LHC
Present Status
and
Future Upgrade

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I[illegible]05

Catania [illegible]ch 2004

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Outlook

- Parameters and structure of the LHC
- Hardware issues
  - Dipole
  - Vacuum
  - Collimation
  - Beam extraction and dump
  - Injection line
  - QRL
- Running in scenarios
- LHC upgrade (and the CARE programme)
  - IR with $\beta^* = 0.25$ m
  - A new injection complex
- Conclusions

Main parameters of LHC

Collision energy	(TeV)	2x7.0
Dipole peak field	(T)	8.3
Luminosity	($cm^{-2} s^{-1}$)	10^{34}
Injection energy	(TeV)	0.45
Circulating current per beam	(A)	0.56
Number of bunches		2808
Particles per bunch		1.15×10^{11}
Stored beam energy per beam	(MJ)	350
Beam size at IP	(μm)	15.9
Beta values at IP	(m)	0.55
Normalised emittance	(μm)	3.75
Crossing angle	(μrad)	300
Beam lifetime	(h)	22
Luminosity lifetime	(h)	10
Radiated power per beam	(kW)	3.7

Accelerator structure

C = 26658.90 m

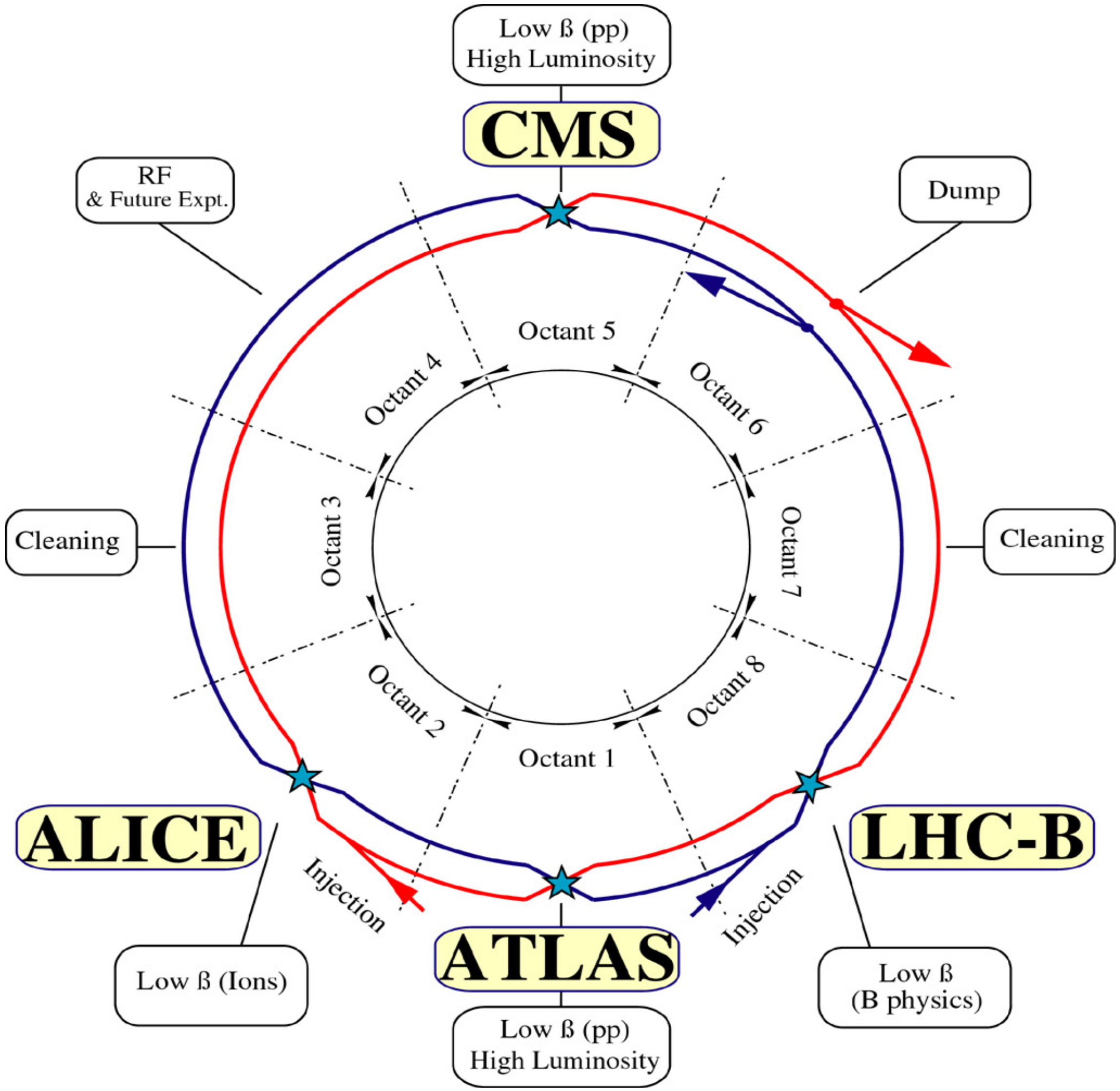
Arc = 2452.23 m

DS = 2 x 170 m

INS = 2 x 269 m

Free space

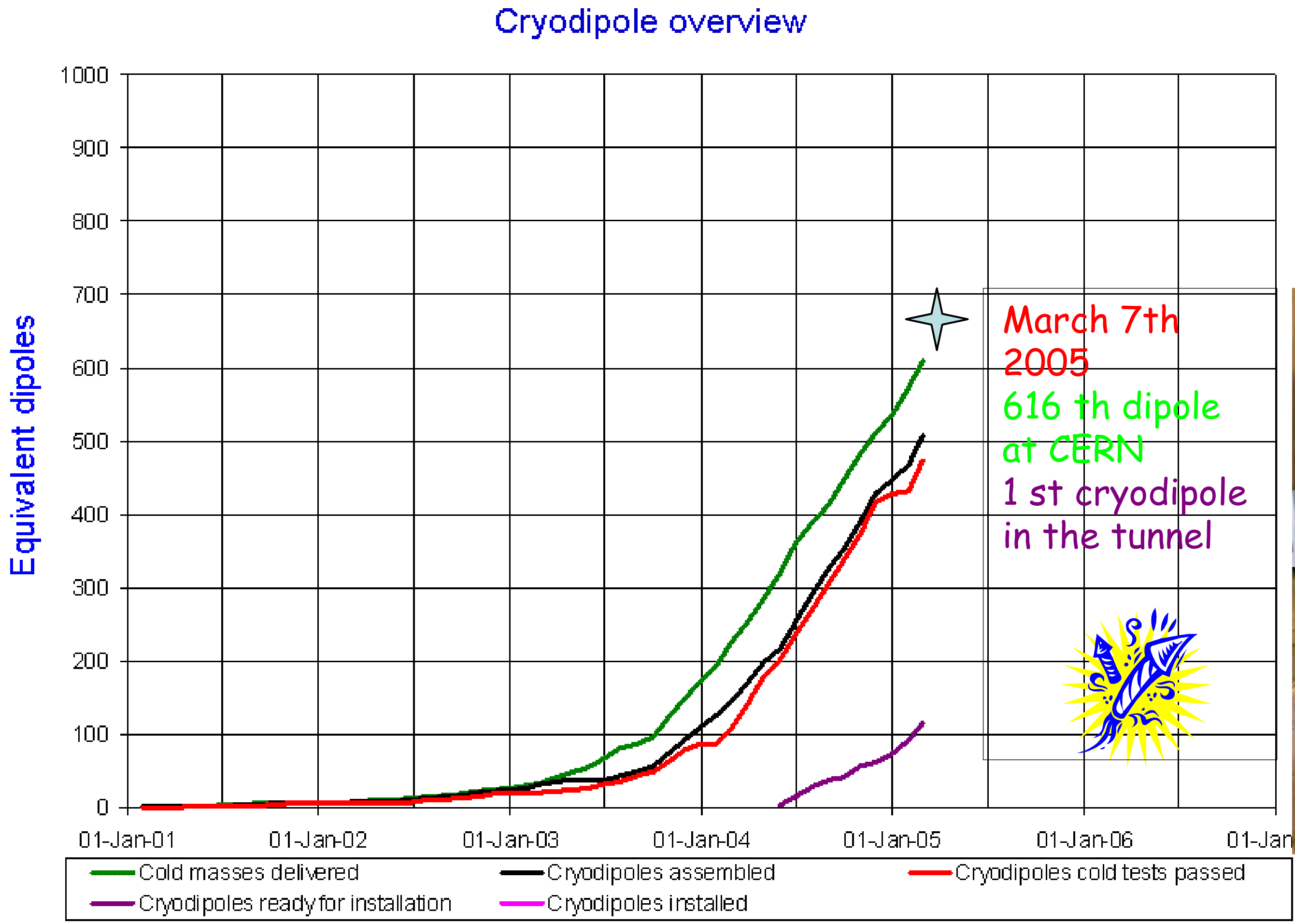
for detectors: ± 23 m



Dipole production

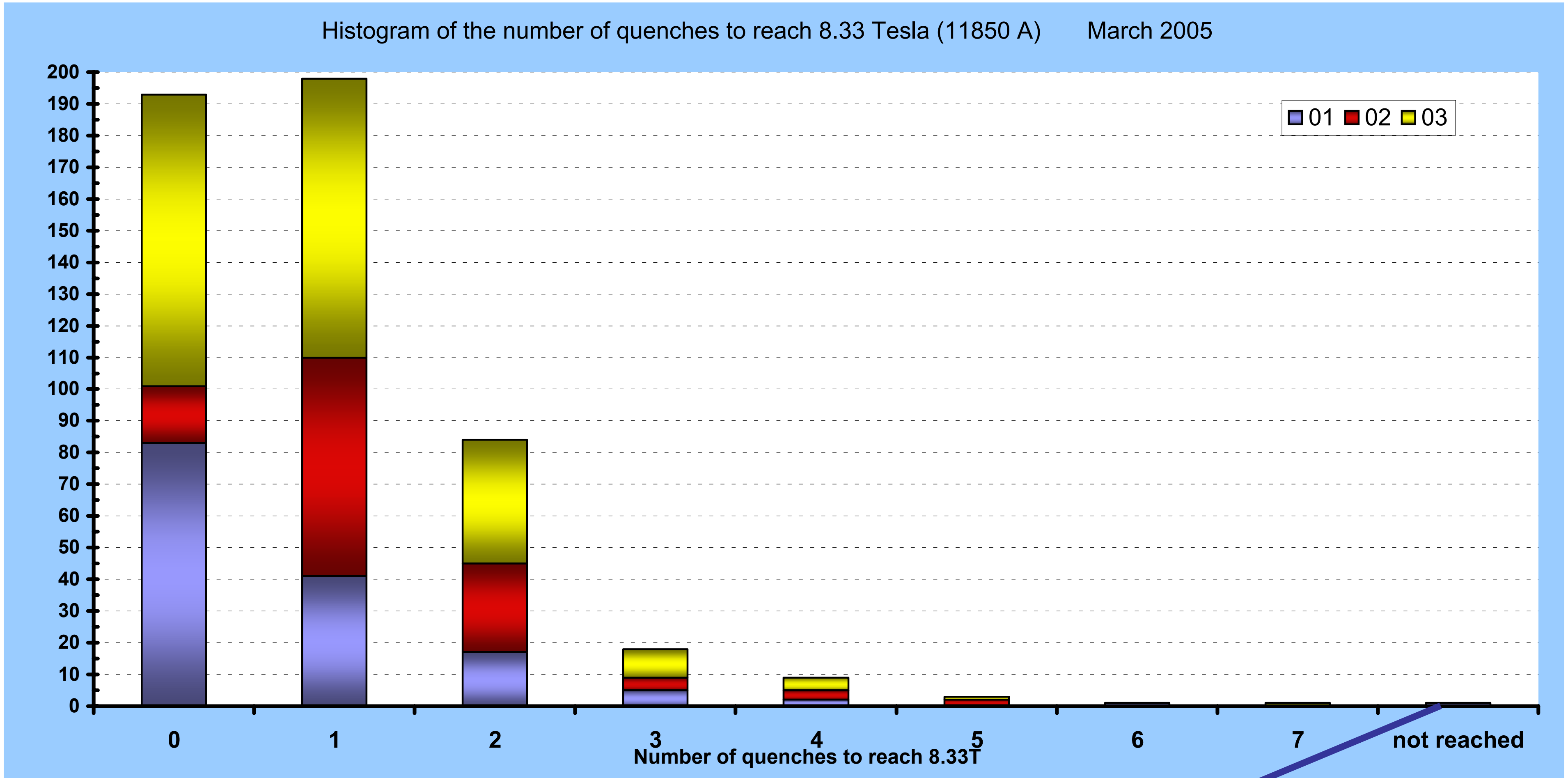
LHC Progress Dashboard

Accelerator Technology Department



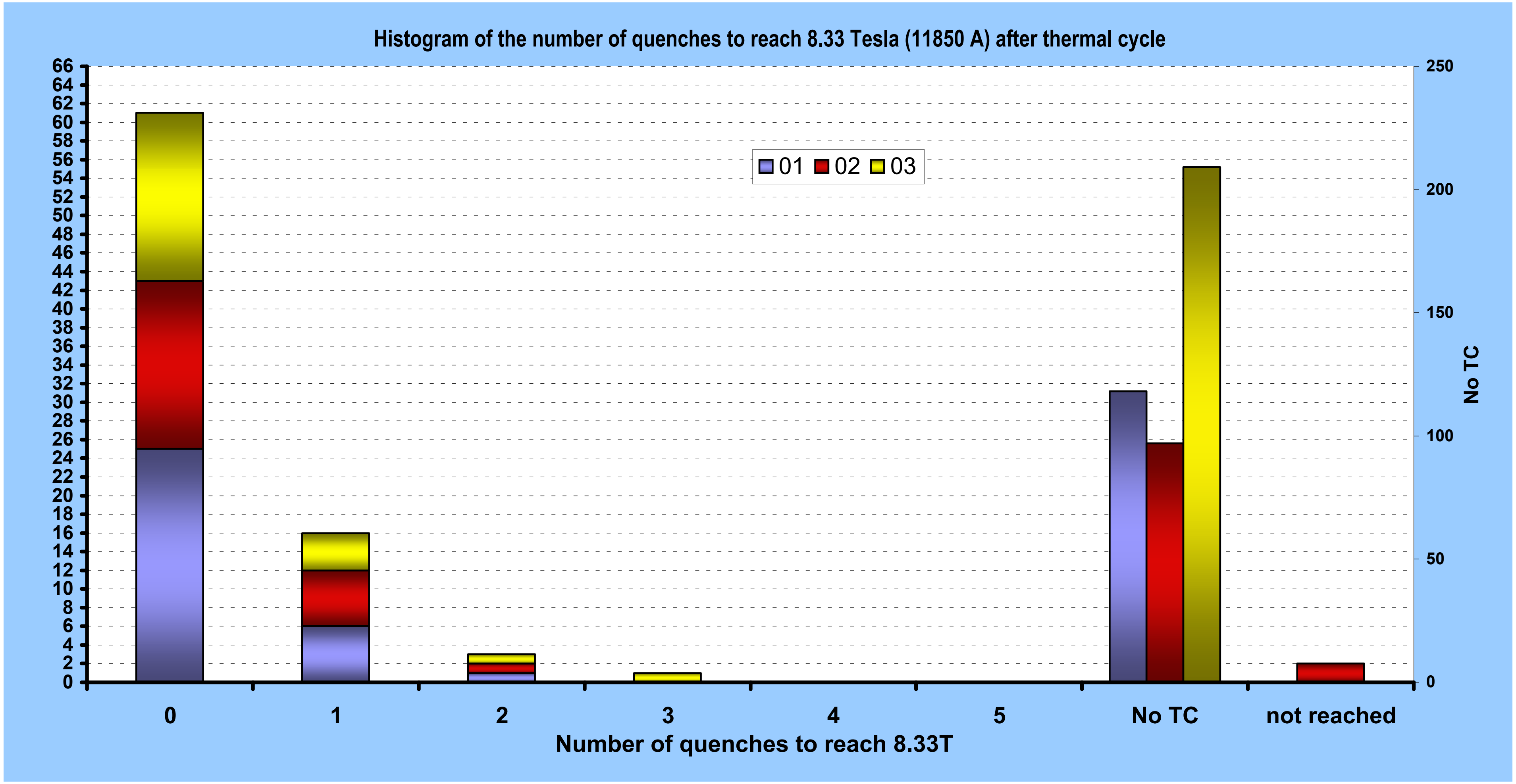
Updated 28 Feb 2005 Data provided by D. Tommasini AT-MAS

Dipole training up to B = 8.3 T



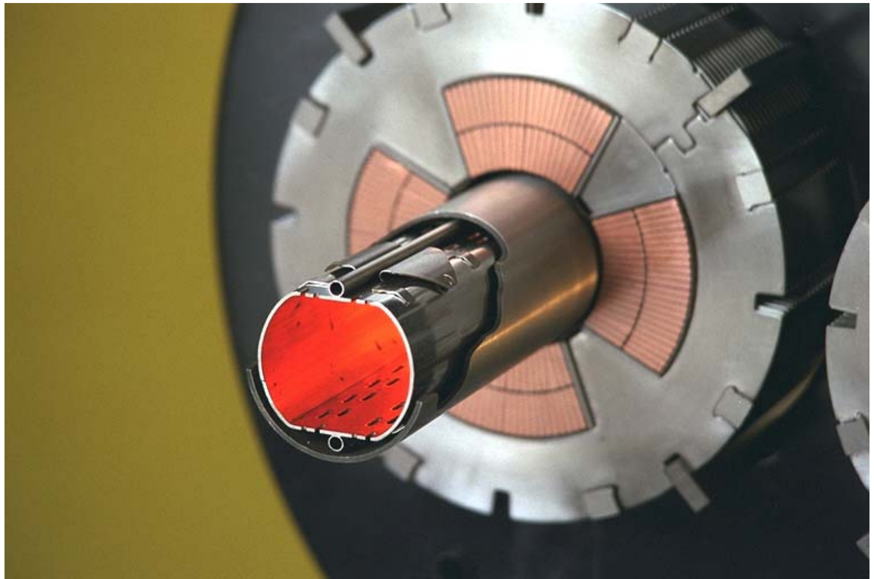
MB1005 (cold weld problem)

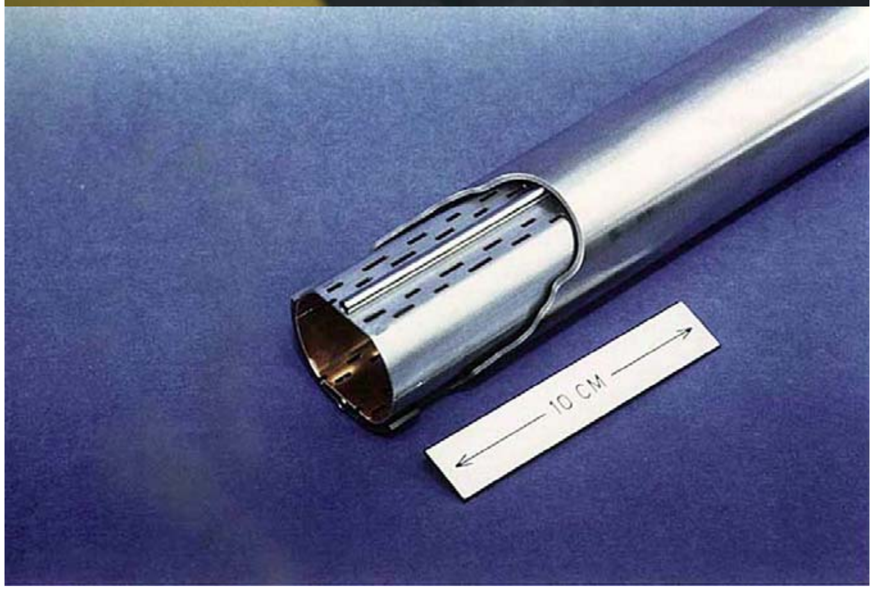
Training memory after a thermal cycle



Vacuum

- In cold bore (1.9 K) there is a beam screen (20 K) intercepting the synchrotron light (3.8 kW per beam, mostly composed of U.V. photons) to reduce the cryogenic loss and hence the cryogenic power.
- The holes in the screen act as cryo-pumps.
- The hole are randomly distributed to avoid beam instability induced by EM power loss and active feedback.
- The screen is in stainless steel to reduce deformations during quenches, and cu-plated in the inner wall to reduce the threshold of the resistive wall instability.
- The screen is could-down by two small pipes welded in the screen



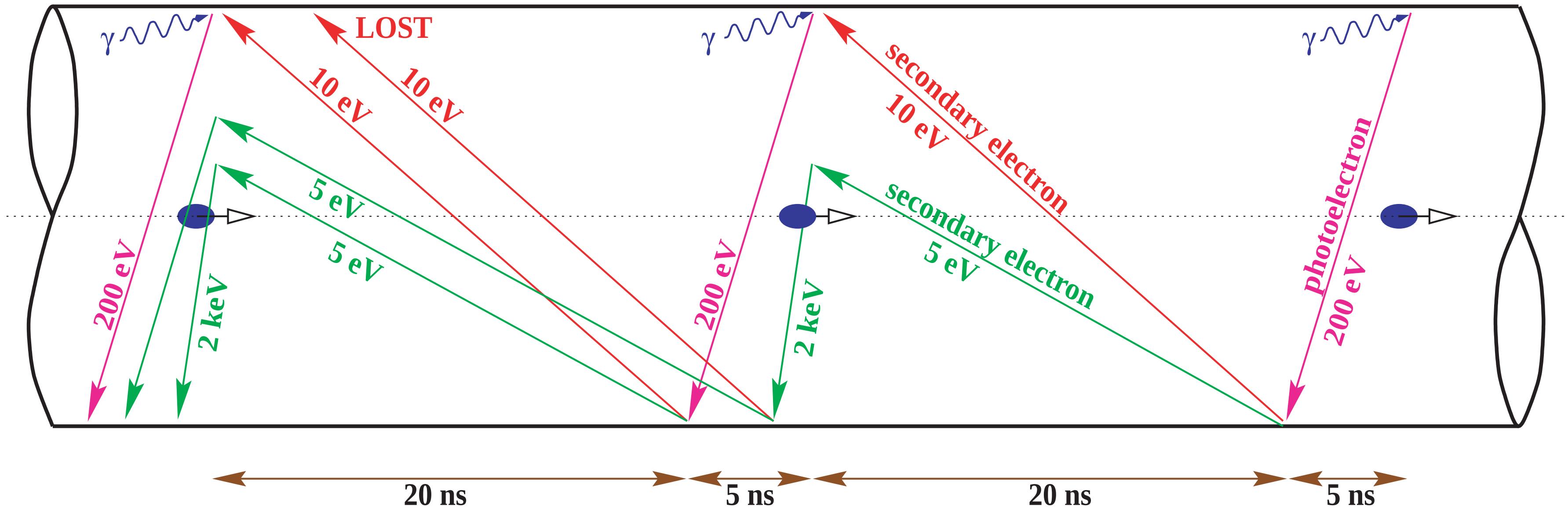


Vacuum

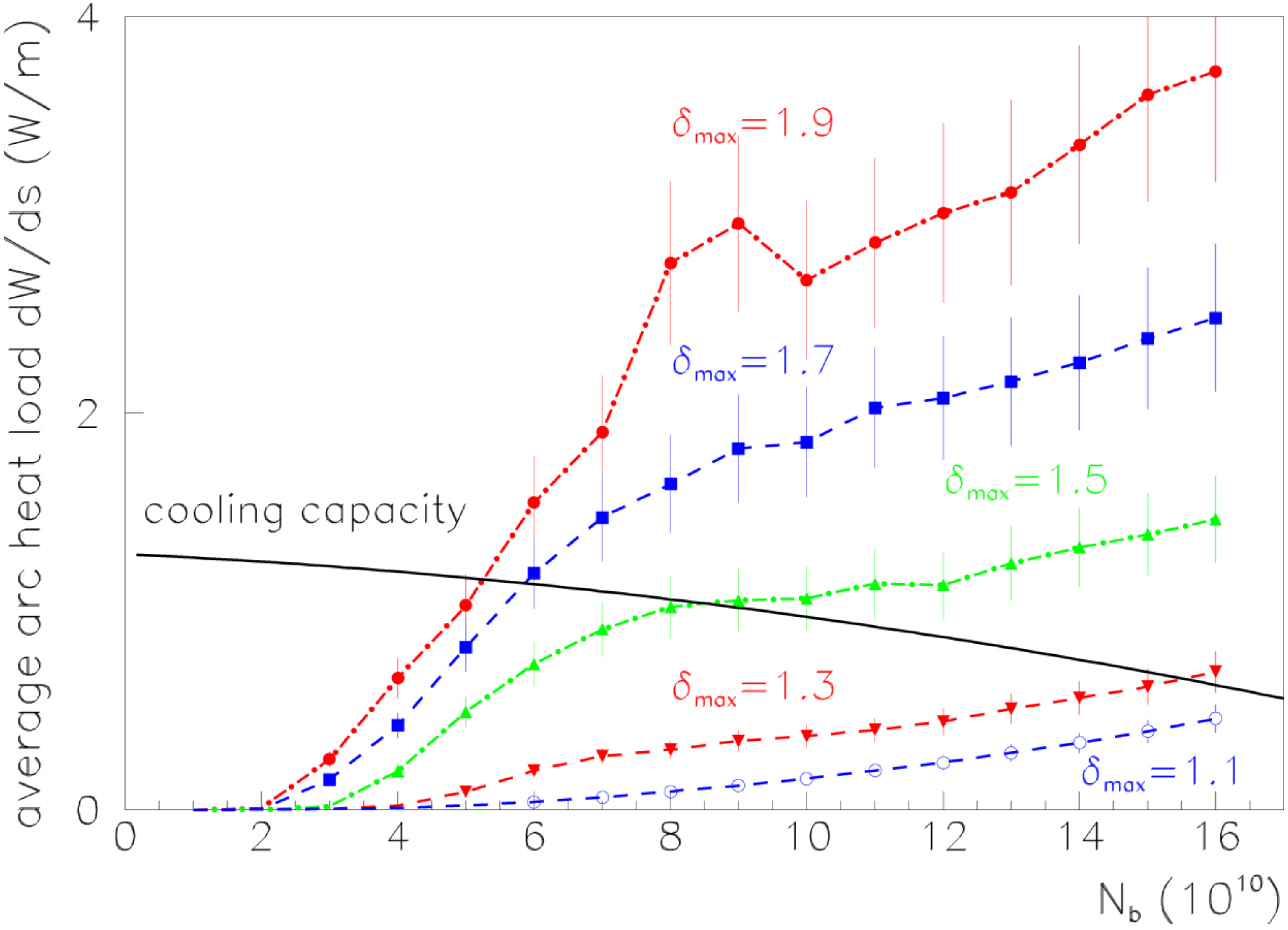
The photons impinging in the screen walls produce a gas desorption:	The photo-electrons are accelerated by the strong positive electric field induced by the proton bunches. This is a cascade process producing a dense electron cloud.
♦ The residual pressure increases ♦ Photo-electrons are produced.	

An instability induced by the electron cloud already observed at the SPS.

- ♦ It produces a strong thermal load to the cryogenic system.
- ♦ It can be cured by reducing the number of bunches and by screen scrubbing.
- ♦ Beam scrubbing tests at the SPS successful



Vacuum



average arc heat load dW/ds (W/m)
4
2
0
0
2
4
6
8
10
12
14
16
N_b (10^{10})
cooling capacity
δ_{max}=1.9
δ_{max}=1.7
δ_{max}=1.5
δ_{max}=1.3
δ_{max}=1.1

Beam collimation

Super-Conducting Environment

Proton losses into cold aperture

⇩

Local heat deposition

⇩

Magnet can quench

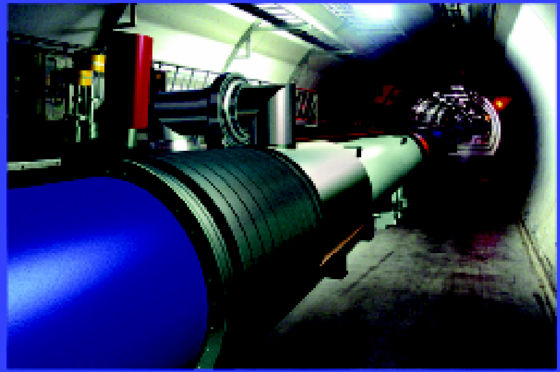


Illustration of LHC dipole in tunnel

Energy [GeV]	Loss rate (10 h lifetime)	Quench limit [p/s/m] (**steady losses**)	Cleaning requirement
450	8.4e9 p/s	7.0e8 p/s/m	92.6 %
7000	**8.4e9 p/s**	**7.6e6 p/s/m**	**99.91 %**

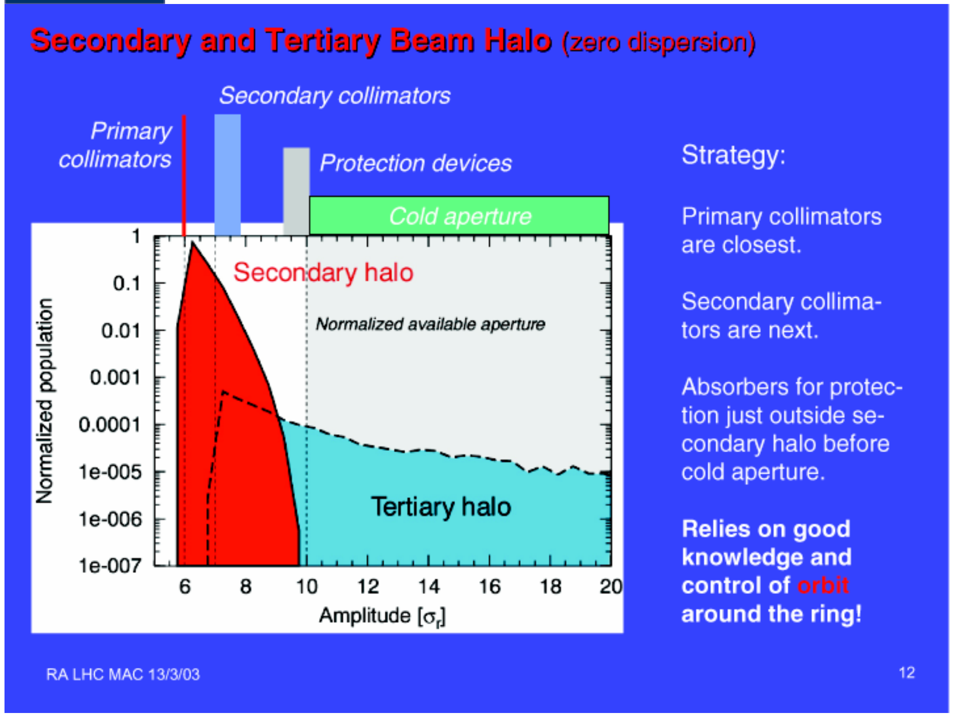
Control **transient losses (10 turns)** to ~1e-9 of nominal intensity (top)!

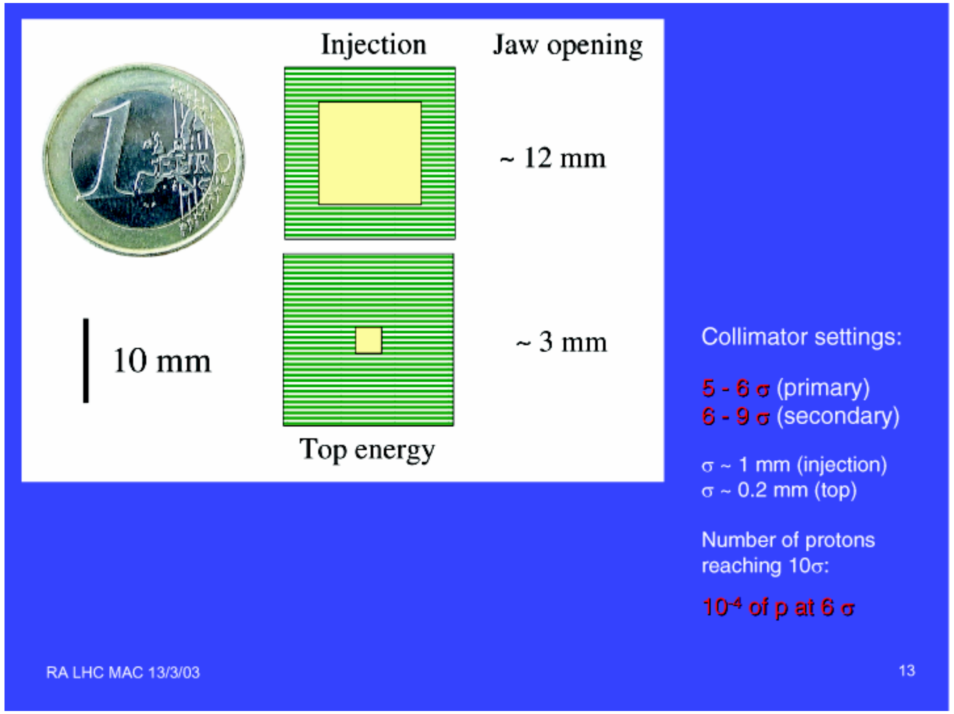
Capture (clean) lost protons before they reach cold aperture!

Required efficiency: ~ **99.9 %** *(assuming losses distribute over 50 m)*

RA LHC MAC 13/3/03 46

Effect of an ideal collimator (due stages)





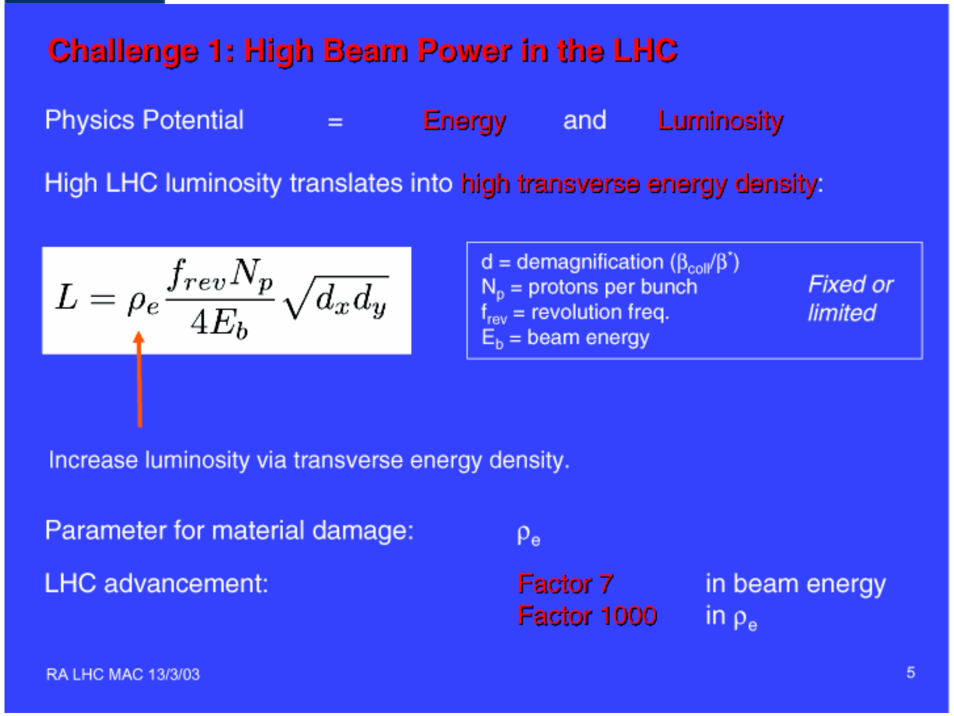
Open problems:

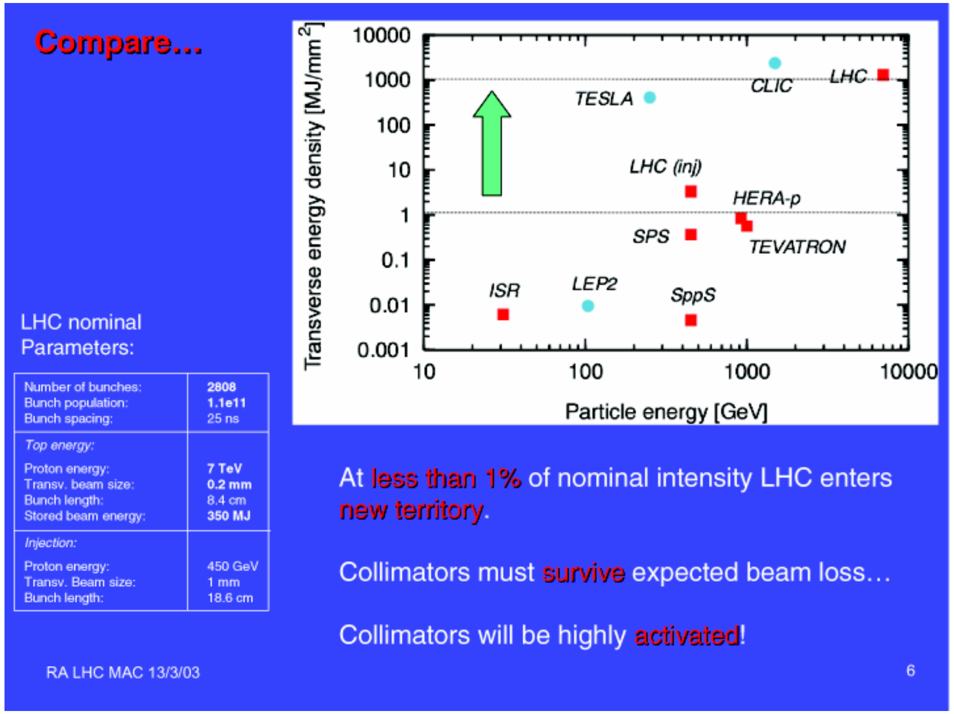
- Choice of the material (large Z => too large thermal load)
- Resistive impedance (up to 100 times the whole LHC)
- Electron cloud (local concentration)

Recent results:

- Successful test of a carbon-carbon collimator at the SPS (good for low-intensity LHC but impedance still too high)

Luminosity and transverse density of energy





Mandatory to stage collimation:

- Required efficiency at full intensity 99.91 % (~70% efficiency required in the Tevatron)
- Carbon-carbon collimator ok for phase 1, but *insufficient* for full intensity
- Initial luminosity reduced (by factor of 3 ?)

Beam dump system

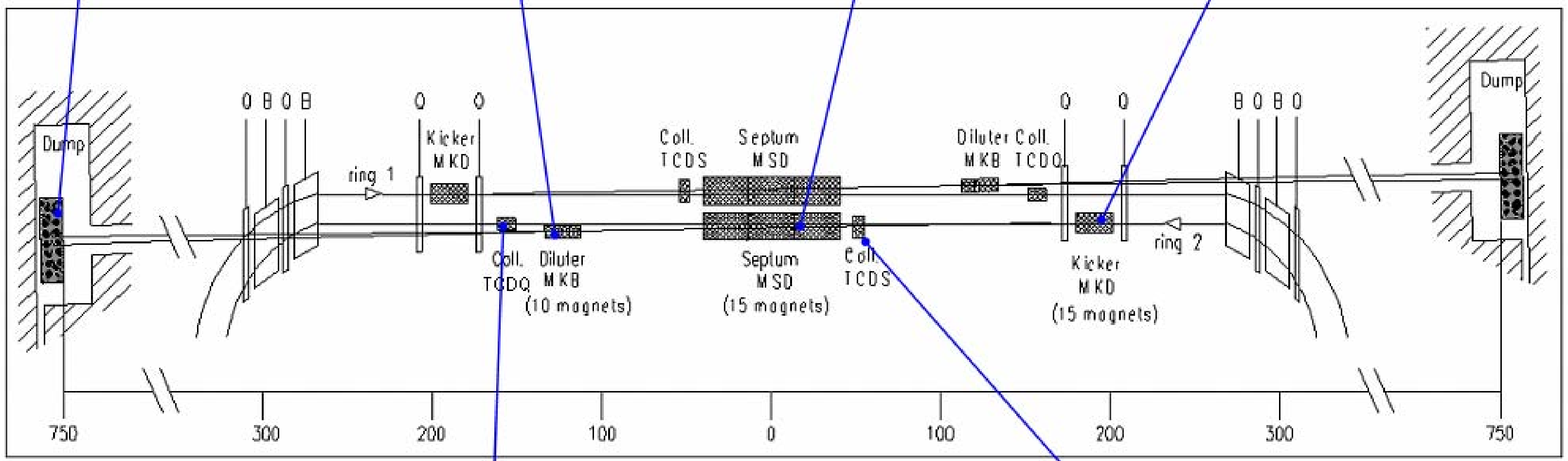
Schematic layout

TDE dump block

10 x MKB kickers

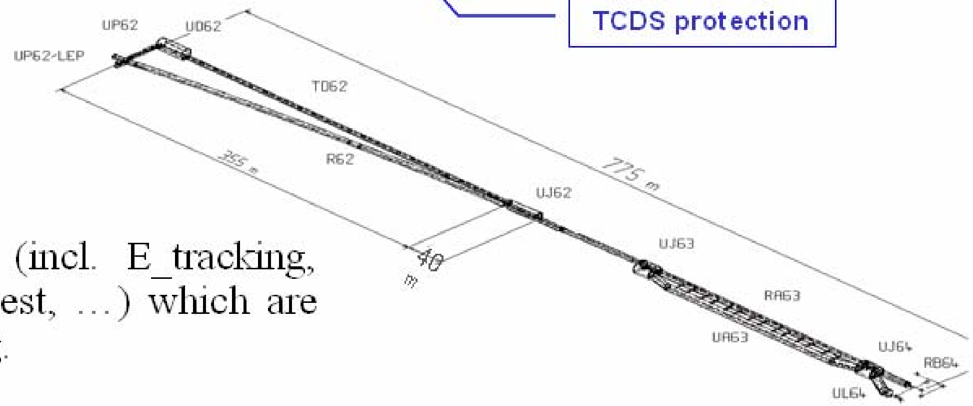
15 x MSD septa

15 x MKD kickers



TCDQ protection

TCDS protection

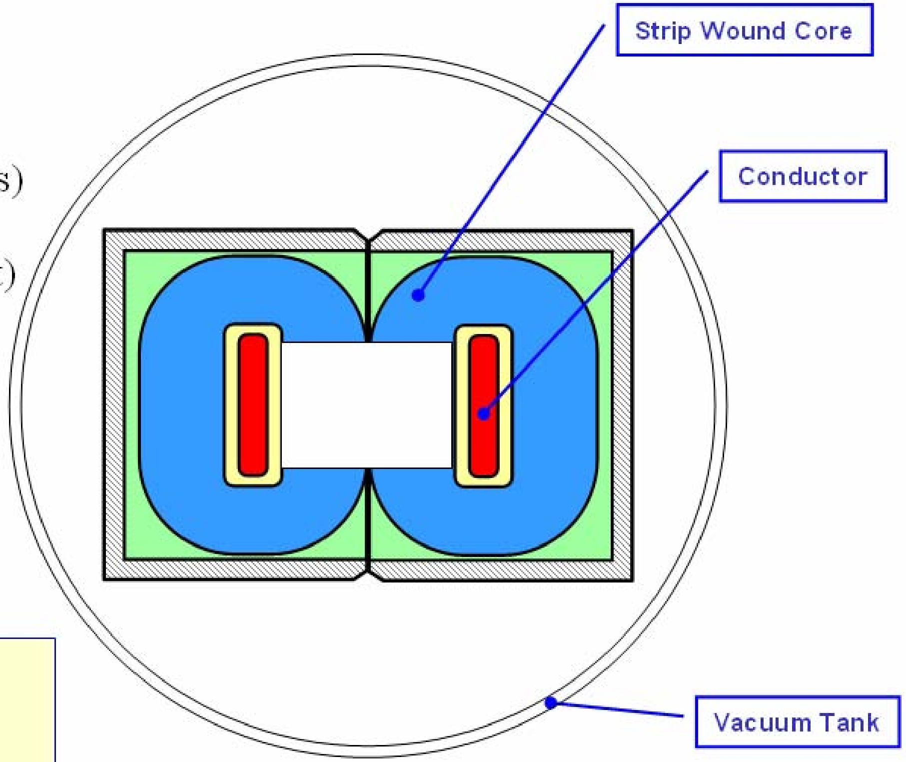


Also – dedicated equipment controls (incl. E_tracking, synchronisation, post-mortem, self-test, …) which are not treated explicitly in the following.

Dilution of the extracted beam

Dilution kickers MKB

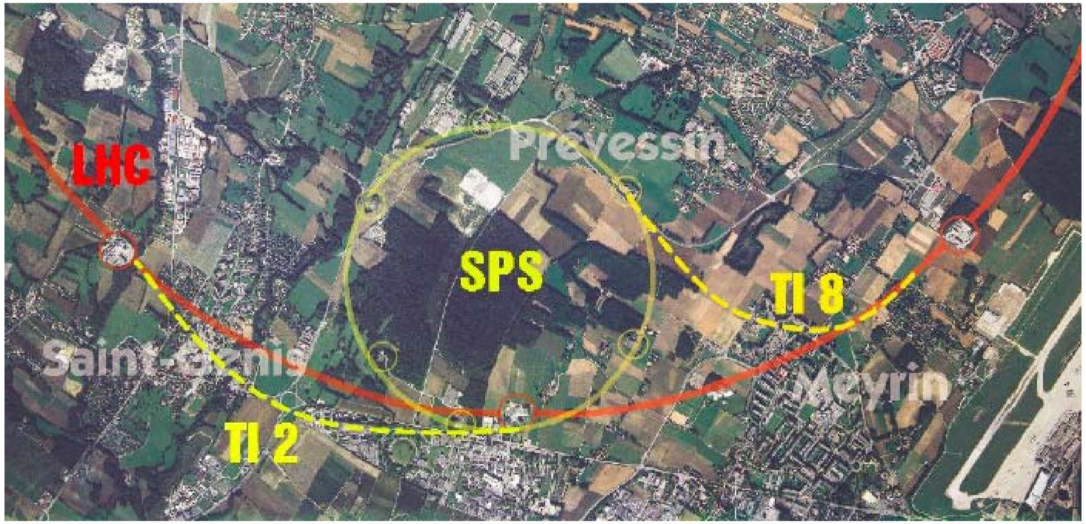
- 10 units per beam (4 x H, 6 x V)
- ± 0.28 mrad (H), ± 0.28 mrad (V)
- Reuse MKD technology
- Issues:
  - Staged installation (4/10 units) limits LHC intensity to 50% (for ~2 years after green light)



Status:
M+G detailed design in progress
Transmission line series at ~10%

Intensity limited by a factor of 2

The injection line

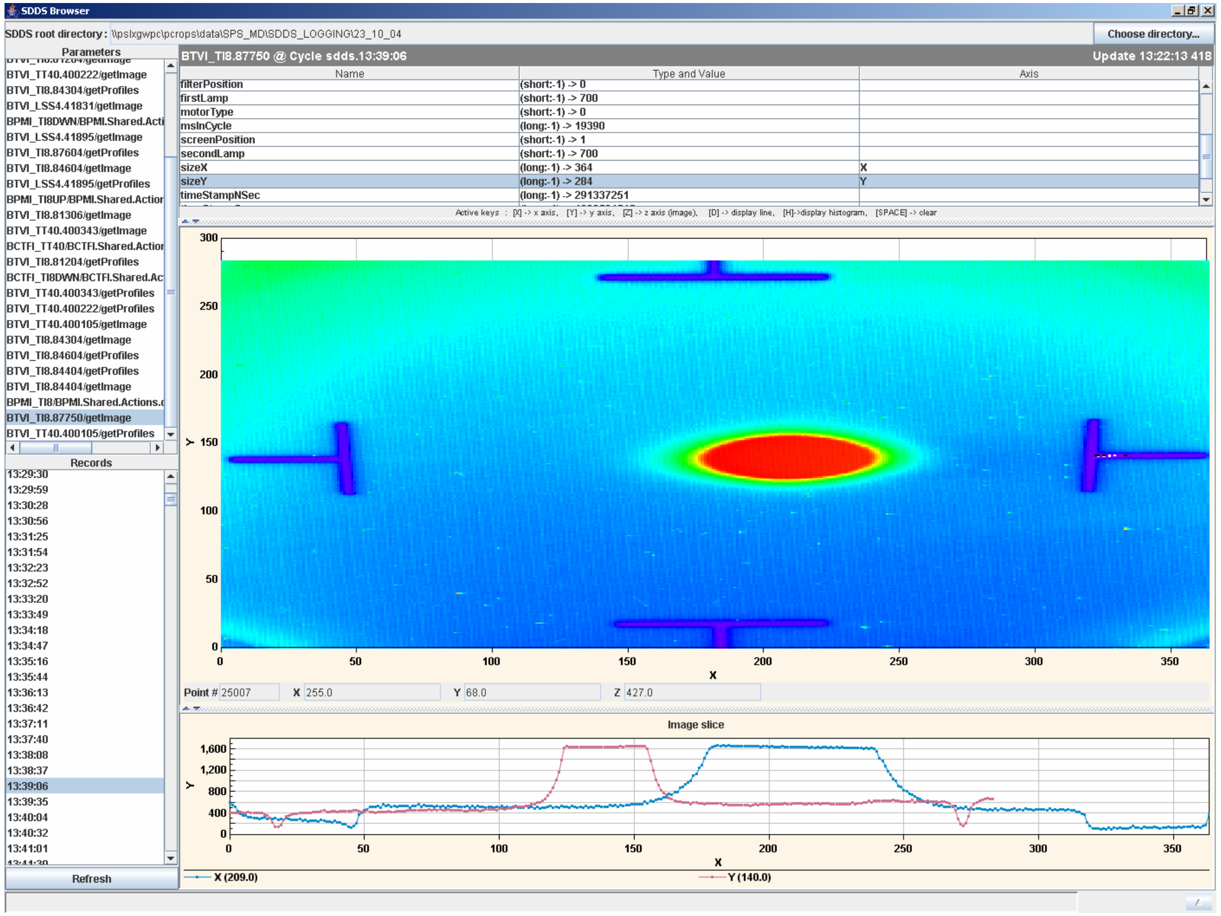


TI8 completed and partly tested

TI 8 Tests

Excellent preparation provided
good optics and tools

Only small problems with
low intensity operation



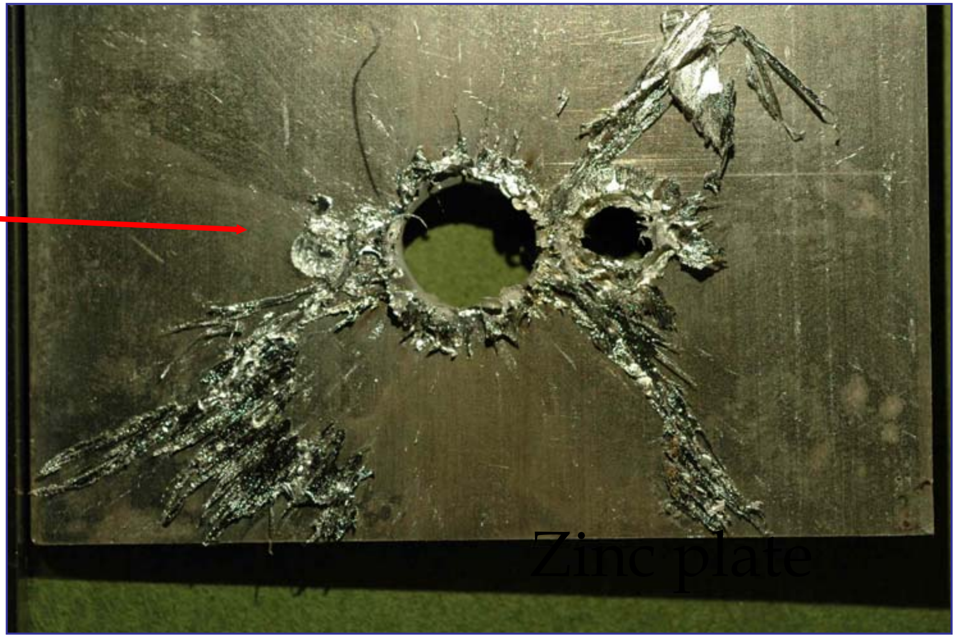
TT40 TED out: First shot all the way down to the TI 8 TED…..

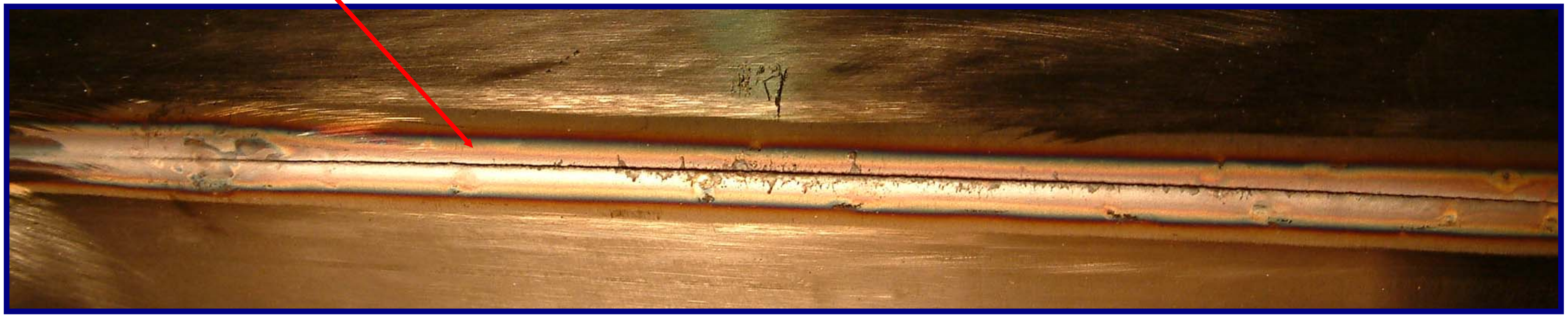
…. through 2.5 km of partially very small beam pipe

Beam impacts

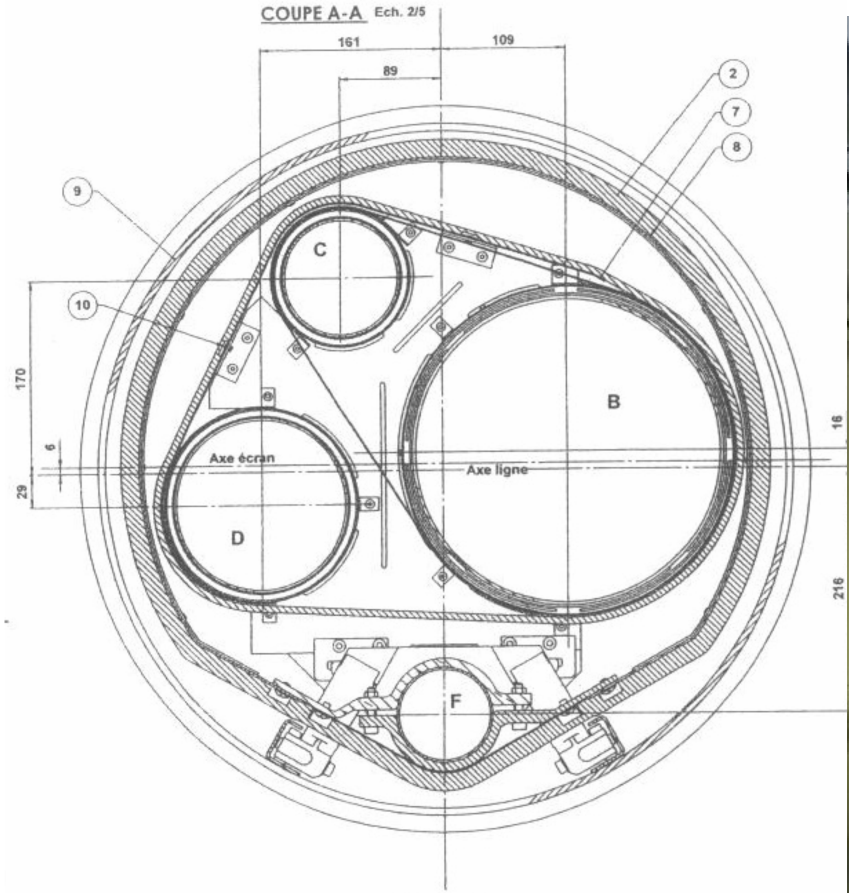
Planned material test: perpendicular impact of 72 nominal LHC bunches

Non-planned material test: grazing incidence of 4 x 72 nominal bunches on QTRF 4002 vacuum chamber





The crisis of the QRL



- We should parallelize the installation in up to 4 fronts
- Cern is committed to repair and reinstall the sector 7-8

Performances limitations

Luminosity:

$$L = \frac{\text{event rate}}{\text{cross section } \square} = \frac{1}{\square} N_1 N_2 k f \frac{\square}{S}$$

protons in a bunch (N_1, N_2); no. of bunches (k); revolution frequency (f); beam cross section (S)

for equal, round, bi-Gaussian beams: $N_1 N_2 = N^2$

S --> 4š σ^2

$$\varepsilon^* = \frac{\sigma^2 \gamma}{\beta^*}$$

invariant emittance (ε^*)

$$L = \frac{N^2 k f \gamma}{4\pi \varepsilon^* \beta^*}$$

$$L = \frac{\gamma}{4\pi\beta^*} \frac{N}{\varepsilon^*} \frac{N}{{}^2t}$$

Transverse beam density: (N/ε^*)

- head-on beam-beam
- space-charge in the injectors
- transfers dilution

Beam current: ($N/{}^2t$)

- long range beam-beam
- collective instability
- synchrotron radiation
- stored beam energy

Head-on beam-beam:

detuning $\xi = \frac{r_p N}{4 \pi \varepsilon^*}$ ξ * nb. of interactions Š 0.02

Limitation of the nominal parameters

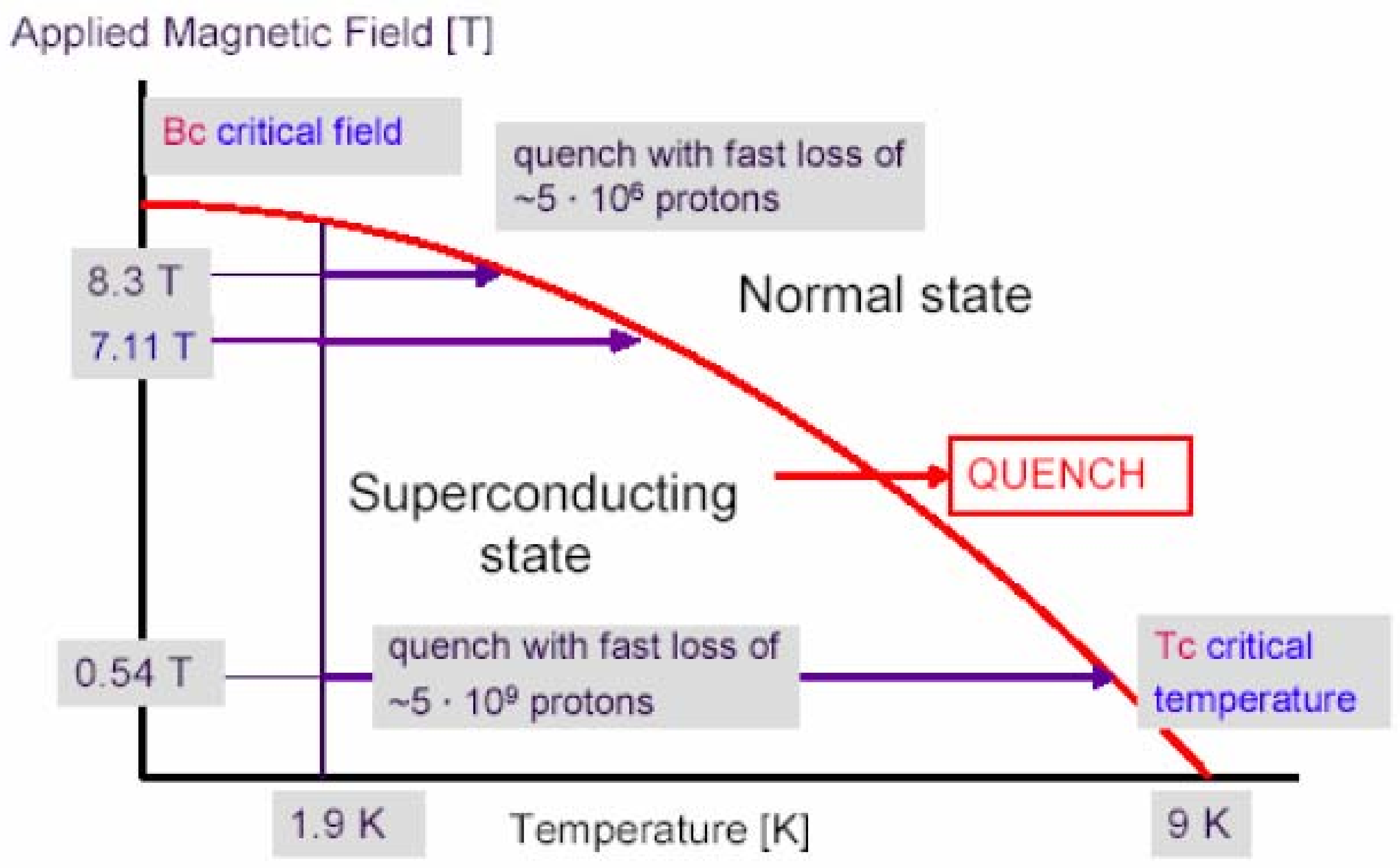
- Dilution kickers 8/20
  - Total intensity ≤ 50 % of the nominal value ($L \leq 0.5 \cdot 10^{34}$)
- Electron cloud
  - Δt = 25 ns => $N_b \leq$ 35 % of the nominal value ($L \leq 1.2 \cdot 10^{33}$)
  - Δt = 75 ns => N_b= nominal value ($L \leq 3.3 \cdot 10^{33}$)
- Collimator optimization
  - $N_b \leq$ 35 % of the nominal value ($L \leq 1.2 \cdot 10^{33}$)

In case of instantaneous beam loss (i.e. in some turns):

- Quench limit $I \leq 5 \cdot 10^{9}$
- Damaging limit $I \leq 2 \cdot 10^{12}$

Beam energy during the running-in

- E_{beam}=6 TeV Larger thermal margin for quenches (factor 2)
- Beam loss control by far more effective to prevent quenches



Possible steps of the running-in

- k = 43 (or 86), equidistant bunches
- Deep test of the accelerator
- Physics in parasitic mode L = $2 \cdot 10^{26}$ up to $1.2 \cdot 10^{31}$ $cm^{-2}s^{-1}$

- k = 936, bunches in nominal trains
- Multi-bunch operation
- Towards β-sqeezing and nominal crossing angle
- Beam screen scrubbing
- Towards nominal i_b
- Physics in parasitic mode L = $5 \cdot 10^{32}$ up to $2.5 \cdot 10^{33}$ $cm^{-2}s^{-1}$ (pile-up > 10)

6 months shut-down for hardware improvement ?

k = 2808, bunches in nominal trains
- Completion of the scrubbing runs
- Physics in nominal conditions L = $2.5 \cdot 10^{33}$ up to $1 \cdot 10^{34}$ $cm^{-2}s^{-1}$ (and beyond)

My forecast

Evolution of L from t_0 to t_0+6 months:

- Physics in parasitic mode (duty factor < 50%, i.e. ~ 10 h per day)
- $L_0 = 10^{31}\ cm^{-2}s^{-1}$ / ev. per xing ~ 1 (-> k = 43, β^* = 6.0 m, $N_b = 0.9\ 10^{11}$)
- $L_{0+6months} = 0.5 \cdot 10^{33}\ cm^{-2}s^{-1}$ / ev. per xing ~ 2 (-> k = 936, β^* = 1.0 m, $N_b = 0.5\ 10^{11}$, $\phi \leq 300\ \mu rad$)

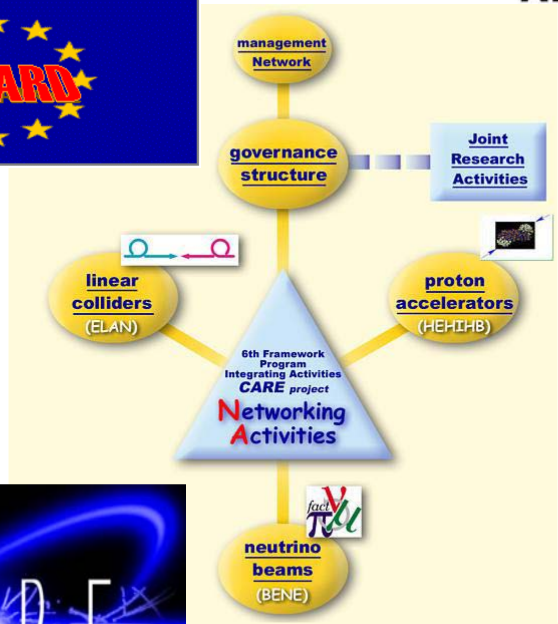
Assuming

- Lifetime 10 h
- $\langle L_0 \rangle = 10^{32}\ cm^{-2}\ s^{-1}$
- Running time 10 h per day

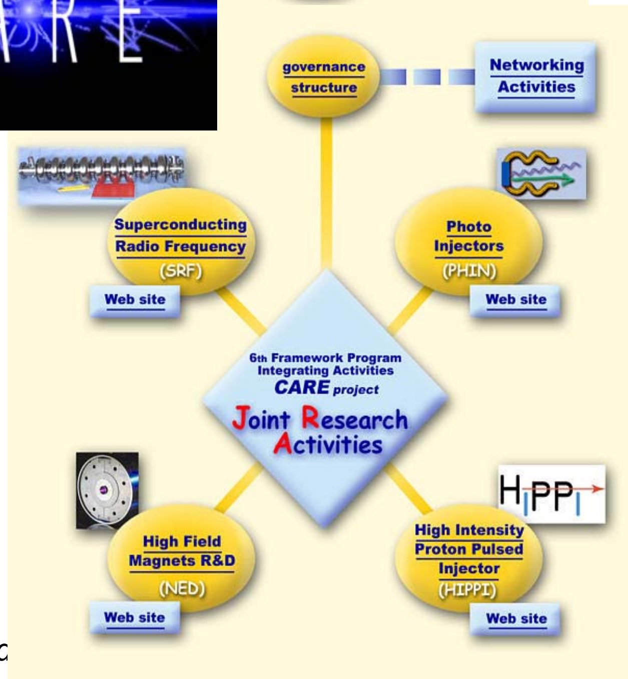
-->> $4 \cdot 10^{38}\ cm^{-2}$ after 200 days (within one order of mag.?)

The future

HHH2004
First CARE-HHH-APD-Workshop
Beam Dynamics in Future Hadron Colliders and
Rapidly Cycling High Intensity Synchrotrons
Geneva, 8-11 November 2004
http://care-hhh.web.cern.ch/CARE-HHH/HHH-2004
This workshop is organized by the "Accelerator Physics and synchrotron Design" (APD) collaboration of the CARE-HHH European Network on "High Energy High Intensity Hadron Beams"
It will be followed by a general meeting of the HHH Network
Local Organizing Committee
Francesco Ruggiero
Walter Scandale
Frank Zimmermann
Per Hagen
Claudine Bosteels
Juliette Thomashausen
conf-hhh-2004@cern.ch
Goals of the workshop
- Identify critical items for LHC luminosity improvements and for high intensity proton rings based on fast cycling magnets
- Sketch scenarios for an upgrade of the LHC IR regions and injectors
- Discuss benchmarking and common repository of simulations/design tools
- Launch a critical analysis of alternative LHC upgrade scenarios, establish a list of pros and cons including beam dynamics and technology constraints, to narrow down the choice of the best scenario
Scope
- Beam optics and Interaction Region magnet layout
- Beam intensity limitations
- Duty cycle limitations in connection with LHC upgrade and GSI project
CARE-HHH

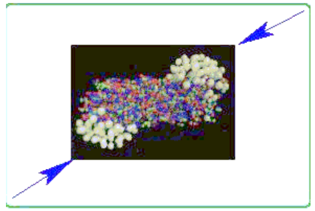


management Network
governance structure
Joint Research Activities
linear colliders (ELAN)
proton accelerators (HEHIHB)
6th Framework Program Integrating Activities CARE project
Networking Activities
neutrino beams (BENE)



governance structure
Networking Activities
Superconducting Radio Frequency (SRF)
Web site
Photo Injectors (PHIN)
Web site
6th Framework Program Integrating Activities CARE project
Joint Research Activities
High Field Magnets R&D (NED)
Web site
High Intensity Proton Pulsed Injector (HIPPI)
Web site

The CARE-HHH Network



Mandate

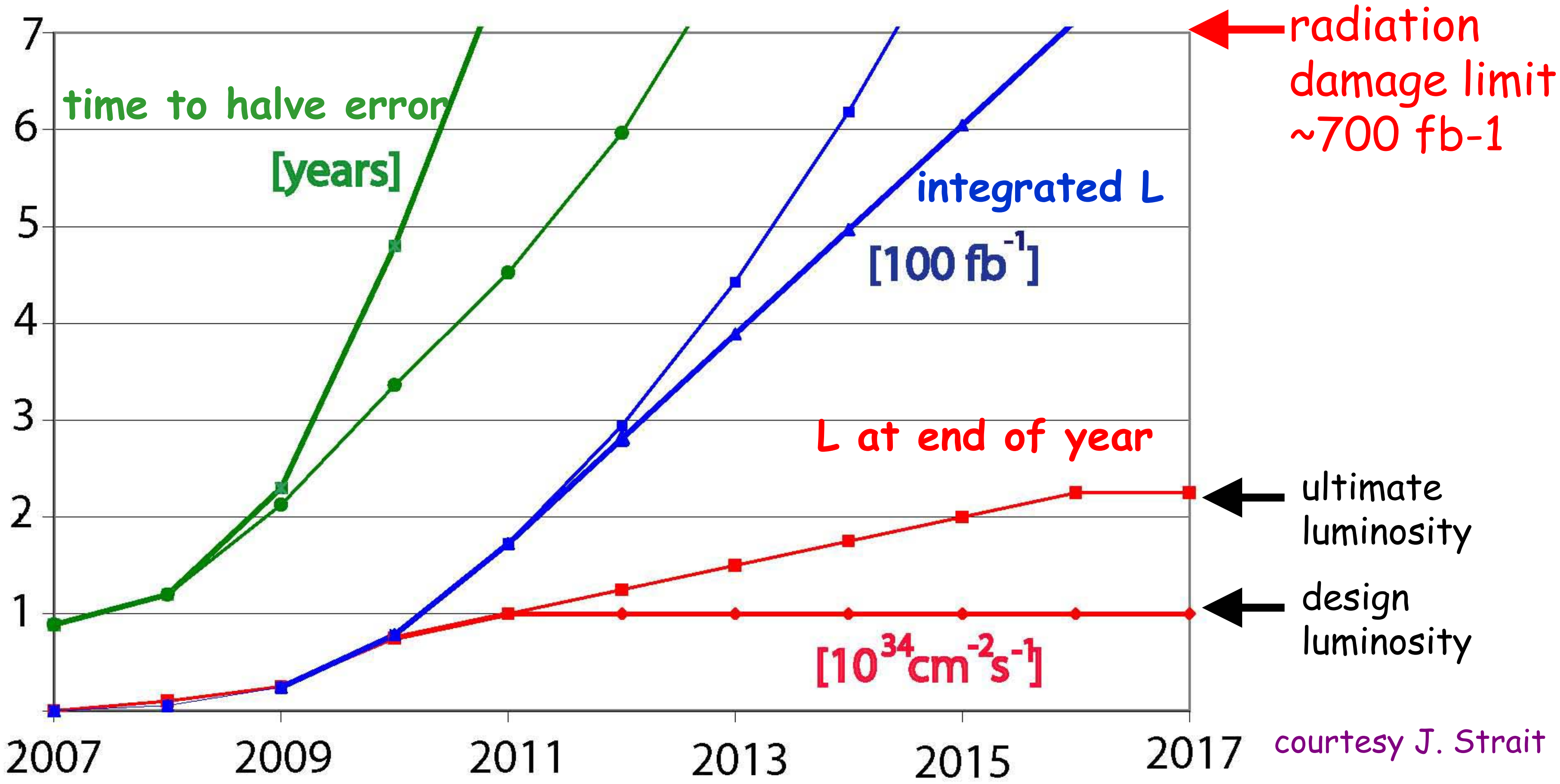
Coordinate and integrate the activities of the accelerator and particle physics communities, in a worldwide context, towards achieving superior High-Energy High-Intensity Hadron-Beam facilities for Europe

- Roadmap for the upgrade of the European accelerator infrastructure (LHC and GSI accelerator complex)
  - luminosity and energy upgrade for the LHC
  - pulsed SC high intensity synchrotrons for the GSI and LHC complex
  - R&D and experimental studies at existing hadron accelerators
  - select and develop technologies providing viable design options
- Coordinate activities and foster future collaborations
- Disseminate information

- **HHH coordination: F. Ruggiero (CERN) & W. Scandale (CERN)**

1. Advancement in Acc. Magnet Technology (AMT): L. Rossi (CERN) & L. Bottura (CERN)
2. Novel Meth. for Acc. Beam Instrumentation (ABI): H. Schmickler (CERN) & K. Wittenburg (DESY)
3. Accelerator Physics and Synchrotron Design (APD): F. Ruggiero (CERN) & F. Zimmermann (CERN)

time scale of LHC upgrade



(1) *life expectancy of LHC IR quadrupole magnets* is estimated to be <10 years due to high radiation doses

(2) the *statistical error halving time* will exceed 5 years by 2011-2012

(3) therefore, it is reasonable to plan a *machine luminosity upgrade based on new low-ß IR magnets before ~2014*

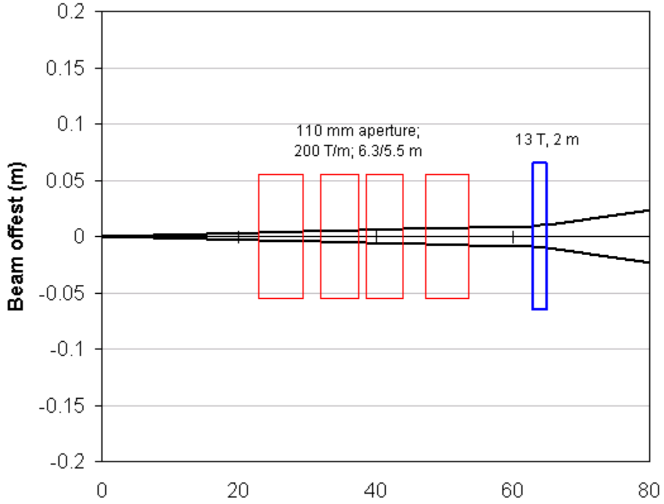
various LHC upgrade options

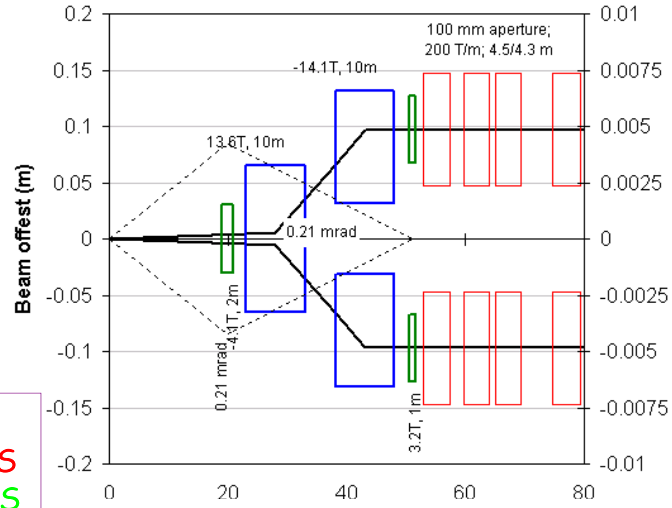
parameter	symbol	nominal	ultimate	shorter bunches		longer bunches
#bunches	n_b	2808	2808	4680	7020	936
protons/bunch	N_b [10^{11}]	1.15	1.7	1.7		6.0
bunch spacing	Δt_{sep} [ns]	25	25	15	10	75
average current	I [A]	0.58	0.86	1.43	2.15	1.0
norm. transv. emittance	ε_n [μm]	3.75	3.75	3.75		3.75
longit. profile		Gaussian	Gaussian	Gaussian		uniform
rms bunch length	σ_z [cm]	7.55	7.55	3.78		14.4
beta at IP1&IP5	β^* [m]	0.55	0.5	0.25		0.25
crossing angle	θ_c [μrad]	285	315	445		430
Piwinski parameter	$\theta_c\sigma_z/(\sigma^* 2)$	0.64	0.75	0.75		2.8
luminosity	L [10^{34} cm^{-2}s^{-1}]	1.0	2.3	7.7	11.5	8.9
events/ crossing		19	44	88		510

IR based on High Fields Magnets with reduced ß*

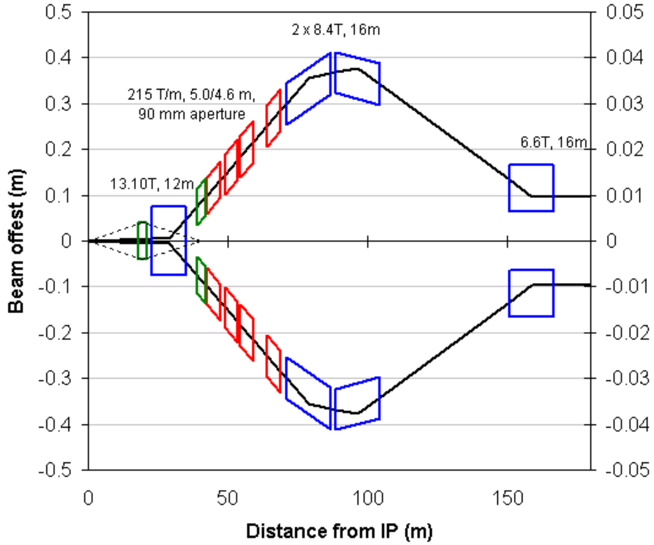
New Interaction Regions with Nb_3Sn magnets:
beam dynamics versus magnet technology and design

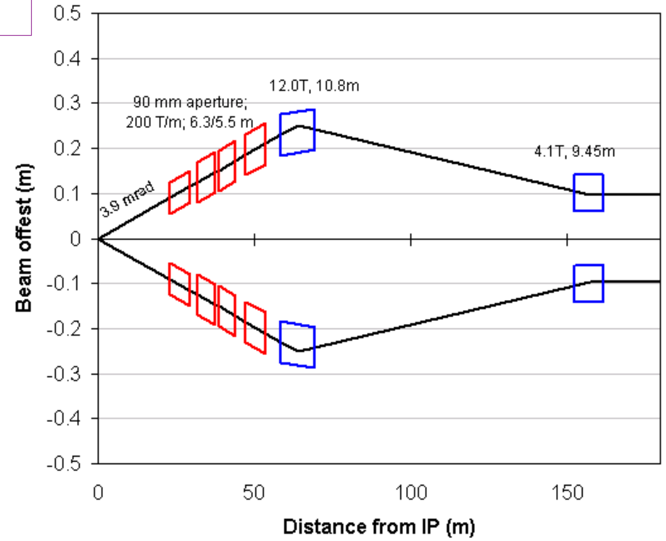
See PAC03 pp 42-44





blue DIPOLES
red QUADRUPOLES
green RF-CAVITIES



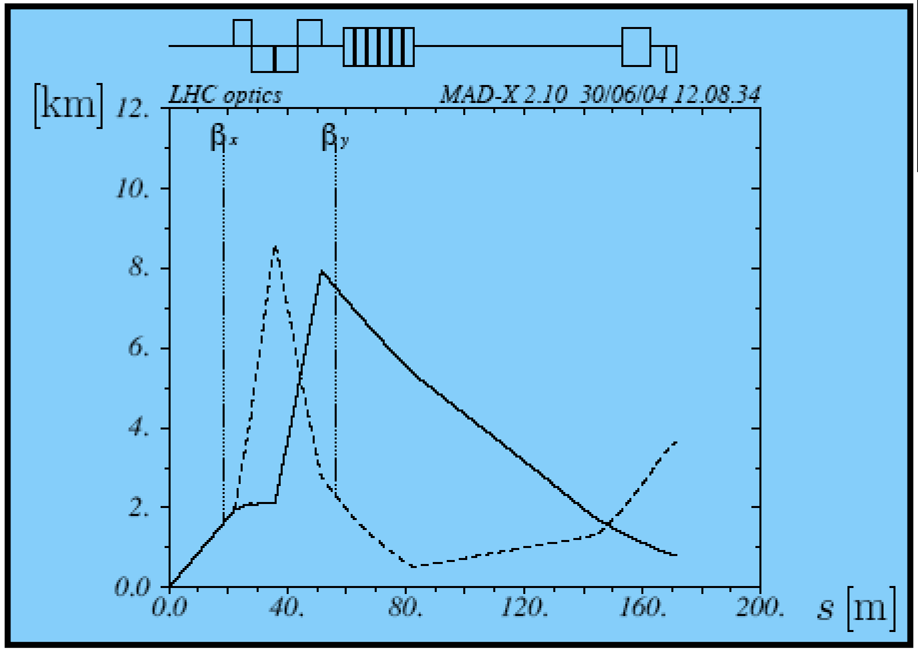


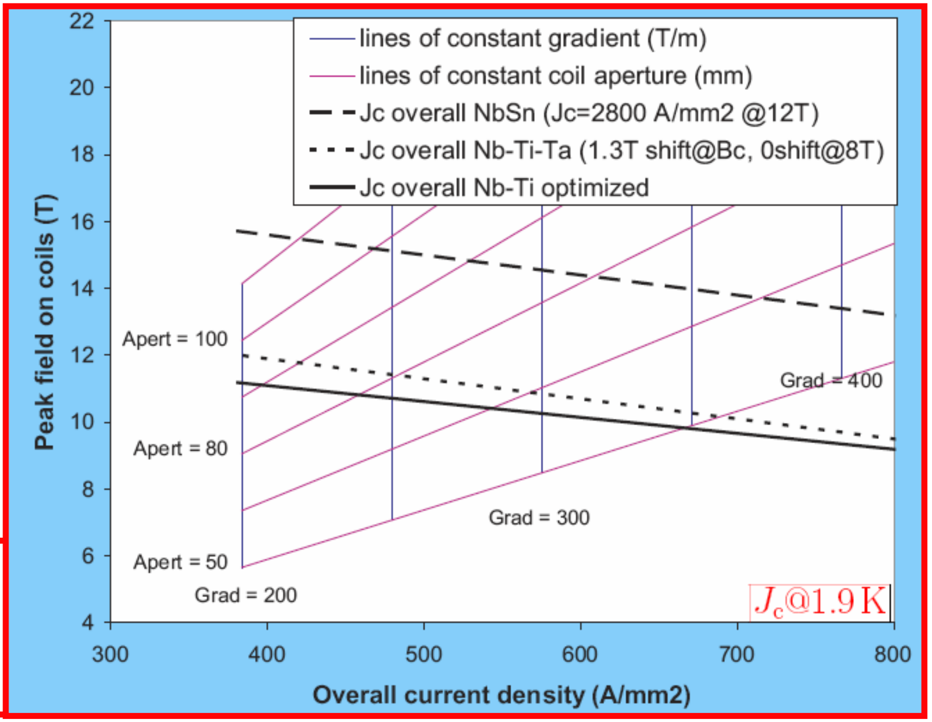
The 'poor man' way: LHC-IR upgrade with new NbTi quadrupoles -> β^*=0.25 m

See EPAC 04 pp 608-10

The quadrupole aperture is matched to the real beam size

quad	length m	gradient at 7 TeV T/m	coil aperture mm
Q1	6.0	275	53
Q2	7.4	197	85
Q3	7.8	196	82





Comparison between NbTi, NbTiTa and Nb_3Sn conductors

Beam Density Increase

Possible upgrade of the injector chain

Poor-man way: RF upgrade for batch compression in the PS

Rich-man way:

- Up to 160 MeV: LINAC 4
- Up to 2.2 GeV: the SPL (or a super-BPS)

→ See CARE-HIPPI

The superconducting way:

- Up to 60 GeV a SC super-PS
- Up to 1 TeV a super SPS
- SC transfer lines to LHC

The normal conducting way:

- Up to 30 GeV a refurbished PS
- Up to 450 GeV a refurbished SPS

→ See CARE-HHH and CARE-NED

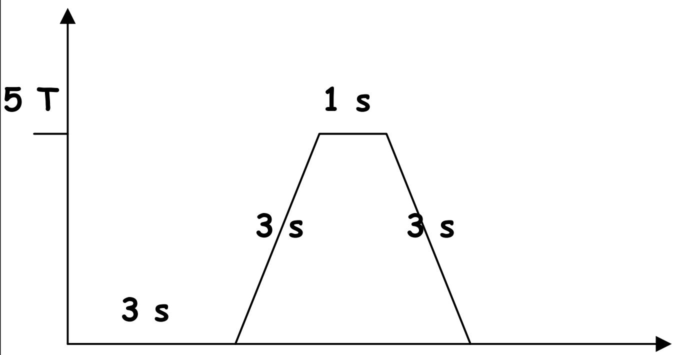
A 1 TeV booster ring in the LHC tunnel may also be considered

- Easy magnets (super-ferric technology?)
- Difficult to cross the experimental area (a bypass needed?)

Technological Challenges

in upgrading the injectors with Sc magnets

Tentative SPS cycle



- A SC dipole for the SPS may produce 70 W/m peak (35 W/m effective ⇒ 140 kW for the SPS, equivalent to the cryogenic power of the LHC !)
- A rather arbitrary 'guess' for beam loss is of about 10^{12}px100GeV/10s= 15 kW
- By dedicated R&D magnet losses should be lowered to 10 W/m peak (5 W/m effective ⇒ 20 kW), comparable to expected beam loss power

Losses are a major concern -> Vigorous R&D program needed

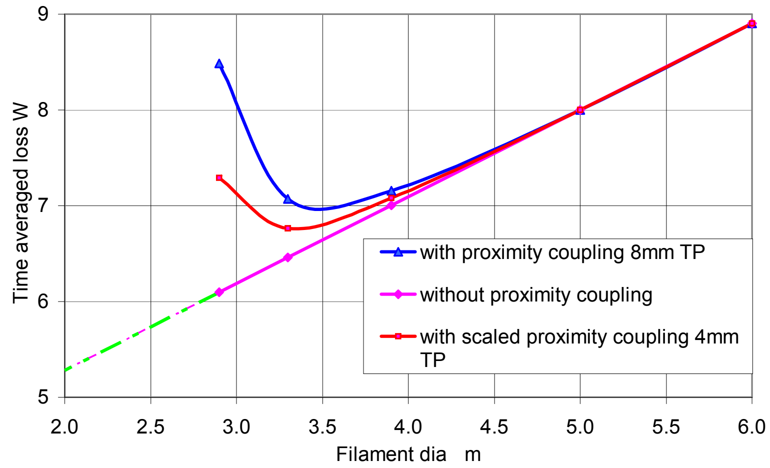
- Study and evaluate different scenarios of beam losses in PS and SPS
- Study and evaluate a maximum allowed cryogenic budget
- Optimize the dipoles not only for good quench performance in condition of cable/iron losses, but also for cryogenic budget

Small filament size wire R&D

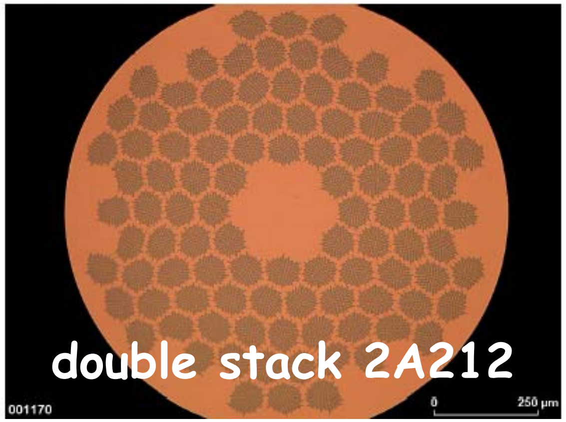
Motivation: 60 -70% of the coil AC- losses caused by wire magnetization

- filament size reduction
- but limit due to 'proximity coupling'

  $d_{fil} \geq 3.5\mu m$ for Copper matrix

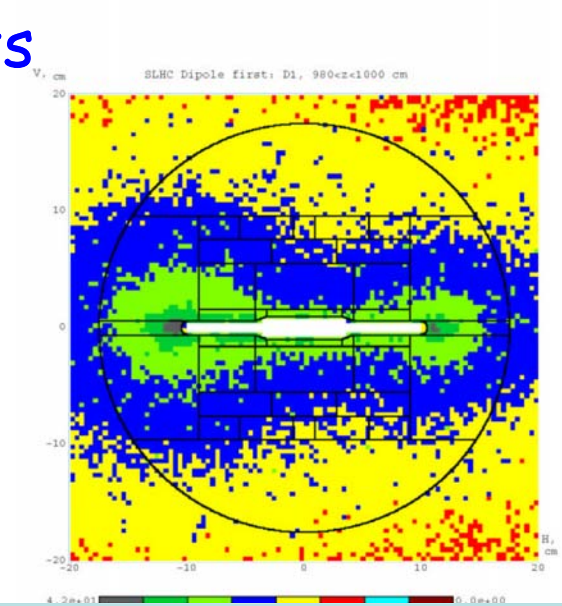


d_{eff} = 3.5 μm, but problems with stacking of 12000 monocores (1.5 mm wide)



d_{eff} = 4.8 μm due to filament distortion (near the copper)

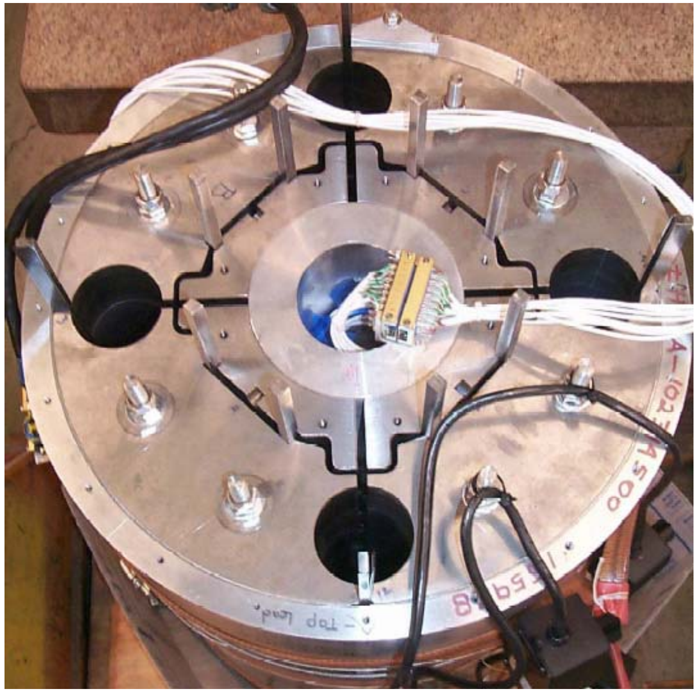
US-LARP developments



Thermal loss calculations from Mokhov

- Nb_3Sn dipole
  - Large aperture, asymmetric
  - Non-cos-theta
  - Split coil geometry

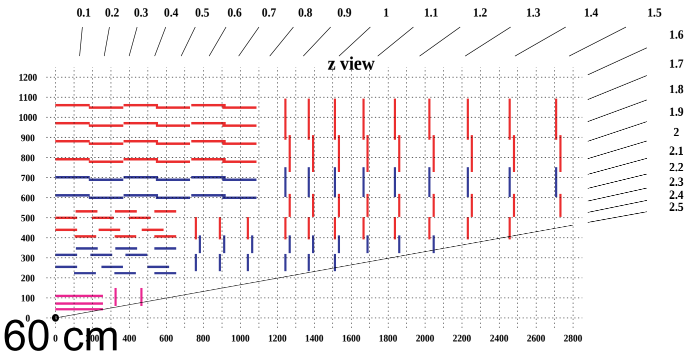
High field (~15T), long (~10m), large radiation heat load (~9 kW) into 70 K



- Nb_3Sn quadrupole
  - Dual-bore
  - Large aperture
- Support Structure
  - Key-bladder-shell
  - Coil-yoke-skin

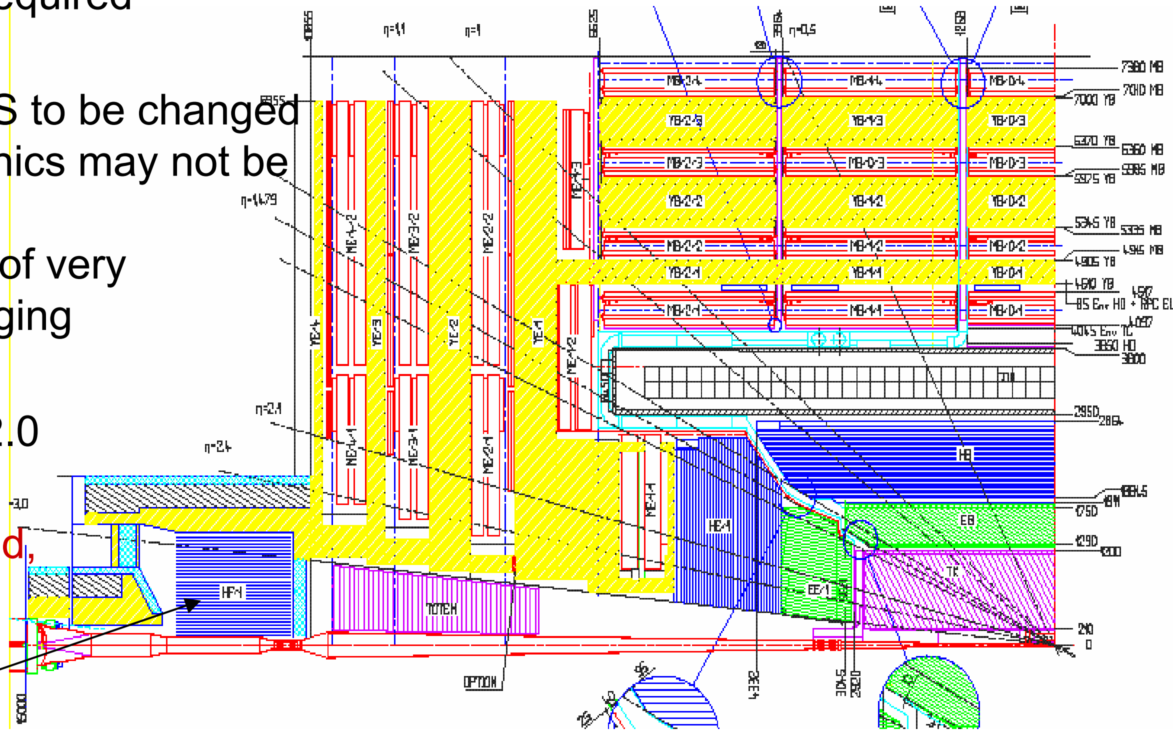
Foreseeable changes to detectors for $10^{35} cm^{-2} s^{-1}$

Courtesy of D. Denegry



changes to CMS and ATLAS :

- Trackers, to be replaced due to increased occupancy to maintain performance, need improved radiation hardness for sensors and electronics
  - present Si-strip technology is OK at R > 60 cm
  - present pixel technology is OK for the region ~ 20 < R < 60 cm
  - at smaller radii new techniques required
- Calorimeters: ~ OK
  - endcap HCAL scintillators in CMS to be changed
  - endcap ECAL VPT's and electronics may not be enough radiation hard
  - desirable to improve granularity of very forward calorimeters - for jet tagging
- Muon systems: ~ OK
  - acceptance reduced to $|\eta|$ <~ 2.0 to reinforce forward shielding
- Trigger(L1), largely to be replaced, L1(trig.elec. and processor) for 80 MHz data sampling



VF calorimeter for "jet tagging"

Conclusion

In July 2007, LHC should be ready to produce collisions (at low luminosity, probably at 12 TeV energy in the centre of mass)

In 2008, it should be possible to start operating lead-lead collisions.

Later the luminosity and the energy will increase as the more sophisticated technologies will be better mastered, i.e.

- Magnets operation,
- Halo control and collimation,
- Electron cloud reduction
- Beam dump control
- Optics control,
- Multi-bunches and high intensity operation
- Control of the beam-beam interaction
- Hardware upgrade etc…

In the next decade, the upgrade of the LHC and its injector chain may become the next challenging duty for the high energy physics community.