Helium and Large Scale Cryogenics in Accelerator Sciences

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Headlines

The Ingredients
- Helium: The star of cryogenics
  - ✓ Liquid helium: 100 years
  - ✓ Superfluid helium
- Accelerator examples

CERN and the Large Hadron Collider
- The LHC accelerator
- The low-β magnets systems

Fermilab Accelerator Sciences
- The Tevatron and its cryo-plant
- New cryogenic areas and era

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- Fermilab Accelerator Sciences
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Few milestones of interest

1868 - Astronomers Janssen and Lockyer observed Helium

1908 - Kamerling Onnes Liquefied Helium (4.2 K)

1911 - Kamerling Onnes Discovered Superconductivity (Hg)

1938 - Superfluid Helium properties by Kapitza, Allen and Misener

1949 – Landau & Tizsa introduced the two-fluid model for superfluid helium

1957 - BCS Theory

1980 - Tevatron, First Accelerator using SC Magnets, NbTi

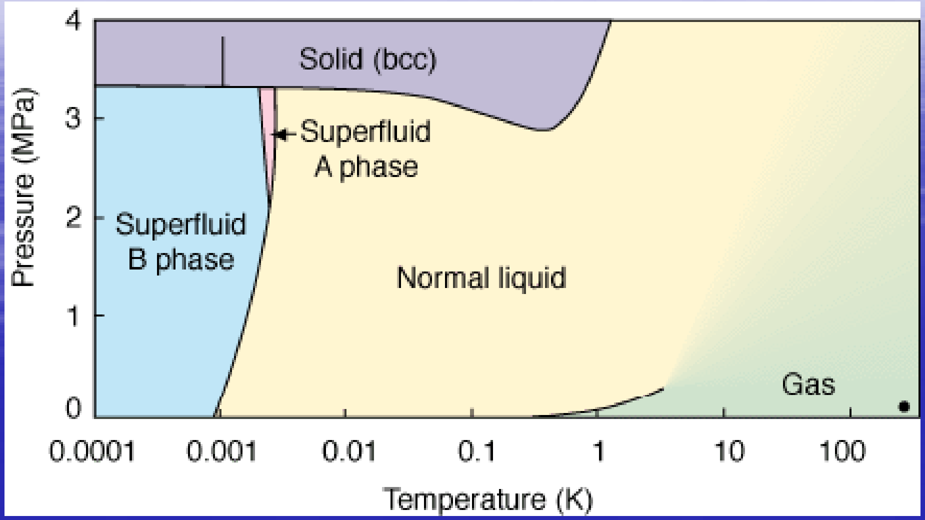
1986 - High Temp. Superconductors (> 77 K), YBCO, BSCCO

2001 – High Temp. SC (MgB_2) with High Tc (39 K)

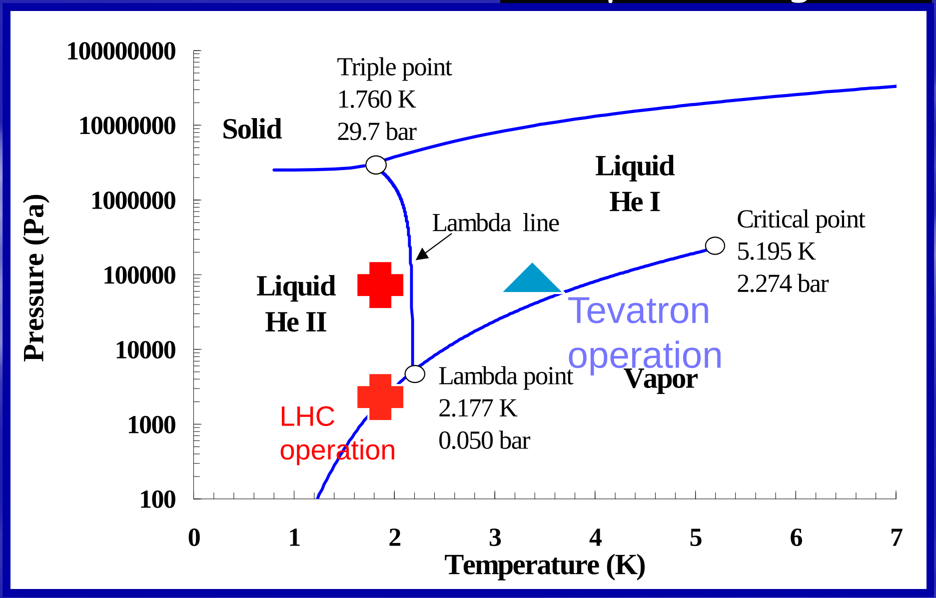
2007 - LHC operation (Largest Cryogenics)

The different facets of helium

^{3}He phase diagram



^{4}He phase diagram



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

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

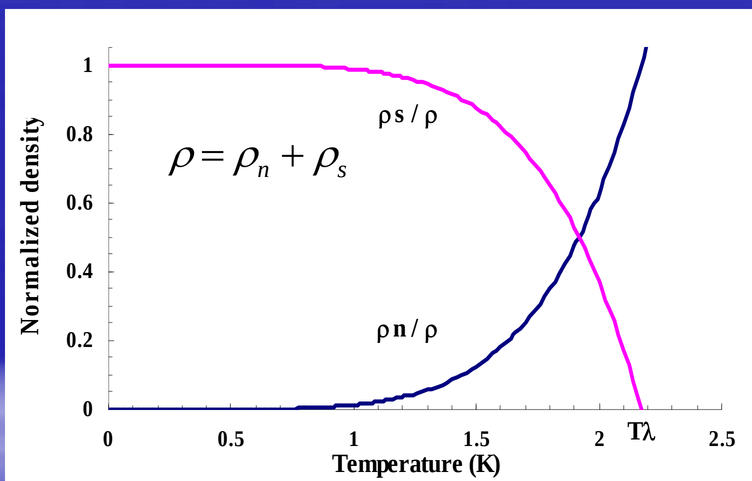
Helium II - Quantum fluid

- 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)

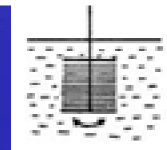
A two-fluid model for helium II

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

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



Androniskashvili experiment



Superfluid fraction:
- atoms that have undergone BEC

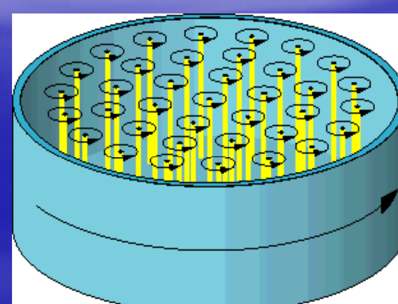
➔ like an ideal inviscid liquid resulting in the absence of classical turbulence.
- finite density, ρ_s
- NO viscosity
- carry NO entropy

→ irrotational behavior for an inviscid fluid

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

→ but vortices can be generated in the superfluid component

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

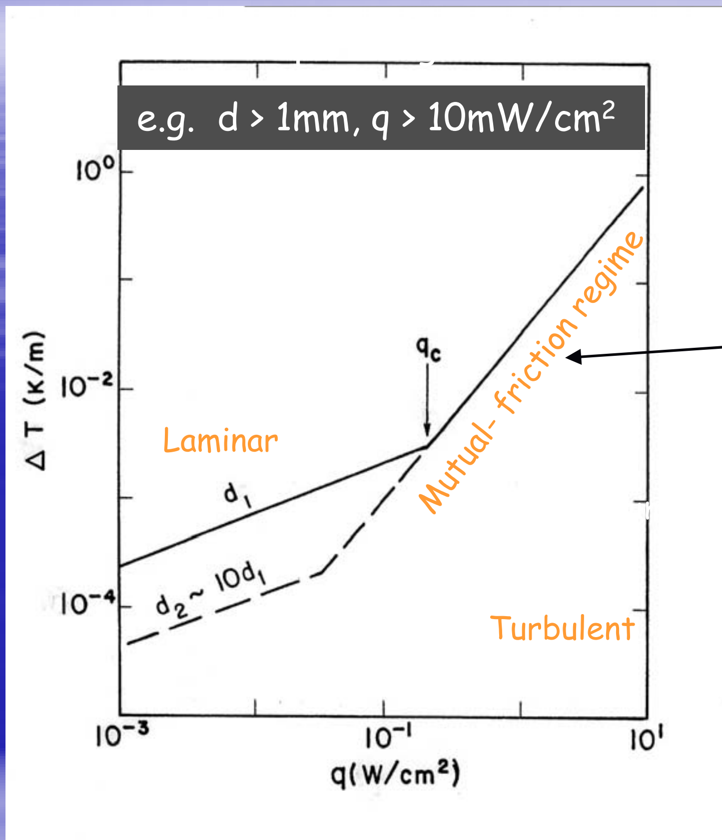


Quantized vortices

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

Counter-flow turbulence

Thermal conductivity of helium II



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

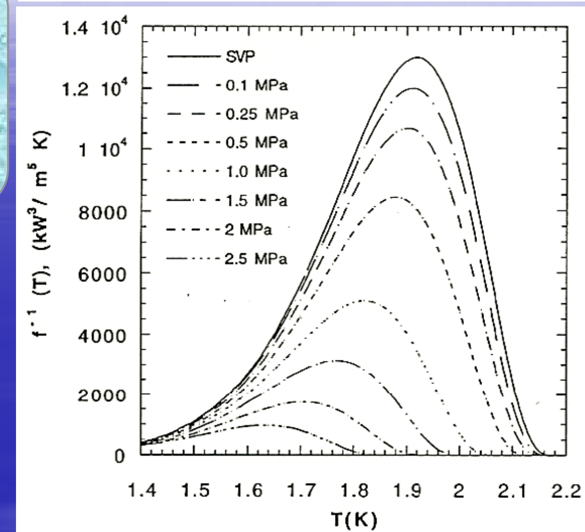
In mutual friction regime:

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

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

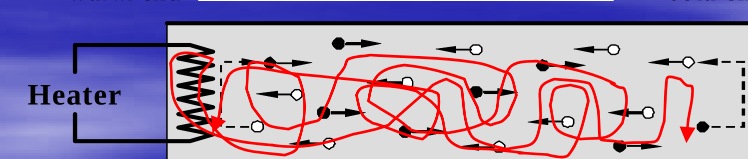
A_{GM} Gorter-Mellink mutual friction parameter

Thermal resistivity function



Counter-flow mechanics

No bulk flow
Heat flux



• normal-fluid component

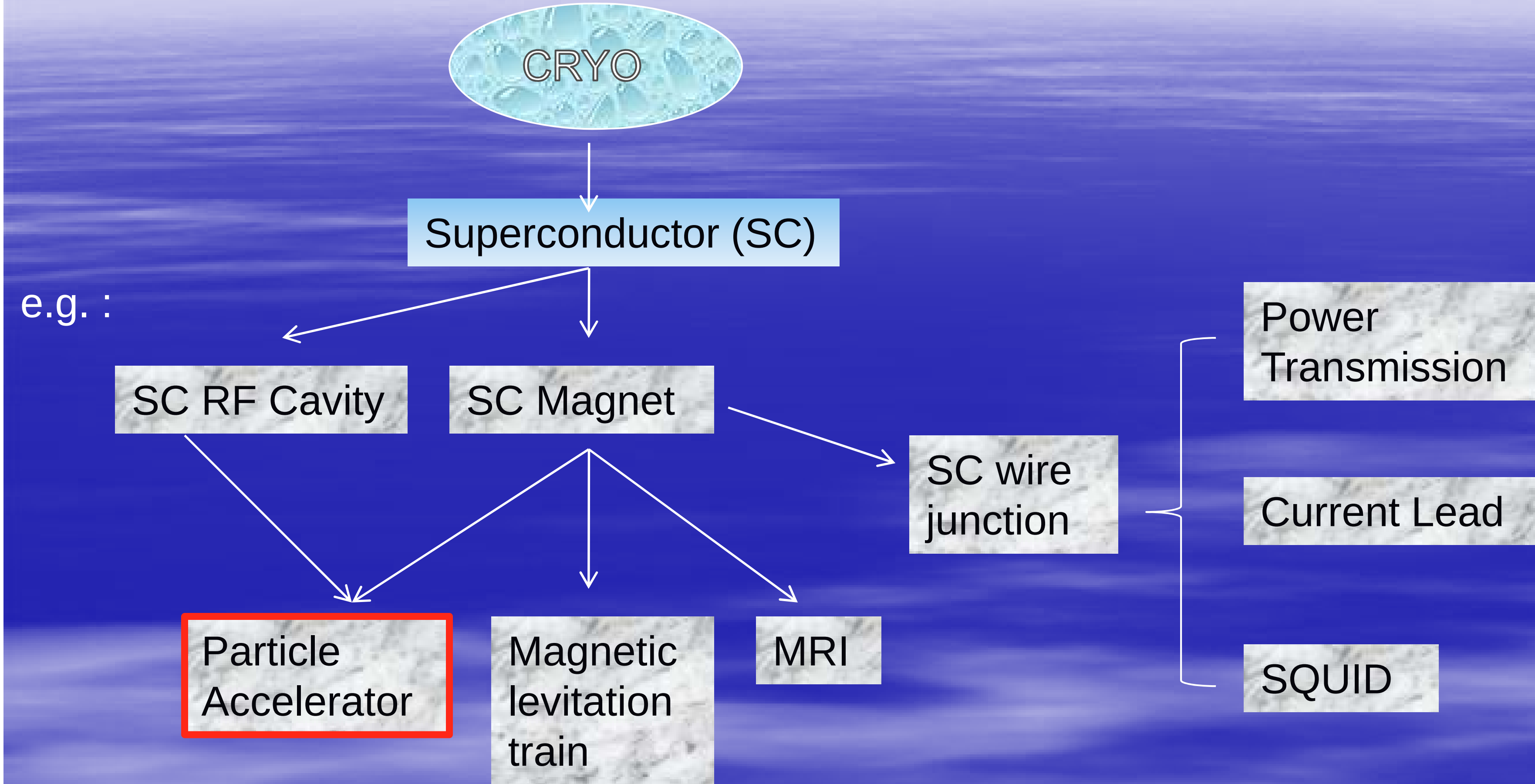
◦ super-fluid component

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

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

Thermo-mechanical - fountain effect

Cryogenic applications - Superconductors

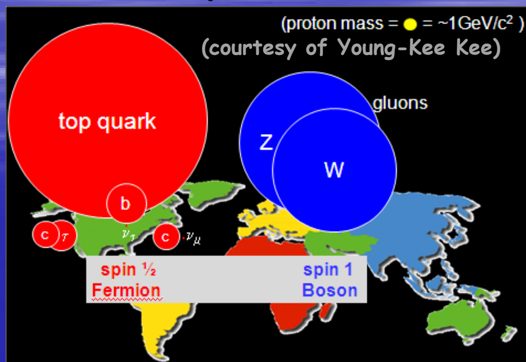


Anomalous transport properties used to cool high-field superconducting magnets and RF cavities

Why do we need accelerators ?

Today: > 30,000 accelerators are in operation around the world

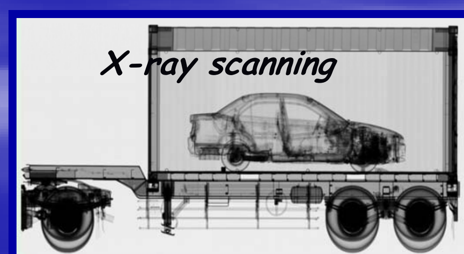
- Discovery science: e.g. High Energy Physics



FNAL:

- 1900 employees
- 2300 users (~1/2 from abroad)
- 6800 acres, park-like site

- Materials research / manufacturing:
e.g. light sources

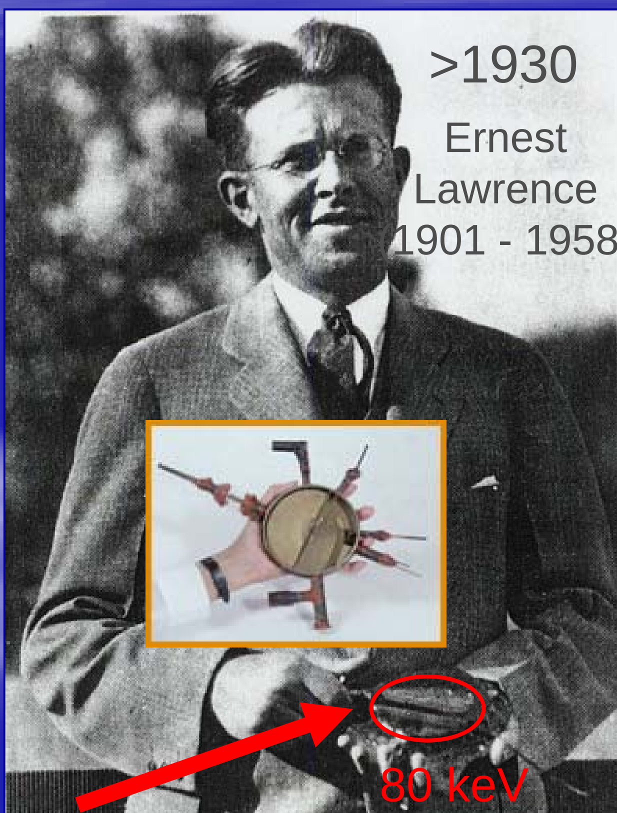


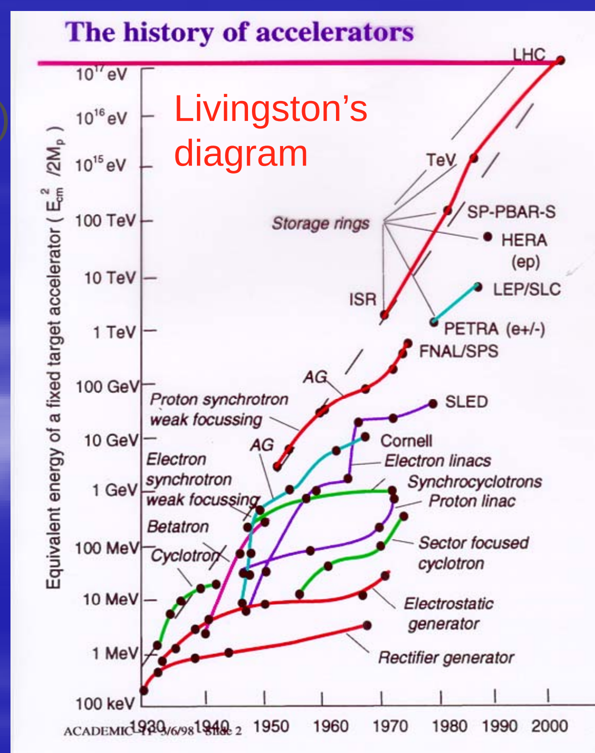
- National security

- Medical Applications:
e.g. Neutron and Proton Therapies
MRI and NMR

Many generations of accelerators

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





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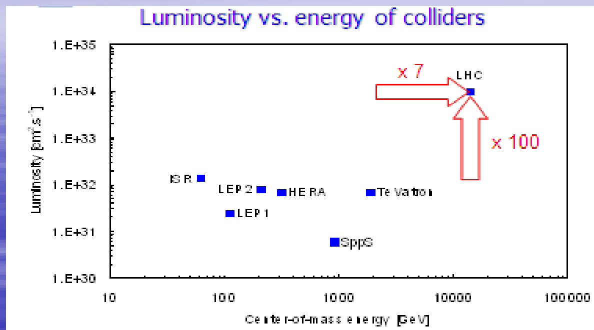
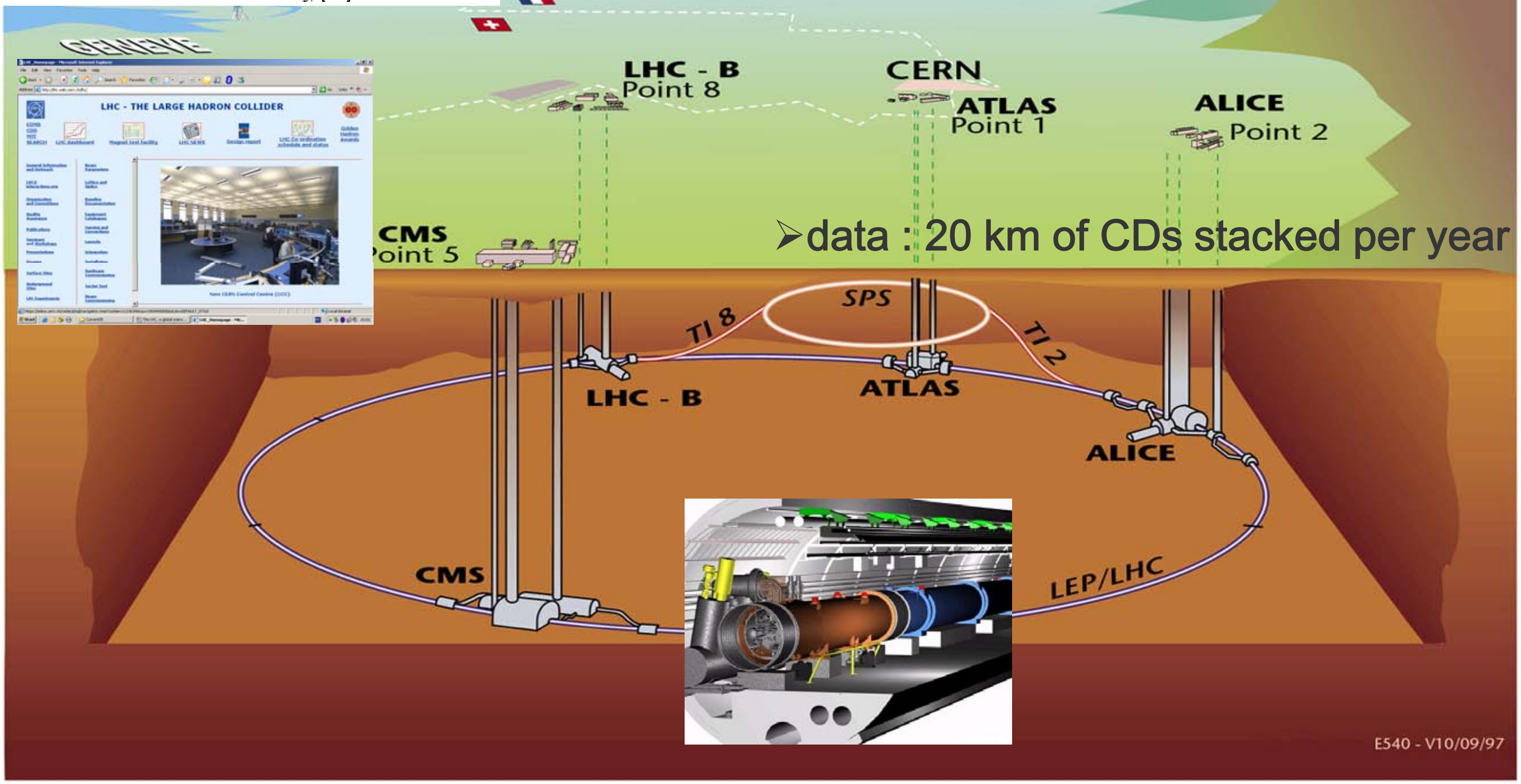
CERN and the Large Hadron Collider

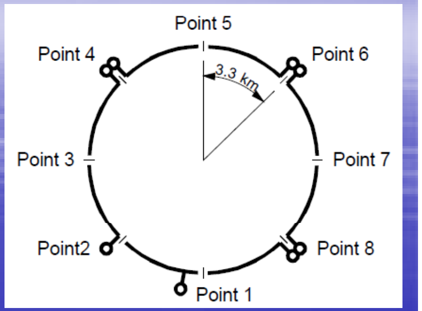
Searching for the Higgs boson !

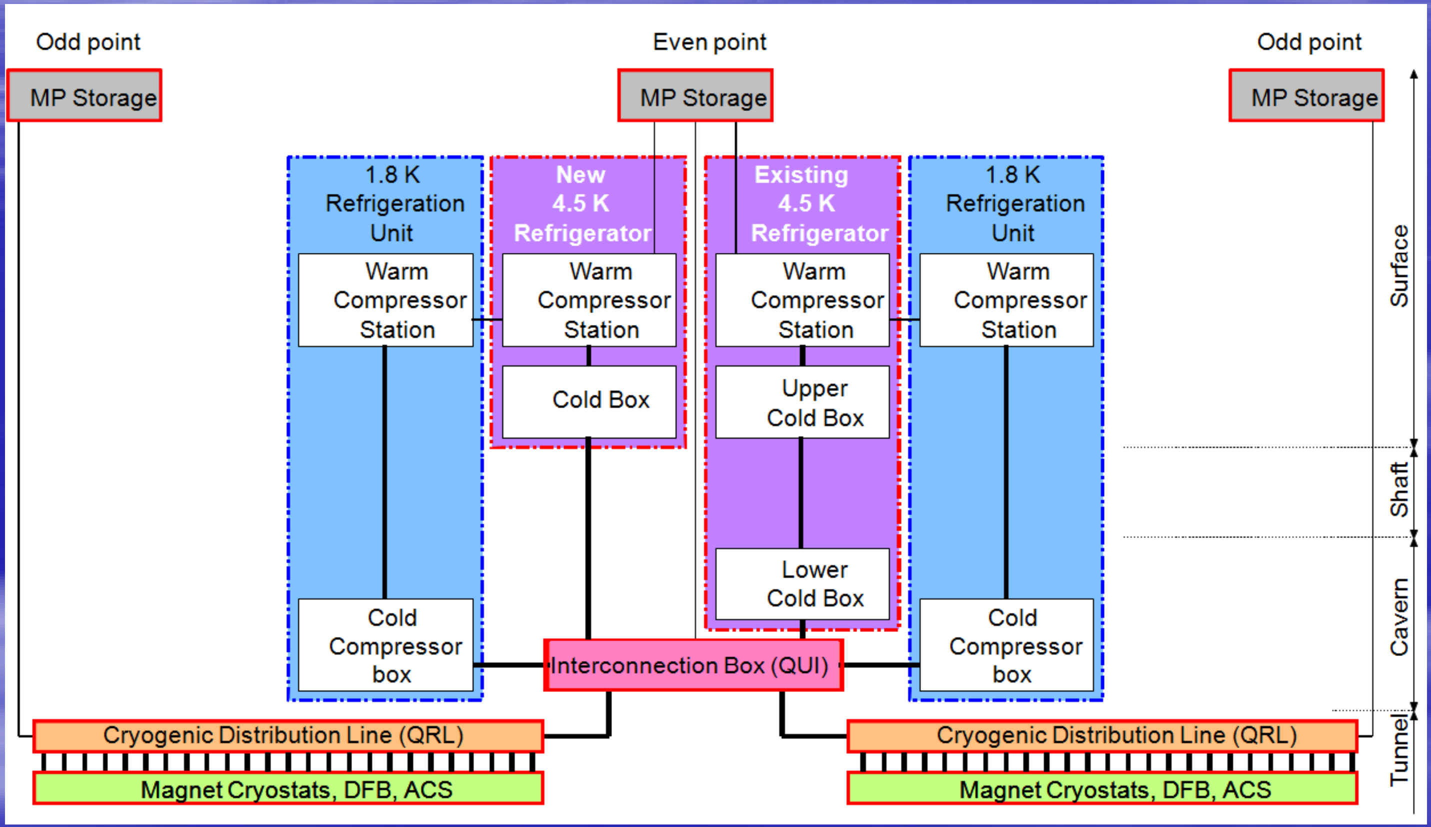




➢data : 20 km of CDs stacked per year

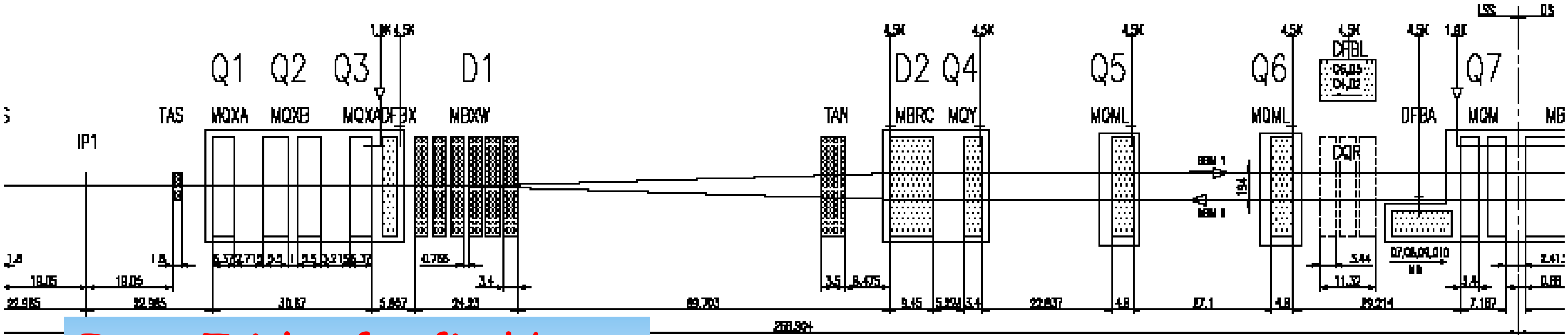
General architecture of the cryogenic system





3300 m

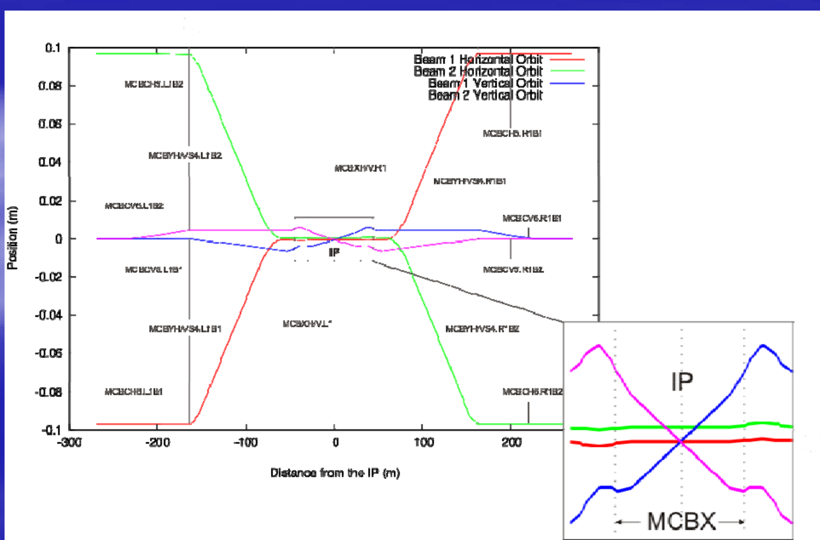
The low-β magnet systems at the LHC

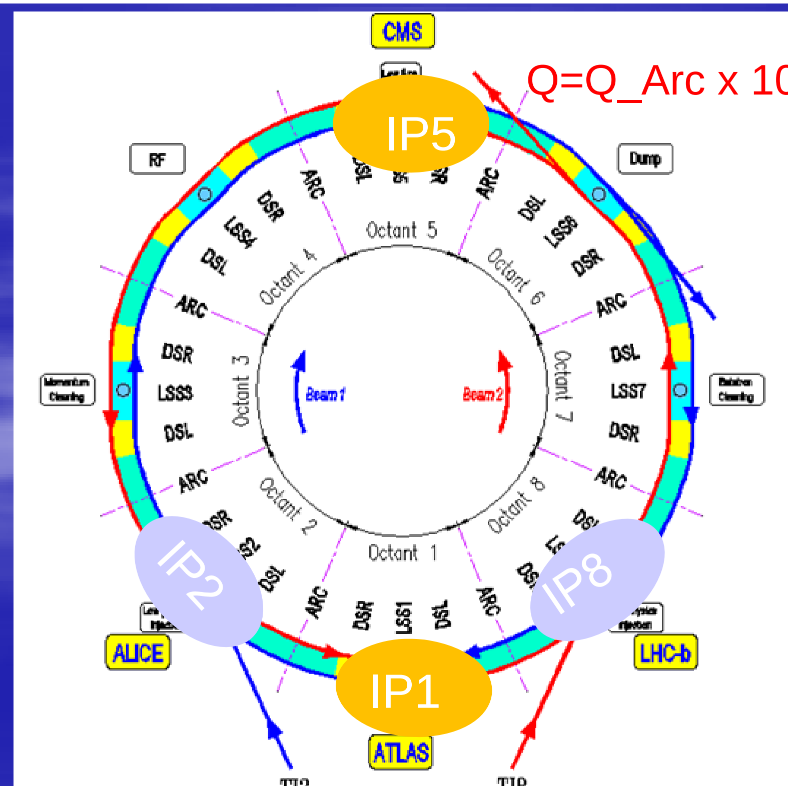


Inner Triplet for final beam focusing/defocusing

➔ Critical system for LHC performance

American contribution to the LHC machine

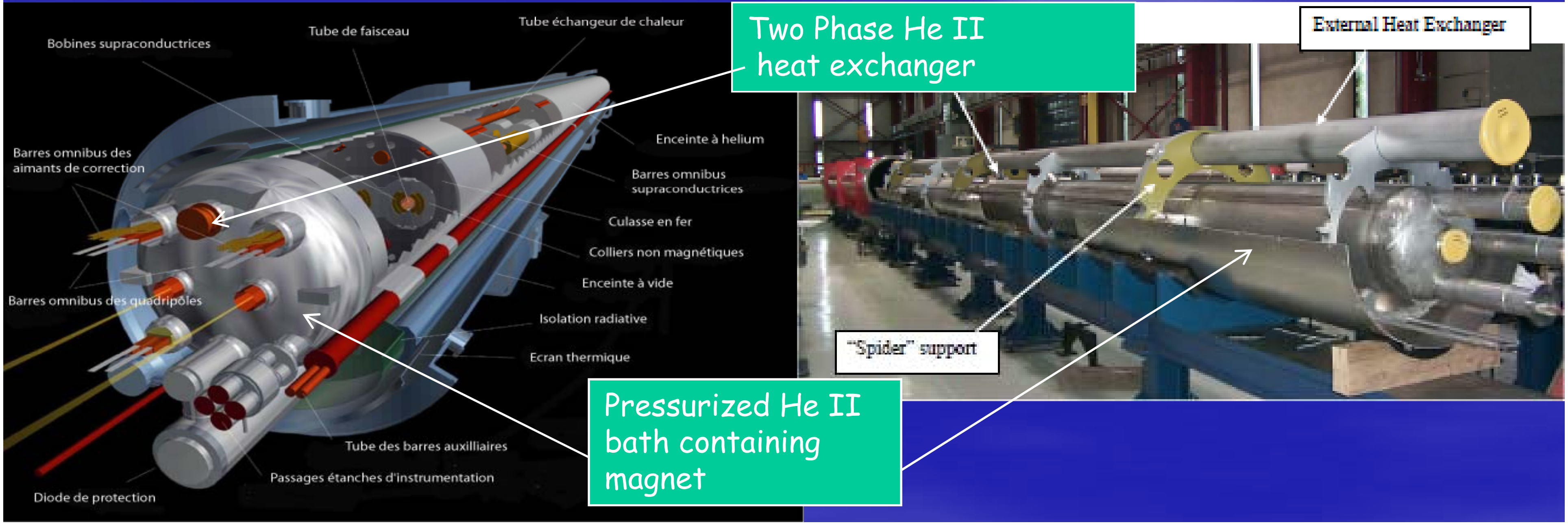




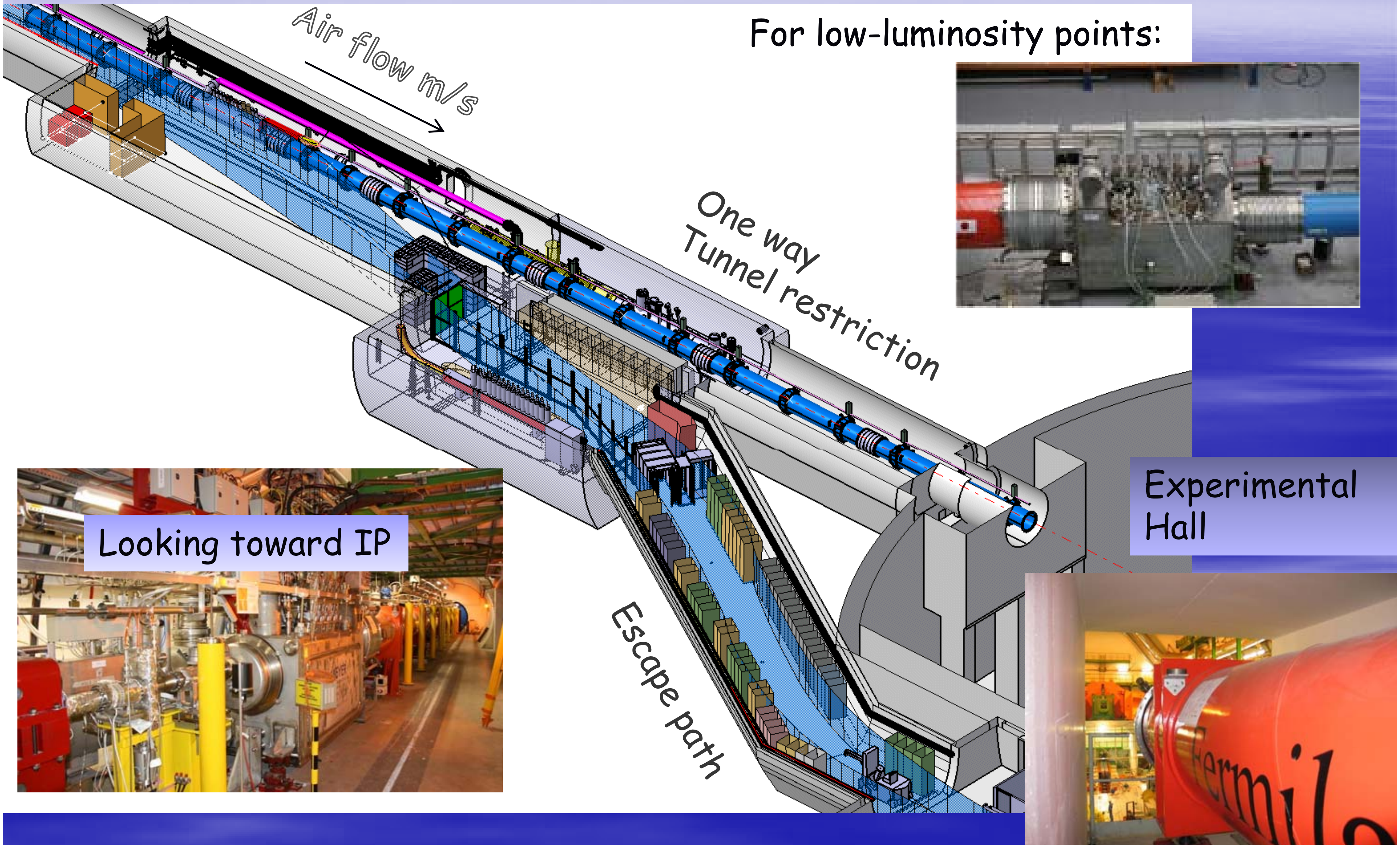
Key technologies of the LHC accelerator

- Superconducting magnets
  - 1,250 ton of NbTi superconducting materials
  - 7,600 km of superconducting "Rutherford" cables
  - 9,600 magnets (incl.1,232 dipoles, 392 quadruples)

- Superfluid helium cryogenics (< 2 K) and vacuum techniques
  - Pressurized and saturated superfluid helium, in two-phase flow
  - Cryostats and thermal insulation
  - Efficient and large capacity helium refrigerators
  - Cryogen storage and management (120 ton of helium)



Underground views : 80-120 m below ground level



The low-β magnet system safety specification

Design and operation requirements:

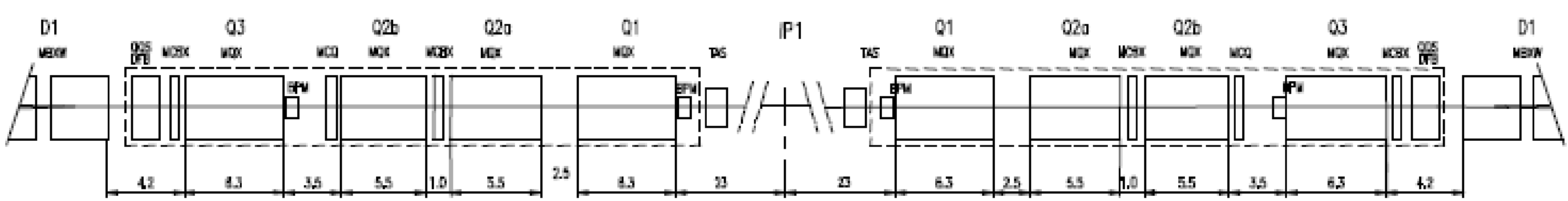
- Critical system for LHC performance, but the system operation and maintenance should remain safe for personnel and for equipment,

  e.g. escape path, absorbed radiation dose, embrittlement, polymer prop. decay.
- Equipment, instrumentation and design shall comply with the CERN requirements,

  e.g. ES&H, LHC functional systems, Integration
- Risks identified: Mechanical, electrical, cryogenics, radiological

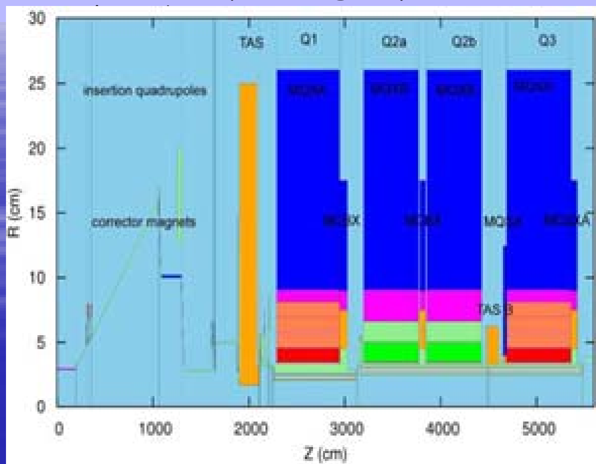
- ☐ Cryogenic risk → FMEA, Use the Maximum Credible Incident (MCI)

- ☐ Radiological → Use materials resistant to the radiation rate permitting an estimated machine lifetime, even in the hottest spots, exceeding 7 years of operation at the baseline luminosity of $10^{34}cm^{-2}s^{-1}$.
- ☐ Personnel safety: Keep residual dose rates on the component outer surfaces of the cryostats below 0.1 mSv/hr.
- ☐ Apply the ALARA principle (As Low As Reasonably Achievable).

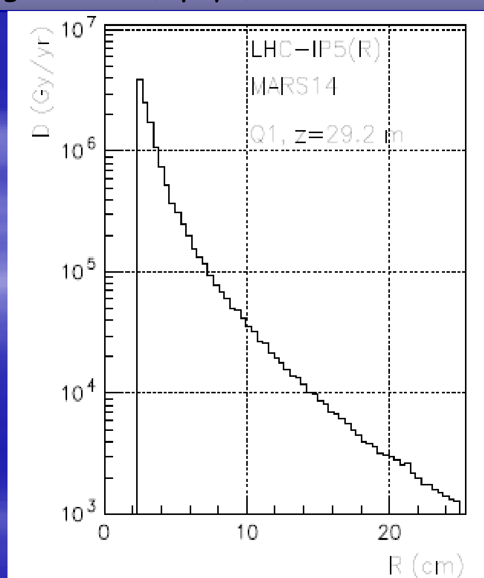


Radiological risk (*By courtesy of N. Mokhov*)

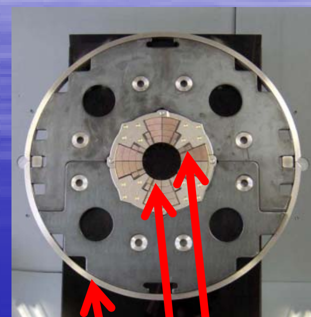
IR5 azimuthally averaged power

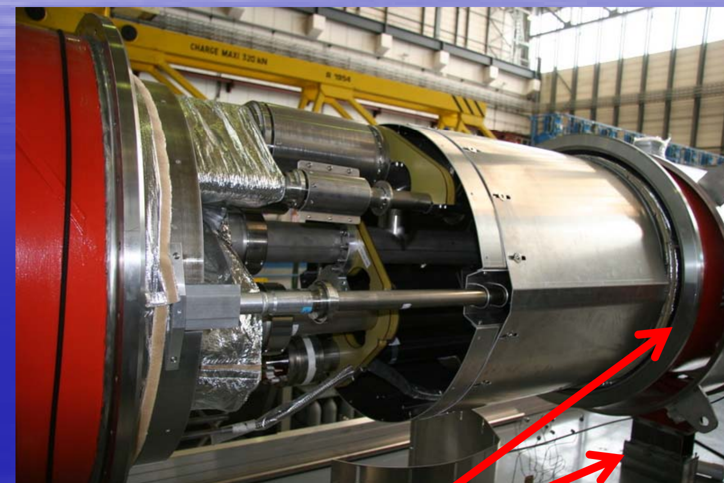


Radial distribution of azimuthally averaged dose (Gy/yr)



→ Magnet quench limit =1.6 mW/g



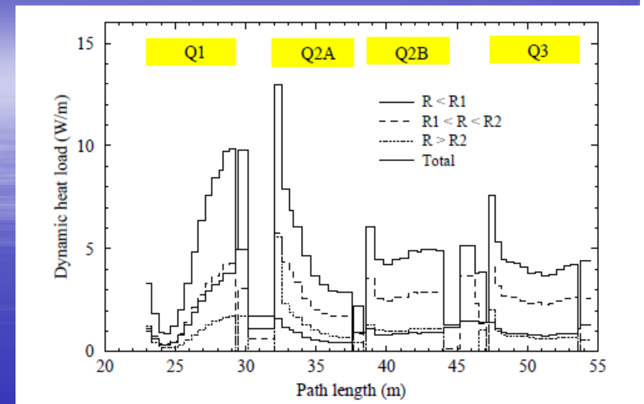


Element	z-region (m)	P (W)	D (kGy/yr)
Pipe		0.841	
Bore		1.994	
Helium	54.45-58.83	0.108	523.2
Jack		0.936	310.6
Ins+vessel		0.488	
r=9 cm		1.014	74.18
r=15 cm	54.485-58.795	0.470	20.85
r=30 cm		0.272	6.074

For comparison : Arc magnet ~ 1 Gy/yr

Radiological risk mitigation

LHC operation annual radiation dose for the arc magnet and for the CMS/ATLAS low-β regions are 1 and 1000 Gy, respectively



Beam-induced energy deposition:

Quadruple quench limit ~1.6 mW/g

→ No easy repair when inherent radiation !

→ Instrum. & equipment: radHard

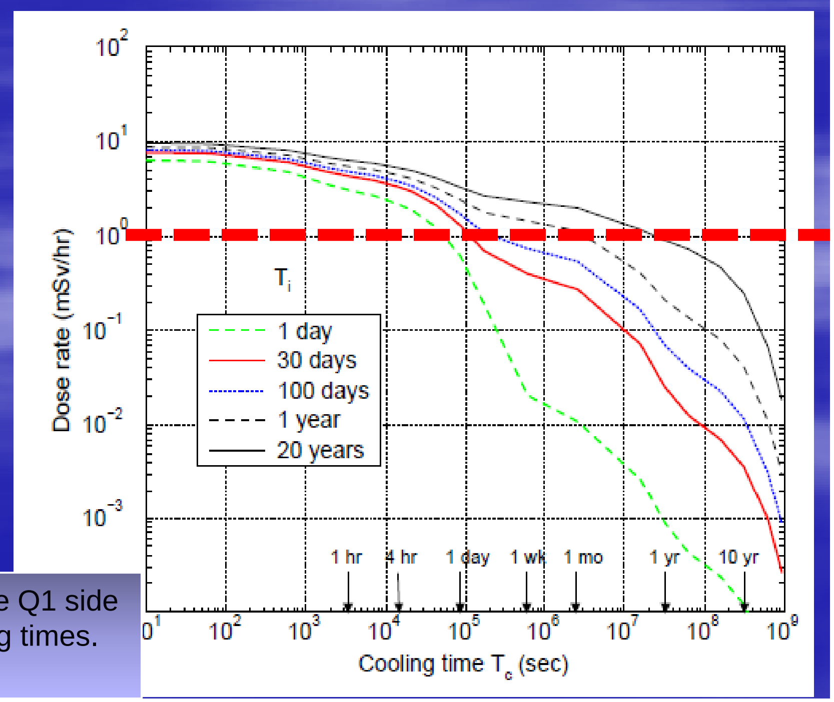
→ Use of redundancy

→Specific hazard analysis is requested before personnel intervention

→ Radiological survey is systematical performed prior intervention (< 1mSv/hr)

→ Limit the personnel exposition time (individual and collective radiation doses)

→ Radio-Protection Procedures to be written based on lessons learned and other institutes experiences

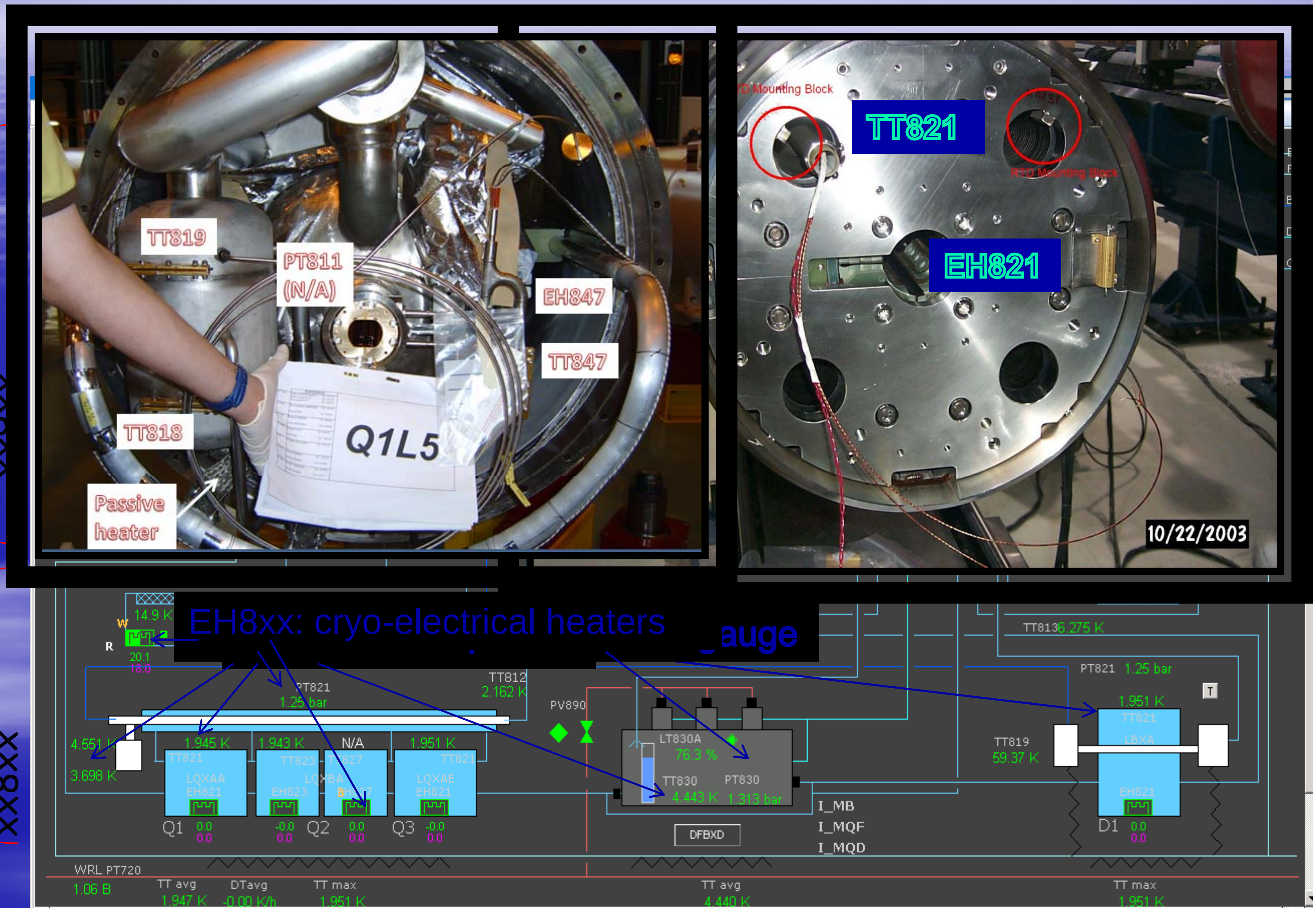


Averaged over surface residual dose rate (mSv/hr) on the Q1 side (z=2125 cm, bottom) of the TAS vs irradiation and cooling times.
By courtesy of N. Mokhov

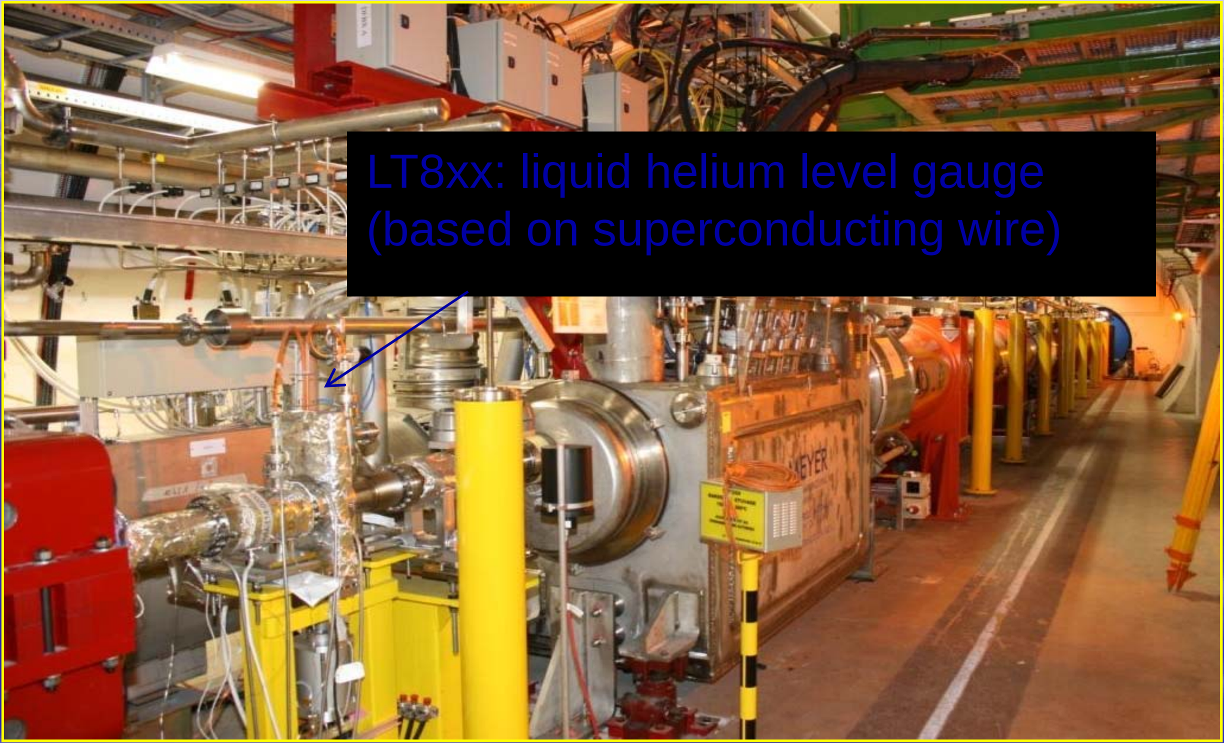
Type of instrumentation : cryo-magnets

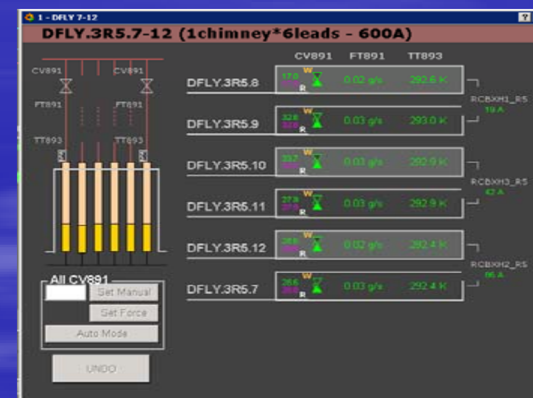
Interface with QRL xx9xx

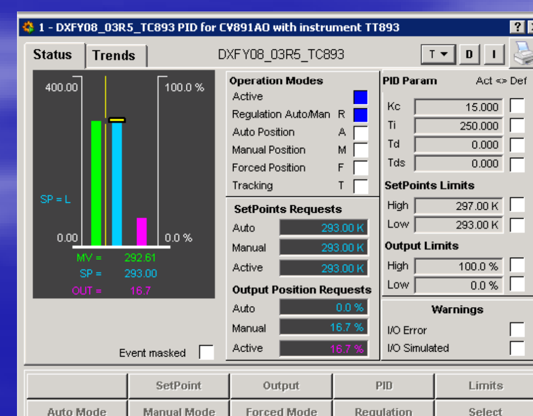
Low-beta system xx8xx

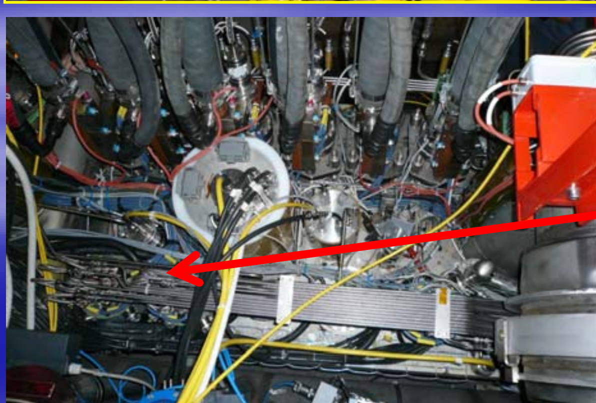


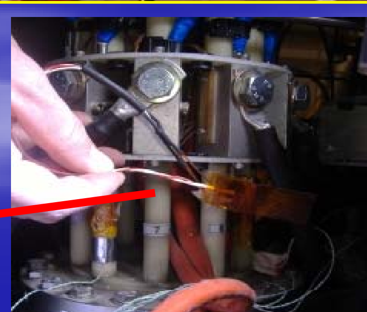
Electrical feed-boxes











*HTS leads

*Vapor cooled leads

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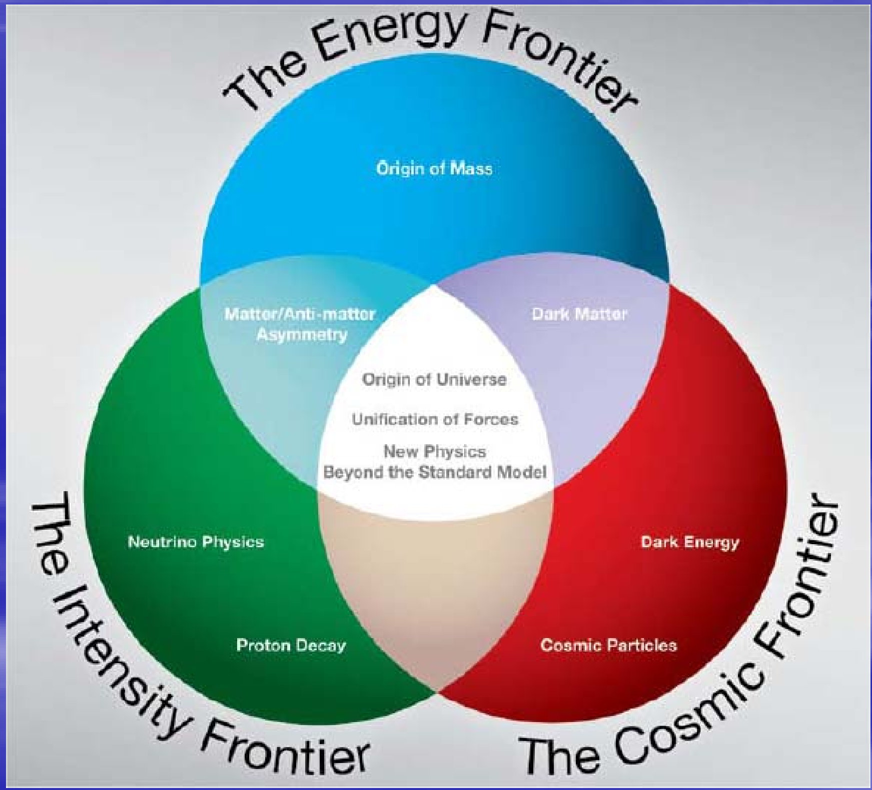
Fermilab - New areas and era

"Three frontiers of research in particle physics form an interlocking framework that addresses fundamental questions about the laws of nature and the cosmos.

- The Energy Frontier, using high-energy colliders to discover new particles and directly probe the architecture of the fundamental forces.

- The Intensity Frontier, using intense particle beams to uncover properties of neutrinos and observe rare processes that will tell us about new physics beyond the Standard Model.

- The Cosmic Frontier, using underground experiments and telescopes, both ground and space based, to reveal the natures of dark matter and dark energy and using high-energy particles from space to probe new phenomena."



http://www.fnal.gov/pub/presspass/pdf/UsersPictureBook_022510_FINAL.pdf

Milestones

In 2009, Fermilab set records for proton-antiproton collisions at the Tevatron accelerator. Physicists expanded the horizons of particle physics in experiments at the Energy, Intensity and Cosmic Frontiers.

January / Technicians complete the first assembly of a string of 3.9-GHz superconducting cavities at Fermilab.

Feb. 10 / Four Indian institutions sign a Memorandum of Understanding with Fermilab to collaborate on superconducting materials and superconducting acceleration technology.

March 9 / CDF and DZero announce the discovery of collisions that produce single top quarks, proof of a second kind of subatomic production mechanism for top quarks.

March 13 / CDF and DZero narrow the search for the elusive Higgs boson, setting more stringent constraints on the particle's mass.

March 18 / CDF finds evidence of a new composite particle, Y(4140), whose curious characteristics may reveal new ways that quarks can combine to form matter.

March / DZero obtains the world's most precise measurement of the mass of the *W* boson.

April 1 / The MINERvA neutrino experiment observes the first interactions of neutrinos with carbon and hydrogen atoms.

May 1 / Officials from the U.S. Congress, the U.S. Department of Energy, Fermilab and the University of Minnesota break ground for the NOvA experiment in Minnesota.

May 27 / The ArgoNeuT experiment, which uses a new neutrino detection technology, records the first neutrino signals.

June 29 / CDF announces the discovery of the Omega-sub-*b* baryon, a distant relative of the proton.

July / Fermilab begins the upgrade of its neutrino beamline from 400 to 700 kilowatts for the NOvA project.

August / Construction begins on a high-availability computing center at Fermilab.

September / Working with Fermilab and other DOE laboratories, a U.S.-based manufacturer produces the first SRF acceleration cavity that meets the performance goal for the next-generation linear accelerator.

Sept. 28 / The Department of Energy announces Mission Need for the MicroBooNE neutrino experiment at Fermilab.

October / Technicians begin installing the first cryomodule in Fermilab's new superconducting radio-frequency test accelerator facility.

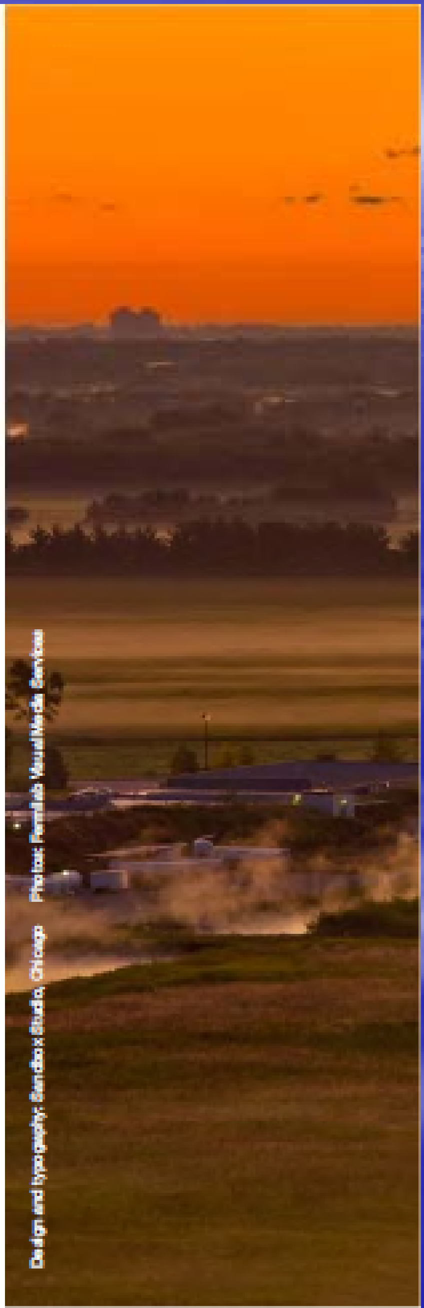
December / The Muon-to-Electron Conversion Experiment (Mu2e) receives DOE's Mission Need approval.

Dec. 4 / A superconducting prototype magnet made of niobium-tin achieves its design goal of 200 Tesla/m.

Dec. 8 / Scientists in the LHC Remote Operations Center at Fermilab observe the first particle collisions in the CMS detector at CERN at the world-record energy of 2.36 TeV.

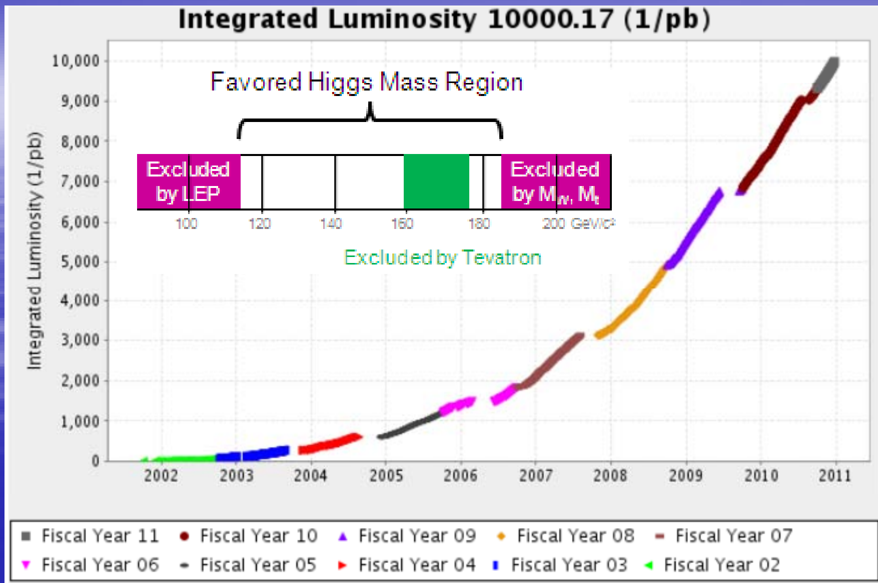
Dec. 17 / The Cryogenic Dark Matter Search announces the observation of two candidate events for dark-matter particles.

Dec. 21-27 / The Fermilab accelerator complex sets a record for the hours of particle collider operation in a single week, producing 151 hours of physics data.



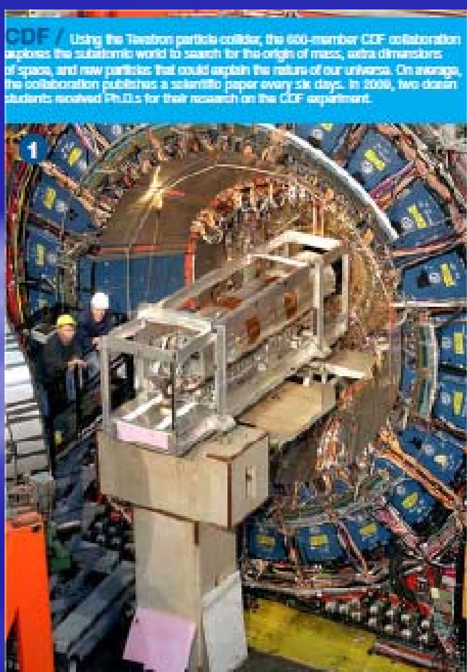
Design and typography: Sandbox Studio, Chicago Photos: Fermilab Visual Media Services

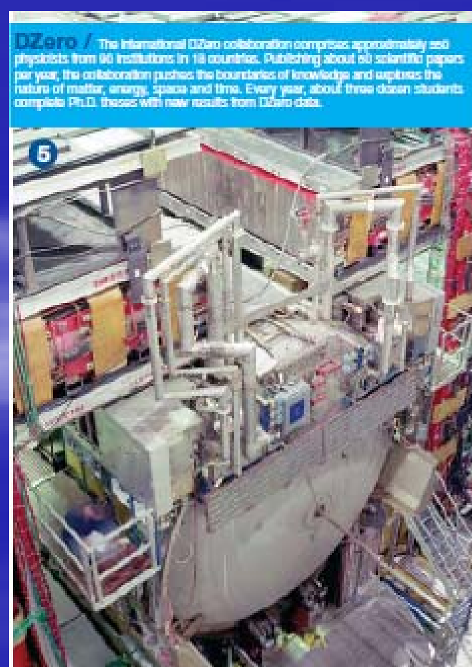
The Tevatron ! Results as per january 4th, 2011

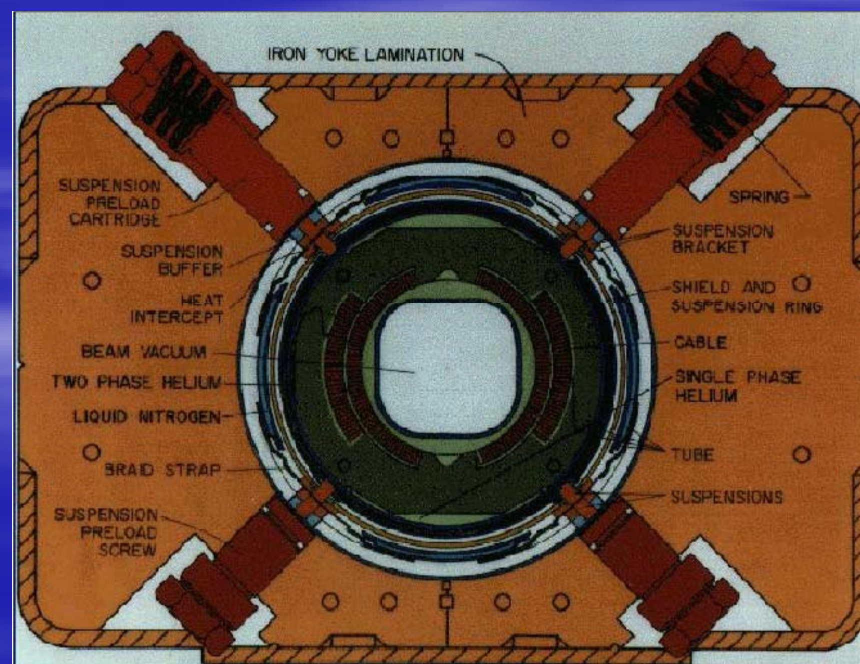


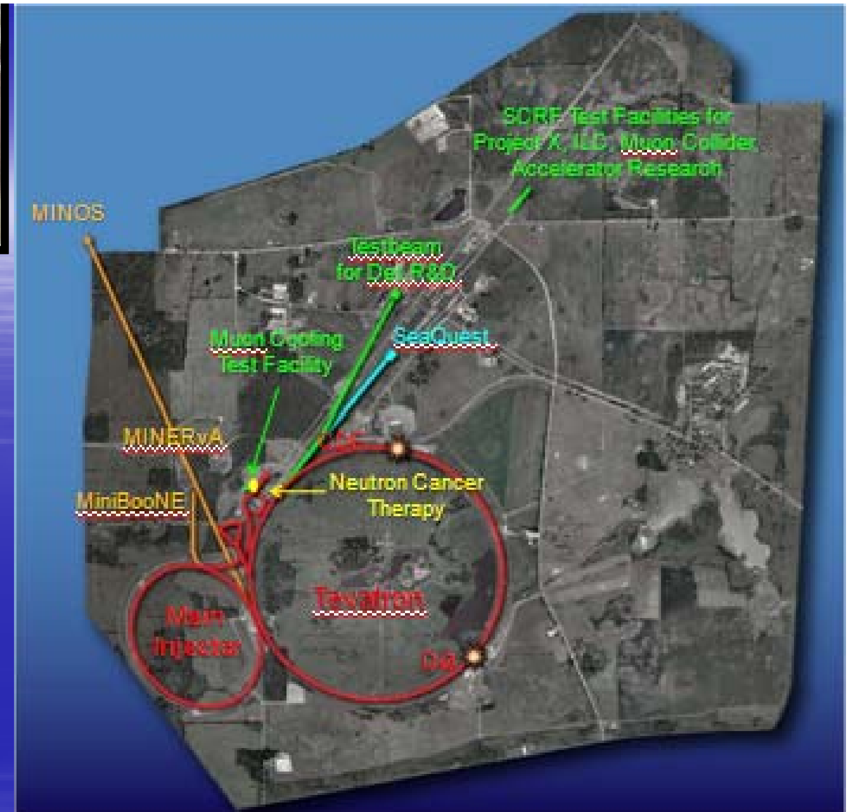
6.5 km of superconducting magnets operating @ 3.6 Kelvin:
+777 dipoles
+216 quads
+204 correction elements

+ 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









<u>Unified control system for the entire complex</u>

- 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

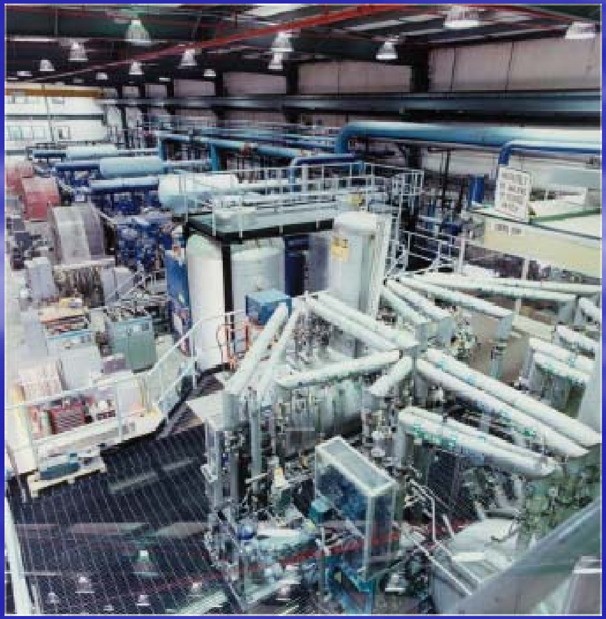
<u>Simultaneous operation of</u>

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

Central Helium Liquefier - CHL

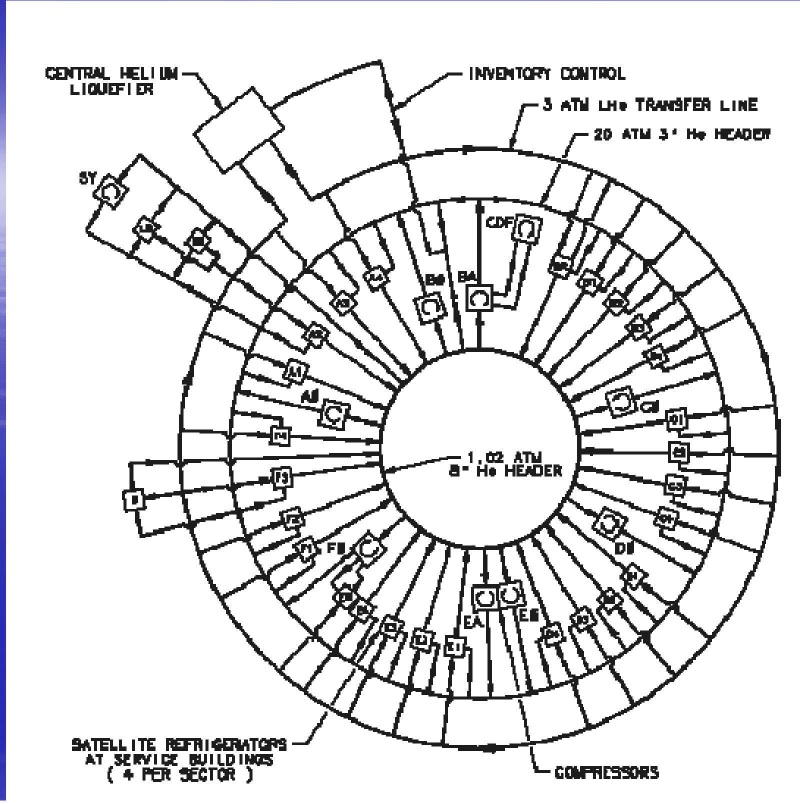
The Central Helium Liquefier consists of:

- 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



d1

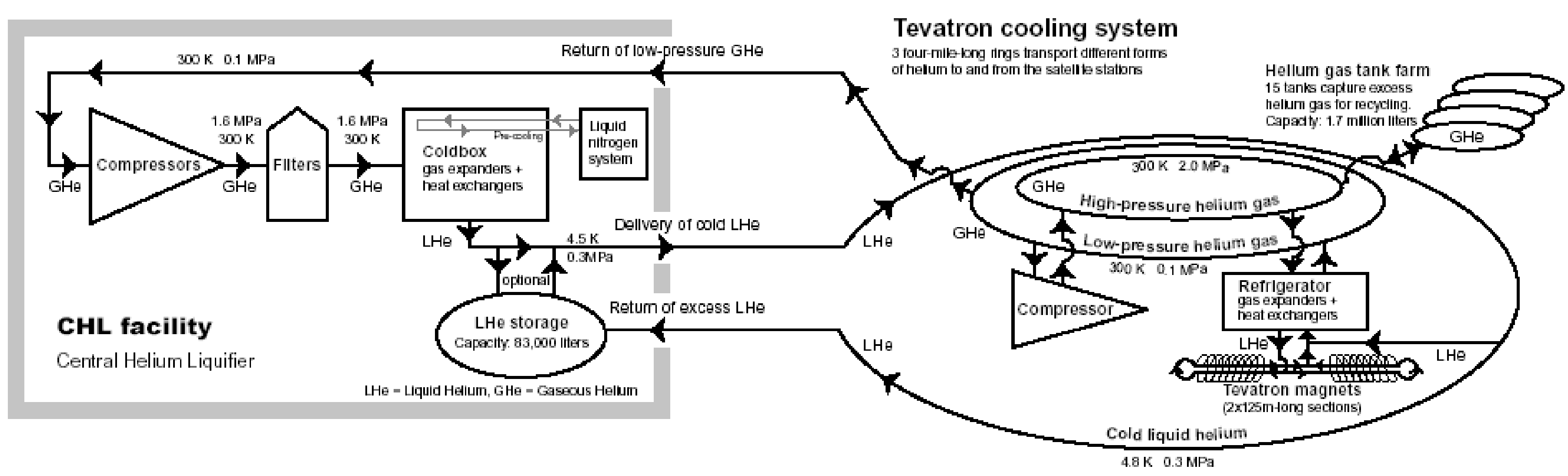
Cryogenics system for the Tevatron



- Six sectors each composed of:

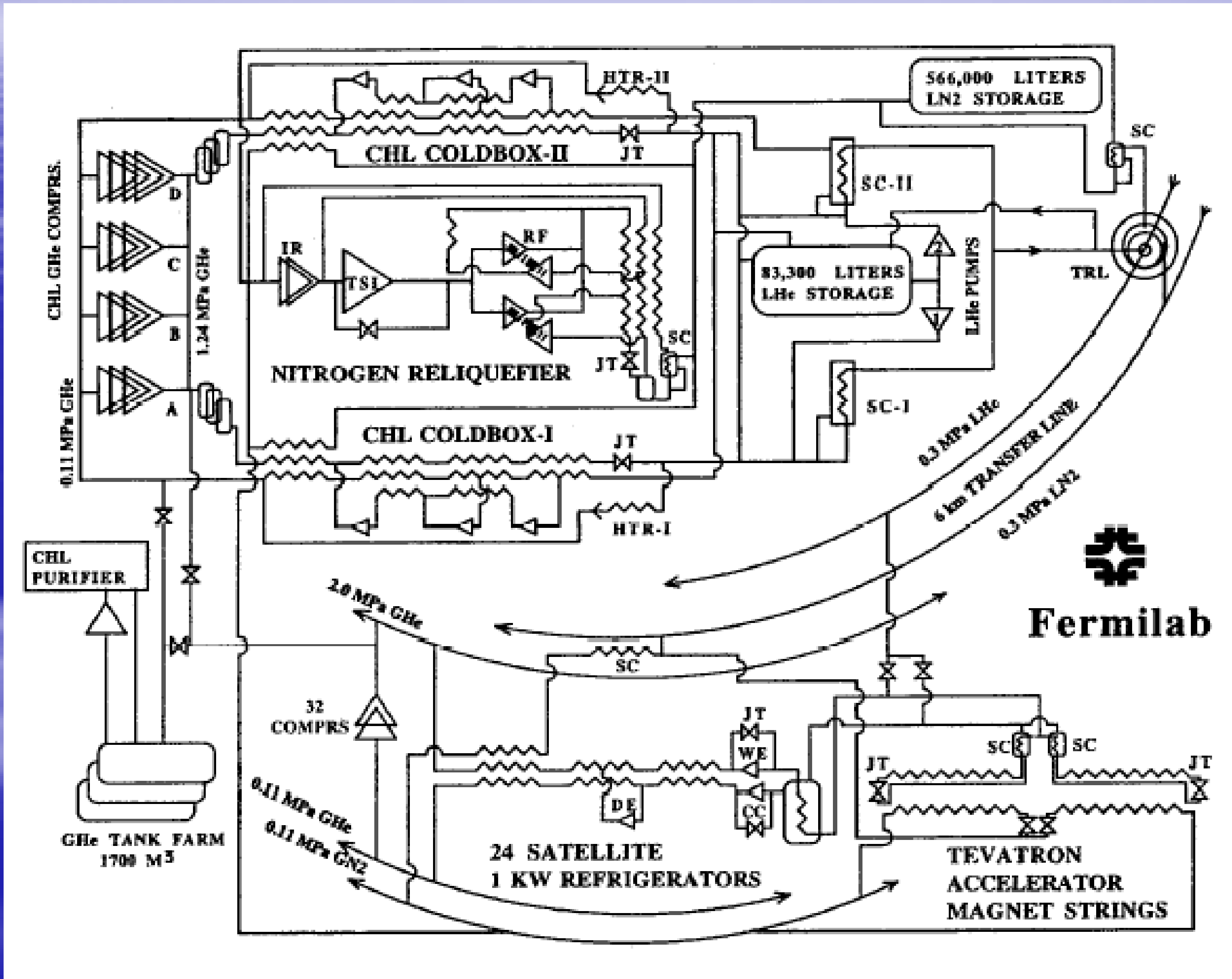
+four 1-kW refrigerators

+four Mycom 2-stage 300 kW screw compressors

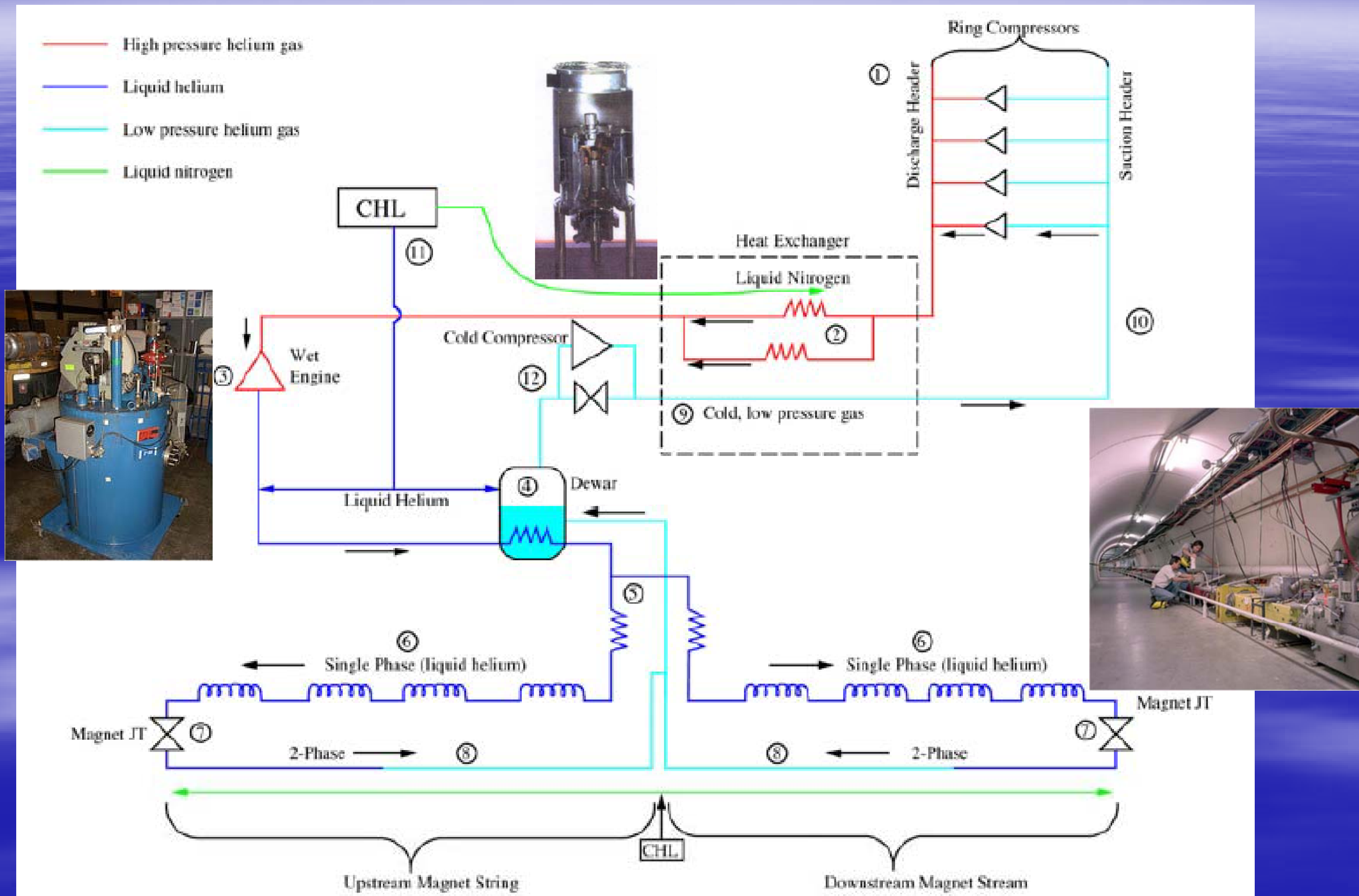


d1 aging system
20 000 LHe in refrigeration and 10 000 in transfer line
darve, 6/10/2007

Cryogenic system for the Tevatron



One typical cooling loop for the Tevatron

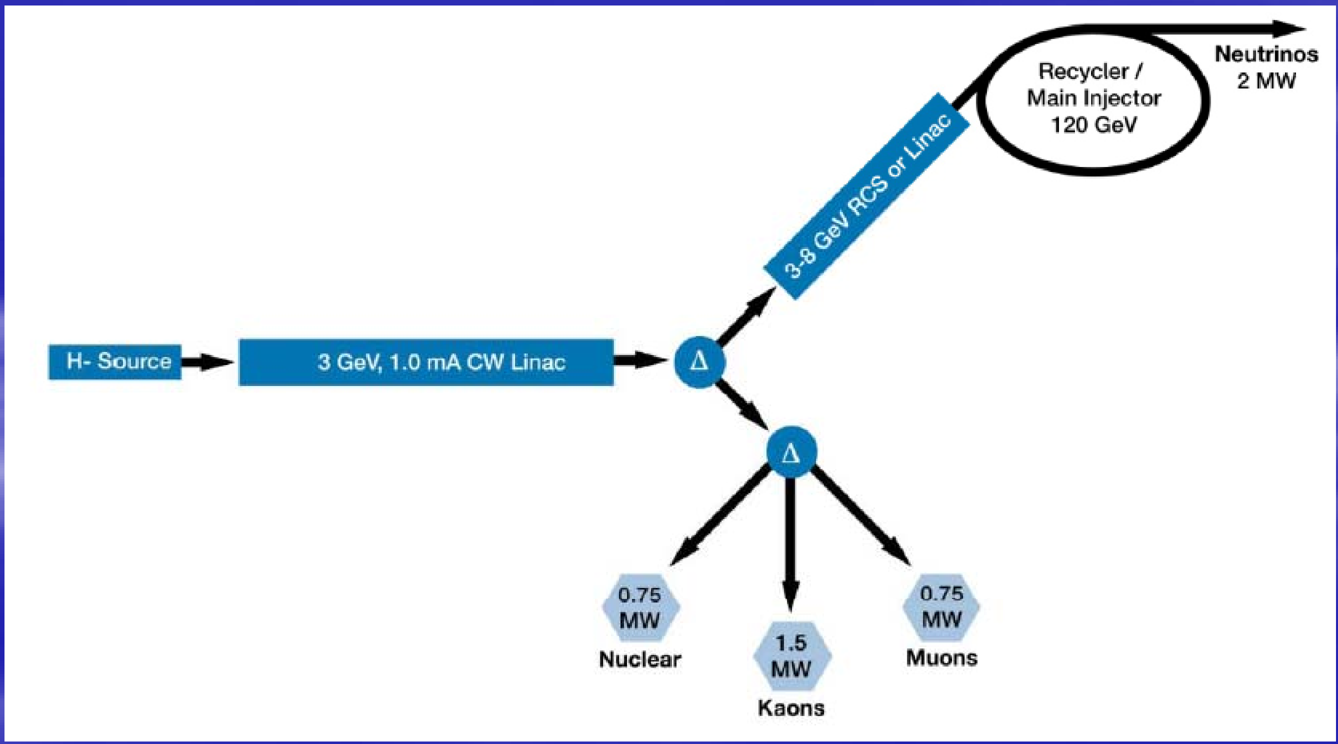


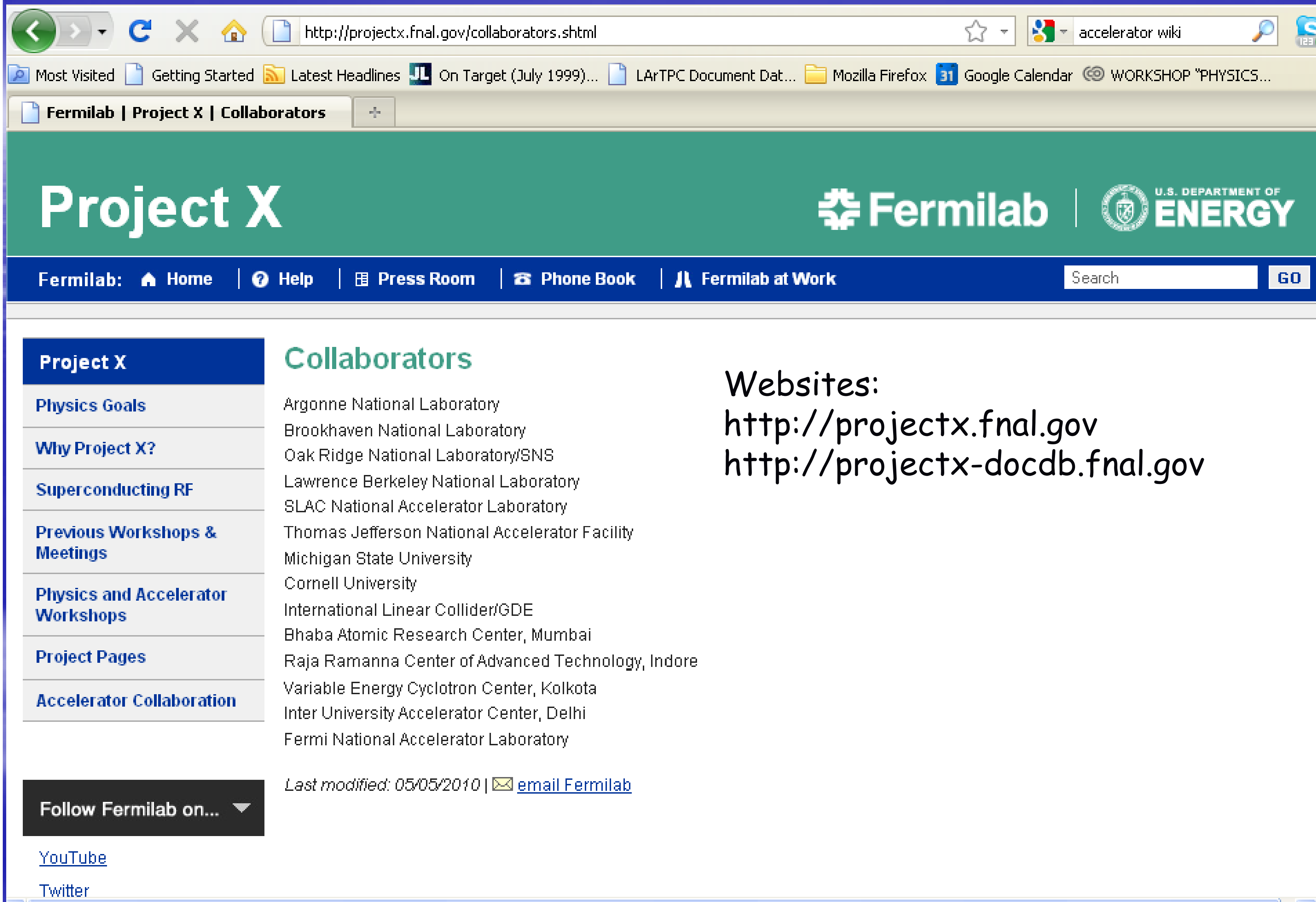
New cryogenic areas and era

Project X on the intensity and energy frontiers:

– Intensity Frontier:
NuMI → NOvA → LBNE/mu2e → Project X → NuFact

– Energy Frontier:
Tevatron → ILC or Muon Collider

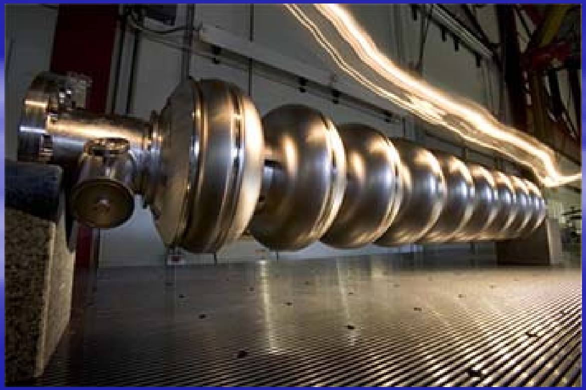




Websites:
http://projectx.fnal.gov
http://projectx-docdb.fnal.gov

New Cryogenic Areas and Era

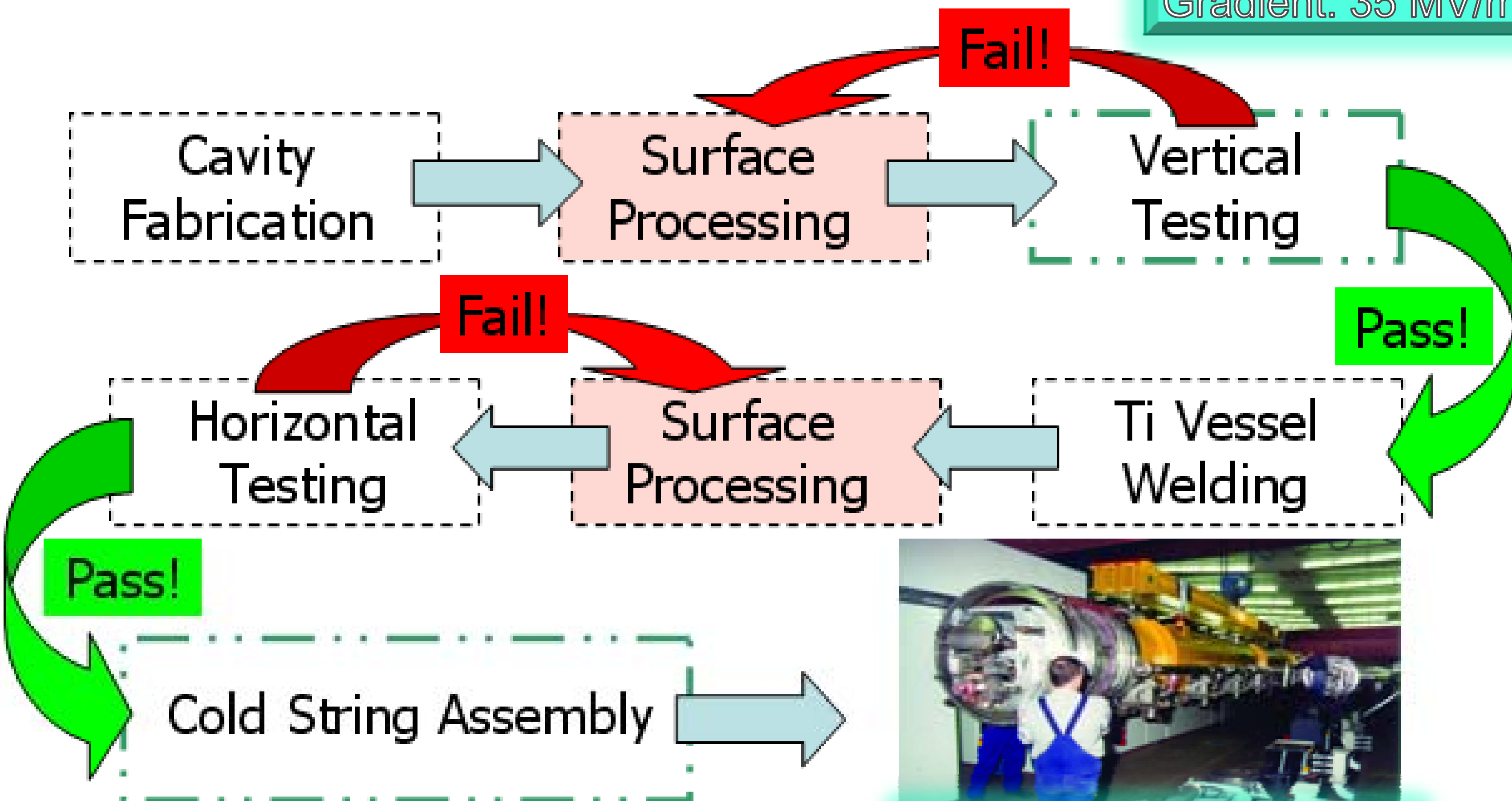
- Fermilab is developing a broad capability to assemble and test SRF cavities :
  - High gradient cavity (1.3 GHz)
  - 3rd harmonic (3.9 GHz)
  - Capture Cavity 2 (1.9 GHz)
  - High Intensity Neutrino Source (325 MHz)



	Vertical **T**est **S**tand	**H**orizontal **T**est **S**tand
Cavity state	Bare	“dressed”
Power coupler	Axial coupler	Side coupler
RF power	Low power, CW	High power, pulsed
Turnaround	~2 day	~2 week
Raison d’être	Testing cavity surface treatment	Testing cavity handling, accessories

SRF Cavities - Work Flow

Qo=10^10
Gradient: 35 MV/m

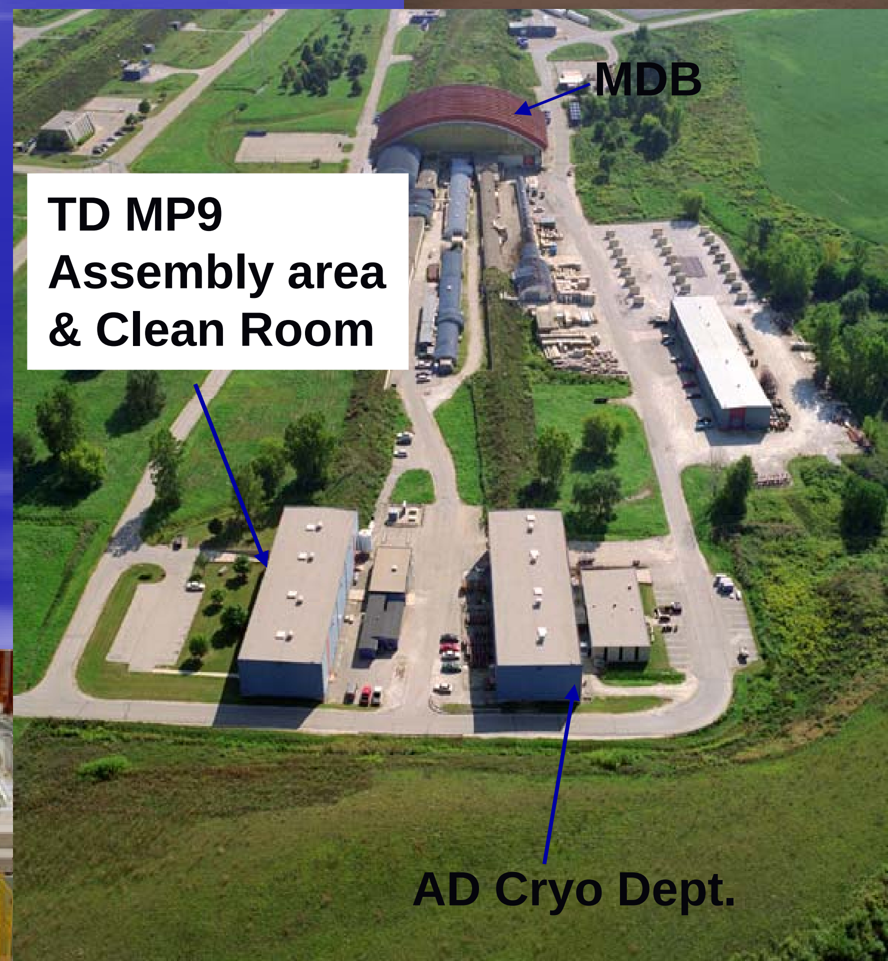


Picture of Desy in 2006

Test Facilities for SRF R&D

Cryogenic Test Facility – CTF

- Three (3) Tevatron satellite refrigerator systems(STAR)
- Four (4) Mycom compressors
- Purifier system, compressor
- Transfer line from CTF to MDB
- Storage tanks and buffer Dewars



Meson Detector Building - MDB

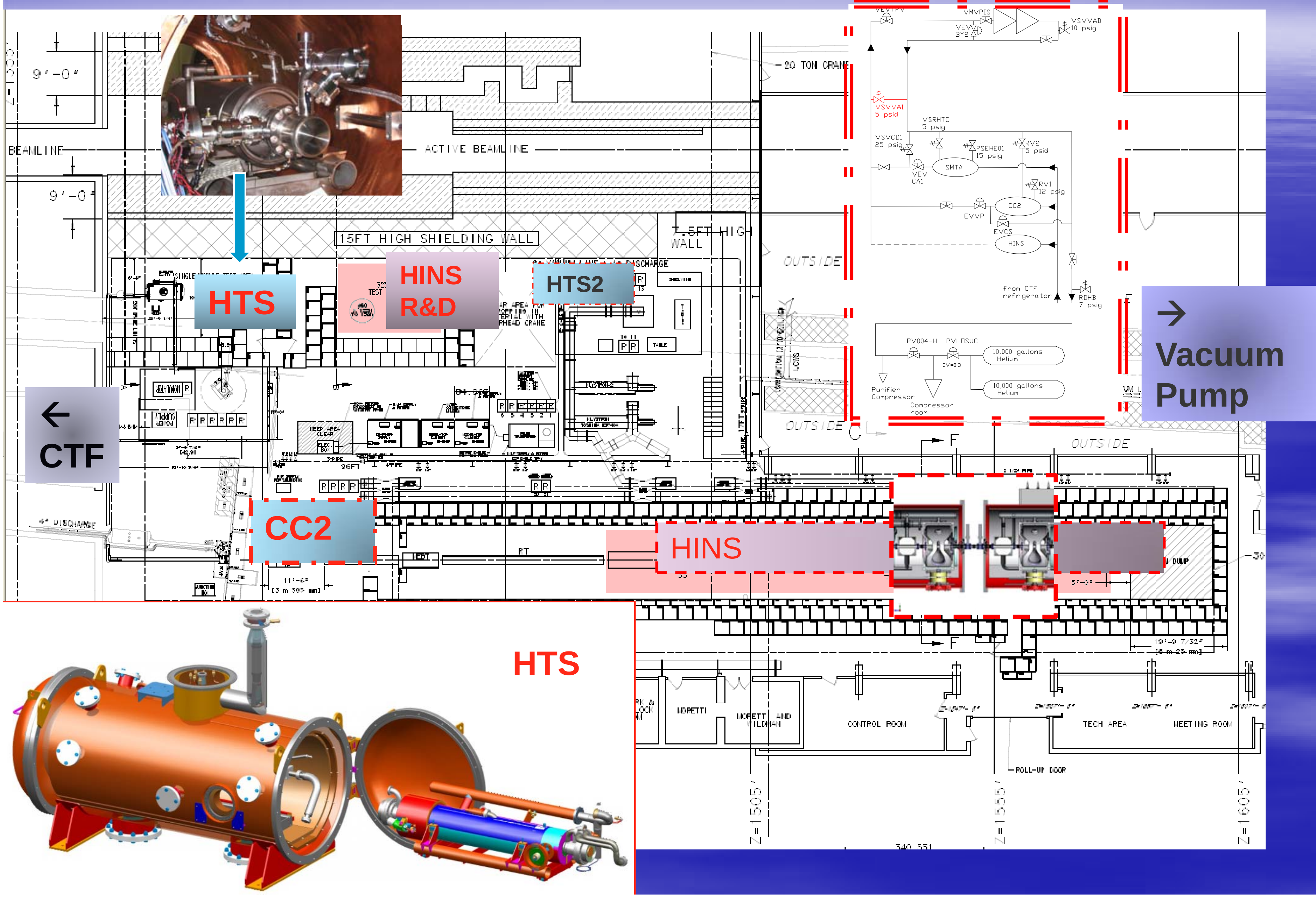
- Test areas: HTS, HINS, etc..
- 2 K operation using a vacuum pump capable of 10 g/sec @1.8 K

New Muon Lab – NML

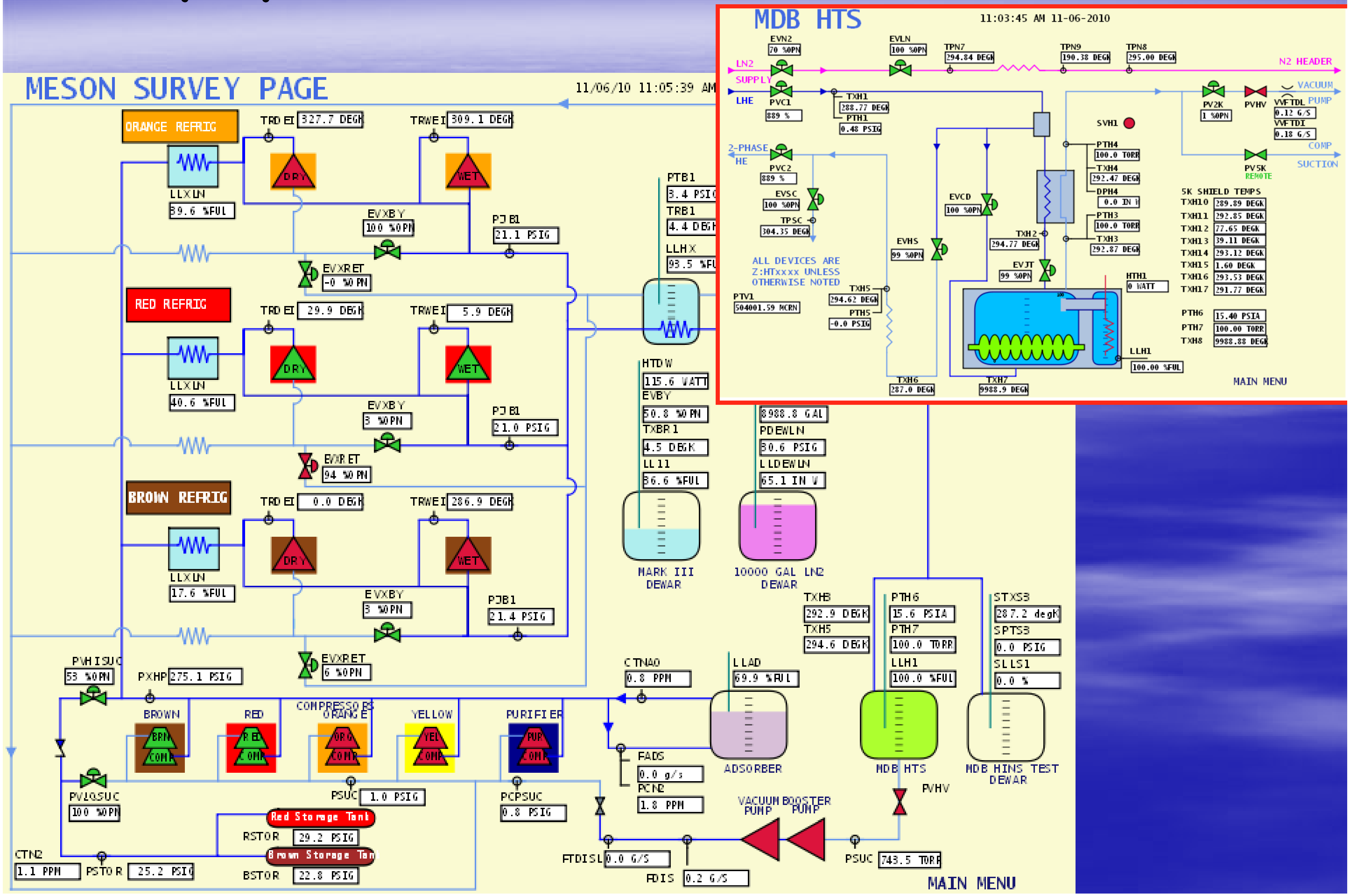
Cryoplant for 1.8 K operation

- Test area for RF units

Meson Detector Building - Layout



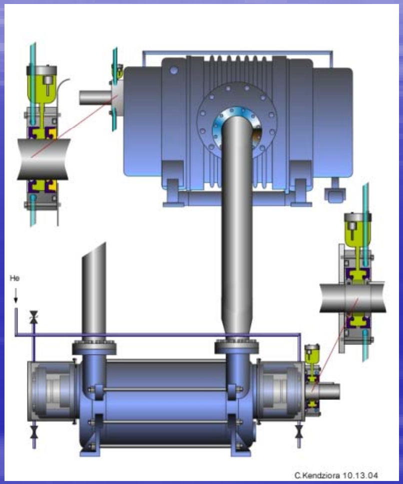
Synoptic /ACNET control



Cryogenic distribution line and Vacuum System

Expansion box and bayonet cans

Vacuum pump modification



Piping between VP and test Areas

Vacuum Pump: booster +Ring pump

Cryogenic Test Facility

Three Refrigerator Systems (STAR)

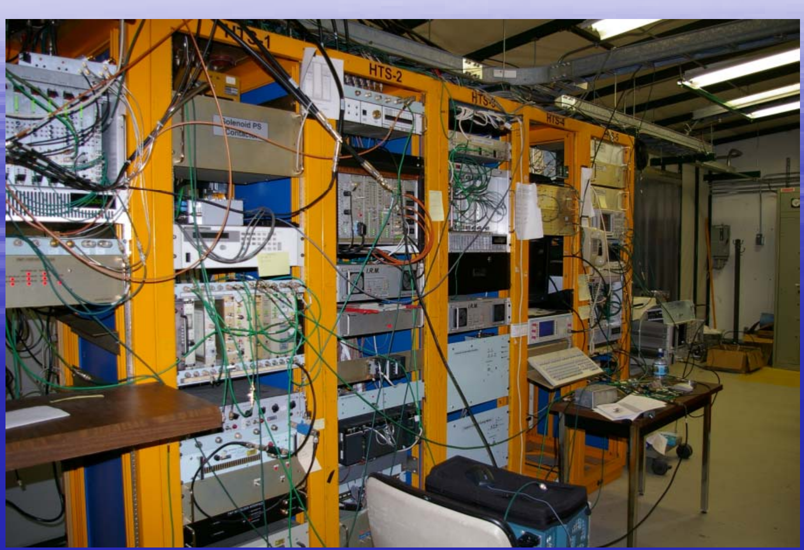
Three Heat Exchangers (STAR)

Control Room

Dewar+heater

Four Mycom Compressors

RF for HINS and HTS



→RF controls:.

- Klystrons: 1.3 and 3.9 GHz; 1.5ms@5Hz
- Fast phase shifter control (100 kHz)

→Development system in the LLRF test lab

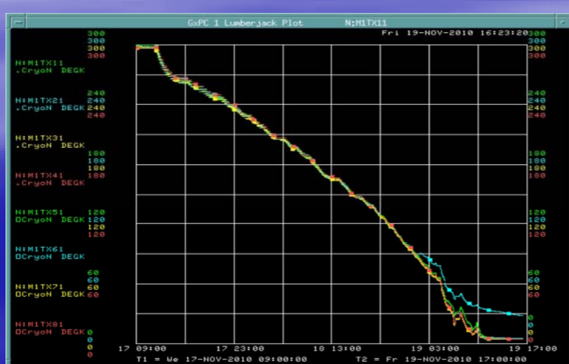
→ CW system (650 MHz) – Commissioning in progress

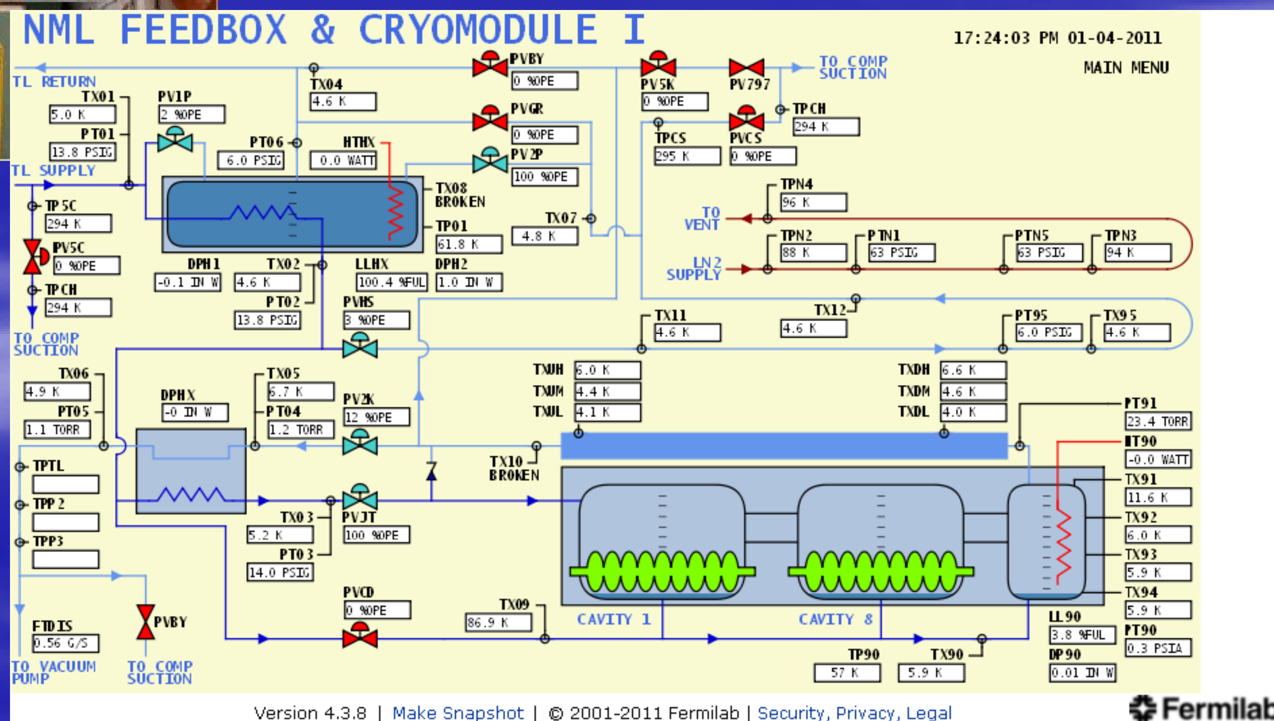
New Muon Lab (NML)

Currently, 2 Tevatron style refrigerators
→2 CryoModules

Future, add new cryo-plant
→6 CryoModules

November 19th, 2010
@ 1.9 K





Other FNAL test area using He capacity - MTA

Muon Collaboration

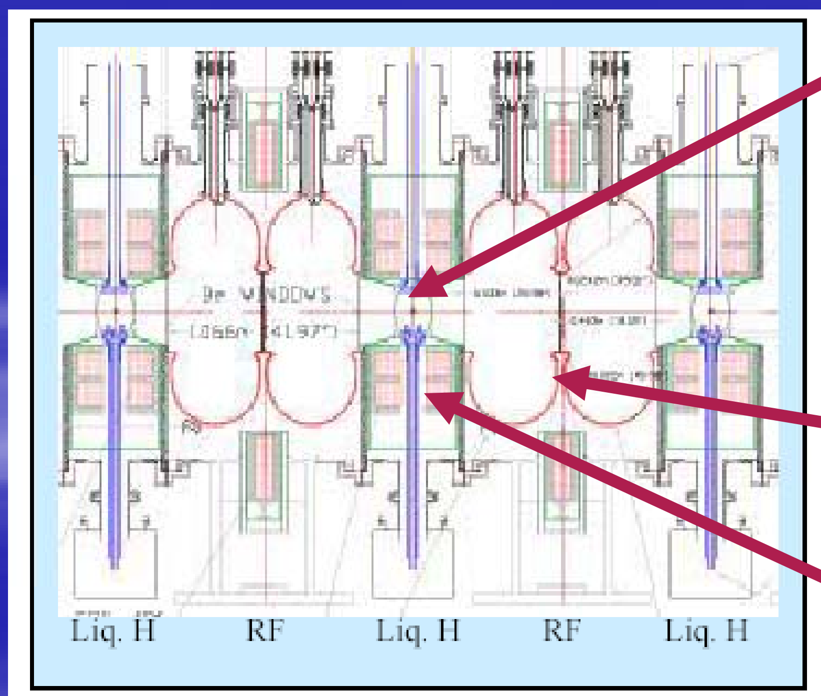
Mission for 18 institutions from US, Europe and Japan

- Design, prototype and bench test all cooling-channel components (RF, LH_2 absorber,etc.)
- Dev.of intense ionization beam (400 MeV beam up to 2.4×10^{14} p/s: 570 W in 35-cm LH_2 absorber)

FNAL cryo:

- Provide 14K and LHe cooling

→ LH_2 absorber
→ SC magnet
→ RF cavity



Absorbers (LH2)
- Convection scheme - MICE
- Forced-flow scheme - MuCool
- High Pressure Hydrogen gas

RF cavities
201 MHz
805 MHz for design concept

Solenoid magnet
4 Tesla

Conclusion

After his success in liquefying helium, and in discovering the phenomena of superconductivity, 100 years ago, Onnes opened the doors to amazing scientific fields.

Here we are now … defeating new scientific frontiers using large scale tools (accelerators) and making use of tones of superconductor and superfluid helium.

- ✓ The Tevatron has celebrated its 25th birthday this year.
- ✓ The LHC has started its race towards unprecedented energy frontiers.
- ✓ New projects will permit to drive our unlimited scientific appétit towards new discoveries..