Usage of DSP and in large scale power converter installations (LHC)*

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Seminar prepared for the
CAS on Digital Signal Processing

Sigtuna (Sweden), June 2007

A CERN power converter is everybody else's power supply

Contents

- The main features of the LHC
- One of the problems of the LHC:
  Persistent current decays and « Snapback » of the multi-pole components of the magnetic field
- The specifications of the power converters
- The solution
  - hardware
  - software, the control algorithm

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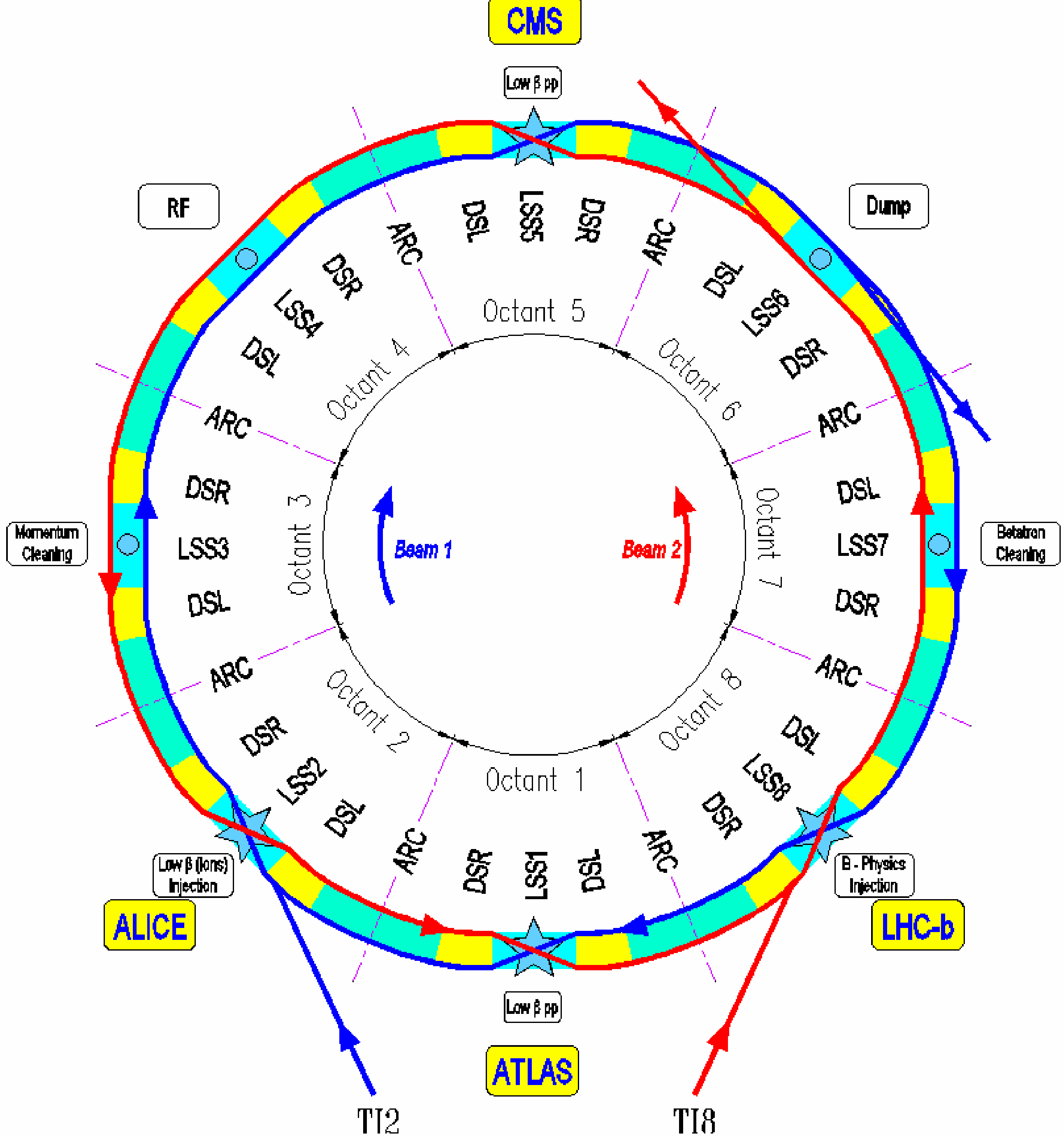
Key features of the LHC

We want to produce high luminosity at high energy so we can discover the Higgs, supersymmetry and other exciting stuff.

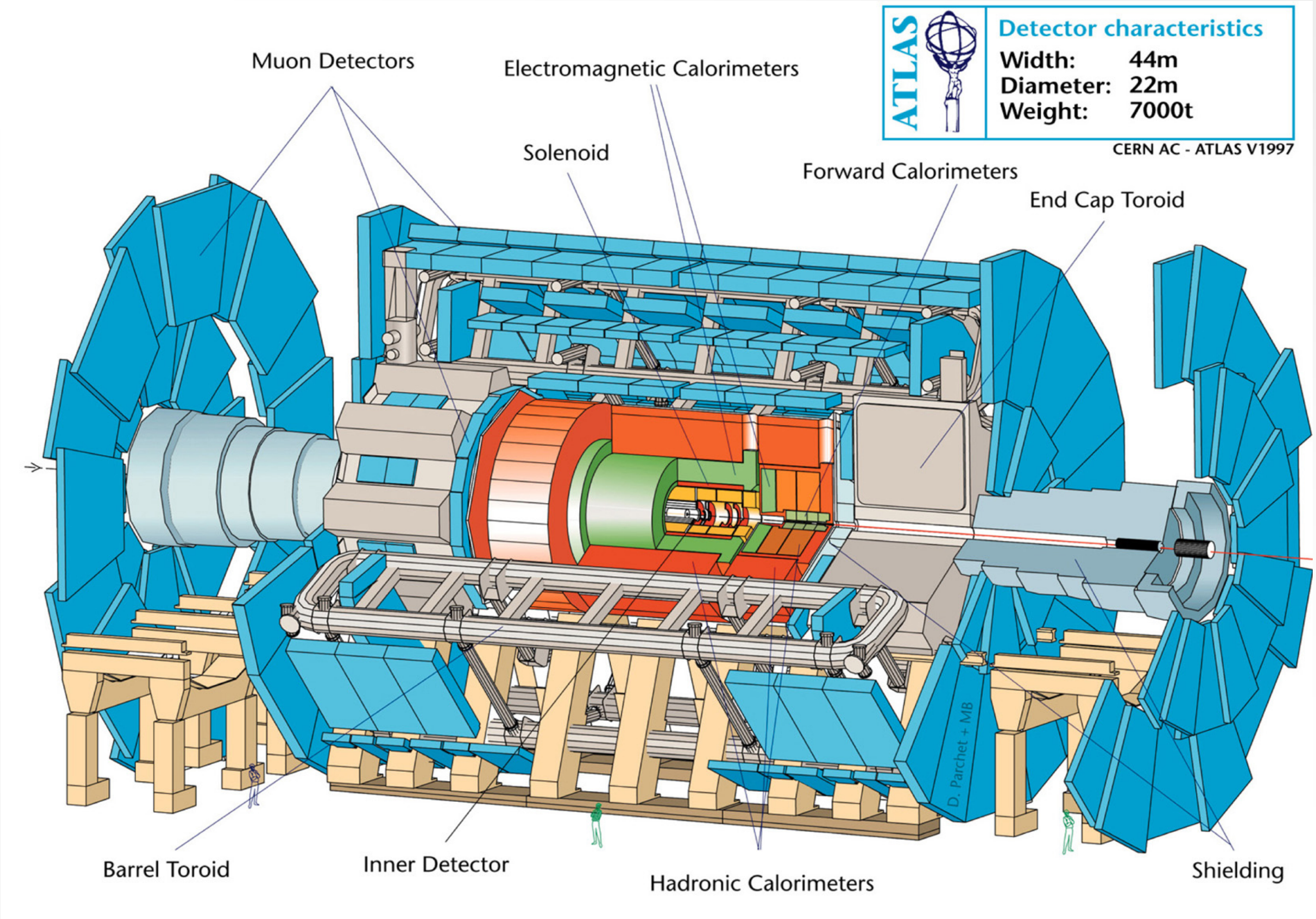
- **Protons and Ions**
- **450 GeV to 7 TeV: SPS is already there**
- **High luminosity:**
  - **Many bunches: 2808 bunches per beam**
  - **High beam currents**
  - **Small beam size at the interaction points**
- **Two rings:**
  - **Got to keep the beam apart**
  - **2 in 1 dipole design**
- **LEP tunnel: might as well use that $\rightarrow$ B $\approx$ 8.4 T**
- **High field: Superconducting magnets for the most part with dipoles and lattice quadrupoles working at 1.9 K – superfluid helium (30 kTons cold mass; 90 Tons of Helium)**

- **Two high luminosity experiments**
- **Two more specialised experiments (Ions and b physics) – lower luminosity**



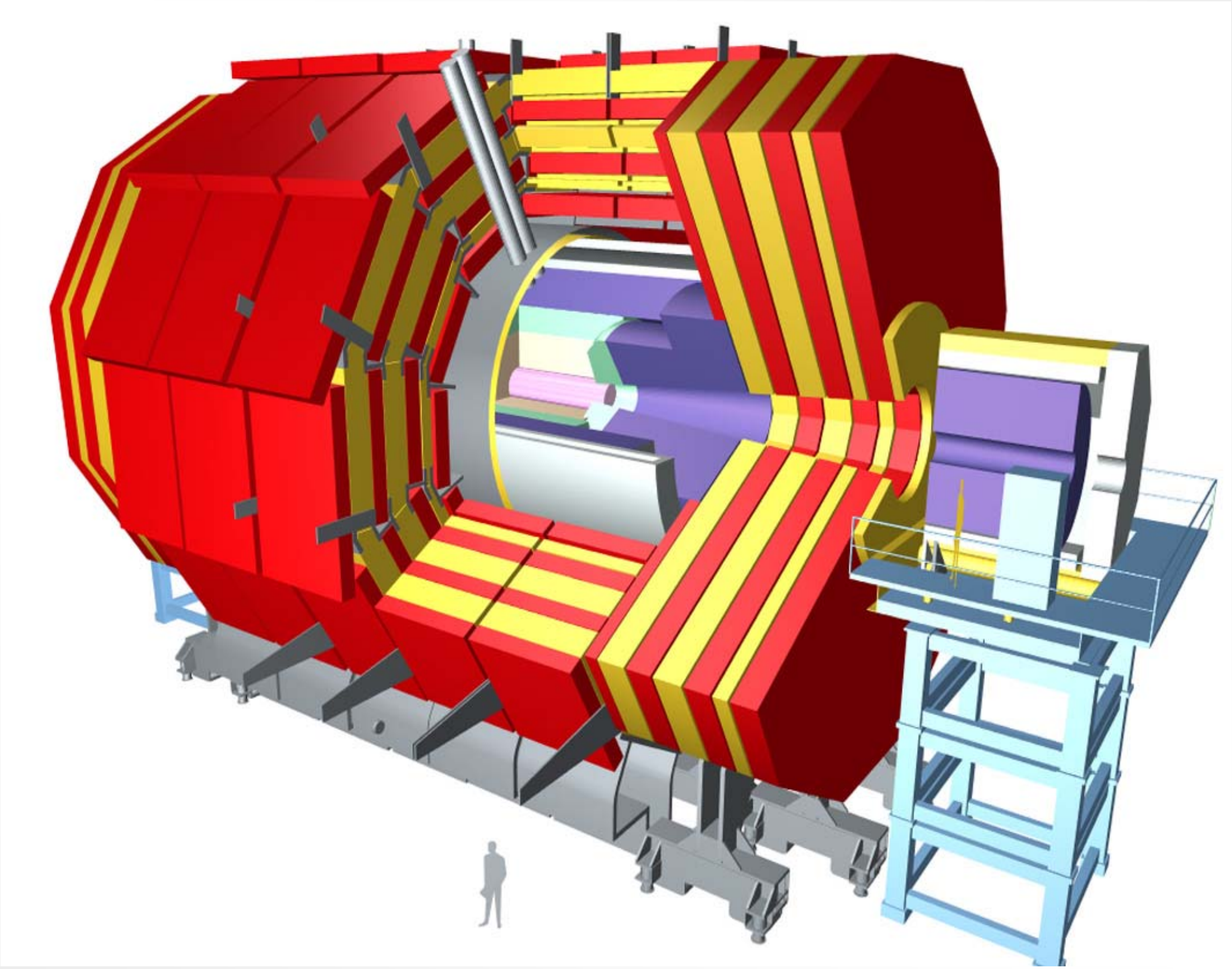
LSS1	DSr	ARC	DSl	LSS2	DSr	ARC	DSl	LSS3	DSr	ARC	DSl	LSS4	DSr	ARC	DSl	LSS5	DSr	ARC	DSl	LSS6	DSr	ARC	DSl	LSS7	DSr	ARC	DSl	LSS8	

Atlas

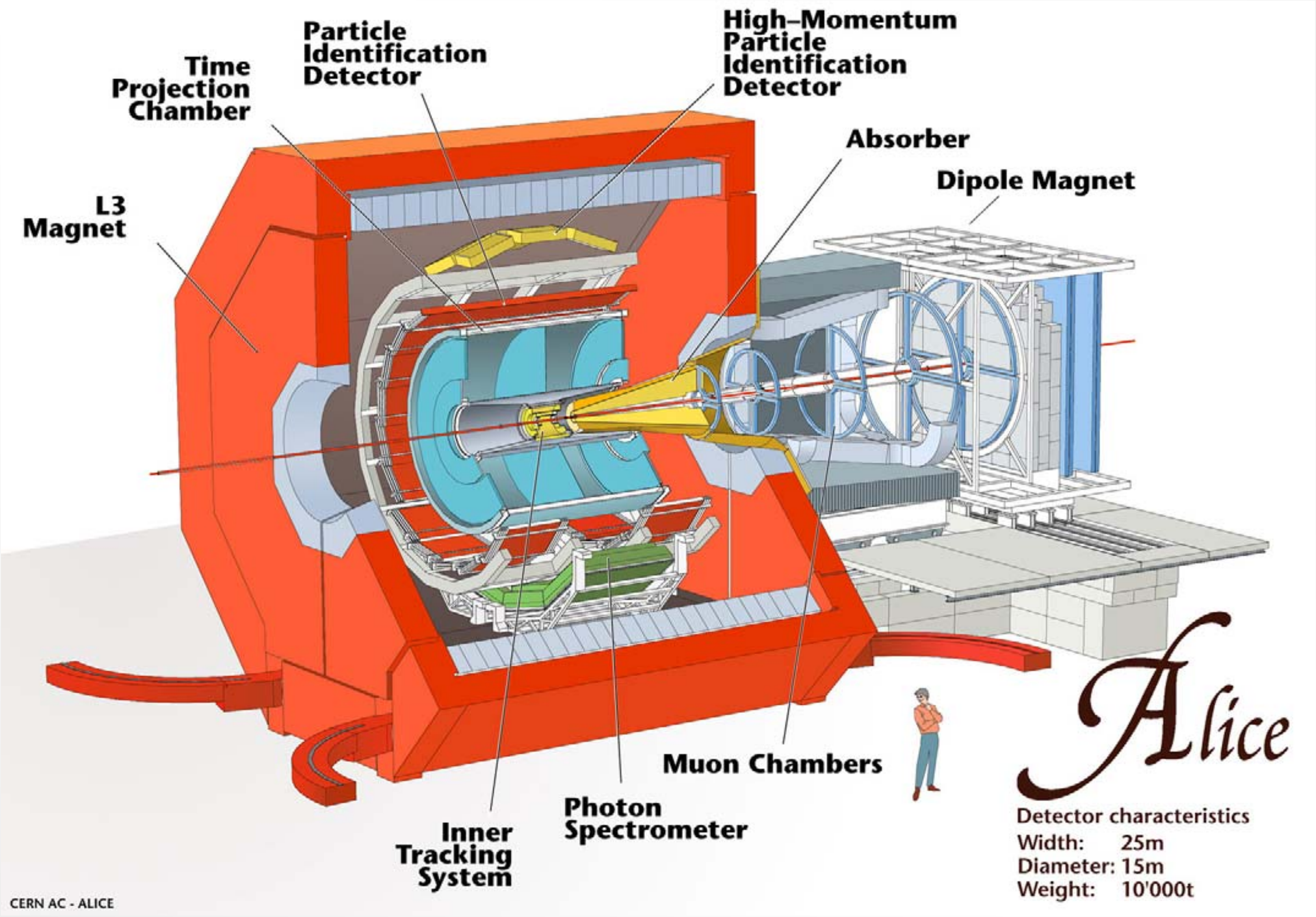


Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
ATLAS
CERN AC - ATLAS V1997
D. Parchet + MB
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding

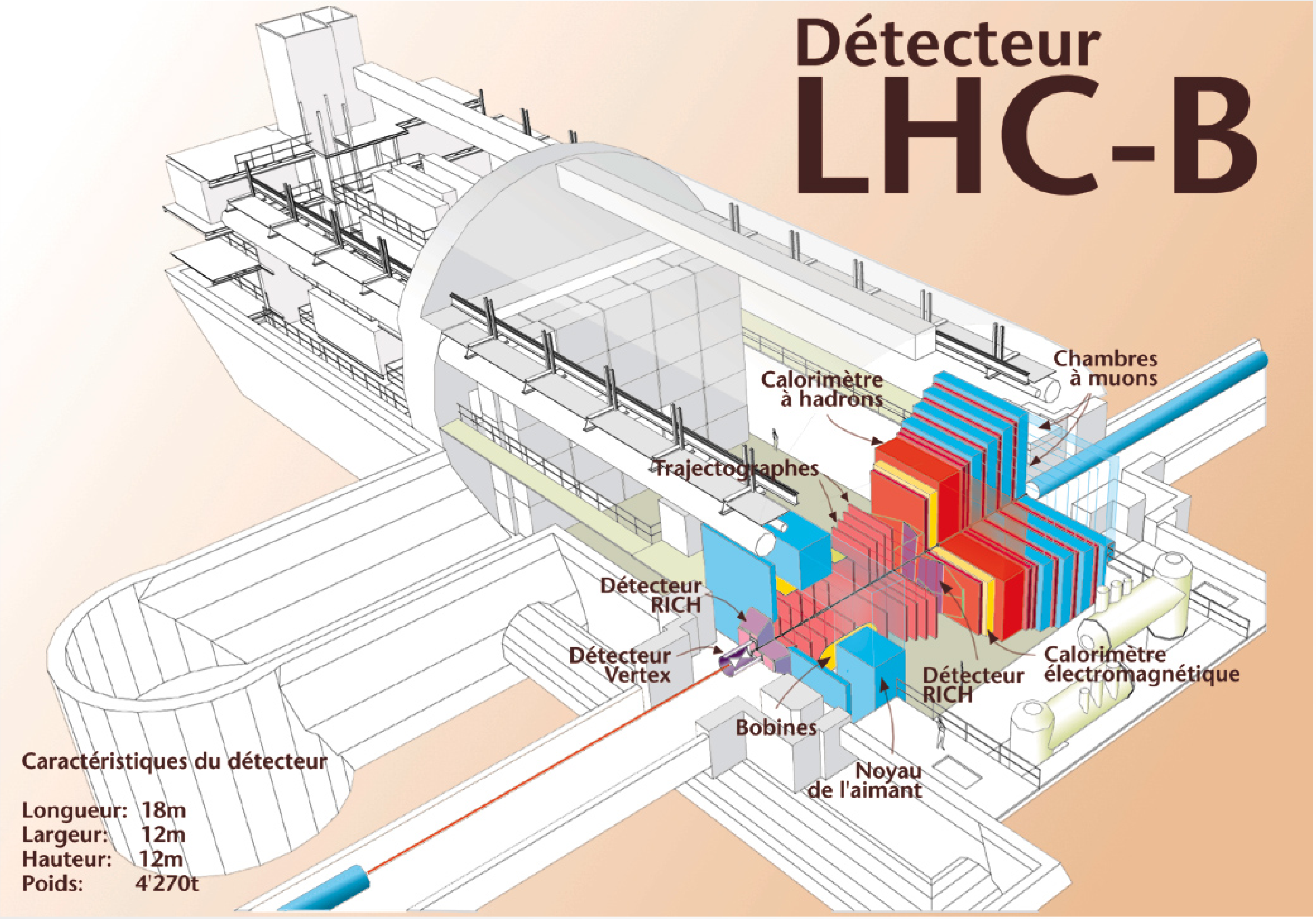
CMS



Alice


Particle
Identification
Detector
Time
Projection
Chamber
High–Momentum
Particle
Identification
Detector
Absorber
Dipole Magnet
L3
Magnet
Muon Chambers
Photon
Spectrometer
Inner
Tracking
System
CERN AC - ALICE
Alice
Detector characteristics
Width: 25m
Diameter: 15m
Weight: 10'000t

LHCb



Détecteur
LHC-B
Chambres
à muons
Calorimètre
à hadrons
Trajectographes
Détecteur
RICH
Détecteur
Vertex
Bobines
Noyau
de l'aimant
Détecteur
RICH
Calorimètre
électromagnétique
Caractéristiques du détecteur
Longueur: 18m
Largeur: 12m
Hauteur: 12m
Poids: 4'270t

7 TeV beam in the LEP tunnel (100 GeV)

$$B\rho = \frac{mv}{e} = \frac{p}{e}$$

$$\frac{1}{\rho} = \frac{eB}{p} = \frac{0.2998 \times B[T]}{p[GeV/c]}$$

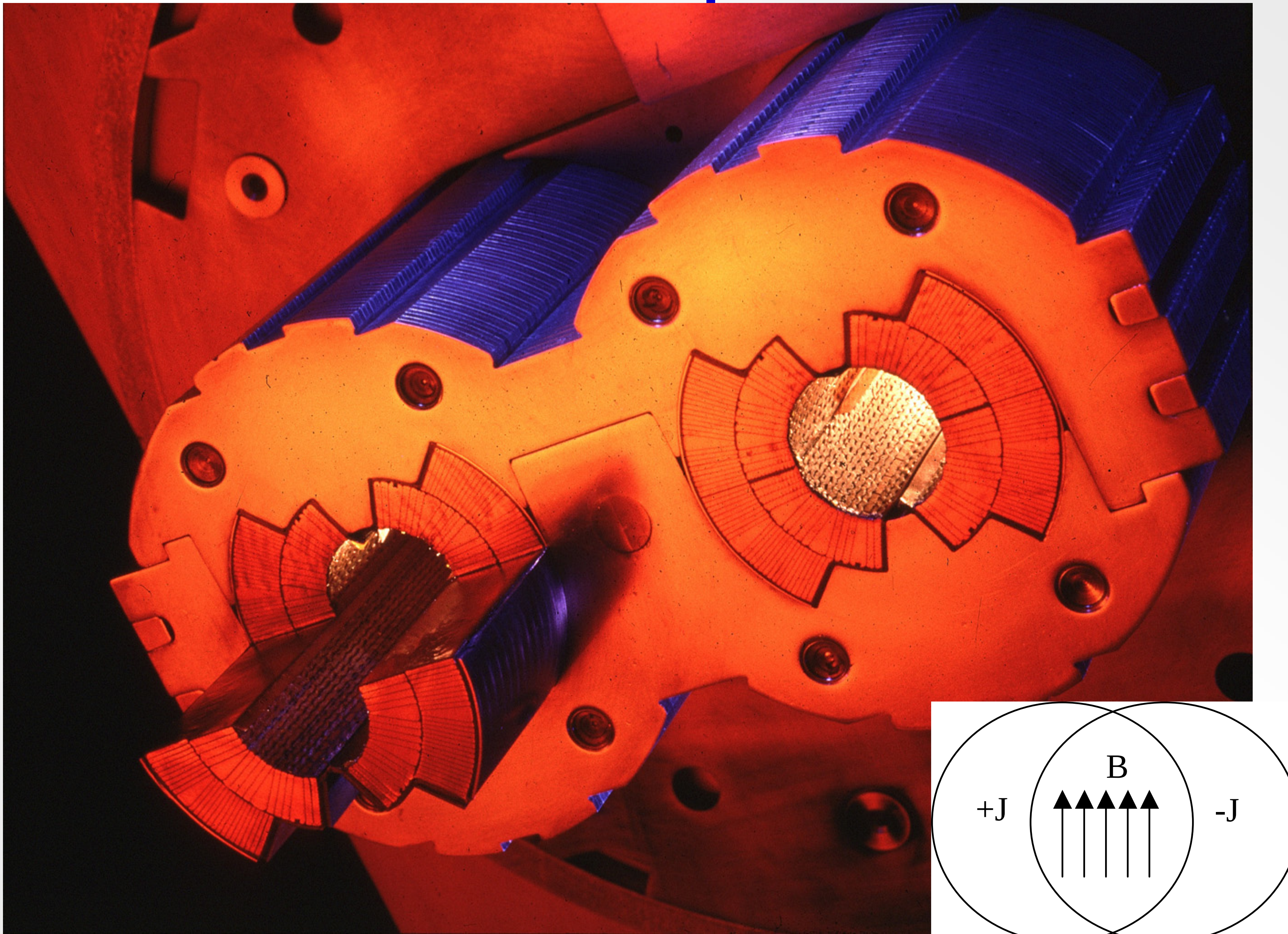
1232 magnets to get us round in a circle

$$\theta = \frac{l}{\rho} = \frac{2\pi}{1232} = 5.1 \times 10^{-3}$$

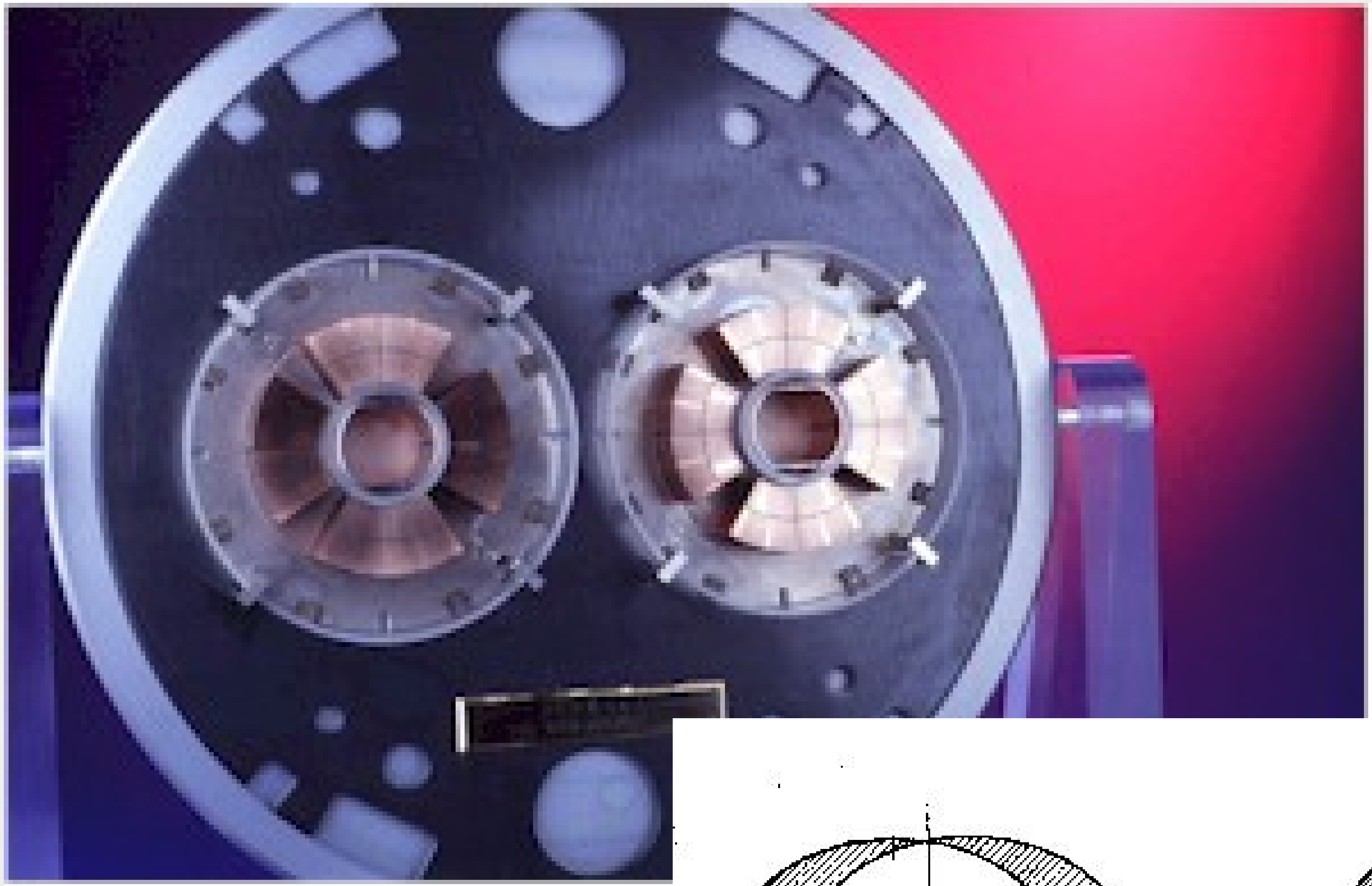
$$B[T] = \frac{\theta \times p[GeV/c]}{l \times 0.2998} = \frac{5.1 \times 10^{-3} \times 7000}{14.3 \times 0.2998} = 8.33T$$

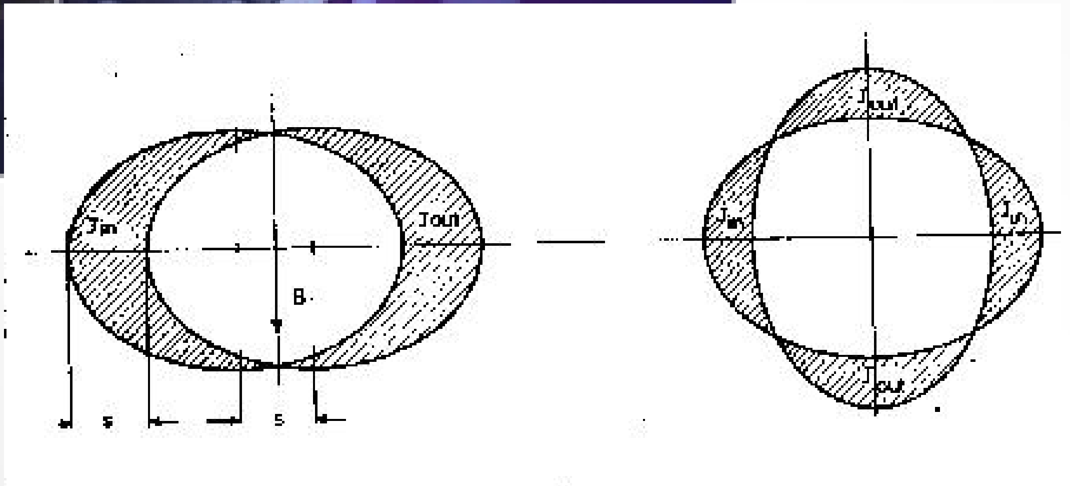
Needs superconducting magnets

LHC - dipole



LHC - quadrupole





Two intersecting ellipses, rotated by 90°, generate a perfect quadrupole fields

Corrector Circuits

Name	Quantity	Purpose
MSCB	376	Combined chromaticity/ closed orbit correctors
MCS	2464	Dipole spool sextupole for persistent currents at injection
MCDO	1232	Dipole spool octupole/decapole for persistent currents
MO	336	Landau octupole for instability control
MQT	256	Trim quad for lattice correction
MCB	266	Orbit correction dipoles
MQM	100	Dispersion suppressor quadrupoles
MQY	20	Enlarged aperture quadrupoles

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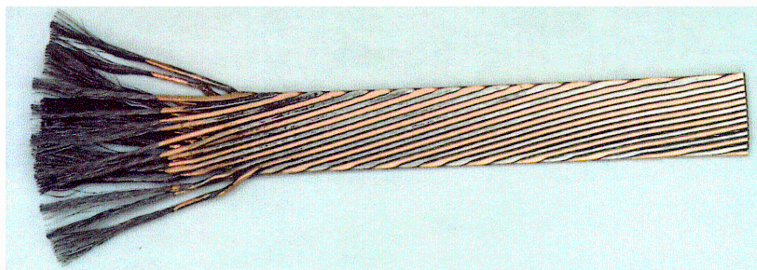
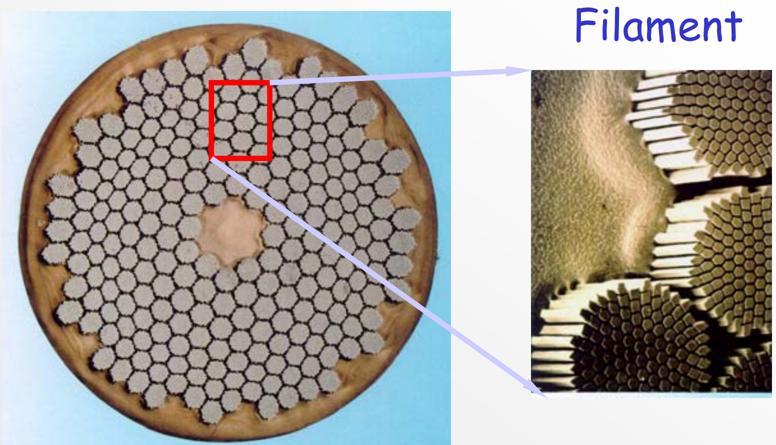
In order to generate 8,33 T in the dipoles, about 11.000 Amperes have to flow in the superconducting cable

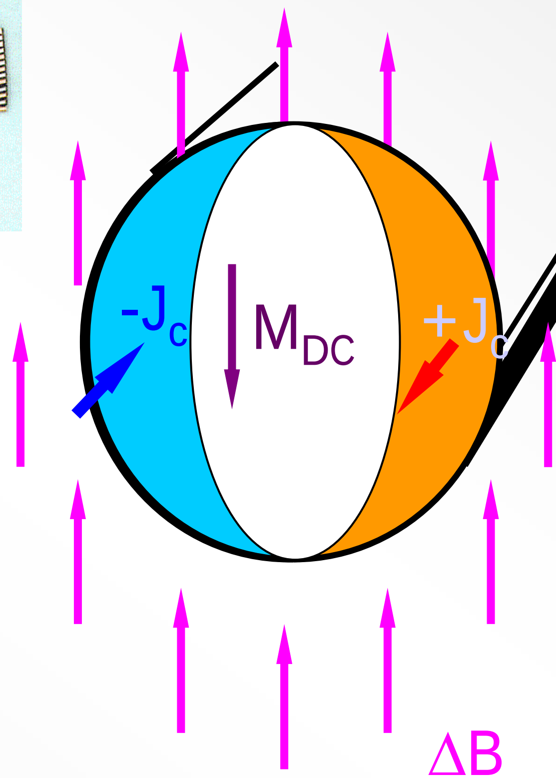
Cable



Strand

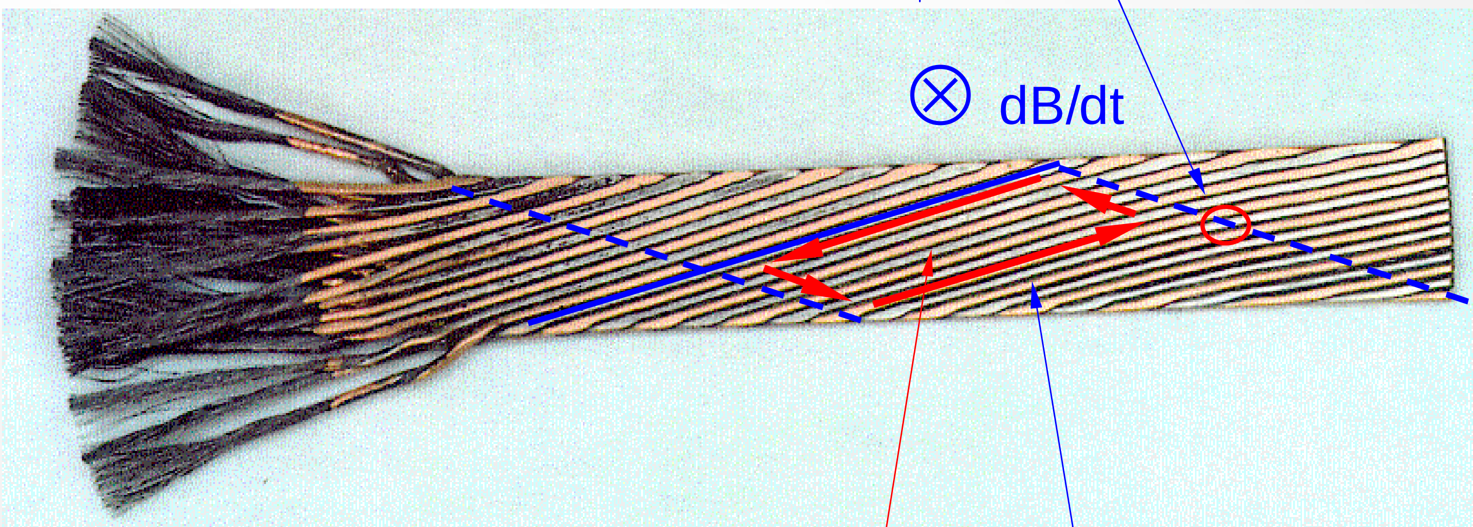
Filament





Eddy Currents

resistive contact R_c
at cross-over point

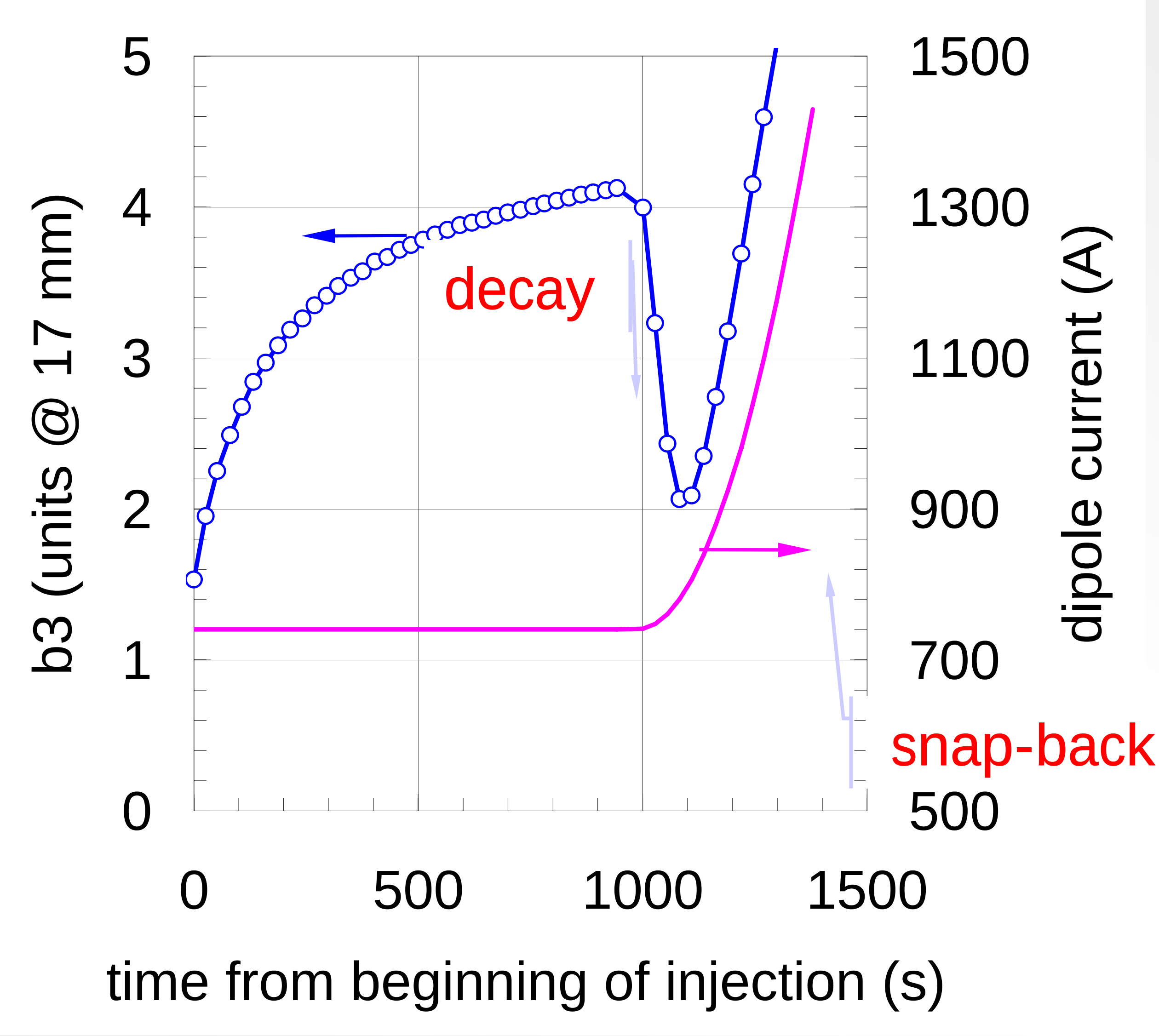


superconducting
path in the strands

induced eddy currents in the loop
$I \propto -dB/dt$ and $I \propto 1/R_c$

Courtesy of L. Bottura - CERN

Snapback



5
4
3
2
1
0
1500
1300
1100
900
700
500
b3 (units @ 17 mm)
dipole current (A)
decay
snap-back
0
500
1000
1500
time from beginning of injection (s)

Effect of Snap-back in LHC

- An uncorrected snap-back (of the expected magnitude) will cause in LHC:

$\Delta b_1(\mathrm{MB})=2.6 \rightarrow \Delta Q = 0.026$ vs. 0.003

$\Delta b_2(\mathrm{MQ})=1.7 \rightarrow \Delta Q = 5.4\ 10^{-3}\ \Delta b_2 = 0.009$ vs. 0.003

$\Delta b_3(\mathrm{MB})=3.3 \rightarrow \Delta \xi = 52\ \Delta b_3 = 172$ vs. 1

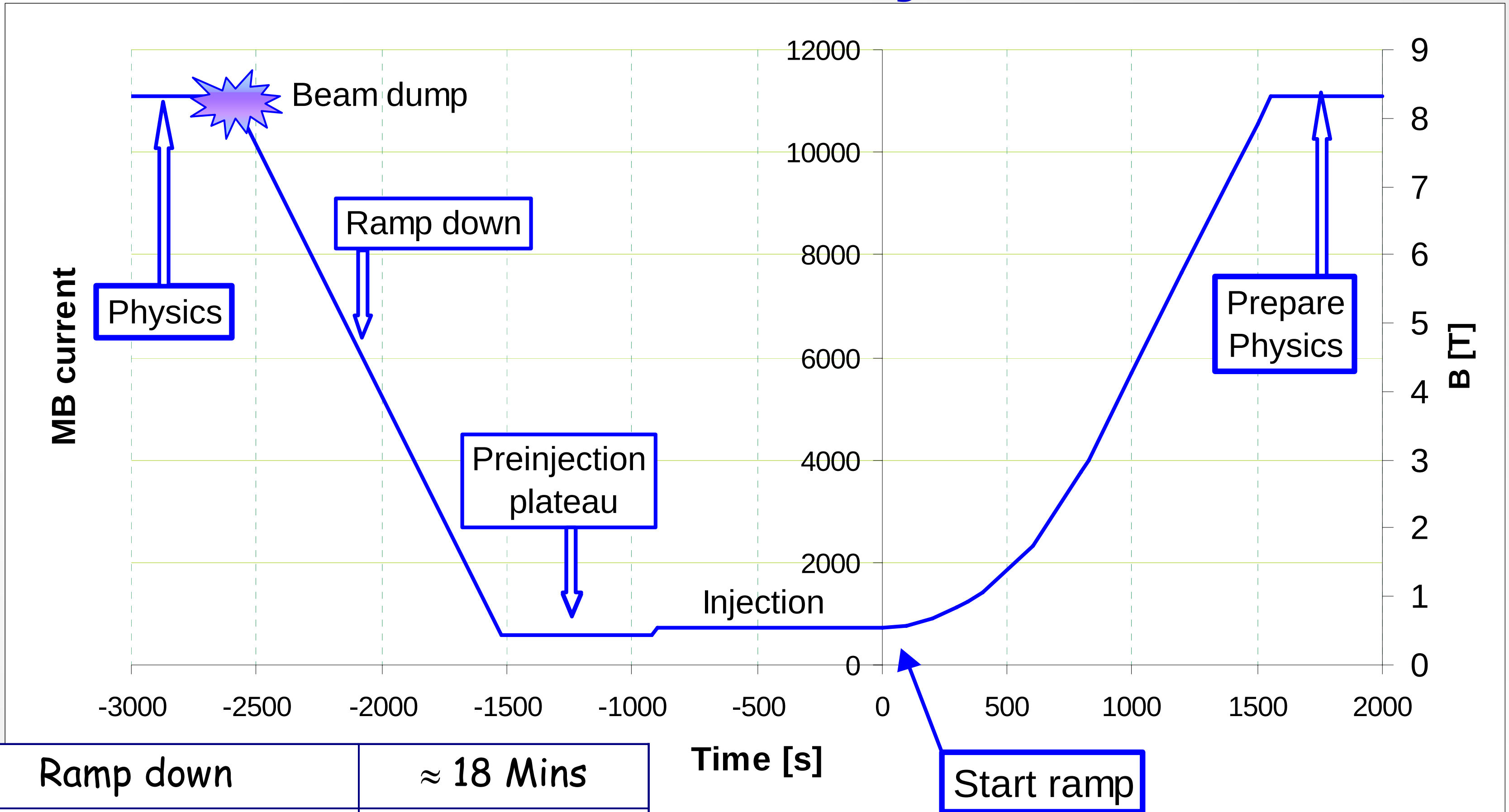
Value vs. tolerance

(source: O. Bruening, CERN)

Dynamic Effects problem

- **Decay of persistent currents & snap-back**
  - **large variations in multipole errors**
  - **unacceptable effect on key beam parameters**
- **Strong dependence on magnetic history**
- **Strategy:**
  - **Reproducibility**
    - well defined operational cycle
    - full recycle in case of problems
    - feed-forward of experience
  - **Multipole factory:**
    - magnetic measurements
    - models of multipole behaviour which can take into account powering history
    - on-line magnetic measurements
  - **Feedback on beam based measurements**

Baseline cycle



Ramp down	≈ 18 Mins
Pre-Injection Plateau	15 Mins
Injection	≈ 15 Mins
Ramp	≈ 28 Mins
Squeeze	< 5 Mins
Prepare Physics	≈ 10 Mins
Physics	10 - 20 Hrs

In the normal operations the LHC will perform a standard cycle which will be more-or-less set in stone.

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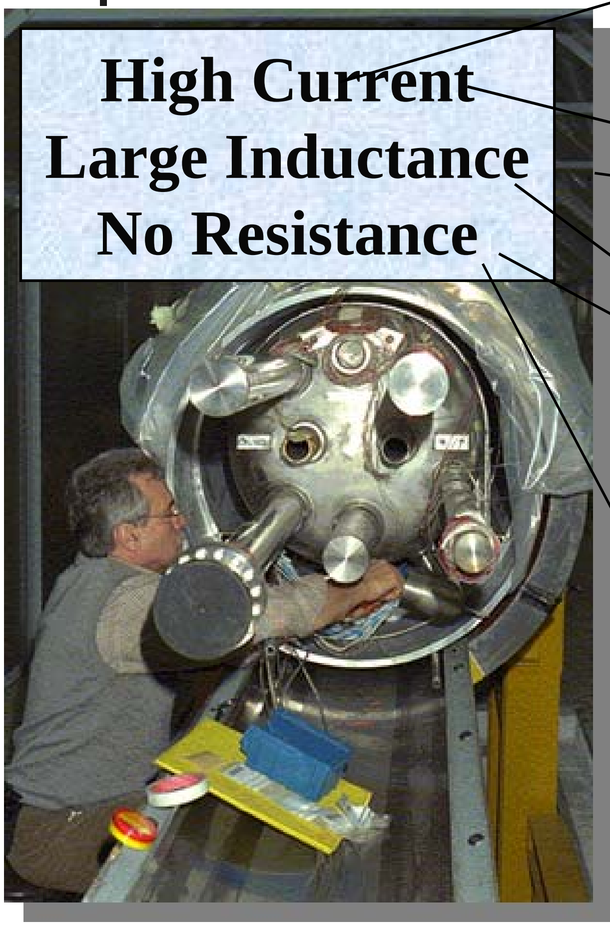
What's special about Powering Superconducting Magnets ?



High Current
Large Inductance
No Resistance

Need heavy warm cabling

- Need to be near to feed point

Difficult and expensive power converter output stage

Large Stored Energy, $\frac{1}{2} LI^2$

- Need to handle carefully!

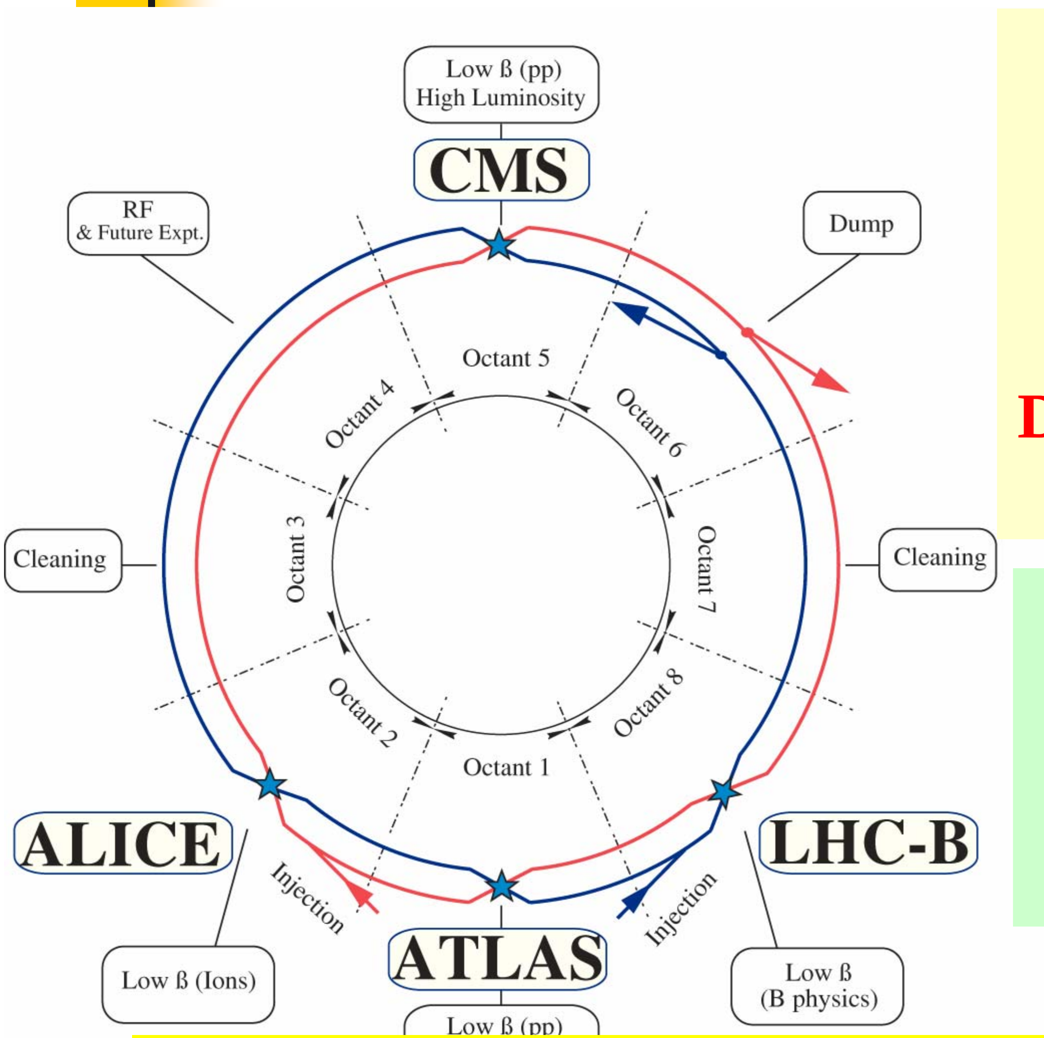
Large Time Constant, L/R

- Boost voltages (high voltage only during the ramps)
- Difficult control loops

Tendency to quench

- Need to take special precautions (energy)

LHC : 1232 SC Main Dipole magnets



Magnet inductance :
L = 108 mH

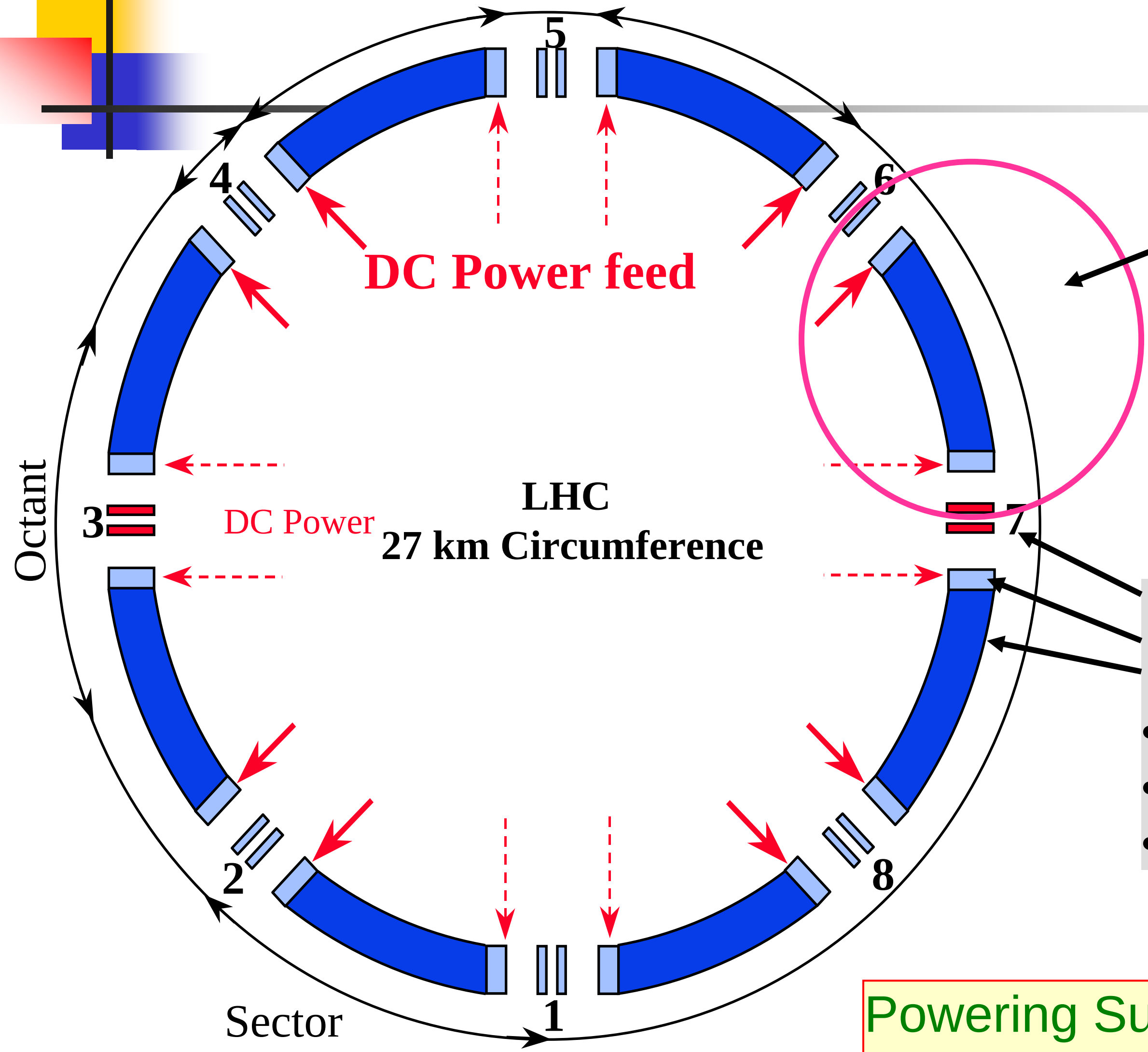
L_{total}=1232 * 0.108 = 133 H
Ramp: LdI/dt = 1330V
Discharge (quench; 120 A/s): ≅ 16kV

Nominal current 11.8 kA
Stored Energy = 9.3 GJ

Ultimate current = 13kA
Stored Energy = 11.3 GJ

One circuit or several circuits ?

LHC Powering in 8 Sectors



Powering Sector:

154 dipole magnets
about 50 quadrupoles
total length of 2.9 km

Powering Subsectors:

- long arc cryostats
- triplet cryostats
- cryostats in matching section

Powering Subsectors allow for progressive Hardware Commissioning - 2 years before beam

Power Converter Tolerances for LHC

Circuit Type	Nominal Current (A)	Current Polarity	One Year Accuracy (ppm of Inominal)	One day Reproducibility (ppm of Inominal)	1/2 hour Stability (ppm of Inominal)	Resolution (ppm of Inominal)
Main Bends, Main Quads	13000	Unipolar	± 50 ± 20 with calibration	± 5	± 3	1
Inner triplet	8000/ 6000	Unipolar	± 70 ± 20 with calibration	± 10	± 5	1
Dispersion suppressor	6000	Unipolar	± 70	± 10	± 5	15
Insertion quadrupoles	6000	Unipolar	± 70	± 10	± 5	15
Separators (D1,D2,D3,D4)	6000	Unipolar	± 70	± 10	± 5	15
Trim quadrupoles	600	Bipolar	± 200	± 50	± 10	30
SSS correctors	600	Bipolar	± 200	± 50	± 10	30
Spool pieces	600	Bipolar	± 200	± 50	± 10	30
Orbit correctors	120/60	Bipolar	± 1000	± 100	± 50	30

Precision

Control

LHC Power Converters

PC-V 6·4 : General Information

Last_modif 24/3/2003

Optics version Type	Eq.Code	Current kA	Voltage: Steady V	Voltage: Boost V	Voltage: Peak V		Module: I mod kA	Module: I tot kA	Mains Input: Peak kW	Mains Input: Peak kVA	Losses: Water kW	Losses: Air kW	Dimensions: Length m	Dimensions: Depth m	Dimensions: Height m	Equiv. No. Racks	Provisional Quantity
6·4 01	RPTE	13.000	10	±180	190			16.250	2680.6	3540.0	157.9	52.6	10.8	1.8	2.0	36.00	8
6·4 02	RPHE	13.000	13	±5	18				264.9	288.0	27.8	3.1	4.2	0.9	2.0	7.00	16
6·4 03	RPHF	8.000	6	±2	8				78.2	85.0	12.8	1.4	3.0	0.9	2.0	5.00	20
6·4 04	RPHG	6.000	6	±2	8				58.7	63.8	9.6	1.1	2.4	0.9	2.0	4.00	132
6·4 05	RPHH	4.000	6	±2	8				39.1	42.5	6.4	0.7	2.4	0.9	2.0	4.00	40
6·4 10	RPMB	0.600	±8	±2	10					9.1	2.1	0.2	0.6	0.9	1.0	0.50	330
6·4 11	RPMC	0.600	±35														24
6·4 12	RPMB	0.600	8														70
6·4 13	RPMC	0.600	35														2
6·4 14	RPLB	0.120	±8														290
6·4 15	RPMC	0.120	±35														10
6·4 16	RPLA	0.060	±2														752
6·4 20	RPTL	0.650	160														3
6·4 21	RPTF	0.810	450														4
6·4 22	RPTG	0.810	950														4
6·4 23	RPTM	1.000	600														2
6·4 24	RPTI	6.500	950														2
6·4 25	RPTN	1.000	±180														3
6·4 30	RPTJ	20.000	±26														1
6·4 31	RPHK	20.500	18														1
6·4 32	RPTH	33.000	170	0													1
6·4 40	RPTK	0.040	100000	0	100000	1	0.040	0.040	4240.1	5300.9	180.1	60.0					4

Number of Converters: > 1700

Total Current :1860 kA

Steady State Input : 63 MW

Peak Input : 85 MVW

Underground volume ≅ 1700 m3

Surface volume ≅ 300 m3

Total Current required 1861 kA

Steady State Input 63018 kW

Peak Input 85906 kW

Total Number of PCs 1719

LHC Powering Challenges :

Performance :

-High current with high precision (accuracy, reproducibility, stability, resolution) and large dynamics
-current range (for 1-quadrant converter: from 1% to 100%)
- a lot of 4-quadrant converters (energy from magnets)
- tracking : ☹ Need to track from sector to sector
- voltage ripple and perturbation rejection

Installation (LEP infrastructure) and Operation:

- volume (a lot of converter shall be back-to-back)
- weight (difficult access) => modular approach
- Repairability and rapid exchange of different parts
- radiation for [±60A,±8V] converters
- losses extraction : high efficiency (>80%) , water cooling (90% of the losses)
- High reliability (MTBF > 100’000 h)
- EMC : very close to the others equipment ; system approach

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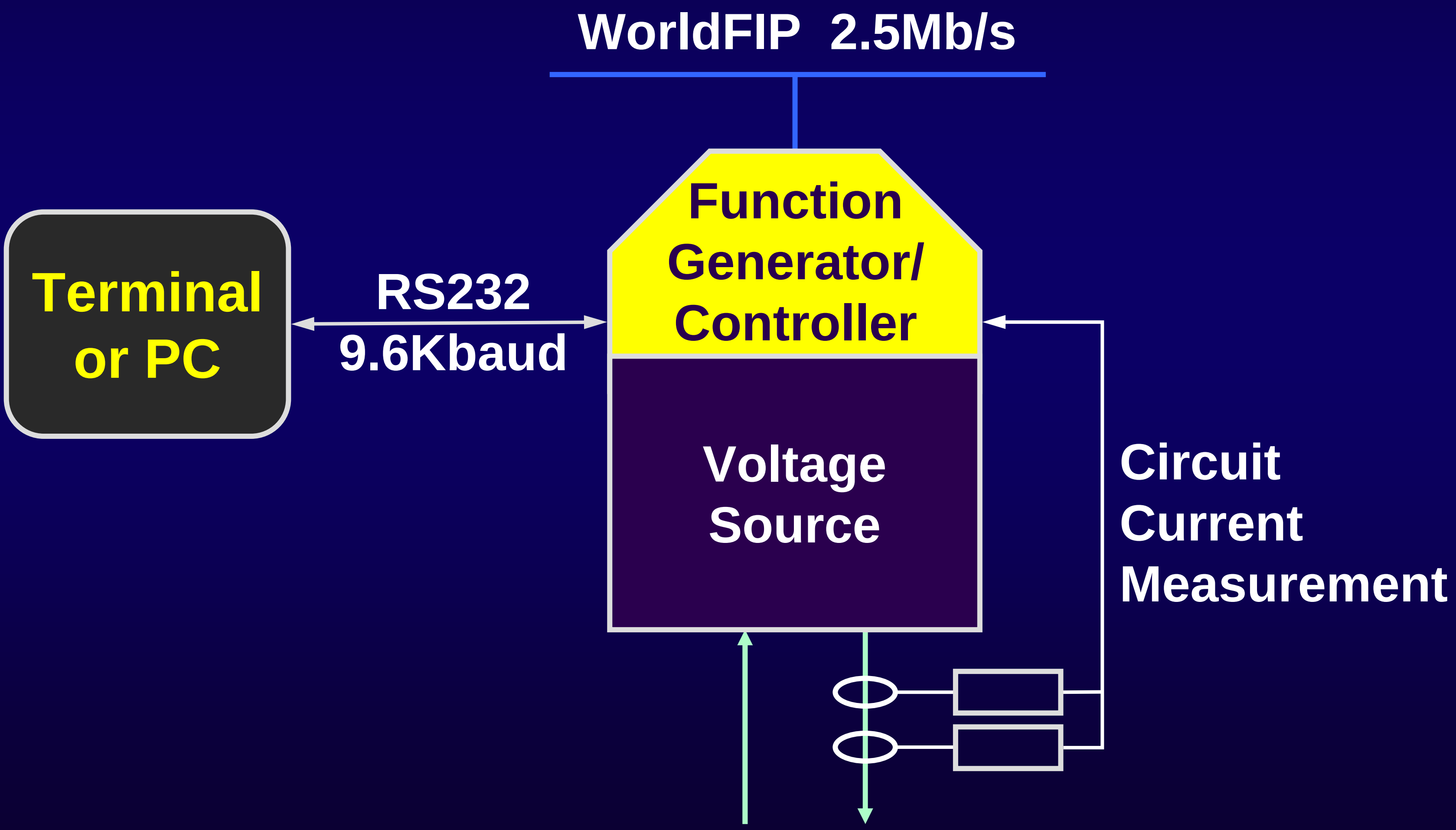
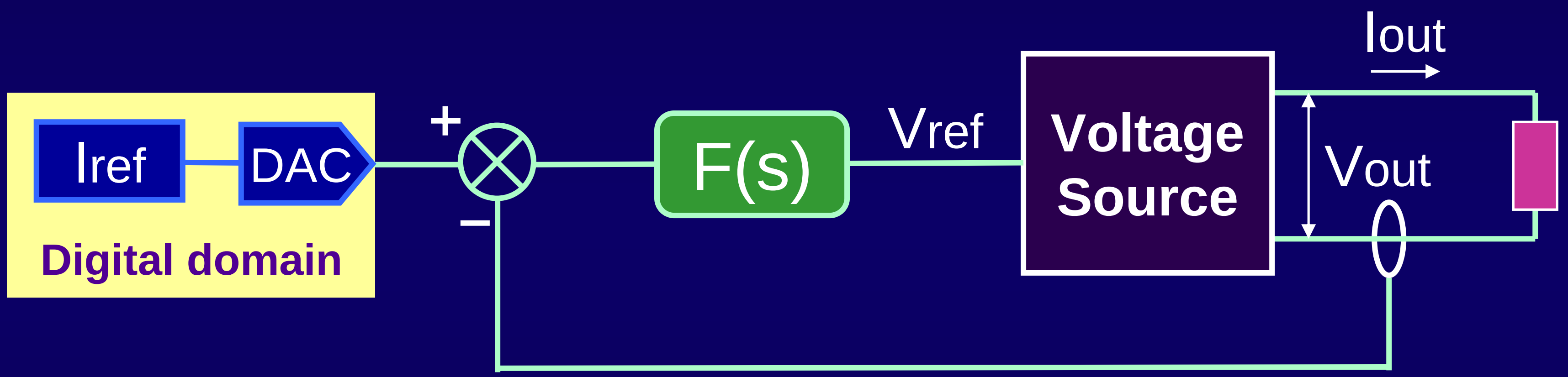
Overview – A Power Converter



Overview – Analogue Regulation

Traditional Method used for PS, SPS and LEP

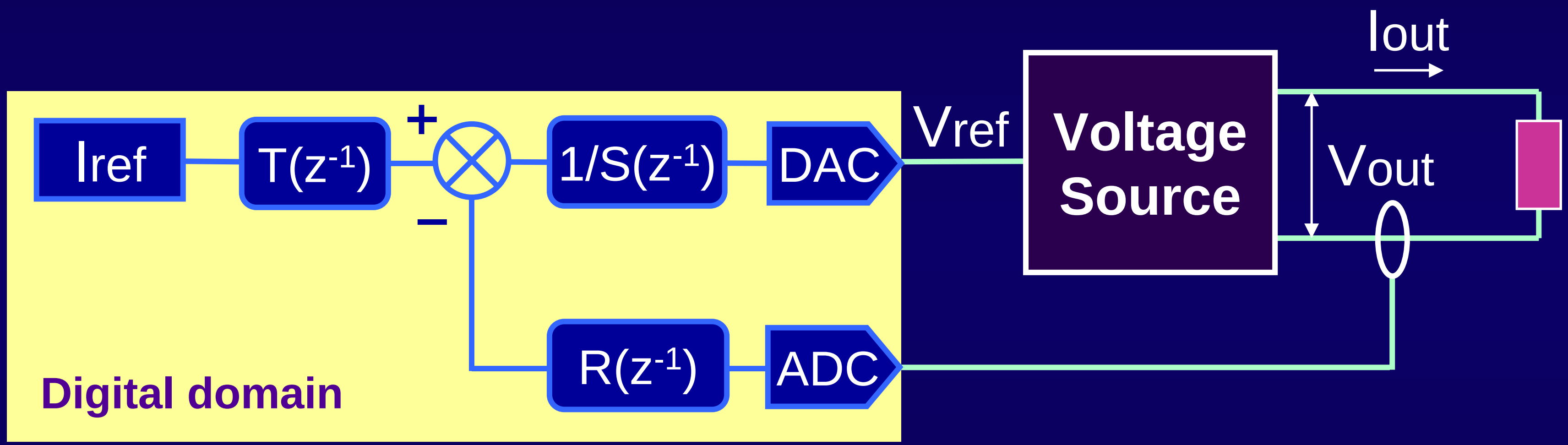


Traditional analogue regulation suffers from serious limitations:

- Inaccurate for very slow circuits (superconducting magnets)
- Simple analogue control suffers from dynamic errors
- Accuracy depends upon current transducer and DAC

Overview – Digital Regulation

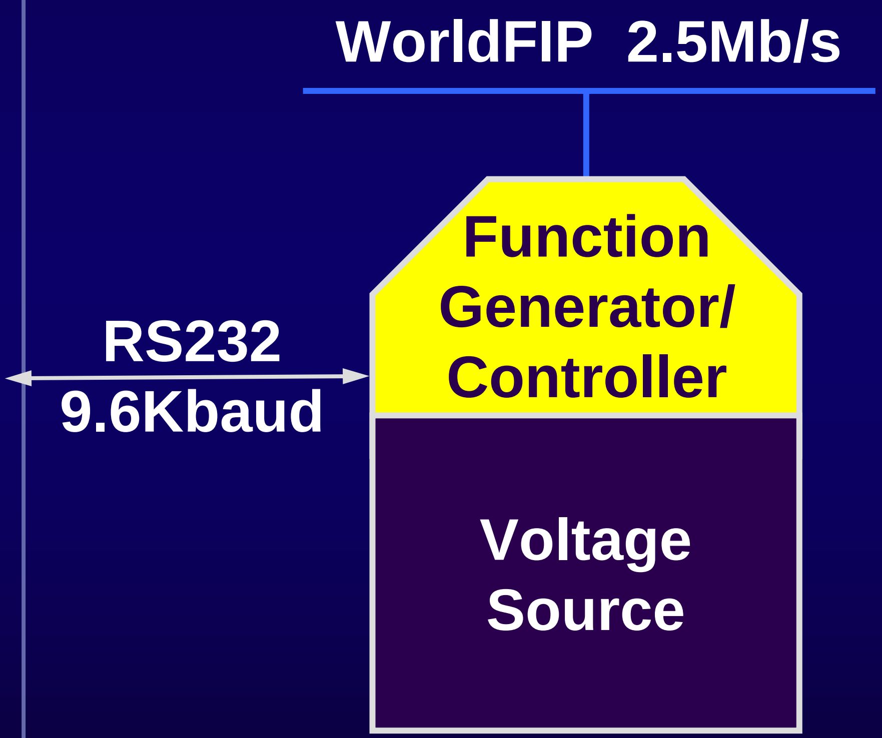
New method for LHC



Digital regulation has been chosen for LHC because:

- It accommodates all circuit time constants (0.1 – 20000 s)
- Advanced digital control algorithm can eliminate dynamic errors
- Accuracy depends “only” upon current transducer and ADC

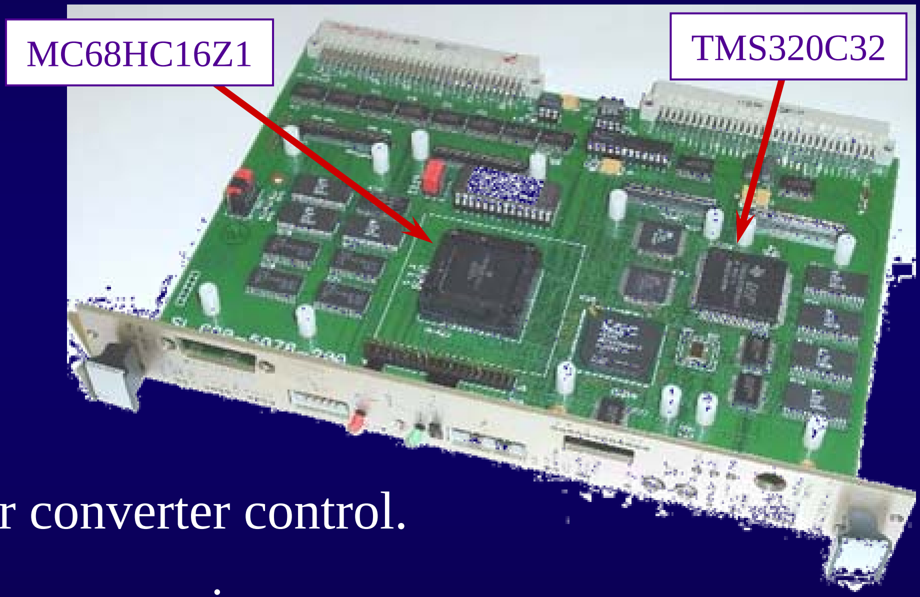
Controller Hardware Overview



- Twin Processor
  - 16 bit micro-controller (MC68HC16Z1 @ 16 MHz)
  - 32 bit floating point DSP (TMS320C32 @ 32 MHz)
- Radiation tolerance
  - Error detection and correction on all SRAM
  - Multiple watchdogs including power cycling

DSP Applications: LHC FGC

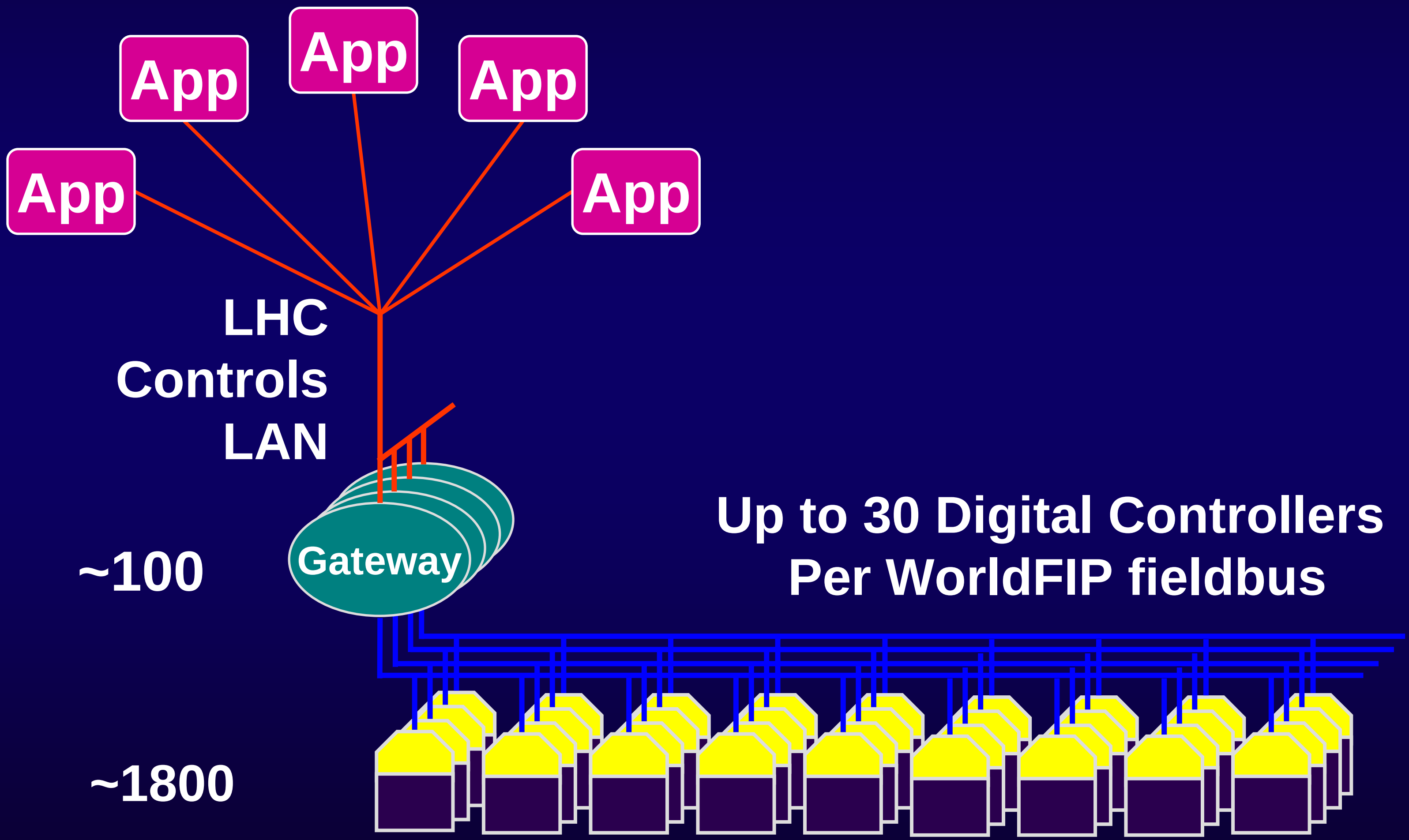
FGC designed and built by CERN; series production of ~2000 pieces



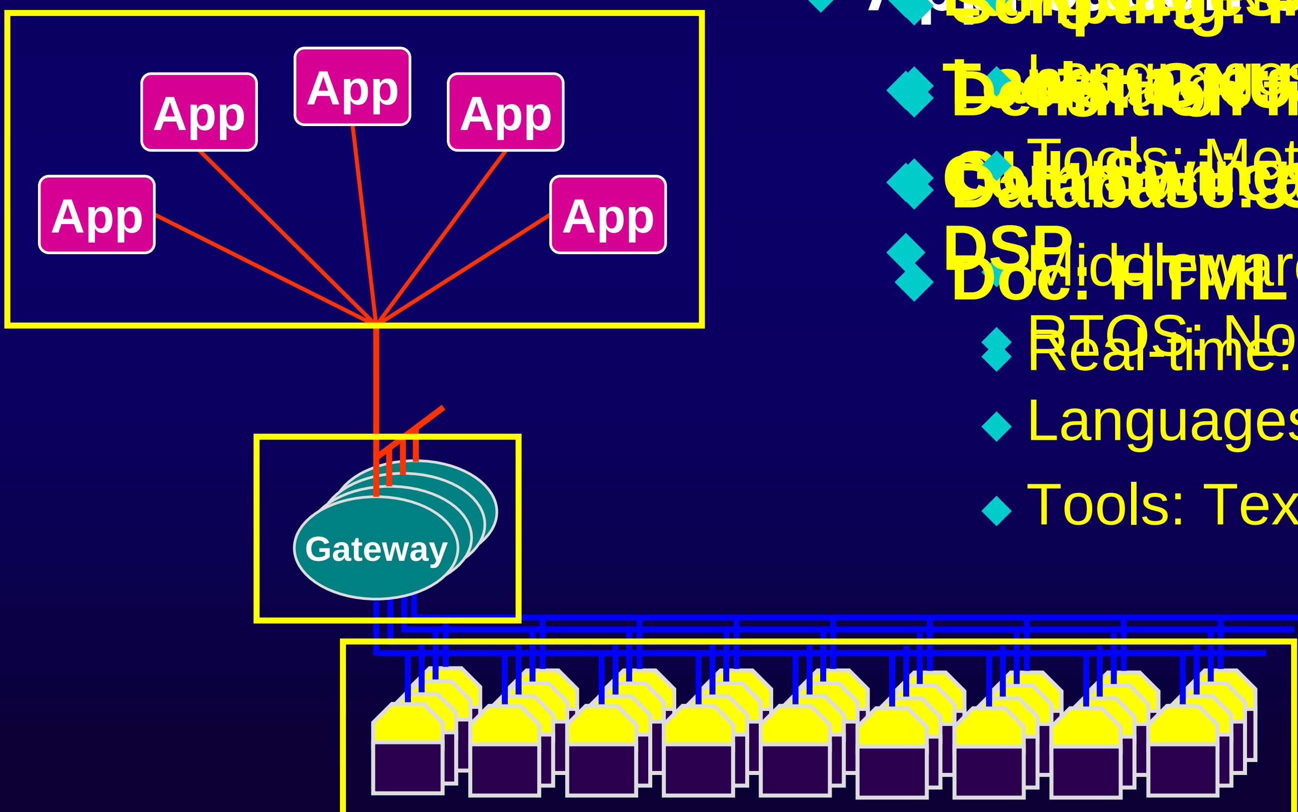
LHC Function Generator/ Controller project:

- 2000 units, mostly for power converter control.
- Motorola MC68HC16Z1 chosen a main processor.
- Significant floating point maths requirement.
- TI TMS320C32 DSP chosen as a co-processor.

Overview – System Architecture



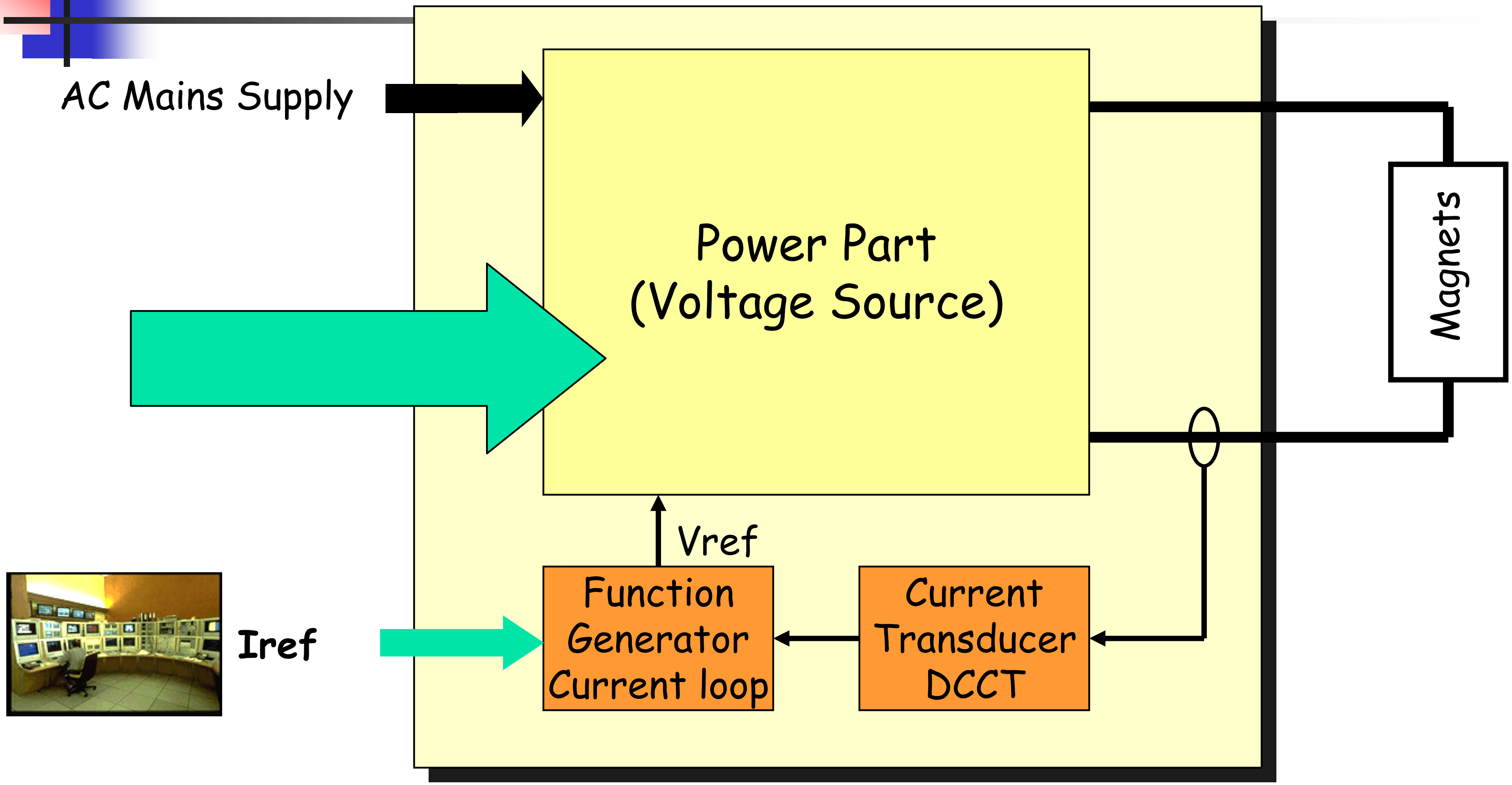
System Software Overview



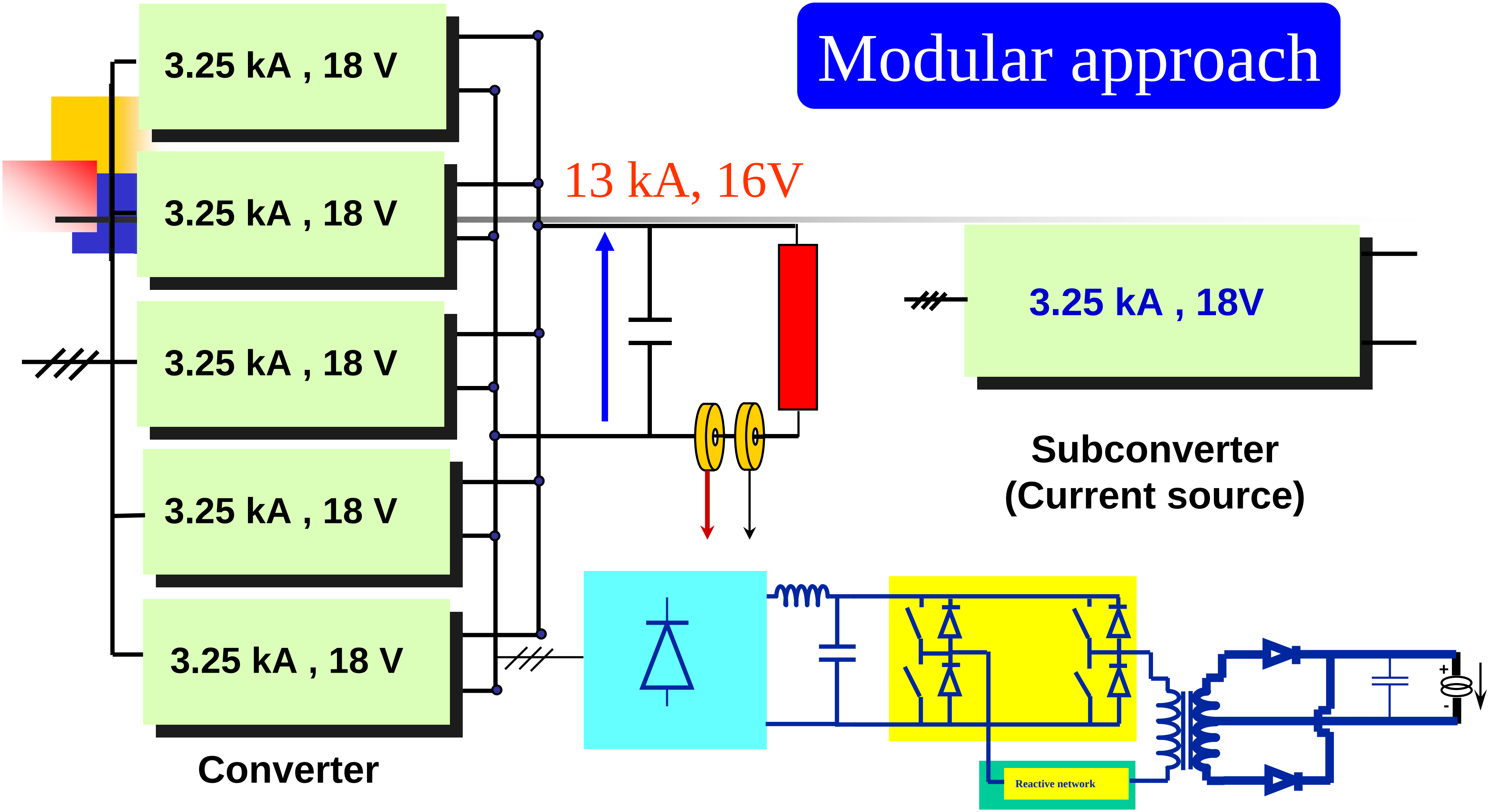
- Gateway Software
- Offline Software
- Application Software
  - Scripting: PERL
  - Definition files: XML
  - Database: ORACLE
  - GUI: Swing
  - Doc: HTML
  - Languages: C, Assembler
  - Tools: Metrowerks
  - Middleware: CORBA
  - Real-time: UDP
- DSP
  - RTOS: None
  - Languages: C, Assembler
  - Tools: Texas Instruments

- Now a closer look

  ……. at the system components


AC Mains Supply
Power Part
(Voltage Source)
Magnets
Vref
Iref
Function
Generator
Current loop
Current
Transducer
DCCT

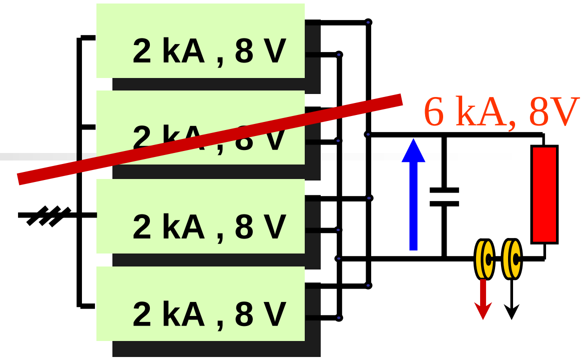
Modular approach

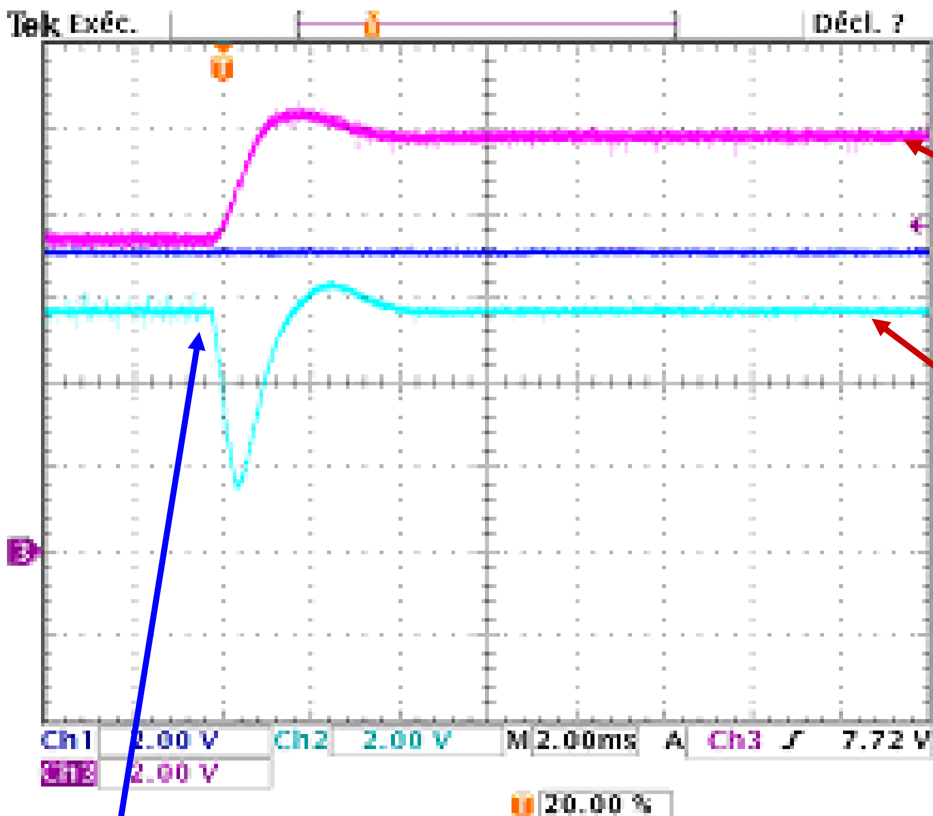


- n + 1 subconverters : redundancy, reliability
- repairability
- ease of handling underground
- versatility (6.5kA, 9.75kA, 13kA, 21 kA)

Converter Operation during a subconverter failure

Example: [6kA,8V] converter :
(3+1) x [2kA,8V] subconverters





Iout
(sub-converter) 200A/V

Vref

Vout (Converter)

ΔI < 10 ppm of Imax
on magnet(s) with L > 0.1 H

One subconverter failure

EMC : ELECTROMAGNETIC COMPATIBILITY

COMPATIBILITY : Emission - Immunity

IEC 61204 -3

Norms for the power converters :

Emission :

IEC 61204-3 (replaced IEC-60478-3)
(CISPR 11 ; EN 55011)

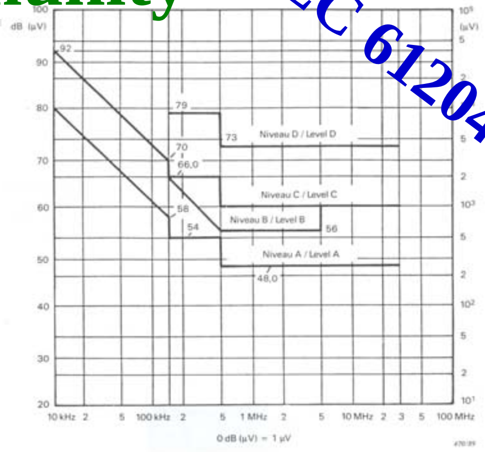
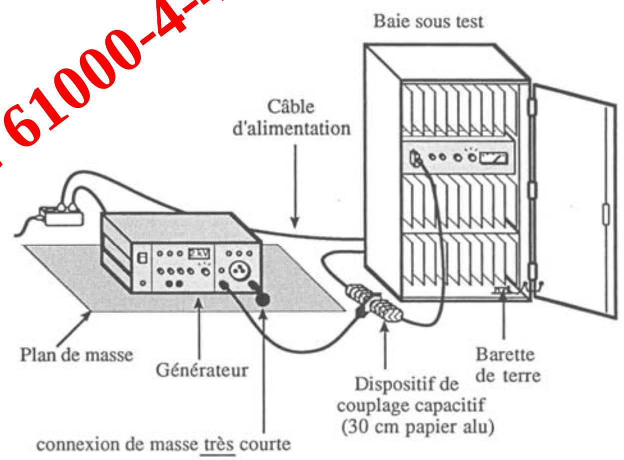


Figure 3 - Valeurs limites pour PEM par conduction
Limit values for conducted EMI

Immunity :

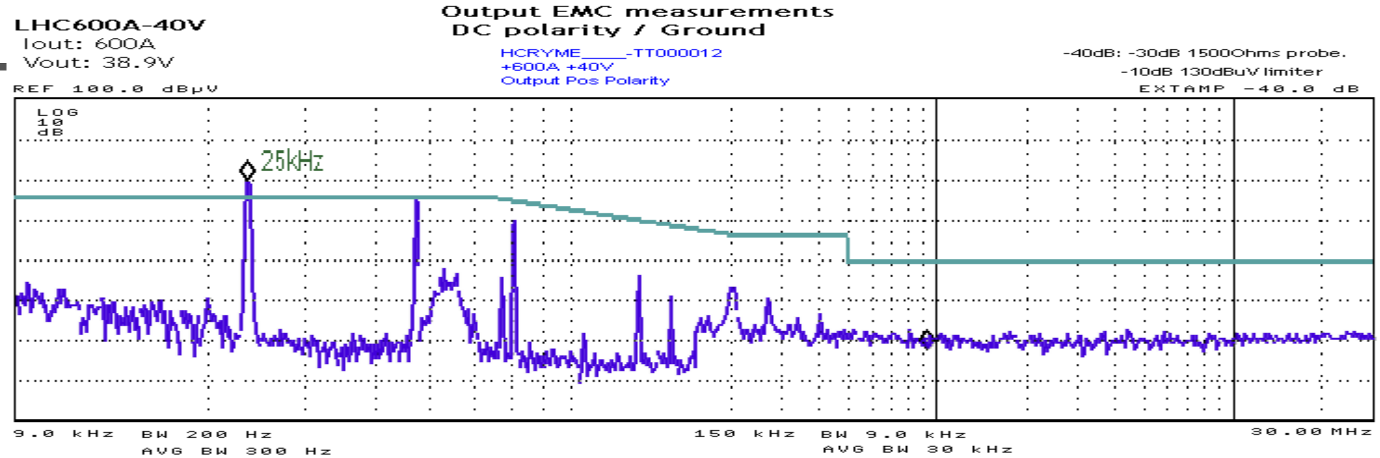
IEC 61000 - 4 :
Burst 61000 - 4 - 4
Surge 61000- 4 - 5

IEC 61000-4-4

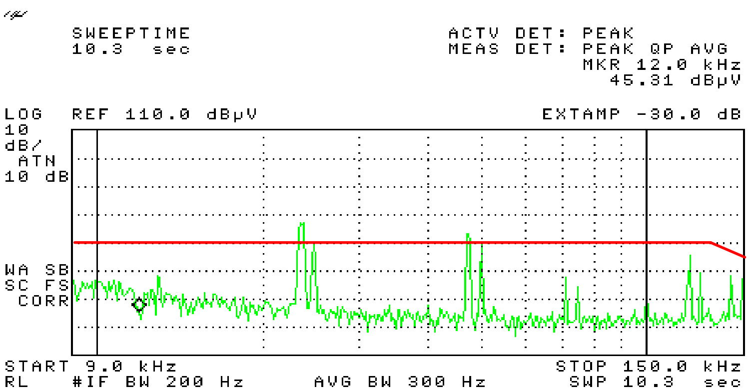


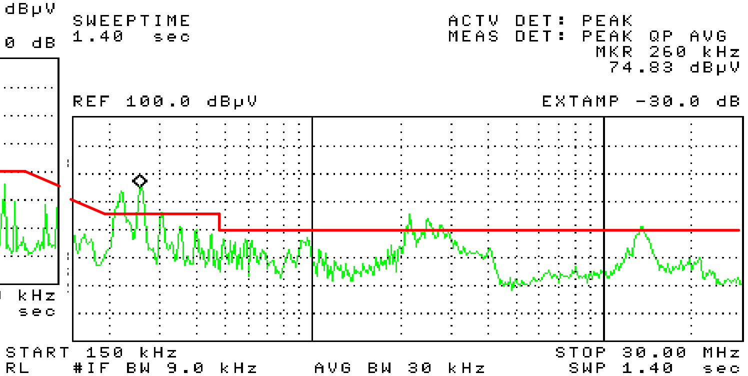
EMC conducted noise: Common Mode Emissions (9 kHz - 30 MHz) DC- Side

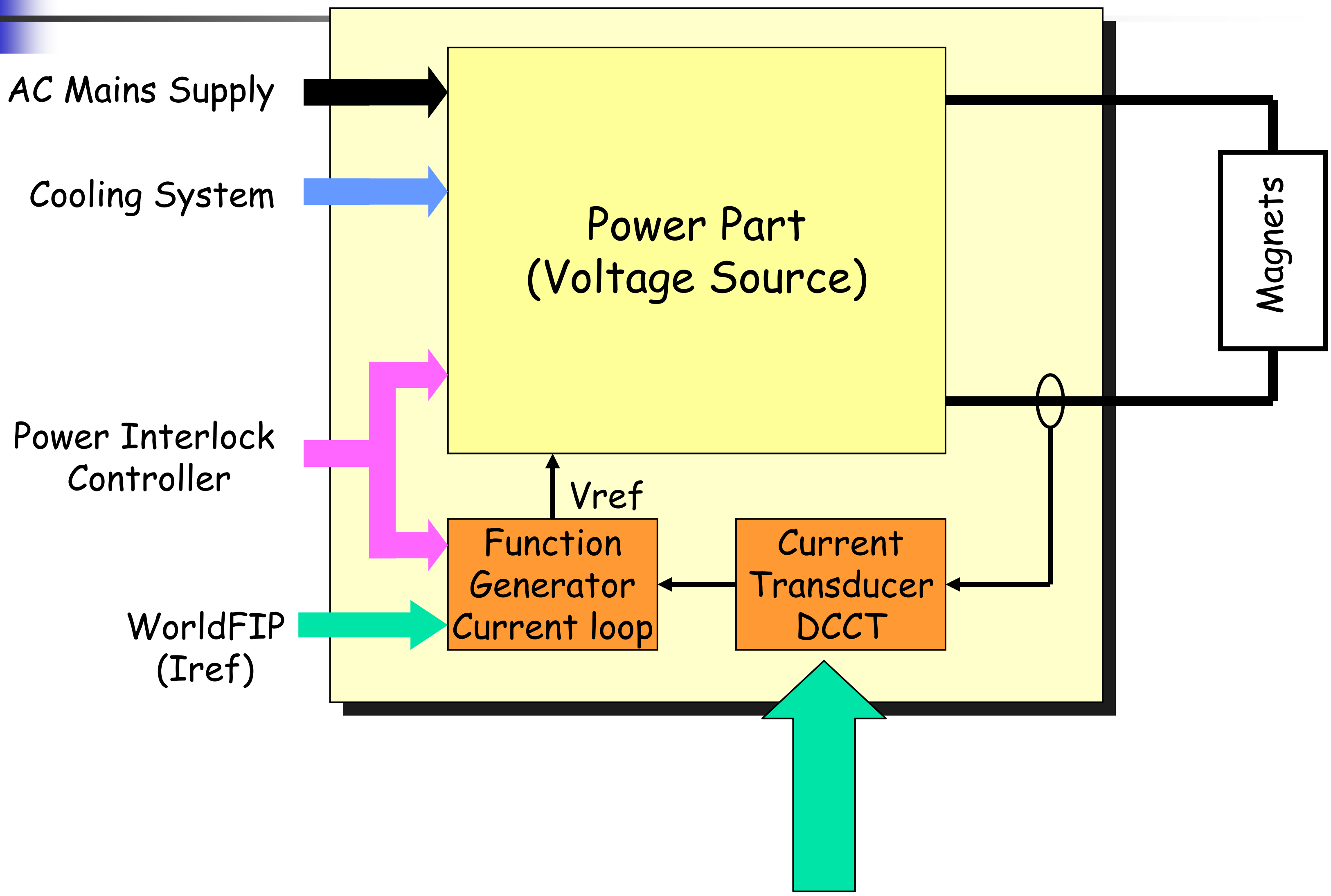
[±600A, ±40V] at 600A, 39V



[6kA, 8V] at 6kA, 8V






AC Mains Supply
Cooling System
Power Interlock Controller
WorldFIP (Iref)
Power Part (Voltage Source)
Vref
Function Generator Current loop
Current Transducer DCCT
Magnets

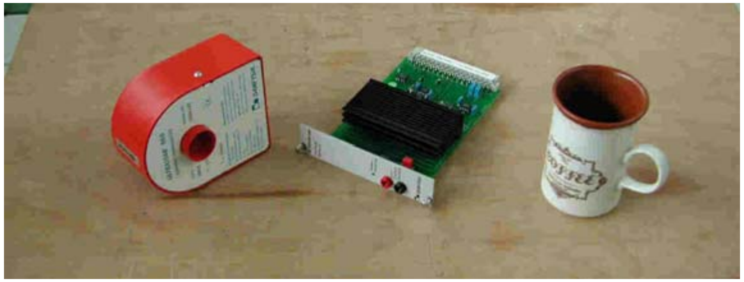
DCCTs (13kA)

- Highest performance - state of the art
- Separate Head and electronics chassis 19” rack mounting.
- Fitted with Calibration Windings
- Temperature-controlled environment in the Accelerator.
- Full testing and calibration at CERN on a 20kA Test Bed.

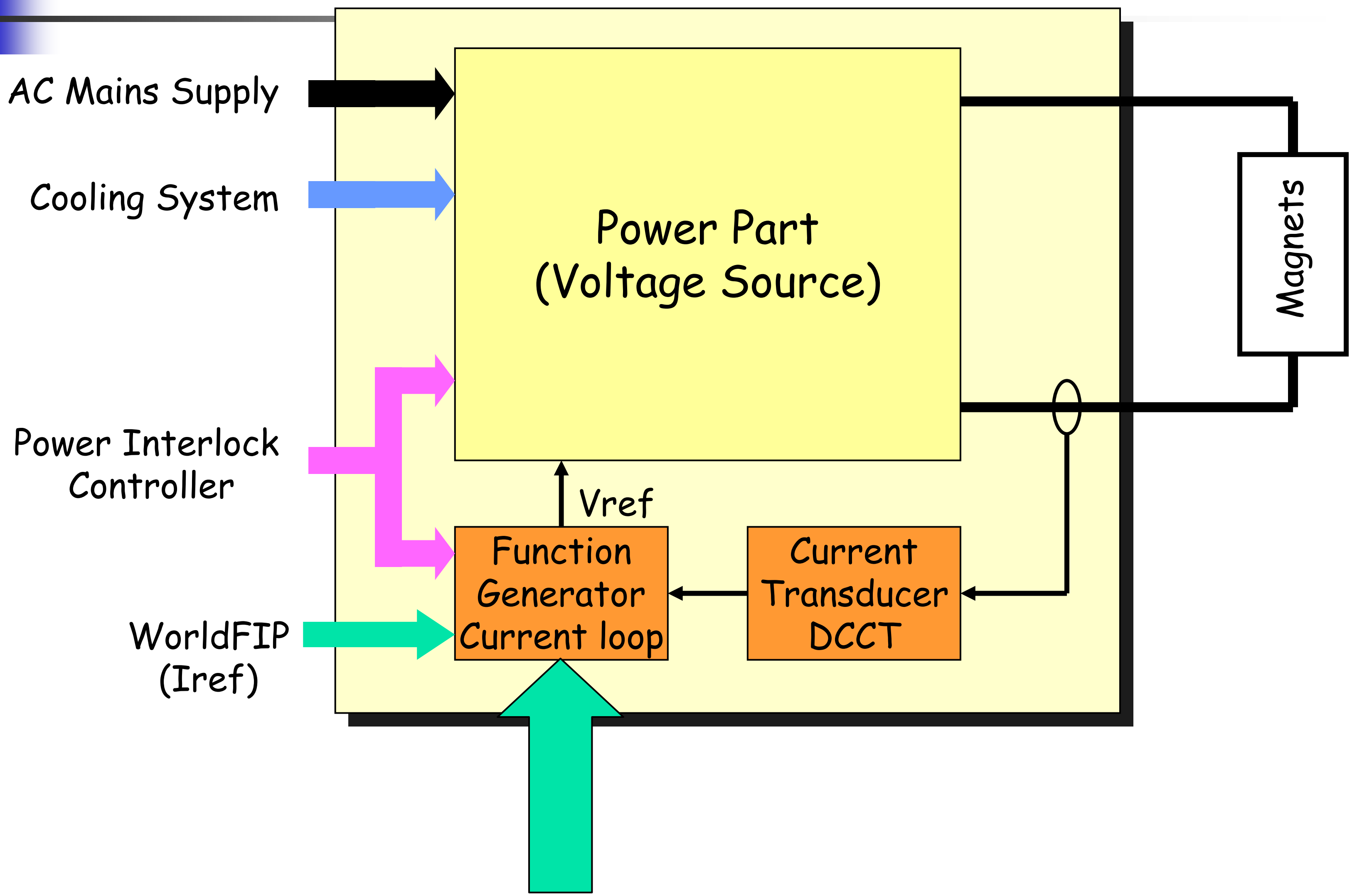
DCCTs

4kA to 8kA

600A

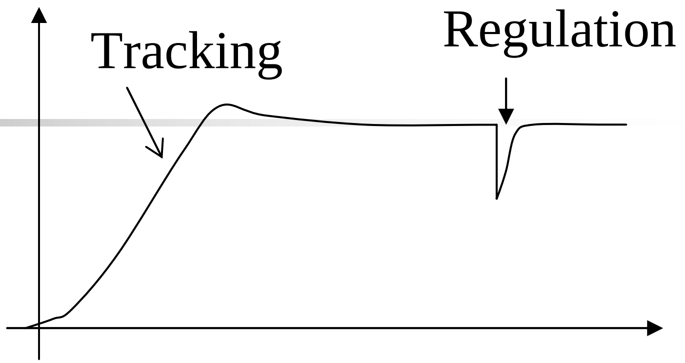


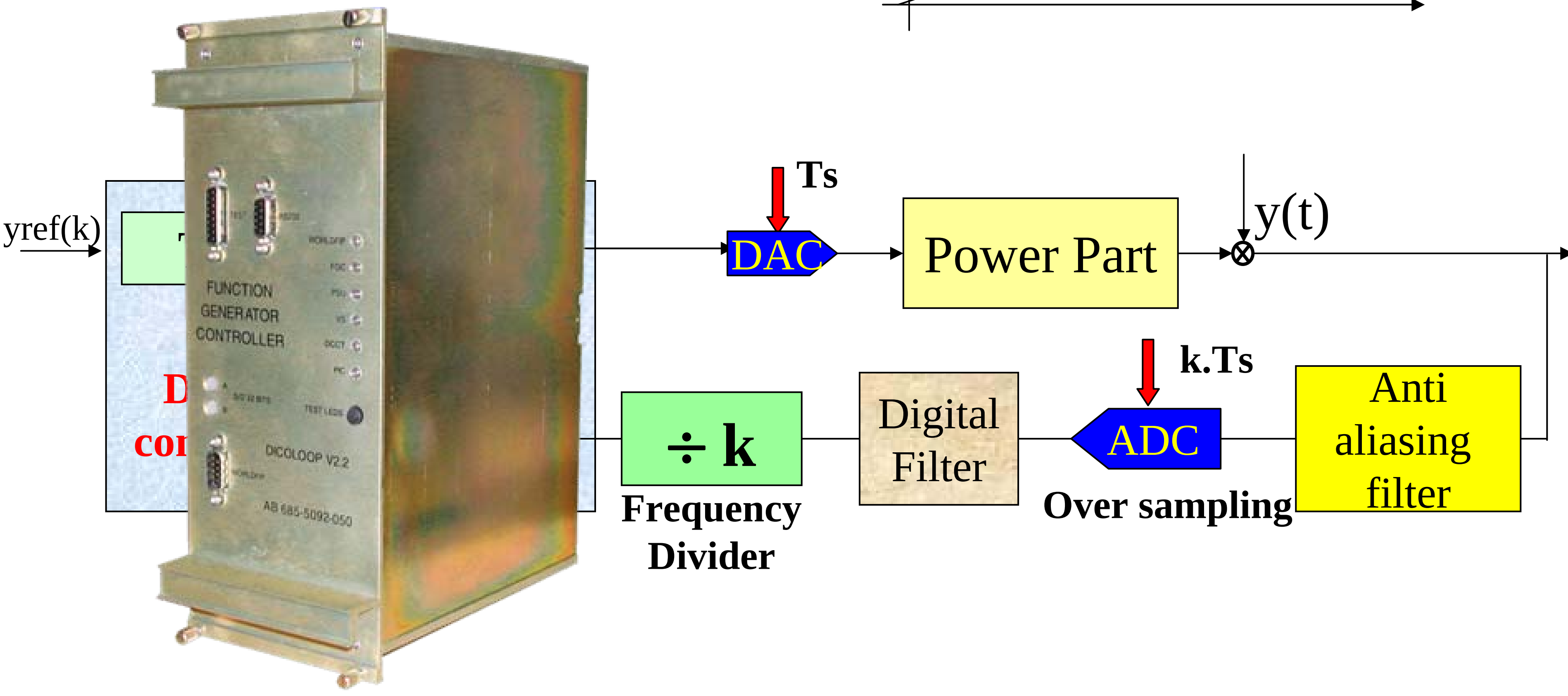
120A


AC Mains Supply
Cooling System
Power Interlock
Controller
WorldFIP
(Iref)
Power Part
(Voltage Source)
Magnets
Vref
Function
Generator
Current loop
Current
Transducer
DCCT

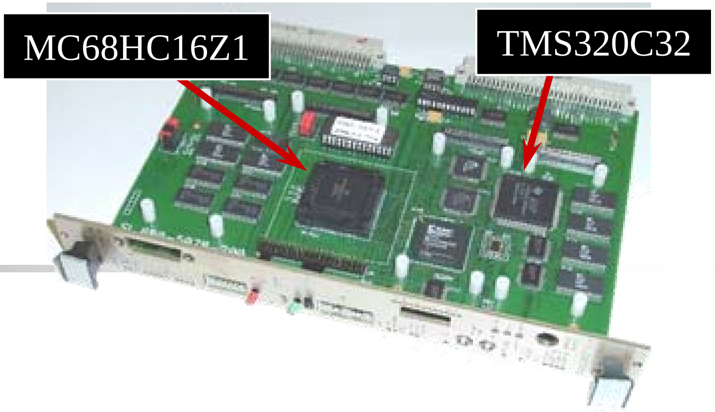
Digital current loop : RST algorithm

Tracking and Regulation with independent objectives





RST CONTROLLER DESIGN



Tracking:

To get a good tracking of the reference (no lagging error, no overshoot), the transfer function that the controller must achieve between the reference iref* and the output im* is:

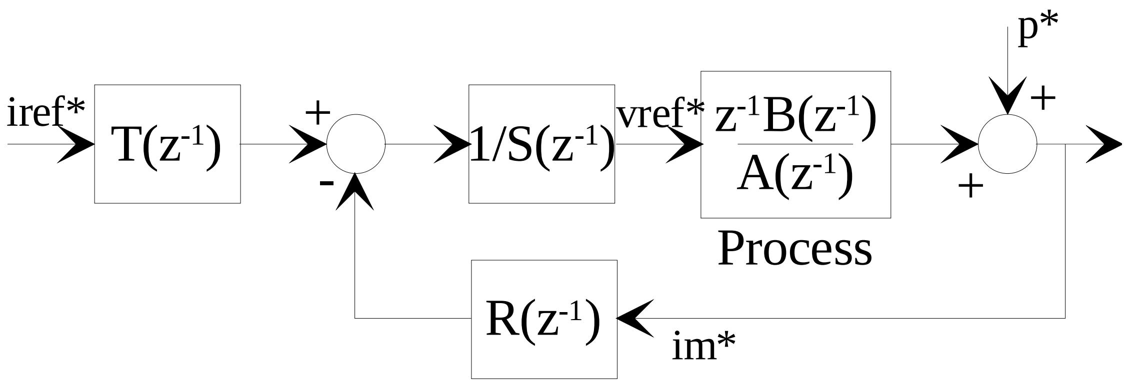
$$\frac{im^*}{iref^*} = z^{-1}$$

Regulation:

According to the LHC cycle, the bandwidth for the closed-loop system is chosen $f_B^{CL} \in [0.1Hz, 1Hz]$. The regulation is defined by the pole placement with a natural frequency wcl $\in [0.628rad/s, 6.28rad/s]$ and with a damping factor greater than 1. To ensure a zero steady-state error when the reference is constant, the transfer function $1/S(z^{-1})$ must contain two integrators .

$$\left(1 - z^{-1}\right)^2$$

R.S.T



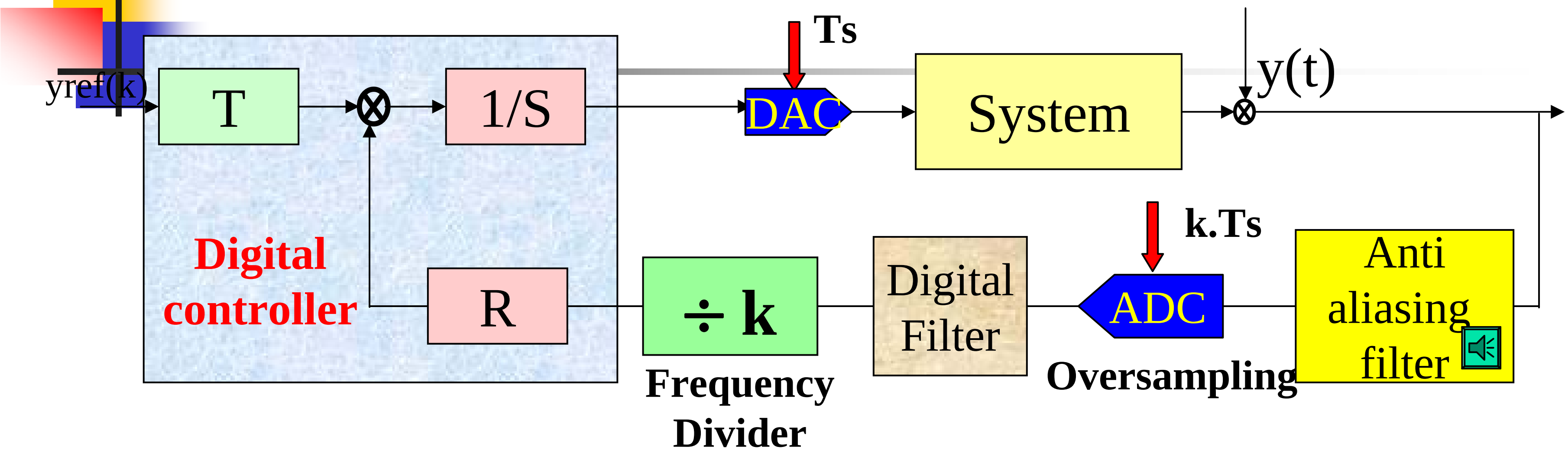
Tracking:

$$\frac{im^*}{iref^*} = \frac{z^{-1}.B.T}{A.S + R.B.z^{-1}}$$

Regulation:

$$\frac{im^*}{p^*} = \frac{A.S}{A.S + R.B.z^{-1}}$$

Summary

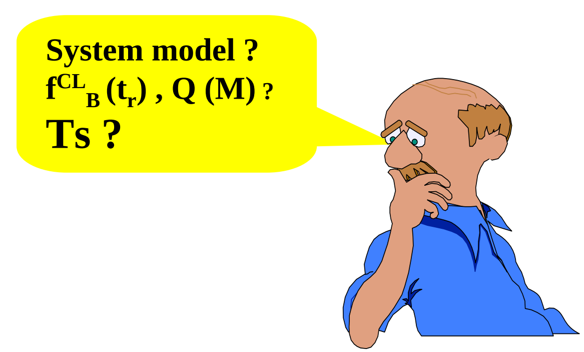


Based on f^{OL}_B and power of the actuator : choice of the closed-loop performance [f^{CL}_B (t_r) and Q (M)]
Robustness ; f^{CL}_B / f^{OL}_B (Internal saturation : controlability)

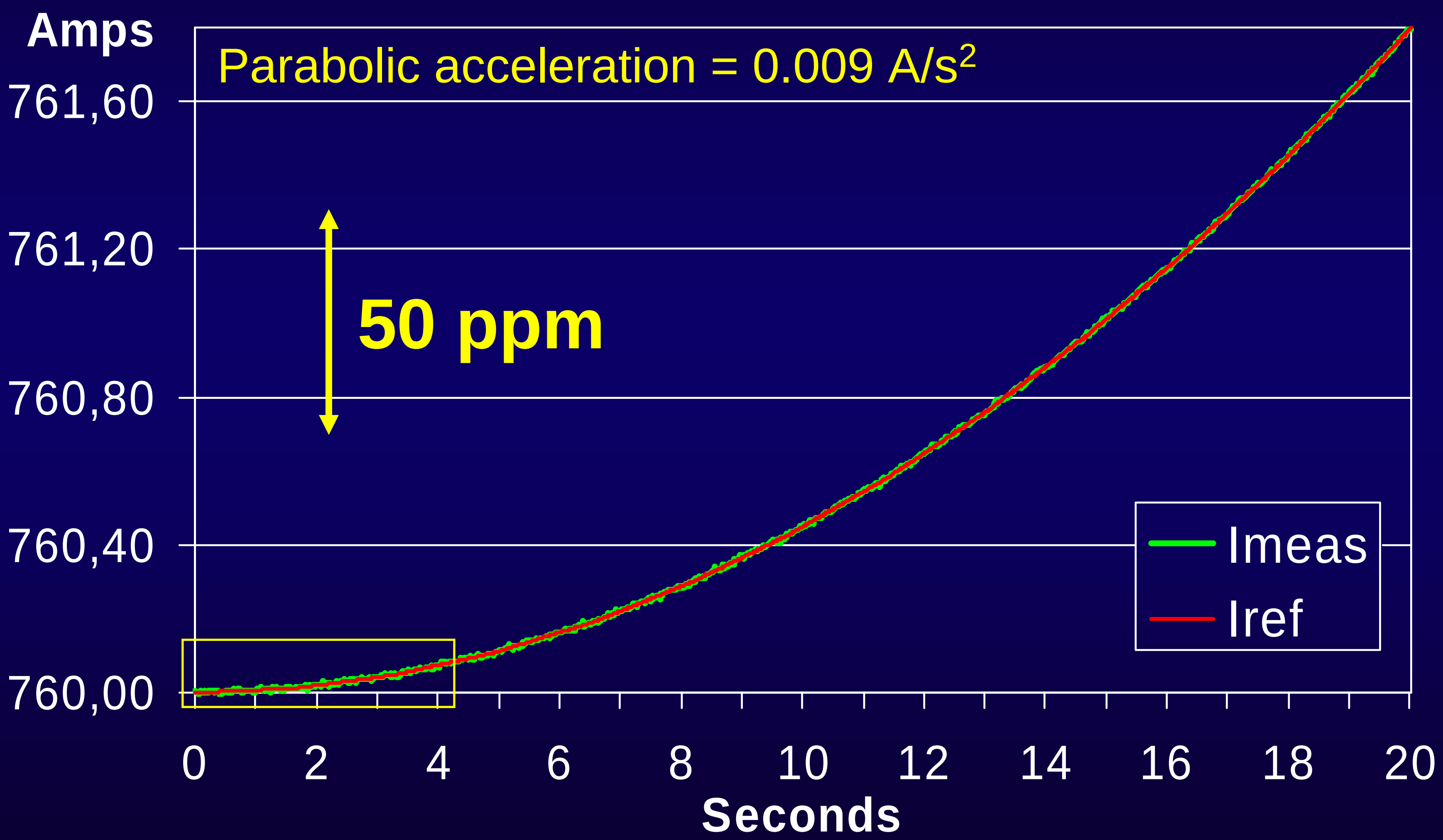
fs (sampling frequency) : choice based on the f^{CL}_B

$$fs = 1/Ts = (6 \text{ to } 25) * f^{CL}_B$$

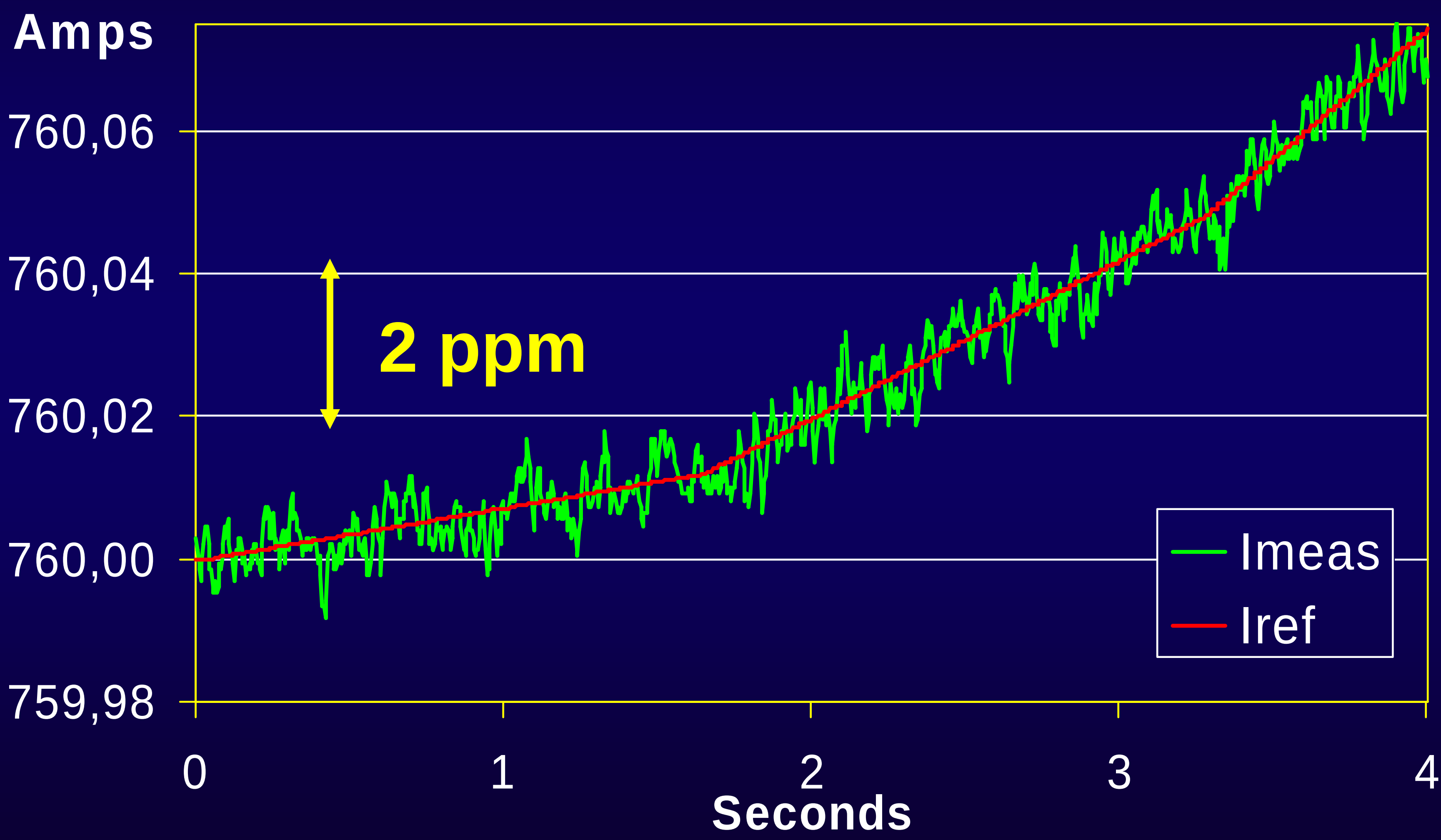
Discrete model $H(z^{-1})$ at Ts



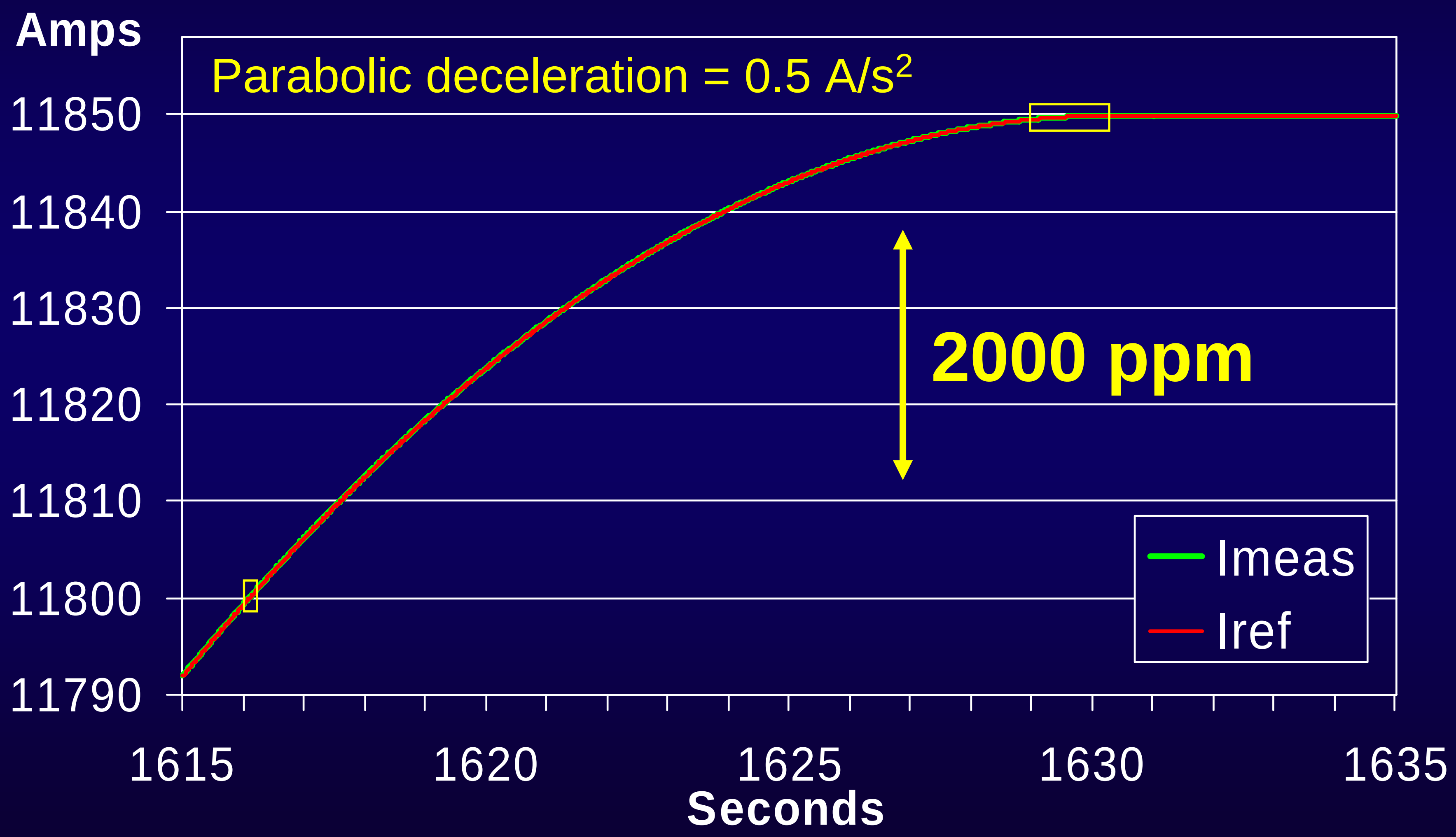
LHC dipole circuit ramp (0-20s)



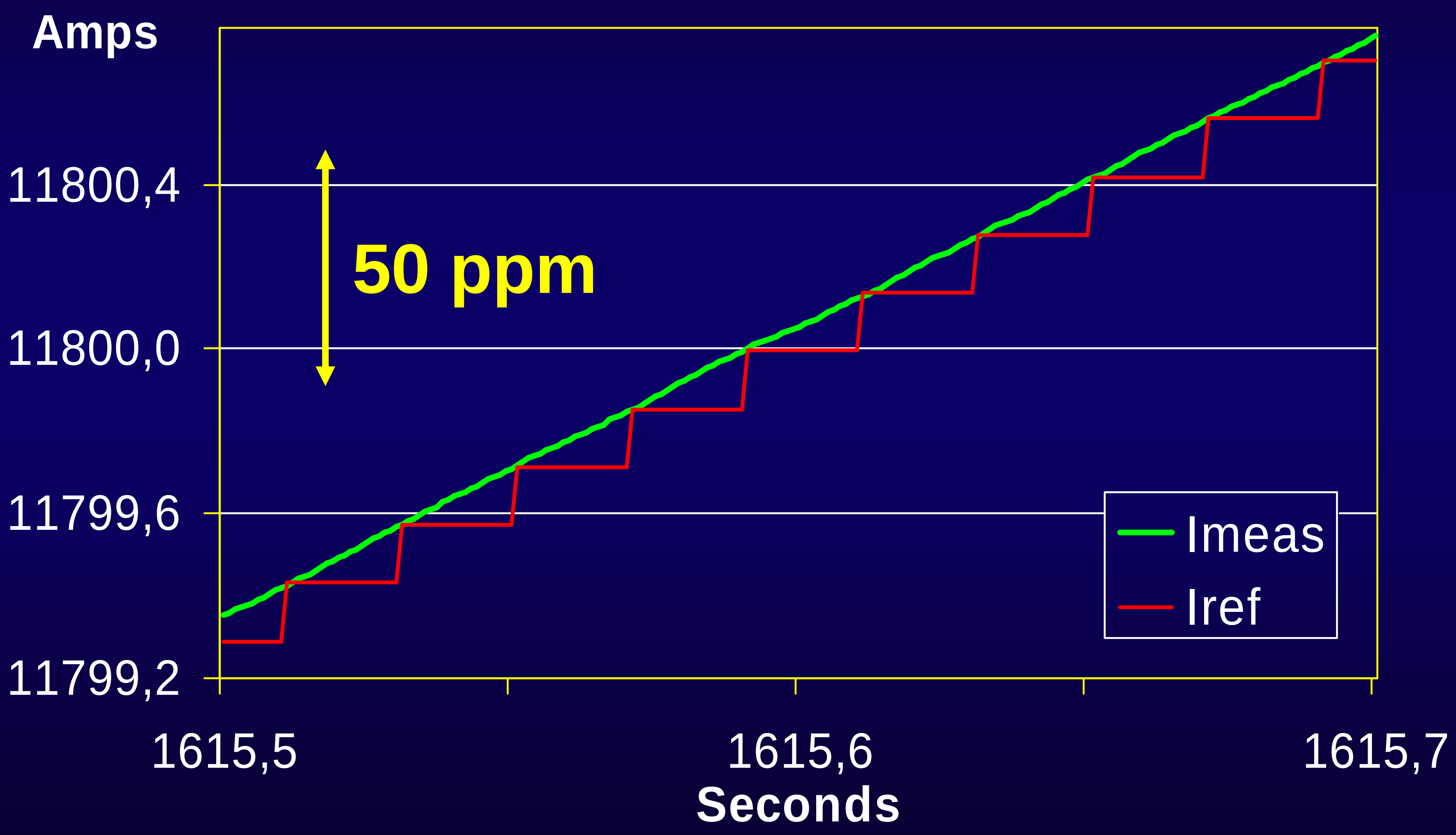
LHC dipole circuit ramp (0-4s)



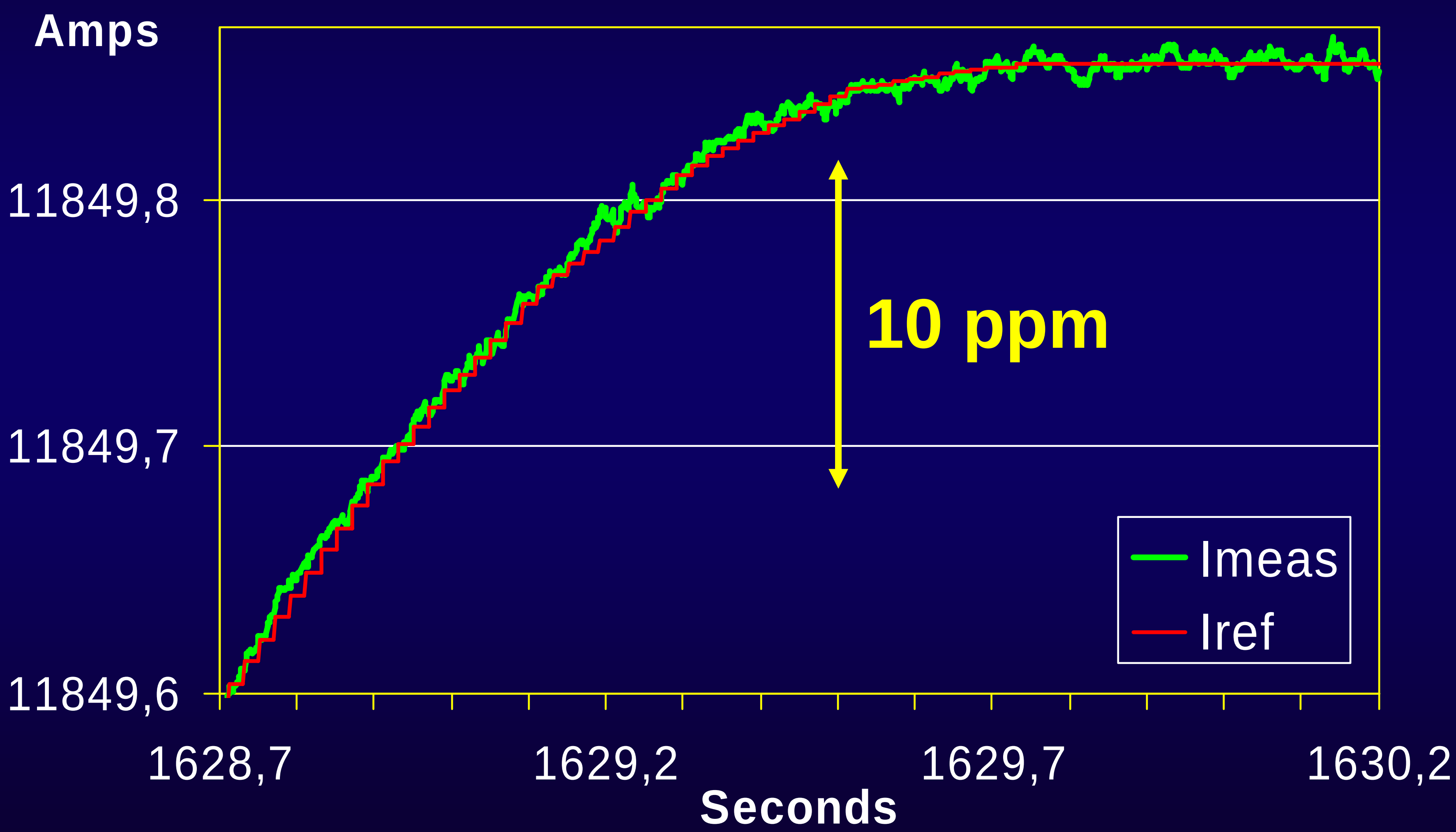
LHC dipole circuit ramp (last 15s)



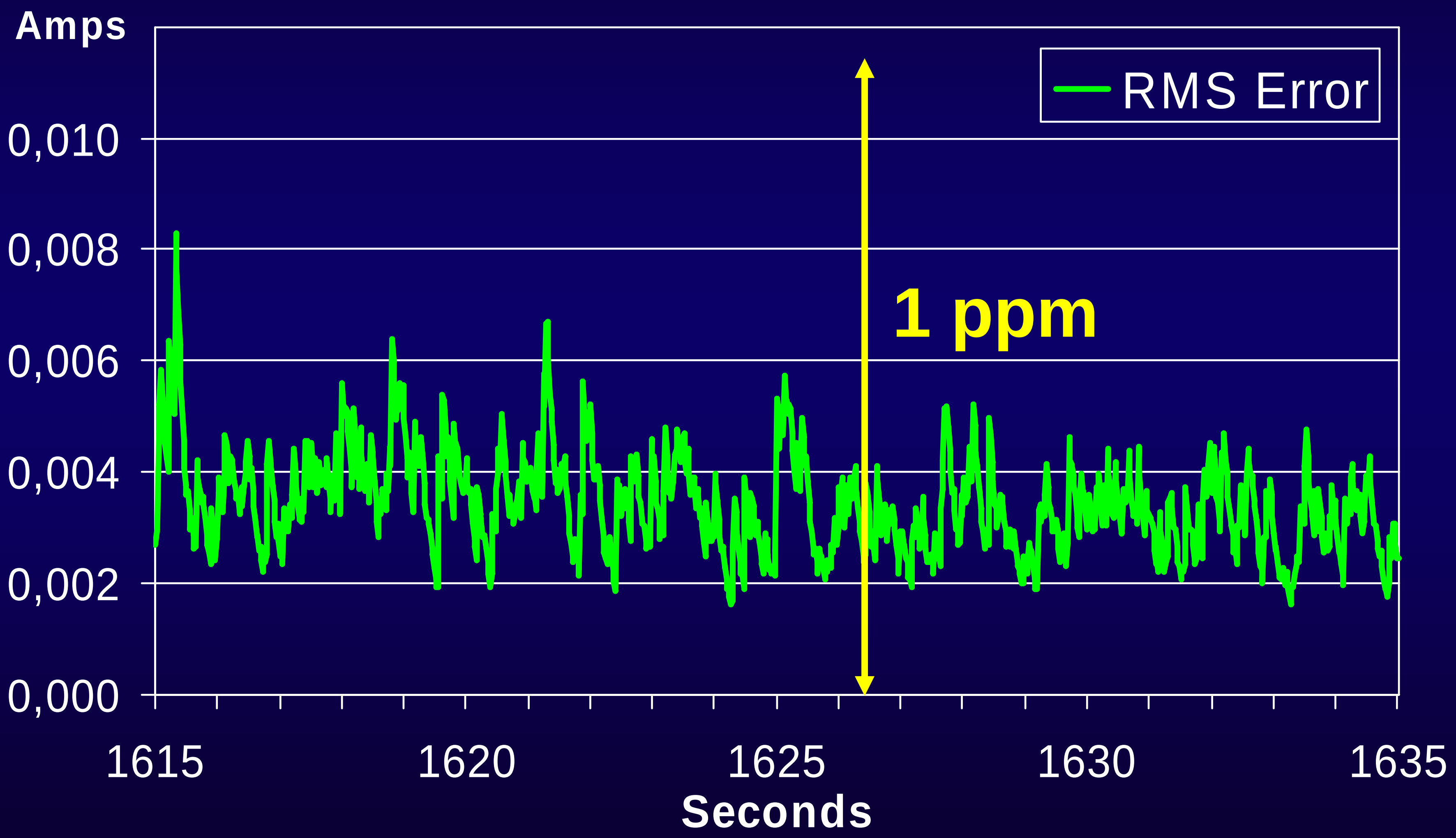
LHC dipole circuit ramp (200ms)



LHC dipole circuit ramp (last 1s)



Control Algorithm RMS Error



Quick Summary:

- The LHC represents many technological challenges
- One challenge is cost effective time synchronous control of 1700 power converters with very high precision… plus radiation resistance
- The challenge is met with a CERN built system based on floating point DSPs

Thanks to:

- Freddy Bordry, Quentin King; Luca Bottura and Mike Lamont for their slides

- To you for listening!