Theme of the School:

REFLECTIONS ON THE NEXT STEP FOR LHC

Technology and Computing

in relation to

“Reflections on the Next Step for LHC”

References:
CERN Photo Library (copy rights), CERN programs and achievements, CERN current long-term plan, “The European Strategy for Particle Physics”, ISSP2012 (Erice), CAS School 2013 (Erice), EPS Technology & Innovation Workshop (Erice 2012) private communications (L.Rossi, S. Myers L. Evans ..)
Theme of the School:

REFLECTIONS ON THE NEXT STEP FOR LHC

before discussing next steps
let us look back
CERN 1975 -1980
before 1980 CERN used to built accelerators and detectors
ECFA – LEP Working Group
Progress Report
(15 April 1980)

Chairman: A ZICHICHI

which paved the way to build a 27km tunnel for

LEP & LHC
The exploitation of the CERN complex: Injectors, LEP tunnel, and infrastructures

..the construction of the new CERN complex within a constant budget..

Courtesy L. Rossi
when CERN entered the LEP era
forced CERN from 1980 to 1989 to dedicated its resources mainly to the SPS-pp\_bar and the LEP project

not much was left for other activities the ISR, all bubble chambers etc. had to be closed to free resources for LEP construction
Prof. A. Zichichi initiated the LAA Project. It was implemented at CERN in 1986 as „another CERN programme of activities“.

Recruitment of 40 LAA staff & over 80 unpaid scientists

All worked for the project with focus on R&D preparing LHC

boosting micro-electronics and silicon-pixel technology at CERN
It was the requirements for LHC which drove the development of hybrid pixel detectors within the LAA project. The Medipix2 and Medipix3 Collaborations have taken the approach and applied it to all kinds of particle imaging applications.

Many different application are foreseen....

- Electron microscopy
- Neutron imaging
- Nuclear power plant decommissioning
- Adaptive optics
- Dosimetry in space
- Gas detectors
- Beam collimation studies for LHC
- Upgrade plans for LHCb VELO detector
We will celebrate this year the 25 years of the LAA project.

Microelectronics and Silicon pixel detector R&D (Erik Heijne)
Technology R&D related to LEP

- Low field „ concrete magnets „
- Control systems
- Getter pumping for LEP vacuum
  NEG = Non Evaporable Getter
  (a sticky paper for molecules C.Benvenuti)
- Sputtered superconducting RF cavities
Deflecting Cavities at CERN

**Early Example - Superconducting Separators:**

- Developed early 70’s by Karlsruhe and CERN for SPS physics, to separate kaons and antiprotons in energy range 10 to 40 GeV/c (W. Bauer/H. Lengeler)
- Early use of SC cavities ... Precursor LEP etc.

[Images: Superconducting RF separator for Omega Spectrometer and Still in beam line at Serphukov – May 2009 (Courtesy Boris Prossine IHEP)]
Rough outline of all the steps..
• High “RRR” material (300 and above)
• Careful measurements on cavity prototype (bead pull)
• Check of tight mechanical tolerances
• Buffered Chemical Polishing (BCP) (HF, HNO₃, H₂PO₄, approx 1:1:2) (100-200 μm surface removal)
• UHV baking (600-800°C) (Remove H₂)
• Electro-polishing (HF – H₂SO₄), + possible 120°C baking for 48hrs
• High pressure rinsing (remove residues & contamination)
• Fitting of accessories and sealing for cavity test in Clean Room
• Test bare cavity in vertical cryostat – Measure Qo Vs. E, at low power with near critical coupling
• If specs not met start again with BCP etc.
Technology R&D related to LEP

- Low field „concrete magnets“
- Getter pumping for LEP vacuum
  NEG = Non Evaporable Getter (a sticky paper for molecules C.Benvenuti)
- Sputtered superconducting RF cavities
- Control systems
  superconducting – solenoids (ALEPH, DELPHI)
- Si - pixel detectors
- BGO photon detectors (L3)
- TPC
- Spagetti calorimeters
- ......

ISSP 2013 - H.Wenninger
CERN long term plan ...

The exploitation of the CERN complex: Injectors, LEP tunnel, and infrastructures

Some highlights of the LEP1 and LEP2 physics programmes

The precision measurements at the Z resonance (3 families), W+W- production, ZZ production, indirect limits on the Higgs mass, contributions to the exploration of the Cabibbo-Kobayashi-Maskawa quark mixing matrix and on the LEP measurements of the coupling constant $\alpha_s$ .......
CERN long term plan ...

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures
LHC Magnet timeline

- **First ideas**
  - Twin Dipoles
  - Hell cooling

- **1985**
  - Magnet designs at first LHC workshop, 1984

- **1990**
  - R&D for 8-10 T: 13 kA cables, short models, 10 m long prototypes, 1st string test

- **1995**
  - Final design, industrialization start pre-series

- **2000**
  - Magnet construction, performance test, tunnel preparation

- **2005**
  - Installation, LHC start Incident

- **2010**
  - Re-start 4.2 T

- **2018**
  - 8 T

- **First LHC dipole prototype on the test bench (June 1994)**

- **Final dipole cross section (frozen 1999)**

- **Assembly of 15 m long coils in industry, 2003**

- **Continuous magnet line installed in the 27 km LHC tunnel, 2006**

**Courtesy** L. Rossi
CERN Large Magnet Facility

180
Superconductivity and HE Physics

Courtesey: H. Ten Kate

Accelerators, like LHC, can not be realized without extensive use of superconductivity and high quality magnets

- 1232 dipole magnets for bending
- 386 quadrupole magnets for focusing
- ~7000 Correction magnets
- Insertion and Final Focusing magnets
- Nb/Cu cavities for acceleration
- ATLAS and CMS detector magnets

No Higgs without Superconductivity!
One end of the barrel of the ATLAS detector during the installation phase in February 2007. The calorimeter endcap is still retracted before its insertion into the barrel toroid magnet structure.

The CMS detector while open in June 2009. To the right is one end cap, which slides into the barrel, left.
The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures
“Higgs” Boson

4. Juli 2012
CERN long term plan ...

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures

Shut-down LS1
- To fix interconnects (LHC incident of Sept. 2008)
- To prepare LHC for design energy and luminosity
Cryo-dipole  △ SSS

△ High resistance internal splice
△ Highest leak
△ Electrical integrity issue
△ Critical reversed beam screen
△ △ Beam optics
△ SAM (He, DN160)
△ Y-lines repair
△ CC Consolidation / Inspection
△ DN 200 installation
△ △ △ Triplet braid (End of LS1 for rad prot)
△ Circuit and splices issues

Spread all around: work on leaks, PIMs,

Courtesy J.Ph. Tock

ISSP 2013 - H.Wenninger
The main 2013-14 LHC consolidations

1. 1695 Openings and final reclosures of the interconnections
2. Complete reconstruction of 1500 of these splices
3. Consolidation of the 10170 13kA splices, installing 27 000 shunts
4. Installation of 5000 consolidated electrical insulation systems
5. 300 000 electrical resistance measurements
6. 10170 orbital welding of stainless steel lines
7. 18 000 electrical Quality Assurance tests
8. 10170 leak tightness tests
9. 4 quadrupole magnets to be replaced
10. 15 dipole magnets to be replaced
11. Installation of 612 pressure relief devices to bring the total to 1344
12. Consolidation of the 13 kA circuits in the 16 main electrical feedboxes
Long Shutdown 1 (2013-2014)

Then operation at 6.5TeV per beam (2015-...)

Conditions
Å E=6.5TeV
Å 25ns
Å β* = 0.5m (maybe lower)
Å All other conditions as in 2012 i.e. LHC availability same etc
CERN long term plan ...

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures


LEP
Construct. Physics Upgr

LHC
Design, R&D Proto Construct. Physics

Shut-down LS1
- To fix interconnects (LHC incident of Sept. 2008)
- To prepare LHC for design energy and luminosity

Shut down LS2
- Injector and LHC Phase I upgrades (Dispersion Suppressor area collimation, New Cryo P4,...)
- Go to design- luminosity of present LHC

Courtesy L. Rossi

ISSP 2013 - H.Wenninger
Aim of the High-Luminosity Project

Increase Large Hadron Collider luminosity from $1-2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ to $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ peak luminosity

How?

~ halve the beam size at the interaction points →
~ Double the triplet aperture

→ heat loads
→ radiation damage

From 300 fb$^{-1}$ to 3000 fb$^{-1}$ depending on shielding

5 $10^{34}$ levelled lumi
(25 $10^{34}$ virtual peak lumi)
140 pile up (average)
3 fb-1 per day
60% of efficiency
250 fb-1 /year
300 fb-1/year as «ultimate»
The critical zone: magnet changes, cryogenics +...

1. Deep change in the IRs and interface to detectors; relocation of Power Supply

2. Deep change also matching section: Magnets, collimators and CC

3. For collimation we need to change also this part, DS in the continuous cryostat

300 m x 4 +... ~ 1.5 km long accelerator
In high radiation environment: 10...100 MGy
CCs and LHC Luminosity Upgrade HL-LHC

With non-zero crossing angle, luminosity gain by squeezing beams further is small - red curve on plot below.

Crab cavities can compensate for this geometric effect by tilting the bunch giving a luminosity increase of about 50% at $\beta^*$ of 25 cm. – green curve

Crab cavities also provide an ideal knob for luminosity levelling, optimizing integrated rather than peak luminosity!

EPS Technology & Innovation Workshop (Erice 2012)
There is a longer term plan ... 

... that implies lots of work on the SC magnet side

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures


LEP
- Construct.
- Physics
- Upgr

LHC
- Design, R&D
- Proto
- Construct.
- Physics

HL-LHC
- Design, R&D
- Construct.
- Physics

Shut down LS3  LHC Phase II
upgrades: HL-LHC  New focusing magnets, CRAB cavities very high lumi

Courtesy  L. Rossi

ISSP 2013 - H.Wenninger
HL-LHC

Cryoplant for IR’s

Cryoplant for RF cavities

≈ 1 BCHF

IR quadrupoles

Collimation

SC links

F. Savary

ISSP 2013 - H.Wenninger
Will an increased integrated luminosity or rather a higher energy allow to find physics beyond Higgs?

– P. Jenni talk
The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures

In both cases, SC challenge to develop 16-20 Tesla magnets! Magnets for HL_LHC is an indispensable first step.

Either using existing LEP/LHC tunnel to reach 26-32 TeV collisions

Or build a new tunnel to reach 80-100 TeV collisions
The study of an exceptionally large proton-proton collider, the Eloisatron, has been initiated by Professor Zichichi.

The goal is to reach 200 TeV centre-of-mass energy in a tunnel of 300 km circumference. The bending field of the collider will have to be about 10 Tesla. This requires intensive superconducting magnet development programs.
Pre-Feasibility Study for an 80-km tunnel at CERN
John Osborne and Caroline Waaijer, CERN, ARUP & GADZ, submitted to the European Strategy Preparatory Group

the same tunnel could host an $e^+e^-$ Higgs factory “TLEP” and a highest-luminosity highest-energy $e^-p/A$ collider “TLHeC, VHE-TLHeC”

Courtesy Steve Myers
pp Higgs factories by Steve Myers

LHC is the 1st Higgs factory!

$E_{CM} = 8-14$ TeV, $L = 10^{34}$ cm$^{-2}$s$^{-1}$

HL-LHC (~2022-2030):

$E_{CM} = 14$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ (leveled)

HE-LHC: in LHC tunnel (2035-?)

$E_{CM} = 33$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$

VHE-LHC in new 80-100 km tunnel (2040?)

$E_{CM} = 84-104$ TeV, $L = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$
Optimistic view

• Doubling the energy of the LHC is feasible
  • Another 10 years of R&D is required unless funding increases dramatically
    • Improve $J_c$ of Nb$_3$Sn and reduce cost (scale-up)
    • Demonstrate viability of Canted Cosine-Theta concept or something equally acceptable
    • Quench protection
    • Need rad hard materials for impregnation
    • I’m not betting on HTS

• Machine issues are at least as challenging (but feasible)
  • Machine protection
  • Vacuum

Courtesy S. Gourly Berkeley
ACCELERATOR MAGNET R&D IN THE PERSPECTIVE OF A LHeC AND A HE-LHC
- SYNERGY OR COMPETITION?

L. Bottura, B. Auchmann, M. Bajko, A. Ballarino, F. Borgnolutti, P. Ferracin, P. Fessia,
M. Karppinen, G. Kirby, L. Oberli, J.C. Perez, L. Rossi, G. de Rijk, S. Russenschuck, D. Smekens, E. Todesco, D. Tommasini

When looking at the “life after the LHC”, it is natural to pose the question of the possibility of a higher energy accelerator in the existing tunnel. This evidently calls for magnets with significantly higher bore field than the LHC. Nb₃Sn would allow a factor of two increase with respect to Nb-Ti, i.e. a dipole with a bore field in the range of 16 to 18 T. This would be a major step, but possibly not sufficient for the physics reach. Any increase beyond this value requires the use of High Temperature Superconductors (HTS). HTS materials have critical temperature around 80 to 100 K, but, and especially, they exhibit exceedingly large critical fields (100 T and larger), and can hence be used at low temperature as high field superconductors. Finding a use for HTS in Very High Field Magnets (VHFM) for accelerators, whose range we place somewhat arbitrarily above 20 T, would have immense implications for applications such as solenoid magnets for NMR spectroscopy, but also a scale and cost impact on superconducting power generation, storage and transmission.

Presently all this is at the stage of the concept. Although we have proposed a hybrid magnet concept design that uses HTS [22], and active work is on-going at national laboratories (e.g. the FP-7 EuCARD HTS insert, or the VHFSM collaboration of the US-DOE) and industries (e.g. work on 30 T NMR solenoids), none of this research has reached the stage of an accelerator application. Indeed, the basic question that is still unanswered is on the sheer feasibility of such a magnet. For this reason we are in the process of launching a worldwide collaborative work aiming at producing a small-scale demonstrator magnet, built with a HTS cable, and producing a field of 5 T in a 40 mm bore with sufficient field quality to be suitable for use in an accelerator [23]. This small dipole is intended as the demonstration of the technology necessary for a very high field insert in a hybrid Nb-Ti-Nb₃Sn-HTS magnet, a field booster from 15 T to 20 T. At the same time, thanks to the enormous temperature margin, such a dipole could find applications in regions of high radiation or energy deposition, operating at intermediate temperature, above the liquid helium range. Table IV gives the targets for the EuCARD2 proposal.
There is a longer term plan ...

... that implies lots of work on the SC magnet side

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, and infrastructures


LEP Construct. Physics Upgr

LHC Design, R&D Proto Construct. Physics

HL-LHC Design, R&D Construct. Physics

HE-LHC Design, R&D Proto Construct. Physics

Courtesy L. Rossi
HE-LHC – (33 TeV cms)

HE-LHC 2030-33
SPS+, 1.3 TeV, 2030-33
2-GeV Booster

 Courtesy: F. Savary - ISSP 2013 - H. Wenninger
SPS injector energy upgrade

The R&D developments for SIS300 dipole at INFN demonstrated the feasibility of superconducting magnets 4.5 T ramped at 1T/s.

Advanced designs, construction techniques and first low loss conductors were developed.

We need more information regarding the effects due to mechanical fatigue.

On the basis of present knowledge some extrapolations can be done for future fast ramped magnet (e.g. HE LHC injector magnets).

In particular it appear one can get ac losses as low as 10W/m when ramping the magnet (5W/m as minimum limit).

The field quality at injection energy could be an issue.
What is the possibility for HE-LHC?

- US basic programs and LARP R&D EU FP6-CARE-NED
- EuCARD 13 T large dipole + 18 T small insert
  - US 13 T Quads FP7-HiLumi US NbSn-HTS development
- LARP 11 T long quad EuCARD R&D
- 15-20 T R&D dipole models and prototypes
- 15-20 T dip final proto & Industrialization
- Final delivery Magnets HE-LHC

HE-LHC preliminary study
- EuCARD 2 full bore dipole HTS
- HTS for HE-LHC: yes.or.no
- Industry contracts, start construction
- HE-LHC start-up

F. Savary - SC Magnet Development & SC Magnet TT to Industry

6/25/2013
Magnet shopping list

<table>
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<th></th>
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<td>Dipole</td>
<td>FRESCA2</td>
<td>Ic Test station upgrade</td>
<td>1-2</td>
<td>13</td>
<td>120</td>
<td>1.5</td>
<td>3.6</td>
<td>15</td>
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<td>LHC</td>
<td>=</td>
<td>=</td>
<td>8.3</td>
<td>56</td>
<td>14.3</td>
<td>7</td>
<td>3.4</td>
<td>=</td>
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<td>11T</td>
<td>HL-LHC DS</td>
<td>10-20</td>
<td>11</td>
<td>60</td>
<td>11</td>
<td>11</td>
<td>7.3</td>
<td>2017-2020</td>
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<td>Quad</td>
<td>Low-β Q1-Q3</td>
<td>HL-LHC IR</td>
<td>16</td>
<td>12</td>
<td>150</td>
<td>8-10</td>
<td>12</td>
<td>=</td>
<td>2020</td>
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<td>D1</td>
<td>HL-LHC IR</td>
<td>4</td>
<td>5</td>
<td>160</td>
<td>8</td>
<td>6</td>
<td>7</td>
<td>2020</td>
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<td>D2</td>
<td>HL-LHC IR</td>
<td>4</td>
<td>3-5?</td>
<td>100 ?</td>
<td>5-10</td>
<td>?</td>
<td>?</td>
<td>2019</td>
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<td>Q4</td>
<td>HL-LHC IR</td>
<td>4</td>
<td>8</td>
<td>85-90</td>
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<td>8 ?</td>
<td>70</td>
<td>4.5</td>
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<td>HE-LHC demo</td>
<td>1</td>
<td>20</td>
<td>40</td>
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**HiLumi LHC**

**HiEnergy LHC**

 EPS Technology & Innovation Workshop (Erice 2012)

**Courtesy** L. Rossi
LHeC Options

Ring-ring option: new ring in LHC tunnel, with bypasses around experiments

Linac-ring option: recirculating linac with energy recovery (ERL), (or straight linac)

R-R LHeC e-/e+ injector 10 GeV, 10 min. filling time

EPS Technology & Innovation Workshop (Erice 2012)
ILC - TDR 12 June 2013
The Update of the European Strategy for Particle Physics

M. Krammer

HEPHY, Vienna, Austria

The Nobel Symposium on LHC Results
Krusenberry, Sweden, May 13-17, 2013
Compact Linear Collider

Two beam acceleration: low energy, high current drive beam powers RF cavities of main linac (cavities ~100 MV/m), energy up to 3 TeV c.m. in stages.

Project at CDR level,
Prove of principle of two beam acceleration
(Proposal for a Clystron version for start up at low energy)

May 17, 2013
Muon Collider

Muon collider as Higgs factory, precursor or follow-on of neutrino factory.

Advantages of $\mu$ over $e$: smaller facility, very low synchrotron radiation, smaller energy spread, $s$-channel Higgs production $\sim m^2$

vSTORM as entry-point:
Neutrino Experiments

- Long Baseline Neutrino Experiment with conventional beams

Discovery potential for CP violating, Precision for δ measurement and sensitivity to Mass Hierarchy:

LBNO...Europe,
LBNE...US,
T2HK...Japan

Figure shows values
LBNO, LBNE for 10y,
T2HK for 5y

- Experiments to address (answer!) the question of sterile Neutrinos:
  νSTORM, ICARUS/NESSIE (possibly at CERN)
# Proton Proton Colliders

<table>
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<tr>
<th>Years</th>
<th>$E_{cm}$ TeV</th>
<th>Luminosity $10^{34} \text{cm}^{-2}\text{s}^{-1}$</th>
<th>Int. Luminosity 300 fb$^{-1}$</th>
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<td>2014-21</td>
<td>14</td>
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<td>2024-30</td>
<td>14</td>
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<td>HE-LHC</td>
<td>&gt;2035</td>
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<tr>
<td>V-LHC**</td>
<td>&gt;2035</td>
<td>42-100</td>
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</table>

**HE-LHC:**
16 T magnets with classical low temperature superconducting magnets ($\text{Nb}_3\text{Sn}$) $\rightarrow$ 26 TeV c.m.
To reach 20 T need high temperature superconductors ($\text{YBCO-123}$, BSCCO-2212) $\rightarrow$ 33 TeV c.m.

A possible 20 T design:
(CERN-ATS-2012-237)

Replace SPS by 1 TeV SC ring, etc...

May 17, 2013 European Strategy Update
51st Course: Reflections on the Next Step for LHC - Erice: 24 June – 3 July 2013

Accelerators – Detectors - Computing

Highlights from the EPS-TIG Workshop 2012 at Erice

EPS Technology & Innovation Workshop (Erice 2012)
The technology workshop covered:

- history and new trends in accelerators & detectors
- new accelerator & detectors projects
- LHC upgrades: accelerators & detectors

  applications: health and medical
  applications: industrial & environmental
  applications: computing & networks
Theme of the School:
REFLECTIONS ON THE NEXT STEP FOR LHC

EPS-TIG Workshop
Accelerators – Detectors - Computing

- sc-magnet development & sc magnet technology

- crab cavity development
Main dipoles of existing machines but structure quite different

Rutherford cable
Collars Aust. Steel
Warm iron

Collars Al alloy
Cold iron

Cold yoke as collar

Collars Aust. Steel + yoke
Twin + Hell

Tevatron
HERA
RHIC
LHC

6/25/2013
ISSP 2013 - H.Wenninger
HL-LHC project at CERN with EU partners

Conductor development

High Field Magnets
- Small Model Coil
- FRESCA2 Magnet
- HTS insert (racetrack)

Magnets for collimation
- 11 T «Twin» LHC dipole

Magnets for the IRs
- Low β quads
- Separation Dipoles

Large aperture quadrupoles for the MS

Study for the 15-20 T dipole HE-LHC

Study and for pulsed magnets for HE-LHC injectors

SC links 10x500 m long
50-200 kA/1-5 KV

 Courtesy S. Myers
High Field Magnet Development and Prospects for an Energy Upgrade of LHC

LHC Energy Upgrade is now a topic of considerable discussion

EuCARD Workshop on a High Energy LHC Malta
October 14, 2010

Joint Snowmass-EuCARD/AccNet-HiLumi LHC Workshop
CERN February 21-22, 2013

LBNL Magnet R&D Program in High Field Magnets
LHC Accelerator R&D Program (LARP)
and agreed between CERN and US LARP
MQXF Model/Prototype Program ... that is currently starting

- Demonstrate that the technologies and techniques used for the 120 mm aperture can be successfully adopted for the 150 mm aperture
- Extend the applicability of the LARP LHQ (3 m) results to the 150 mm aperture, to open directly the path to full-length prototype (up to 8 m)
- Test as many features as possible of the full-length magnets (in particular iron yoke design)
- Demonstrate that the coil fabrication technology is well mastered, allowing to use all the produced coils for magnet assembly
- Verify that conductors from different suppliers can be efficiently and successfully managed in the same magnet production
Nb-Ti is limited at 10 T

\( \text{Nb}_3\text{Sn} \) allows to go towards 15 T

Approaching the limits of each material implies very large coil and lower current densities

Operational current densities are typically ranging between 300 and 600 A/mm\(^2\)

EPS Technology & Innovation Workshop (Erice 2012)
For good magnets we need to understand in depth and control the entire chain of development from lattice & grains, through wires and cabling, to coil winding, assembly, cryostating, protection, proper controls.
Wire with Superconductor

A wire with a matrix embedding superconducting material

- NbTi wire, good for 8 - 9T at 1.9K
- Nb3Sn wire, good for 14 - 16T at 1.9K
- B2212 wire, good for 17->30T at 4.2K
- Re123 tape, good for 17->30T at 4.2K

What counts is current density \( J_{\text{eng}}(B,T,\varepsilon) \) of \( \sim 400\text{A/mm}^2 \) and Temperature margin \( \Delta T_{\text{margin}} = T_{cs}(B,I) - T_{\text{bath}} \) of >2-5K

- Filament diameter <50\( \mu \text{m} \) to warrant filament stability and <5\( \mu \text{m} \) to limit field errors in NbTi and <40\( \mu \text{m} \) in Nb3Sn

- Twist pitch of ~20-30mm to limit ramp losses
- Wire diameter <1.3mm to avoid self-field instability

EPS Technology & Innovation Workshop (Erice 2012)

6/25/2013
What to do to get into the region of high energy LHC?

- Superconductors; Nb3Sn needs to get better

  RRP® strands with smaller filaments

  - Smaller sub-elements can minimize flux jumps and improve stability.
  - Filament Magnetization decreases

Courtesy of Jeff Parrell (OST) and A. Gosh BNL
Cables with strands

Highly compacted Rutherford cable with 20-50 strands
Cable width 12-24mm depending on cable current, number of layers.
Key-stoned section to accommodate cos-Φ type winding blocks.
Coating on strand (SnAg,Ni,Cr) to limit and control interstrand loss and cable magnetization, or avoid sintering (Nb₃Sn).
Cable pitch of ~100-200mm to limit ramp loss, cable integrity & stiffness.
Superfluid Helium in NbTi cable voids at 1.9K to enhance enthalpy.
For Nb₃Sn, no He in cable but vacuum impregnated to freeze wire movement and reduce wire-to-wire point strain.
3-4 x 0.4mm² Re123 tapes in Roebel type cables or may be in CORC.
So far no Cable-in-conduit-Condutors used in accelerator magnets but possible……..may be a way to get helium cooling directly on the Nb₃Sn strands and solve the training issue in these magnets.

EPS Technology & Innovation Workshop (Erice 2012)
Coils with cables and wedges

- Blocks of cable-turns, Cu wedges in-between, to control field errors.
- Two layers or even more, 4, 6.
- Cable insulation (NbTi: Kapton/glass tapes; Nb₃Sn: glass tapes, glass/mica, glass braid)
- A dielectric film included is preferred to avoid risk of shorts in series production.
- Ground insulation (usually thick Kapton).
- Coil layer helium cooling (fishbone).
- Cooling in-between layers if high heat load.
- Windings superfluid He transparent at 1.9K (NbTi) or vacuum impregnated (Nb₃Sn).
- Coil instrumentation: voltage taps, temperature sensors, strain and pressure sensors, quench heaters.

EPS Technology & Innovation Workshop (Erice 2012)
Coil ends

- **Coil ends with end-spacers**: different layouts for cosd coils and block coils.
- In either design this is a weak area causing premature quenching/training.
- Axial wedges “connected” to end spacers, mechanically not uniform, different materials, gaps by fabrication and winding tolerances.
- A continuous and ”natural” support has to be aimed at, still lot of discussion on best solutions.

EPS Technology & Innovation Workshop (Erice 2012)
Collars, Yoke and Cylinder

- A laminated collar pack surrounding the coils
- Provides structural precision and is spacer to yoke,
- Transfers the Lorentz forces to yoke and cylinder.
- Plates of stamped SS or Al alloy.
- Two halves, key locked or single ring shrink-fitted.
- Also bladder techniques are used to lock & pre-stress.
- Collar plates are spaced, so open for sf Helium.

- A laminated iron yoke in between collars and
- Support cylinder
- Iron yoke plates, field enhancement & spacer
- To support cylinder.

- Support cylinder and helium can with ends
- Reacts the Lorentz forces (100-200t/m) by elastic tensile stress.
- Shapes the helium bath.

F. Savary - SC Magnet Development & SC Magnet TT to Industry
Cold mass in Cryostat

Â A cryostat with vacuum vessel, thermal shield, cold mass supports, bus bars, helium lines (for 1.9 or 4K cooling) and instrumentation ports.

Â Normal steel vacuum vessel.

Â Aluminum alloy thermal shield with cooling tubes and layers of MLI.

Â Cold mass supports to take the weight, 1 fixed, others sliding.

Â Instrumentation and cables.

Â Bus lines and at either side, interconnections to neighboring coils.
Quest for high current conductors

200 A HTS tape

Not useful when not cabled

65000 A@5T Al-NbTi/Cu

This works!
Herman Ten Kate

- One cannot build large scale magnets from single NbTi, Nb$_3$Sn, Bi-2212, or Re123 wires or tapes.
- We need superconductors that can be cabled and survive a quench!
SC strand & Cable challenges

We are looking for very high current
- LHC main dipole Nb-Ti $I_C$ (10 T; 1.9 K): 13750 A
- Fresca 2 Nb$_3$Sn $I_C$ (12 T; 4.2 K): 31420 A

Impact on technology (magnet fabrication):
- Reaction heat treatment (additional operation, long duration, needs T uniformity)
- Insulation materials (usual polyimides cannot be used for cable insulation)
- R&D program is currently on going with industry specialized in making SC filaments/strands ... with CERN support

Small filaments and high RRR needed for high field magnets

Cable fabrication at CERN, BNL and Fermilab (US)

Mechanical properties after reaction requires attention, e.g. elongation at break

«Manufacturability» / series production / QA-QC
- In terms of materials, cable and characteristics ... needs to be for accelerator magnets

Target performance:
- $J_C > 3 \text{kA/mm}^2$
- $D_{\text{fil}} < 20 \ \mu\text{m}$
- RRR > 100

F. Savary - SC Magnet Development & SC Magnet TT to Industry
USA: Strand and Cable Design

Conductor design:

- TQ01: OST MJR 54/61
- TQ02: OST RRP 54/61
- TQ03: OST RRP 108/127

Cable:

- 27 strands, 0.7 mm diameter
- Width: 10.05 mm
- Mid-thickness: 1.26 mm
- Keystone angle: 1.0 deg
- Insulation: S-2 glass sleeve

Based on the DOE-CDP

**Conductor Development Program**

Launched in 1998 has doubled the $J_c$ (1400 → 3000 A/mm² @ 12T, 4.2K) in 2001...

But to make it really usable in our magnets at 2700 A/mm² is still an endeavour...

F. Savary - SC Magnet Development & SC Magnet TT to Industry

6/25/2013
REVIEW OF QUADRUPOLES LAY-OUTS

LHC MQ Nb-Ti, 1.9 K
- Main quadrupole of the LHC
- 400 magnets built in 2001-2006

LHC MQXA Nb-Ti, 1.9 K
- Large aperture quadrupole LHC IR
- 18 magnets built in 2001-2006

LHC MQXC Nb-Ti option LHC upgrade
- LHC dipole cable, graded coil 2 layers
- 2 short models built in 2011-13

F. Savary - SC Magnet Development & SC Magnet TT to Industry

6/25/2013
A REVIEW OF QUADRUPOLES LAY-OUTS

LARP TQ/LQ  90 mm aperture Nb$_3$Sn option for LHC upgrade (IR triplet)
   - ~5 short model tested in 2005-2010
   - 3 3.4-m-long magnets tested in 2010-13

LARP HQ  120 mm aperture Nb$_3$Sn option for LHC upgrade (IR triplet)
   - 2 short model tested in 2011/2013

MQXF  150 mm aperture Nb$_3$Sn option for LHC upgrade (IR triplet)
   - first short model tested in 2014

F. Savary - SC Magnet Development & SC Magnet TT to Industry
Where do we start?

The 11-T Dipole, and welding of short models

<table>
<thead>
<tr>
<th>Outer diameter</th>
<th>534 mm (for 12 mm shells)</th>
<th>580 mm (for 15 mm shells)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>2168 mm (t.b.c.)</td>
<td>2130 mm (t.b.c.)</td>
</tr>
<tr>
<td>Expected date</td>
<td>1-in-1 #1: Q2-13</td>
<td>FNAL 2- in-1 Demonstrator (Q3-13)</td>
</tr>
<tr>
<td></td>
<td>1-in-1 #2: Q3-13</td>
<td>CERN 2-in-1 Demonstrator (Q4-13)</td>
</tr>
<tr>
<td></td>
<td>1-in-1 #3: as needed</td>
<td></td>
</tr>
</tbody>
</table>

F. Savary - SC Magnet Development & SC Magnet TT to Industry
## 11-T Model Dipole Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Single aperture FNAL</th>
<th>Single aperture CERN</th>
<th>Twin aperture CERN / FNAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture [mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yoke outer diameter [mm]</td>
<td>400</td>
<td>510</td>
<td>550</td>
</tr>
<tr>
<td>Nominal bore field @11.85 kA [T]</td>
<td>10.86</td>
<td>11.25</td>
<td>11.25</td>
</tr>
<tr>
<td>Short-sample bore field at 1.9 K [T]</td>
<td>13.6</td>
<td>13.9</td>
<td>13.9</td>
</tr>
<tr>
<td>Margin $B_{\text{nom}}/B_{\text{max}}$ at 1.9 K</td>
<td>0.80</td>
<td>0.81</td>
<td>0.81</td>
</tr>
<tr>
<td>Stored energy at 11.85 kA [kJ/m]</td>
<td>473</td>
<td>484</td>
<td>969</td>
</tr>
<tr>
<td>$F_x$ per quadrant at 11.85 kA [MN/m]</td>
<td>2.89</td>
<td>3.16</td>
<td>3.16</td>
</tr>
<tr>
<td>$F_y$ per quadrant at 11.85 kA [MN/m]</td>
<td>-1.57</td>
<td>-1.59</td>
<td>-1.59</td>
</tr>
</tbody>
</table>

Courtesy M. Karppinen and the 11 T team at FNAL
## The Two-In-One 11 T LHC dipole

![Diagram of the LHC dipole with labels]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MSUT (UT)</th>
<th>D20 (LBNL)</th>
<th>HFDA (FNAL)</th>
<th>HD2 (LBNL)</th>
<th>Demo-1 (FNAL/CERN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-section</td>
<td><img src="image1" alt="Cos-theta" /></td>
<td><img src="image2" alt="Cos-theta" /></td>
<td><img src="image3" alt="Cos-theta" /></td>
<td><img src="image4" alt="Block" /></td>
<td><img src="image5" alt="Cos-theta" /></td>
</tr>
<tr>
<td>Design</td>
<td>Cos-theta</td>
<td>Cos-theta</td>
<td>Cos-theta</td>
<td>Block</td>
<td>Cos-theta</td>
</tr>
<tr>
<td>Technology</td>
<td>W&amp;R</td>
<td>W&amp;R</td>
<td>W&amp;R</td>
<td>W&amp;R</td>
<td>W&amp;R</td>
</tr>
<tr>
<td>Aperture [mm]</td>
<td>50</td>
<td>50</td>
<td>43.5</td>
<td>36-43</td>
<td>60</td>
</tr>
<tr>
<td>Length [m]</td>
<td>~1</td>
<td>~1</td>
<td>~1</td>
<td>~1</td>
<td>~2</td>
</tr>
<tr>
<td>$B_{\text{max}}$ ($B_{\text{q, max}}$) [T]</td>
<td>11.5(11.4)</td>
<td>13.35 (13.5)</td>
<td>12.2 (10.2)</td>
<td>15.4 (13.8)</td>
<td><strong>13.62</strong></td>
</tr>
<tr>
<td>$W_{\text{max}}$ [MJ/m]</td>
<td>0.46</td>
<td>0.88</td>
<td>0.30</td>
<td>0.87</td>
<td>0.744</td>
</tr>
<tr>
<td>$L$ [mH/m]</td>
<td>2.5</td>
<td>46</td>
<td>1.5</td>
<td>7.3</td>
<td>5.6</td>
</tr>
<tr>
<td>Fx/quadrant [MN/m]</td>
<td>3.2</td>
<td>5.2</td>
<td>3.4</td>
<td>5.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Fy/quadrant [MN/m]</td>
<td>-1.5</td>
<td>-2.6</td>
<td>-1.4</td>
<td>-2.4</td>
<td>-2.5</td>
</tr>
</tbody>
</table>

A. Zlobin, FNAL
20-T dipole magnet

beam pipe
Scaling \( I_{\text{safe}} \propto J \times B^2 \times \text{Volume} \)

- 0.0001 m\(^3\) 200 A
- 2 m\(^3\) 200-800 A
- 25 m\(^3\) 8 kA
- 50 m\(^3\) 12 kA
- 400 m\(^3\) 20 kA
- 1000 m\(^3\) 40-70 kA
High power proton accelerators

Production of intense flux of secondary particles relevant for several domains of fundamental or applied science

- Muons, neutrinos... for Particle physics

- Neutrons for condensed matter physics, material physics, irradiation, transmutation of long-lived nuclear wastes...

- Radioactive ions... for Nuclear physics
One example: SNS (Oak Ridge, USA)
Other machines & projects

- SPIRAL-2 project @ GANIL (Caen, F)
- CERN – Linac 4 & SPL project
- J-PARC facility (Japon)
- IFMIF project
- FAIR project (Germany)
- PSI (Switz.)
- ESS project (Sweden)
- MYRRHA project (Belgium)
New acceleration technics

Å plasmas & crystals demonstrate large focusing forces, $10^3$-$10^4$x stronger than SC quadrupoles

Å they could also provide large dipole field; so far bending fields of 5-100 T demonstrated

Å beam-matter interaction & efficiency are the critical issues for circular ring applications

Å straightforward use in single-pass systems

Å incentive to strengthen crystal R&D!

Å Frank Zimmermann  EuCARD2013, 11 June 2013
Theme of the School:
REFLECTIONS ON THE NEXT STEP FOR LHC

EPS-TIG Workshop
Accelerators – Detectors – Computing

ATLAB
an organized effort to support detector R&D in ATLAS
finding end user applications for detector technology

ERDIT
PROPOSAL FOR A NETWORK FOR RADIATION DETECTOR DEVELOPMENT IN EUROPE
European survey shows that 85% of detectors R&D is done within experiments and hence R&D is more and more driven by present or incoming experiments.

Layout and detection technology will not change much for LHC experiments.

Upgrades are:

- **Vertex**: will see advanced 3D electronics
- **Trackers**: will see new trigger strategy (electronics)
- **Particle identification**: will see improved read-out
- **RICH, DIRC, TOF**: will see improved read-out
- **TPC**: will see improved read-out
- **Calorimetry**: will see improved granularity
European survey shows that 85% of detectors R&D is done within experiments and hence R&D is more and more driven by present or incoming experiments.

Layout and detection technology will not change much for LHC experiments.

Upgrades are:

**LHCC Detector Upgrade Review (11 juin 2013)**

- CMS Level 1 Trigger Upgrade
- ATLAS New Small Wheels Phase-I TDR
- ATLAS Fast Track Trigger Phase-I TDR
- ALICE Muon Forward Tracker LOI
LHC Schedule Assumptions

- LHC startup, \( \sqrt{s} = 900 \text{ GeV} \)
- \( \sqrt{s}=7\sim8 \text{ TeV}, L=6\times10^{33} \text{ cm}^{-2} \text{ s}^{-1}, \text{ bunch spacing 50 ns} \)
- Go to design energy, nominal luminosity (Phase-0)
  - \( \sqrt{s}=13\sim14 \text{ TeV}, L\sim1\times10^{34} \text{ cm}^{-2} \text{ s}^{-1}, \text{ bunch spacing 25 ns} \)
  - Injector and LHC Phase-I upgrade to full design luminosity
  - \( \sqrt{s}=14 \text{ TeV}, L\sim2\times10^{34} \text{ cm}^{-2} \text{ s}^{-1}, \text{ bunch spacing 25 ns} \)
- HL-LHC Phase-II upgrade, IR, crab cavities
  - \( \sqrt{s}=14 \text{ TeV}, L=5\times10^{34} \text{ cm}^{-2} \text{ s}^{-1}, \text{ luminosity levelling} \)
ATLAS upgrade (see P. Jenni talk)

1) ATLAS will add a fourth layer of pixels, known as the Insertable B-Layer, to its pixel detector.

The increased number of pixels will enable measurements at a location closer to where particle collisions occur and allow scientists more accurately to identify jets of particles produced from bottom quarks.

2) The ATLAS collaboration will also install and integrate more muon chambers to strengthen the detectors’ measurement of muons produced in particle collisions.

3) They will also put in place new beam pipes made of aluminum and beryllium to help reduce background particles in future collisions.

4) At higher luminosity, the experiments will deal with more collisions and therefore will need better trigger systems.
ALICE upgrade

1) A new Di-Jet Calorimeter will broaden the experiment’s ability to measure the energy of individual gamma rays to infer the energy of the quark from which it was emitted.

Since the gamma ray doesn't undergo the strong interaction, it escapes the hot, dense matter produced, and its transverse momentum is equal and opposite to that of the recoiling quark.

2) Complete the Transition Radiation Detector, during the long shutdown. The detector is close to completion, with 13 out of 18 modules installed.

3) Electronics upgrade for 50kHz Pb-Pb interaction rate

Time Of Flight Detector (TOF), Transition Radiation Detector (TRD), Muon System, Photon Spectrometer (PHOS), EMCal. HMPID
1) During the long shutdown, the CMS experiment plans to add a new layer to their muon detector, which will help them to decide which collisions are worth studying. This fourth layer of the muon system was left off because it wasn’t necessary at low luminosity. Now, in order to be able to maintain good trigger selectivity at high luminosity, ... you need this fourth layer.

2) Another priority of the CMS experiment during the shutdown is ensuring that their tracking detector, which tracks the paths of individual particles, can operate at dramatically colder temperatures. The tracking detector is made of silicon, which radiation degrades even at freezing temperatures. To preserve the silicon amid higher radiation, the temperature will be lowered to roughly -15 degrees Fahrenheit.
LHCb upgrade

1) replace a segment of beam pipe and its support structures. The new pipe will be able to withstand temperature changes and radiation better, and the lighter support structure will reduce background in the detector.

LHCb will also begin to prepare for the next planned shutdown, in 2018, when they will install an upgrade to their detector.

They want to increase the speed with which we can read out the detector from 1 MHz to 40 MHz, using the 2013 shutdown to prepare the infrastructure and lay cables, needed for the new detector.
Cooling of future detectors

Carbon Foam + Metal Pipe

Silicon Microchannels

\[ \%X_0 + C_4F_{10} = 0.28\% \]

\[ \%X_0 = 0.2\% \]

\[ \%X_0 + C_4F_{10} = 0.12\% \]

\[ \%X_0 = 0.1\% \]

Metal Pipe
Carbon Foam

10°C
5°C

\[ \Delta T \text{ between heat source and heat sink for power dissipation of } \sim 1W/cm^2 \]

no CTE difference
towards integrated micro-cooling

1. thin silicon cooling plate
   NA62
   LHCb

2. silicon cooling frame
   NA62
   ALICE

3. silicon cooling plate with TSVs
   3D architectures
   project will start in Sept. 2012

   TSV: Through Silicon Via

   ... integration of the μ-channels
   in-plane connectivity
   in the bulk of the Si detector
   in the read-out chips
- study the heat transfer of superfluid He in microchannels
- improve the insulation of LHC magnets for upgrade plans.

P.P. Granieri, A. Mapelli et al., “Steady-state transfer through micro-channels in pressurized Hell”
Presented at CEC/ICMC 2011
(http://cdsweb.cern.ch/record/1416393/)
Improving timing performance

The time-resolution achievable by particle detectors is continuously being improved!

QGCW

Incoming Particles

\[ p, n, \pi, K, \mu, e, \gamma, \nu \]

Outcoming Particles

Studying and developing new technologies \( \Rightarrow \) will allow to probe the QGCW with particle beams
Theme of the School:
REFLECTIONS ON THE NEXT STEP FOR LHC

EPS-TIG Workshop
Accelerators – Detectors – Computing

Grids in Particle Physics

Courtesy  Bob Jones CERN all slides
Solution: the Grid

The Grid unites computing resources of particle physics institutes
The Grid runs more than one million jobs per day.
Peak rates, 10 gigabytes of data transferred from its servers/second.

The World Wide Web provides seamless access to information that is stored in many millions of different geographical locations

The Grid is an infrastructure that provides seamless access to computing power and data storage capacity distributed over the globe
How CERN got into grids

- Partially decentralized model
  - replicate the event data at about five regional centres
  - data transfer via network or movable media


GRID 3  OSG
GriPhyN, iVDGL, PPDG
EGEE 1
EGEE 2
EGEE 3
EU DataGrid
LCG 1
LCG 2
WLCG

Service Challenges
Cosmics
First physics
Data Challenges
Significant use of Tier 2s for analysis
By early 2013 CERN had increased the power capacity of the centre from 2.9 MW to 3.5 MW, allowing installation of more computers.

**Wigner Research Centre for Physics** in Budapest, Hungary, operates as an extension to the DC acting as a remote Tier 0.

The Meyrin site currently provides some 30 petabytes of data storage on disk, and includes the majority of the 65,000 processing cores in the CERN DC.

The Wigner DC will extend this capacity with 20,000 cores and 5.5 petabytes of disk data, and will see this doubling after 3 years.
The Physics community took the concept of a grid and turned into a global production quality service aggregating massive resources to meet the needs of LHC collaborations.

The results of this development serve a wide range of research communities have helped industry understand how it can use distributed computing have launched a number of start-up companies and provided the IT service industry with new tools to support customers.
A European Cloud Computing Partnership
big science teams up with big business

Email: contact@helix-nebula.eu  Twitter: HelixNebulaSC  Website: http://www.helix-nebula.eu/
Initial flagship use cases

- **ATLAS High Energy Physics Cloud Use**
  - To support the computing capacity needs for the ATLAS experiment

- **Genomic Assembly in the Cloud**
  - A new service to simplify large scale genome analysis; for a deeper insight into evolution and biodiversity

- **SuperSites Exploitation Platform**
  - To create an Earth Observation platform, focusing on earthquake and volcano research

- **Scientific challenges with societal impact**
- **Sponsored by user organisations**
- **Stretch what is possible with the cloud today**
Monte Carlo jobs (lighter I/O)
- 10s MB in/out
- ~6-12 hours/job

Ran ~40,000 CPU days

Difficulties overcome
- Different vision of clouds
- Different APIs
- Networking aspects

Ramón Medrano Llamas, Fernando Barreiro, Dan van der Ster (CERN IT), Rodney Walker (LMU Munich)
EMBL Flagship project: Whole-Genome Assembly

Cloud Storage

Integration with other cloud services / Archiving

On-demand processing

Cloud Service

Data acquisition

Scientists

Access

NGS Labs
Earth Observation Application Platform exploiting 20 years of satellite data

Å EO Application Platform
  - OpenNebula
  - Data Catalogue and Access
  - Map-Reduce computing model
  - Software repository
  - Utilities for sw development and testing

Å Cloudification of application
  - CNR / IREA (Italian Research Council in Naples) developed an application (SBAS) measuring the vertical movement of ground in sub cm from space.
  - SBAS targets
    - Time series over 20 years with ESA archive
    - Points of Interest are at world scale
    - TBytes of data to process
Many research communities and business sectors are now facing an unprecedented *data deluge*. The Physics community with its LHC program has unique experience in handling data at this scale.

Cloud computing uses many of the advances pioneered by grid computing and makes it accessible to business sectors, governments and the general public.

The on-going work to evolve the LHC computing infrastructure to make use of cloud computing technology can serve as an excellent test ground for the adoption of cloud computing in many research communities, business sectors and government agencies.

The Physics community is exploring how commercial cloud services can serve the research infrastructures of the future and provide new markets for European industry.
Thanks for your attention