Techniczne aspekty LHC

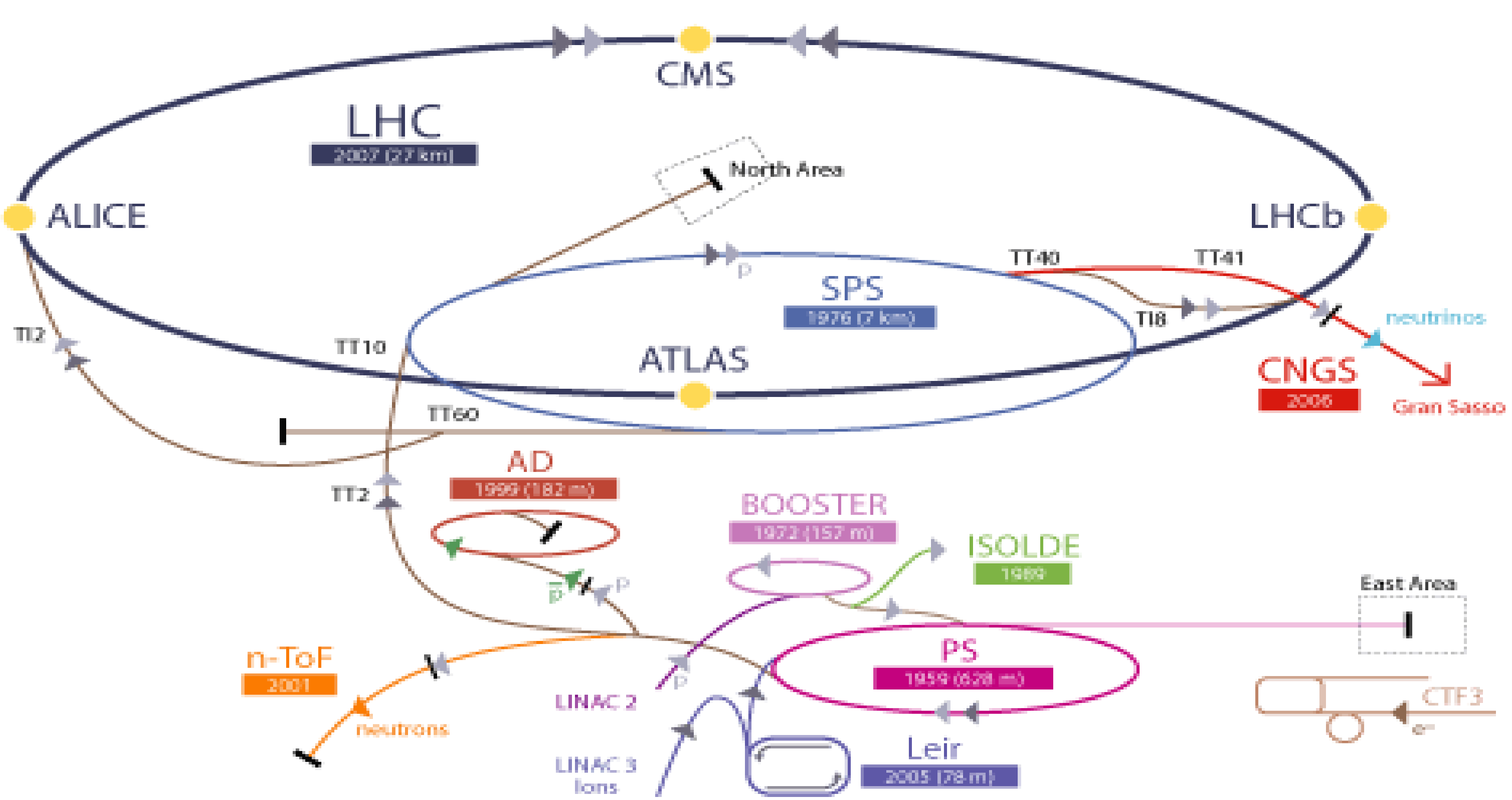
(Large Hadron Collider)

Jan Kulka

27-02-2009

- - Zespół akceleratorów wokół LHC
- - Podstawowe systemy LHC oraz udział WFiIS AGH w uruchomieniu
  - Magnesy dipolowe i kwadrupolowe
  - Obwody kriogeniczne
  - Systemy ochrony magnesów i systemy ekstrakcji energii
  - Klimatyzacja i wentylacja
- - Uruchomienie LHC
- - Awarie
- - Perspektywy

CERN Accelerator Complex



p (proton) ion neutrons $\bar{p}$ (antiproton) neutrinos electron

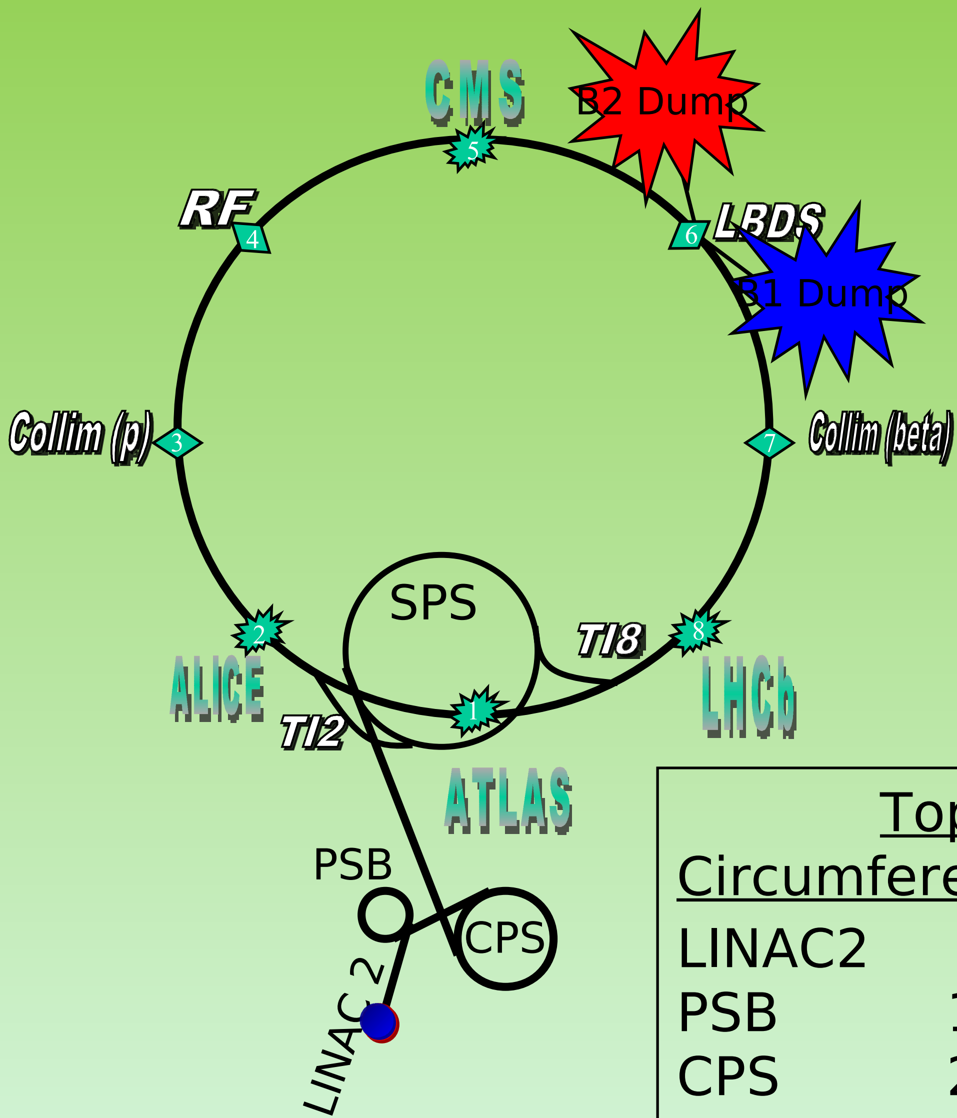
proton/antiproton conversion

LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility

CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight



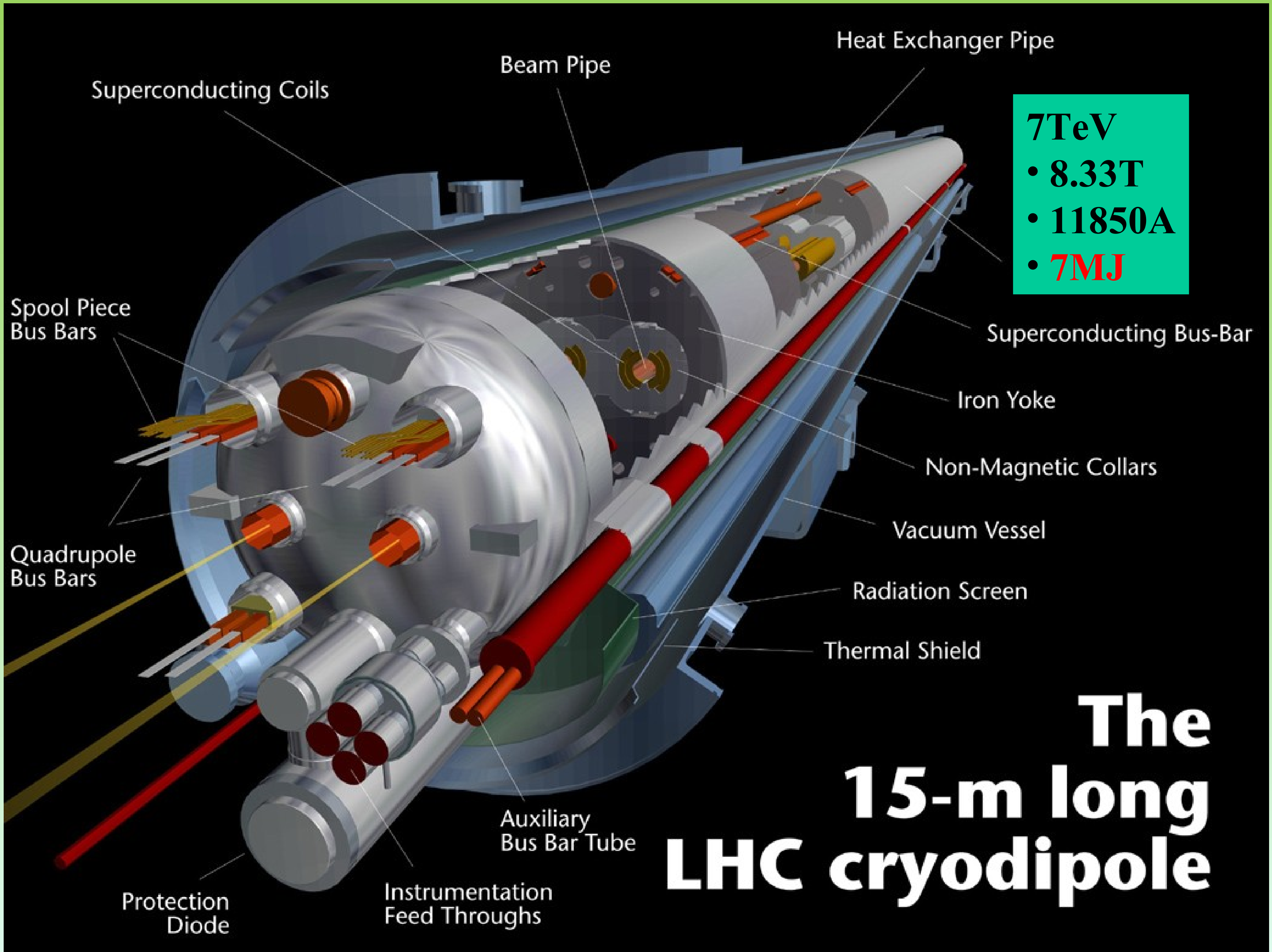
	Top energy(GeV)	Circumference(m)
LINAC2	0.12	30
PSB	1.4	157
CPS	26	628 = 4 PSB
SPS	450	6911 = 11 x PS
LHC	**7000**	**26657 = 27/7xSPS**

Ważniejsze daty LHC

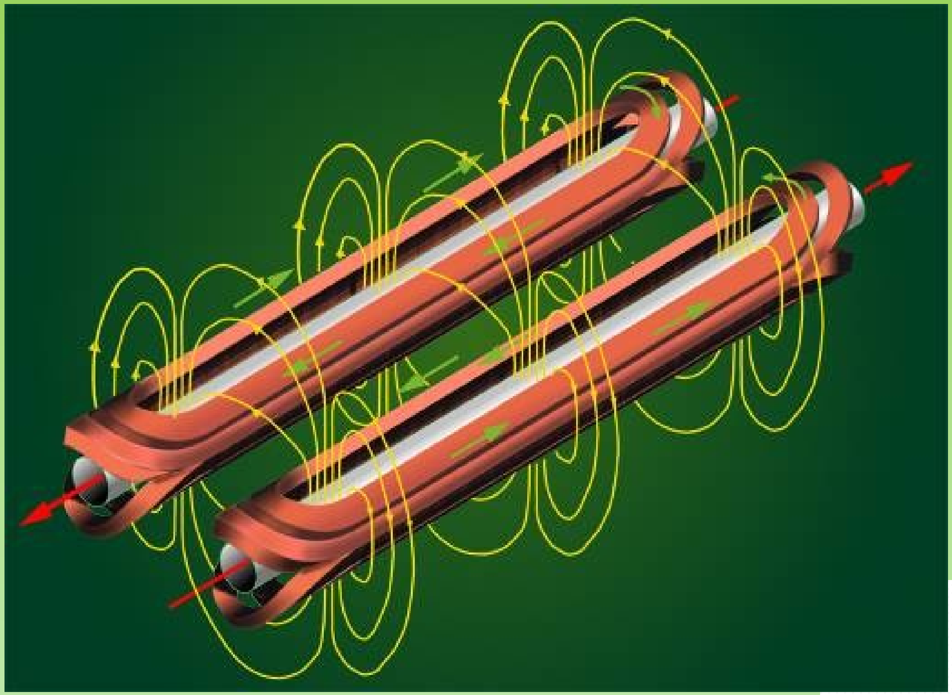
- 1982 : Pierwsze prace studialne nad LHC
- 1994 : Zatwierdzenie LHC przez CERN Council
- 1996 : Ostateczne decyzja o konstrukcji LHC *(7TeV)*
- 2003 : Rozpoczęcie instalacji LHC
- 2006 : Rozpoczęcie odbioru technicznego
- 2007 : Zakończenie instalacji i start chłodzenia

- 🡐1984 : Rozpoczęcie budowy LEP
- 🡐1989 : Uruchomienie LEP
- 🡐1995 : Rozpoczęcie prac przy budowie hal eksperymentów LHC
- 🡐2000 : Koniec działania LEP

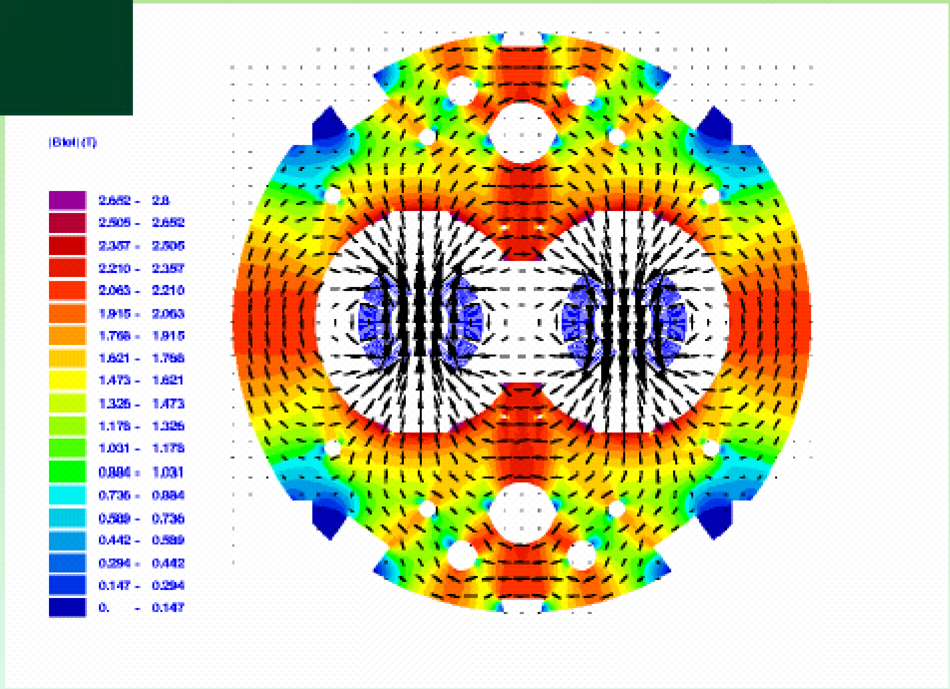
Magnes dipolowy, jeden z 1232 w LHC, temp. pracy 1,9K



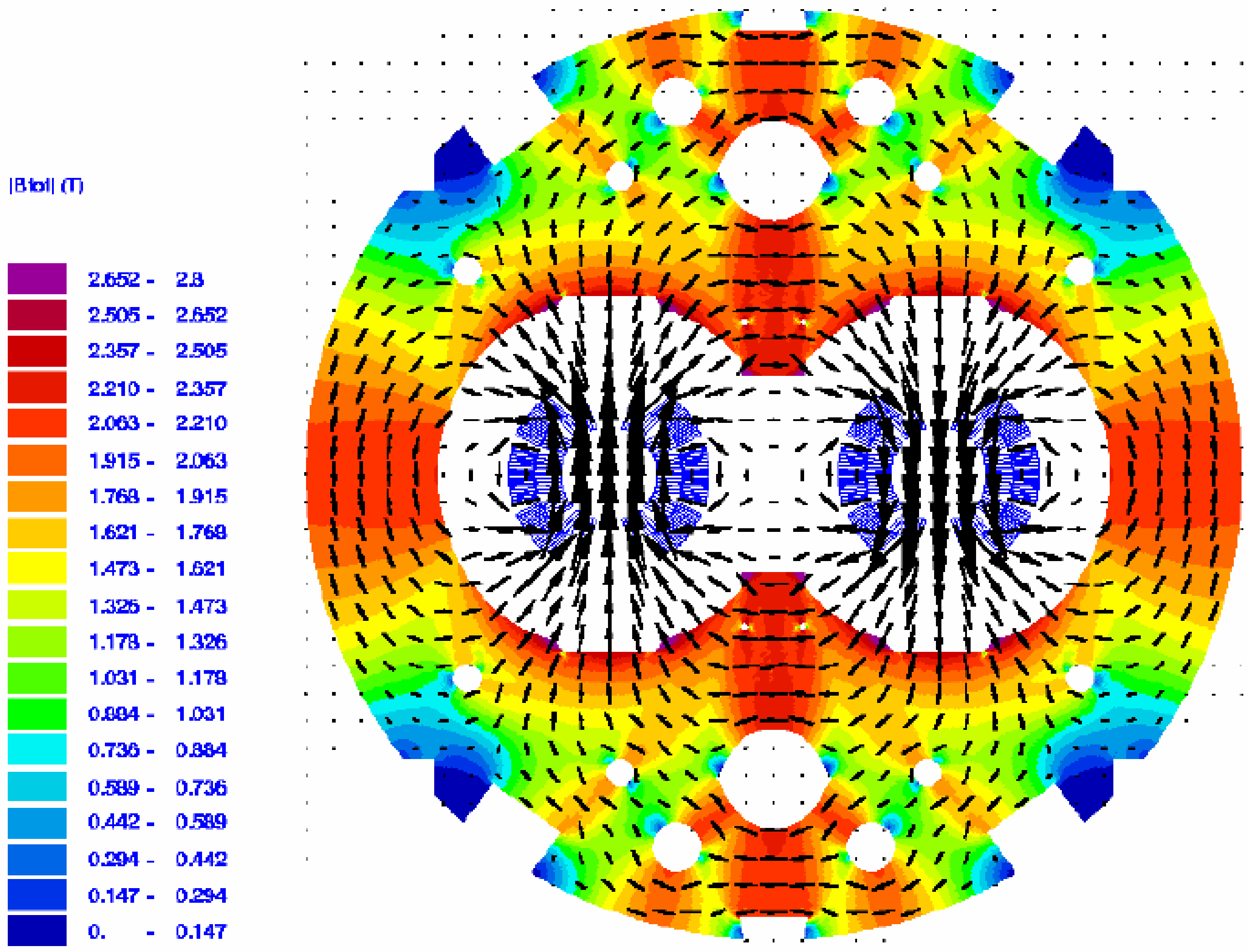
Magnesy dipolowe LHC



- Energia każdej paczki protonów- 7TeV ⬄ Indukcja w dipolu 8.33T



Indukcja magnetyczna w dwu-aperturowym dipolu

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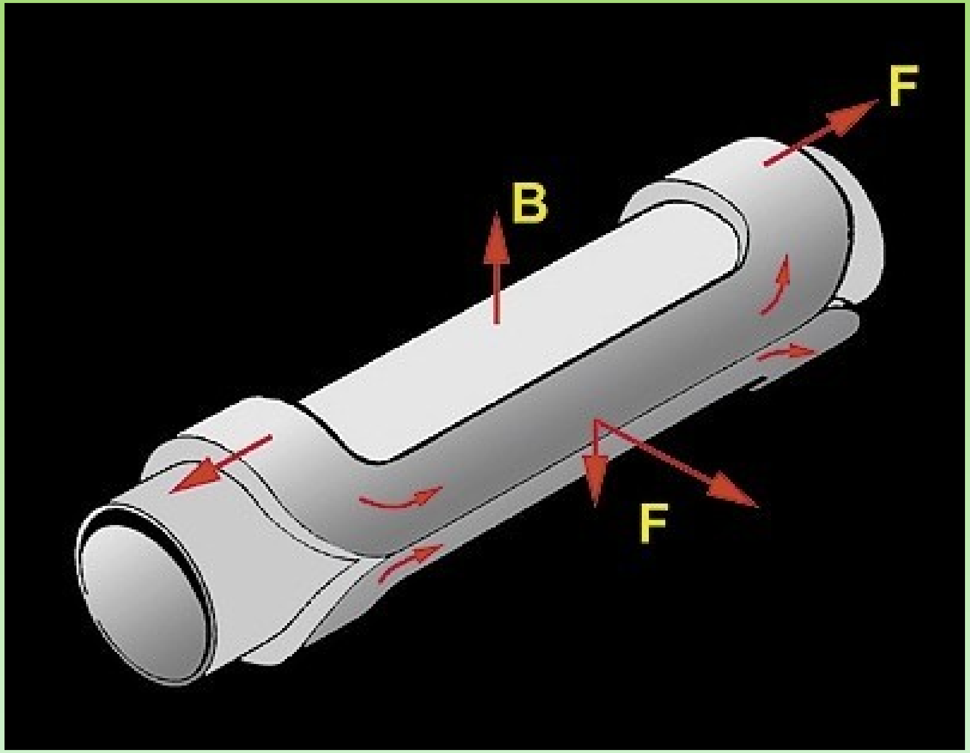
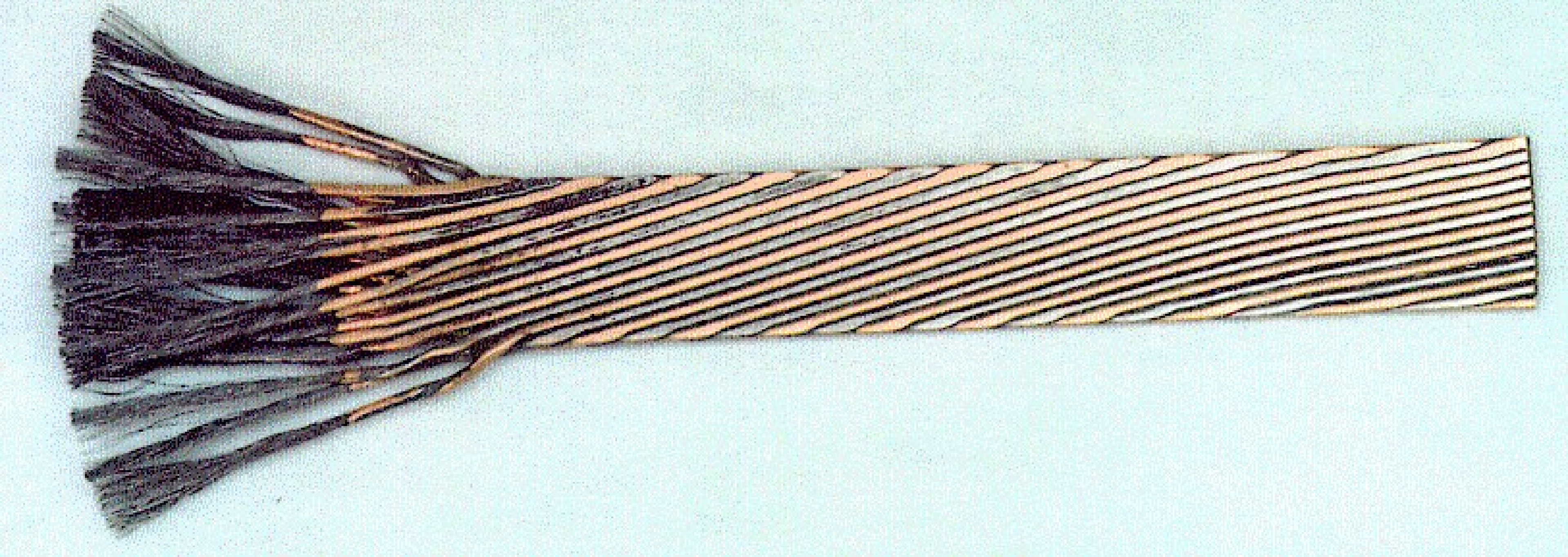
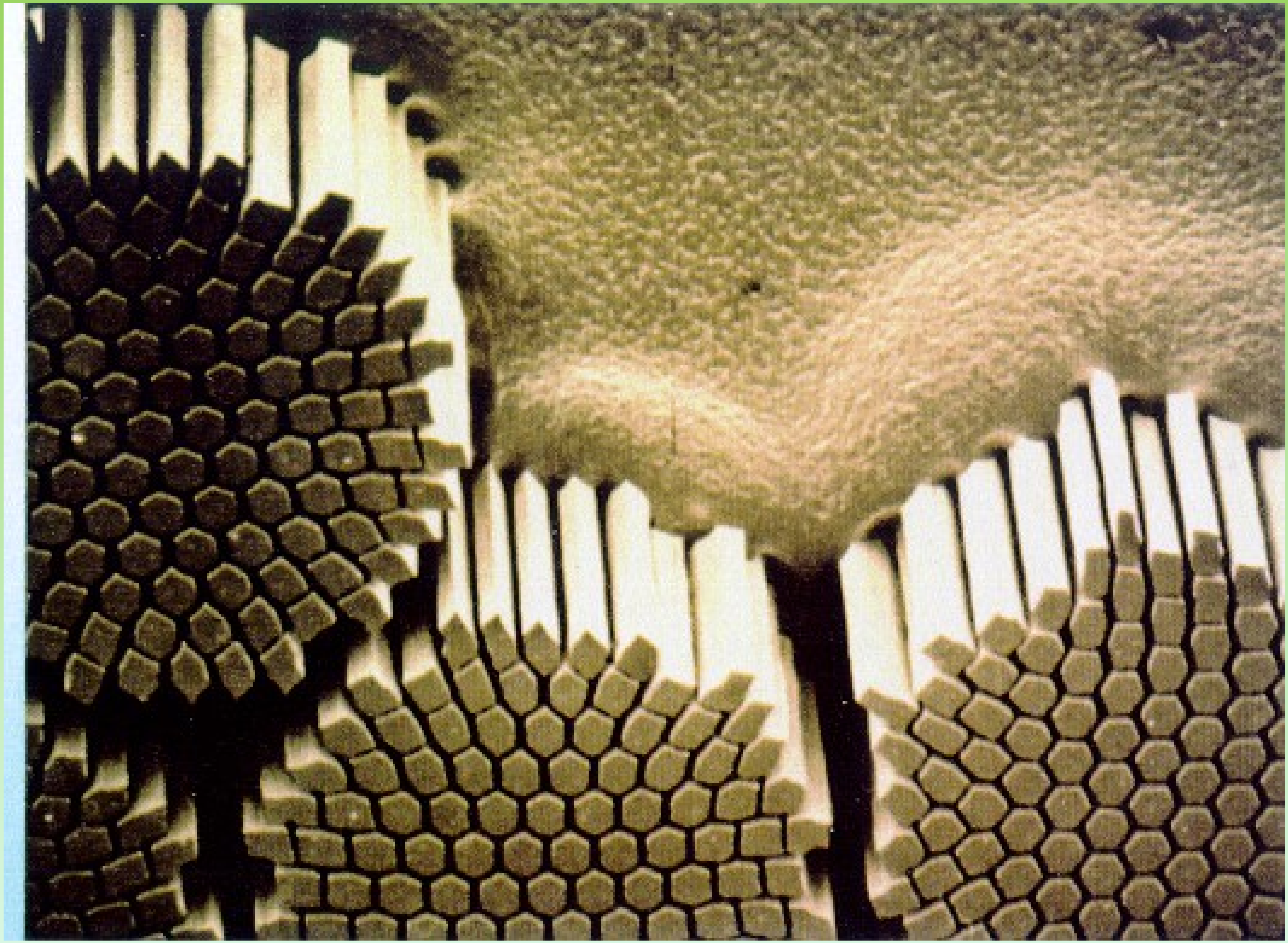
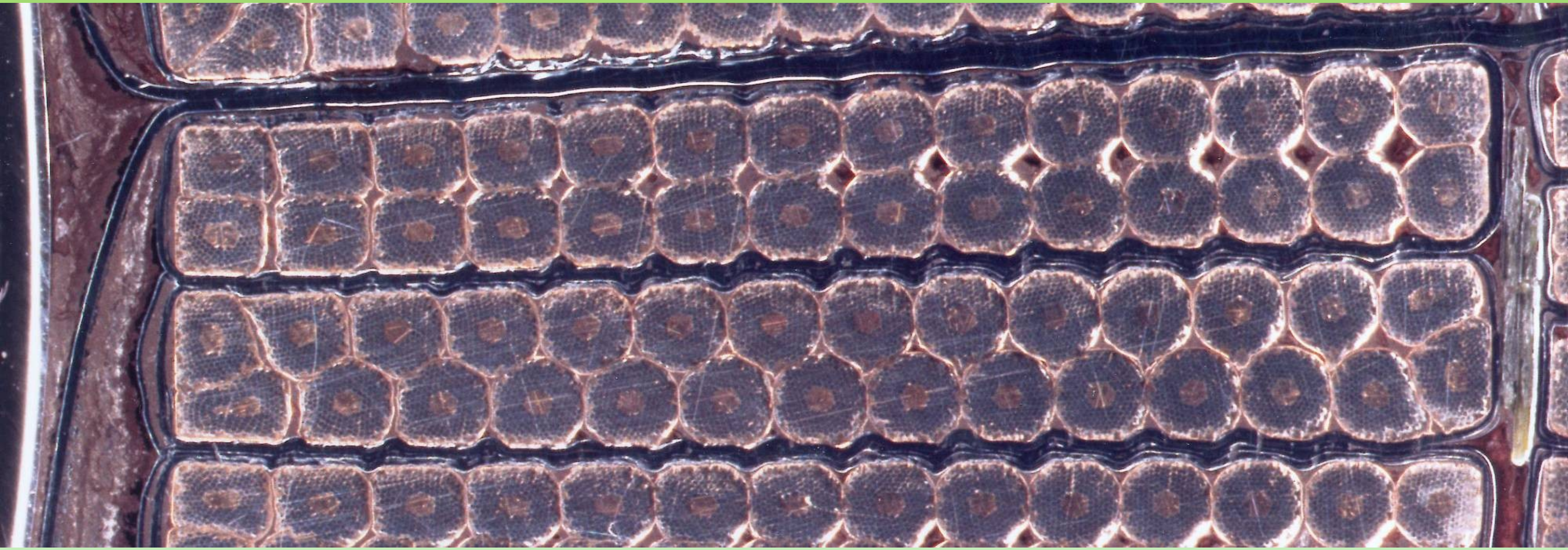
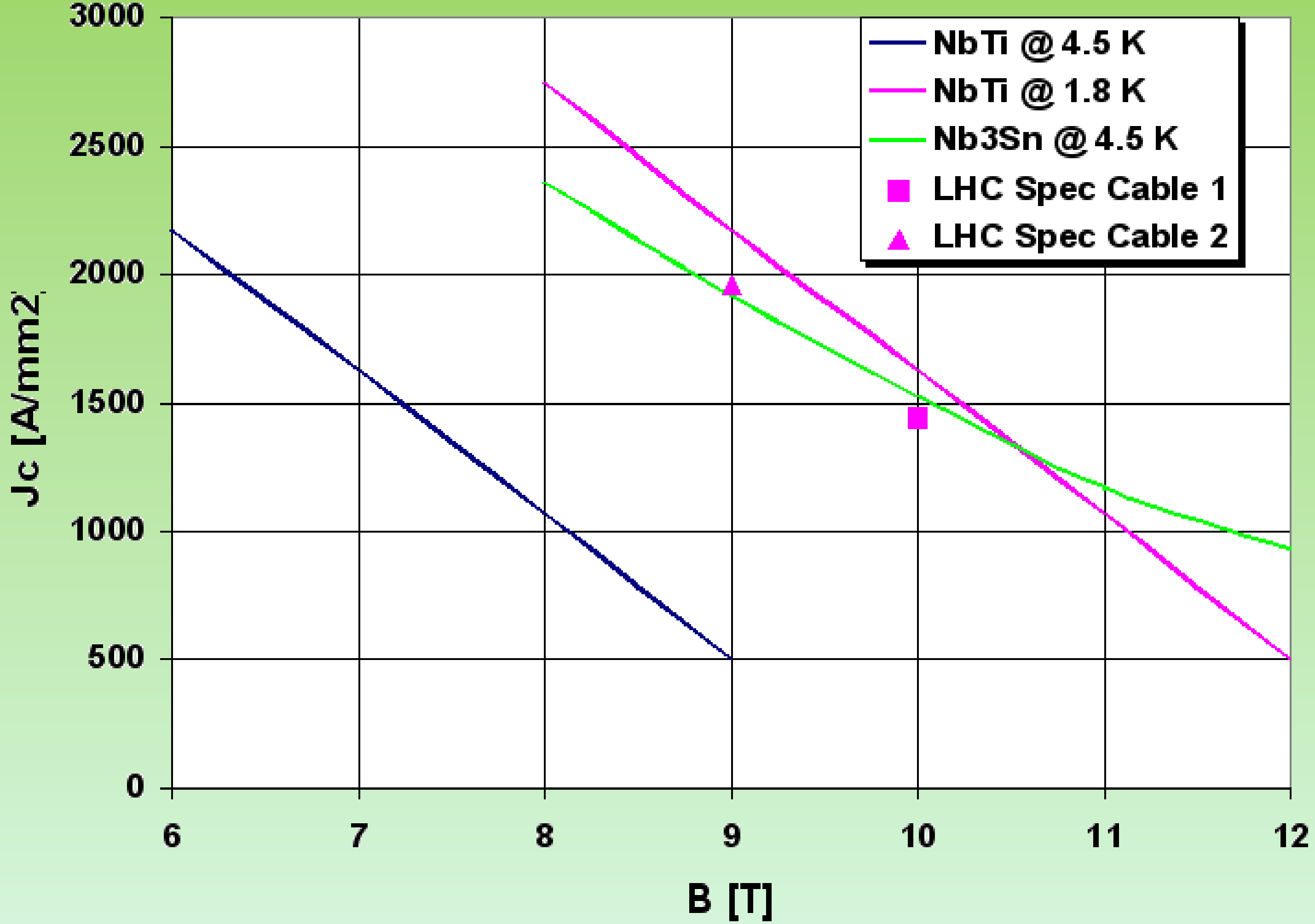

F
B
F



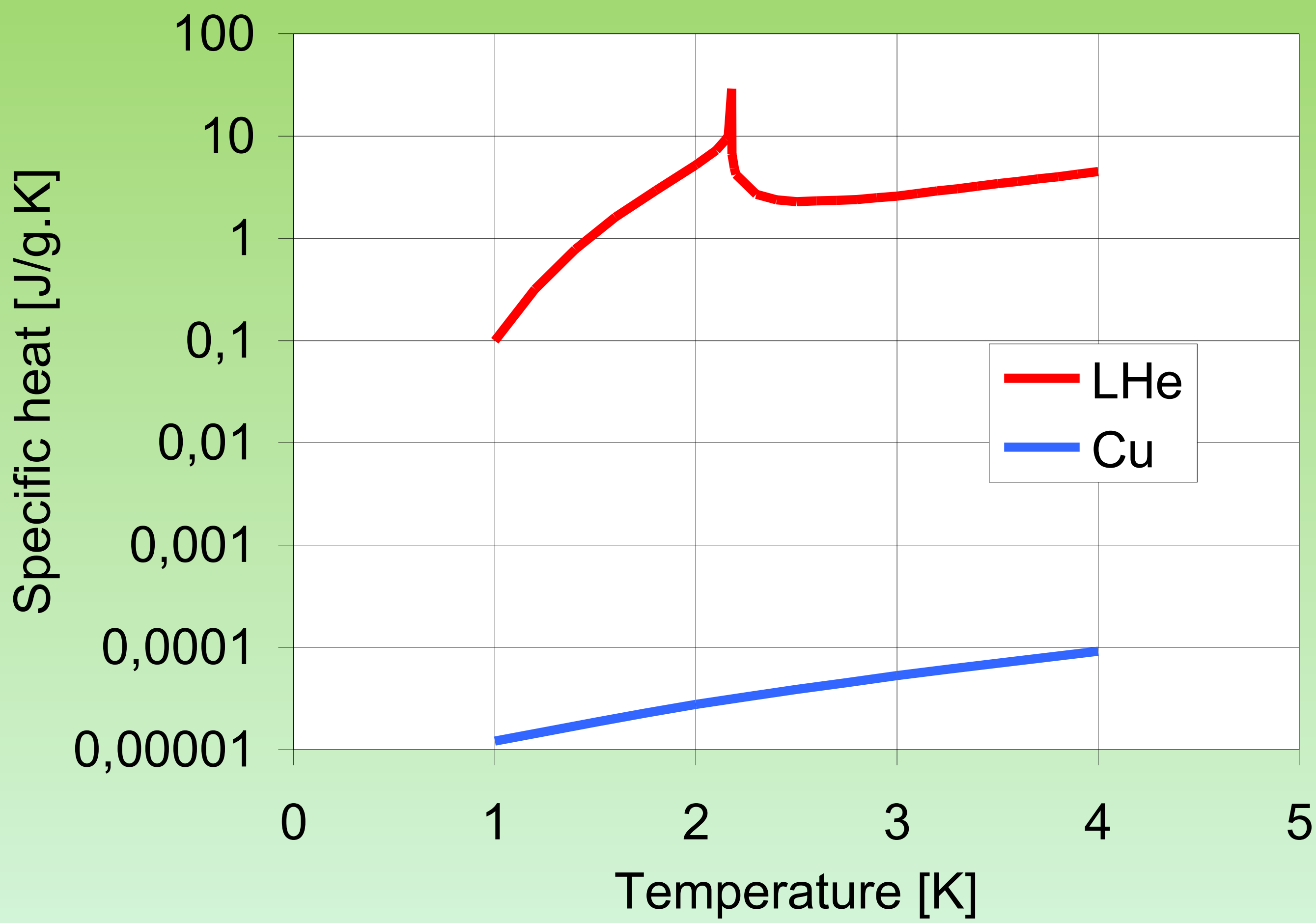




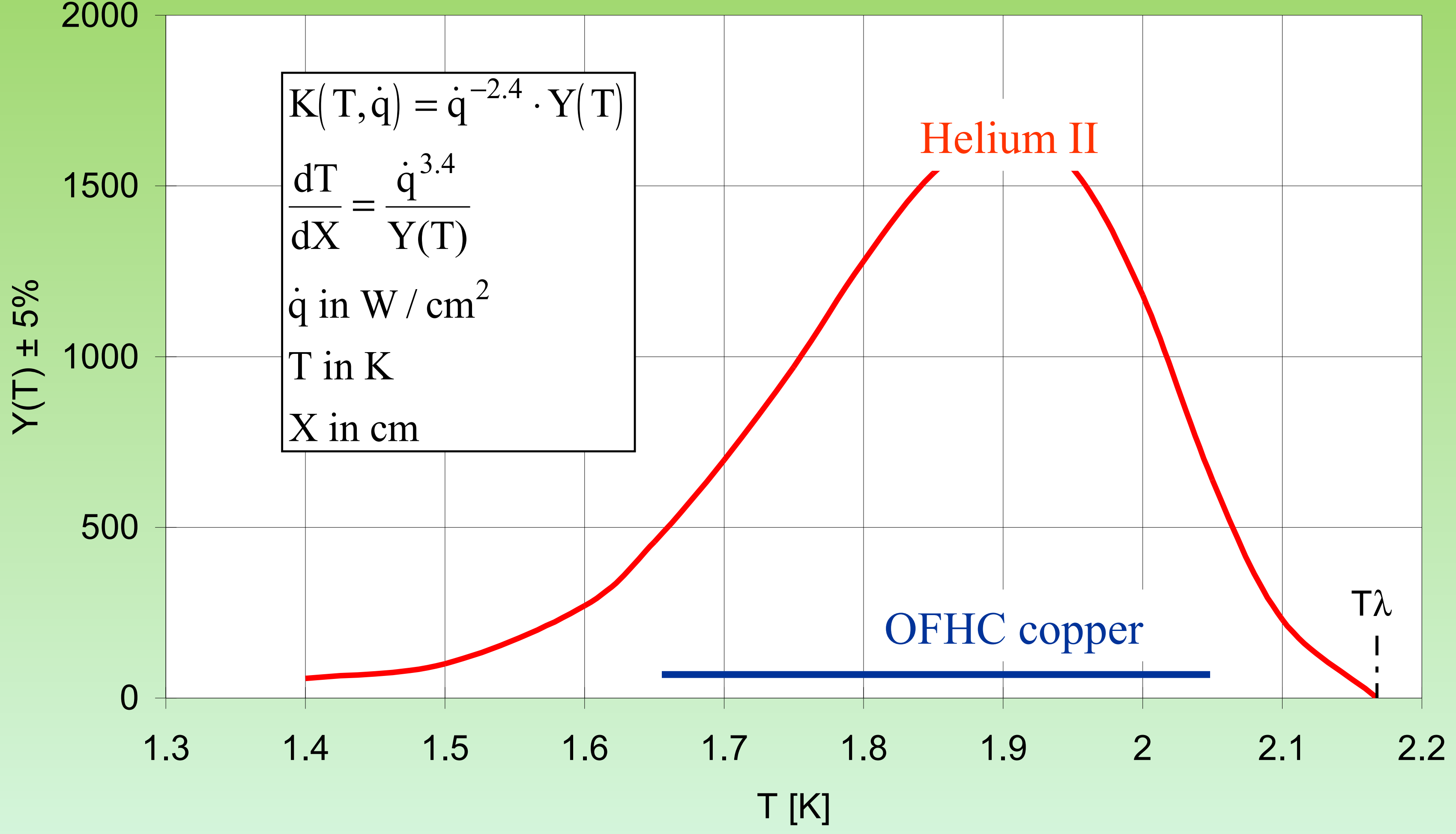
Critical current density of technical superconductors



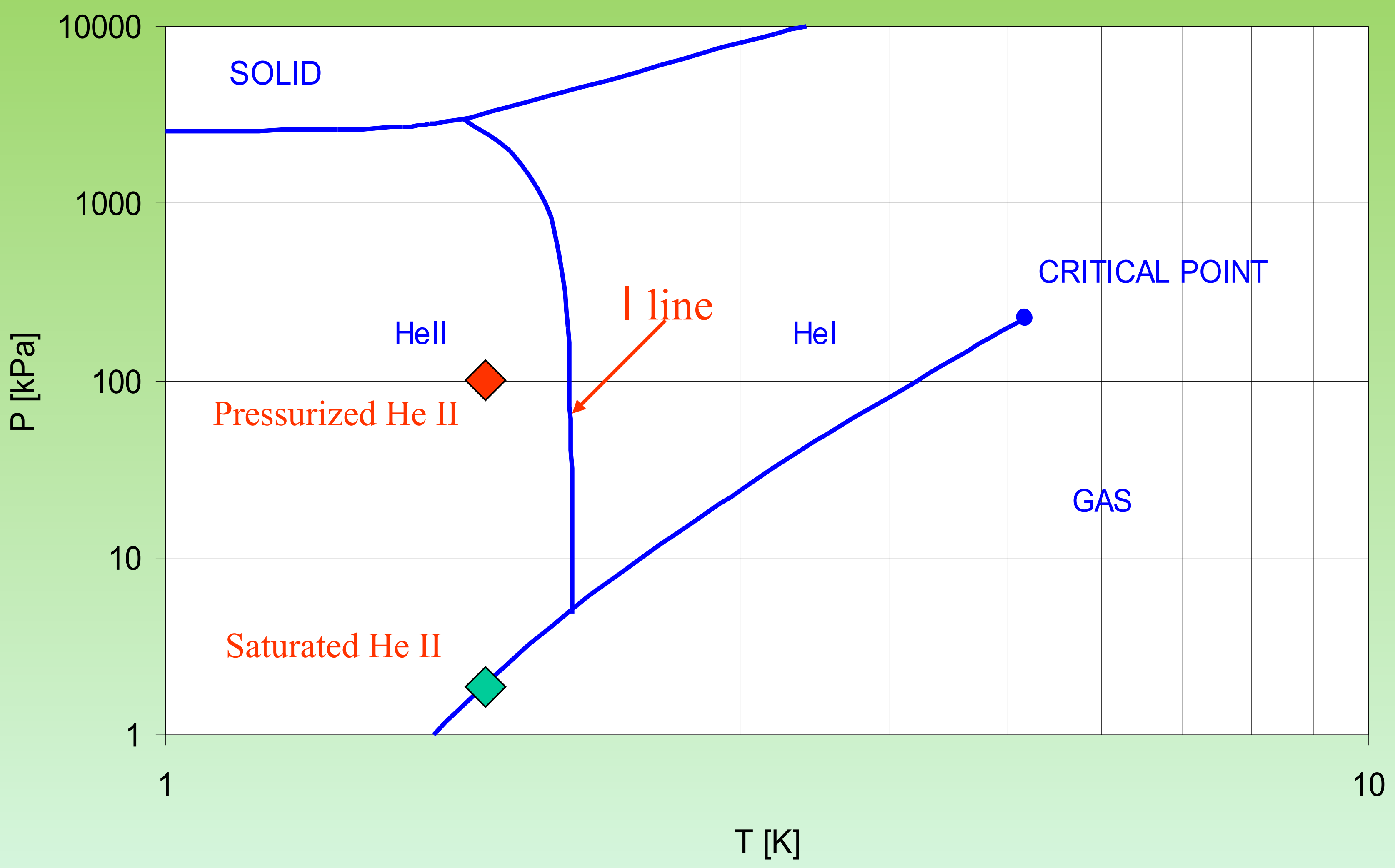
Specific heat of LHe and Cu



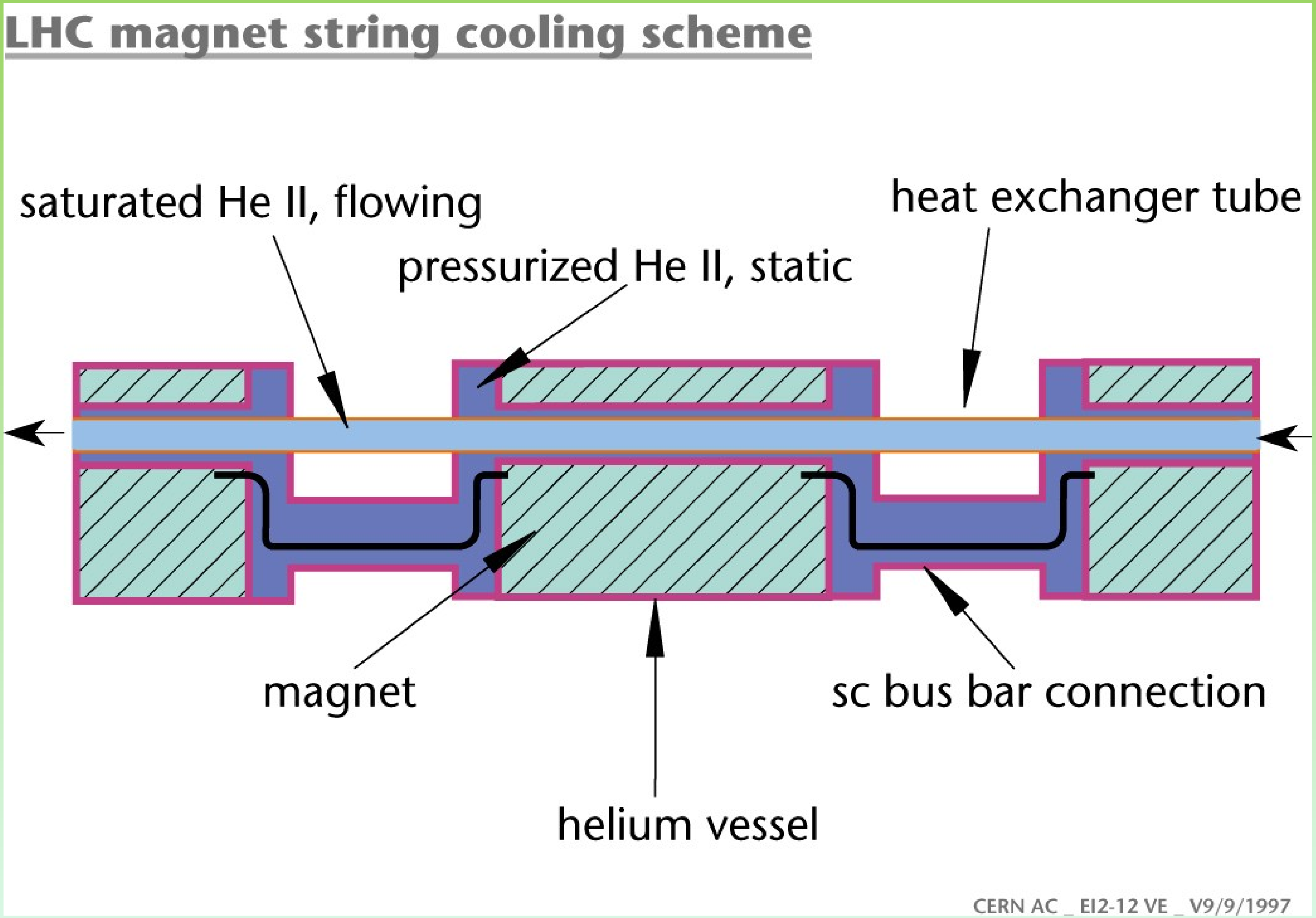
Equivalent thermal conductivity of He II



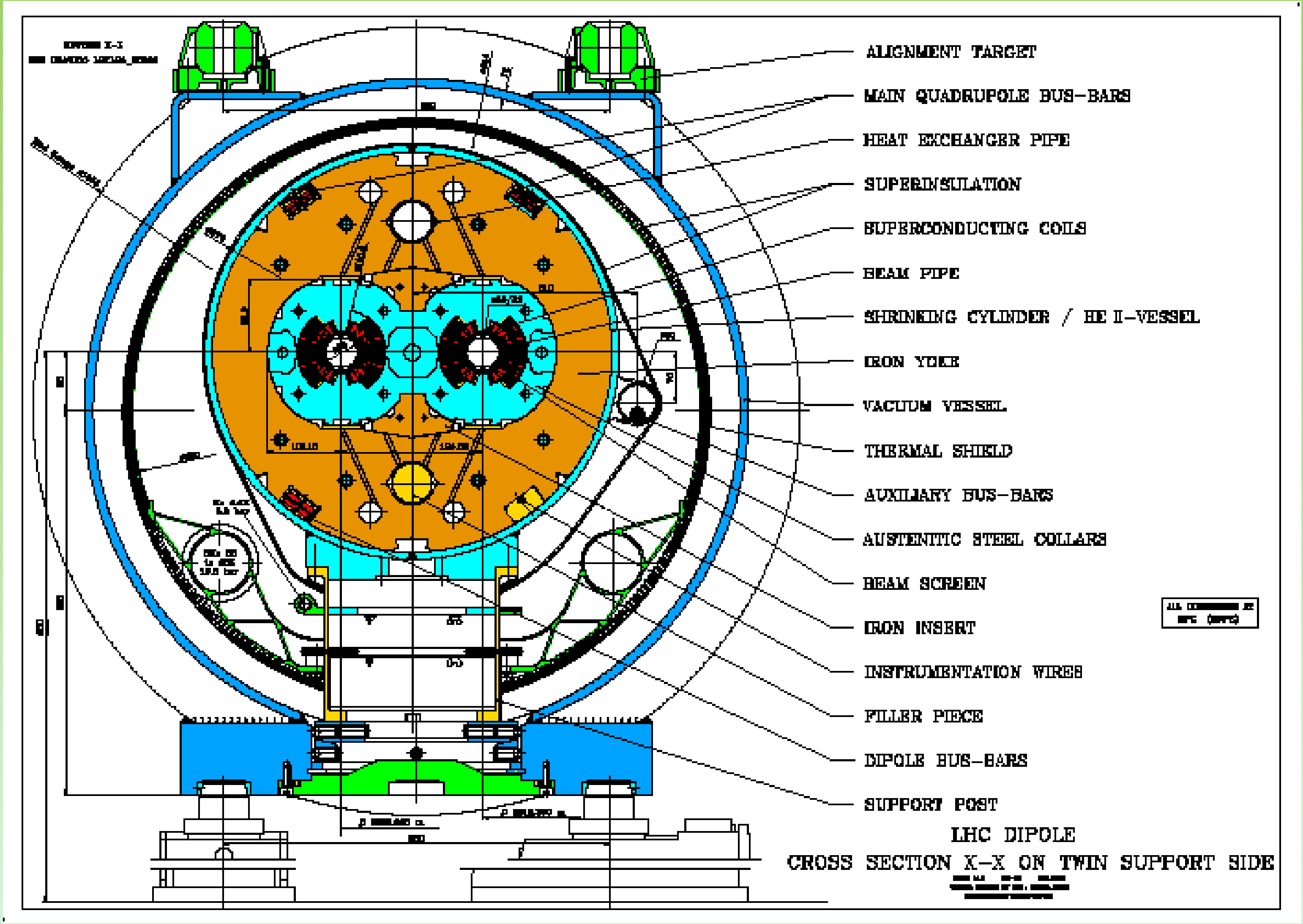
Phase diagram of Helium



Linear heat exchanger

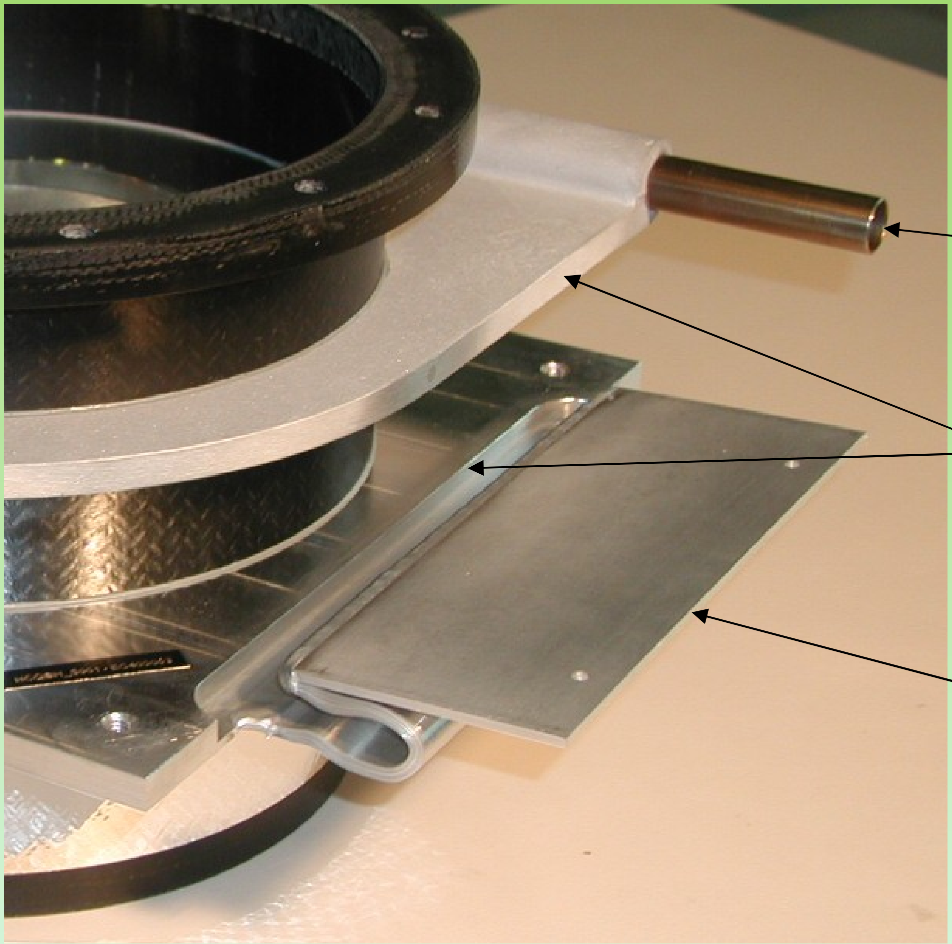


Przekrój dipola LHC



Kompozytowa noga magnesu
G10 Glass-fibre Reinforced Epoxy

Blokada dopływu ciepła



Zasilanie ciekłym helem 4,5K (linia C')

Płyty aluminiowe klejone do nogi kompozytu G-10

Łączniki do łoża aluminiowego ekranu termicznego 50-75 K

Aluminiowe łoże magnesu
wspornikiem ekranu termicznego

Izolacja aluminiowa zimnej masy

Wielowarstwowy koc izolacji termicznej (MLI)

Kriostaty próżniowe

Stal węglowa zbiornik, flansze stal nierdzewna

Skład osobowy pracowników AGH pracujących przy uruchomieniu LHC w okresie 2005-2009

MEL	
Bednarek	Mateusz
Ludwin	Jaromir
Prochal	Bogusław
Setkowicz	Józef

QP	
Drózd	Adam
Filipek	Wiesław
Gorzawski	Arkadiusz
Nowak	Edward
Nowak	Elżbieta
Seweryn	Grzegorz
Skała	Aleksander
Skoczeń	Andrzej
Wojanek	Piotr

QRL	
Bolewski	Andrzej
Ciechanowski	Marek
Donizak	Jędrzej
Dubert	Paweł
Fluder	Czesław
Gaj	Wawrzyniec
Jodłowski	Paweł
Klisch	Michał
Macuda	Paweł
Malinowski	Paweł
Palica	Jan
Skotnicki	Ryszard
Sosin	Mateusz
Wróbel	Bartłomiej
Zwaliński	Łukasz
Lis	Krzysztof
Wolak	Tomasz

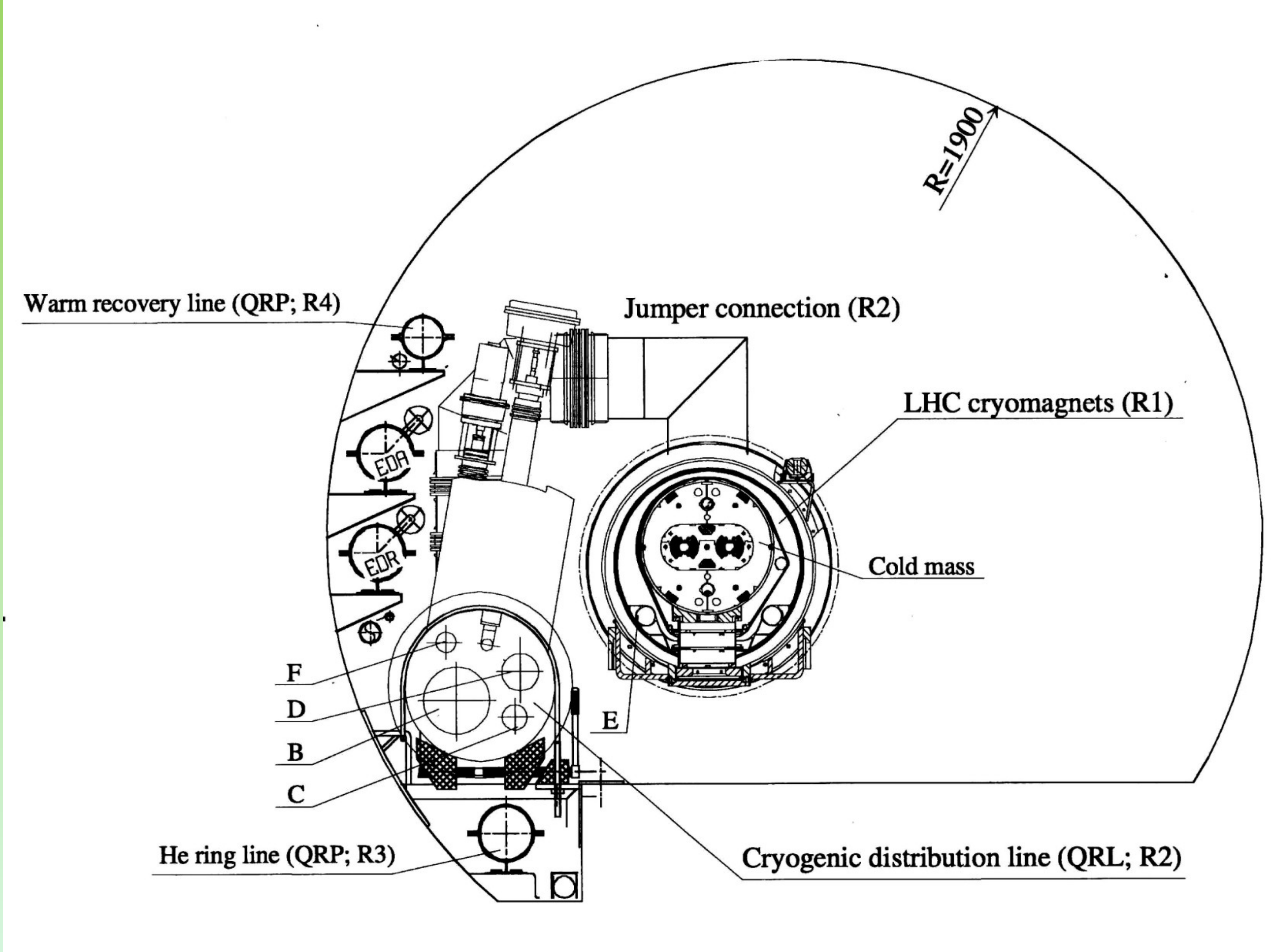
TS	
Macuda	Małgorzata
Szkutnik	Jacek

TS/CV	
Baran	Krzysztof
Dubert	Anna
Pomocka	Marek
Urbaniec	Bartłomiej
Wiencek	Mateusz

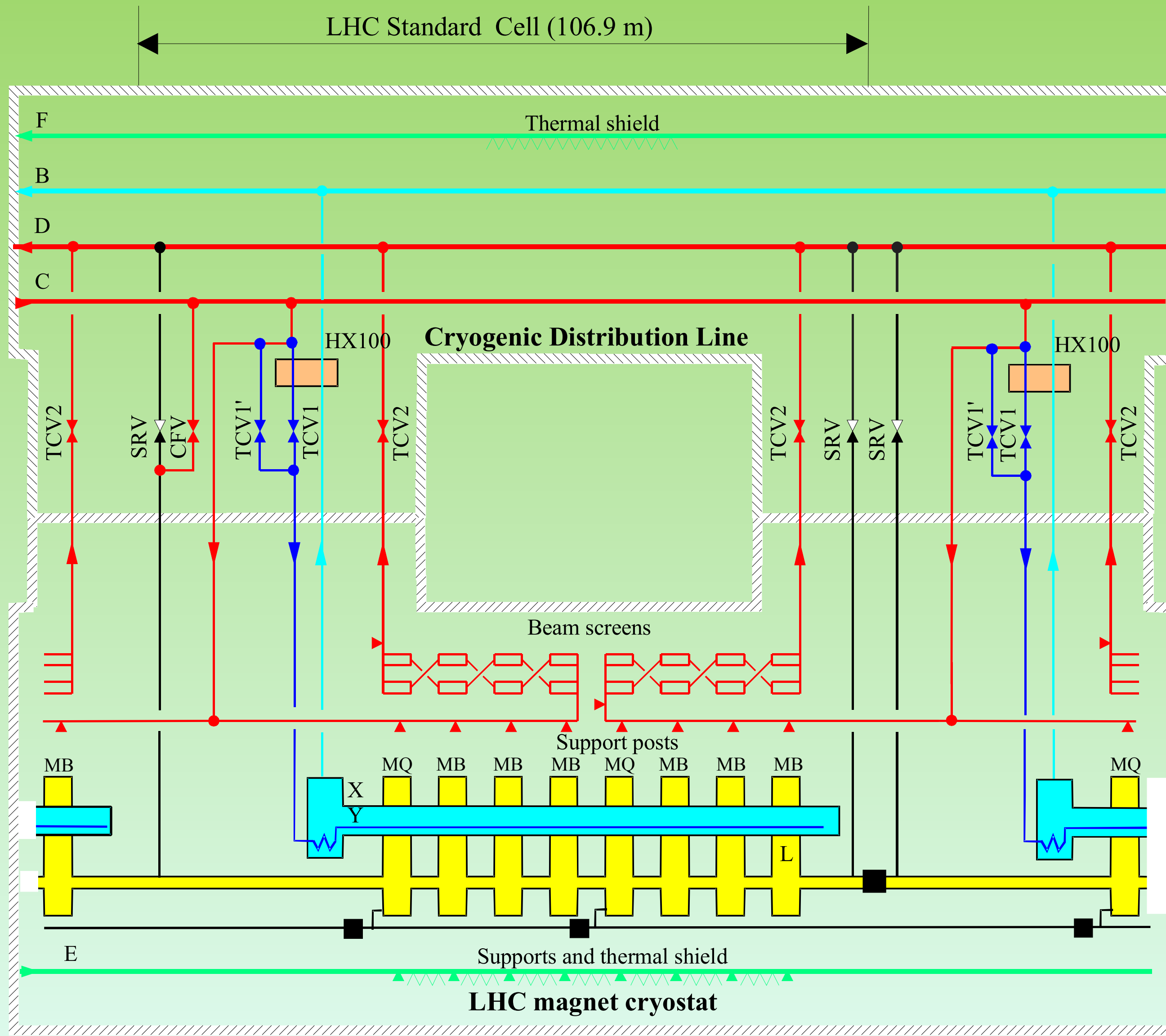
CRI	
Kulka	Jan

Linia dystrybucyjna ciekłego helu o długości 3,3km

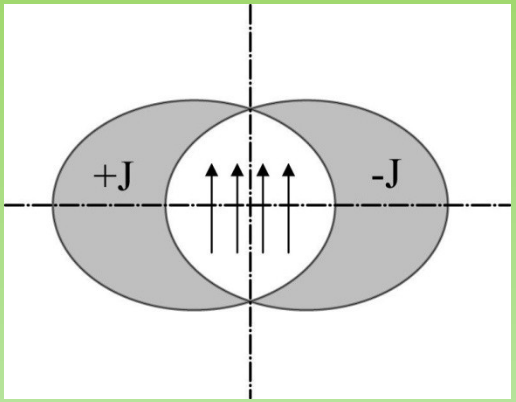
Elementy sytemu kriogenicznego

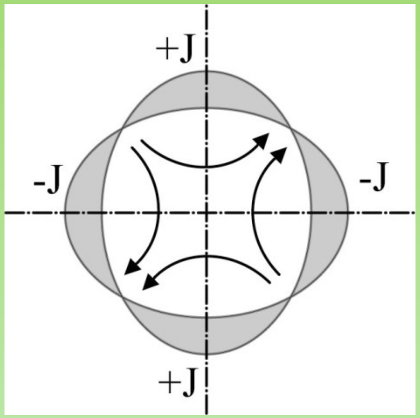


Przepływy helowe w komórce kriogenicznej LHC



indukcja



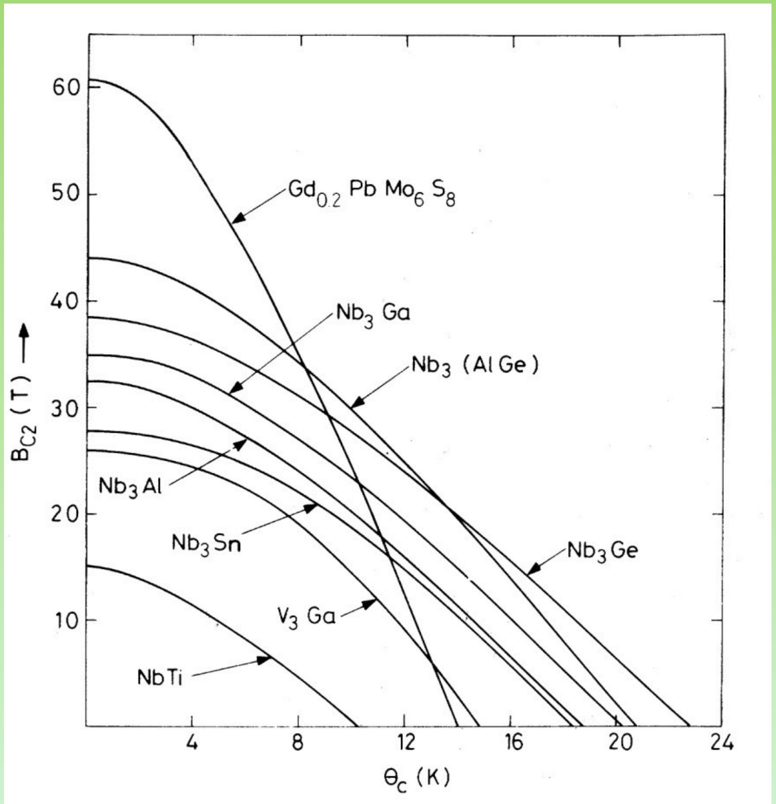


$$B_y = \frac{\mu_0 Jbd}{a+b}$$

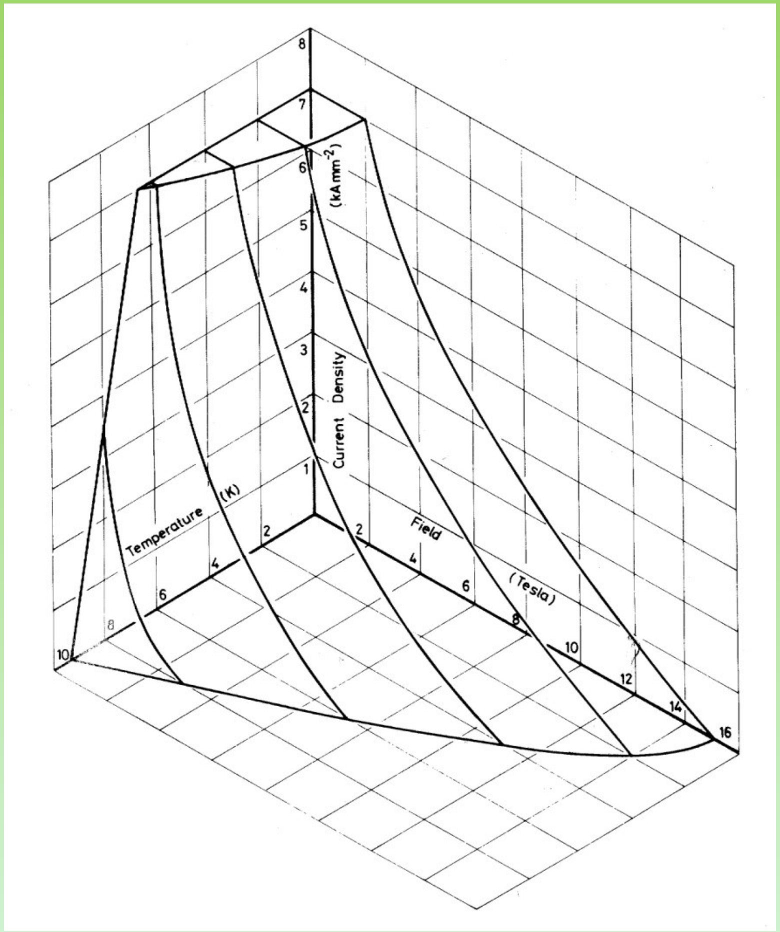
$$B_x = \frac{\mu_{\cdot} J(a-b)}{a+b} y$$

$$B_y = \frac{\mu_{\cdot} J(a-b)}{a+b} x$$

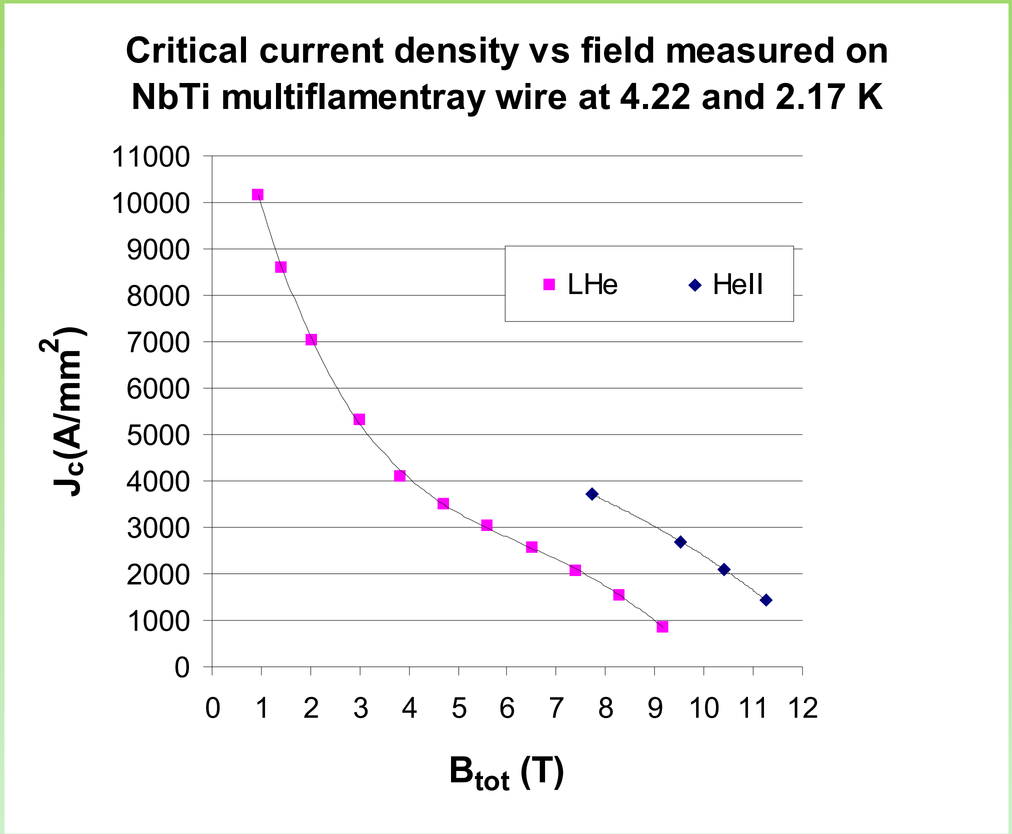
Kryterium selekcji	*Liczba*
Nadprzewodnik	~ 10,000
$T_c \cong 10$ K .and. $B_{c2} \cong 10$ T	~ 100
$J_c \cong 1$ GA/m^2 @ B > 5 T	~ 10
Magnet-grade superconductor	~ 1



Niob-Tytan

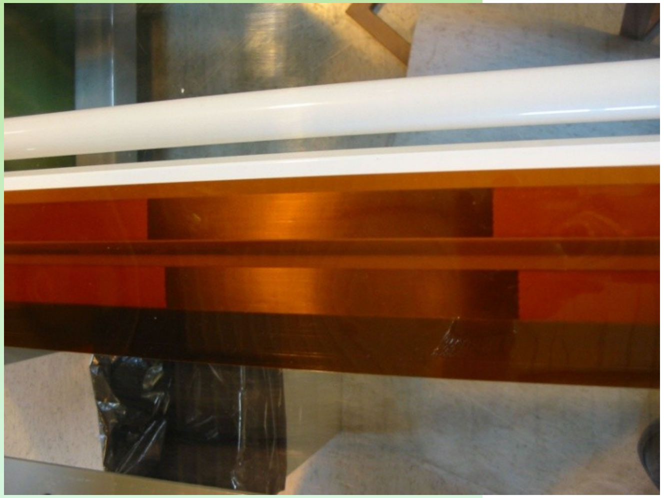


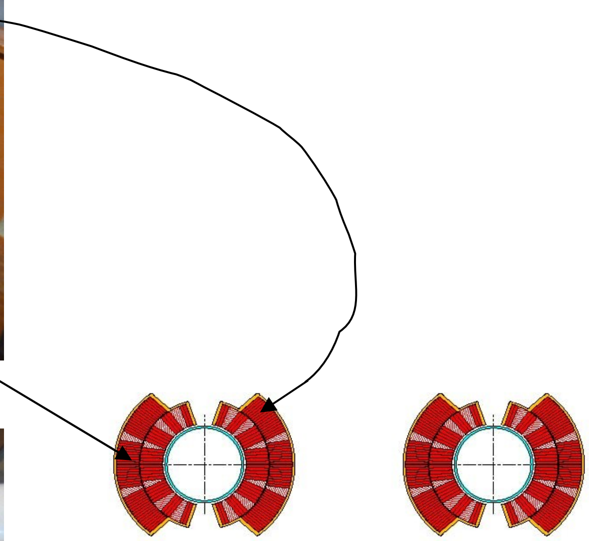
Critical surface of NbTi (from Wilson textbook)



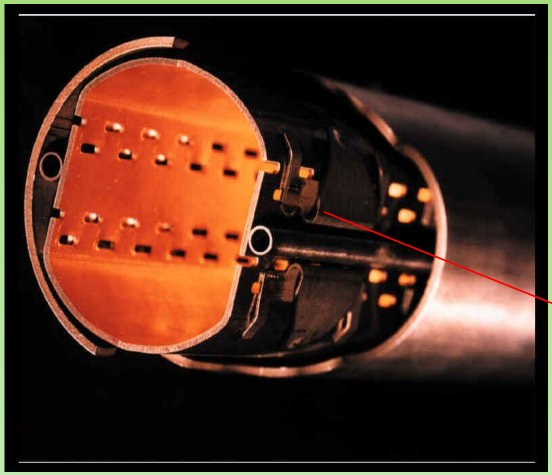
Critical current of best Cu/NbTi with typical **3 T field shift at superfluid helium** (INFN-LASA lab, february 2000)

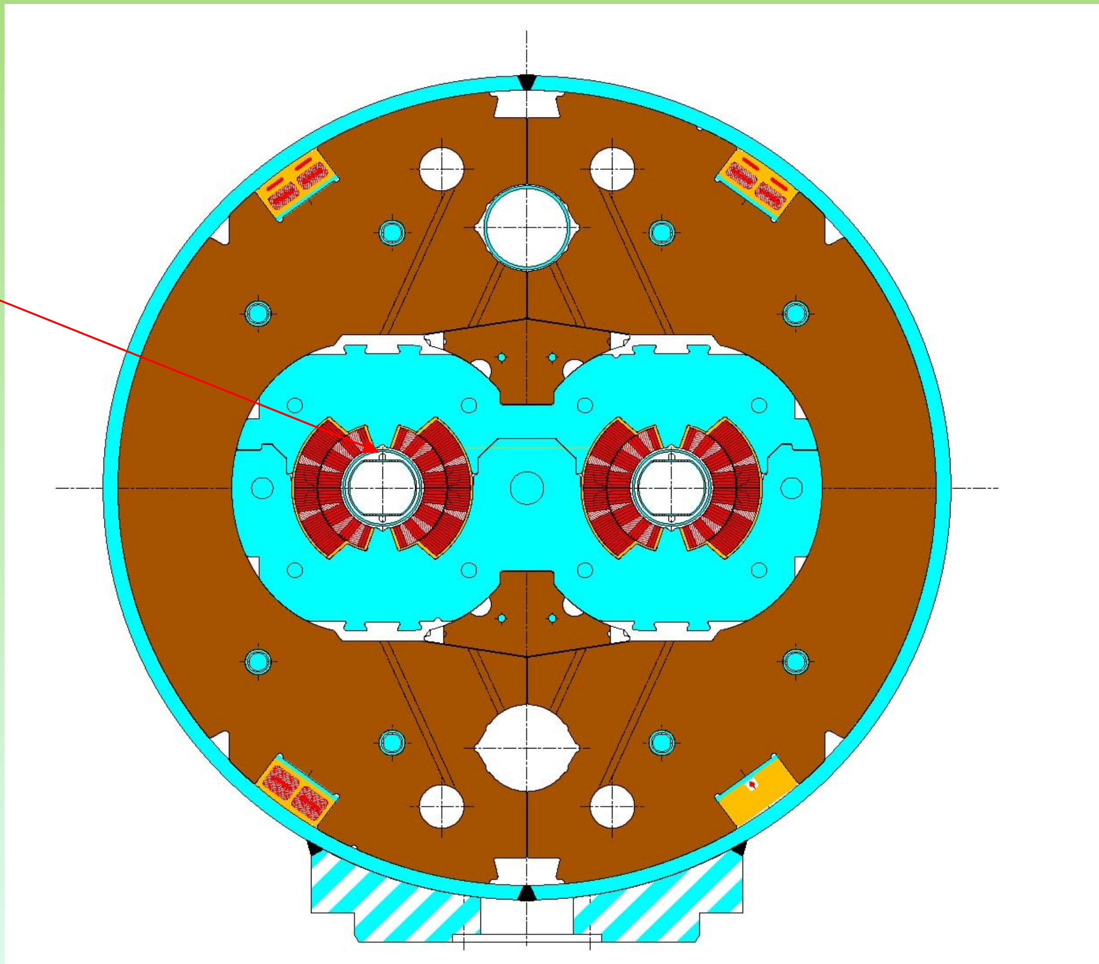
Grzejnik quenchowy



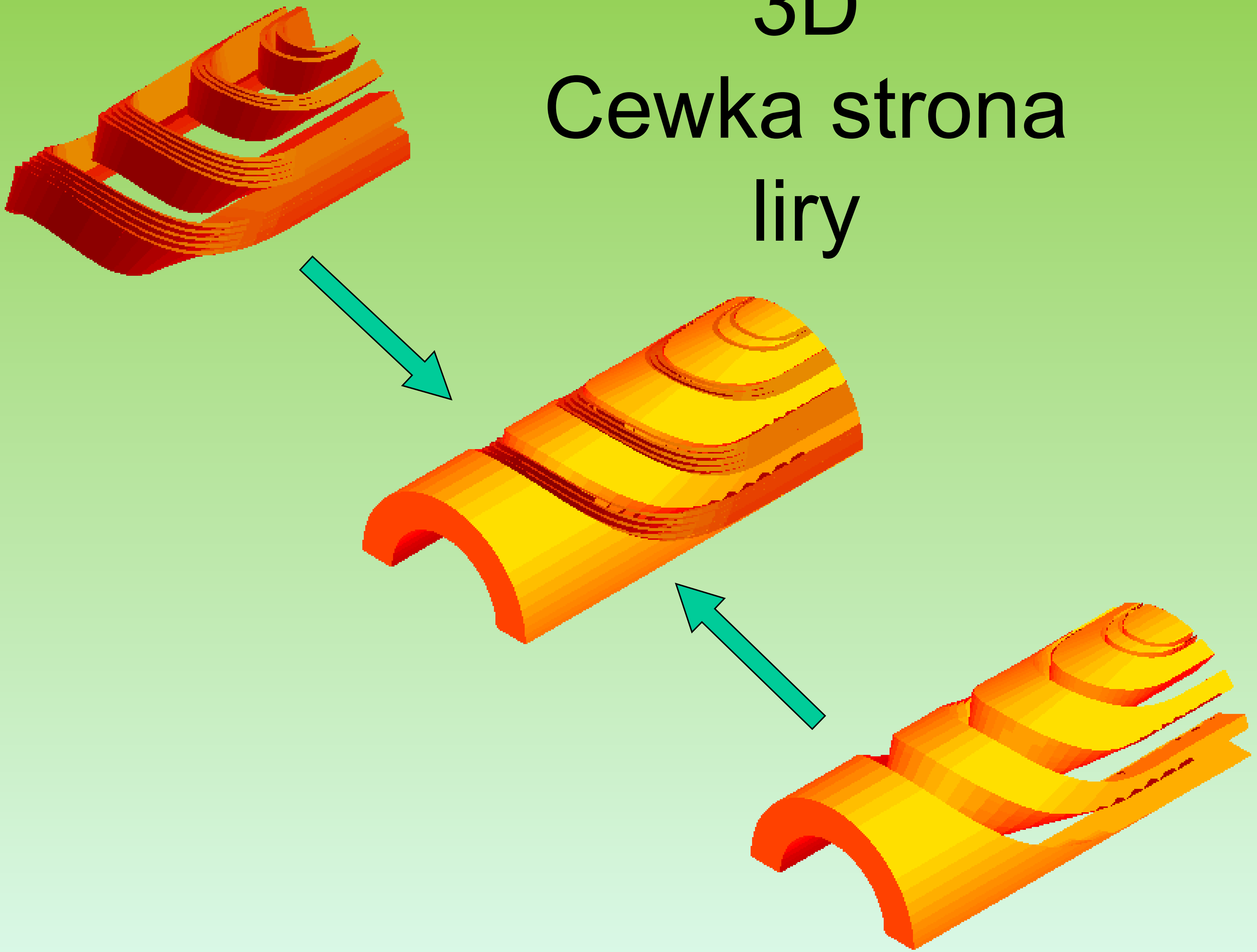


Ekran wiązki

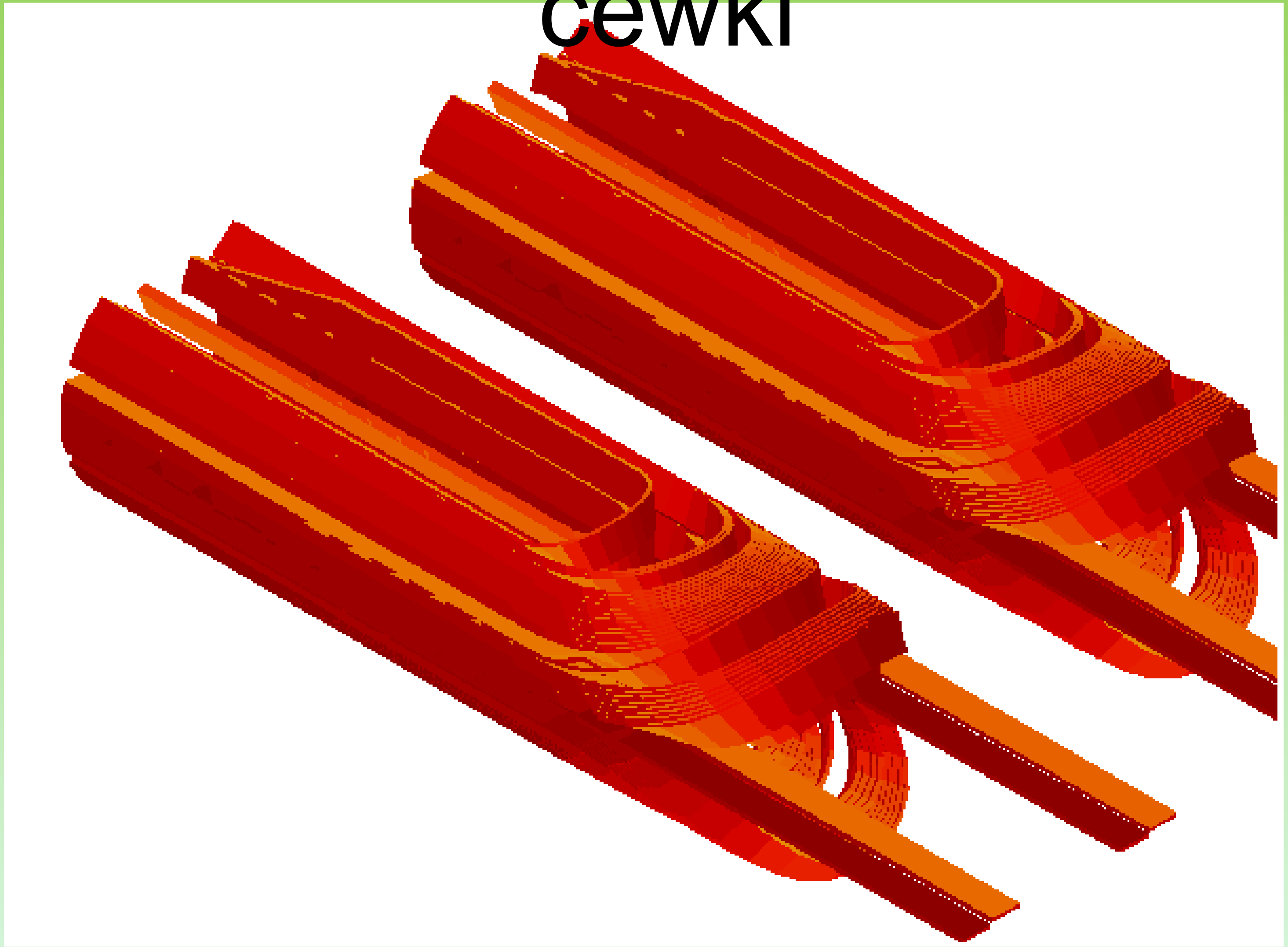




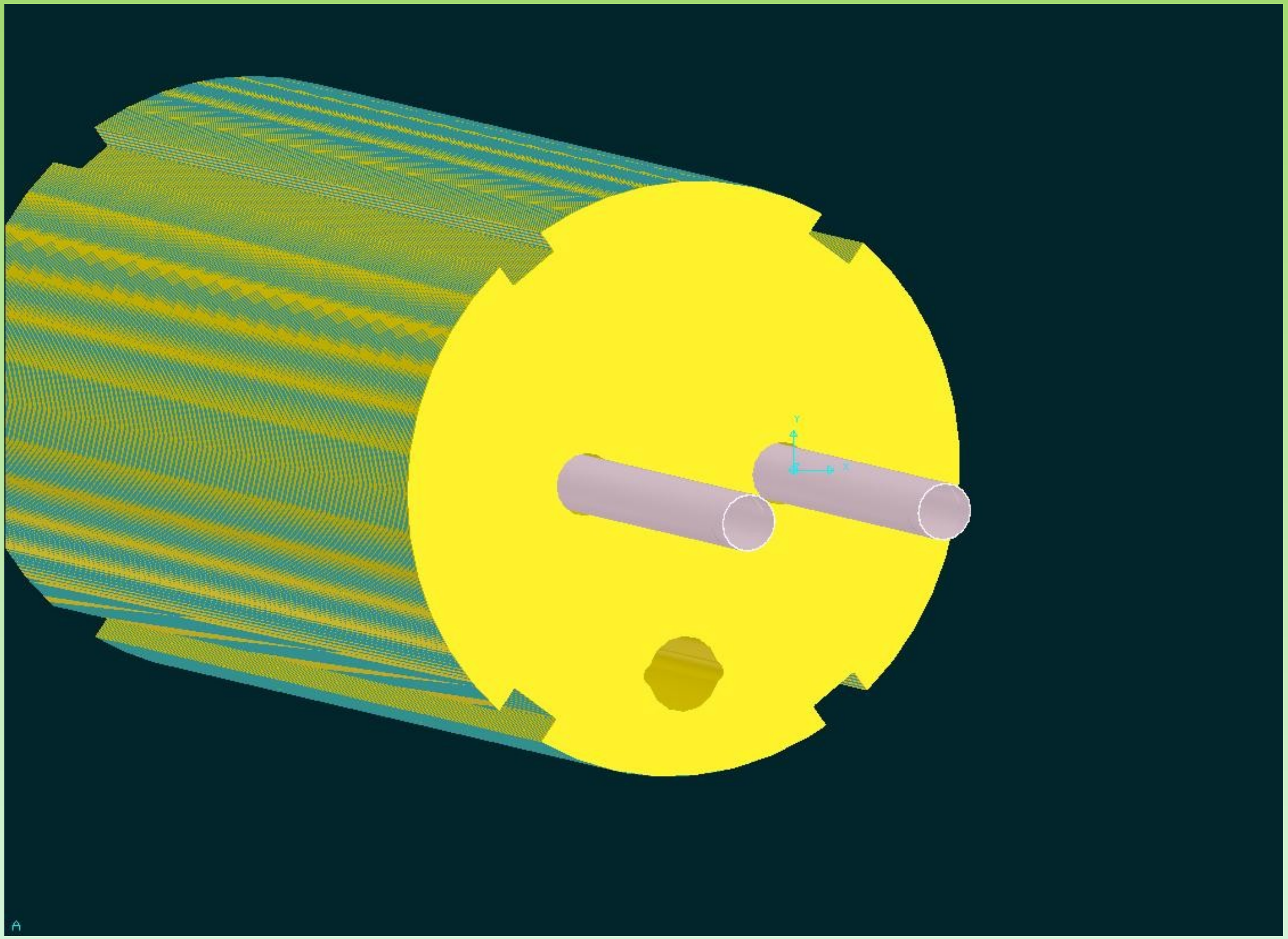
3D
Cewka strona liry



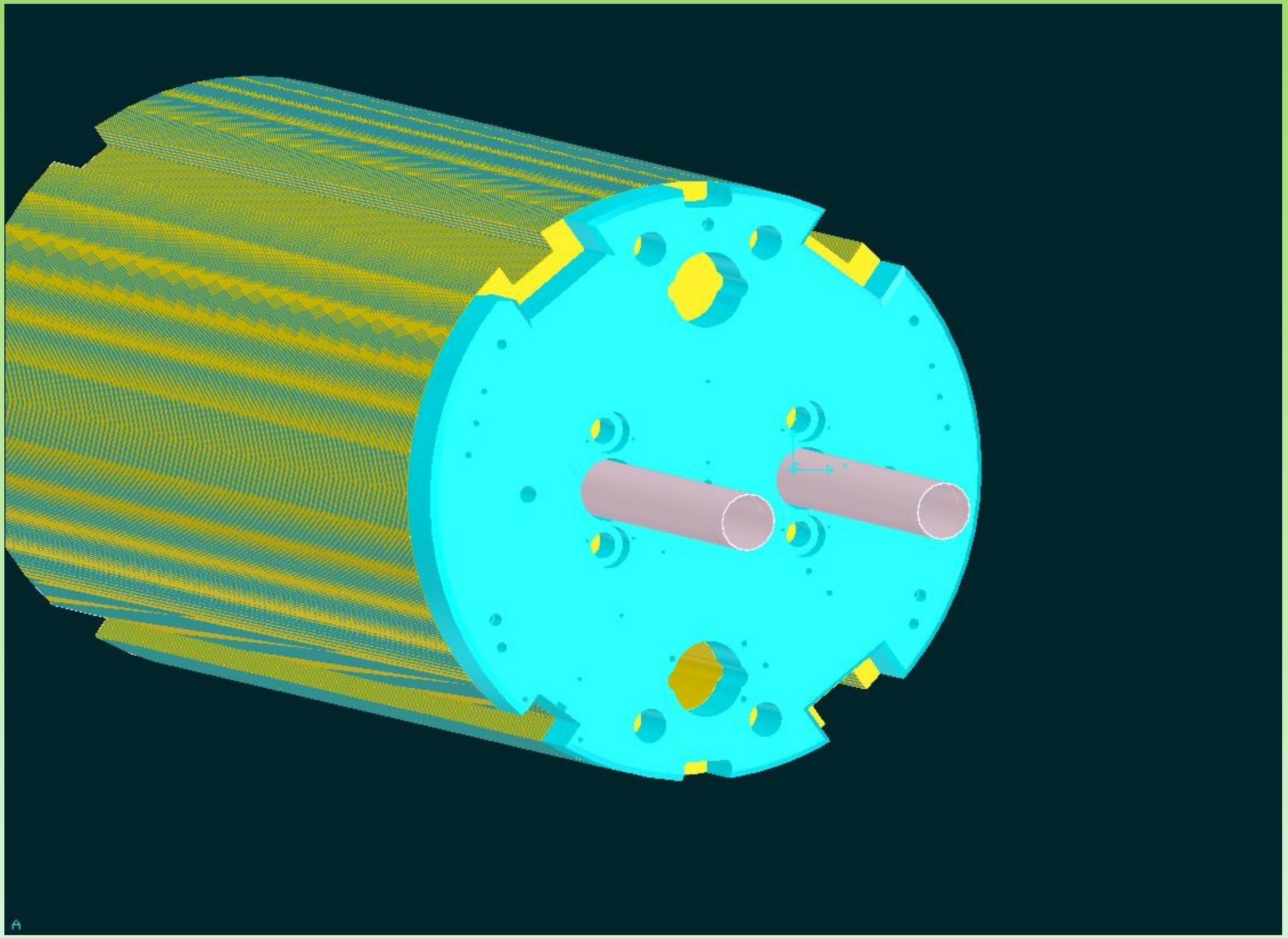
Strona podłączeniowa cewki



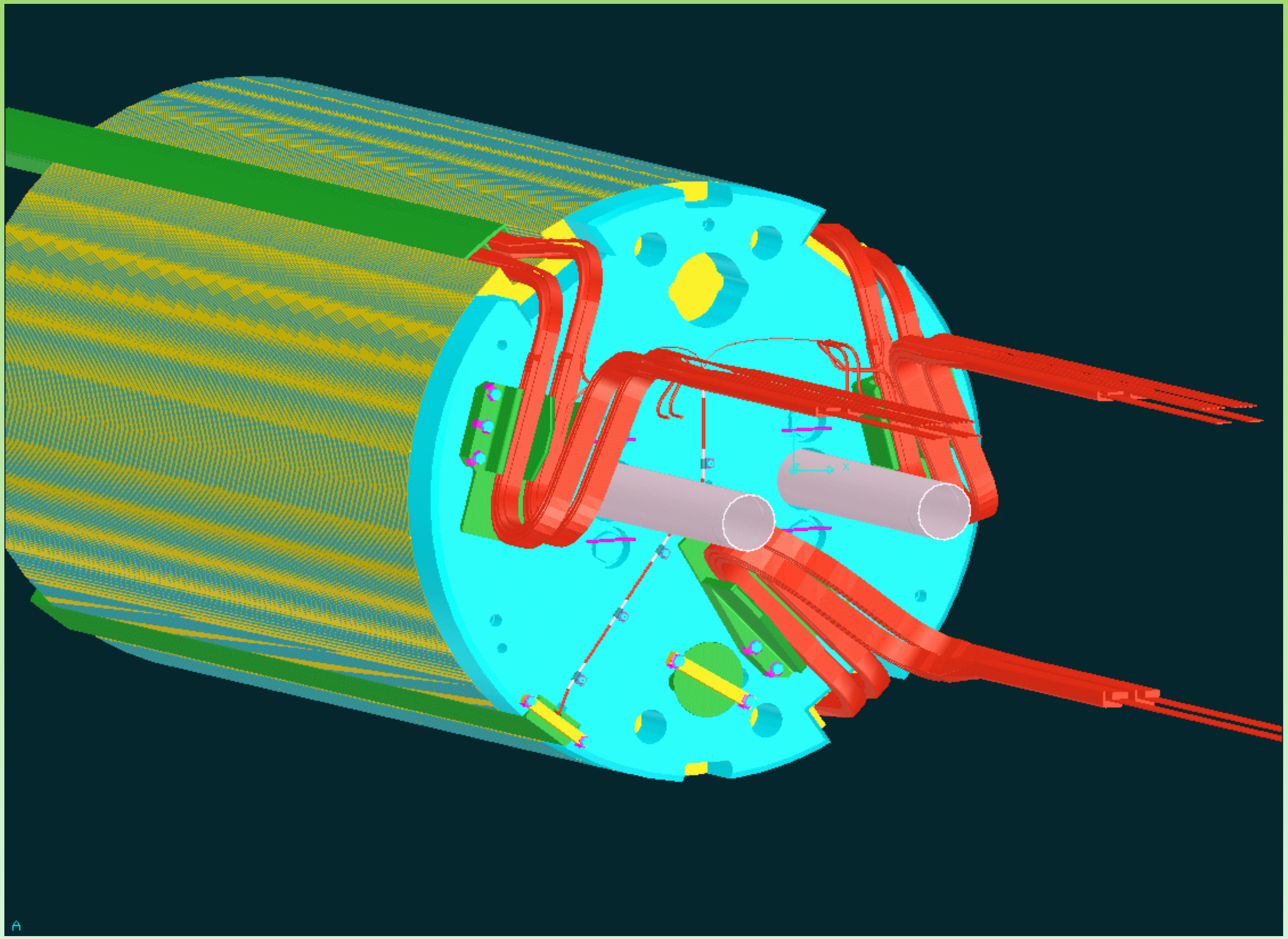
Jarzmo stalowe dipola



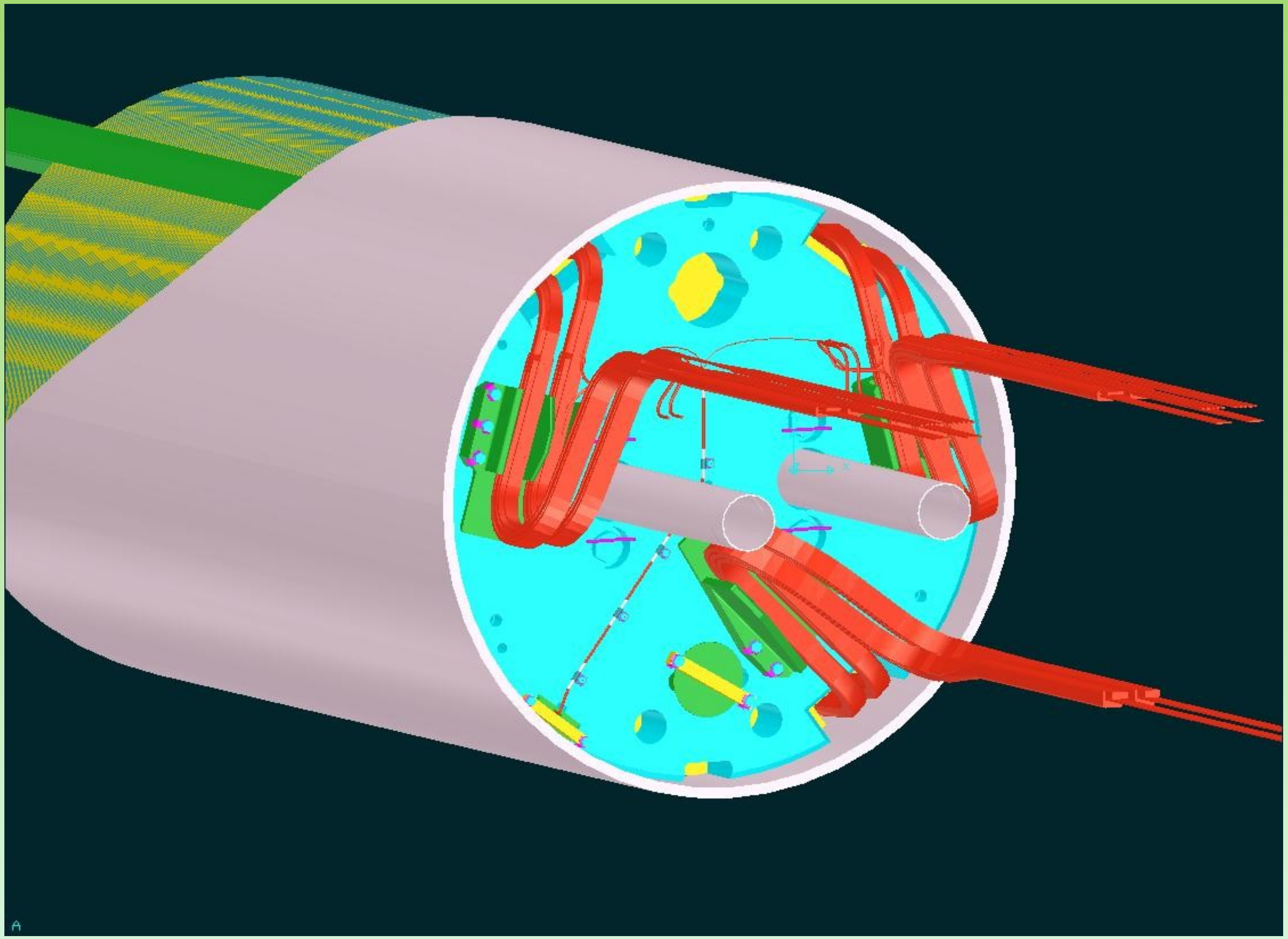
Płyta kończąca dipola



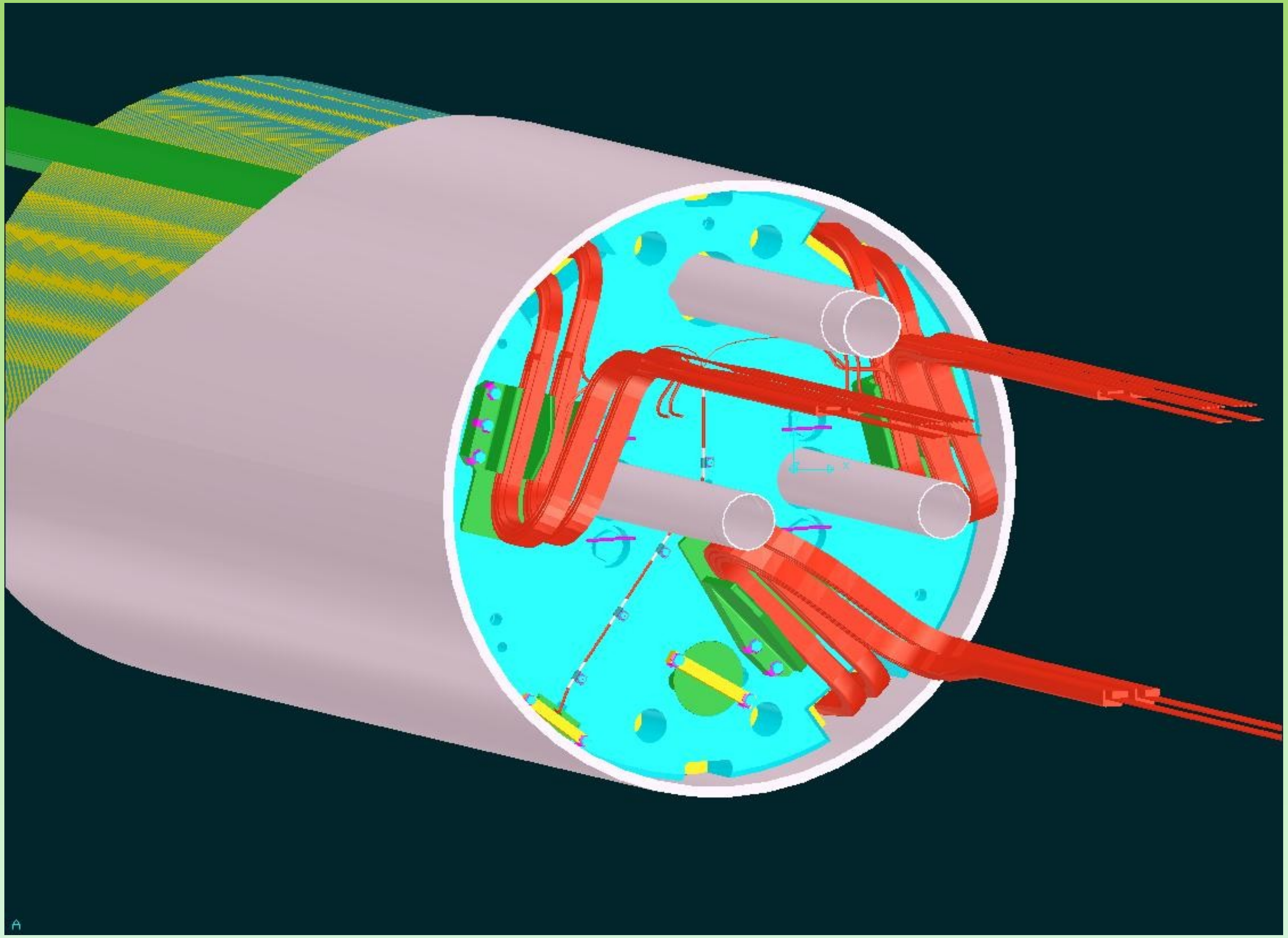
Formowanie liry



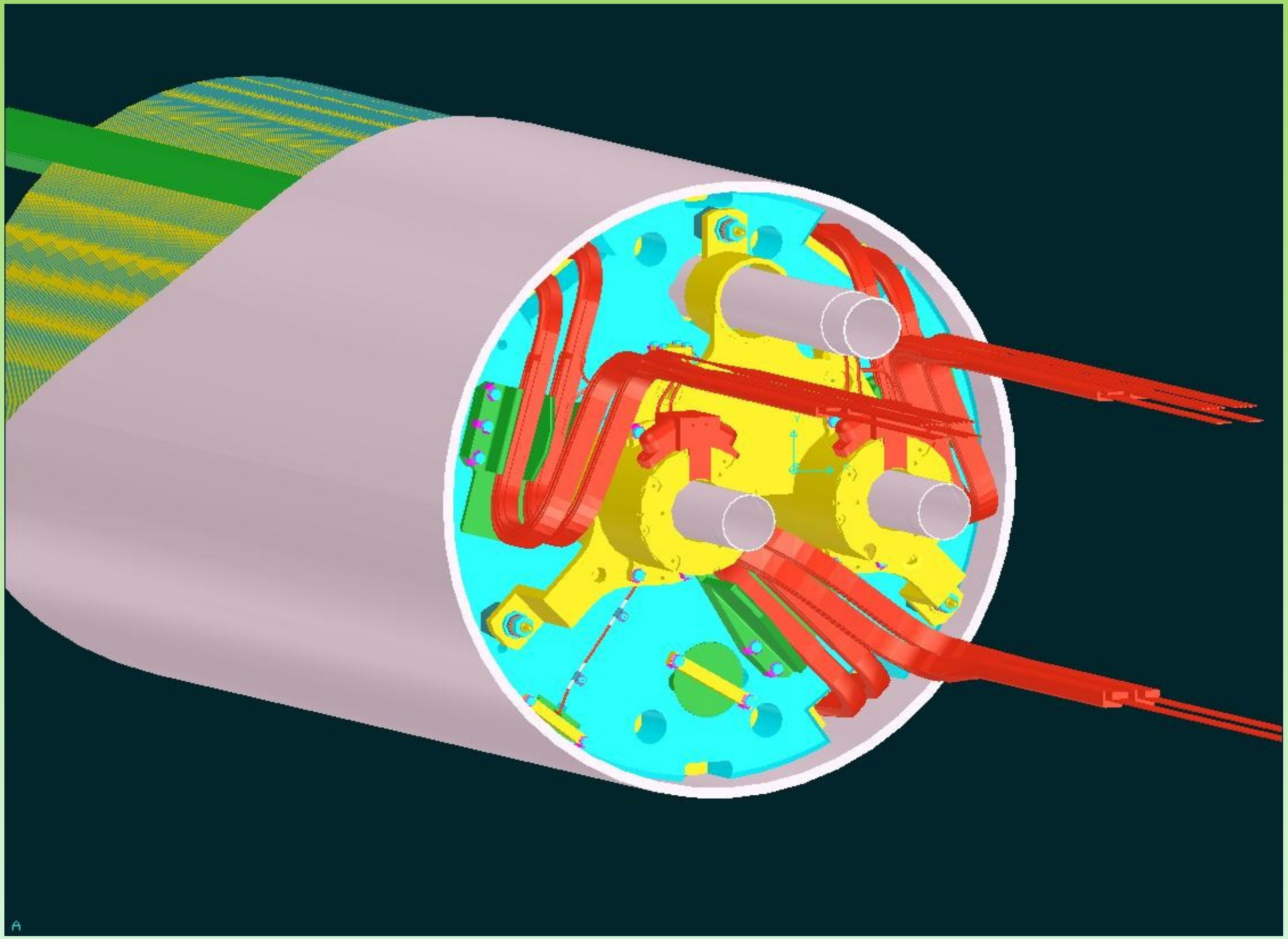
Korpus ciśnieniowy zimnej masy



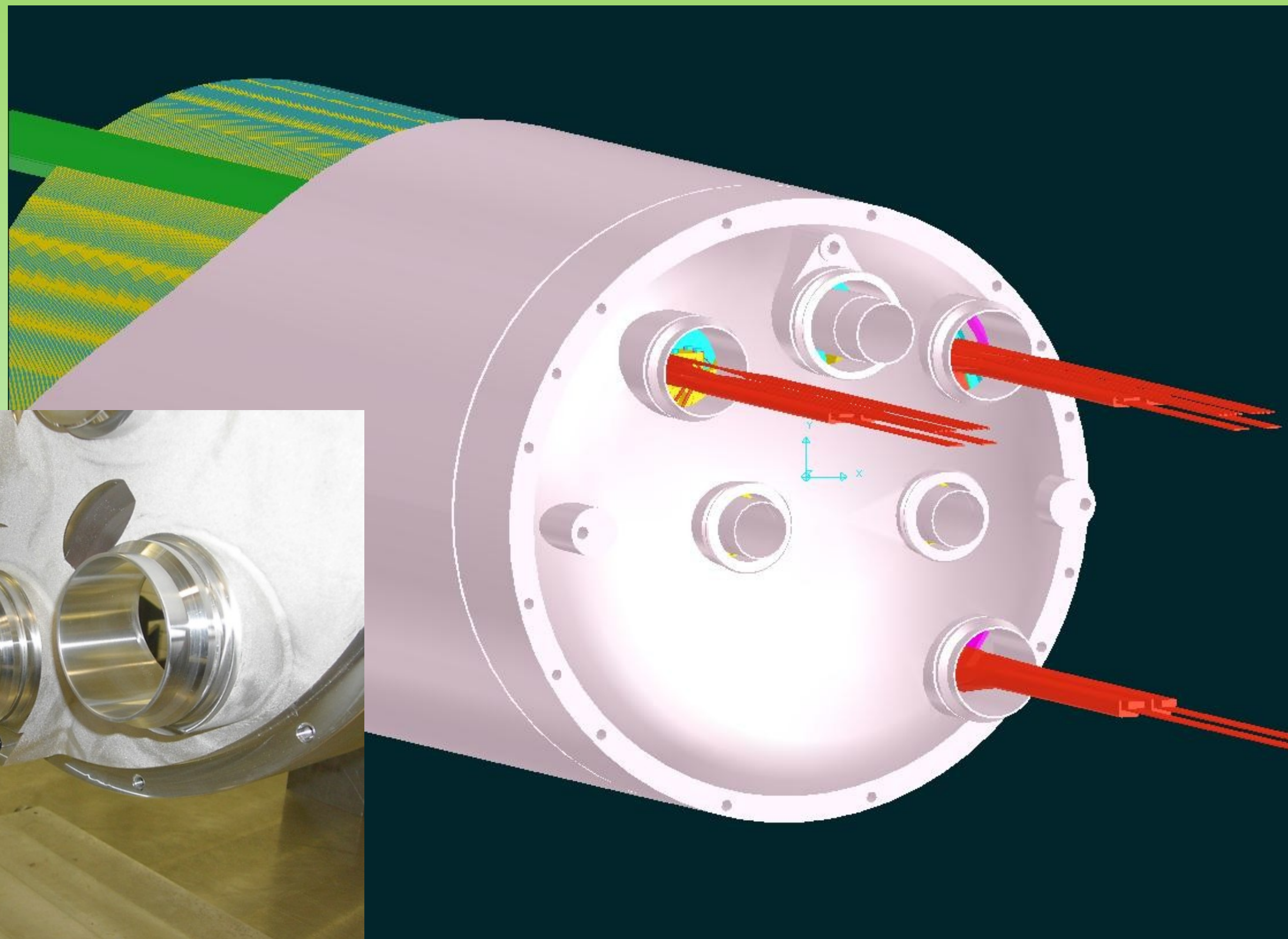
Wymiennik ciepła

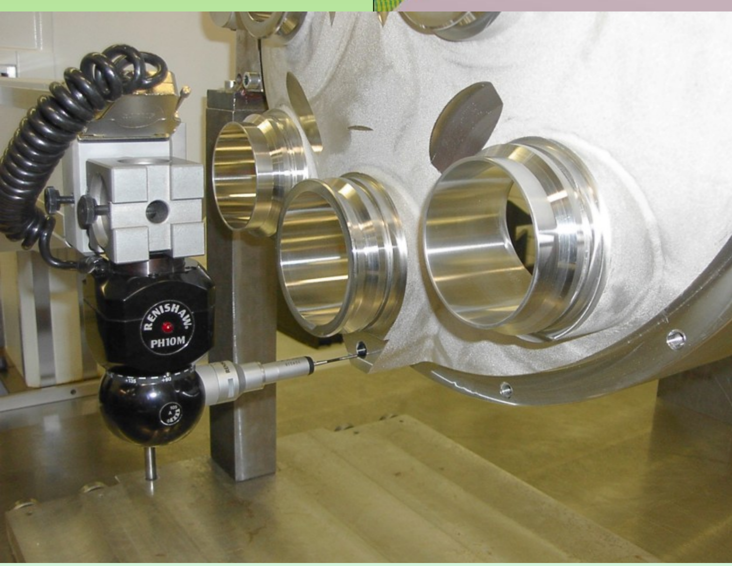


Magnesy korekcyjne dipola (spool pieces)

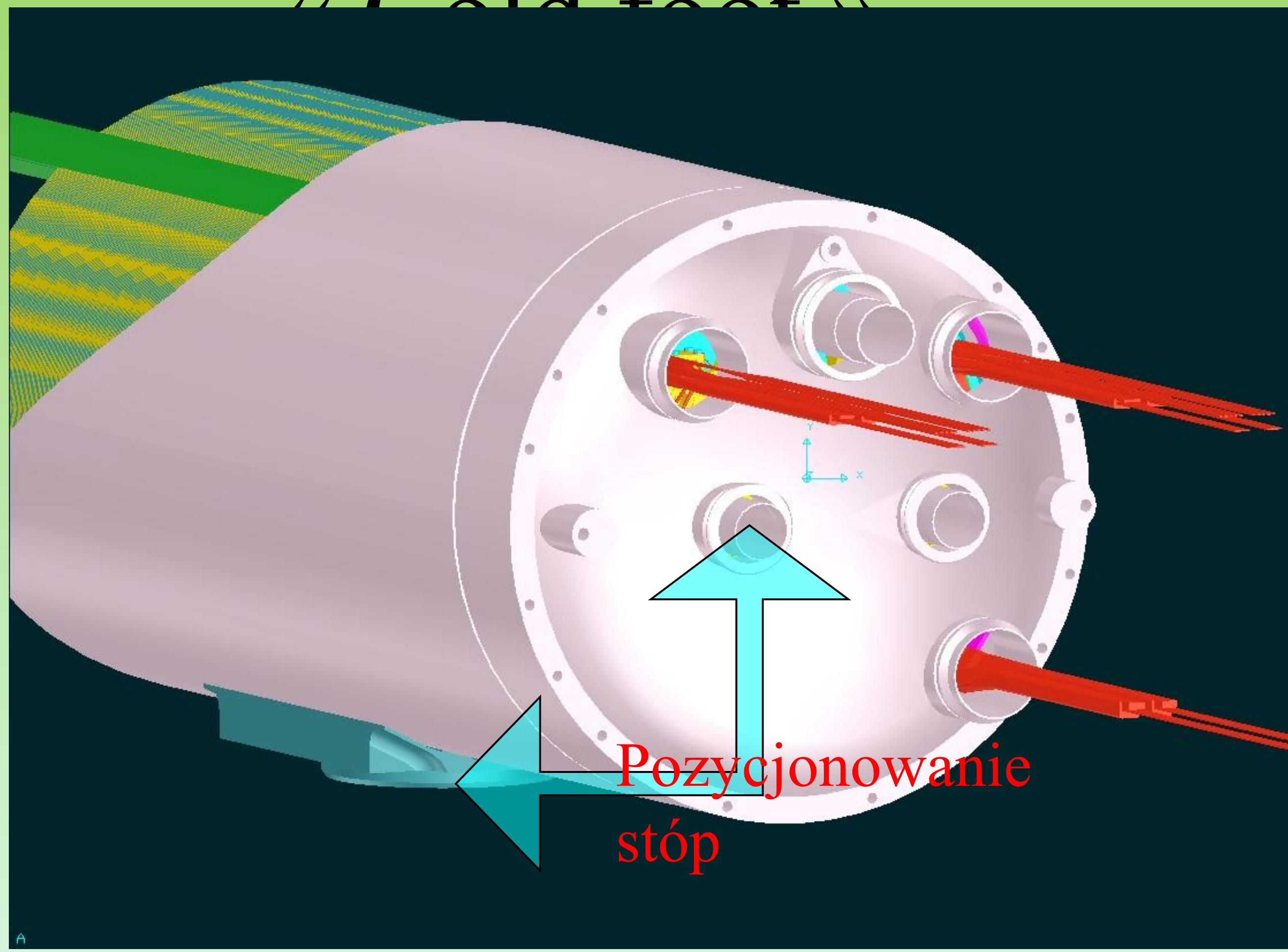


Zamknięcie zimnej masy dipola dennicą

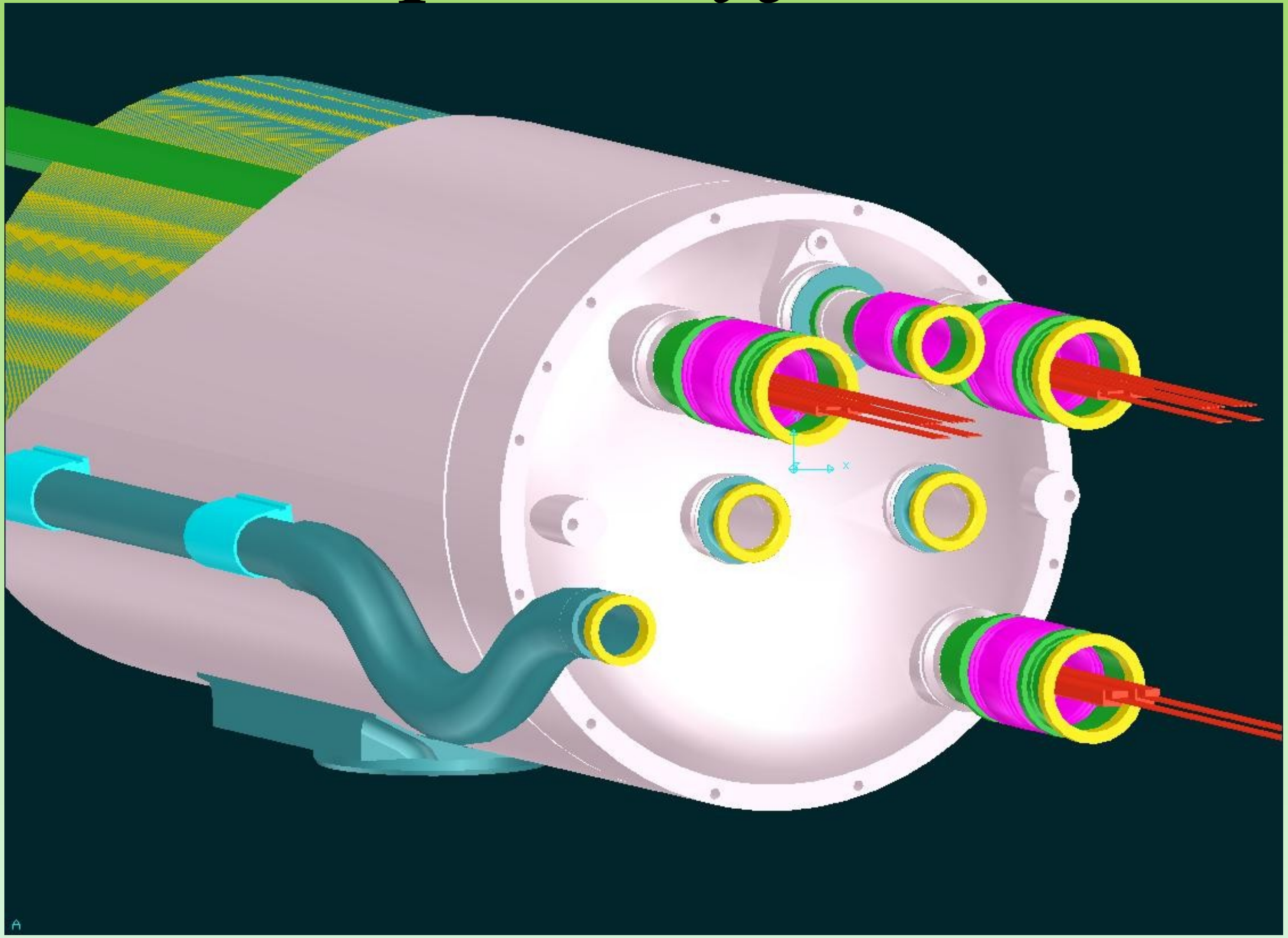




Dennica dipola i pozycjonowanie « Cold foot »



Mieszki kompensacyjne + linia N



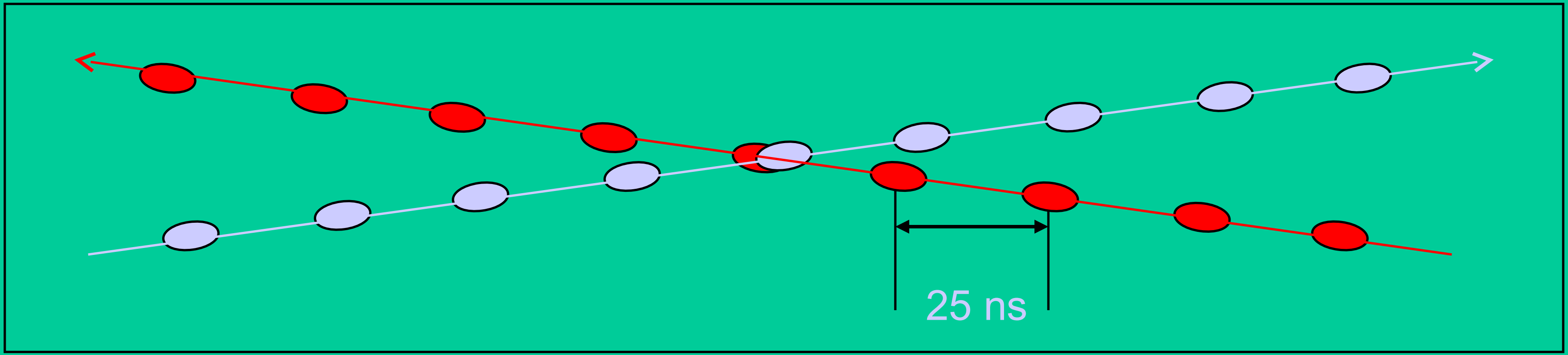
Energy stored in LHC magnets

$$E_{dipole} = 0.5 \bullet L_{dipole} \bullet I^{2}_{dipole}$$

Energy stored in one dipole is 7.6 MJoule

For all 1232 dipoles in the LHC: 9.4 GJ

Energy stored in the beams



Beam energy: Proton Energy • Number of Bunches • Number of protons per bunch

Proton Energy: 7 TeV

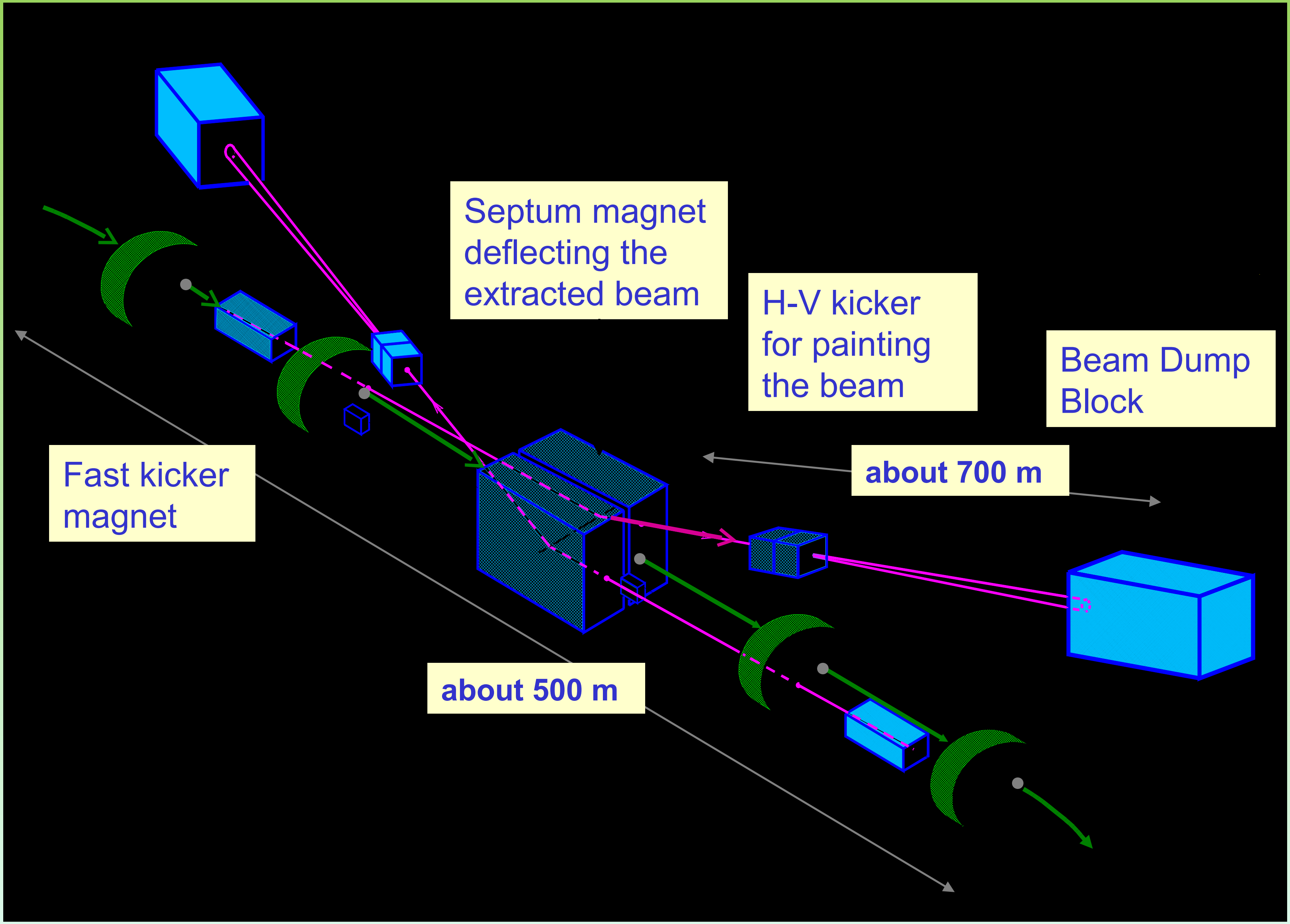
In order to achieve very high luminosity:

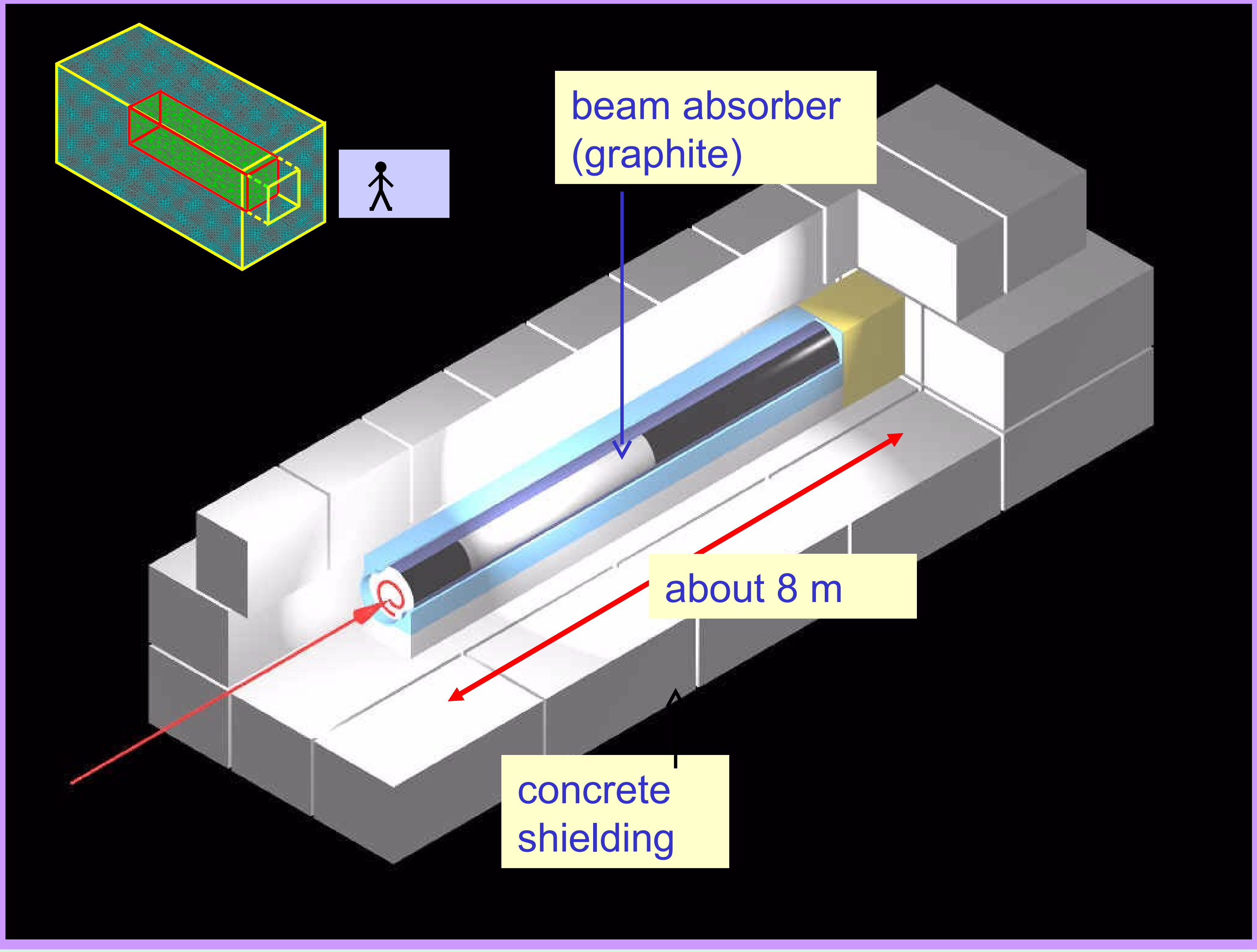
Number of bunches per beam: 2808

Number of protons per bunch: $1.05 \bullet 10^{11}$

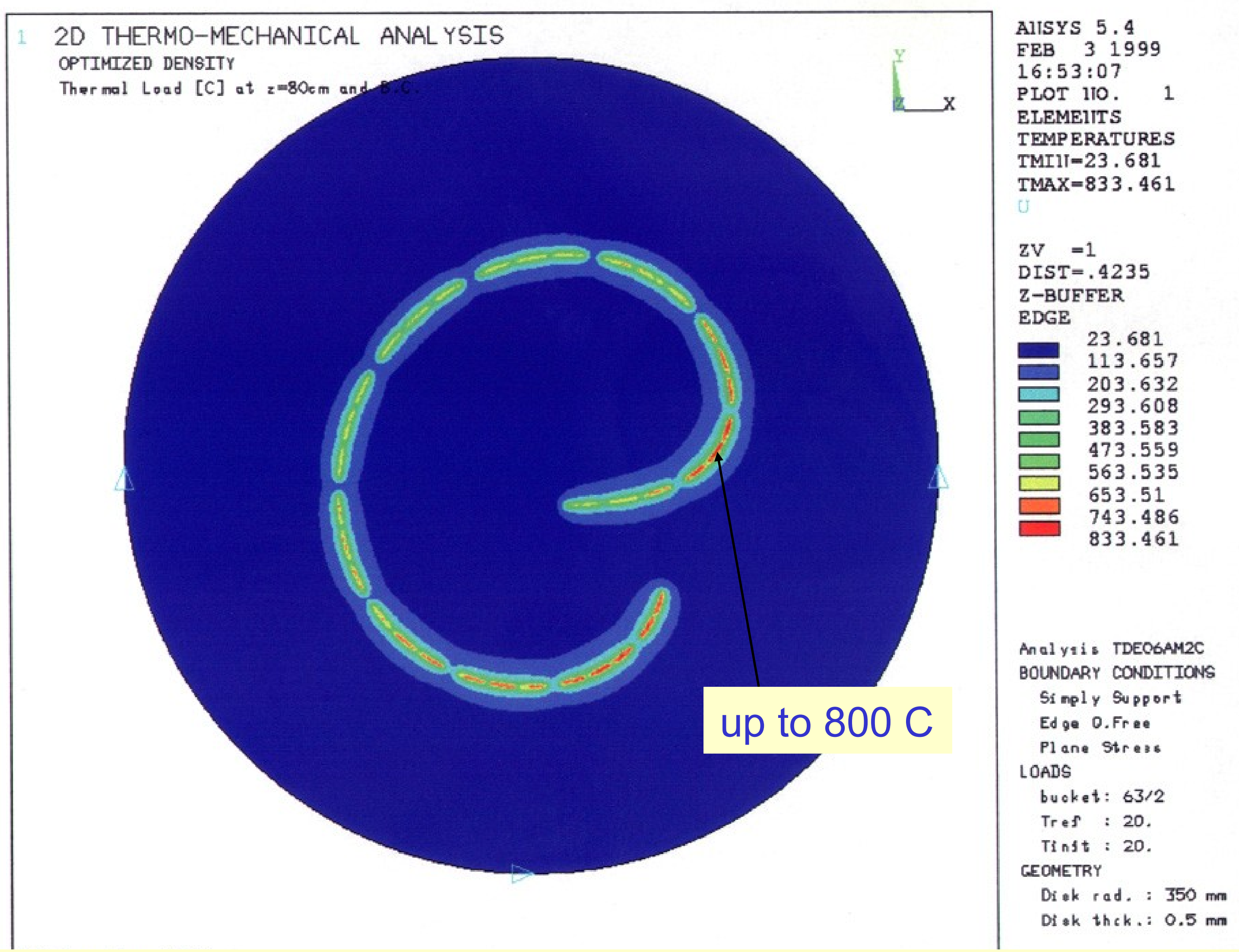
Energy per beam: 346 MJoule

Schemat zrzucania wiązki



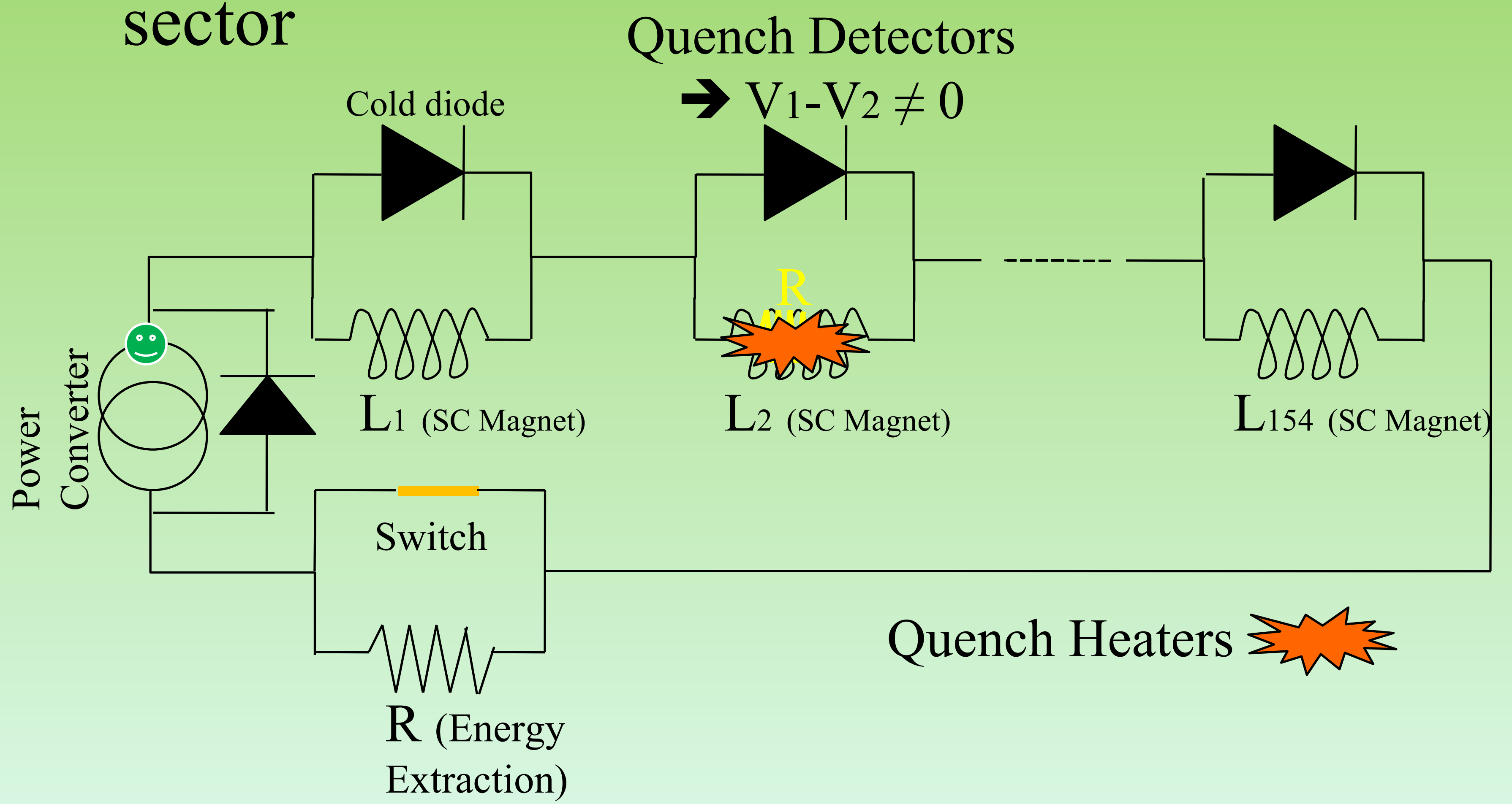

beam absorber
(graphite)
about 8 m
concrete
shielding

Temperatura w bloku grafitu - 80 cm



L.Bruno: Thermo-Mechanical Analysis with ANSYS

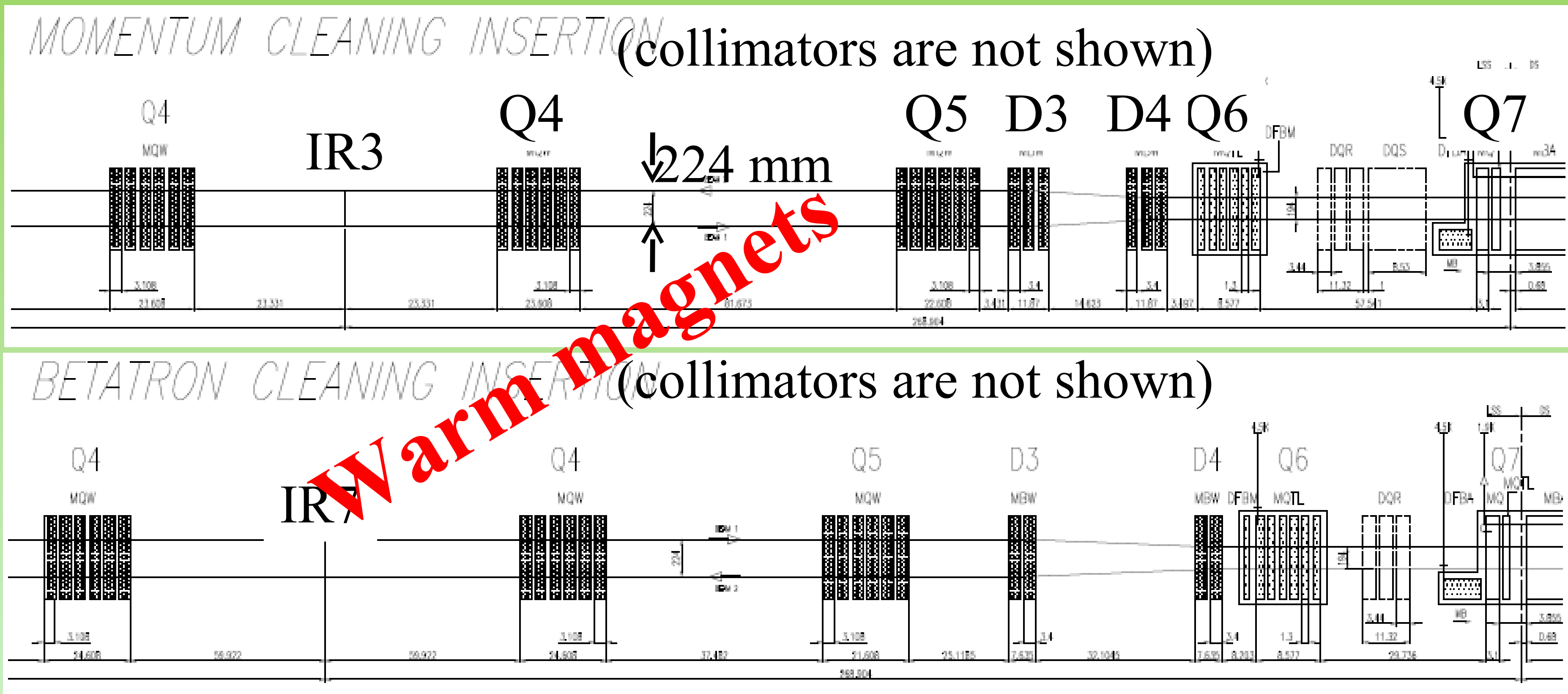
- Schematics of the QPS in the main dipoles of a sector



If not fast and safe ...

During magnet test campaign, the 7 MJ stored in one magnet were released into one spot of the coil (inter-turn short)

III.II Momentum and betatron



Particles with large momentum offset are scattered by the primary collimators in IR3.

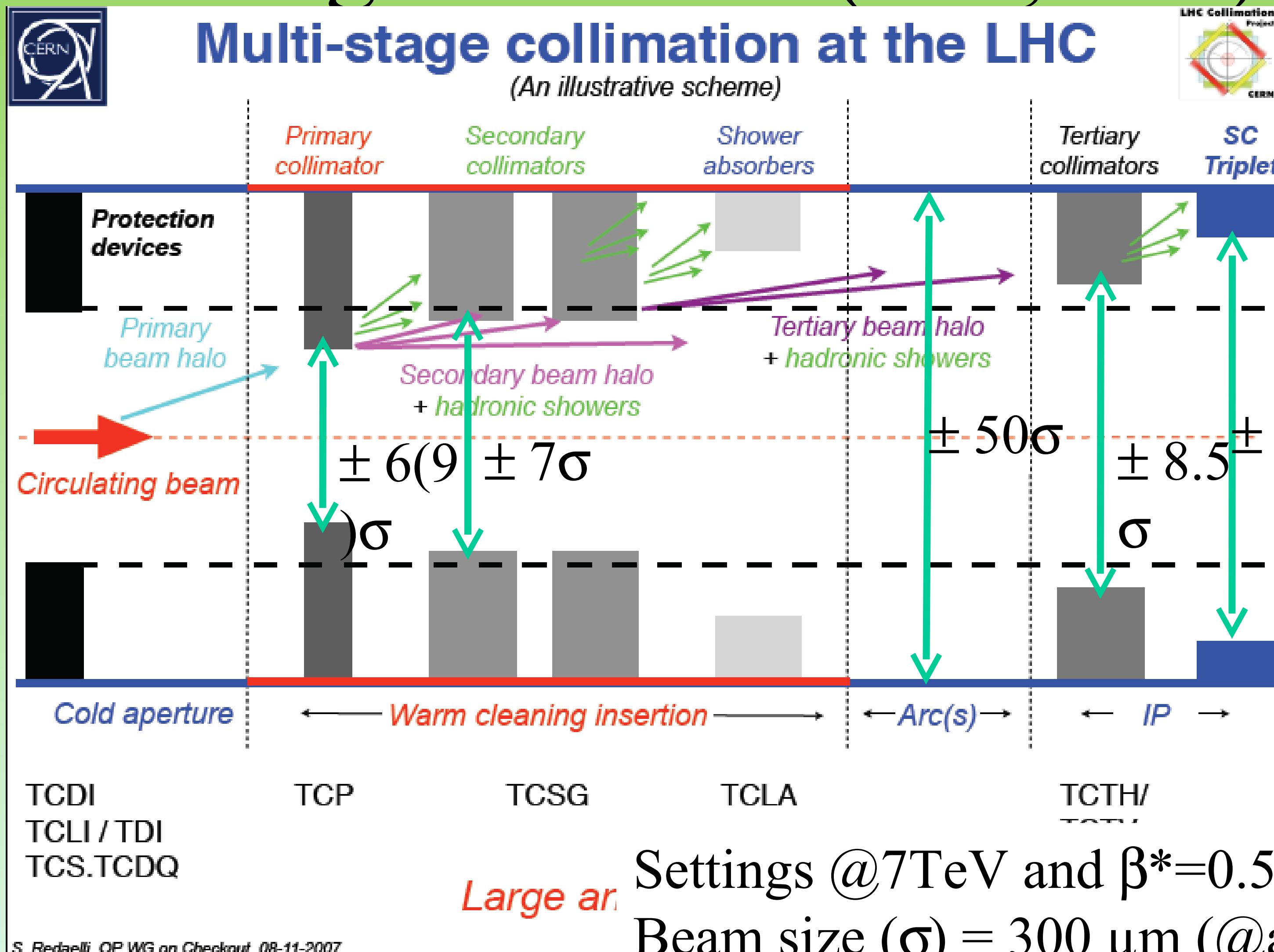
Particles with large H, V or H&V betatron amplitudes are scattered by the primary collimators in IR7.

In both cases the scattered particles are absorbed by secondary collimators.

Typical quadrupole strength 30-35 T/m

Note: IR3 & IR7 have special DS (arc quadrupoles in series + trim quadrupoles) because of lack of space to place the power converters.

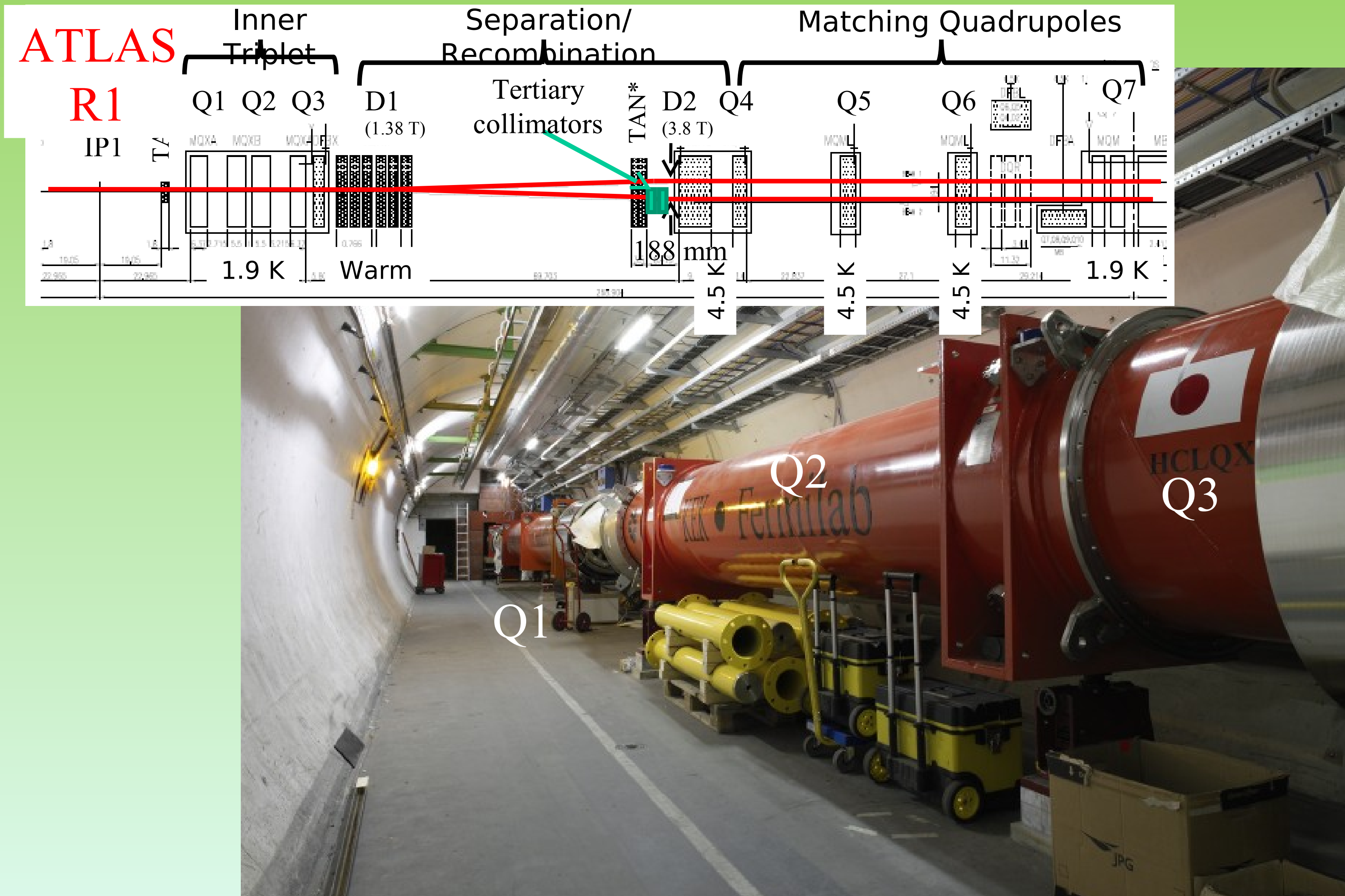
III.II Momentum and betatron cleaning insertions (IR3, IR7)



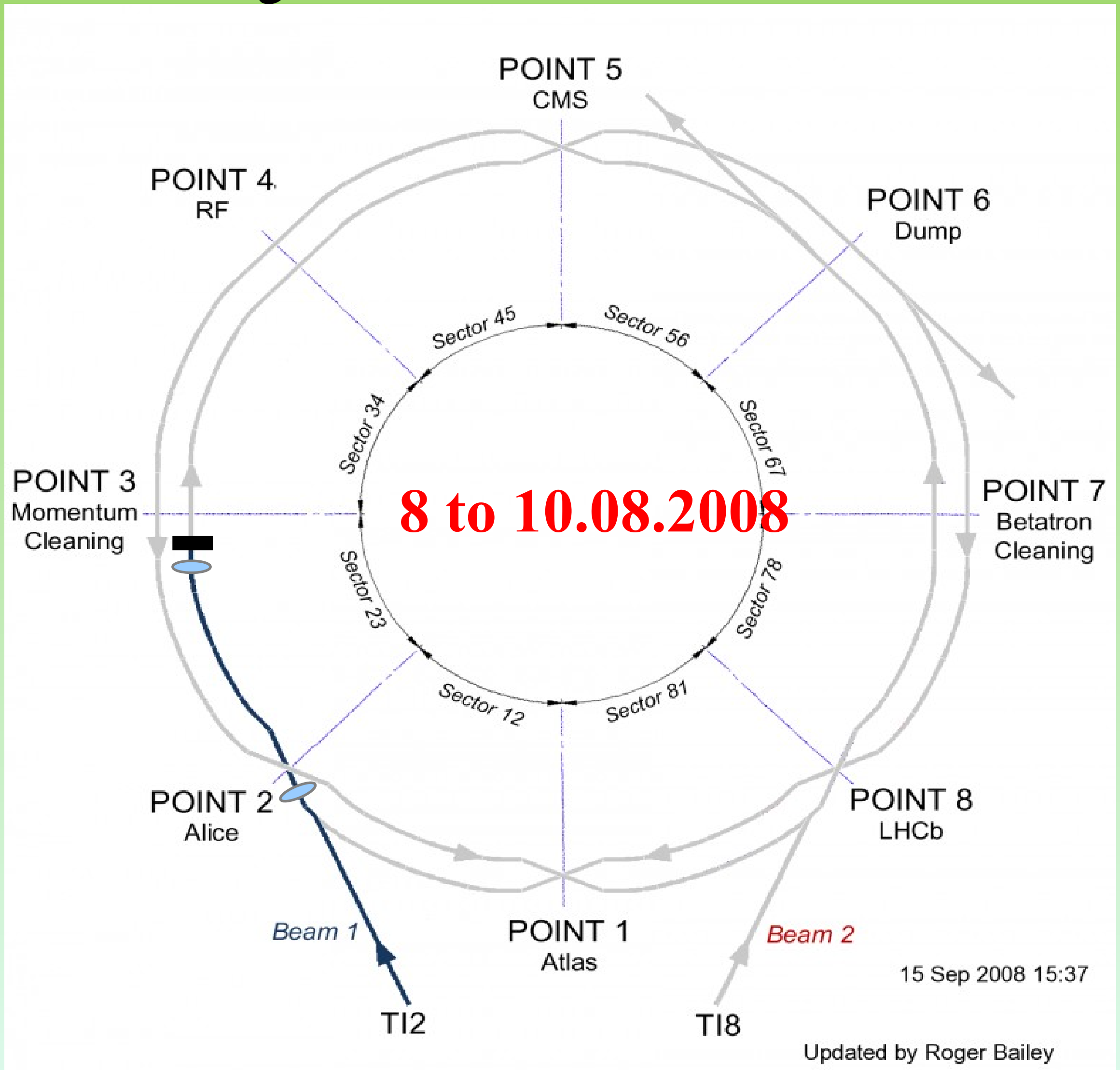
Settings @7TeV and β*=0.55 m

Beam size (σ) = 300 μm (@arc)

Beam size (σ) = 17 μm (@IR1, IR5)

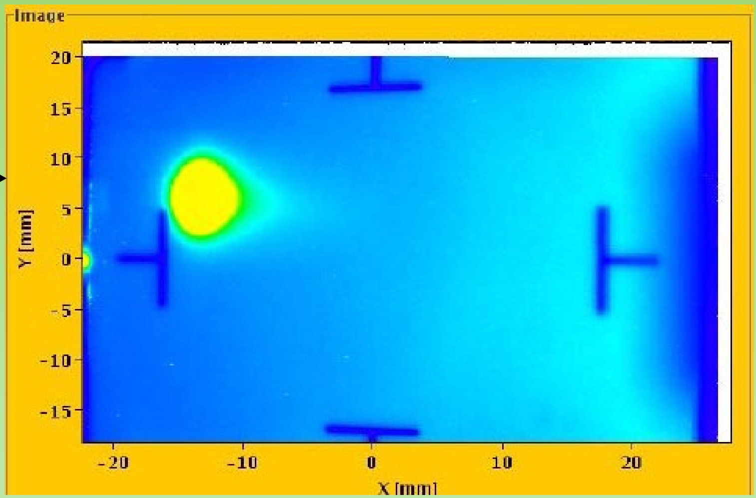

ATLAS
R1
Inner Triplet
Separation/ Recombination
Matching Quadrupoles
IP1
Q1 Q2 Q3
D1
(1.38 T)
Tertiary collimators
TAN*
D2
(3.8 T)
Q4
Q5
Q6
Q7
188 mm
1.9 K
Warm
4.5 K
4.5 K
4.5 K
1.9 K
Q1
Q2
Q3
KEK • Fermilab
HCLQX

Injection Test 1



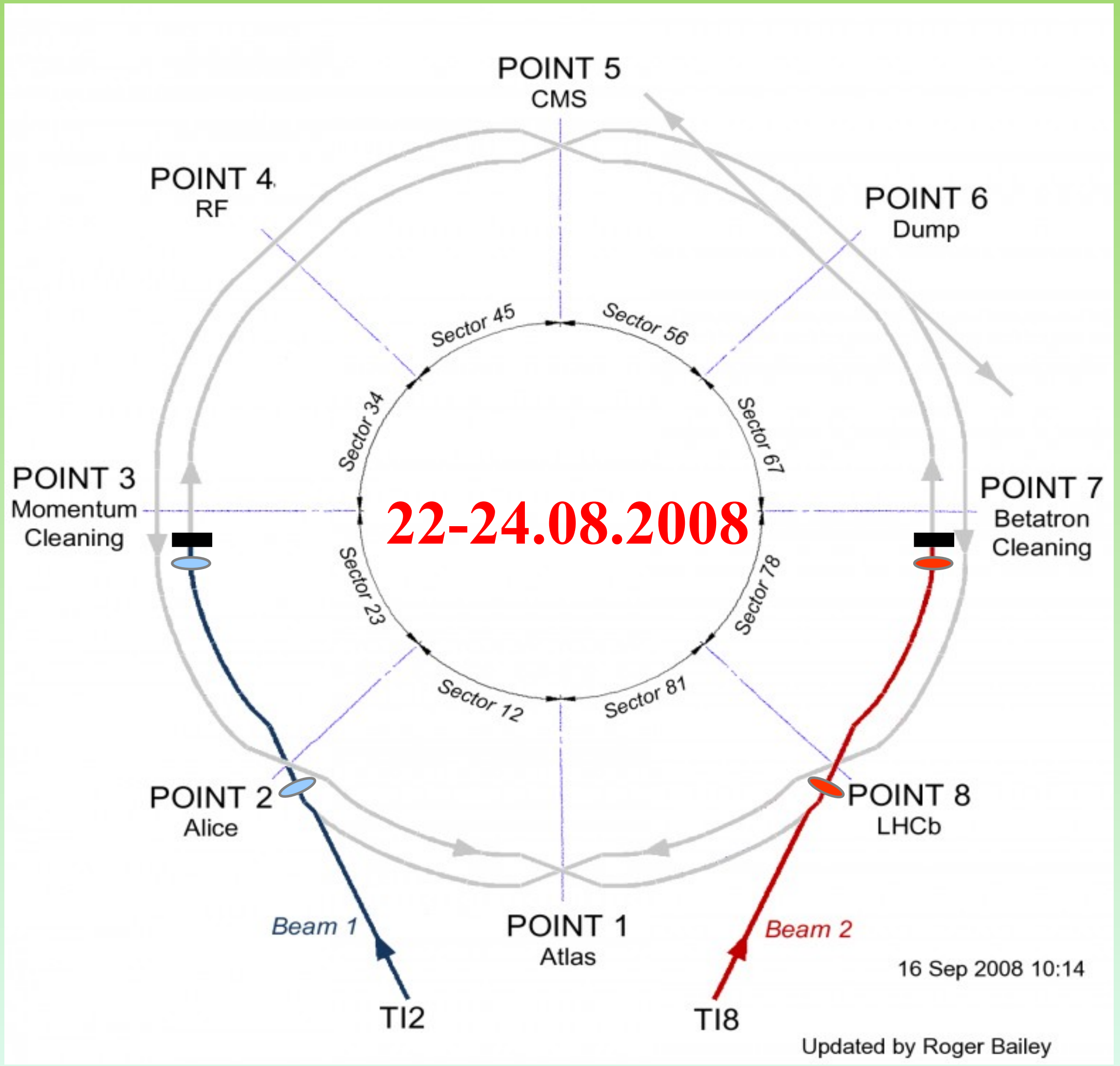
Injection Test 1

- Achieved
  - Synchronization SPS – LHC
  - **Beam 1** injected IP2
  - Through to collimators in IP3 first shot
  - Trajectory correction
  - Kick-response measurements
  - Off-energy measurements (dispersion)
  - Explored the aperture
  - First beam induced quench



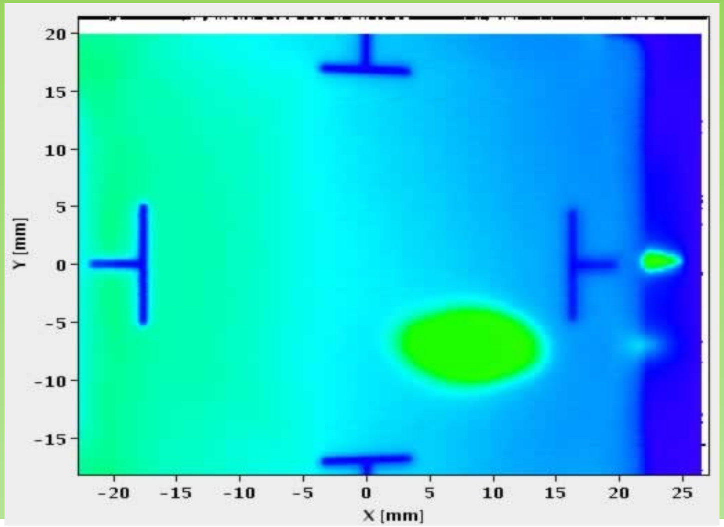
- Discovered
  - Aperture restriction in the injection line
    - Traced to misaligned vacuum pump
  - Optics problem IP3
    - Polarity convention QTL

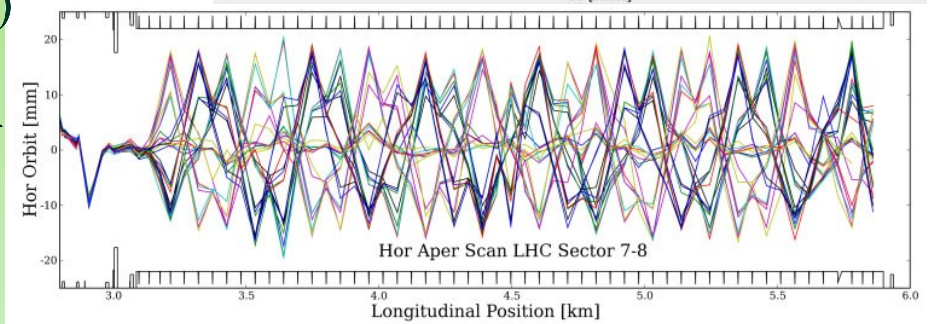
Injection Test 2

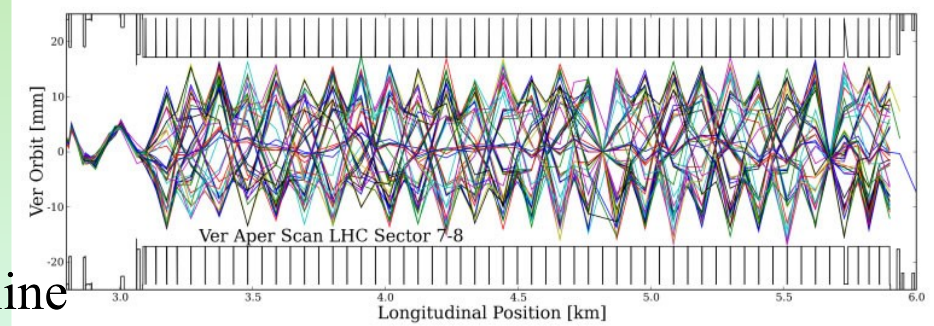


Injection Test 2

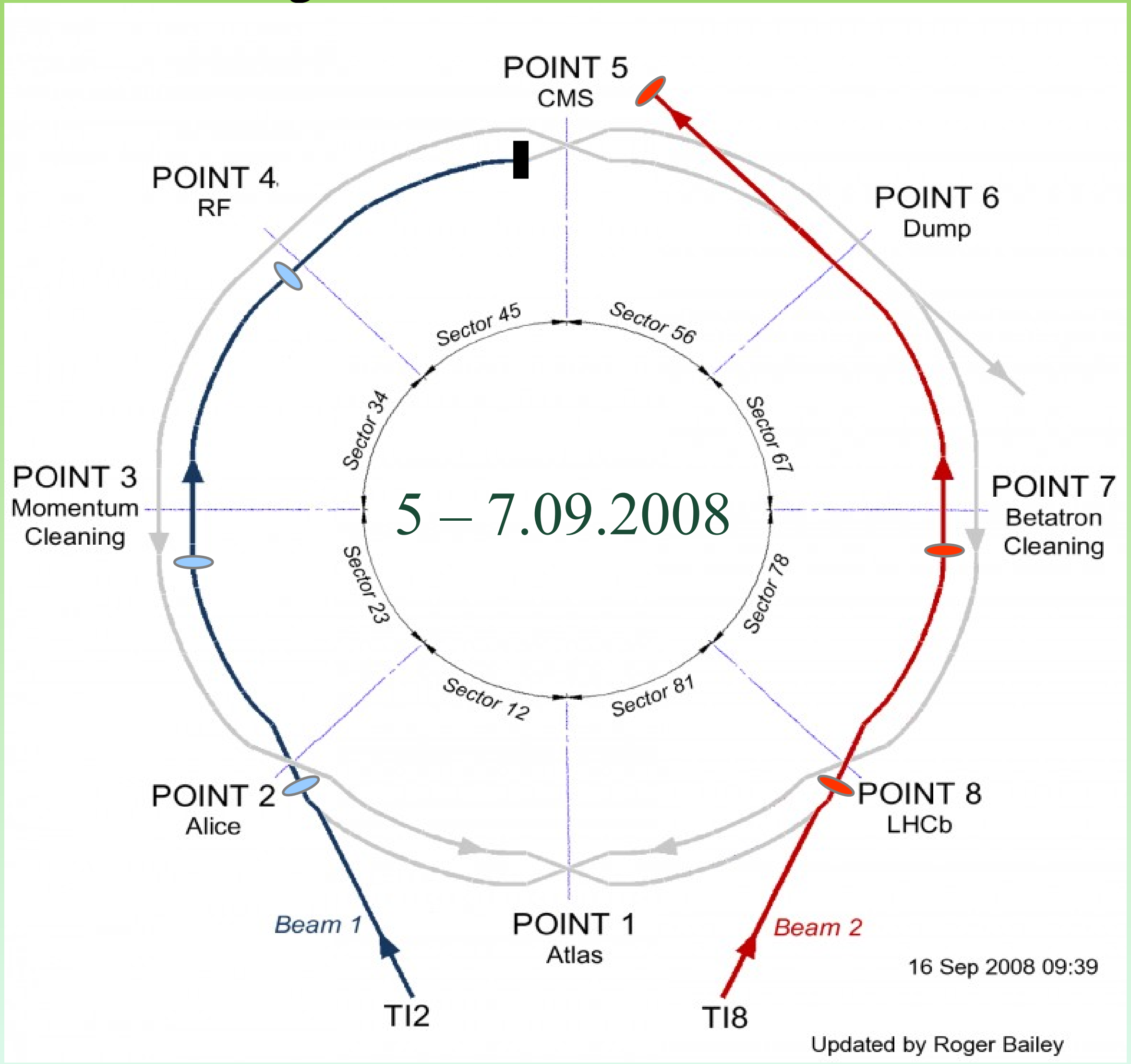
- Achieved
  - Beam 2 injected IP8
  - Through to collimators in IP7 first shot
  - Trajectory correction
  - Kick-response measurements
  - Off-energy measurements (dispersion)
  - Explored the aperture
  - Beam 1 injected IP2
  - Through to collimators in IP3
  - Aperture in injection region OK
  - Polarity correction confirmed
  - Interleaved injection
- Discovered
  - Optics problem at the end of the TI8 line





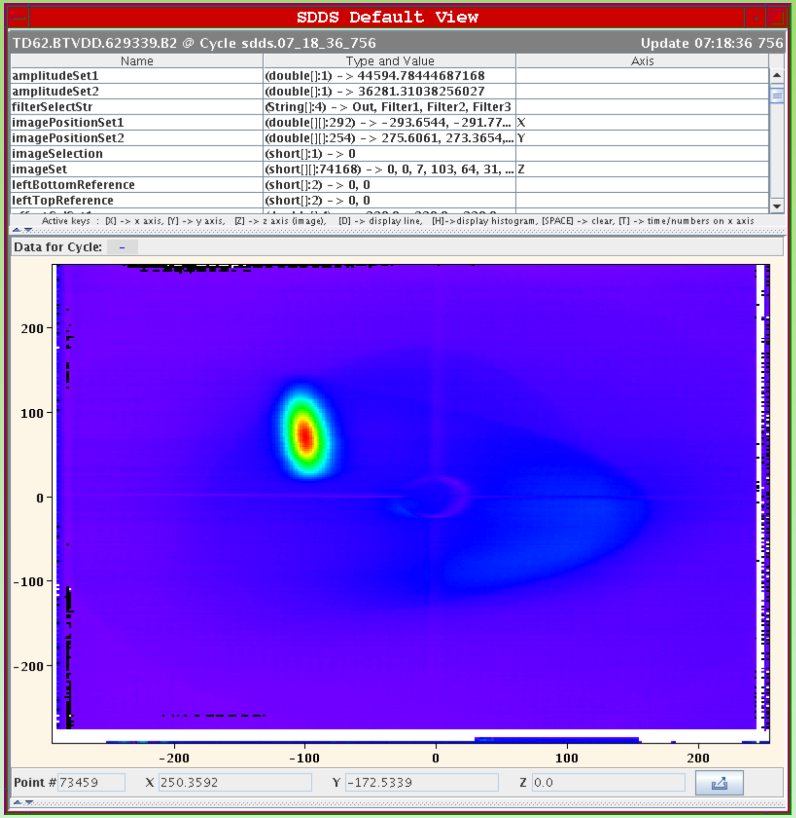


Injection Test 3



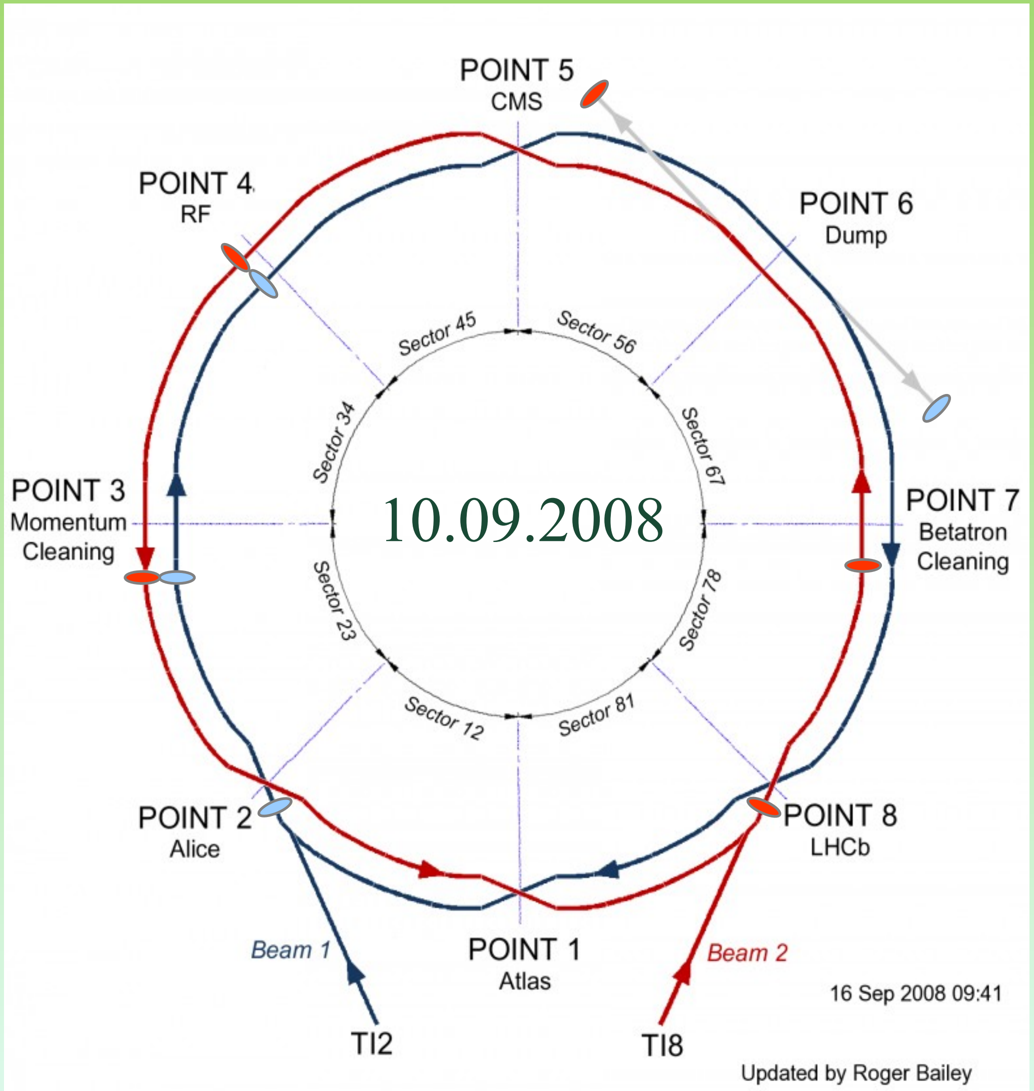
Injection Test 3

- Achieved
  - Beam 2 injected IP8
  - Threaded to dump in IP6
  - Steered then inject and dump
  - Beam 1 injected IP2
  - Threaded through to coll in IP5



- Discovered
  - Optics problem in IP7
    - Polarity convention on Q6
  - Optics problem in IP4
    - Polarity convention

10th of September

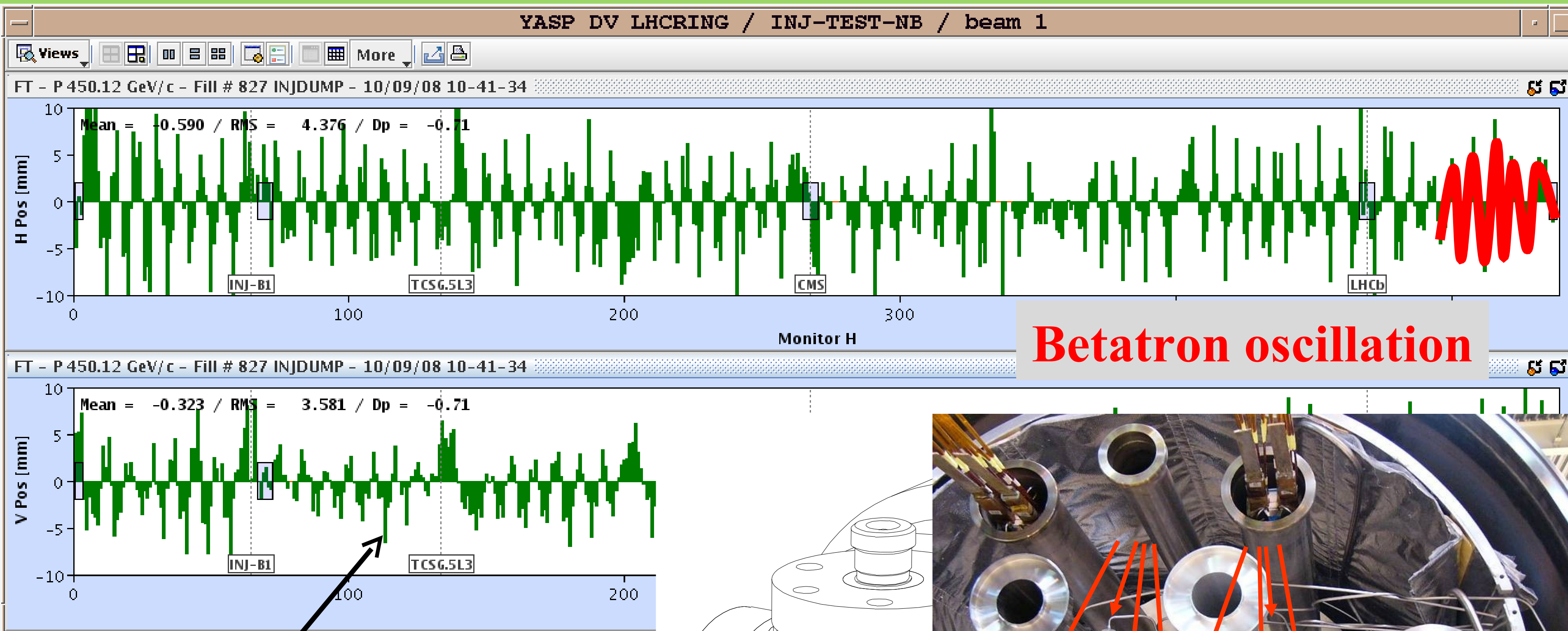


10^{th} of September

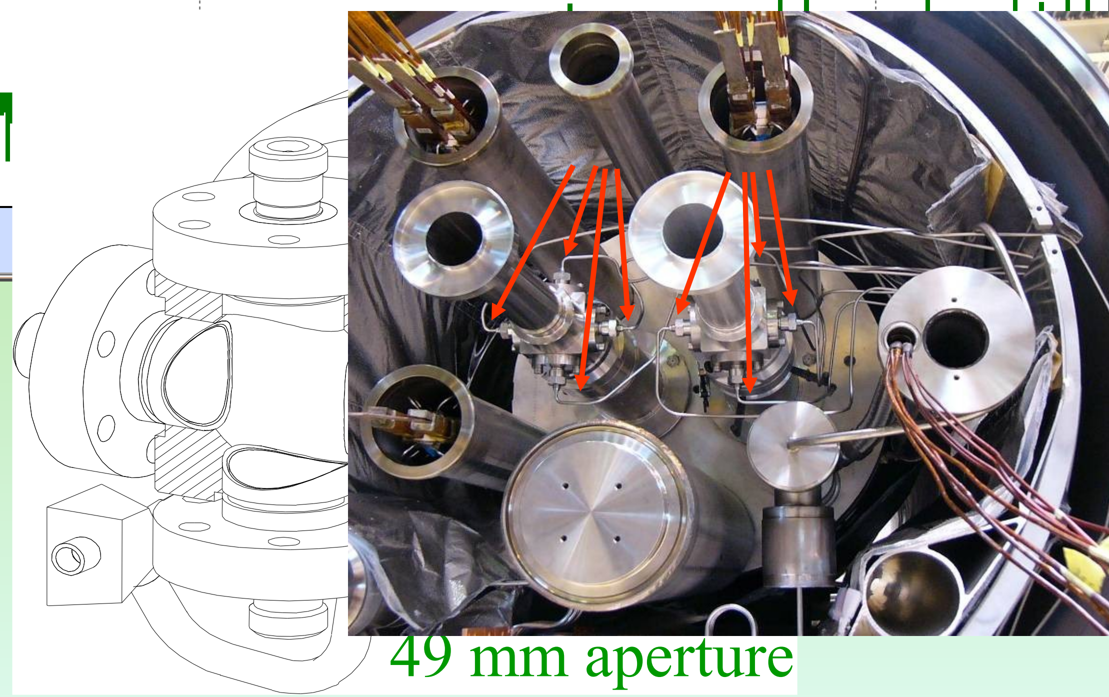
- Achieved
  - Beam 1 injected IP2
  - Threaded around the machine in 1h
  - Trajectory steering gave 2 or 3 turns

  - Beam 2 injected IP8
  - Threaded around the machine in 1h30
  - Trajectory steering gave 2 or 3 turns
  - Q and Q' trims gave a few hundred turns

10th of September Beam 1 – First turn trajectory

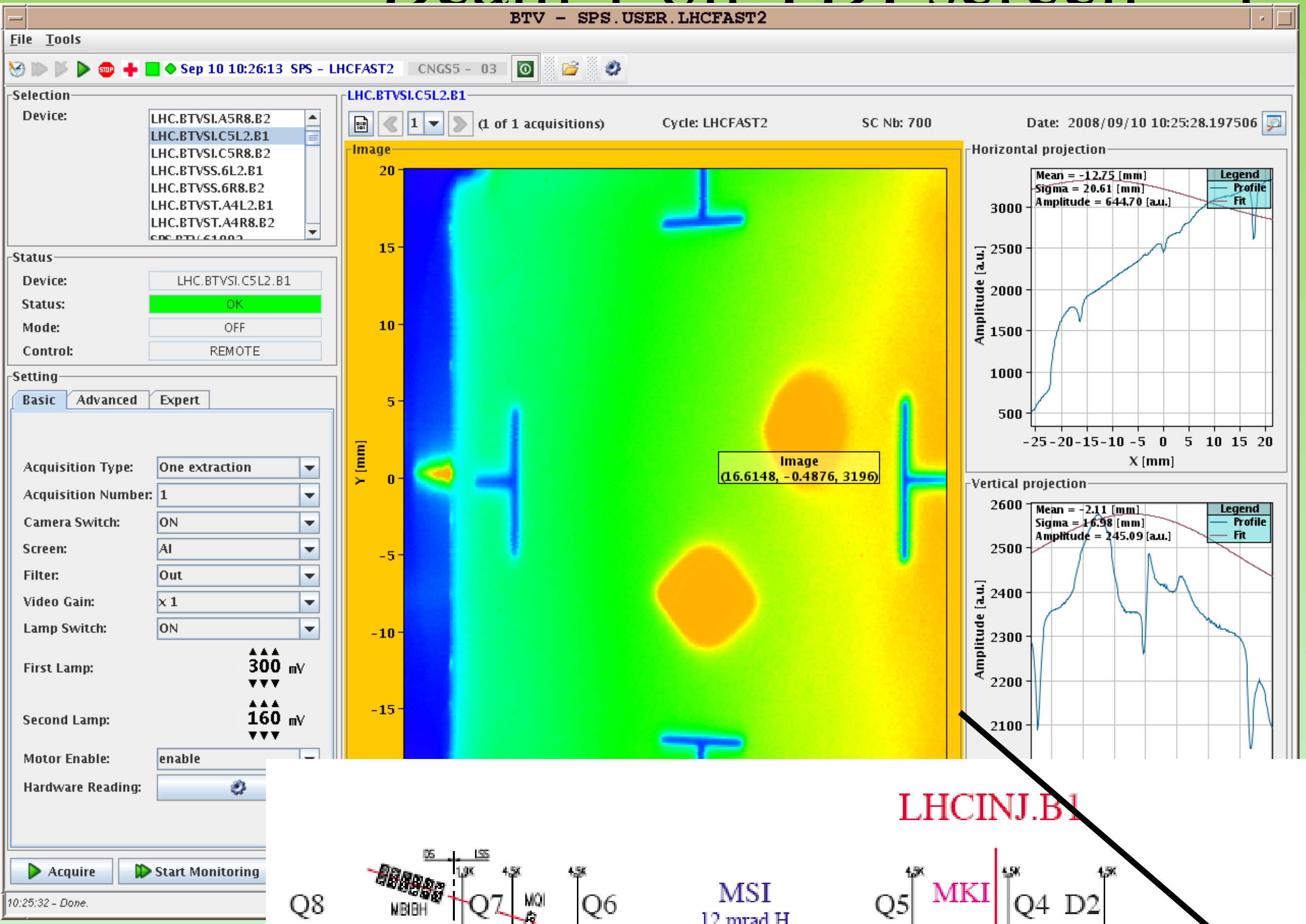


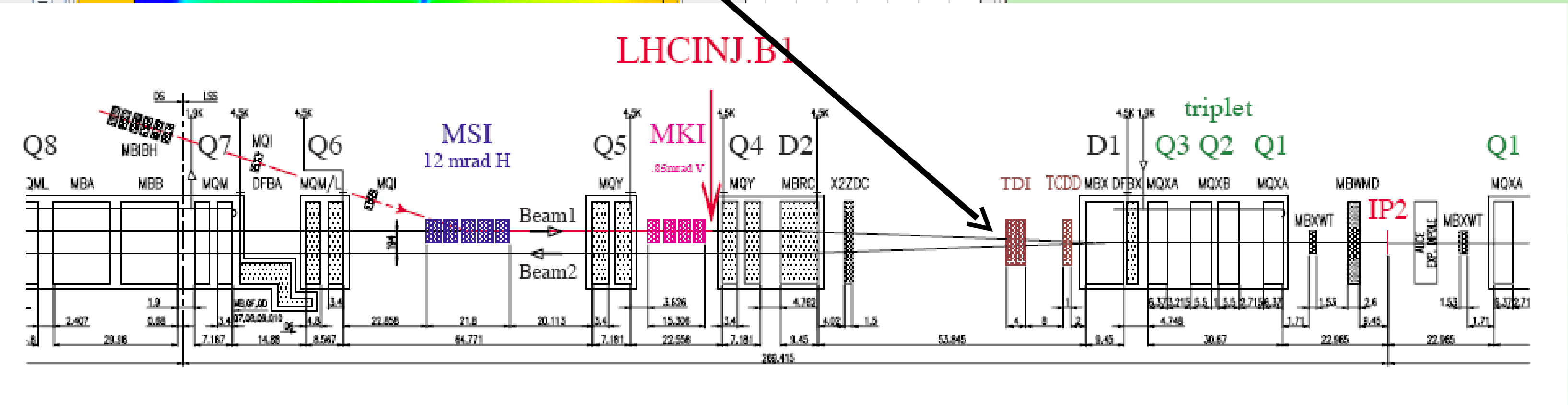
Each point is a BPM (Beam Position Measurement)



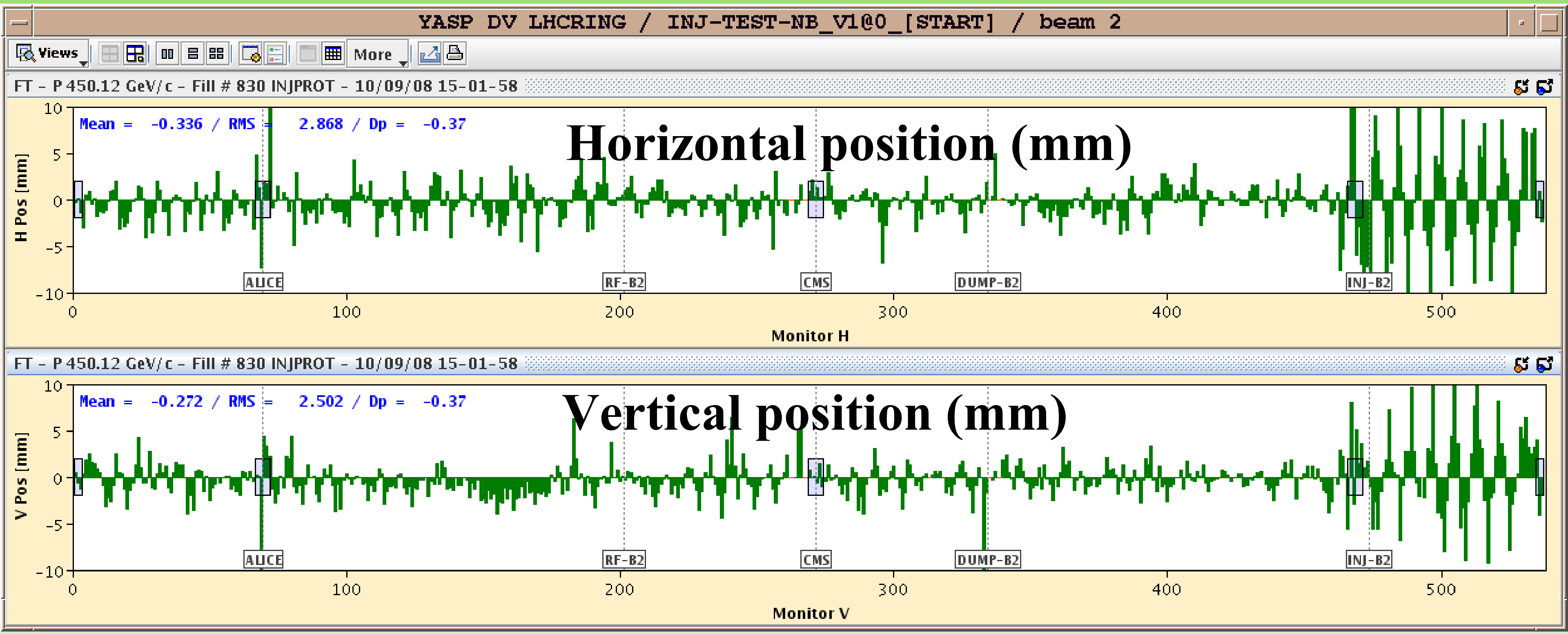
10th of September

Beam 1 on TDI screen – 1st and 2nd turns

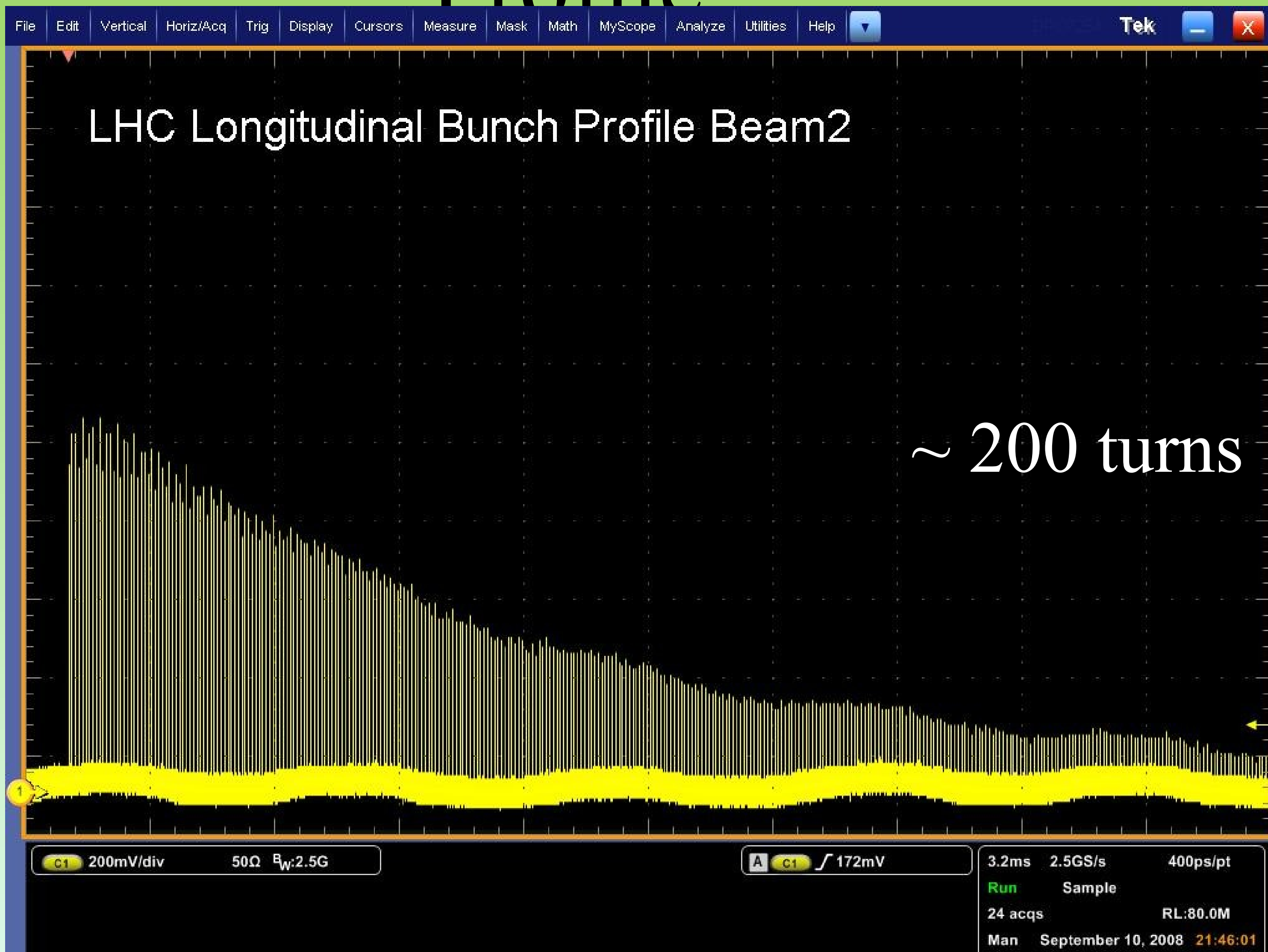




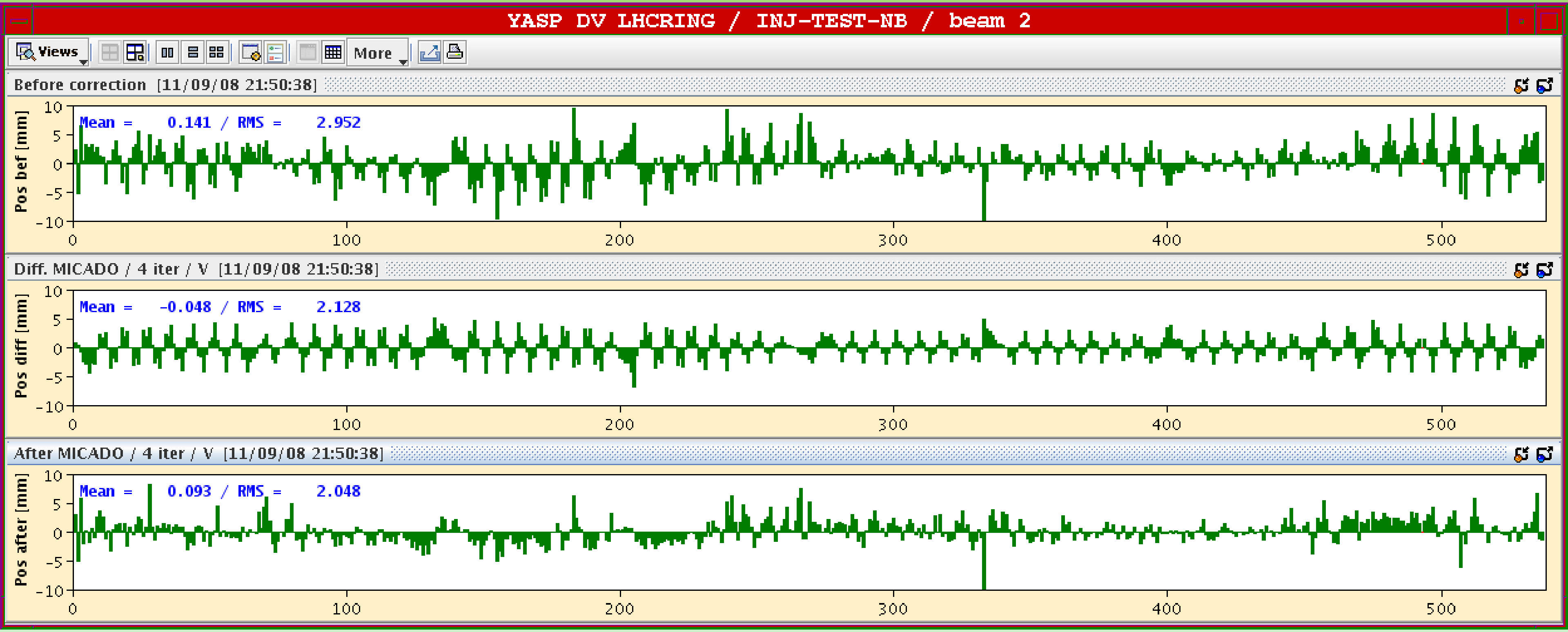
10th of September
Beam 2 – First turn trajectory



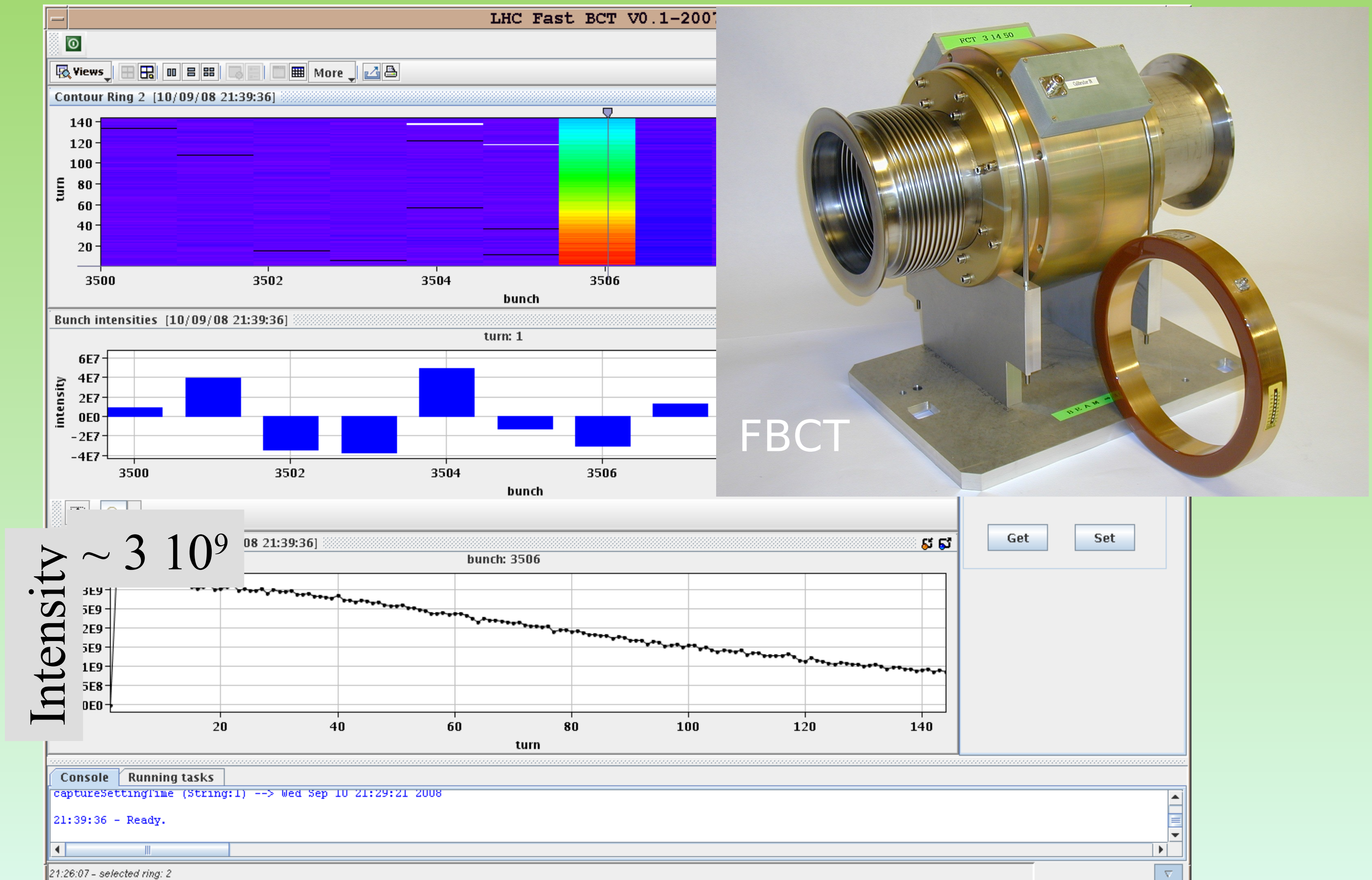
IV.IV: 10 of September
Beam 2: Longitudinal Bunch Profile



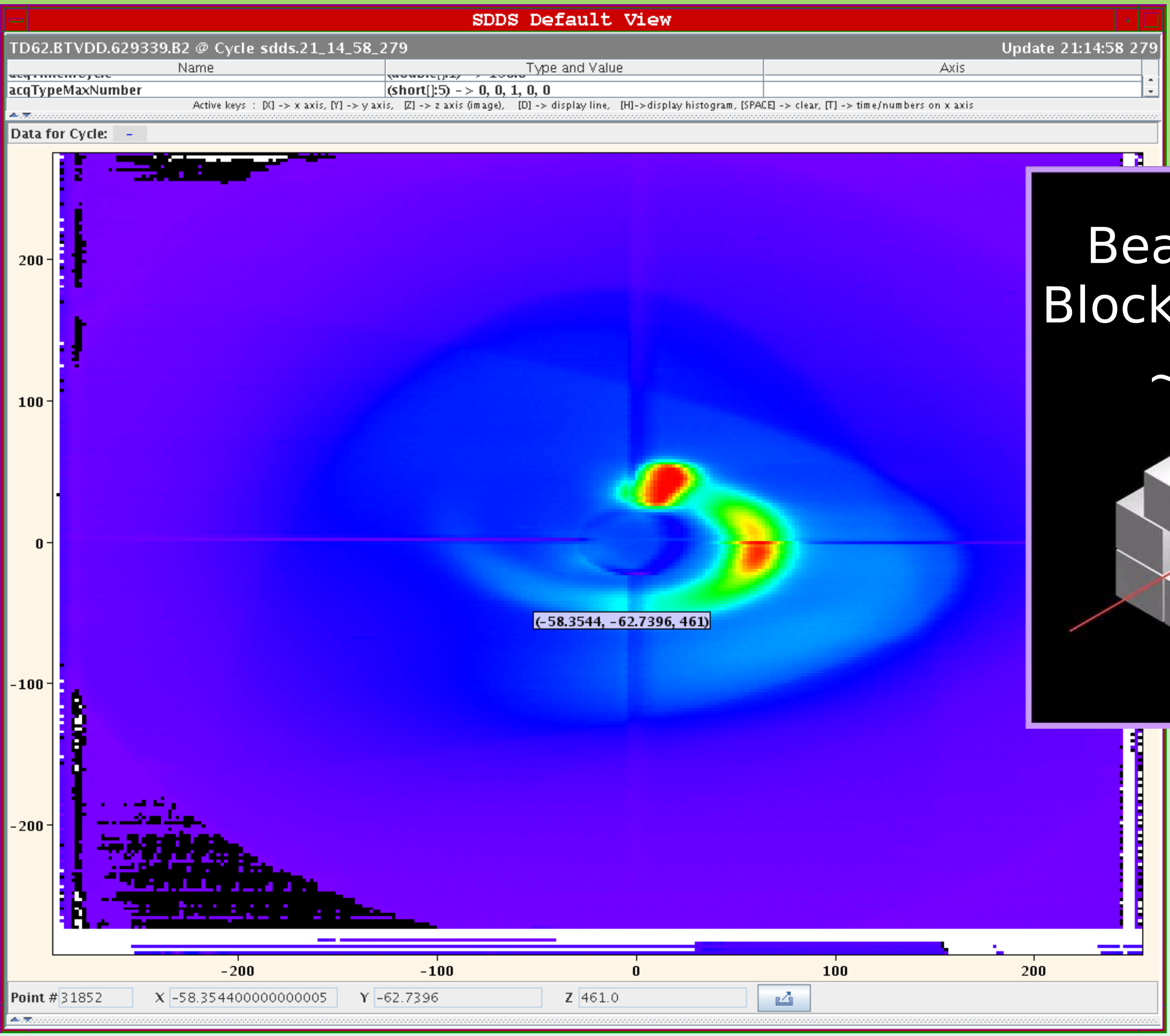
IV.IV. 10th of September Beam 2 closed orbit

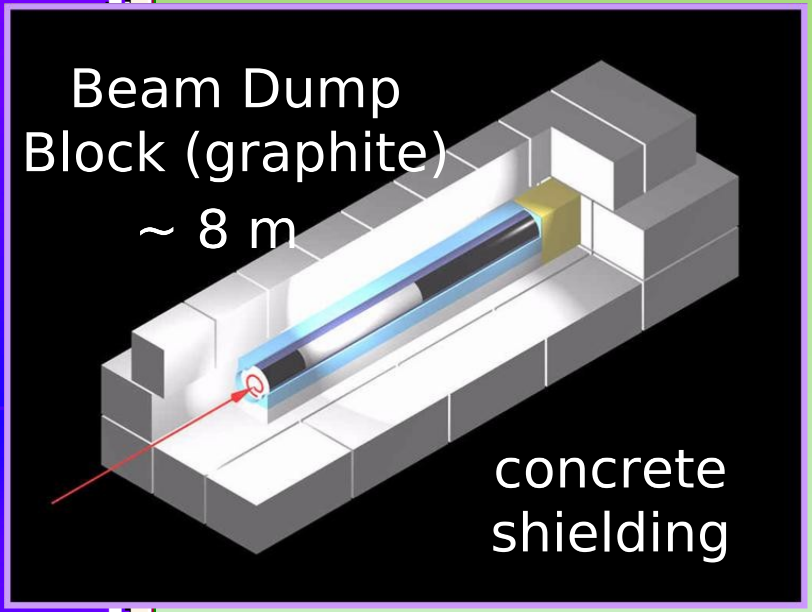


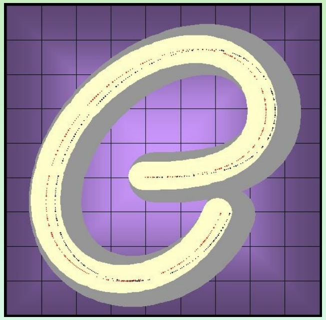
IV.IV. 10th of September
Beam 2 fast BCT (Beam Current Transformer)



10th of September Beam dilution on dump block

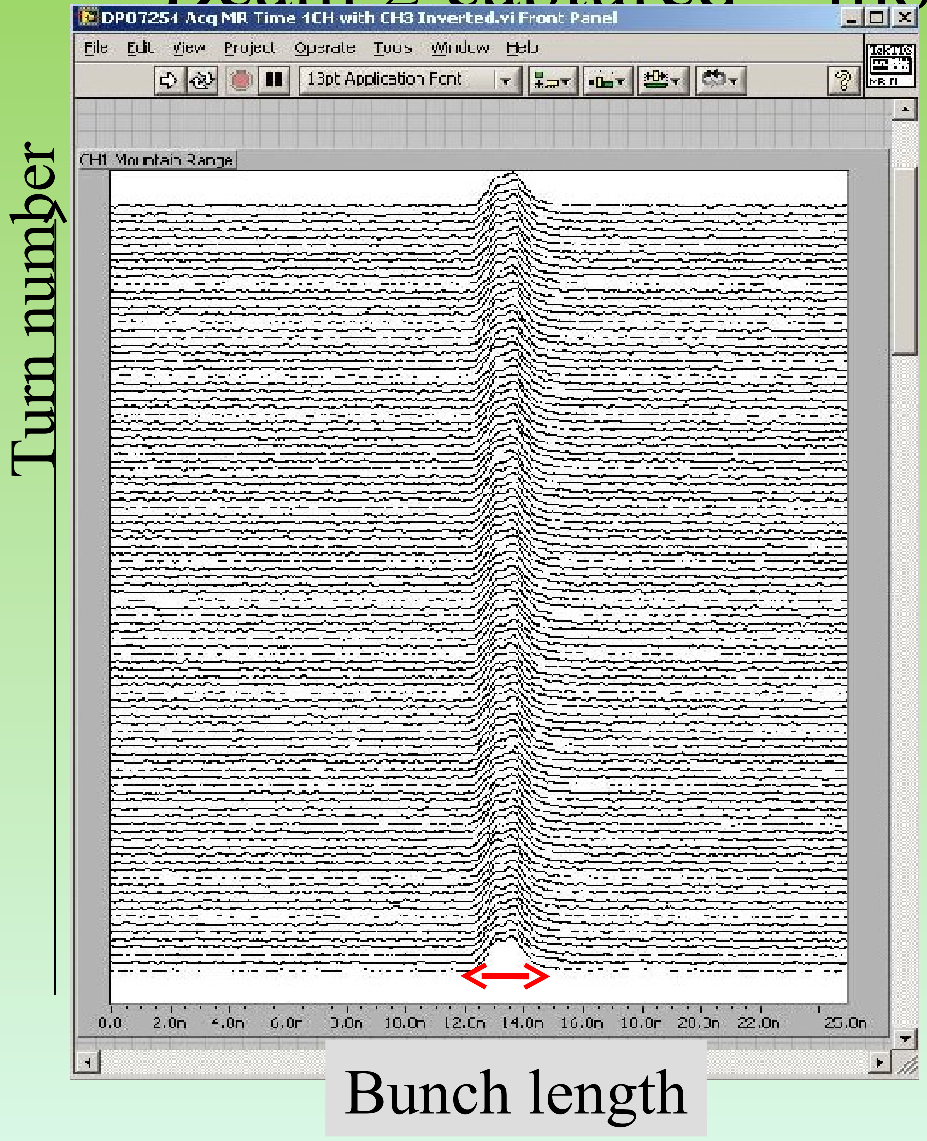






10th of September

Beam 2 captured – mountain range display



Now RF ON

10th of September

HTS in the LHC machine

Powering of the LHC magnets

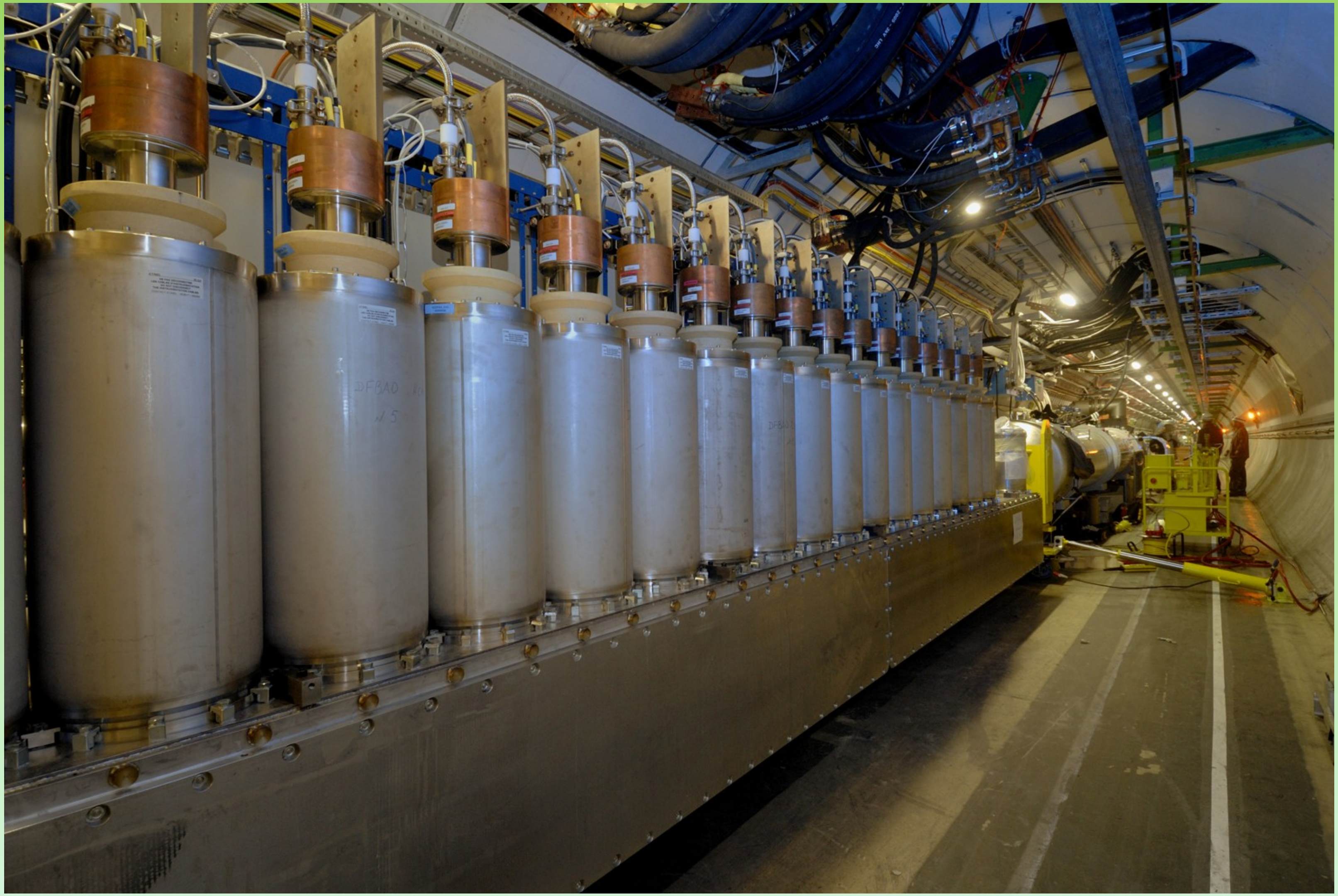
About <u>3 MA</u> of rated current for 1800 circuits

3286 current leads

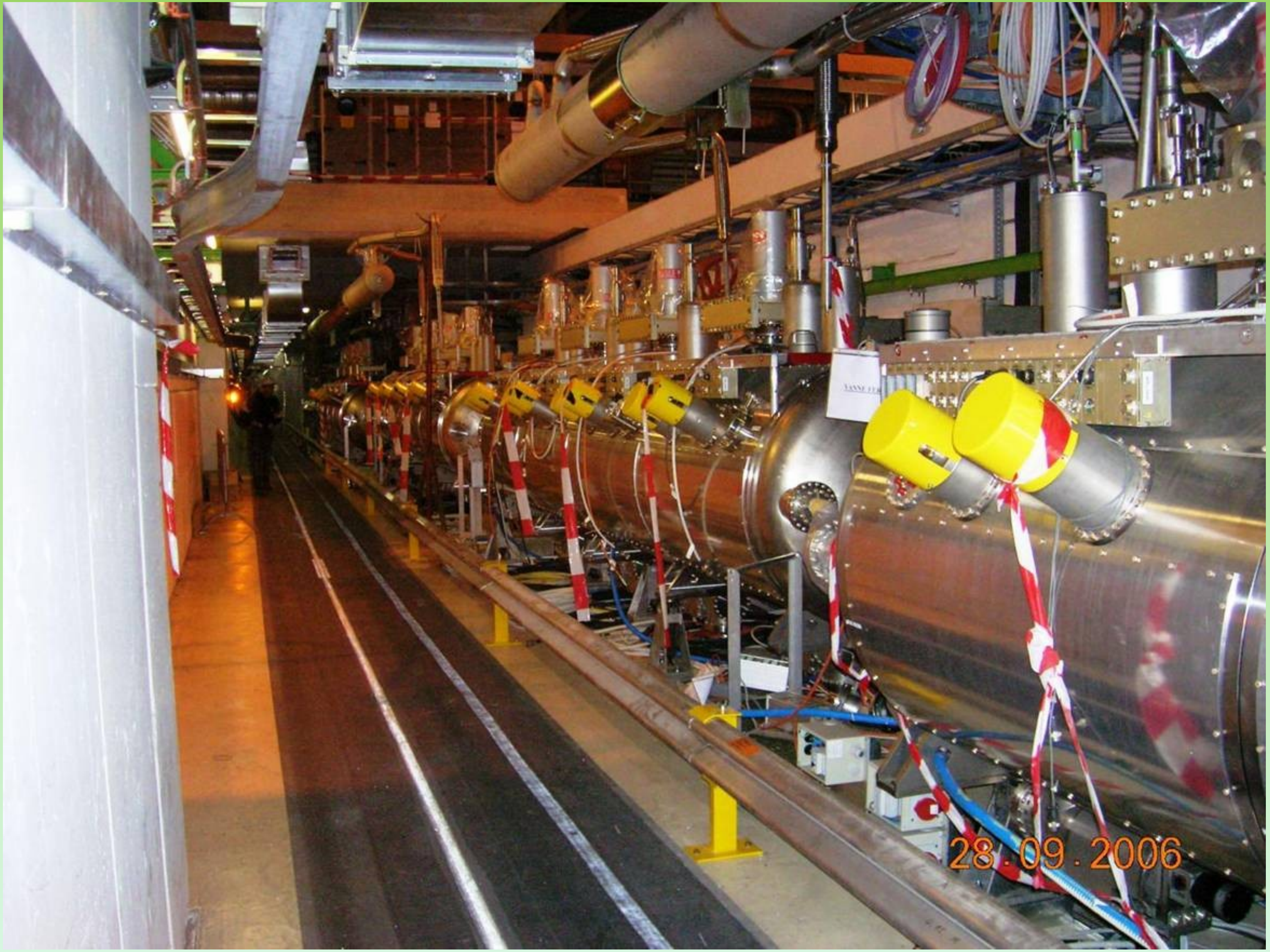
Quantity	Current rating (A)
64	13000
298	6000
820	600
2104	60-120

HTS (applies to the 13000 A, 6000 A and 600 A rows)

DFBAO in Sector 7-8



RF cavities



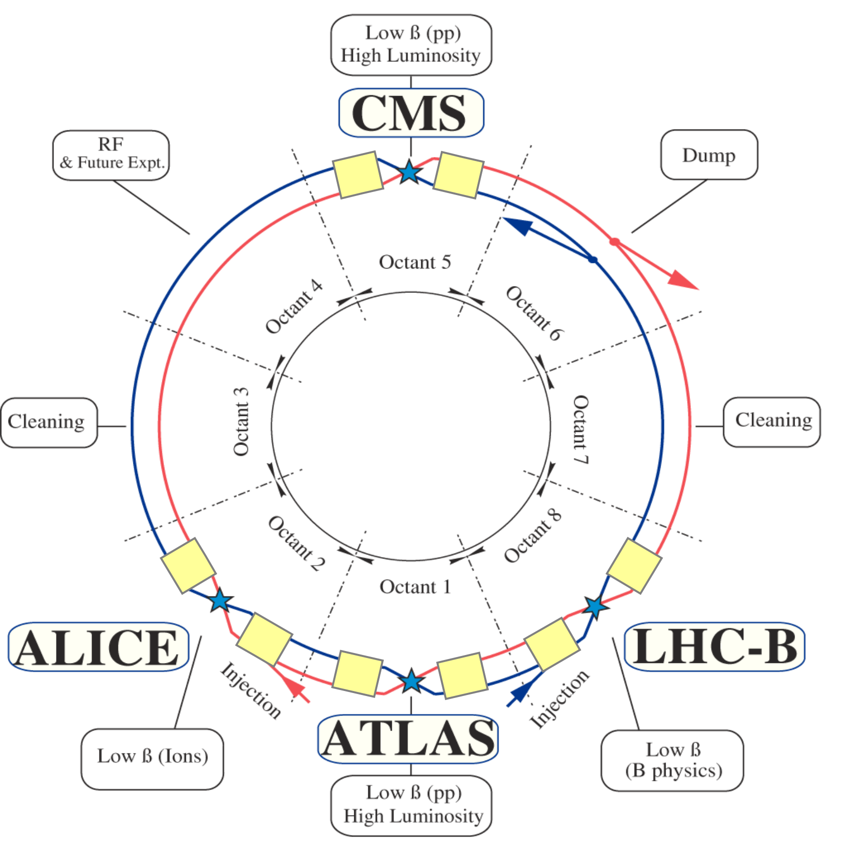
Two 300 kW klystrons with circulators and loads

Construction and commissioning 2002-2008

Tunnel activity determined by

Triplet

2002	2003	2004	2005	2006	2007	2008



Inner Triplets
Either side of each experiment
Provide focusing at the Interaction

Construction and commissioning 2002-2008

Tunnel activity determined by

Triplet (2007)

2002	2003	2004	2005	2006	2007	2008

During the pressure test of Sector 7-8 (25 November 2006) the corrugated heat exchanger tube in the inner triplet failed by buckling at 9 bar (external) differential pressure

On Tuesday March 27 2007 there was a serious failure in a high-pressure test at CERN of a Fermilab-built inner-triplet series of three quadrupole magnets left of Point 5

Construction and commissioning 2002-2008

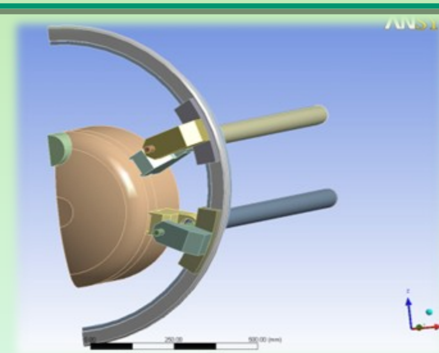
Tunnel activity determined by

Triplet

2002	2003	2004	2005	2006	2007	2008

Redesign of the heat exchanger: new Cu tubes with larger buckling pressure, and new bi-metallic transitions in the ends.

Redesign of the support system based on four cartridges that react to the longitudinal forces and retain the fixed point of the cold mass in its original position



Both repairs had to be made on all 8 triplet assemblies

Some were already installed in the machine

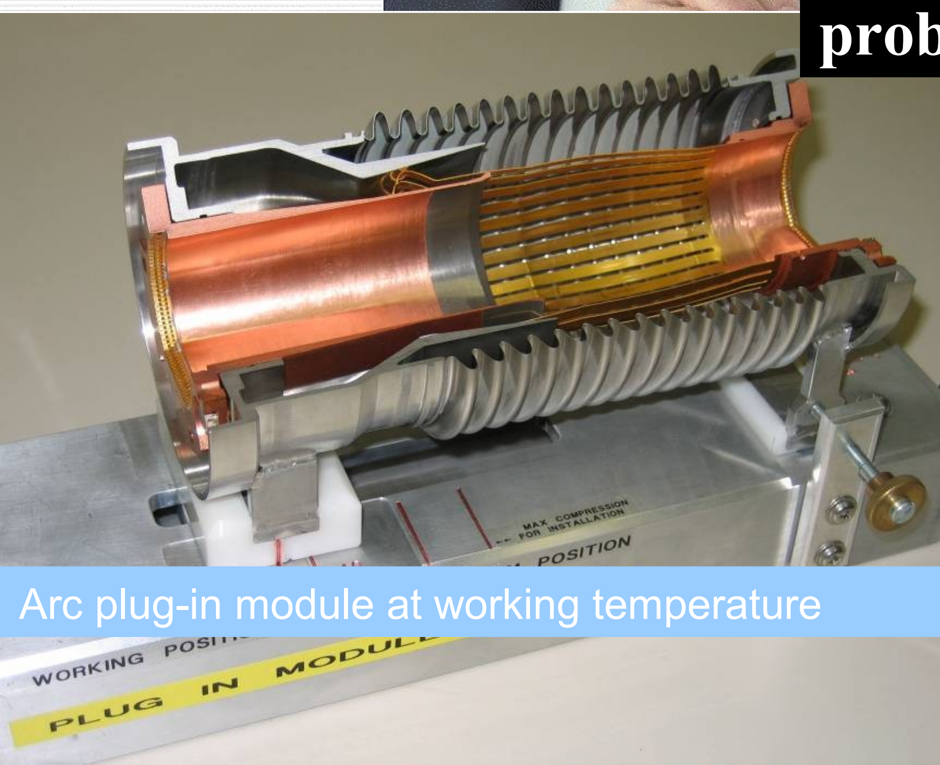
Construction and commissioning 2002-2008

Tunnel activity determined by

Triplet (2007)

2002	2003	2004	2005	2006	2007	2008

QQBI.26R7 line V2



Arc plug-in module at working temperature

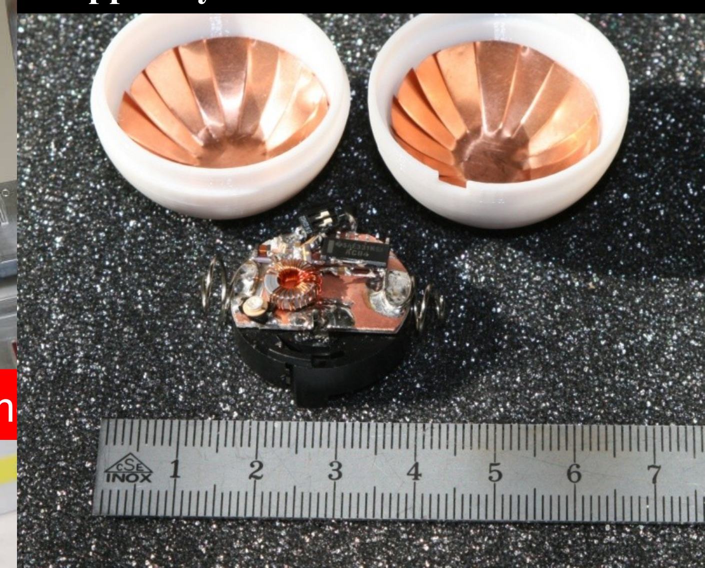
The PiM problem

Arc plug-in m

-- Innovation --

Light ball transmitting at 40MHz
Blown through an LHC arc
Detected by Beam Position Monitors

Stopped by buckled PiMs



Incident of September 19th 2008

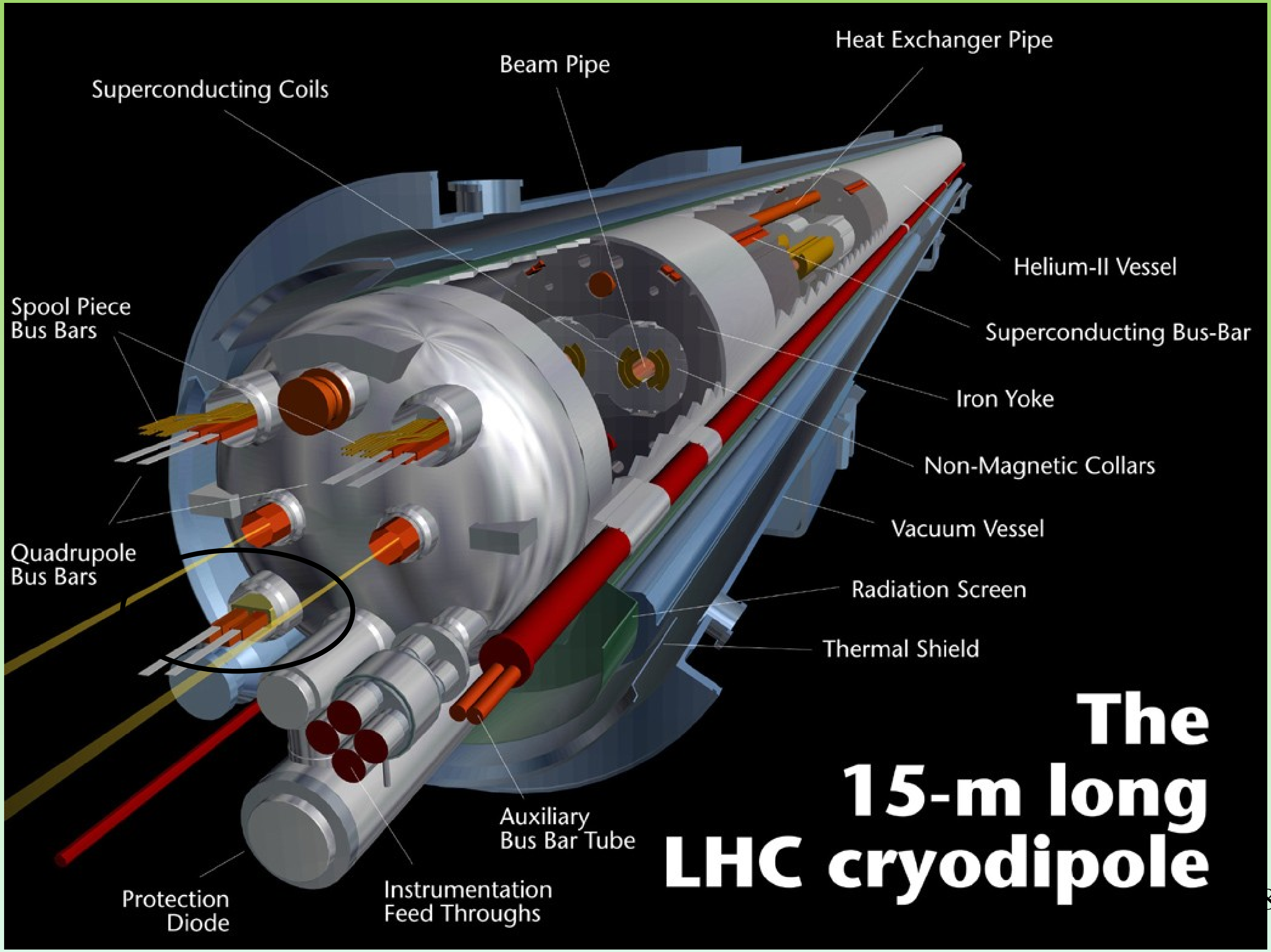
- During a few days period without beam

- Making the last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in the dipole bus bar splice between Q24 R3 and the neighbouring dipole

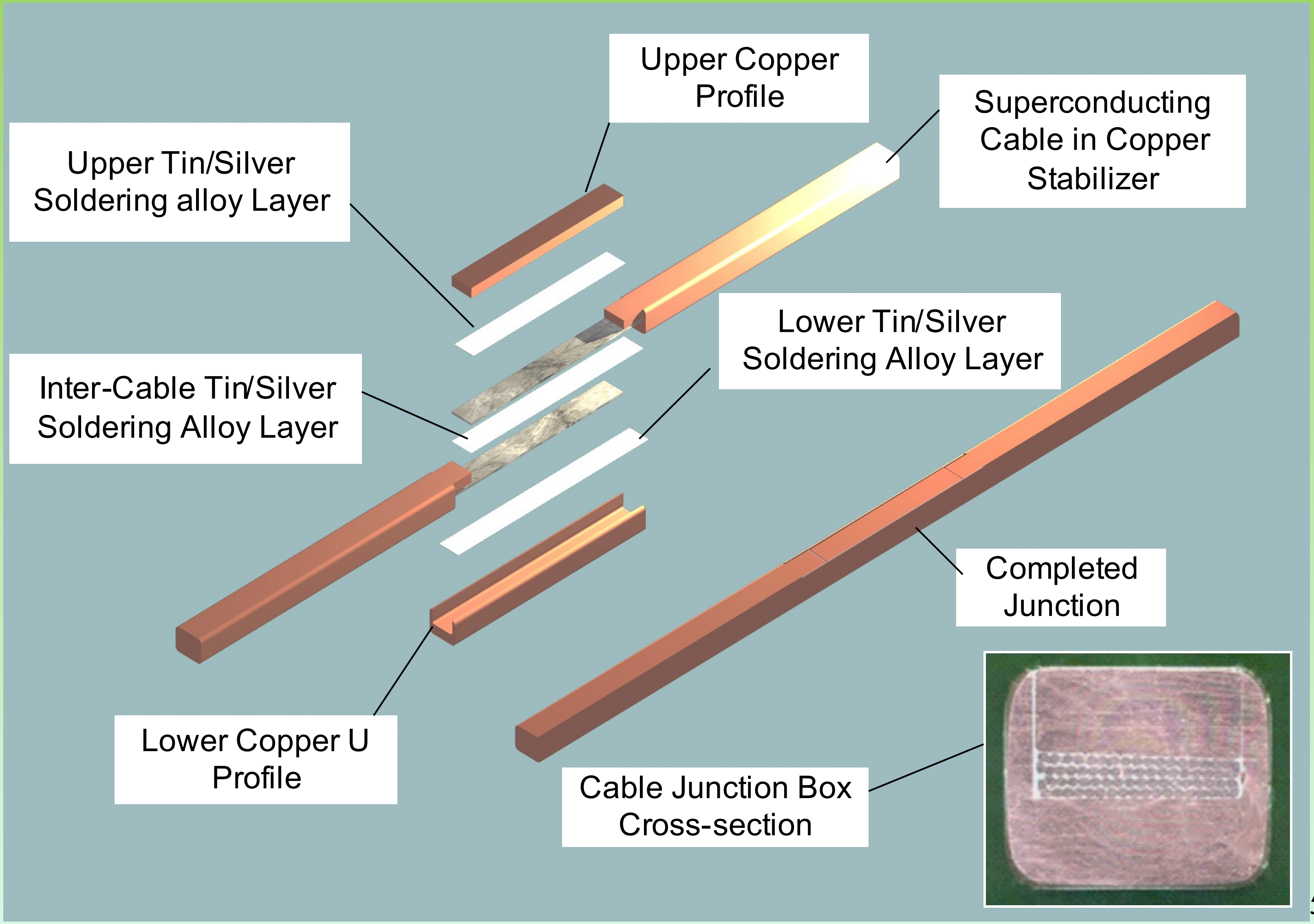
- Electrical arc developed which punctured the helium enclosure
- Helium released into the insulating vacuum

- Rapid pressure rise inside the LHC magnets
  - Large pressure wave travelled along the accelerator both ways
  - Self actuating relief valves opened but could not handle all
  - Large forces exerted on the vacuum barriers located every 2 cells
  - These forces displaced several quadrupoles and dipoles
  - Connections to the cryogenic line affected in some places
  - Beam vacuum also affected

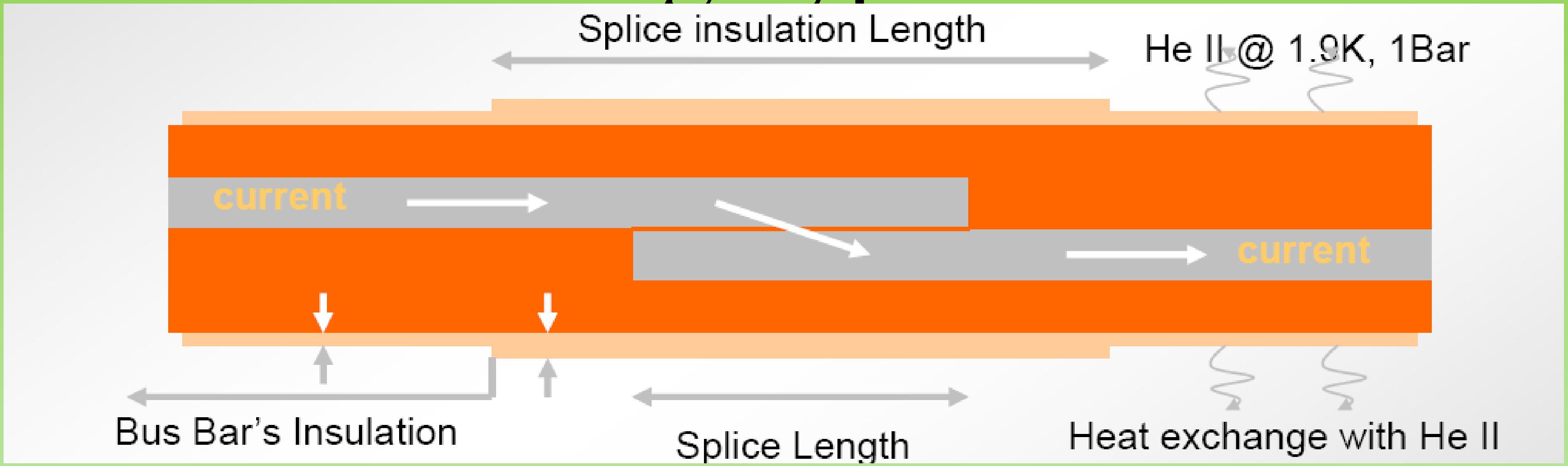
Development of resistive zone in dipole bus bar splice



Bus bar splice



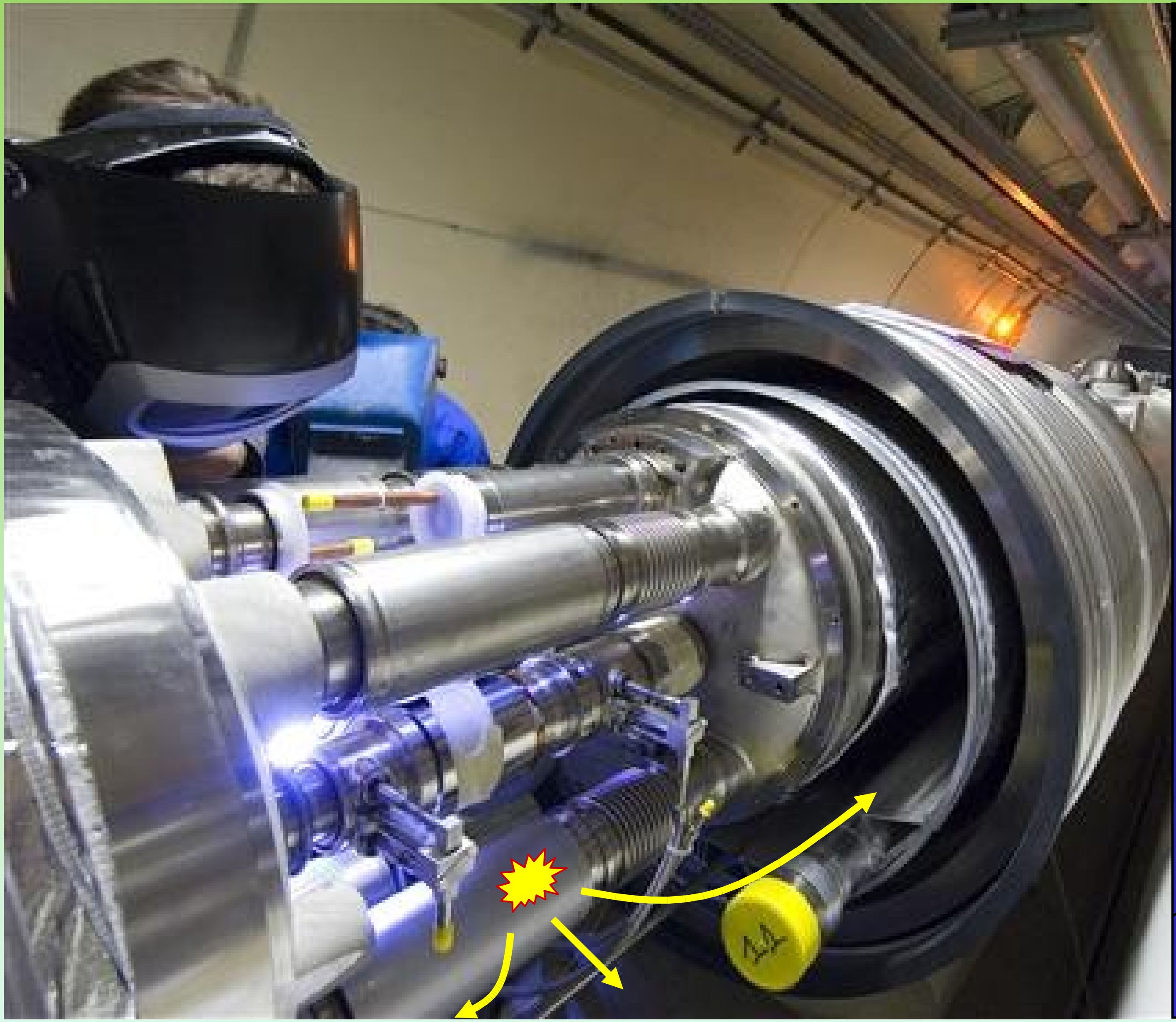
Working hypothesis

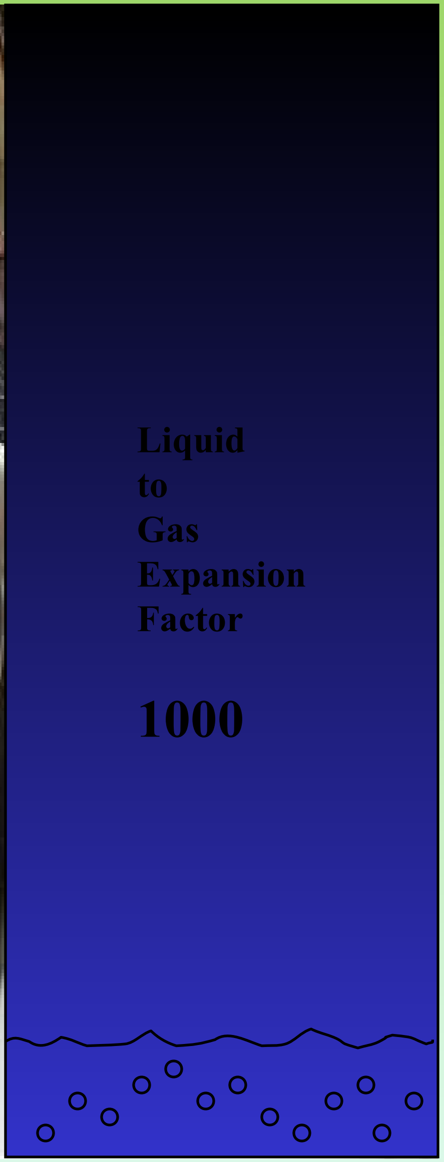


Favored *hypothesis* for the S34 incident cause :

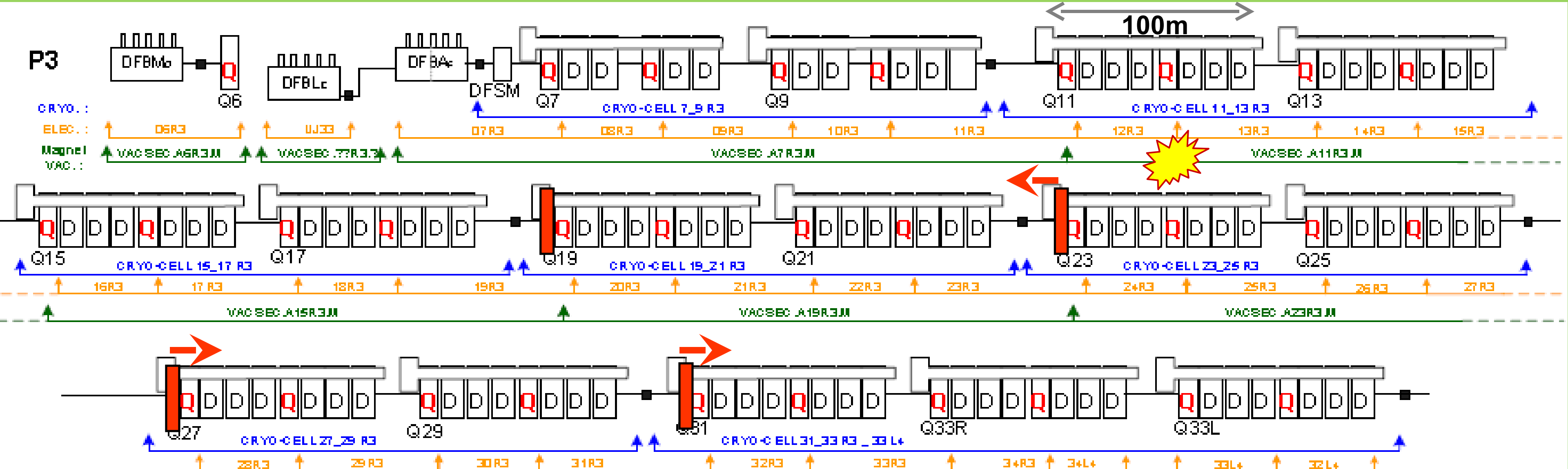
- Temperature increase due to excessive resistance (estimate ~ 200nΩ)
- Superconductor quenches and becomes resistive at high current
- Up to a certain current, the copper can take it (cooled by the He II)
- Beyond a certain current, 'run-away' of the temperature, splice opens, electrical arc …

Helium released into the





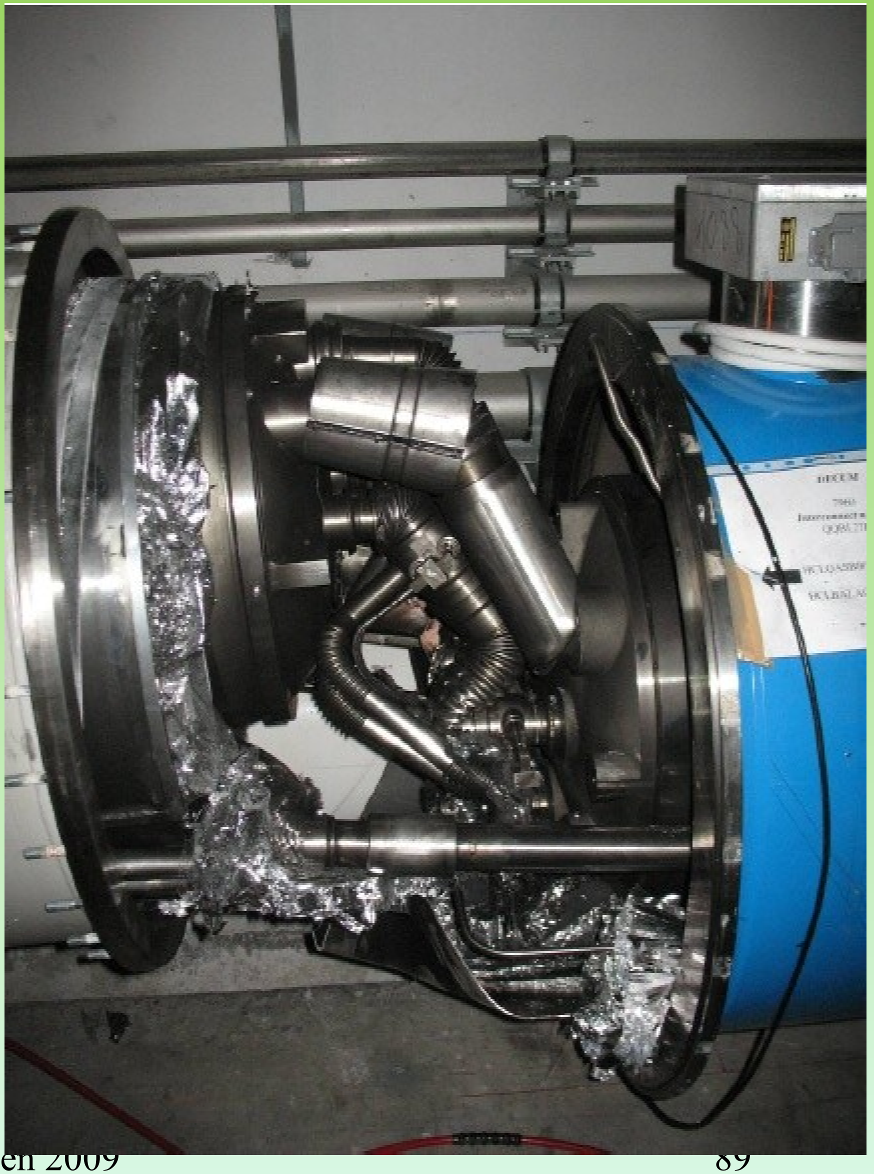
Consequences



Insulating vacuum barrier every 2 cells in the arc → Some moved

- Considerable collateral damage over few hundred metres
- Damage to superinsulation blankets
- Contamination (by soot and insulation blankets) of beam pipes
- Large release of helium into the tunnel (6 of 15 tonnes)

Consequences



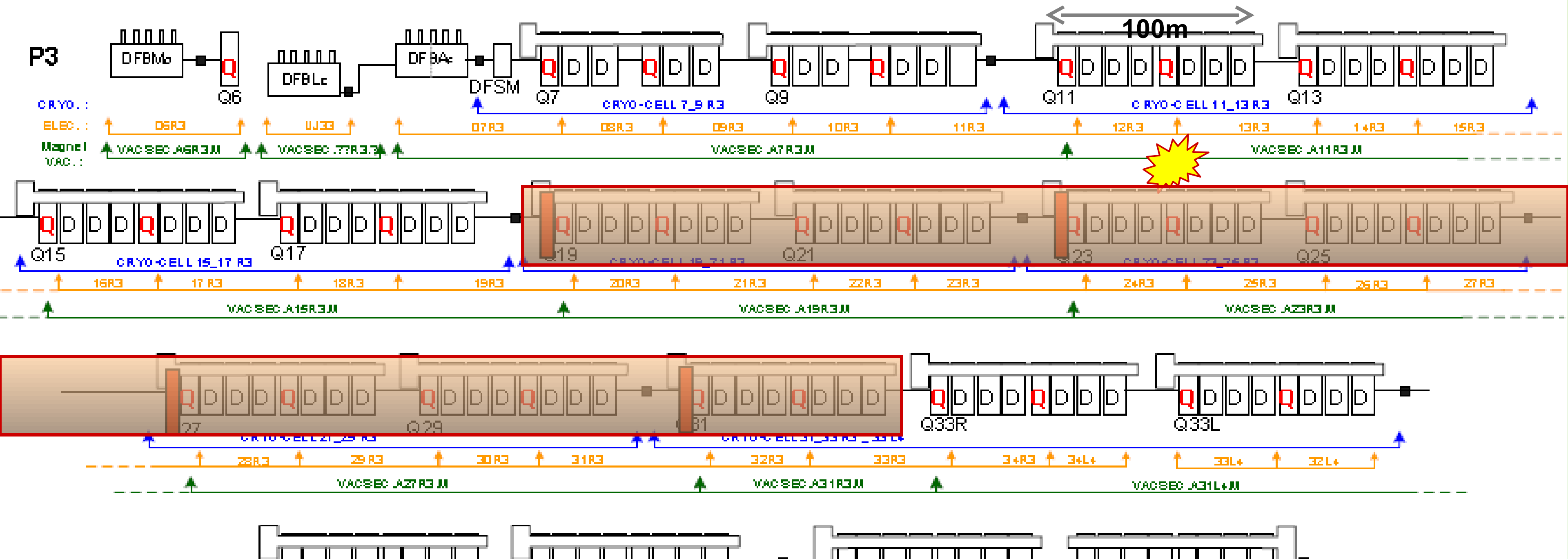
What is it (for) ?

Construction

Beam

Breakdown

Repair



- Present strategy assumes treating all magnets Q19 to Q33 as shown
- 53 have to be brought to the surface (39 dipoles and 14 quads)
- Will be replaced with spare / refitted retested and reinstalled
- Estimate for magnets November 08 to March 09
- Not forgetting cleaning the beam pipes
- Then have to finish interconnection, cool down, power test

Post Mortem (needles and haystacks)

- Following the incident, a close look at the logged cryogenic data (temperatures and valve states) indicated **abnormal behaviour** in the cell that was at the origin of the fault

mK

- This was followed by systematic scrutiny of all data logged during the weeks of power testing of all 8 sectors
- **Anomalous cryogenic behaviour** found in sector 12 at 7kA
  - Higher than nominal **heat load** in cryogenic sec

W

15 R1

- Confirmed by detailed tests in late 2008

90nΩ

!

- Corresponding **electrical resistance** calculated

0.3nΩ

!

100nΩ

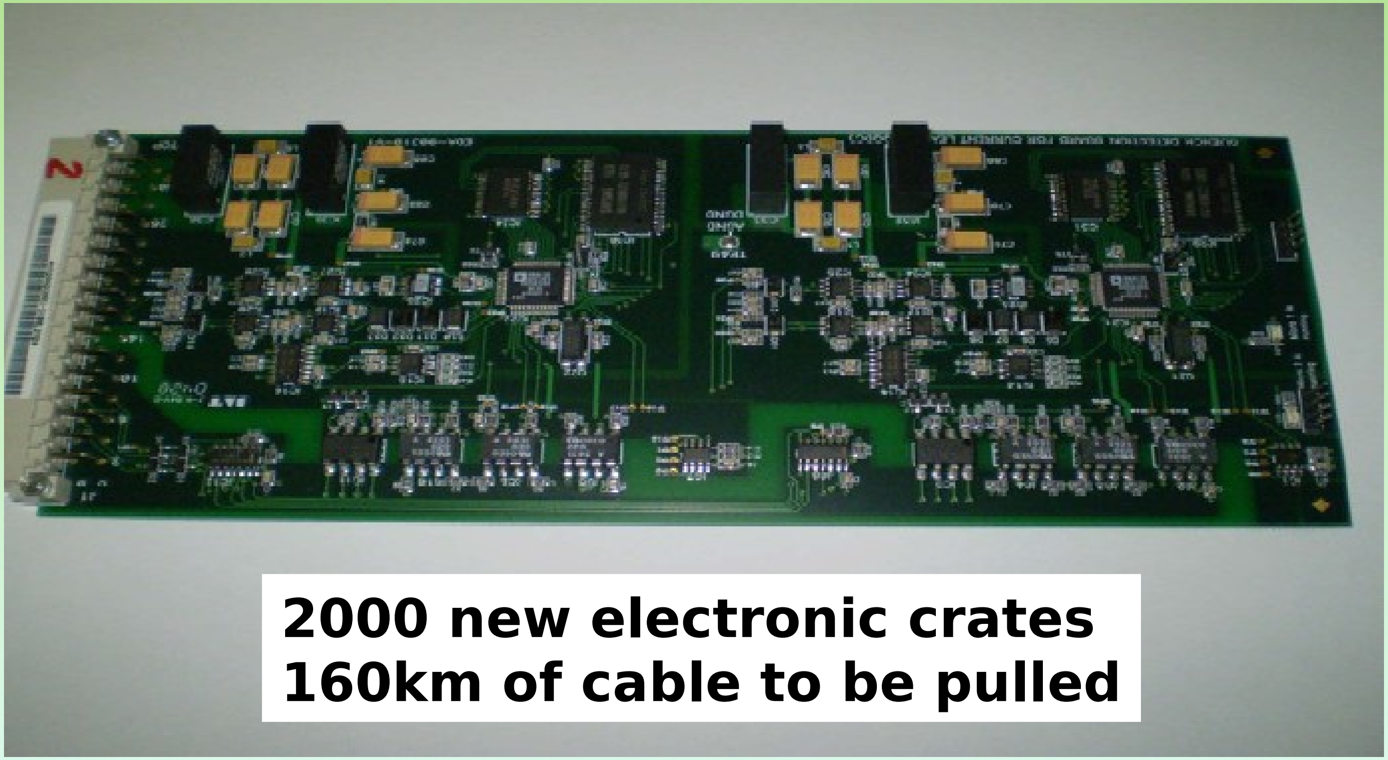
- **No other faulty splice has been found**
- Electrical measurements located it to **inside** a dipole

47nΩ

- Another resistance found **inside** a dipole in sector 67

Protection

- These investigations have led to the development of **powerful calorimetric and electric methods** to detect excessive resistances in the main LHC magnet circuits
- These methods have been prototyped and will be further improved before being installed machine-wide and applied as **dedicated procedures** during the machine commissioning



2000 new electronic crates
160km of cable to be pulled

Further measures

- Mitigate the consequences of any event similar to that in sector 34 by increasing the helium gas release capability

- All quadrupole cryostats have spare flanges
  - Equip them with new full-flow release valves
  - Gives Factor 8 in discharge cross section
  - Can and will be done *in situ* at cold

- Addition of full-flow release valves on EVERY dipole cryostat (all 1232)
  - Brings overall discharge cross section increase to Factor 40
  - Can only be done at warm

Present major activity foreseen in the different sectors	
Sector	Activity
34	Repair of magnets and beam pipes
56	Warmed up for repair of known non-conformity
12	Warmed up for exchange of dipole B16.R1
67	Warmed up for exchange of dipole B32.R6
Others	Kept cold

Restart in 2009

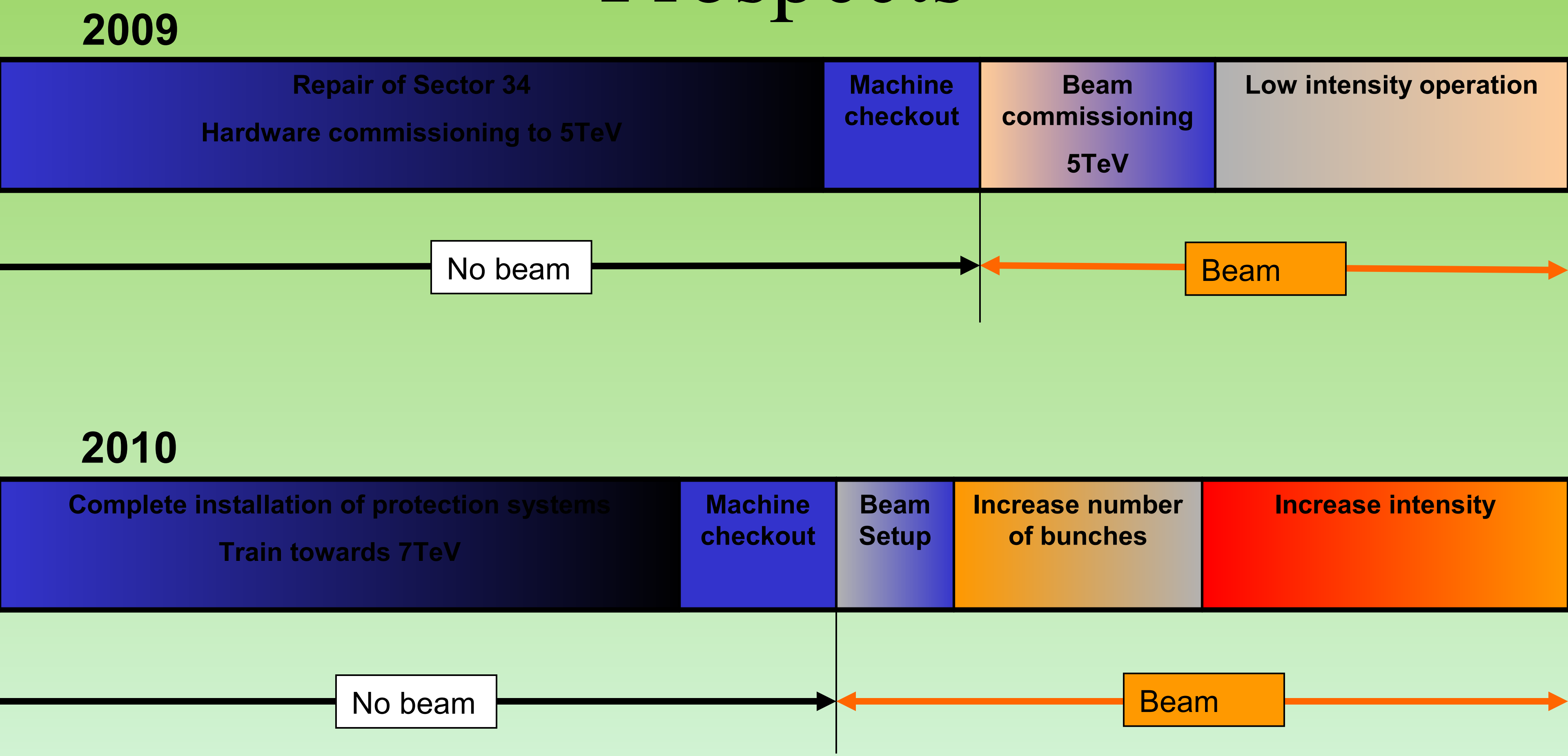
- Installation of ALL protection systems would preclude a run in 2009
  - Install as much as possible in shadow of sector 34 repair
  - Run with reduced risk in 2009
  - Complete installation of new protection systems for 2010

- Restart in 2009 will be determined by
  - Efficiency of logistics of magnets removal / installation
  - Efficiency of magnet repair
  - Efficiency of beam pipe repair / cleaning
  - Efficiency of interconnection activities
  - Time to cool down whichever sectors are warmed up
  - Time to re-commission all power circuits

- Target is beam operation in second half of 2009
  - Lower energy (450GeV to 5TeV)
  - Lower intensity (43 to 156 bunches per beam)

- Push performance in 2010

Prospects


2009
Repair of Sector 34
Hardware commissioning to 5TeV
Machine checkout
Beam commissioning
5TeV
Low intensity operation
No beam
Beam
2010
Complete installation of protection systems
Train towards 7TeV
Machine checkout
Beam Setup
Increase number of bunches
Increase intensity
No beam
Beam

Podziękowania:

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T. Taylor
L. Rossi