Superconductive Materials

Part 10
Introduction to accelerators
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?

source
Accelerating cavities
revelators
target
Sub-atomic microscopes and time machines

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

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 high density of energy produced allows to reproduce and study the evolution of first instant of the Universe.
**Industrial applications**

**Cargo Scan with X-ray**

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

**Treatment of polymeric materials: cross-linking**

**Ionic implantation (semiconductors)**
Synchrotrons

Introduction to accelerators

Superconductive Materials
Material Test Facility for Nuclear Fusion Reactors

L’International Fusion Materials Irradiation Facility (IFMIF)
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.

Protons/carbon released energy mainly in the tumor cells.
Water Treatment

Forever chemicals

*Wikipedia*: POPs - “Persistent Organic Pollutants”

Pollutants “resistant to degradation through chemical, biological, and photolytic processes” — typically halogenated, organic compounds $\leftrightarrow$ strong bond halogen-carbon

How to remove?

*Ebeam* treatment of water

*(don’t attack contaminants directly)*

$\rightarrow$ “activate” water with beam

\[
e^{-} + H_{2}O \rightarrow e_{aq}^{-} + HO^{-} + H^{+} + \text{HO}_{2} + H_{3}O^{+} + \text{OH}^{-} + H_{2}O_{2} + H_{2}
\]

$\leftrightarrow$ create oxidants and reductants (not just any, some of the strongest)

Big benefit $\rightarrow$ no addition of further chemicals required

$\leftrightarrow$ very cost-effective generation of free radicals

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

$\leftrightarrow$ stay below 10 MeV $\leftrightarrow$ neutron activation threshold

- Yet, public acceptance oft an issue — *treatment* vs *irradiation*
Water Treatment

Technology already exist

• Deagu dyeing treatment plant in South Korea (2006)
  - 1 MeV, 400 kW accelerator – 10,000 m³/h

• Guanhua Knitting Factory wastewater treatment in China (2020)
  - 7 accelerators in total – 30,000 m³/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
Water Treatment

→ combine cryocoolers & Nb$_3$Sn cavities to build compact irradiation sources

• 2018 G. Ciovati et al.
  1 MeV & 1 MW

1 MeV penetration depth $\varepsilon^-$ in water $\sim$ 3 - 4 mm

→ not very practical

move to 10 MeV *(remember threshold) $\rightarrow$ 3 - 4 cm

single cell $\rightarrow$ multi-cell cavity

→ not new for SRF but for CC
Accelerators installed worldwide
Applications in society are as well important to motivate large scale experiments

Information from Manjit Dosanjh, “From Particle Physics to Medical Applications”, IOP Publishing 2017, Bristol, UK
Applications in society are as well important to motivate large scale experiments

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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)

Planned for 2040

> 1200 Cavities
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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A decision from the Japanese community is expected soon, in 2019, 2020, 2021, 2022, 2023, 2024, ...
Probably ILC will be not financed, 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)

International Linear Collider (ILC)

~1800 cryomodules of ~12m

in Liquid He vessel

~16000 superconductive cavities of ~1m
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
(slides from FCC week 2018, Amsterdam 9-13 April 2018 and TTC Meeting, Milan 6-9 February 2018)

Maps of new accelerator projects in China

Large Accelerator Projects in China (2005-2025)

<table>
<thead>
<tr>
<th>Year</th>
<th>BEPC-II</th>
<th>SSRF</th>
<th>SCLF</th>
<th>HEPS</th>
<th>HIAF &amp; CADS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>500MHz SRF</td>
<td>500MHz SRF</td>
<td>1.3GHz SRF</td>
<td>166/500 MHz SRF LE</td>
<td>81-650MHz SRF</td>
</tr>
<tr>
<td>2010</td>
<td>Phase-II</td>
<td>CSNS</td>
<td>FEL-TF</td>
<td>CEPC R&amp;D</td>
<td>NHEP-CD</td>
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<tr>
<td>2015</td>
<td>Operation</td>
<td>Construction</td>
<td>Proposal</td>
<td>650/1300MHz SRF</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td>CEPC?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

~1000 sc cavities in ~7 years
How works an accelerator?
How works an accelerator?

Linear Accelerator (Linac)

Particles Source → Acceleration → User

Circular Accelerator

Particles Source → User → User
How to curve accelerating particles?

\[ \frac{dp}{dt} = q(E + \dot{v} \times B) \]

Lorentz Force

- **Dipoles to curve**
- **Quadrupole to focus**

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

\[ R \propto \frac{E_0}{B} \]

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)**

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).

**Nb$_3$Sn (12 T for HL-LHC, 16 T for FCC)**

Cross-sections of prototype Nb$_3$Sn 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 Nb$_3$Sn compound from the niobium filaments and tin. (Credit: KAT/JASTEC. The image originally appeared in the CERN Courier, June, 2018)

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)
Dipoles

4.5T

5.3T

3.5T

8.3T

Tevatron,
6 m, 76 mm
774 dipoles

HERA,
9 m, 75 mm
416 dipoles

RHIC,
9 m, 80 mm
264 dipoles

LHC,
15 m, 56 mm
1276 dipoles
Magnetic field of a current line

• From the Maxwell equation: \( \nabla \times \mathbf{B} = \mu_0 \mathbf{J} \)

\[
\int \mathbf{B} \, dl = \mu_0 I
\]

• It’s easy to find that: \( B(r) = \frac{\mu_0 J}{2\pi r} \)

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

\[ B_y = \frac{\mu_0 J w}{2} \]
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:

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

\[
B_x = \frac{\mu_0 J}{2} (+r_1 \sin \Theta_1 - r_2 \sin \Theta_2) = 0
\]
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 contribution we replace $I$ with $J dS = J \cos \vartheta \cdot r dr d\vartheta$ and integrate from 0 to $2\pi$

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

- $B_y \propto$ current density (obvious)
- $B_y \propto$ coil width $w$ (less obvious)
- $B_y$ is independent of the aperture $R$ (surprising)
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)

Stefania Farinon, INFN, EASISchool3 Genoa 2020
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 ( $\sigma<$150 MPa at warm and <200 MPa at cold)
PROS

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

CONS

• Hardway bending in coil ends
**PROS**

- Particularly indicated for thick coils (turns 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)
**Common coil**

**PROS**
- Very simple coils (flat racetrack shape)

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

Stefania Farinon, INFN, EASISchool3 Genoa 2020
Results of the comparison

• The cosθ 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

Stefania Farinon, INFN, EASISchool3 Genoa 2020
Quadrupoles

Quadrupole magnets generate constant and uniform gradient $G$:

Similar as for dipoles:
Quadrupoles
Realize big magnets is not trivial…

Collaring press

LHC - dipole

Collaring completed

N. Valle, ASG, EASI School3 Genoa 2020
HiLumi D2 dipole
D2 - Model INFN-ASG

- Collaring operation
D2 - Model INFN-ASG

Aluminum sleeves introduction

N. Valle, ASG, EASISchool3 Genoa 2020
Integration inside the iron yoke
D2 - Model INFN-ASG

View from LOC Side

View from LC Side

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Detectors require bid magnet too!

**ATLAS - LHC CERN**

\[ B_{\text{nom}} = 2 \, \text{T} \]

\[ I_{\text{nom}} = 20.5 \, \text{KA} \text{ in an Aluminium coextruded NbTi Rutherford} \]

**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

N. Valle, ASG, EASISchool3 Genoa 2020
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 indirectly cooled
Force 1100 t/coil
ATLAS - LHC CERN

ATLAS-CERN 2003 - Winding at ASG premises

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Challenge

Scale of components and integration accuracy

Tolerances $<< 1$ mm in 26m
ATLAS - LHC CERN
ATLAS - LHC CERN

ATLAS-CERN 2003
Transported to CERN by truck

N. Valle, ASG, EASISchool3 Genoa 2020
B_{\text{nom}} 4T
Solenoid in 5 modules Outer diameter = 7 m
Cold mass overall length L = 5 \times 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
Conductor  $I_c = 55.6 \text{ kA} @ 4.2\text{K}, 5\text{T}$

1.28 mm Dia Strand, Cu:SC Ratio = 1:1
CMS - INFN/CERN 2004 Impregnation Test (throughout R&D activity)
CMS - LHC CERN

CMS - INFN/CERN 2004 - Outer Aluminium structures under fabrication at ASG premises
CMS - INFN/CERN 2004 - Winding and ground insulation glass cloths positioning

N. Valle, ASG, EASI School 3 Genoa 2020
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!!
January 2006: End of the CMS Magnet Manufacturing
How works an accelerator?

Linear Accelerator (Linac)

Particles Source \rightarrow Acceleration \rightarrow User

Circular Accelerator

Particles Source \rightarrow User
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)**

Particles Source → Acceleration → User

**Circular Accelerator**

Particles Source → Circular Accelerator → User
Particle Energy and Speed

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

Accelerate a particle means increase \( p = mv \).

An electron becomes relativistic \((v_{el} \approx c)\) when \( E > 5 \text{ MeV} \) \((m_e = 9 \times 10^{-31} \text{ kg})\).

For a proton \( E \) is 1000 times higher \((m_p = 1.6 \times 10^{-27} \text{ kg})\).

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

<table>
<thead>
<tr>
<th>Particle</th>
<th>( v ) (c)</th>
<th>( E ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( e^- )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( \text{Light particles} )</td>
<td>( \beta = 0.999 )</td>
<td>1</td>
</tr>
<tr>
<td>( \text{Heavy particles} )</td>
<td>( \beta = 0.9999 )</td>
<td>10</td>
</tr>
<tr>
<td>( p^+ )</td>
<td>( \beta = 0.99999 )</td>
<td>1000</td>
</tr>
</tbody>
</table>

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?

\[ 1 \text{ eV} = 1 \text{V} \times 1.6 \times 10^{-19} \text{ C} = 1.6 \times 10^{-19} \text{ J} \]

\[ 1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J} \]

\[ 1 \text{ GeV} = 1.6 \times 10^{-10} \text{ J} \]

\[ 1 \text{ TeV} = 1.6 \times 10^{-7} \text{ J} \]

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\(_{p,n} \) \( \sim 7 \times 10^{-23} \text{ J} \)

\( \sim 5 \times 10^{-4} \text{ eV} \)

The density of energy in LHC is 16 order of magnitude higher than in a bullet!
Particles are accelerated using **Electric Fields**

**Electrostatic Acceleration**

**Limited by dielectric breakdown**
RF acceleration

Limited by LINAC length

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**  
  \[ T = \frac{1}{V_c} \int E_z(z) \cdot e^{j\Phi(z)}dz \]
An important figure of merit is the **quality factor**, which for any resonant system is

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

One can see that the ratio of two integrals in the equation of \( Q_0 \) determined only by cavity geometry.

Roughly \( 2\pi \) times the number of RF cycles it takes to dissipate the energy stored in the cavity.
Geometry Factor $G$

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

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

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

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

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

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

\[ \text{RRR} = \frac{\sigma(4.2\,\text{K})}{\sigma(300\,\text{K})} = 300 \]

\( R_s(4.2\,\text{K}) \approx 1.3\,\text{mW} \)

...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 \(~8!\)

To reduce \( R_s \) below the m\( \Omega \) range for RF application we need Superconductivity!
SC cavities reduce the wall dissipation by many orders of magnitude compared to NC cavity.

Cu, 1.5 GHz: $R_s$ (300 K) $\sim$ 10 m$\Omega$, $R_s$ (4 K) $\sim$ 1.3 m$\Omega$

Nb, 1.5 GHz: $R_s$ (4 K) $\sim$ 500 n$\Omega$, $R_s$ (2 K) $\sim$ 20 n$\Omega$
The advantages of SC Cavities

1) **AC power requirement less than normalconductors**
(also taking into account cryogenic efficiency)

\[ R_s \text{Cu} \approx 10^{-3} \Omega \rightarrow Q_{\text{normal conductor}} \approx 10^4 \]
\[ R_s \text{Nb} \approx 10^{-9} \Omega \rightarrow Q_{\text{superconductor}} \approx 10^9 - 10^{10} \]

2) **Reduction of the Linac length**

\[ E_{\text{acc}} \text{Cu} < 1 \text{ MV/m} \quad \text{Limited by Joule effect} \]
\[ E_{\text{acc}} \text{Nb} \approx 55 \text{ MV/m} \quad \text{Limited by } H_{\text{SH}} \]
ZOO of SRF cavities

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

Elliptical 1 cells (LHC), protons and Pb, 400 MHz 5 MV/m, $\beta = 1$

Elliptical 5 cells (ESS), protons, 704 MHz, $\beta = 0.86$

RFQ, (PIAVE) ions, 80 MHz

Quater wave (ALPI) ions, 160 MHz, $\beta = 0.11$

Spoke 2 gaps, protons, 352 MHz, $\beta = 0.15$
SRF Cavities: design example

more on V. Palmieri - Superconducting Resonant Cavities
Elliptical cavities

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

Elliptical 5 cells (ESS), protons, 704 MHz, $\beta = 0.86$

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

Cristian Pira  Superconductive Materials  10. Introduction to accelerators
Elliptical cavities

- **E Field**
- **B Field**
- **Field max.**

- Re-entrant
- Cornell KEK
- Low Loss lab
- KEK
- Tesla Shape
Half and Quarter Wave Resonators

- **Half wave** (IFMIF) deuterons, 175 MHz, $\beta = 0.092$
- **Quater wave** (Spiral 2) deuterons & ions, 88 MHz, $\beta = 0.07$
Quarter Wave Resonators

Figure 1: Magnetic field distribution of the FRIB QWR.

(Spiral 2) deuterons & ions, 88 MHz, $\beta = 0.07$
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

\[ E_{\text{acc}} \approx 6-8 \text{ MV/m a 7 W} \]
Spoke Cavities

Spoke 2 gaps, protons, 352 MHz, $\beta = 0.15$

- Spokes operate at lower frequency at the same size and $\beta$ compared to elliptical ones
- Larger acceptance in particle velocity

ESS Superconducting Spoke Cavities
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
Table 1: The ESS RF parameters

<table>
<thead>
<tr>
<th></th>
<th>Length (m)</th>
<th>Input energy (MeV)</th>
<th>Frequency (MHz)</th>
<th>Geometric $\beta$</th>
<th>No of sections</th>
<th>Temp (K)</th>
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</thead>
<tbody>
<tr>
<td>LEBT</td>
<td>2.1</td>
<td>$75 \times 10^{-3}$</td>
<td>352.2</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>5.0</td>
<td>3</td>
<td>352.2</td>
<td></td>
<td>1</td>
<td>RT</td>
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<tr>
<td>MEBT</td>
<td>3.5</td>
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</tr>
<tr>
<td>DTL</td>
<td>32.5</td>
<td>3</td>
<td>352.2</td>
<td>0.50 (optimal)</td>
<td>3</td>
<td>RT</td>
</tr>
<tr>
<td>Spoke</td>
<td>58.6</td>
<td>79</td>
<td>352.2</td>
<td></td>
<td>14 (2c)</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>Medium $\beta$</td>
<td>113.9</td>
<td>201</td>
<td>704.4</td>
<td>0.67</td>
<td>15 (4c)</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>High $\beta$</td>
<td>227.9</td>
<td>623</td>
<td>704.4</td>
<td>0.92</td>
<td>30 (4c)</td>
<td>$\approx 2$</td>
</tr>
<tr>
<td>HEBT</td>
<td>100</td>
<td>2500</td>
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</table>
Elettra Third Harmonic SC Passive Cavities

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

EFFECT: lengthens the bunch by reducing the charge density