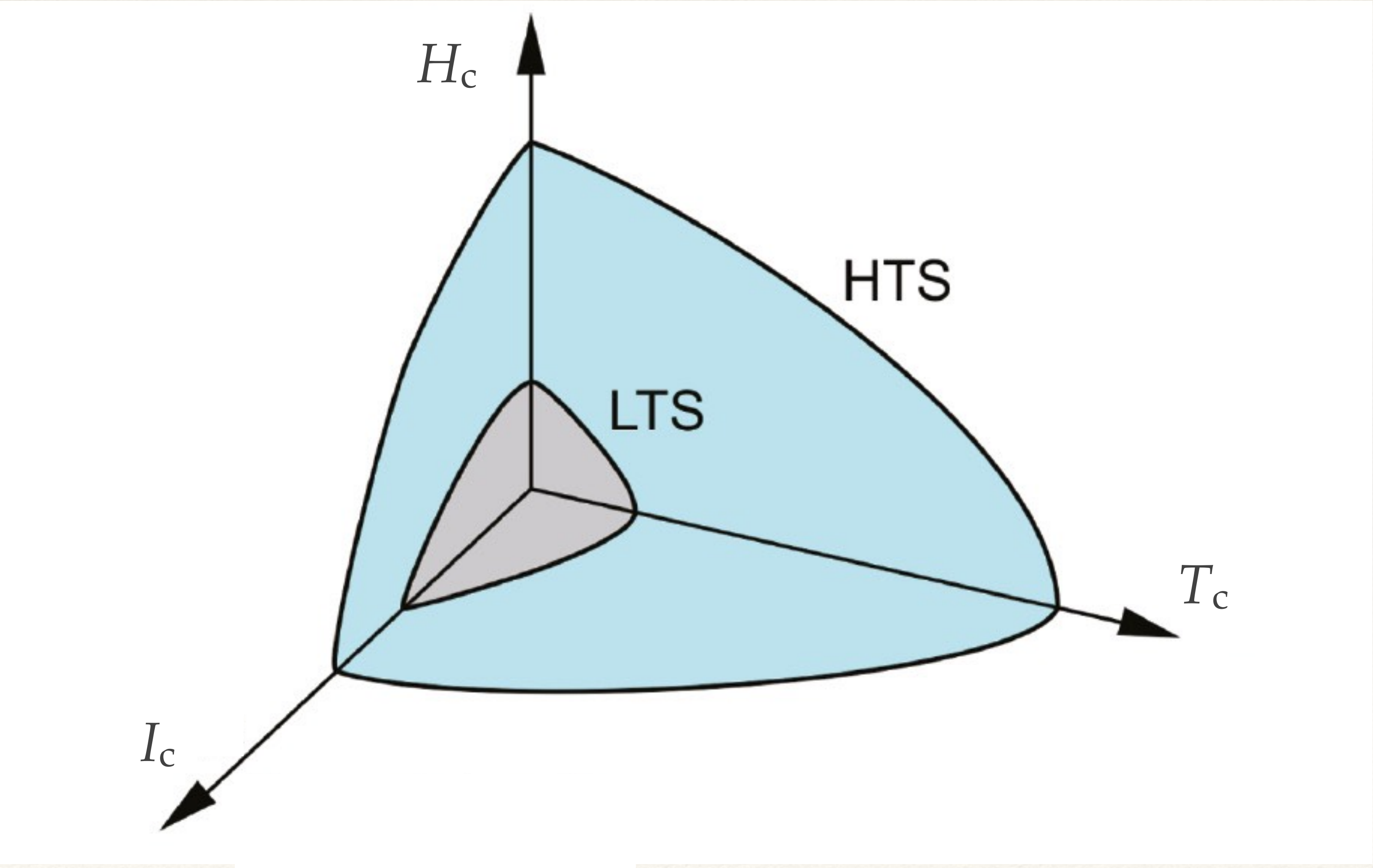
https://www.nanowerk.com/news2/newsid=32602.php

Basic property

- What makes a conductor "a superconductor"?
- One fundamental property: **No resistance** therefore no Joule dissipation **at low temperature** and under certain conditions
- What are these conditions? -> depend on the material
  - Low temperature (below -163ºC)
  - Maximum magnetic field (larger than any field produced in an electrical machine!)
  - Maximum current (very high energy density, > 100 A in 1 μm x 4 mm layer at -196ºC in self-field)
- Introduction of critical values: critical temperature (T_c), critical magnetic field (H_c) and critical current (I_c)

Critical values

- The critical values are the maximum values for which the conductor is still in its superconducting state
- "Above" the critical values (critical surface), the superconductor becomes highly resistive



Critical surface:

$$I_c = f\left(T_c, \mu_0 H_c\right)$$

Modified from: Bussmann-Holder, A., & Keller, H. (2020). Zeitschrift für Naturforschung B, 75(1-2), 3-14.

Superconductors for PSE

- Even though LTS are the most used, the trend in Power Systems Engineering is HTS
- Reason -> high energy density at a simplified cryogenic system (use of liquid nitrogen for instance)
- Materials:
  - BSCCO, REBCO with LN2 around 77 K -> first prototypes installed in the electrical grids
  - MgB_2 with LH around 20 K -> laboratory scale

Applications

- The following tables show the applications considered nowadays for commercial superconductors

	BSCCO	REBCO	MgB_2
Cables	X	X	X
Transformers	X	X	
Fault-current limiters	X	X	
Motors/ Generators		X	X
Railways		X	

Some examples of applications

Cobra: https://www.mdpi.com/2078-2489/11/11/531/htm

https://esdnews.com.au/superconductors-super-solution/

M.P. Staines, et al., "Superconductors in the Power Grid", Woodhead Publishing, 2015,Pages 367-397, ISBN 9781782420293.

https://www.voltimum.co.uk/articles/superconducting-fault-current-limiters

Some examples of applications

- ECOSWING: real superconducting generator for real power gird

Youtube: https://www.youtube.com/watch?v=noMtjX3uvnw

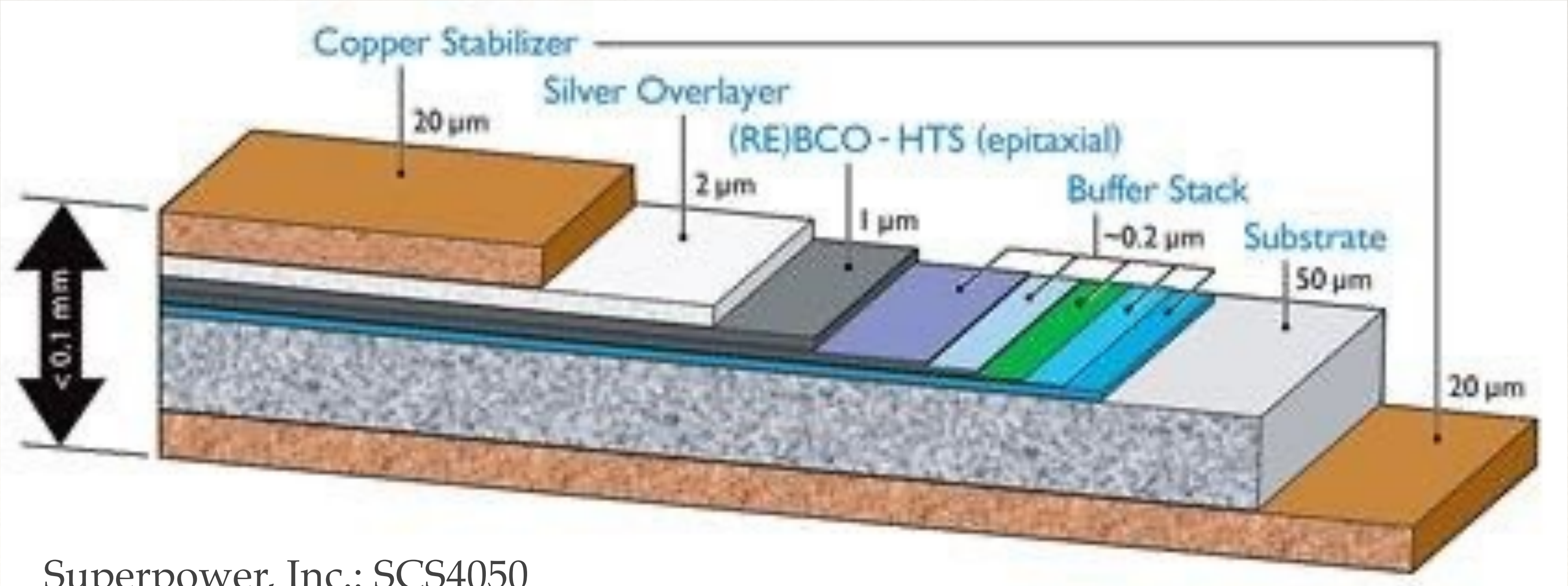
Quench

- What happens when things go wrong?
- Our work is to provide safe and reliable technology through design modeling and testing

Youtube: https://www.youtube.com/watch?v=CXWqIz68eqw

REBCO

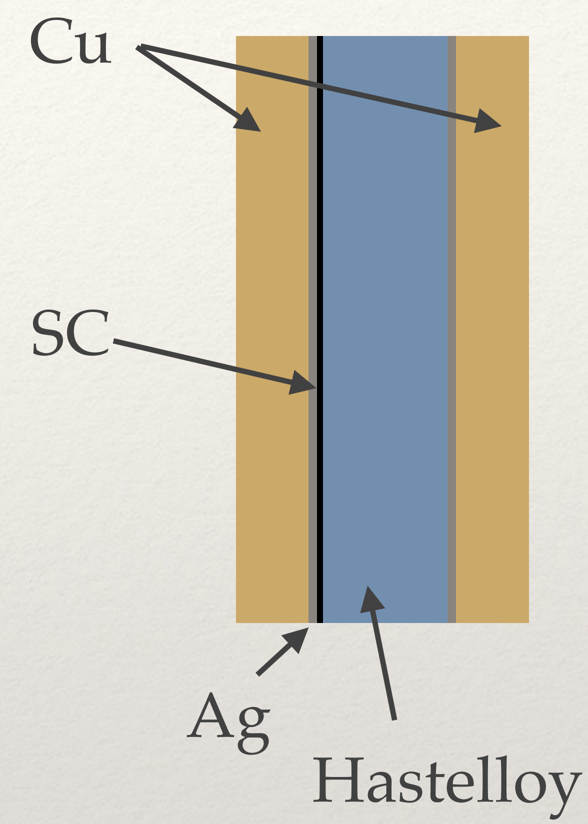
- Very promising technology due to its:
  - High energy density (high transport current in small, compact dimensions)
  - Low hysteresis losses in alternating current applications
  - Operating temperating at around 77 K (LN2)
- Drawback: can easily be damaged, careful handling is required

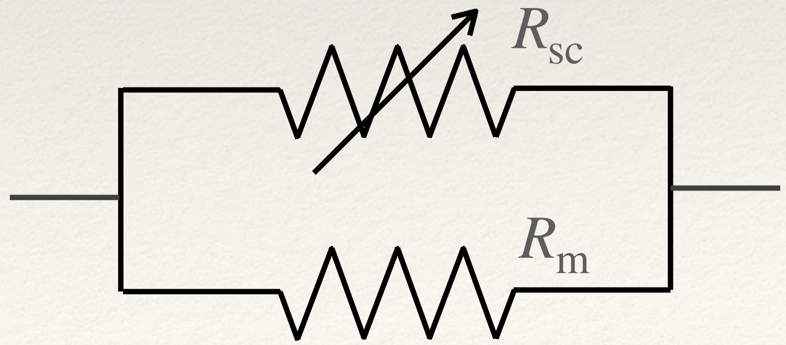


Superpower, Inc.: SCS4050

Modeling of REBCO

- Two approaches:
  - Refined models based on finite element method to study the current density distribution and the losses in the REBCO layer (SC) in the tapes -> expert level, specific studies and optimum design
  - Equivalent models including the lumped-parameter models to include a realistic thermoelectric and magnetic behavior of the tapes in an electrical machine -> Appropriate for PSE studies, trends and general challenges



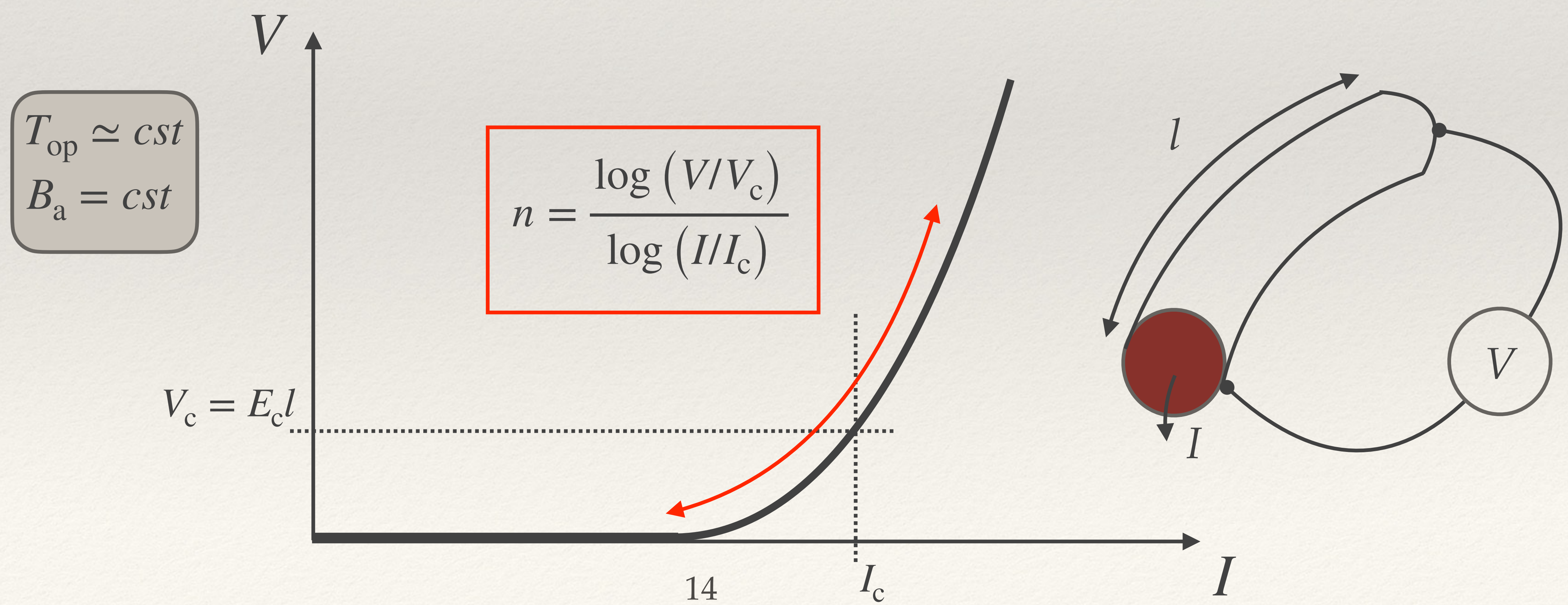


Resistance of SC: the power law

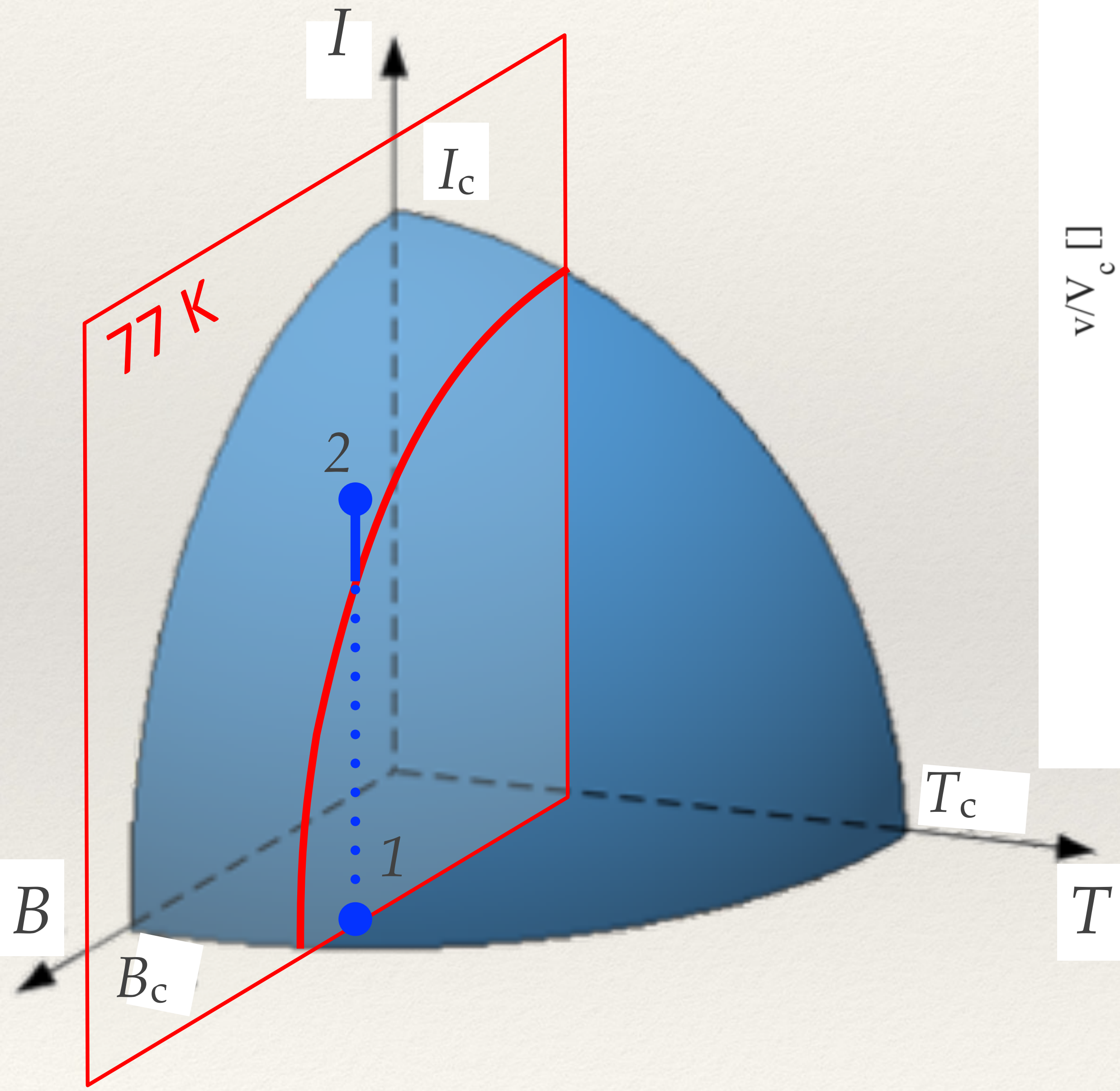
- Power model of the $V - I$ characteristics of a superconductor around its critical current I_c:

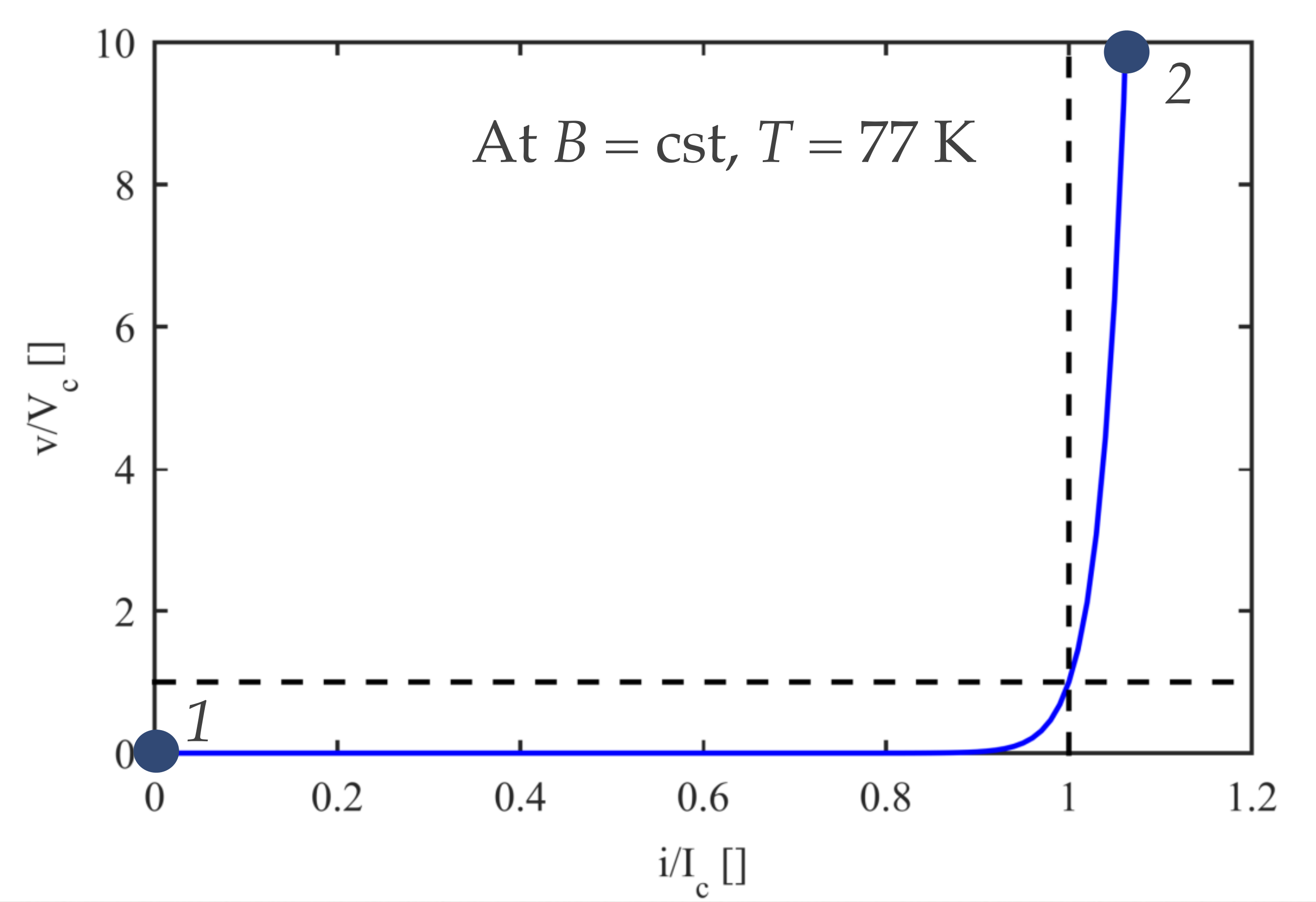
$$V = V_c \left(\frac{I}{I_c} \right)^n \quad \Rightarrow \quad R_{sc} = \frac{V}{I} = \frac{V_c}{I_c^n} I^{n-1}$$

with $V_c = E_c l$, l is the length between the voltage taps and E_c is the electrical field assumed constant across the thickness of the tape with values ranging from 0.1 to 10 μV/cm. The critical current is defined as $I_c = f\left(T, B_a\right)$



Critical surface and *V-I* characteristics



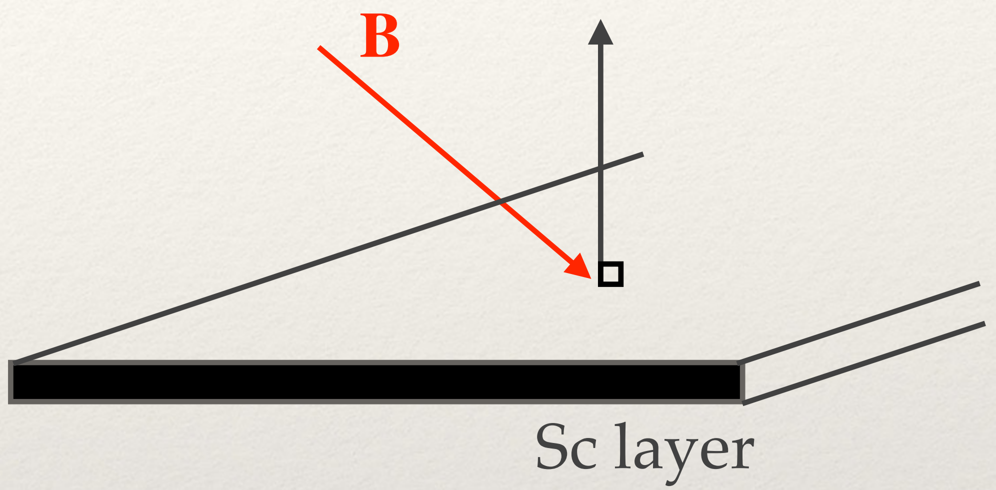


Modified from: B.B. Jensen, et al, US-China Education Review A, vol. 3, no. 3, 141-152, 2013.

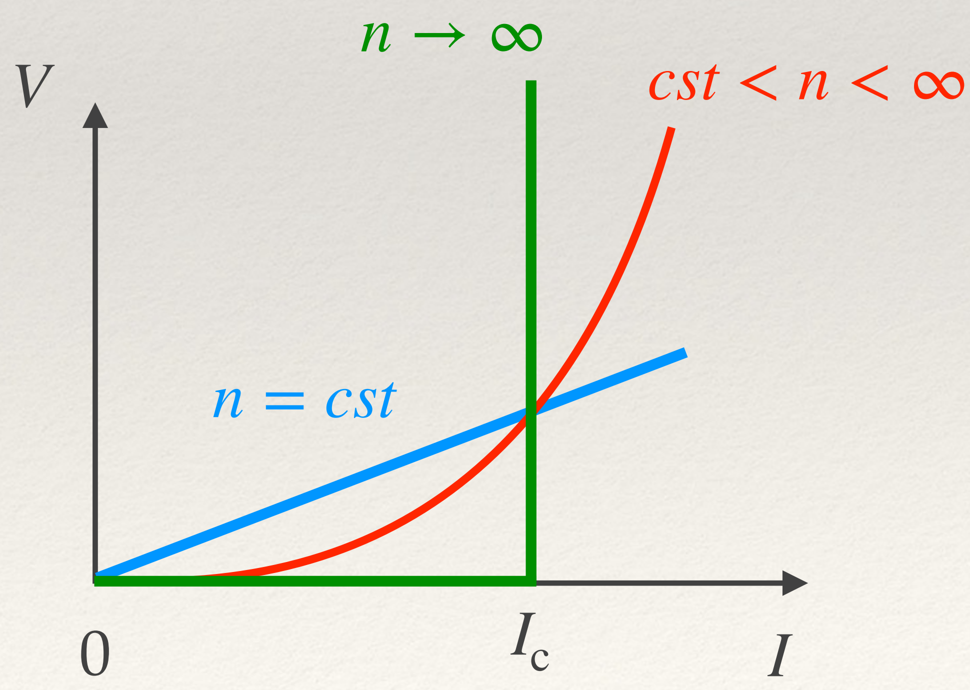
“Properties” of the superconductor

- Permeability of vacuum: $\mu_0 = 4\pi \times 10^{-7}$ H/m
- Resistivity depending on temperature, magnetic flux density and current density: $R_{sc}(T, \mathbf{B}, I)$

  Include its orientation

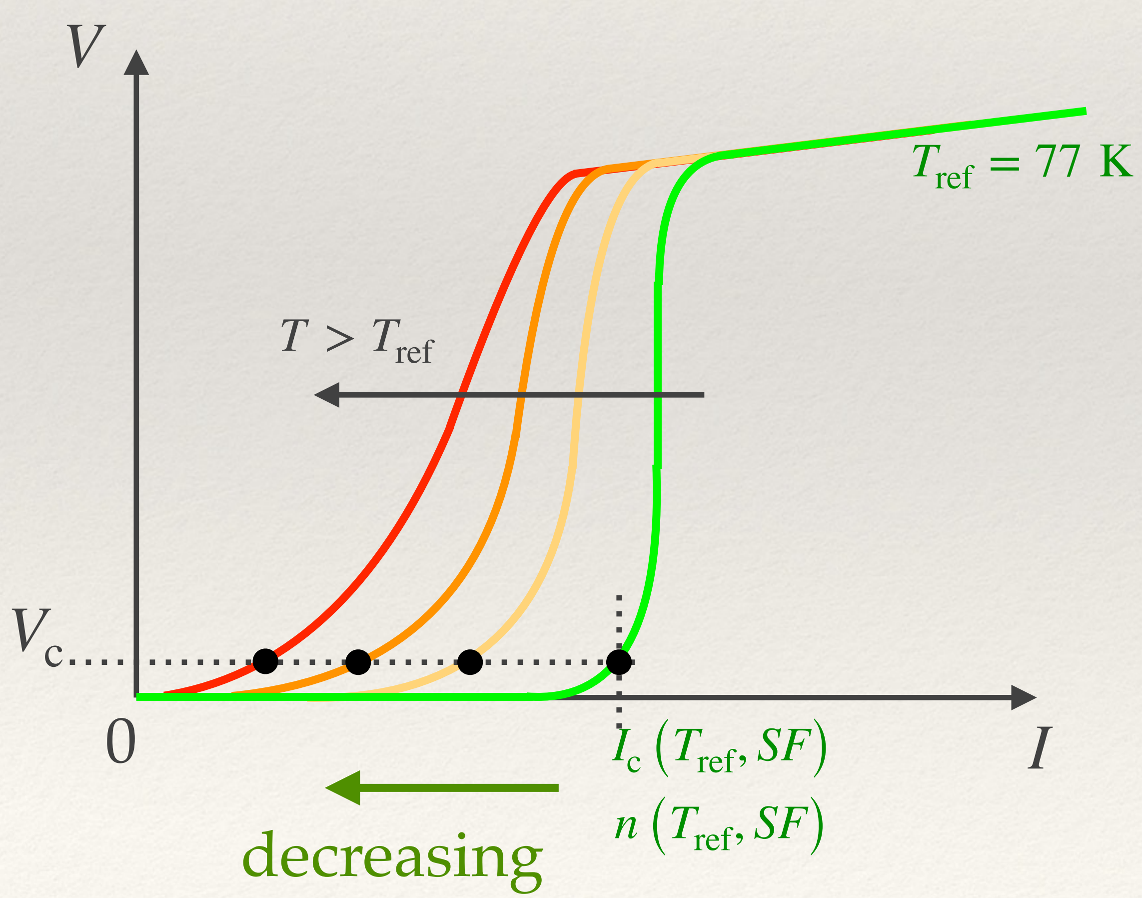


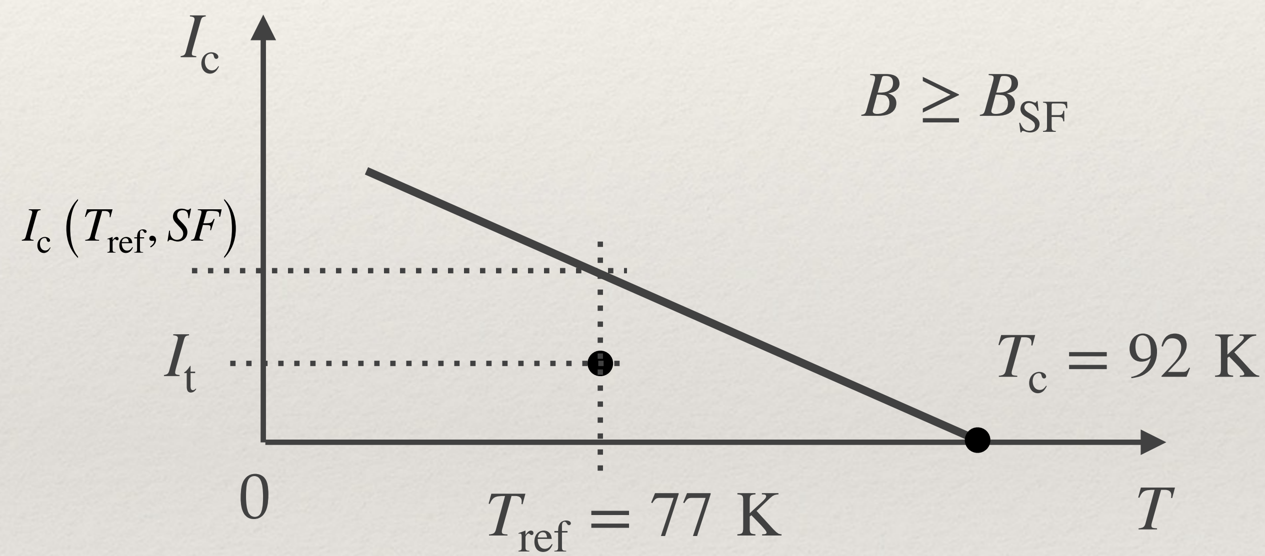
- Engineering properties depending on temperature and magnetic flux density:
  - Critical current I_c: “measure of the capacity to transmit current”
  - Index value n: “Measure of the rate of transition from the superconducting state to the normal resistive state”. For an “ideal” superconductor: $n \to \infty$

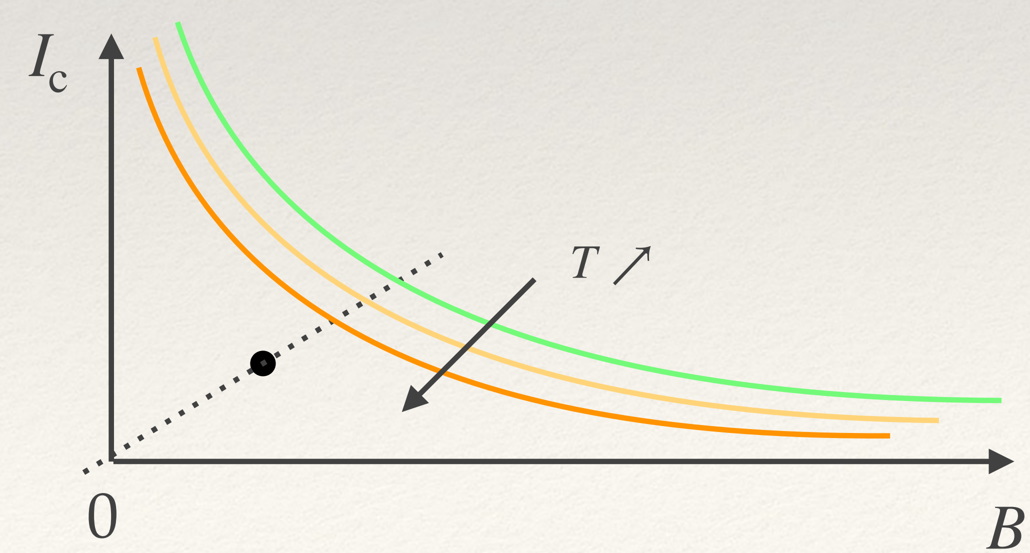


Evolution of I_c and index n

- The characteristic *V-I* depends on temperature T and magnetic flux density B
- At current magnitude passed I_c, the matrix acts as a shunt at a near constant resistance value
- The index value follows the same degradation as the temperature increase and/or the magnetic field.

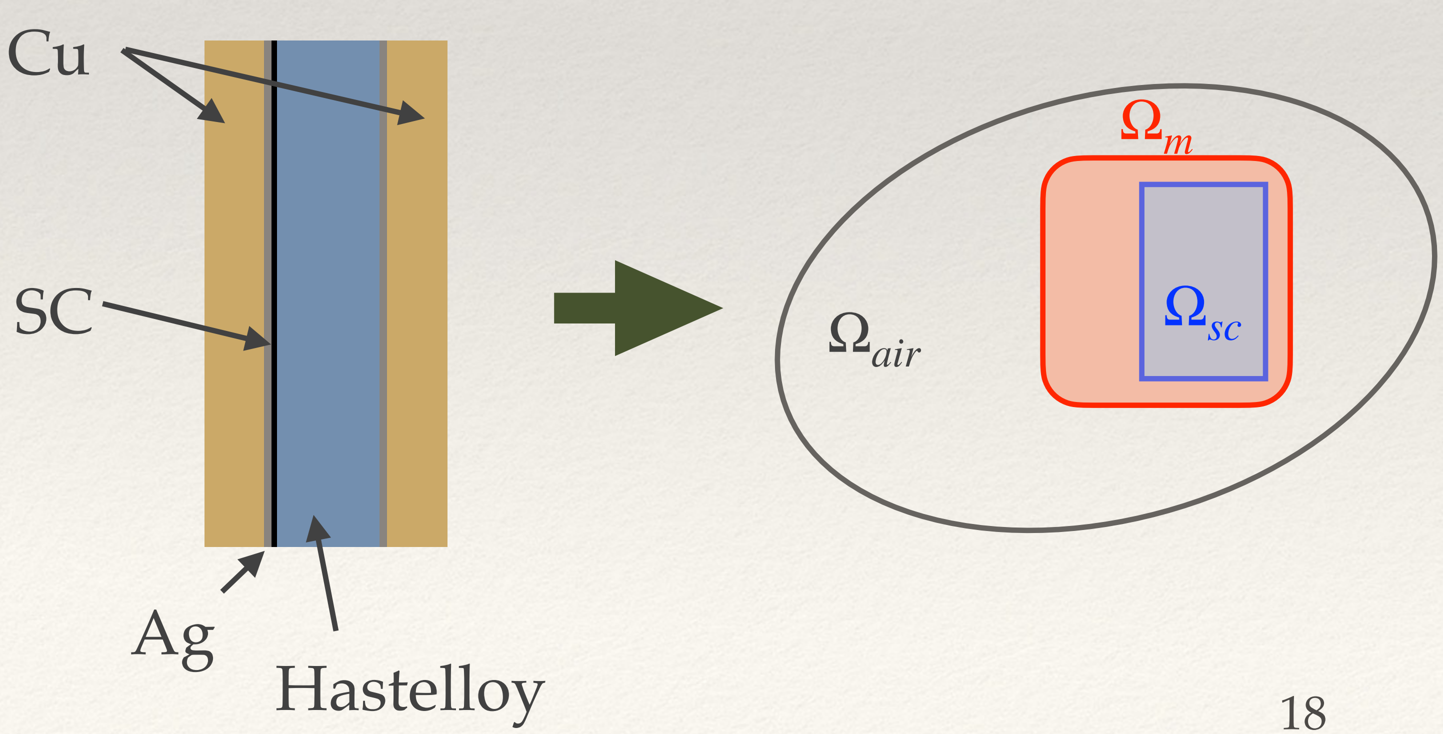




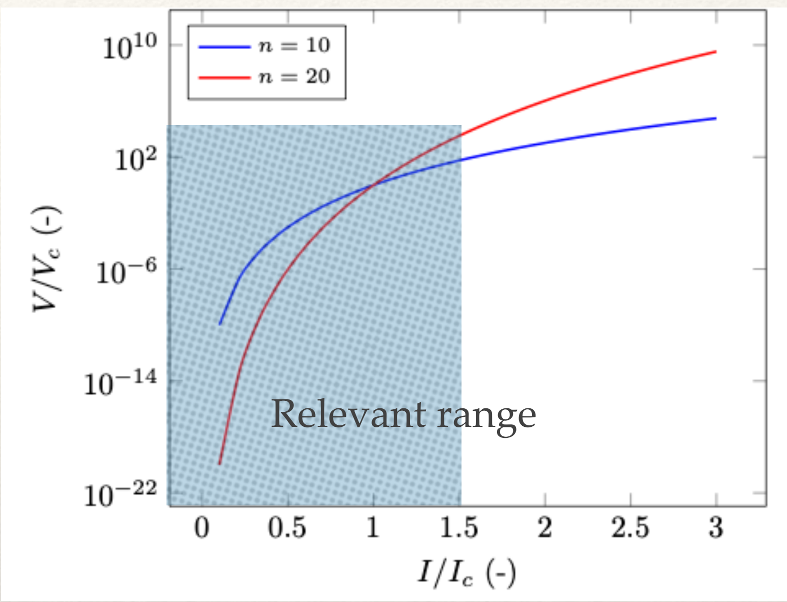


Range of validity

- Nonlinear resistivity: $R_{sc} = \frac{V_c}{I_c^n} I^{n-1}$, **validity around** I_c.
- Extension of the validity range by including the resistance of the metallic layers R_m (stabilizer)
- Equivalent parallel resistance: $R_{eq} = \frac{R_{sc} + R_m}{R_{sc} R_m}$

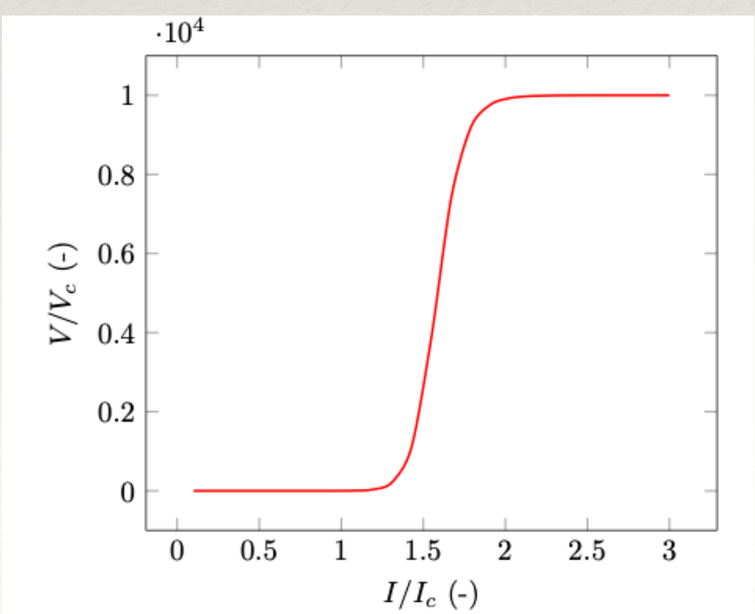


SC alone*



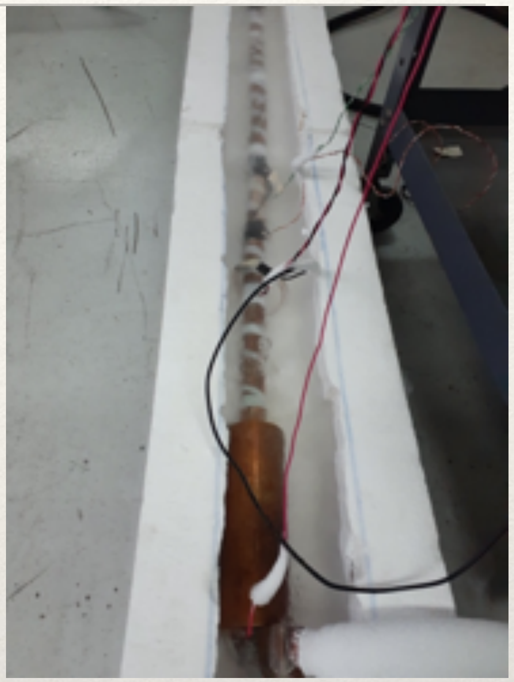
*: conceptual figures

Combined: SC and stabilizer*



Projects in Power Systems Engineering

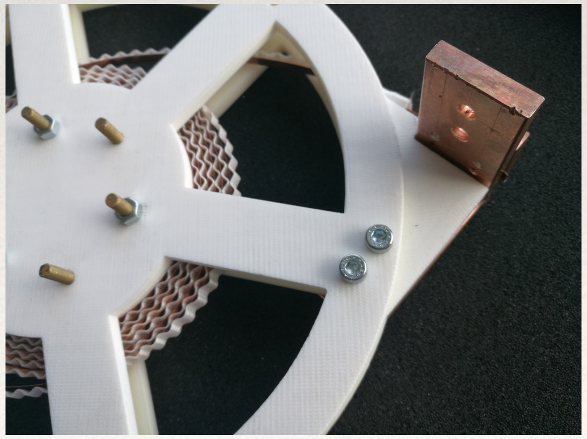
- **Power cable:** collaboration with the University of Guanajuato, Mexico (design, construction, tests in AC) and the French Engineering school CentraleSupélec, Paris-Saclay, France (Modelling and DC applications)



https://www.dgcs.unam.mx/boletin/bdboletin/2020_234.html

- **Fault-current limiter:** collaboration with the French Engineering school CentraleSupélec, Paris-Saclay, France and the Faculty of Mechanical Engineering of the UNAM, Mexico

- **Power filter:** the University of Lorraine in France and the French Engineering school CentraleSupélec, Paris-Saclay, France



Private communication, Dr. Loïc Quéval, GEEPS, France

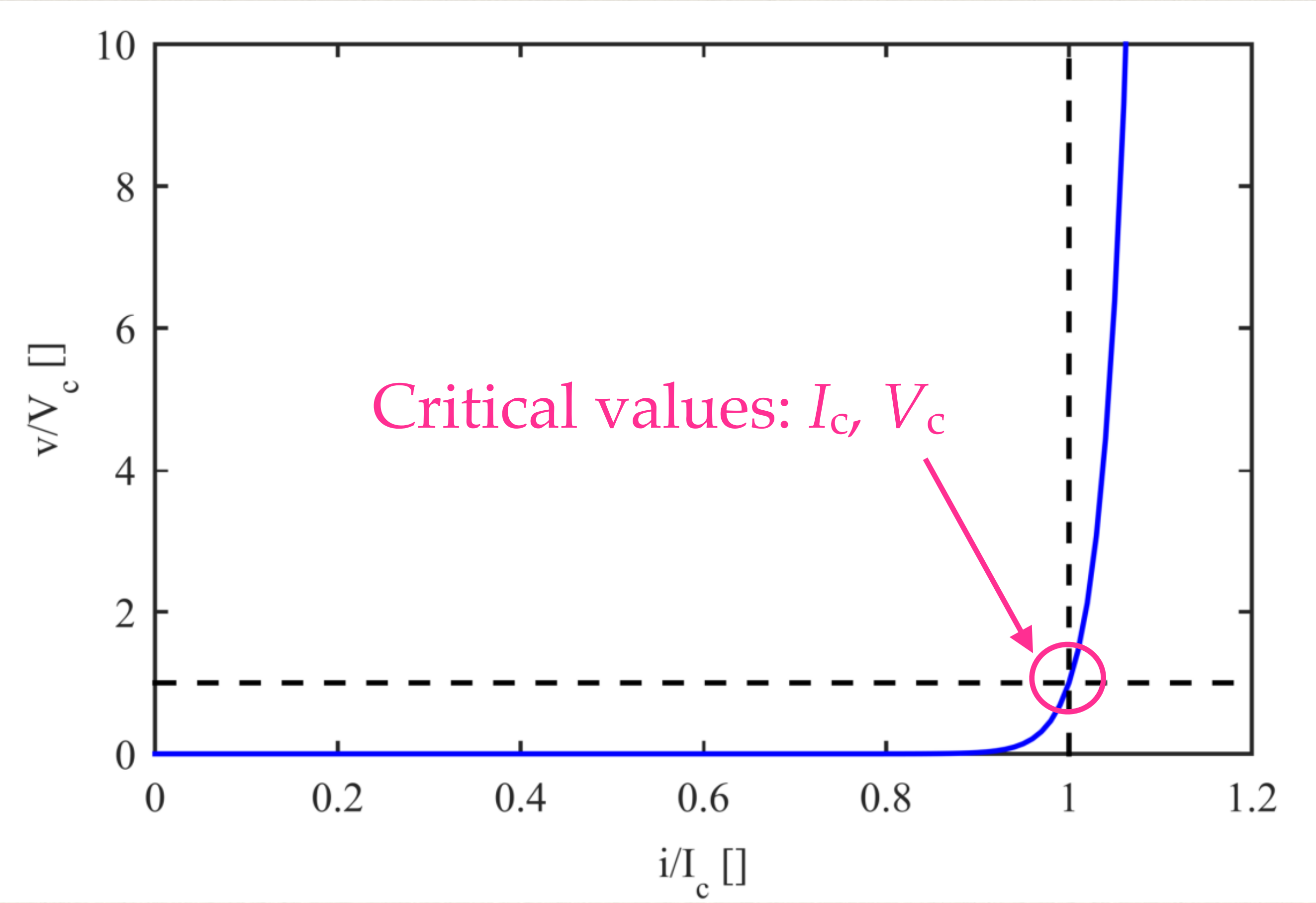
From tape to device

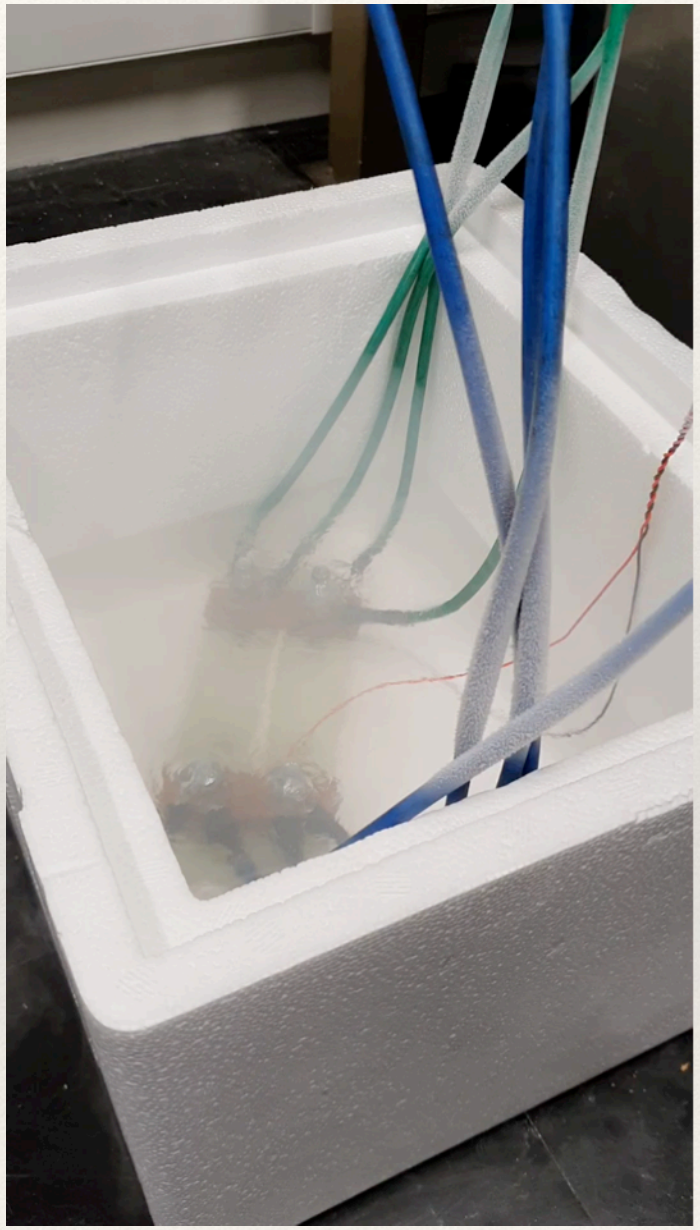
- What are our objectives?

1. Tape characterization (commercial tapes) in liquid nitrogen at -196ºC
2. Conceptual design and Modelling (Finite Element Method and/or equivalent lumped-parameter models)
3. Construction and tests in laboratories (national or foreign)

Tape characterization in LN2

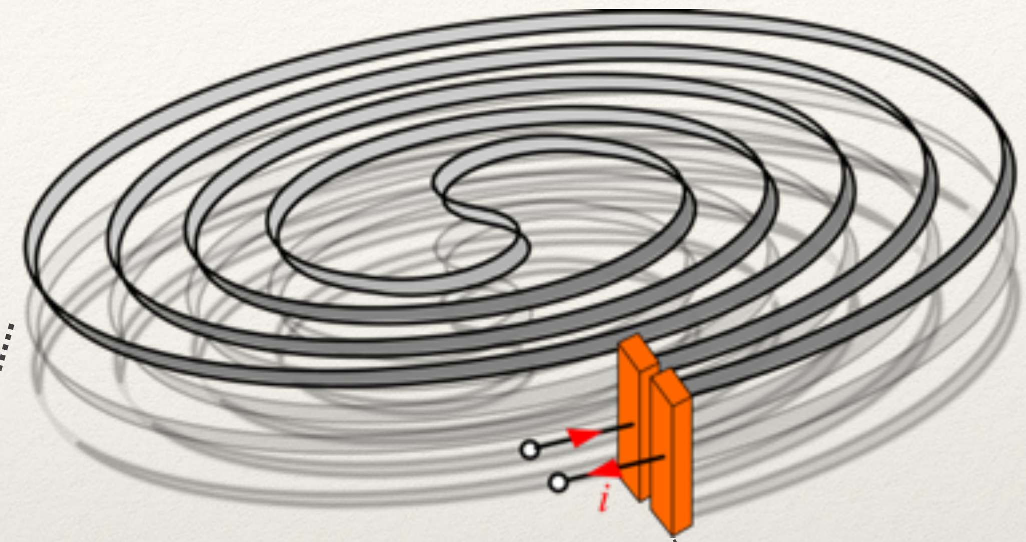
- We work exclusively with commercialized technology
- Some providers of commercial REBCO tapes are SuperPower Inc. (Japan) and SUNAM (Korea)
- Characterization in LN2 at -196ºC (77 K) -> measurement of the *V*-*I* curve and estimation of critical current I_c and *n*-index



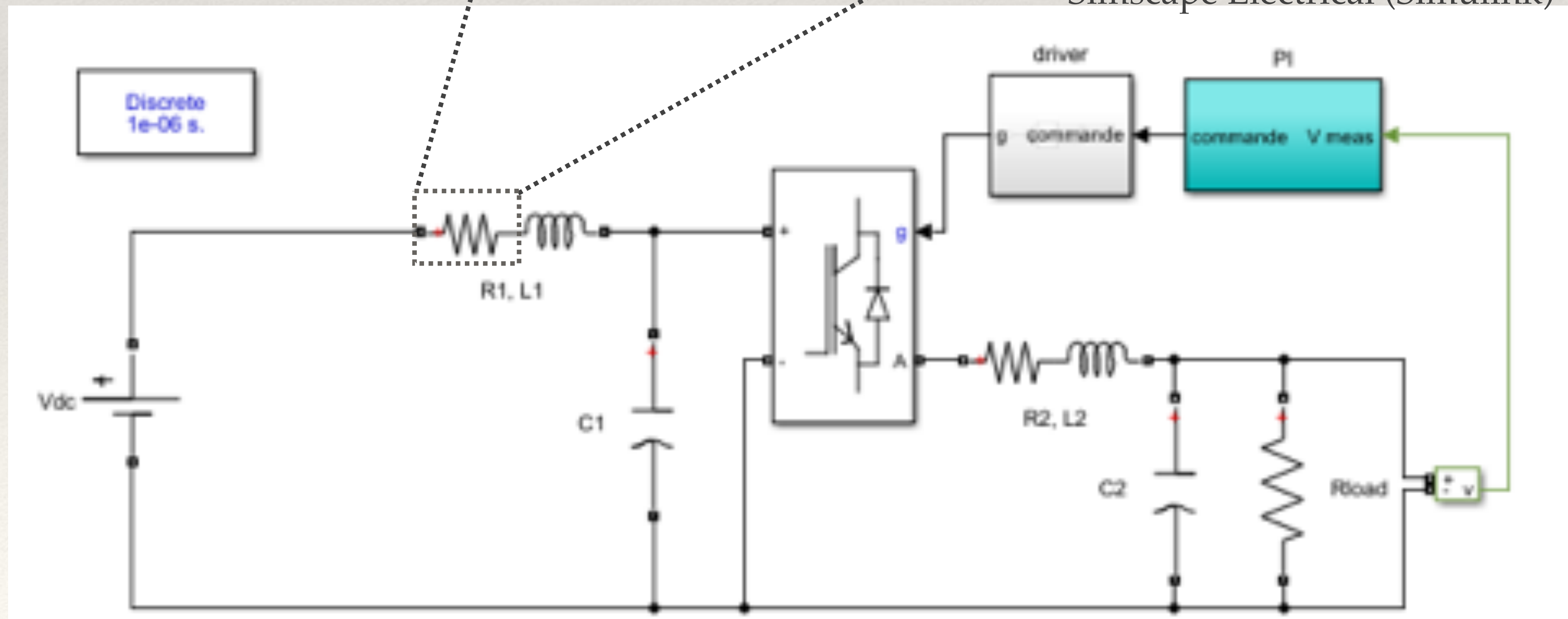


Conceptual design and modelling

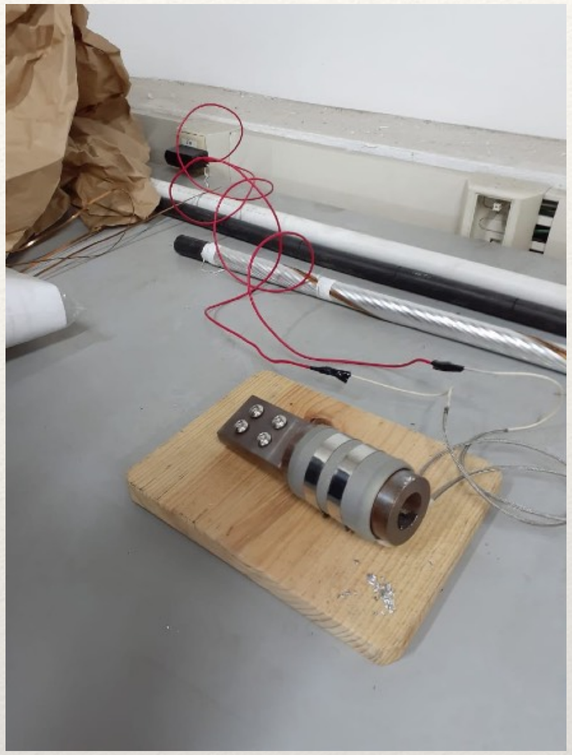
- Conceptual design on paper
- Modelling
  - Finite Element Solver
  - Grid simulator (ATP or Simscape Electrical of Matlab/Simulink)



Simscape Electrical (Simulink)



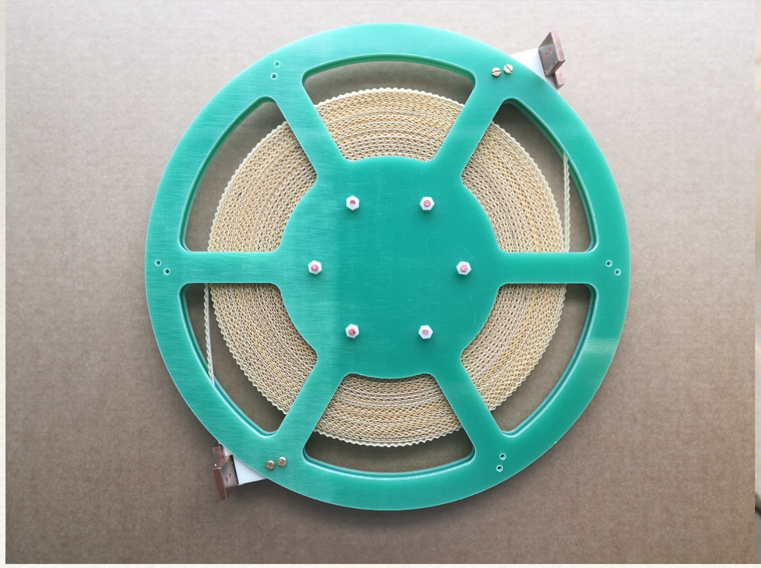
Pre-tests and tries-out



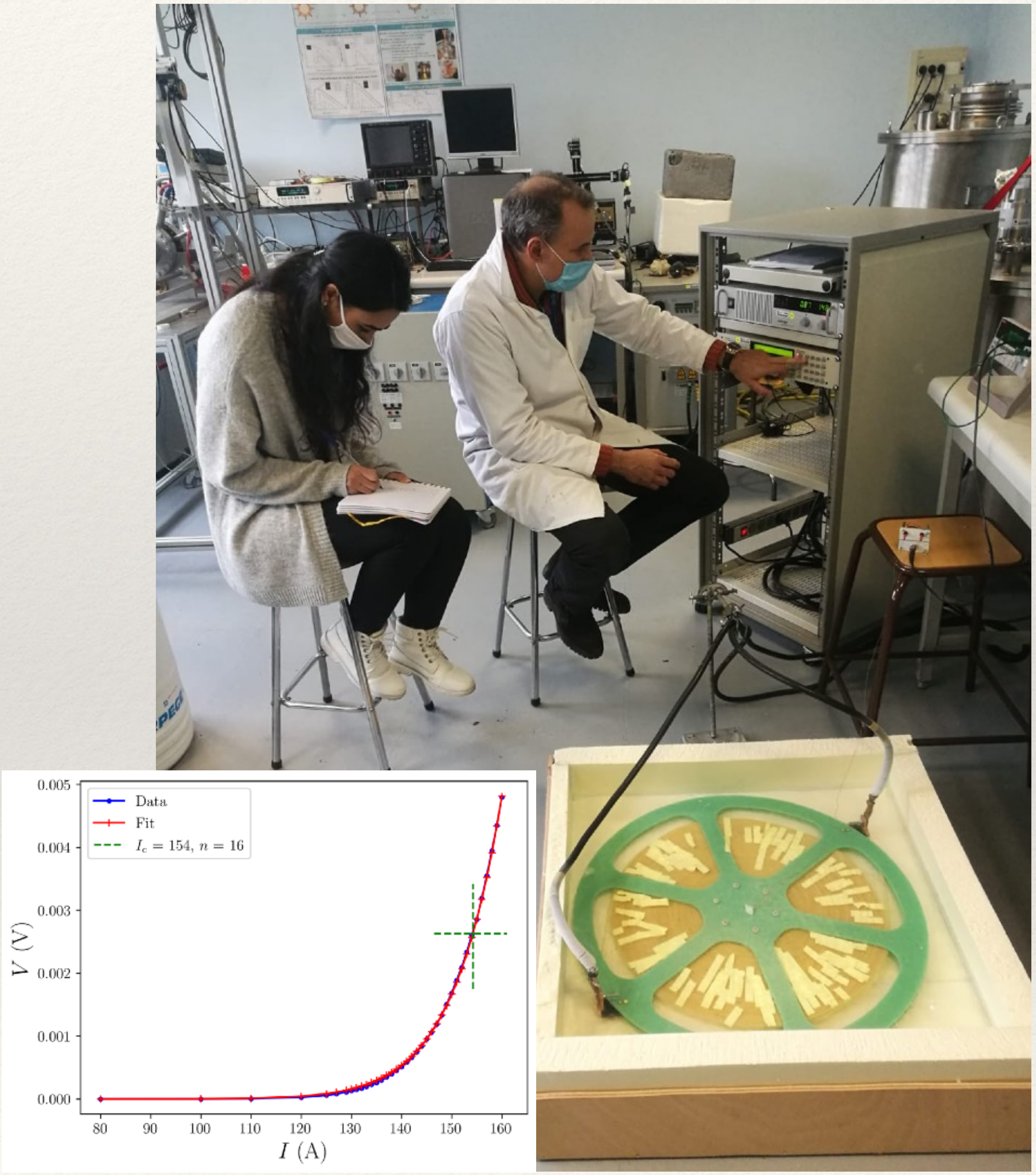
- Can we solder Cu terminals on the superconducting cable?

- Can a couple of turns of winding with its 3D-printed support hold at low temperature?

Let us give it a try!!



Tests of the device design

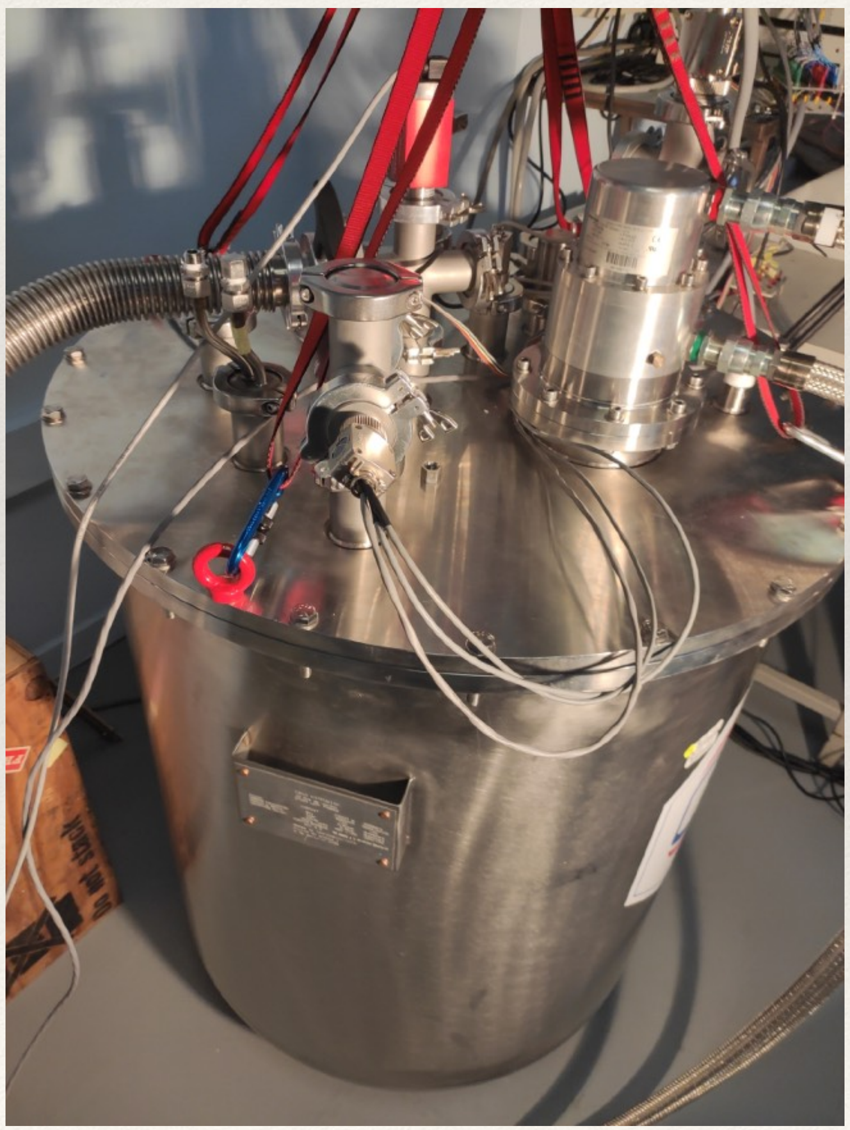


Tests of Superconducting Power Filter at the University of Lorraine, France (100 m of tape)

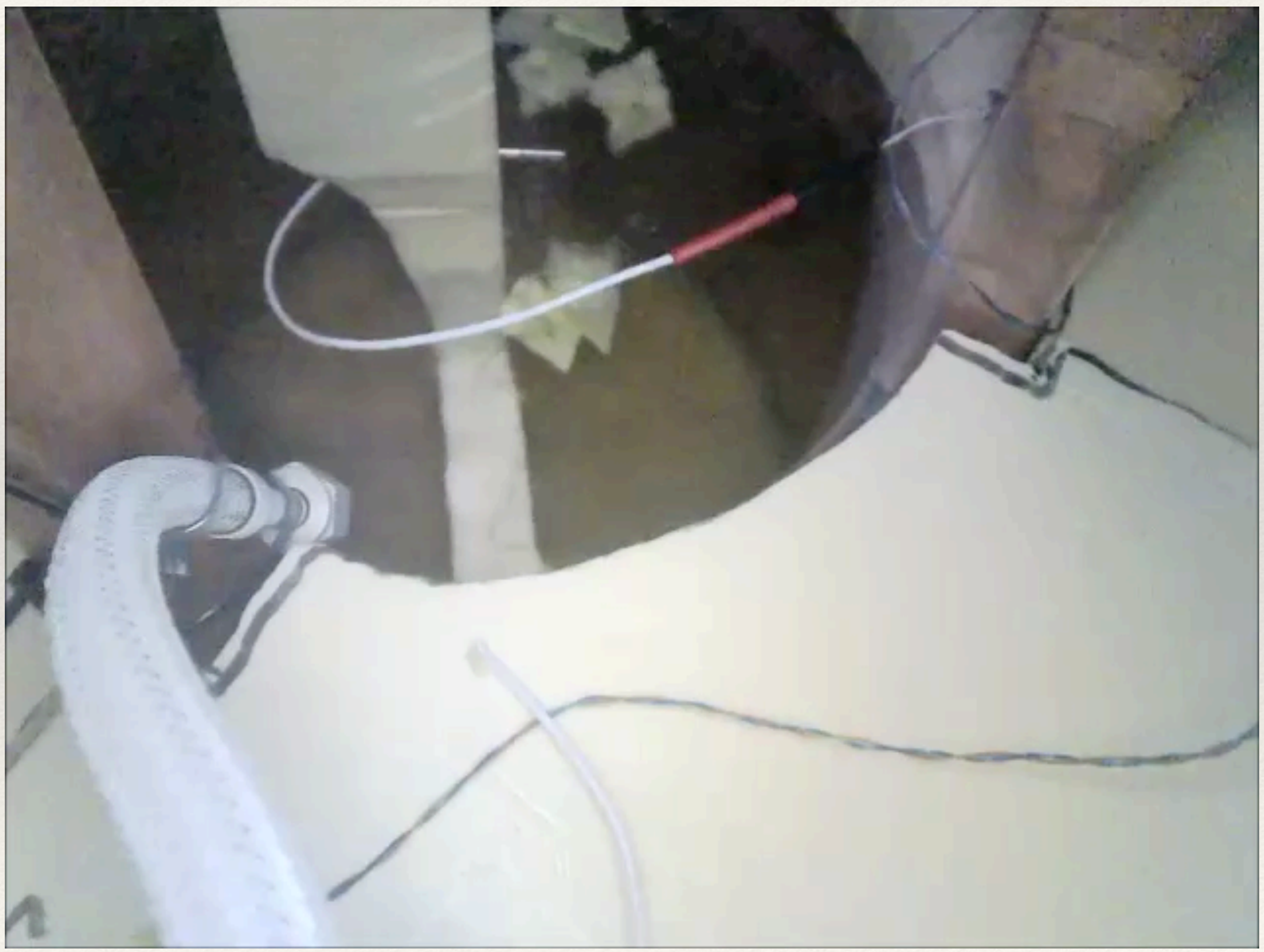
Tests of Superconducting Power Cable at the University of Guanajuato, Mexico (First 2G cable in Latin America)

Cryogenic environment

- Manipulation of liquid nitrogen and solid nitrogen
- Control and measurement in cryogenic environment (below -193°C)

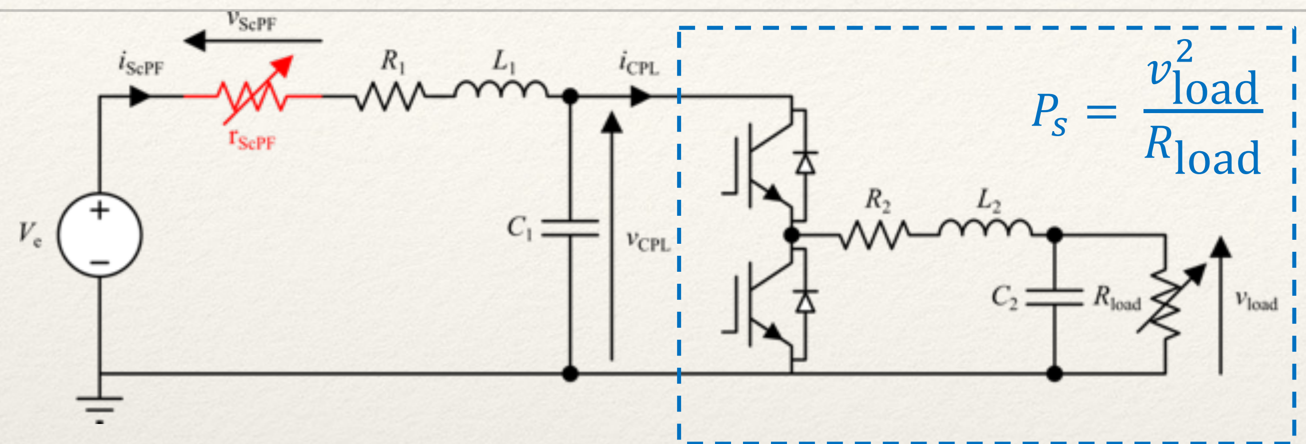


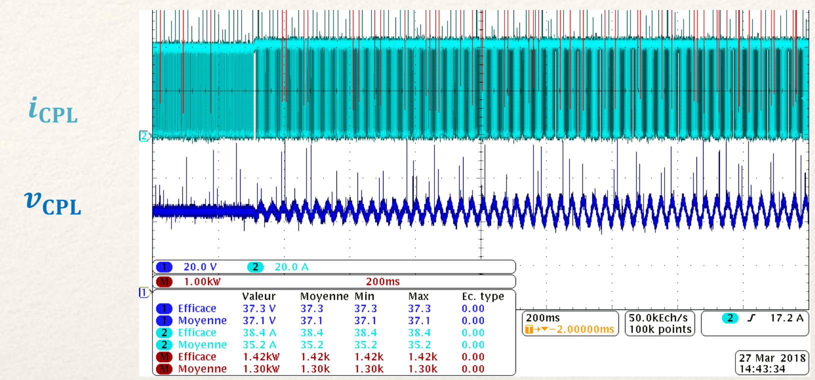
Cryostat equipped with sensors and actuators (dr. Kévin Berger, University of Lorraine, France)



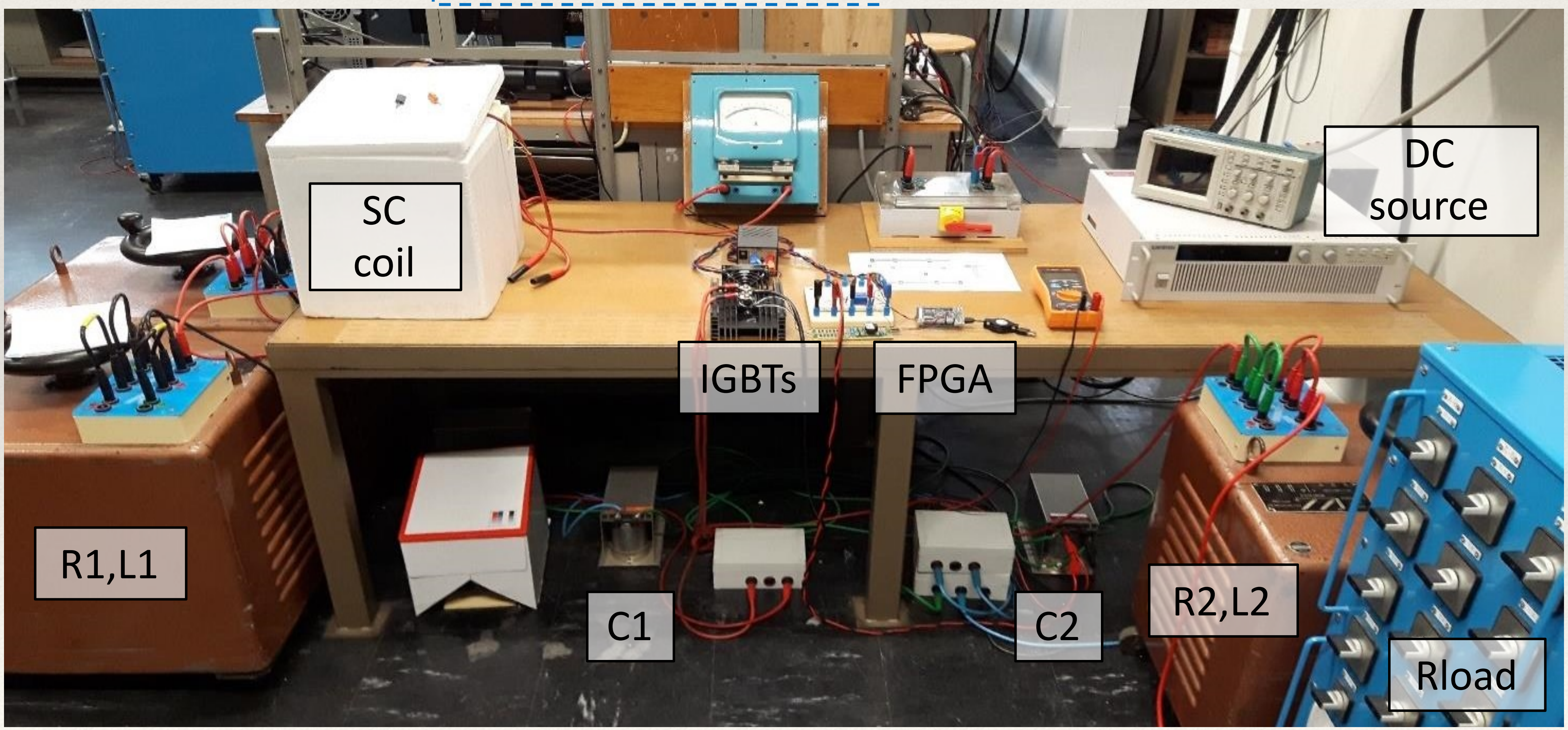
Solidification of nitrogen (dr. Kévin Berger, University of Lorraine, France). Video accelerated 64 times.

Tests of the device





P_s = 1305 W
unstable



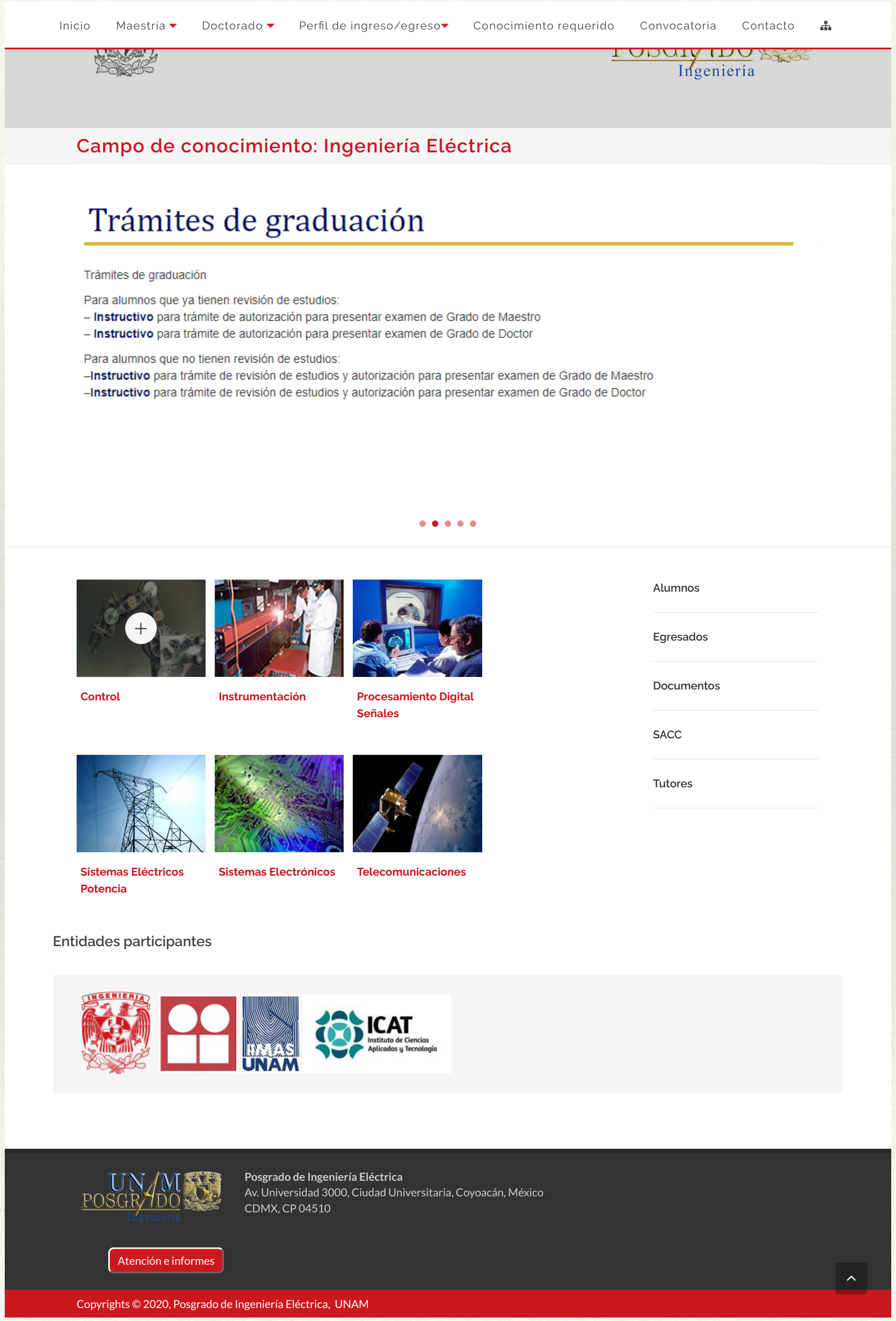
DC100 Test bench for Superconducting Power Filter at GEEPS, Engineering school CentraleSupélec, Paris-Saclay, France.

Conclusion

- Broad range of applications
- From conceptual design to laboratory tests
- Strong participation of the UNAM in the modeling aspects
- Innovative and exiting applications of new materials in Power Systems Engineering

Posgrado en Ingeniería Eléctrica, UNAM

- Pagina: http://posgrado.electrica.unam.mx/index.php
- 5 disciplinas:
  - Control
  - Instrumentación
  - Procesamiento digital de señales
  - **Sistemas Eléctricos de Potencia** (11 professors): http://posgrado.sep.unam.mx
  - Sistemas Electrónicos
  - Telecomunicaciones
- Convocatoria para Maestría anual
- Convocatoria para el doctorado bi-anual



Thanks for you interest