Accelerator Technology Department

OPERATION FOR LHC CRYOMAGNET TESTS: CONCERNS, CHALLENGES & SUCCESSFUL COLLABORATION

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CERN, Geneva, Switzerland

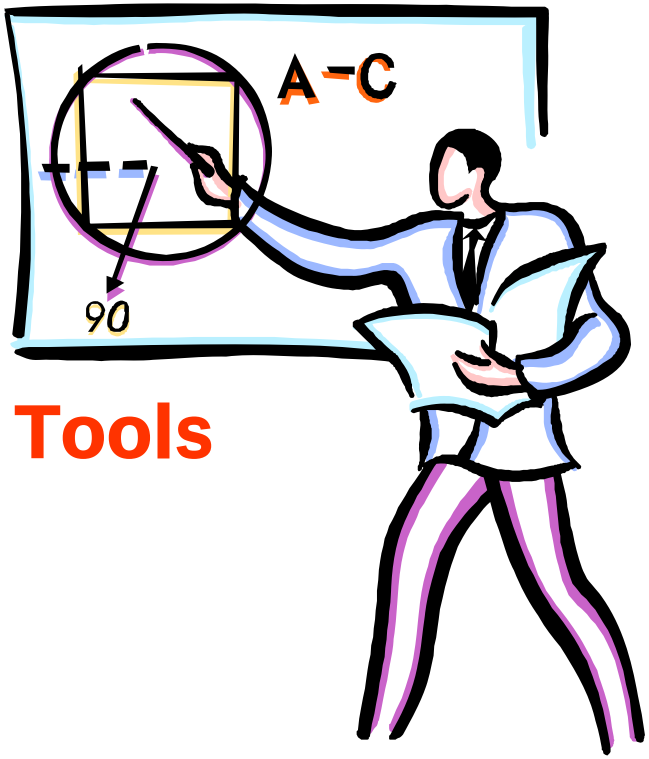
Asian Particle Accelerator Conference

Indore, India

30 January 2007

Outline

- Introduction
- Concerns & Hurdles
- Early Performance
- Operational Strategies & Tools
- Results
- Concluding Remarks



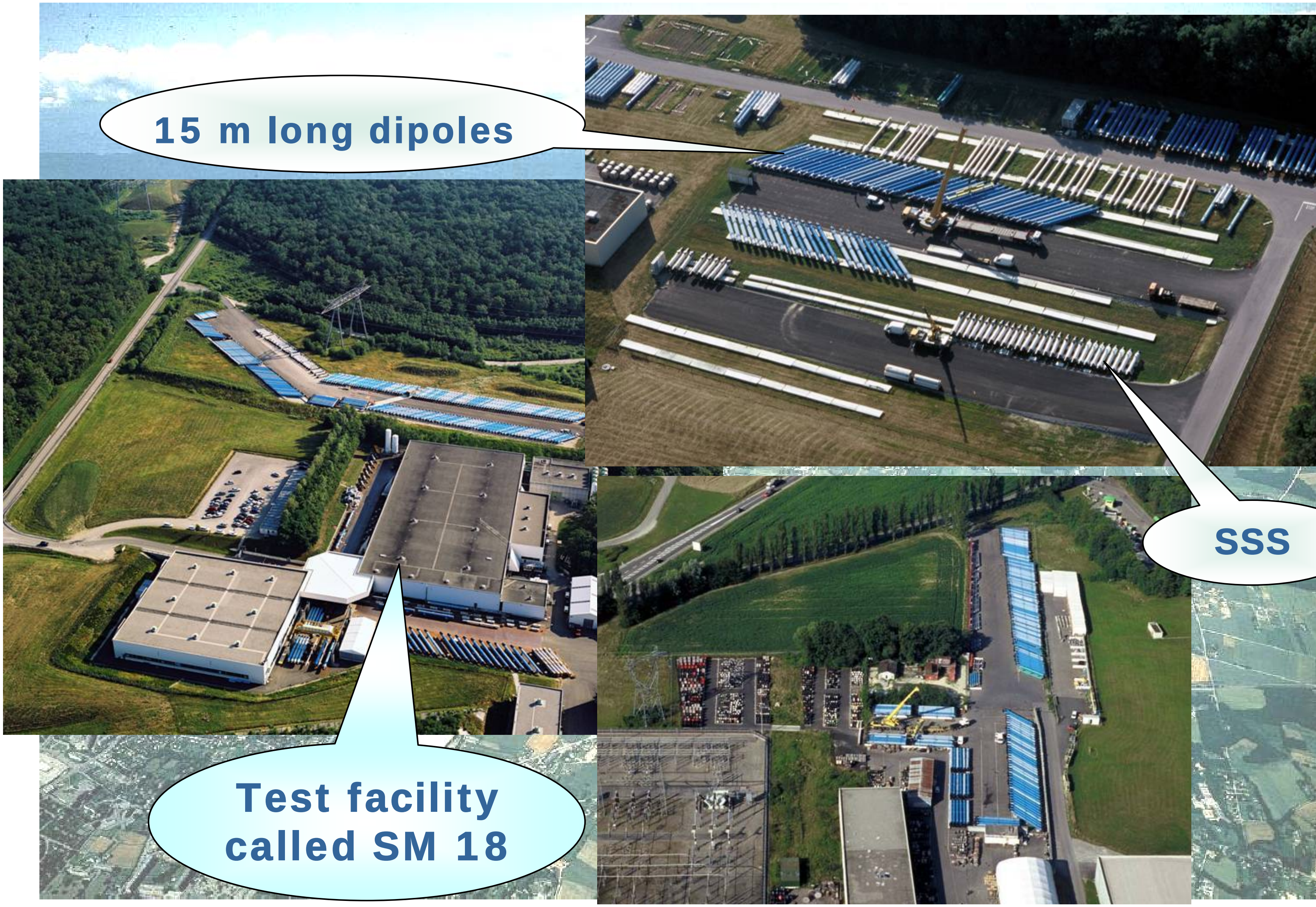
Introduction

- **LHC Requires:**
  - **1232 Dipoles (~19 km out of 27 km ring)**
  - **360 Short Straight Sections (MQ - SSS)**
  - **114 Insertion Region SSS (IR-SSS)**

- **Testing & Qualification (& Training!) of each of them for:**
  - **Cryo, mechanical & electrical insulation**
  - **Quench performance**
  - **Field Quality**

- **Total of ~ 1900 magnets (incl. spares & repeats) to be tested before early 2007!**

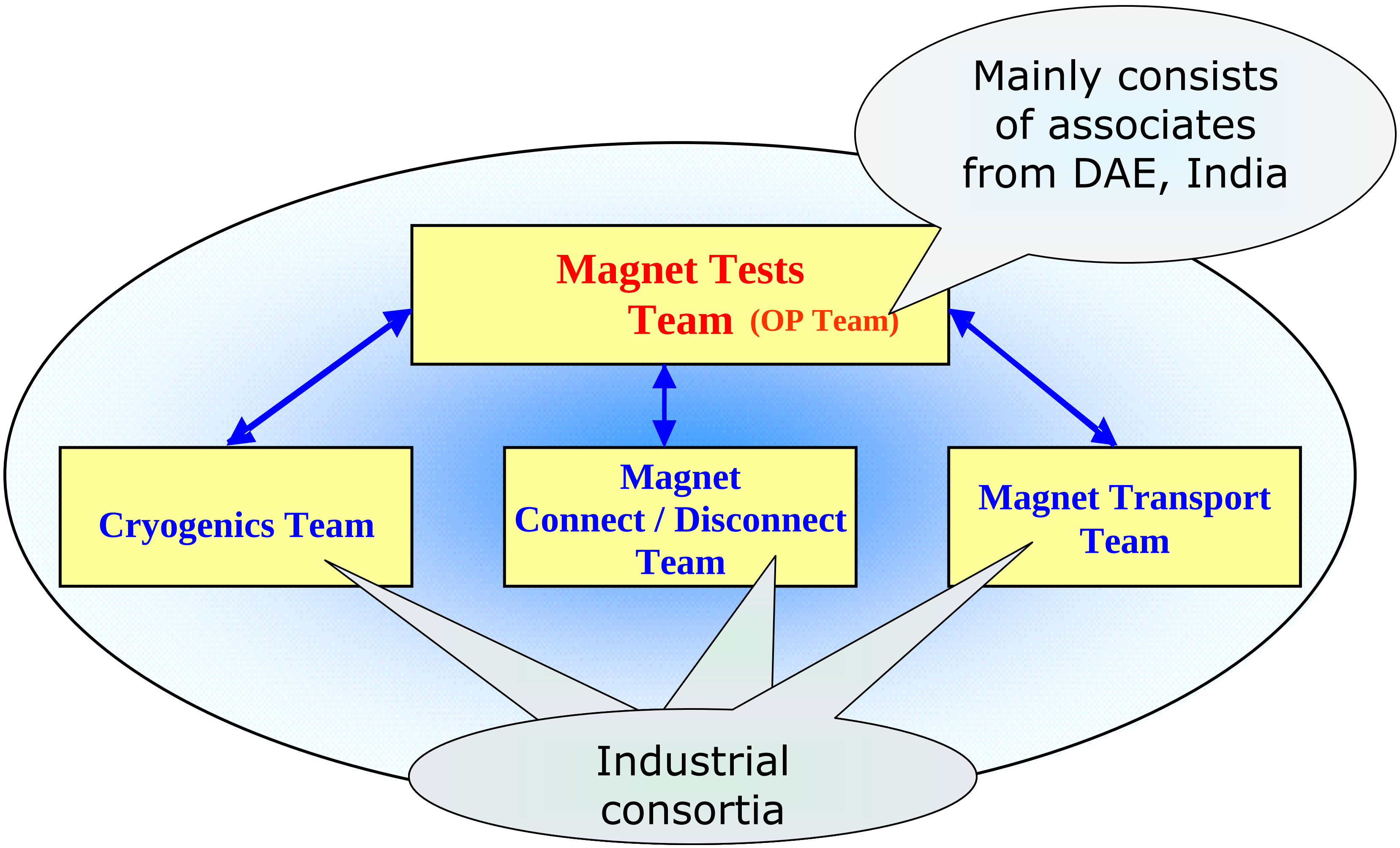
Massive Effort !



SM18 Test Facility

- With 12 test benches & Cryogenic infrastructure
- Testing of first series magnets: early 2001 – with only 2 test benches
- All 12 benches ready only by June 2004 !

Various Teams of SM18



Magnet Tests.. What do we do ?

New magnet arrives..

Insulation test, connection to CFB

Preparatory tests (functioning of protection systems & instrumentation, insulation…)

Cool down to 1.9K

Preparatory tests (tuning DAQ..)

Insulation tests

Functioning of protection systems

Power tests (&Training)

Magnetic measurements

Final insulation tests @cold

Warm –up

Final warm tests

Electrical integrity

Resistance measurements..

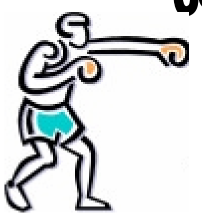
Final insulation tests

Disconnection from CFB

SM18 Magnet Tests : What it's all about

Project Management

Collision by 2007



Magnet Production

Manufacturing Specifications

Demands on SM18 Operation

LHC Beam Running in & *Minimum dI, dE provision*

LHC First Beams

Accelerator Physicists

LHC Final Beams & Field Quality

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Concerns & Hurdles

Who's & How's of Tests

1. **Novelty Aspects**
   - Early R&D culture – lack of transparency!
   - Magnets trained to ultimate field, Extensive magnetic measurements, Qualification of 'poor' magnets..
2. **Infrastructure Limitations**
   - Cryogenics, Water, Electronics, Power Converter..
3. **Personnel Logistics**
   - Minimum staff strength of 4 per shift (24 hr operation, 45 weeks..)
4. **Co-ordination of Work & Teams**
   - Indian Staff & Language barrier!
5. **Nature of Industrial Contracts**
   - Work slowed down during weekends, lack of adequate technical support beyond normal hours..

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Early Performance

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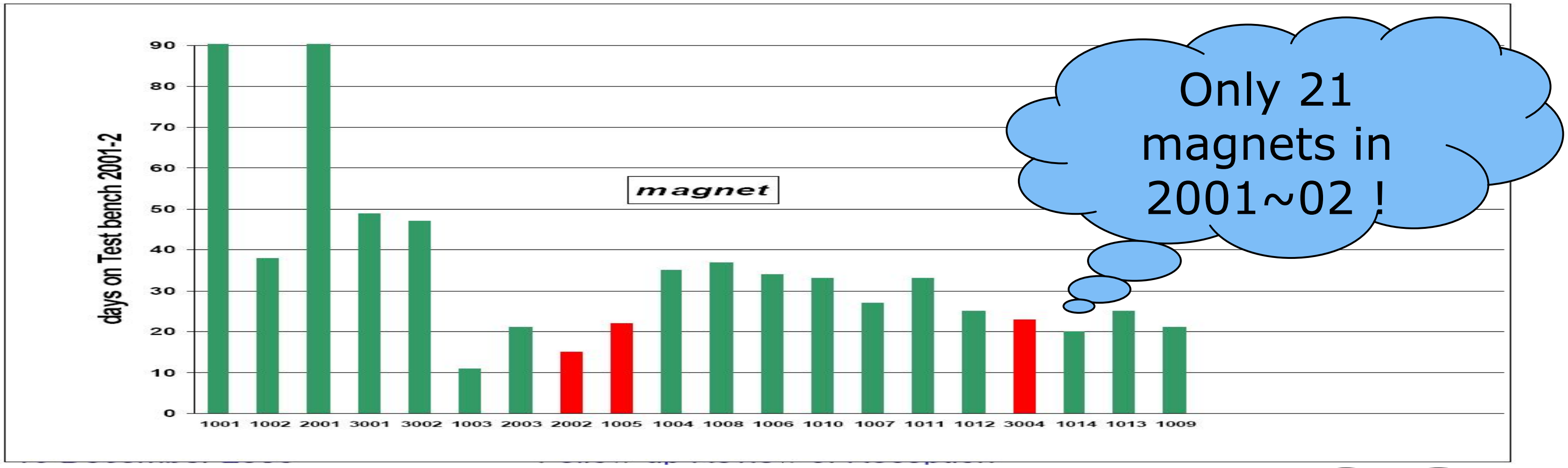
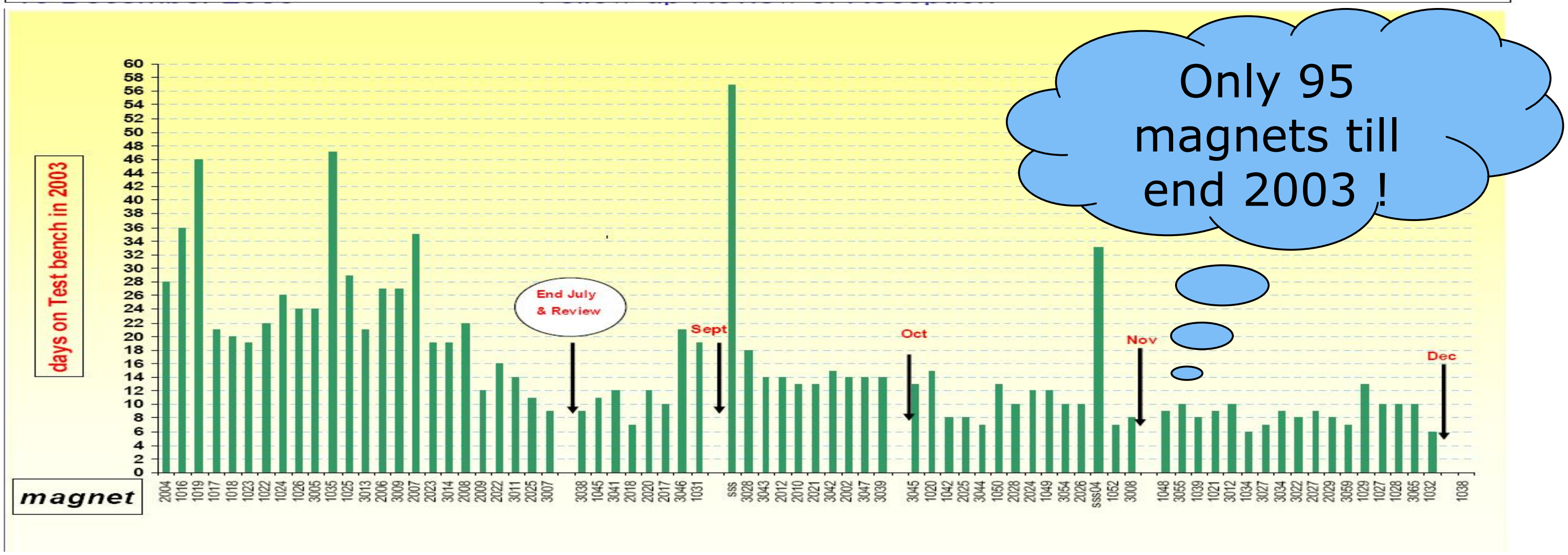
Early Performance





Finish testing of remaining ~1800 magnets by early 2007 ???

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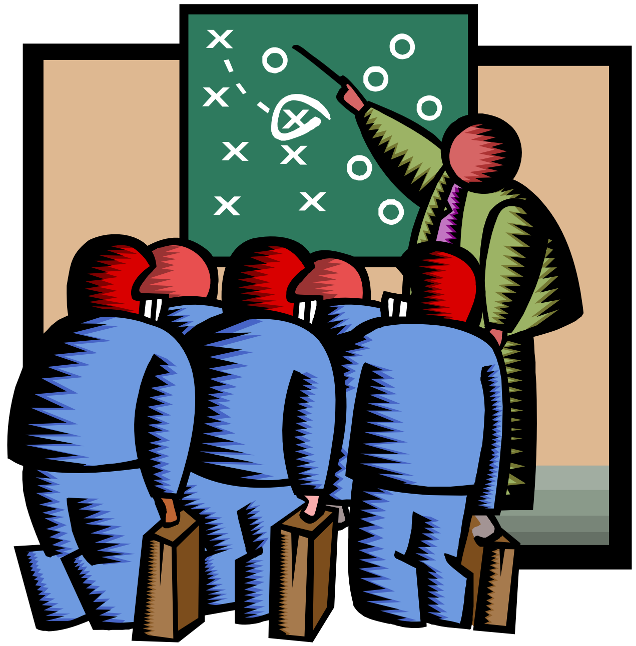

Operational Strategies & Tools

Strategies

1. Addressing Manpower Issues

Who?

2. Addressing Technical Issues

How?

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Addressing Manpower Issues

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Staffing Profile 2003

7 from CERN

5 from India

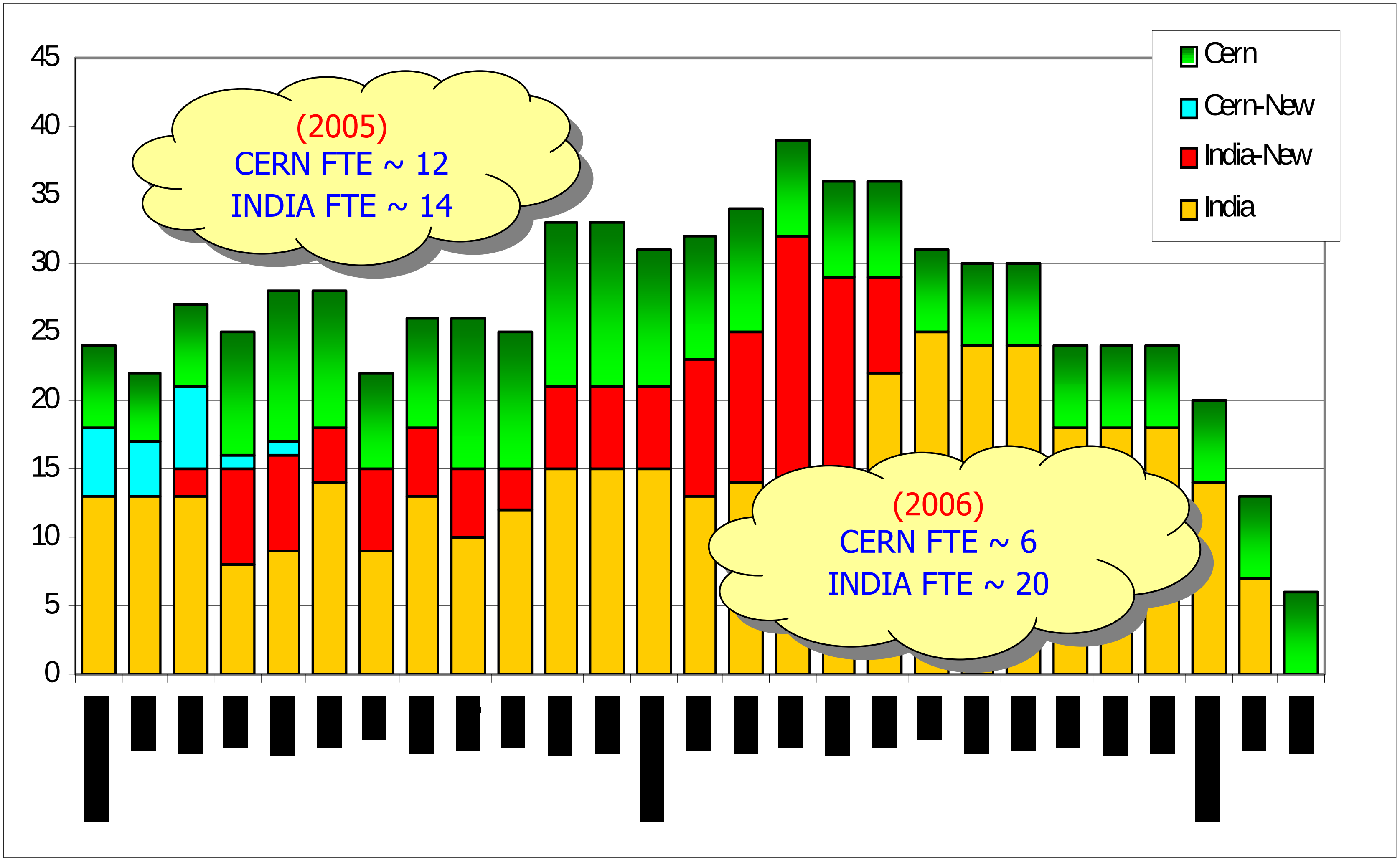
Year2003	Feb	March	april	may	june	july	aug	sept	Oct	nov	dec	
1	kevin	kevin	kevin	kevin	kevin	kevin	kevin	kevin	kevin	kevin	kevin	
	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	G-HH	
	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	Jackie	
	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	Ismael	
	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	Niquille	
6	Jakob				Florence	Florence	Florence	Florence	Florence	Florence	Florence	
7									AB7	AB7	AB7	
8	JacquesO	JacquesO									JacquesO	
9	Dave	Dave									Dave	
10											G.Adrian	
11												
12												
13	gandhi	gandhi	gandhi	gandhi	daniel	daniel	daniel	daniel	daniel	daniel	daniel	1
	marathe	marathe	marathe	marathe	uttam	uttam	uttam	uttam	uttam	uttam	uttam	2
	pramod	pramod	pramod	pramod	pramod	pramod	pramod	M22	M22	M22	M22	3
	madhu	madhu	madhu	madhu	madhu	madhu	madhu	M23	M23	M23	M23	4
	sanjay	sanjay	sanjay	sanjay	sanjay	sanjay	sanjay	sanjay	sanjay	M24	M24	5
18										M25	M25	6
19					shetty	shetty	shetty	shetty	shetty	shetty	shetty	7
20					ram	ram	ram	ram	ram	ram	ram	8
21							Khare	Khare	Khare	Khare	Khare	9
22							Pareek	Pareek	Pareek	Pareek	Pareek	10
23							Kasliwal	Kasliwal	Kasliwal	Kasliwal	Kasliwal	11
24							Sridhar	Sridhar	Sridhar	Sridhar	Sridhar	12
25												
26												
27												

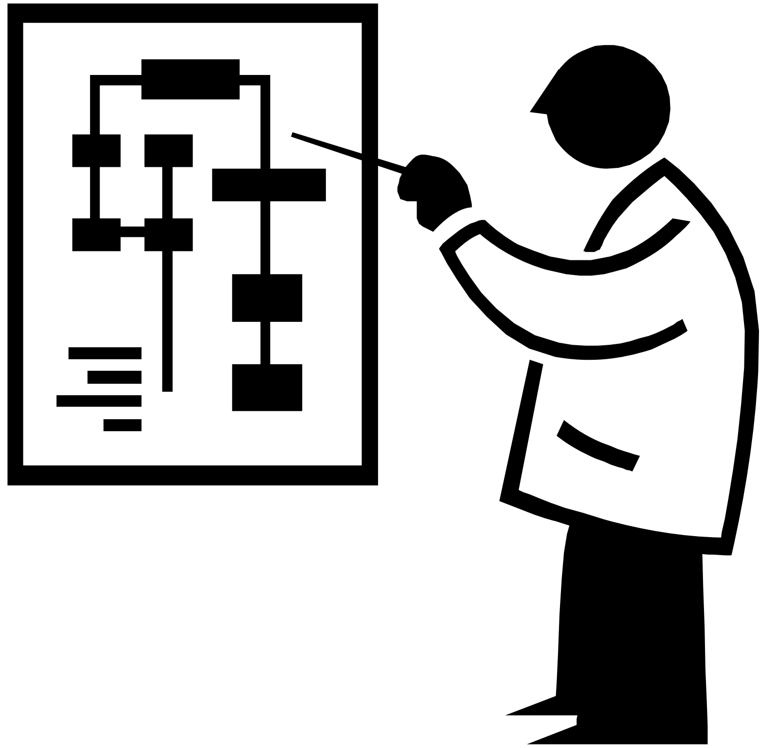
Green Means Experienced
Yellow Means New Arrivals

	Feb	March	april	may	june	july	aug	sept	Oct	nov	dec
TOTAL	13	12	10	10	13	13	17	17	18	20	22
INDIA	5	5	5	5	7	7	11	11	11	12	12
AB Div	8	7	5	5	6	6	6	6	7	7	10
Exprinced if Tests frozen & systems Consolidated	5	5	5	7	6	8	10	11	11	14	16

Manpower Issues

- **Staff strength : 4 per shift (≈ total 24)**





Addressing Technical Issues

Operational Strategies

1. **To-Do List**
   - Describes minimum set of tests on each magnet
2. **Magnet Test Report (MTR)**
   - Paper log of test results
3. **Get higher throughput**
   - Training rules:
     - Two-Quench Rule
     - Three Quench Rule
   - Reduced magnetic measurements
4. **Rapid On-Bench Thermal Cycle (ROBTC)**
   - Thermal cycle of a poor magnet without disconnection from test bench
5. **Overall & Cryo priority setting**
   - 24 hour priority decision by OP team for effective & clash-free utilization of resources

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To-Do List & MTR

Tests numbered sequentially

Prefixes define type of test

Version	LIST OF TESTS FOR A NEW DIPOLE With Magnetic Measurements - No Thermal Cycle		Estimated Time	estimate count [hours]	Documents
	Preparatory tests at Warm				
	ICS1	HV Test performed by ICS. "Warm initial before bolting"			
	ICS2	Electrical Connection to CFB (ICS - BOLTING)			
	SCAN1	Scan Bench, Magnet Name, Gamelles and Anticryostats (or the MRB end-plates if no anticryostats are installed) or Enter the magnet Name in TEMA if MTF & hwrec are not active.	0:15	0:15	
	1	Lyre Test. (With ICS)	0:30	0:45	
	2.1	IAP @ warm. LF heater discharge	0:30	1:15	
	2.2	IAP @ warm. HF heater discharge	0:30	1:45	
	2.3	Resistance Measurement. (Quench Heaters after discharge)	0:30	2:15	CDW1 Resistance
Prep	SCAN2	Scan the HV mobile rack. Check Gamelle entry in MTF.	0:15	2:30	
	3	HV Insulation Test. "Warm initial after bolting to CFB"	1:30	4:00	CDW1 HV
	ICS3	SIGN TRAVELLER.			WP04 9.1.9.2.9.3 Page 6/10
	CR1	Cryo Team Leak test	0:30	4:30	
	ICS4	Final Connection to CFB /CFU (ICS)			
	SCAN3	Scan the Shafts, TRU and Mobile Rack, or Quench Antennae.	0:15	4:45	
	4	Connect the TRU with the mobile rack if shafts are available. Start T-COIL if the bench is active.	0:30	5:15	
	5	Cool Down. Put 2A in the magnet and launch Thermal Cycle in TEMA.	30:00	35:15	
	Cold tests at 1.9K				
	SCAN4	Scan the HV Mobile Rack	0:15	35:30	
PT	2	HV Insulation test. "Cold initial before test connected to CFB"	1:45	37:15	CDBP HV
PT	1	IAP @cold. (Check of T-Coil, tuning of offset and compensation for Potain cards and Qloc)	1:30	38:45	
PT	3	Resistance Measurement. (Quench Heaters)	0:15	39:00	CDBP Resistance
PT	4	Slow Power Abort Check @ 1000A.	0:30	39:30	
MM	1	Shaft alignment and MMP Checks @ 1500A.	0:45	40:15	
PT	5.1	HALF LF. (Provoked Quench at 1.5 kA. Triggered by one card and protected by the other)	1:00	41:15	
	5.2	HALF HF. (Provoked Quench at 1.5 kA. Triggered by one card and protected by the other)	1:00	42:15	
PTE		Minimum Energy Quench @ 3kA (fast PA disabled) for Diode Test.	2:30	44:45	
PT	6	Training Quenches. According to the current training flowchart.	20:00	64:45	
MM	2	LHC cycle.	2:30	67:15	
MM	3	Full load line. (+ Joints Measurements)	3:00	70:15	
PT	8	De-excitation. Ramp to 12000A and Slow PA. (If Slow PA was not done at ultimate)	0:30	70:45	
MM	4	Single Stretched Wire.	6:00	76:45	
	SCAN5	Scan the HV Mobile Rack	0:15	77:00	CDPT
PT	9	HV Insulation Tests: "Cold final after test connected to CFB"	1:45	78:45	CDAP HV
PT	10	Minimum Energy Quench @ 11850A (fast PA disabled) to warm up the magnet	0:30	79:15	
		Make sure Quench Heaters are discharged before starting Thermal Cycle.		79:15	
PT	12	Warm Up. Put 2A in the magnet and launch Thermal Cycle in TEMA.	0:15	79:30	
		Electrical disconnection of the cables between TRU and mobile rack.			
	Warm-up				
PT	13.1	IAP @warm. No Quench Heater Discharge Test.	1:00	80:30	
	13.2	Resistance Measurement. (Quench Heaters, Voltage taps, Correctors, Cryo Heater and Temp. sensor)	0:30	81:00	CDW2 Resistance
	ICS5	SIGN TRAVELLER.			WP07
	SCAN6	After disconnection, scan the EMPTY label on the CFB.			
		Total Duration without Thermal Cycle : all Prep + Cooldown(30hrs)+ Power + MM tests + SSW		81:00	

Obeys To-Do List

Checklists & notes appended

MBAF136 MBAL1136 on TBF1

PREP 1	LYRE TEST (carried out with ICS personnel, put 2A at 15 V, in the magnet)		
Carried out By:	TEAM MEMBER(S) SHIFT LEADER		
Date and Time:			
Voltmeter Reading (Max. Value during Test)		Voltmeter Reading (Min. Value during Test)	
Results			
Note	The convalescence voltage expected ~ 11.5 V		
IMPORTANT	Sign ELECTRONIC traveller as soon as the test is performed		

PREP 2.1	IAP AT WARM (LF HEATER DISCHARGE) (put 2.5 A at 18 V, in the magnet)	
Carried out By:	TEAM MEMBER(S) SHIFT LEADER	
Date and Time:		
File Name(s)		
Results	Quench Heaters	
	Voltage Taps	
	Temperature sensor Reading	

PREP 2.2	IAP AT WARM (HF HEATER DISCHARGE) (put 2.5 A at 18 V, in the magnet)	
Carried out By:	TEAM MEMBER(S) SHIFT LEADER	
Date and Time:		
File Name(s)		
Results	Quench Heaters	
	Voltage Taps	

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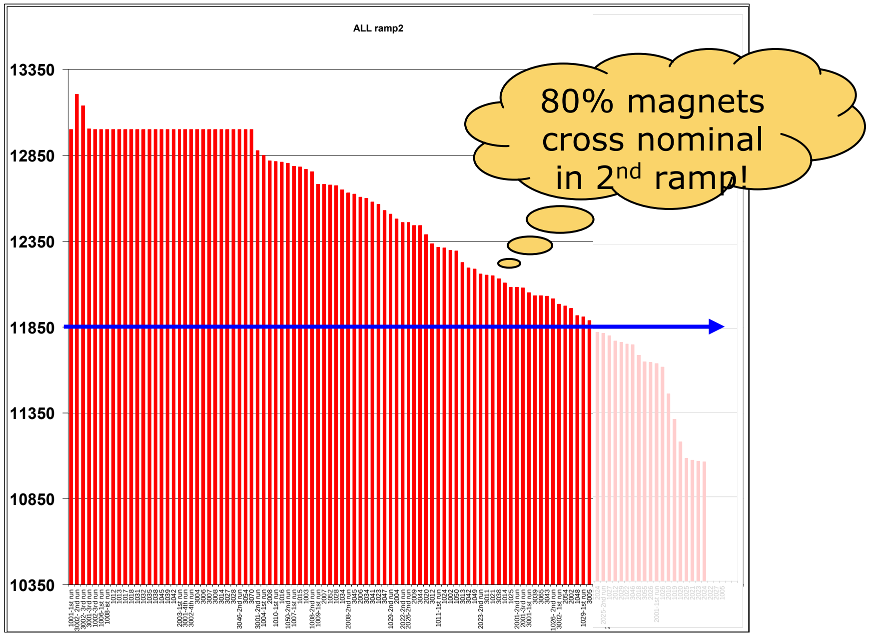
Training Rules & ROBTC

Most of the 'good magnets' cross nominal field (11850A ~ 8.33T) in the second training ramp..



—**Two-Quench Rule: Accept the magnet if it crosses nominal field in Second training with small margin!**

—**Three-Quench Rule: Accept the magnet if it crosses 12250 A (~8.66 T) in third training, even if it had not passed the preceding rule..**

ROBTC: Rapid thermal cycle of a poor magnet without disconnection from test bench

—**Saves disconnection & connection time….**

—**And mounting the quench location devices (often a futile exercise!)**

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Overall & Cryo Priority Setting

Cold Tests	Bench	Temp.	Priority
11 - QUENCH since 0' (PT 6.7 Training 7)	TBA1	5.77	2
10 - 1.9 [K] since 14h 15' (Extra Provoked Quench)	TBB1	1.90	1
52 - OVC PURGE since 3h 57' (ICS 4 Final connection)	TBC1	290.71	8
10 - 1.9 [K] since 2h 33' (PT 6.5 Training 5)	TBD2	1.91	3
Warming up or Cooling Down	**Bench**	**Temp.**	**Priority**
7 - QUENCH DEPRESSURIZATION since 12' (Prep 5 Pumping + Cool Down)	TBA2	88.74	9
6 - COOLDOWN TO 80 [K] since 12' (Prep 5 Pumping + Cool Down)	TBB2	284.01	10
13 - WARM UP TO 300 [K] since 9h 35' (PT 12 Warm Up)	TBC2	232.19	4
6 - COOLDOWN TO 80 [K] since 4h 14' (Prep 5 Pumping + Cool Down)	TBE1	218.71	7
13 - WARM UP TO 300 [K] since 1h 25' (PT 12 Warm Up)	TBF2	84.05	6
Cooling 80 K to 4K	**Bench**	**Temp.**	**Priority**
9 - LHe FILLING since 5h 38' (Prep 5 Pumping + Cool Down)	TBE2	50.58	5
Warm	**Bench**	**Temp.**	**Priority**
2 - CONNECTING MAGNET since 16h 29' (ICS 2 Connect Magnet (ICS))	TBD1	291.78	11
2 - CONNECTING MAGNET since 29' (PT 13.2 Resist. Meas.)	TBF1	297.41	12
Other	**Bench**	**Temp.**	**Priority**

Send those priorities to Cryo team

– **Ensure that magnets follow the desired cryogenic phase distribution, within the limits of possibilities due to the varying training performance (a priori not known)**

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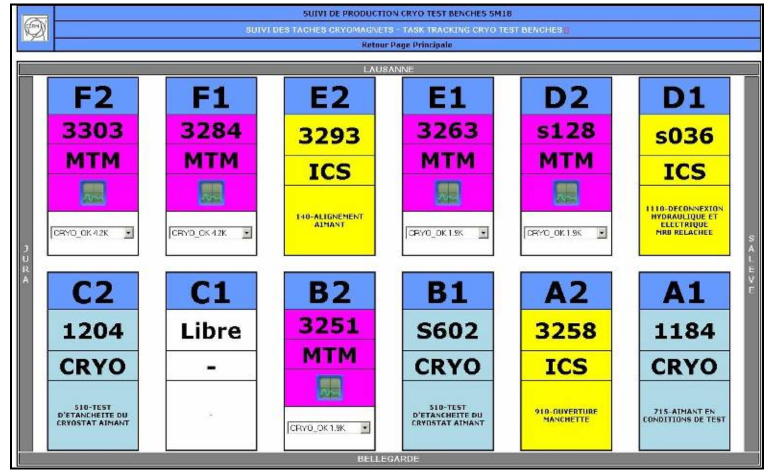
Operational Tools

1. **SM18 Test Management System (SMTMS)**
   - All relevant test data stored in it
2. **E-traveller**
   - Web based electronic work flow manifest with mobile phone interface
3. **Integrated Resource Display**
   - On-line display of usage of various resources
4. **E-logbook**
   - Maintains log of activities, categorizes & records faults
5. **MAPS**
   - Single page record of 'rule based magnet goodness evaluation'
6. **Operations Web page**
   - Easy access to all tools & documents

SMTMS & E-Traveller



- **Saves all test data into the system**
- **Tracks test progress & test statistics**
- **Automatic generation of test reports**

- **Smooth team interaction**
- **Interface with mobile phones – alert teams**

  Minimizes verbal communication..
- **Maintains automatic record of test flow**

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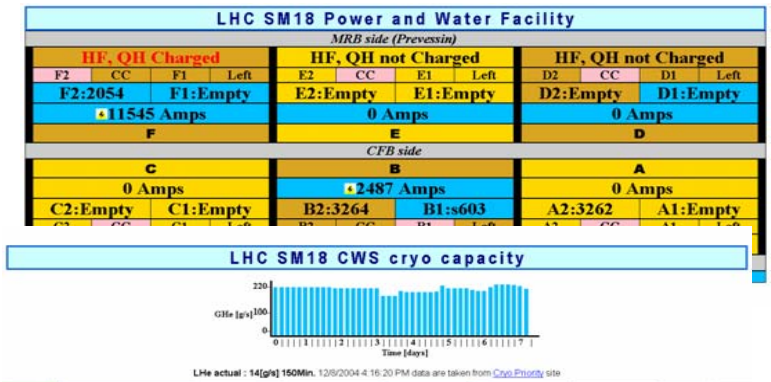
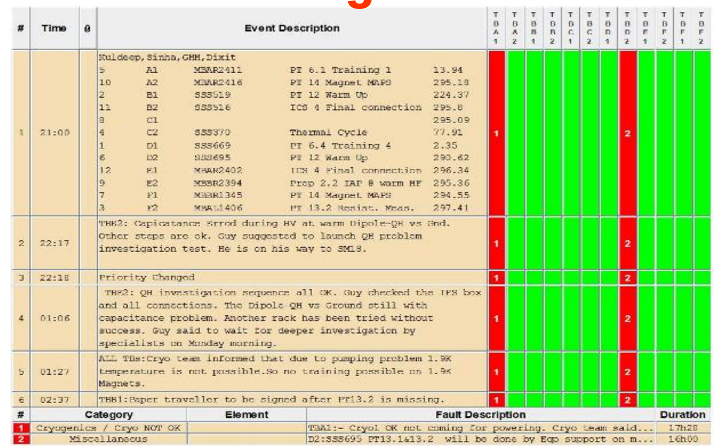
Other Tools

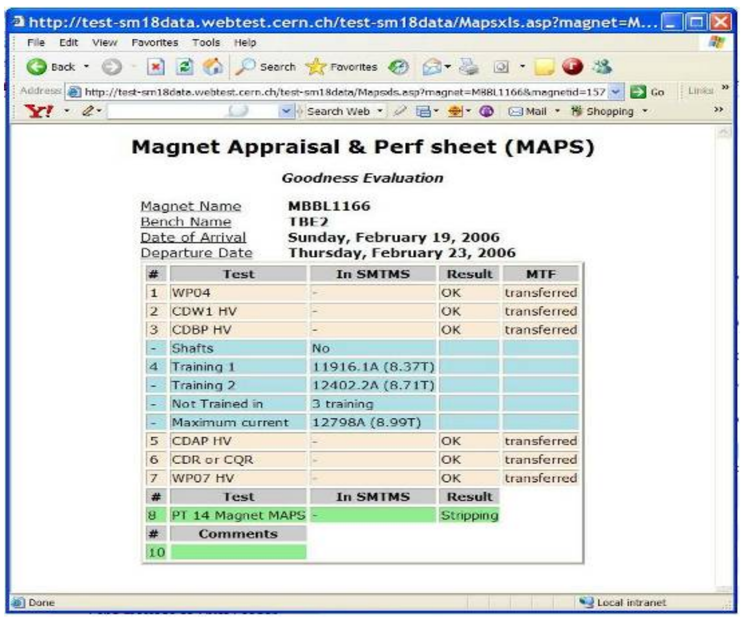
Integrated Resource Display



E-log book



MAPS



Operations Web page

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SM18 OPERATION

Back

Dipoles Documents

Cold Test Methods

Powering Methods			Instrumentation, Insulation & MM Methods			Preparation & Miscellaneous Methods		
Seq.	**Method**	**Prepared By**	**Seq.**	**Method**	**Prepared By**	**Seq.**	**Method**	**Prepared By**
PT4	Slow Power Abort	P.Daniel, S.Sridhar, P.Radheshyam	Prep2.2 Prep2.3 PT1 PT13.1	Instrument Analysis Procedure	S. Malhotra	Prep1	Lyre Test	P. Pareek, R. Narayanan
PT5.1	Provoked Quench at 1500 A, All LF	"	Prep3 PT2	HV Test	P. Pareek, R. Narayanan	-	Launching the test for dipoles without TEMA	P. Pareek
PT5.2	Provoked Quench at 1500 A, All HF	"	MM1	MM positioning at 1500A				
PT6	Training Quenches	"	MM2	LHC Cycle	B. Arun Kumar, P.Daniel	-	RRR measurement with keithley	S. Malhotra
PT8	De-excitation test	"	MM3	Full Load Line	"	-	RRR measurement without keithley	"
PT10	Minimum Energy Quenches Revised Version	"			"	-	Joints Resistance Measurement (Along with MM3)	Olav Berrig
SSL	Short Sample Limit Quenches Revised Version	"						
PTE27.1	Direct Ramp To Quench Revised Version	"				PrepE PTEAC	AC Transfer Function	Jackie Mazars, R. Narayanan
PTE11	V-Precycle Ramp To Quench Revised Version	"						

Warm Test Methods

Method	Prepared by
AC Mole (Cold) Measurement, AC Mole Cold Measurement with Vacuum, AC Mole (Warm) Measurement Method With short form annexure, Analysis of ACMole Measurement	Palanisami Kuppusamy
Dipole correctors Sextupole mesurment	S. Kane, I Vadillo
Dipole / Quadrupole Shaft Calibration	Sasidhar Rao Boyidi, I. Vadillo

Dipoles Quench Related Documents

Method	Prepared by
Quench Analyse Procedure (How to analyze the quench ?)	U. Bhunia (Revised by D. A. Roy, J. K. Mishra)
Guideline examples for Quench Heater analysis.	F. Pirotte, A. Kasbekar, K. Dubey

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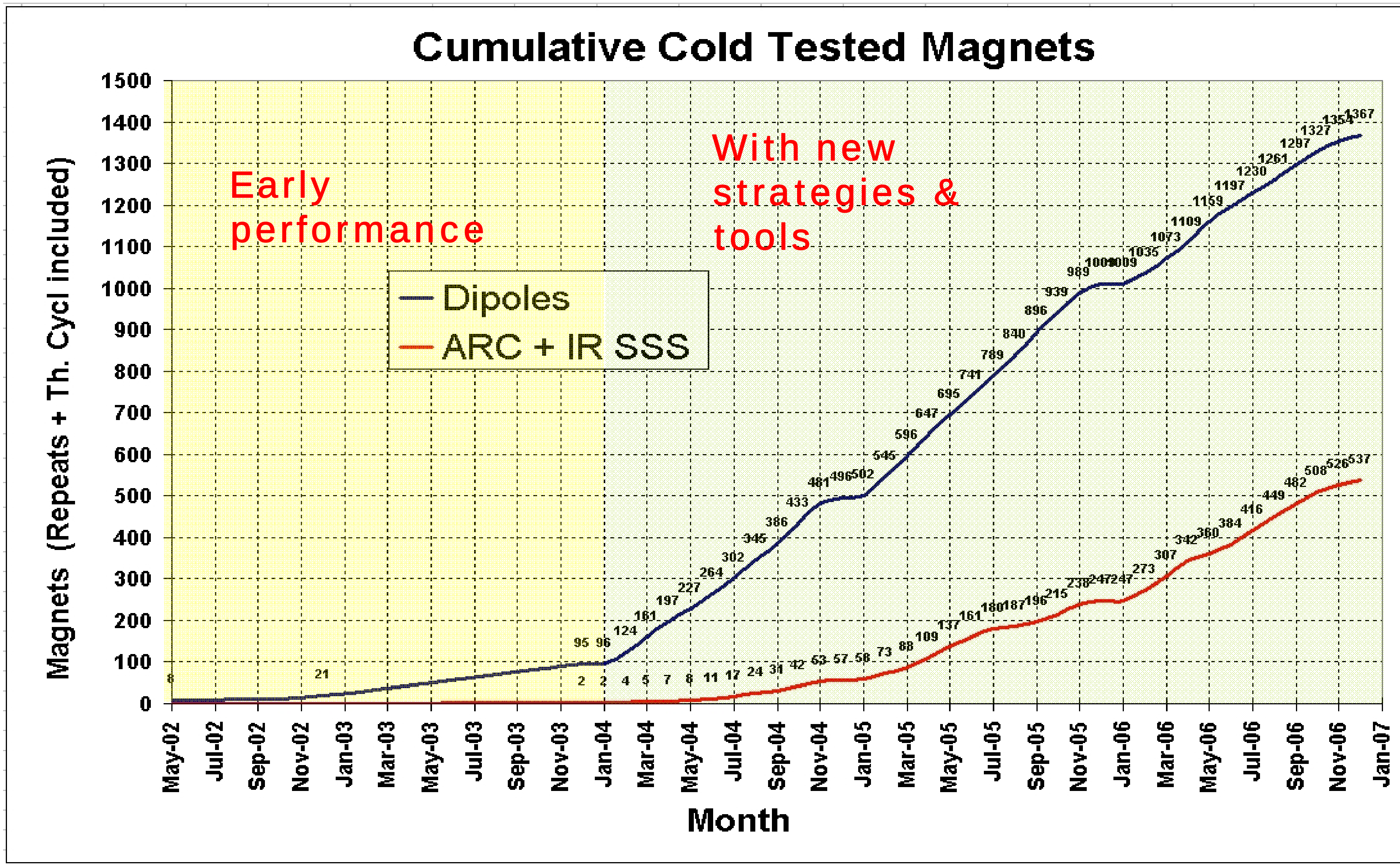
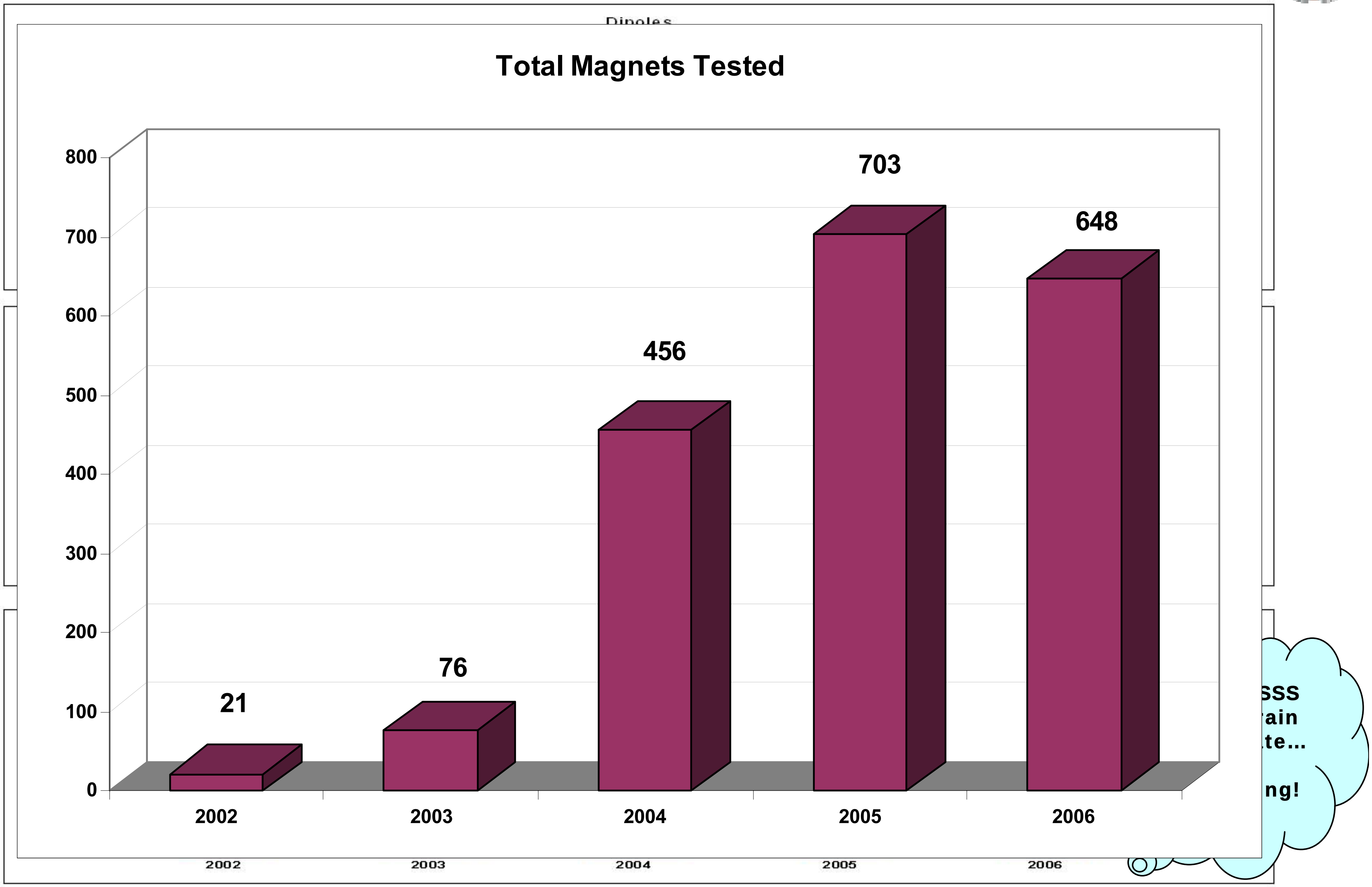
Results


Cumulative Cold Tested Magnets
Early performance
With new strategies & tools
Dipoles
ARC + IR SSS
Magnets (Repeats + Th. Cycl included)
Month

Annual Statistics



Repeat Rates & Magnetic Measurements

	Repeat Rate %	Mag. Meas. (MM) %	Repair / Rejection %
Dipoles	9	18.36	~ 3
SSS	12.5	13.32	~ 6
IR-SSS	12.8	30.85	--

Concluding Remarks

1. **Magnet tests completed ~Feb 2007**
2. **Major contributions of Indian Associates:**

Unique, large scale international collaboration in the accelerator domain!
(in human resources: ~90 persons in 5 years)

- **Dedication, Sincerity and Hard work**
- **And much more….**

Indian Associates in SM18
(2002 – 2006)

Collaborators from Bhabha Atomic Research Centre (BARC), Mumbai, India:

Clement Verghese, Prem Kumar Kavalan, Laddha Anand, Maurya Beachai, Malhotra Sanjay, Perupayikkad Daniel Babu, Shetty Satish Shankar, Narayanan Ramkumar, Satyanarayana Arunkumar, Nair Kesavan, Awale Prashant Kamalakar, Patil Mahesh Balasaheb, Dubey Krishna, Roy Amitava, Thota Venkatesulu Shyam, Gupta Rakesh Kumar, Mascarenhas Martin Lucio, Surendran Puthiyedath, A Kasbekar, J Mishra, P Motiwala, P Adibabu, P Joshi, P Kashyap, Naushad Ali, D Roy, Jacob John, K Ambastha, Jaydeep Gore, Vasu Kakkat, Sanjeev Sharma, D Bhattacharjee, Sudheer Singh, Surajit Sen, Manna, Swagat Mukherjee, Vikas Chauhan, Mukesh Sharma, Vikas Telang, Subrat Kaushik, Sumeet Maity, Sampath Kumar, Charudatta Kulkarni, S. Padmakumar, P. K. Panda, N.S. Dalal, Sunil G Kulkarni, Sreyas R Shimjith, Sushil K Bahuguna, Vijendra Sinha, Kuldeep Joshi, E Kandaswamy, M Y Dixit, Amit Tikaria, R I Bhaktsingh, B V Rama Rao, S T Sonnis, N G Tayade, Vivek Yadav

G Aravamuthan, S. Gomu, Gangoor, Vineet Sinha, M Naskar,Y Chaudhari, A Basu, P Behere

Collaborators from Centre for Advanced Technology (CAT), Indore, India:

Gandhi Manoj, Marathe Ravindra G, M Jathar, Radheshyam Pramod, A Kasliwal, Khare Krishna Mohan, Pareek Prashant, Jain Akhilesh, Pagare Anand, Yash Pal Singh, Mandar Joshi, Praveen Deshpande, Jitendra Patil, Rajkumar Gupta, Seshnath Singh

S Kane, S Pralod, Vimal Bhatnagar

Collaborators from Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India:

T S Selvakumaran, R Dhandapani, Sethumadhavan Sridhar, B Rao, K Palanisami

Collaborators from Variable Energy Cyclotron Centre (VECC), Kolkata, India:

Bhunia Uttam, Bhole R, Sandip Pal, J Debnath

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Making it possible ..

It is pretty cool...

With food for thought..

With a little workout..

& Bit of aerobics for health !


Thank You !

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Extra Slides

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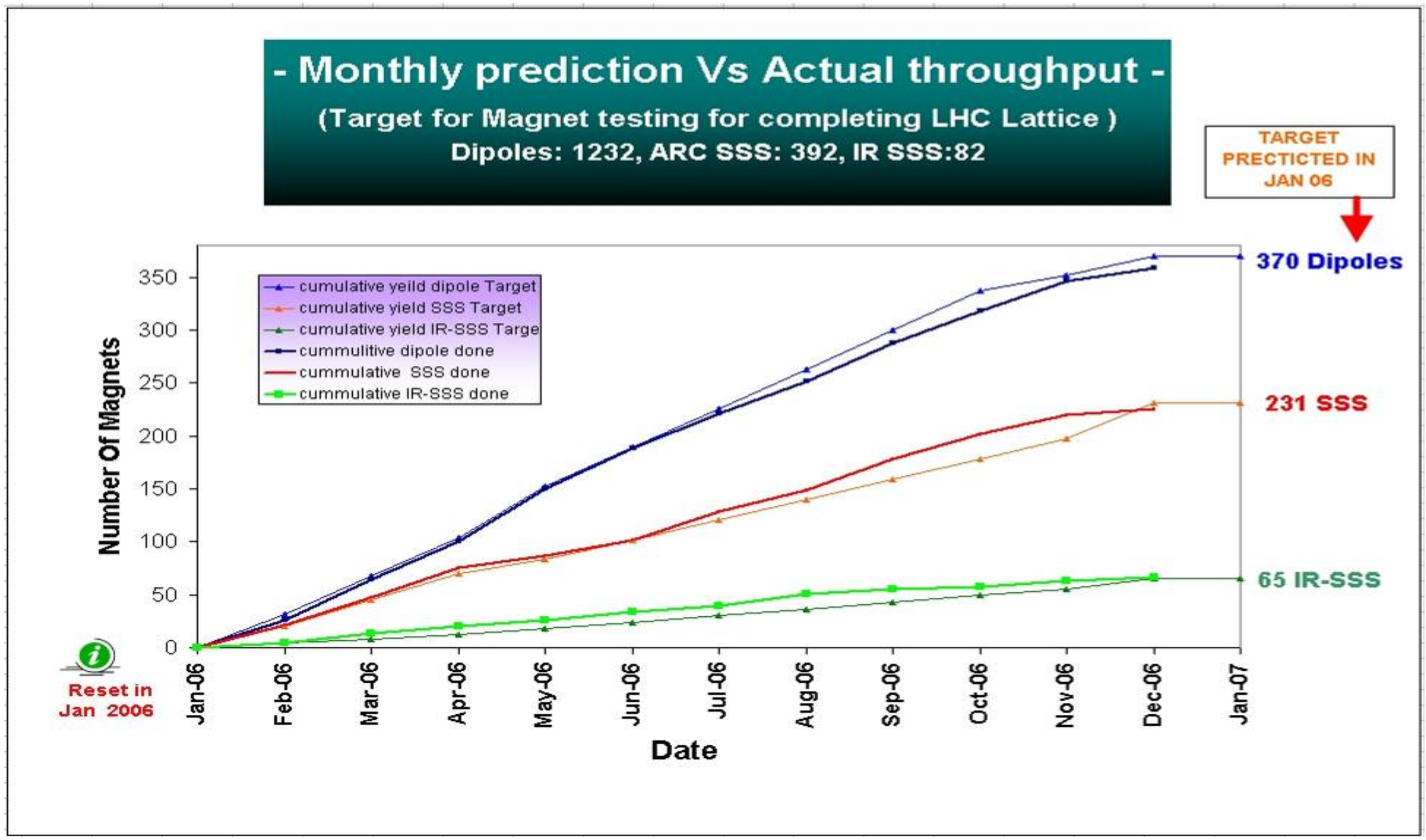
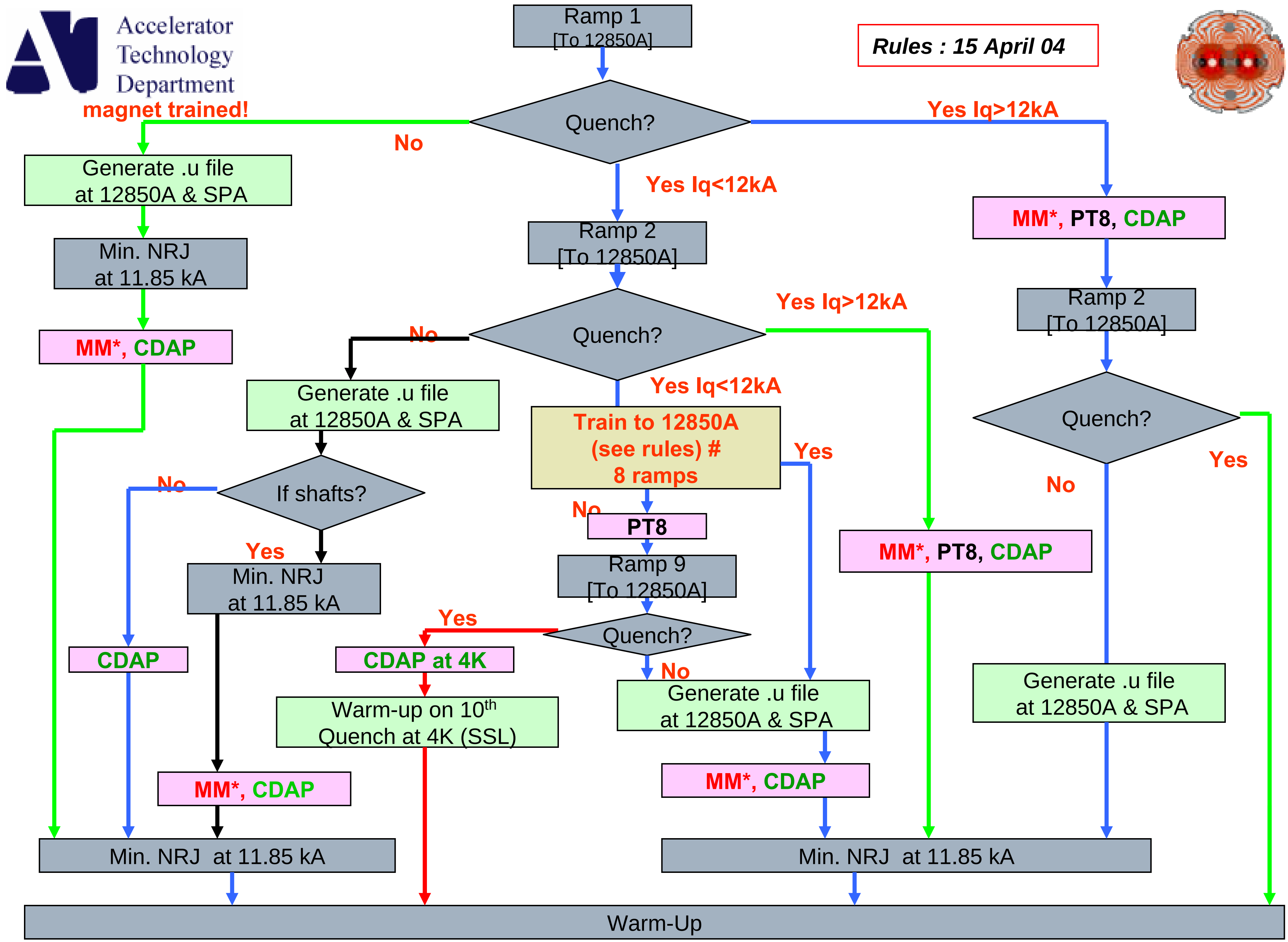
Statistics: Actual Vs. Predicted Throughput



- **For the dipoles actual throughput has coincided with the prediction.**
- **For the special SSS and arc SSS the actual throughput is better then the prediction.**


Accelerator
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Department
magnet trained!
Ramp 1
[To 12850A]
Rules : 15 April 04
Quench?
No
Yes Iq>12kA
Yes Iq<12kA
Generate .u file
at 12850A & SPA
Min. NRJ
at 11.85 kA
MM*, CDAP
Ramp 2
[To 12850A]
MM*, PT8, CDAP
Ramp 2
[To 12850A]
Quench?
No
Yes Iq>12kA
Yes Iq<12kA
Generate .u file
at 12850A & SPA
Train to 12850A
(see rules) #
8 ramps
Quench?
Yes
No
If shafts?
No
Yes
Min. NRJ
at 11.85 kA
Yes
No
PT8
Ramp 9
[To 12850A]
MM*, PT8, CDAP
CDAP
Yes
CDAP at 4K
Quench?
No
Generate .u file
at 12850A & SPA
Warm-up on 10th
Quench at 4K (SSL)
Generate .u file
at 12850A & SPA
MM*, CDAP
MM*, CDAP
Min. NRJ at 11.85 kA
Min. NRJ at 11.85 kA
Warm-Up

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- # Max 9 Ramps to 12850A; If this terminated in <= 9 ramps
- Then follow flowchart , else:
- magnet is poor & do warmup on 10th with 4K quench
- Instead of PT10
- THEN: Thermal Cycle if AntiC exist & so put in shafts
- ELSE((if no AntiC) – Magnet removed & Standby

MM* If Shafts Are Present!

PT8 = Ramp to 12 kA & SPA

Min NRJ = Quench provoked
FPA Disabled

Thermal Cycle Rules with Shafts Inserted :

In the 2^{nd} Run:

if 1^{st} Q above (8.4 T) 12000A then MB accepted

if 2^{st} Q above (8.6 T) 12350A then MB accepted

ELSE MAGNET REJECTED WITH poor perf non-conformity but with the rules :

if Quenches are localised only in 2^{nd} run (with shafts inserted only in the 2^{nd} run): perform 5 quenches only

And END the Tests

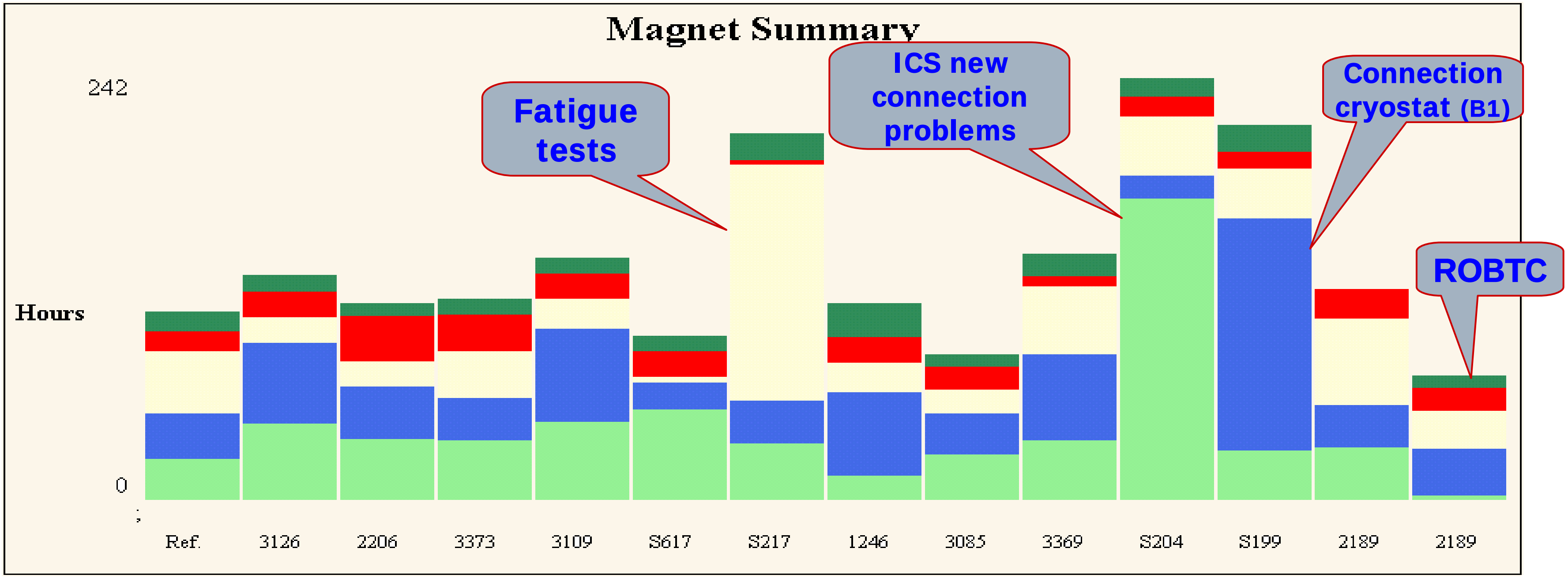
.

if Quenches were localised in first RUN :

then perform max 2 localized quenches only in 2^{nd} run

Typical magnet test times

(For the week starting 26th July 2005)



Reference Times

Light green : Connect (up to Cryo pump down)	**24 h**
Blue : Wait + Cool down	**26 h**
Ivory: Tests at Cold	**36 h**
Red : Wait + Warm up	**12 h**
Dark Green: Disconnect	**12 h**

SM18 Test Operation

Available Resources

- **Test Equipment**

  Fixed
  - **12 Test Benches arranged in pairs so, 6 clusters(A to F)**
  - **6 Main Power Converters**
  - **6 sets of Electronics for testing 1 per cluster**

  Mobile
  - **For Q-location & MM special 15 m Shafts to be installed in magnets**
  - **Mobile Racks for HV insulation tests & Magnetic Measurements**
  - **SSW Units**

- **Shared Utilities**
  - **Water for 4 magnet powering at the same time**
  - **Cryogenics capacity and limits**

- **Manpower [24 hr Tests Operation Staff] in 2005**
  - **14 CERN staff (~12 FTE) on loan from CERN Accelerator Operation (some only part-time)**
  - **20-25 persons on exact 1 year contracts from India & constantly rotating, so (~16 FTE)**
  - **ICS "Magnet connectors/disconnectors" working 24 hours (but ROCLA not)**
  - **Cryogenic Support staff**

- **Technical Support**
  - **Equipment support for magnet test equipment and electronics**

Utilities : Cryogenics Capacity

Cryogenics capacity (in 2005) and limits :

- **3 to 5** Magnets **@ 1.9K** and under cold tests,

- **Up to 2** magnets in 300K to 90 K **(Cool down)** phase ,
- **Up to 2** magnets in Last **(Warm up)** Quench to 300K phase,

(but not exceeding 3 magnets in cool-down or warm-up phase altogether - this limit was 2 up to end 2004)

- **1** magnet in **90K to 1.9 K** phase

Cryogenics capacity was enhanced in 2005, with

- Faster cooling & warming times
- Better quench recovery
- Increased limits on number of quenches

However it still requires a judicious and optimized setting of bench cryo priorities by OP crew

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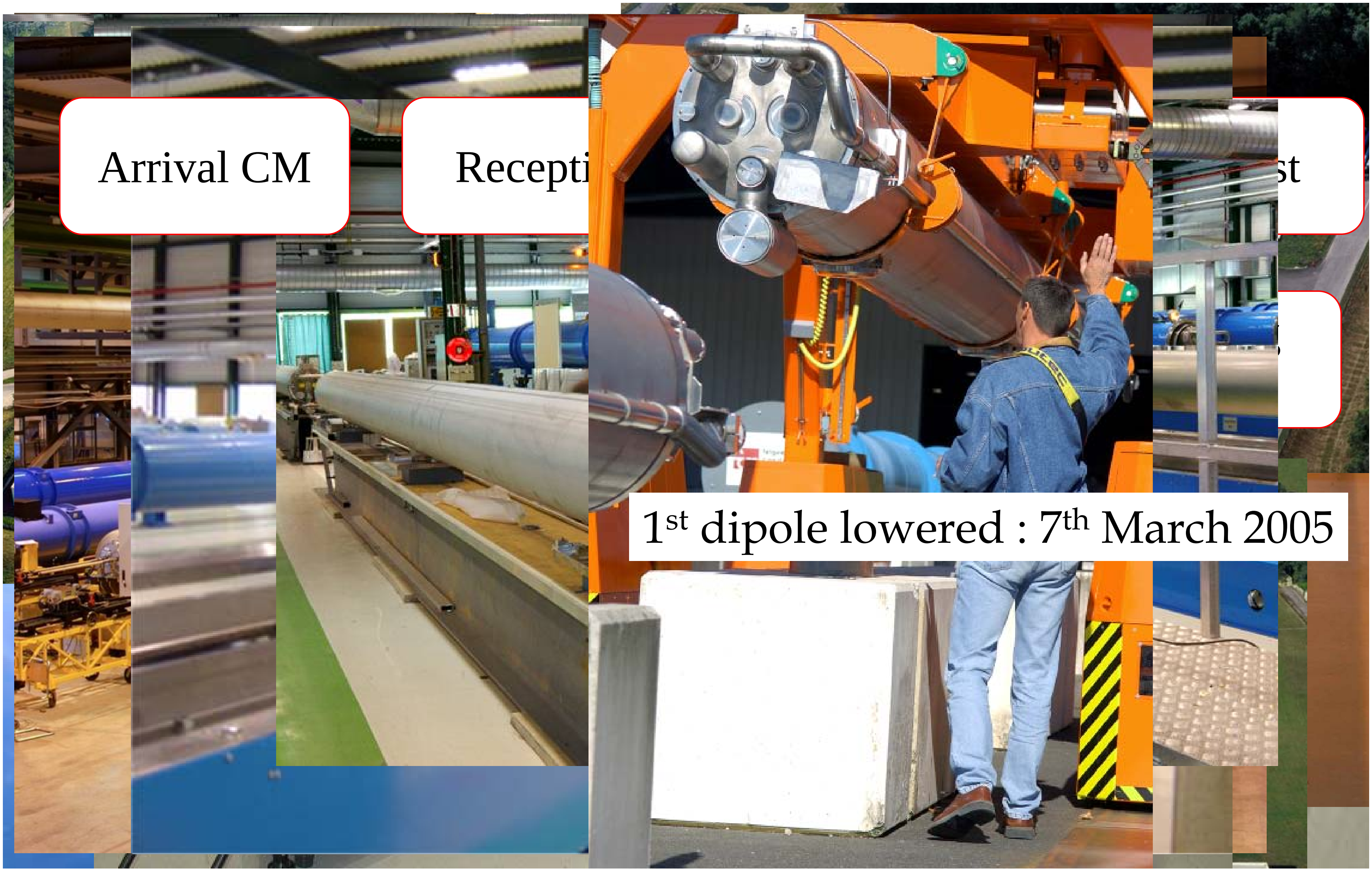
Magnet work flow at CERN before beam test

Courtesy: L.Rossi



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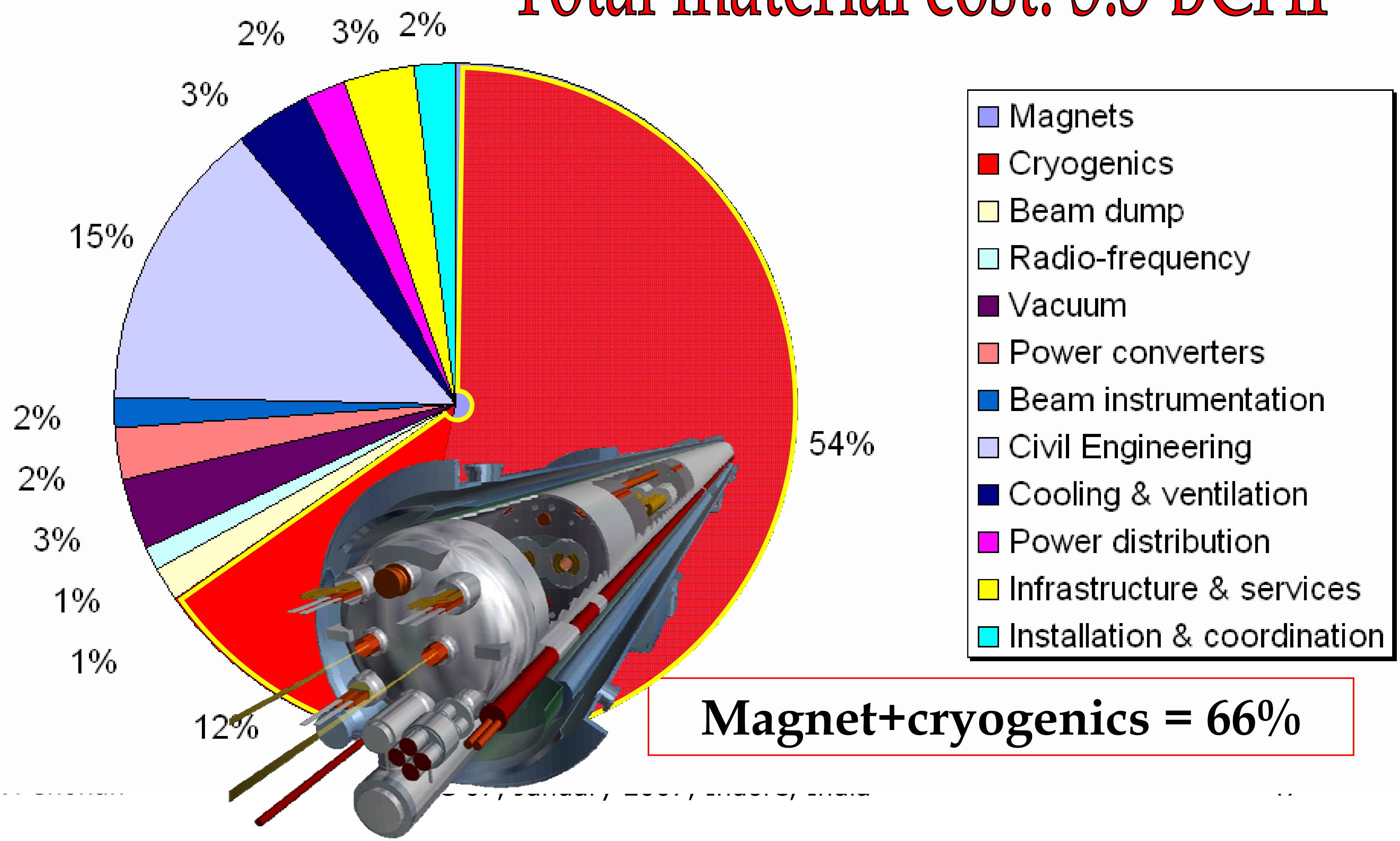
Cost structure of the LHC

Courtesy: L.Rossi

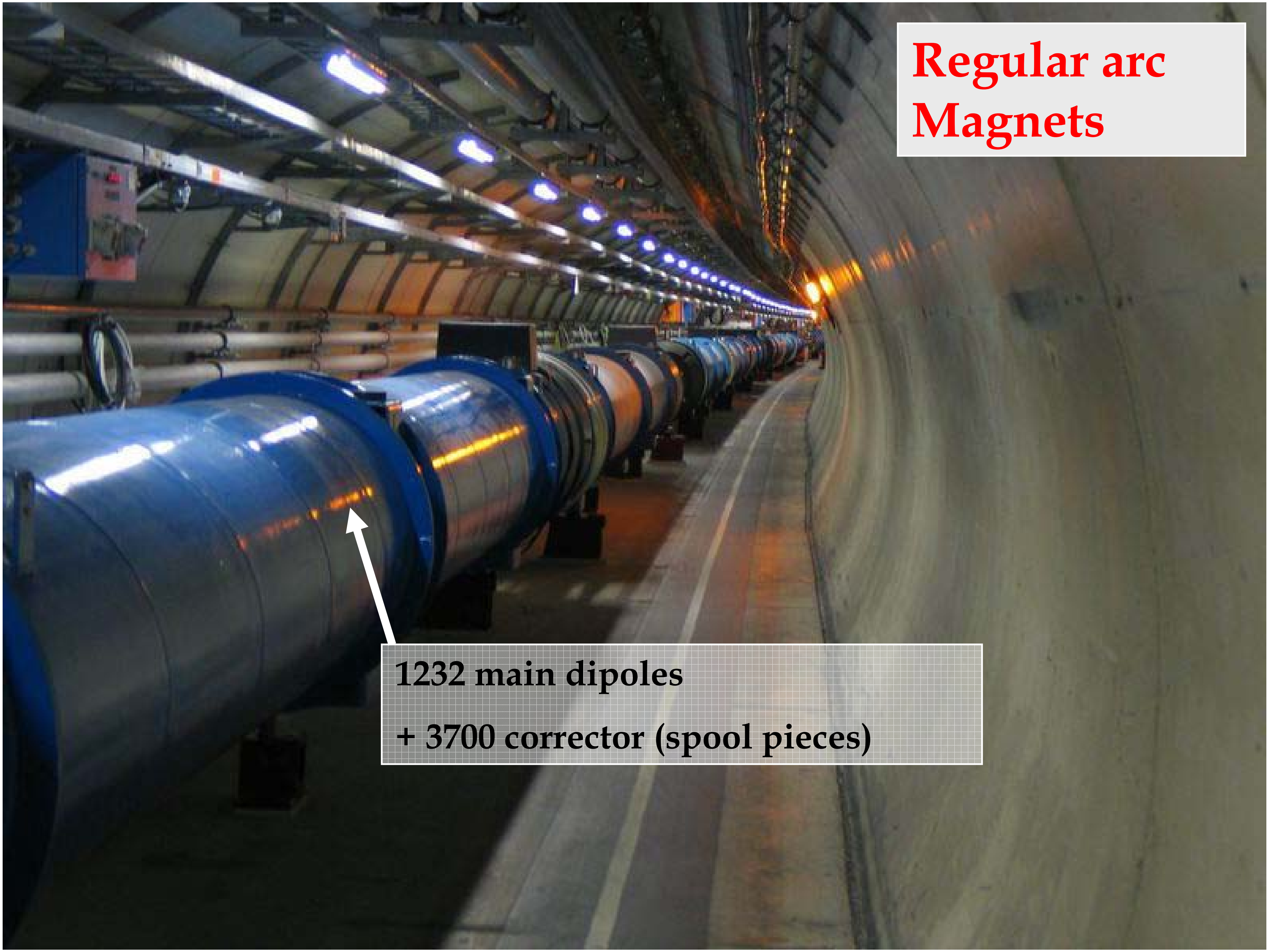
Total material cost: 3.3 BCHF



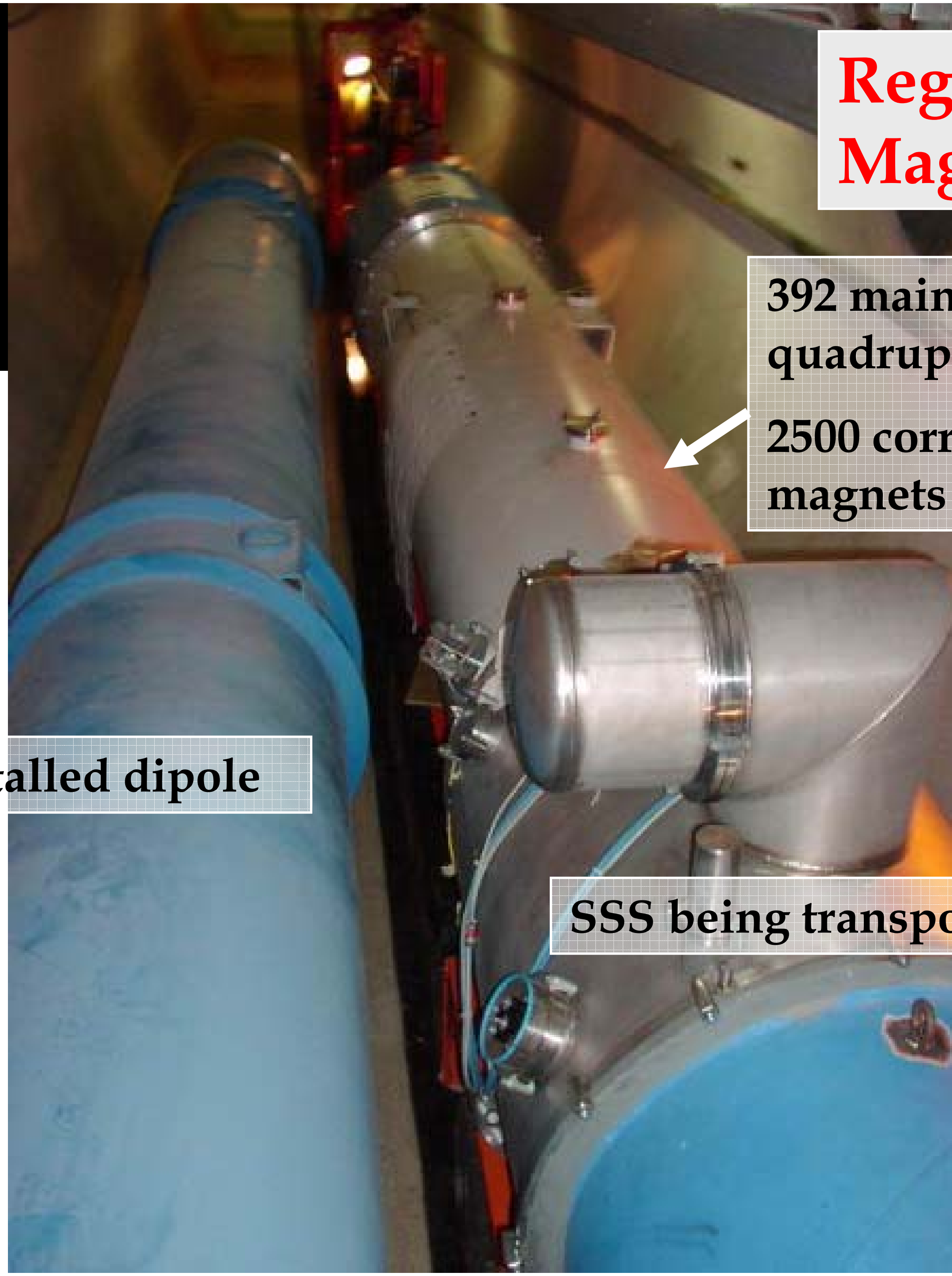
Magnet+cryogenics = 66%

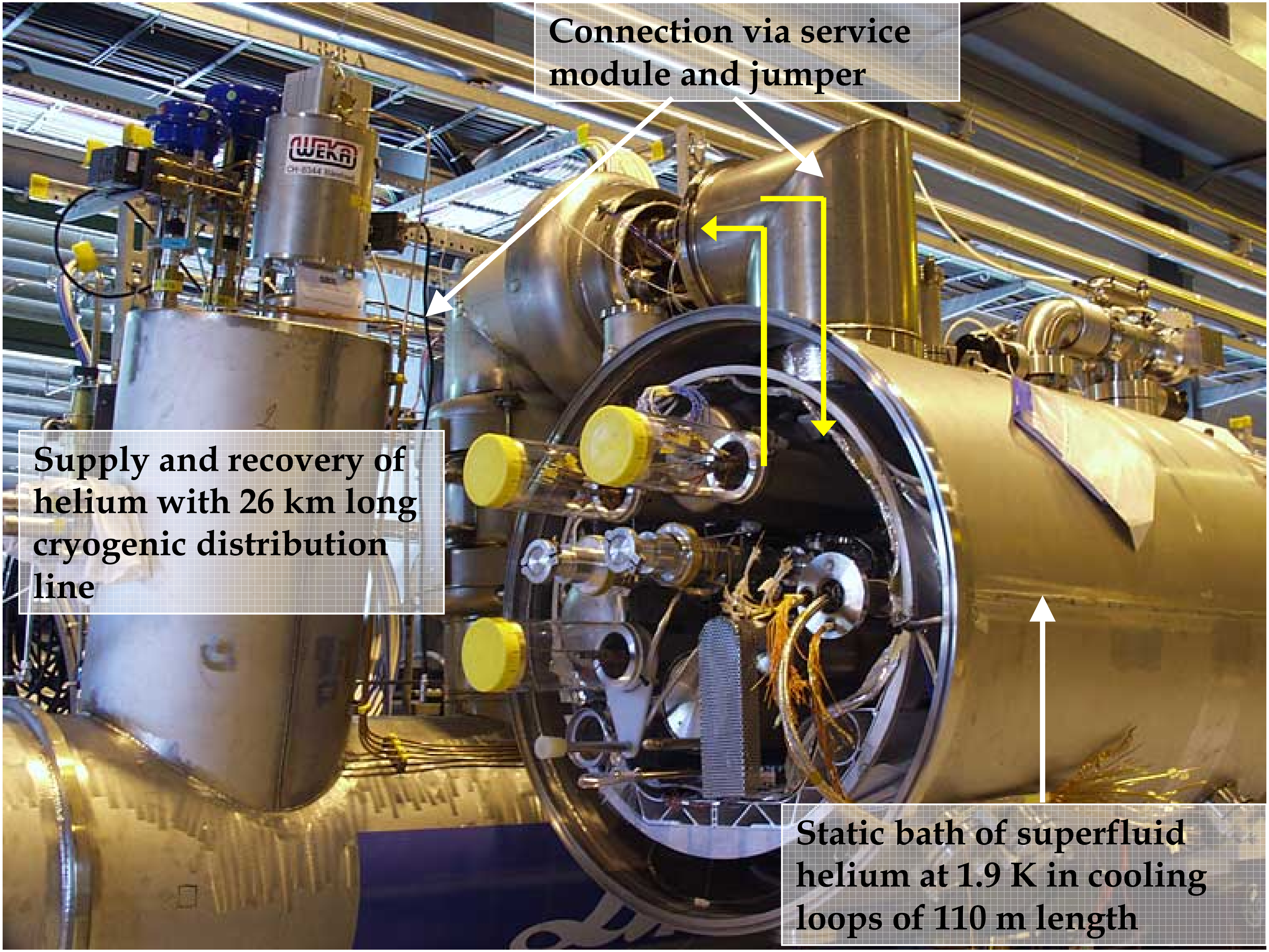

LHC tunnel 2002

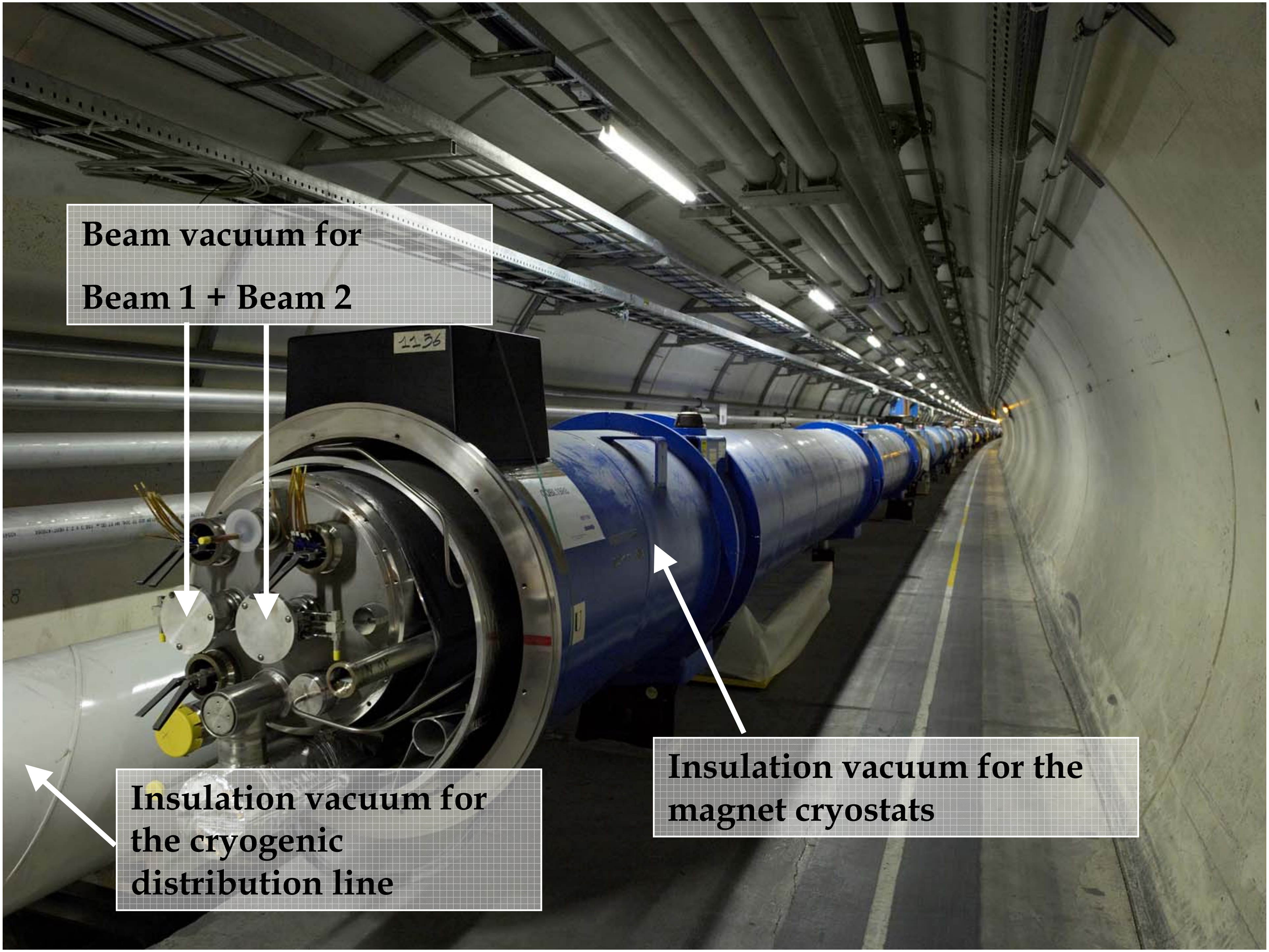

LHC tunnel 2006

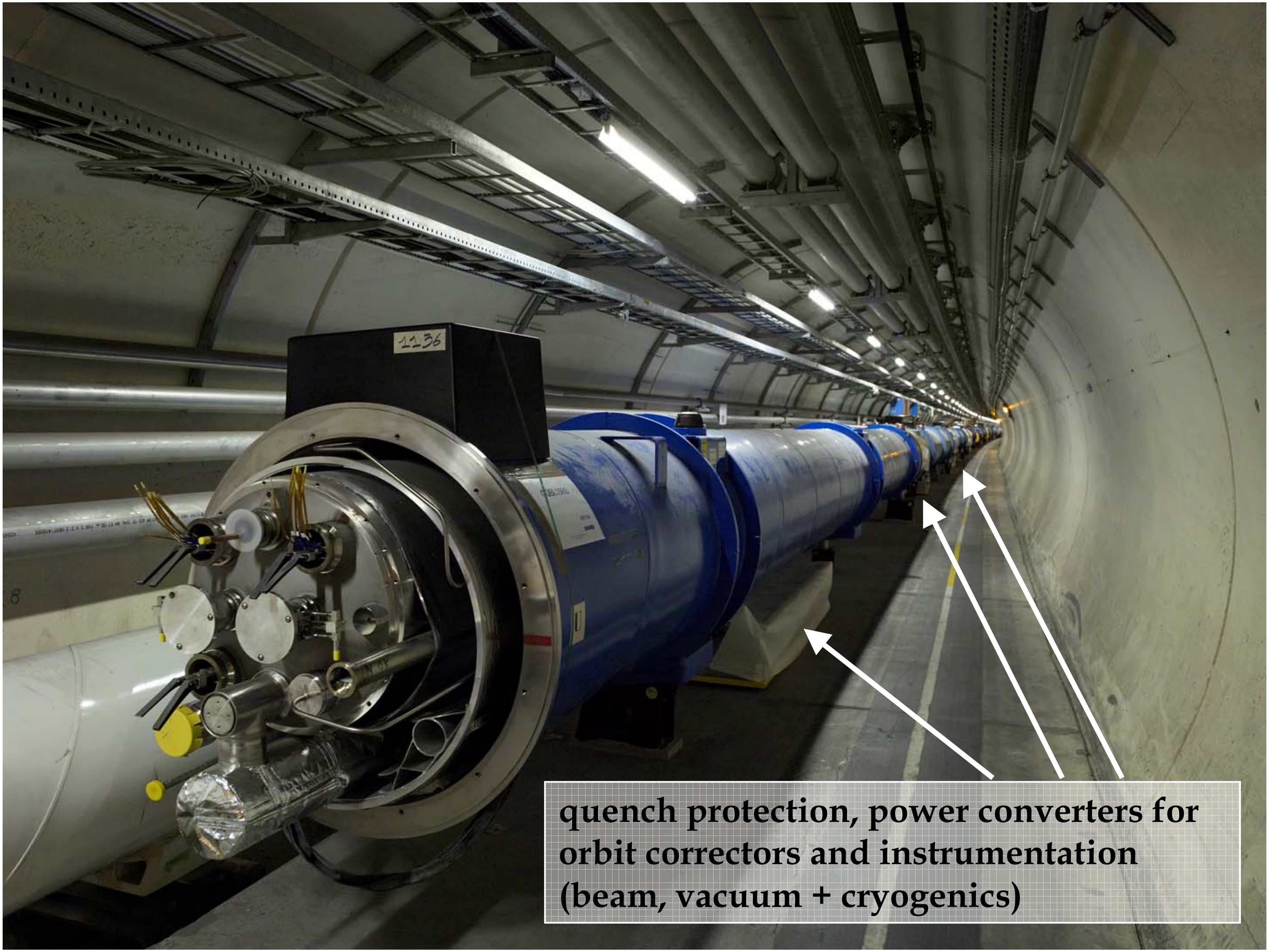

Regular arc
Magnets
1232 main dipoles
+ 3700 corrector (spool pieces)

Regular arc Magnets

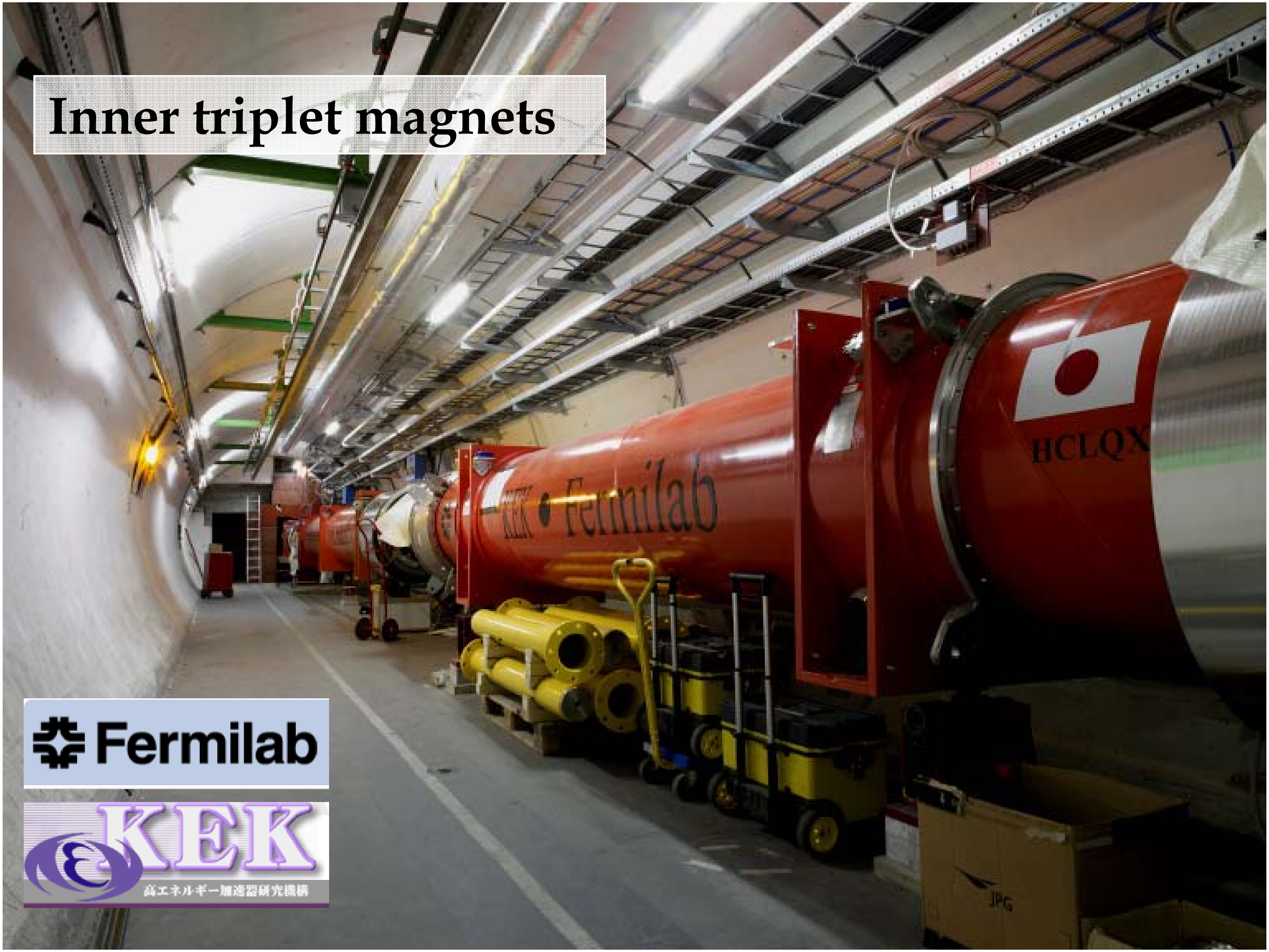



Connection via service module and jumper
WEKA
Supply and recovery of helium with 26 km long cryogenic distribution line
Static bath of superfluid helium at 1.9 K in cooling loops of 110 m length


Beam vacuum for
Beam 1 + Beam 2
Insulation vacuum for the cryogenic distribution line
Insulation vacuum for the magnet cryostats


quench protection, power converters for
orbit correctors and instrumentation
(beam, vacuum + cryogenics)
1136

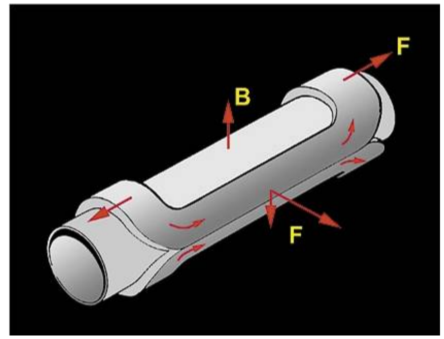
Inner triplet magnets



Accelerator magnets issues

Courtesy: L.Rossi

- In iron dominated magnets the pole shape dictates field quality
- In superconducting magnets the conductor position dictates the accuracy of the field.
- Coils not self-supporting
- Beam will circulate 500 Millions times in the LHC Field accuracy: 10-100 ppm
- Necessity to have all dipoles equal in length within ~ 100 ppm (1.5 mm over 15 m of the LH[C] dipole length !)

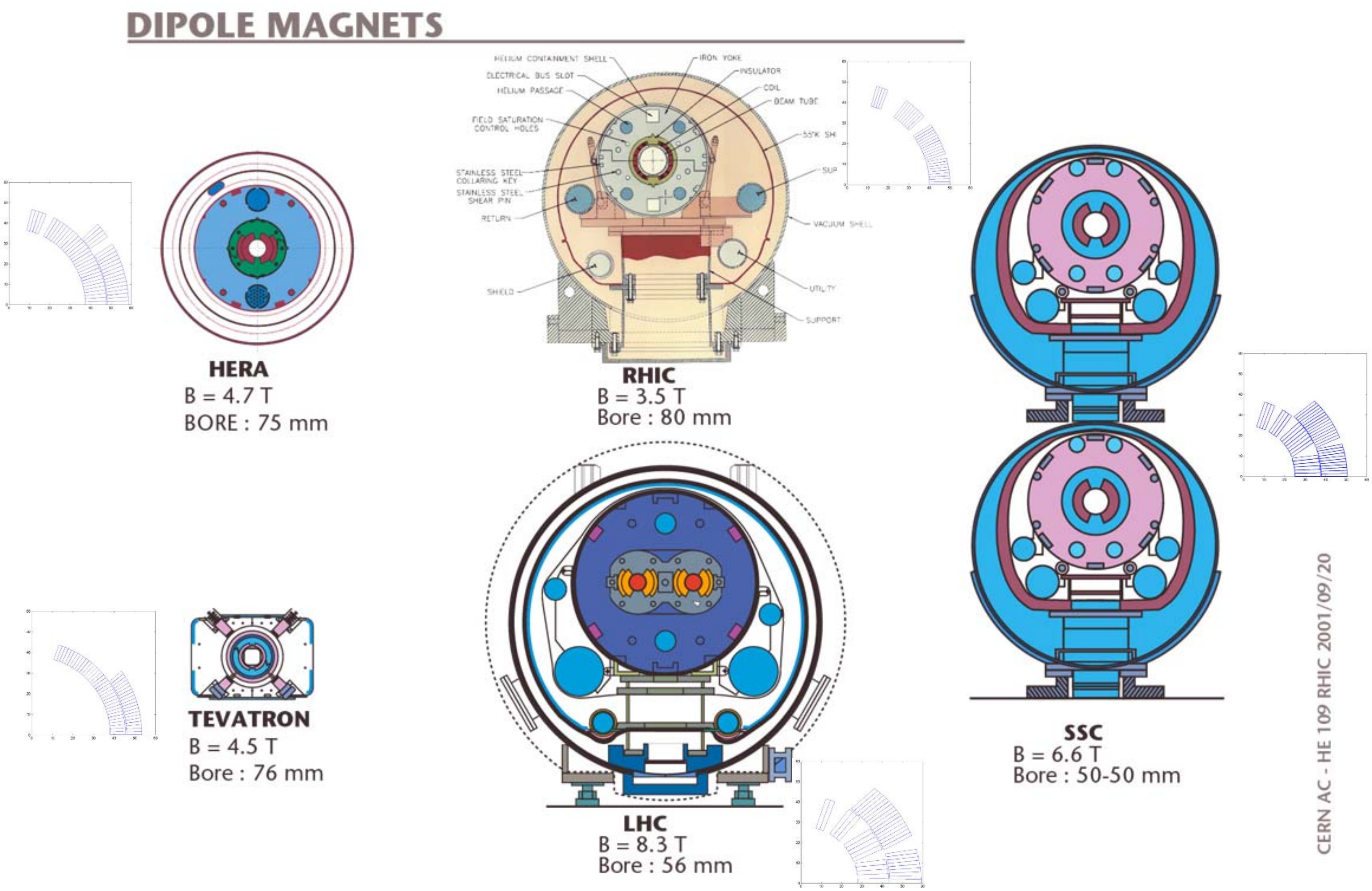


LHC main dipoles

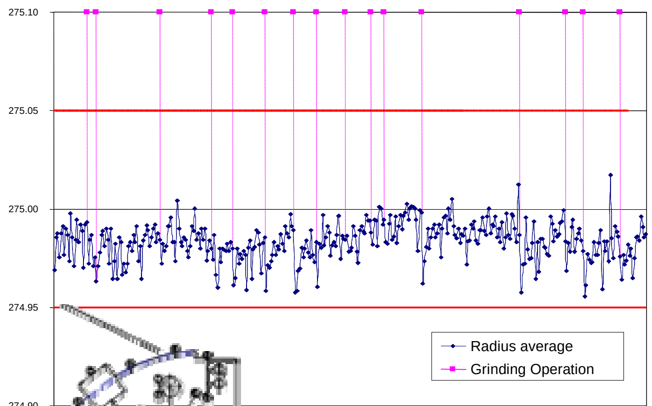
- Quantity: 1232 dipoles $\times$15 m = 18.5 km
- Operated at same current: 154 circuits
- Extremely high current density: operation 85% of Ic (on load line), little stabilizer to increase J$\Rightarrow$ Training. BUT we cannot train them at long (it costs too much) and **they should not re-training.**
- After the cool down the **worst magnet will determine the energy of the accelerator.**

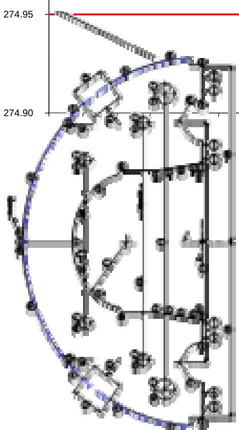
The historical outlook

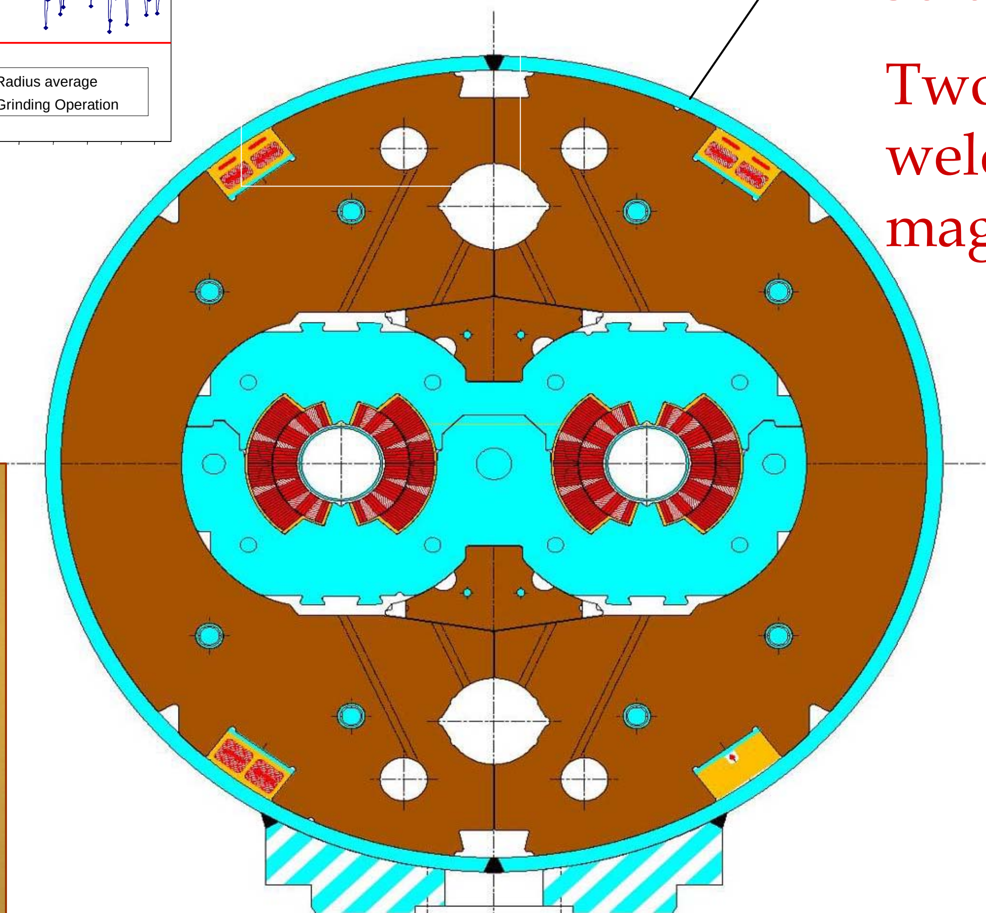
Courtesy: L.Rossi



Dipole cross section: yoke & shrinking cylinder







Curvature released from ± 1 to ± 2.5 mm:

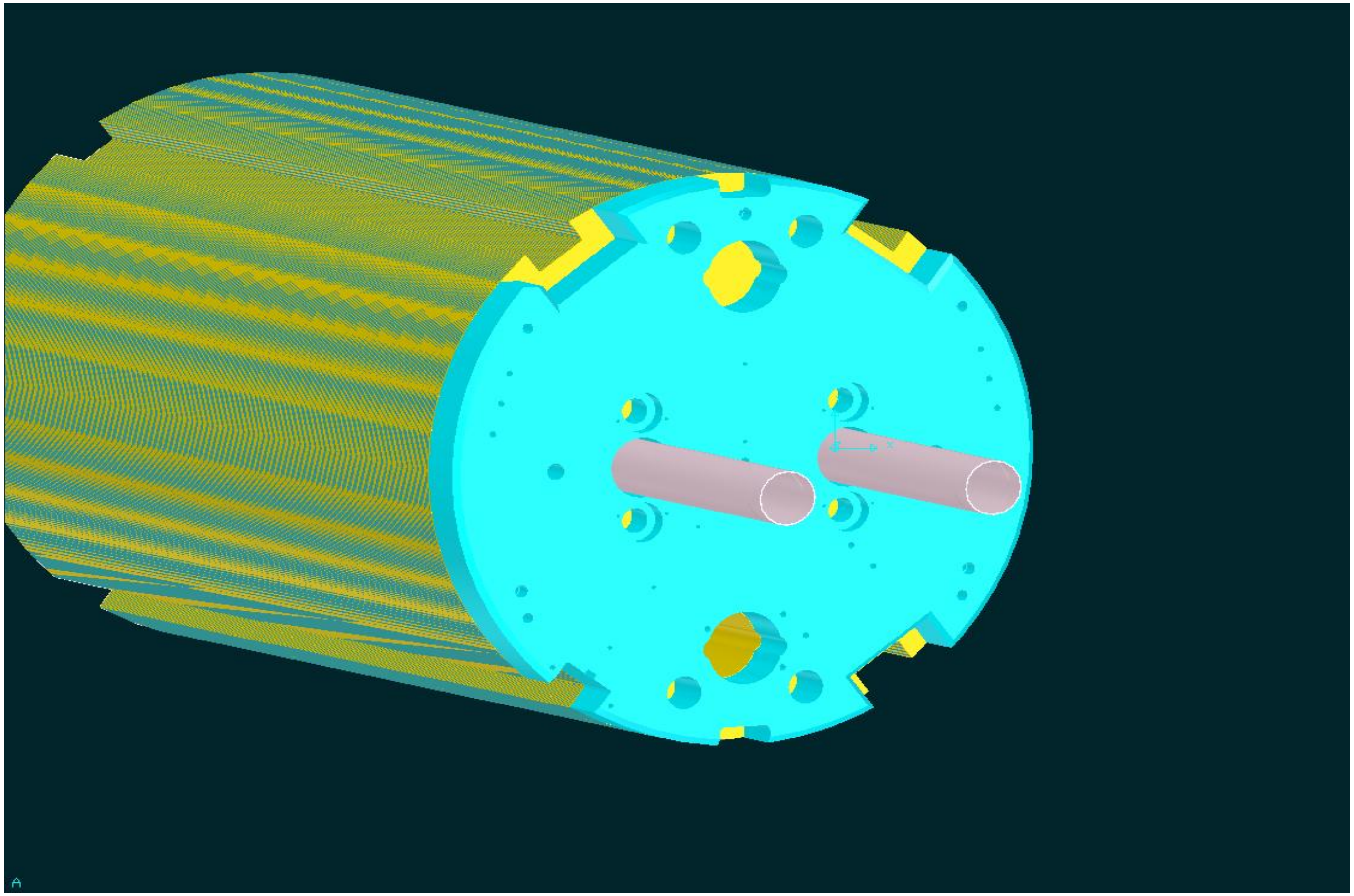
Solution: pairing

Two half shells, welded on the magnet

Courtesy: L.Rossi

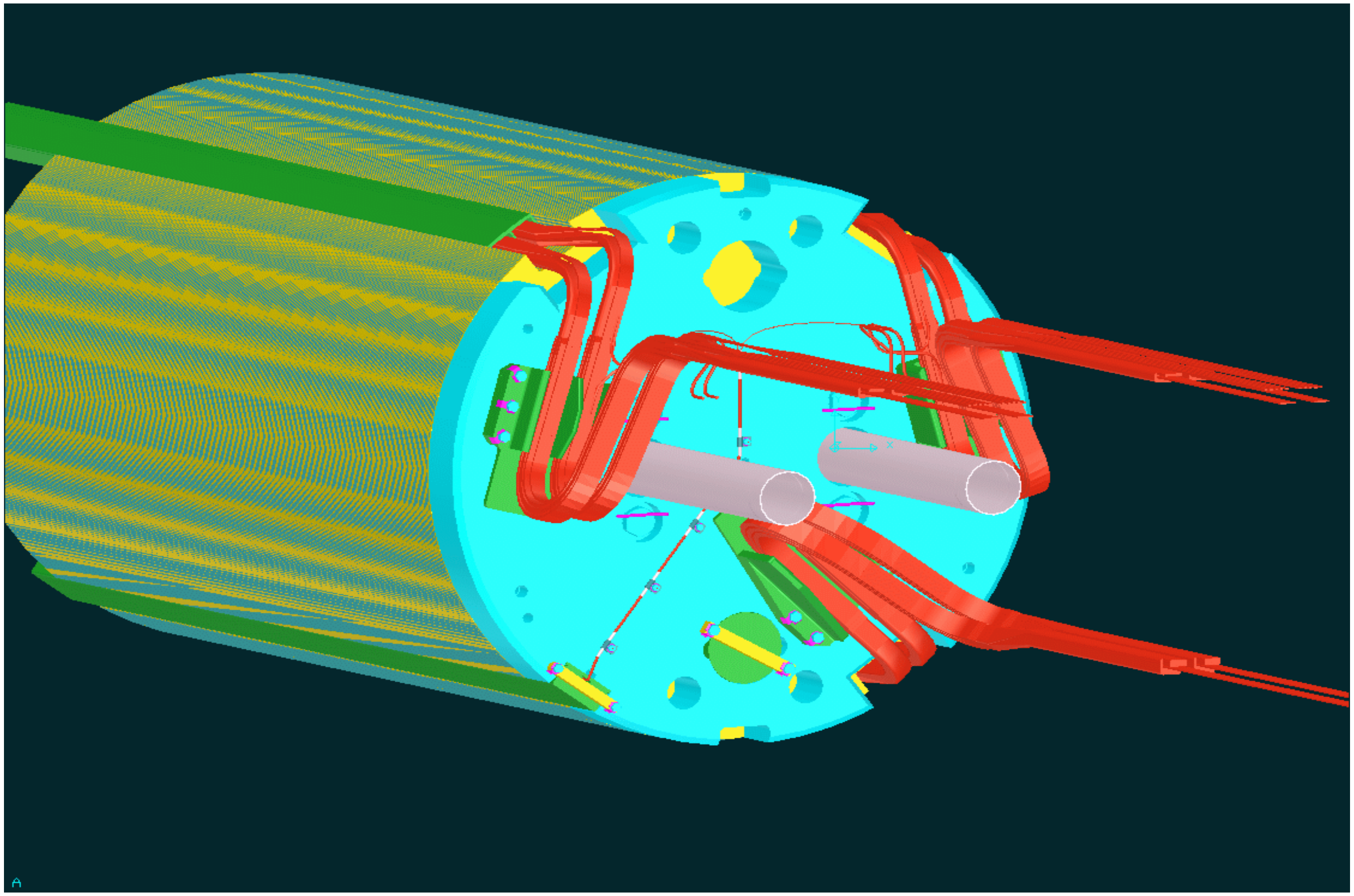
Courtesy: L.Rossi

Dipole -end part end plate



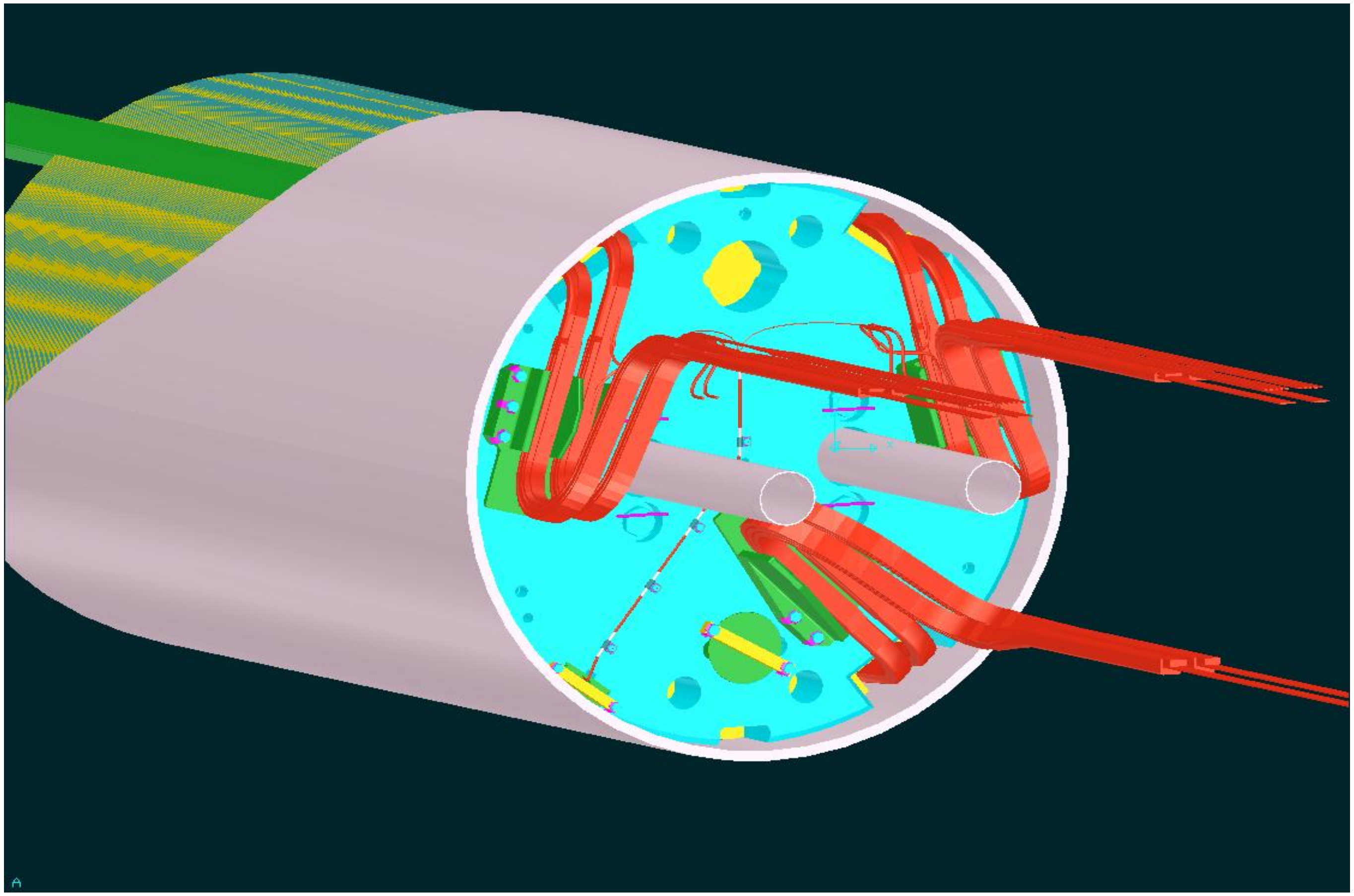
Dipole-end part
Bus Bars

Courtesy: L.Rossi



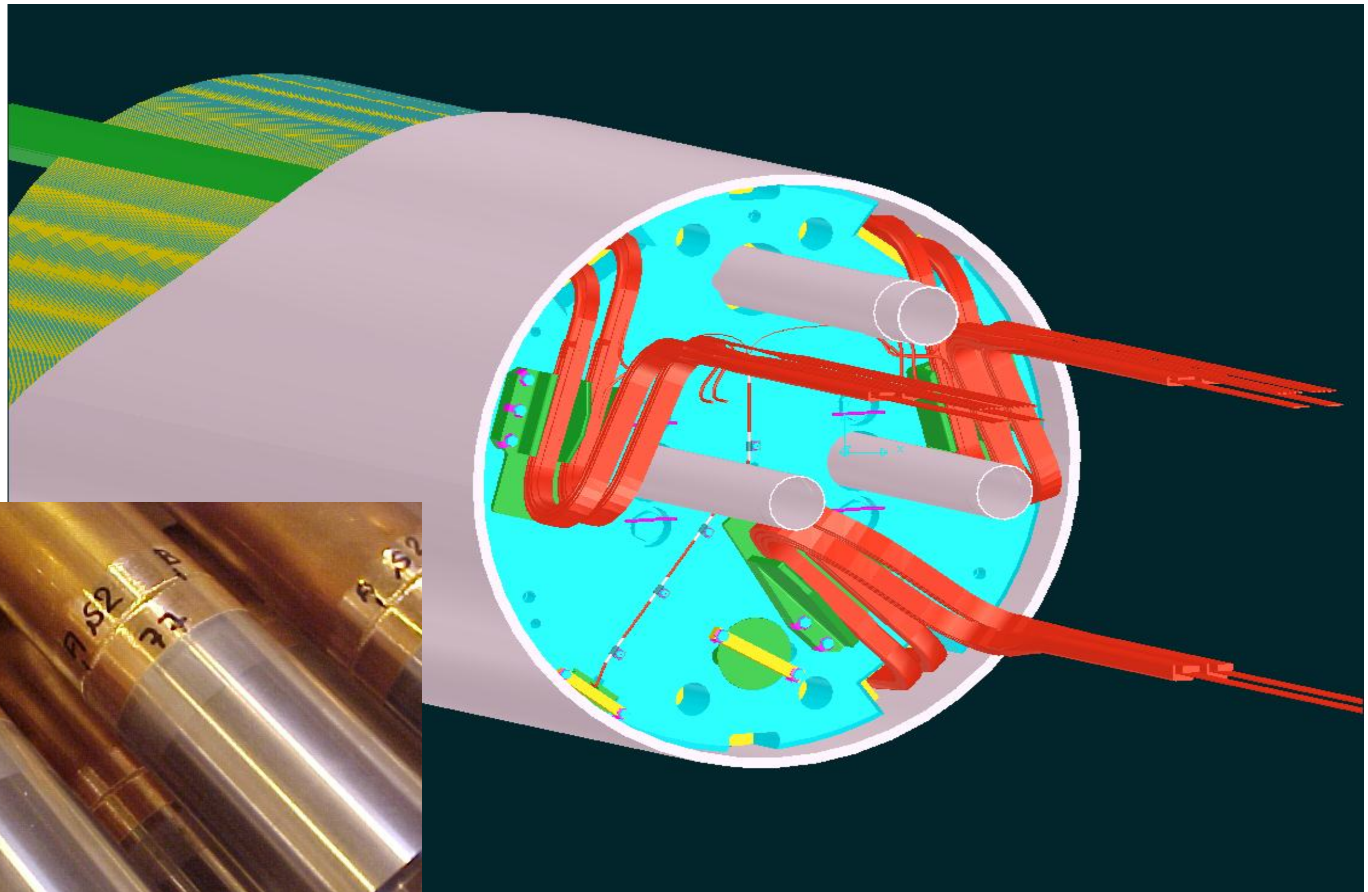
Dipole -end part Shrinking cyilinder

Courtesy: L.Rossi



Courtesy: L.Rossi

Dipole -end part
Cu HXT



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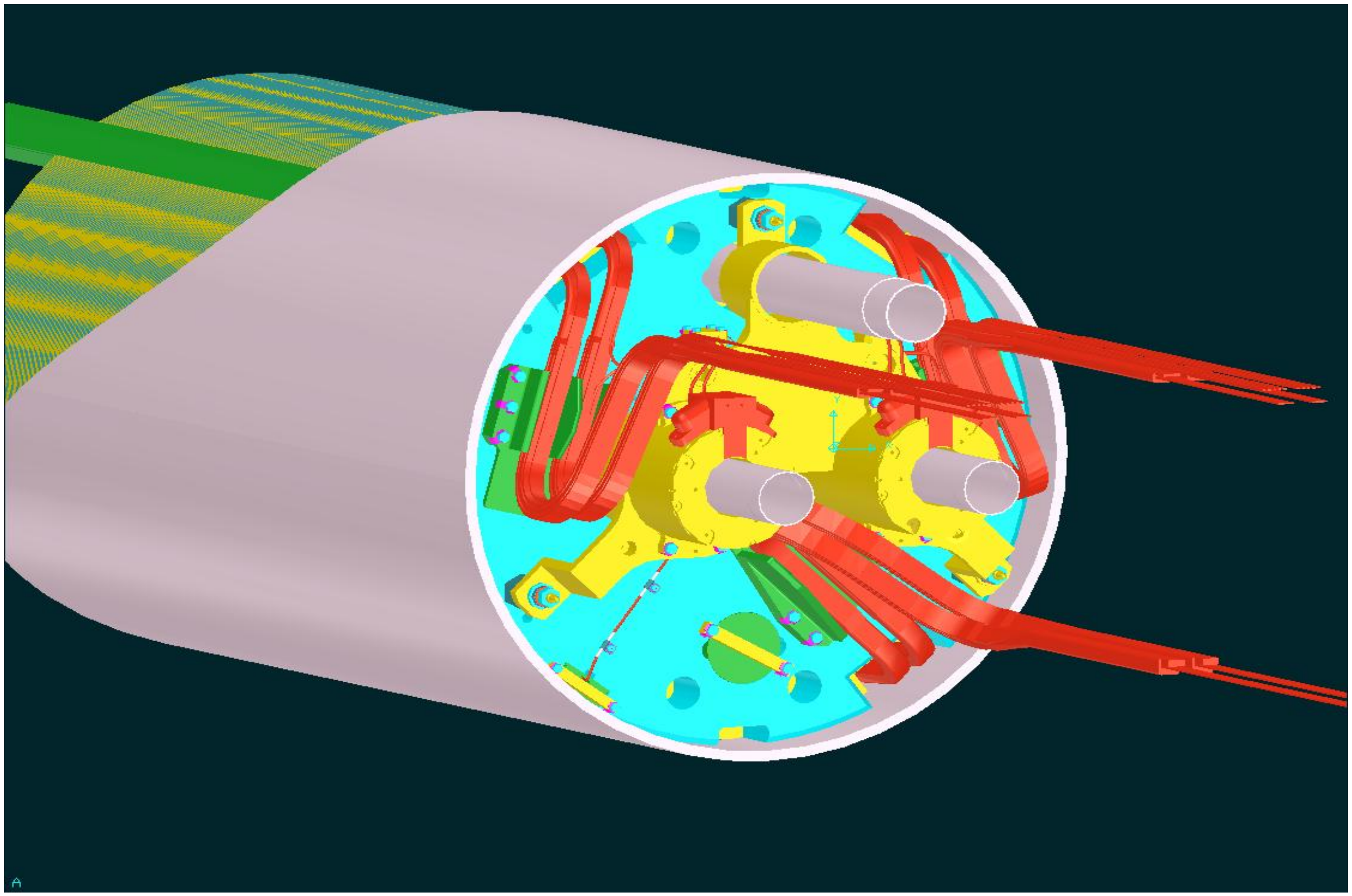
Courtesy: L.Rossi

Dipole -end part Corrector Magnets



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Dipole -end part
Cold foot, Bellows and N-line

Courtesy: L.Rossi