Superconductive Materials

Part 10

Introduction to accelerators

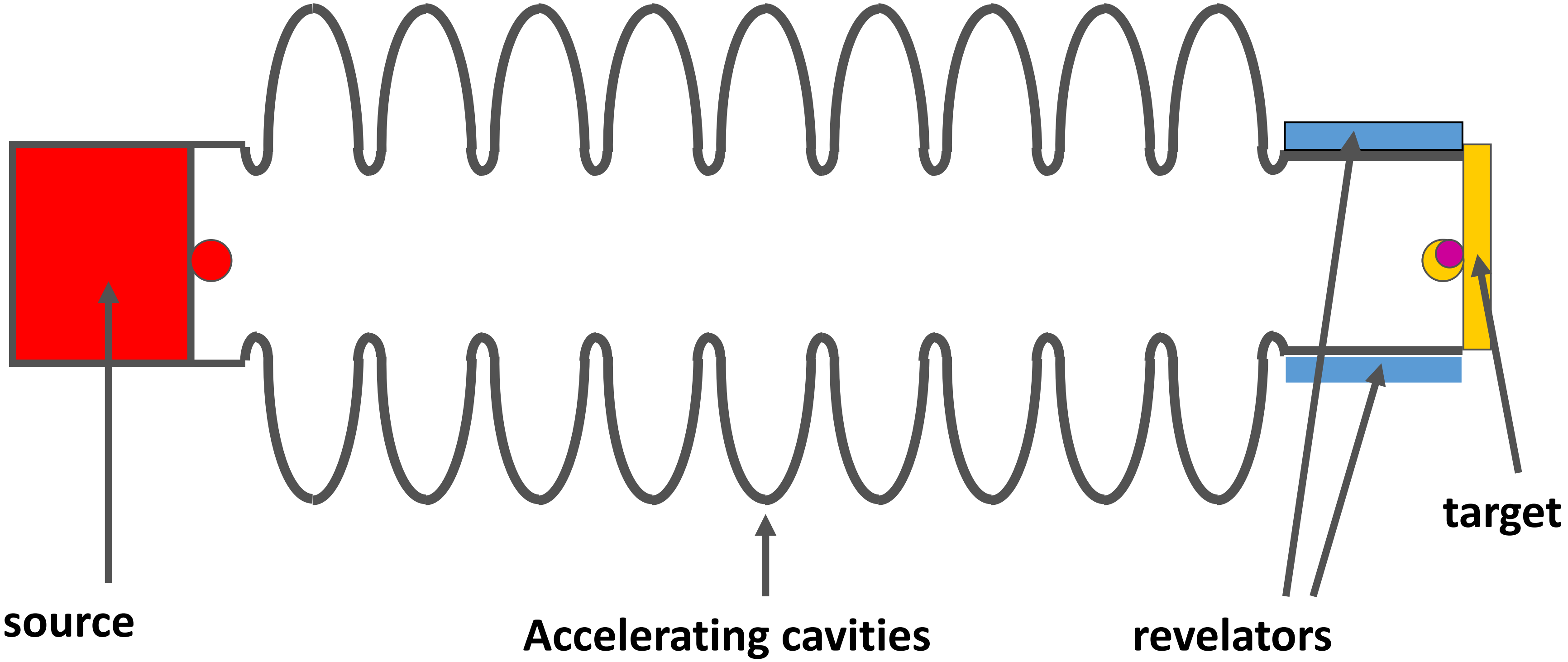
Outline

In this lecture we will address these questions:

- What is an accelerating cavity?
- Superconductivity means no resistance. Why can’t we reduce the losses to zero?
- Why is niobium the material choice which requires costly helium cooling?
- What are the fundamental and technical limitations of niobium SRF cavities? *(2nd part)*
- What are possible future materials and what are the challenges? *(3rd part)*

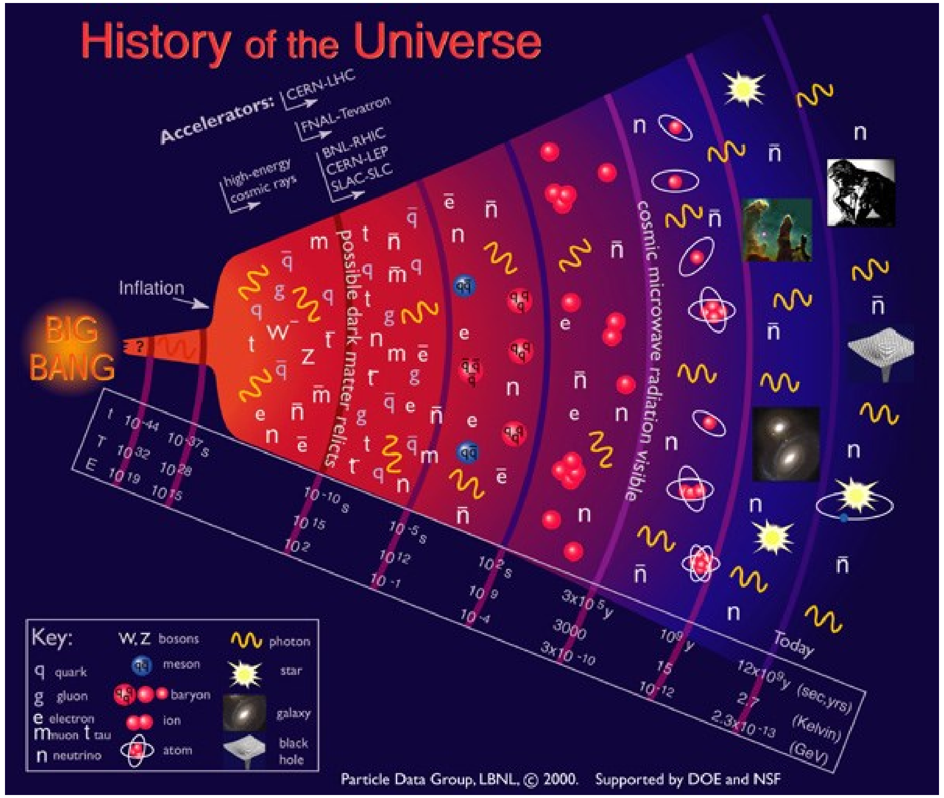
Why is important the R&D on accelerating cavities?

How works an accelerator?

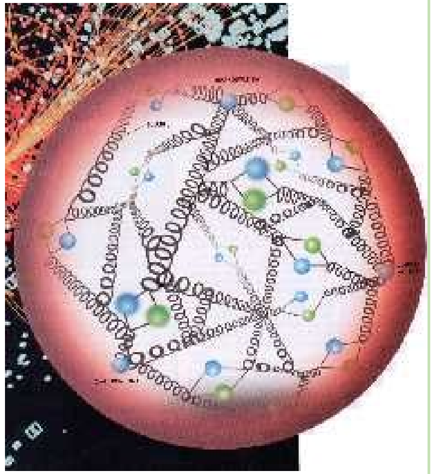


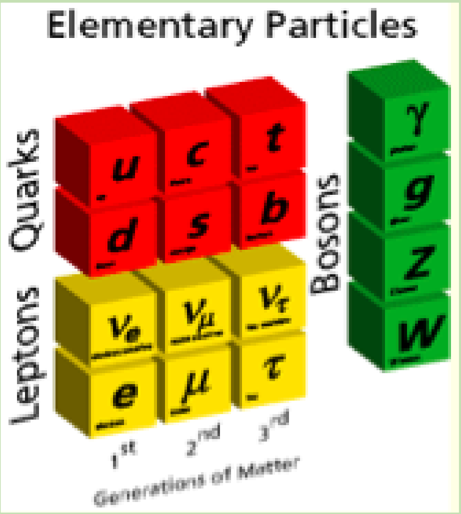
Sub-atomic microscopes and time machines

The high density of energy produced allows to reproduce and study the evolution of first instant of the Universe



The collision between two particles bunches or a particles bunch and a target provide information on the elementary particles





The impact of accelerators on Society

Fundamental physics
Biological & chemical sciences
Materials science

Research

Cleaning flue gases of thermal power plants

Energy & Environment

Treating cancer
Medical Imaging

Health & Medicine

Ion implantation for electronics
Hardening surfaces
Hardening materials
Welding and cutting
Treating waste & medical material

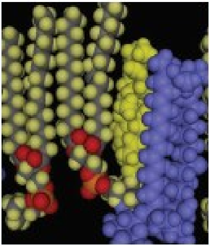
Industrial applications

Non-destructive testing
Cultural heritage
Authentication
Cargo scanning

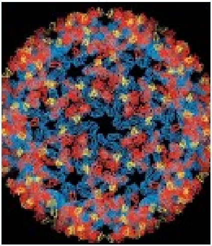
Material identification

Safe nuclear power
Replacing ageing research reactors

Prospects

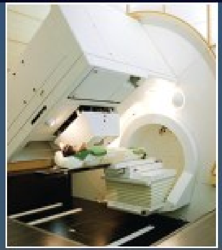


Materials research
Beams of photons, neutrons and muons are essential tools to study materials at the atomic level.



Protein modelling
Synchrotron light allows scientists to solve the 3D structure of proteins e.g. the Chikungunya virus.

Controlling power plant gas emission
In some pilot plants, electron beams are used to control emission of sulphur and nitrogen oxides.

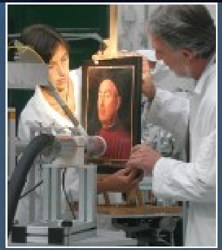


Hadron therapy
Proton and ion beams are well suited for the treatment of deep seated tumours.

Positron Emission Tomography (PET)
Radioisotopes used in PET-CT scanning are produced with accelerators.

Ion implantation for electronics
Many digital electronics rely on ion implanters to build fast transistors and chips.

Hardening materials
Replacing steel with X-ray cured carbon composites can reduce car energy consumption by 50%.



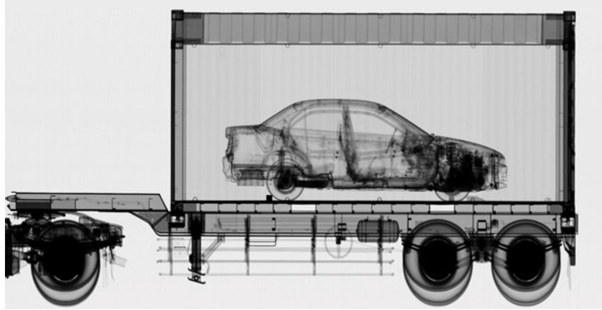
Cultural heritage
Particle beams are used for non-destructive analysis of works of art and ancient relics.

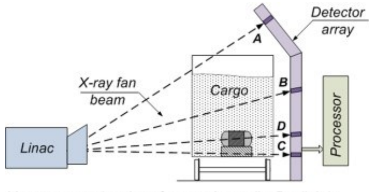
Energy
Accelerator technologies may bring the power of the sun "down to earth", treat nuclear waste and allow for safer operation of reactors.

Slide from TIARA website

Industrial applications

Cargo Scan with X-ray



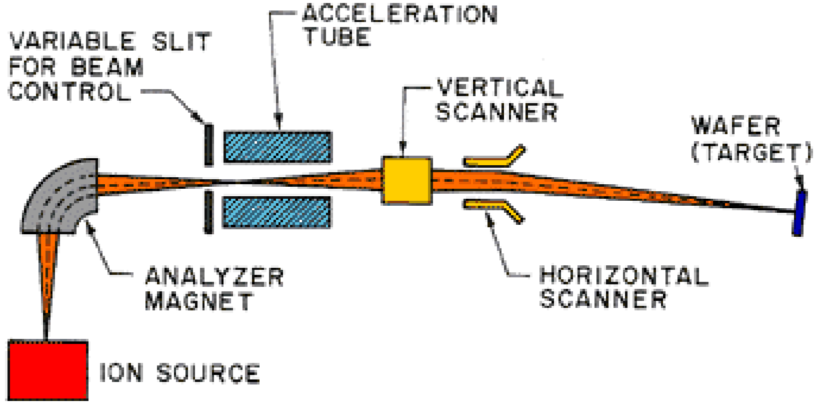


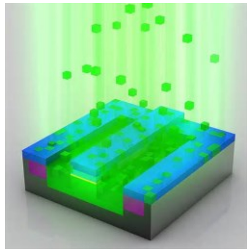
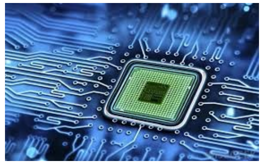
X-ray traversed region of cargo: **A** – walls; **B** – lightly loaded region; **C** – intermediately loaded region; **D** – heavy loaded region

Sterilisation and irradiation of food for preservation ("cold pasteurisation")

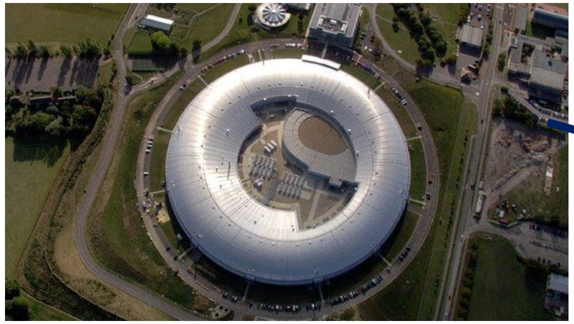
Treatment of polymeric materials: cross-linking


Ionic implantation (semiconductors)

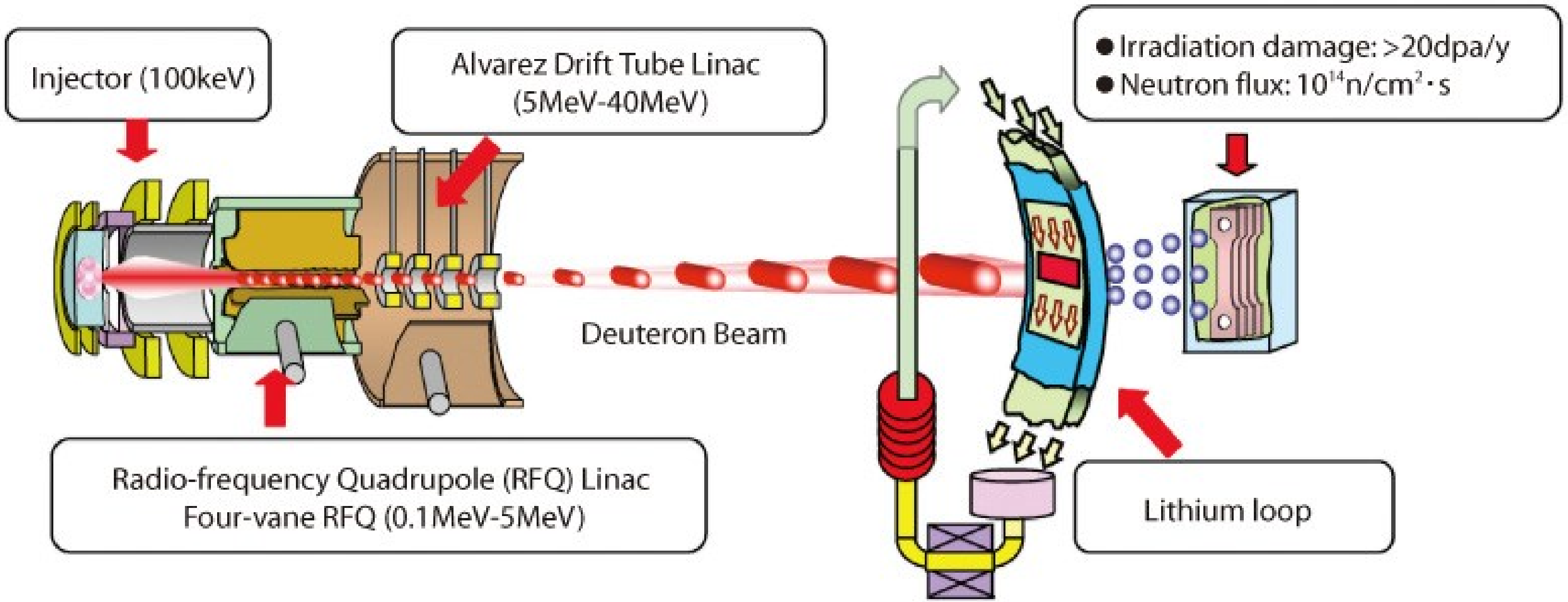


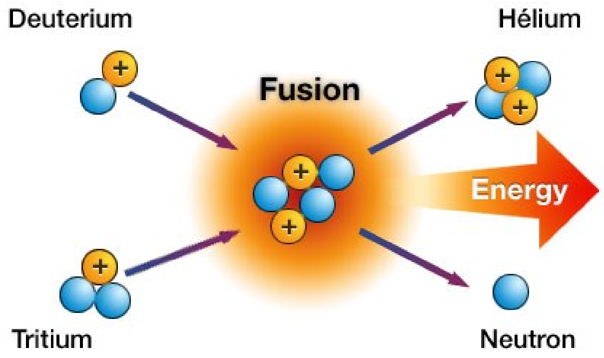



Synchrotrons

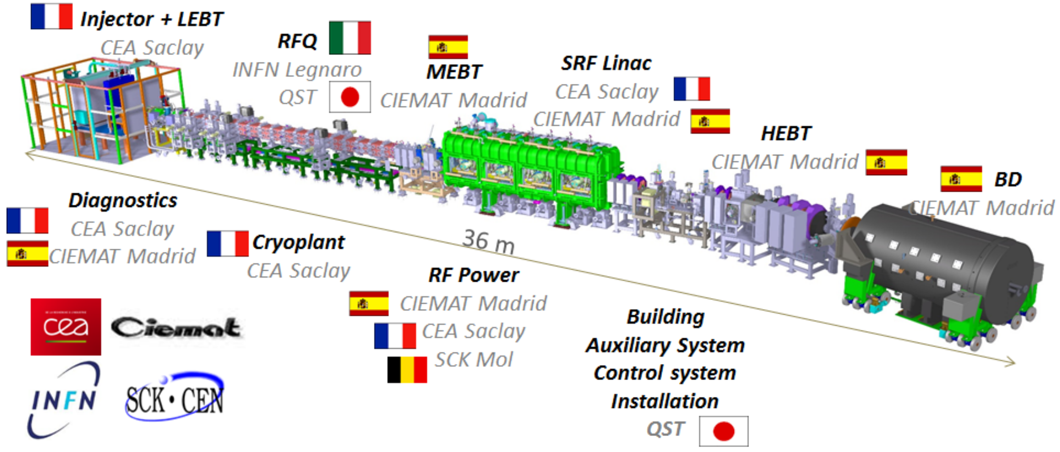


Material Test Facility for Nuclear Fusion Reactors





L'International Fusion Materials Irradiation Facility (IFMIF)

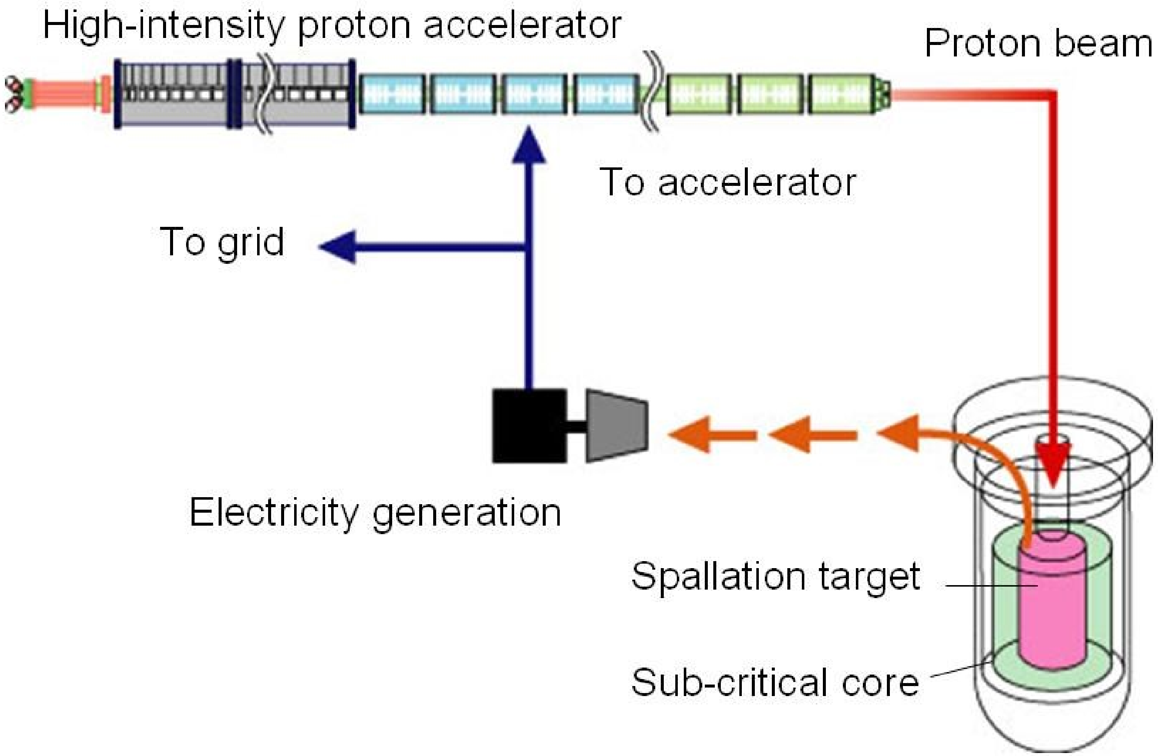


Energy production with accelerators (ADS)

An accelerator-driven subcritical reactor is a nuclear reactor design formed by coupling a substantially subcritical nuclear reactor core with a high-energy proton accelerator (600 MeV – 1 GeV). It could use thorium as a fuel, which is more abundant than uranium

Advantages:

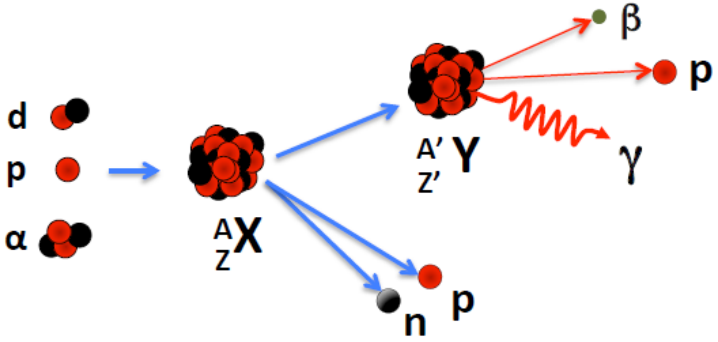
- Use thorium as fuel, much more abundant than uranium and plutonium
- Short life span of waste products (in the order of 100 years versus hundreds of thousands of years of current reactors)
- Intrinsically safe reactor (controlled fission)



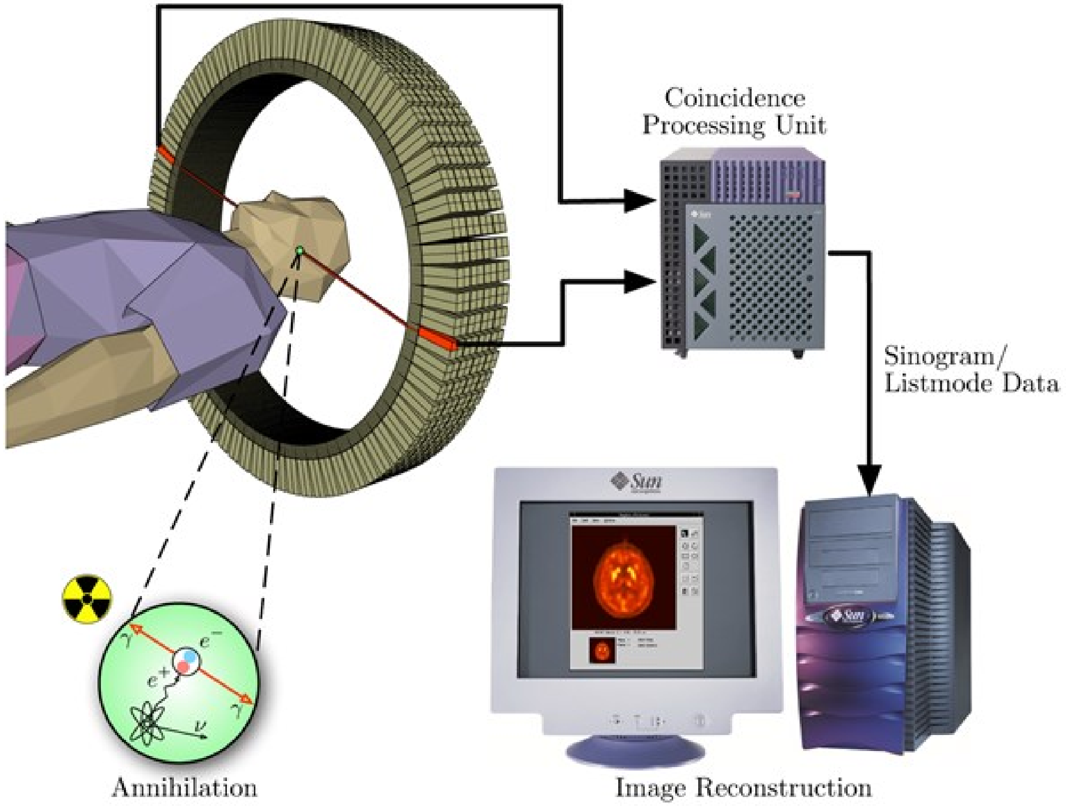
Radioisotope production

Cyclotron for the radioisotope production

A 70 MeV Cyclotron installed at LNL INFN in the framework of Laramed project



Theranostics possible with specific radionuclides



PET - Positron Emission Tomography

Radiotherapy

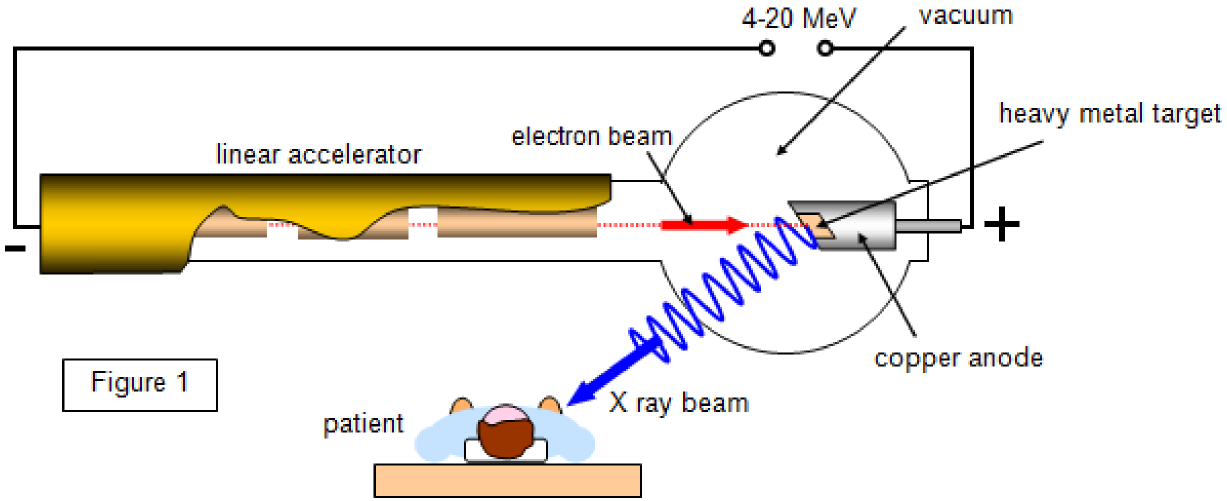
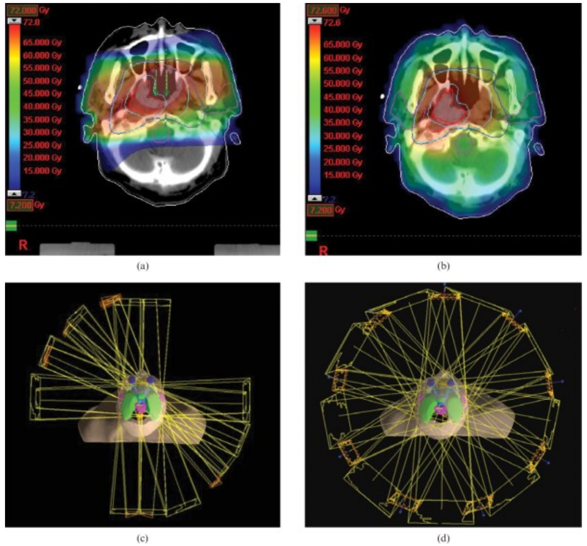
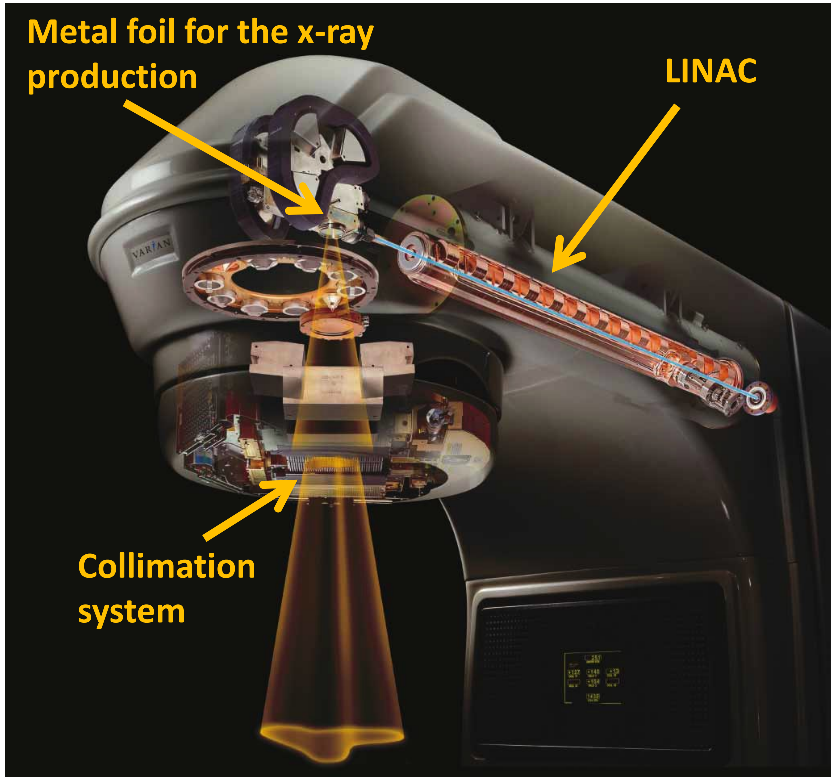


Figure 1





Metal foil for the x-ray production

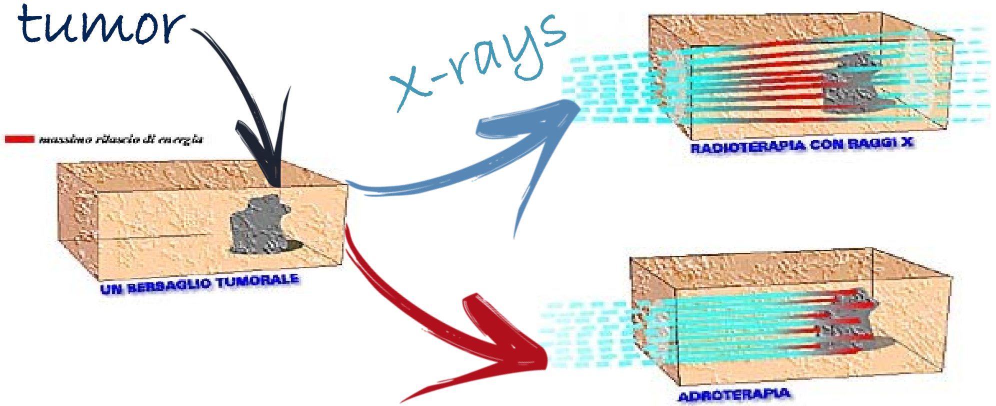
LINAC

Collimation system

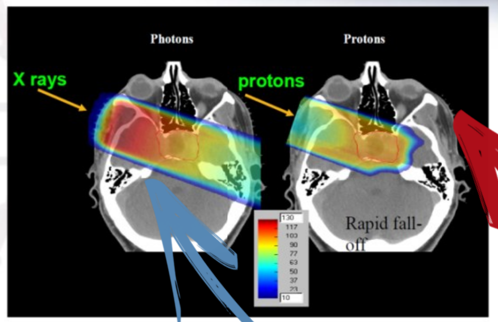
Hadrontherapy

Form of radiotherapy for the **treatment and cure of tumors** that are often surgically inoperable or resistant to traditional radiotherapy treatments

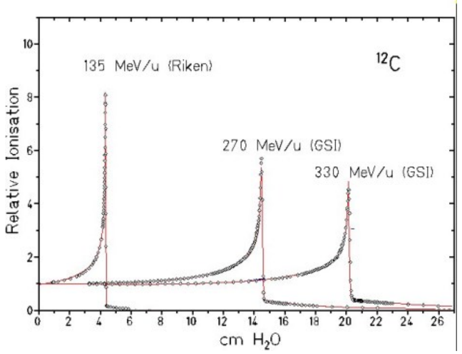
CNAO (Pavia)

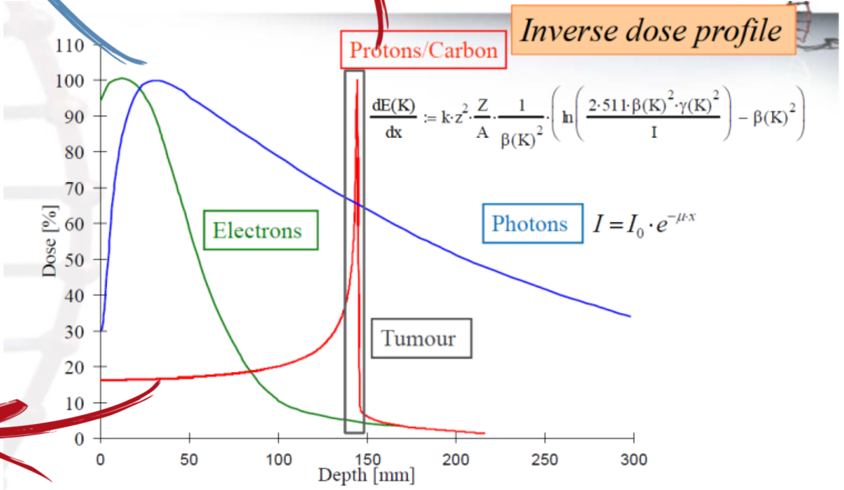


Protons, carbon ions



Protons/carbon released energy mainly in the tumor cells





Water Treatment


≡ All Sections

The Virginian-Pilot

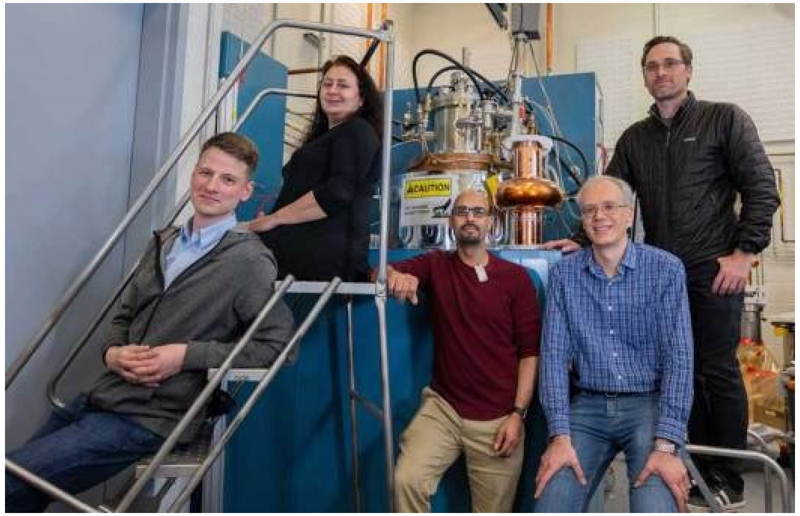
44°F

Tuesday, April 23rd 2024
e-Pilot
e-Pilot Evening Edition

News

NEWS

Jefferson Lab receives $7.5 million grant to adapt technology to break down ‘forever chemicals’



Forever chemicals

Wikipedia: POPs - “Persistent Organic Pollutants”

pollutants “resistant to degradation through chemical, biological, and photolytic processes” — typically halogenated, organic compounds ↔ strong bond halogen- carbon

How to remove?

Ebeam treatment of water
(don’t attack contaminants directly)

→ “activate” water with beam

$$e^- \Rightarrow \quad H_2O \rightarrow e^-_{aq} + HO^{\cdot} + H^{\cdot} + HO_2 + H_3O^+ + OH^- + H_2O_2 + H_2$$

↪ create oxidants **and** reductants (*not just any, some of the strongest*)

big benefit → no addition of further chemicals required

↪ very cost-effective generation of free radicals

And no, we don’t (radio)activate your water!

↪ stay below 10 MeV ↔ neutron activation threshold

- *Yet, public acceptance oft an issue – “**treatment**” vs “irradiation”*

Treatment of “Forever Chemicals” in Wastewater with Electron Beams – J. Vennekate IPAC ‘23

Water Treatment

Technology already exist

- Deagu dyeing treatment plant in South Korea (2006)
  - 1 MeV, 400 kW accelerator – 10,000 m^3/h
- Guanhua Knitting Factory wastewater treatment in China (2020)
  - 7 accelerators in total – 30,000 m^3/h
- Current technology: HV DC accelerators
  - based on 1970s BINP developed ELV-type
  - usually limited to 1-2 MeV few 100s kW

  ↪ scaling by adding multiple machines


Wastewater Treatment Facility in
Daegu Dyeing Industrial Complex

Treatment of “Forever Chemicals” in Wastewater with Electron Beams – J. Vennekate IPAC ‘23

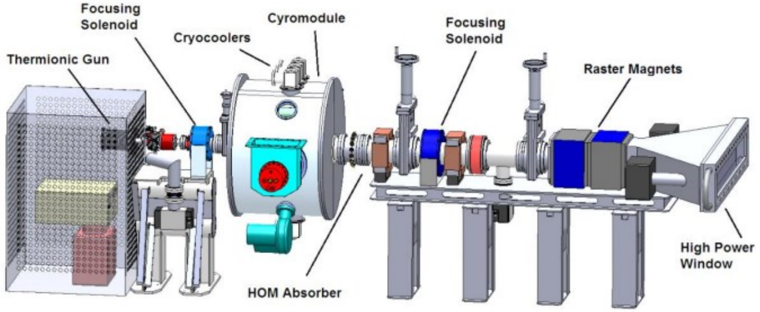
Water Treatment

Superconductive (SRF) version on R&D phase

→ combine cryocoolers & Nb_3Sn cavities to build compact irradiation sources

- 2018 G. Ciovati et al.

  1 MeV & 1 MW



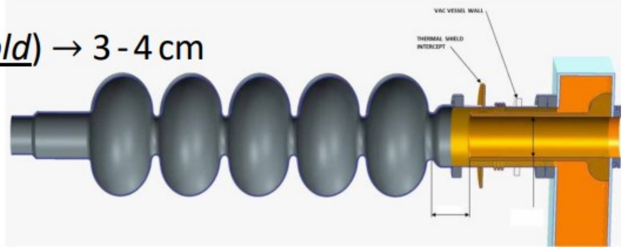
1 MeV penetration depth e^- in water ~ 3 - 4 mm

↪ not very practical

move to 10 MeV (*remember threshold*) → 3 - 4 cm

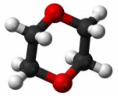
single cell → multi-cell cavity

↪ not new for SRF but for CC



Treatment of "Forever Chemicals" in Wastewater with Electron Beams – J. Vennekate IPAC '23

- collaboration with local sanitation district HRSD
- UITF – existing 10 MeV *SRF CW* machine
- first study on 1,4-dioxane
  - also pollutant, not biodegradable
  - usually treated with ozone (bromate) and/or peroxide & UV light (low transm.)



c&en CHEMICAL & ENGINEERING NEWS TOPICS MAGAZINE COLLECTIONS VIDEOS JOBS

POLLUTION

1,4-Dioxane: Another forever chemical plagues drinking-water utilities

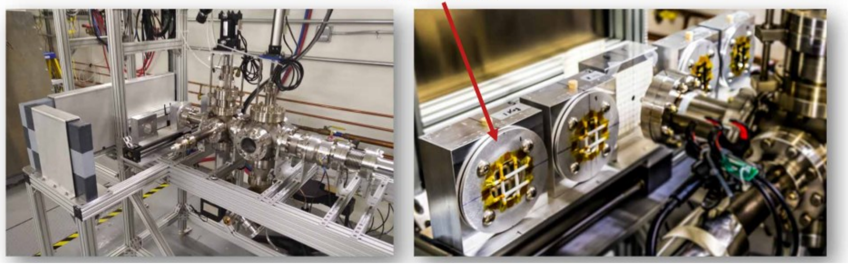
Highly miscible in water, the likely carcinogen is challenging to remove

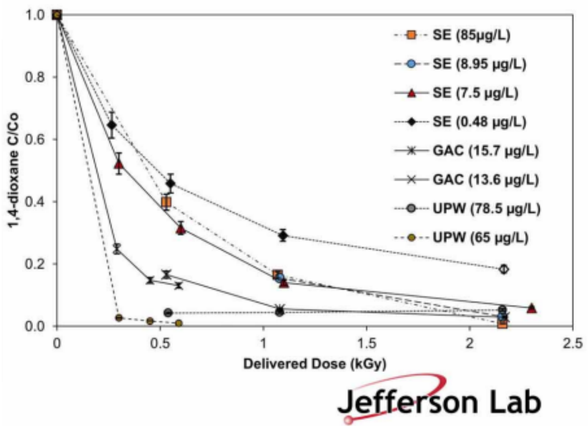
by Cheryl Hogue

November 8, 2020 | A version of this story appeared in Volume 98, Issue 43

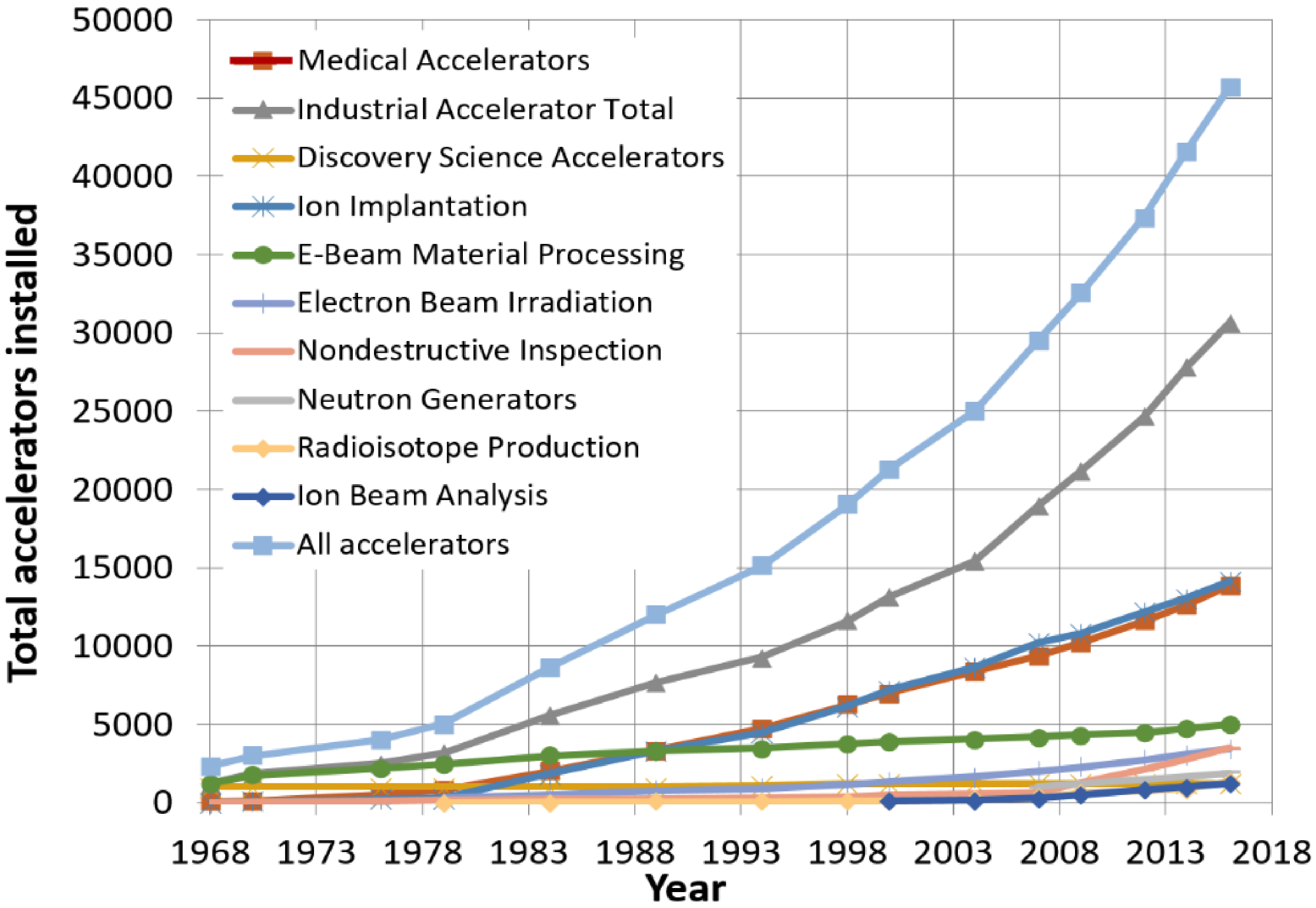
- great success → significant reduction @ low dose ↔ no chemical added & no bromate formation(!)

water targets





Accelerators installed worldwide



From accelerator technology to society

Applications in society are as well important to motivate large scale experiments

Particle therapy centres in Europe - 2002

(a)

Source: PTCOG, October 2015

Particle therapy centres in Europe - 2015

Source: PTCOG, October 2015

(b)

Information from Manjit Dosanjh, “From Particle Physics to Medical Applications”, IOP Publishing 2017, Bristol, UK

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Particle therapy centres in Europe - 2002

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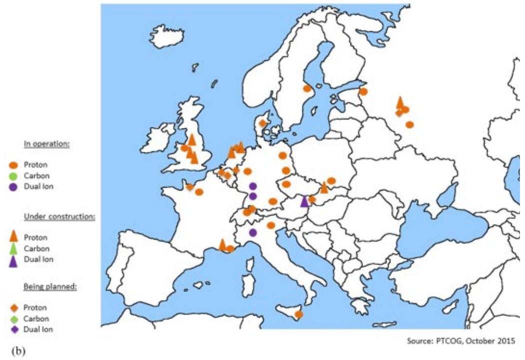
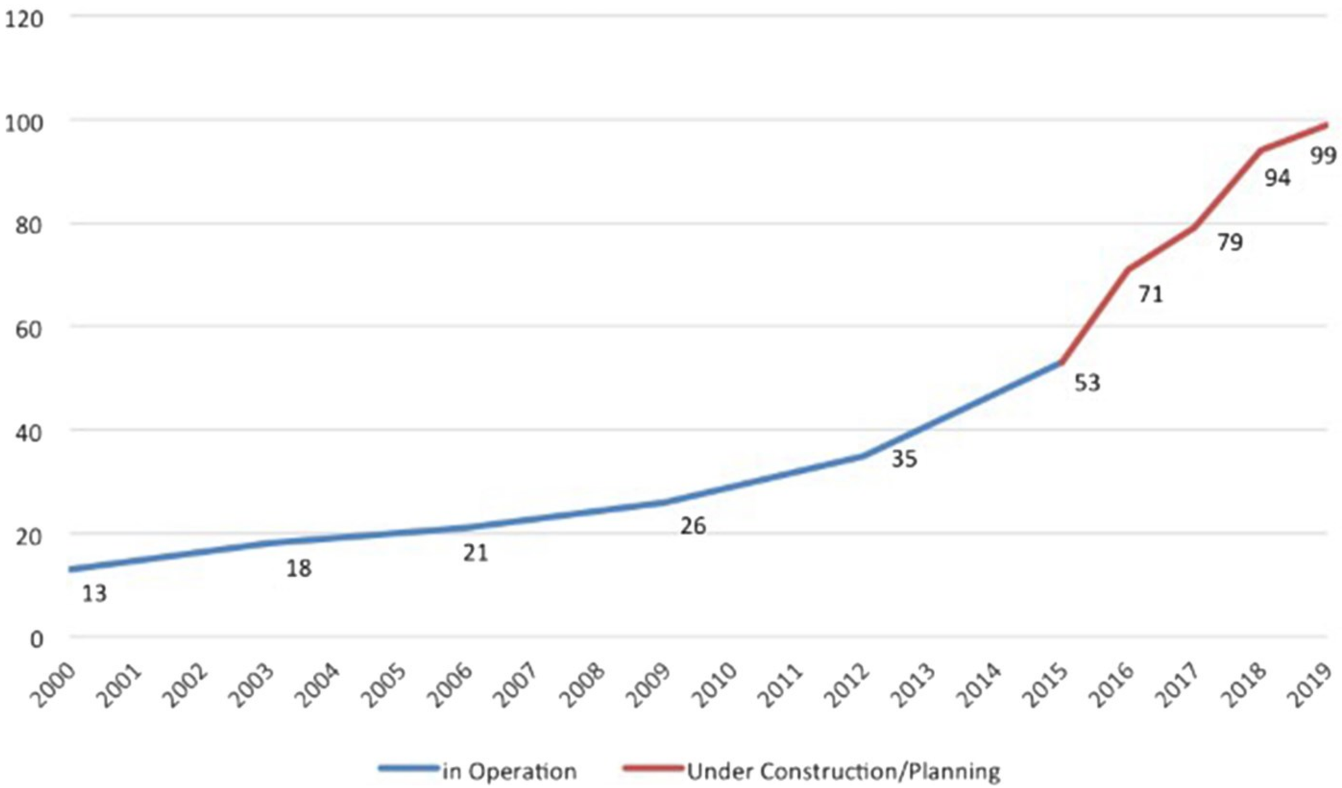


Source: PTCOG, October 2015

Particle therapy facilities in operation



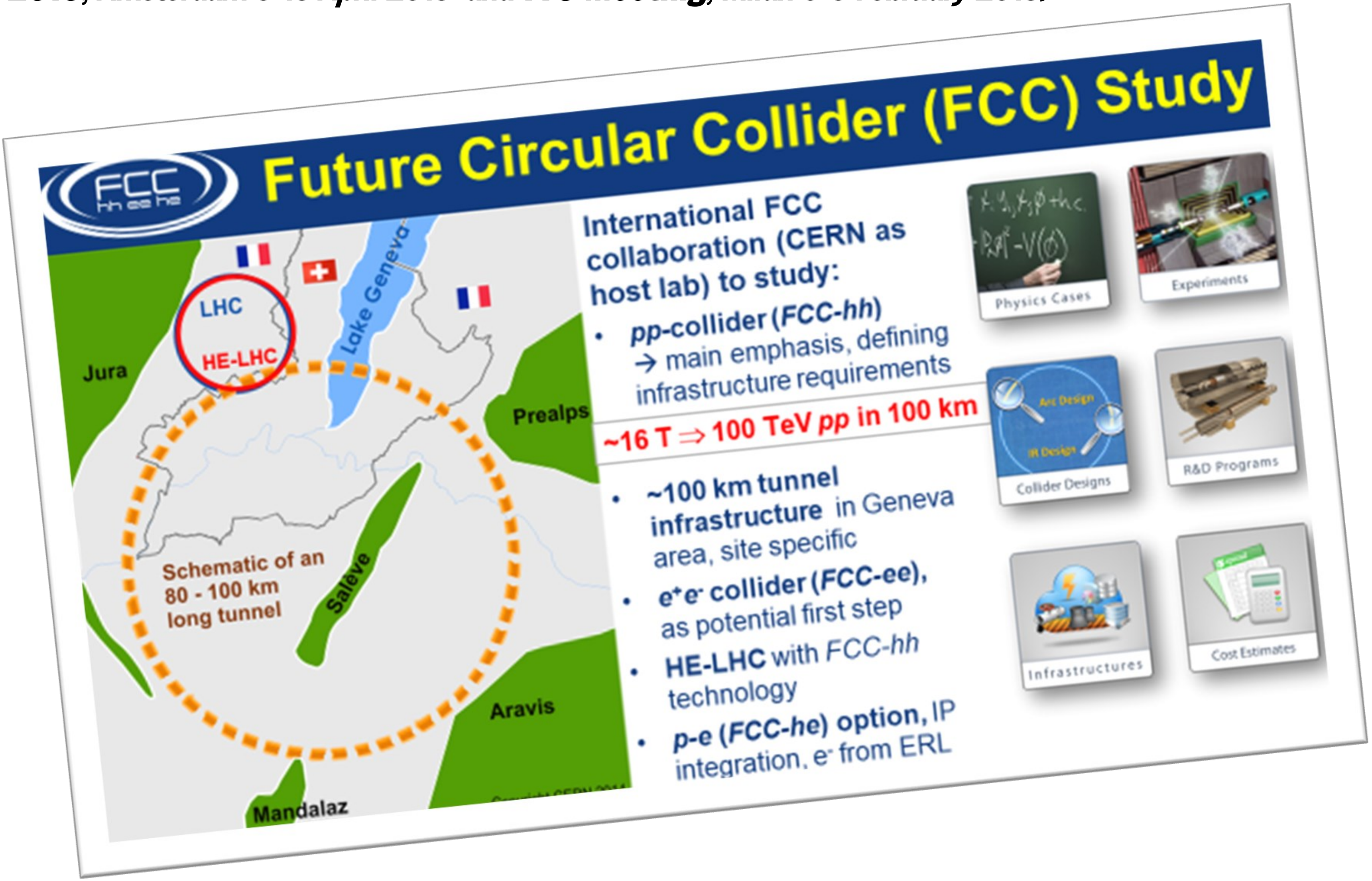
Information from Manjit Dosanjh, “From Particle Physics to Medical Applications”, IOP Publishing 2017, Bristol, UK

Brief and incomplete panorama on the next accelerators

(slides from ***FCC week 2018***, *Amsterdam 9-13 April 2018* and ***TTC Meeting***, *Milan 6-9 February 2018*)

Planned for 2040

> 1200 Cavities



Future Circular Collider (FCC) Study

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e⁺e⁻ collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e⁻ from ERL

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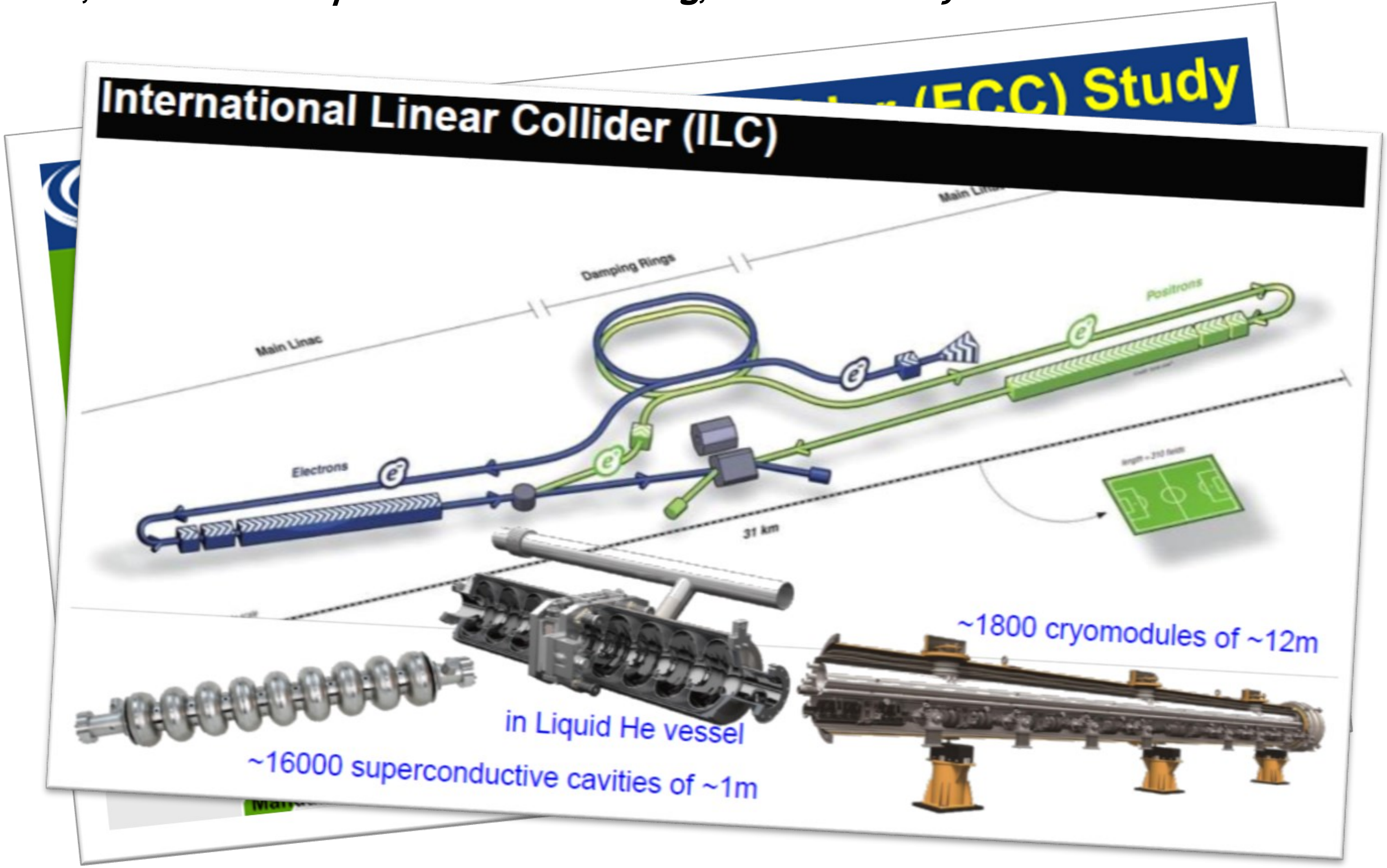

International Linear Collider (ILC)

~1800 cryomodules of ~12m

in Liquid He vessel

~16000 superconductive cavities of ~1m

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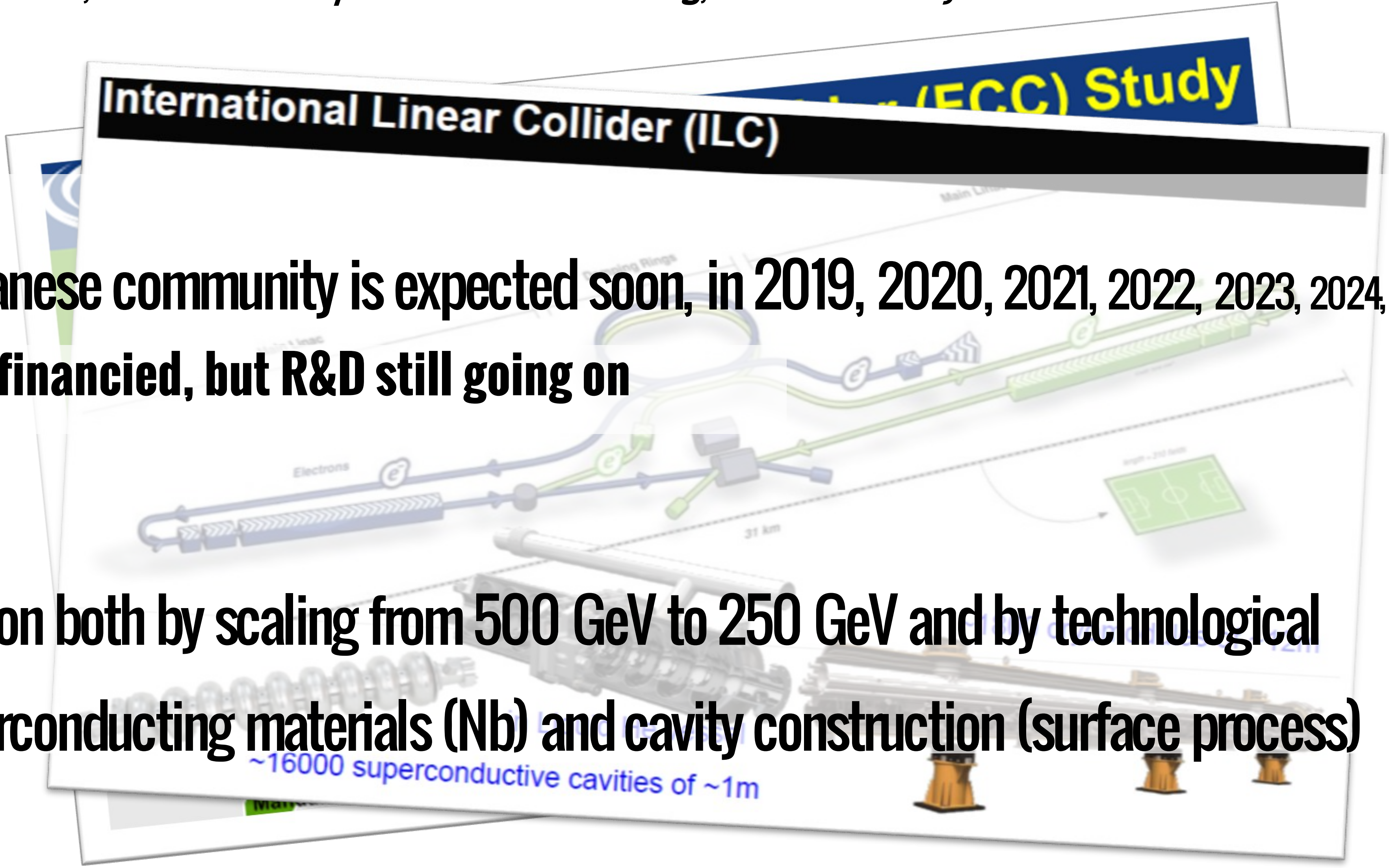


(FCC) Study

International Linear Collider (ILC)

~16000 superconductive cavities of ~1m

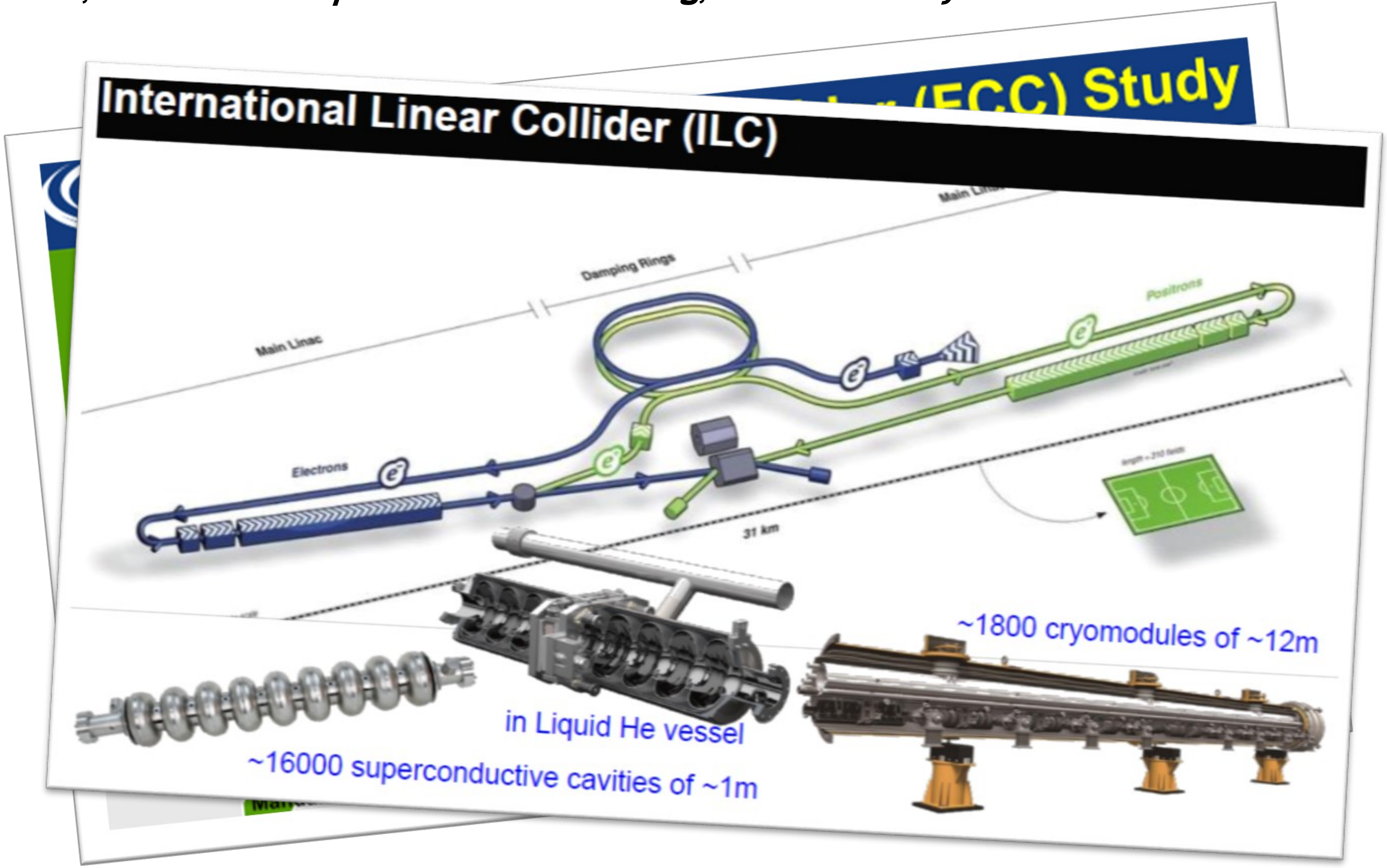
A decision from the Japanese community is expected soon, in 2019, 2020, 2021, 2022, 2023, 2024, …

Probably ILC will be not financied, but R&D still going on

Proposed a cost reduction both by scaling from 500 GeV to 250 GeV and by technological innovations on the superconducting materials (Nb) and cavity construction (surface process)

Brief and incomplete panorama on the next accelerators

(slides from ***FCC week 2018****, Amsterdam 9-13 April 2018* and ***TTC Meeting****, Milan 6-9 February 2018*)



(FCC) Study

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Brief and incomplete panorama on the next accelerators

(slides from *FCC week 2018, Amsterdam 9-13 April 2018* and *TTC Meeting, Milan 6-9 February 2018*)

X-ray free-electron

Based on European XFEL technology

280 SC cavities

First light in 2021

Brief and incomplete panorama on the next accelerators

(slides from ***FCC week 2018***, *Amsterdam 9-13 April 2018* and ***TTC Meeting***, *Milan 6-9 February 2018*)

Brief and incomplete panorama on the next accelerators

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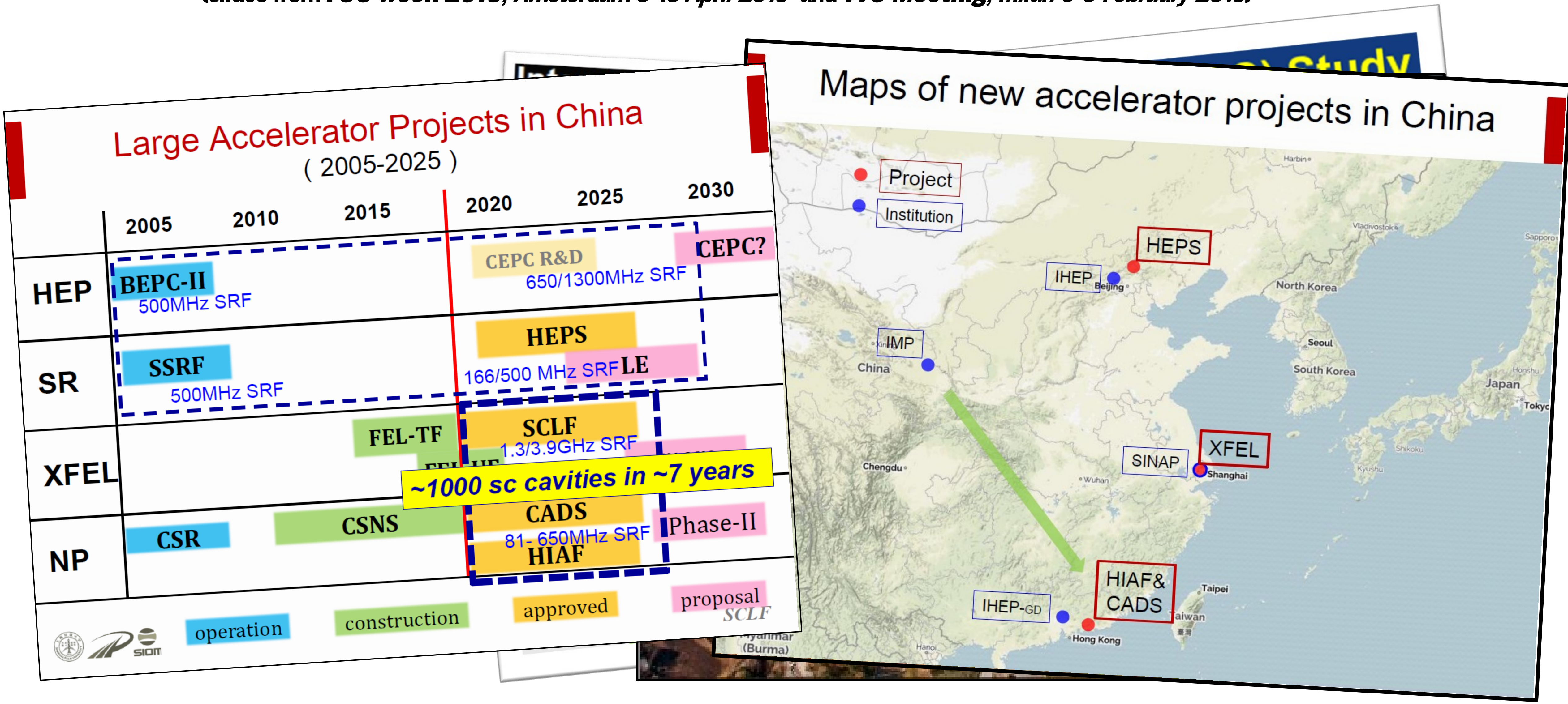


Large Accelerator Projects in China

(2005-2025)

	2005	2010	2015	2020	2025	2030
HEP	**BEPC-II** 500MHz SRF			**CEPC R&D** 650/1300MHz SRF		**CEPC?**
SR	**SSRF** 500MHz SRF			**HEPS** 166/500 MHz SRF	**LE**	
XFEL			**FEL-TF** **FEL-UF**	**SCLF** 1.3/3.9GHz SRF		
NP	**CSR**		**CSNS**	**CADS** 81- 650MHz SRF **HIAF**	**Phase-II**	

~1000 sc cavities in ~7 years

operation · construction · approved · proposal

SCLF

Maps of new accelerator projects in China

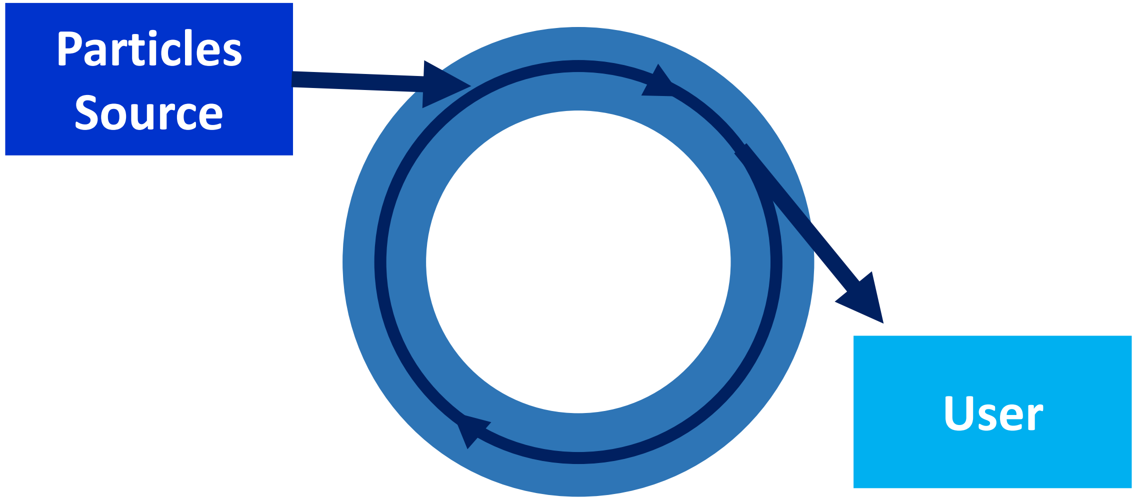
How works an accelerator?

How works an accelerator?

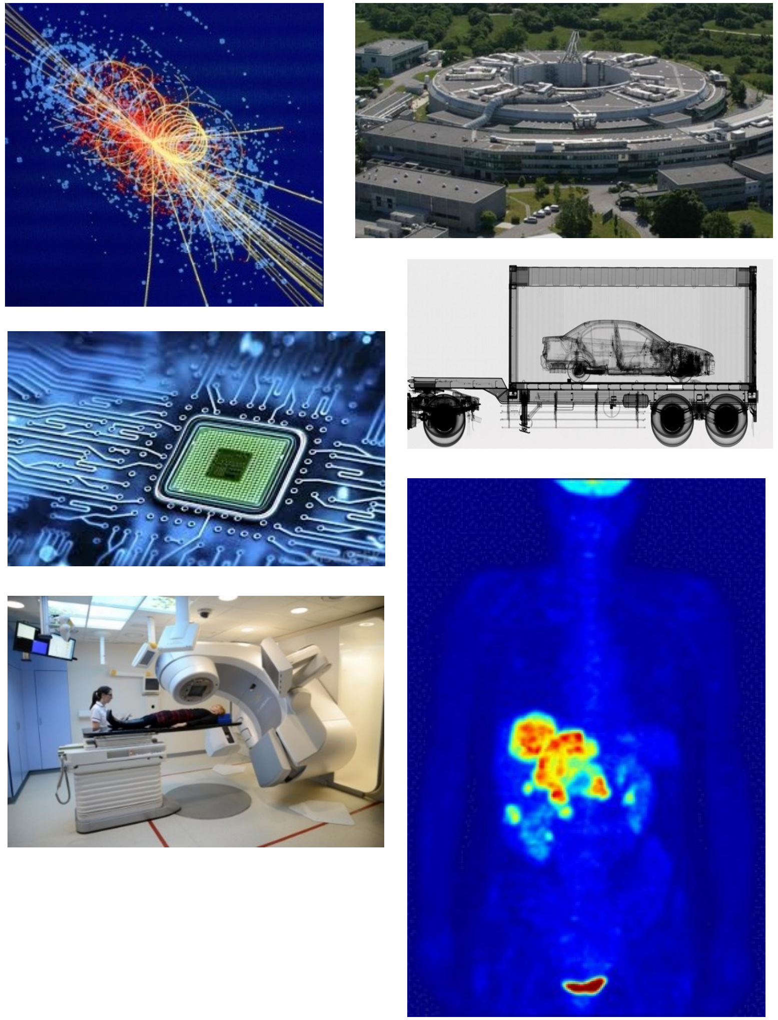
Linear Accelerator (Linac)

Particles Source → **Acceleration** → **User**

Circular Accelerator

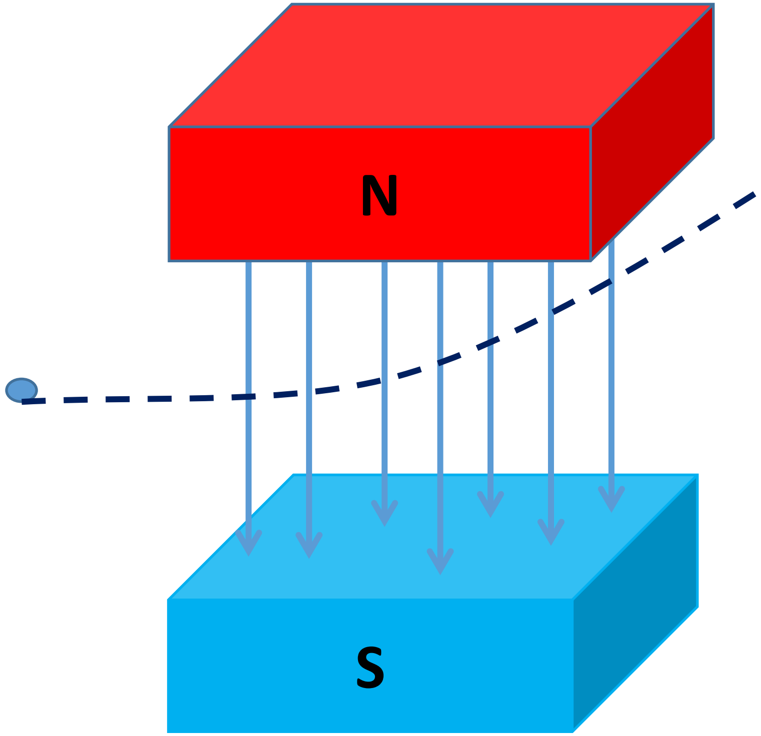


User



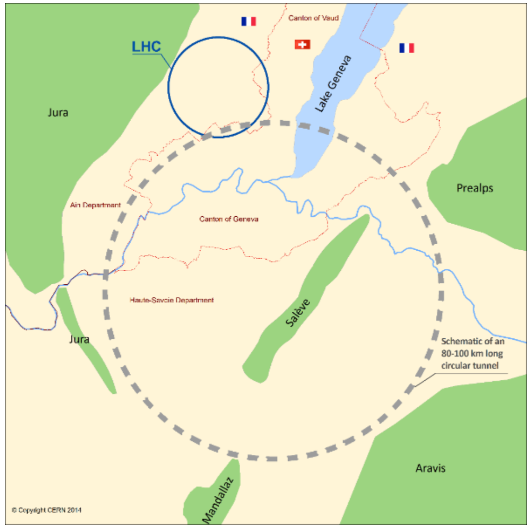
How to curve accelerating particles?

$$\frac{\overrightarrow{dp}}{dt} = q\left(\vec{E} + \vec{v} x \vec{B}\right)$$ *Lorentz Force*



Dipoles to curve

Quadrupole to focus



$$R \propto \frac{E_0}{B}$$

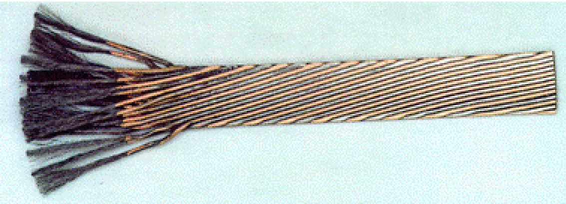
100 TeV for FCC h-h
(LHC 14 TeV)

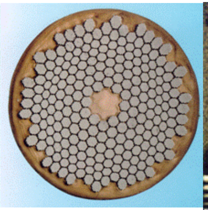
16 Tesla are necessary!

Impossible to obtain with Copper Coils or permanent magnets
For High Energy Circular Colliders
SUPERCONDUCTORS are mandatory!

FCC dipoles: a new challenge

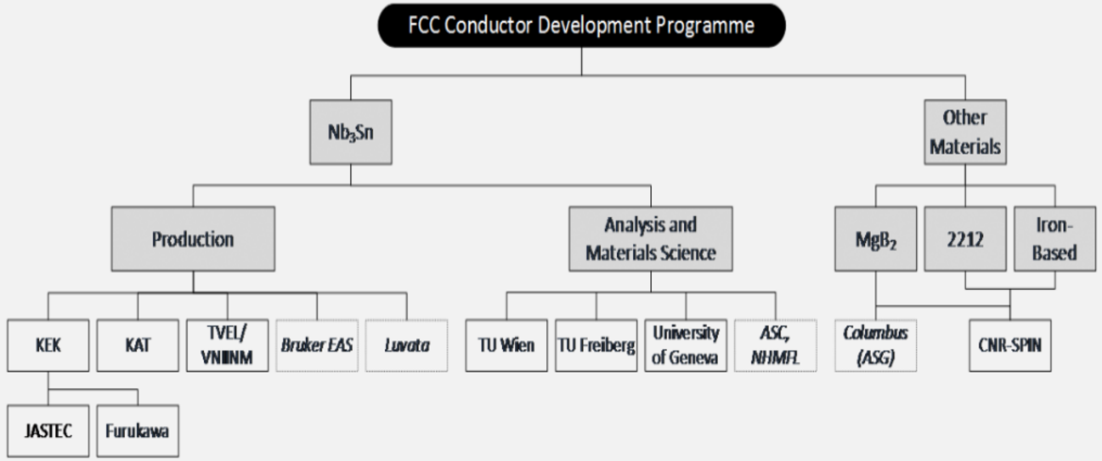
NbTi (9-10 T for LHC)


Cable

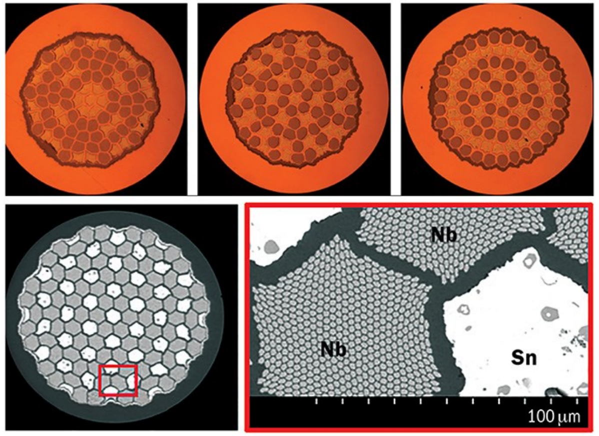

Strand


Filaments

The cables house 36 strands of superconducting wire, each strand being exactly 0.825 mm in diameter. Each strand houses 6300 superconducting filaments of Niobium-titanium (NbTi). Each filament is about 0.006 mm thick, i.e. 10 times thinner than a normal human hair. Total superconducting cable required 1200 tonnes which translates to around 7600 km of cable (the cable is made up of strands which is made of filaments, total length of filaments is astronomical - 5 times to the sun and back with enough left over for a few trips to the moon)


- FCC Conductor Development Programme
  - Nb_3Sn
    - Production
      - KEK
        - JASTEC
        - Furukawa
      - KAT
      - TVEL/ VNIINM
      - *Bruker EAS*
      - *Luvata*
    - Analysis and Materials Science
      - TU Wien
      - TU Freiberg
      - University of Geneva
      - *ASC, NHMFL*
  - Other Materials
    - MgB_2
      - *Columbus (ASG)*
      - CNR-SPIN
    - 2212
      - CNR-SPIN
    - Iron-Based
      - CNR-SPIN

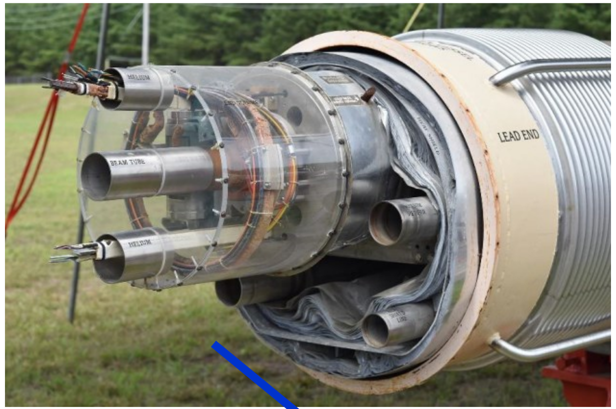
The structure of the FCC Conductor Development Programme, showing the activities (shaded boxes) and partners. A dotted outline and italic text indicate pending participants, whose participation is currently being finalised. (Credit: CERN)

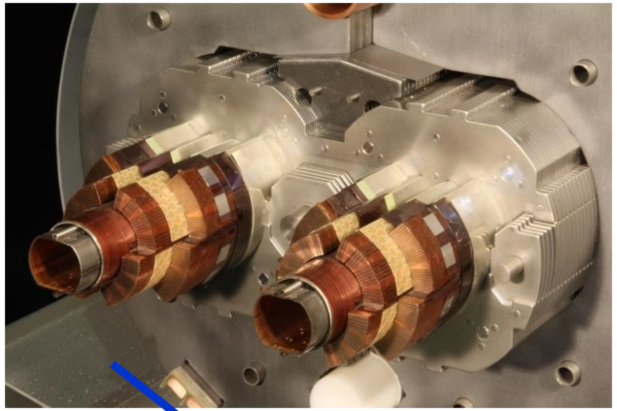


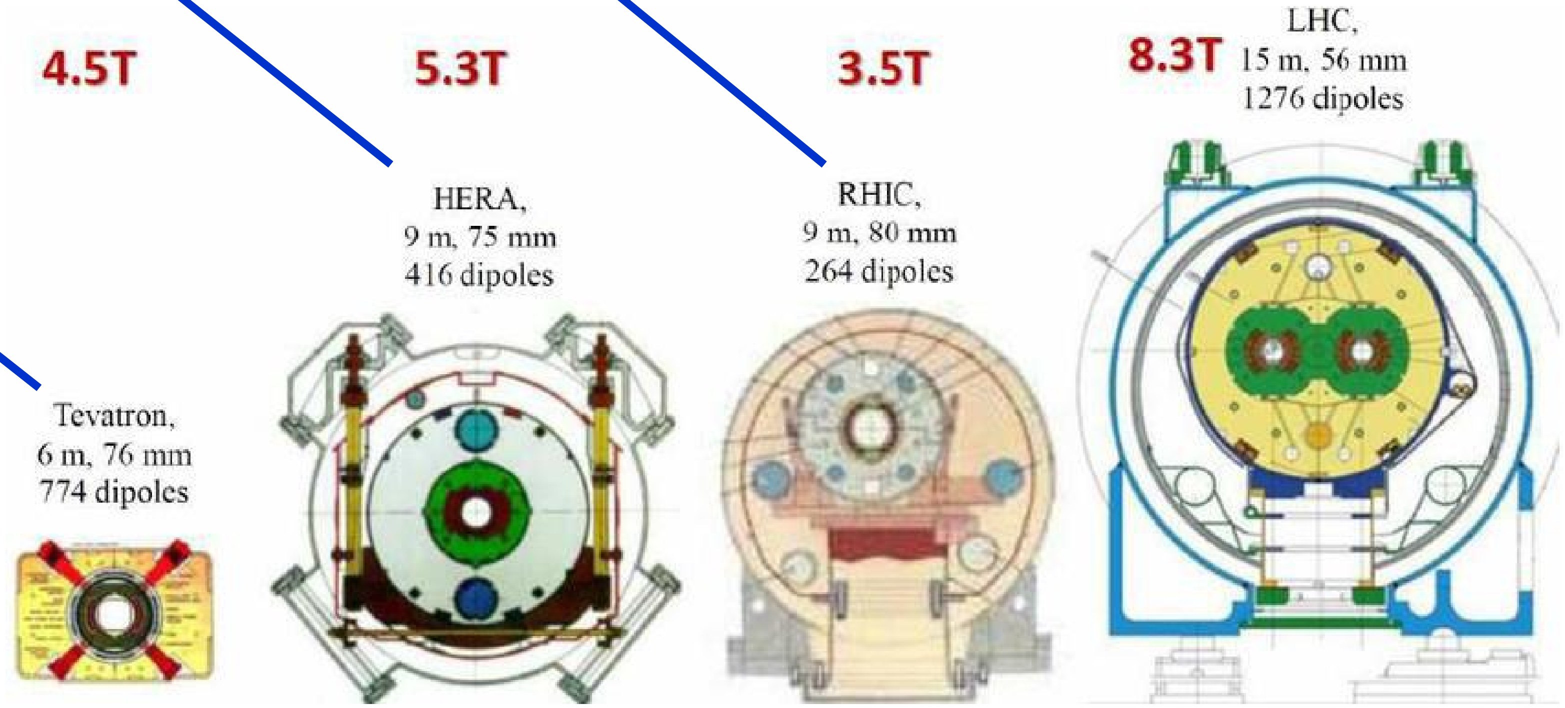
Nb_3Sn (12 T for HL-LHC, 16 T for FCC)

Cross-sections of prototype Nb3Sn wires developed in collaboration with CERN as part of the FCC conductor development programme.Top: optical micrographs of wires from Kiswire Advanced Technology. Bottom: electron micrographs showing a wire developed by JASTEC in collaboration with KEK. Both show the unreacted wire before the heat treatment to form the Nb3Sn compound from the niobium filaments and tin. (Credit: KAT/JASTEC. The image originally appeared in the CERN Courier, June, 2018)

Dipoles


LEAD END

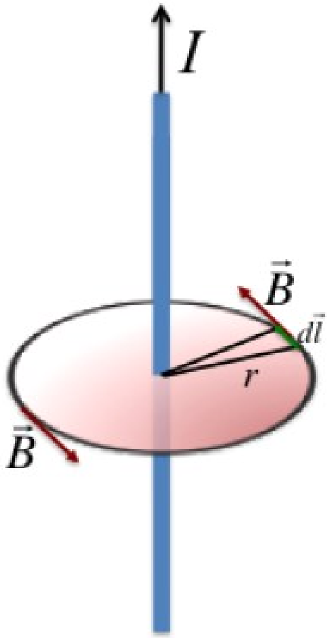



4.5T
Tevatron,
6 m, 76 mm
774 dipoles
5.3T
HERA,
9 m, 75 mm
416 dipoles
3.5T
RHIC,
9 m, 80 mm
264 dipoles
8.3T
LHC,
15 m, 56 mm
1276 dipoles

Magnetic field of a current line

- From the Maxwell equation: $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J}$ $\oint \boldsymbol{B}\, dl = \mu_0 I$

- It's easy to find that: $B(r) = \dfrac{\mu_0 J}{2\pi r}$



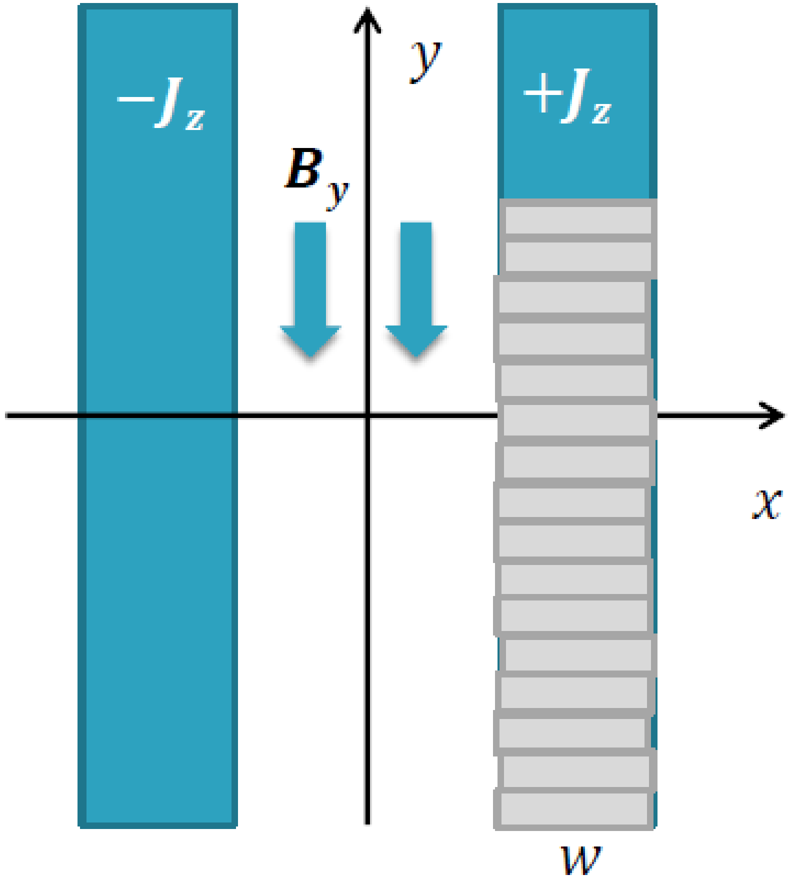
Lying on a plane perpendicular to the current line and tangent to the circumference of radius r

Ideal Dipoles shapes: #1: wall dipole

A uniform current density flowing in two parallel walls of infinite height generates a pure dipolar field

- Winding and mechanical structure are not particularly complicated
- The coil is theoretically infinite
- Coil truncation results in an acceptable field quality only for large dimensions
- Simply applying the Biot Savart law

$$B_y = \frac{\mu_0 J w}{2}$$



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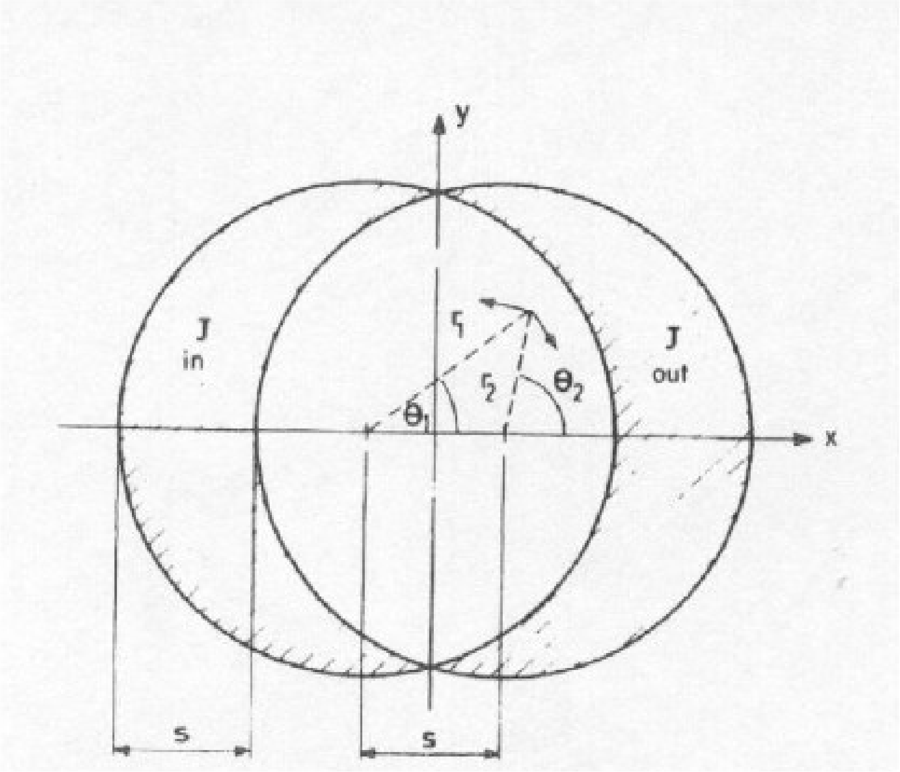
Ideal Dipoles shapes: #2: intersecting circles

- Within a cylinder carrying uniform J, the field is directed tangentially $B(r) = \frac{\mu_0 J r}{2}$

- Combining the effect of the two cylinders:

$$B_y = \frac{\mu_0 J}{2}(-r_1 cos\Theta_1 + r_2 cos\Theta_2) = -\frac{\mu_0 J s}{2}$$

$$B_x = \frac{\mu_0 J}{2}(+r_1 sin\Theta_1 - r_2 sin\Theta_2) = 0$$



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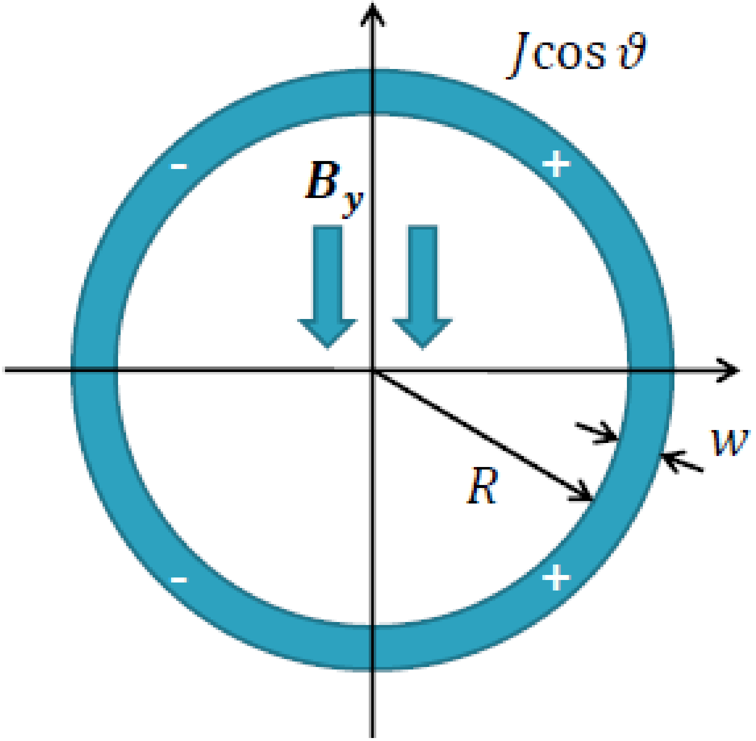
Ideal Dipoles shapes: #3: $J\cos\vartheta$ distribution

- Let us consider a current density distribution $J\cos\vartheta$in a shell of inner radius R and thickness w

- To get the total cotribution we replace $I$with JdS=$J\cos\vartheta\cdot rdrd\vartheta$and integrate from 0to 2$\pi$



$$B_y = -\frac{\mu_0 Jw}{2}$$

By ∝ current density (obvious)
By ∝ coil width w (less obvious)
By is independent of the aperture R (surprising)

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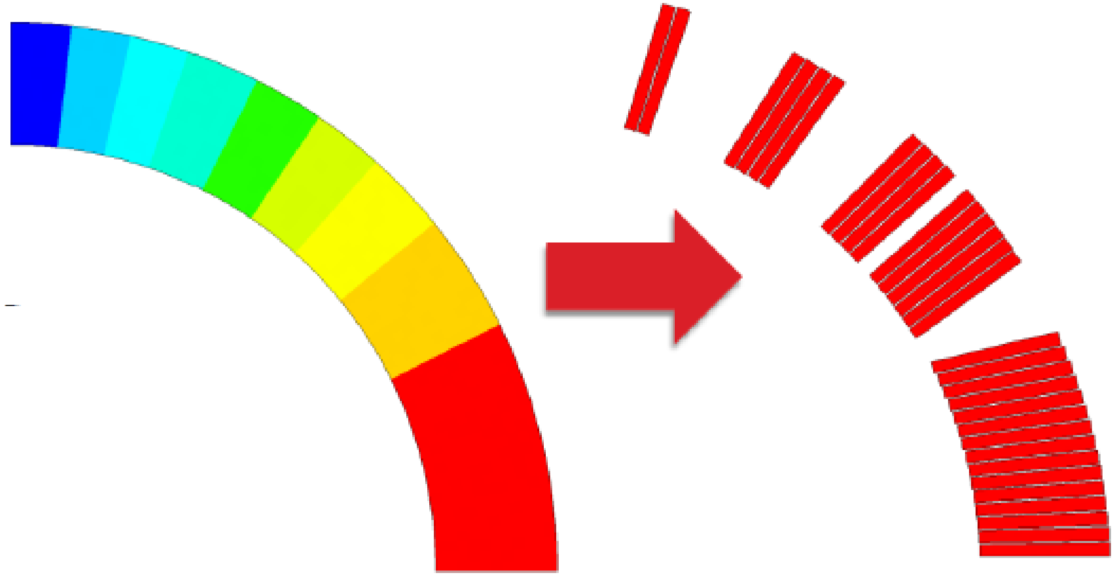
Perfect dipole vs real dipole

Using real conductors, current density need to be uniform

The **perfect $J\cos\vartheta$ distribution** is approached **accumulating turn close to the midplane** (where $\cos\vartheta \sim 1$) and **reducing them at 90°** (where $\cos\vartheta \rightarrow 0$)



- *the aperture is circular*
- *the winding is self supporting (roman arc)*

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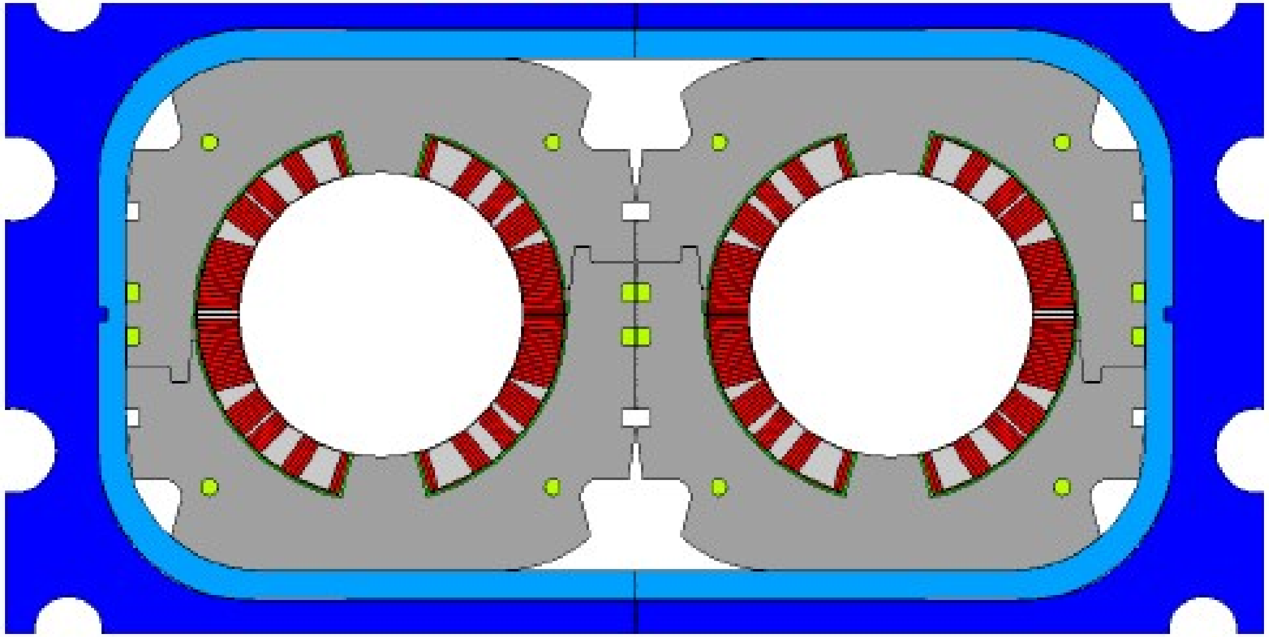
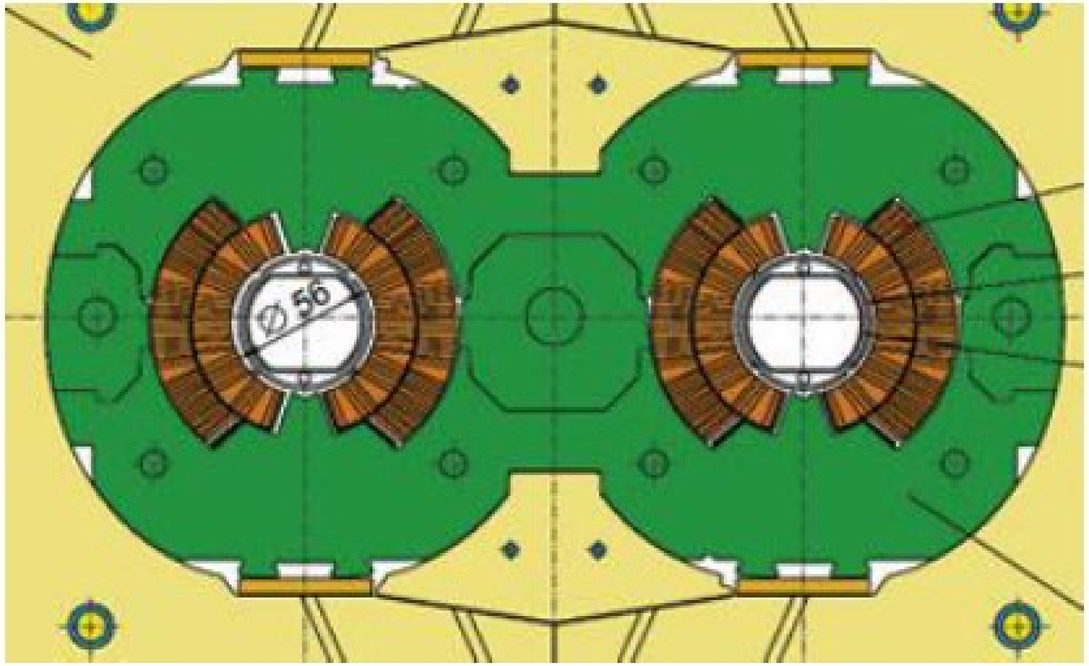
Real dipoles

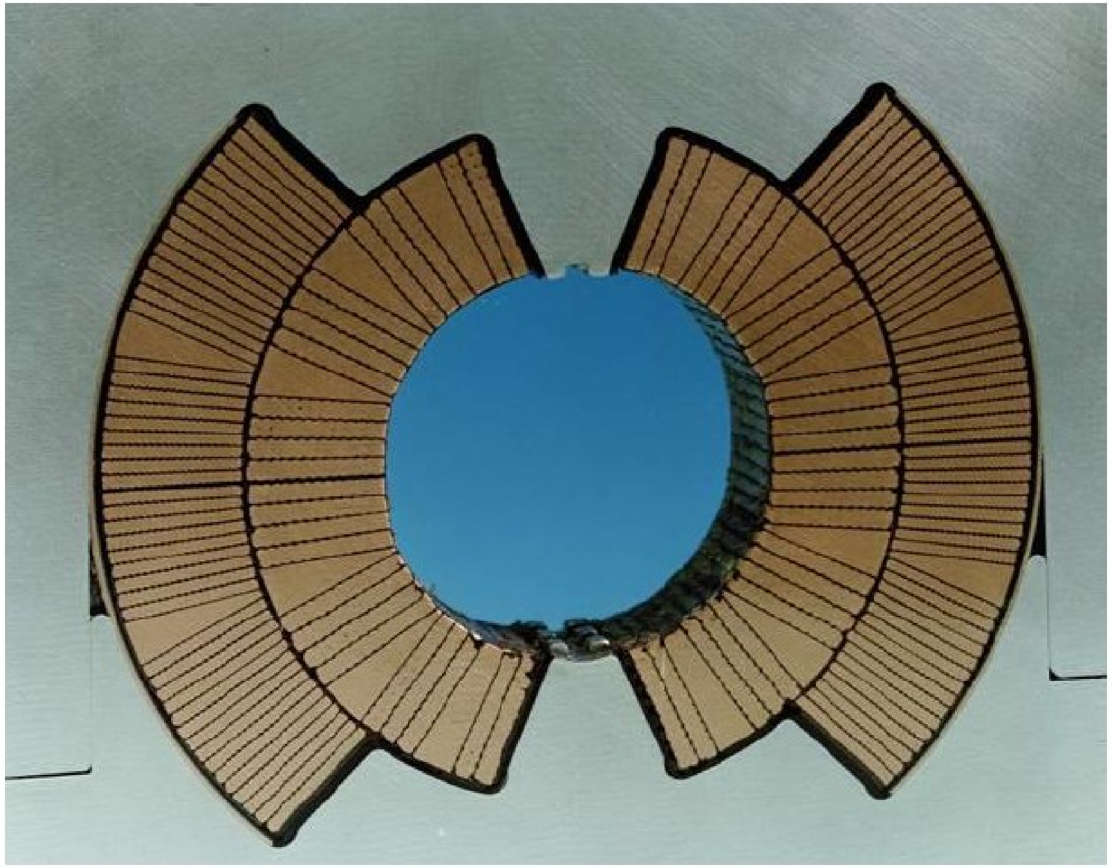
HiLumi D2 dipole



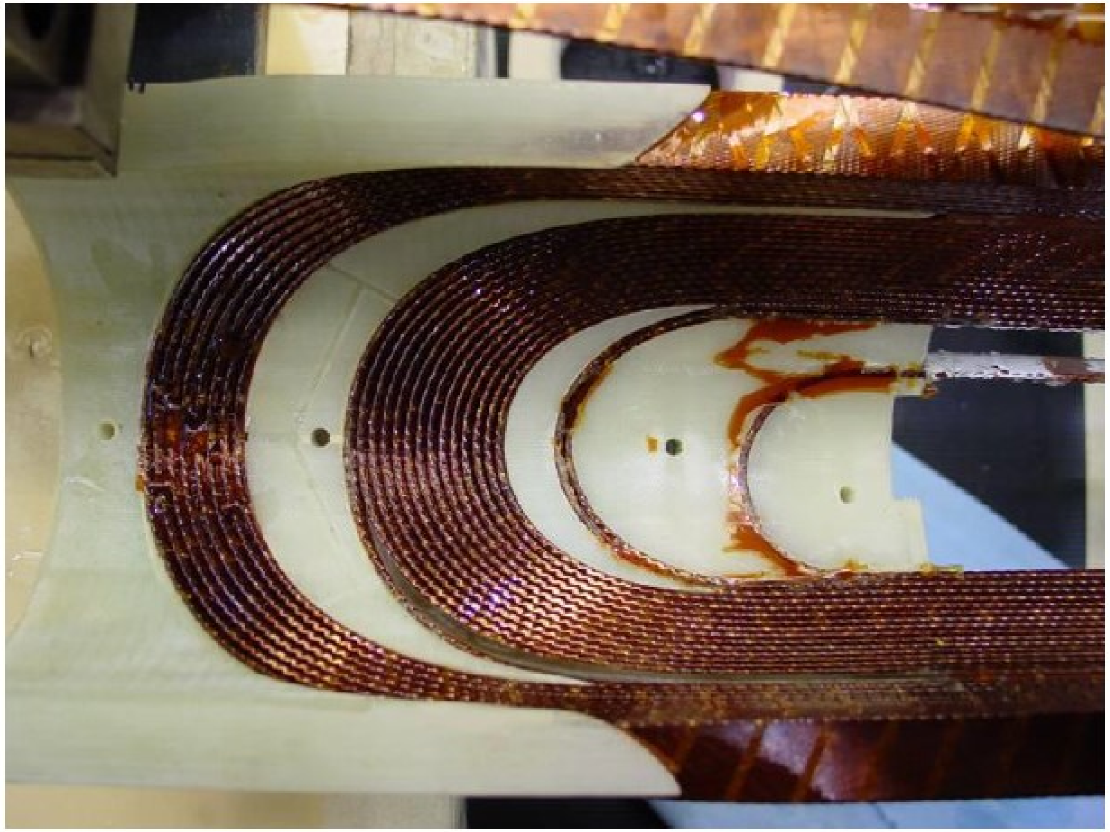
LHC dipole



LHC dipoles



Cross section of one aperture

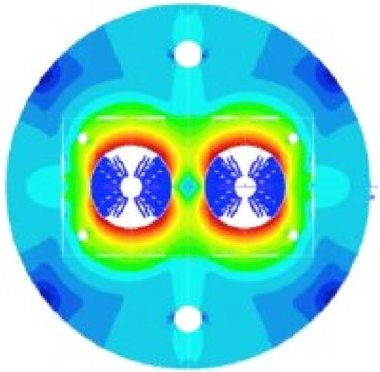


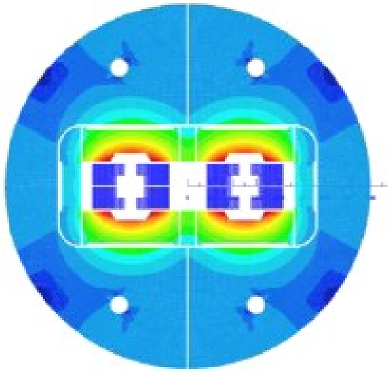
Detail of the LOC side end

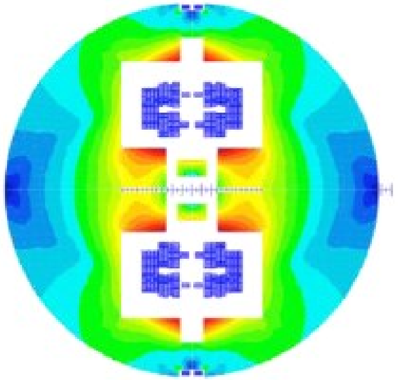
Dipole winding shapes - EuroCirCol project

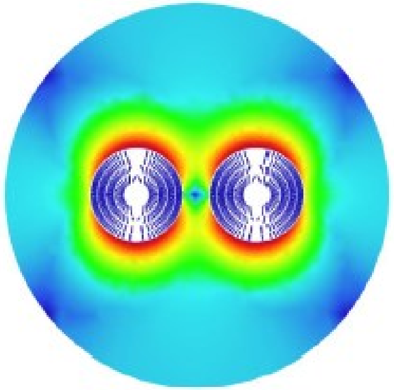
- Results of the **optimization of a double aperture 16 T dipole for the FCC in 4 different options** as part of WP5 of Eurocircol project (www.eurocircol.eu)

- All optimizations share common assumption: same magnet aperture (50 mm), conductor performance ($J_{c\ @16T,4.2K}$ = 1500A/mm^2), margin on the loadline (>14%), allowed mechanical constraints (σ<150 MPa at warm and <200 MPa at cold)


Cos-theta


Blocks


Common coils


Canted Cos-theta

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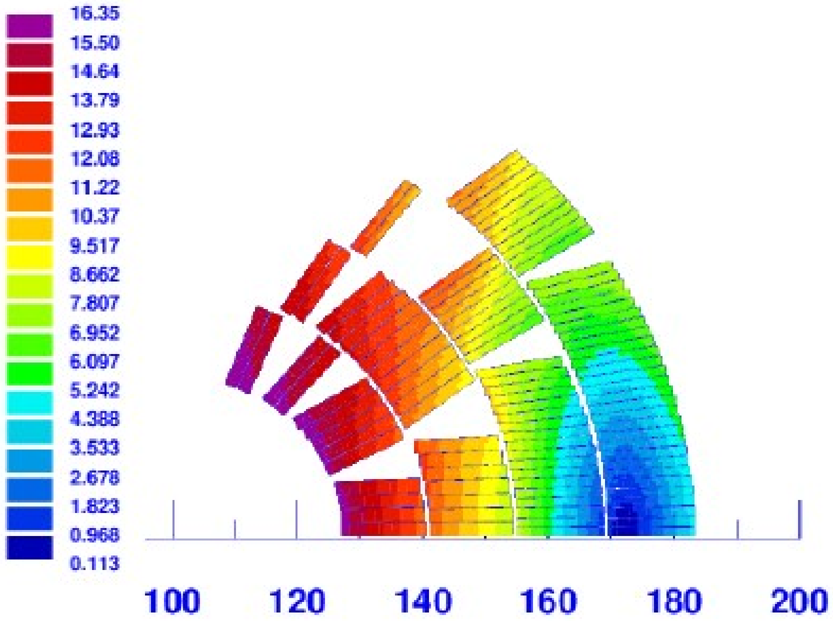
Cos-theta coil

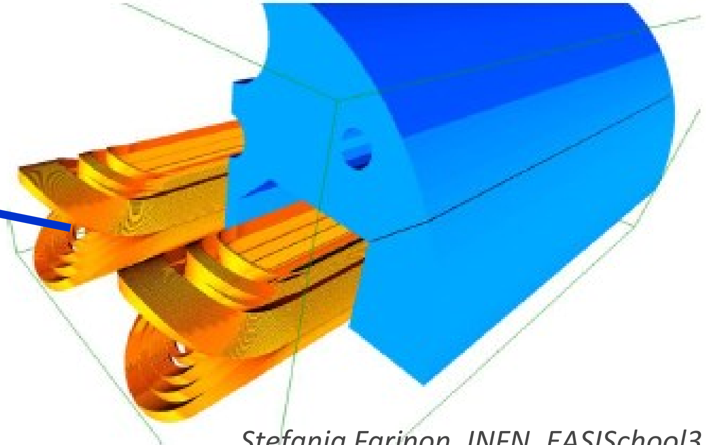


PROS

- Natural choice (LHC dipoles)
- Circular aperture fully available for beam
- Self -supporting winding (roman arc)

CONS

- Hardway bending in coil ends



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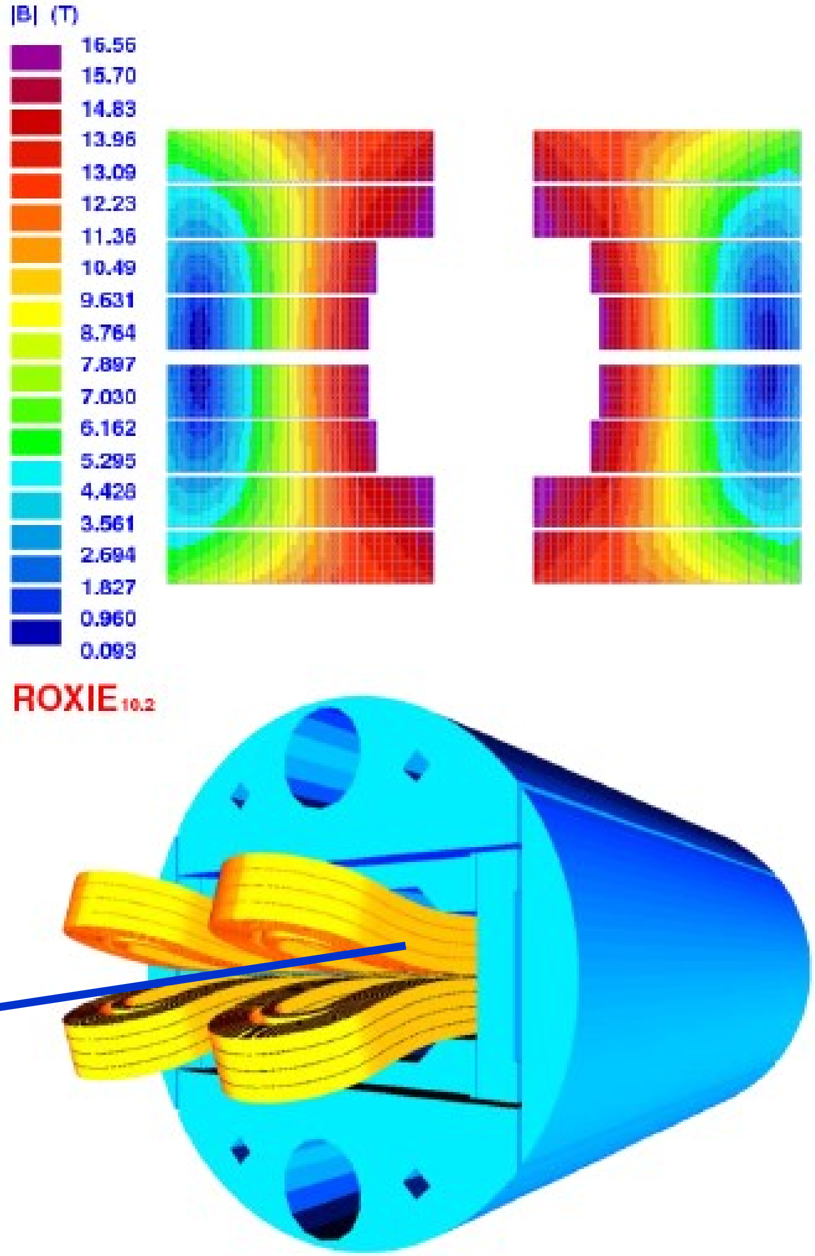
Block coil

PROS

- Particularly indicated for thick coils (turn are stacked vertically)
- No wedges (saddle shape ends)
- Peak stress during powering in the low field region

CONS

- Need of internal support (reducing available aperture)
- Very complicated coil ends (hardway bending)



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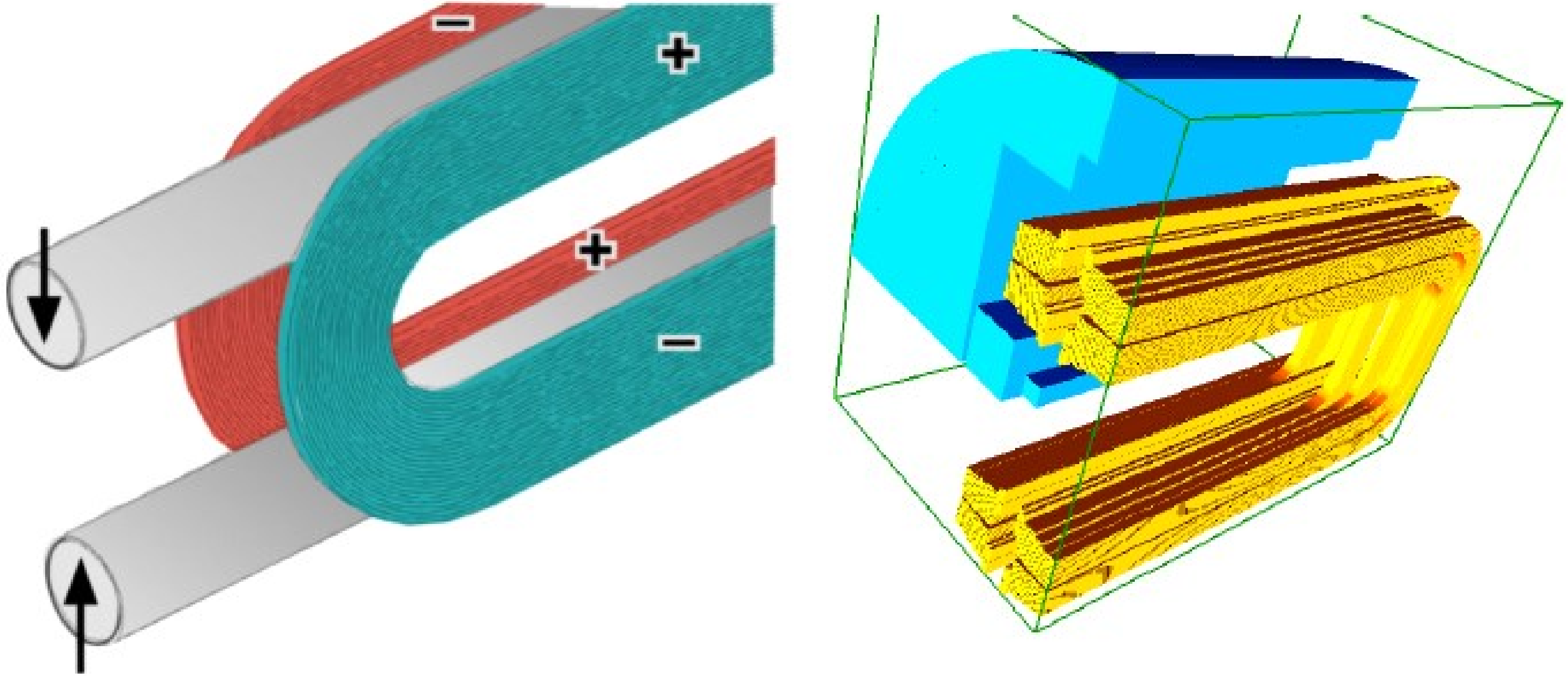
Common coil



PROS

- Very simple coils
  (flat racetrack shape)

CONS

- Complicated stress management
  (huge radial Lorentz force)
- Needs more superconductors

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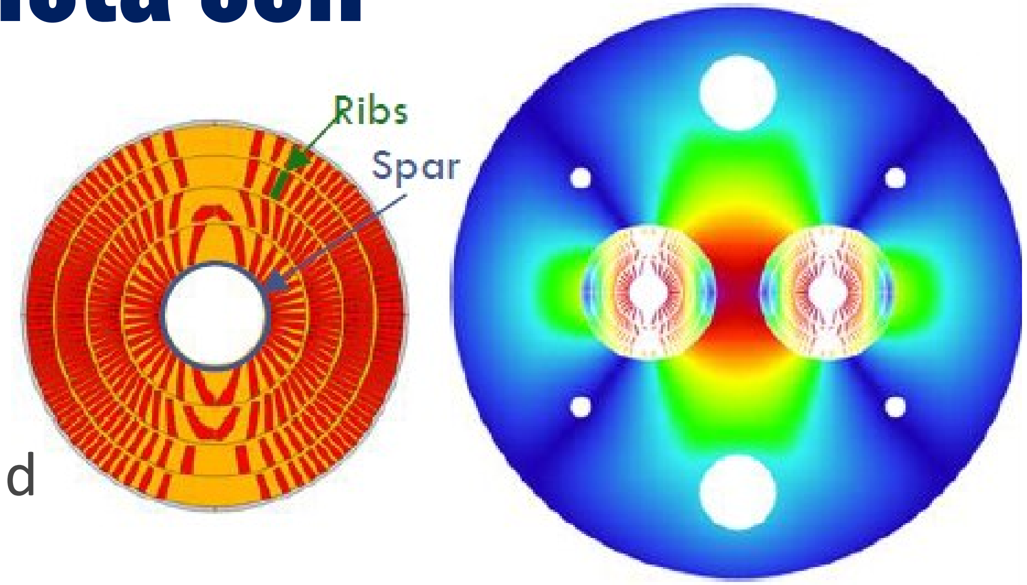
CCT Canted Cos Theta coil



PROS

- Each turn is individually supported
- 360° continuity of the winding: no azimuthal pre-load
- No field distortion in coil ends
- Small number of mechanical components

CONS

- Part of the current density lost in generating solenoidal field
- Need more superconductors
- Complicated winding if large Rutherford cables
  (bonding of cable inside channels, reliable insulation against former)

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Results of the comparision

- **The $\cos\vartheta$ configuration has been selected as baseline** for the Conceptual Design Report of the EuroCirCol project (http://cds.cern.ch/record/2651300/files/CERN-ACC-2018-0058.pdf?version=6)
- *“Each of these alternatives features some interesting characteristics which may have a potential to become competitive to the baseline cosine-theta design in terms of performance, in particular if they would allow operation at a lower margin on the load-line, thus reducing the required amount of conductor”*

Short model magnets (~1.5 m lengths) of all the options will be built from 2018–2022

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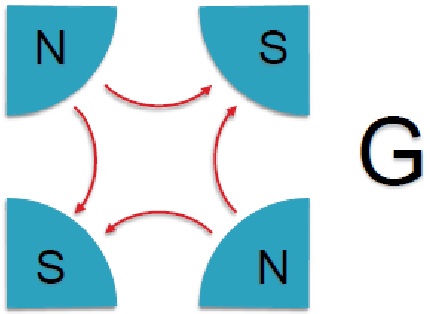
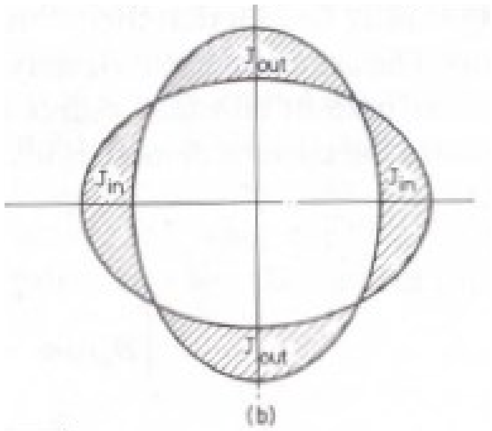
Quadrupoles

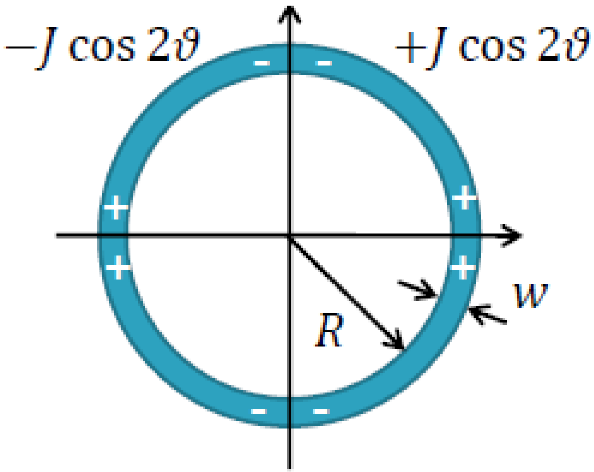
Quadrupole magnets generate constant and uniform gradient G:



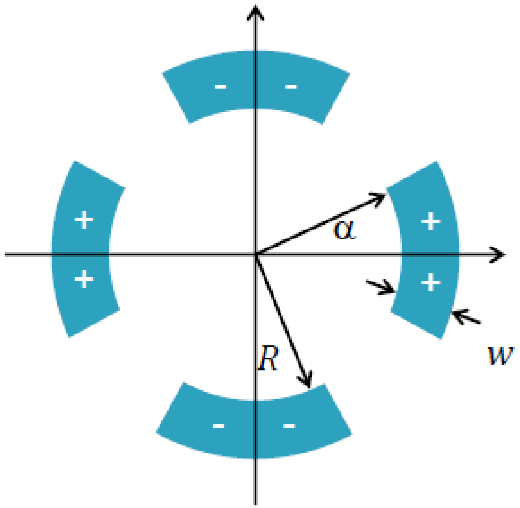
Similar as for dipoles:



Intersection of two crossed ellipses

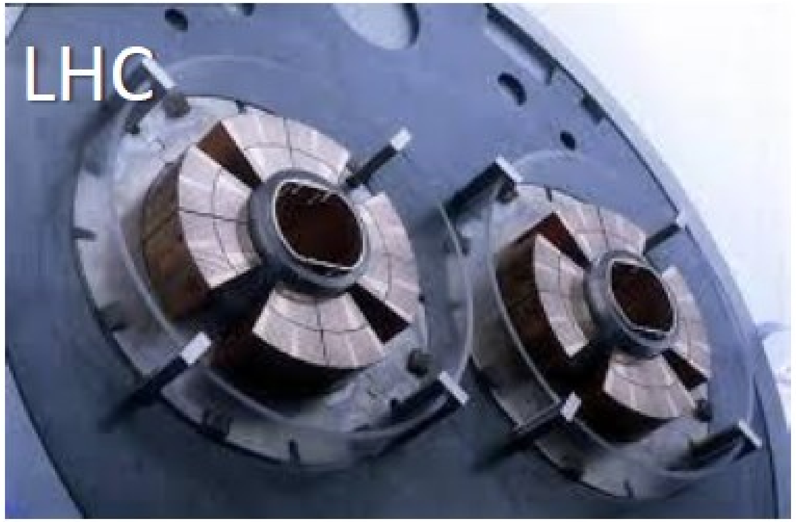


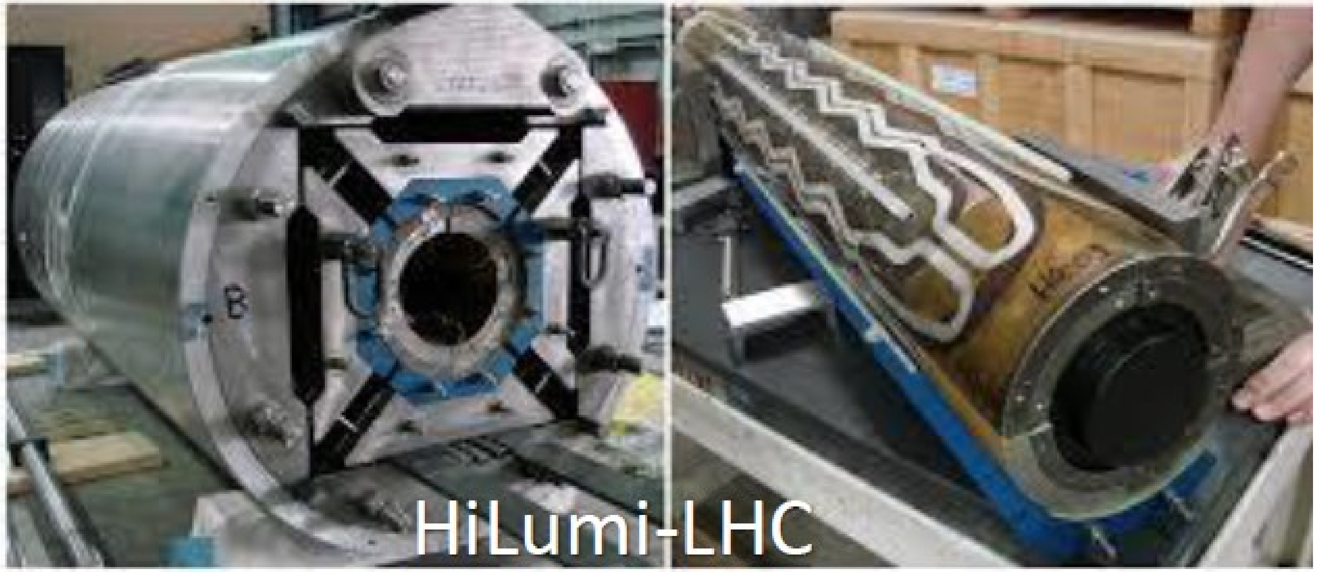
Intersection of two crossed ellipses

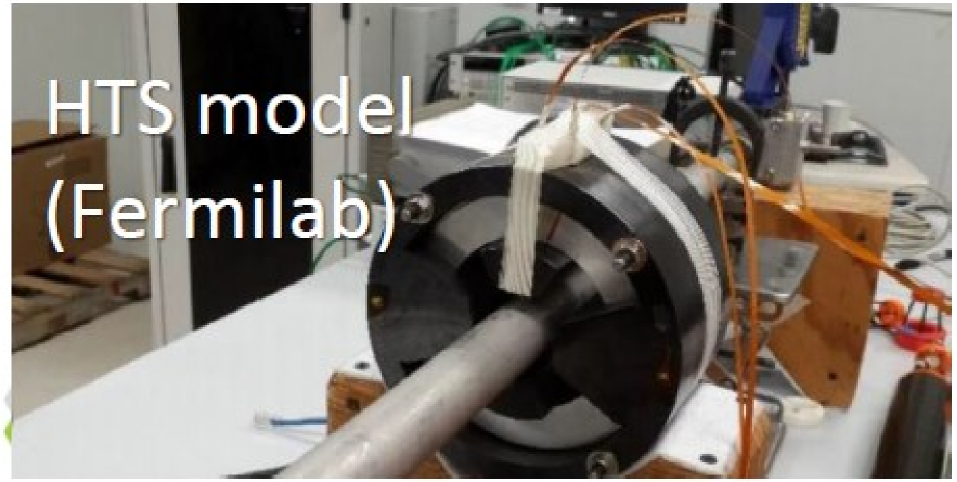


Sector quadrupole

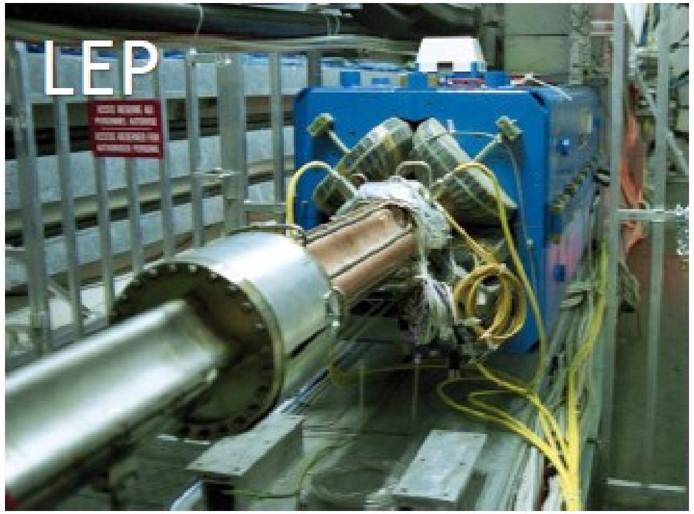
Quadrupoles


LHC


HiLumi-LHC


HTS model (Fermilab)

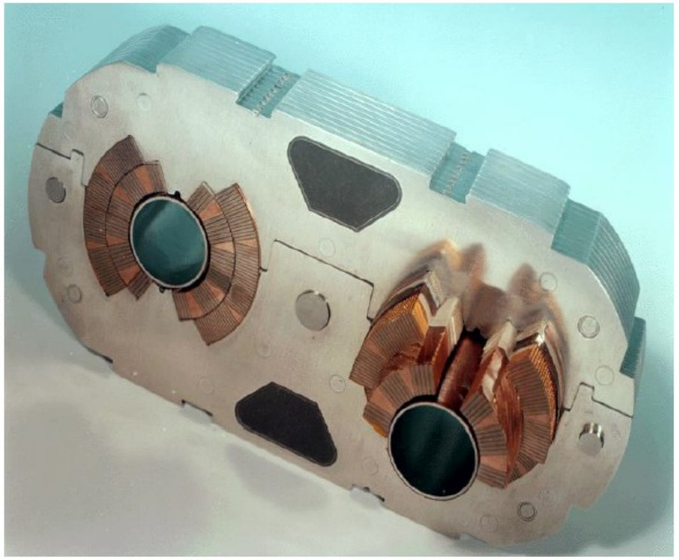

SIS300


LEP

Realize big magnets is not trivial…

Collaring press

ASG SUPERCONDUCTORS



Collaring completed

LHC - dipole

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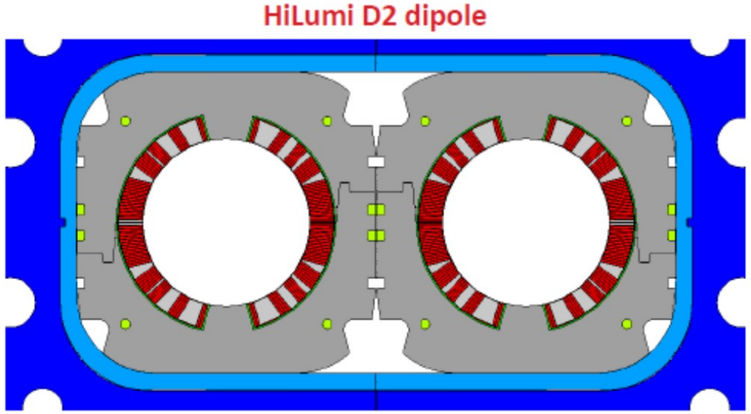
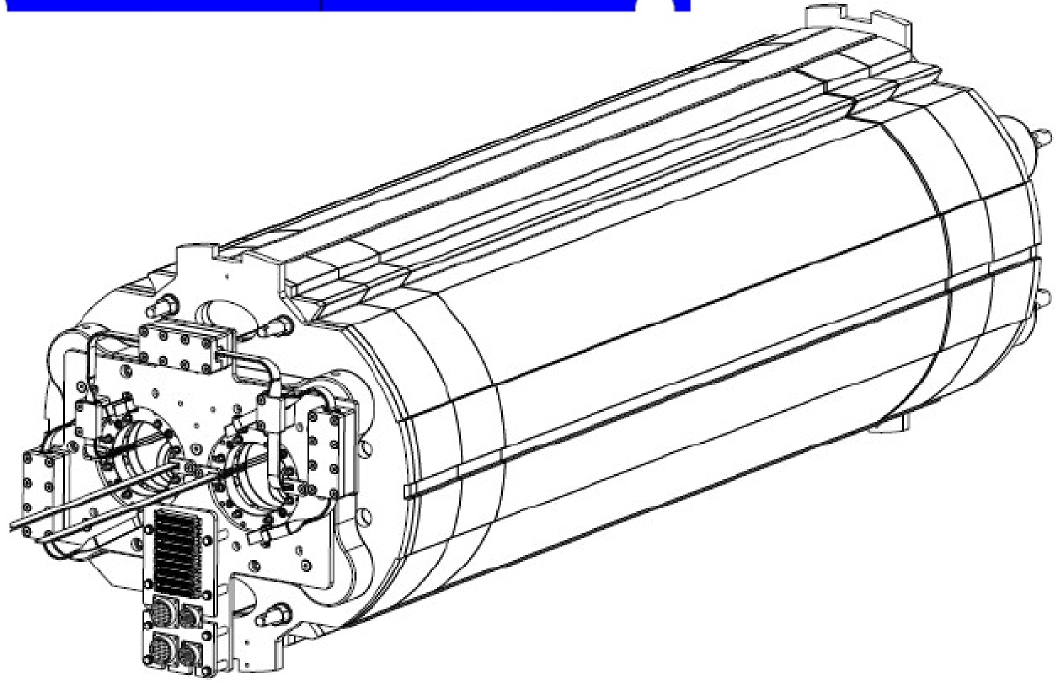
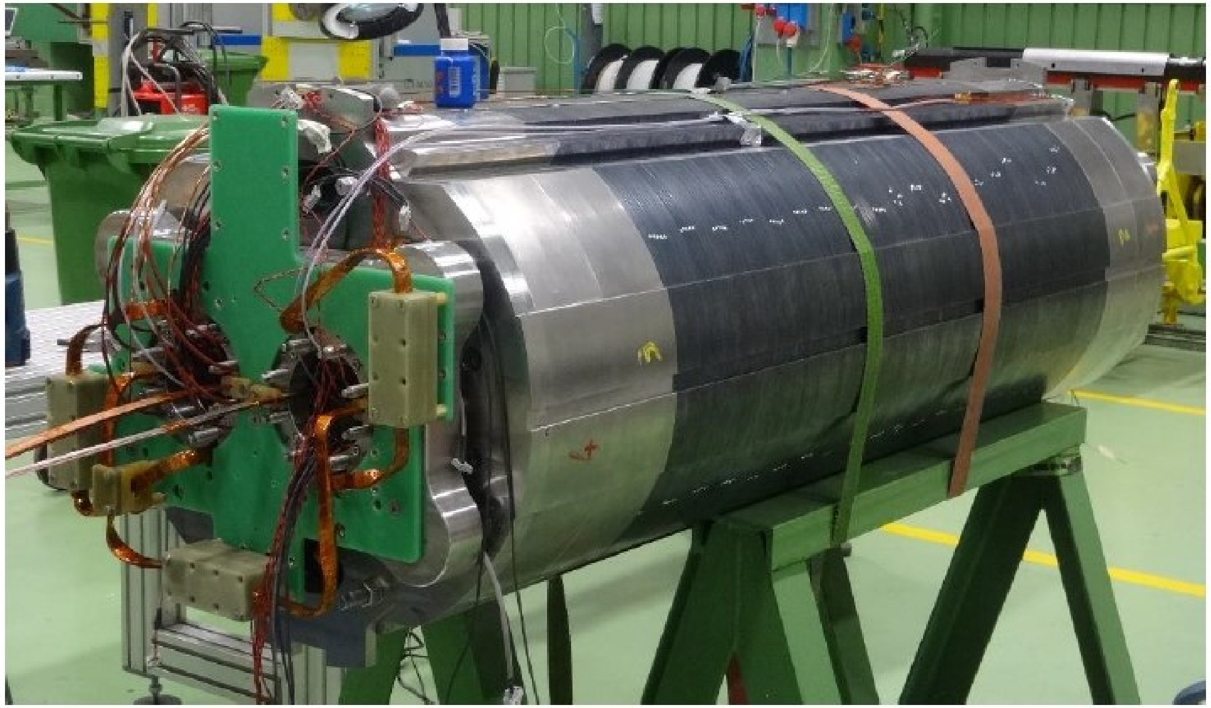
D2 - Model INFN-ASG







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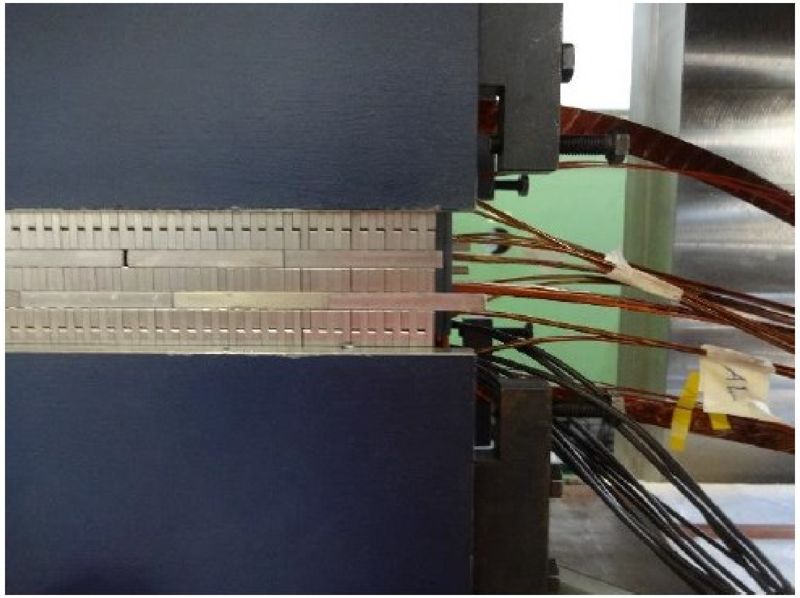
D2 - Model INFN-ASG

- Collaring operation



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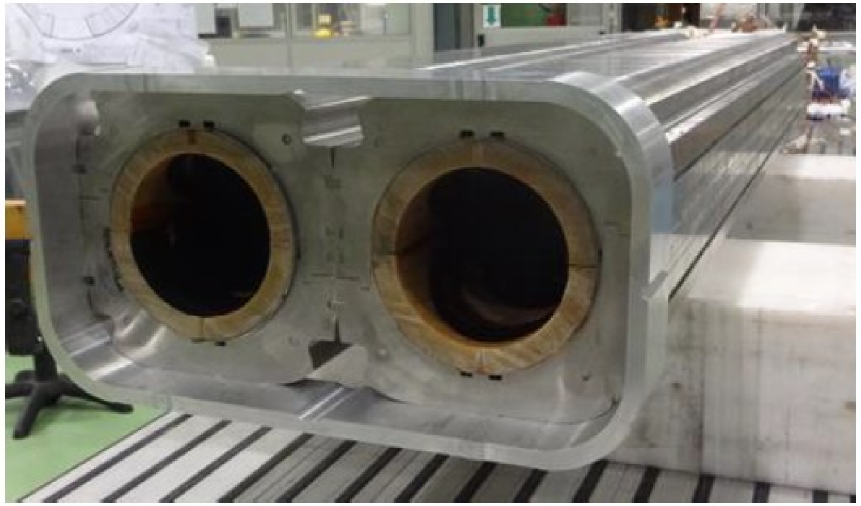
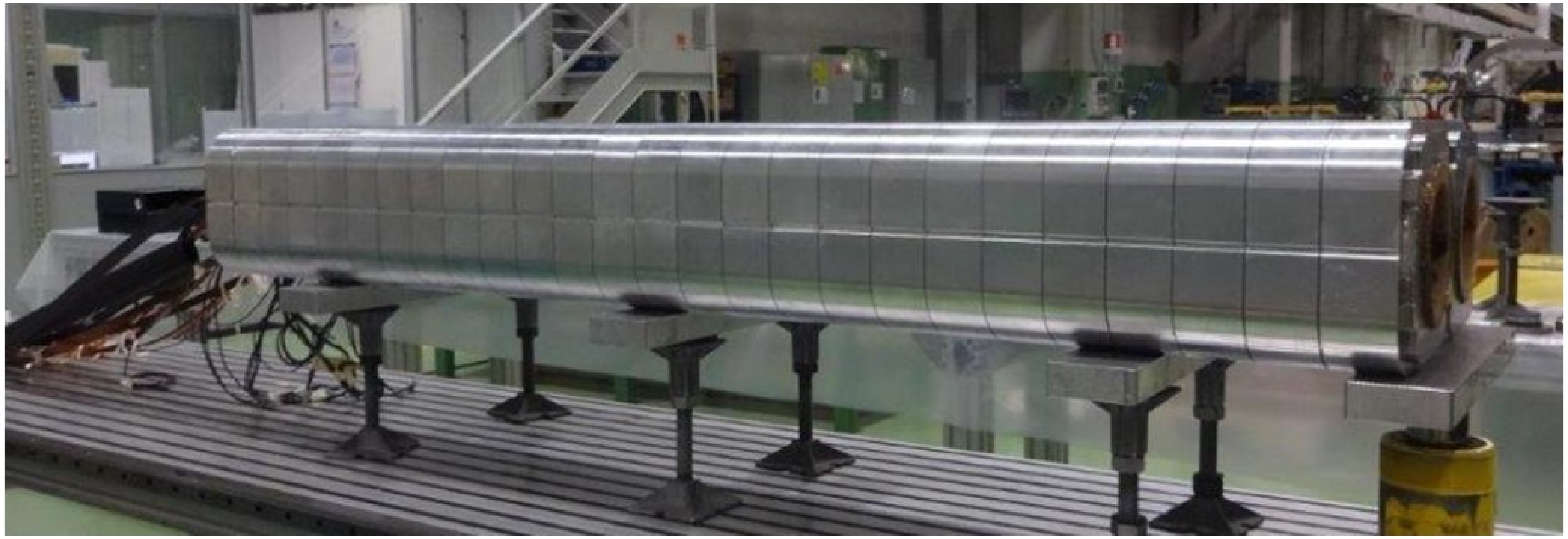
D2 - Model INFN-ASG

Aluminum sleeves introduction





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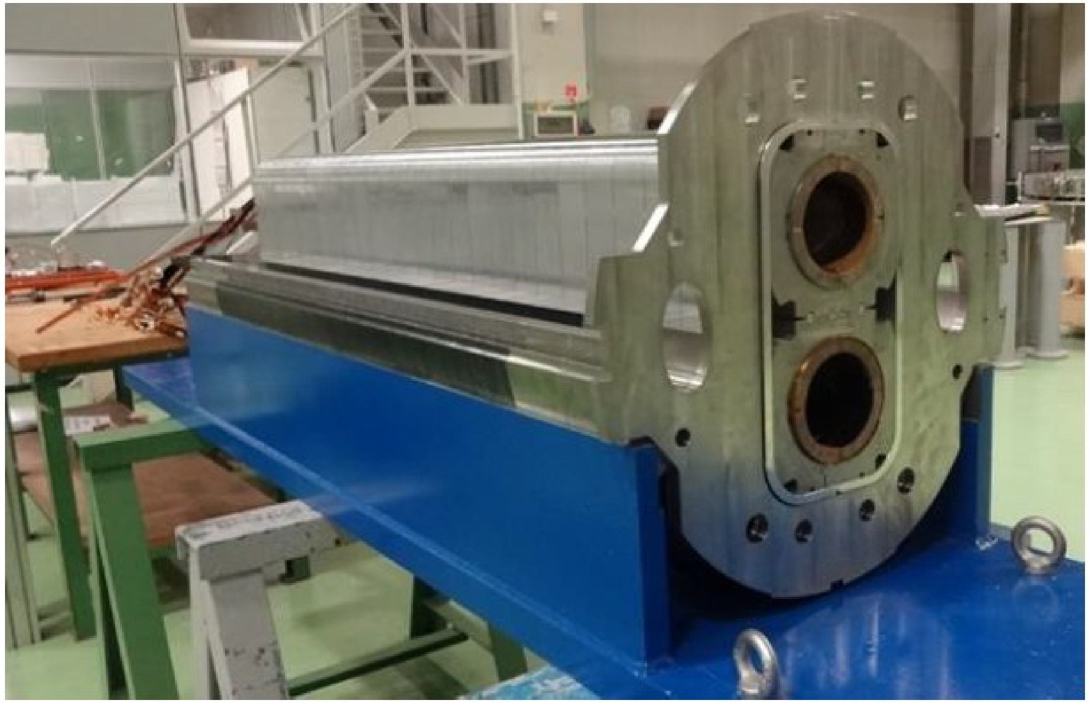
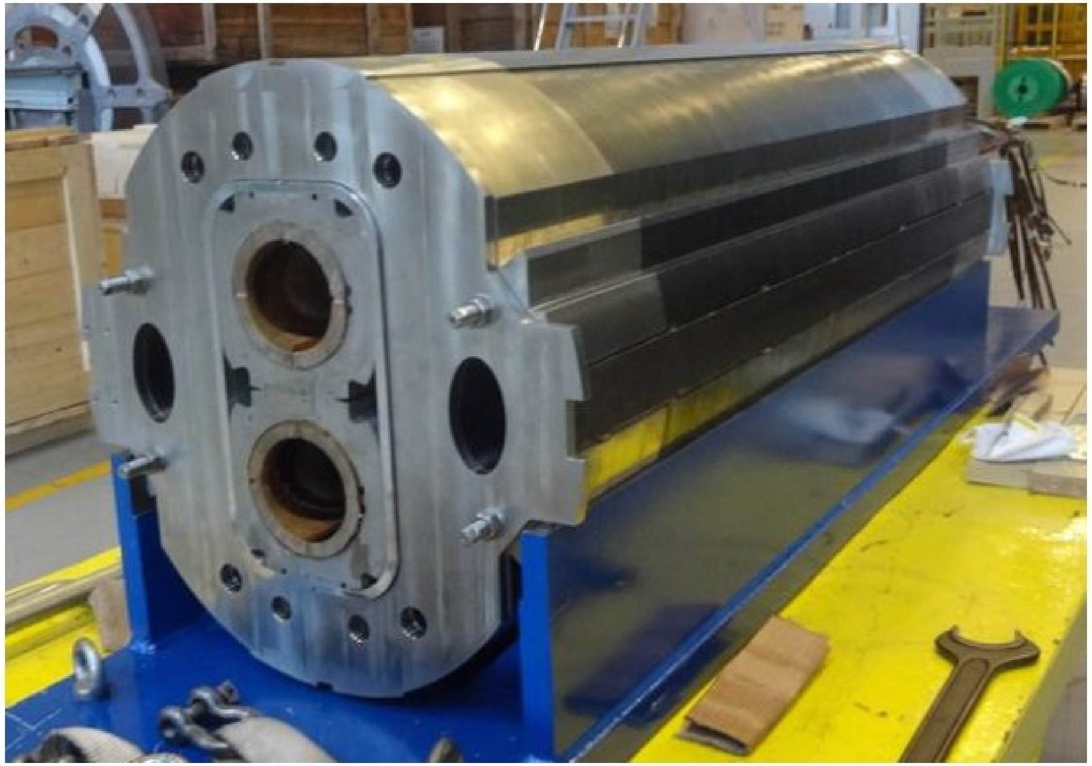
D2 - Model INFN-ASG

Integration inside the iron yoke





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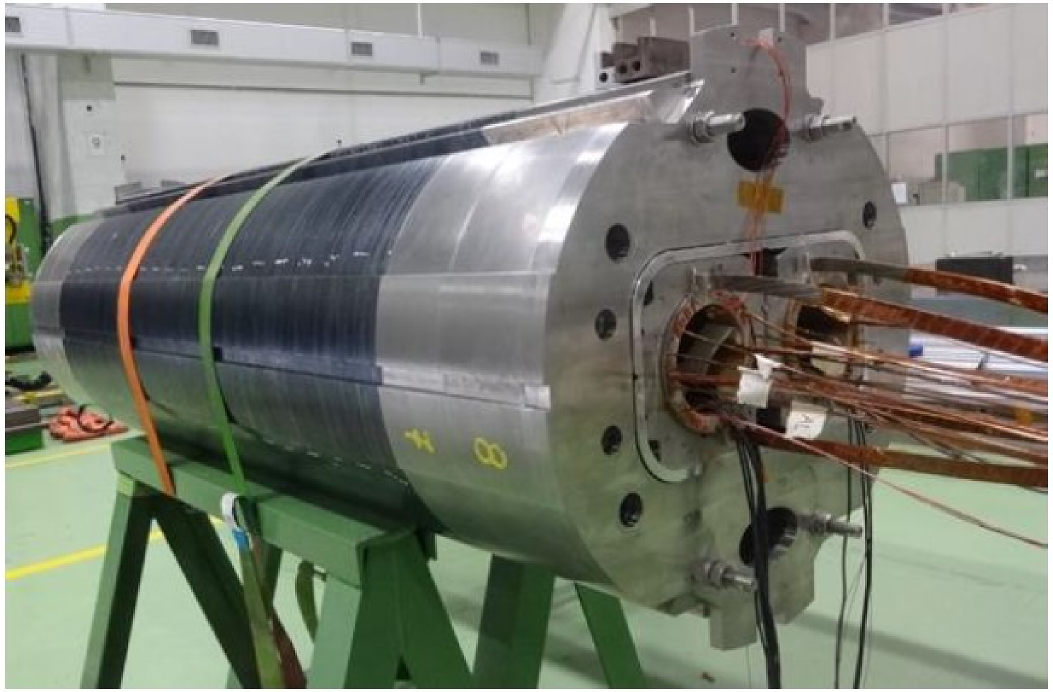
D2 - Model INFN-ASG

View from LOC Side

View from LC Side



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Detectors require bid magnet too!

ATLAS - LHC CERN

B_{nom} = 2 T

I_{nom} = 20.5 KA in an Aluminium coextruded NbTi Rutherford

COOLING

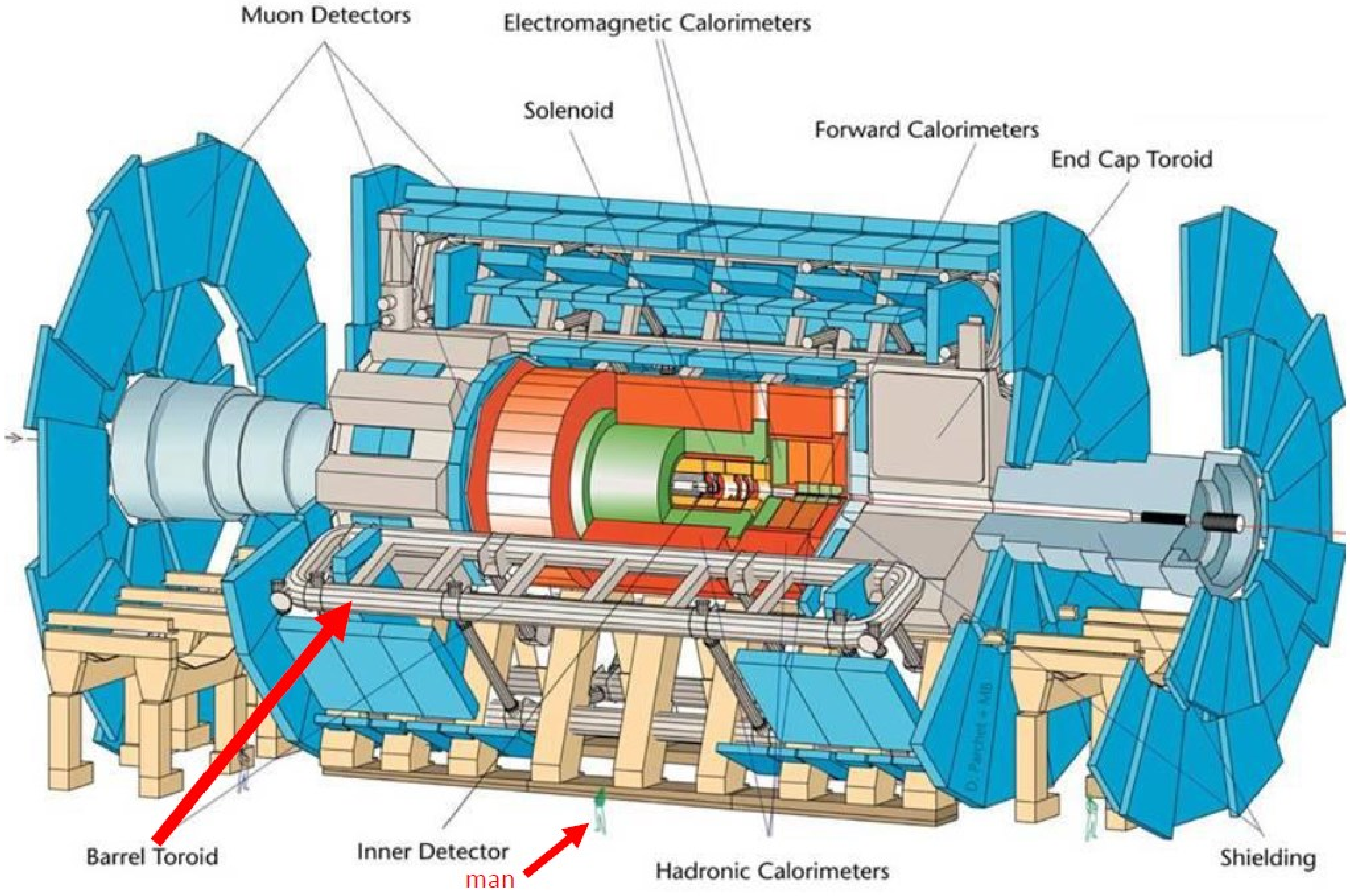
Double pancake indirect cooled by Helium

E-Glass taping + Vacuum impregnation under pressure

FORCE CONTAINMENT

Forces supported by an external Aluminium 5083 case

The windings are prestressed by epoxy pressurized bladders and tie-rods



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Detectors require bid magnet too!

ATLAS - LHC CERN

Barrel Toroid: 8 coils in separate cryostats

20 m diameter

25 m length

8200 m3 volume

118 t superconductor

370 t cold mass

830 t total weight

56 km conductor

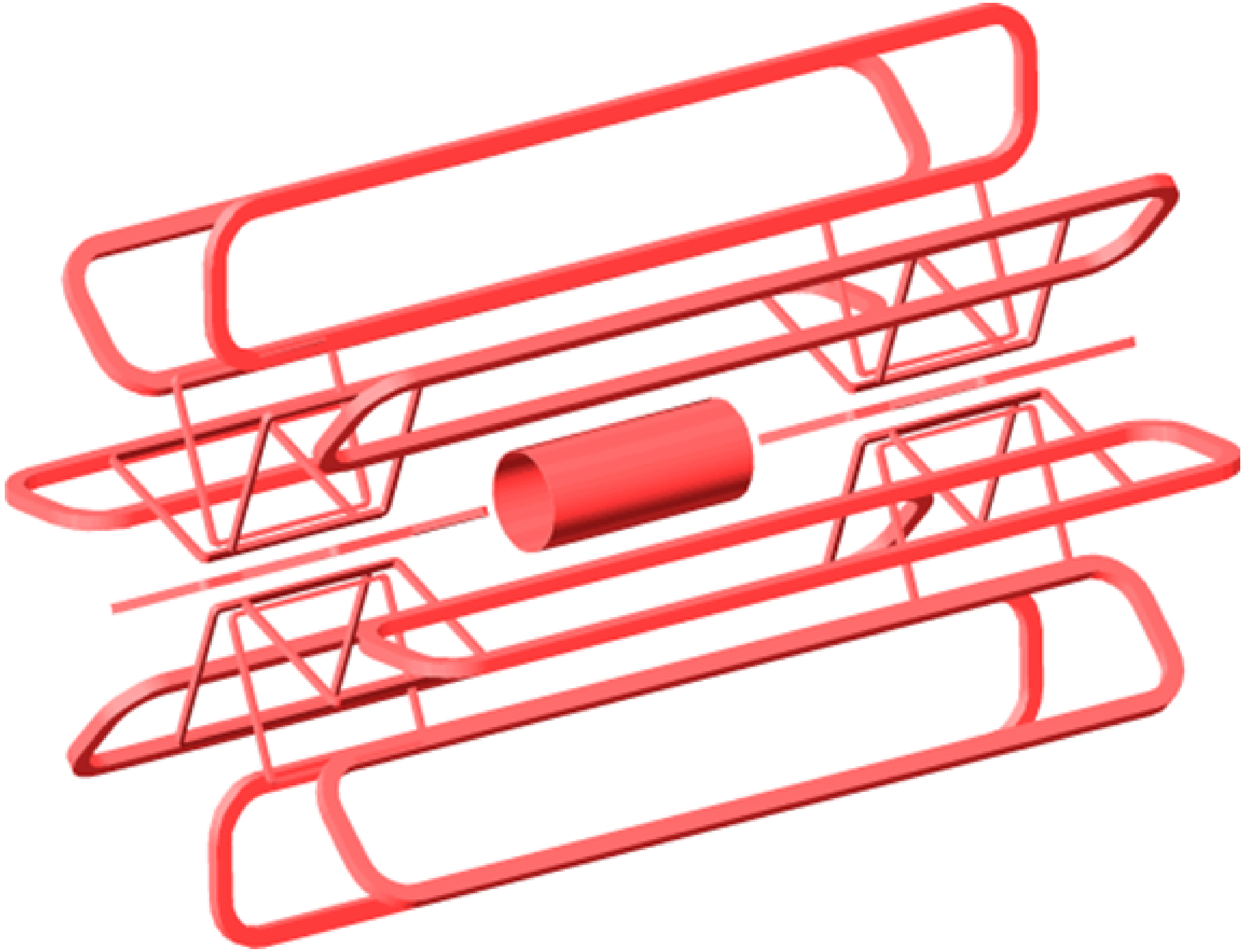
20.5 kA current

3.85 T peak field

1 GJ stored energy

4.8 K indirectely cooled

Force 1100 t/coil



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ATLAS - LHC CERN

ATLAS-CERN 2003 - Winding at ASG premises

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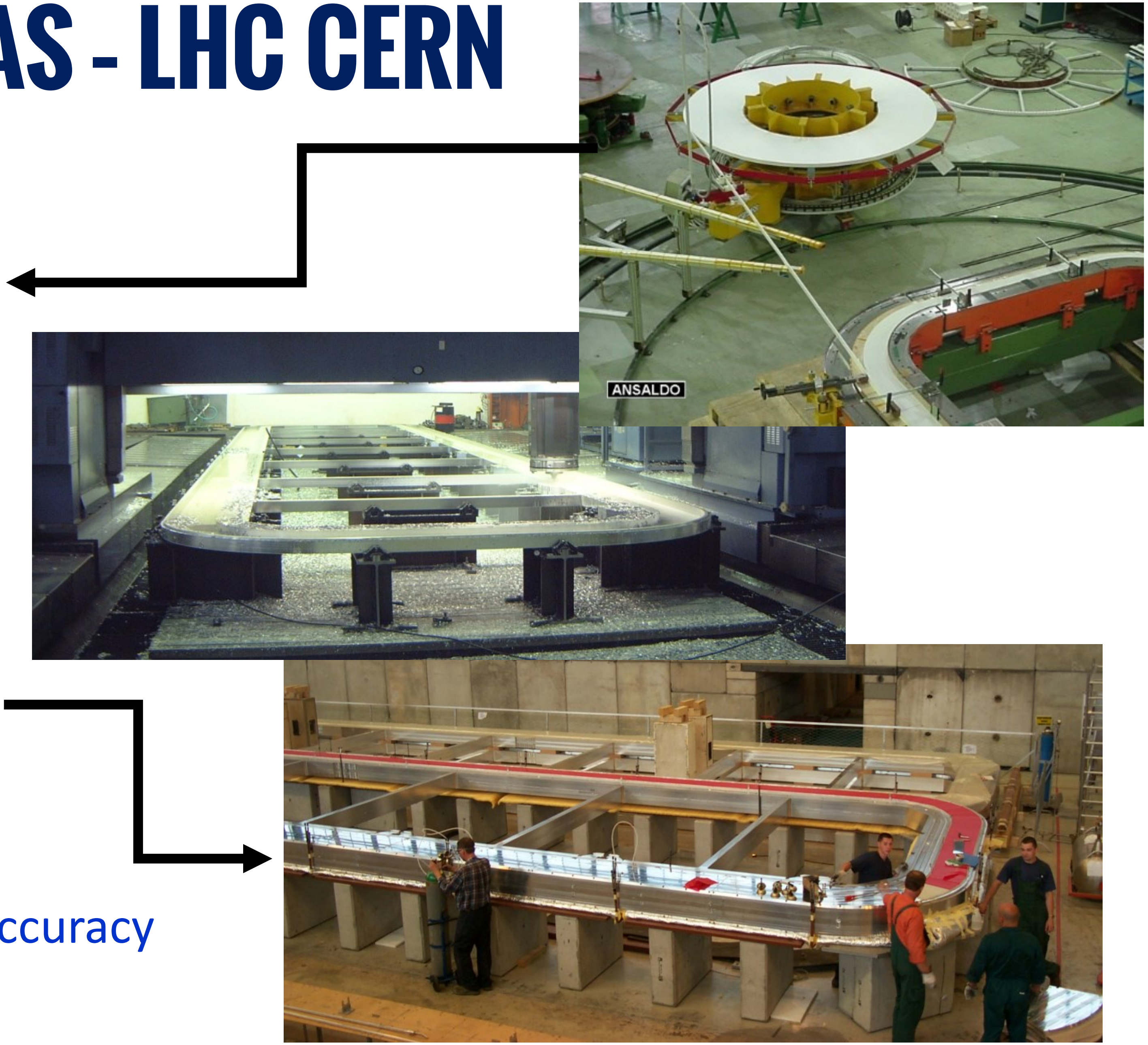
ATLAS - LHC CERN



Challenge

Scale of components and integration accuracy

Tolerances << 1 mm in 26m

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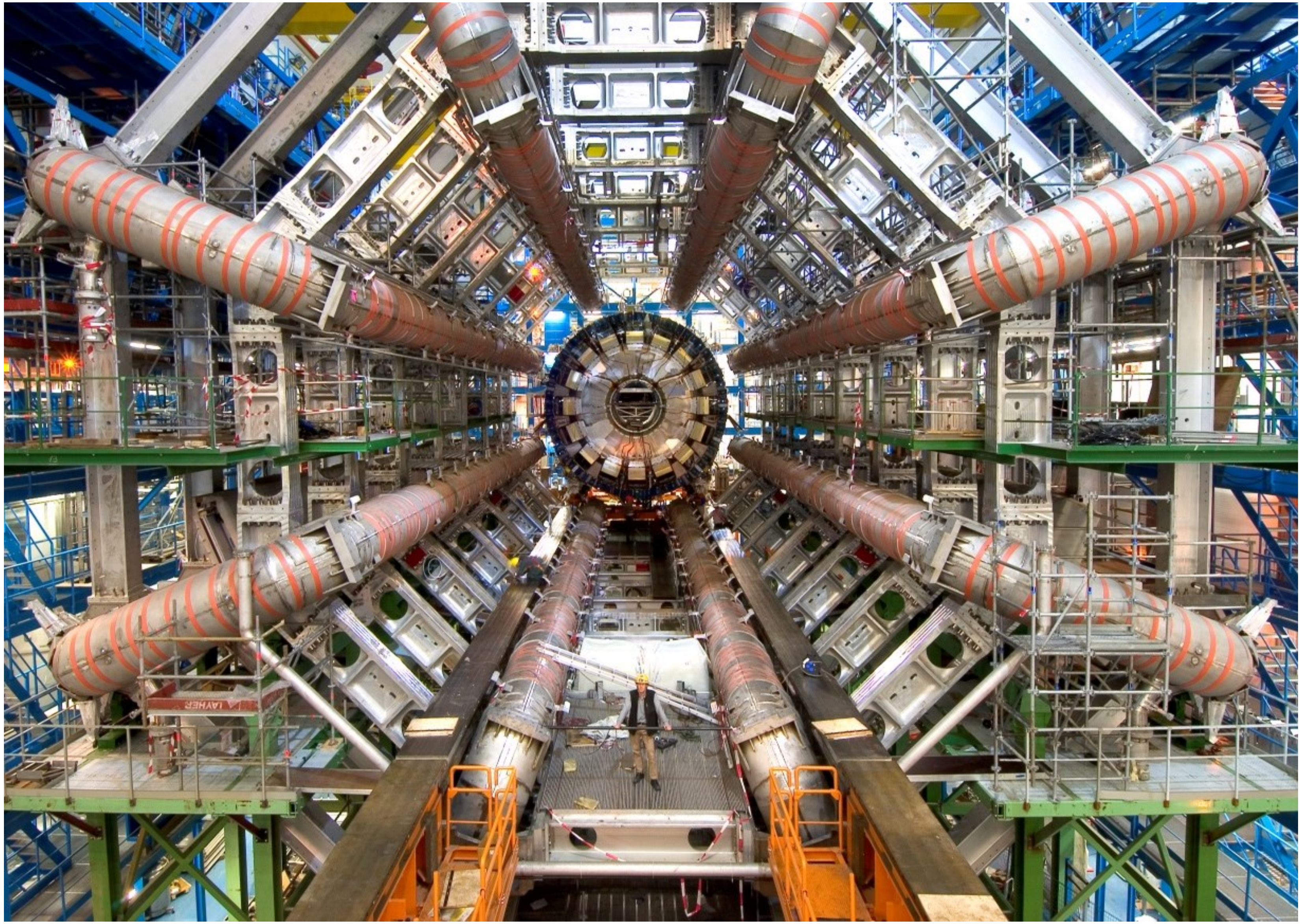
ATLAS - LHC CERN



ATLAS - LHC CERN

ATLAS-CERN 2003
Transported to CERN by truck

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CMS - LHC CERN

CMS - LHC CERN

B_{nom}4T

Solenoid in 5 modules Outer diameter = 7 m
Cold mass overall length L = 5 x 2.5 =12.5 m

4 layers coil of cable made of pure aluminium coextruded + NbTiRutherford + structural aluminium alloy

COOLING

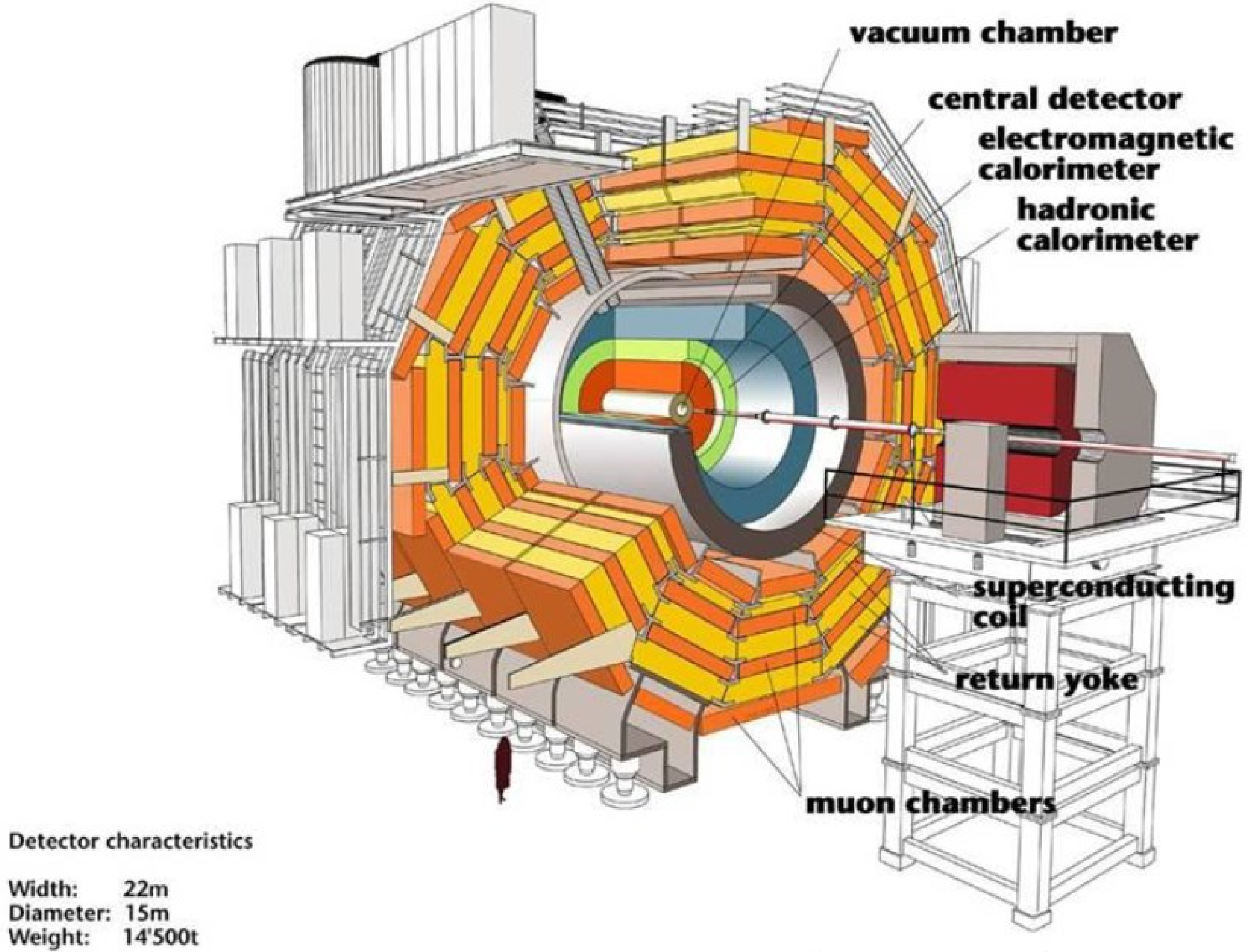
Indirect cooled by bi-phase Helium

E-Glass taping + Vacuum impregnation

FORCE CONTAINMENT

INNER Winding with tangential force + axial compression during impregnation

Forces supported by the cable itself + external Aluminium 5083 H321 cylinder



Detector characteristics

Width: 22m
Diameter: 15m
Weight: 14'500t

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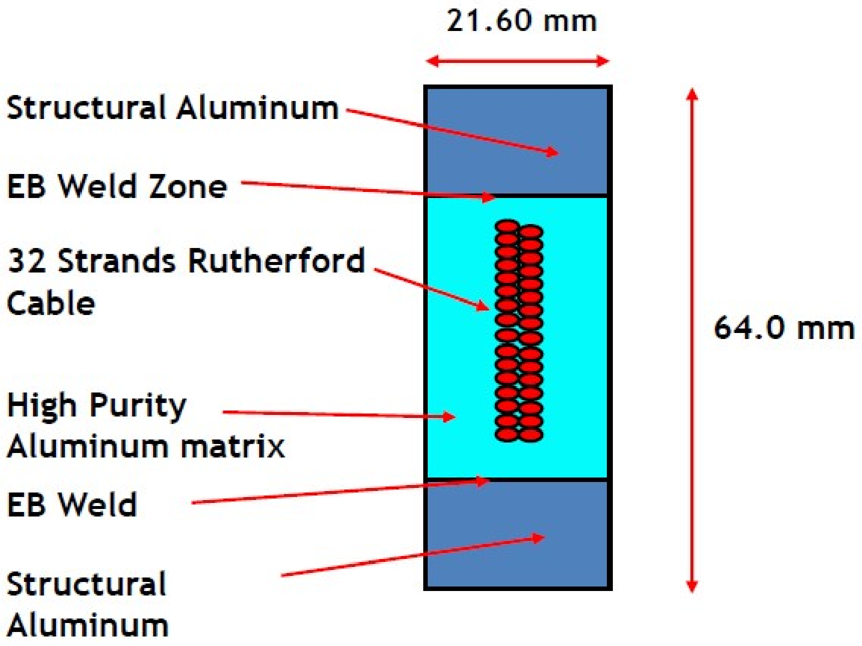
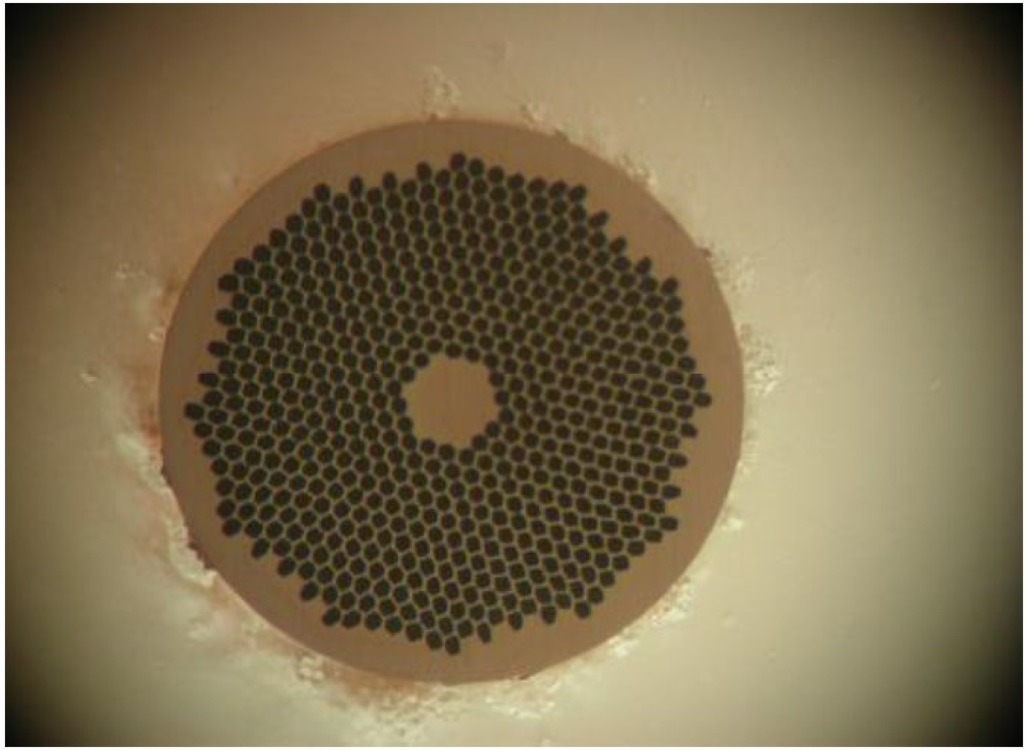
CMS - LHC CERN

CMS – INFN/CERN 2004 - The Conductor





Conductor Ic = 55.6 kA @ 4.2K, 5T

1.28 mm Dia Strand, Cu:SC Ratio = 1:1

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CMS - LHC CERN

CMS – INFN/CERN 2004 Impregnation Test (throughout R&D activity)

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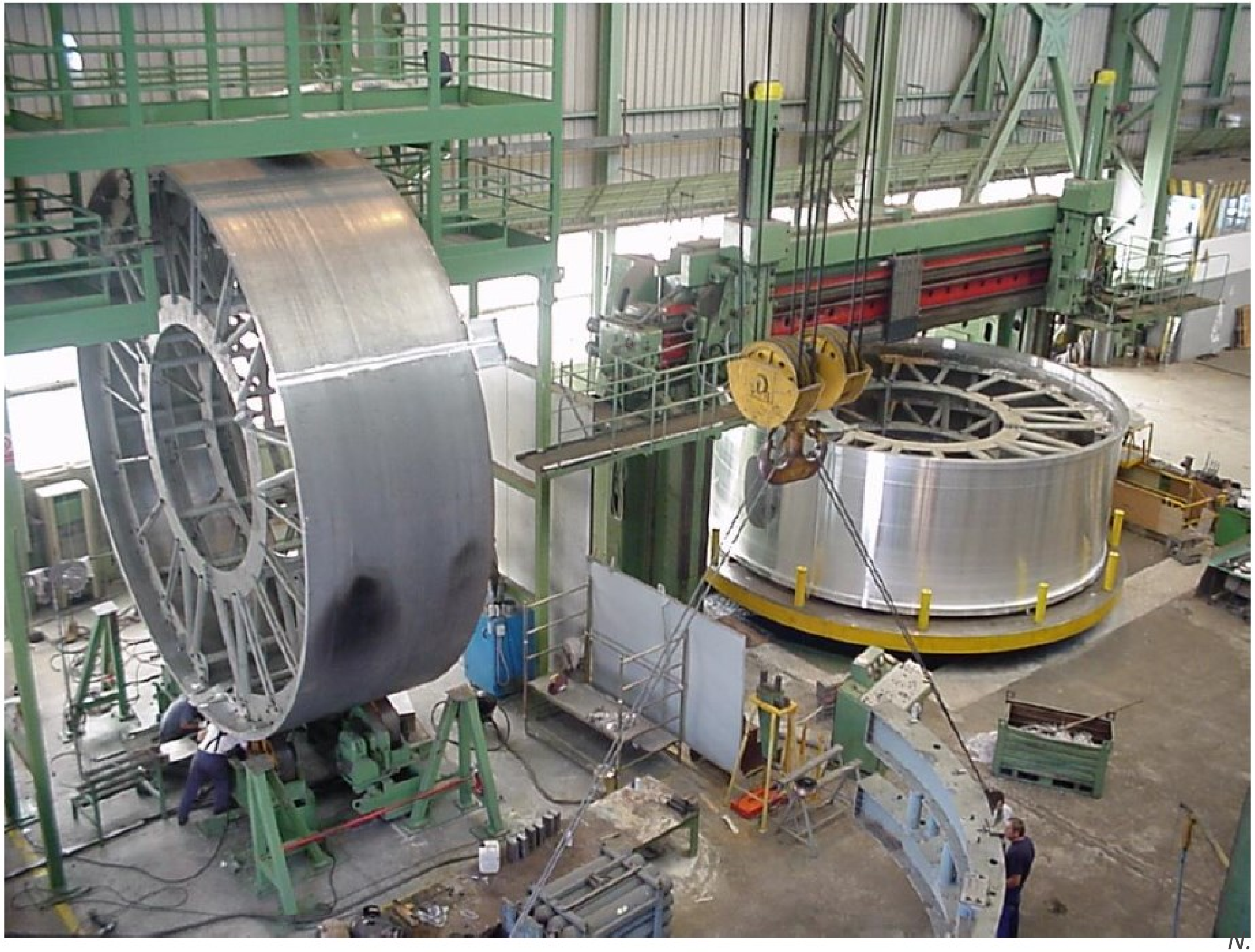
CMS - LHC CERN

CMS – INFN/CERN 2004 – Outer Aluminium structures under fabrication at ASG premises



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CMS - LHC CERN

CMS - INFN/CERN 2004 - Winding and ground insulation glass cloths positioning

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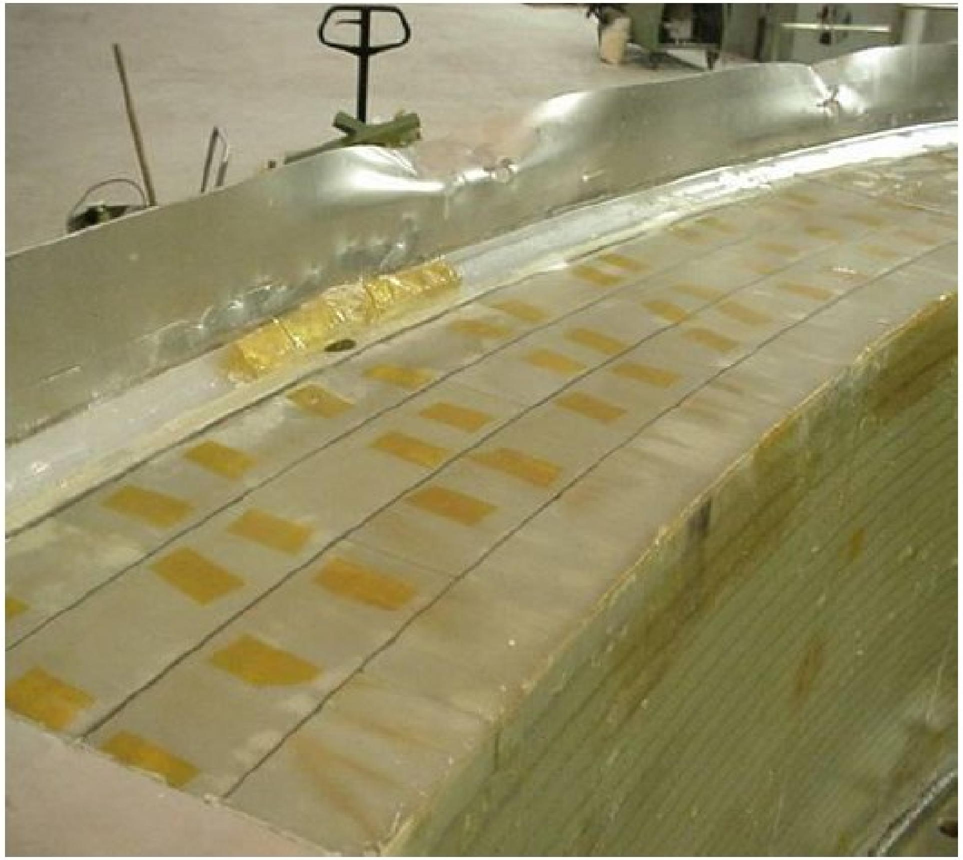
CMS - LHC CERN

CMS – INFN/CERN 2004 – Winding completion and resin excess removal

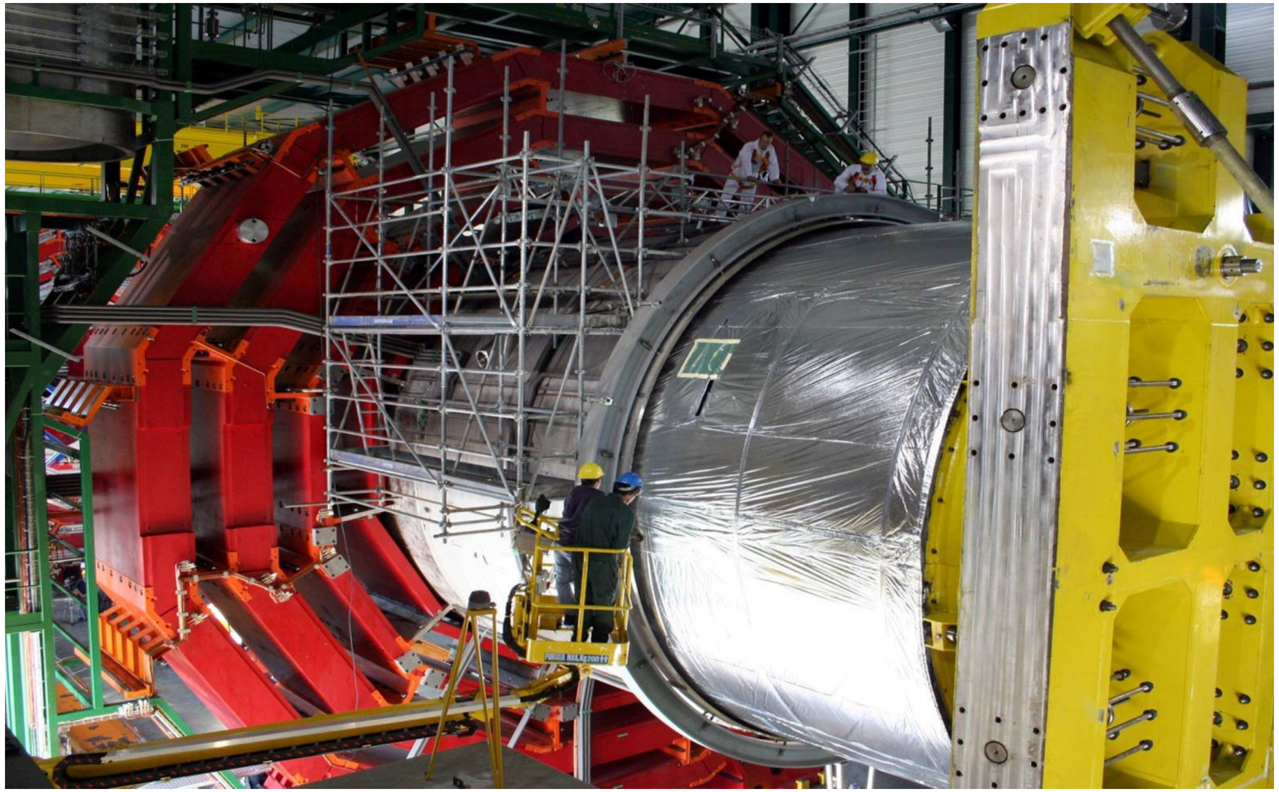


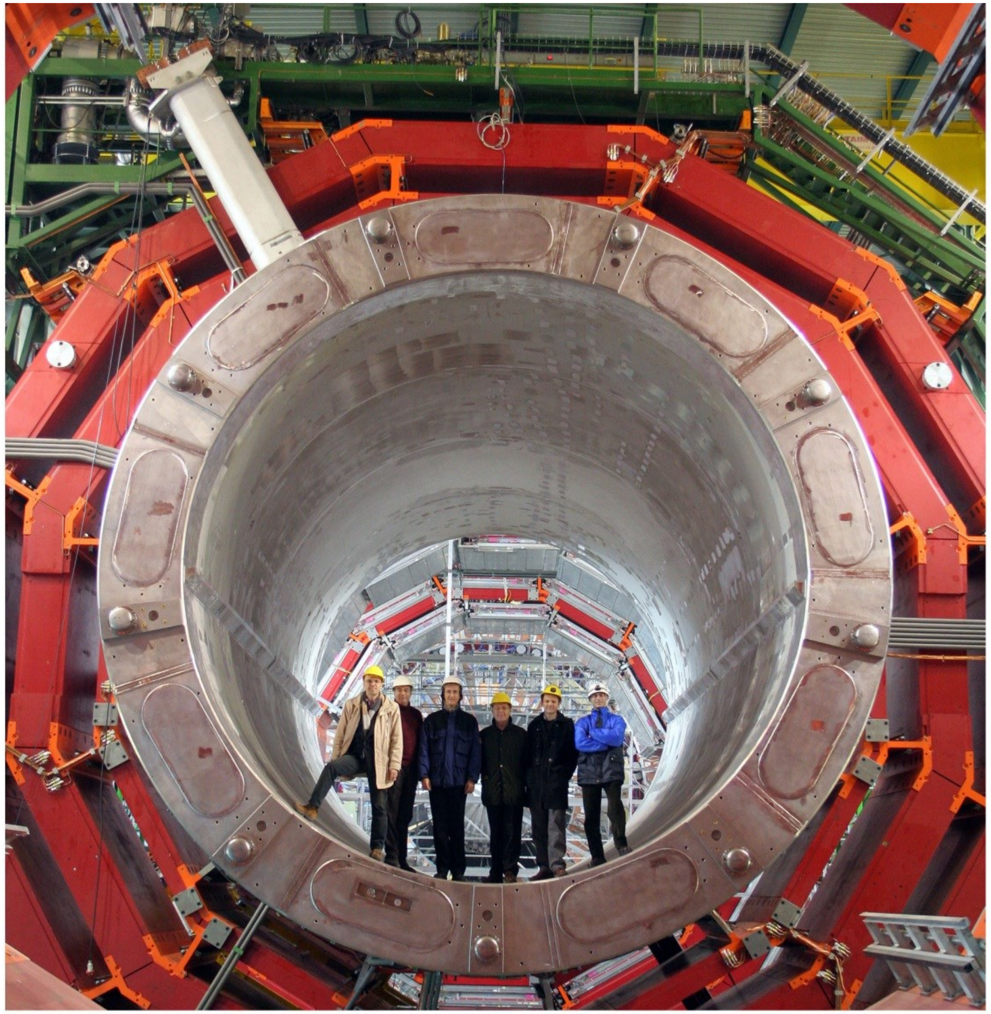
N. Valle, ASG, EASISchool3 Genoa 2020

Also transportation of these large coils is not trivial!!

P. Fabbricatore, ASG, EASISchool3 Genoa 2020

CMS - LHC CERN





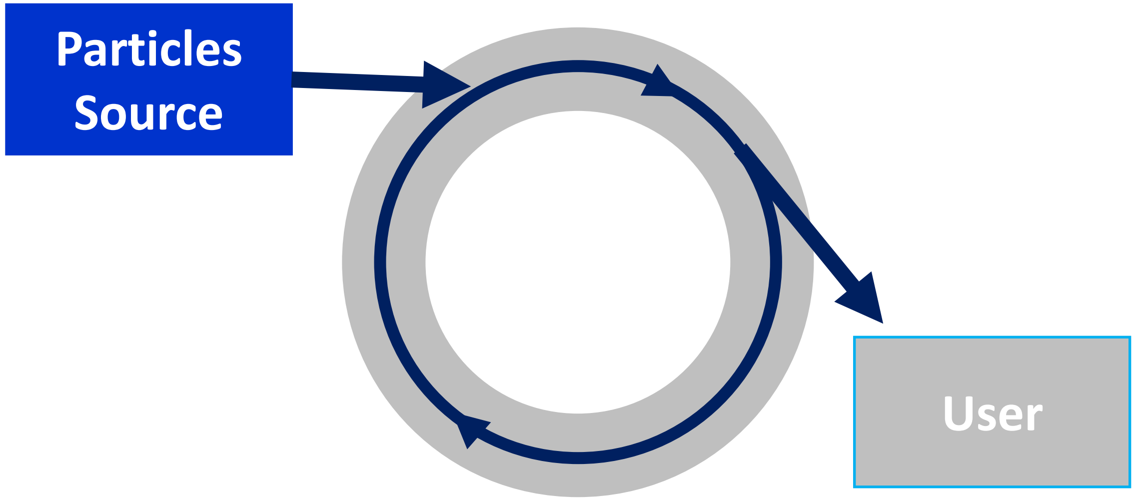
January 2006: End of the CMS Magnet Manufacturing

P. Fabbricatore, ASG, EASISchool3 Genoa 2020

How works an accelerator?

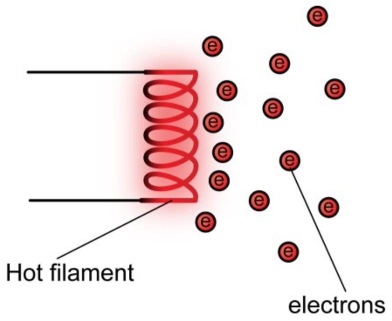
Linear Accelerator (Linac)

Circular Accelerator

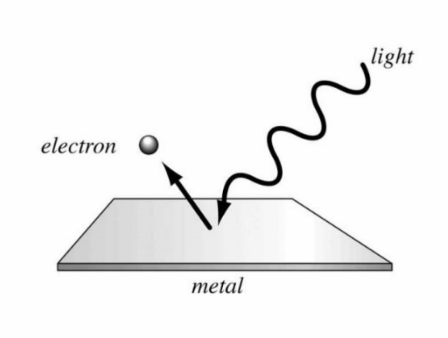


Particle sources

Electrons

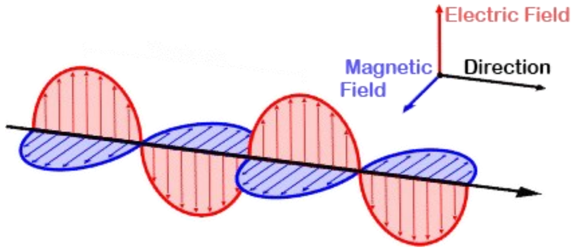


Thermoionic electron emitters



Photocathodes (photo-electric effect)

Ions

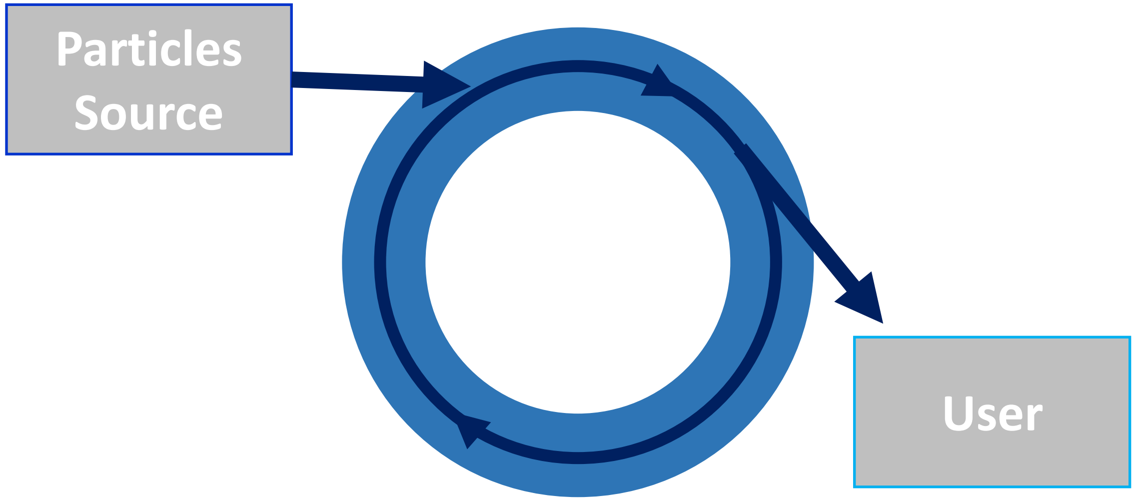


RF plasma on metal target or gas species

How works an accelerator?

Linear Accelerator (Linac)

Circular Accelerator



Particle Energy and Speed

1 electron accelerated by 1 V of difference of potential acquires the **kinetic energy** of **1eV**

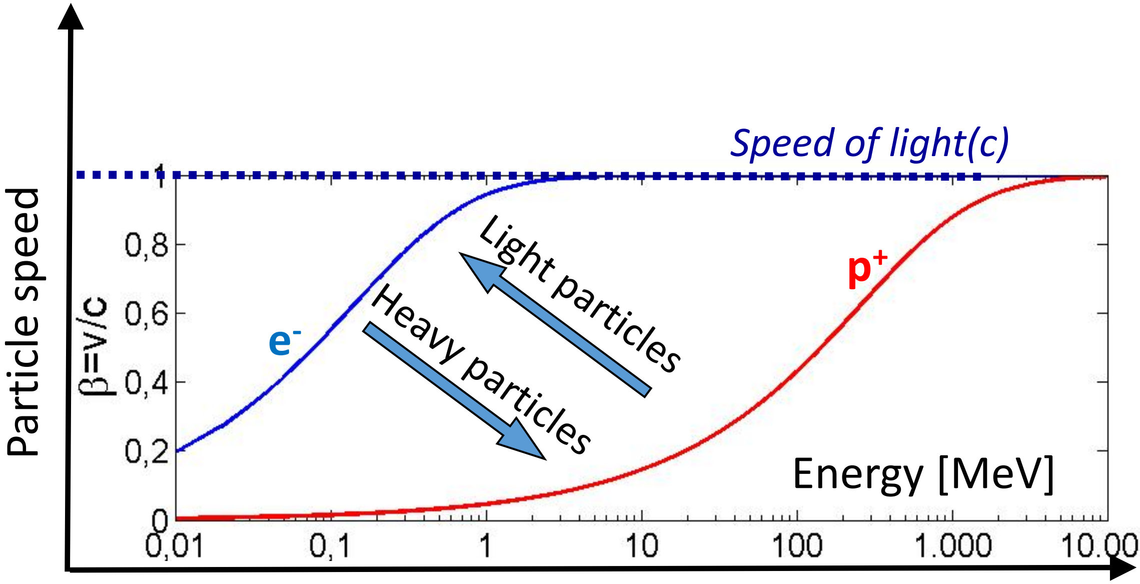
Small unit: 1eV ~ 10^{-19} J

Accelerate a particle means
increase p=mv

An **electron** becomes **relativistic**
(v_{el} ~ c) when **E > 5 MeV** (m_e=$9x10^{-31}$kg)

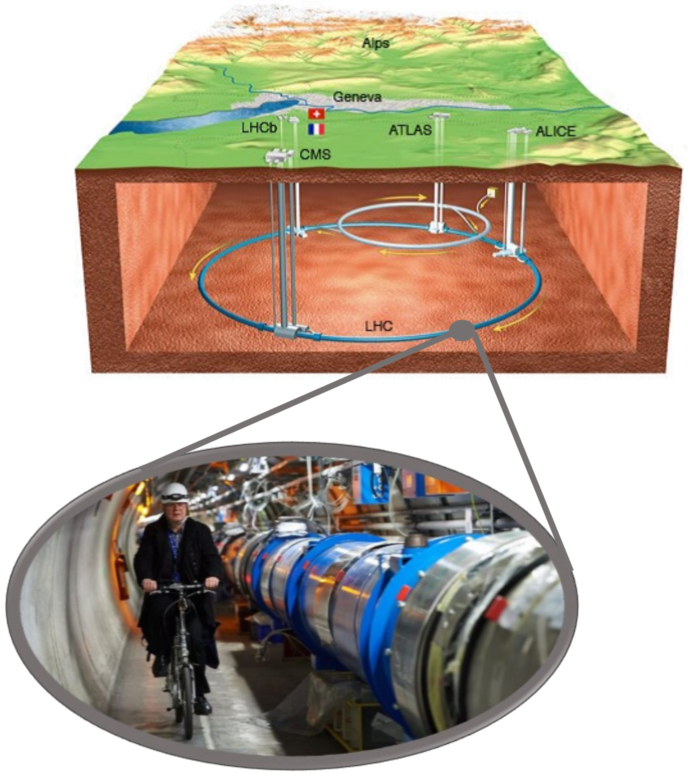
For a **proton E** is **1000 times higher**
(m_p=$1.6x10^{-27}$ kg)

Above a certain threshold the speed of the particle becomes constant and an **increment of energy corresponds only to an increment of relativistic mass**



From David Alesini (LNF-INFN), Introductions to particle accelerators

Particle energy and energy density



14 TeV in center of mass of LHC what does it means?

1 eV = 1V x $1.6{\cdot}10^{-19}$ C = $1.6\text{x}10^{-19}$ J
1 MeV = $1.6\text{x}10^{-13}$ J
1 GeV = $1.6\text{x}10^{-10}$ J
1 TeV = $1.6\text{x}10^{-7}$ J

A **Pb bullet**

of 200 g with a speed of 300 m/s

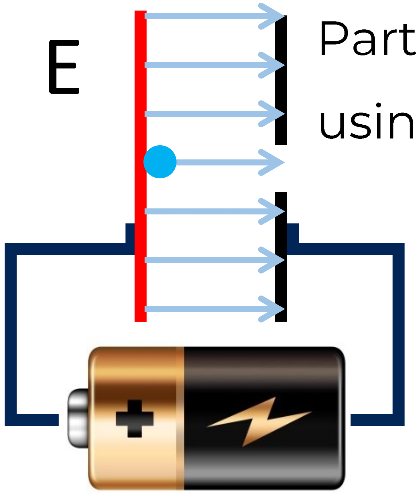
has an energy of **9000 J**

However the single proton or neutron has a E_k of only: $9000/N_{p+n} \sim 7{\cdot}10^{-23}$ J

~ $5\text{x}10^{-4}$ eV

The density of energy in LHC is 16 order of magnitude higher than in a bullet!

Acceleration

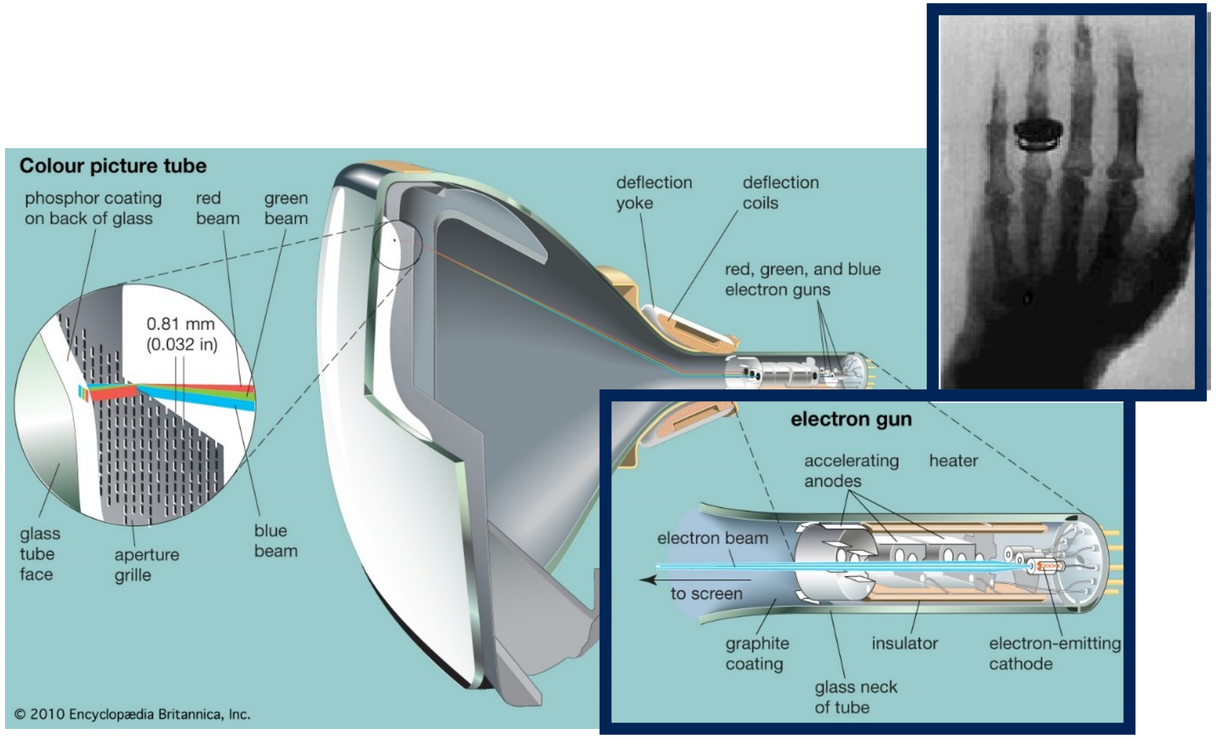


Particles are accelerated using **Electric Fields**

Electrostatic Acceleration

Limited by dielectric breakdown

Bertha Rontgen's Hand
8 Nov 1895



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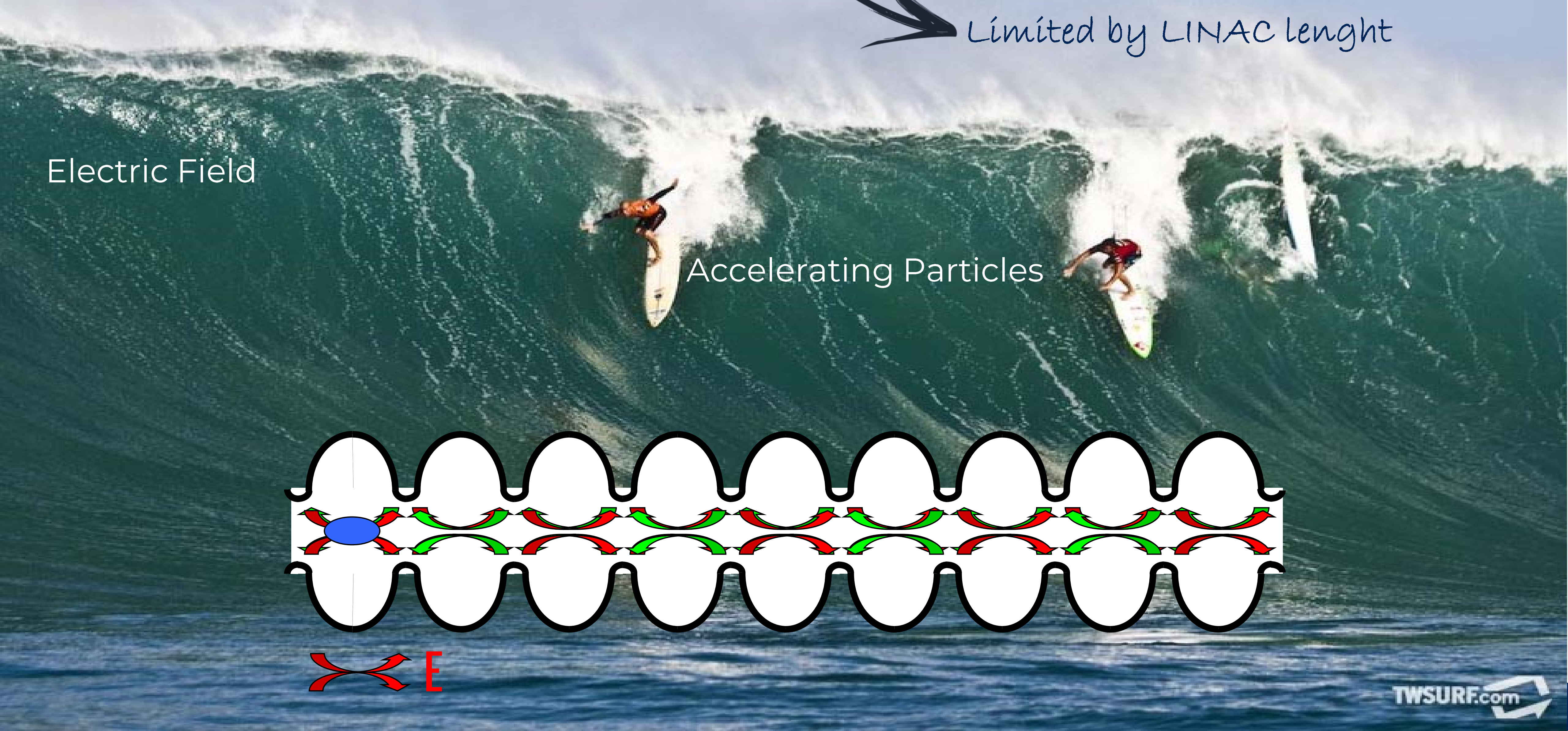
RF acceleration

Limited by LINAC lenght

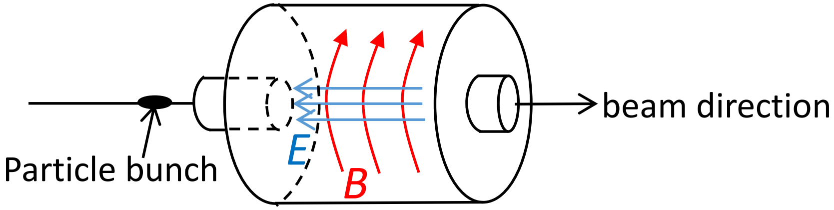


Electric Field

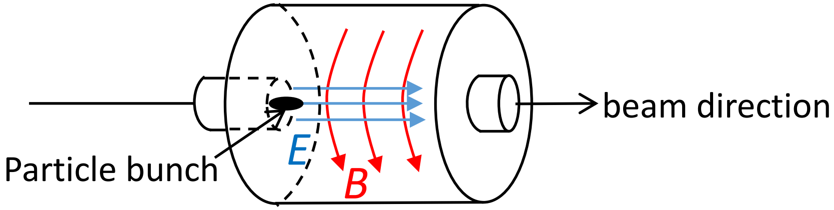
Accelerating Particles

Acceleration with RF cavities

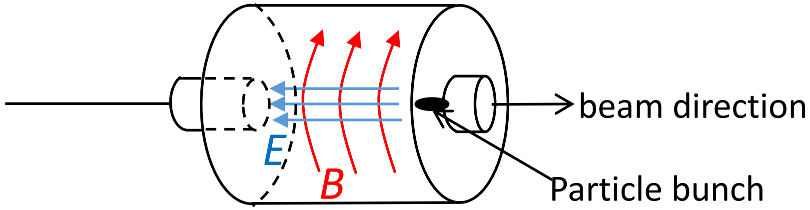
1. Before the particle bunch enters the cavity the electric field is pointing in opposite direction of the beam axis



2. The particle bunch enters the cavity. The electric field is pointing in the direction of the beam axis → The particle is accelerated



3. The particle bunch leaves the cavity. The field direction has changed again



Cavities are used to accelerate particles by an alternating electric field

An alternating electric field causes an alternating magnetic field

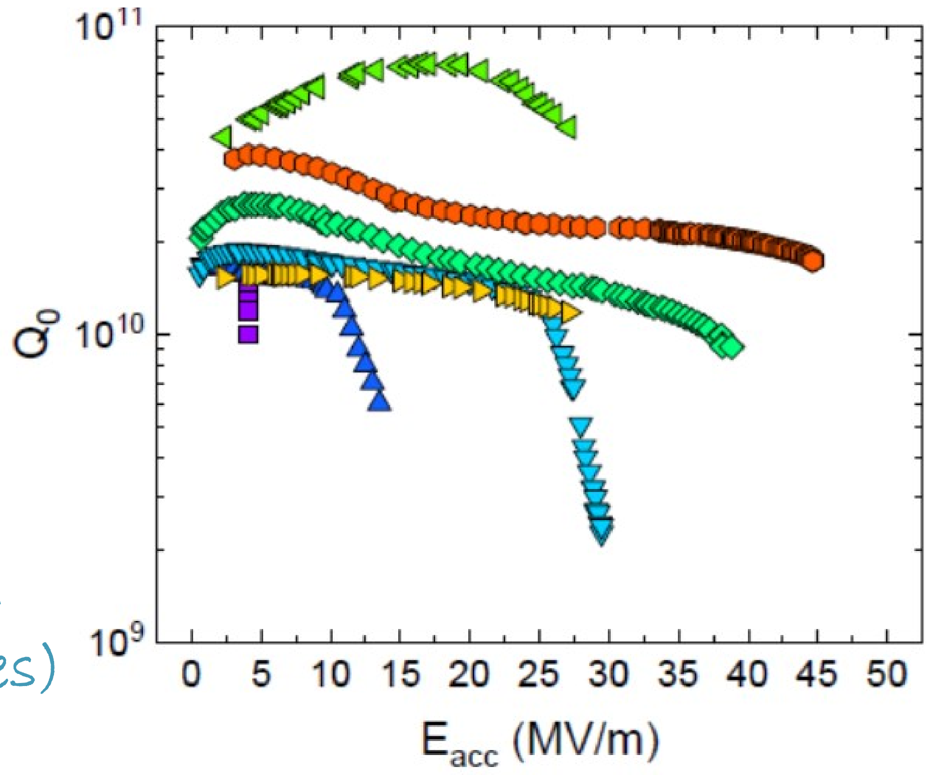
The cavity confines the electromagnetic fields by surface shielding currents

These currents create losses (heating), which can be reduced by using SC materials

Resonant cavities main parameters

Quality Factor Q

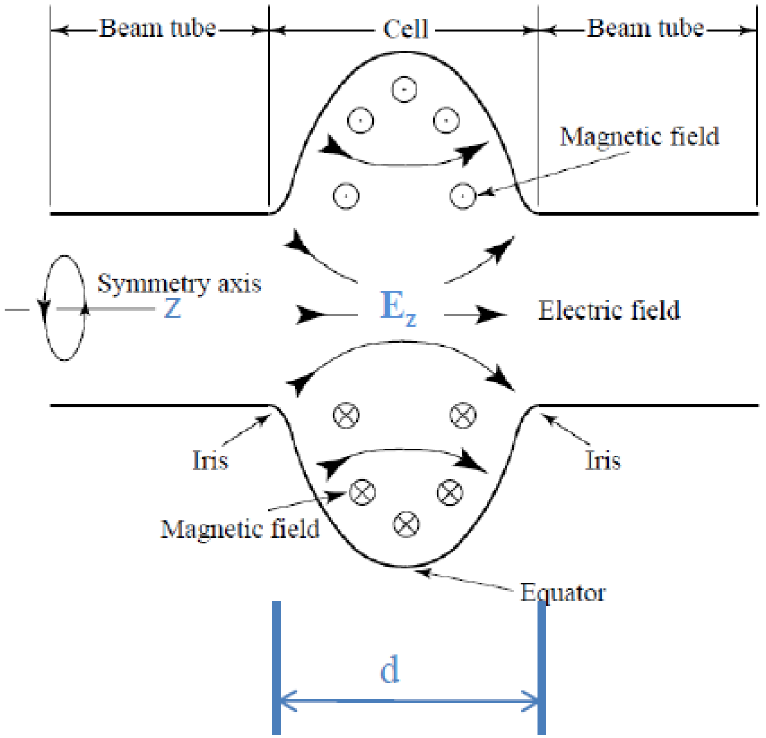
Inversely proportional to losses
(cryogenic costs for SC cavities)



Accelerating Field (MV/m)

Accelerating gradient
(LINAC length)

Figures of Merit



To describe a RF cavity, we will need to know:

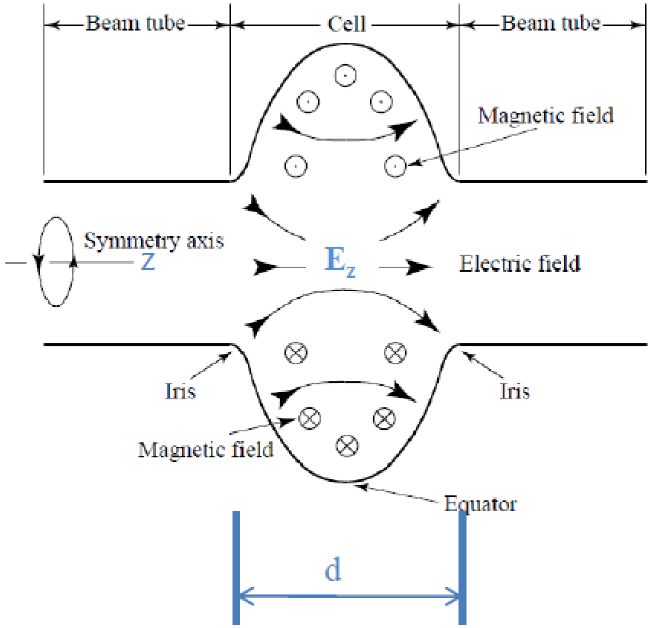
- Accelerating voltage
- Shunt impedance
- Dissipated power
- Transit time factor
- Surface impedance
- Stored energy
- Quality factor (Q)
- Geometry factor (G)
- R/Q

Accelerating Field

The wanted (accelerating) mode is excited at the good frequency and position from a RF power supply through a power coupler. The phase of the electric field is adjusted to accelerate the beam

- **Acceleration field** E_z
- **Acceleration voltage** $V_c = \int E_z(z)dz$
- **Average Accelerating field** $E_{acc} = \frac{V_c}{d}$
- **The maximum energy that can be gained by a particle in the cavity** $\Delta U_{max} = qV_cT$
- **The difference between the particle velocity and the phase velocity of the accelerating field, leads to an efficiency drop of the acceleration. The transit time factor *T* characterizes the actual efficiency**

$$T = \frac{1}{V_c}\int E_z(z) \cdot e^{j\phi(z)}dz$$



Quality Factor Q

An important figure of merit is the **quality factor** which for any resonant system is

$$\boldsymbol{Q_0} = \frac{\boldsymbol{\omega_0 \cdot stored\ energy}}{\boldsymbol{average\ power\ loss}} = \frac{\omega_0 U}{P_c} = \frac{\omega_0 \int_V |\boldsymbol{H}|^2 dv}{R_s \int_S |\boldsymbol{H}|^2 ds}$$

$$\boldsymbol{Q_0} = \frac{\boldsymbol{G}}{\boldsymbol{R_s}}$$

One can see that the
ration of two integrals
in the equation of Q
determined only by
cavity geometry

Roughly 2π times the **number of RF cycles it takes to dissipate the energy stored in the cavity**

Geometry Factor G

$$Q_0 = \frac{\omega_0 \int_V |\boldsymbol{H}|^2 dv}{R_s \int_S |\boldsymbol{H}|^2 ds}$$

One can see that the ration of two integrals in the equation of Q determined only by cavity geometry

$$\boldsymbol{Q_0 = \frac{G}{R_s}}$$

The geometry factor **depends only on the cavity shape and electromagnetic mode, but not its size**

$$G = \frac{\omega_0 \int_V |\boldsymbol{H}|^2 dv}{\int_S |\boldsymbol{H}|^2 ds}$$

It is very useful for comparing different cavity shapes

G = 257 Ohm for the pillbox cavity

Why Superconducting RF cavity?

Skin depth limits performances of NC cavities

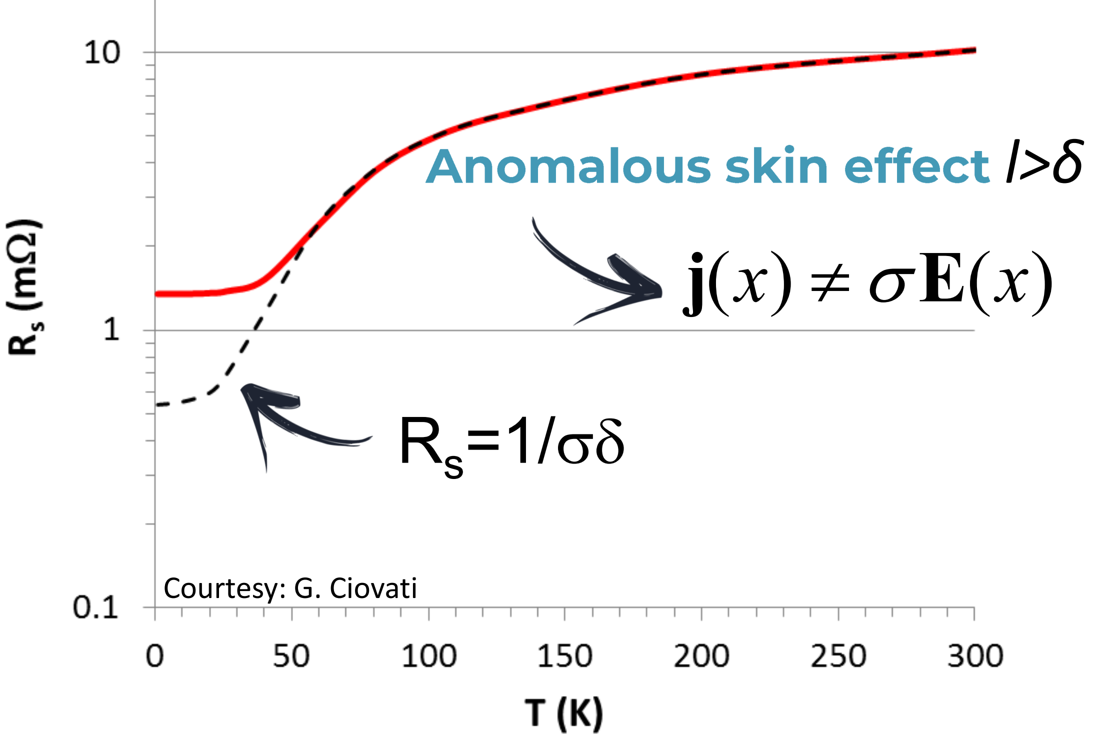
$$R_s = X_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\mu_0\mu\omega}{2\sigma}}$$

RRR = σ(4.2K)/σ(300K) = 300

R_s(4.2 K) ≅ 1.3 mW

…in spite of the resistivity decreasing by a factor 300 from 300 K to 4.2 K,
R_s only decreases by a factor of ~8!

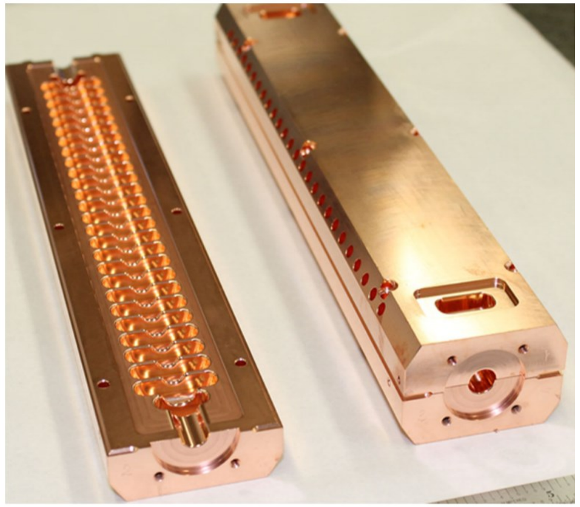
Surface resistance of Cu @1.5 GHz as a function of T



Courtesy: G. Ciovati

To reduce R_s below the mΩ range for RF application we need Superconductivity!

From Cu to SC Cavities



SC cavities reduce the wall dissipation by many orders of magnitude compared to NC cavity

Cu $_{1.5\,\mathrm{GHz}}$: R_s (300 K) ~10 mΩ, R_s (4 K)~1.3 mΩ

Nb $_{1.5\,\mathrm{GHz}}$: R_s (4 K)~500 nΩ, R_s (2 K)~20 nΩ

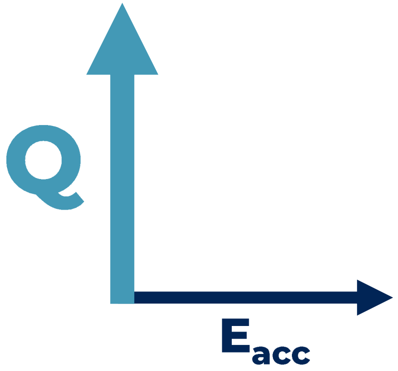
The advantages of SC Cavities

1) AC power requirement less than normalconductors

(also taking into account cryogenic efficiency)

R_s Cu $\approx 10^{-3}\,\Omega \rightarrow Q_{\text{normalconductor}} \approx 10^4$

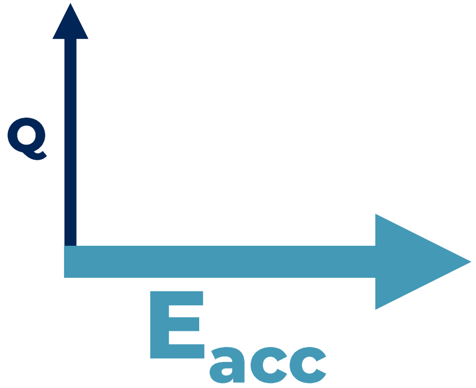
R_s Nb $\approx 10^{-9}\,\Omega \rightarrow Q_{\text{superconductor}} \approx 10^9 - 10^{10}$



2) Reduction of the Linac length

E_{acc} Cu < 1 MV/m → Limited by Joule effect

E_{acc} Nb ≈ 55 MV/m → Limited by H_{SH}

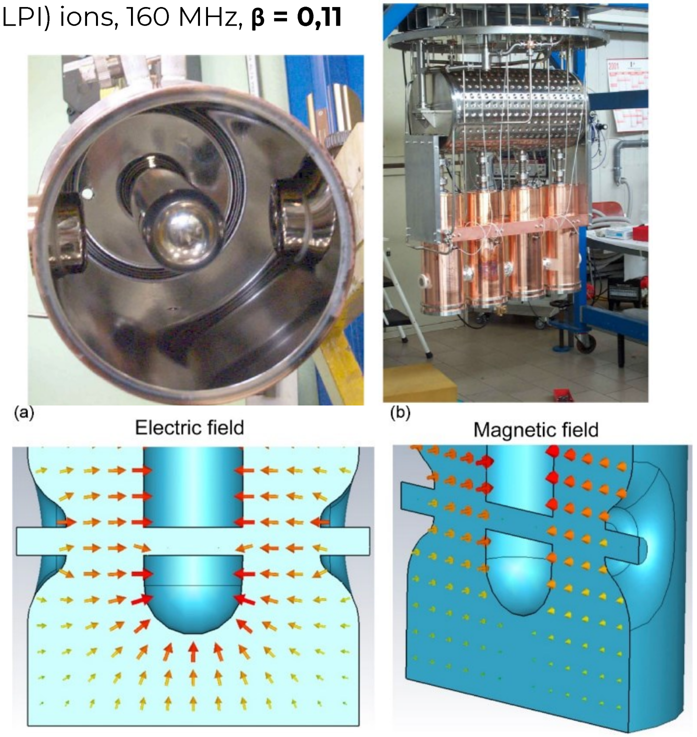


ZOO of SRF cavities

Elliptical 9 cells (XFEL - Tesla type), electrons, 1.3 GHz 20-30 MV/m, **β = 1**

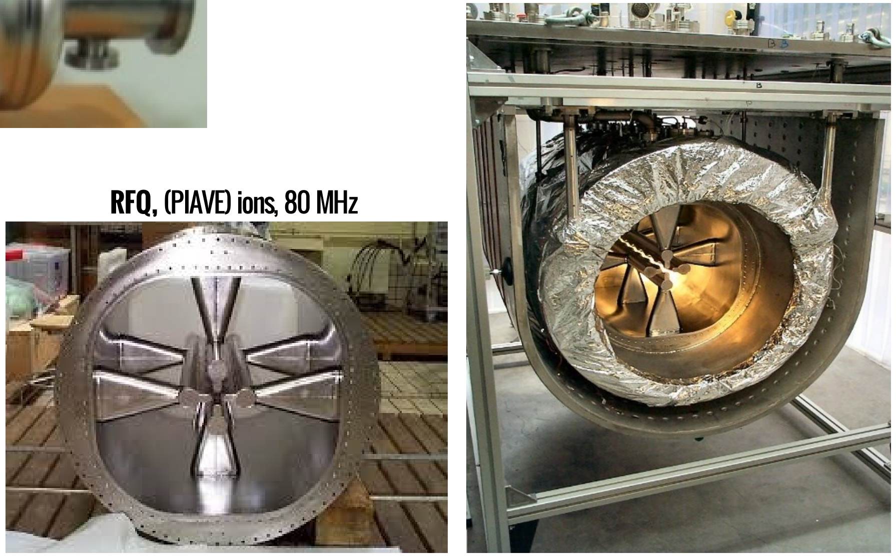
Elliptical 1 cells (LHC), protons and Pb, 400 MHz 5 MV/m, **β = 1**

Quater wave
(ALPI) ions, 160 MHz, **β = 0,11**

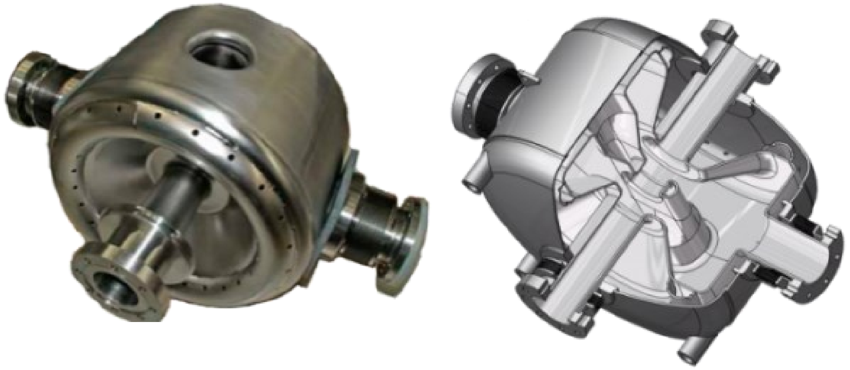


Elliptical 5 cells (ESS), protons, 704 MHz, **β = 0,86**

RFQ, (PIAVE) ions, 80 MHz



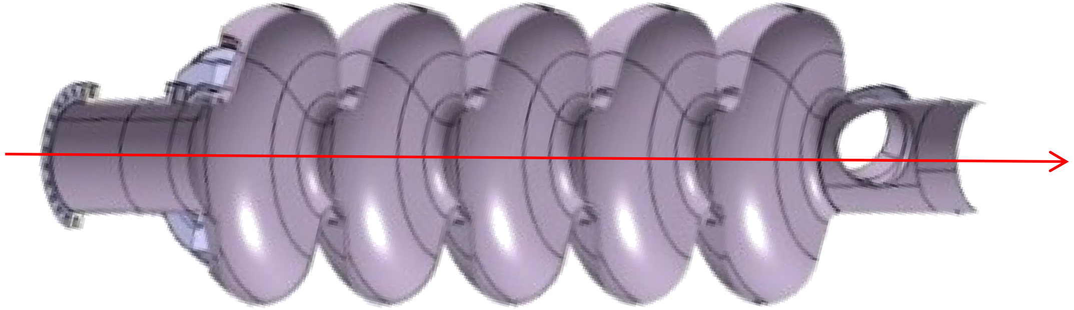
Spoke 2 gaps, protons, 352 MHz, **β = 0,15**



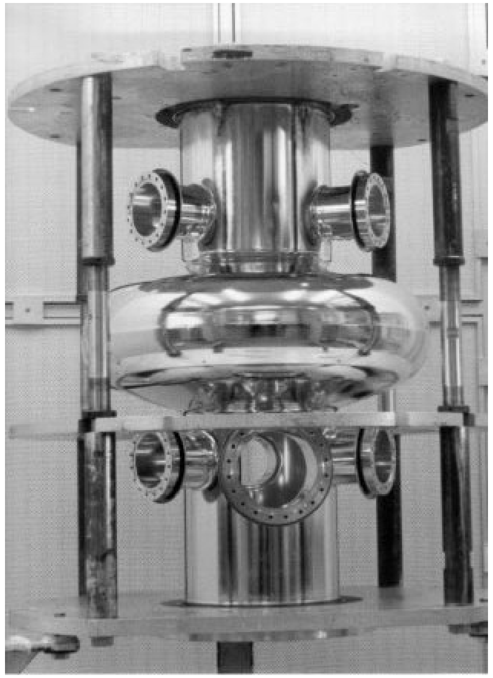
SRF Cavities: design example

more on *V. Palmieri - Superconducting Resonant Cavities*

Elliptical cavities



Elliptic 9 cells (XFEL - Tesla type), electrons, 1.3 GHz 20-30 MV/m, β = 1

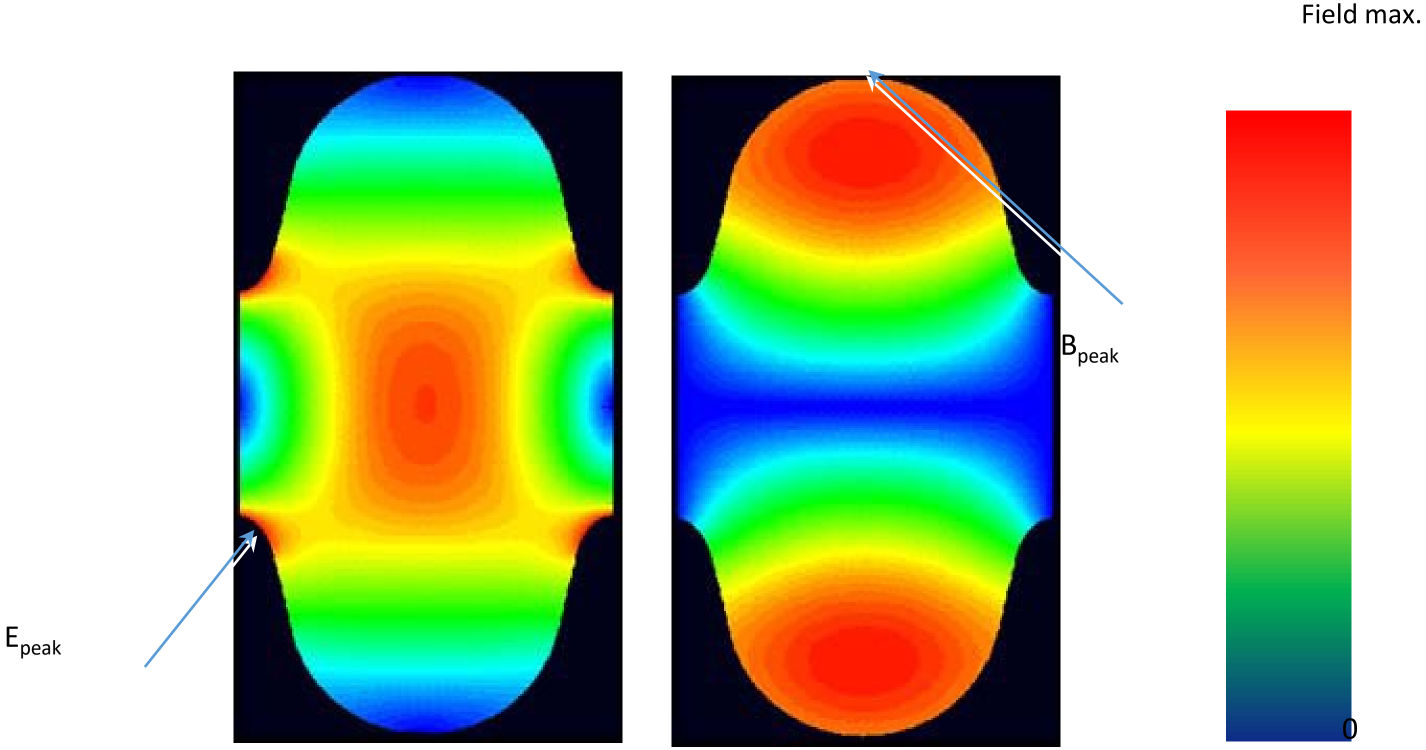


LHC

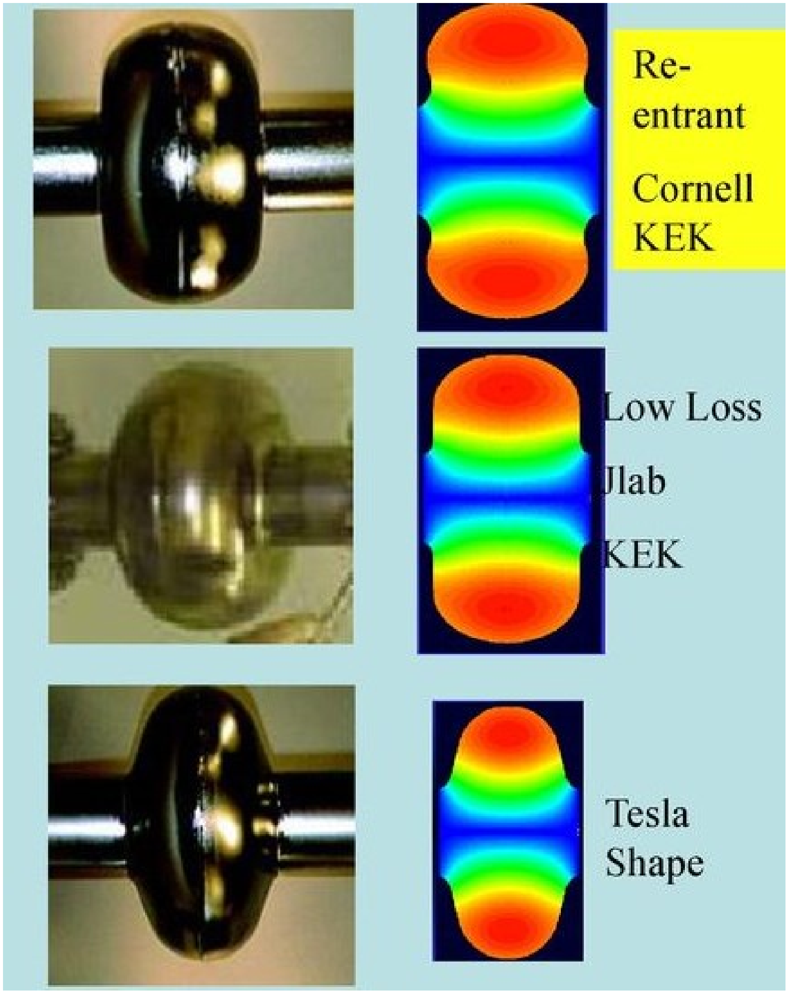
- 8 cavities operating at 400 MHz Nb/Cu
- 5 MV/m for 16 MV tot

Elliptic 5 cells (ESS), protons, 704 MHz, β = 0,86

Elliptical cavities

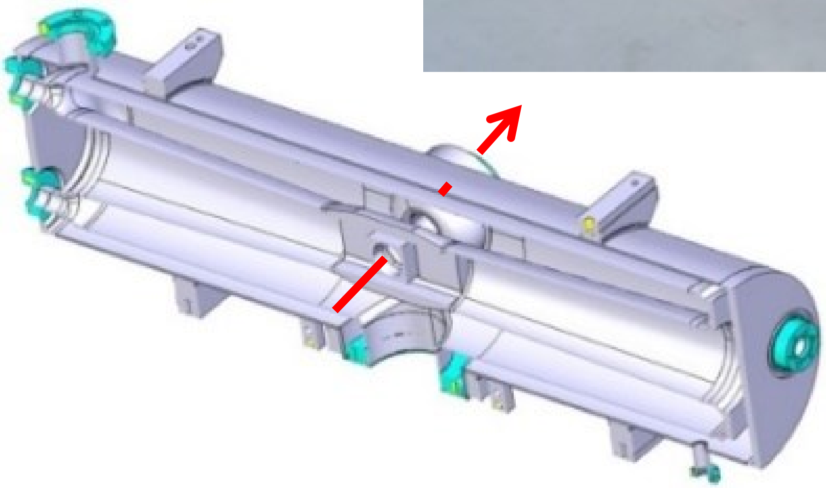


E Field B Field

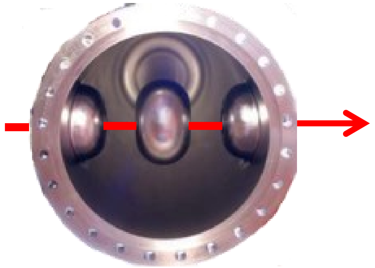


Half and Quarter Wave Resonators

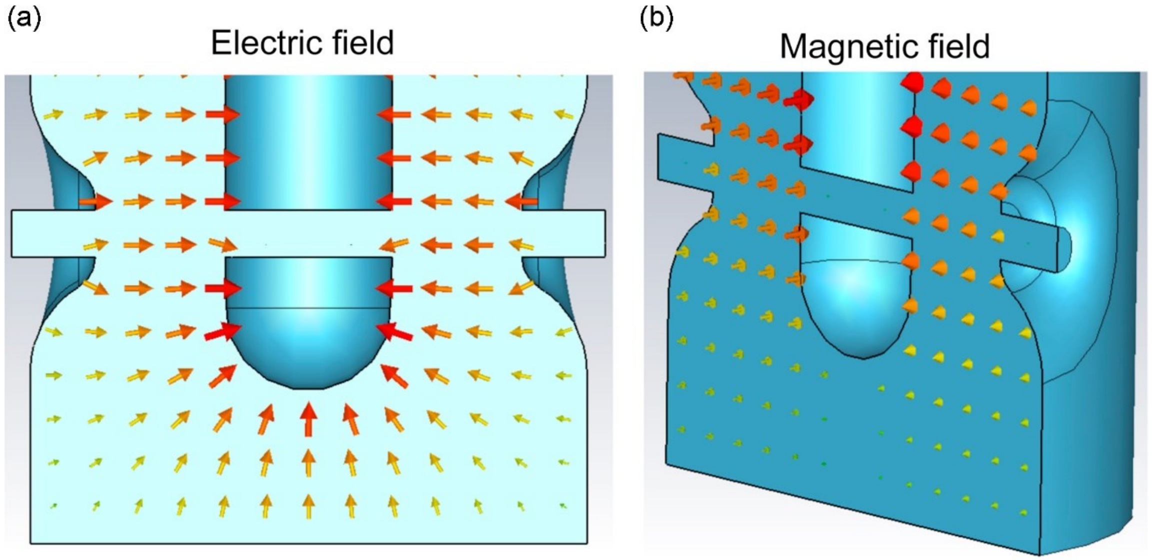
Half wave
(IFMIF) deutons, 175MHz, β = 0,092



Quater wave
(Spiral 2) deutons & ions, 88 MHz, β = 0,07



Quarter Wave Resonators



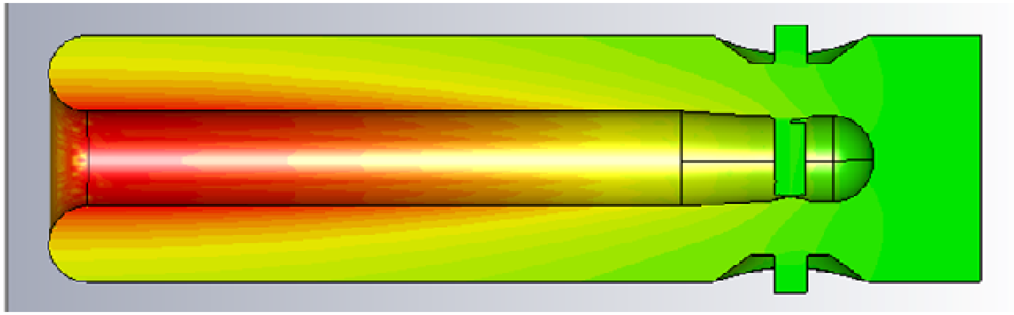
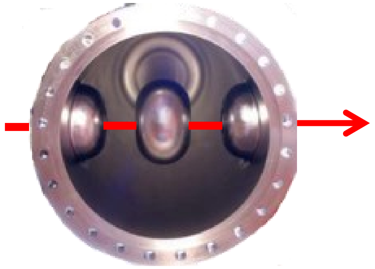


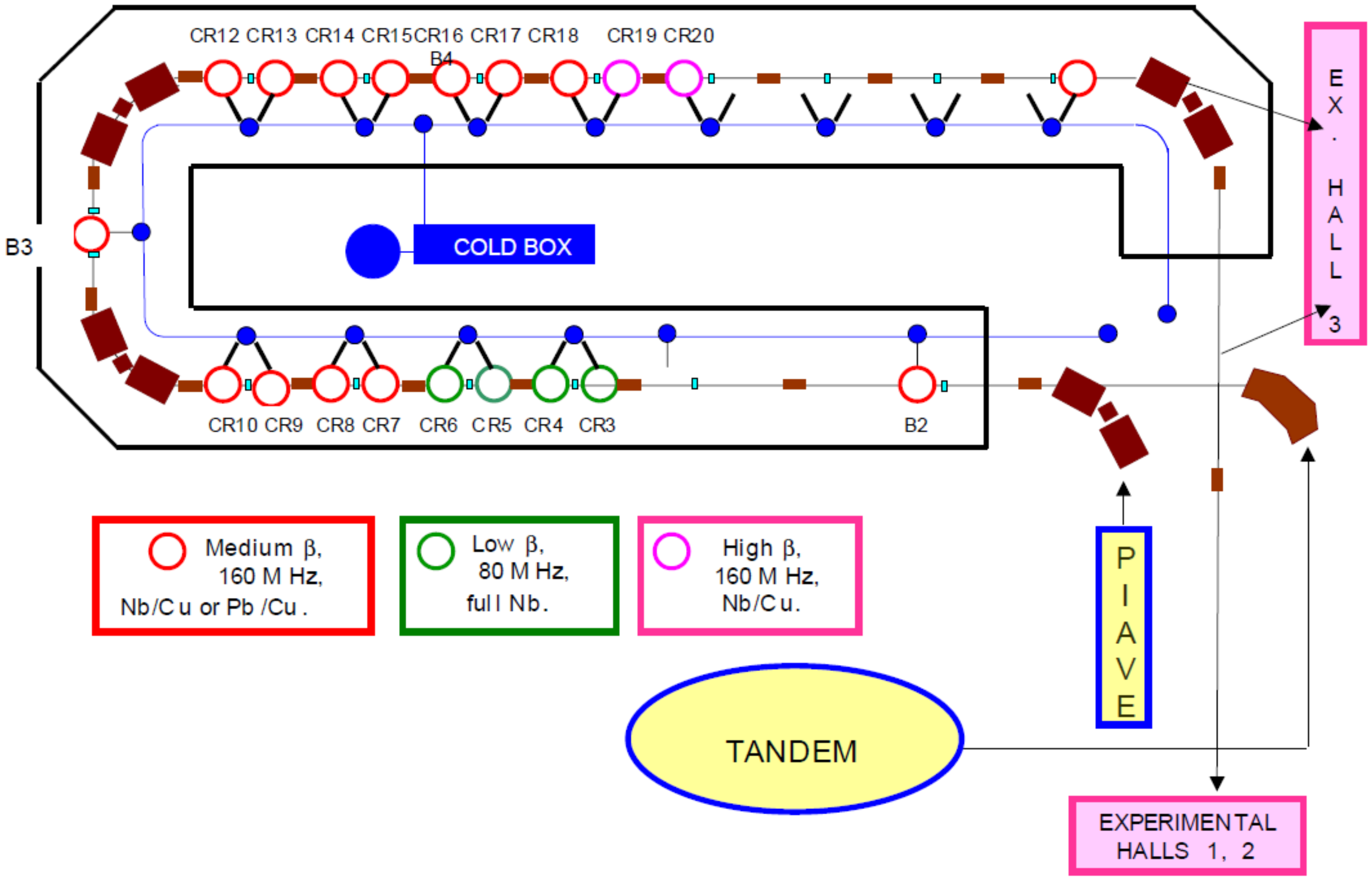
Figure 1: Magnetic field distribution of the FRIB QWR.

Quater wave
(Spiral 2) deutons & ions, 88 MHz, β = 0,07

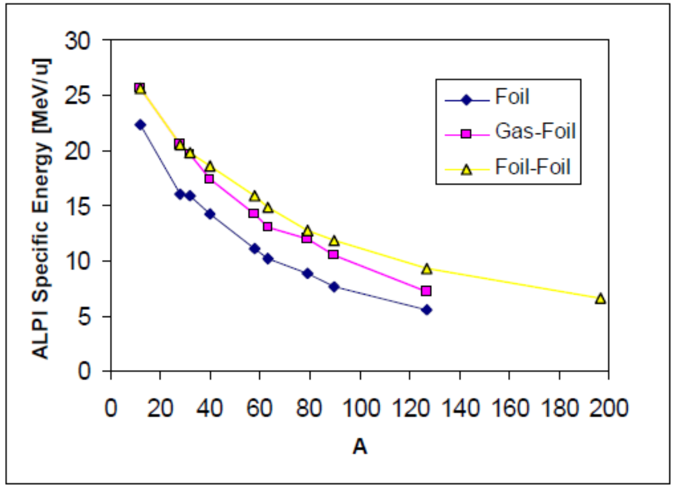


ALPI, INFN

ALPI, INFN - Heavy Ions Linac



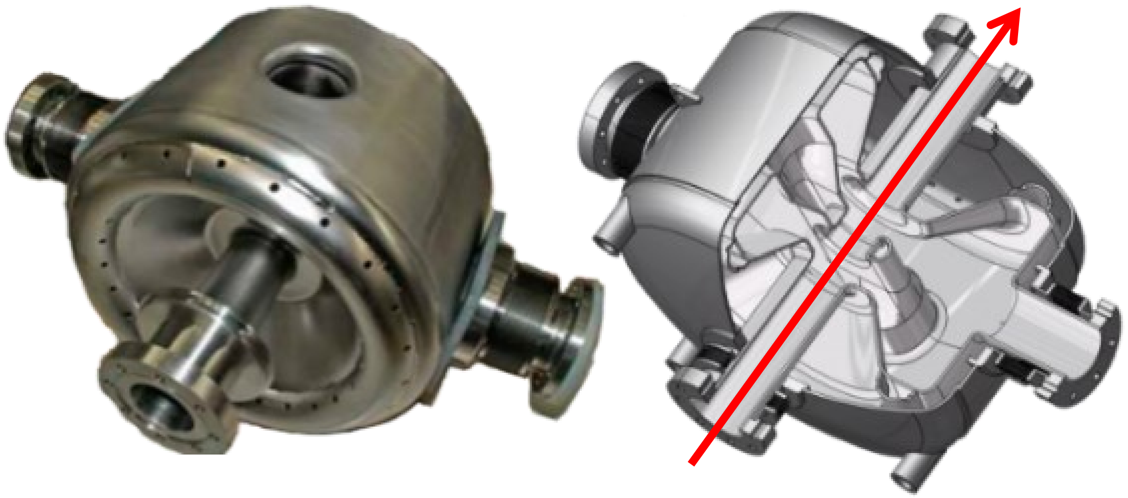
- 64 QWR
- 12 Nb Low-β (0,055) a 80 MHz
- 44 Nb/Cu Medium-β (0,11) a 160 MHz
- 8 Nb/Cu High-β (0,13) a 160 MHz



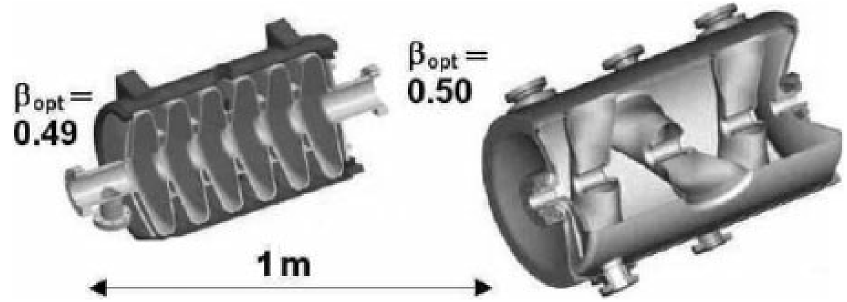
$E_{acc} \approx$ 6-8 MV/m a 7 W

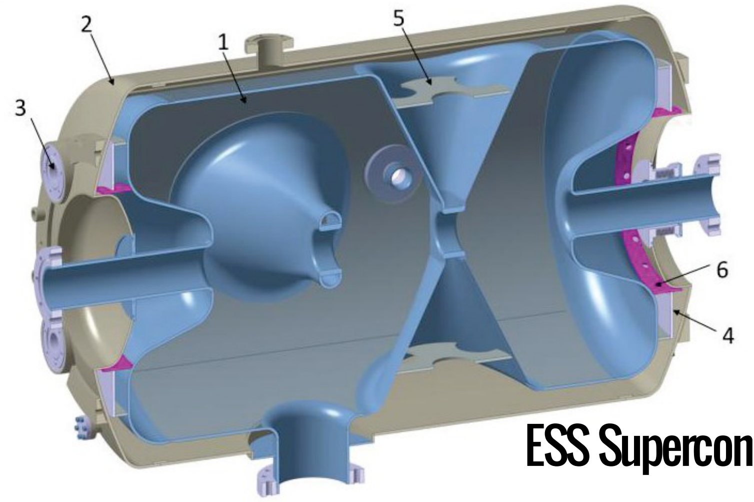
Spoke Cavities

Spoke 2 gaps, protons, 352 MHz, β = 0,15



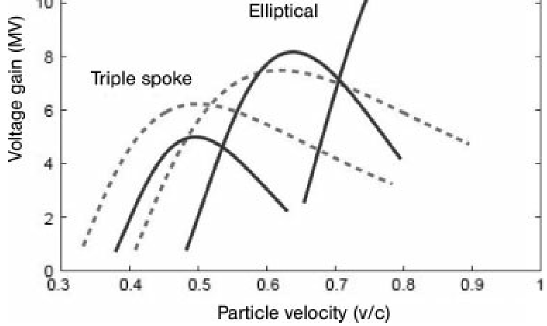
- Spokes operate at lower frequency at the same size and β compared to elliptical ones





ESS Superconducting Spoke Cavities

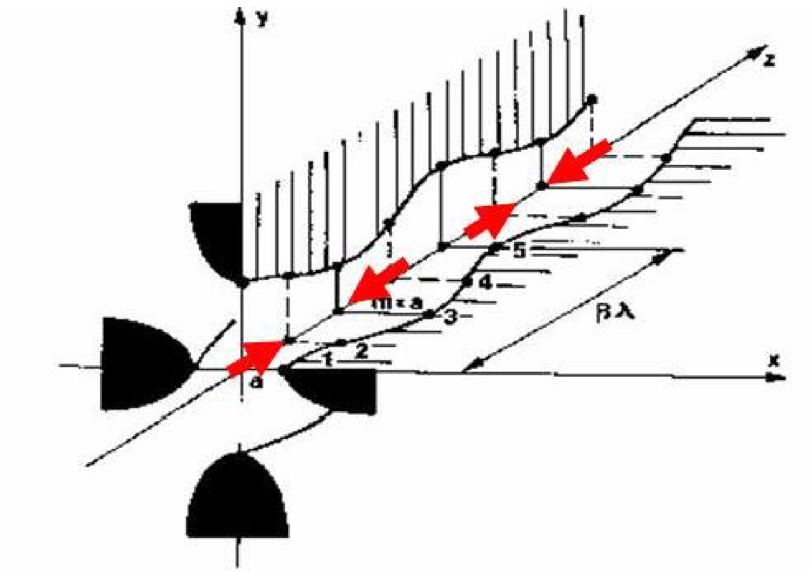
- Larger acceptance in particle velocity

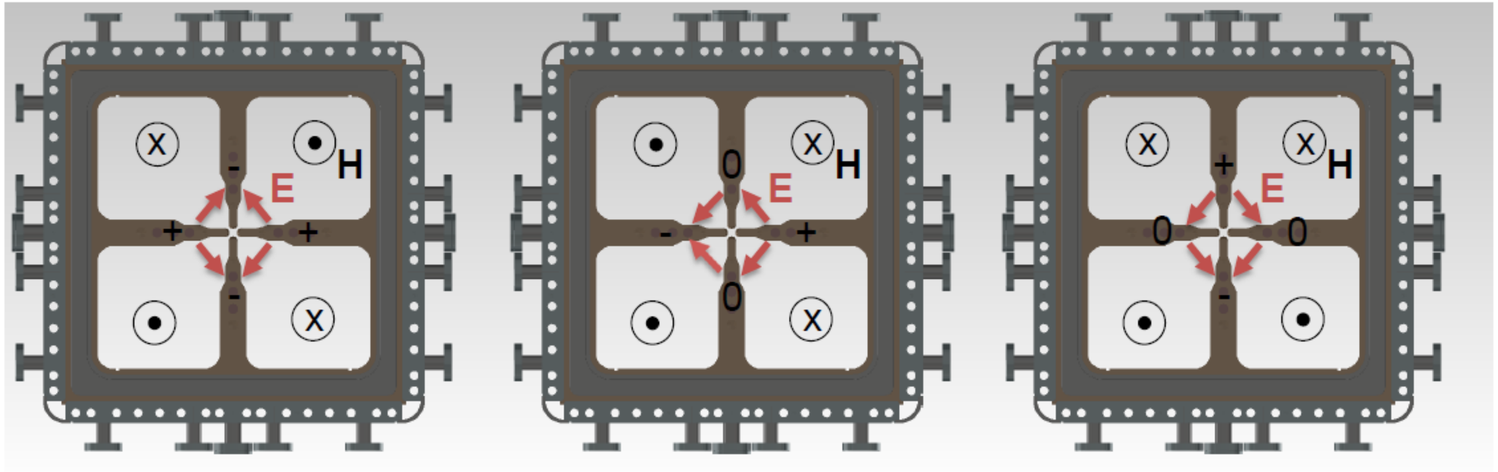


Radio Frequency Quadrupole

Accelerating structure that:

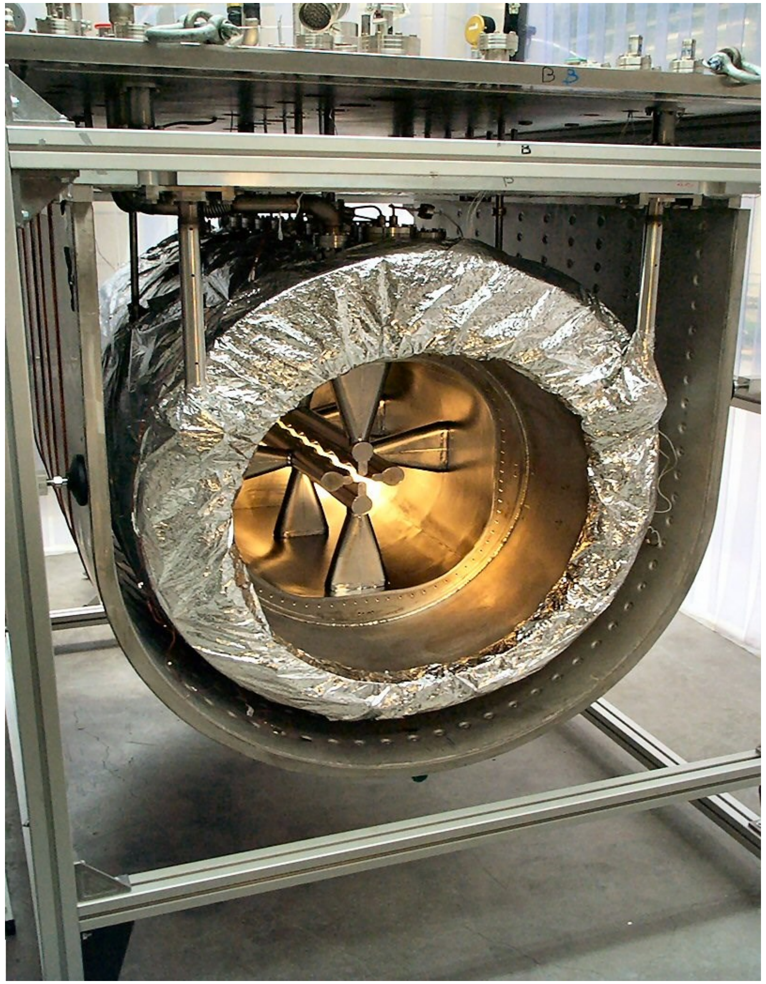
- focus
- Packaging (turns into bunches)
- accelerates





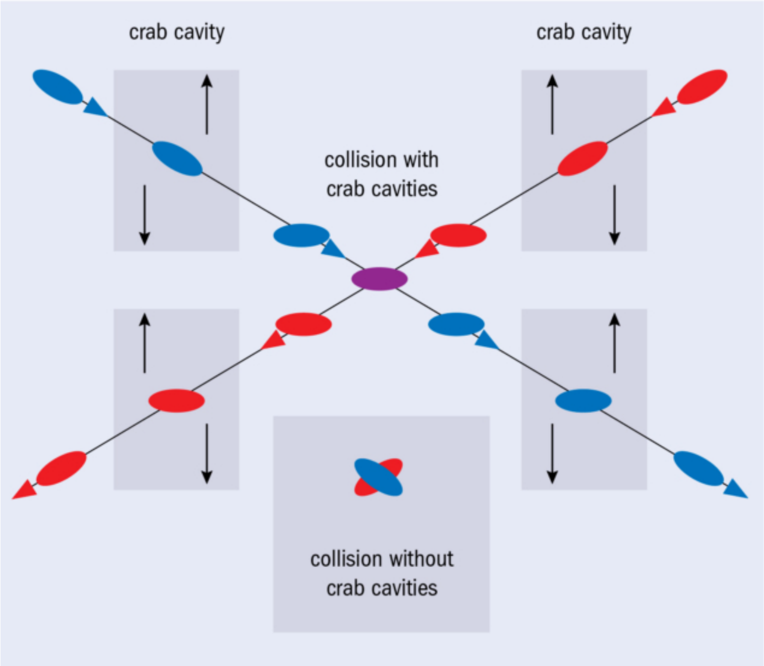
PIAVE - SRFQ

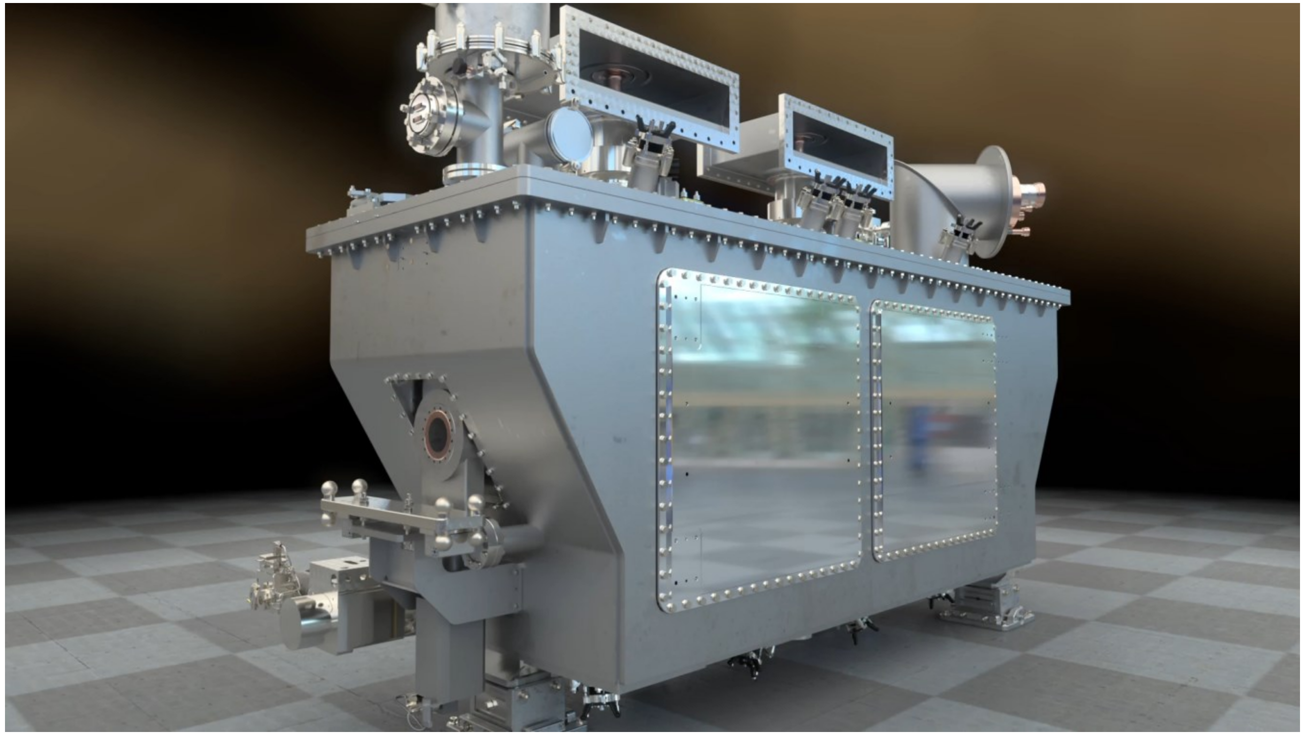
- 2 Bulk Nb RFQ operating at 80 MHz



Crab cavities

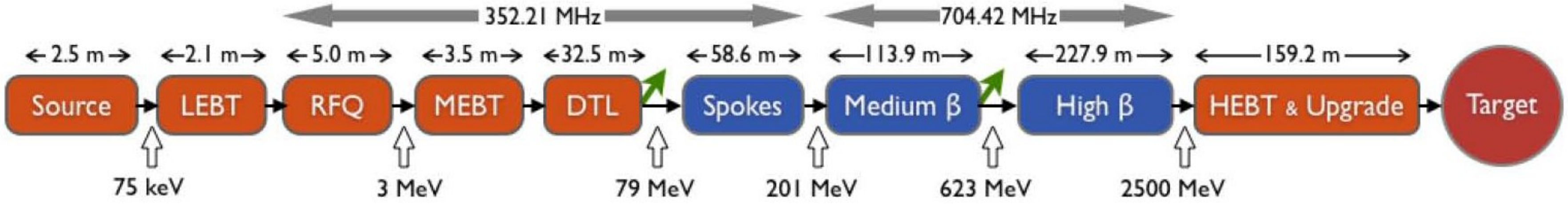
- Goal: rotate the particle beam to increase luminosity
- Installed in KEKB and HL-LHC





European Spallation Source Linac

EUROPEAN
SPALLATION
SOURCE



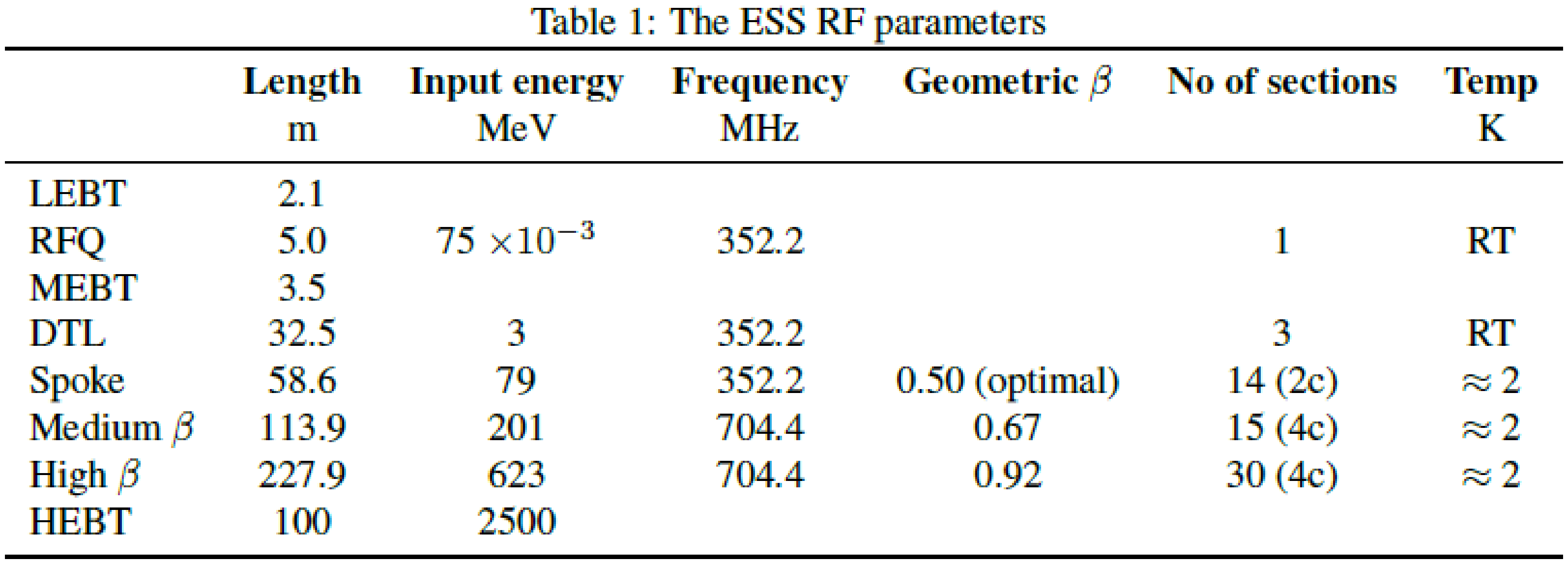
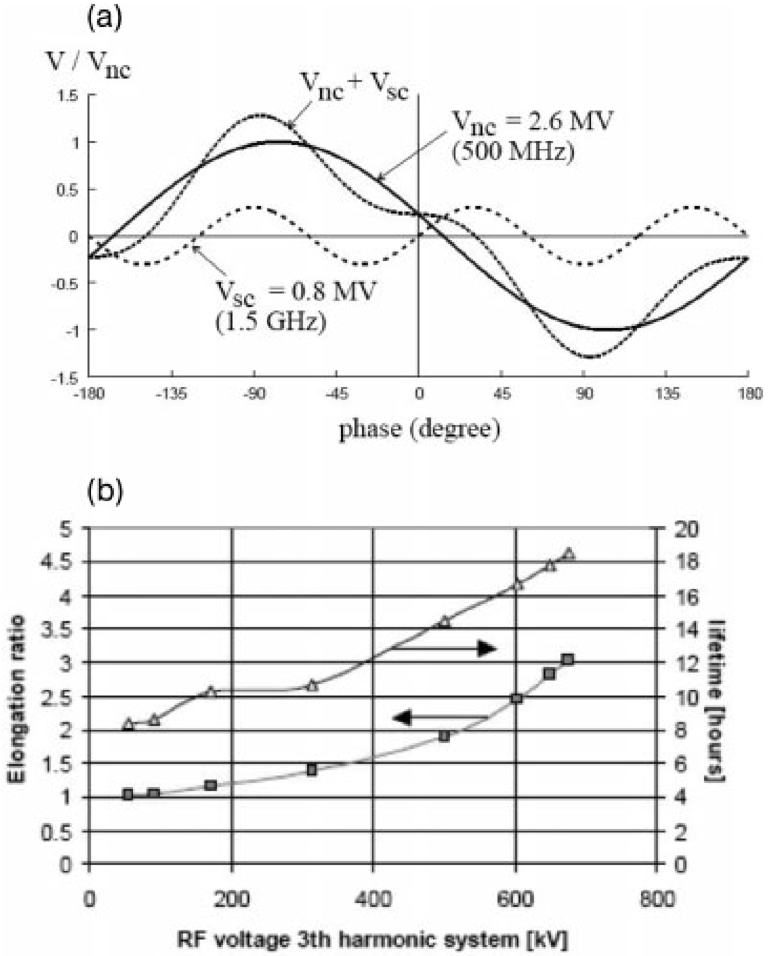


Table 1: The ESS RF parameters

	Length m	Input energy MeV	Frequency MHz	Geometric β	No of sections	Temp K
LEBT	2.1					
RFQ	5.0	75×10^{-3}	352.2		1	RT
MEBT	3.5					
DTL	32.5	3	352.2		3	RT
Spoke	58.6	79	352.2	0.50 (optimal)	14 (2c)	≈ 2
Medium β	113.9	201	704.4	0.67	15 (4c)	≈ 2
High β	227.9	623	704.4	0.92	30 (4c)	≈ 2
HEBT	100	2500				

Elettra Third Harmonic SC Passive Cavities



SCOPE: Increase the life of the beam *(limited by Tousckek effect)*

EFFECT: lengthens the bunch by reducing the charge density