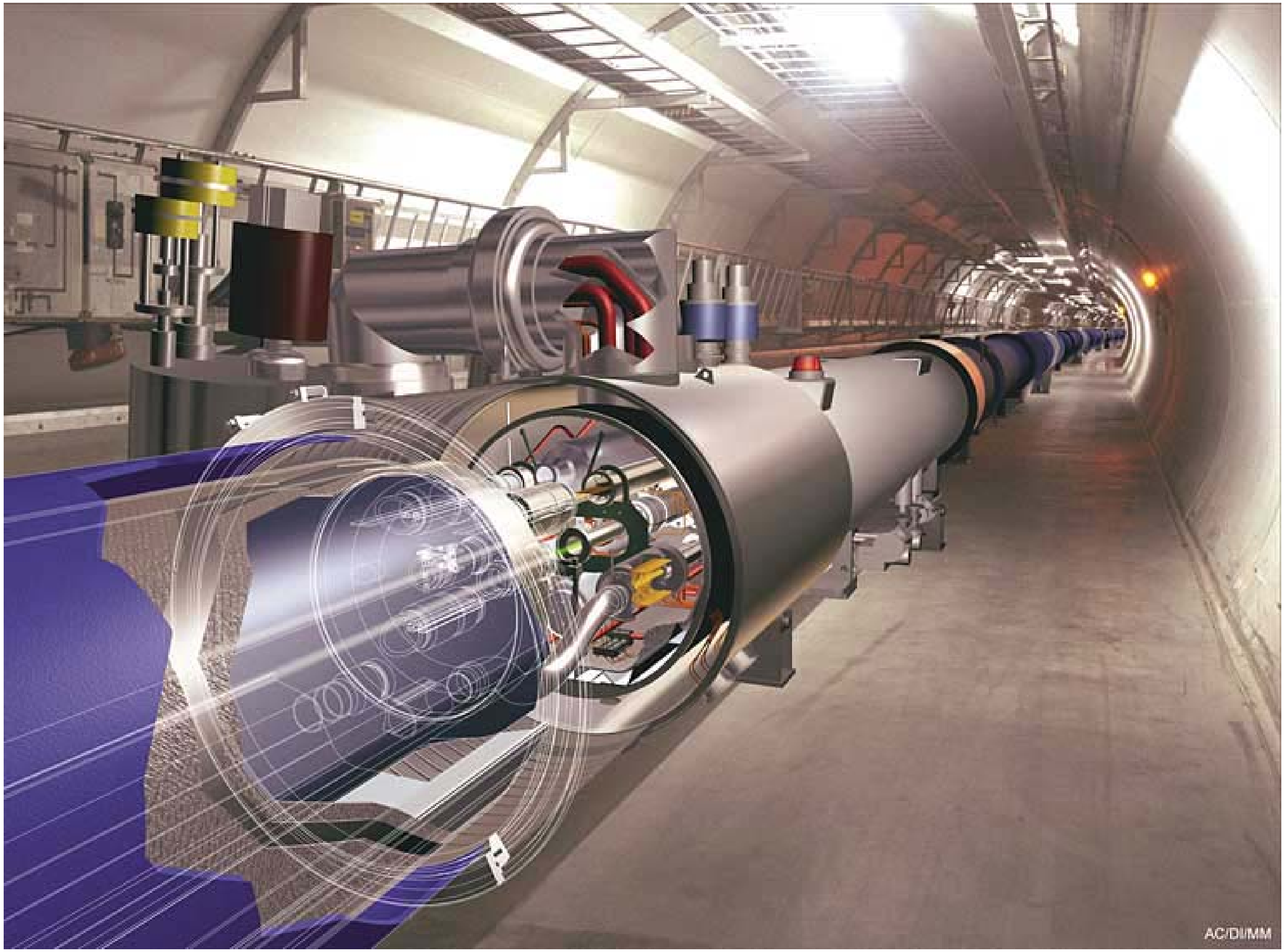
Industrial technology for unprecedented energy and luminosity: the Large Hadron Collider

Ph. Lebrun
CERN, Geneva, Switzerland

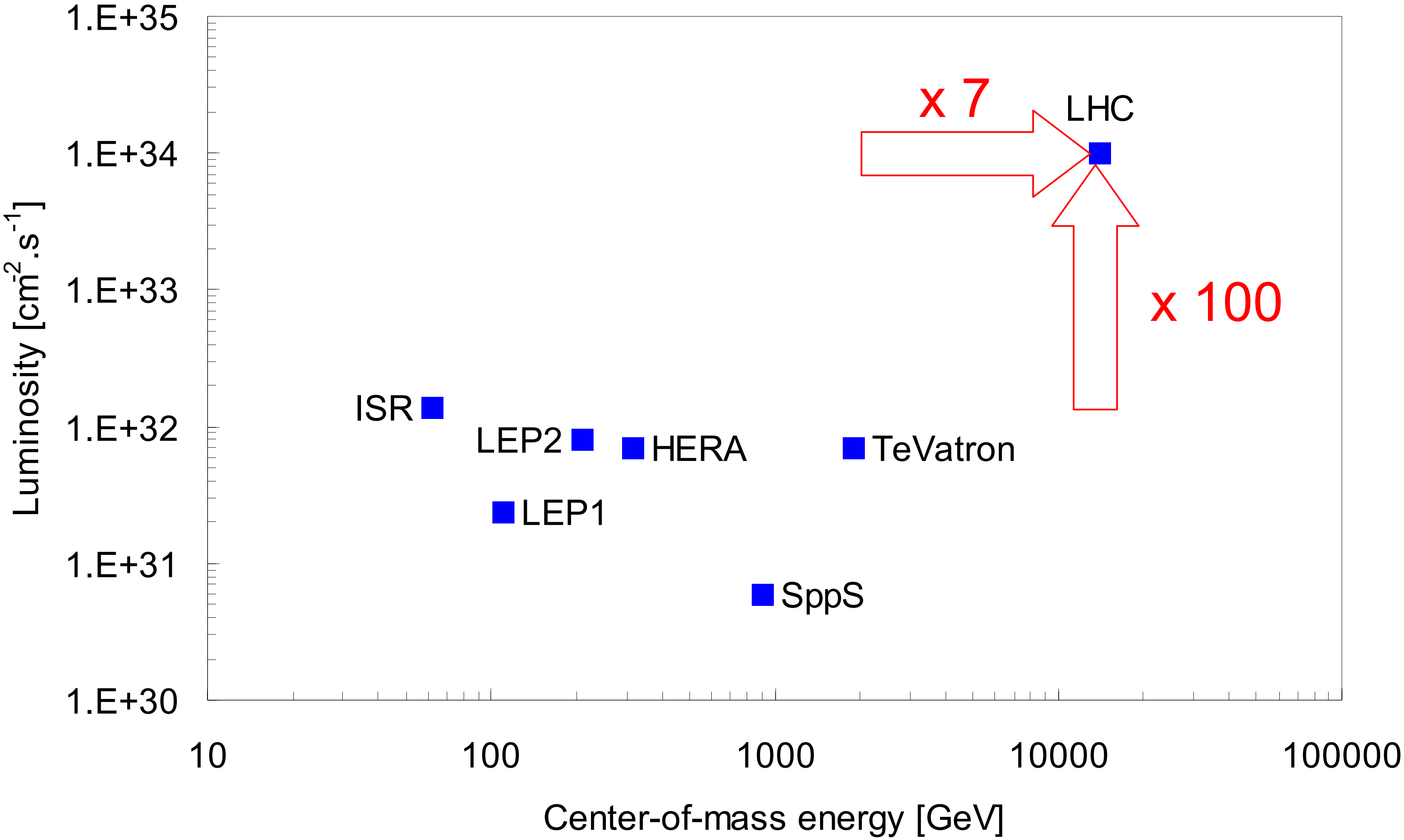
EPAC'04, Lucerne, 5-9 July 2004

A 27 km circumference collider…

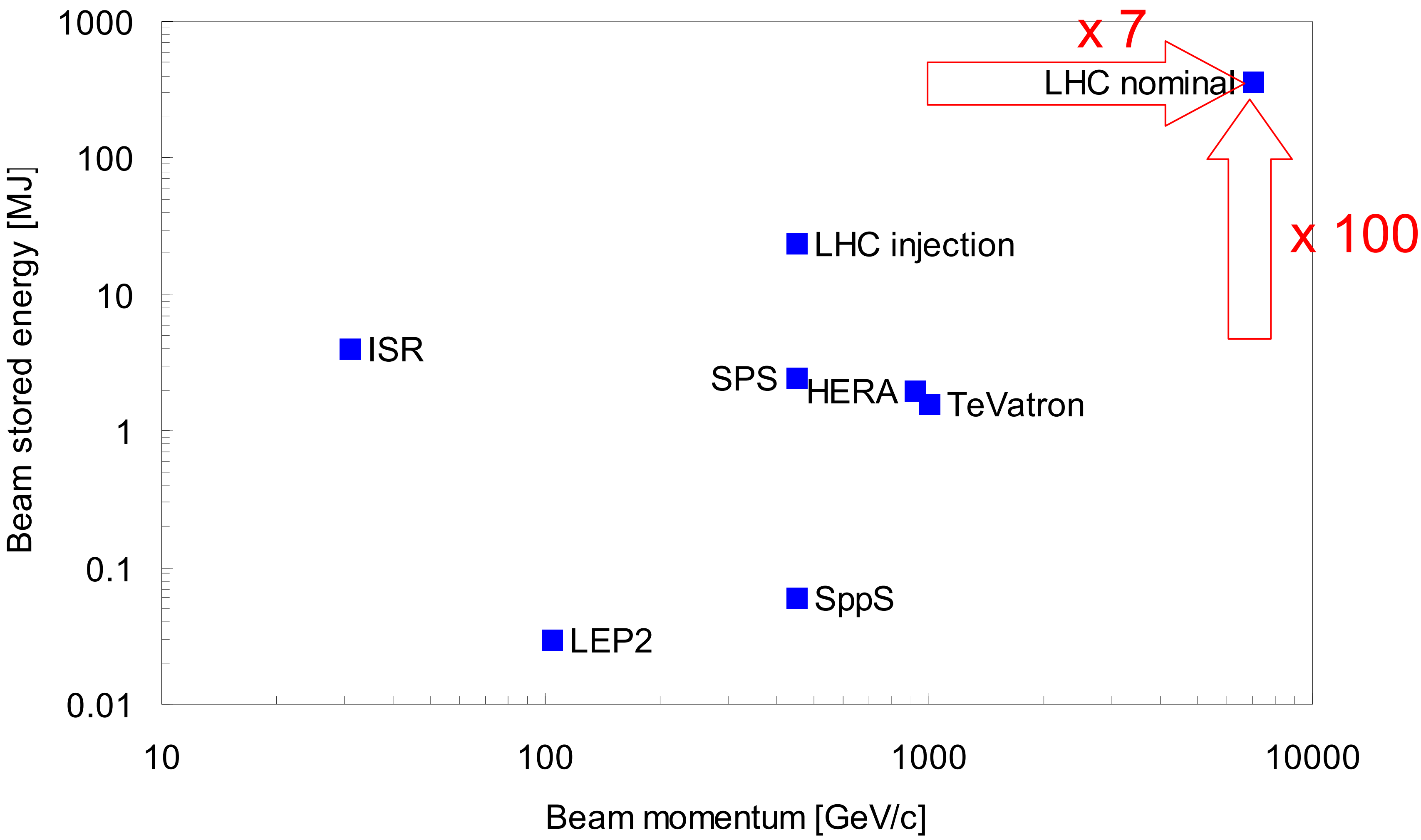
…based on superconducting technology



Luminosity & energy of colliders



Beam momentum & stored energy of colliders

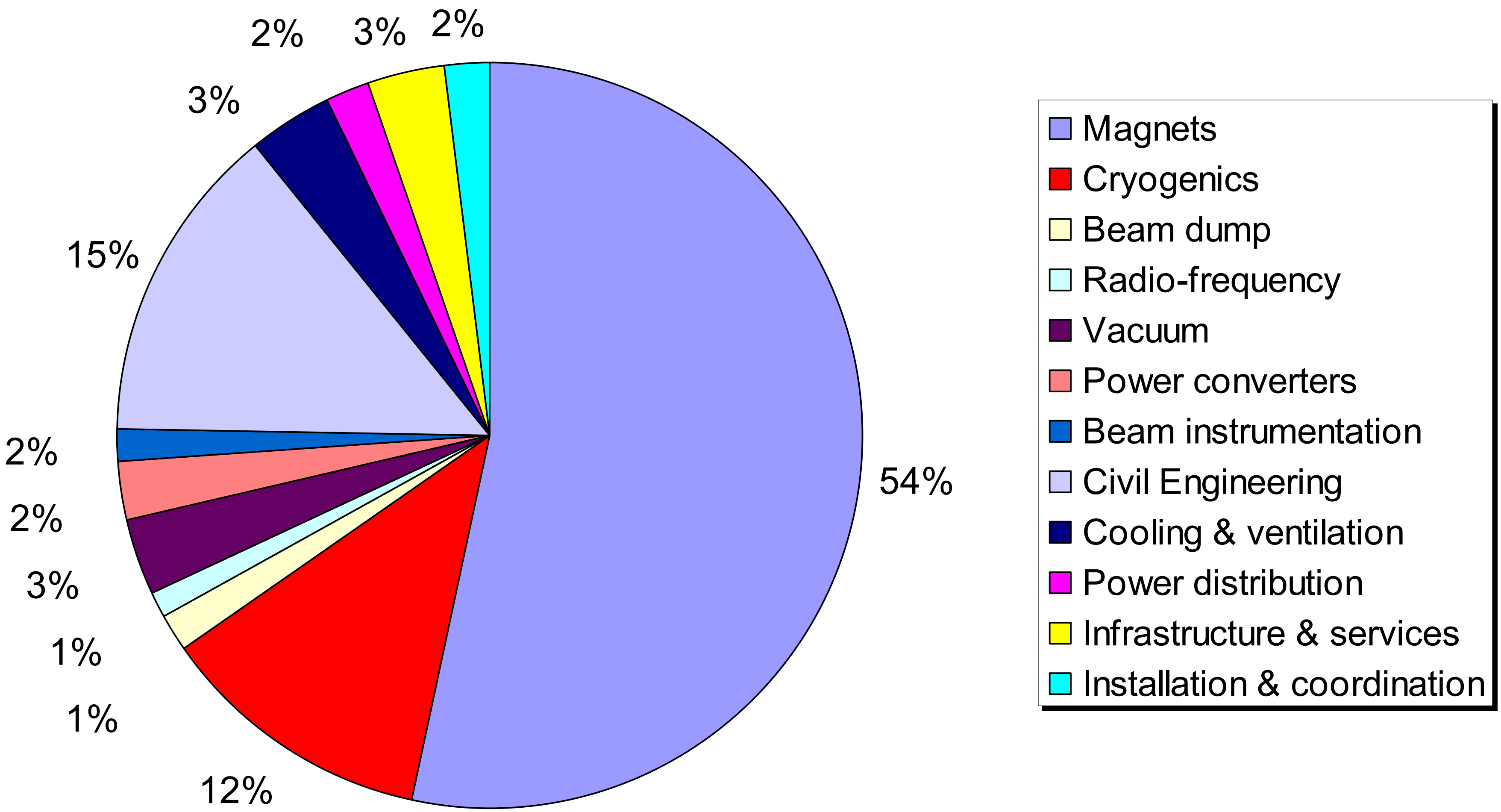


Main parameters of LHC (p-p)

Circumference	26.7	km
Beam energy at collision	7	TeV
Beam energy at injection	0.45	TeV
Dipole field at 7 TeV	8.33	T
Luminosity	10^{34}	$cm^{-2}.s^{-1}$
Beam current	0.56	A
Protons per bunch	1.1×10^{11}	
Number of bunches	2808	
Nominal bunch spacing	24.95	ns
Normalized emittance	3.75	μm
Total crossing angle	300	μrad
Energy loss per turn	6.7	keV
Critical synchrotron energy	44.1	eV
Radiated power per beam	3.8	kW
Stored energy per beam	350	MJ
Stored energy in magnets		
Operating temperature		

R. Schmidt, "Machine protection issues and strategies for the LHC", Tuesday morning

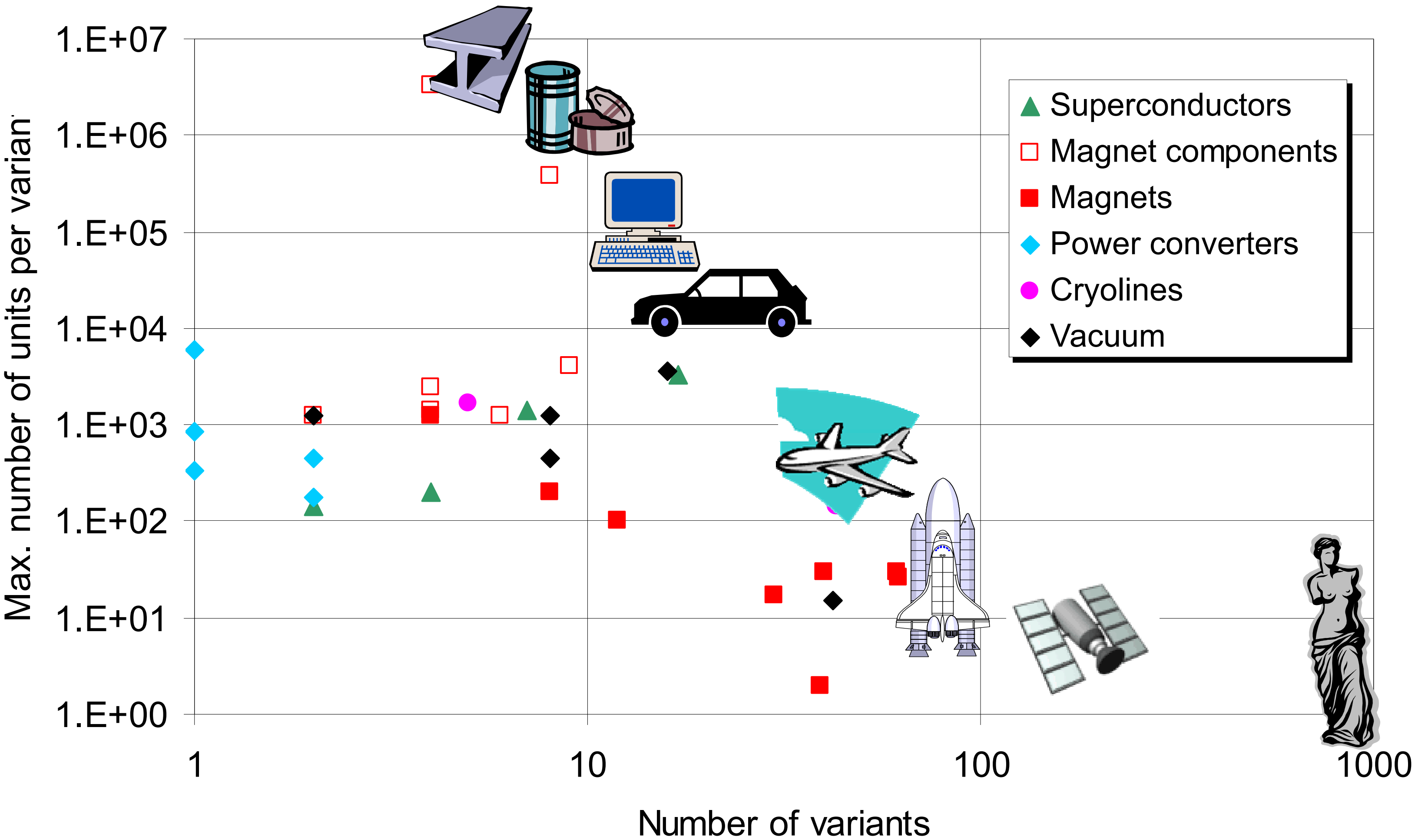
Cost structure of the LHC



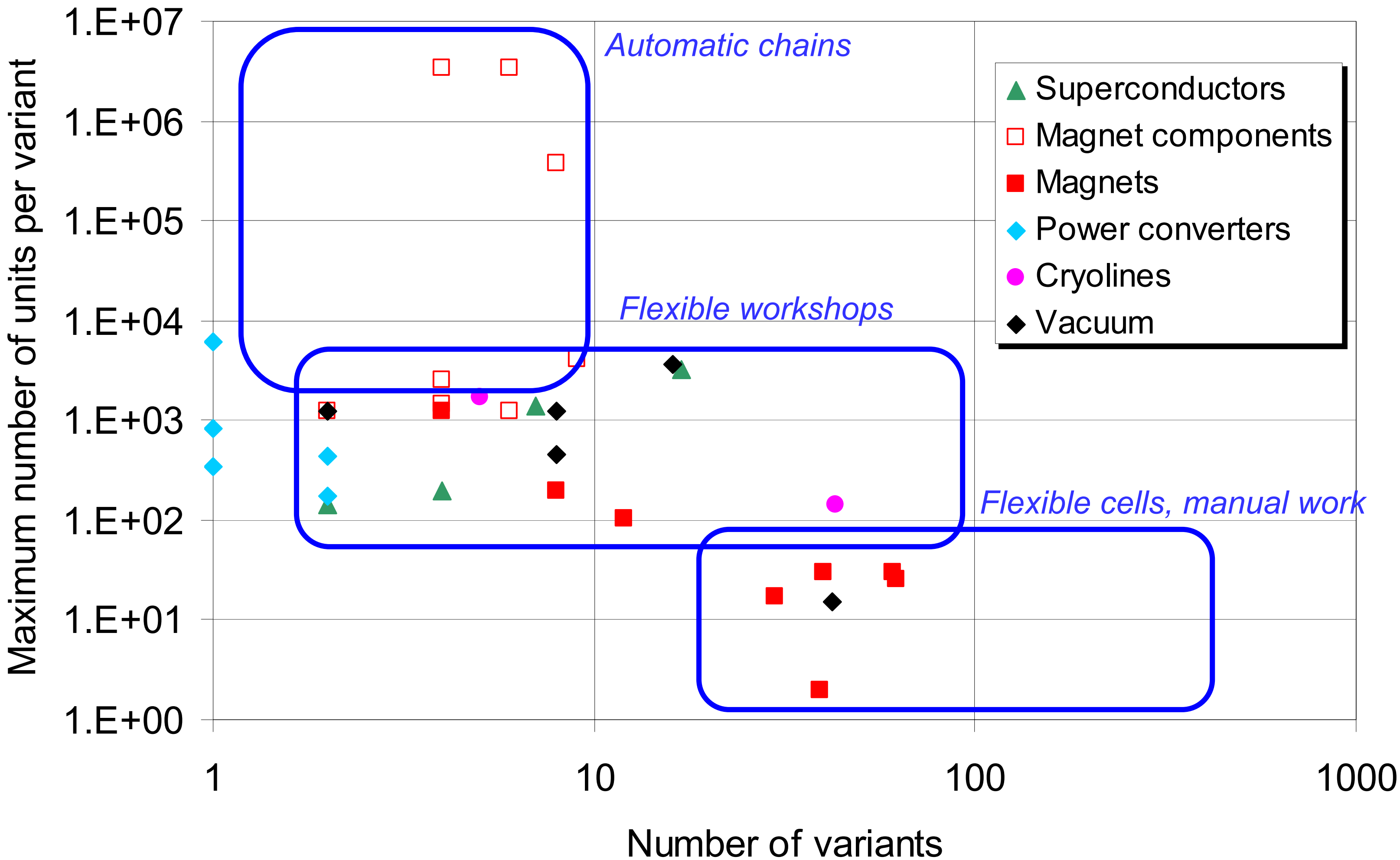
Superconducting magnets in the LHC

Type	Number	Function
MB	1232	Main dipoles
MQ	392	Arc quadrupoles
MBX/MBR	16	Separation & recombination dipoles
MSCB	376	Combined chromaticity & closed orbit correctors
MCS	2464	Sextupole correctors for persistent currents at injection
MCDO	1232	Octupole/decapole correctors for persistent currents at injection
MO	336	Landau damping octupoles
MQT/MQTL	248	Tuning quadrupoles
MCB	190	Orbit correction dipoles
MQM	86	Dispersion suppressor & matching section quadrupoles
MQY	24	Enlarged-aperture quadrupoles in insertions
MQX	32	Low-beta insertion quadrupoles

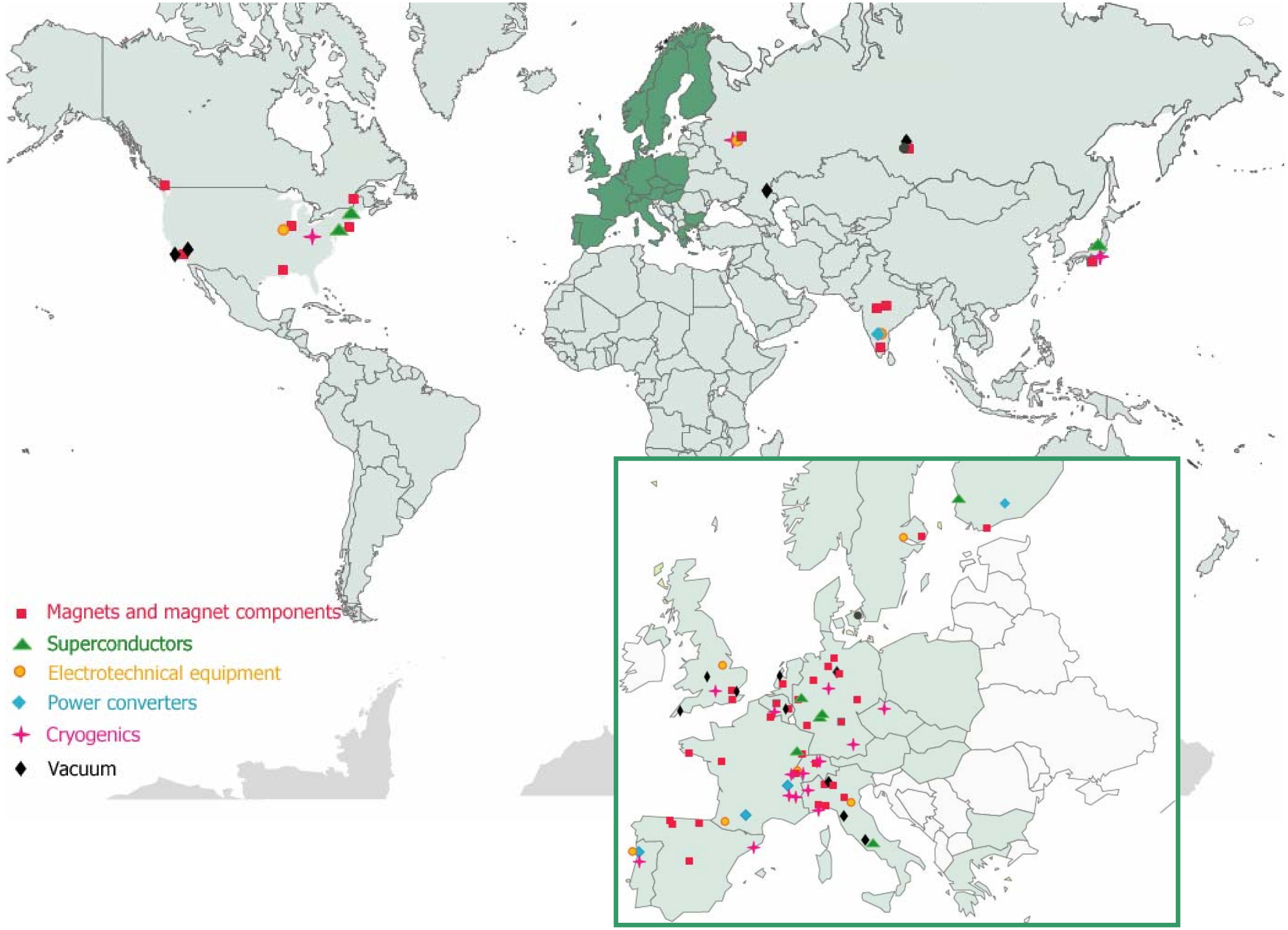
LHC components & industrial products

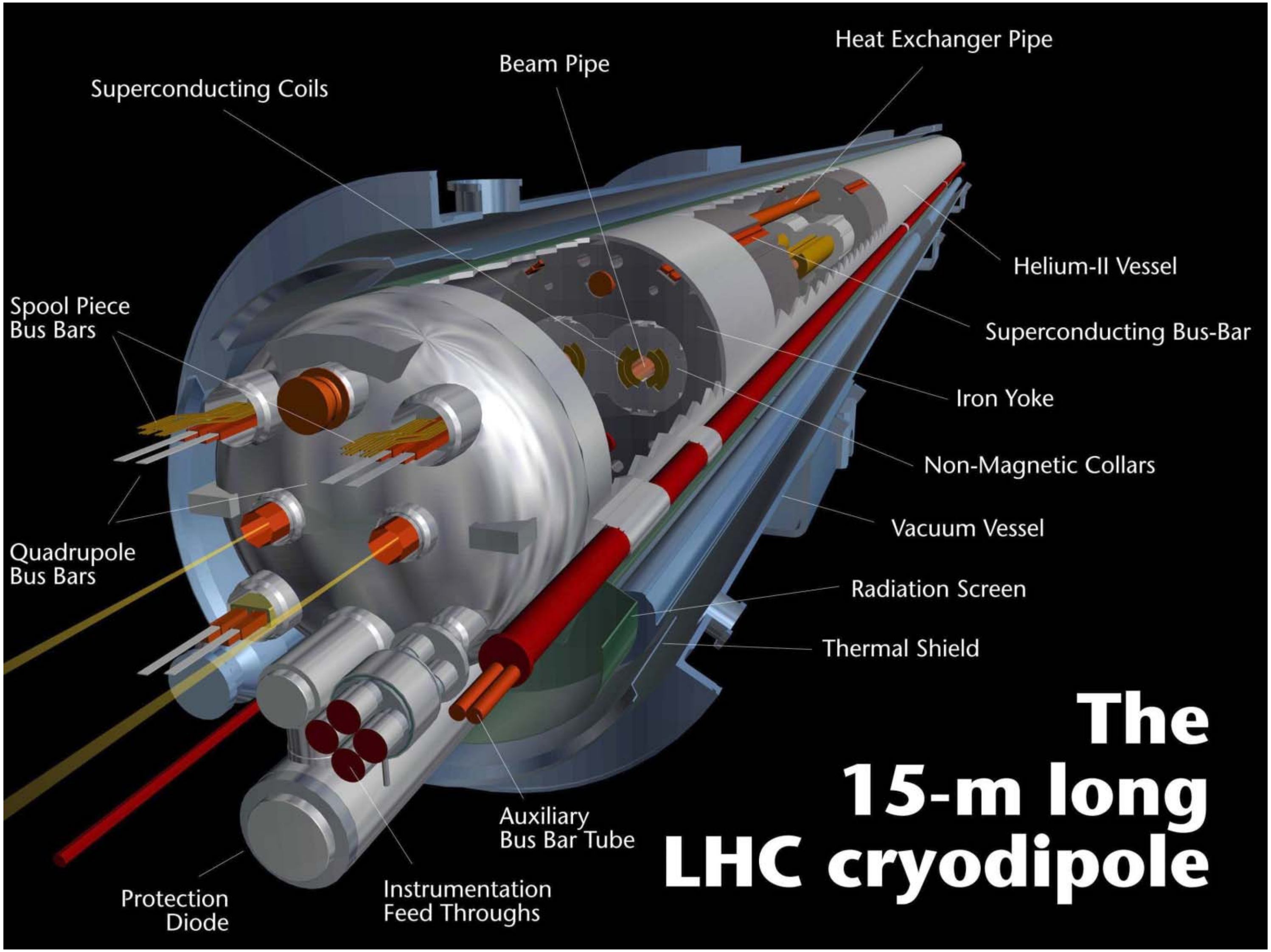


Series production of LHC components

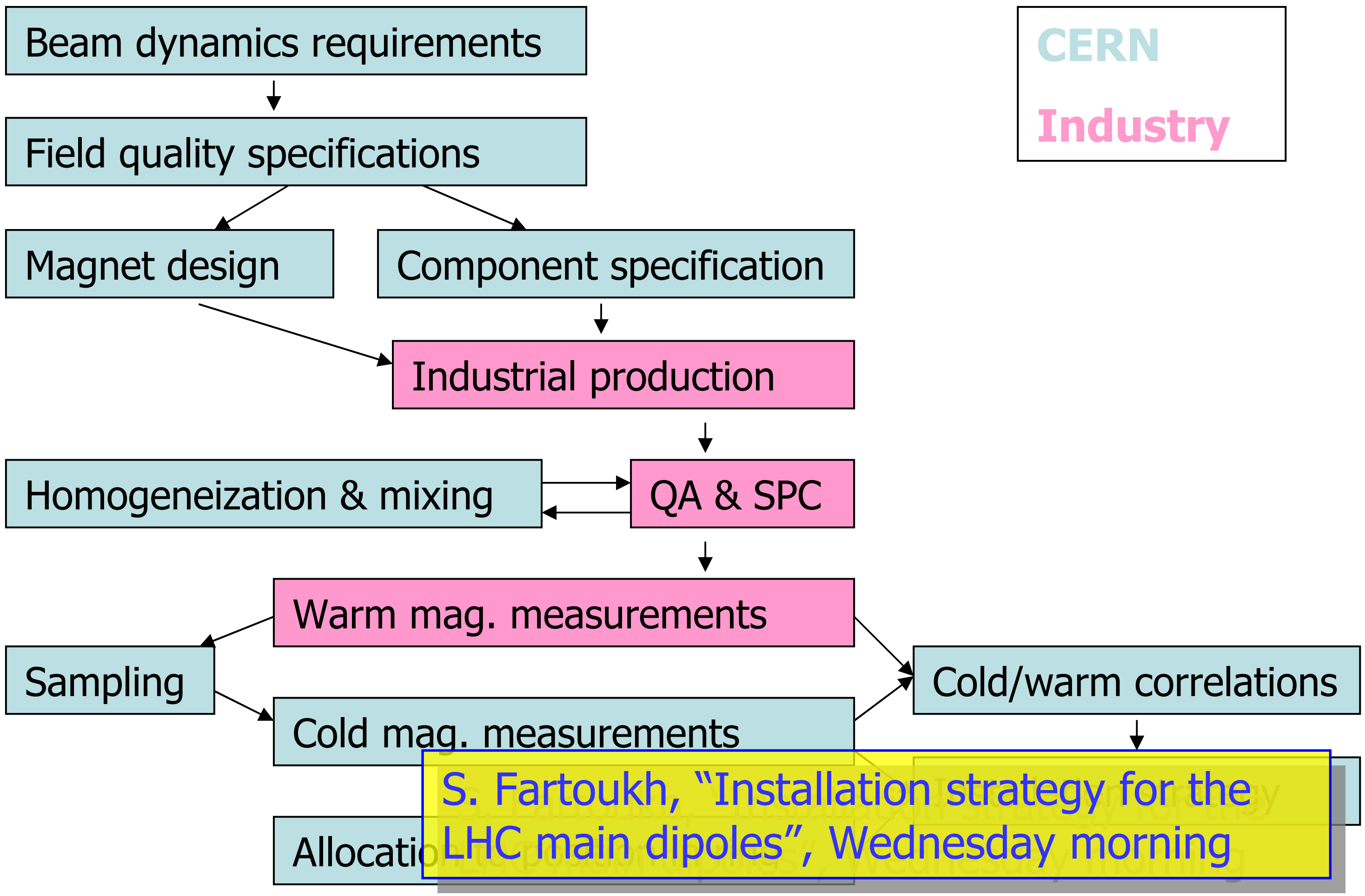


90 main supply contracts worldwide



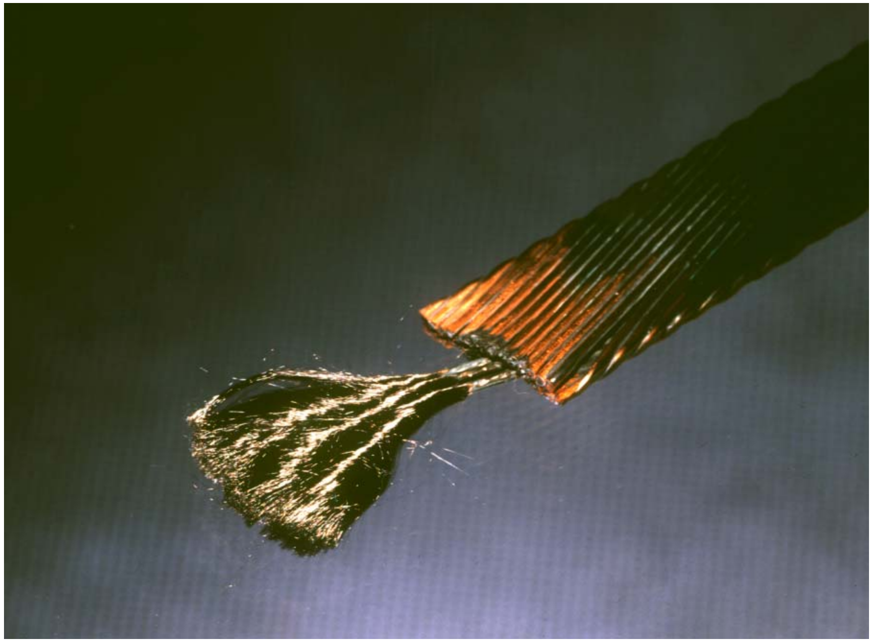

Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole
Bus Bars
Radiation Screen
Thermal Shield
The
15-m long
LHC cryodipole
Auxiliary
Bus Bar Tube
Instrumentation
Feed Throughs
Protection
Diode

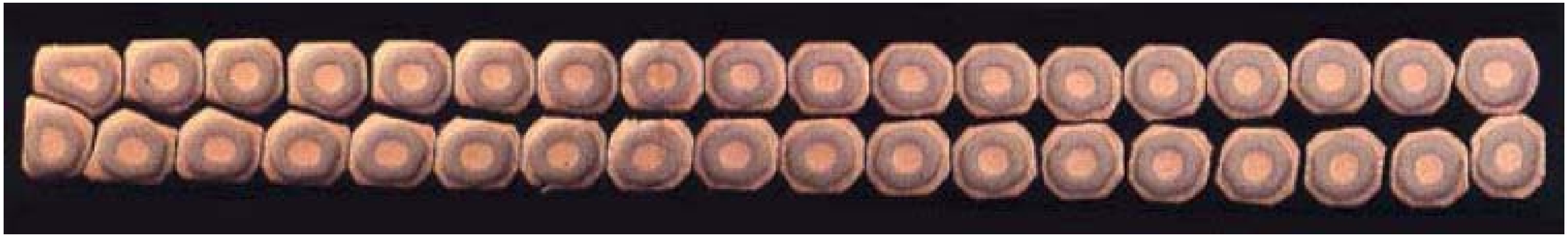
The long road to field quality



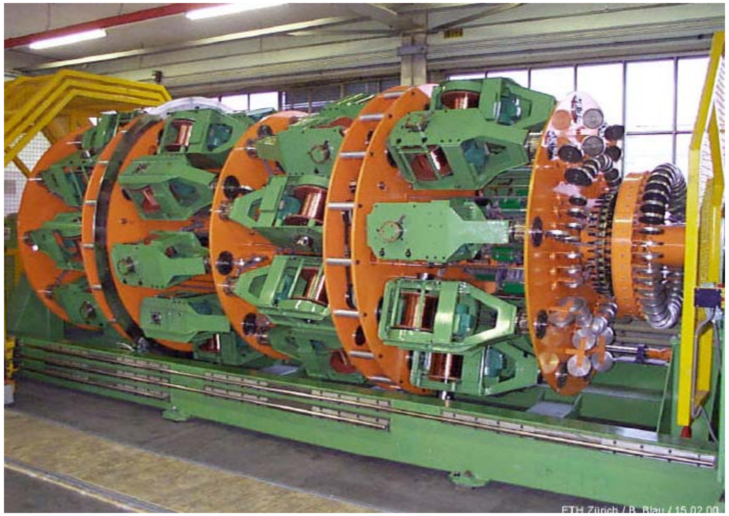
Characteristics of LHC superconducting cables

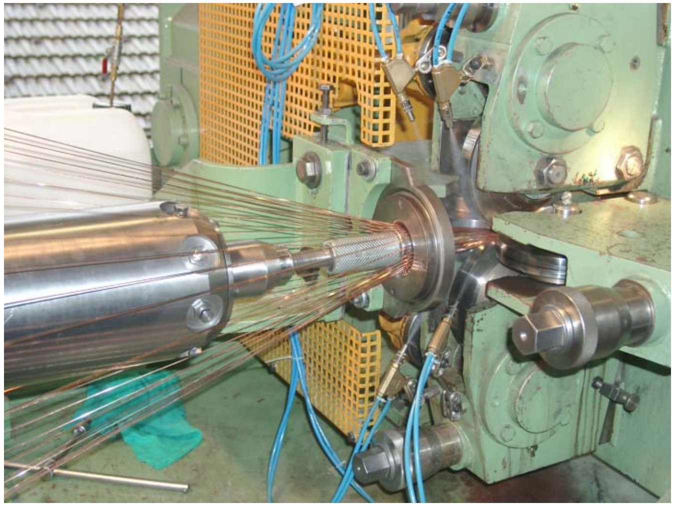
	Inner Cable	Outer Cable
Number of strands	28	36
Strand diameter	1.065 mm	0.825 mm
Filament diameter	7 µm	6 µm
Number of filaments	~ 8900	~ 6520
Cable width	15.1 mm	15.1 mm
Mid-thickness	1.900 mm	1.480 mm
Keystone angle	1.25 °	0.90 °
Transposition length	115 mm	100 mm
Ratio Cu/Sc	≥ 1.6	≥ 1.9



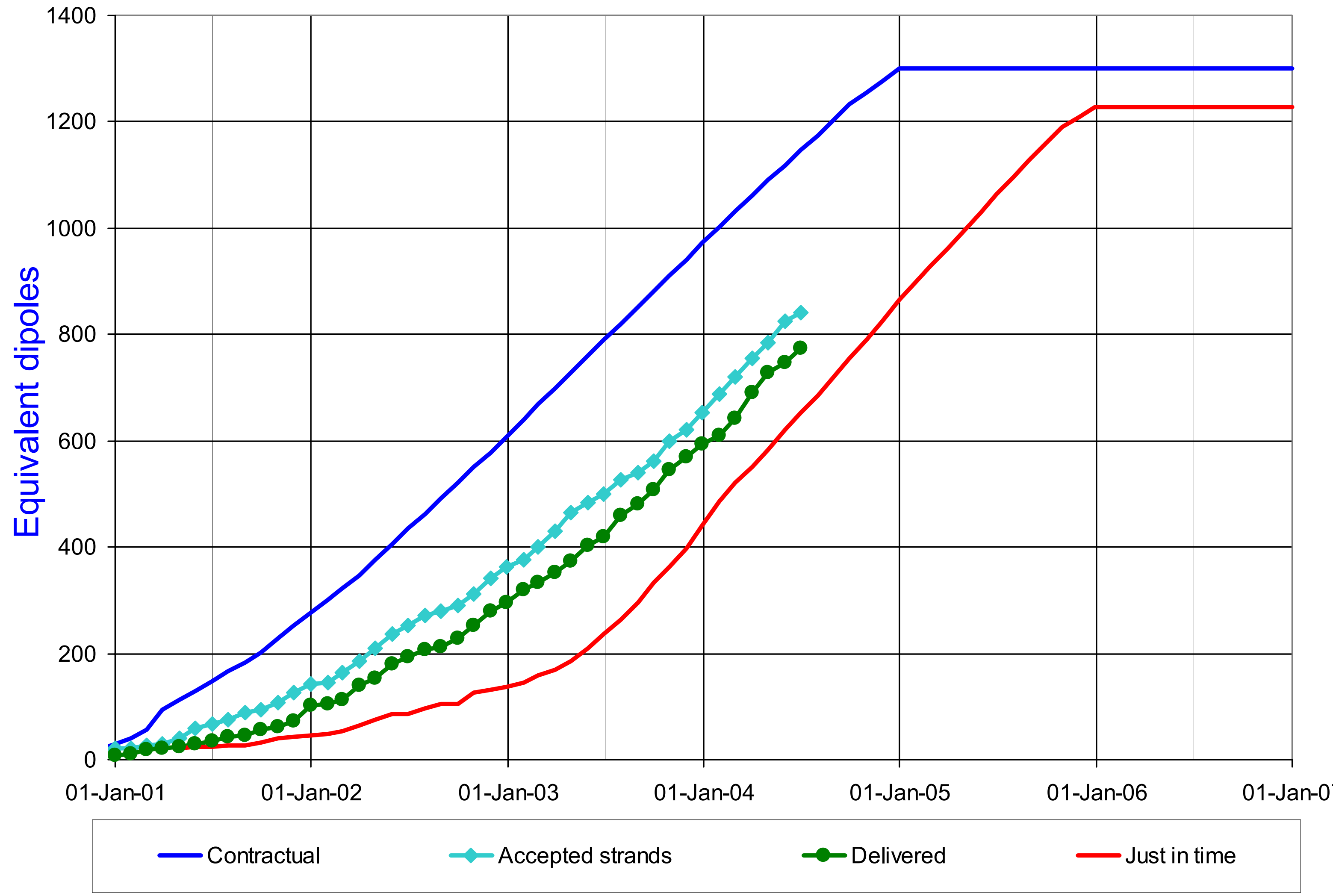


From billet assembly to finished cable





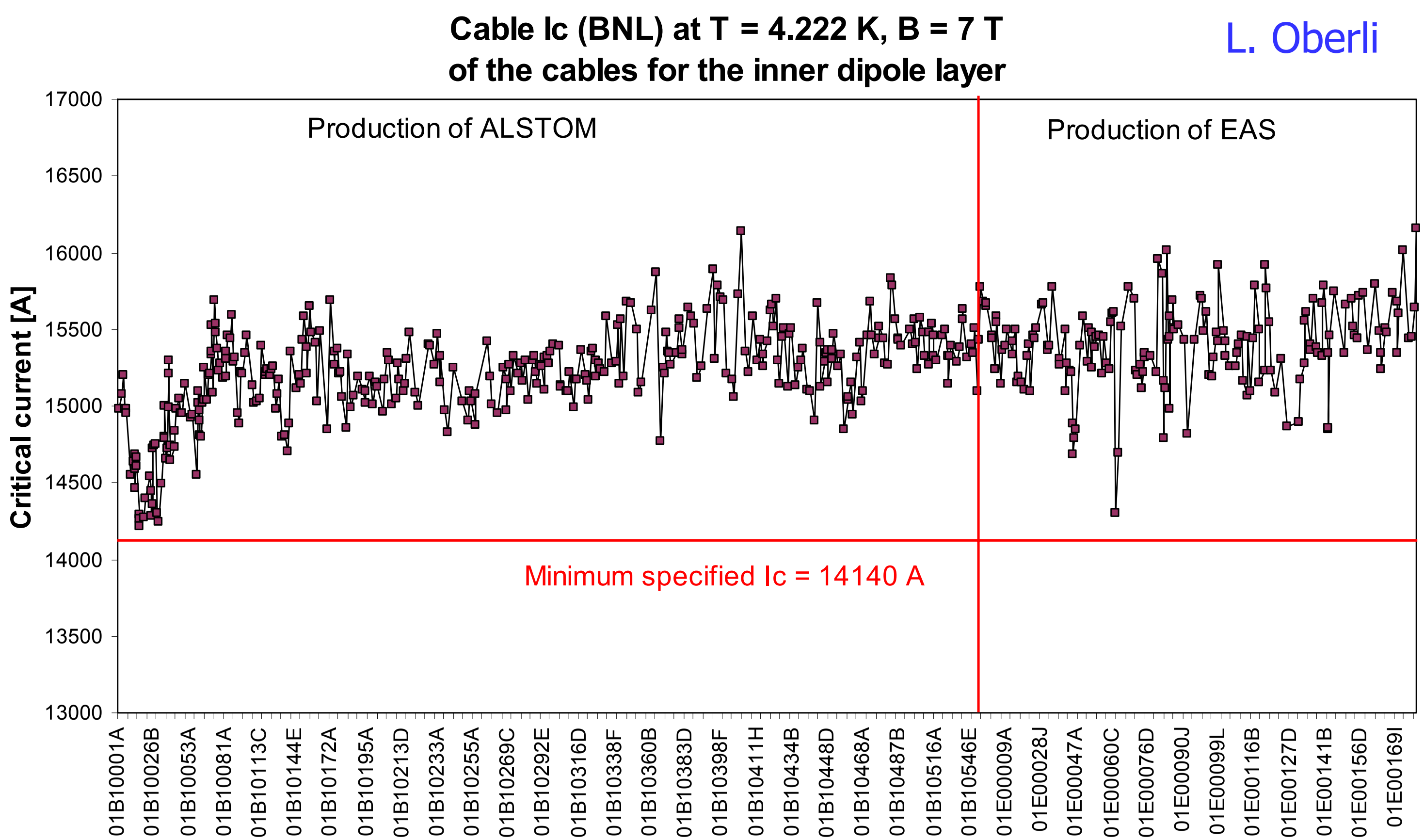
Superconducting cable 1



Critical current

=> ultimate field, low-field remanence

L. Oberli

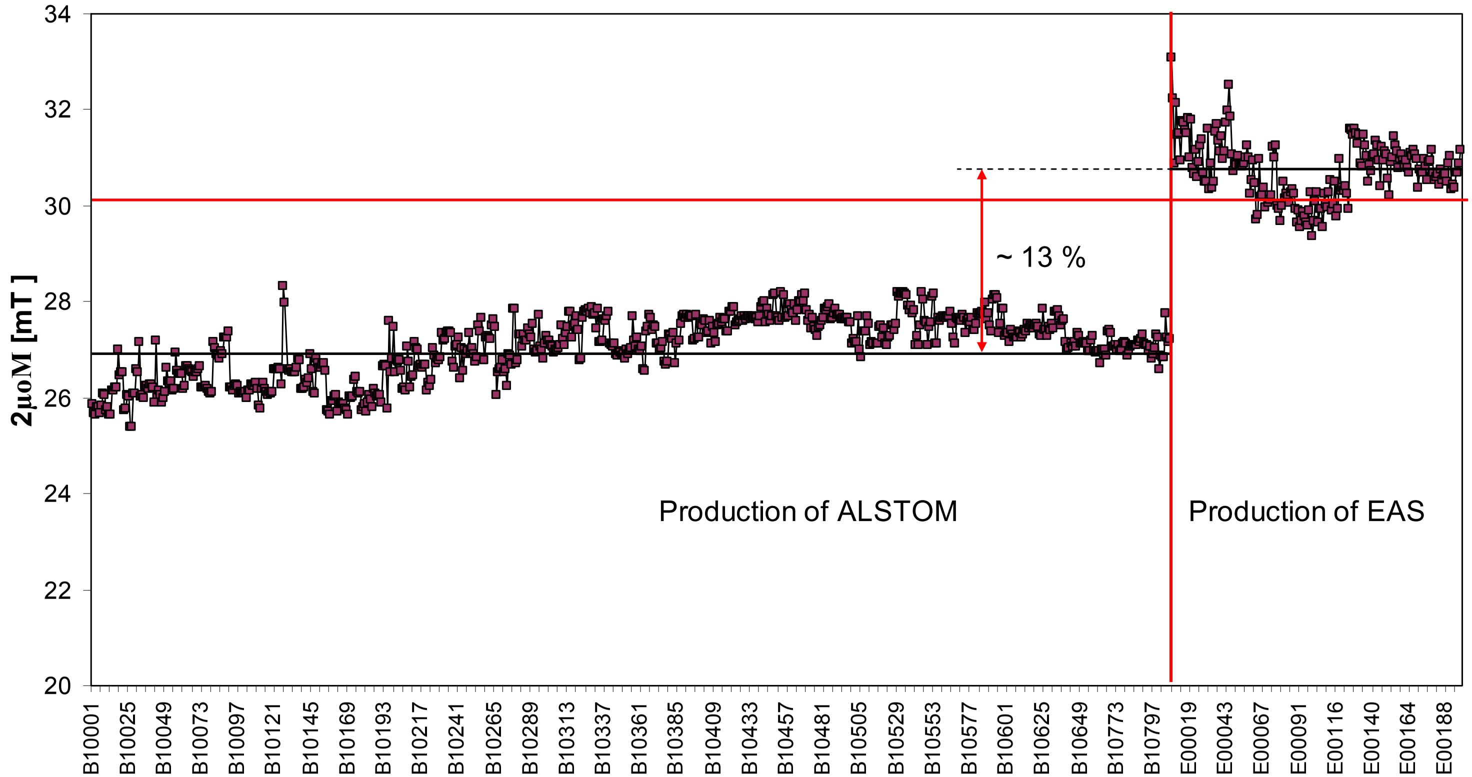


Magnetization

=> field quality at injection

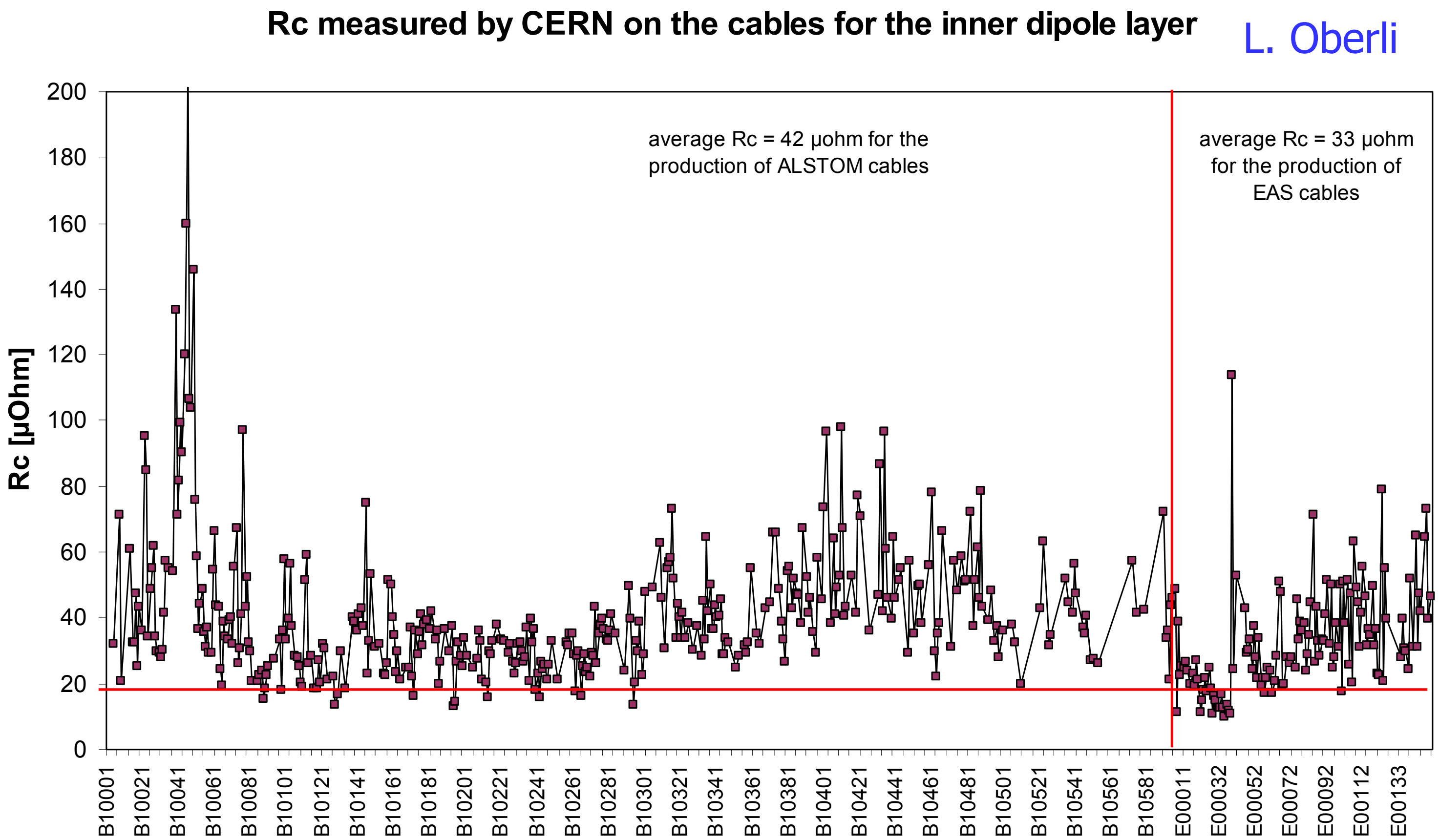
L. Oberli

Magnetization (2µoM) of the cables for the inner dipole layer measured at 1.9 K and 0.5 T



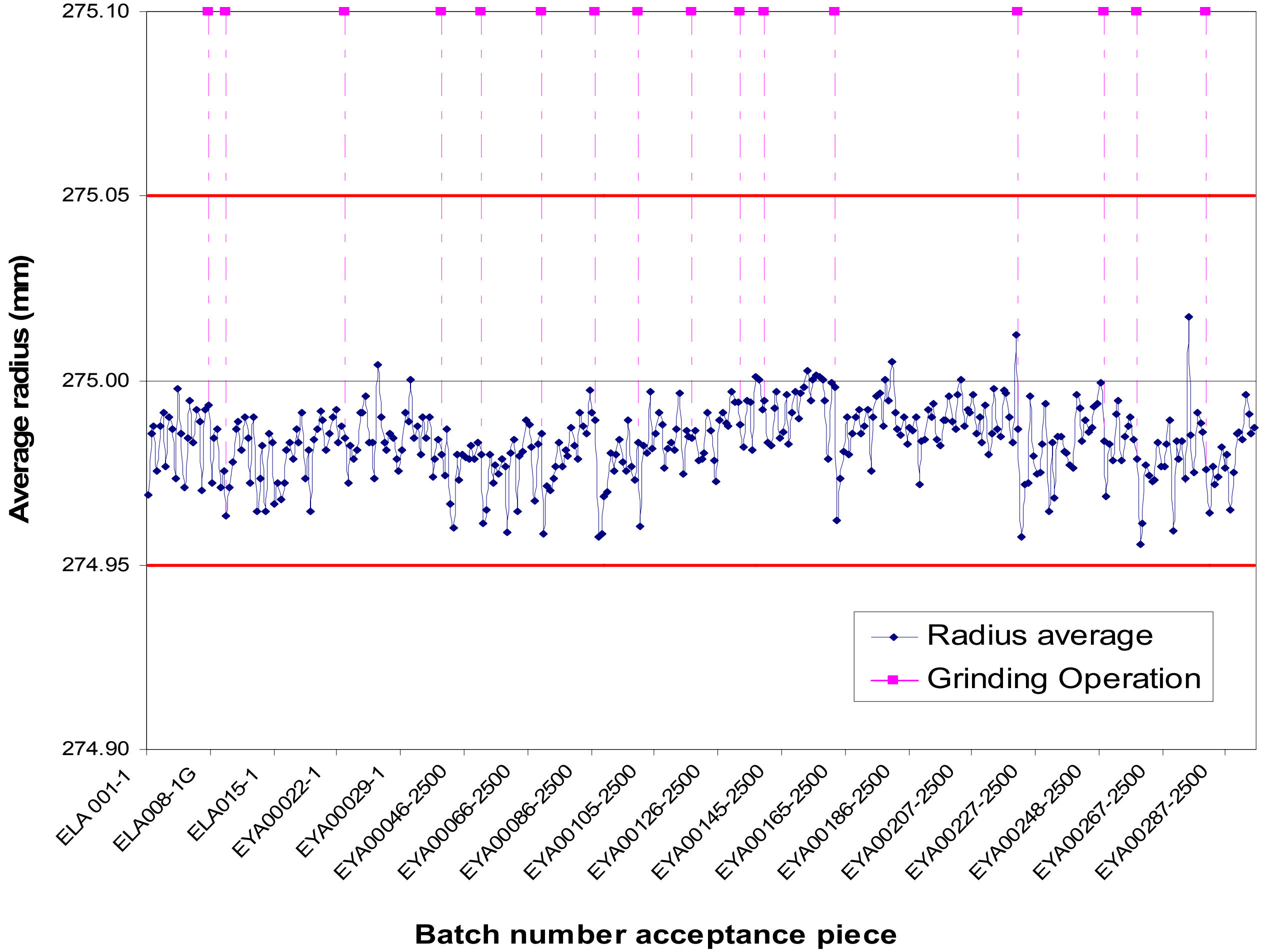
Inter-strand resistance
=> ramping losses, dynamic field quality

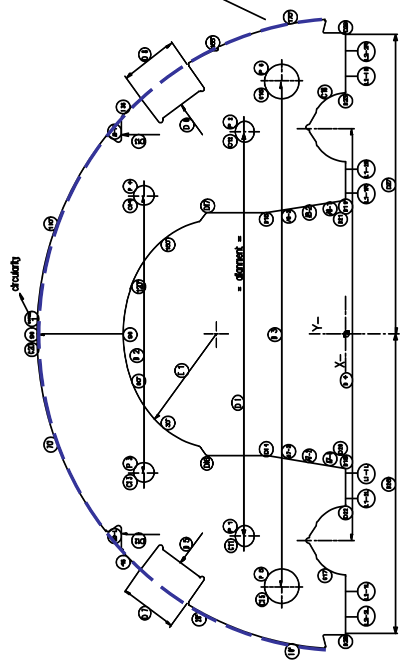
L. Oberli



SPC on magnet yoke laminations

Radius 275±0.05





F. Bertinelli

Integrated supply chain management

Benefits

- Technical homogeneity
- Quality assurance
- Economy of scale
- Security of supply
- Balanced industrial return

Risks & drawbacks

- Responsibility interface
- Additional workload
- JIT breakdown
- Transport, storage & logistics

Coil production

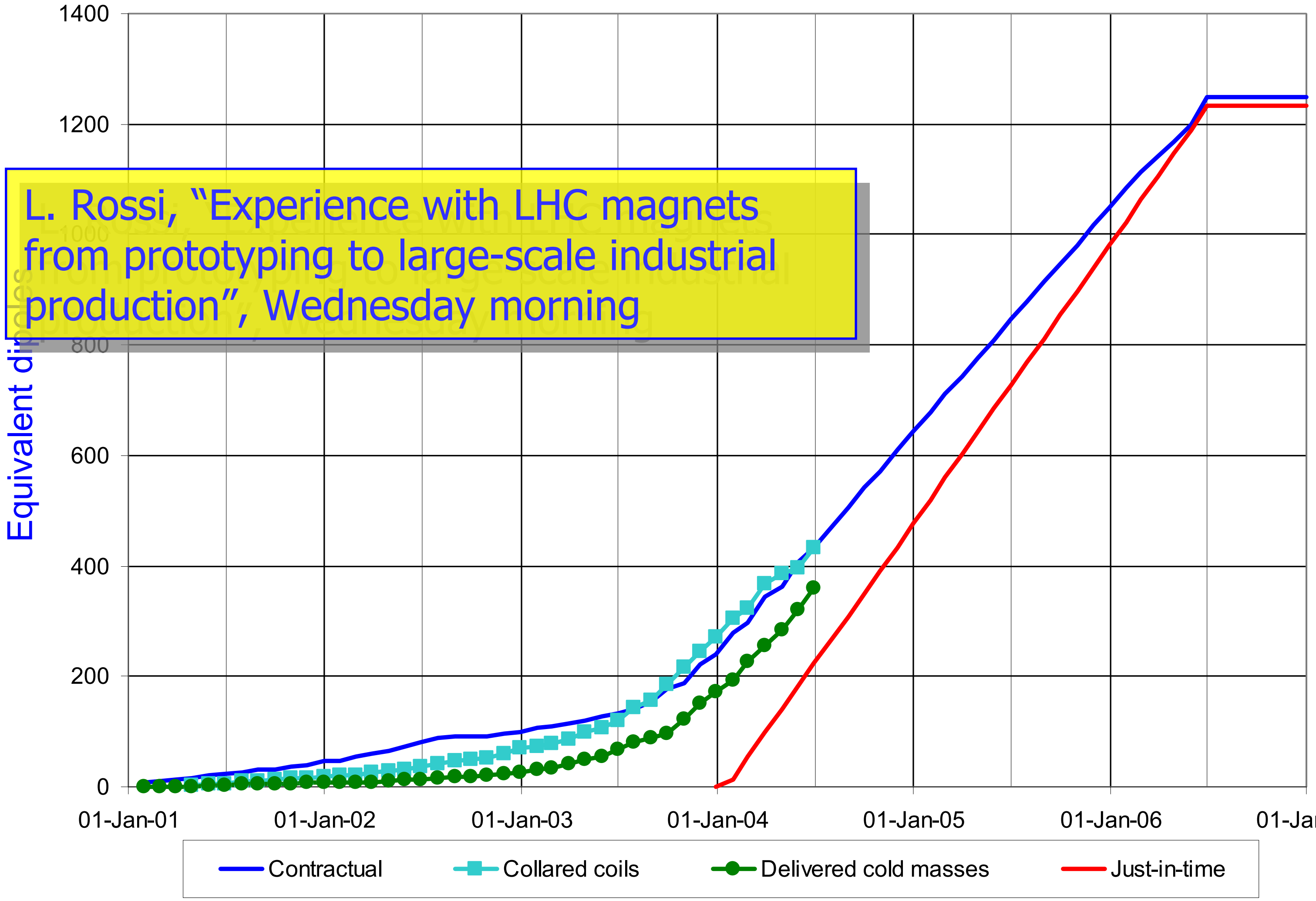
ANSALDO

Cold mass assembly

ALSTOM

NOELL

Dipole cold masses



L. Rossi, "Experience with LHC magnets from prototyping to large-scale industrial production", Wednesday morning

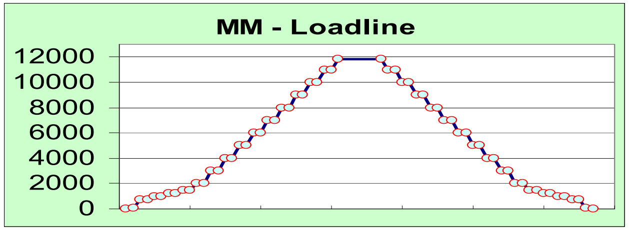
Cryogenic magnet test station

Typical cryogenic test sequence

L. Walckiers

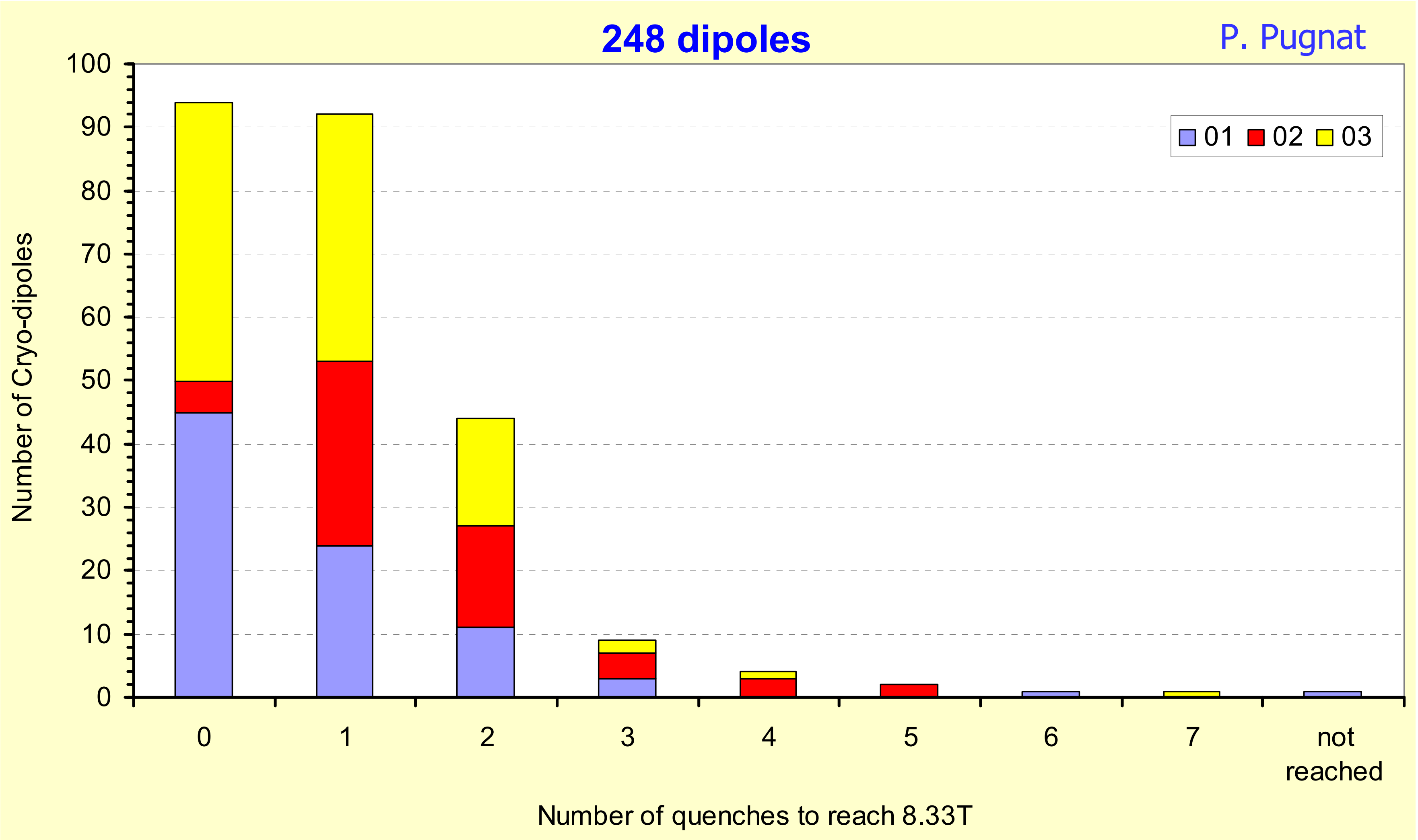
12h	12h	12h	14h	26-30 h	12h	12h
Installation	Pumpdown	Cooldown 300K-90K	Cooldown 90K-1.9K	Tests at 1.9 K	Warmup	Disconnect

1h	1.5h	1.5h	5h	5h	3h	3h	1h	1.5h	5h
Electronics & instrumentation checks	HV tests at 1.9 K	Protection tests at 1.9 K	Training quench at 1.9 K	Training quench at 1.9 K	Dynamic magnetic measurements	Static magnetic measurements	Diode test	HV test at 1.9 K	Warmup quench



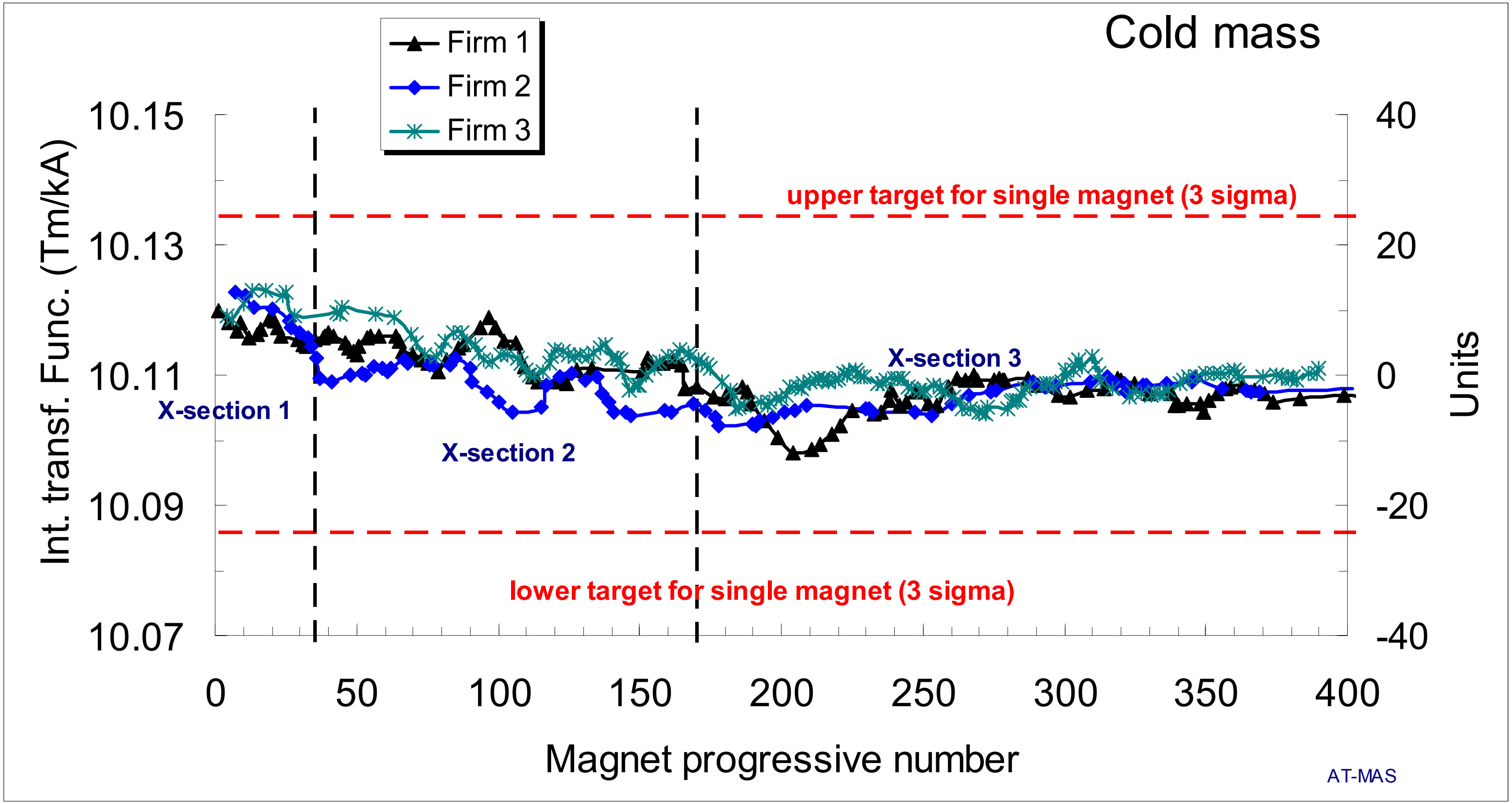
Duration of total sequence ~100 h

Resistive transitions to 8.33 T



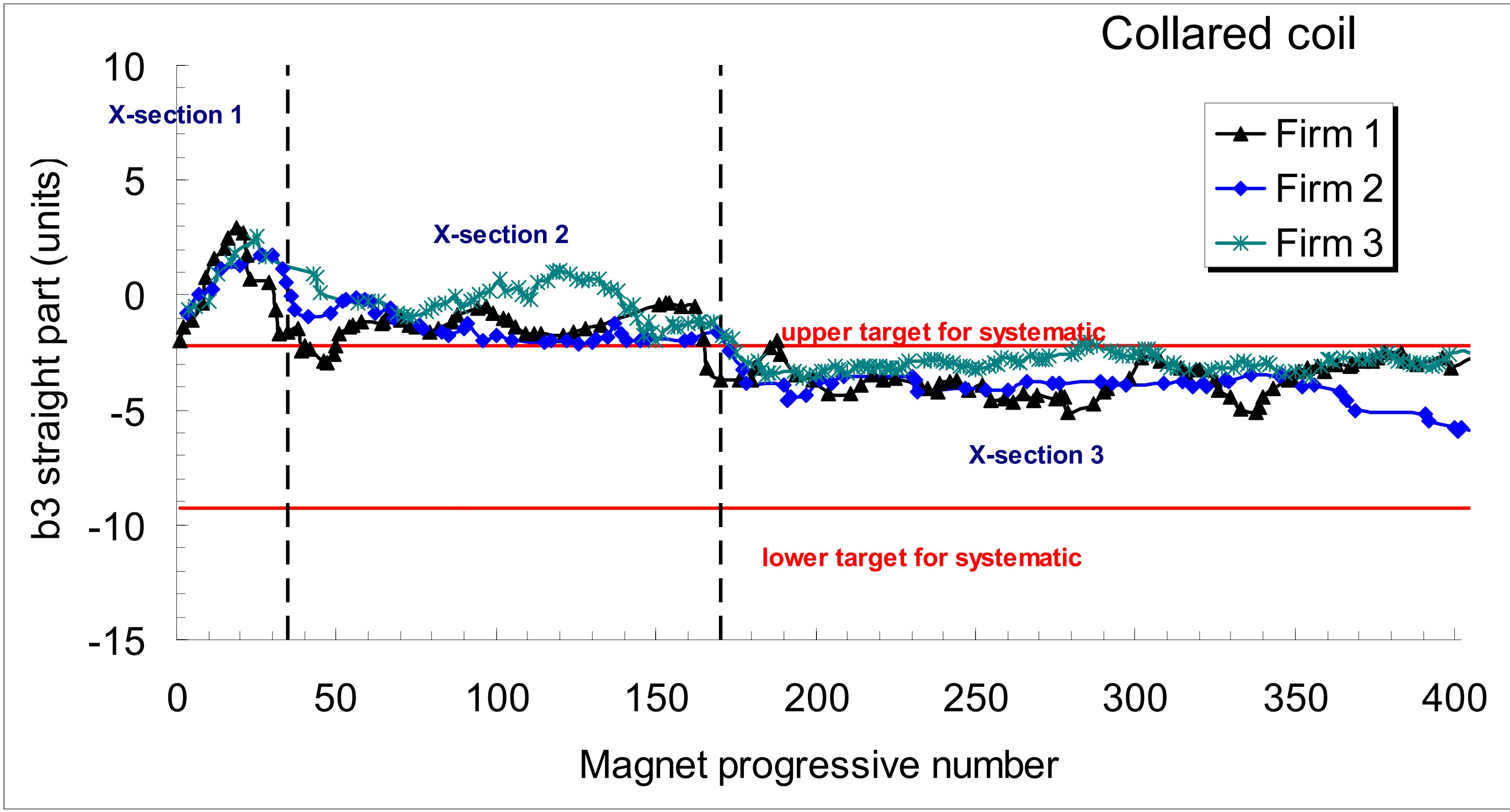
Dipoles: bending strength

E. Todesco



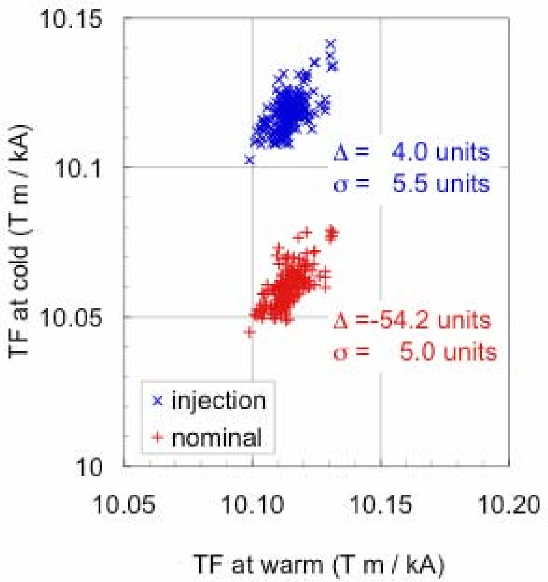
Field quality of dipoles: b3

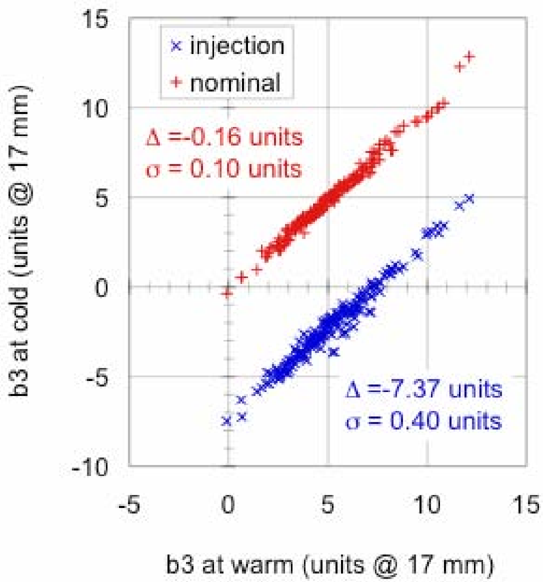
E. Todesco

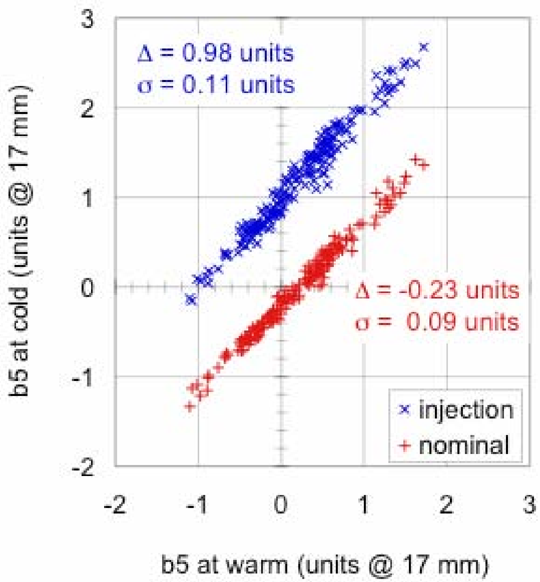


Cold/warm correlations for allowed multipoles (b1, b3, b5)

L. Bottura



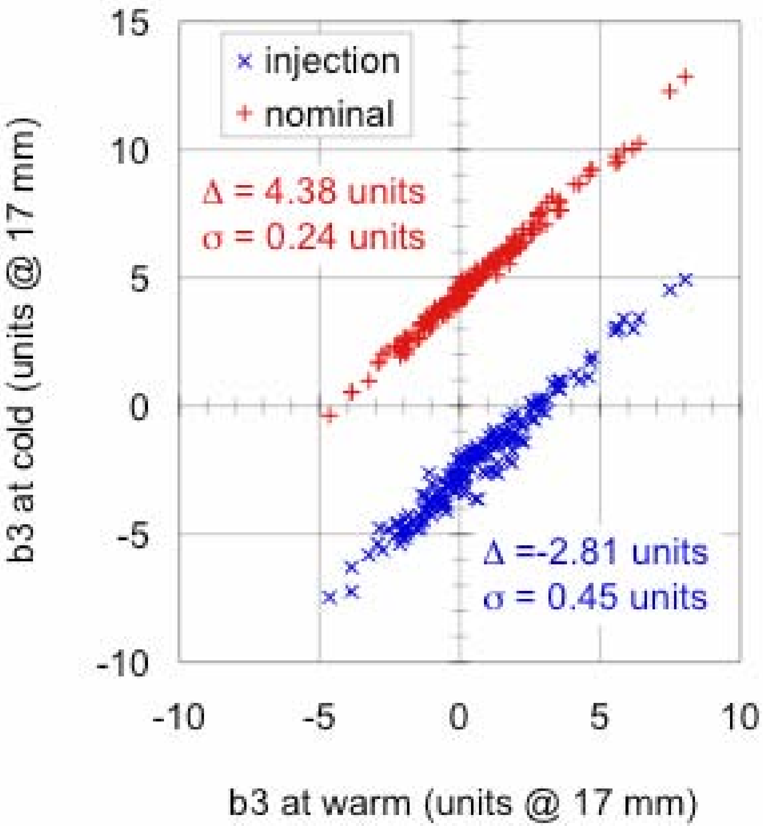




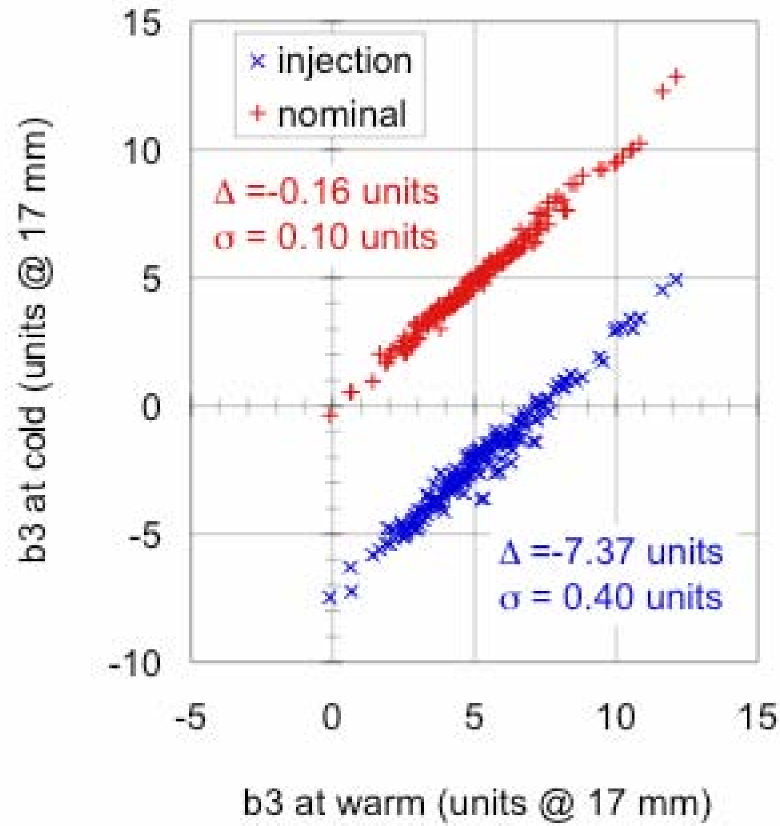
Correlations to collared coil & cold mass

L. Bottura

collared coil



cold mass



Advanced technology from industry

- Performance through shared incentives
  - *Cryogenic helium refrigerators*
- From emulation in R&D to competition in market
  - *Power refrigeration at 1.8 K*
- State-of-the-art components for affordable hi-tech
  - *Cryostats*
- Making use of emerging industrial products
  - *Switched-mode power converters*
  - *High-Tc superconductor current leads*
- Risk of functional vs. build-to-print specifications
  - *Ring cryogenic line*

Four new helium refrigerators

AIR LIQUIDE

LINDE

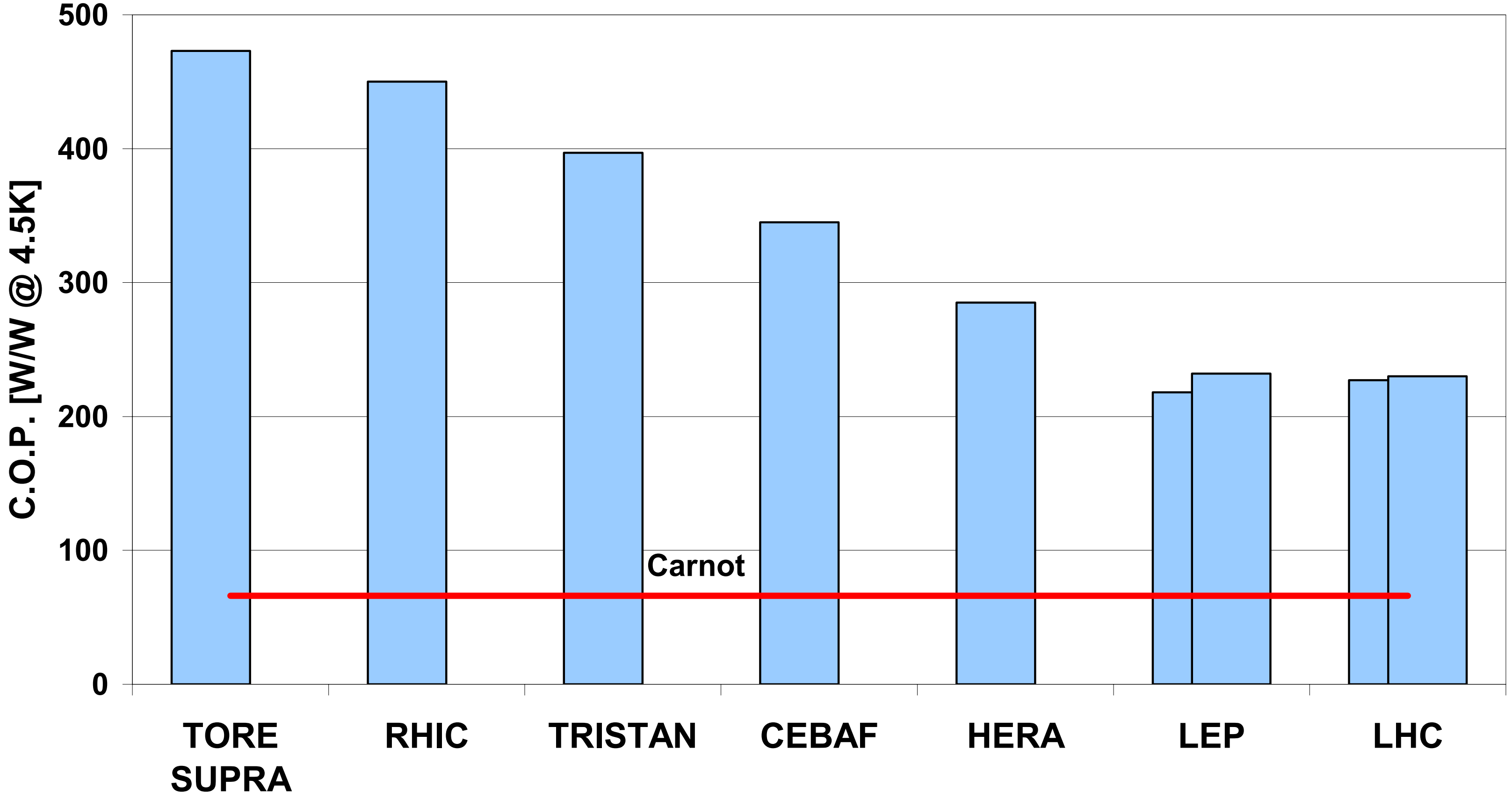
Eight cryogenic plants in total

140 kW at 4.5 K

~40 000 l/h liquid helium

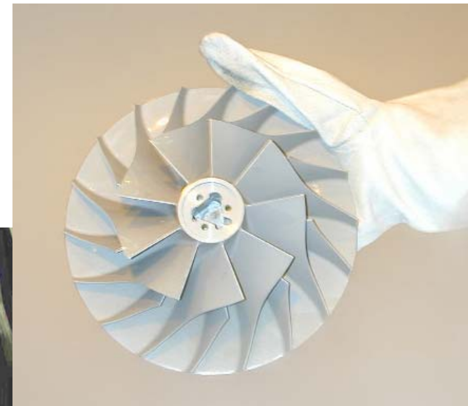
32 MWe

C.O.P. of cryogenic helium refrigerators



Cold compressors for 1.8 K refrigeration units

IHI-LINDE



Impeller

1st stage

The four stages

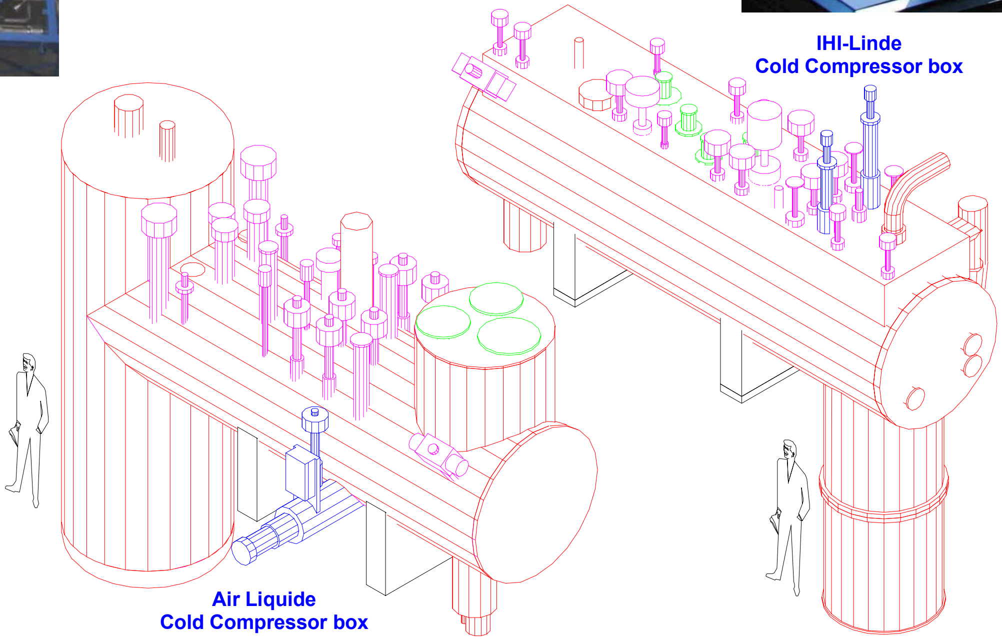
Eight 1.8 K refrigeration units

Eight units

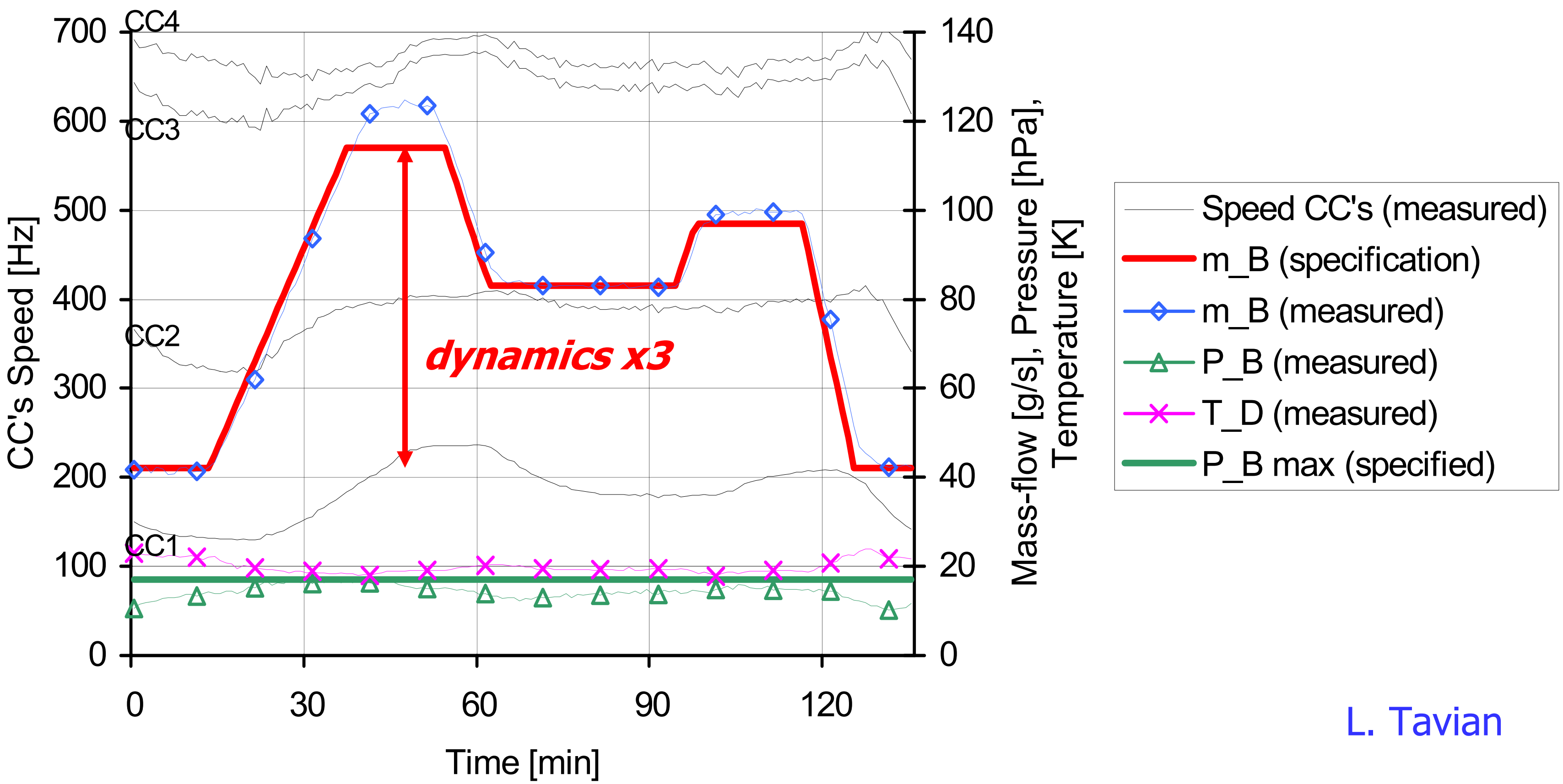
2400 W at 1.8 K each

AIR LIQUIDE

IHI-LINDE



Flow compliance of 1.8 K unit on simulated LHC cycle



L. Tavian

GFRE support post for LHC cryodipole

Cryostat thermal shield bottom tray

Aluminium alloy extrusion

Al to St. steel transition

A. Poncet

Multilayer insulation

Blanket prefabrication

A. Poncet

JEHIER

Installation on cryomagnet

Cryostat vacuum vessels

SIMIC

FCM

Cryostat assembly on site

Powering the LHC

- 1720 power converters
  - high-current (60 A to 12 kA)
  - high-precision (few ppm stability & reproducibility)
  - large dynamic range
  - 1-quadrant, 2-quadrant and 4-quadrant
  - high reliability (MTBF ~ 100 000 h)
  - tracking from sector to sector
- Environmental constraints
  - underground => compactness, efficiency (>80 %)
  - serviceability
  - EMC
  - radiation tolerance (1 Gy/yr for converters in tunnel)

F. Bordry

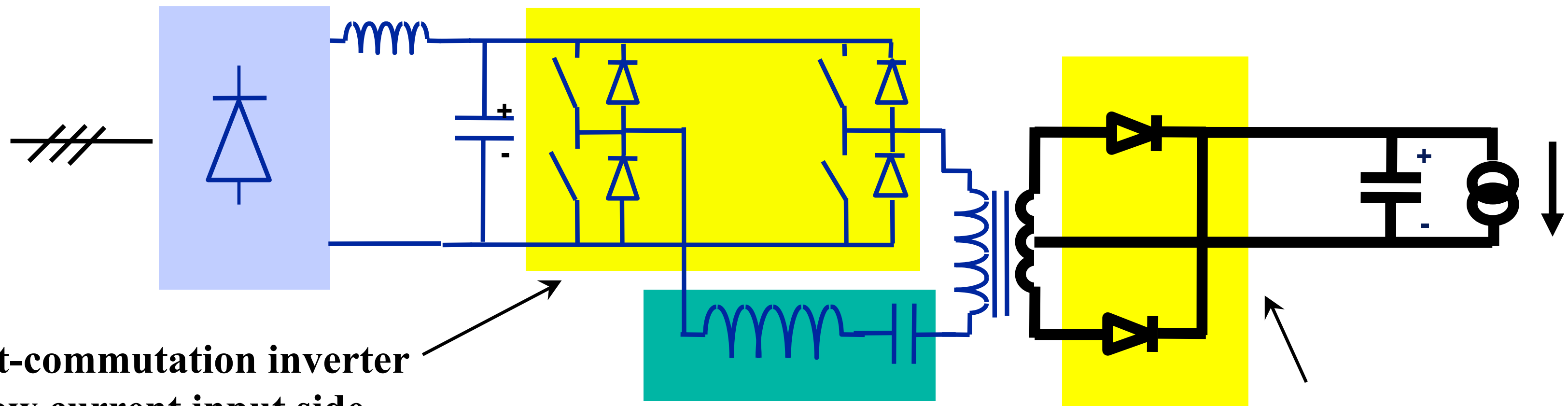
Switched-mode power converters

AC
50 Hz

DC

AC
20 - 100 kHz

DC



HF soft-commutation inverter on low current input side

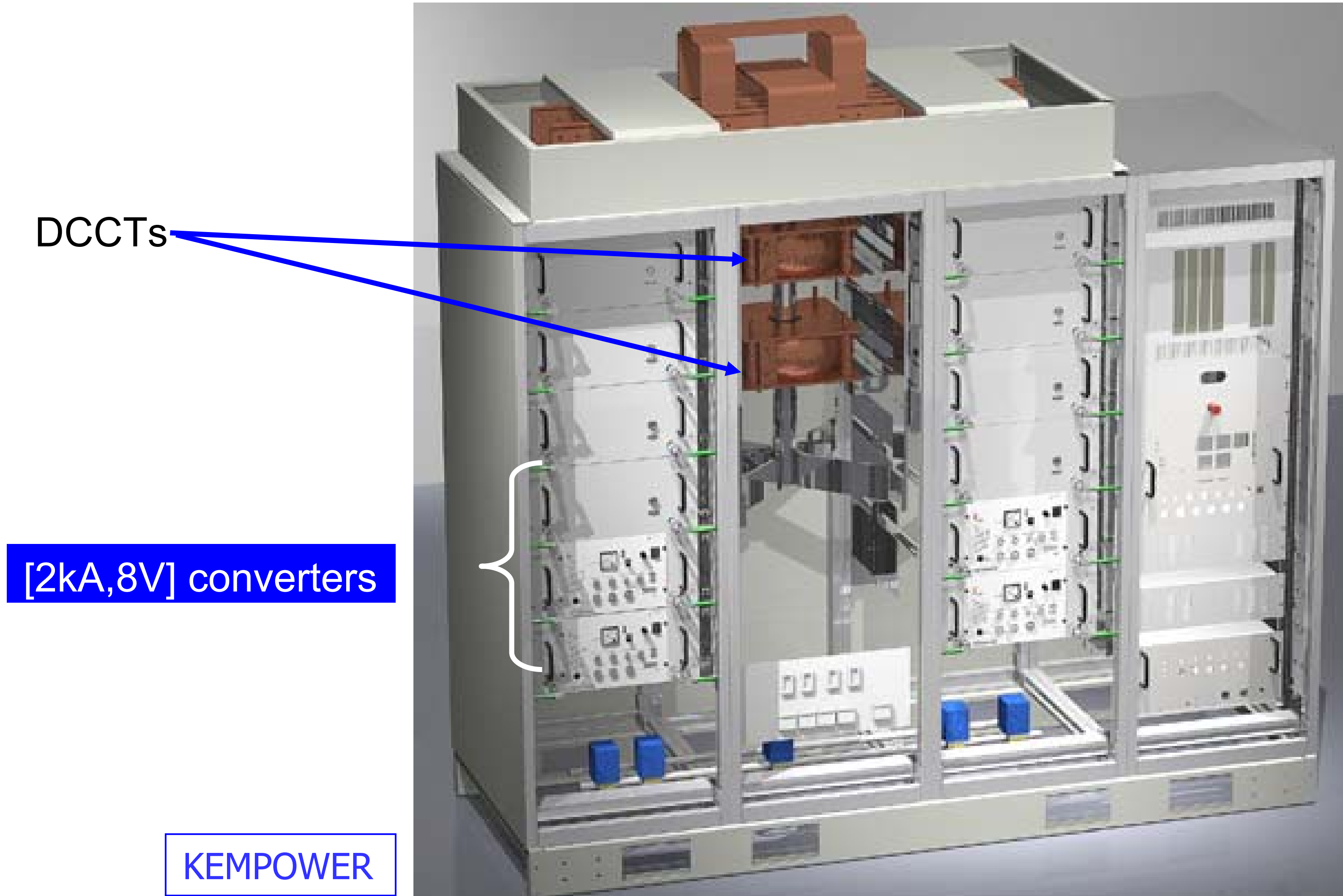
Passive high-current output stage

- light weight, reduced volume (HF transformers and filters)
- good power factor (0.95)
- high bandwidth and good response time
- Soft commutation gives low losses and low electrical noise
- small residual current ripple at output

F. Bordry

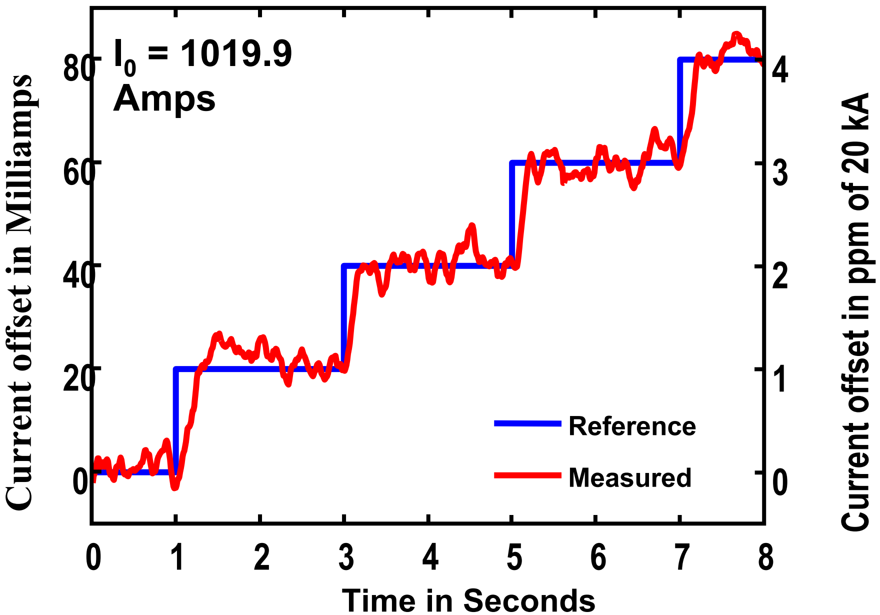
Modular 6 kA, 8 V converter

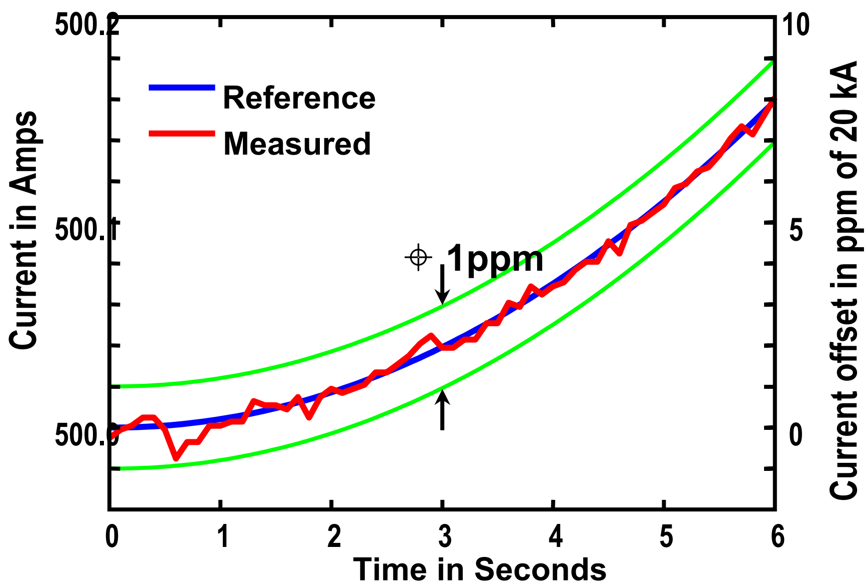
F. Bordry



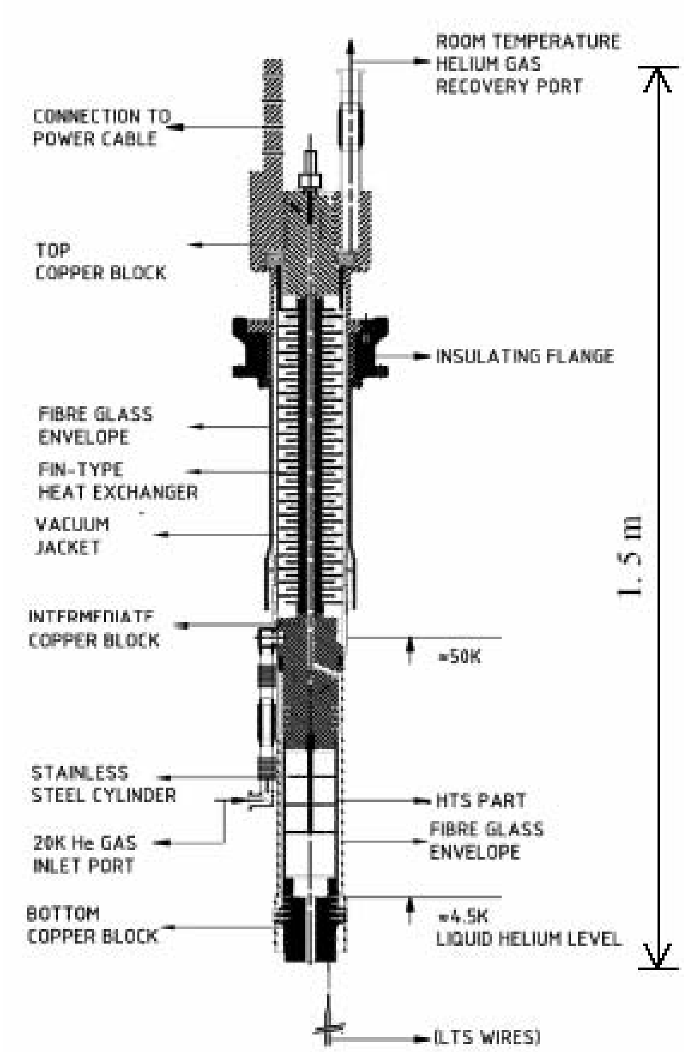
Current tracking performance

F. Bordry

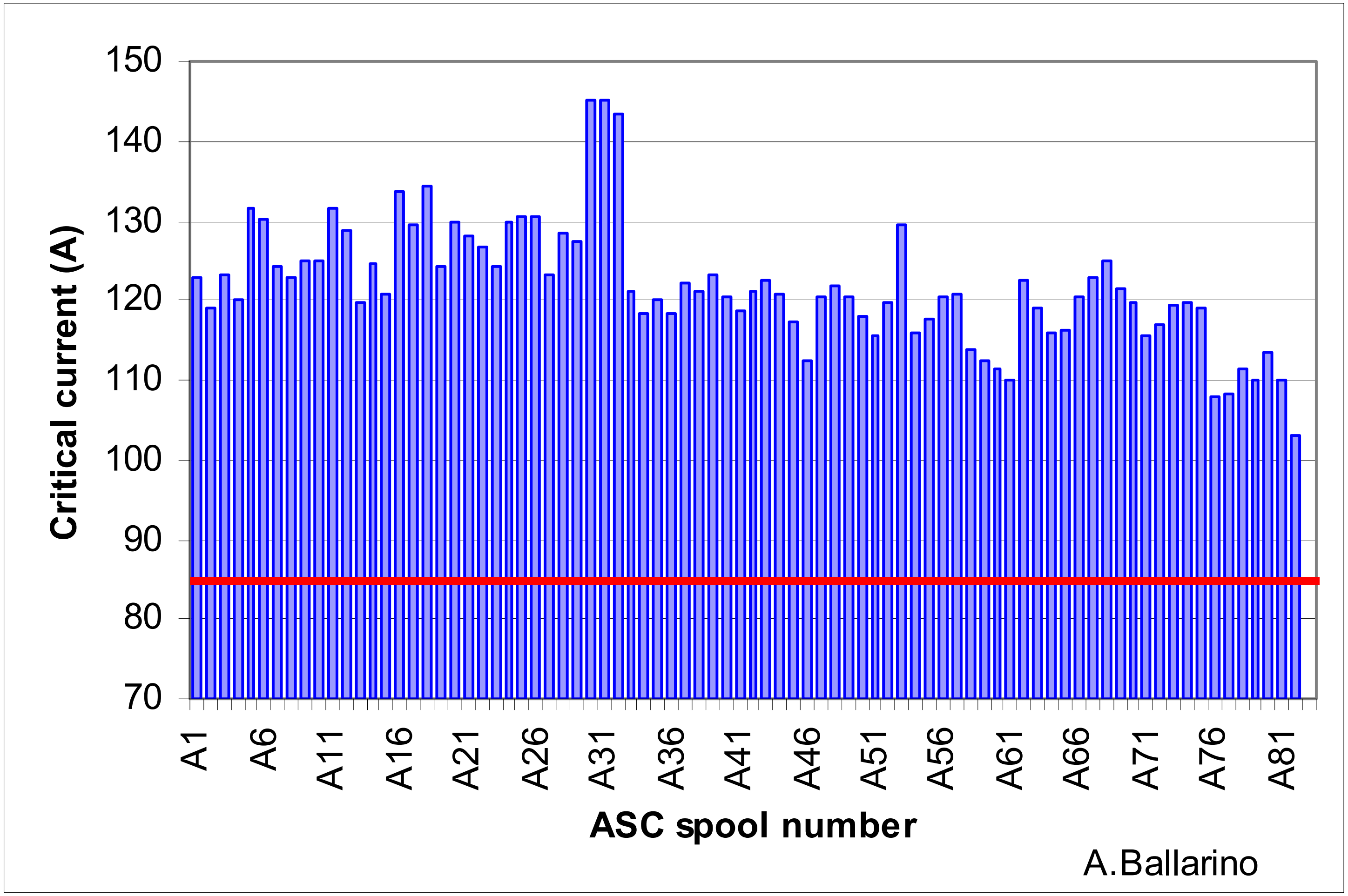




13 kA HTS current leads



Average critical current of BSCCO 2223 spools



First sector of cryogenic line: delayed installation in tunnel

Industrial production in the lab

- Lack of industrial interest or capability

  Cryogenic magnet tests

  NEG coated vacuum chambers

- Transport and handling limitations

  Cryostating of main dipoles

- Complexity & coupling with other systems

  Insertion region quadrupoles

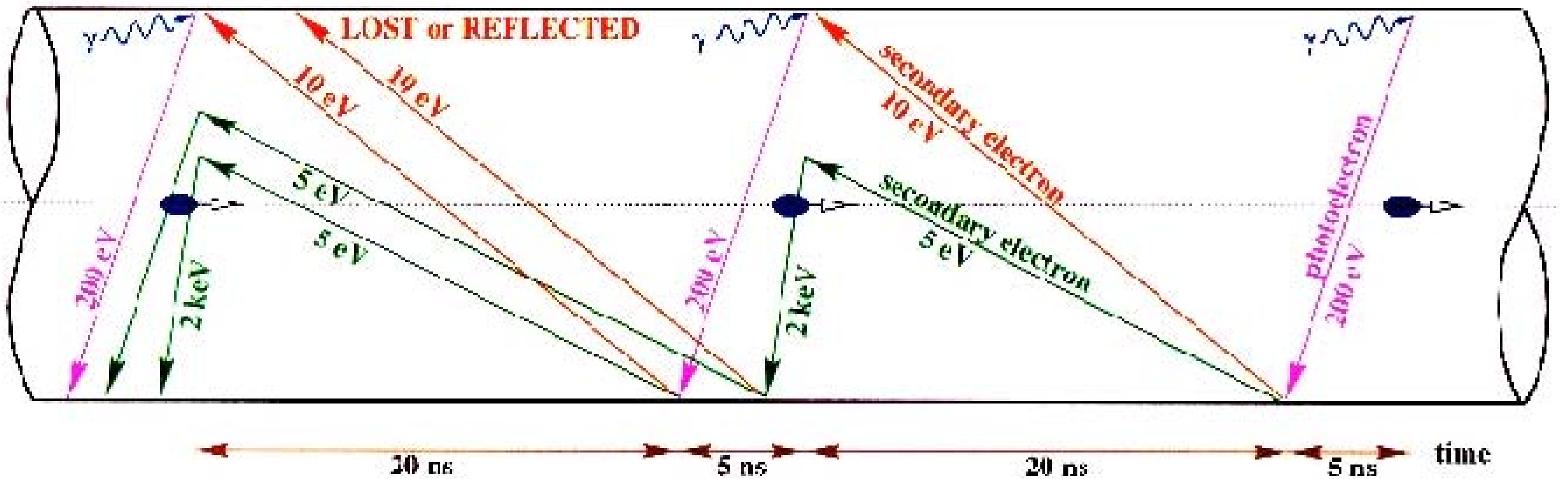
- Re-internalization following insolvency of contractor

  Cryostating of Short Straight Sections

- Special in-kind contributions

  Injection lines

Mechanism of e-cloud in LHC beam pipe



Electrons from synchrotron radiation or ionization, can be resonantly accelerated by the potential well of the successive bunches, creating secondaries on impact

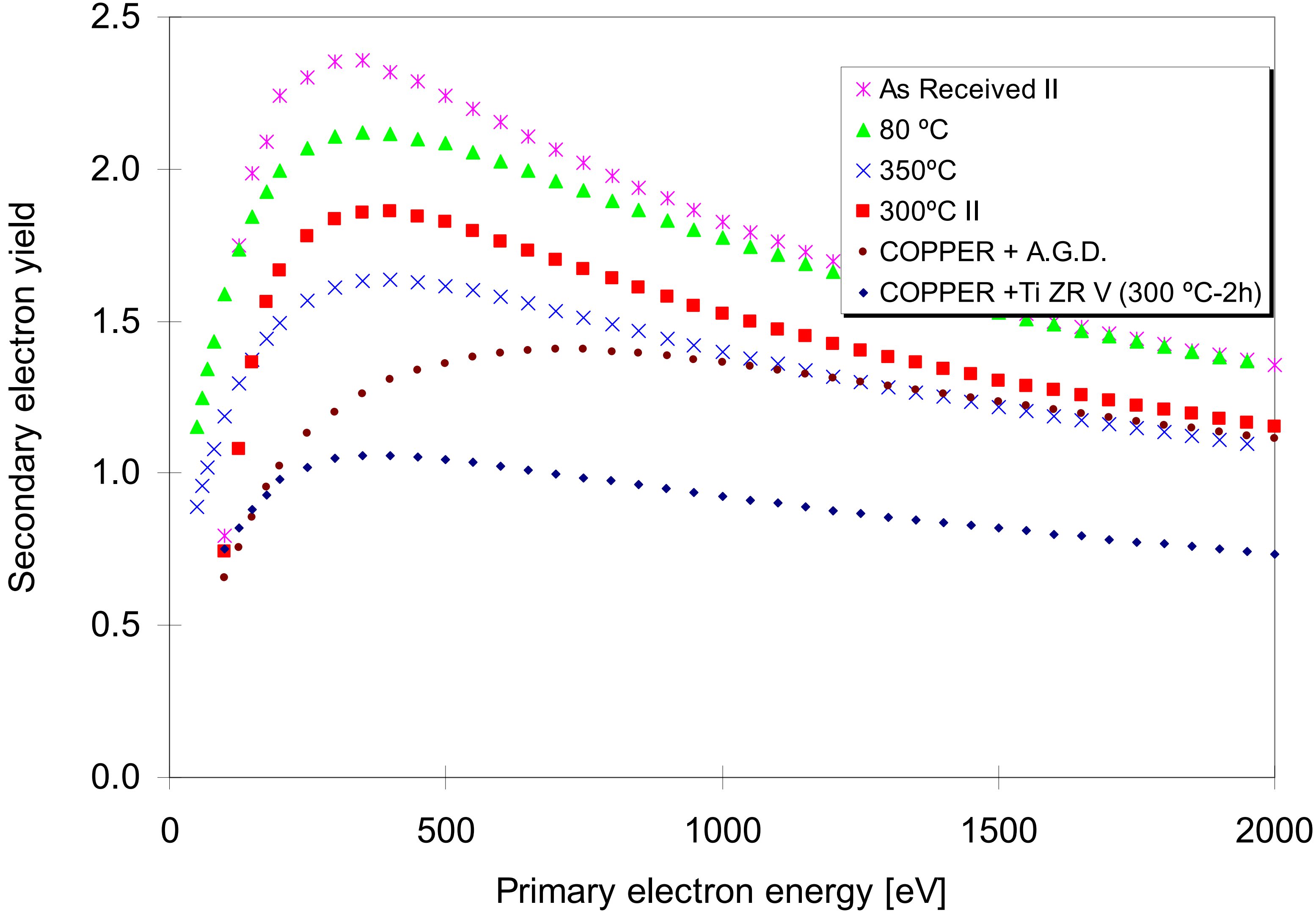
V. Baglin, "Gas condensates onto a LHC-type cryogenic vacuum system subjected to electron cloud", Wednesday morning

This can result in exponential build-up, creating additional heat load and stimulating gas desorption leading to pressure runaway

Electron bombardment has a « scrubbing » effect , observed in SPS

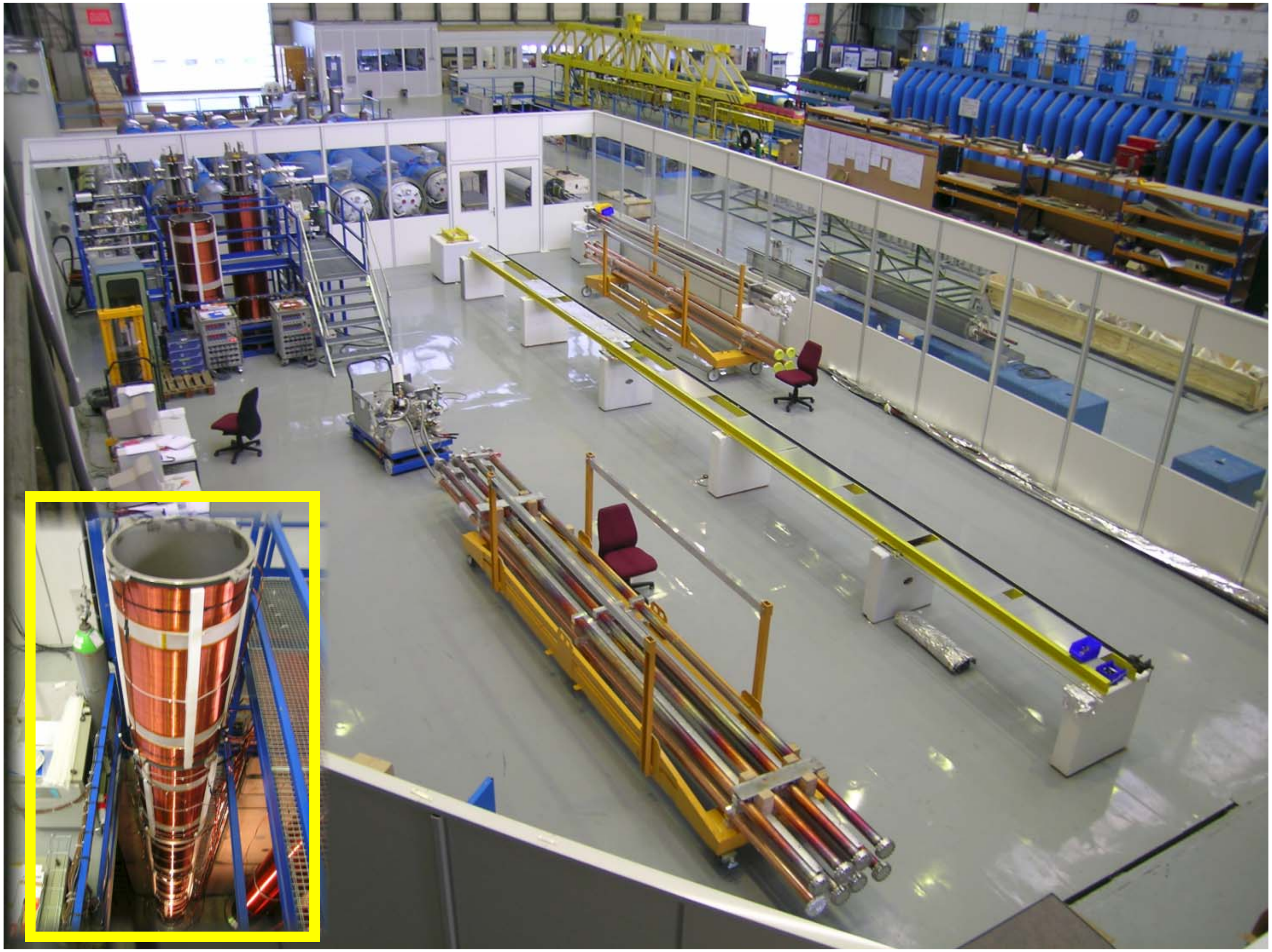
SEY on copper & NEG

N. Hilleret



NEG-coated vacuum chambers

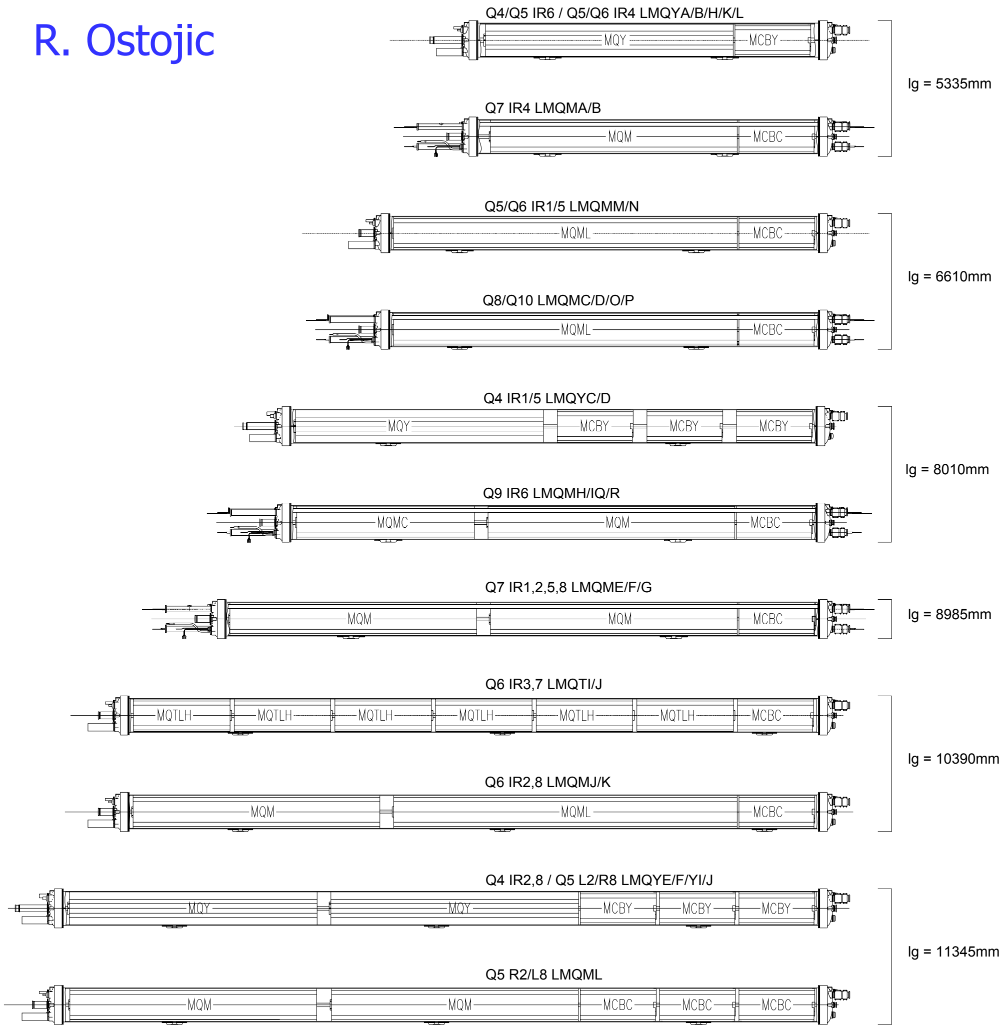
P. Chiggiato

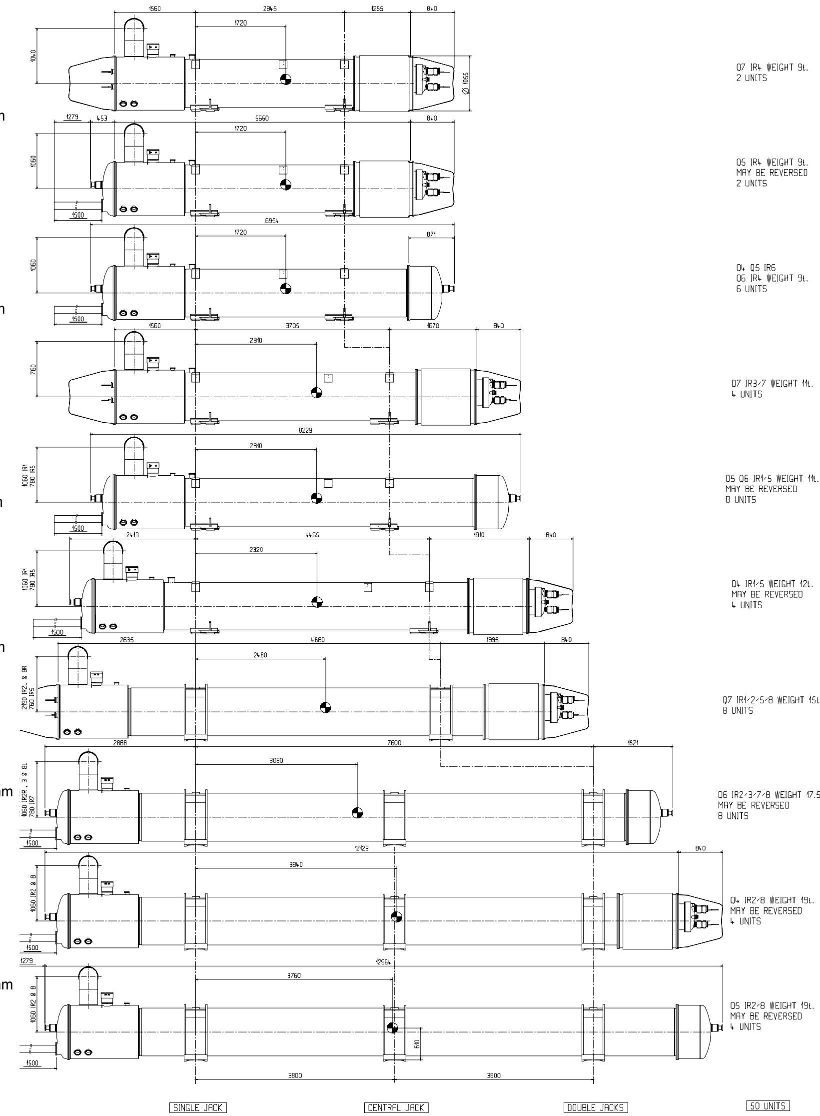


NEG-coated vacuum chambers

Insertion region SSS

R. Ostojic

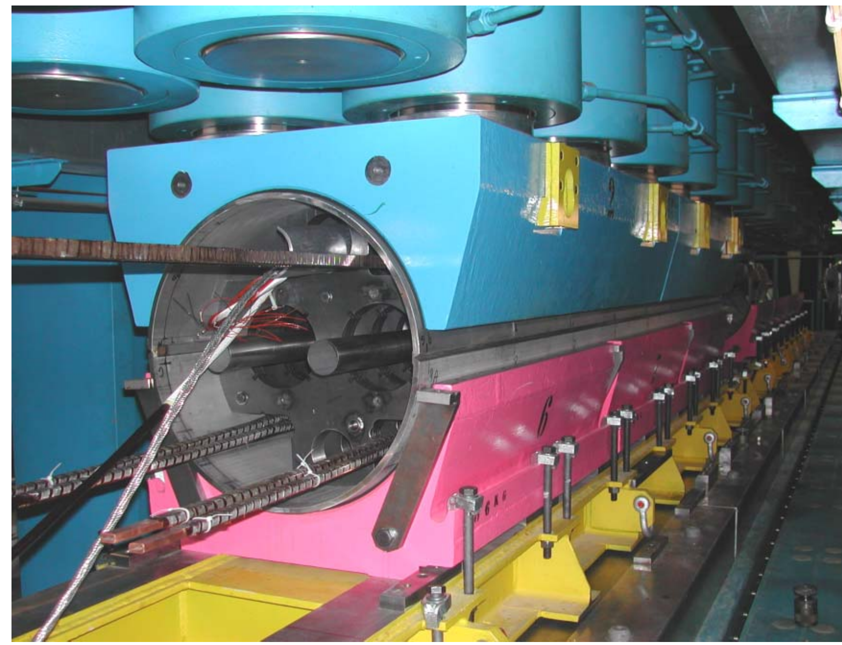




Insertion magnet assembly facility

Cold mass assembly of insertion quadrupole

R. Ostojic



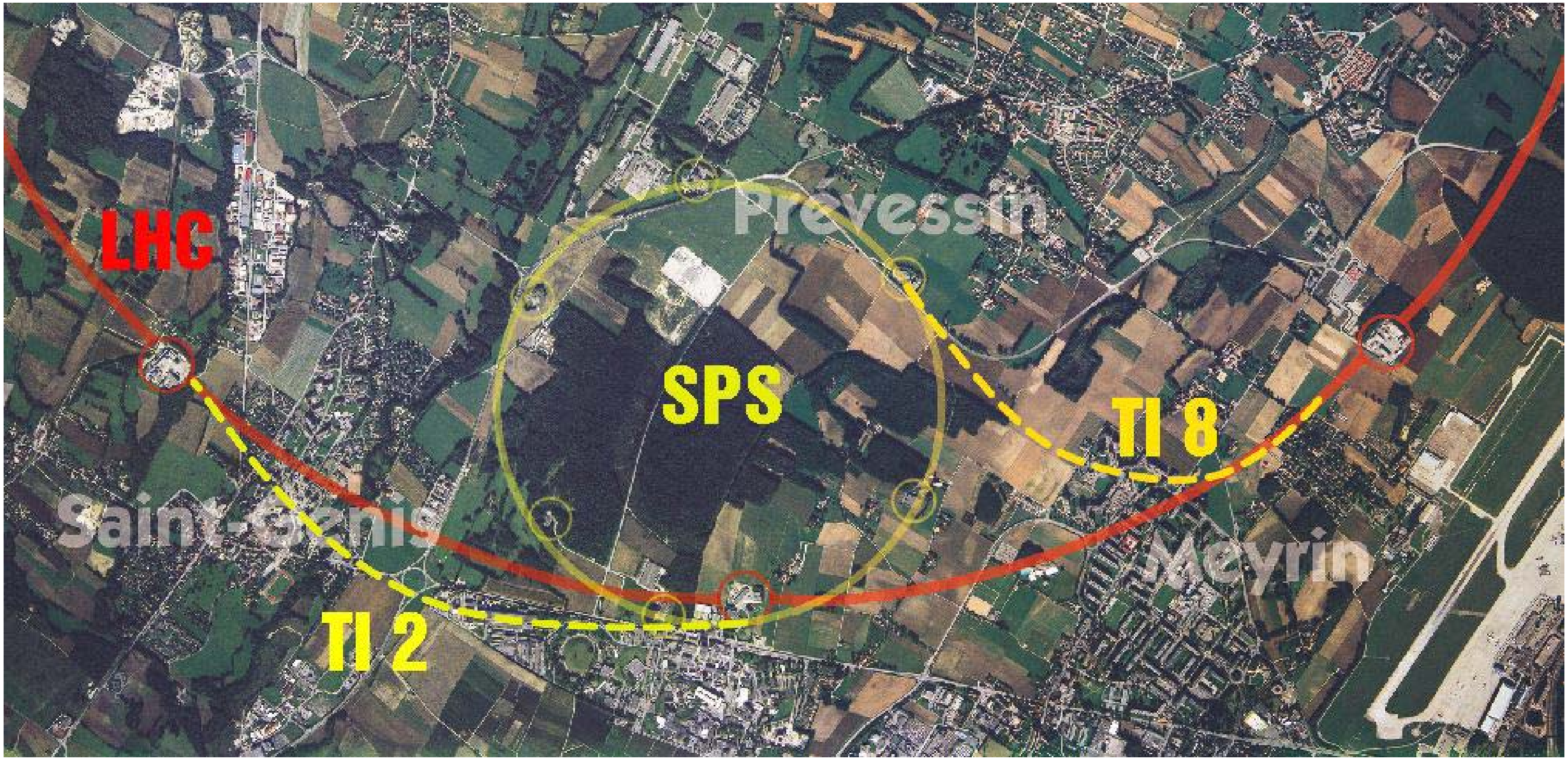
Finishing of insertion quadrupoles

Inner triplet quadrupole (Fermilab)

Internalization of SSS assembly

Assembled arc SSS

Injection lines
5.6 km, 700 magnets



V. Mertens

Installed TI8 injection line

Conclusions

- Large scientific projects also constitute major industrial ventures and as such are exposed to constraints of industry
  - Managing the prototype-to-series-production transition
  - Competition with other related products/markets
  - Risks and dangers of the business jungle
- Industrial production of LHC in full swing, with over 3 BCHF (94 %) committed and over 2 BCHF (65 %) value earned
- Most series component production meets quality and delivery rate
- Difficulty in single major contract for cryogenic line, delays magnet installation in tunnel
- CERN's management firmly committed to recover delays and meet summer 2007 deadline for first collisions