EUROPEAN SPALLATION SOURCE

Accelerator Components and Technologies

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Nordic Particle Accelerator School, NPAS2015

http://www.eit.lth.se/index.php?ciuid=922&L=1

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Outline

- Types of Particle Accelerators
- Accelerator Characteristics
- RF Cavity
- Superconductivity and Superfluidity
- Examples of the Particle Accelerators:
  - The European Spallation Source (SRF cavities R&D)
  - The LHC (low-beta magnets environment and Controls)
  - The Tevatron (accelerator complex and technologies)

Acknowledgements & references

Acknowledgement to D. McGinnis, M. Vretenar and P. Lebrun

- US-Particle Accelerator School, http://uspas.fnal.gov/materials/materials-table.shtml
- CERN Accelerator School http://cas.web.cern.ch/cas

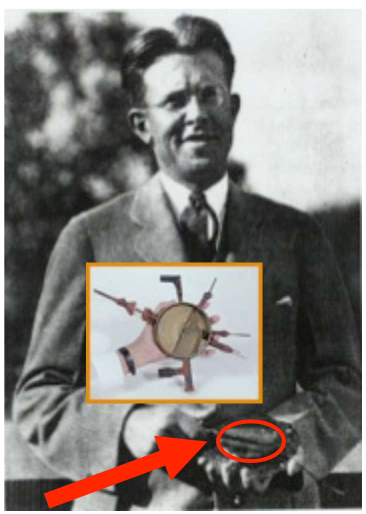
A few books

- RF Linear Accelerators, T.P. Wangler, Wiley, 2008
- RF Superconductivity for Accelerator, H. Padamsee, J. Knobloch, T. Hays, Wiley, 2011
- An introduction to particle accelerators, E.J.N. Wilson, Oxford Univ. Press, 2001
- An introduction to the physics of high-energy accelerators, D.A. Edwards & M.J. Syphers, Wiley, 1993
- The principles of circular accelerators and storage rings, P.J. Bryant & K. Johnsen, Cambridge Univ. Press, 1993

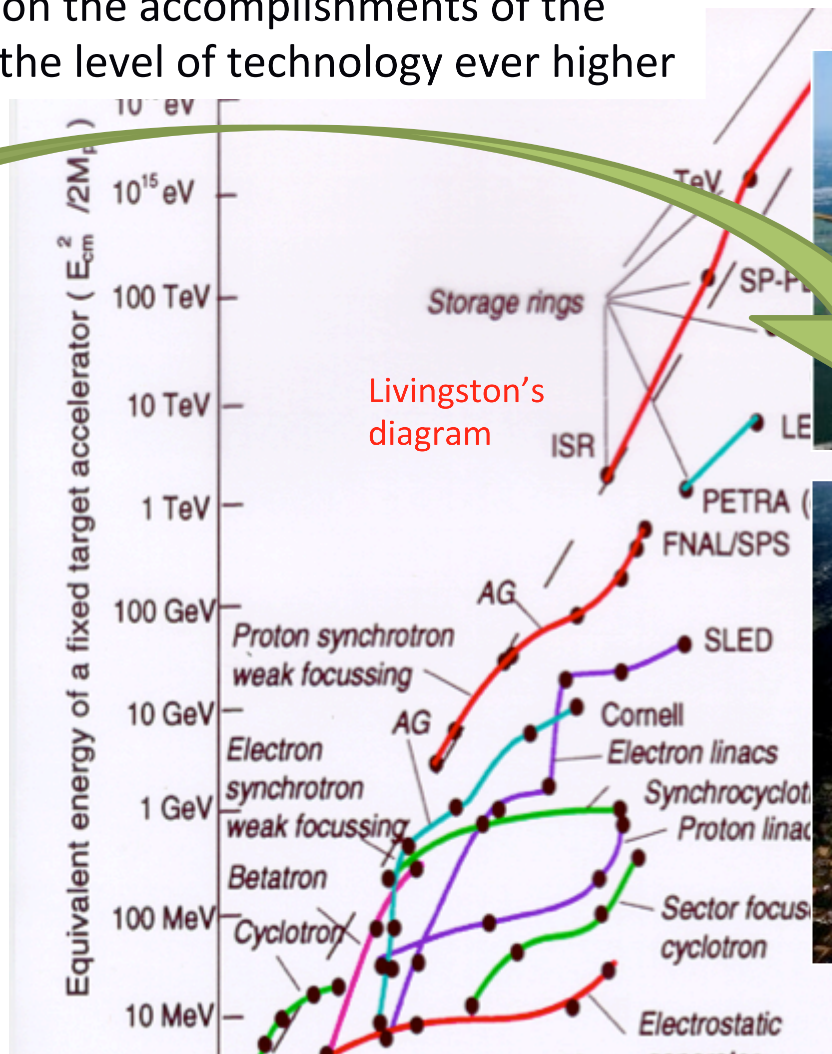
Type of Particle Accelerators

Each generation built on the accomplishments of the previous ones raising the level of technology ever higher

Ernest Lawrence (1901 - 1958)

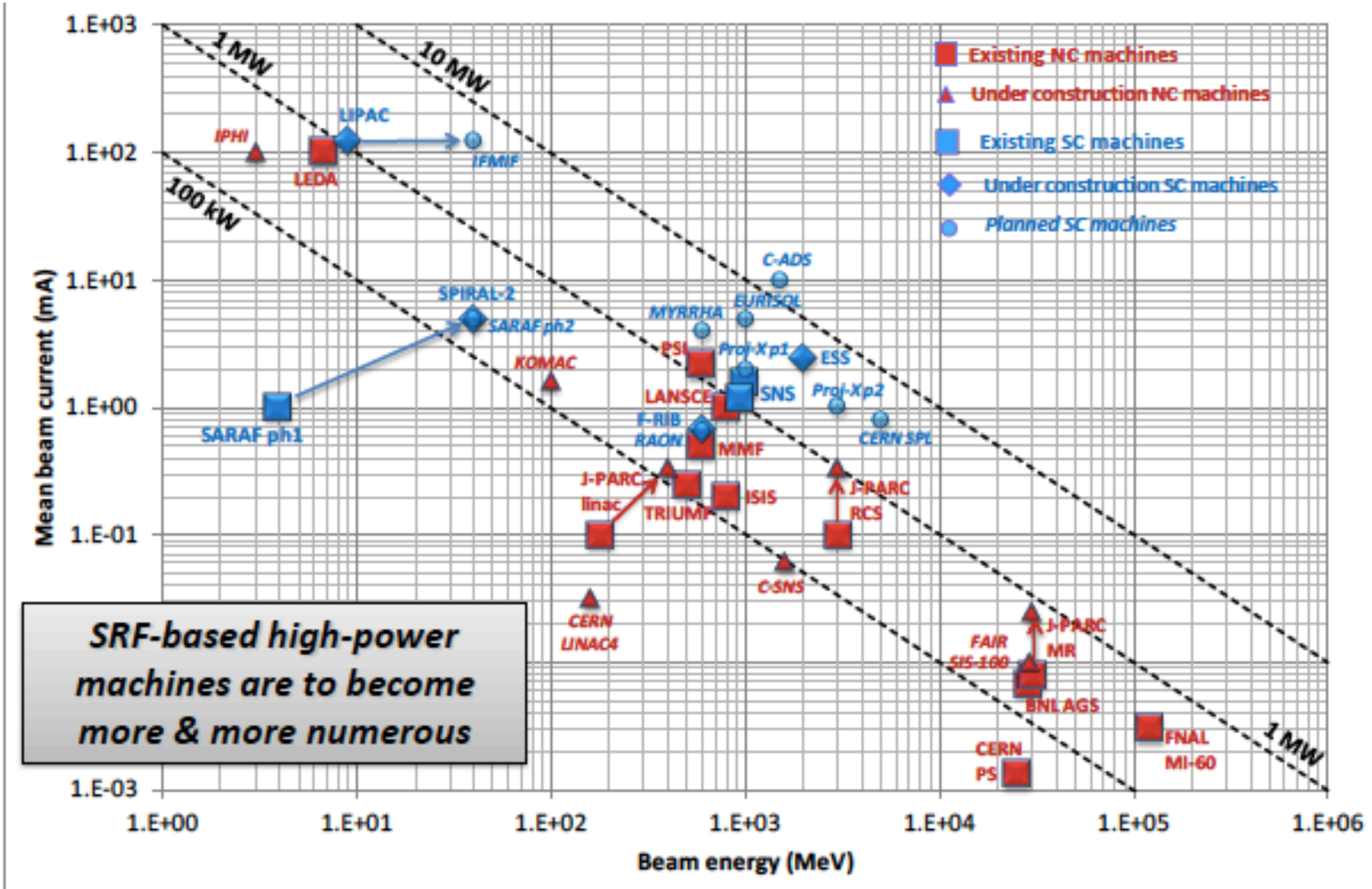


80 keV



Livingston's diagram

High power H/D beams around the world



SRF-based high-power machines are to become more & more numerous

Type of Particle Accelerators

Used for ?

Today: > 35,000 accelerators are in operation around the world

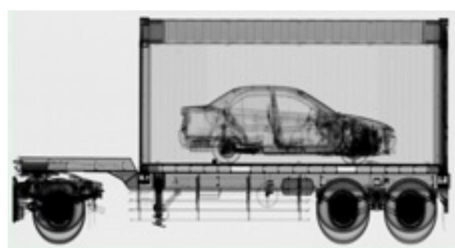
.. and "has been"

FNAL

- Discovery science: e.g. High Energy Physics
- Materials research/manufacturing: e.g. light sources, spallation source, Accelerator Driven Systems (ADS)

SLS

X-ray scanning



- National security
- Medical Applications:

e.g. Neutron and Proton Therapies

MRI and NMR

iThemba LABS

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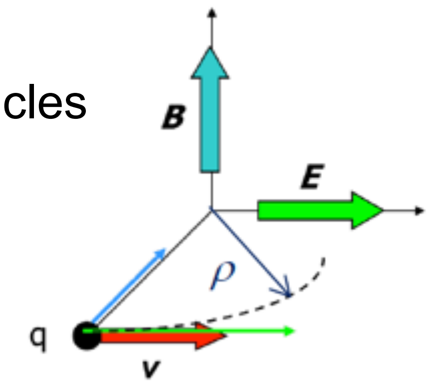
Accelerator Characteristics

ElectroMagnetism - Lorentz

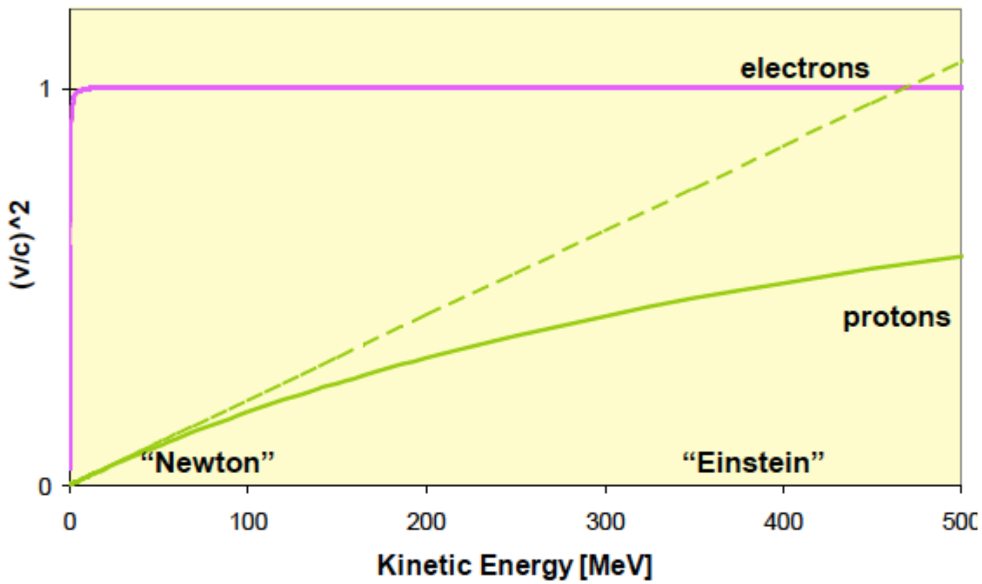
Electric Fields to accelerate charged particles
→ RF accelerator components

Magnetic Fields to bend, steer, (de)focus
→ Magnet components



Lorentz force

$$\vec{F} = \frac{d\vec{p}}{dt} = e(\vec{E} + \vec{v} \times \vec{B})$$

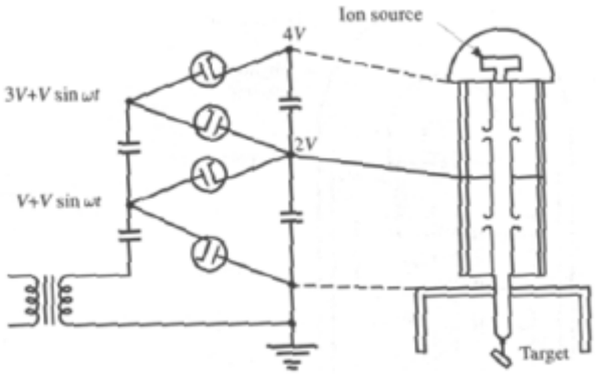


$$\beta = \frac{v}{c} = \sqrt{1 - \frac{1}{\gamma^2}}$$

	Electron	Proton
Rest mass [Kg]	9.11E-31	1.67E-27
Rest mass [MeV]	0.511	938
V~0.95 c [MeV]	1.1	2000
ratio	1	1836

Accelerator Characteristics

ElectroMagnetism - Maxwell

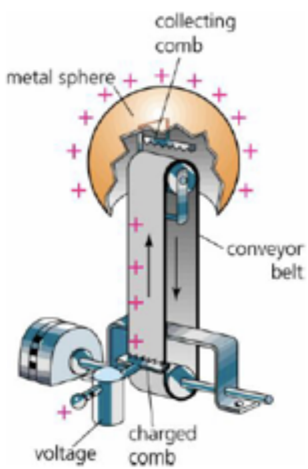


$$\vec{E} = -\vec{\nabla}\varphi - \frac{\partial \vec{A}}{\partial t}$$

electrostatic (DC)

Cockroft & Walton

Van de Graaf



time-varying (AC)

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

unbunched

Betatron

resonant

Linac

Cyclotron

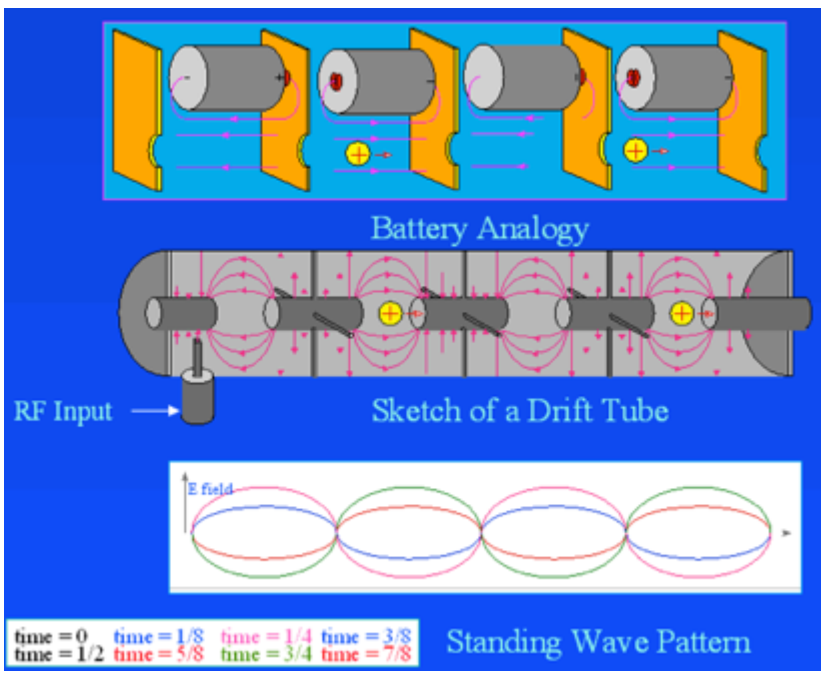
Synchrotron

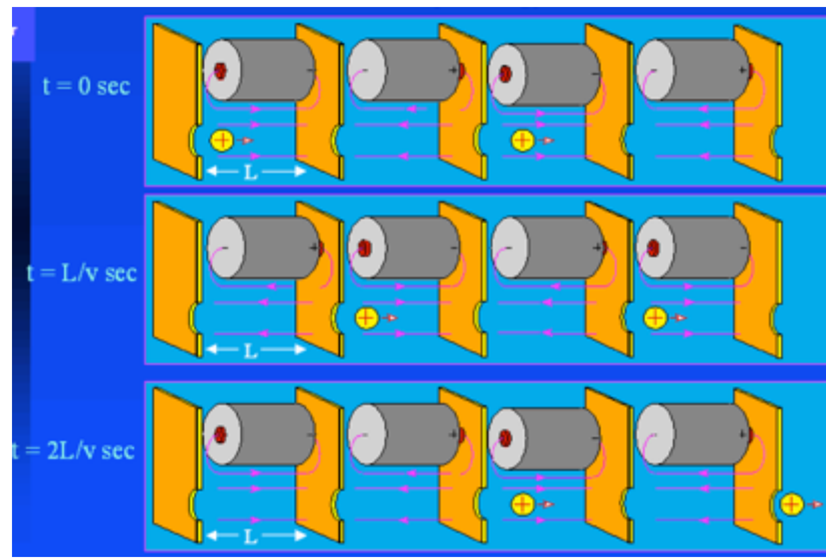
Accelerator Characteristics
DC to AC Accelerators

→ **Linear Accelerators (LINAC):** Large space charge

DC and AC components: Cockroft-Walton and Van de Graff, RFQ, DTL, RF cavities

- Each Linear Accelerator starts by a source followed by DC accelerator components
- Need to switch to AC due to the accumulation of high voltage causing sparking
- So we need to use Radio-Frequency sources
- As an effect, the beam is bunched



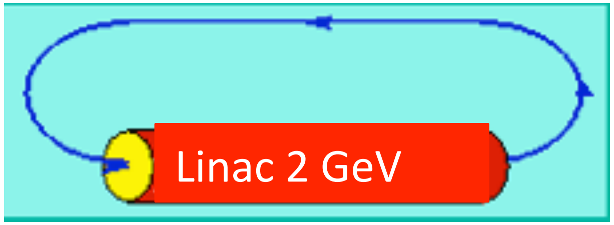


← Principle of the Drift Tube Linac:

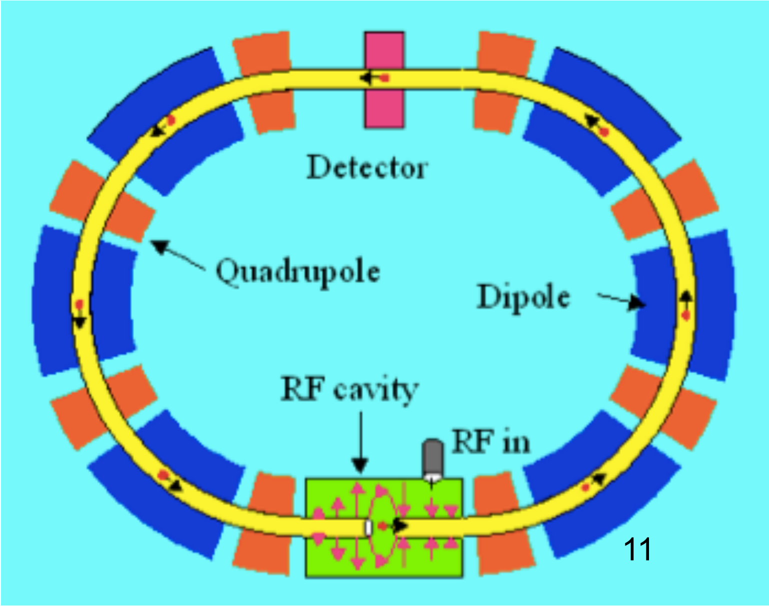
Accelerator Characteristics

ESS LINAC is 600m long (350m of acceleration) and reaches an energy of 2 GeV
Assuming we need a 7 TeV machine (LHC), the Linac should be 1,225 km long !

Linac over and over ?



→ Synchrotron Accelerators:
Space charge effect becomes small
* Cover range where particle velocity is nearly cst.
e.g. LHC, Tevatron



Accelerator Characteristics

Family of Linac component

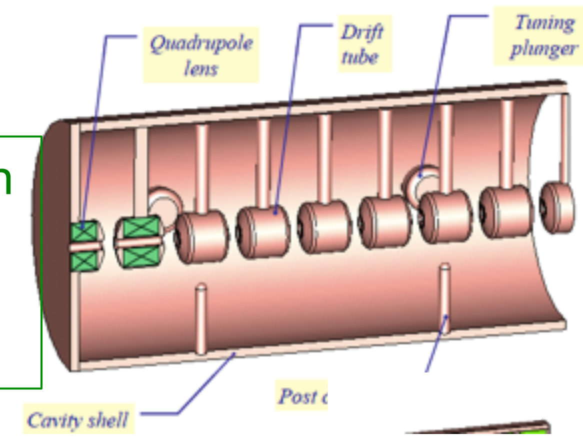
RF Quadrupole

At low energy proton, the RFQ permits:

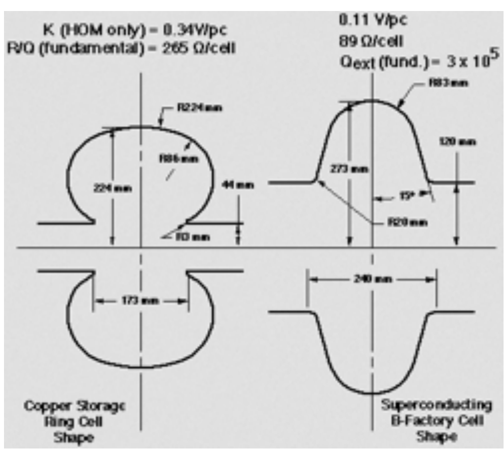
1. Bunching of the beam
2. Focusing quadrupole
3. Accelerating

Drift Tube Linac

Every cell is different, focusing quadrupoles in each drift tube



If f >10 MHz, the DTL acts like an antenna and radiates energy instead of using it for the acceleration



RF cavity

EM fields enclosed in a cavity with resonant frequency matching that of RF generator

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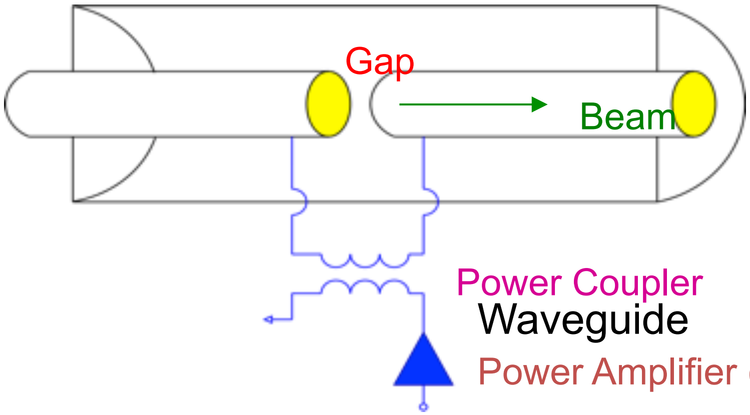
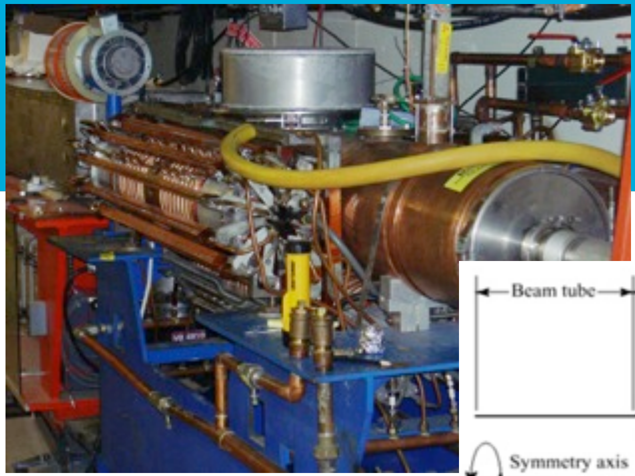
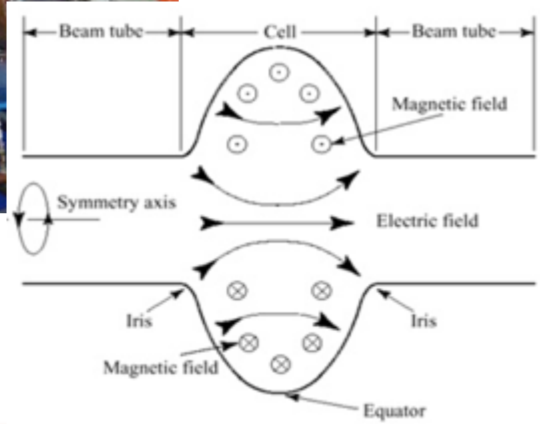
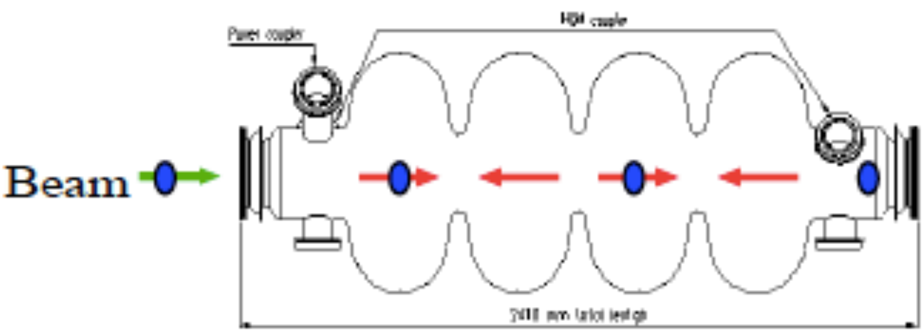
RF Cavity

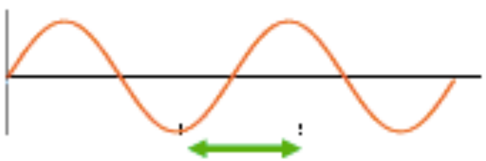


FNAL Booster Cavity









Example: a linac superconducting 4-cell accelerating structure

Synchronism condition bw. particle and wave

t (travel between centers of cells) = $T/2$

$$\frac{d}{\beta c} = \frac{1}{2f} \Rightarrow d = \frac{\beta c}{2f} = \frac{\beta\lambda}{2}$$

d=*distance between centres of consecutive cells*

RF Cavity

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DESIGNING SUPERCONDUCTING CAVITIES FOR ACCELERATORS

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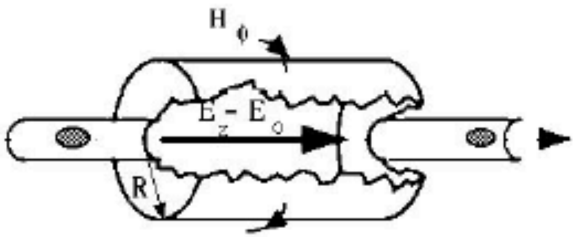


Fig. 7 Pill-box resonator

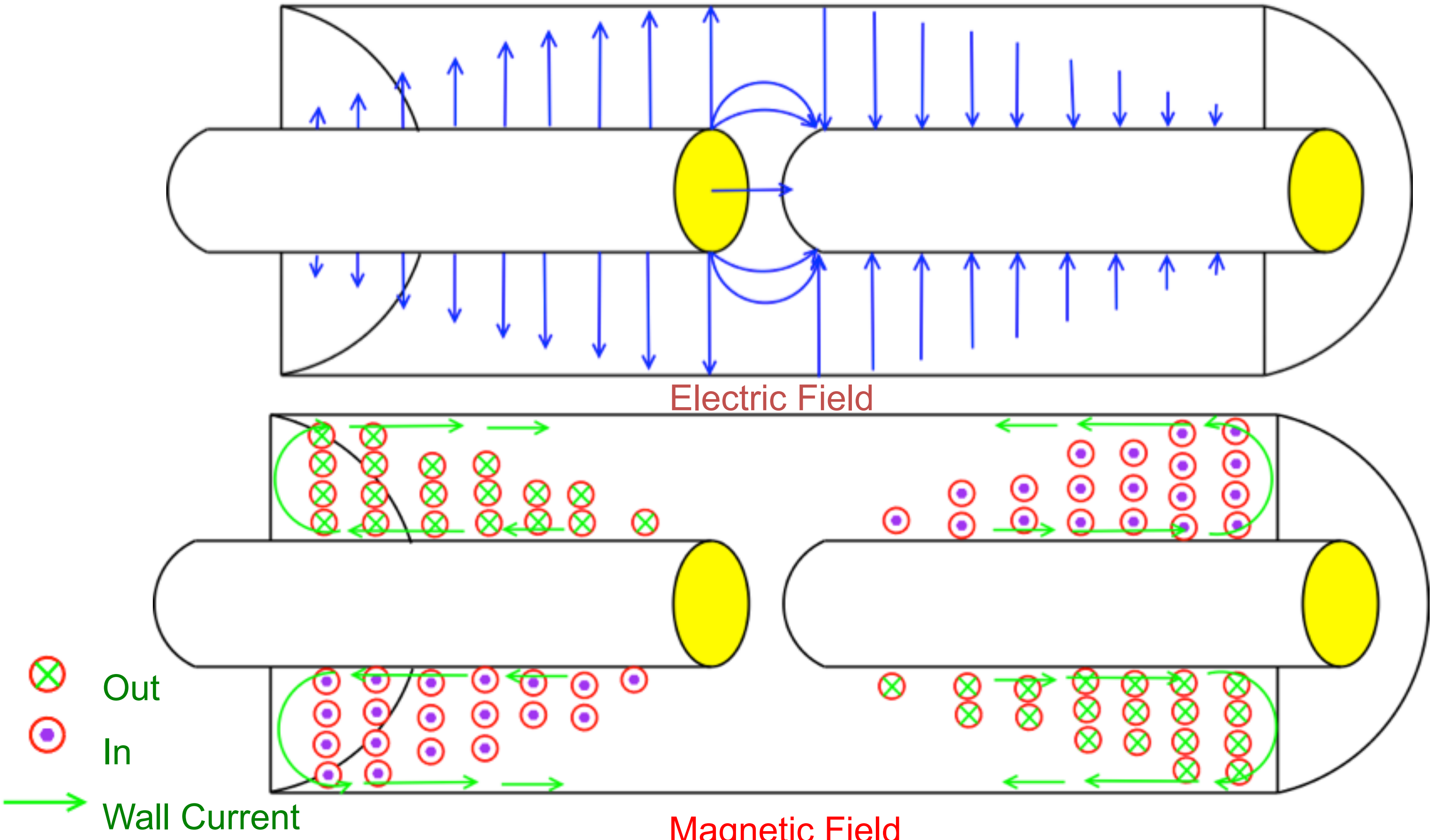
Only simple structures can be calculated analytically, such as a cylinder with no beam holes (Figure 7), referred to as the "pill-box cavity." For our purposes, the analytic calculations of a simple cylindrical cavity are convenient to define the important performance parameters of superconducting cavities. For a cylinder of length d and radius R using cylindrical co-ordinates (ρ, ϕ, z), the electric (E_z) and magnetic (H_ϕ) fields for the TM_{010} mode are given by:

$$E_z = E_0\, J_0\left(\frac{2.405\rho}{R}\right) e^{-i\omega t}, \quad H_\phi = -i\sqrt{\frac{\varepsilon_0}{\mu_0}}\, E_0\, J_1\left(\frac{2.405\rho}{R}\right) e^{-i\omega t} \qquad (1)$$

where all other field components are zero. J_0 and J_1 are Bessel functions. The angular resonant frequency is given by:

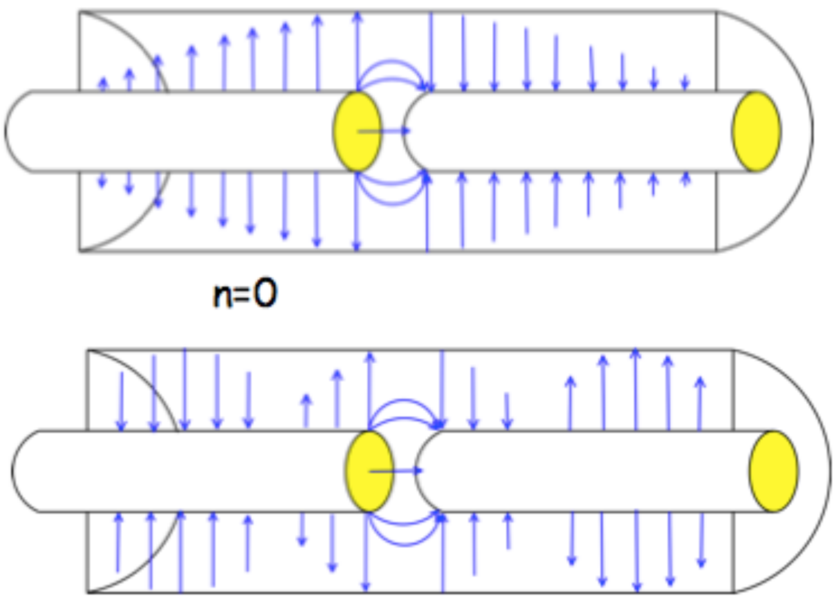
RF Cavity
Cavity Field Pattern

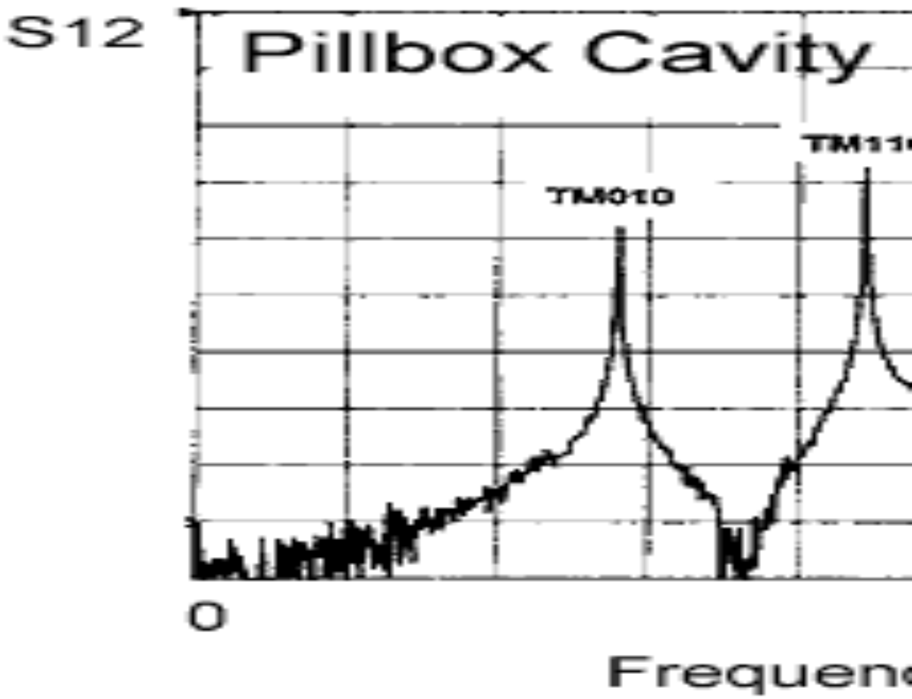
For the fundamental mode at one instant in time:



RF Cavity
Cavities Modes

Fundamental and High Order Modes (HOM)

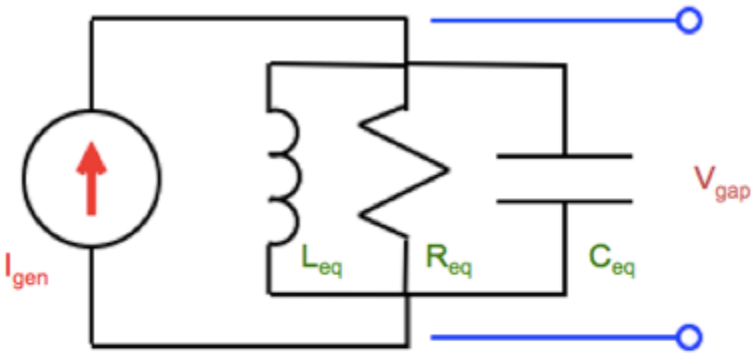




RF Cavity

RLC Model for Cavity Mode

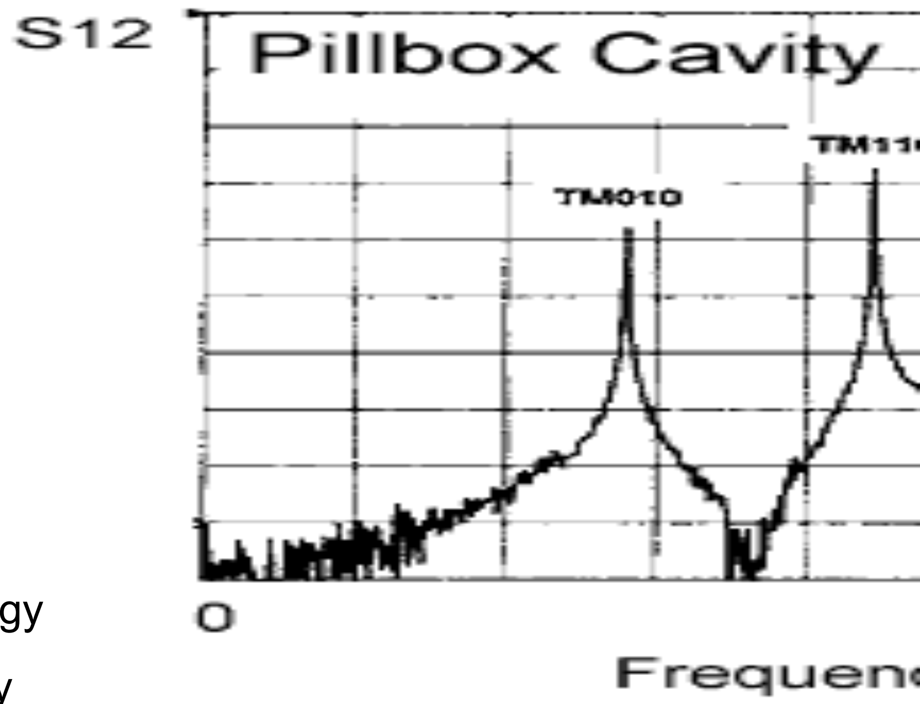
Around each mode frequency, we can describe the cavity as a simple RLC circuit.



R_{eq} is inversely proportional to the energy lost

L_{eq} is proportional to the magnetic stored energy

C_{eq} is proportional to the electric stored energy



Position:

$$\frac{1}{\omega_o} = \sqrt{L_{eq} C_{eq}}$$

Function of geometry

Amplitude:

$$Z_{eq} = R_{eq} = Q\sqrt{\frac{L_{eq}}{C_{eq}}}$$

Width

$$Q = \omega_o R_{eq} C_{eq}$$

Function of geometry and cavity material

RF Cavity

RLC Parameters for a Transmission Line Cavity

For the fundamental mode of the transmission line cavity:

$$P_{loss} = \frac{1}{2}\frac{V_{gap}^{2}}{R_{eq}}$$

$$R_{eq} = 4\frac{Z_o^{2}}{r_l L}$$

$$W_E = \frac{1}{4}C_{eq}V_{gap}^{2}$$

$$C_{eq} = \frac{\pi}{8}\frac{1}{\omega_o Z_o}$$

$$W_H = \frac{1}{4}\frac{V_{gap}^{2}}{\omega_o^{2}L_{eq}}$$

$$L_{eq} = \frac{8}{\pi}\frac{Z_o}{\omega_o}$$

The transfer impedance of the cavity is:

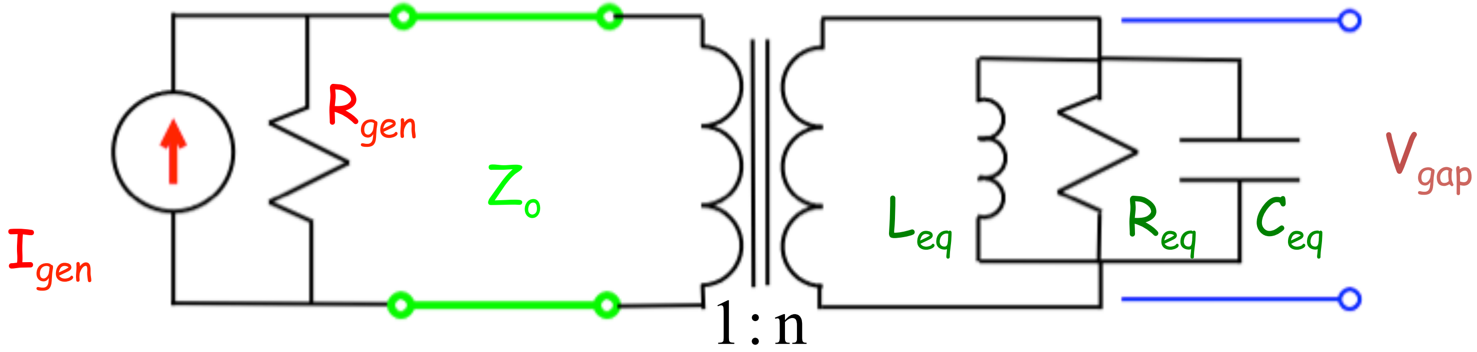
$$Z_c = \frac{V_{gap}}{I_{gen}}$$

$$\frac{1}{Z_c} = \frac{1}{R_{eq}} + \frac{1}{j\omega L_{eq}} + j\omega C_{eq}$$

RF Accelerator

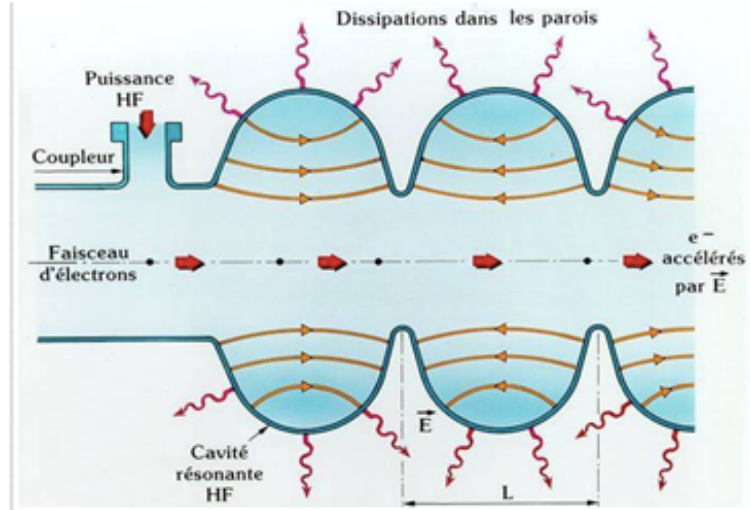
- The cavity is attached to the power amplifier by a transmission line.
- The internal impedance of the power amplifier is usually matched to the transmission line impedance connecting the power amplifier to the cavity.
  - As in the case of a Klystron protected by an isolator
  - As in the case of an infinitesimally short transmission line

$$R_{gen} = Z_o$$



SRF Cavities Performances

- Accelerating gradient
- Peak Surface fields
- Power Dissipation
- Cavity Quality
- Shunt Impedance

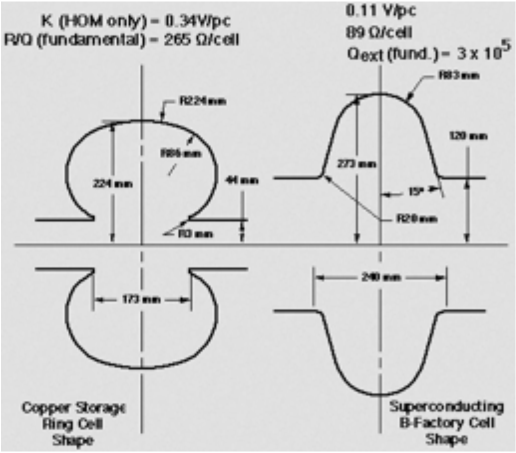


Few limitations of performance:

- Thermal Breakdown, alias quench
- Field Emission: Electron induced by an electrostatic field
- Multipacting: electron avalanche

Limit power loss in the cavity wall:

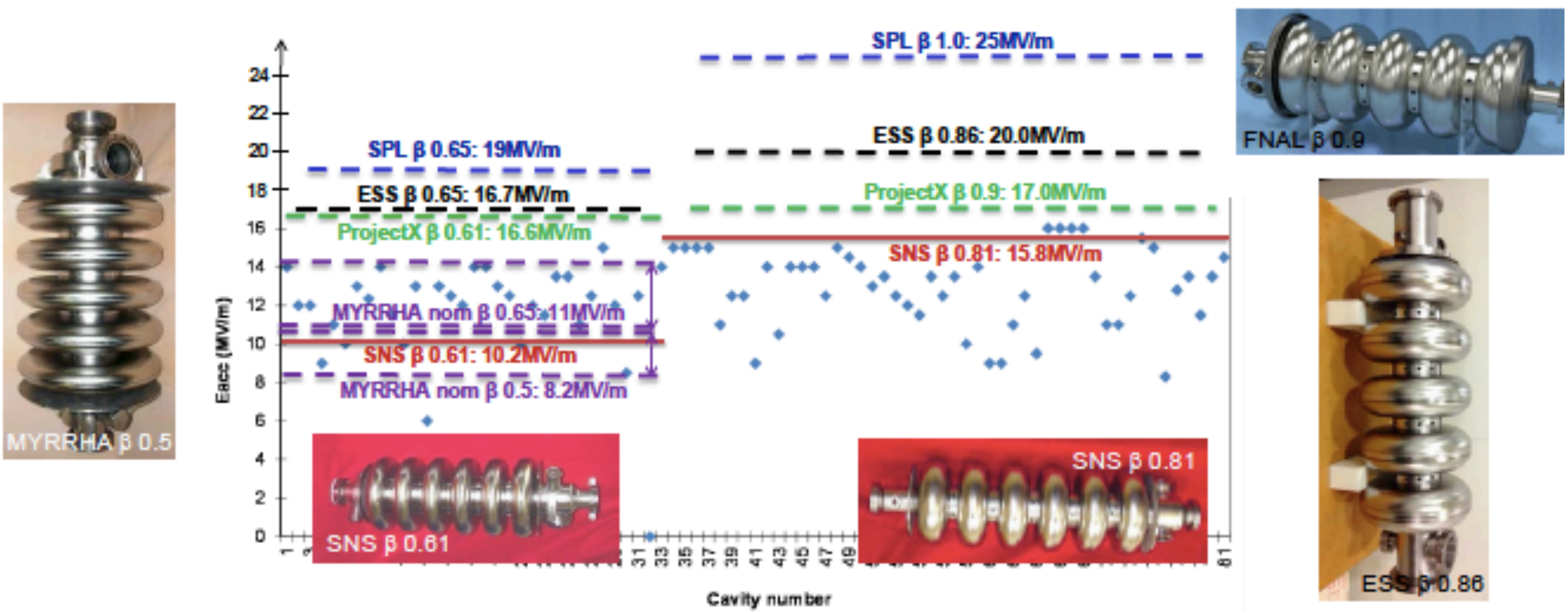
- By using low-resistant material or superconductors
- By rounding the shape to optimize the field distribution
- Limit shape edge to prevent field emission
- Good vacuum to limit breakdown



Cavity gradients

- Cavity gradient is directly related to cost -> tendency to push the gradients
- SNS experiences a huge gradient variability -> needs for margins & operational flexibility !!
  - ✓ Almost every SNS run, a few cavities have problems, resulting in lower E_{acc} or turn-off -> linac retuning
  - ✓ Achievable gradients are mainly limited by heating by electron activity at high duty factor (especially by induced collective limits)

Ex. CM13 individual limits; 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits; 14.5, 15, 15, 10.5 MV/m



Cavity Q

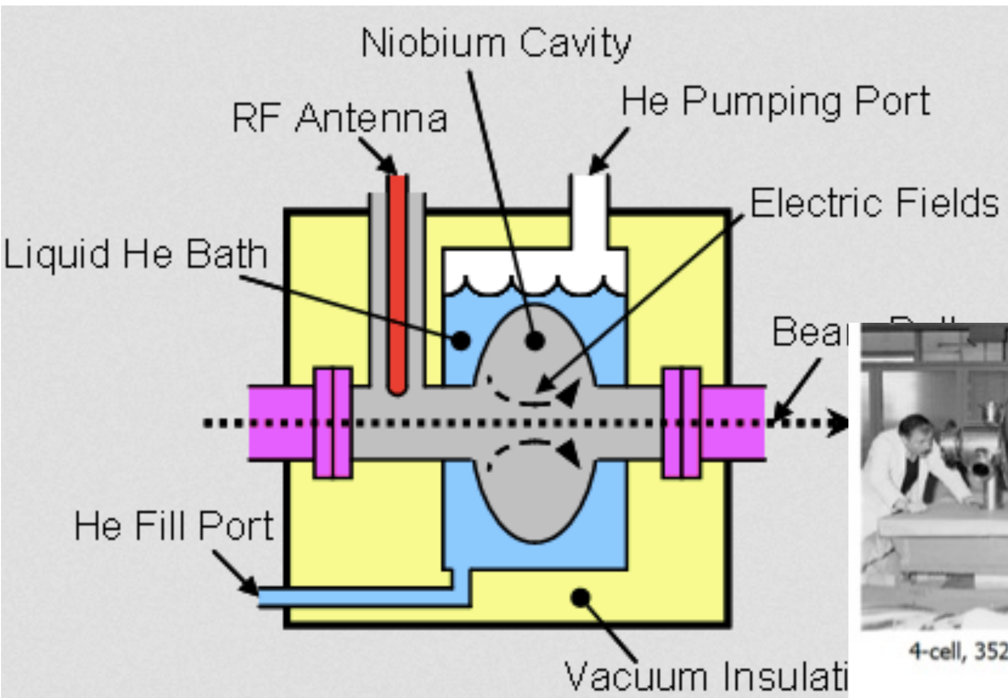
- If the cavity walls are lossless, then the boundary conditions for a given mode can only be satisfied at a single frequency.
- If the cavity walls have some loss, then the boundary conditions can be satisfied over a range of frequencies.
- The cavity Q factor is a convenient way the power lost in a cavity.
- The Q factor is defined as:

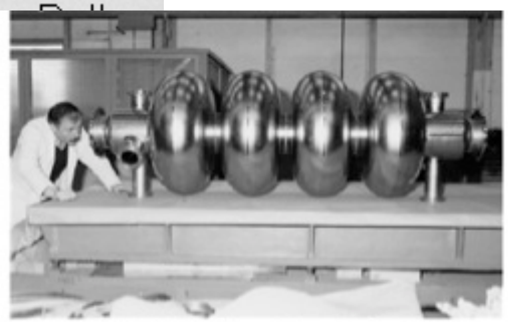
$$Q = \frac{W_{stored}}{W_{lost\,/\,cycle}}$$

$$= \omega_o \frac{W_E + W_H}{P_L}$$

Cavities and Cryomodules

RF cavities housed in cryomodules, which keep the RF cavities working in a superconducting state, without losing energy to electrical resistance





4-cell, 352 MHz Nb on Cu cavity for LEP2

400 MHz Nb on Cu cavities in LHC tunnel

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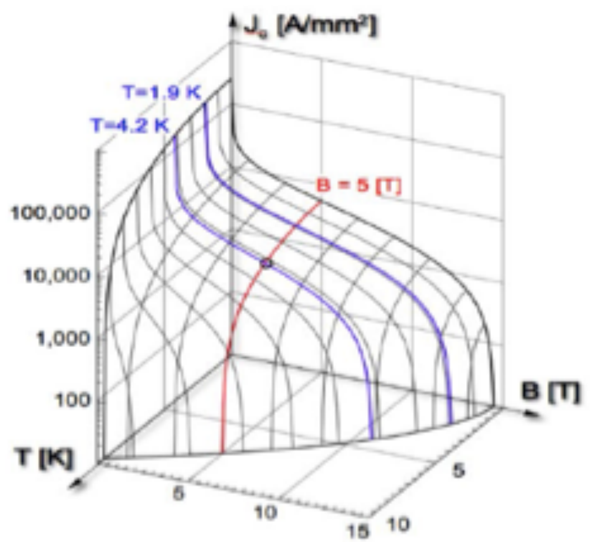
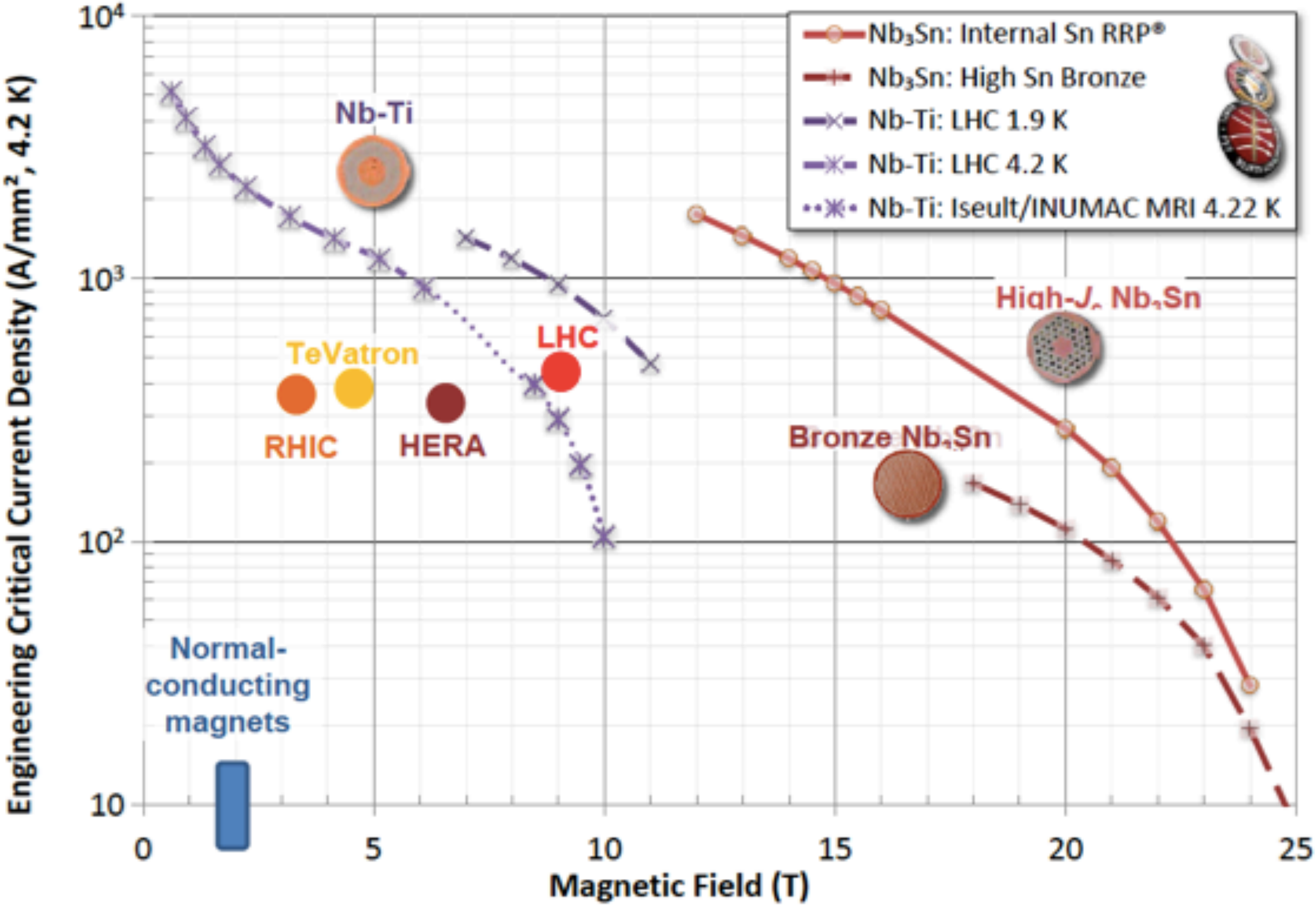
Superconductivity and Superfluidity

- Superconductivity became a key-technology for particle accelerator. Superconductivity allows :
  - To operate high-field, high current density magnet operating above the saturation of iron,
  - To build high-field, low-loss RF Cavities (low wall resistance)
  - Reducing overall electrical consumption of the machines



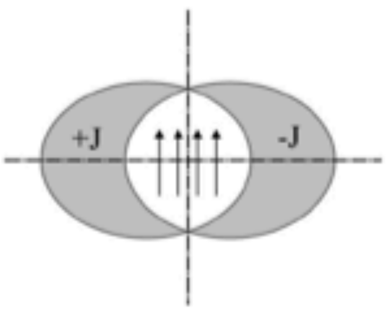
- The superconducting state only occurs in a limited domain of (low) temperature, magnetic field and current density, limited by the «critical surface» of the material
- Superconducting magnets produce high field with high current density
- The working point must remain below the «critical surface» of the superconductor
- Operating at lower temperature increases the working range in the magnet design plane (J_c,B)

Superconductivity and Superfluidity

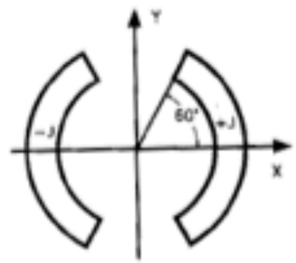


Superconducting Magnets

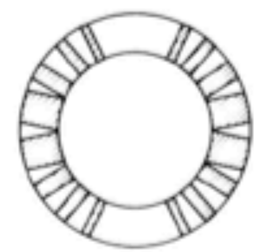
- In a superconducting magnet, the field is given by the current distribution in the windings (Biot & Savart's law).
- When present, the iron only acts as a flux return yoke



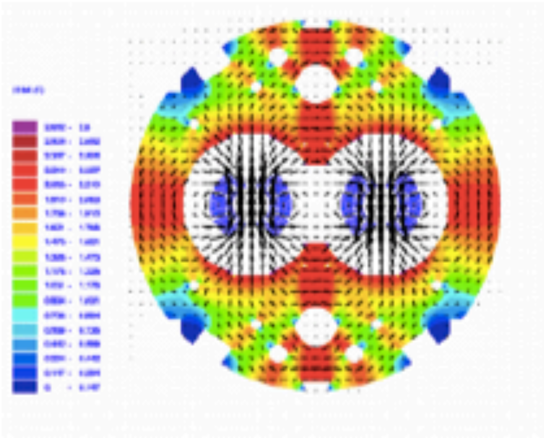
Intersecting ellipses

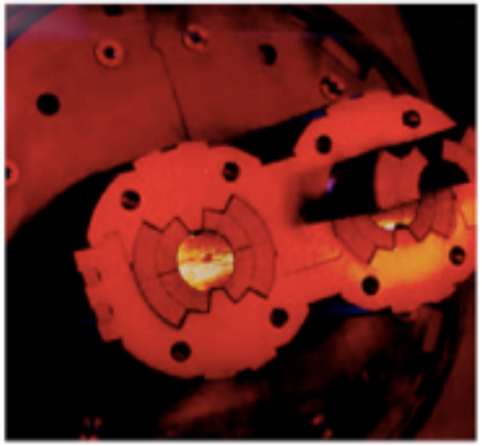


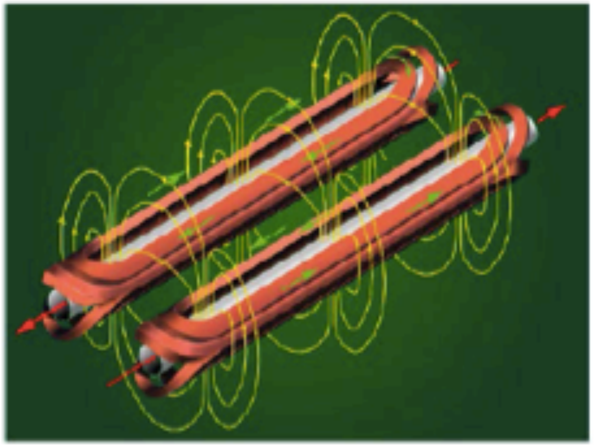
"cos θ"



« block » approximation







Superfluidity of Helium

Helium (25 %) is the most common element in Universe after Hydrogen (73 %)

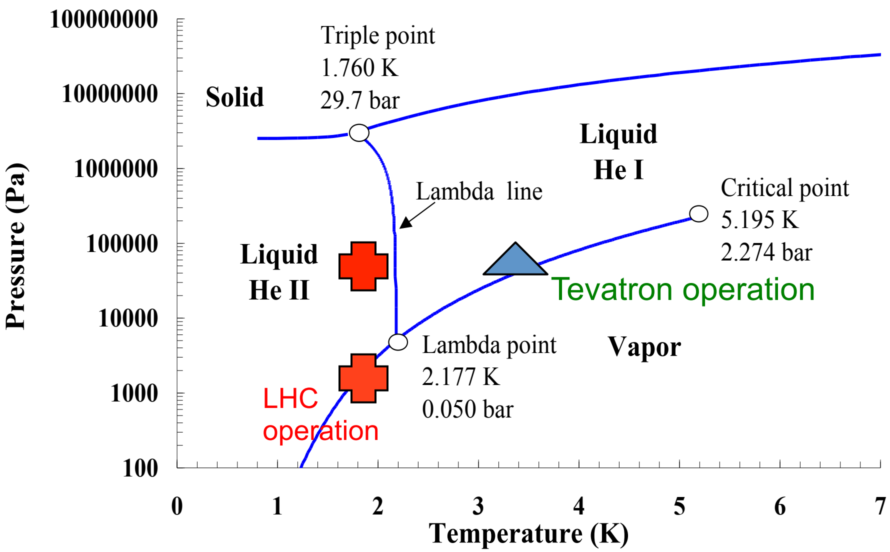
Two isotopes: ^{3}He (fermion) & ^{4}He (boson)

Helium II - Quantum fluid

Exceptional heat transfer

- Specific heat transition at 2.17 K - T_λ

- Enormous heat conductivity at moderate flux (3,000 x OFHC copper at 1.9K)



-> Thermo-mechanical - fountain effect

Superfluidity of Helium
The two-fluid model for helium II

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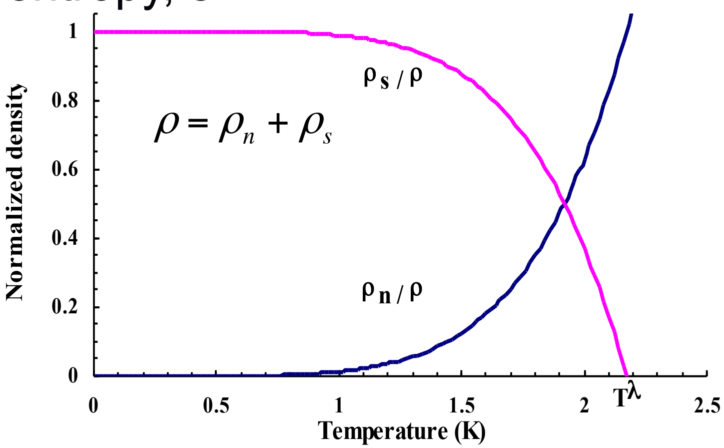
Normal-fluid fraction:
- excited states atom (phonons & rotons)

➔ like a conventional viscous fluid
- finite density , r_n
- finite viscosity, η
- entropy, *s*



Macroscopic quantum physic system simplification
The two-fluid model is only a phenomenological model !

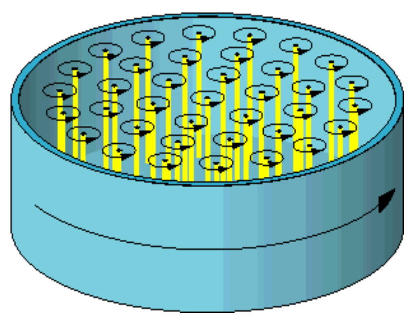
Superfluid fraction:
- atoms that have undergone BEC

➔ like an ideal inviscid liquid resulting in the absence of classical turbulence.
- finite density, r_s
- NO viscosity
- carry NO entropy

→ irrotational behavior for an inviscid fluid

$$\nabla \times \mathbf{v}_s = 0$$

→ but vortices can be generated in the superfluid component



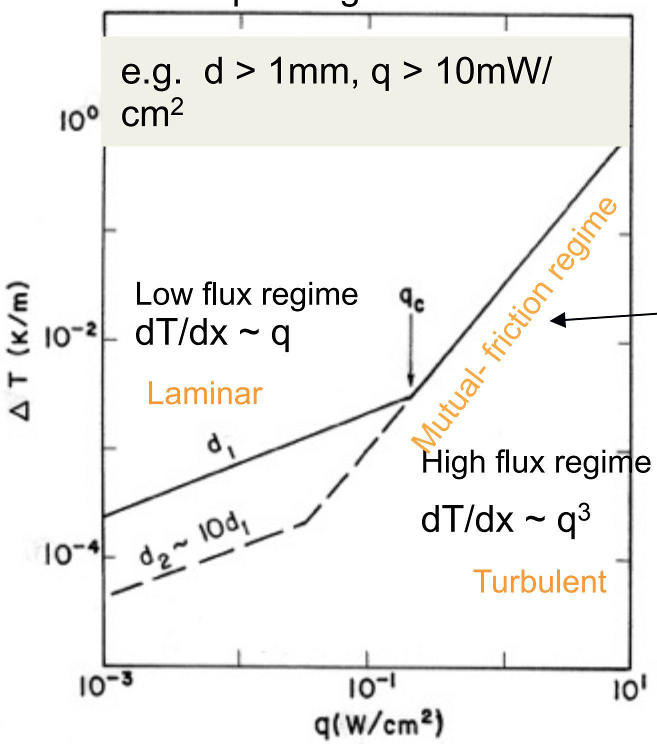
Quantized vortices

$$\Gamma_s = \oint v_s \cdot dr = n\kappa = n\frac{h}{m}$$

Counter-flow turbulence

Thermal conductivity of helium II

Heat transport regimes at 1.9 K



$$\nabla T = \frac{\beta \eta_n}{d^2 (\rho s)^2 T} q - \frac{A_{GM} \rho_n}{\rho_s^3 s^4 T^3} q^3$$

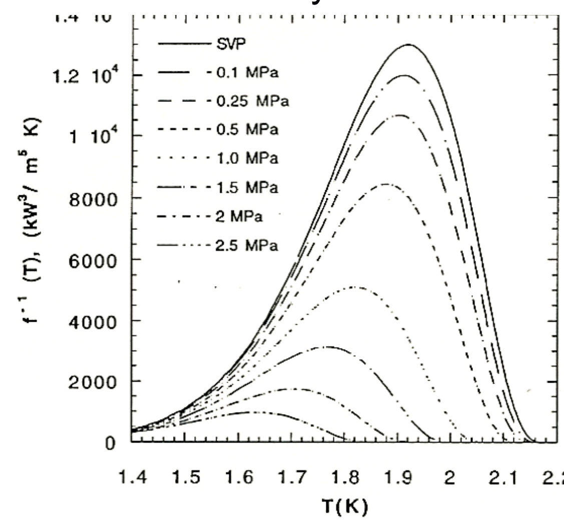
In mutual friction regime:

$$\dot{q} = -\left[f^{-1}(T) \frac{dT}{dx} \right]^{1/3}$$

$$f(T) = \frac{A_{GM} \cdot \rho_n}{\rho_s^3 \cdot s^4 T^3}$$

A_{GM} Gorter-Mellink mutual friction parameter

Thermal resistivity function

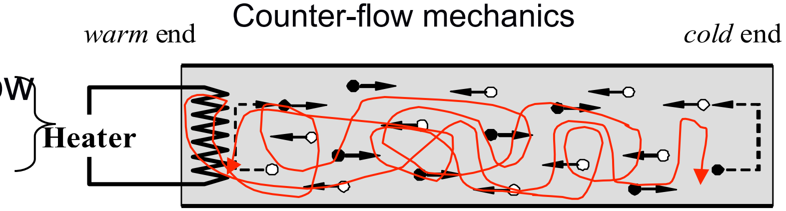


Internal convection of the super-fluid and normal-fluid components

$$\nabla T = \frac{\beta \eta_n}{d^2 \rho s} |v_n| + \frac{A_{GM} \rho_n}{s} |v_s - v_n|^3$$

No bulk flow
Heat flux

Counter-flow mechanics



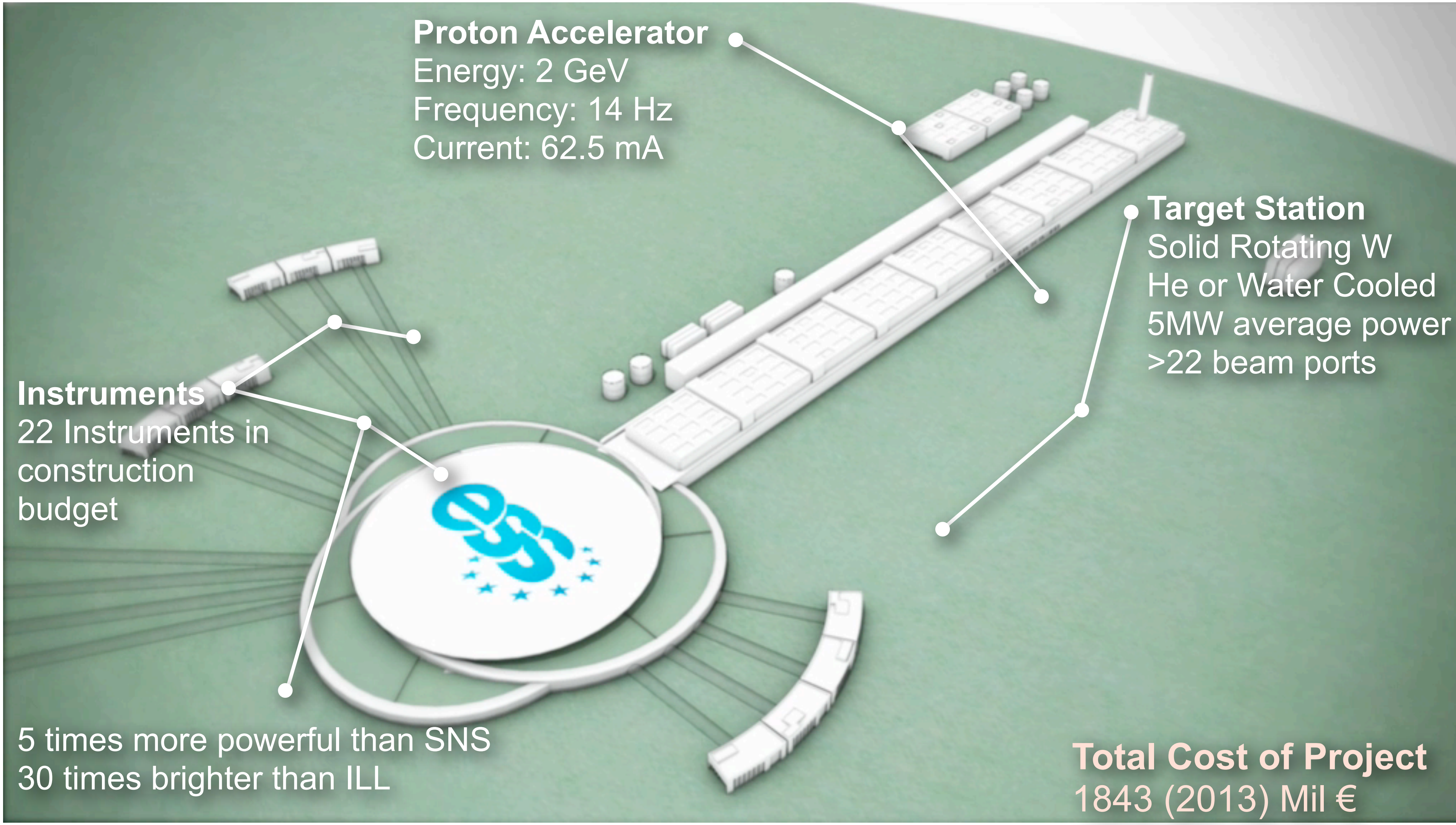
- ● **normal-fluid component**
- ○ **super-fluid component**

Outline

- Types of Particle Accelerators
- Accelerator Characteristics
- RF Cavity
- Superconductivity and Superfluidity
- Examples of the Particle Accelerators:
  - The European Spallation Source (SRF cavities R&D)
  - The LHC (low-beta magnets environment and Controls)
  - The Tevatron (accelerator complex and technologies)

The European Spallation Source

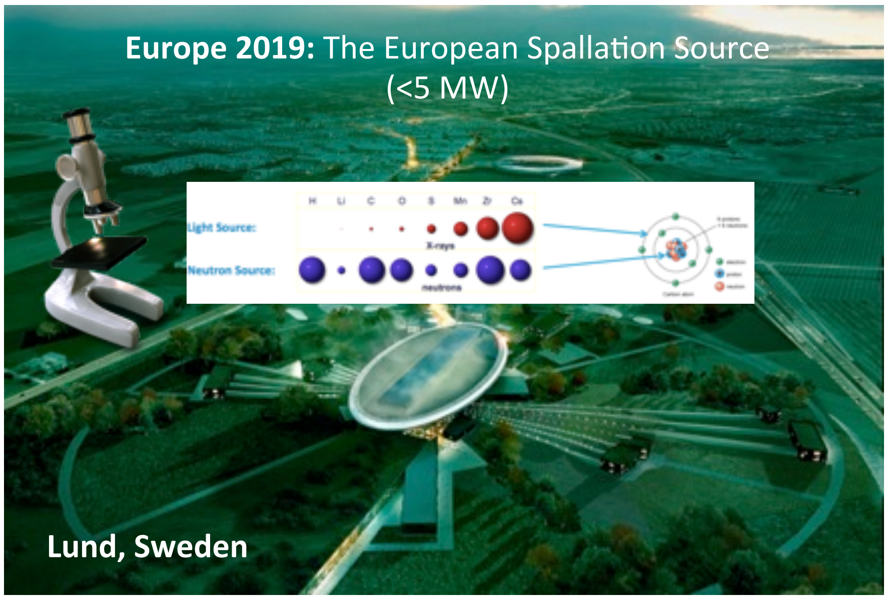
EUROPEAN SPALLATION SOURCE

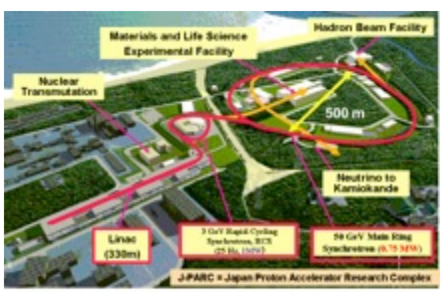


The European Spallation Source

EUROPEAN SPALLATION SOURCE

Philosophie de “Pré-vert”: Greenfield



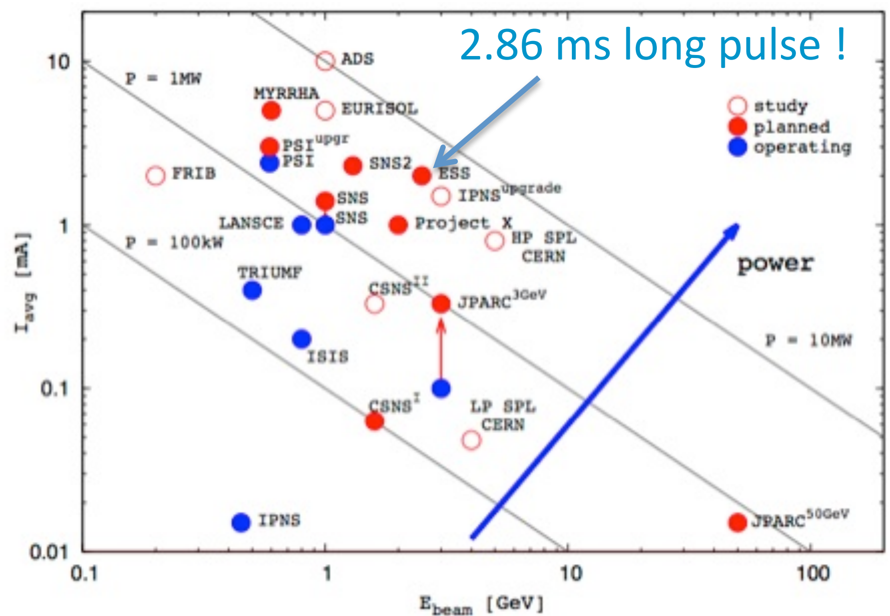


Japan 2008:
JPARC (<1MW)

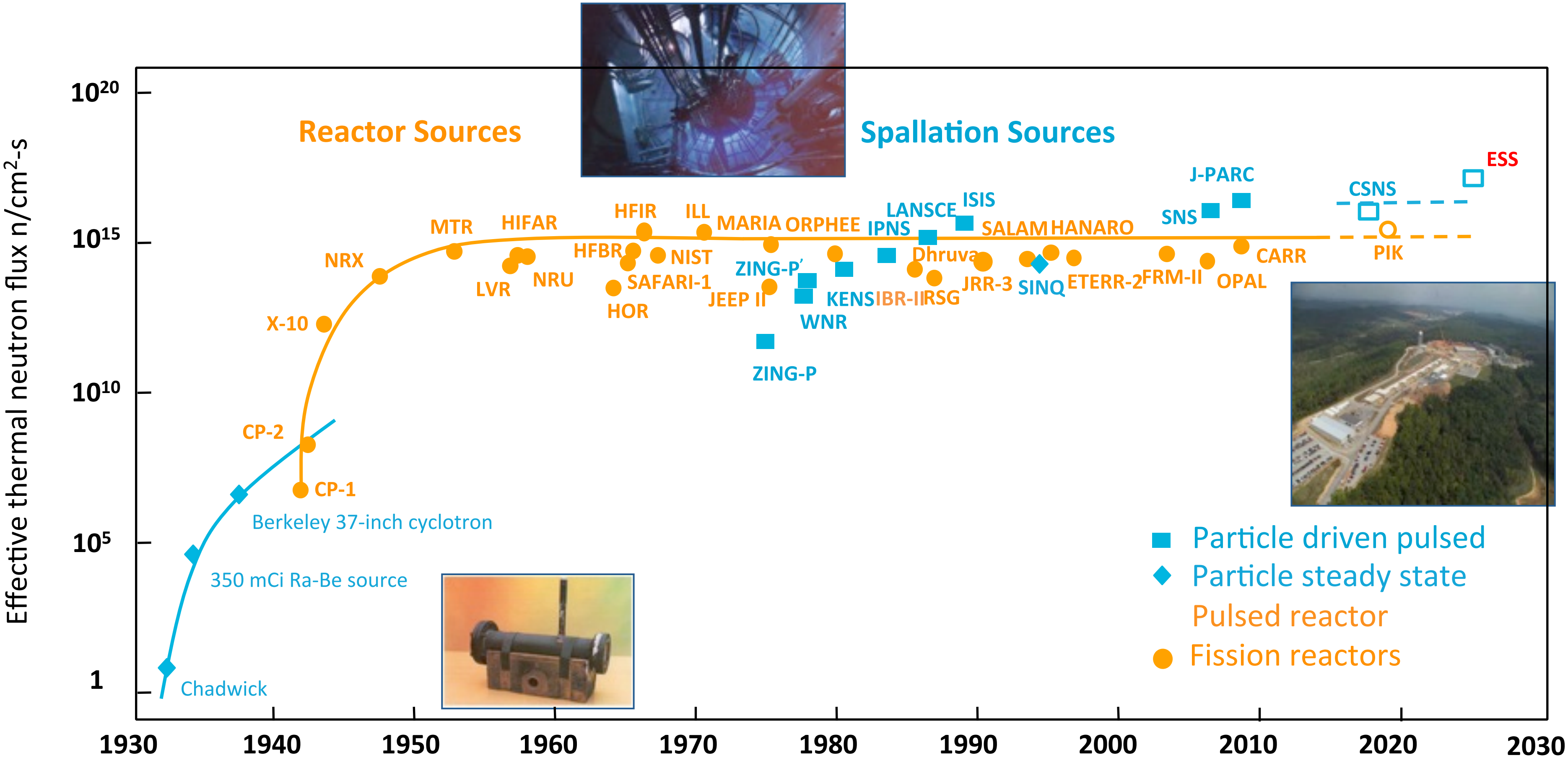
USA 2006:
SNS (<1.4 MW)
1 GeV, 26 mA in linac, 627 ns long pulse, 60 Hz

- Will bring new insights to the grand challenges of science and innovation
- Collaborative project: more than 17 countries
- 2014: Start of construction phase of the world's most powerful linear proton accelerator
- 2019: Provide the world's most advanced tools for studying materials with neutrons

(~ 450 employees; > 2500 users / year)

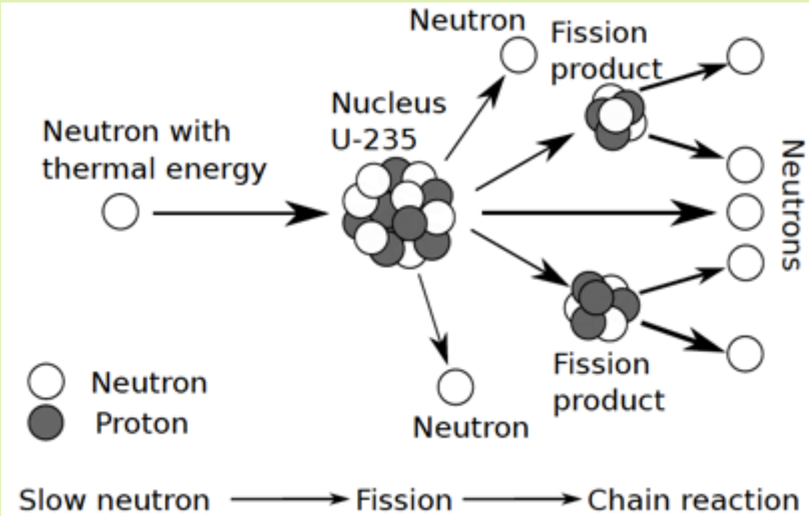


High time average and peak flux



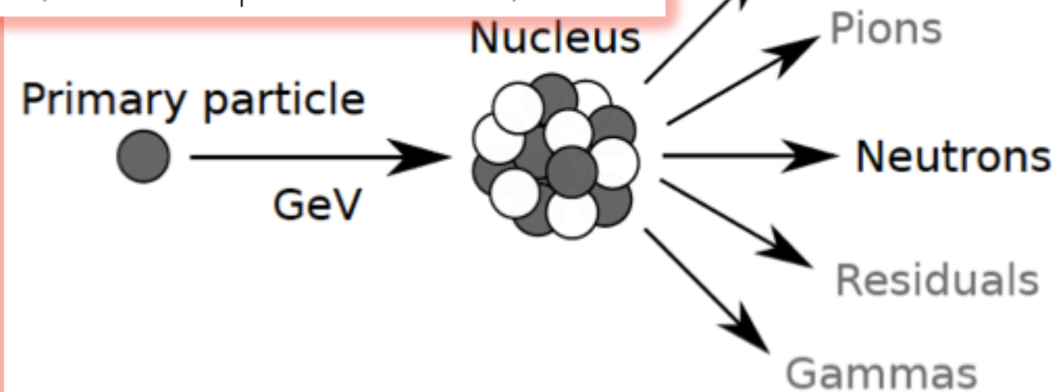
(Updated from *Neutron Scattering*, K. Skold and D. L. Price, eds., Academic Press, 1986)

Fission and Spallation



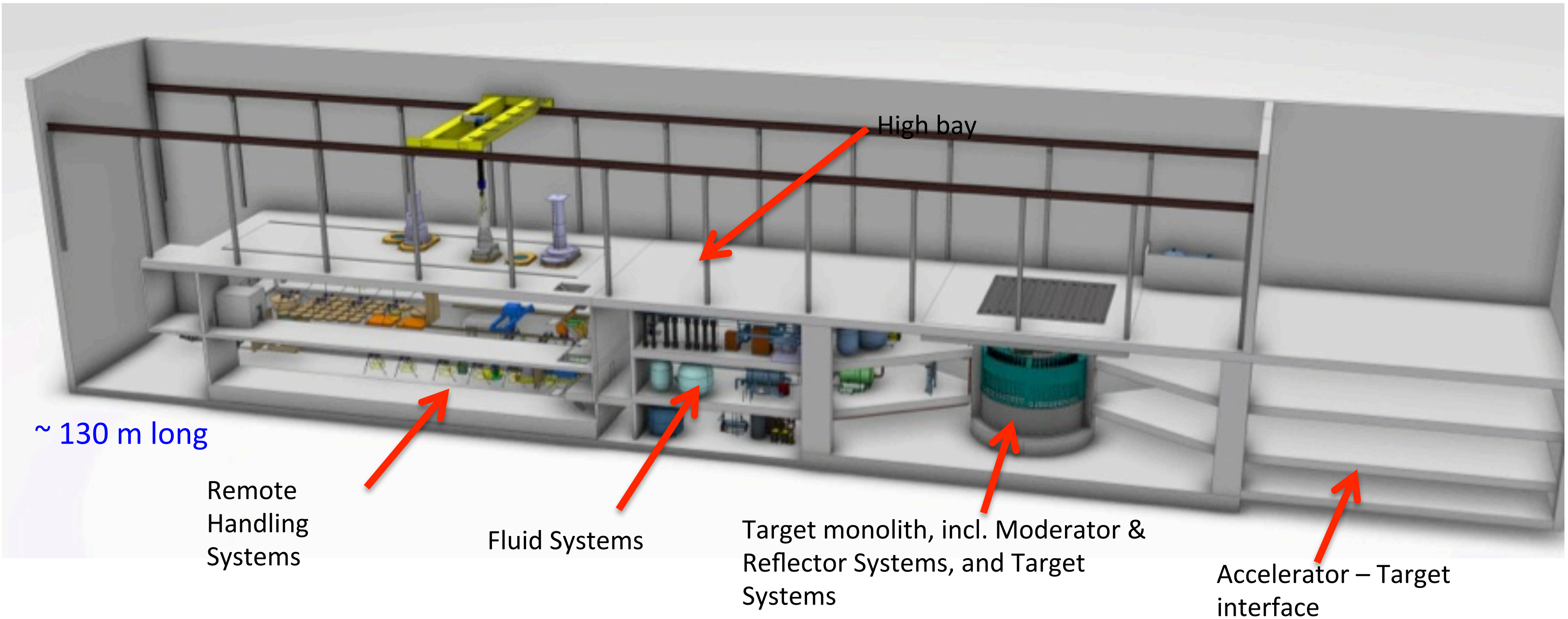
Spallation is a non-elastic nuclear interaction induced by a high-energy particle producing numerous secondary particles

Process	Reaction	Neutron yield	Energy deposition
Fission	$^{235}U(n,f)$	3 n/fission	190 MeV/n
Spallation	p 1 GeV $\rightarrow$ Hg	30 n/proton	55 MeV/n



Target Station includes systems that address nuclear hazards

Spain was one of the first countries to send a Letter of Intent committing to the construction of the European Spallation Source, and a close collaboration has followed. In November 2014, ESS-Bilbao was chosen as the in-kind partner for the ESS target system

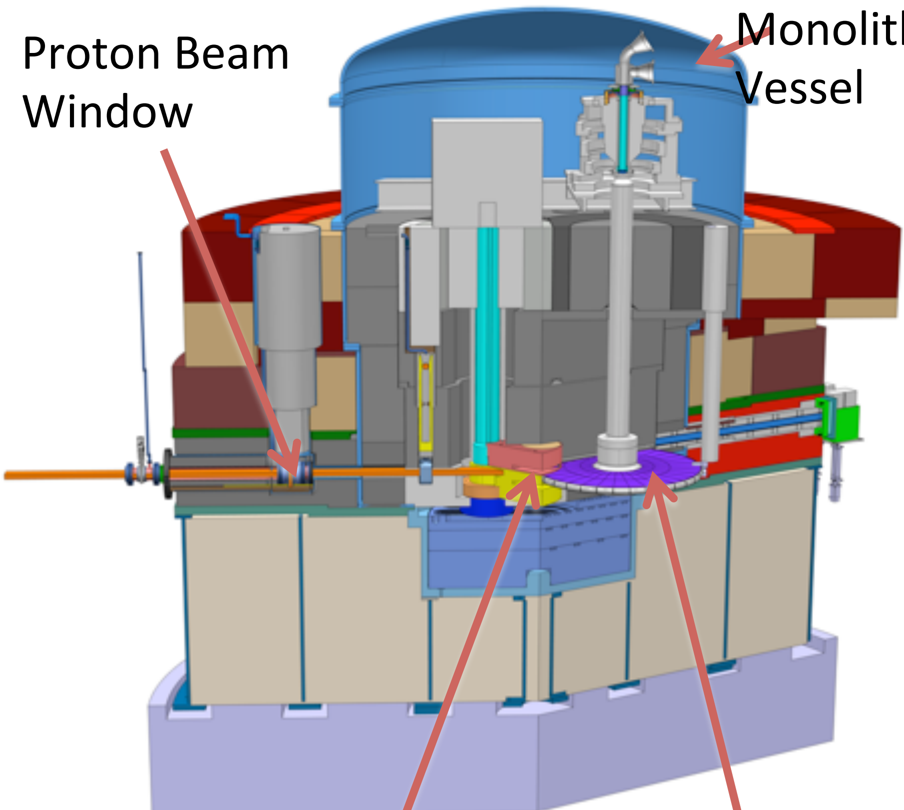


- Remote Handling Systems including hot cells and associated equipment for maintenance and storage of irradiated components
- Target Safety System including credited controls to protect public and environment from radioactive hazard
- Fluid Systems including He and H_2O coolant loops, ventilation, filtering, etc.

Target station converts protons to “slow” neutrons

- Diameter ~ 11 m; Height ~ 8 m
- Mass ~ 7000 tonnes (mainly steel)

Target Monolith



The tungsten wheel concept:

The target wheel will measure 2.5 meters in diameter, is estimated to weight 4 tonnes, and is divided into 36 radial sectors

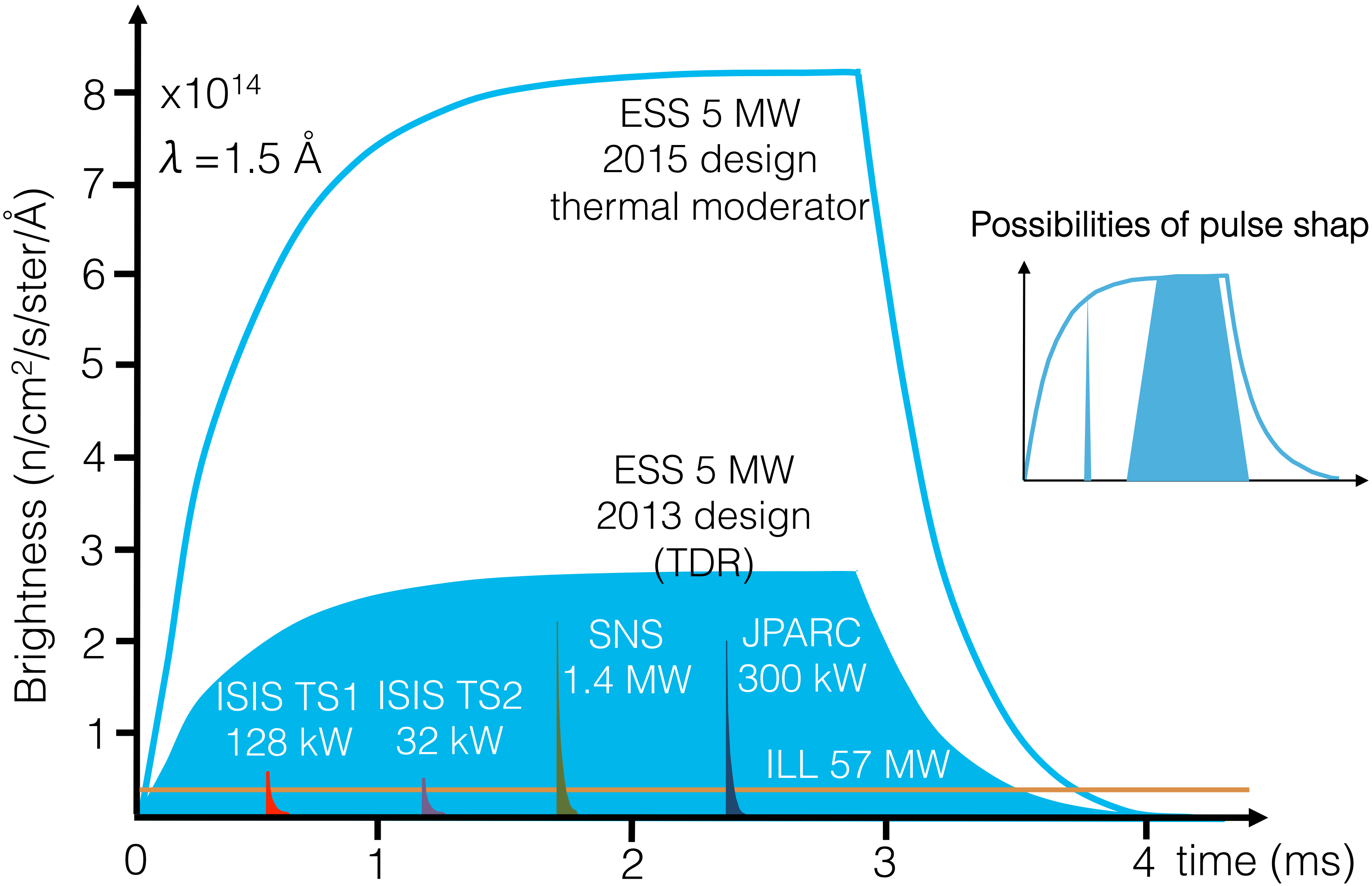
<u>Functions</u>:

- Convert protons to usable neutrons
- Heat removal
- Confinement and shielding

<u>Unique features</u>:

- Rotating target
- He-cooled W target
- High brightness moderators

ESS long pulse potential



Accelerator Technical performances

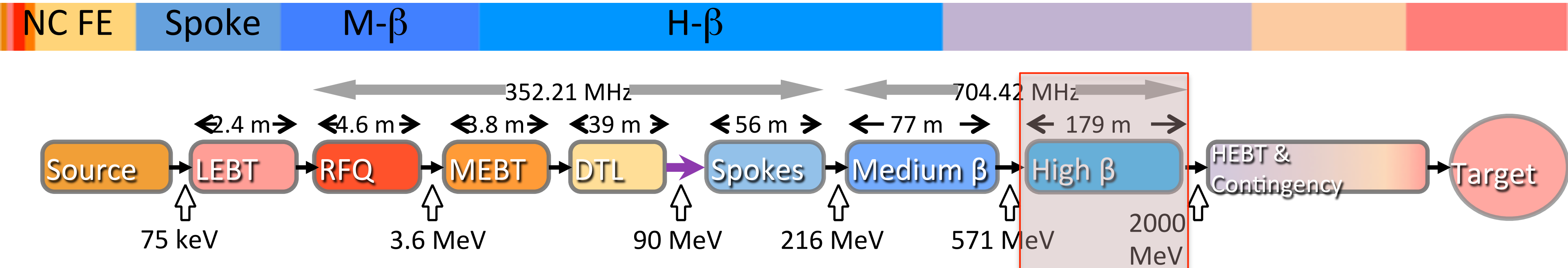
Design Drivers:

High Average Beam Power
5 MW

High Peak Beam Power
125 MW

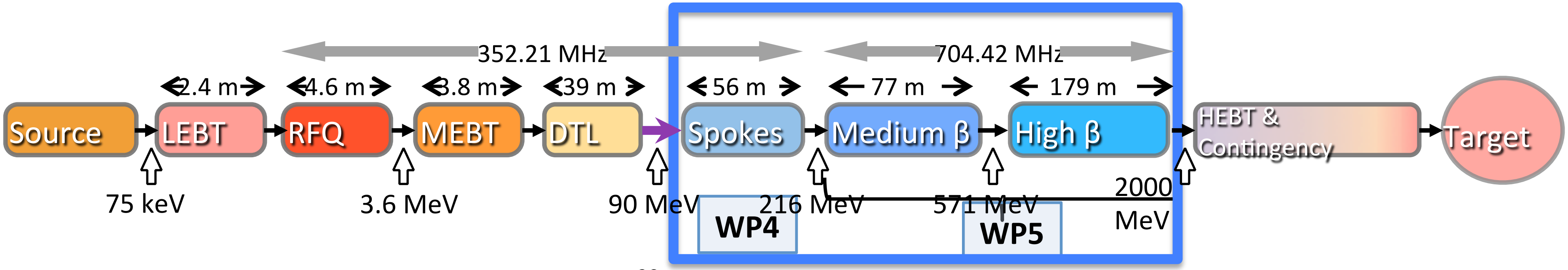
High Availability
> 95%

Key parameters:
- -2.86 ms pulses
- -2 GeV
- -62.5 mA peak
- -14 Hz
- -Protons (H+)
- -Low losses
- -Minimize energy use
- -Flexible design for mitigation & future upgrades

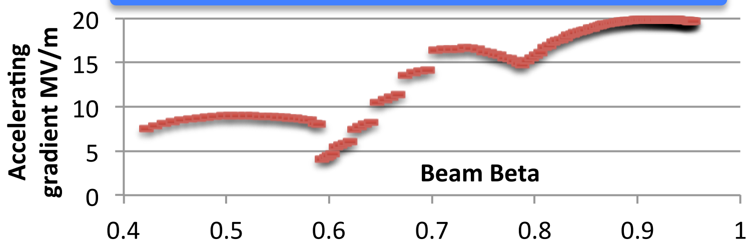


- The **scope contingency** for the accelerator project consists of the RF sources and installation costs (after 2019) for the high beta-part of the linac
- The **fully equipped cryomodule for the high-beta** linac are IK contributions and are **not part of the scope contingency**. The infrastructures needed for the construction of these are only available during ESS construction.

Linac redesign to meet ESS cost objective



Beam power (MW)	5
Beam current (mA)	62.5
Linac energy (GeV)	2
Beam pulse length (ms)	2.86
Repetition rate (Hz)	14



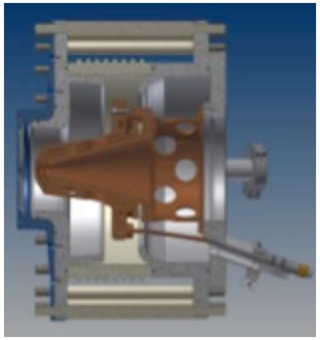
	Num. of CMs	Num. of cavities
Spoke	13	26
Medium β (6-cell)	9	36
High β (5-cell)	21	84

Style	Spoke	Medium-β	High-β
Freq. (MHz)	352.21	704.42	704.42
Cavity #	26	36	84
Velocity range	0.42 to 0.58	0.58 to 0.78	0.78 to 0.95
Nom. Acc. Voltage (MV)	5.74	14.3	18.2
Loaded quality factor	2.85×10^5	8×10^5	7.6×10^5

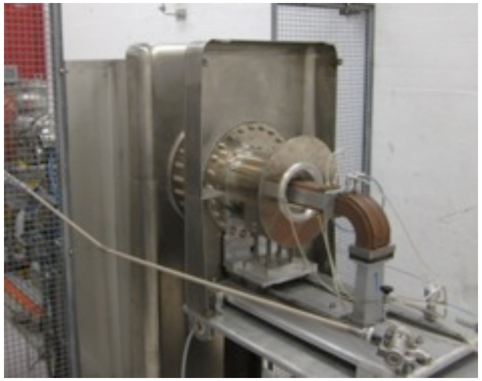
[SRF2013 – "The ESS Superconducting Linear Accelerator", C. Darve, M. Eshraqi, M. Lindroos, D. McGinnis, S. Molloy, P. Bosland and S. Bousson]

Front End Section

- Ion Source
  - Microwave Discharge Ion Source
  - Proton peak current ~75 mA
  - Total drain current ~100 mA
  - Output Energy 75 keV
  - Provided by INFN-LNS, Catania
  - Experience from TRIPS ion sources



Extraction system of the ESS ion source (Courtesy L. Celona)



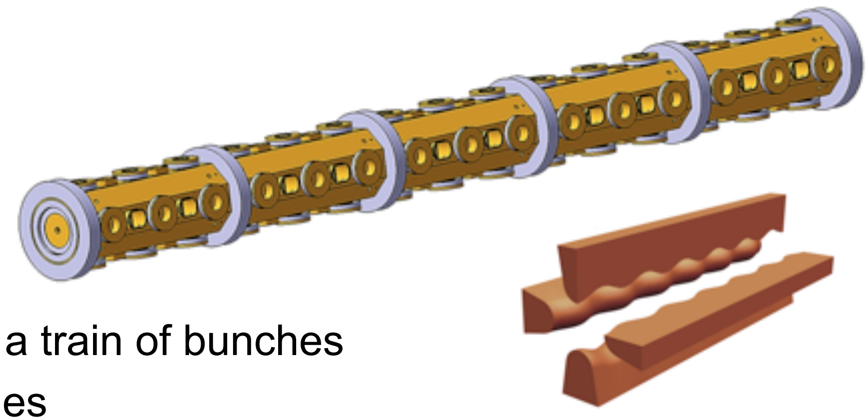
Prototype proton source operational, and under further development, in Catania. Output energy 75 keV.

- LEBT (Low Energy Beam Transport)
  - Dual solenoid layout
  - Functions:
    - Transport and match input the RFQ
    - Clean the beam pulse from the rise/fall time of the source with a slow chopper
    - Provide different level of beam current with an iris
  - Provided by INFN-LNS, Catania
  - Design close to the IFMIF LEBT

IFMIF source and LEBT at CEA-Saclay

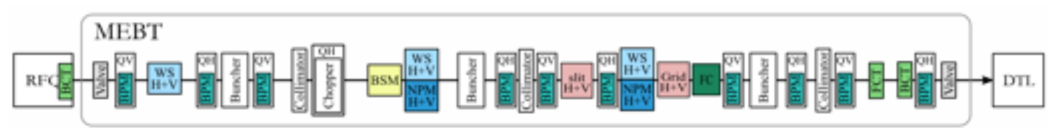
Front End Section

- RFQ
  - 352 MHz 4-vanes RFQ
  - 5 segments of ~90 cm
  - Functions:
    - Accelerates
    - Bunches the pulse in a train of bunches
    - Focuses in the 3 planes
    - Provide different level of beam current with an iris
  - Foreseen transmission > 90 % for 70 mA input beam
  - Provided by CEA-Saclay



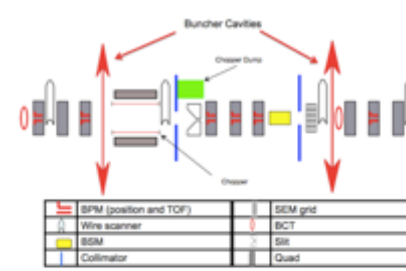
Design exists for ESS RFQ similar to 5 m long IPHI RFQ at Saclay. Energy 75 keV–>3.6 MeV.

- MEBT
  - Fully instrumented MEBT ~ 4.5 m
  - Functions:
    - Transport and match into the DTL
    - Characterize the beam
    - Fast chopping of the beam with rise/fall time ~ 10 ns
  - Provided by ESS-Bilbao



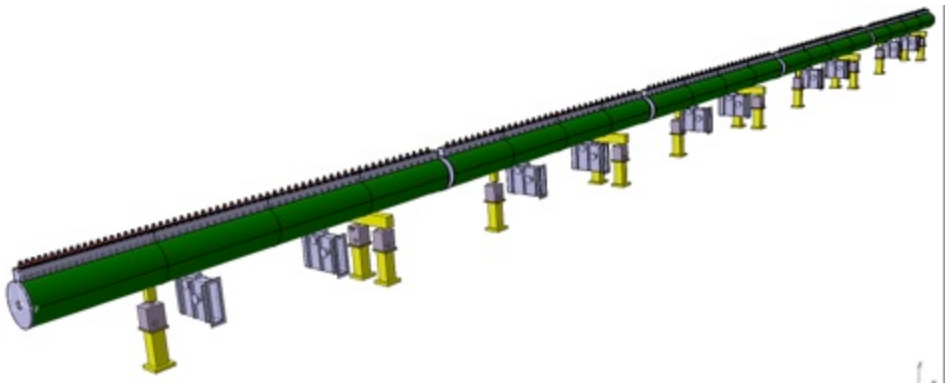
MEBT layout (Courtesy B. Cheymol)

Design work at ESS Bilbao for MEBT with instrumentation, chopping and collimation.

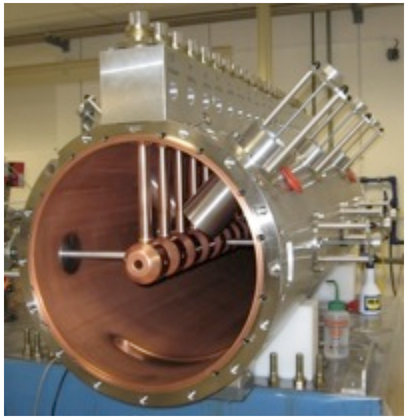


Front End Section

- DTL (Drift Tube Linac)
  - 352 MHz
  - 5 tanks
  - Length ~ 40 m
  - Output energy: ~90 MeV
  - Provided by INFN-LNL, Legnaro



DTL 3D view (Courtesy P. Mereu)



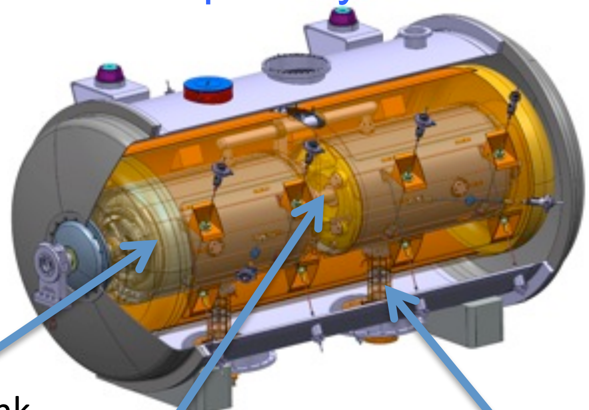
DTL design work at ESS and in Legnaro, 3.6 ->90 MeV.

Picture from CERN Linac4 DTL.

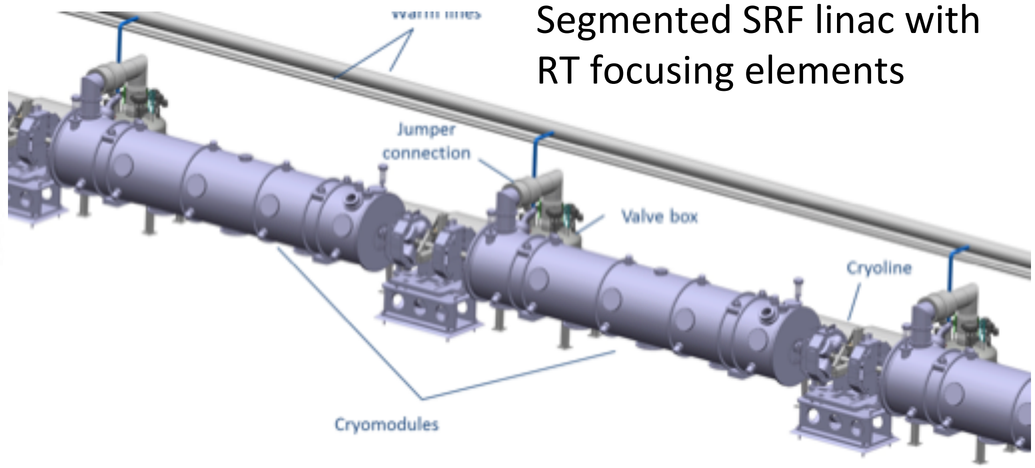
- Six klystrons
  - 352 MHz
  - with a maximum saturated power of 2.8 MW
  - and a duty factor of 4% are required for the Front End

Super-Conducting Linac

2 Spoke Cavities per Cryomodule



Segmented SRF linac with RT focusing elements

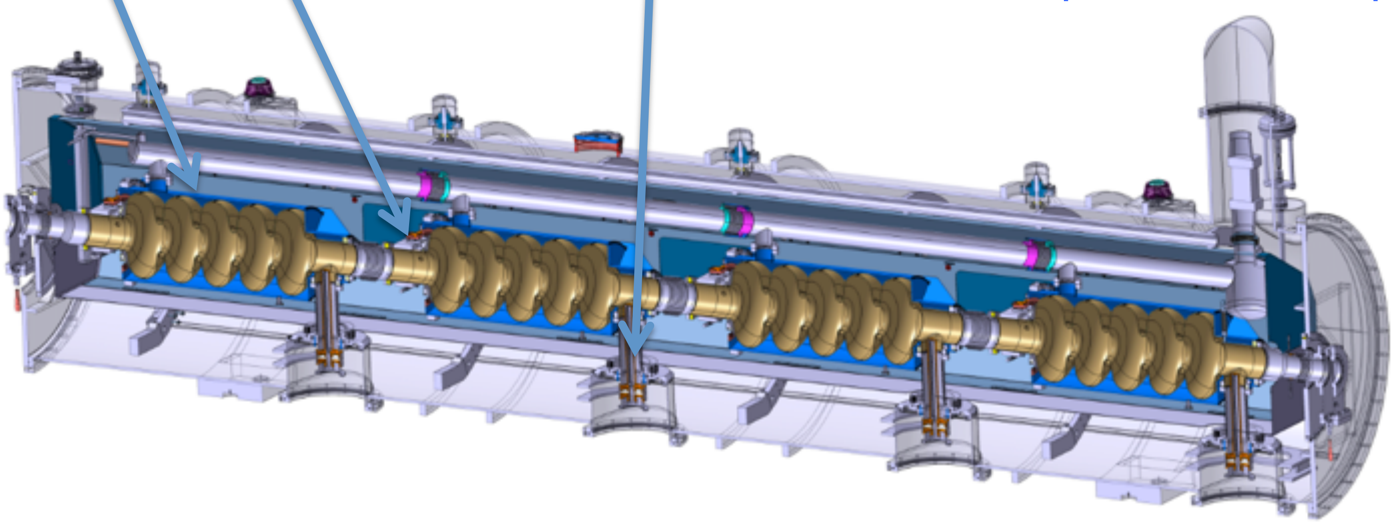


Ti. Helium tank

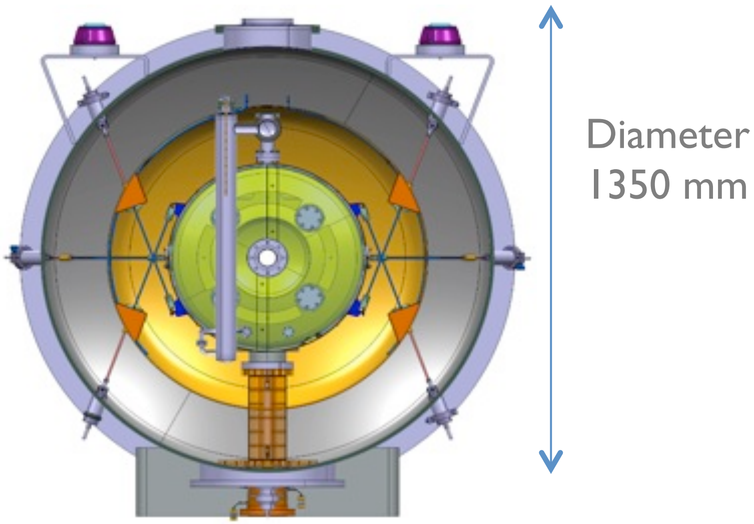
Cold tuning System

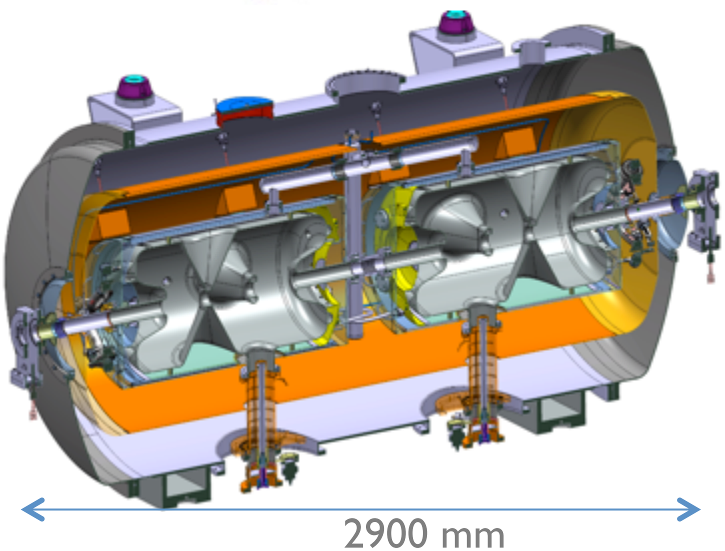
Power coupler

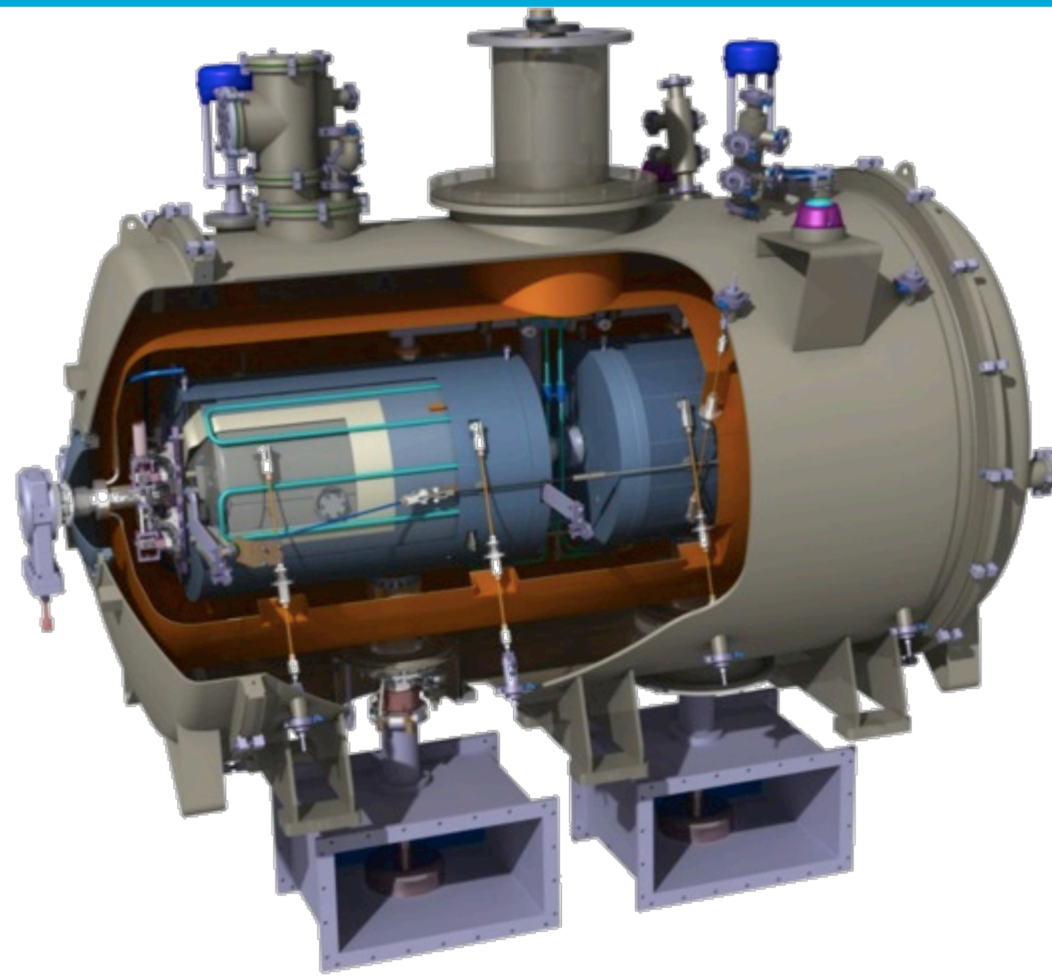
4 Elliptical Cavities per Cryomodule



Spoke cavity string and cryomodule package

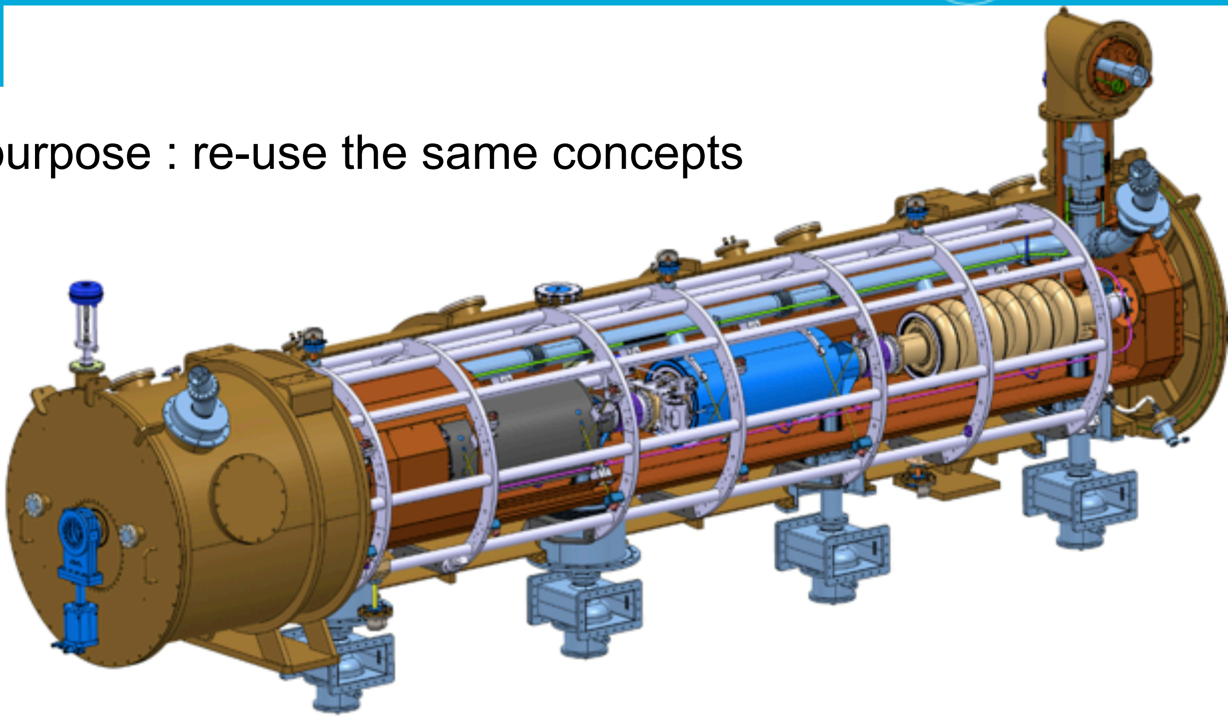






Cavity Cryomodule - Generic

➢ Similar to SNS in size and purpose : re-use the same concepts



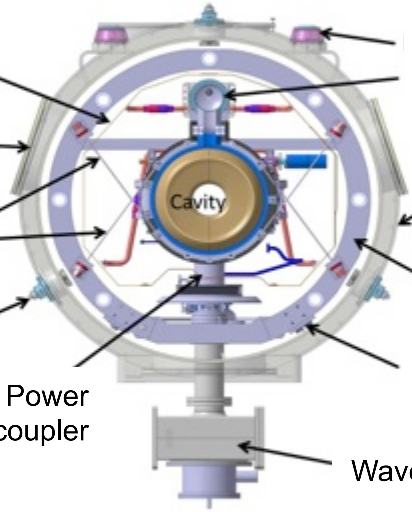
Similar medium and high-beta cavity cryomodules

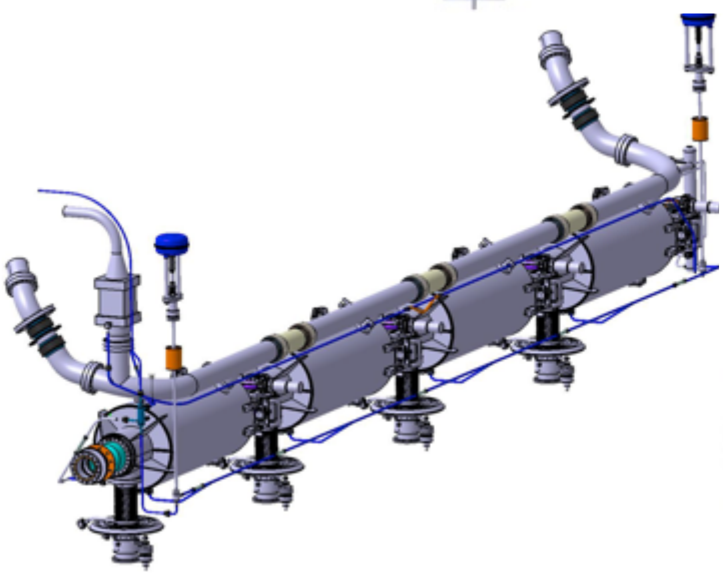
- Common design: Small length difference between medium and high-beta cavities
- Distance between power couplers
- Vacuum vessels, thermal shield, supports, alignment system.

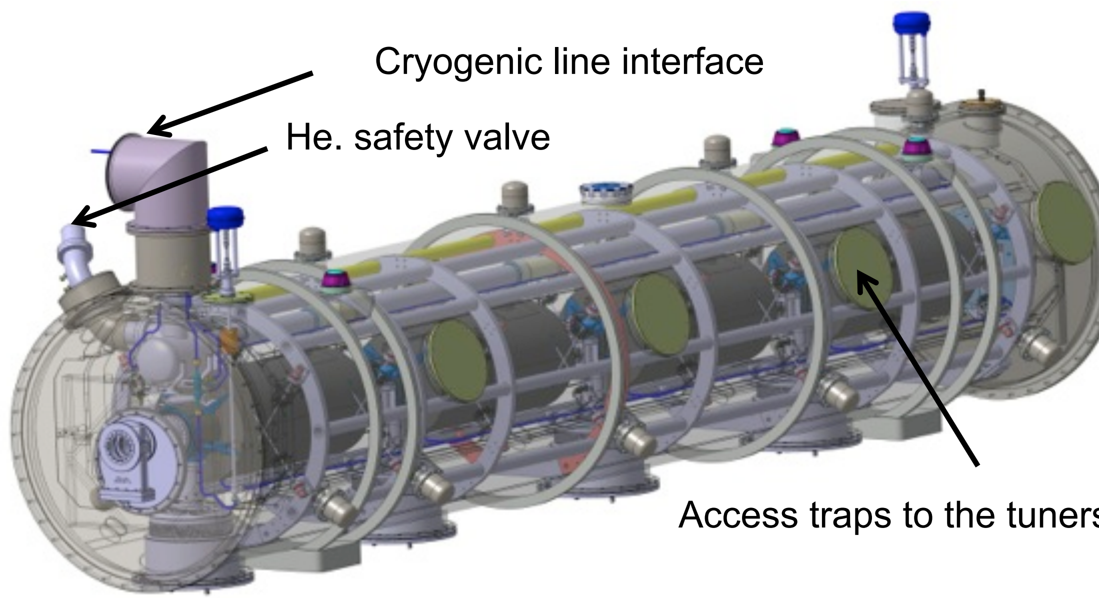
Only minor differences:

- Length of the inter-cavity bellows, details in cryo piping, beam pipe bellows
- Tuner piezo frames
- Penetration of the antenna for Q_{ext} adjustment

Elliptical Cryomodule Components







Elliptical Cryomodule Components

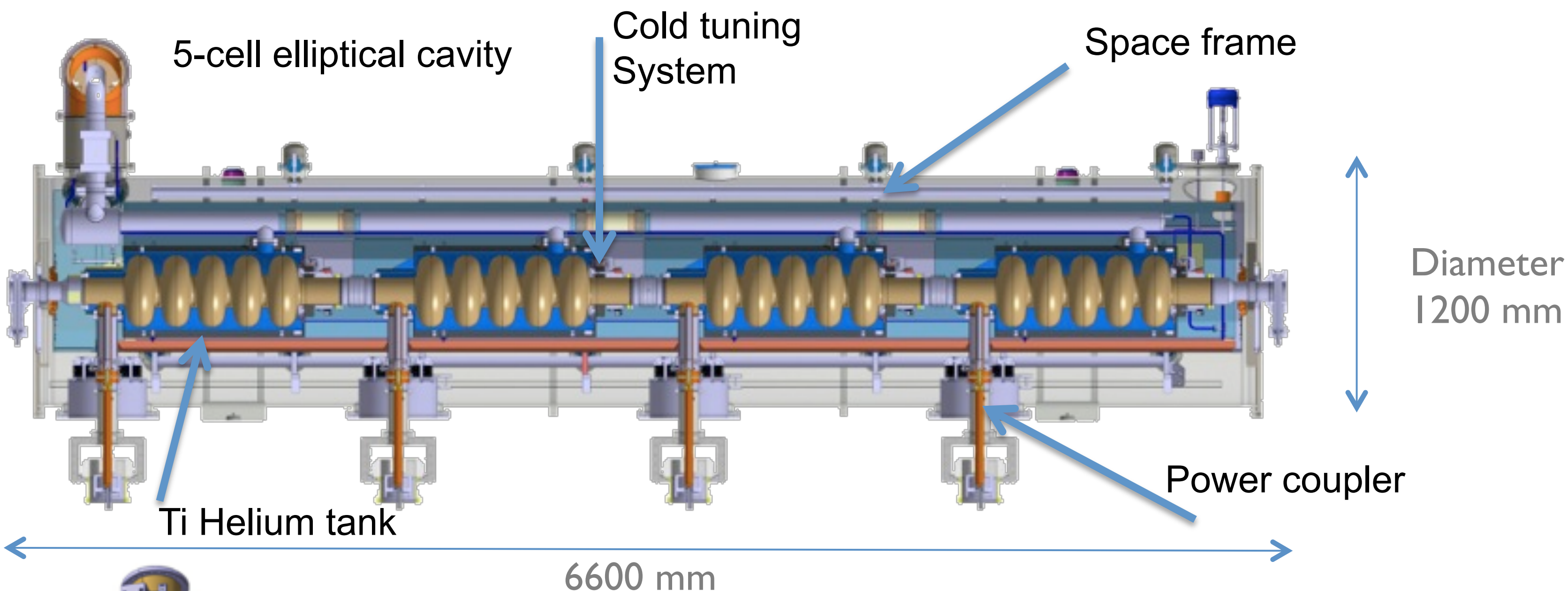
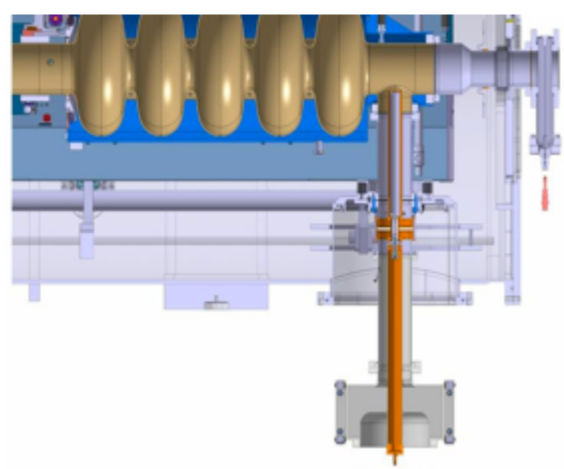
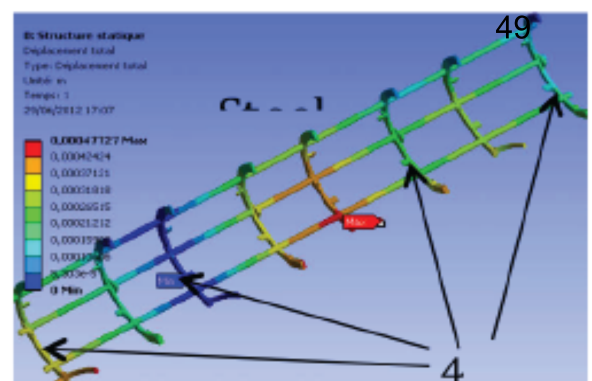


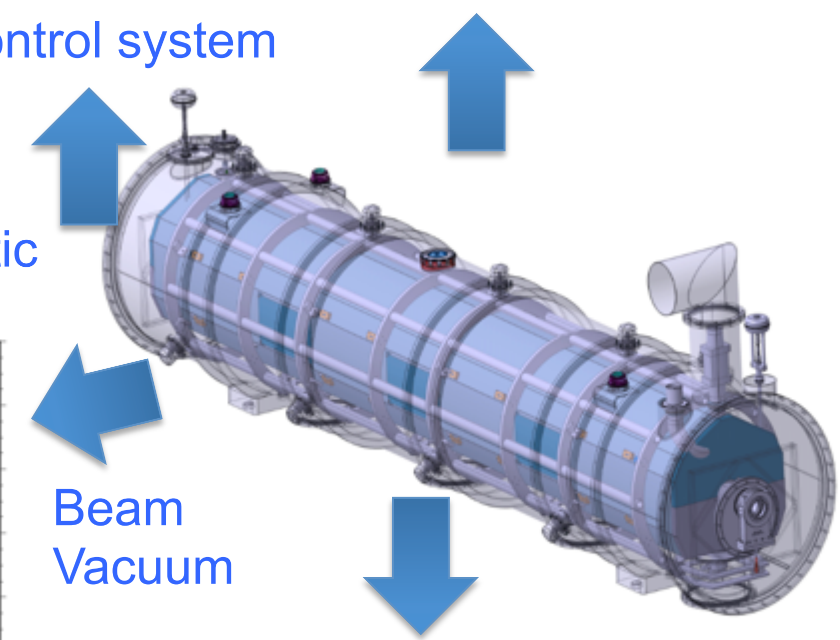
Figure 4.120: Helium vessel with hanging rod



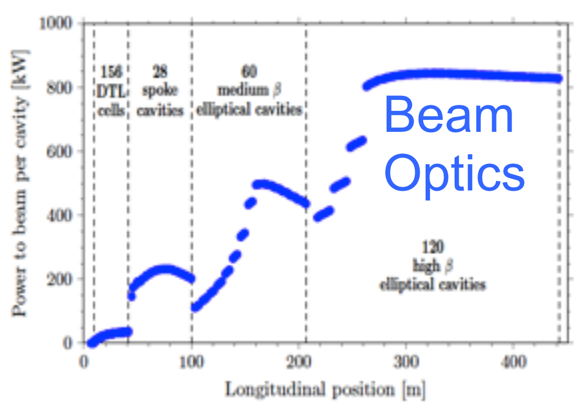


Cryomodule Interfaces

- Most AD internal Work Packages (beam optics, RF, cryo, vacuum, test stands, electrical, cooling, installation)
- External WPs cryomodule, cavity and designers and potential In-Kind collaborators
- Control command (Control Box, PLC, LLRF, MPS, EPICS)
- Data-logging ICS teams
- ESS ES&H
- Conventional Facility
- ESS system engineer, QA
- Survey experts
- Transport

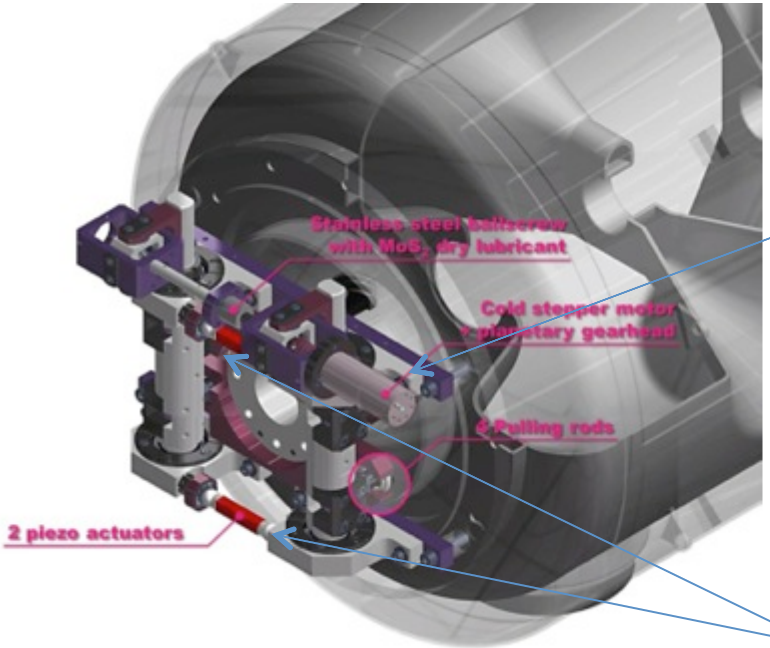


Previous Linac version for comparison ➔



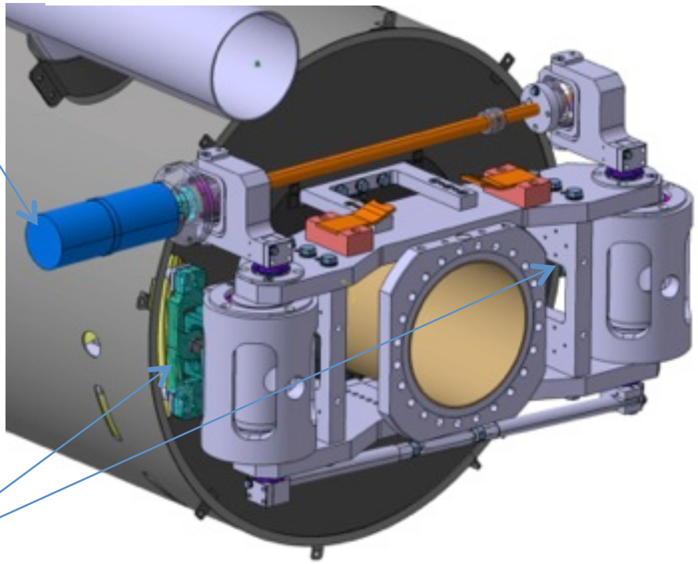
Cold Tuning System

Spoke CTS



Elliptical CTS

Type V ; 5-cell prototype
+/- 3 mm range on cavity



Stepper motor and planetary gearbox (1/100e) at cold and in vacuum

2 piezo stacks

Slow tuner

Main purpose : Compensation of large frequency shifts with a low speed

Actuator used : Stepper motor

&

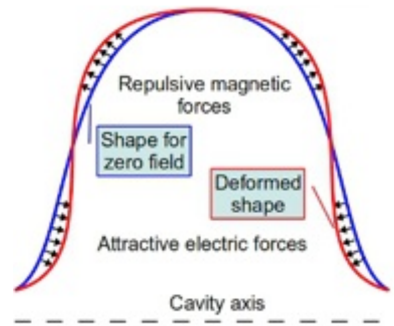
Fast tuner

Main purpose : Compensation of small frequency shifts with a high speed

Actuator used : Piezoelectric actuators

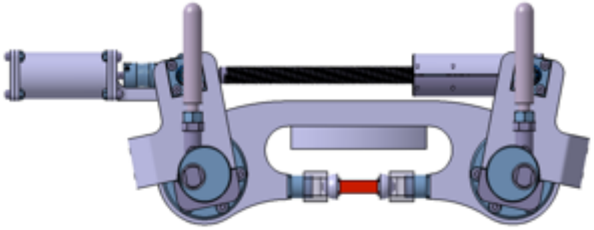
Lorentz De-tuning

- Because of the enormous gradients in superconducting cavities,
  - the radiation pressure deforms the cavities
- We expect over 400 Hz of detuning in the ESS cavities.
  - Unloaded cavity bandwidth = 0.07 Hz
  - Loaded cavity bandwidth = 1 kHz
- The mechanical time constant of the cavities is about 1 ms compared to the pulse length of 3 ms
  - Static pre-detuning as done in SNS will not be sufficient
  - Dynamic de-tuning compensation using piezo-electric tuners is a must!
  - Or else pay for the extra RF power required

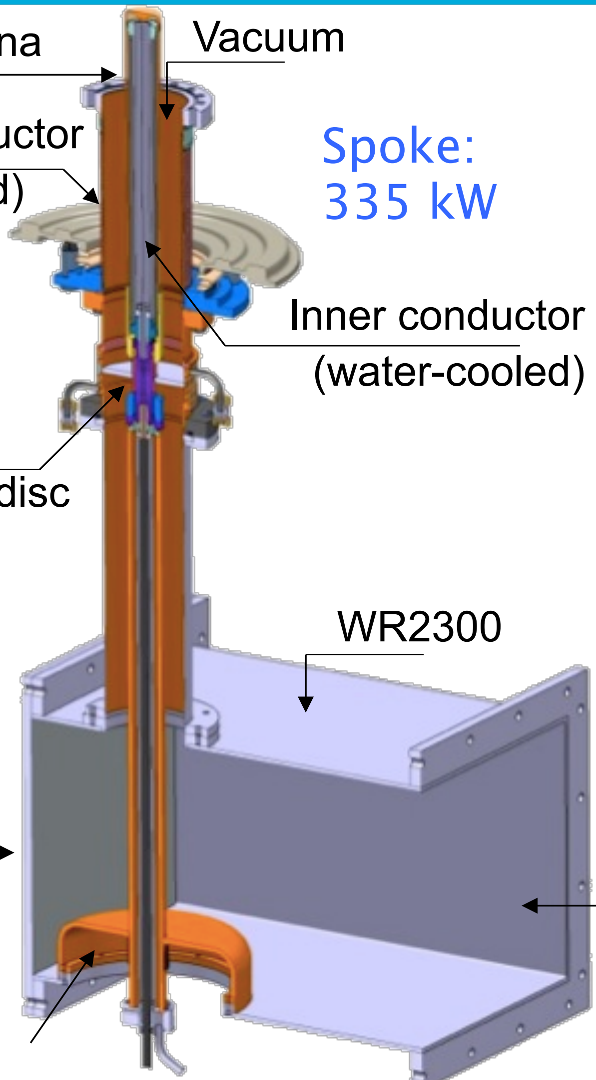


$$P_s = \frac{1}{4}(\mu|\vec{H}|^2 - \varepsilon_0|\vec{E}|^2)$$

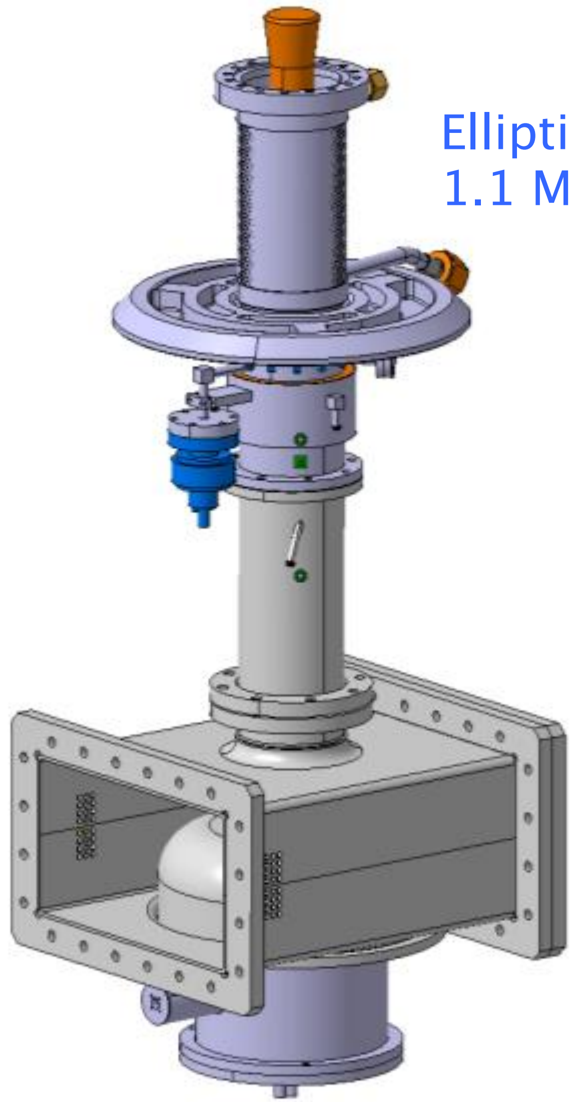
$$\Delta f_0 = (f_0)_2 - (f_0)_1 = -K E_{acc}^2$$



Fundamental Power Coupler



Spoke:
335 kW



Elliptical:
1.1 MW

ESS Requirements and RF Parameters

EUROPEAN SPALLATION SOURCE

Spoke cavities

Frequency (MHz)	352,2
Optimum beta	0,50
Operating temperature (K)	2
Nominal Accelerating gradient (MV/m)	9
Lacc (βopt.x nb gaps x λ/2) (m)	0,639
Bpk (mT)	79 (max)
Epk (MV/m)	39 (max)
Bpk/Eacc (mT/MV/m)	<8,75
Epk/Eacc	<4,38
Beam tube diameter (mm)	50
RF peak power (kW)	335
G (Ω)	130
Max R/Q (W)	427
Qext	$2,85\ 10^5$
Q0 at nominal gardient	$1,5\ 10^9$

Elliptical cavities

	Medium	High
Geometrical beta	0.67	0.86
Frequency (MHz)	704.42	
Number of cells	6	5
Operating temperature (K)	2	
Epk max (MV/m)	45	45
Nominal Accelerating gradient (MV/m)	16.7	19.9
Q_0 at nominal gradient	> 5e9	
Q_{ext}	$7.5\ 10^5$	$7.6\ 10^5$
Iris diameter (mm)	94	120
Cell to cell coupling k (%)	1.22	1.8
p,5p/6 (or 4p/5) mode sep. (MHz)	0.54	1.2
Epk/Eacc	2.36	2.2
Bpk/Eacc (mT/(MV/m))	4.79	4.3
Maximum. r/Q (W)	394	477
Optimum β	0.705	0.92
G (Ω)	196.63	241
RF peak power (kW)	1100	

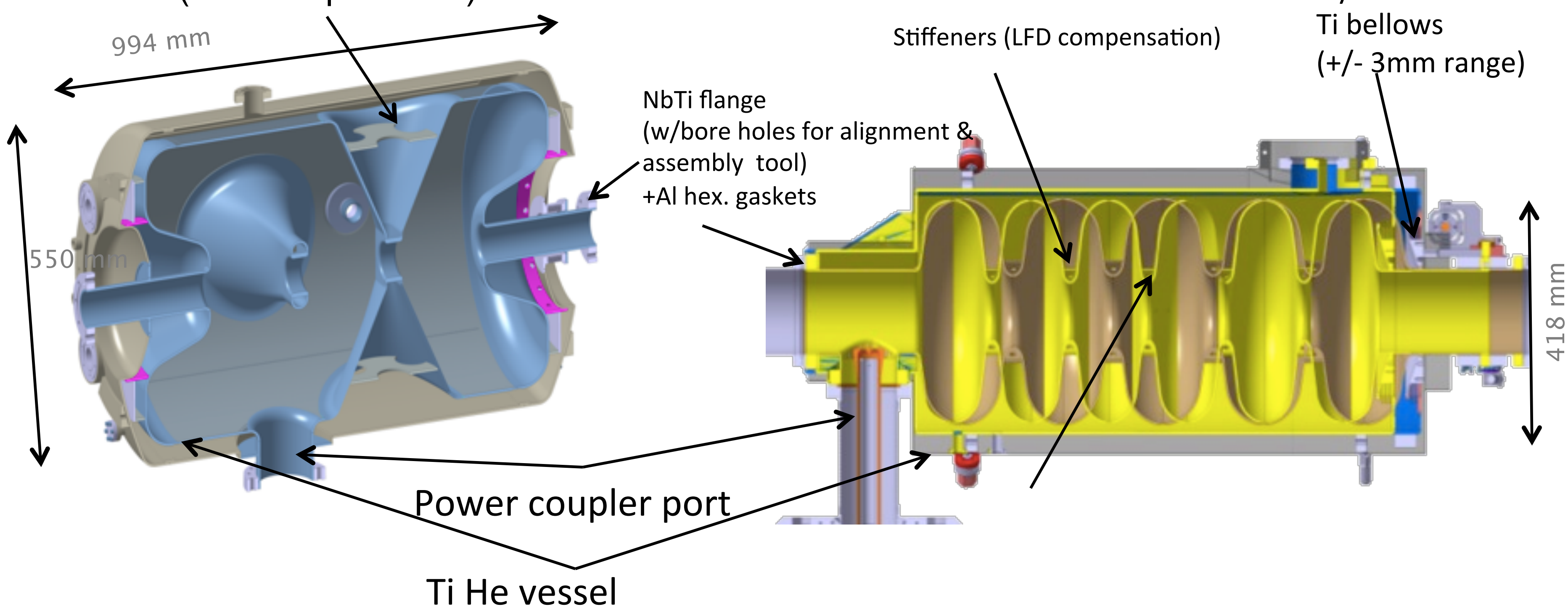
SRF Cavities Development

Spoke cavity

→ Stiffeners on the Spoke bars (vacuum pressure)

Elliptical cavities

→ No HOM power couplers

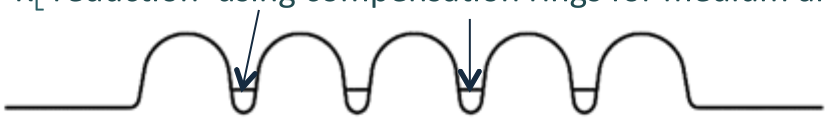


Medium beta:
- **6 cells – beta=0.67**
- **Length 1259,40mm**

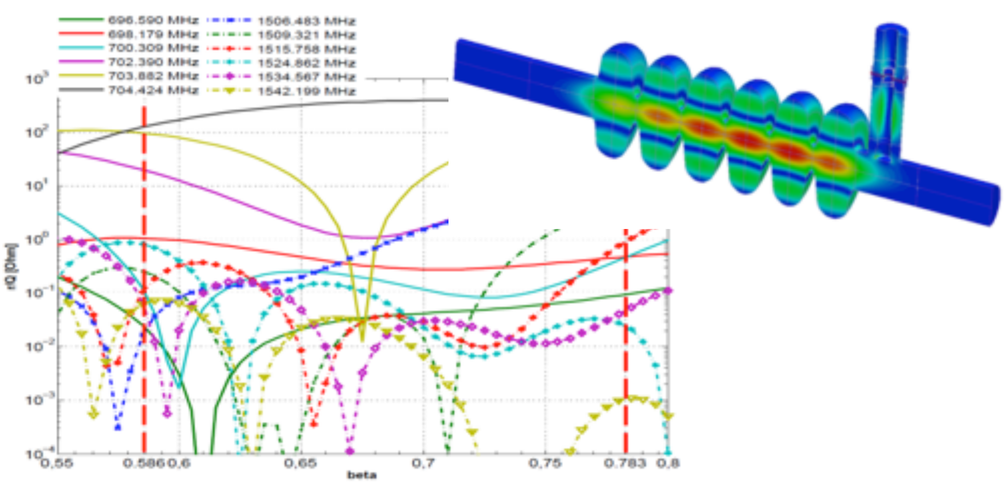
High beta:
- **5 cells – beta=0.86**
- **Length 1316,91mm**

Medium-β Elliptical Cavities

K_L reduction using compensation rings for medium and high-beta



Nominal wall thickness [mm]	3.6
Cavity stiffness Kcav [kN/mm]	2.59
Tuning sensitivity Df/Dz [kHz/mm]	197
K_L with fixed ends [Hz/(MV/m)²]	-0.36
K_L with free ends [Hz/(MV/m)²]	-8.9
Pressure sensitivity K_P [Hz/mbar] (fixed ends)	4.85

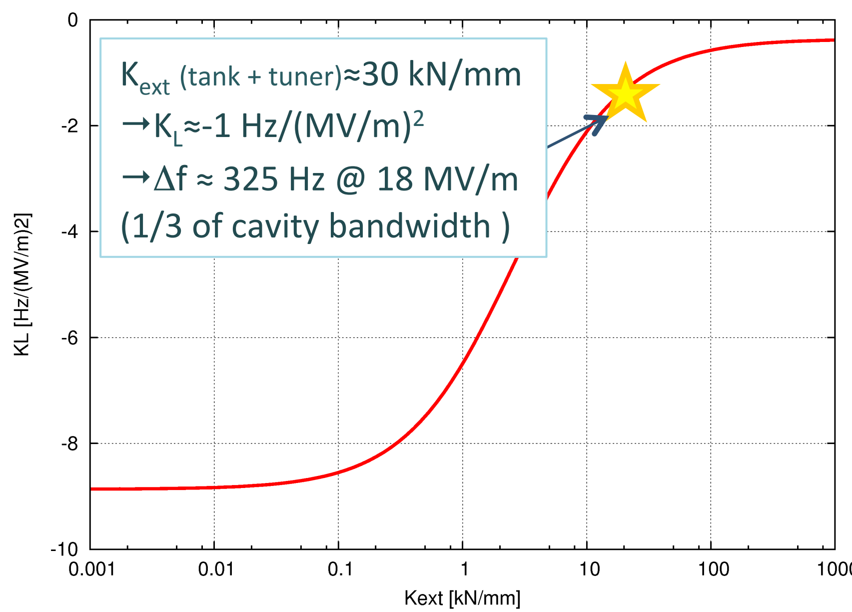


RF/mechanical design

Lorentz detuning

$$K_L = \Delta f / E_{acc}^2$$

$$K_L = K_{L\infty} + \frac{\Delta f}{\Delta z}\frac{\overrightarrow{F_\infty}.\overrightarrow{u_z}/E_{acc}^2}{K_{ext} + K_{cav}}$$



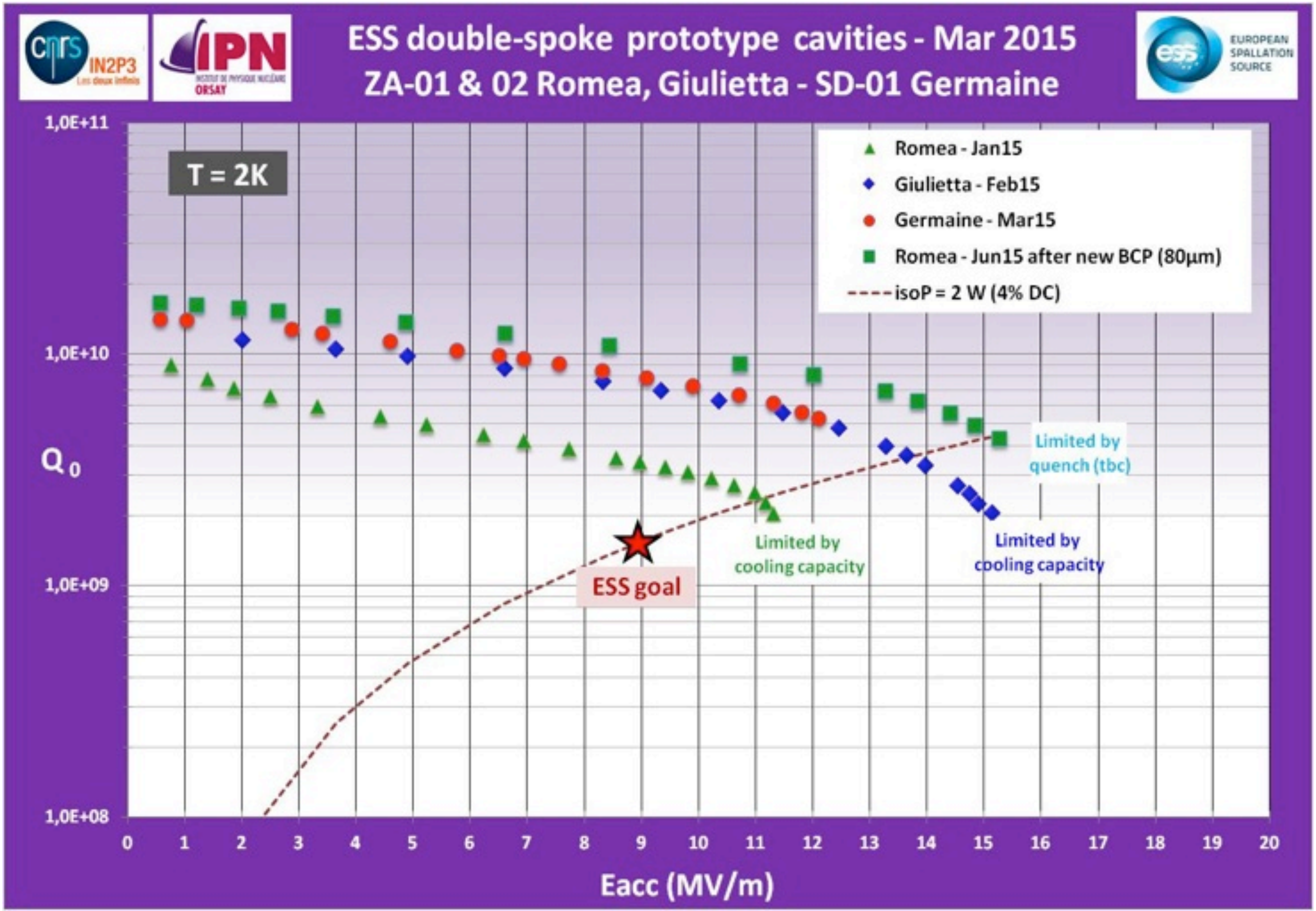
The 3 spoke cavities prototypes:

named: Romea, Giulietta and Germaine

View of the cavity inside: the spoke bars

Spoke cavity Performances (Jan-June 2015)

Spoke cavity exceeding ESS requirements in vertical test on both Eacc and Qo



- Eacc_max=15.3 MV/m achieved with “Romea”
- Several MP barriers but easily processed.
- Qo > 1.6 10^{10}
- Strong FE at max gradient
- Limitation is the cooling capacity (unstable conditions, cavity in vertical position)

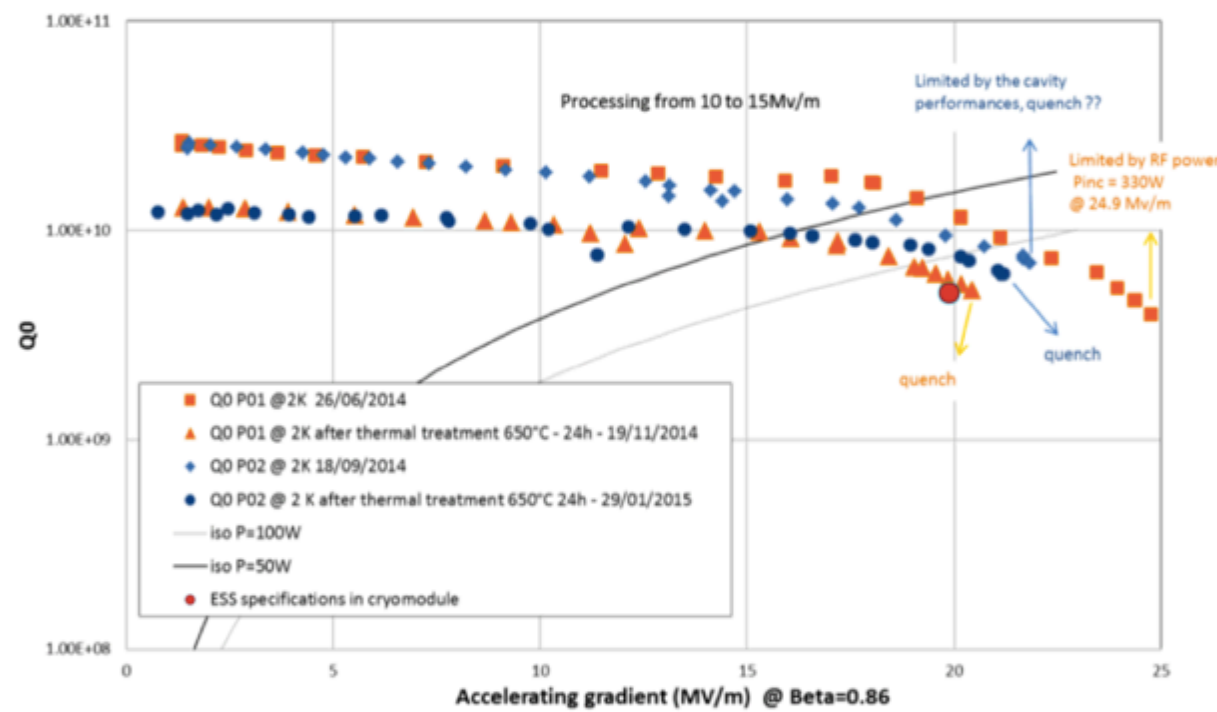
Integration and Verification

Two high beta prototype cavities

P01 - E. ZANON

P02 - RI

Protypes with HOM ports for RF measurement



Both prototype cavities met the ESS requirements after the first test: very encouraging results!

Slight degradation of performances after thermal treatment for hydrogen removing (pollution)

Elliptical Cavity Preparation

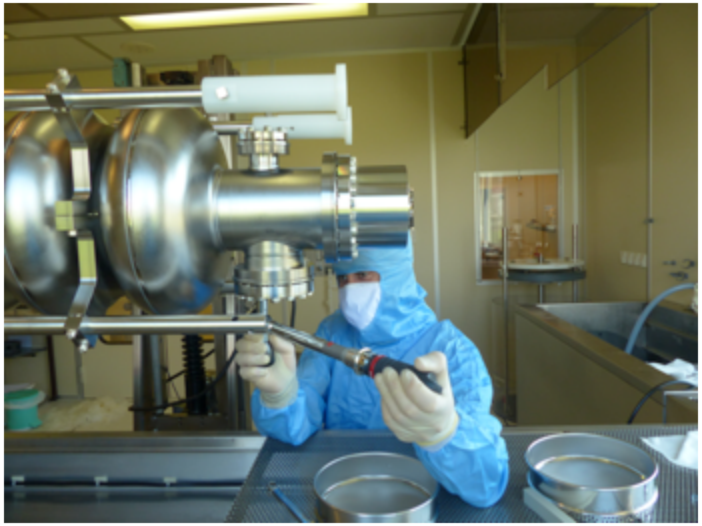
High beta cavity fabrication (Zanon and RI)

Vertical Electropolishing system@ CEA

Study of the tooling in progress @ CEA

Example of the tooling for the assembling of the coupler on the cavity in clean room

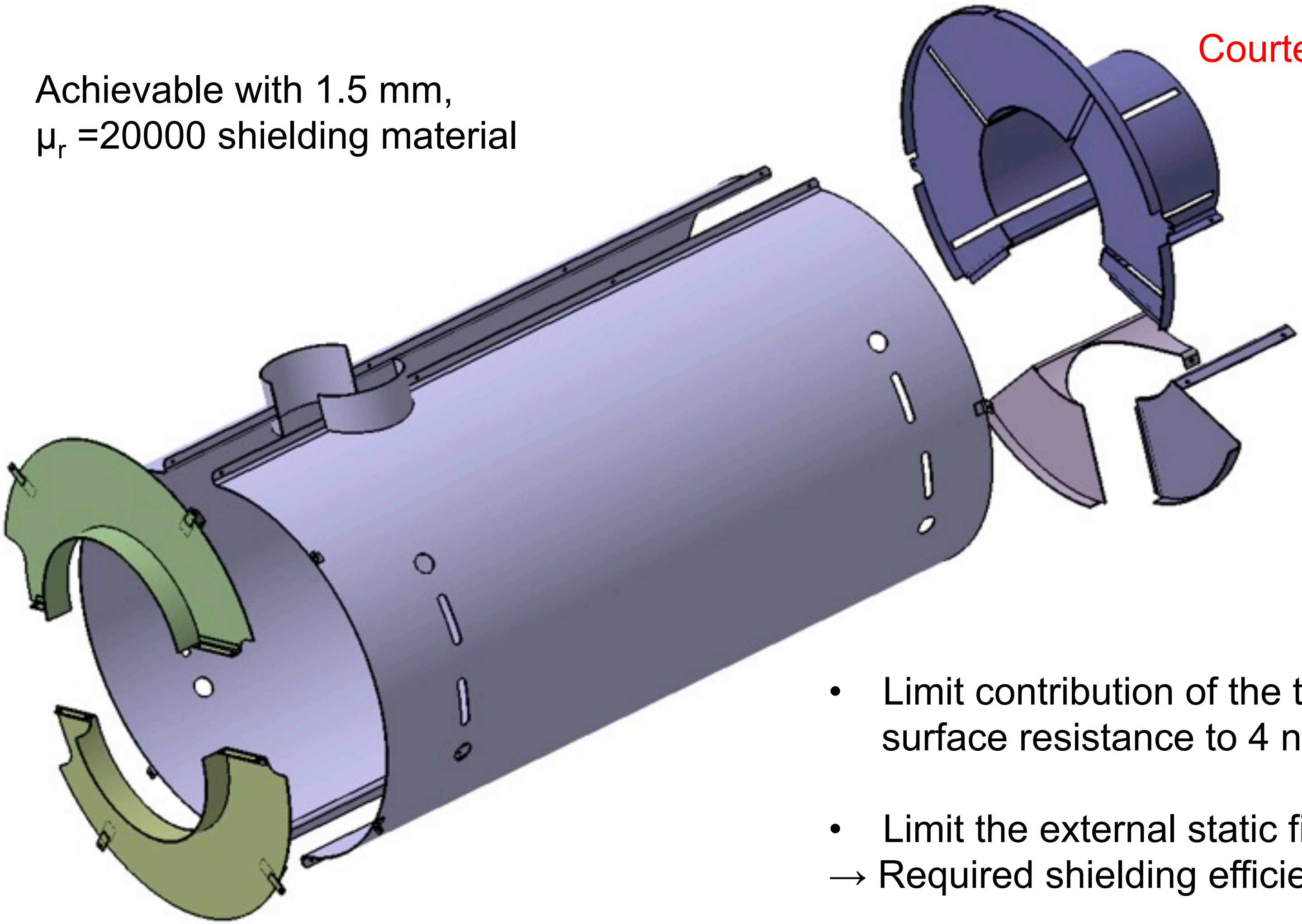
High β Elliptical Cavity Activities in Clean Room



Magnetic shield

Courtesy of J. Plouin/ CEA

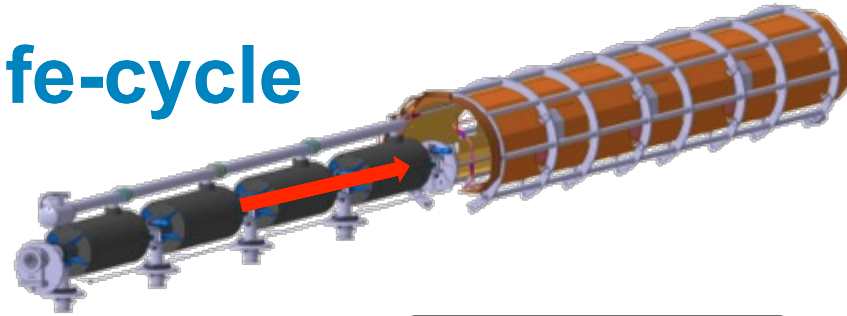
Achievable with 1.5 mm, μ_r =20000 shielding material



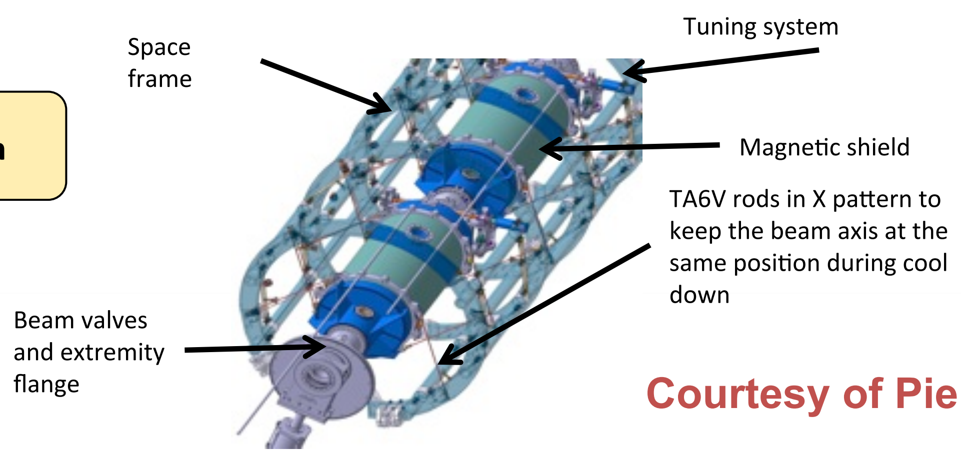
- Limit contribution of the trapped flux to the surface resistance to 4 nΩ
- Limit the external static field to Bext = 14 mG.

→ Required shielding efficiency equal to 35.

Cryomodule life-cycle



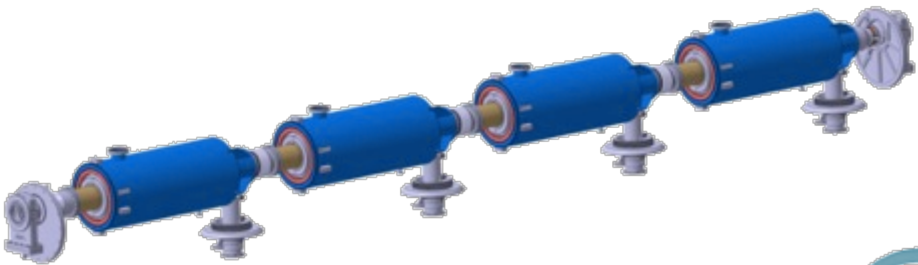
- High pressure rinsing In clean room (ISO5 or ISO4)
- Cavity fabrication
- Chemical treatment
- Validation test of the cavity in vertical cryostat
- Cryomodule components fabrication
- Qualified cavity storage
- Cavity string assembling in clean room
- Cryomodule assembling
- Processed couplers storage
- Tools fabrication
- Coupler RF processing
- Assembling in clean room
- Power coupler fabrication
- Transport
- Cryomodule reception and storage
- Validation test of the cryomodule
- Cryomodule storage
- Cryomodule on beam line



Courtesy of Pierre Bosland CEA/IRFU

Elliptical Assembly Procedure

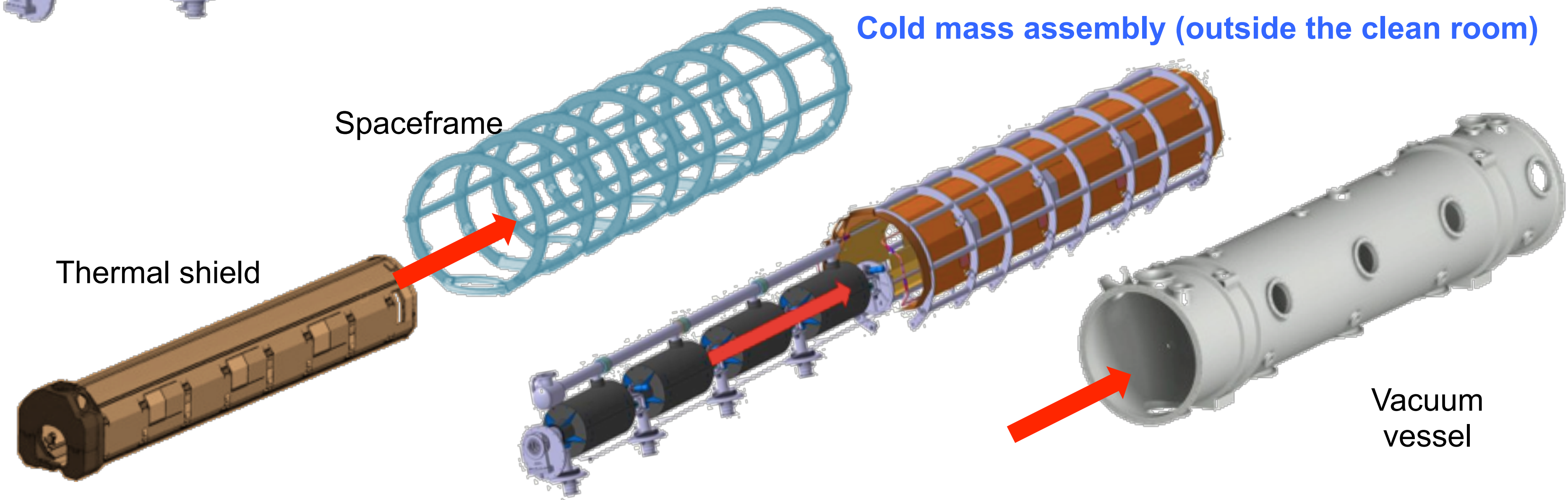
Cavity string assembly in clean room



Build on existing knowledge (SNS, XFEL)

- Develop Training and "Fabrication file"
- Pre-industrialization
- Industrialization

Cold mass assembly (outside the clean room)

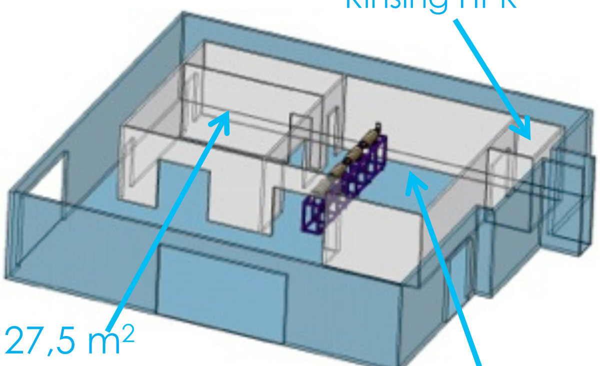


Design concept of the tooling: most of parts will be used for both types of elliptical cryomodules

Infrastructure in Saclay

Clean room for the M-ECCTD
(and H-ECCTD)

High Pressure
Rinsing HPR



ISO 7 27,5 m²
Water cleaning

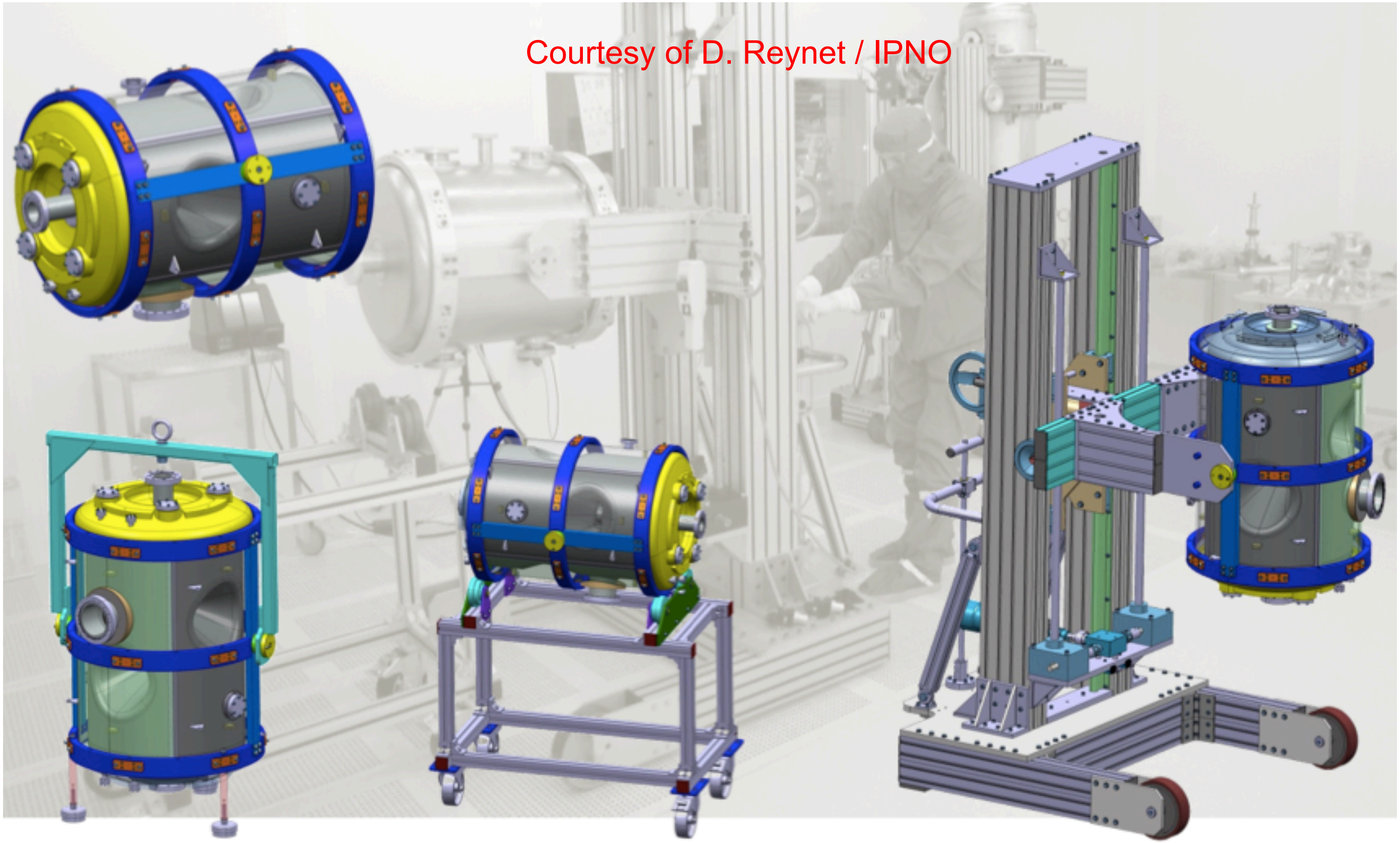
ISO 5
52,69 m²

The clean room inauguration
→ May 13th 2014

Possible IKC for the assembly by industry at Saclay (XFEL cryomodules assembly)

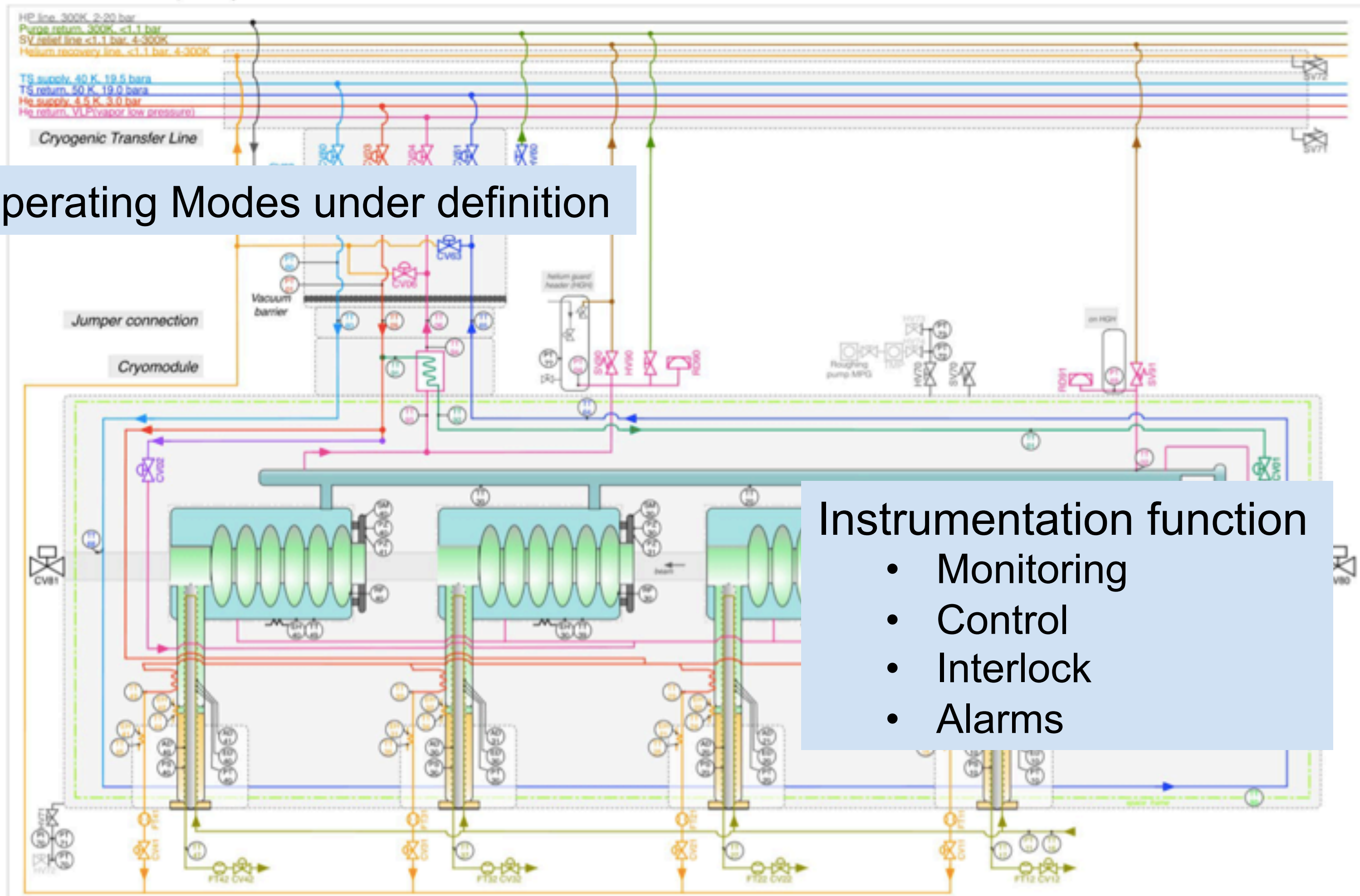
- Uses the current infrastructure at Saclay
- Benefits from the experience of the XFEL cryomodule assembly (ALSYOM)

Spoke assembling in clean room/IPNO



Process and Instrumentation

SERIES Medium Beta Elliptical Cryomodule



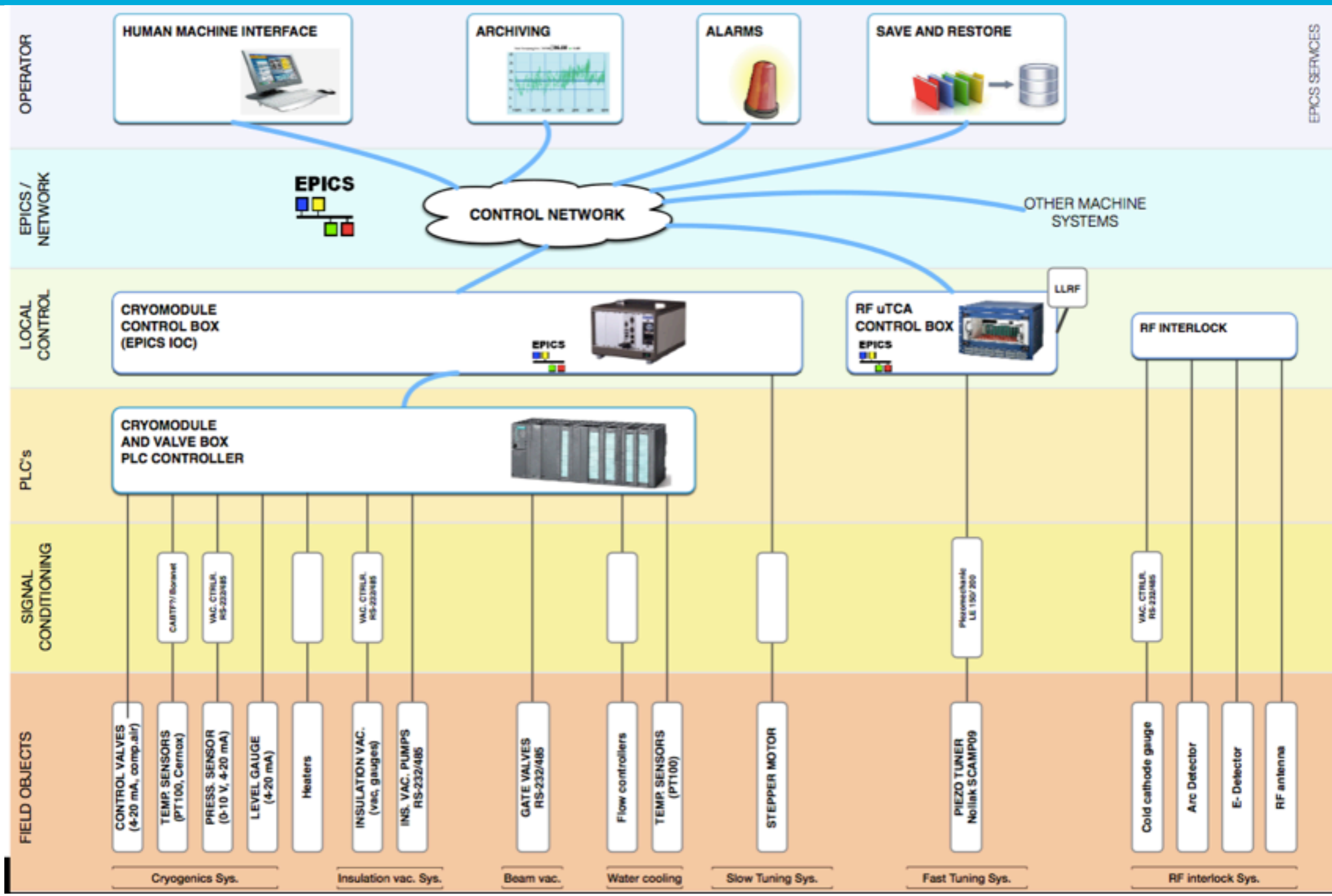
Version 20141208 NE

Operating Modes under definition

Instrumentation function

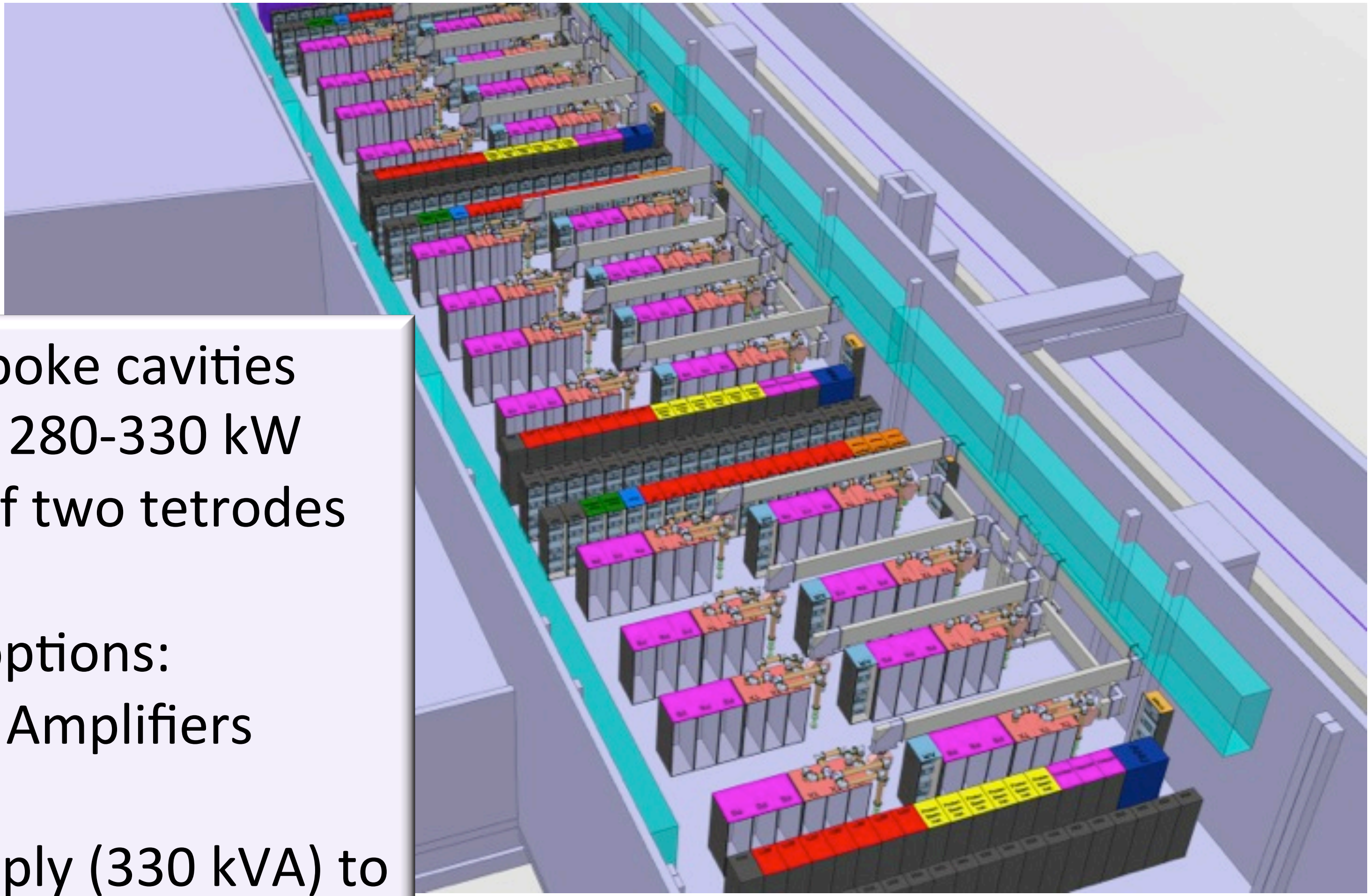
- Monitoring
- Control
- Interlock
- Alarms

Control integration



Spoke linac (352 MHz) RF System Layout

EUROPEAN SPALLATION SOURCE



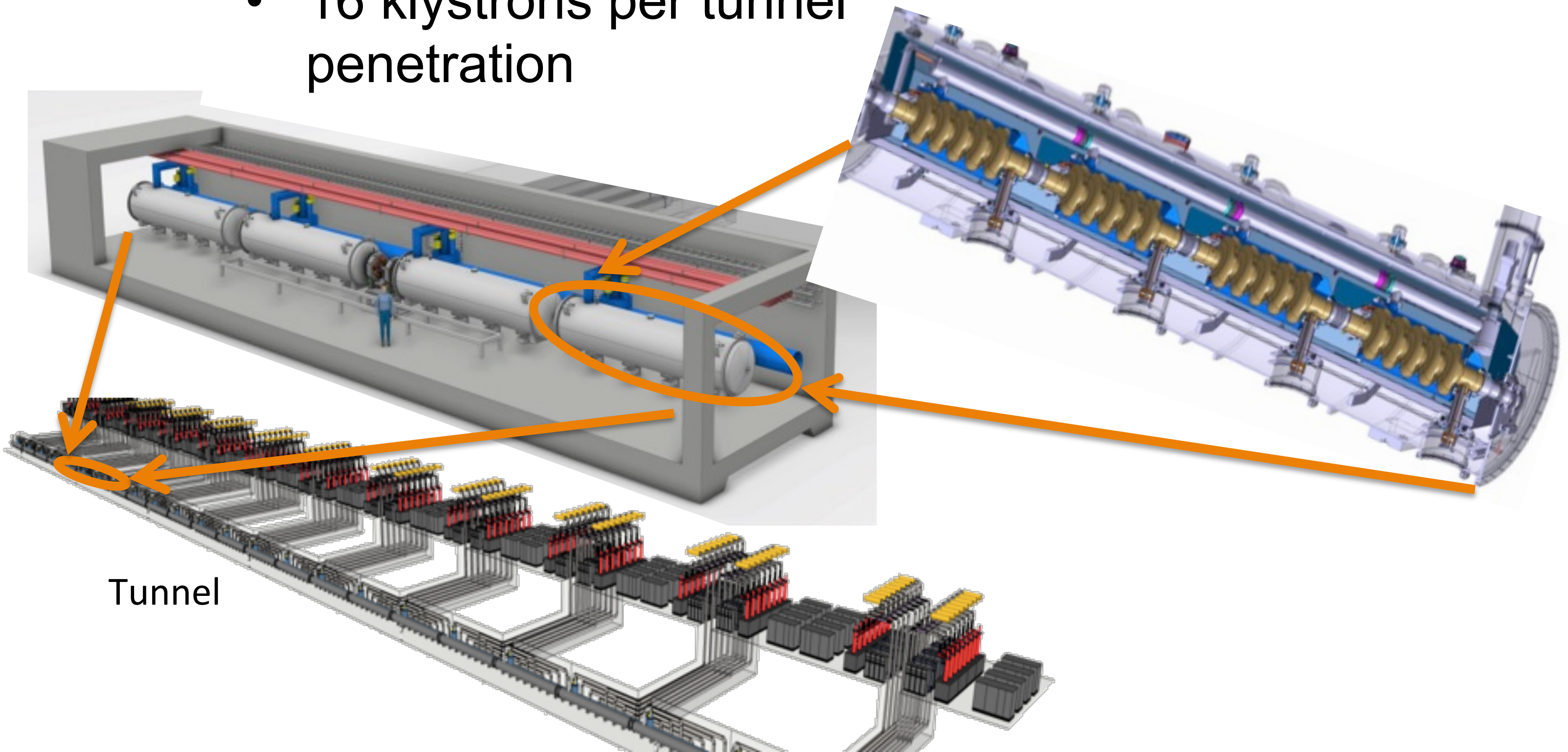
26 Double Spoke cavities
Power range 280-330 kW
Combination of two tetrodes

Other options:
Solid State Amplifiers

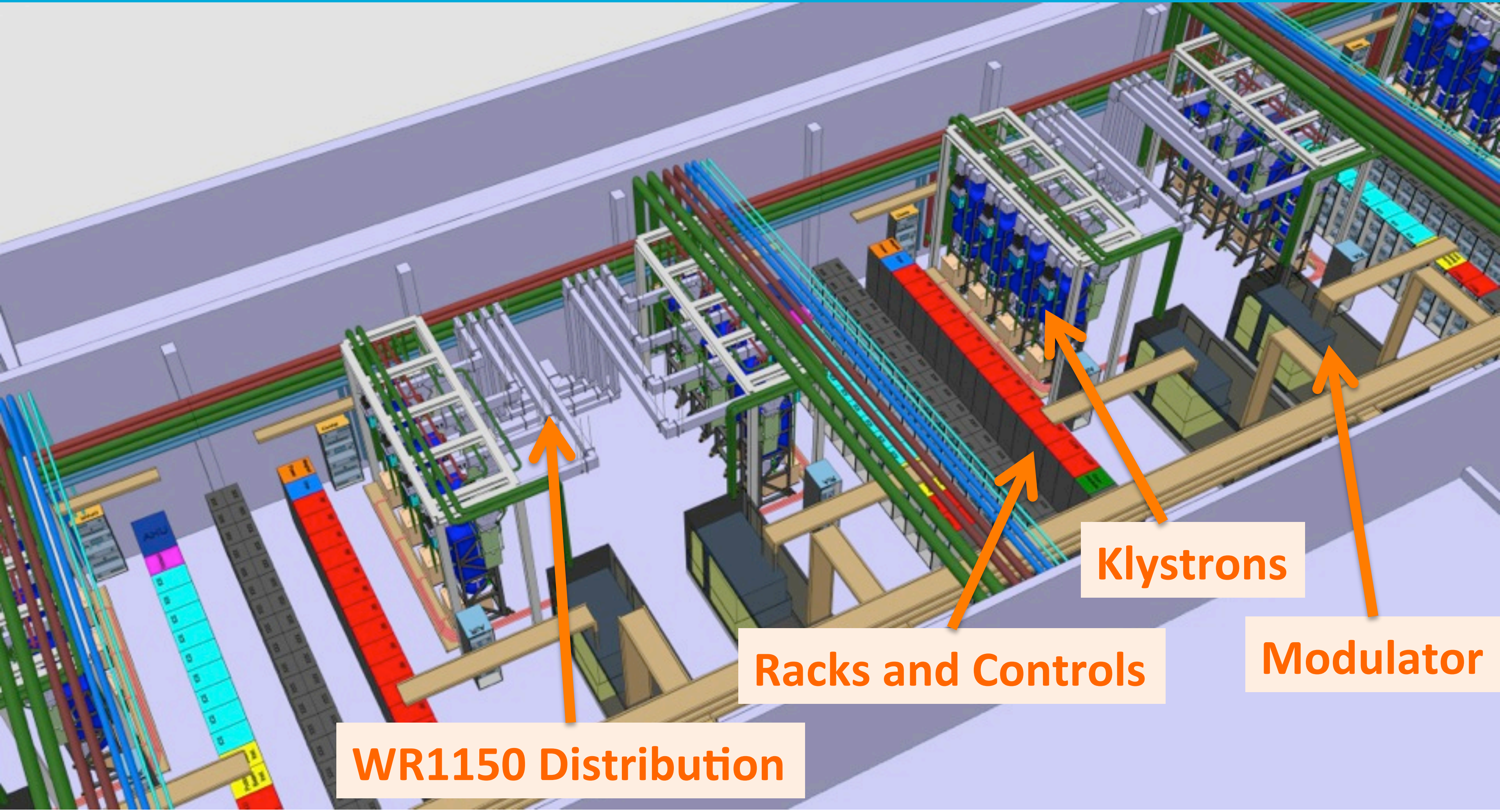
Large power supply (330 kVA) to supply 8 stations (16 tetrodes)

Elliptical (704 MHz) RF System Layout

- One cavity per klystron
- 4 klystrons per modulator
- 16 klystrons per tunnel penetration



Elliptical (704 MHz) RF System Layout

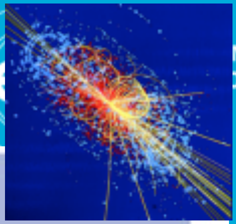


4.5 Cells of 8 klystrons for Medium Beta
10,5 Cells of 8 klystrons (IOTs) for High Beta

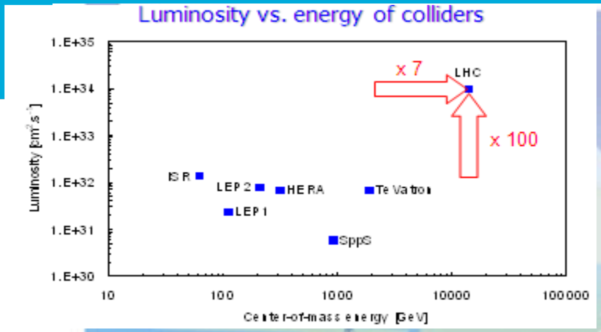
Outline

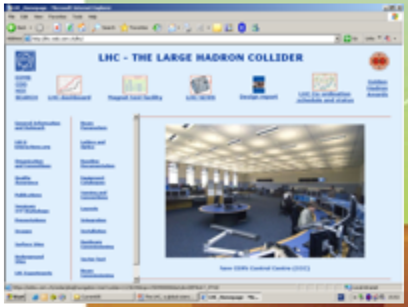
- Types of Particle Accelerators
- Accelerator Characteristics
- RF Cavity
- Superconductivity and Superfluidity
- Examples of the Particle Accelerators:
  - The European Spallation Source (SRF cavities R&D)
  - The LHC (low-beta magnets environment and Controls)
  - The Tevatron (accelerator complex and technologies)

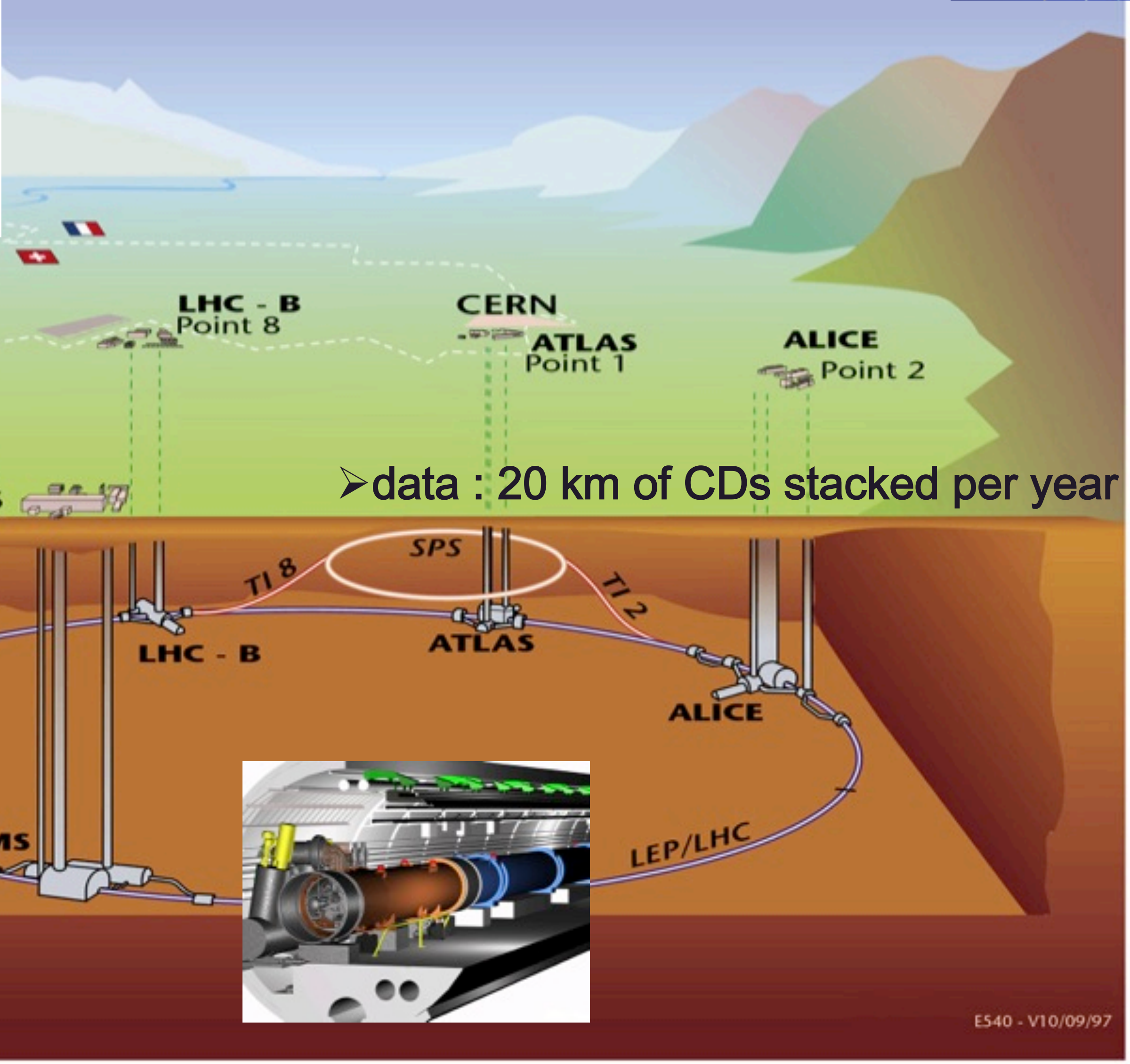
CERN and the Large Hadron Collider



Searching for the Higgs boson !



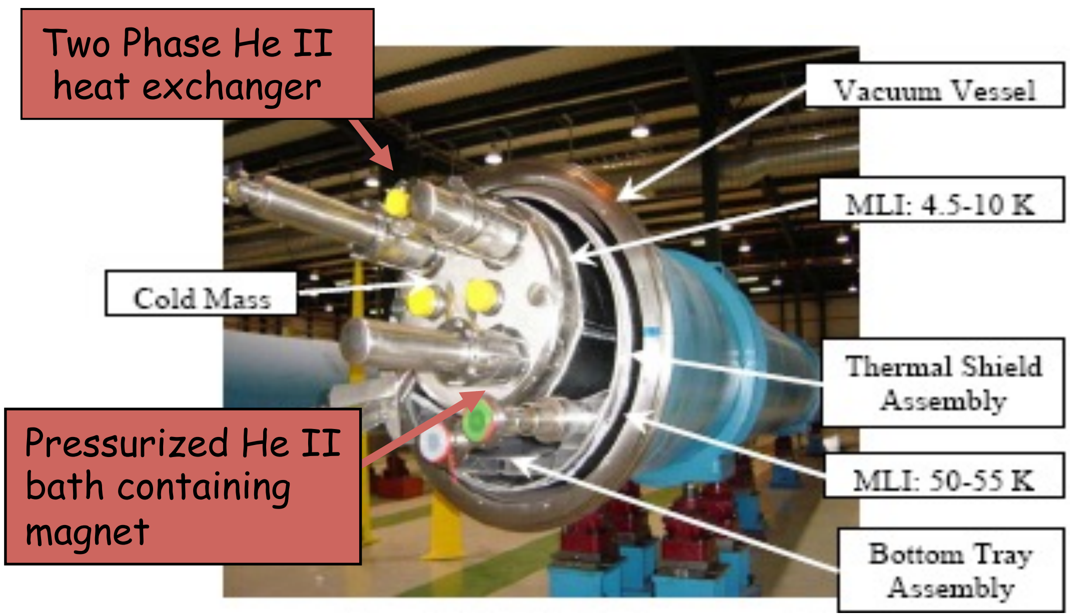


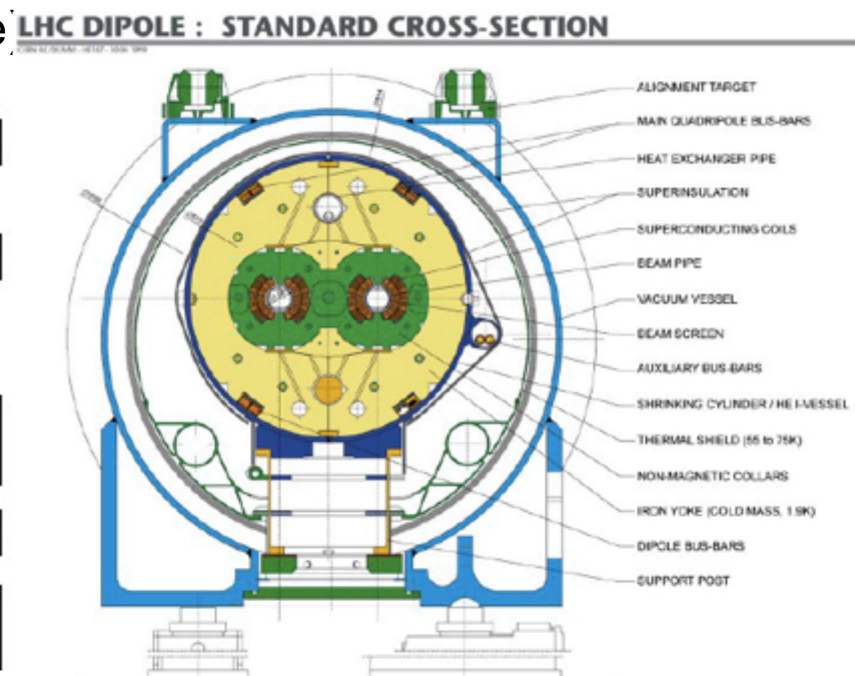


- data : 20 km of CDs stacked per year

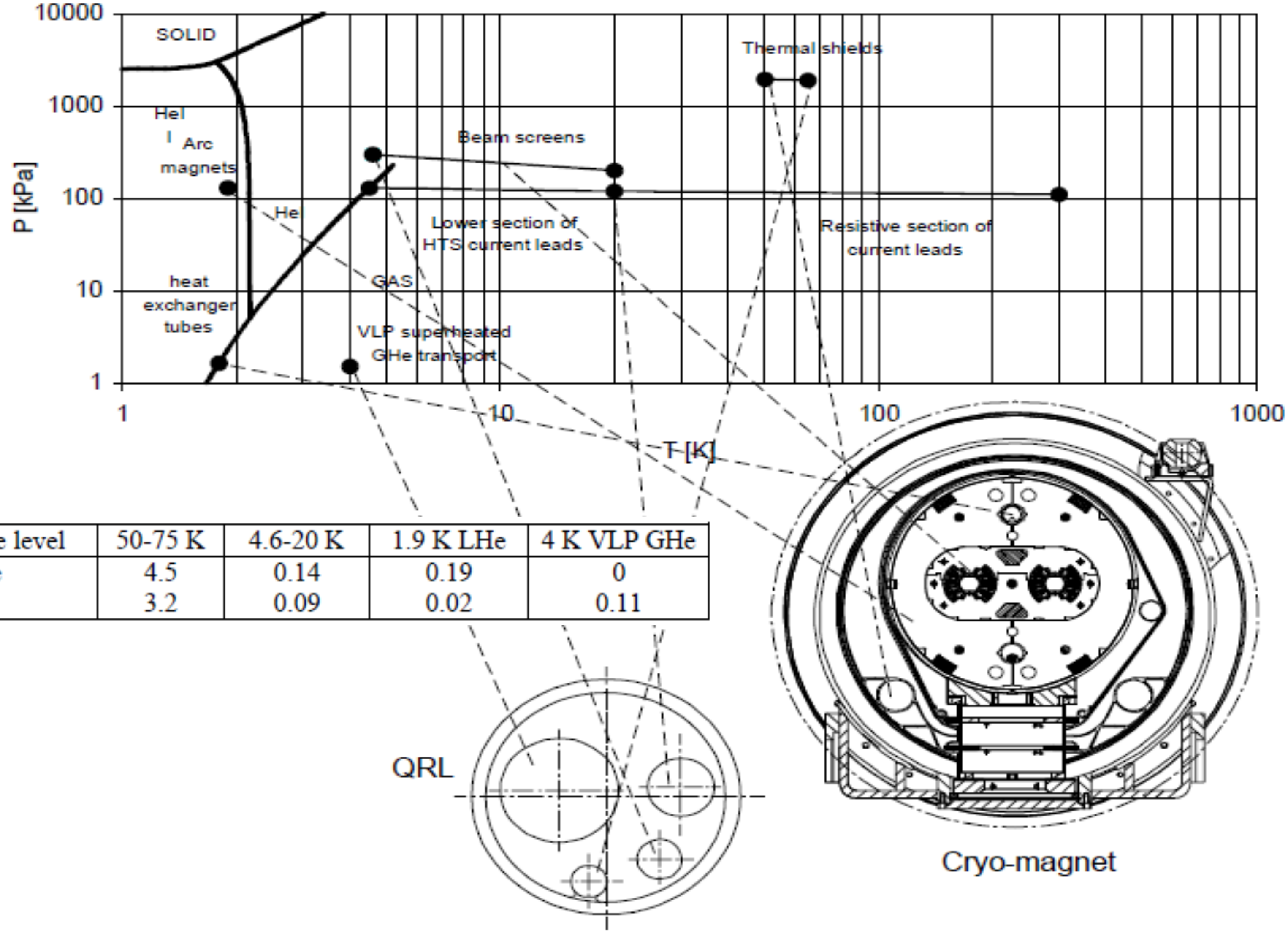
Key technologies of the LHC accelerator

- <u>Superconducting magnets</u>
  - 1,250 ton of NbTi superconducting materials
  - 7,600 km of superconducting "Rutherford" cables
  - 9,600 magnets (incl.1,232 dipoles, 392 quadruples)
- <u>Superfluid helium cryogenics (< 2 K) and vacuum techniques</u>
  - Pressurized and saturated superfluid helium, in two-phase flow
  - Cryostats and thermal insulation
  - Efficient and large capacity helium refrigerators
  - Cryogen storage and mgt (120 ton of He)





LHC Magnets

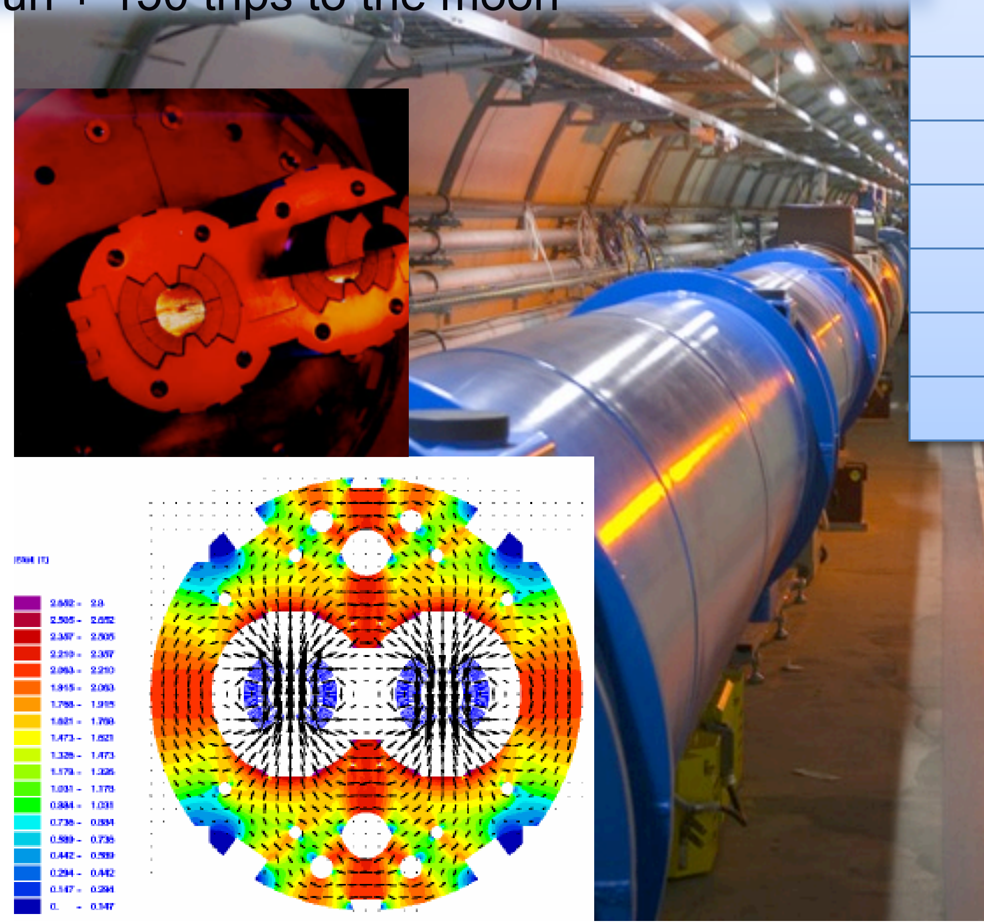
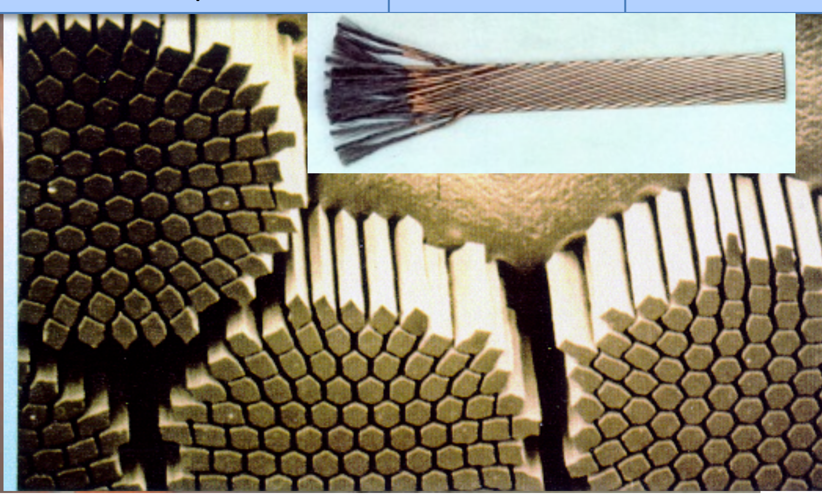


Temperature level	50-75 K	4.6-20 K	1.9 K LHe	4 K VLP GHe
Magnet side	4.5	0.14	0.19	0
QRL side	3.2	0.09	0.02	0.11

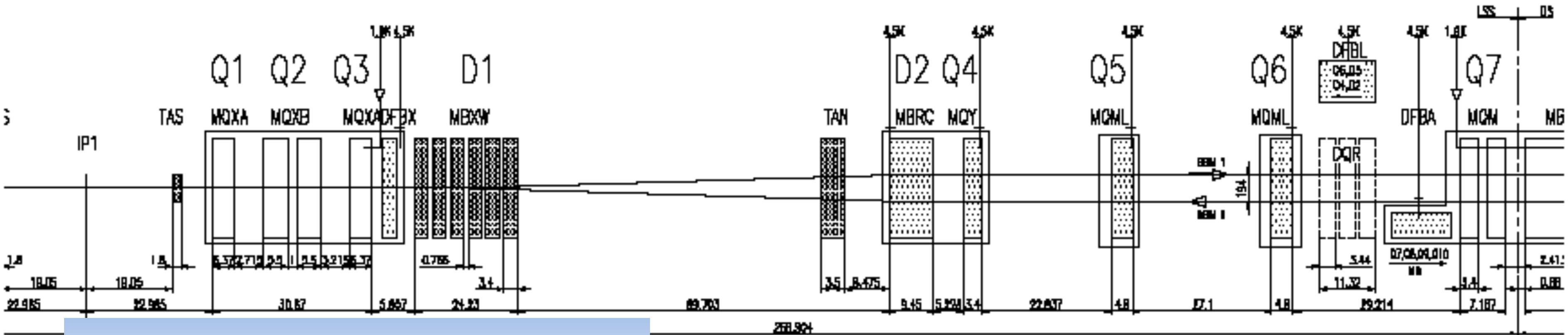
LHC Magnets

7,600 km of cable made of 270,000 km of strand (6 earth circumferences)
→ filaments : 6 times back and forth to the Sun + 150 trips to the moon

	Inner Cable	Outer Cable
Number of strands	28	36
Strand diameter	1.065 mm	0.825 mm
Filament diameter	7 µm	6 µm
Number of filaments	~ 8900	~ 6520
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.900 mm	1.480 mm
Keystone angle	1.25 °	0.90 °
Transposition length	115 mm	100 mm
Ratio Cu/Sc	≥ 1.6	≥ 1.9

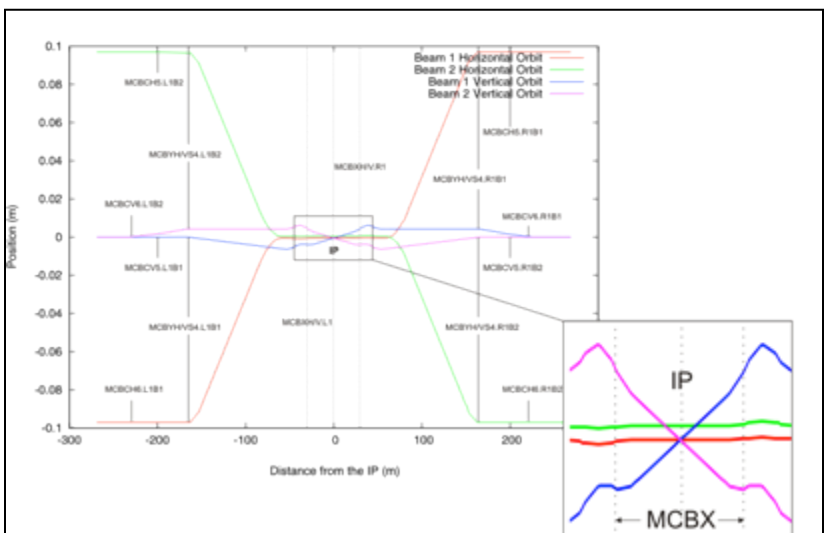
The low-beta magnets at the LHC

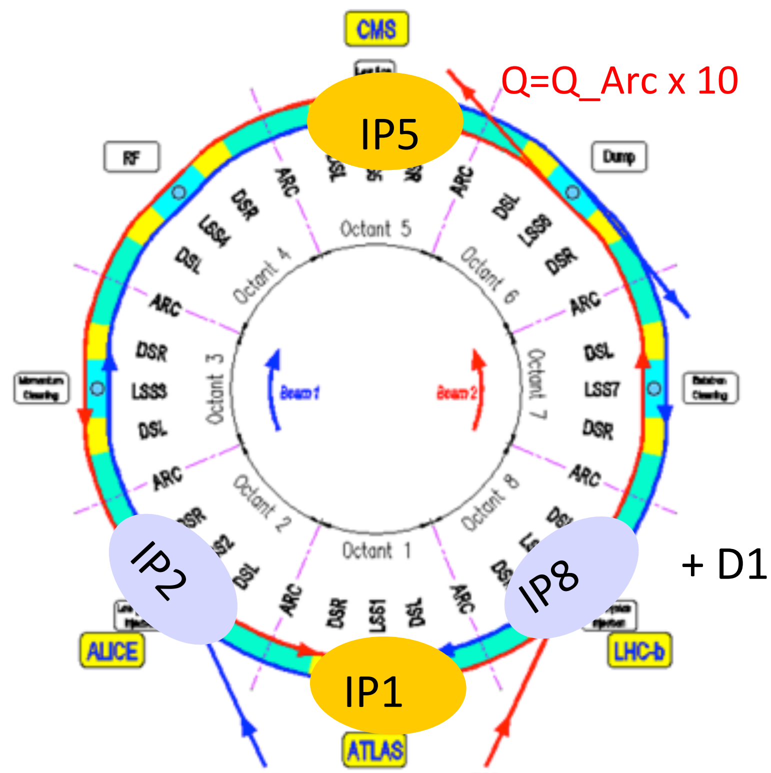


Inner Triplet for final beam focusing/defocusing

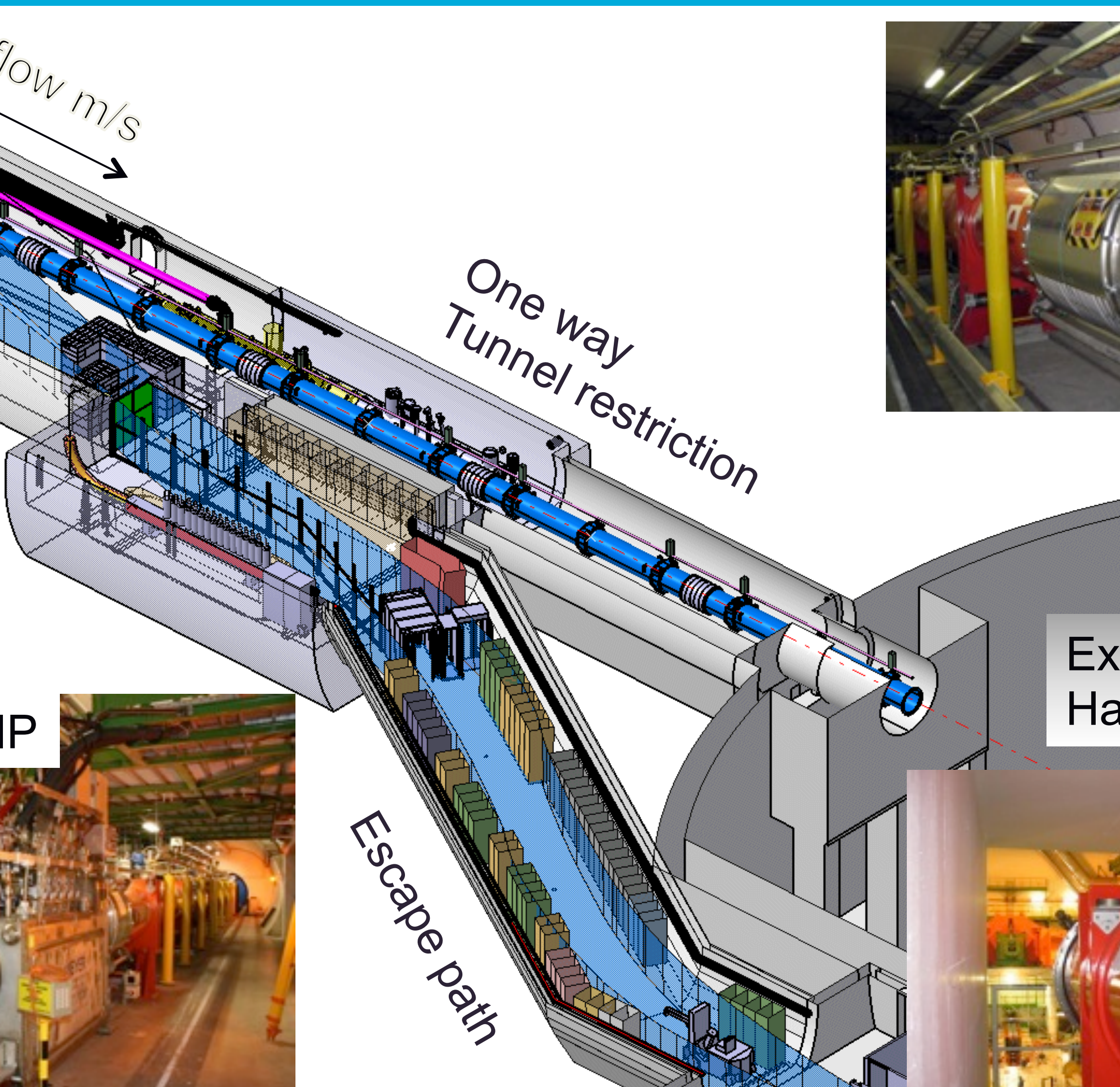
➔ **Critical system for LHC performance**

American contribution to the LHC machine





The low-beta magnets at the LHC

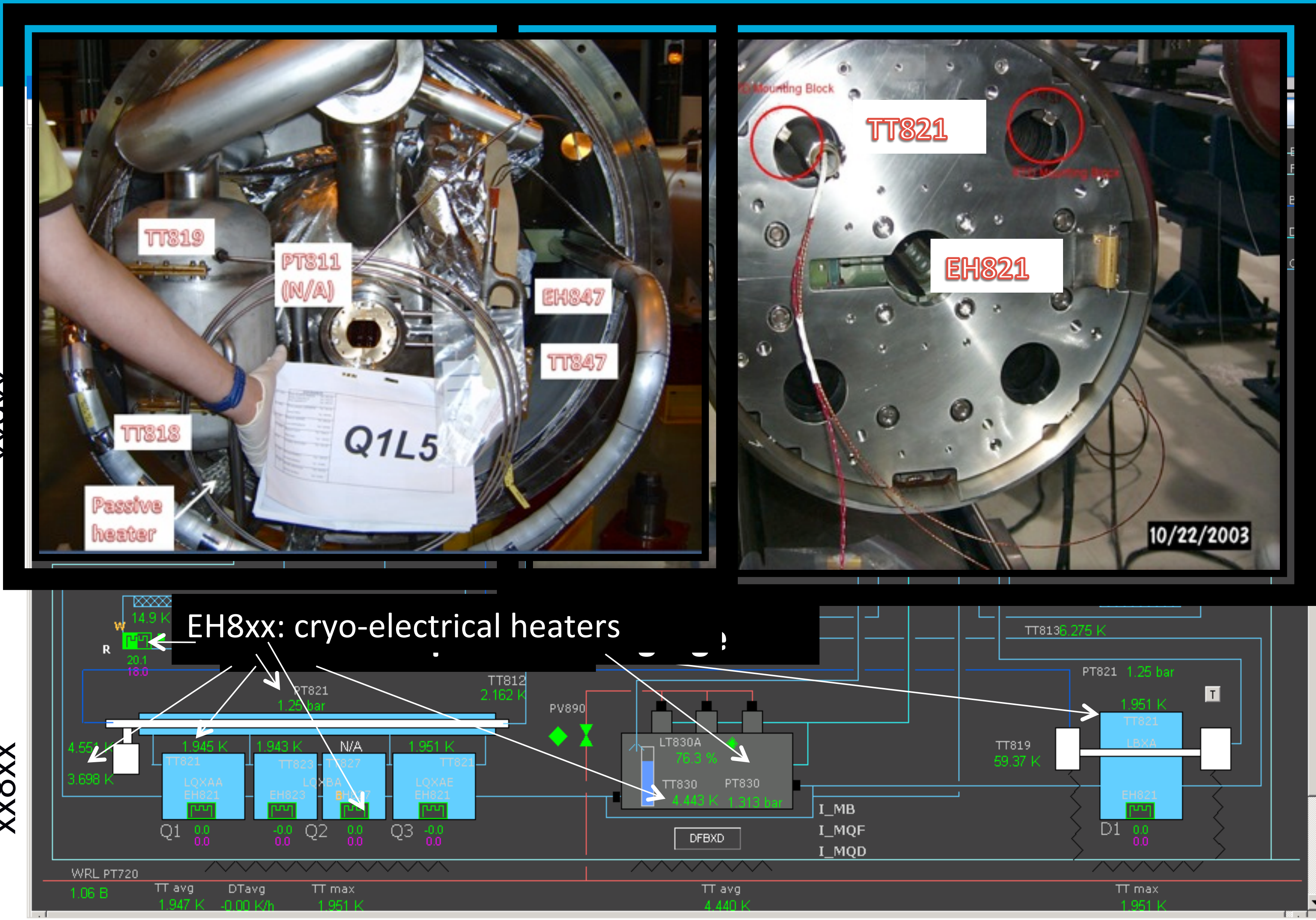


Looking toward IP

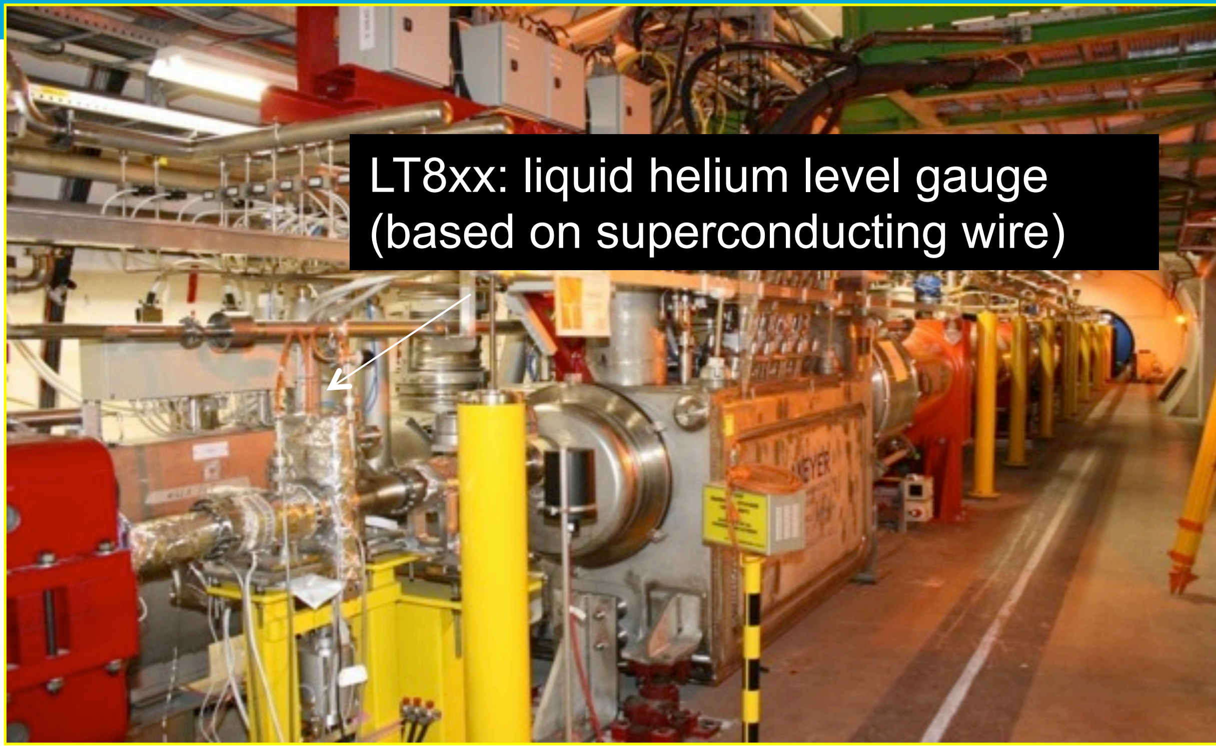
Type of instrumentation : cryo-magnets

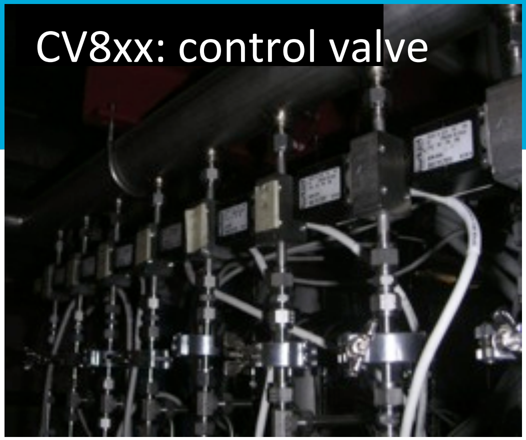
Interface with QRL xx9xx

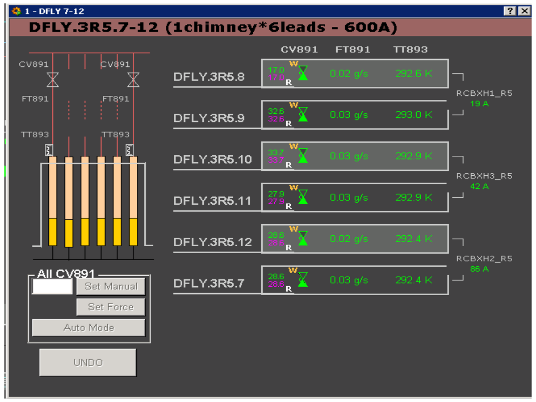
Low-beta system xx8xx

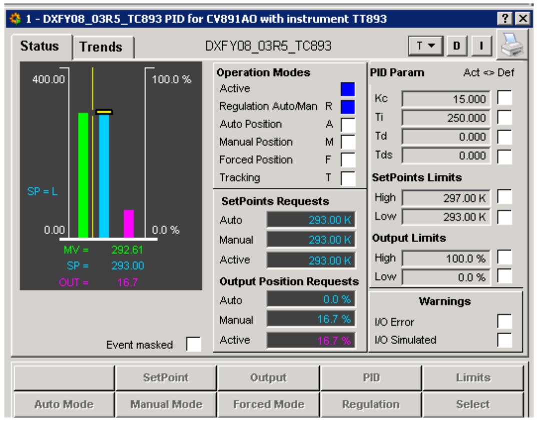


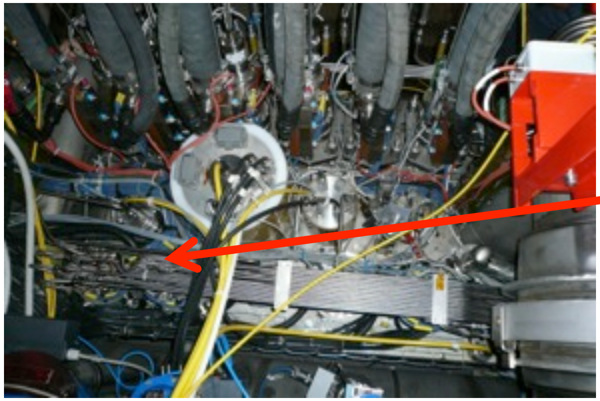
Electrical feed-boxes

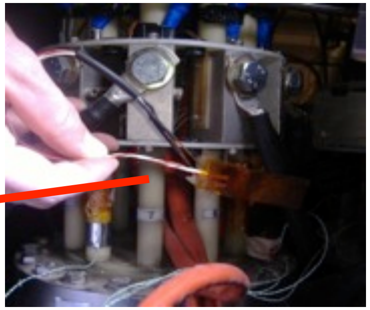






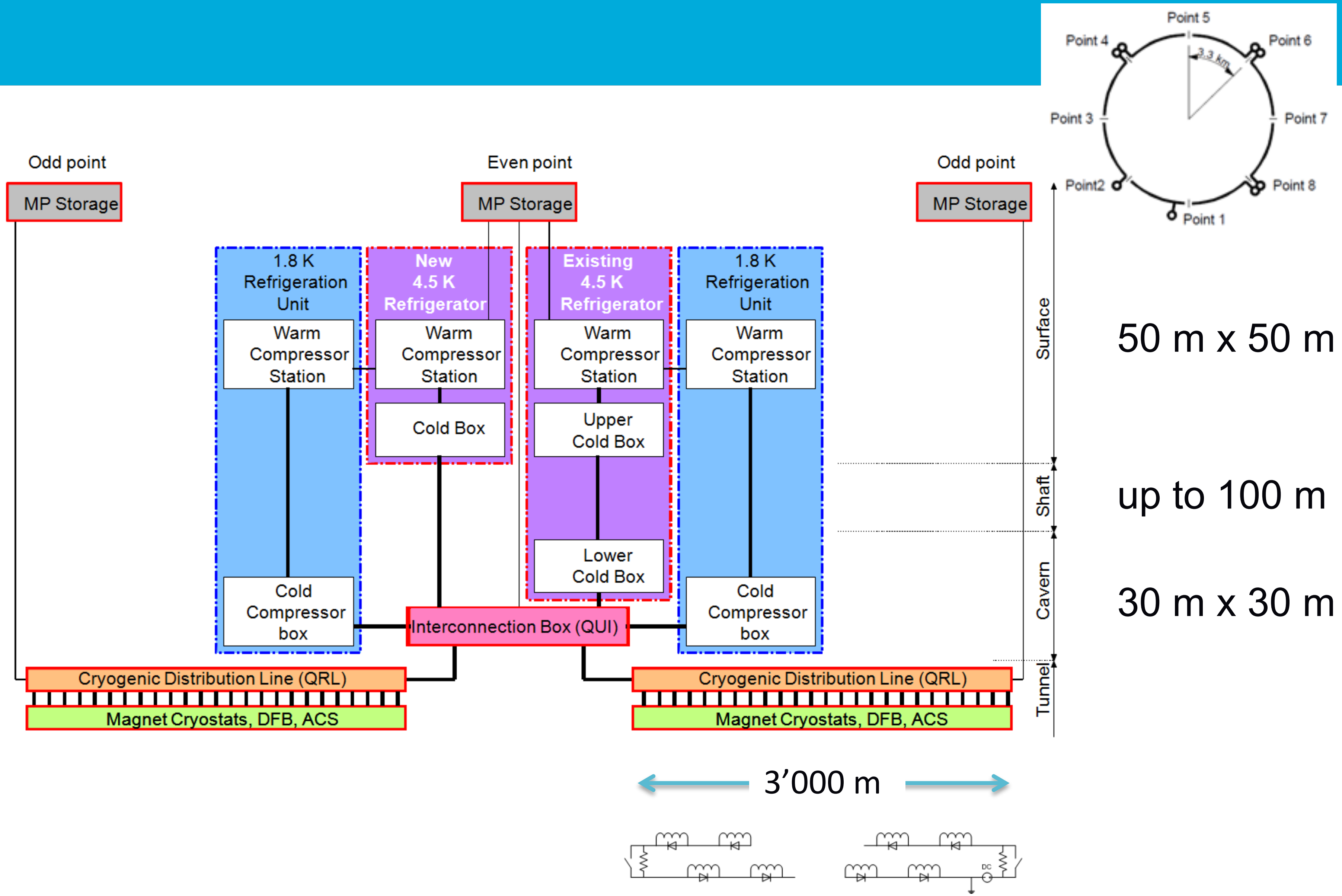




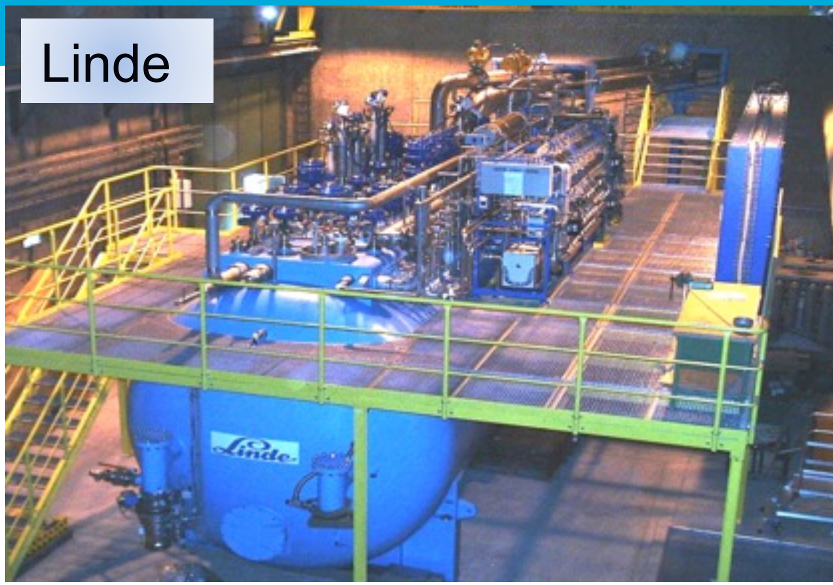


***HTS leads**
***Vapor cooled leads**

General architecture of the cryogenic system



18 kW @ 4.5 K helium refrigerators



33 kW @ 50 K to 75 K

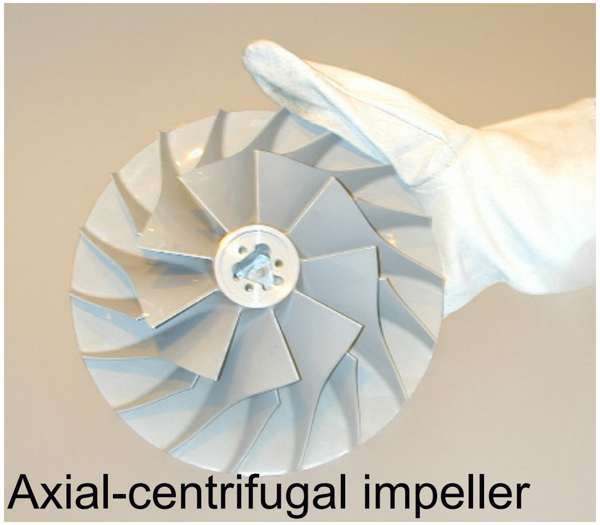
23 kW @ 4.6 K to 20 K

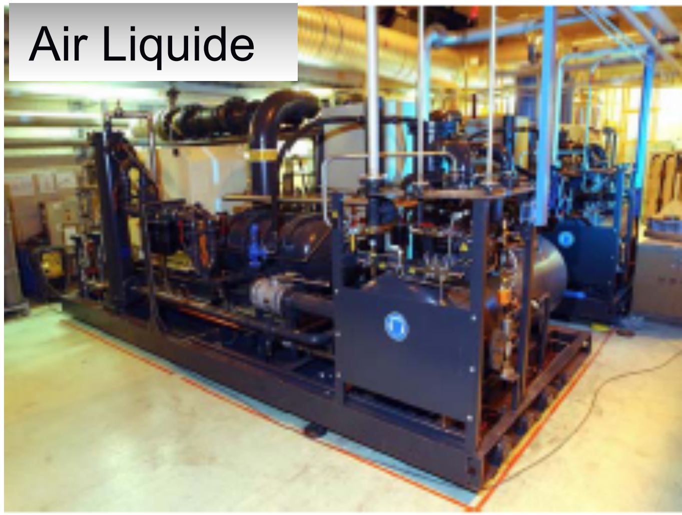
41 g/s liquefaction

Warm compressors

2.4 kW @ 1.9 K refrigeration units

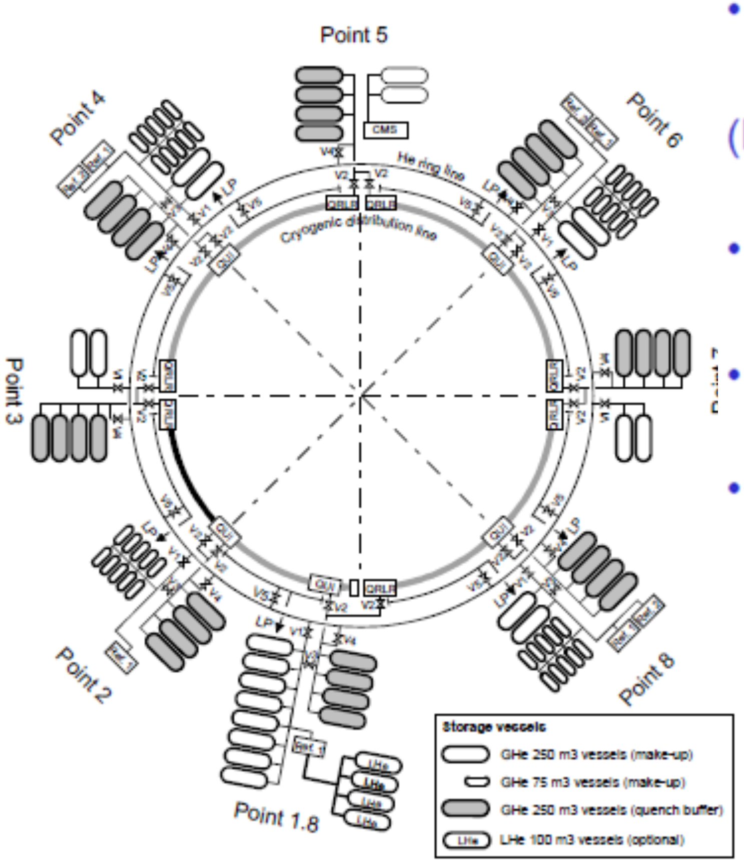
Cold compressor key technology





Cryogen management (helium, nitrogen)

Cryogen storage



25 L. Tavian, D. Delikaris, 22th-26th September 2008

- LHC (accelerator & detectors) helium full inventory:

  136 t, completed by July 08

(LHC accelerator storage capacity: 75 t in situ, 55 t of "virtual storage" in collaboration with industrial suppliers)

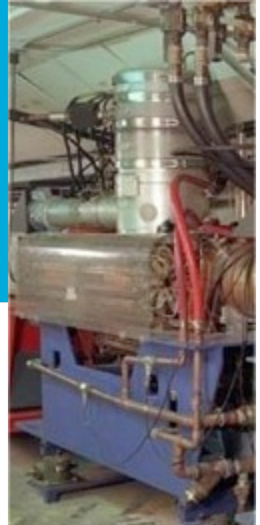
- Present total helium inventory at CERN: **150 t**

- LHC (accelerator & detectors) liquid nitrogen needs for a full cool down: **11'500 t**, completed by end of June 08
- (LHC accelerator full cool down: **10'000 ton in 33 continuous days**; equivalent to 500 standard transportable containers delivered by industrial suppliers)

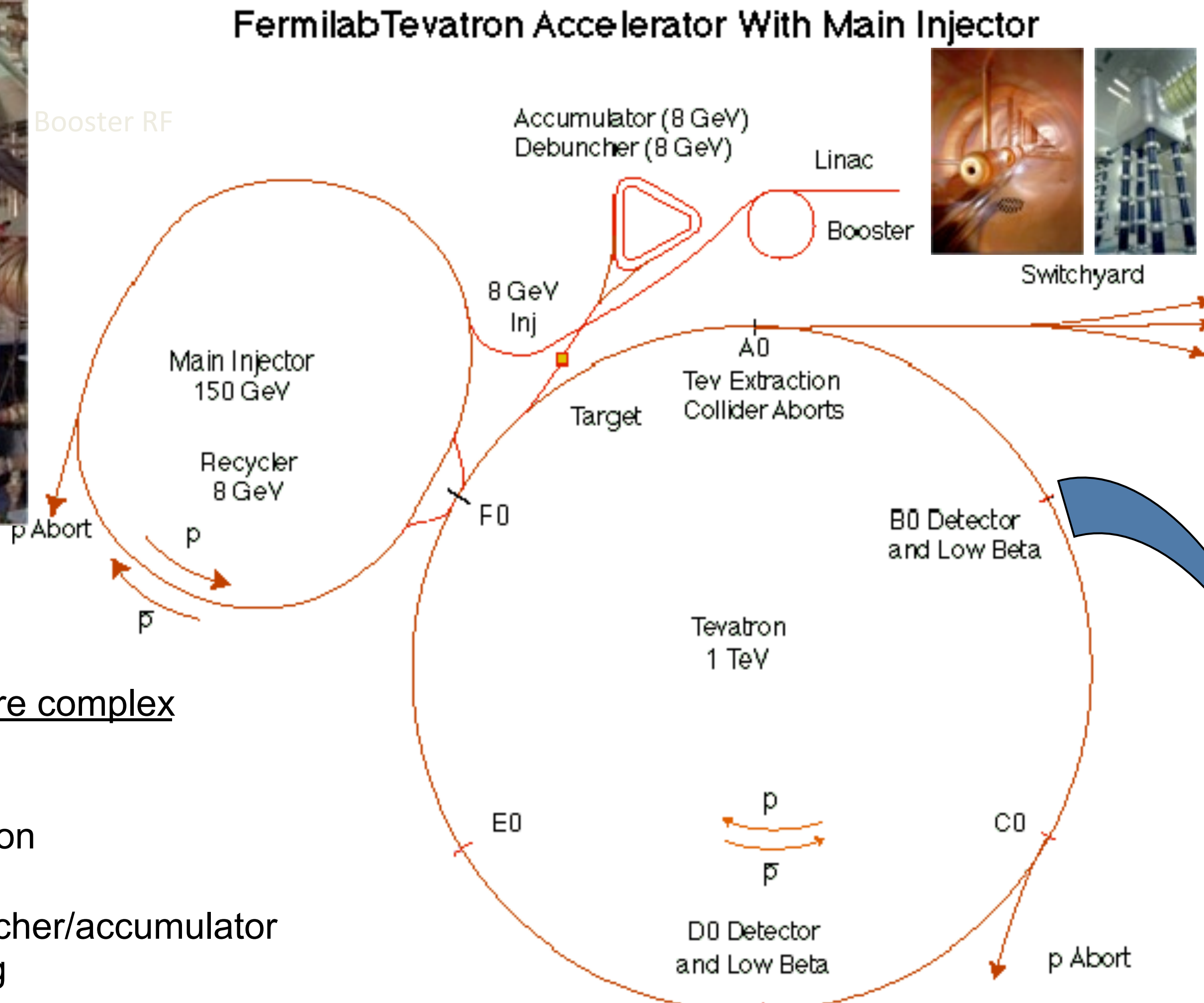
Courtesy of Laurent Tavian

Outline

- Types of Particle Accelerators
- Accelerator Characteristics
- RF Cavity
- Superconductivity and Superfluidity
- Examples of the Particle Accelerators:
  - The European Spallation Source (SRF cavities R&D)
  - The LHC (low-beta magnets environment and Controls)
  - The Tevatron (historical accelerator complex and technologies)



Booster RF



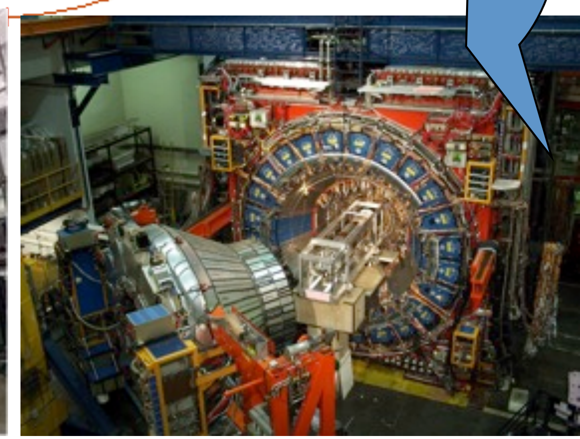
Cockcroft Walton

Unified control system for the entire complex

- 400 MeV Linac
- 8 GeV Booster Synchrotron
- 120 GeV Main Injector Synchrotron
- 1 TeV Tevatron Synchrotron
- antiproton source – target/debuncher/accumulator
- antiproton “Recycler” storage ring
- fixed target lines

Simultaneous operation of

- Tevatron proton-antiproton collider (storage ring)
- Antiproton production and storage (~0.5 Hz)
- 120 GeV fixed target to Meson lab (~0.1 Hz)
- 120 GeV fixed target to NUMI/MINOS (~0.5 Hz)
- 8 GeV fixed target to MiniBoone (~5 Hz)



Fermilab Accelerator Division

Superconducting Magnets

- Magnets in the TEVATRON are superconducting.
- There are about 1000 magnets in the TEV
- The coils are made of niobuim-titanium alloy wire.
  - The size of the wire is 0.0003 inches (8 um)
  - There are 11 million wire-turns in a coil.
  - The dipole magnet is 21 feet long
  - There are 42,500 miles of wire in a magnet
- For 900 GeV operation, the magnets are kept at 4.6° Kelvin.
- For 1000 GeV operation, the cryogenic system has been upgraded to obtain a temperature of 3.6° Kelvin (-453°F)

Fermilab
Accelerator
Division

Superconducting Magnets

- The field in the magnets at 900 GeV is 4 Tesla (The Earth's magnetic field is 0.0003 Tesla, 13,000 times weaker then a TEV magnet)
  - An LHC magnet (Large Hadron Collider in Geneva, Switzerland) will have a magnetic field between 8-10 Tesla.
  - The theoretical limit for mechanically constraining a superconducting magnet is about 15 Tesla.
- The current flowing through a magnet at 900 GeV is 4000 Amperes.
  - The total inductance of the TEVATRON is 36 H.
  - The total magnetic stored energy in the TEVATRON at 900 GeV is 288 MegaJoules.
  - The time constant of the current dump system is 12 seconds.
  - If all the current in the TEV needed to be dumped, the dump resistors would have to dissipate energy at 24 megawatts

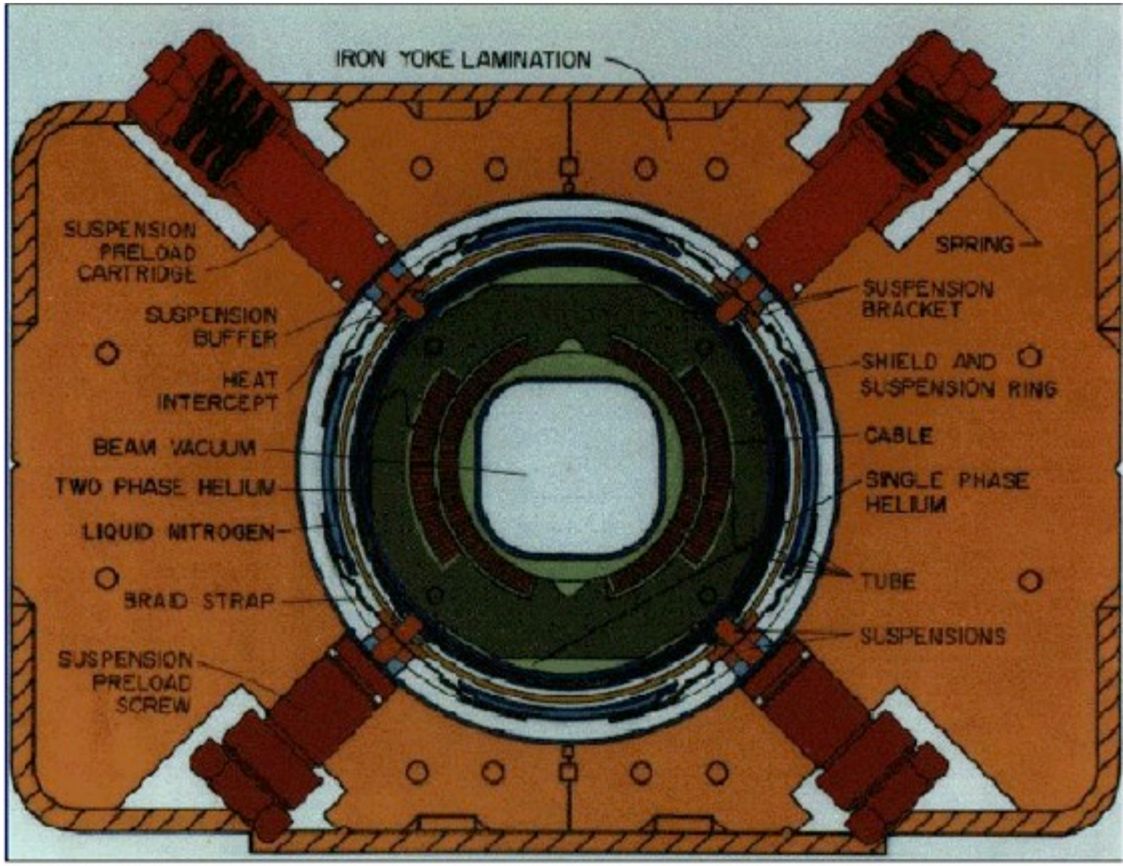
Fermilab
Accelerator
Division

TEVATRON Cryogenic System

- The cryogenic cooling system is:
  - the largest Cryogenic system in the world.
  - an International Historical Mechanical Engineering Landmark
  - capable of supplying 1000 liters/hour (35 grams/sec) of liquid helium at 4.2 K.
  - capable of absorbing heat at a rate of 23 kW and still maintain a temperature of 4.6 K.
- The cryogenic system consists of a:
  - Central Helium Liquifier which is the biggest in the world by a factor of 3 and consists of
    - four 4000 hp helium compressors (flow rate of 539 g/sec at 175psi)
    - two 40 ft tall cold boxes
    - helium gas tank farm with 30,000 liquid liter equivalent storage capacity
    - a nitrogen system with a 152,000 liter storage capacity
  - 24 satellite refrigerators located around the ring.
    - which are connected by twenty six 250 meter liquid helium transfer lines.
    - which are fed helium gas at 290 psi.

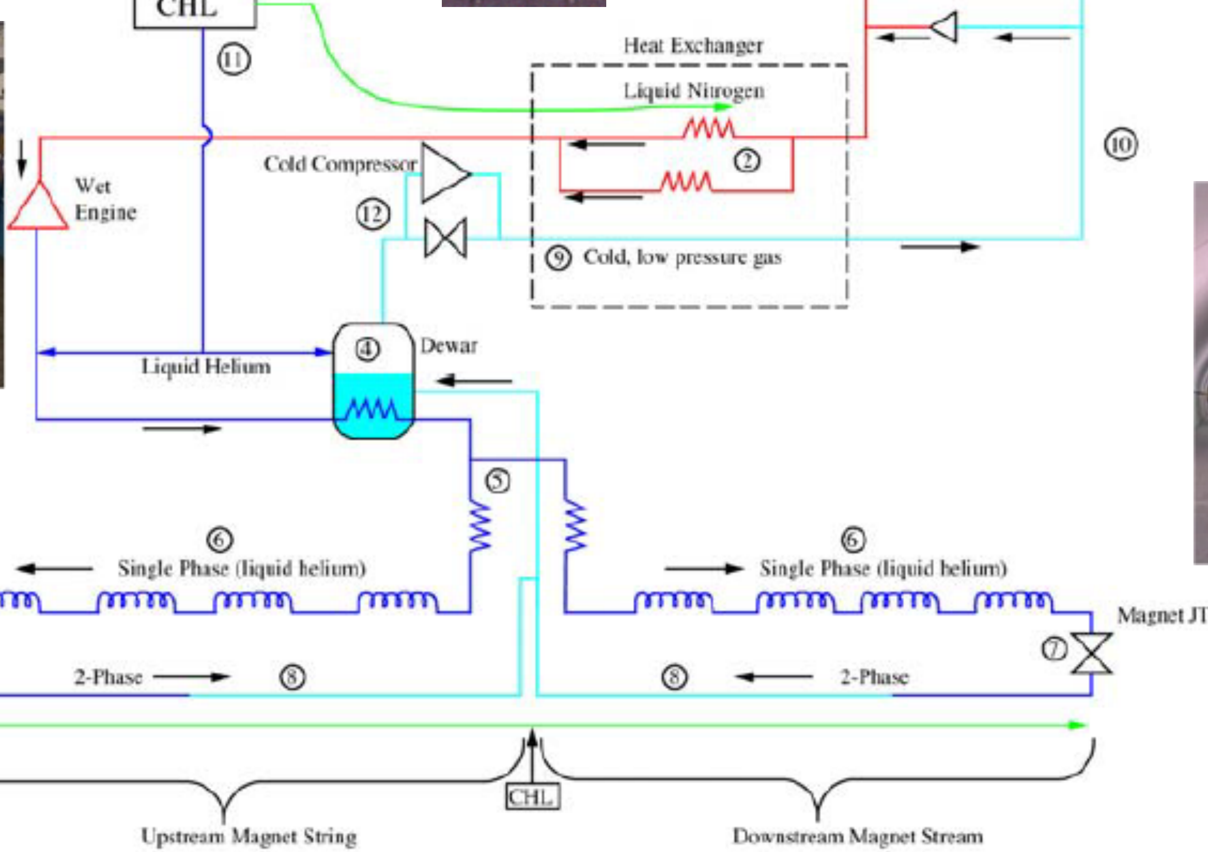
Tevatron magnet cross-section

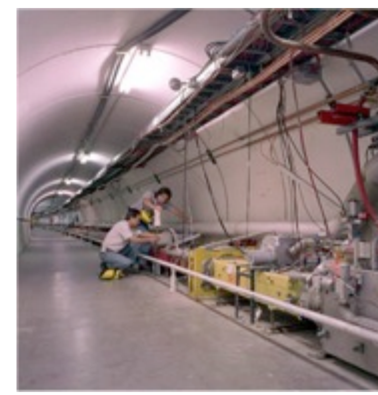
6.5 km of superconducting magnets operating @ 3.6 Kelvin:
+777 dipoles
+216 quads
+204 correction elements



+ coils made of NbTi alloy wire
+ wire size is 8 mm
+11 million wire-turns in a coil
+ 42,500 miles of wire per magnet

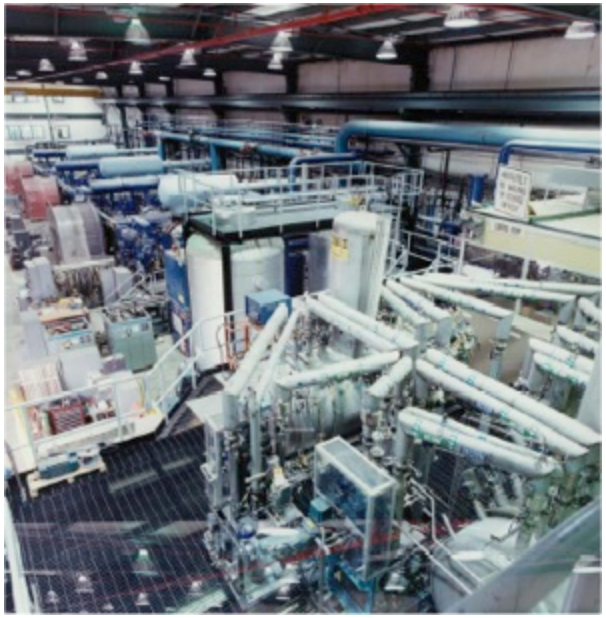
One typical cooling loop for the Tevatron





Central Helium Liquefier - CHL

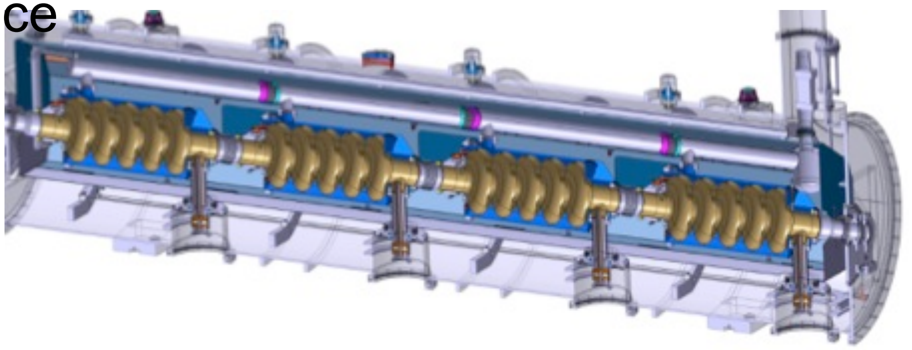
The Central Helium Liquefier consists of:
- Four parallel reciprocating 4,000 HP helium compressors (6.8 MW total power)
- Two Claude cycle cold boxes (6,400 liters/hr, peak at 9000 liters/hr)
- 15 helium gas storage tanks (1,500 m3, 1.7 MPa, at RT)
- One Nitrogen Reliquefier (4,680 liters/hr)
- 600,000 liters of LN2 storage
- Purification system



Summary

Accelerator Components requires:

- State-of-the-art material performance
- Challenging design
- Unique technologies



Lots of materials available at:

- US-Particle Accelerator School, http://uspas.fnal.gov/materials/materials-table.shtml
- CERN Accelerator School http://cas.web.cern.ch/cas
- Joint Universities Accelerator School

The domain of Particle Accelerator needs YOU !!!