Introduction to Big Science Applications of Superconductivity and Superconducting Magnets

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Outline

- Clean energy: can the superconducting technologies contribute more?
- Superconductivity in the healthcare
- Superconductivity for the discovery potential of science
- Final Remarks

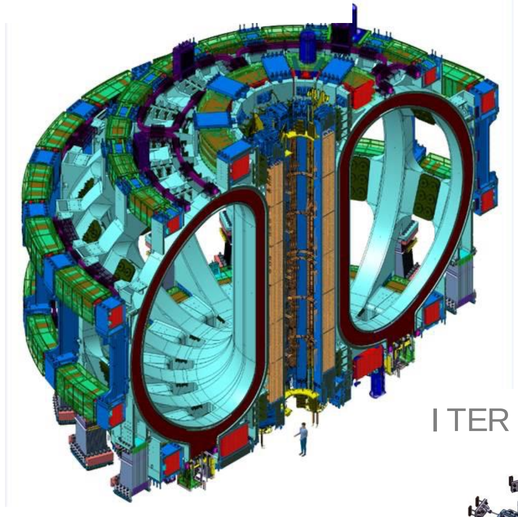
Clean Energy: can the superconducting technologies contribute more?

Fira Barcelona

ITER - the most ambitious clean energy project in the world

ITER Magnet System

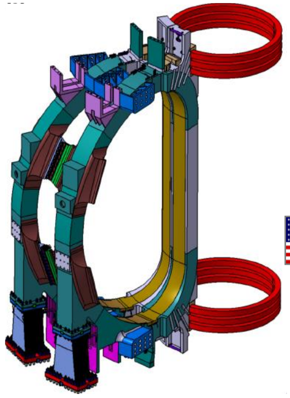
china eu india japan korea russia usa



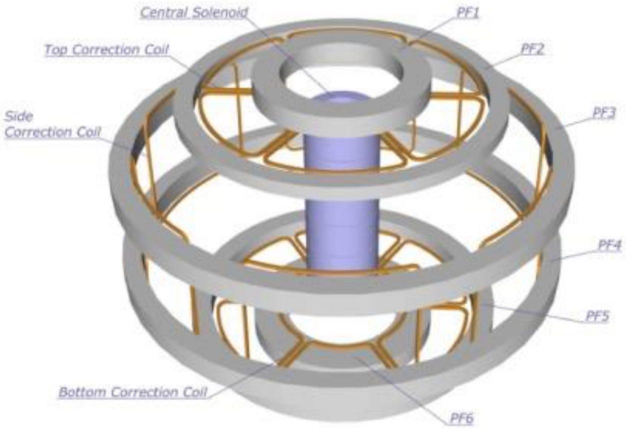
- The ITER magnet system is made up of
  - 18 Nb_3Sn Toroidal Field (TF) Coils,
  - a 6-module Nb_3Sn Central Solenoid (CS),
  - 6 Nb-Ti Poloidal Field (PF) Coils,
  - 9 Nb-Ti pairs of Correction Coils (CCs).

ITER Magnet System

Pair of TF Coils

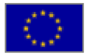


CS Coil



(PF1)

PF Coils



(PF2-6)

CCs

- The ITER magnet system, with a combined stored magnetic energy of 51 GJ is the largest superconducting magnet system ever built
- The magnets will produce the magnetic fields that will initiate, confine, shape and control the ITER plasma
- ITER uses Nb-Ti and Nb_3Sn cable-in-conduit conductors
- The Nb_3Sn strands are used in ITER's toroidal field and central solenoid magnet systems

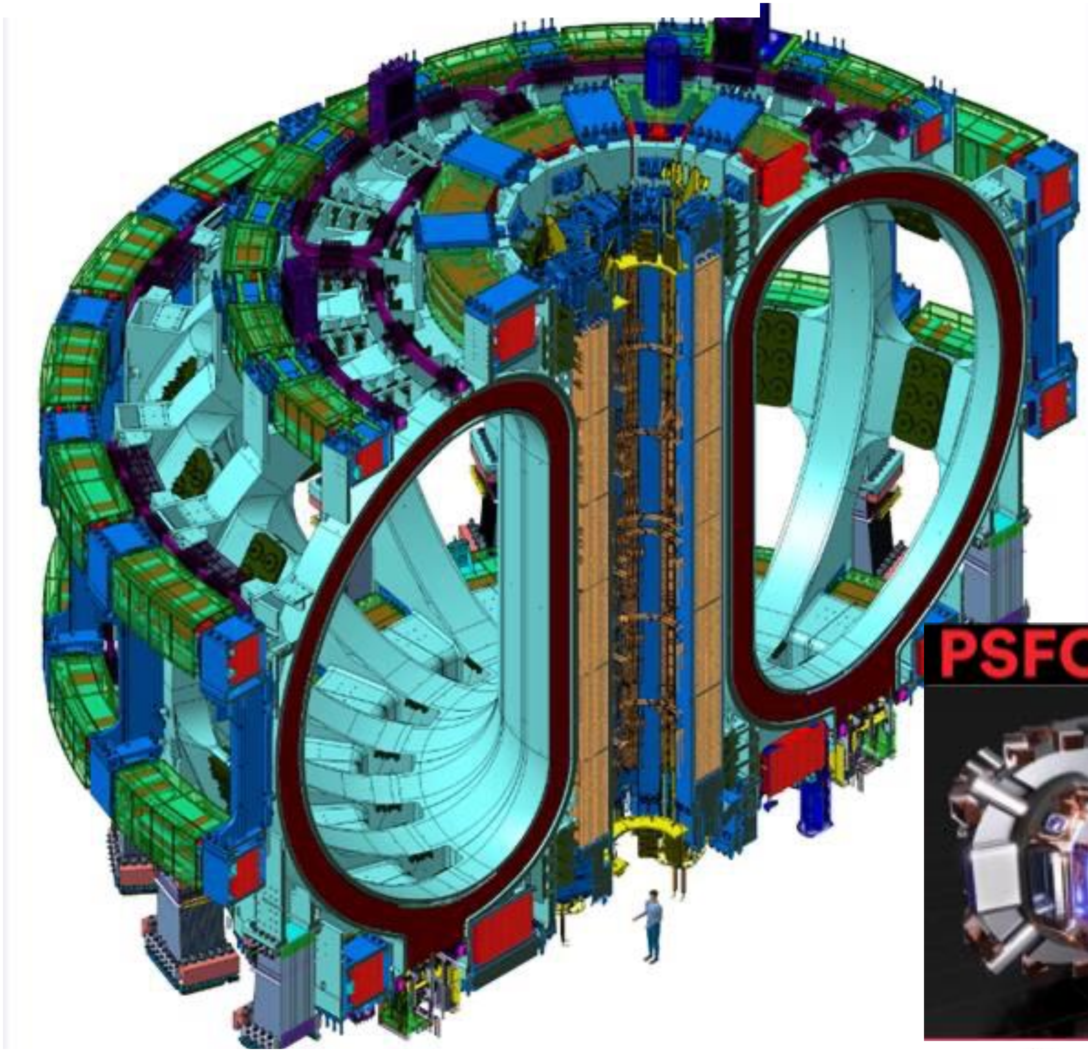
Post-ITER projects – a new technological milestone towards compact fusion reactors

- Though the breakthrough in fusion energy generation (Q>1) remains yet undemonstrated, More than twenty private and government-funded consortia in the US, Europe, China and Australia are currently investing in efforts to build commercial compact fusion reactors

- Some of the consortia are building new, very powerful magnets, which will be a crucial component in a compact nuclear fusion Tokamak reactor

Credit of MIT/CFC

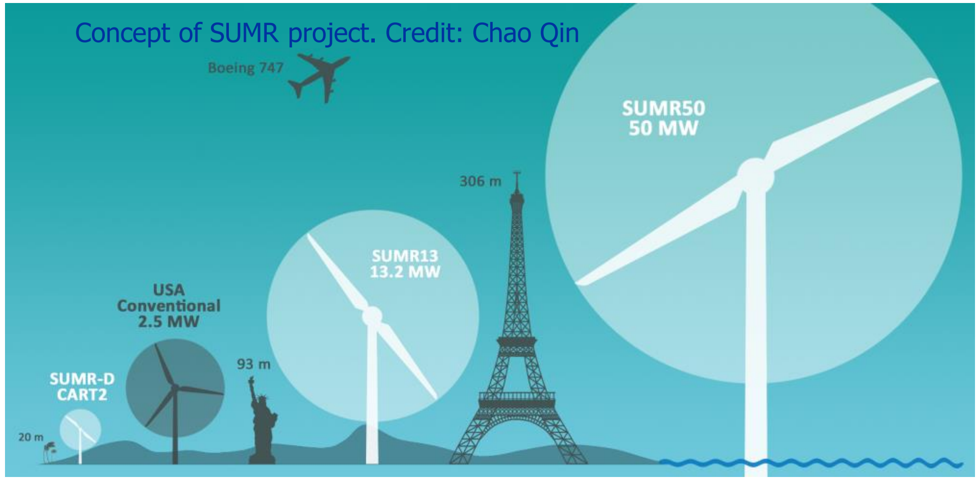
Post-ITER projects – a new technological milestone towards compact fusion reactors



- The SPARC is hoping that its prototype, like ITER, will produce 10 times the energy it consumes (Q=10)
- The fusion power density produced in a tokamak is proportional to its TF magnetic field strength to the fourth power.
- Much higher magnetic fields make it possible to obtain the same energy in a much smaller size of Tokamak reactor .

Superconducting technologies in wind power generation

- SC technologies can contribute to the wind power generation
- Renewables: solar, wind, biomass, waste, geothermal and small hydro
  - 2019: generated 13.4% of global electricity vs 5.9% in 2009
  - 2022 expectation: add 320 GW (8% growth)
- Wind power - added capacity:
  - 487 GW capacity in 10 years (2009-2018)
  - 2020: >100 GW incl. 71.6 GW in China and 14 GW in USA
- Targets: add 800 GW renewable capacity by 2030, total investment worldwide: >€1 trillion



Superconducting technologies in wind power generation

- Advantages of superconducting wind generators
  - Main advantage is higher field in air gap vs traditional technologies limited by magnetization of core material
  - Higher efficiency
  - Reduced size and weight of the generator and turbine
  - High torque density
  - Scalability to higher power
  - Eliminates (LTS) or reduces (HTS) use of rare earth elements

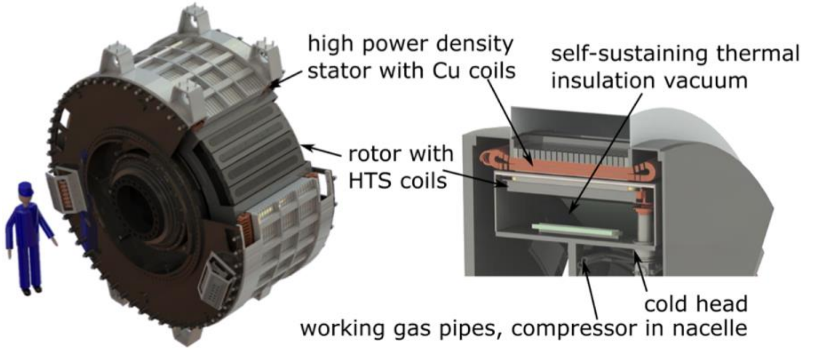
- Running LTS wind turbine demonstrators show that commercially competitive offshore units are over 15 MW of nominal turbine power

Credit of GE in Saint-Nazaire

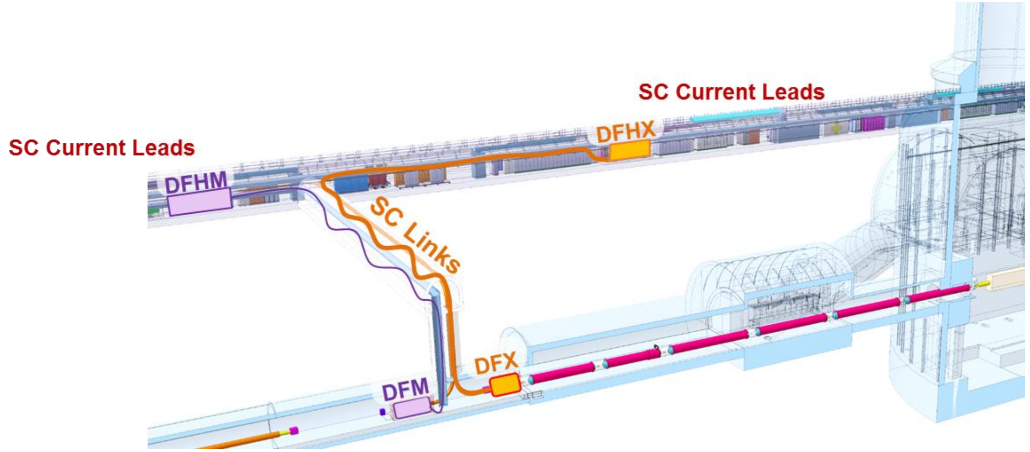
Superconducting technologies in wind power generation

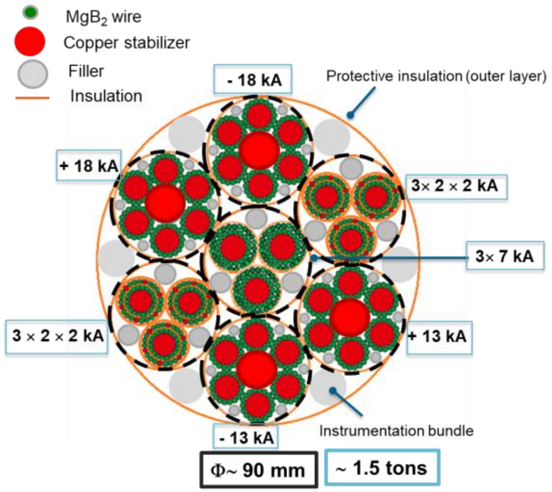
- HTS generators for wind turbines are so far technology demonstrators
  - Not optimized for volume production, system cost, manufacturability, reliability, etc.

- The EU-funded EcoSwing project (Energy Cost Optimization using Superconducting Wind Generators) successfully demonstrated world's first HTS low-cost and lightweight generator on a large-scale commercial wind turbine
  - EcoSwing generator and power converter reached target range +3 MW
  - Core technologies, namely the superconducting rotor coils and the cryogenic cryocooling technology showed stable and reliable system operation and great performance and reliability

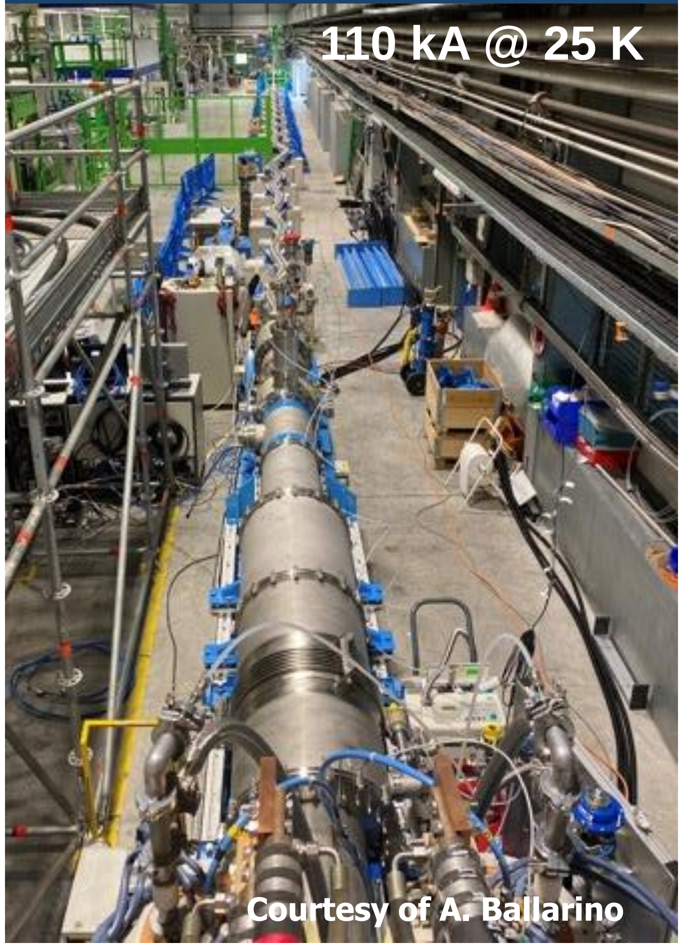


HL-LHC superconducting power transmission lines





HL-LHC MgB_2 60 m long Prototype Power Transmission Line



- Innovative multi-circuits system developed at CERN to supply current to HL-LHC Interaction Region magnets
- Lengths in excess of 100 m
- MgB2 cable cooled by forced flow of GHe at temperatures in the 4.5-17 K range, carrying up to ~129 kA @ 25 K
- First industrial production of MgB2 wires (project needs: 280 + 1050 km)

HL-LHC REBCO HTS Current Leads (up to 18 kA)

Superconducting HVDC high-power energy transmission

- Bulk power transmission over several hundred kilometers is necessary to bring the electricity produced by remote renewable energy farms to the consumption centers
- The Institute for Advanced Sustainability Studies (IASS), Potsdam together with academia and industry partners have developed a 3-gigawatt-class (320kV DC, 10kA) MgB2 superconducting cable for very high-power transmission and demonstrated competitiveness of this technology compared to conventional cables

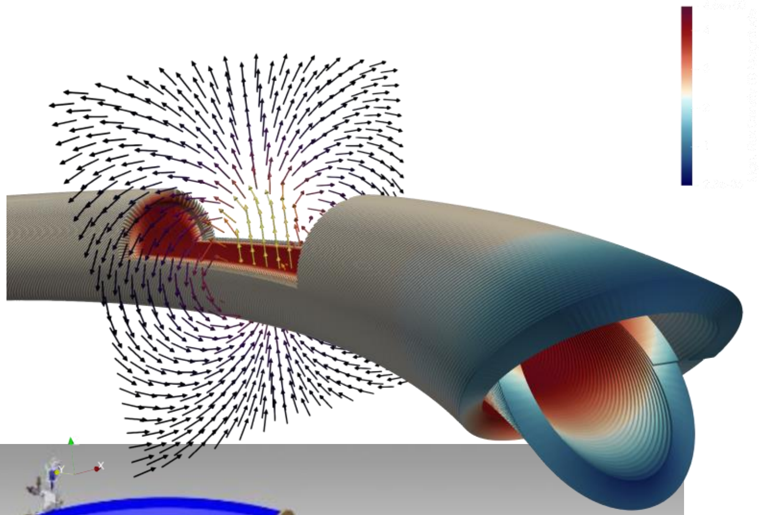
Superconductivity in the healthcare

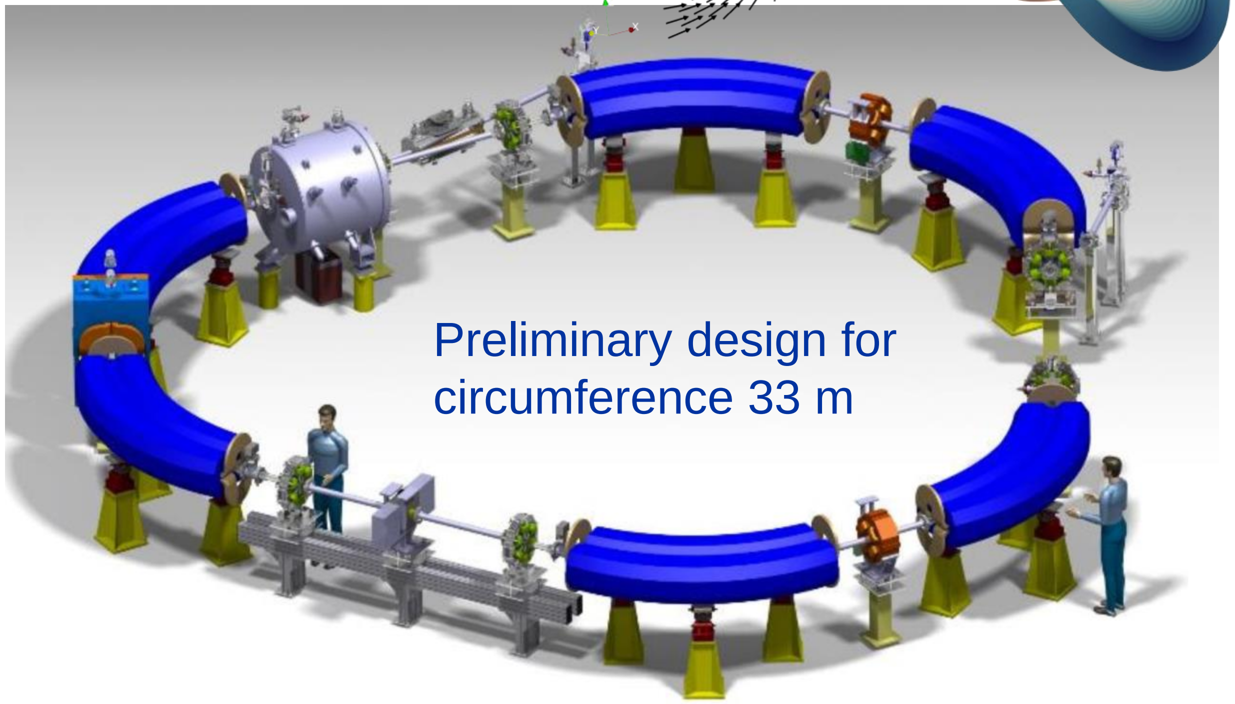
The MedAustron proton/carbon-ion synchrotron was constructed in collaboration with CERN, the TERA Foundation, INFN and the CNAO Foundation, with help from PSI. (Image: MedAustron)

The CERN Next Ion Medical Machine Study (NIMMS)

- Basic requirements of the next generation ion therapy accelerator:
  - Operation with multiple ions (protons, helium, carbon, oxygen) for therapy and research
  - Lower cost and dimensions, compared to present
  - Faster dose delivery with higher beam intensity and new delivery schemes (FLASH)
  - A gantry device to precisely deliver the dose to the tumor
- Enabling technology: curved LTS or HTS CCT (Canted Cosine Theta) dipole and combined function magnets

Concept design of curved LTS CCT (Canted Cosine Theta) dipole (I.FAST project)



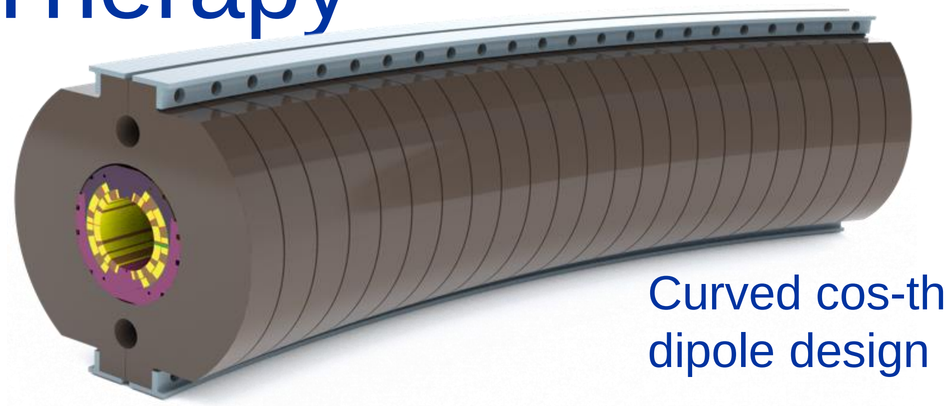


Preliminary design for circumference 33 m

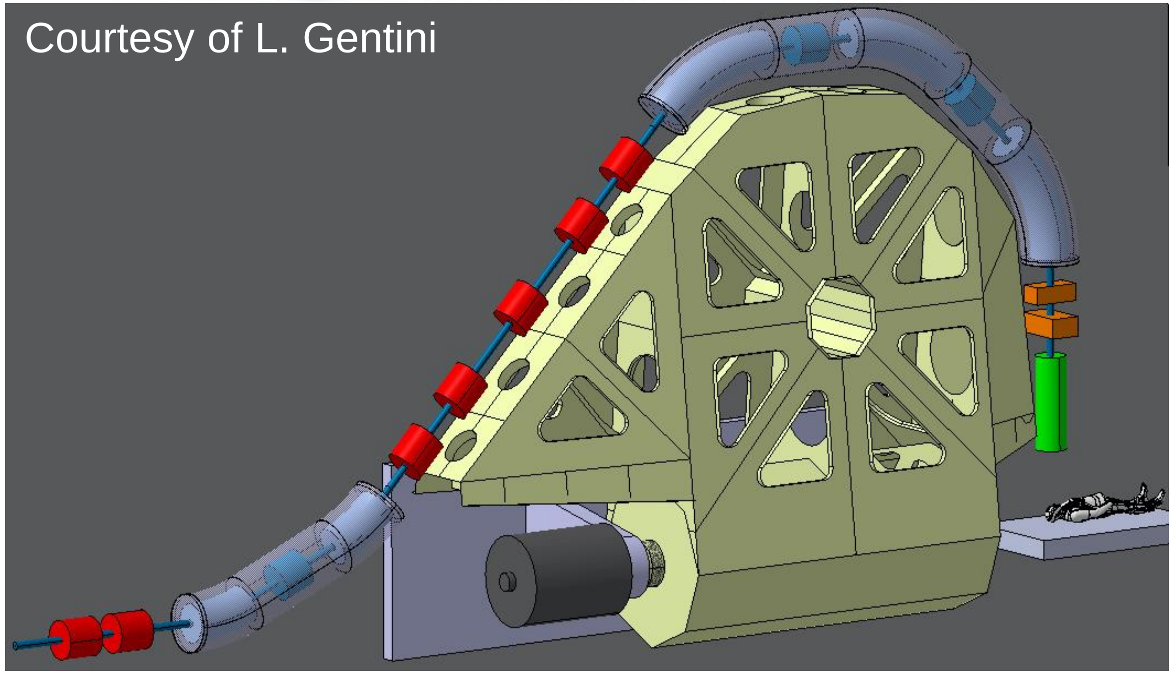
SIGRUM - New Concept of Rotating Compact Gantry for C^{6+} Therapy

- Main characteristics of SIGRUM project, a Superconducting Ion Gantry with Riboni's Unconventional Mechanics:

  - Beam orbit radius 6.37 m
  - Length ~16 m
  - Weight <30 tons
  - Momentum acceptance 1%
  - Reduced complexity of the main magnet system for maximum reliability
    - Two cryo-assemblies: 2x22.5°, 3x 45°
    - B_{nom} = 3 T
    - G_{nom} = 2 T/m (Combined function)



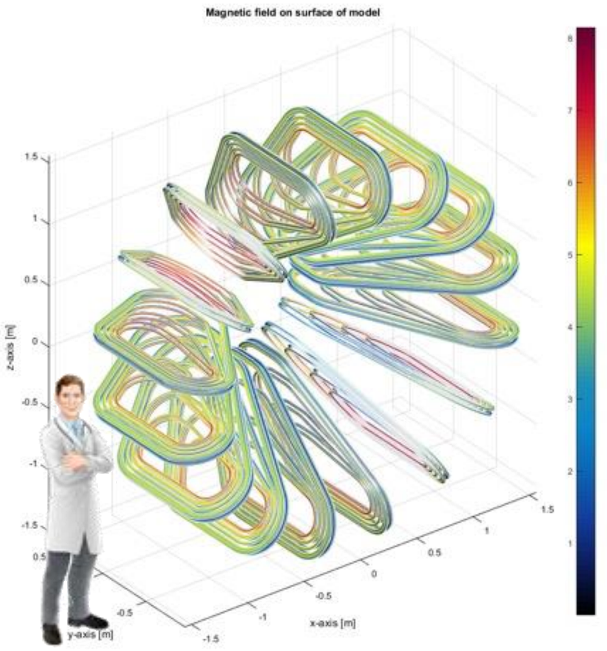
Curved cos-theta dipole design



Novel GaToroid Gantry Concept

A GaToroid for protons

(the smallest possible size)



Number of angles	16
Peak magnetic field	8 T
Stored Energy	30 MJ

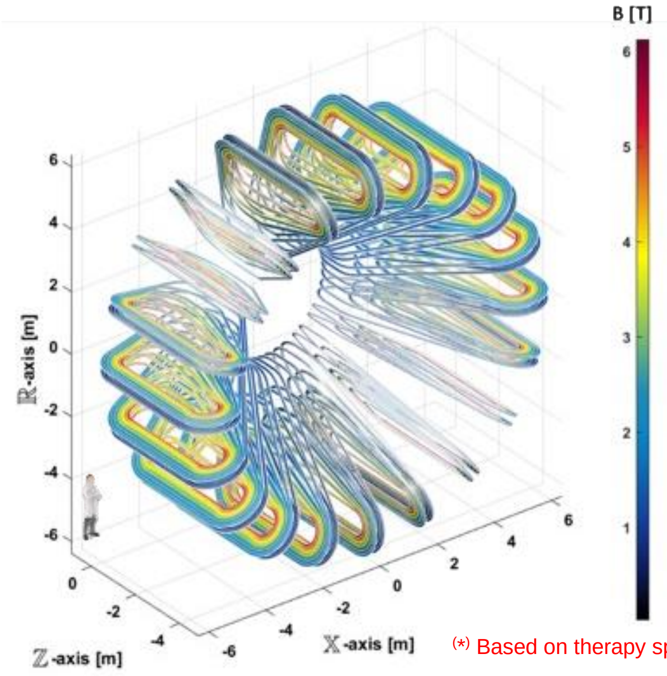
Coil dimension	1.5 m x 1 m
Torus dimension	1.5 m x 3 m
Bore size	0.8 m
Vector Magnet position	4.5 m

Operating temperature	4.2 K
Operating current	1.8 kA

Estimated total mass	25 tons

A GaToroid for ions

(the largest possible size)



Number of angles	20(*)
Peak magnetic field	6.1 T
Stored Energy	1300 MJ

Coil dimension	5.8 m x 4.5 m
Torus dimension	5.8 m x 12.8 m
Bore size	3.7 m(*)
Vector Magnet position	9.2 m

Operating temperature	4.2 K
Operating current	10.8 kA

Estimated total mass	300 tons

(*) Based on therapy specifications and practice at CNAO and MedAUSTRON

Courtesy of L. Bottura

GaToroid: Technology Development Towards a Feasibility Demonstrator

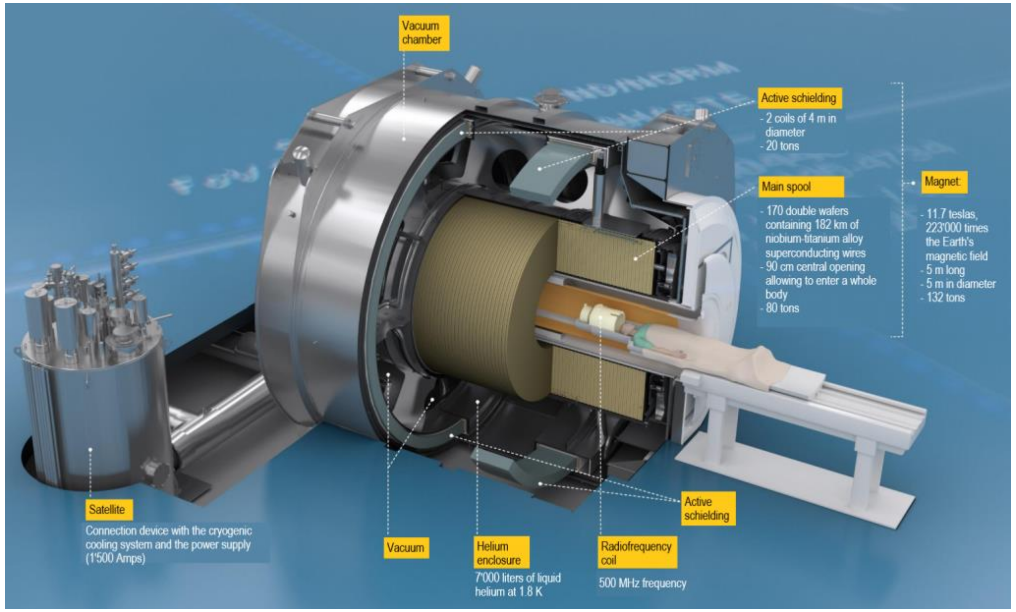
Stainless Steel dummy winding with 3D printed spacers

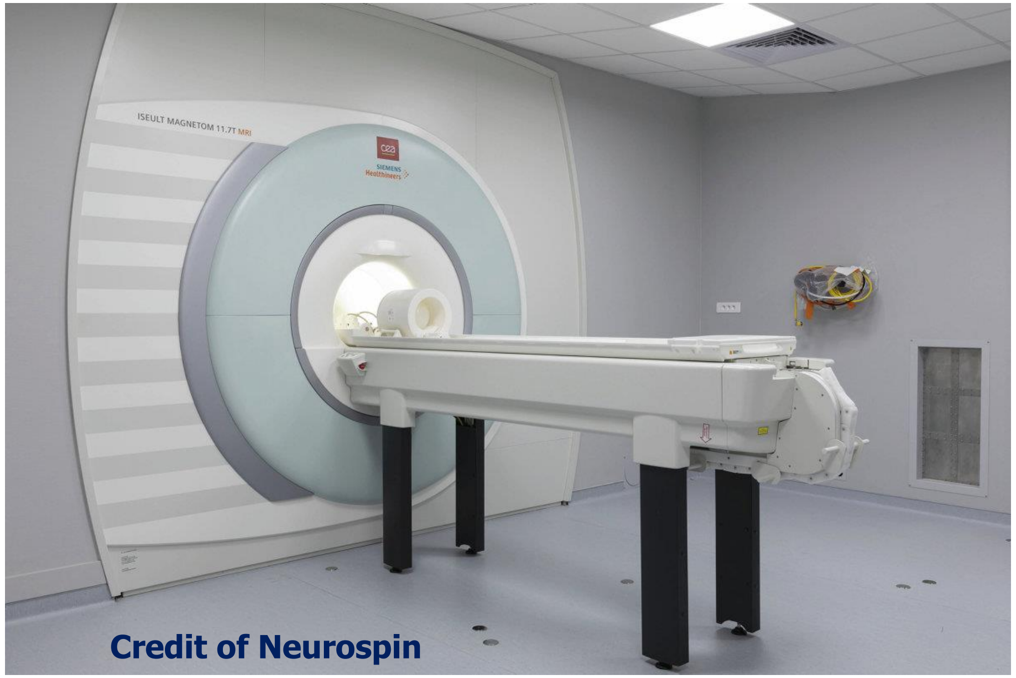
Courtesy of L. Bottura

A breakthrough in high-resolution MRI

- Project Iseult: the most powerful full-body MRI in the world!

  - Magnetic field of 11.7 Tesla against 1.5 to 3 found today in hospitals. An unprecedented technological achievement by scientists from the Atomic Energy Commission (CEA), the result of twenty years of research
  - Iseult paves the way for high-resolution full-body MRI
  - …and promises a leap forward in knowledge about the human brain





Credit of Neurospin

Superconductivity for the discovery potential of science

Superconducting RF cavities for future collider projects - FCC-ee collider

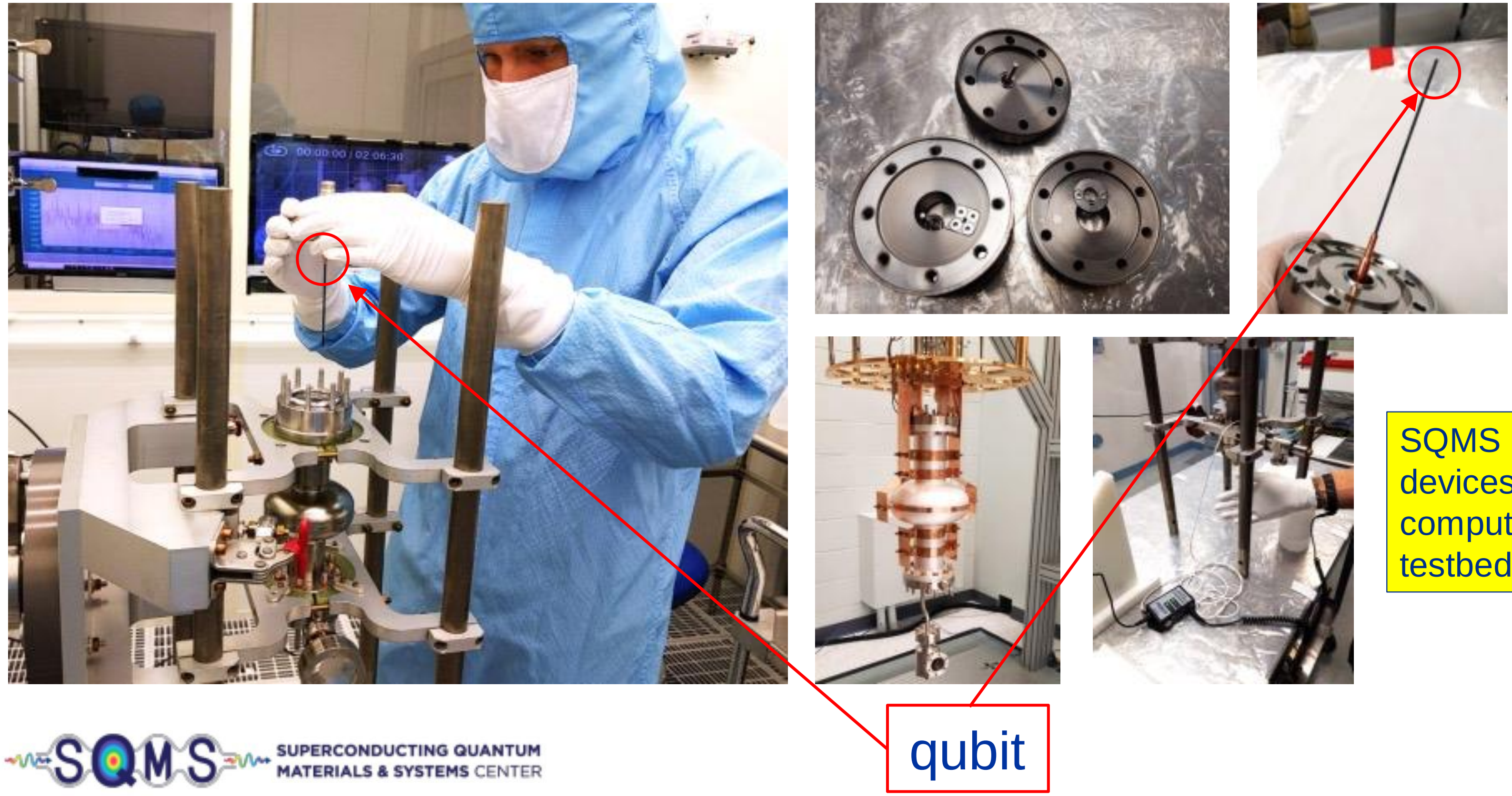
- FCC-ee SRF needs: focus on surface losses and HOM loading:
  - RF systems and associated cryogenics represent 50% of the FCC-ee electricity consumption.
  - A factor 2 in Q will reduce the cryogenic consumption by 50% (for ttbar from 47.5 MW to 23.7 MW)

Machine part	Frequency [MHz]	Cells/cavity	Gradient [MV/m]	# cavities
Booster	800	5	6 - 25	496
Main ring (Z)	400	1	6	56
Main ring (W, H)	400	2	12	280
Main ring (ttbar)	800	5	24	400

Courtesy of W. Venturini and F. Gerigk

A new future for SRF technology

Goal: insert qubit into SRF cavity, to enhance coherence time thanks to very high Q of SRF cavities



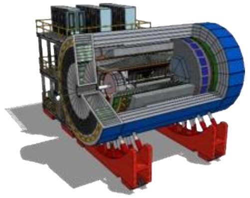
SQMS devices, computing testbeds

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Detector magnet projects for existing & future colliders, non-colliders and space experiments

- Strong industrial expertise and capabilities for building superconducting detector magnets are available in industry, provided that the needed conductor is available

- Many future superconducting detector magnets are under developmernt, with strong demand for suitable conductor types, especially aluminum-stabilized Nb-Ti/Cu conductor technology
  - Industrial production capabilities of aluminum-stabilized Nb-Ti/Cu conductor is at present an issue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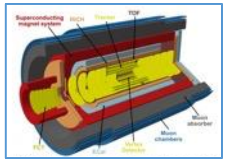
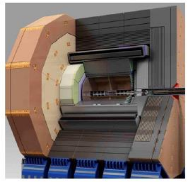
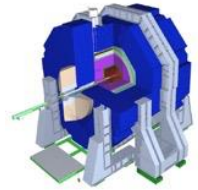
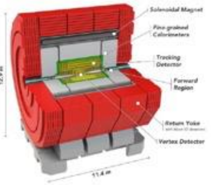

ALICE-3


ILC-ILD


ILC-SiD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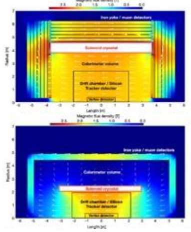
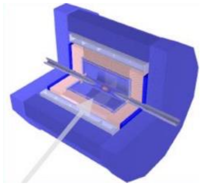
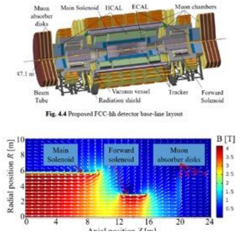
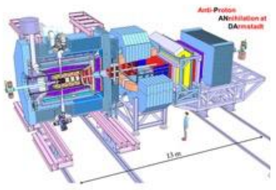

FCC-ee


CEPC


FCC-hh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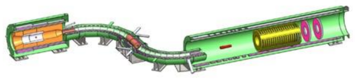
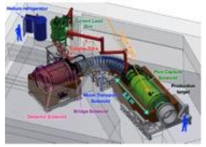
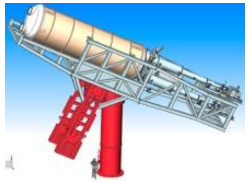
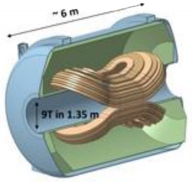
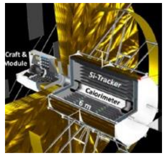

Mu2e


Comet


BabyIAXO


MadMax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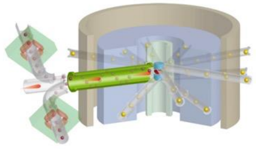
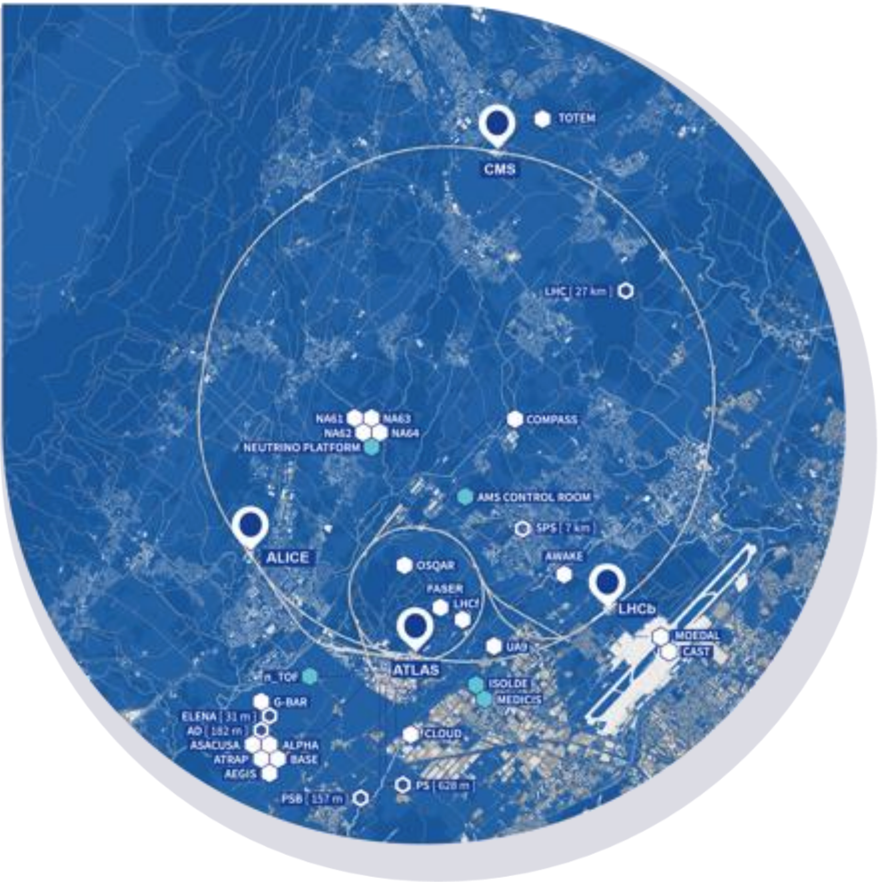

J-Parc MLF

Courtesy of M. Mentink

Final remarks



Big Science provides tools to other fields: medicine/climate/energy/…

It always remains a good investment for the future of mankind