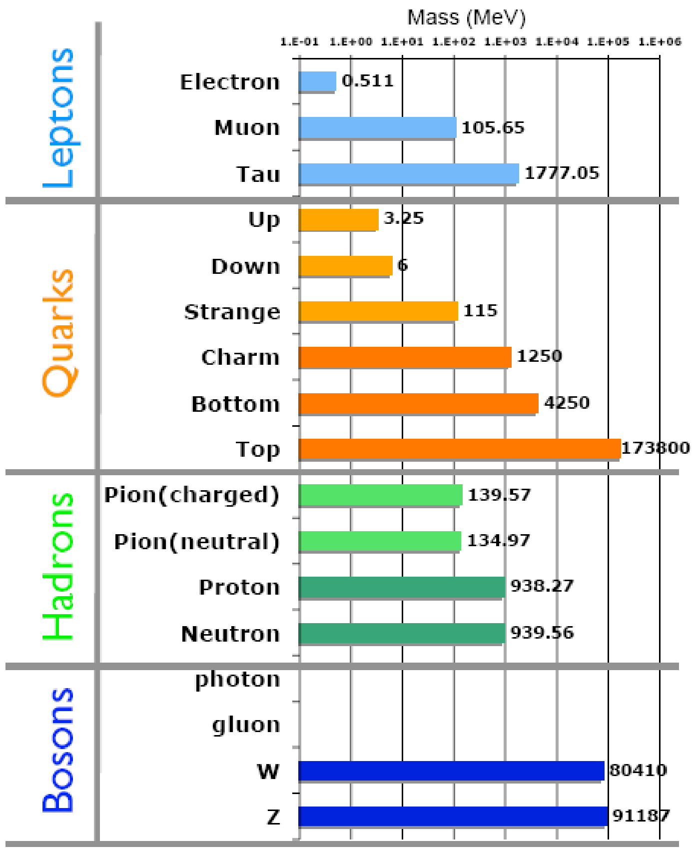
LHC status and future plans

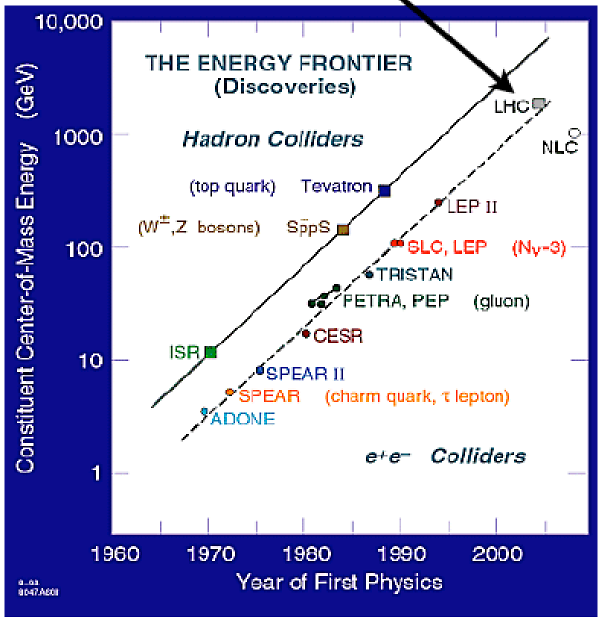
Lyn Evans

From the LHC to a future collider (Theory Workshop)
CERN 10 February 2009

History/energy line vs discovery



Higgs and super-symmetry ?
Or something else maybe

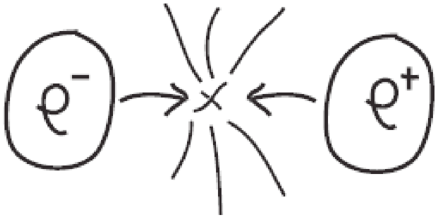


Behind the history plot is hidden the technological development required for each step

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either $\bar{p}$-p as Tevratron, p-p as LHC)

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure



The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

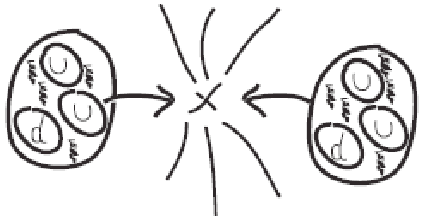
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region

Precision measurement (LEP)

Cons: above a certain energy is no more convenient to use electron because of too high synchrotron radiation

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

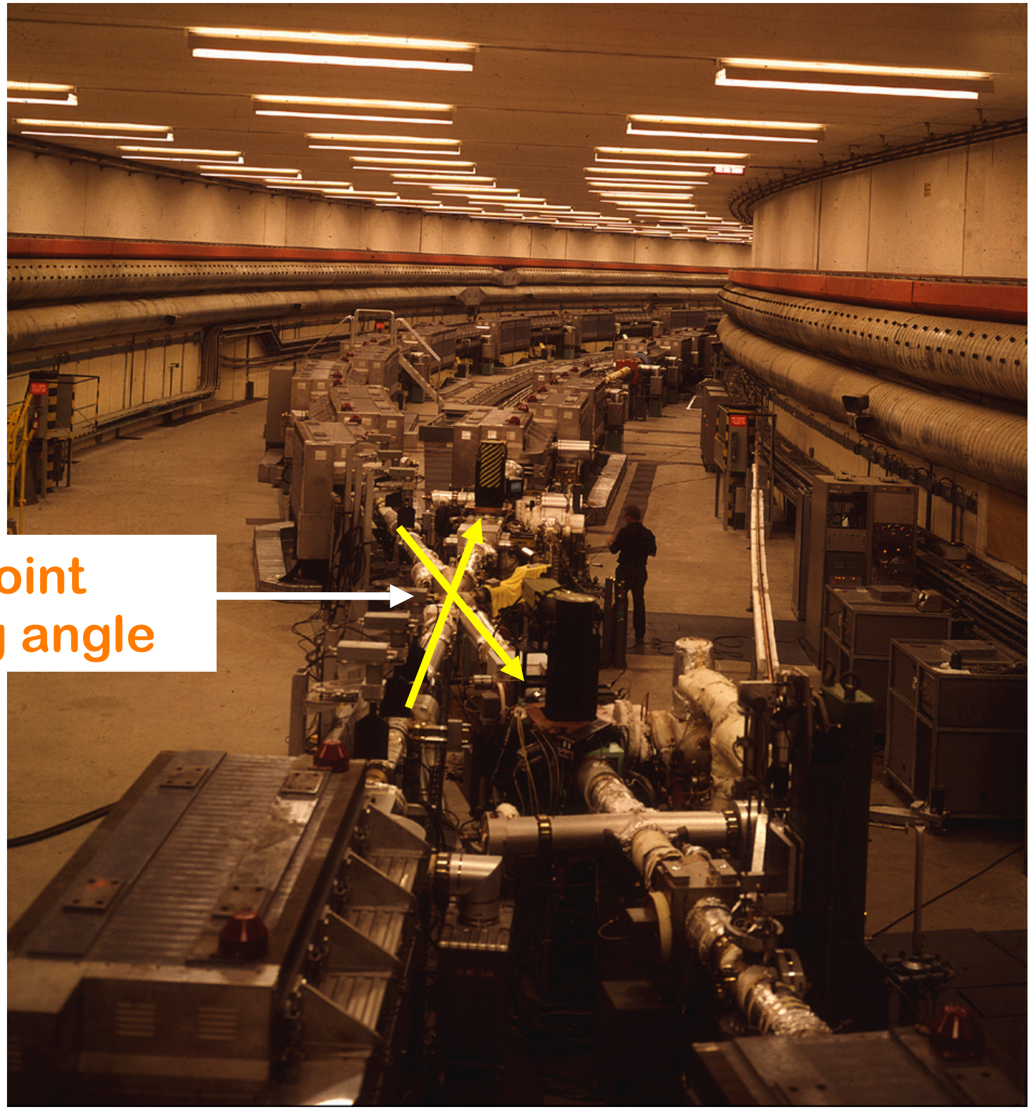
Ecoll < 2Eb

Pros: with a single energy possible to scan different processes at different energies

Discovery machine (LHC)

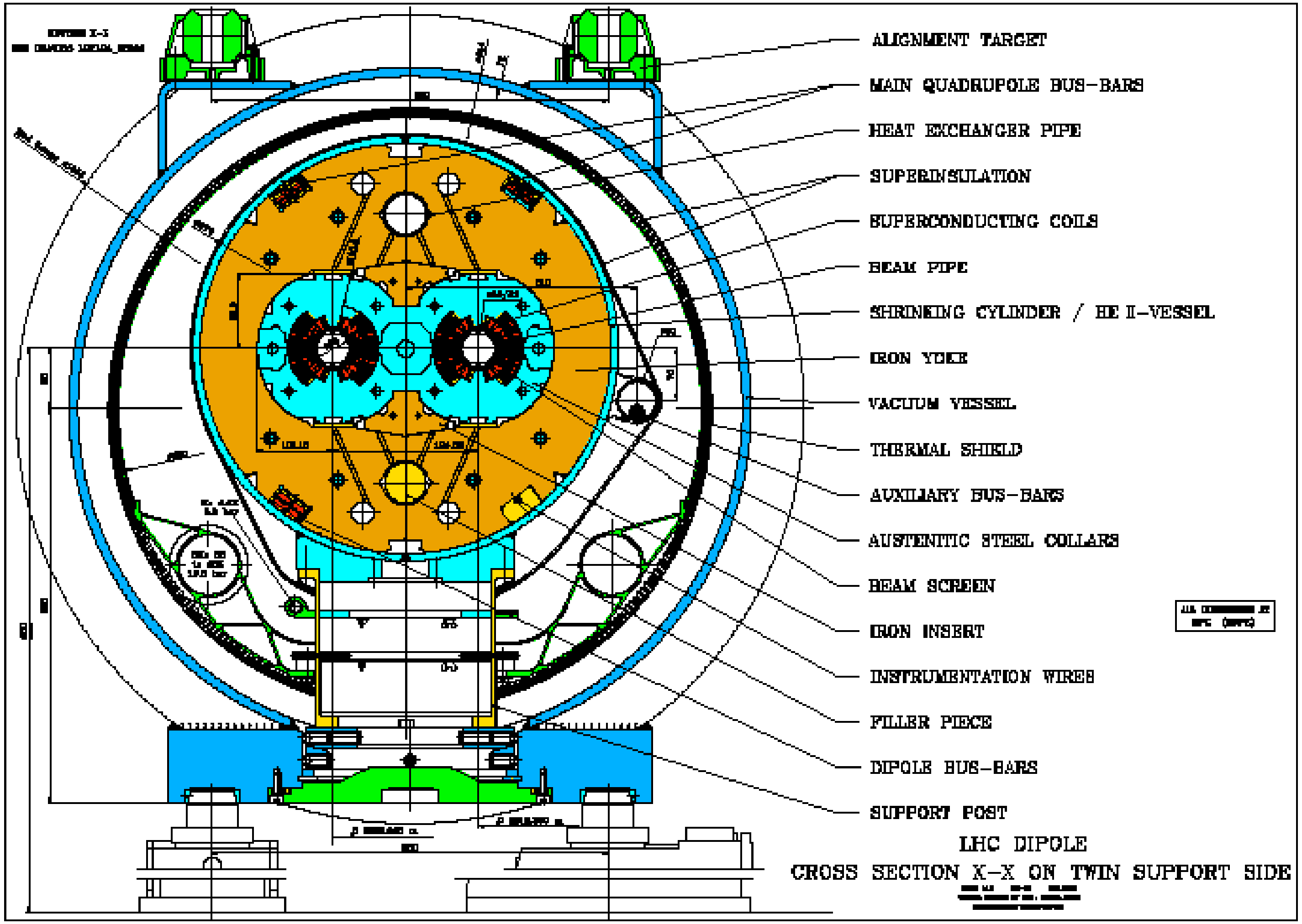
Cons:the energy available for the collision is lower than the accelerator energy and there is a large background

ISR

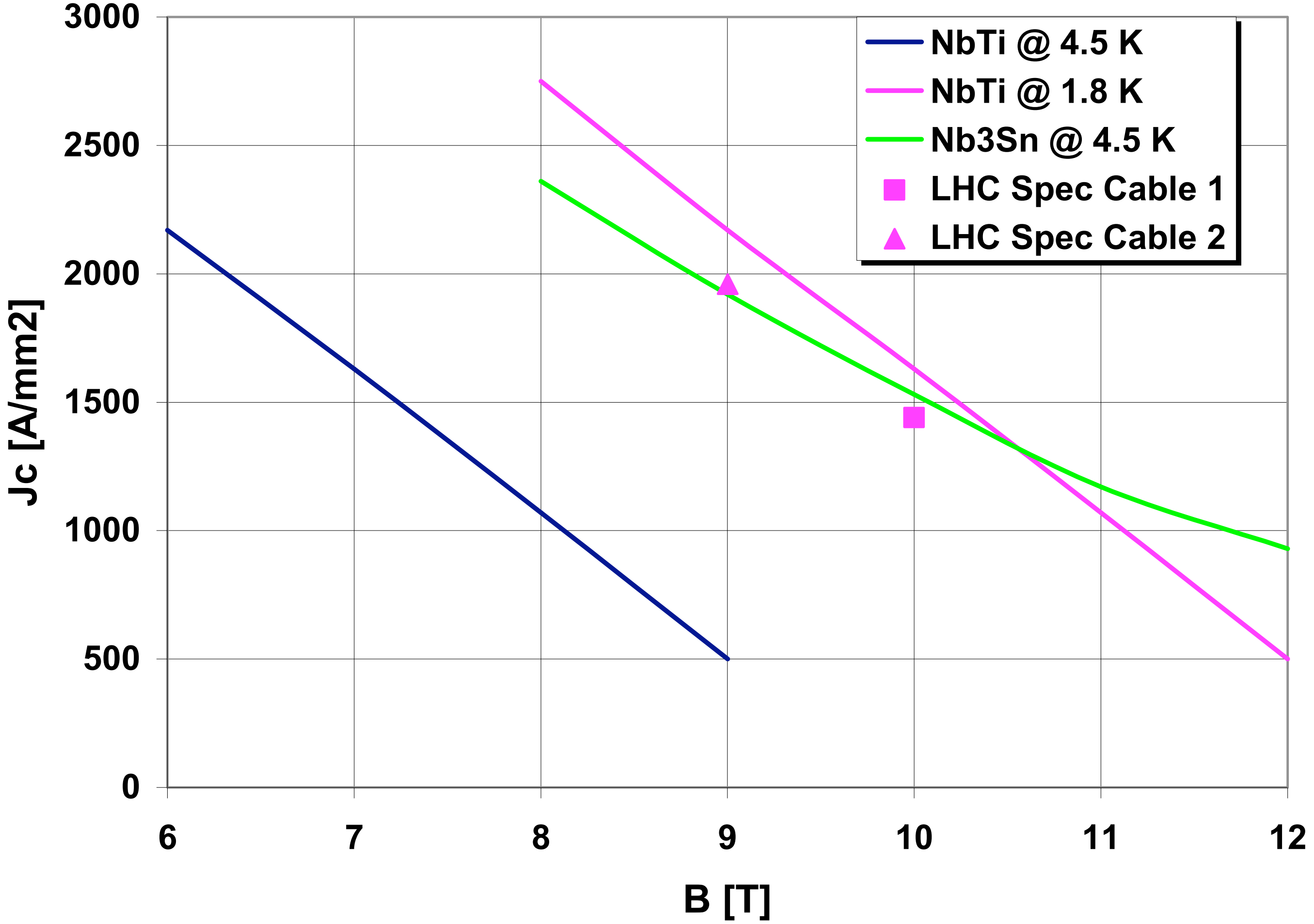


Interaction point
with crossing angle

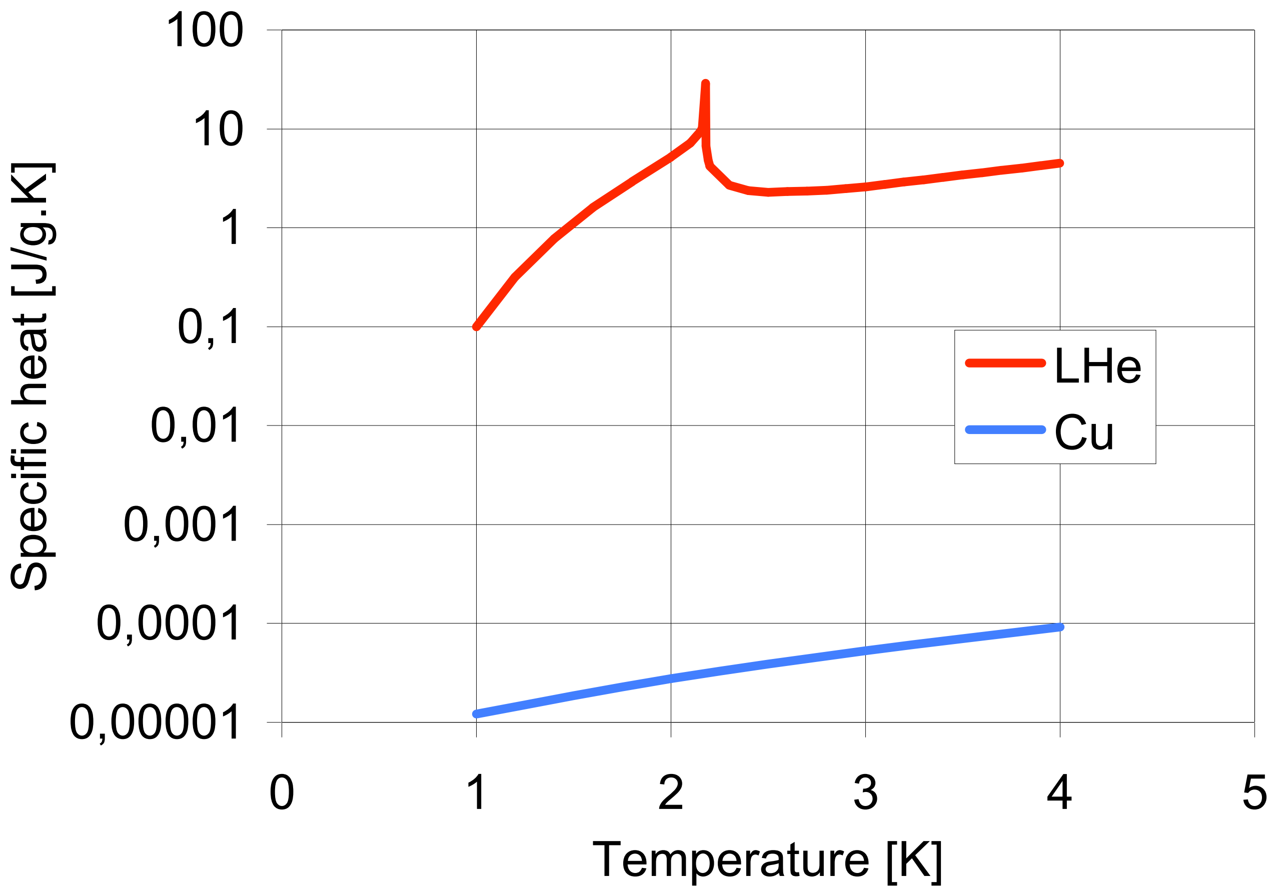
Cross-section of LHC cryodipole



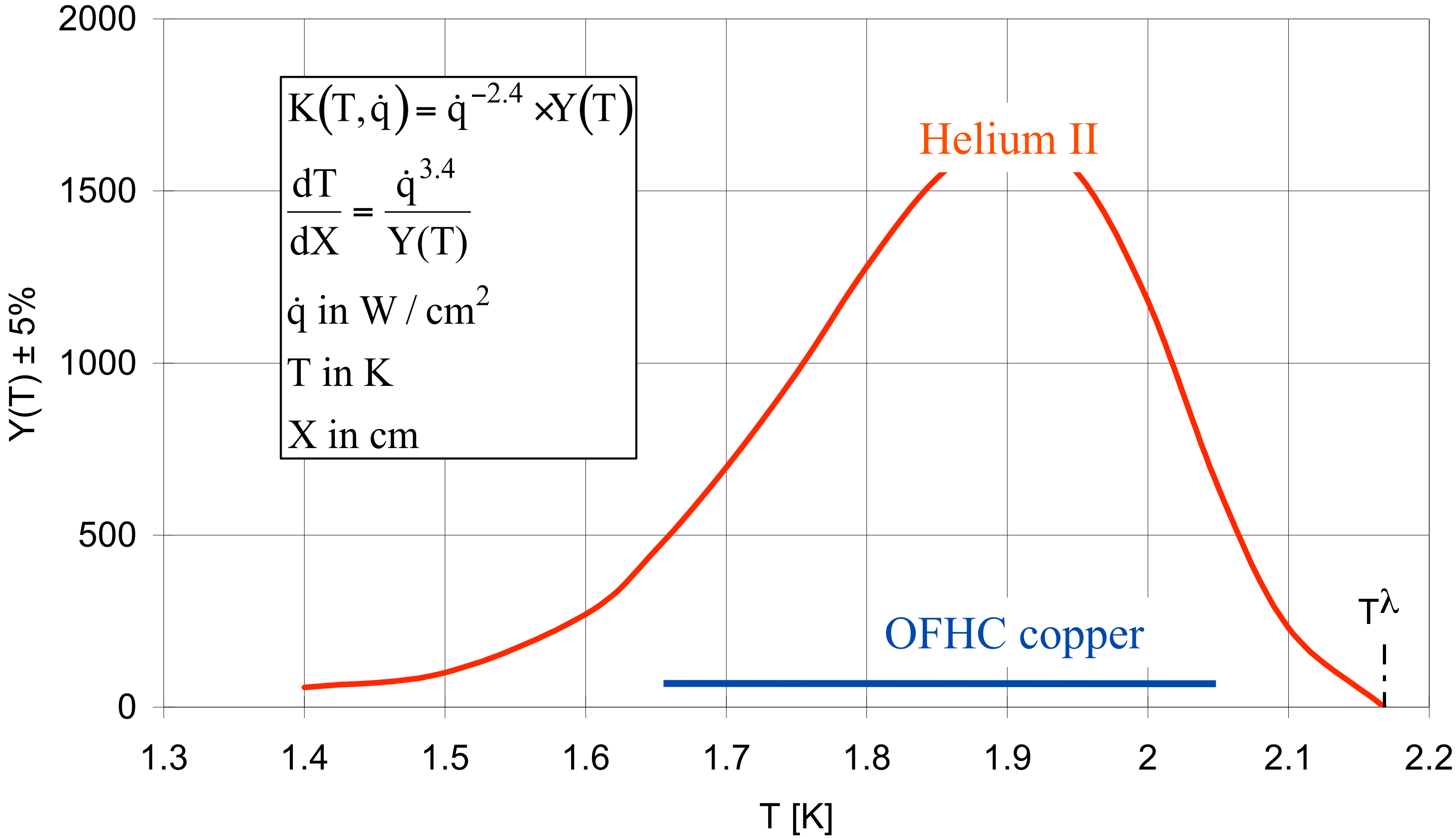
Critical current density of technical superconductors



Specific heat of LHe and Cu



Equivalent thermal conductivity of He II



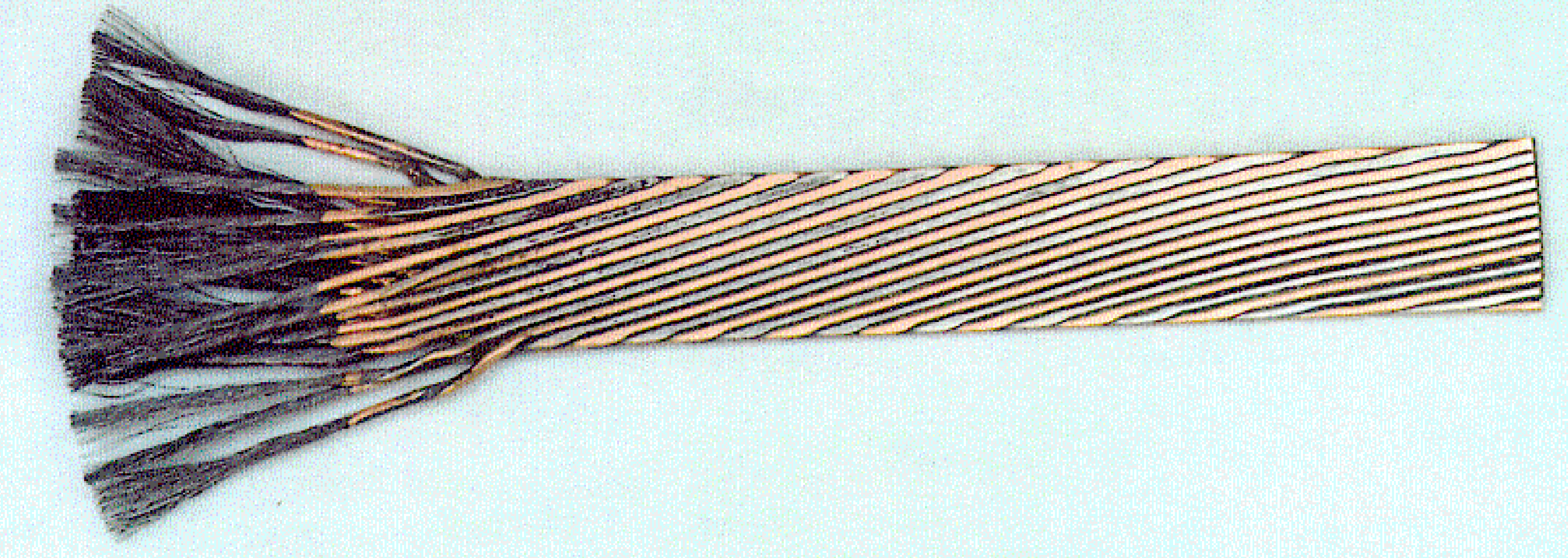
$$K(T,\dot{q}) = \dot{q}^{-2.4} \times Y(T)$$

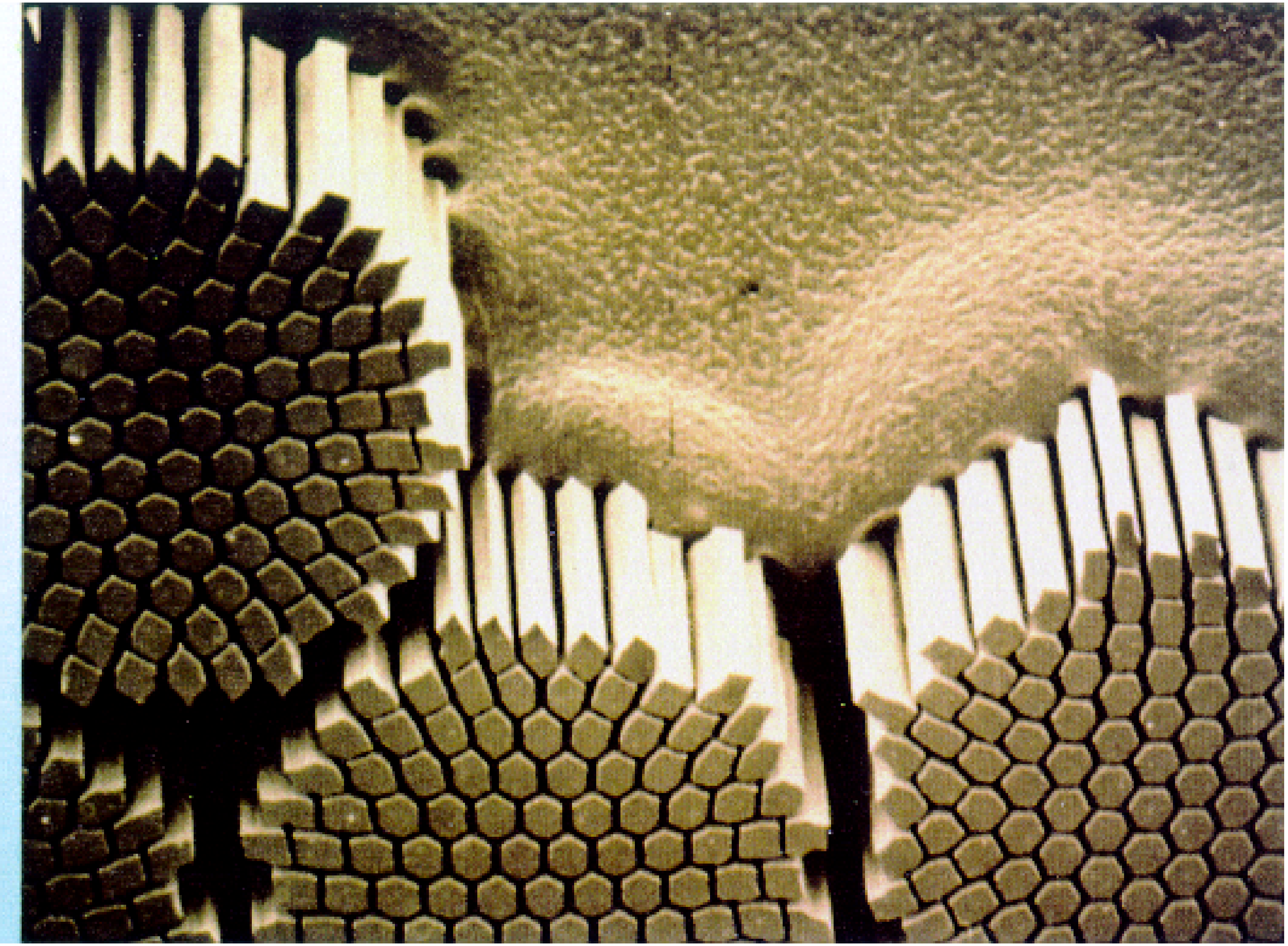
$$\frac{dT}{dX} = \frac{\dot{q}^{3.4}}{Y(T)}$$

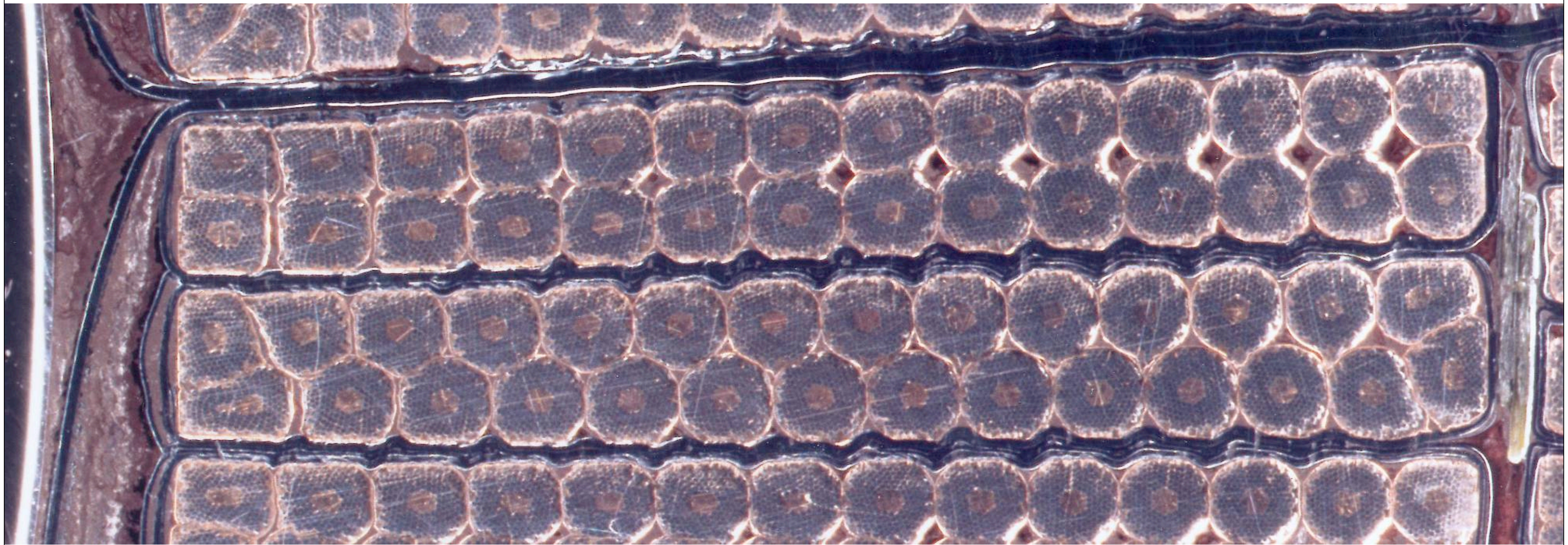
$\dot{q}$ in W / cm^2

T in K

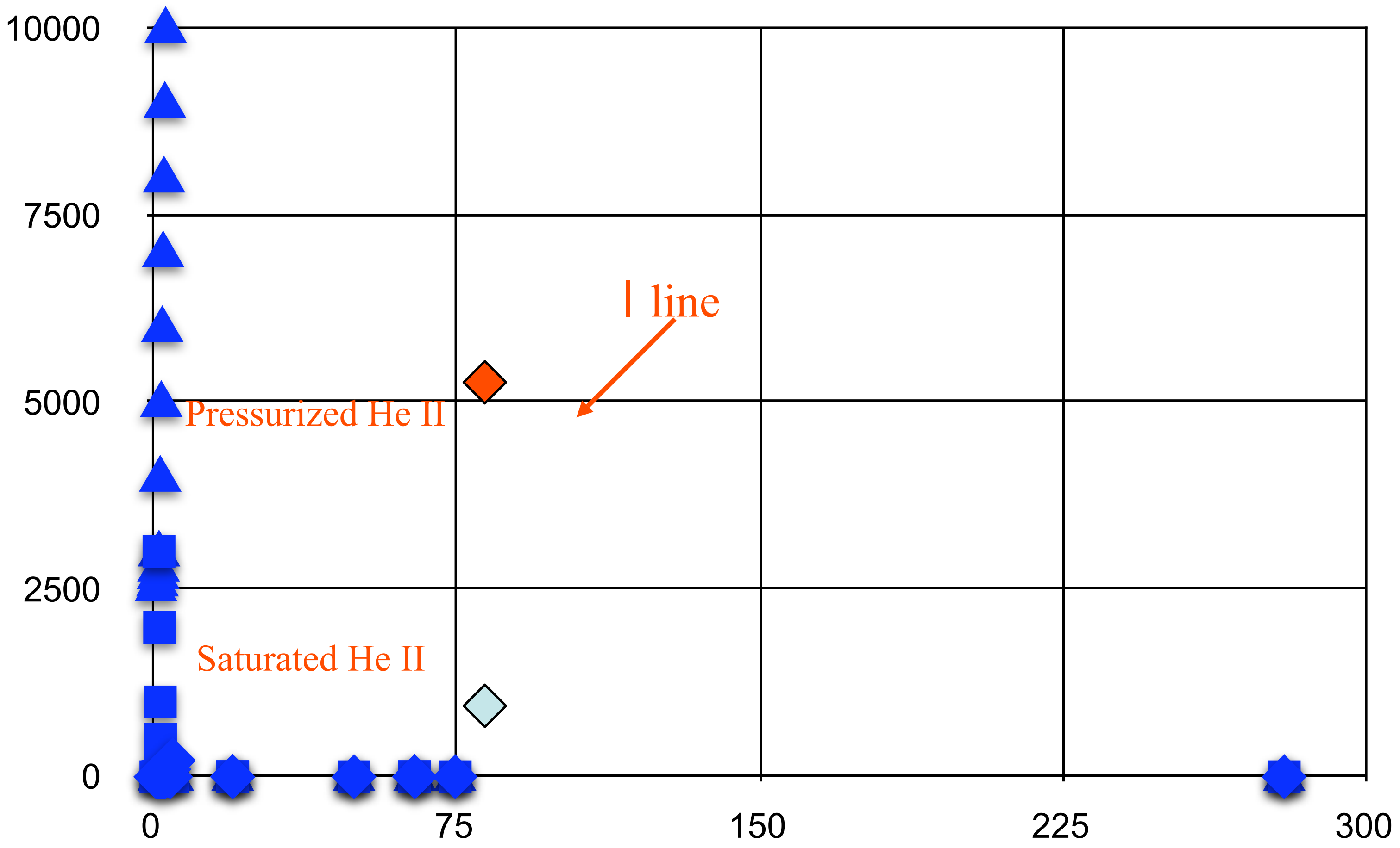
X in cm





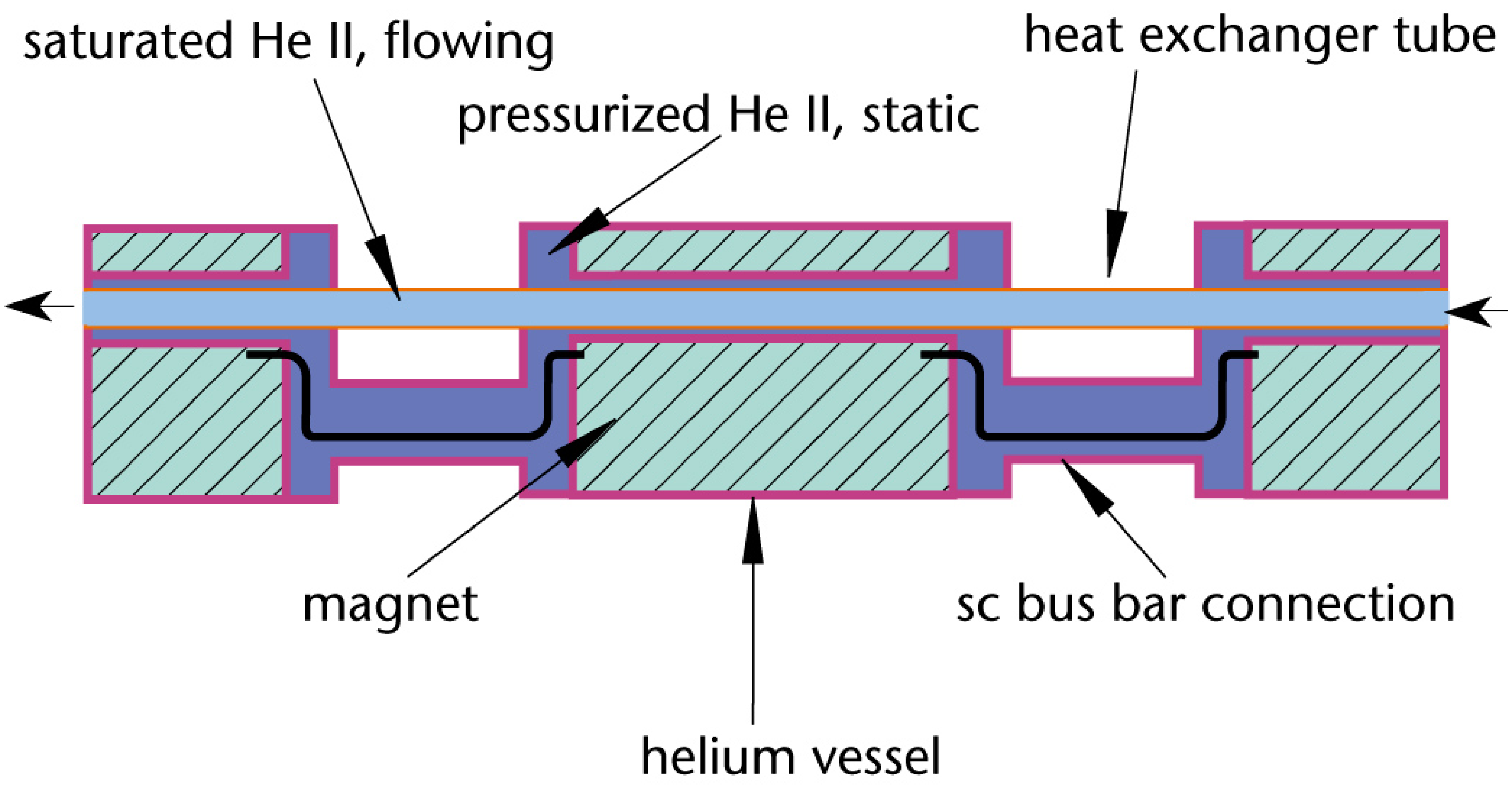


Phase diagram of Helium



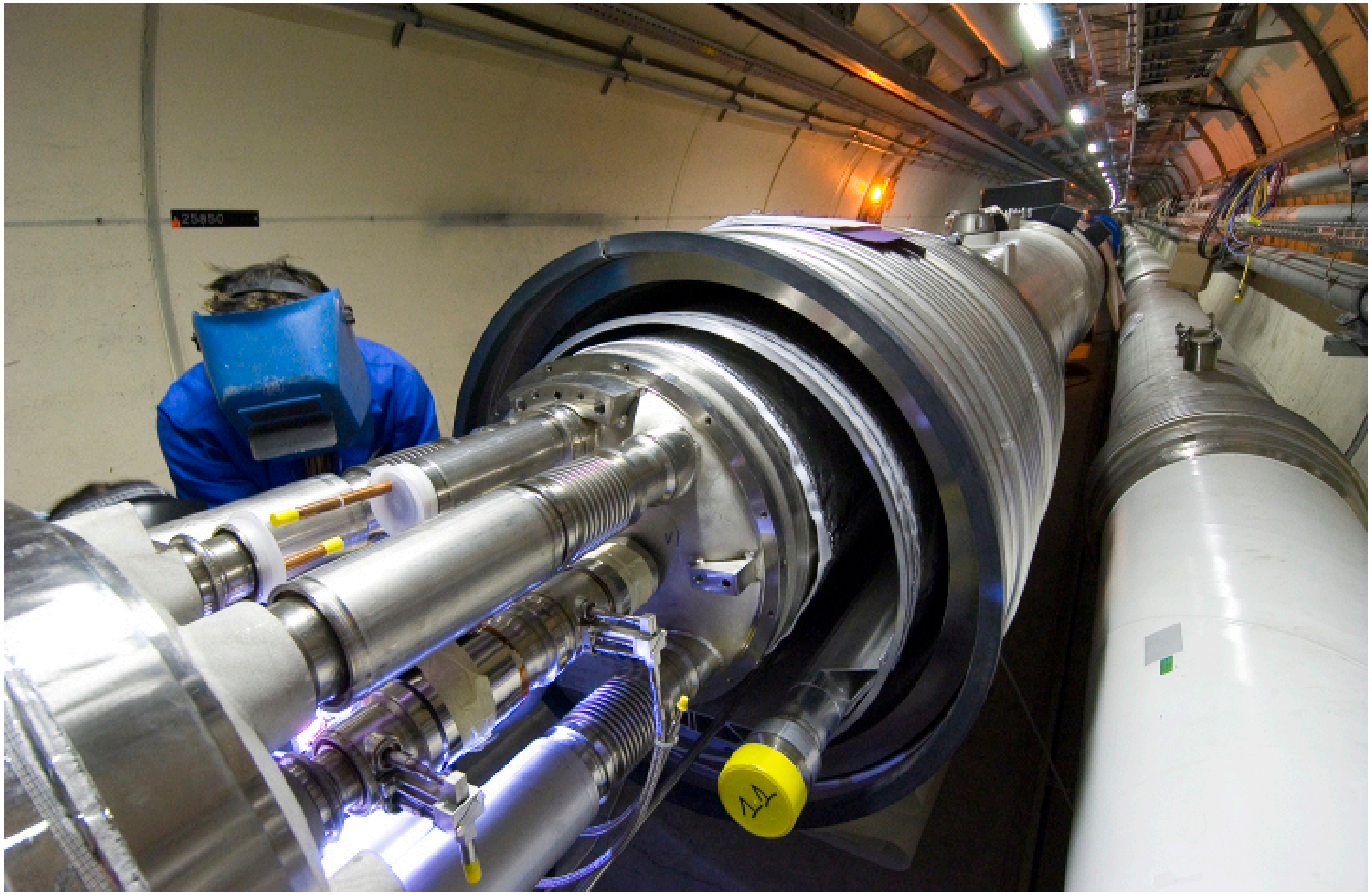
Linear heat exchanger

LHC magnet string cooling scheme



CERN AC _ EI2-12 VE _ V9/9/1997

Dipole-dipole interconnect

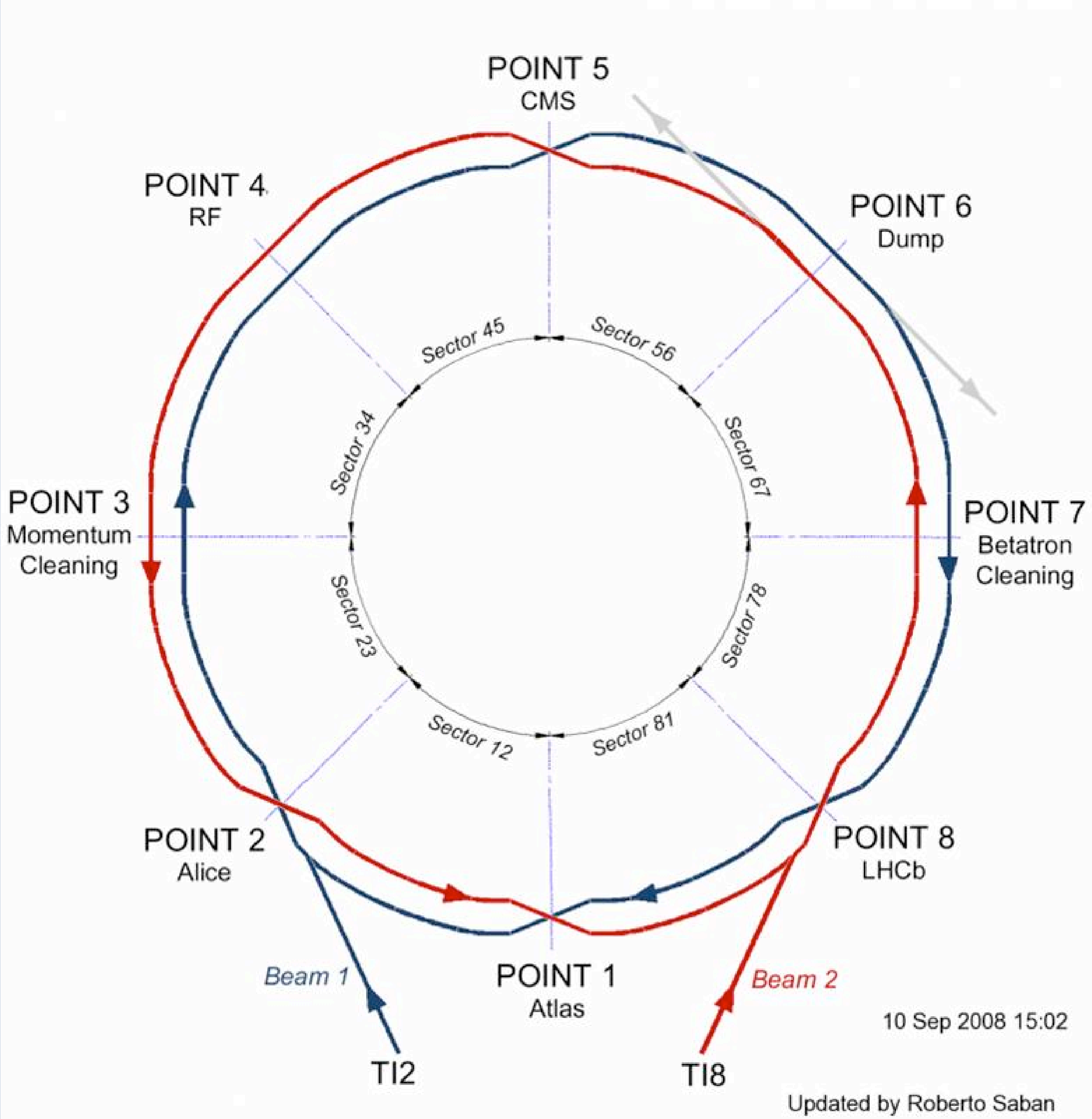


Cooldown of sectors

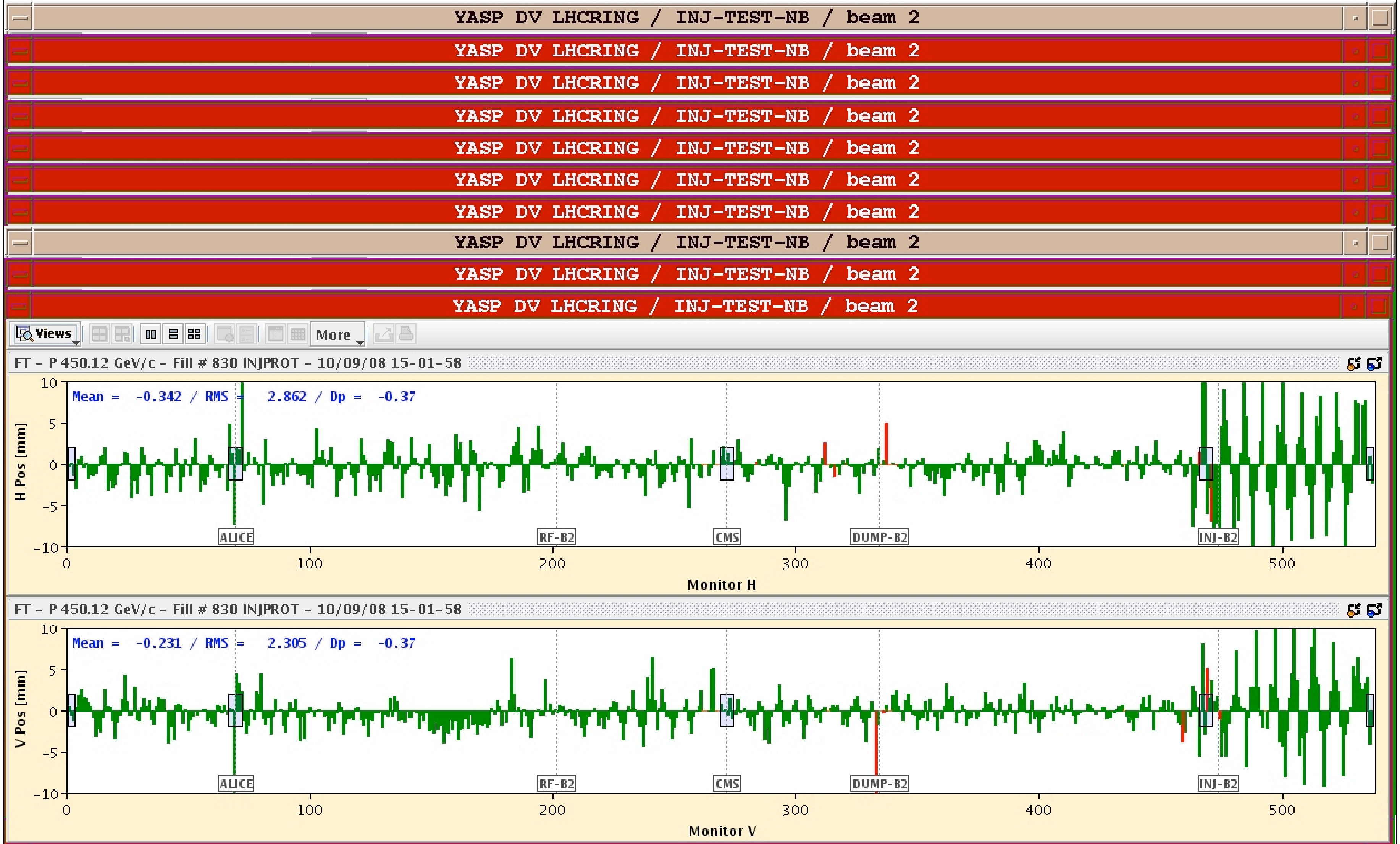
- From RT to 80K precooling with LN2. 1200 tons of LN2 (64 trucks of 20 tons). Three weeks for the first sector.
- From 80K to 4.5K. Cooldown with refrigerator. Three weeks for the first sector. 4700 tons of material to be cooled.
- From 4.5K to 1.9K. Cold compressors at 15 mbar. Four days for the first sector.

Situation on 10th September

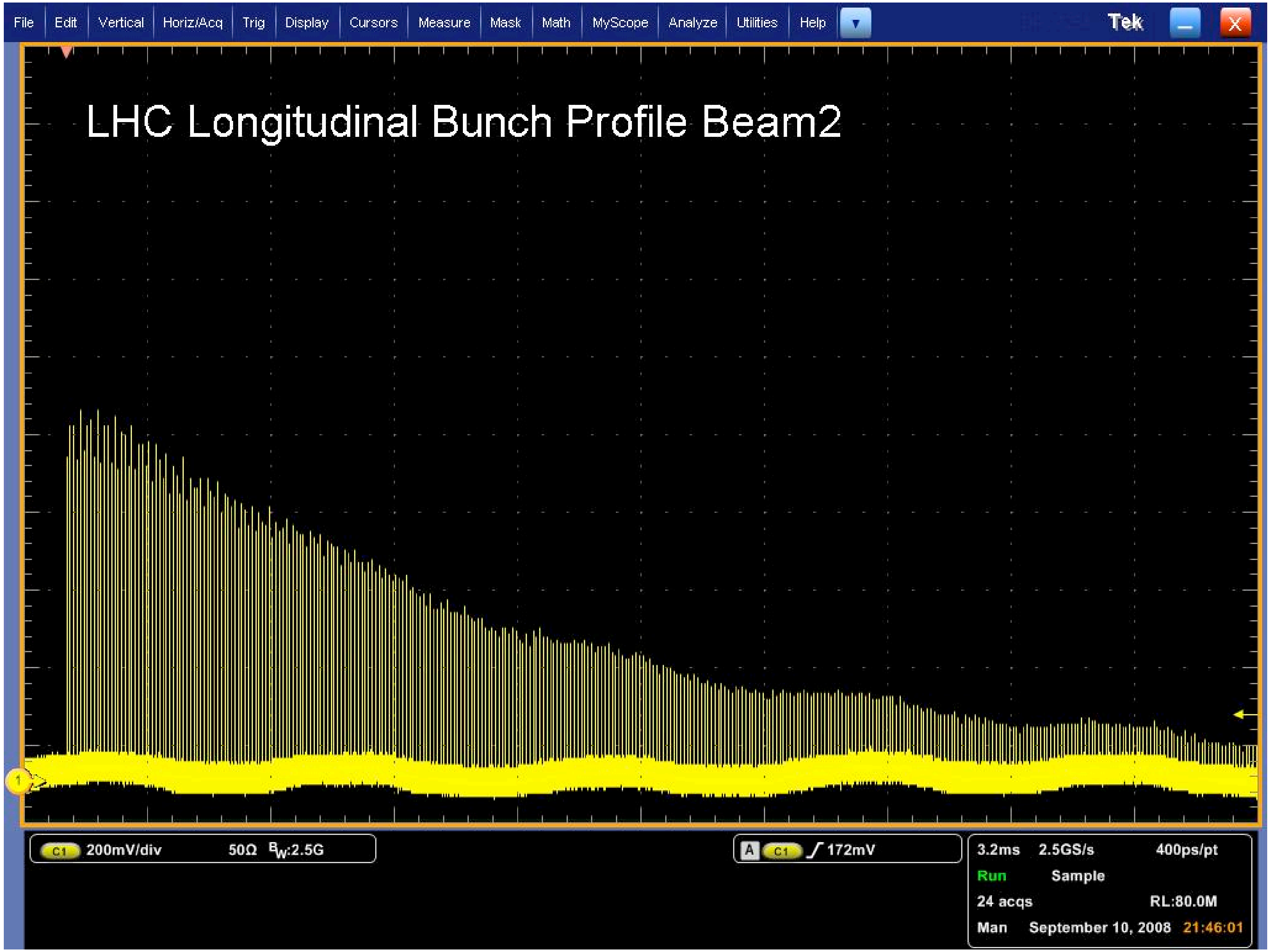
- 7 out of 8 sectors fully commissioned for 5 TeV operation and 1 sector (3-4) commissioned up to 4 TeV (the fault occurred at 5.1 TeV).


POINT 5
CMS
POINT 4
RF
POINT 6
Dump
Sector 45
Sector 56
Sector 34
Sector 67
POINT 3
Momentum
Cleaning
POINT 7
Betatron
Cleaning
Sector 23
Sector 78
Sector 12
Sector 81
POINT 2
Alice
POINT 8
LHCb
Beam 1
POINT 1
Atlas
Beam 2
10 Sep 2008 15:02
TI2
TI8
Updated by Roberto Saban

Beam 2 first beam – D-Day



Few 100 turns

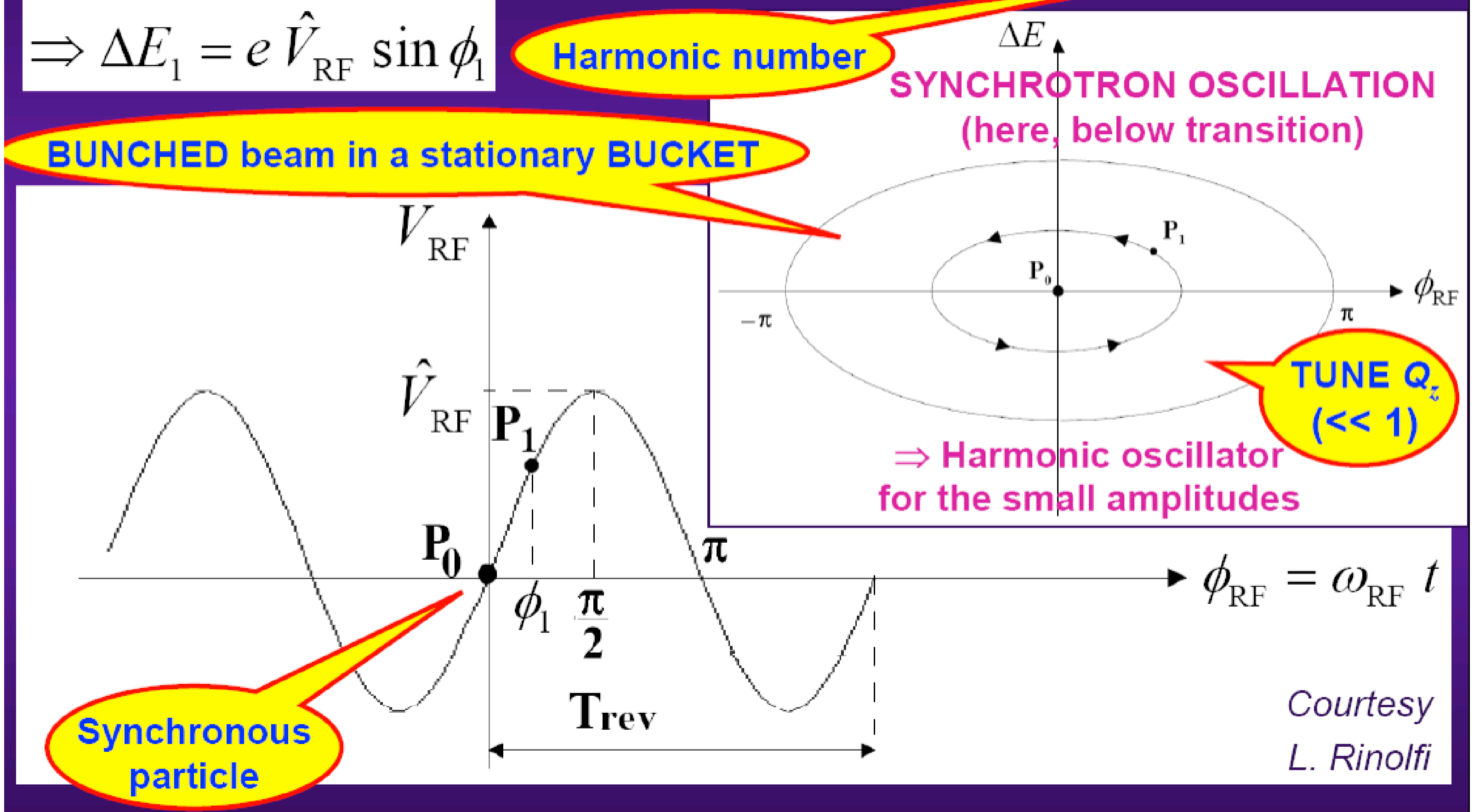


Courtesy R. Bailey

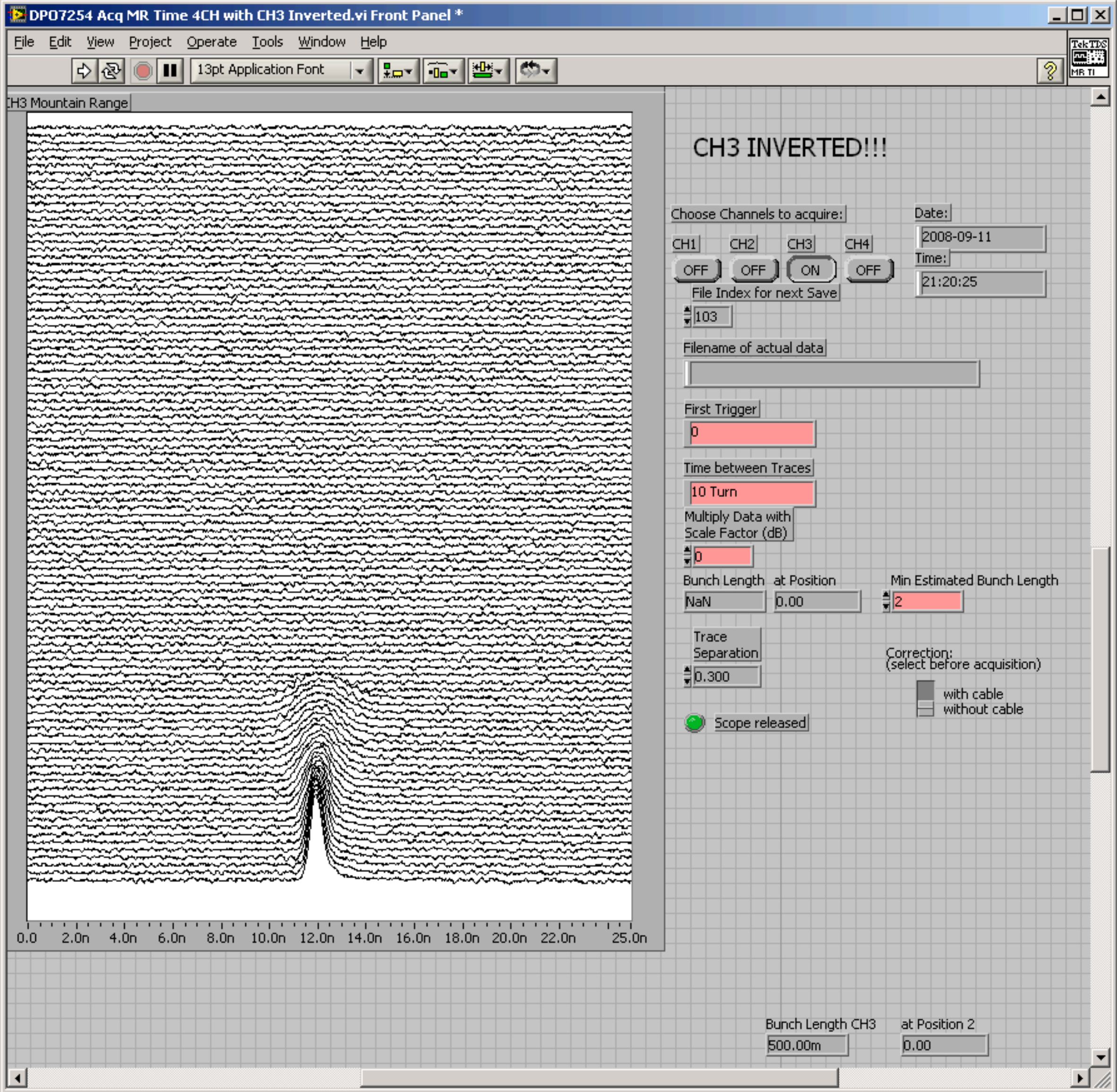
Longitudinal beam dynamics

- **Sinusoidal voltage applied** $V_{RF} = \hat{V}_{RF} \sin \phi_{RF}(t)$ $\omega_{RF} = h\,\omega_{rev}$

$$\Rightarrow \Delta E_1 = e\,\hat{V}_{RF} \sin \phi_1$$

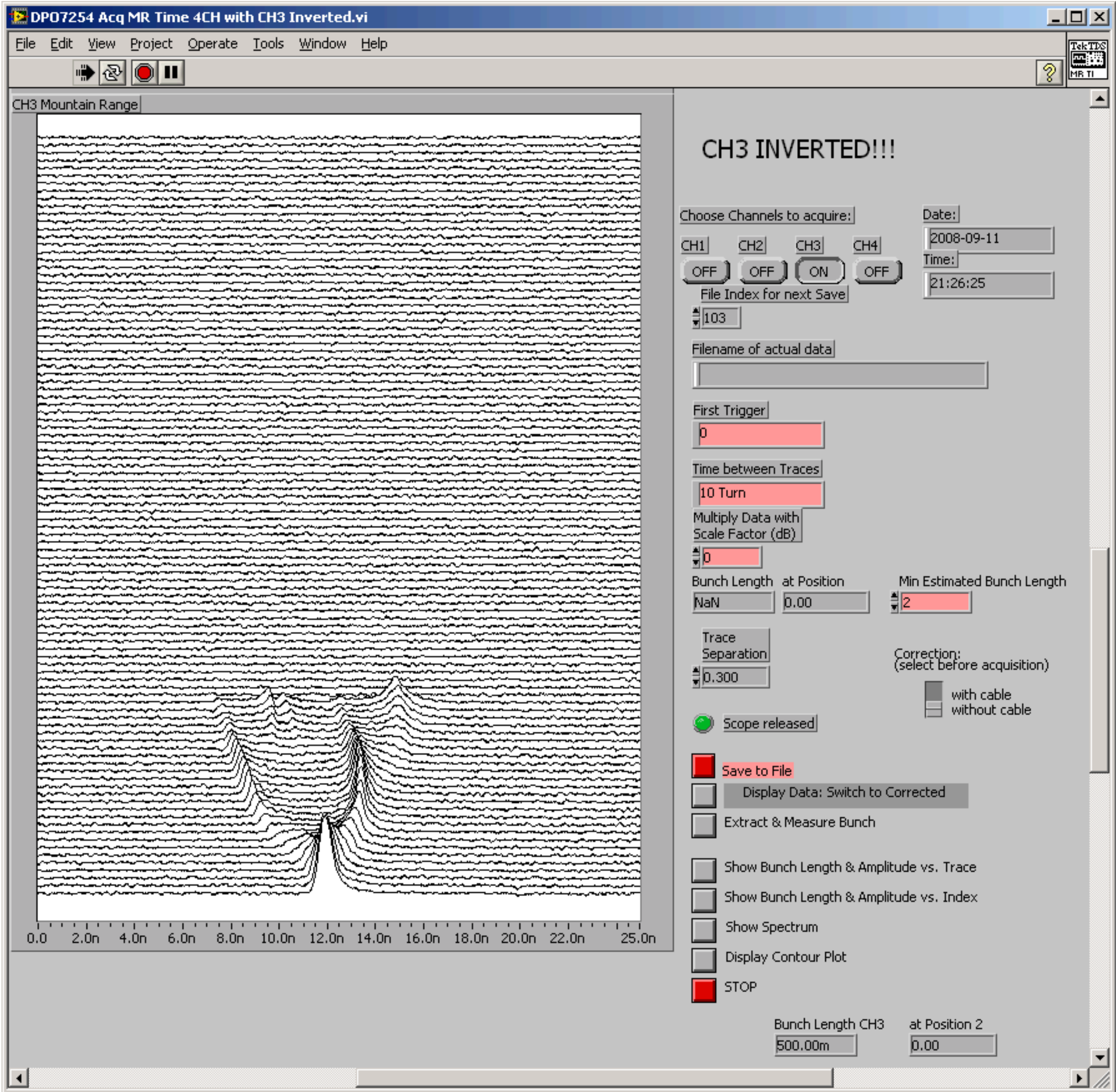


No RF, debunching in ~ 25*10 turns,



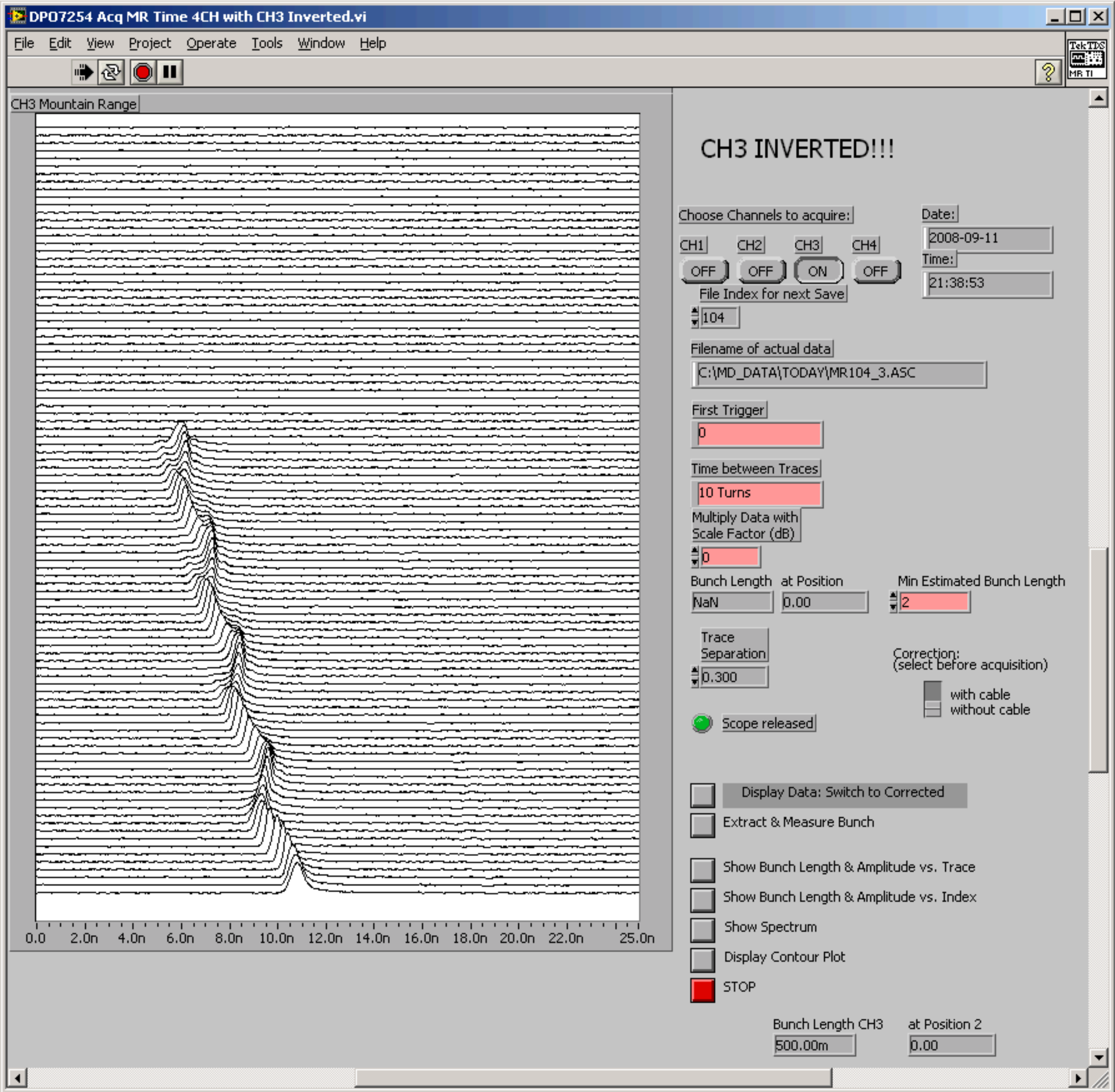
Courtesy E. Ciapala

First attempt at capture, at exactly the wrong



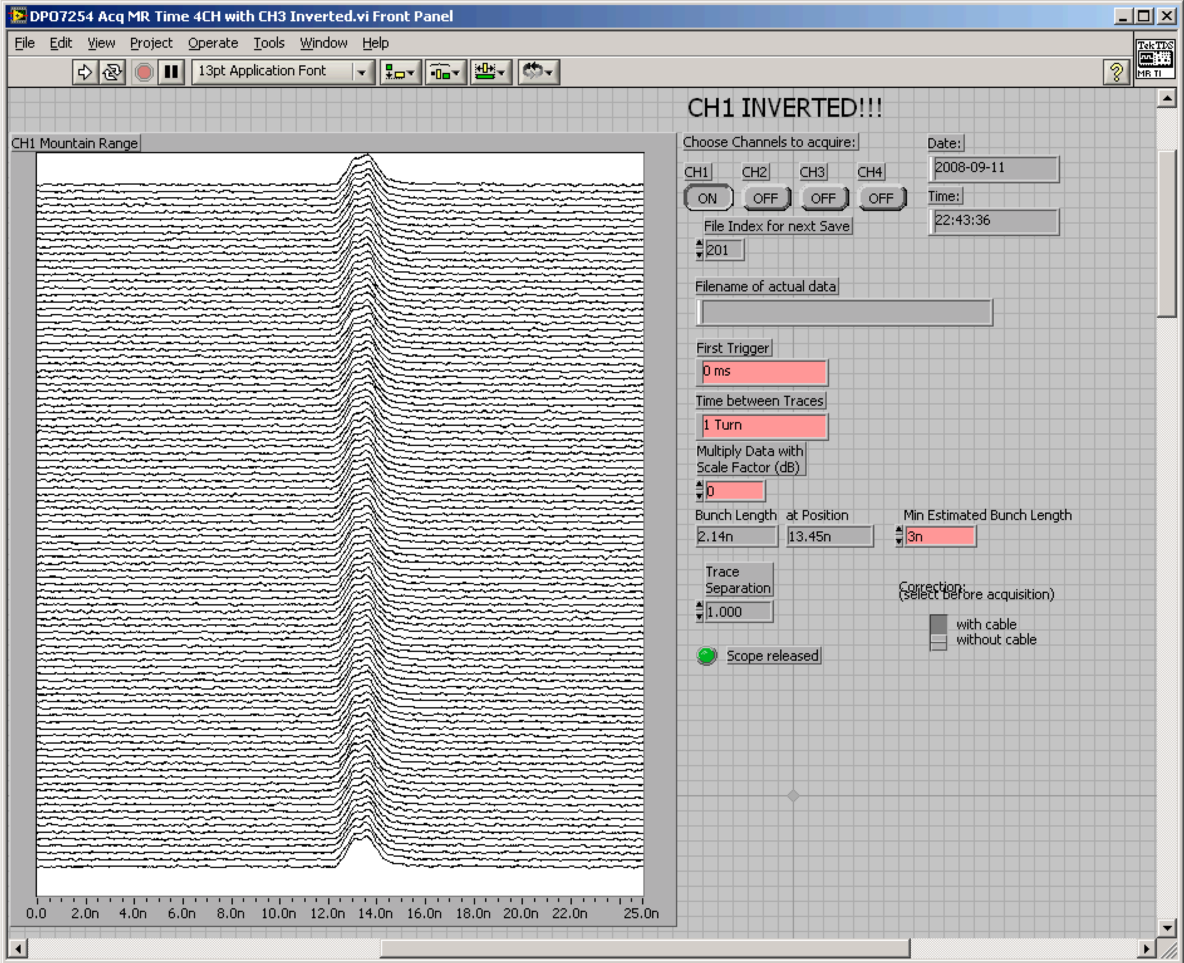
Courtesy E. Ciapala

Capture with corrected injection phasing

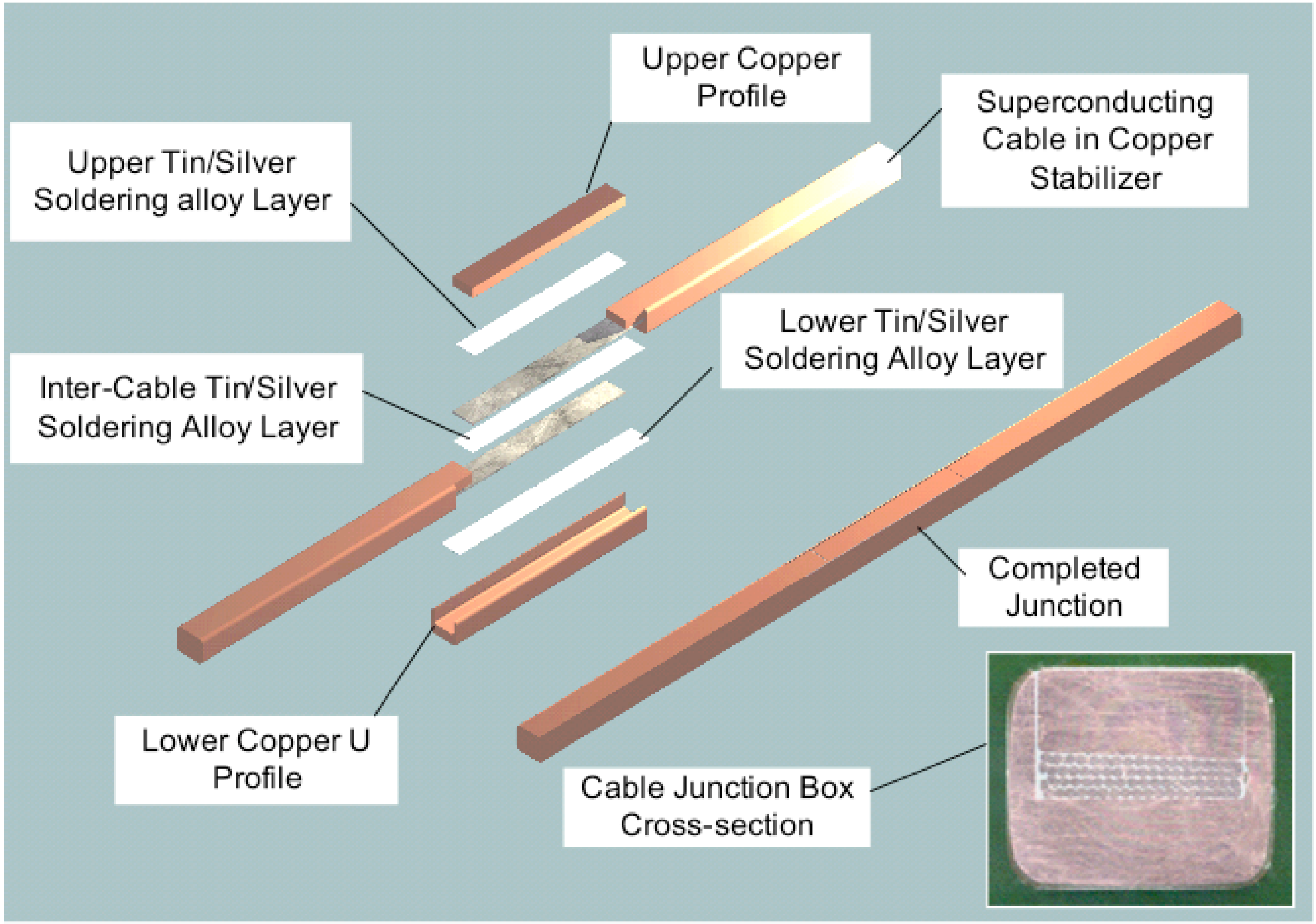


Courtesy E. Ciapala

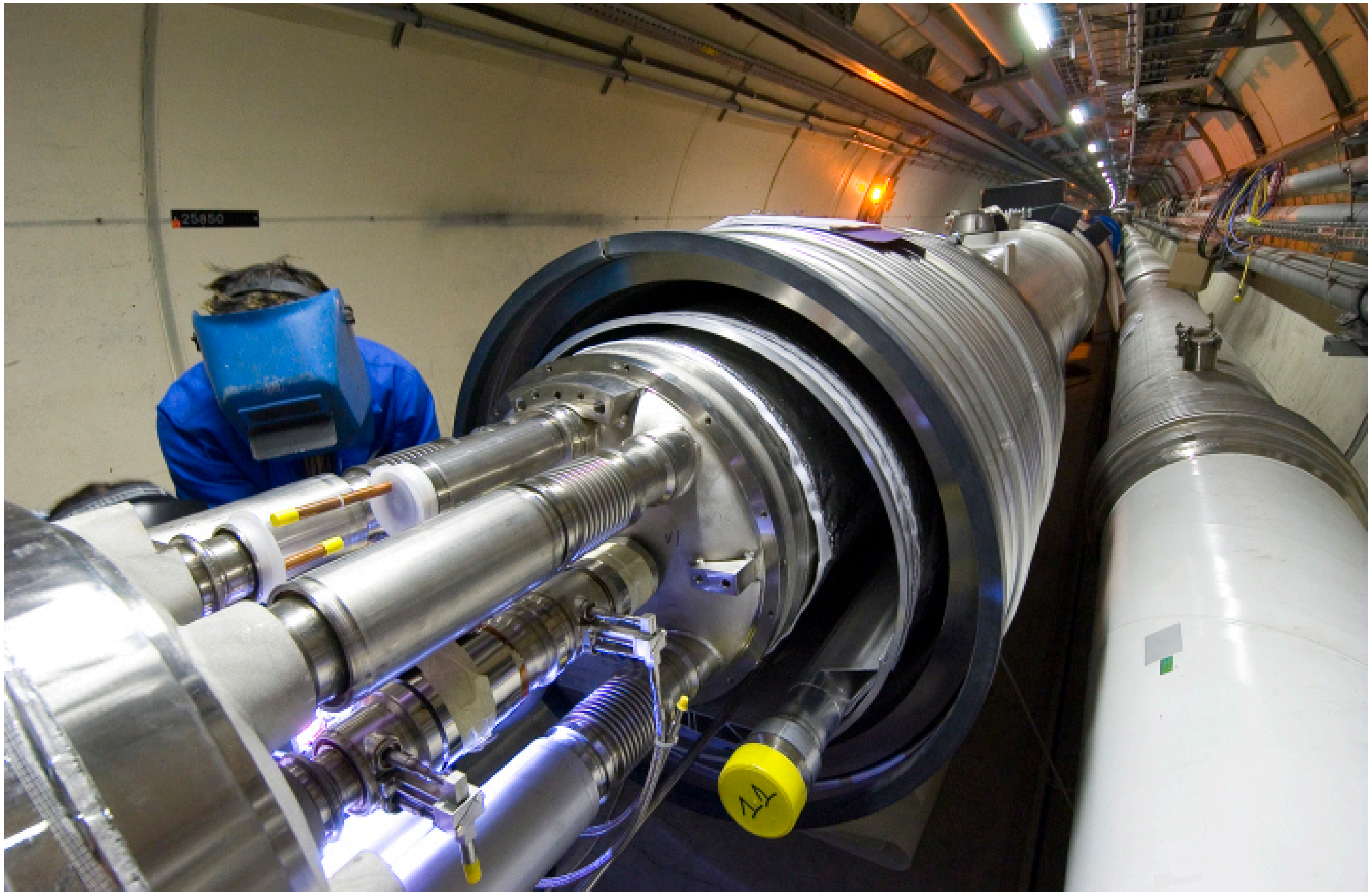
Capture with optimum injection phasing, correct



Busbar splice



Dipole-dipole interconnect



Cryostat and cold masses longitudinal displacements

Displacements status in sector 3-4 (From Q17R3 to Q33R3) : P3 side

Based on measurements by TS-SU, TS-MME and AT-MCS

	Q17	A18	B18	C18	Q18	A19	B19	C19	Q19	A20	B20	C20	Q20	A21	B21	C21	Q21
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	?	?	?	?	?	?	?	?	?	?	<5	<5	<5	<5	<5	<5	<5

	Q21	A22	B22	C22	Q22	A23	B23	C23	Q23	A24	B24	C24	Q24	A25	B25	C25	Q25
Cryostat	<2	<2	<2	<2	-7	<2	<2	<2	-187	<2	<2	<2	<2	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	-25	-67	-102	-144	<5	-190	-130	-60	<5	<5	<5	<5	<5

	Q25	A26	B26	C26	Q26	A27	B27	C27	Q27	A28	B28	C28	Q28	A29	B29	C29	Q29
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	474	-4	<2	<2	11	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	57	114	150?	-45	230	189	144	92? Vert	50	35	<5	<5

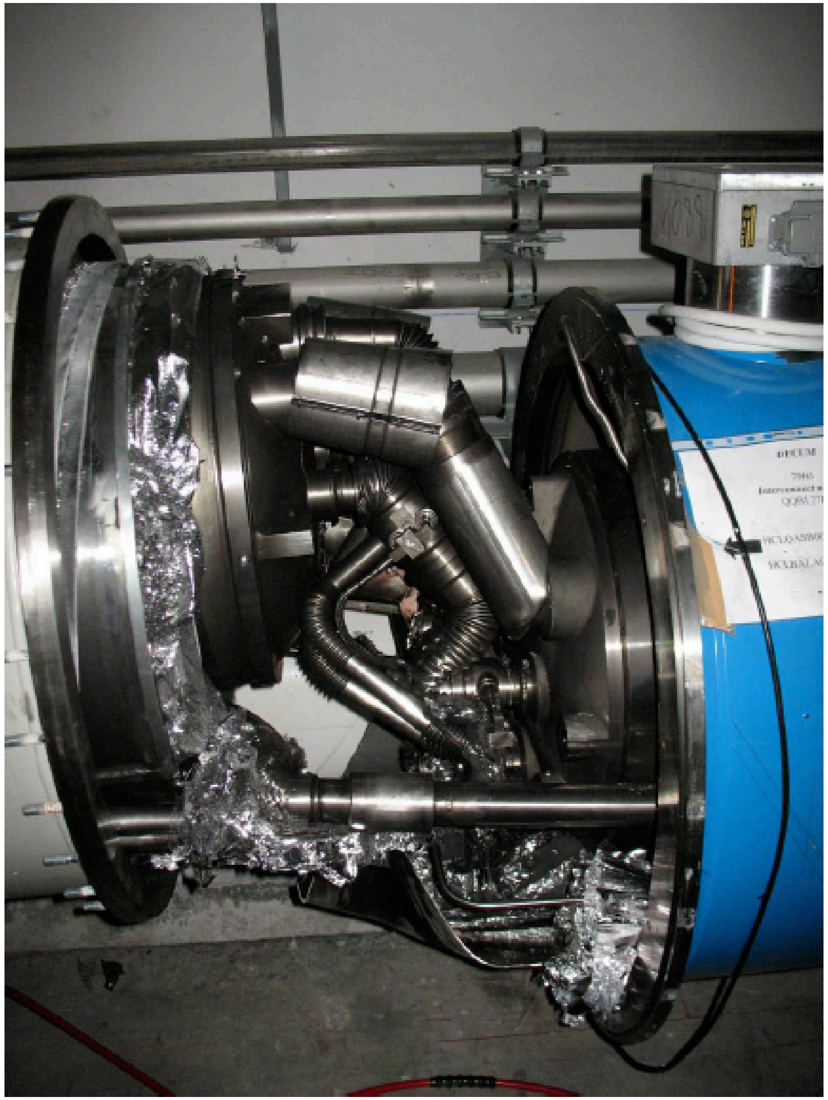
	Q29	A30	B30	C30	Q30	A31	B31	C31	Q31	A32	B32	C32	Q32	A33	B33	C33	Q33
Cryostat	<2	<2	<2	<2	<2	<2	<2	<2	188	<2	<2	<2	5	<2	<2	<2	<2
Cold mass	<5	<5	<5	<5	<5	19	77	148	<5	140	105	62	18	<5	<5	<5	?

SSS with vacuum barrier
>0 Towards P4
[mm] Values are in mm
? Not measured yet
Cold mass displacement
Cryostat displacement

Open interconnection
Electrical interruptions
Dipole in short circuit
Electrically damaged IC
Buffer zones

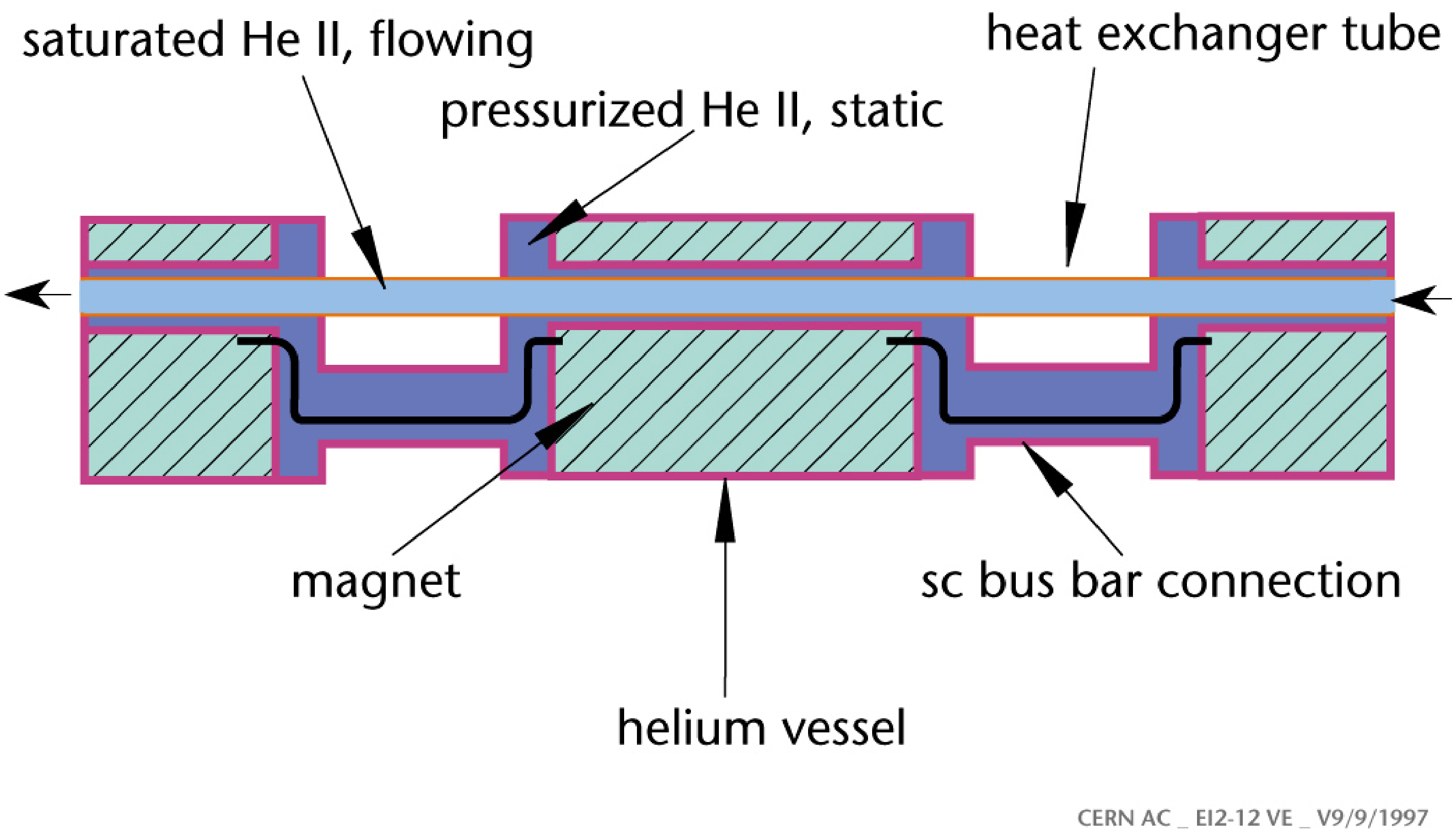
Disconnected

QQBI.27R3

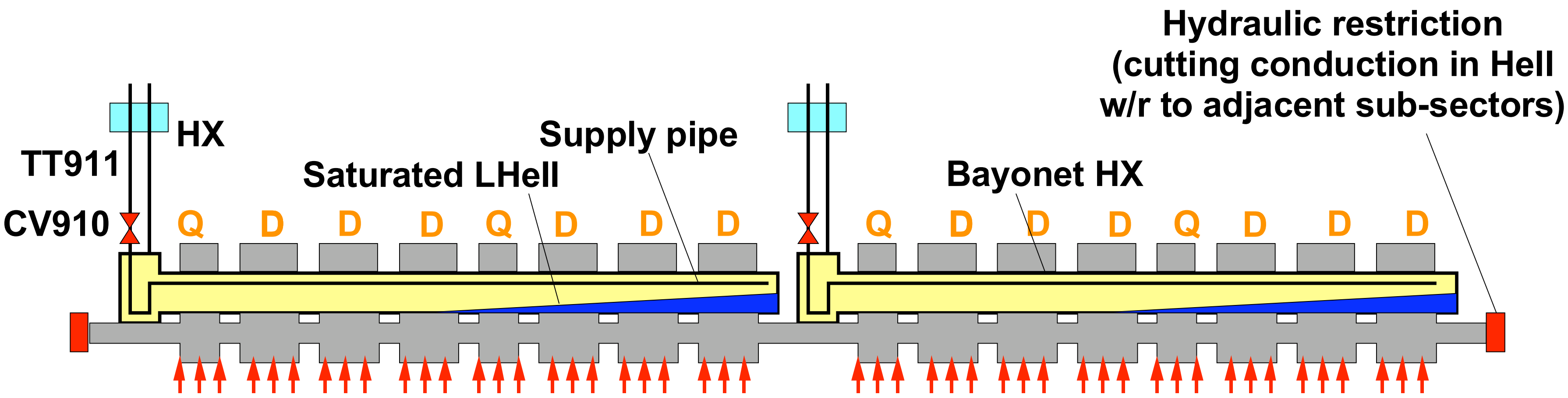


Magnet cooling scheme

LHC magnet string cooling scheme



Sub-sector magnet cooling scheme

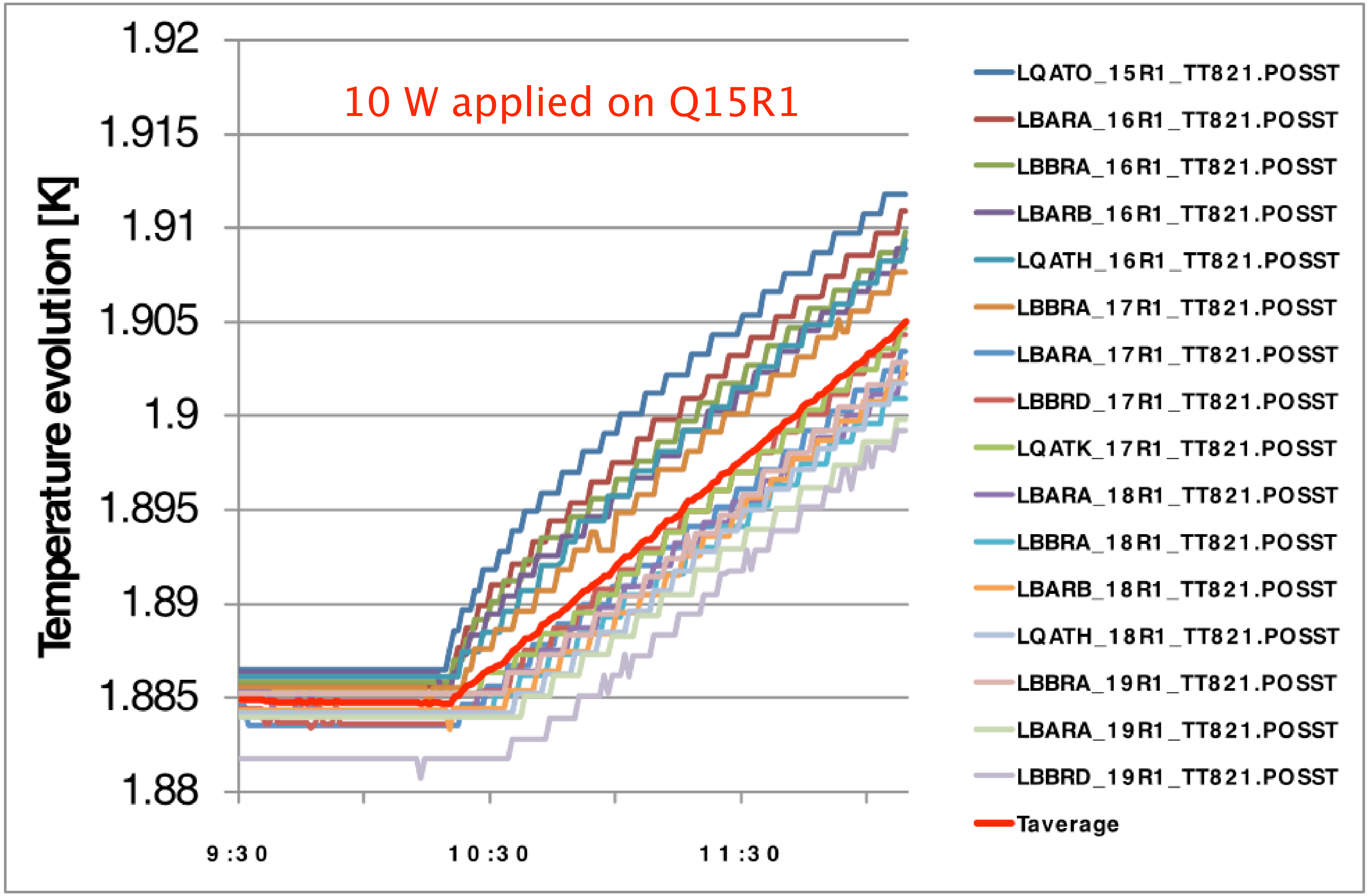


Principle:

→ Blocking of the JT valve (CV910) at a value to extract the static heat inleaks before the powering

→ Then, the temperature drift is mainly due to electrical resistive heating dissipated during the powering

Experimental validation: temperature evolution



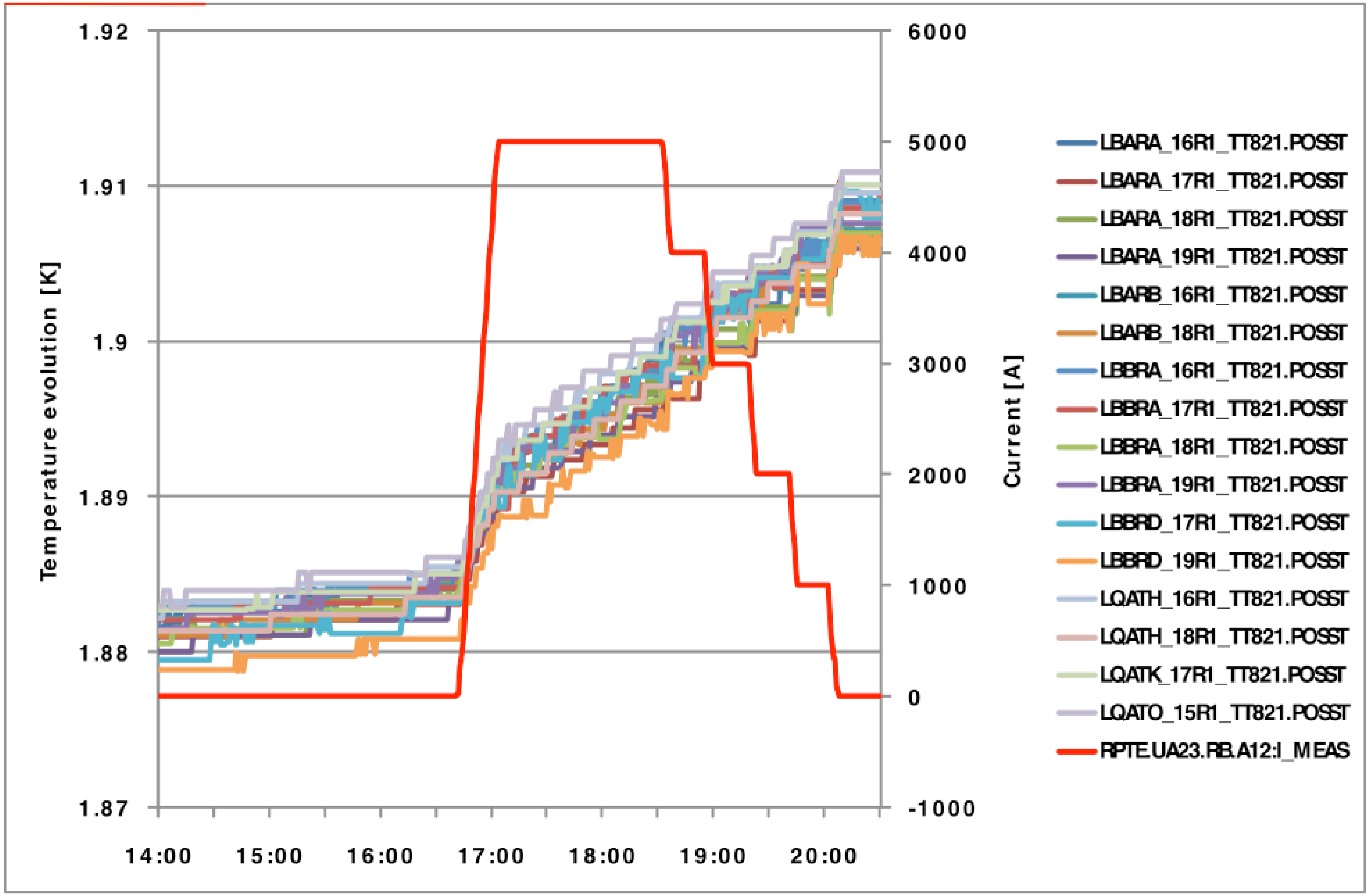
Experimental validation: calorimetry

	Before heating	With heating
ΔU [J/kg]	-1.1	78
M [kg]	823	
ΔU [kJ]	-0.92	64.2
t [s]	2880	6600
W [W]	-0.3	9.7
ΔW [W]	**10**	

→ **The power variation calculated by calorimetry is 10 W and is corresponding to the applied electrical power**

→ **Validation of the method !**

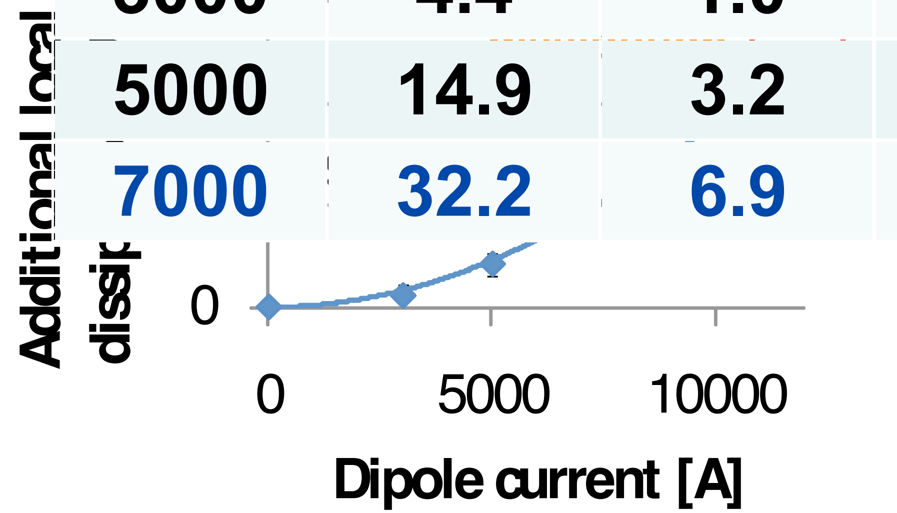
Powering example: 15R1 powering @ 5000A



The 15R1 case: additional heat dissipation due to a

Current	Total (measured)		Nominal Splices*	Add. local dissipation	Uncertainty
3000	4.4	1.0	0.4	0.6	0.6
5000	14.9	3.2	1.1	2.1	0.6
7000	32.2	6.9	2.1	4.8	0.6

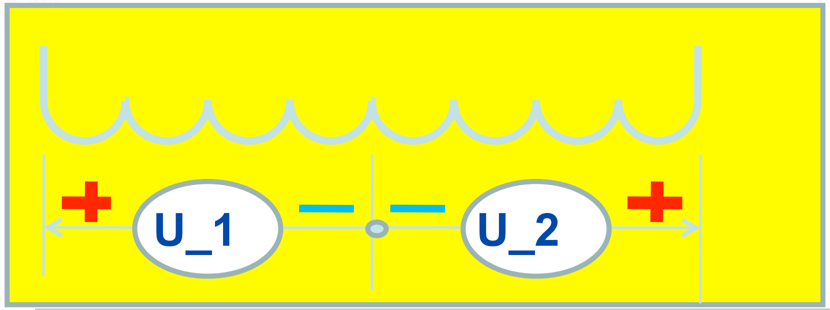
*: Calculated on the basis of 0.33 nW per splice and verified with the 5000 A plateaus



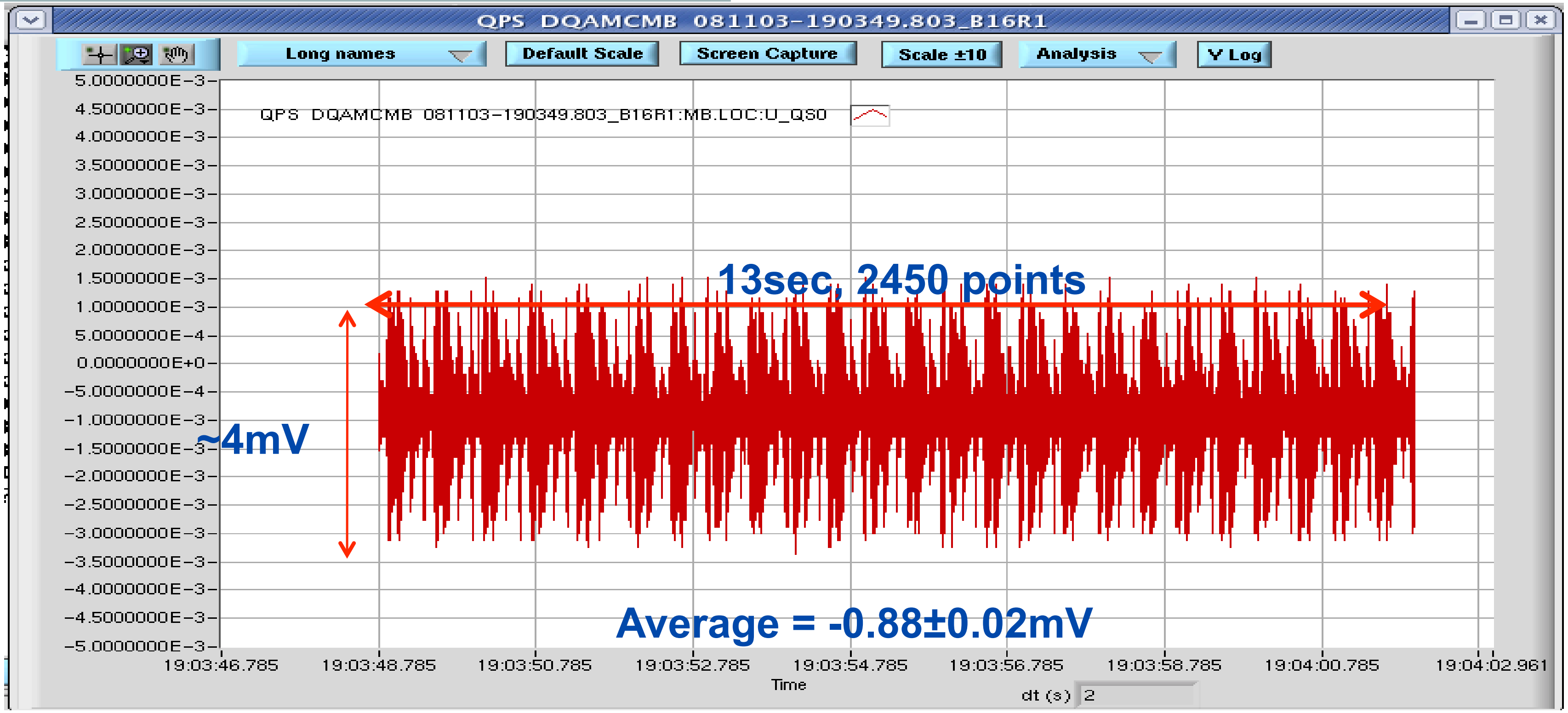
measurement !

→ Nominal dissipation 13 W: OK w/r to the cooling loop capacity margin

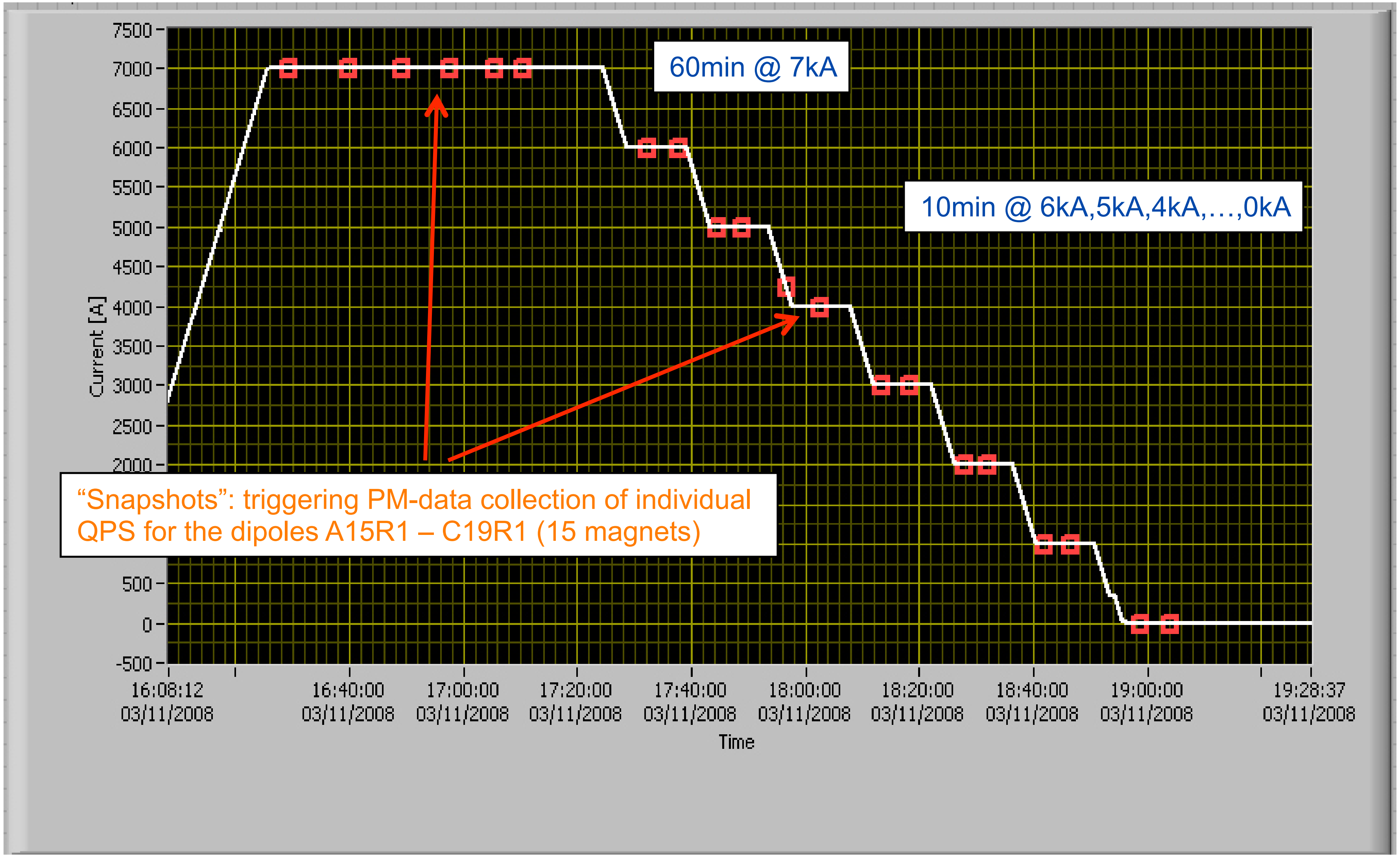
Sector A12: A15R1 – C19R1: "splice"



U_QS0 => -(U_1+U_2)
Sampling Rate = 5ms
Resolution = 0.125mV
Quench Threshold = 100mV@10ms



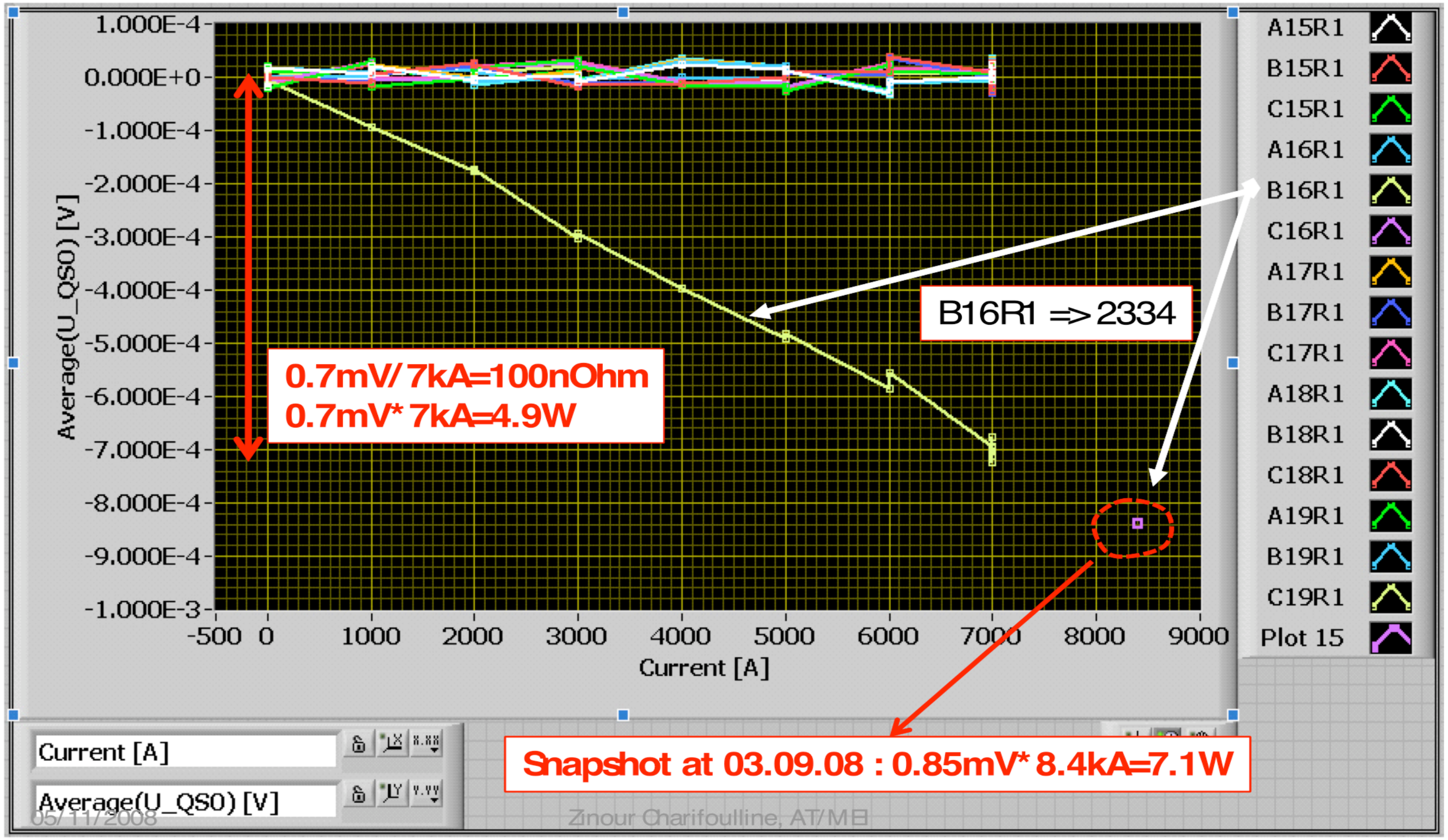
Sector A12: A15R1 – C19R1: measurements on



Courtesy Z. Charifoulline

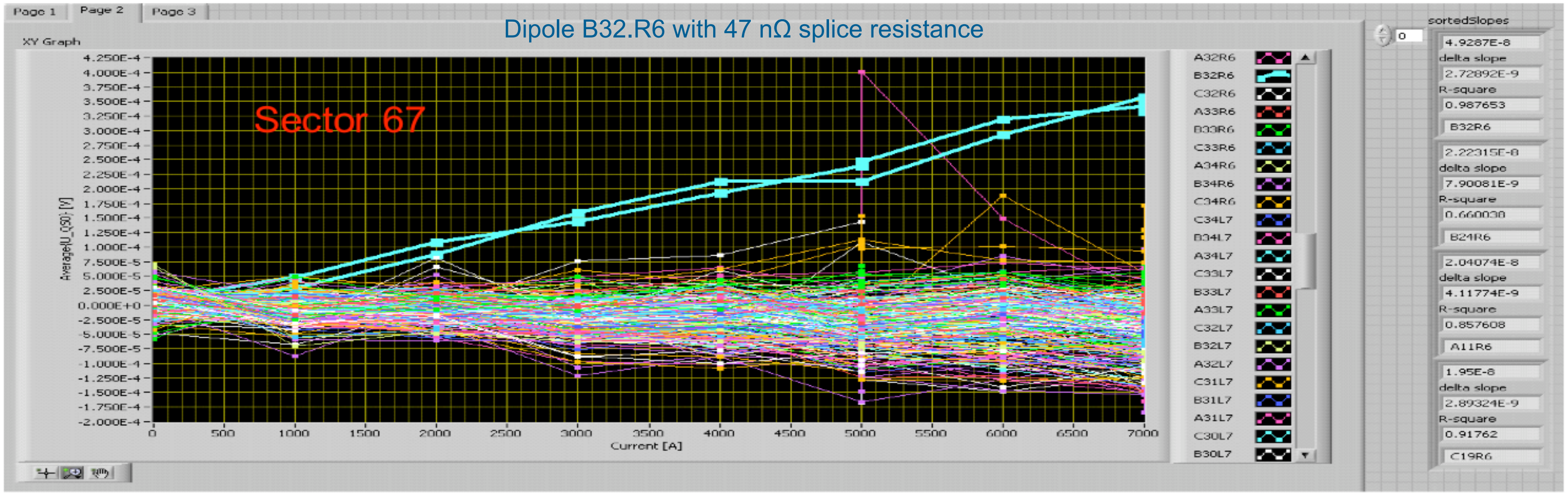
Proof of the missing source of heating, representing 100 nΩ, located in dipole B16.R1 (in the joint between the two apertures).

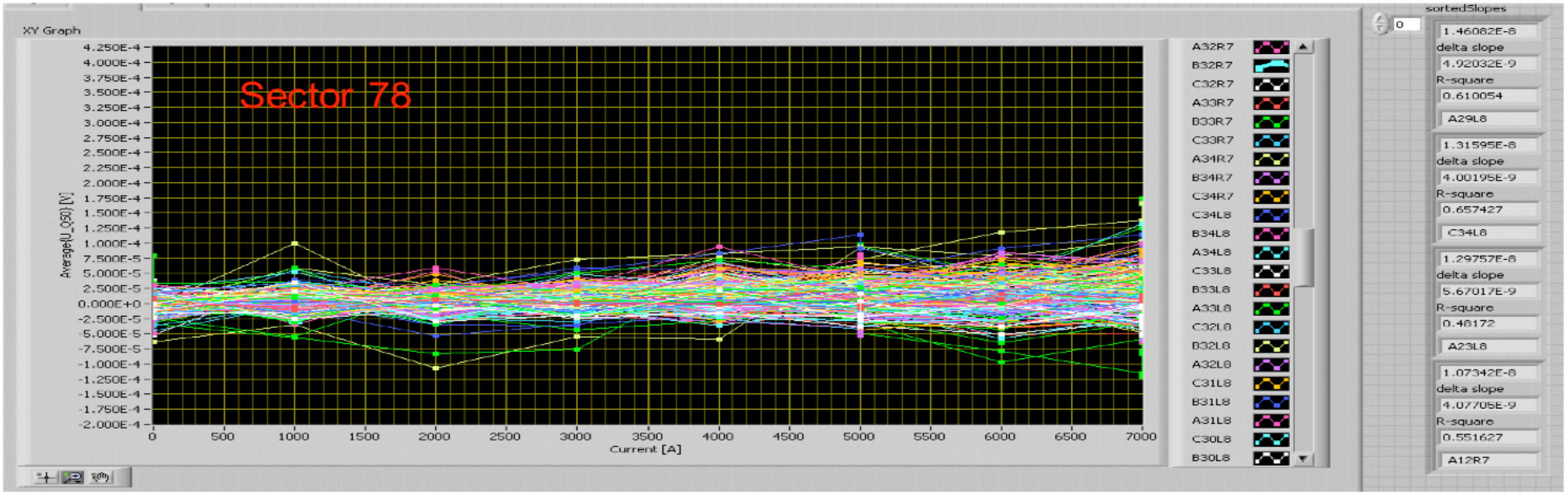
Sector A12: A15R1 – C19R1: Dipole Measurements made on 03.11.08



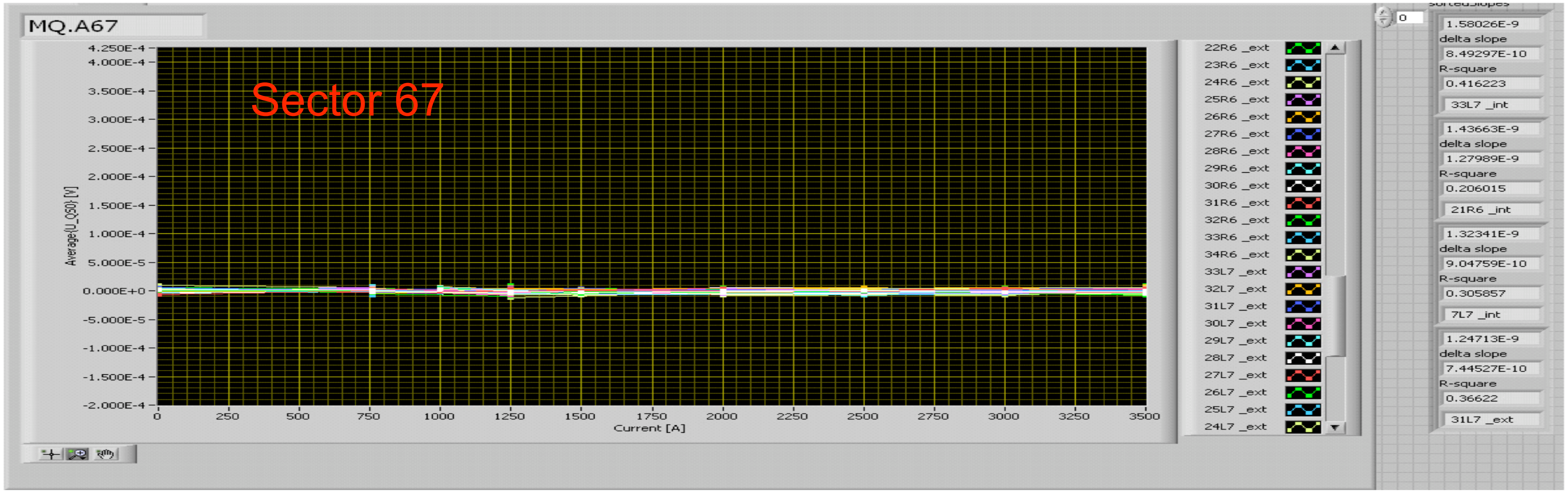
Snapshots in S67 and S78 on all 154 dipoles - B32.R6 with a high (47 nΩ) joint resistance between the poles of one aperture

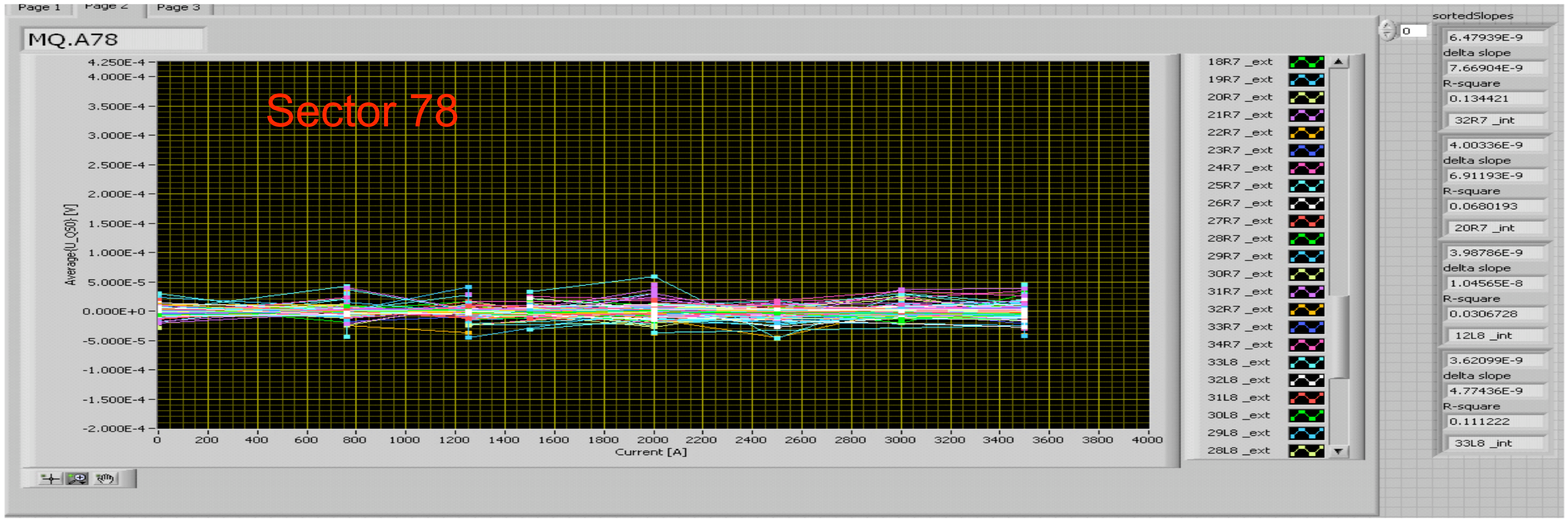
Results from provoked massive Post-Mortem of all dipoles in sectors 67 & 78



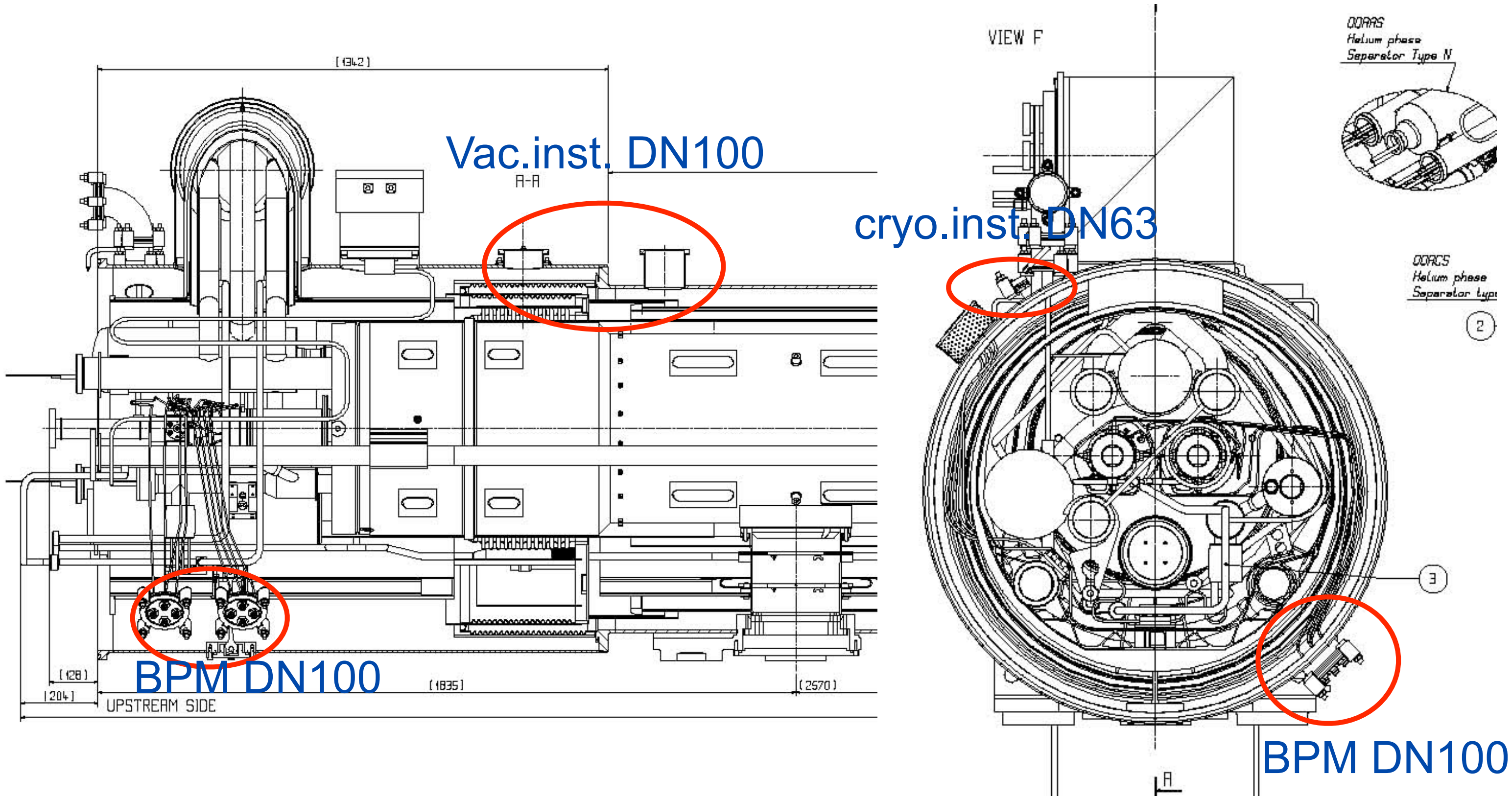


Main quadrupoles in S67 and S78 – Results of global snapshots





Existing ports: all on SSS



Each SSS:

- **4 DN100 ports (2 for vac.devices, 2 for BPM cable feedthrough)**
- **1DN63 port (for cryo instrumentation)**

Repairs and restart

- The four warm sectors will be equipped with extra pressure relief valves on all dipole cryostats.
- The four cold sectors will get extra PRVs on all short straight section cryostats. This can be done with the sectors cold and is adequate for 5 TeV operation.
- The quench protection system will be upgraded everywhere to cover all busbar splices.
- The whole machine will be cold by mid August, ready for first injected beam in late September.
- The machine will run at 5 TeV until autumn 2010 after which the remaining 4 sectors will be equipped with PRVs and will be prepared for high energy operation.

LHC upgrade: future plans

Peak Luminosity

$$L = \frac{N_b^2 n_b f_r \gamma}{4\pi \varepsilon_n \beta^*} F$$

N_b number of particles per bunch

n_b number of bunches

f_r revolution frequency

ε_n normalised emittance

β^* beta value at Ip

F reduction factor due to crossing angle

N_b, ε_n → injector chain

β^* → LHC insertion

F → beam separation schemes

n_b → electron cloud effect

LHC Upgrade-Phase I

Goal of "Phase I" upgrade:

Enable focusing of the beams to $\beta^*=0.25$ m in IP1 and IP5, and reliable operation of the LHC at double the operating luminosity on the horizon of the physics run in 2013.

Scope of "Phase I" upgrade:

1. Upgrade of ATLAS and CMS experimental insertions. The interfaces between the LHC and the experiments remain unchanged at ± 19 m.
2. Replace the present triplets with wide aperture quadrupoles based on the LHC dipole cables (Nb-Ti) cooled at 1.9 K.
3. Upgrade the D1 separation dipole, TAS and collimation system so as to be compatible with the inner triplet aperture.
4. The cooling capacity of the cryogenic system and other main infrastructure elements remain unchanged.
5. Modifications of other insertion magnets (e.g. D2-Q4) and introduction of other equipment in the insertions to the extent of available resources.

Participants and Milestones

Several departments are involved in the "Phase I" project:

AT Department: low-beta quadrupoles and correctors, D1 separation dipoles, magnet testing, magnet protection and cold powering, vacuum equipment, QRL modifications.

AB Department: optics and performance, power converters, instrumentation, TAS and other beam-line absorbers, …

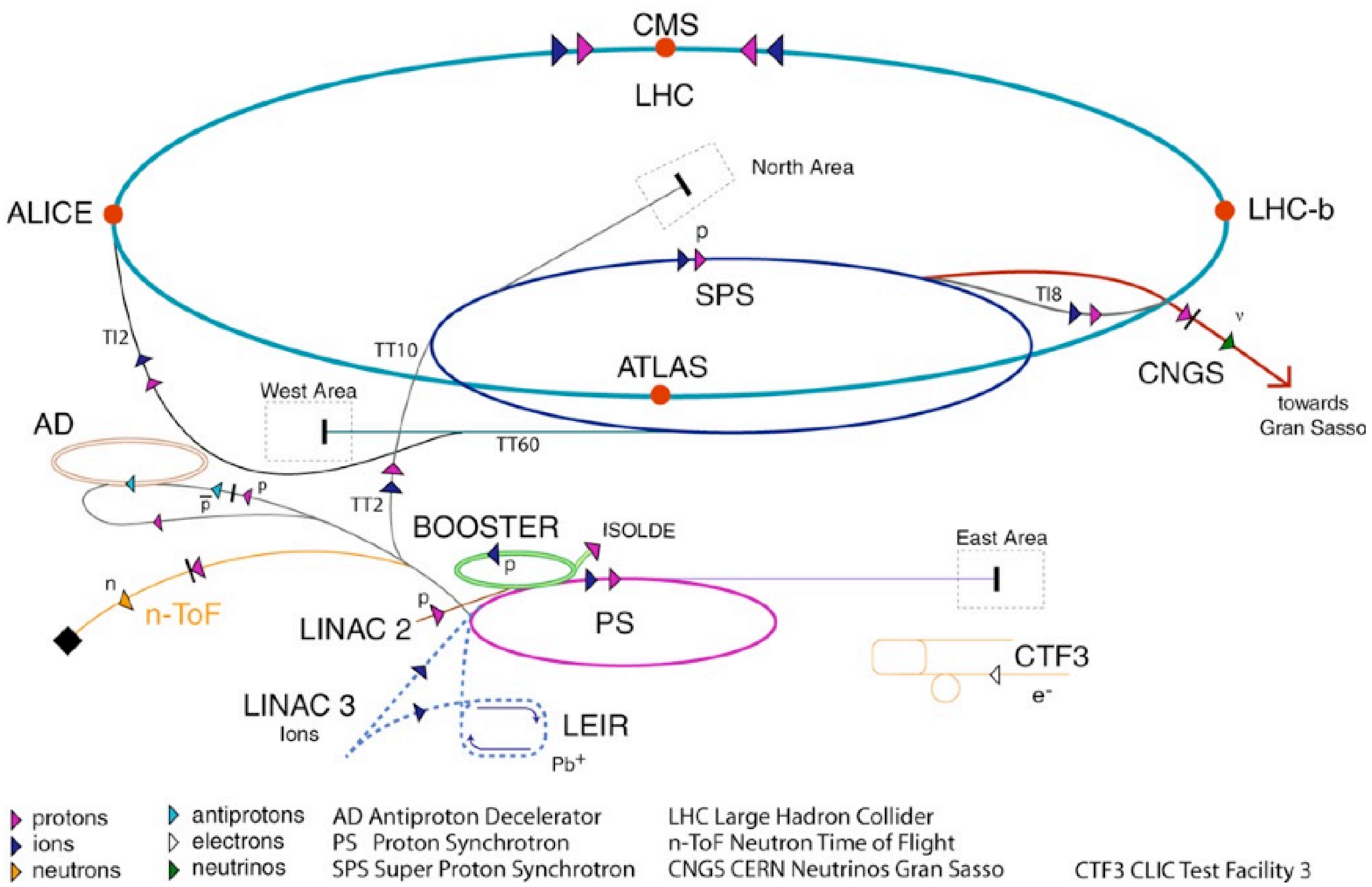
TS Department: cryostat support and alignment equipment, interfaces with the experiments, installation, design effort, …

SLHC-PP collaborators.

Milestones:

Conceptual Design Report	mid 2008
Technical Design Report	mid 2009
Model quadrupole	end 2009
Pre-series quadrupole	2010
String test	2012
Installation	shutdown 2013

CERN accelerator complex



Present limitations

1. Lack of reliability:

Ageing accelerators (PS is 48 years old !) operating far beyond initial parameters

➡ need for new accelerators designed for the needs of SLHC

2. Main performance limitation:

Excessive incoherent space charge tune spreads DQSC at injection in the PSB (50 MeV) and PS (1.4 GeV) because of the high required beam brightness N/e*.

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \times \frac{R}{\beta\gamma^2}$$

with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: normalized transverse emittances

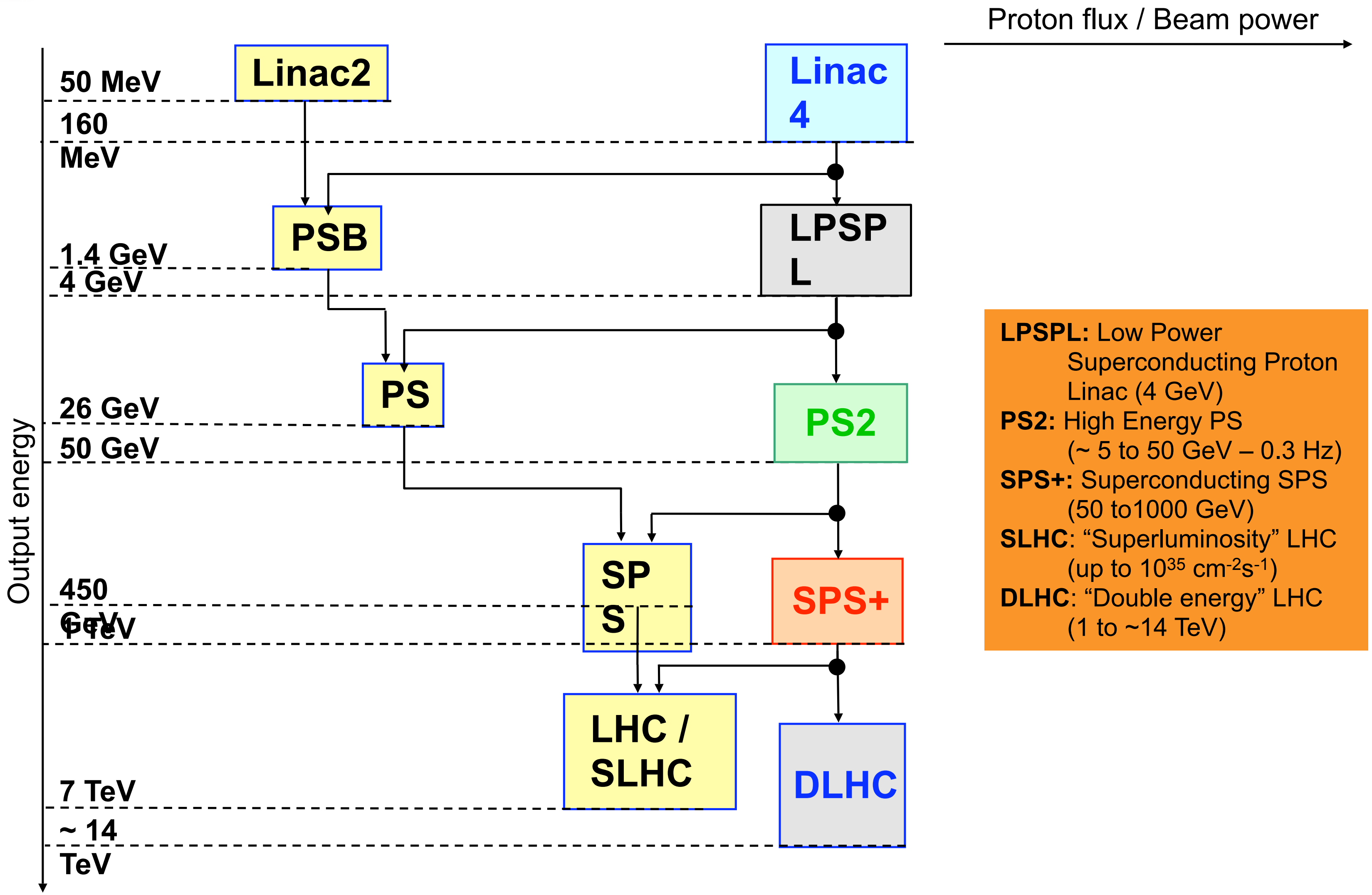
R : mean radius of the accelerator

$\beta\gamma$: classical relativistic parameters

➡ need to increase the injection energy in the synchrotrons

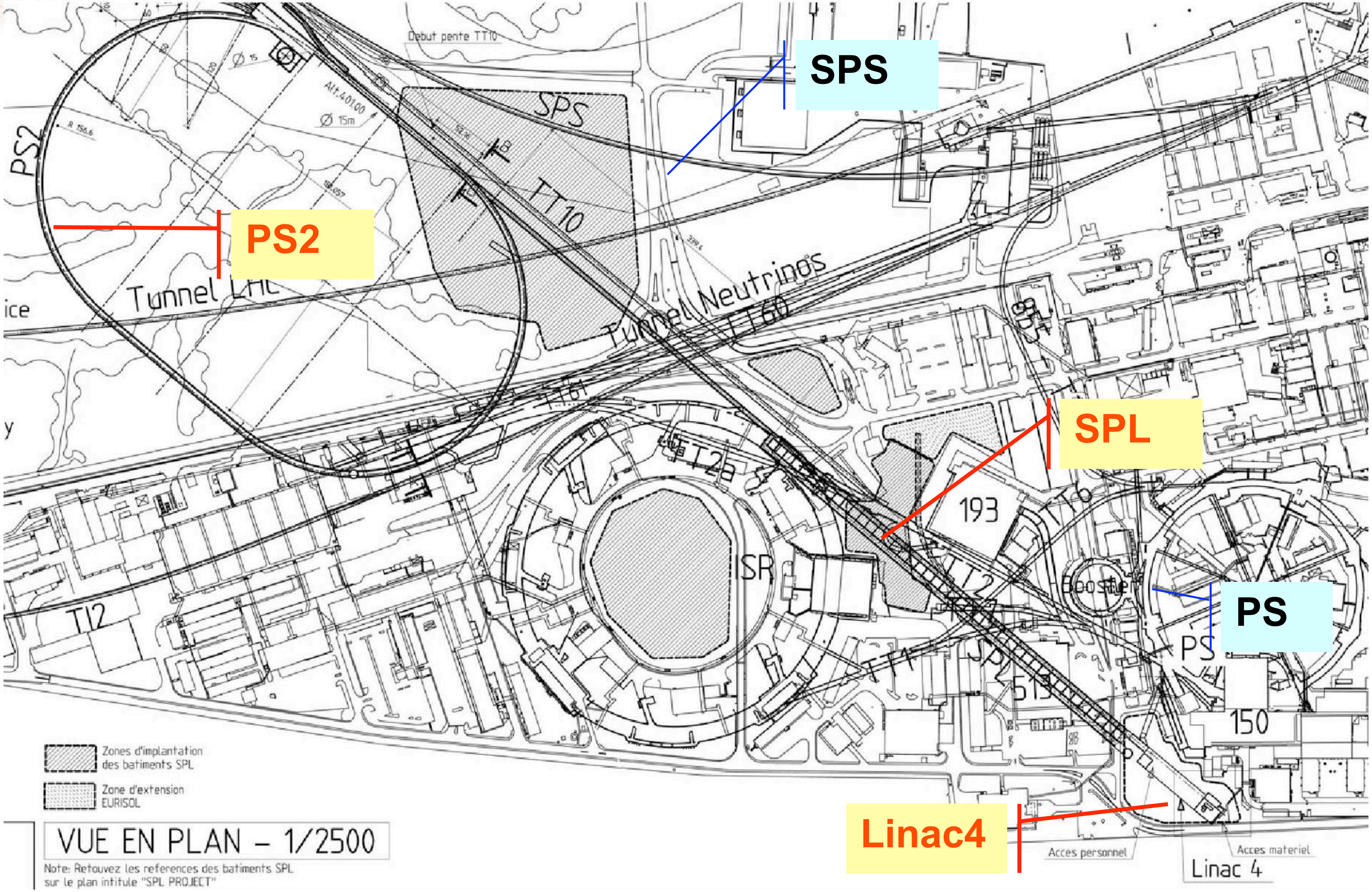
- Increase injection energy in the PSB from 50 to 160 MeV kinetic
- Increase injection energy in the SPS from 25 to 50 GeV kinetic
- Design the PS successor (PS2) with an acceptable space charge effect for the maximum beam envisaged for SLHC: => injection energy of 4 GeV

Upgrade components



LPSPL: Low Power Superconducting Proton Linac (4 GeV)
PS2: High Energy PS (~ 5 to 50 GeV – 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10^{35} $cm^{-2}s^{-1}$)
DLHC: "Double energy" LHC (1 to ~14 TeV)

Layout of the new injectors



Stage 1: Linac4

- **Direct benefits of the new linac**

Stop of Linac2:

- End of recurrent problems with Linac2 (vacuum leaks, etc.)
- End of use of obsolete RF triodes (hard to get + expensive)

Higher performance:

- Space charge decreased by a factor of 2 in the PSB

  => potential to double the beam brightness and fill the PS with the LHC beam in a single pulse,

  => easier handling of high intensity. Potential to double the intensity per pulse.
- Low loss injection process (Charge exchange instead of betatron stacking)
- High flexibility for painting in the transverse and longitudinal planes (high speed chopper at 3 MeV in Linac4)

First step towards the SPL:

- Linac4 will provide beam for commissioning LPSPL + PS2 without disturbing physics.

- **Benefits for users of the PSB**

Good match between space charge limits at injection in the PSB and PS

=> for LHC, no more long flat bottom at PS injection + shorter flat bottom at SPS injection: easier/ more reliable operation / potential for ultimate beam from the PS

More intensity per pulse available for PSB beam users (ISOLDE) – up to 2´

Stage 2: LPSPL + PS2

- **Direct benefits of the LPSPL + PS2**

  Stop of PSB and PS:
  - End of recurrent problems (damaged magnets in the PS, etc.)
  - End of maintenance of equipment with multiple layers of modifications
  - End of operation of old accelerators at their maximum capability
  - Safer operation at higher proton flux (adequate shielding and collimation)

  Higher performance:
  - Capability to deliver 2.2´ the ultimate beam for LHC to the SPS

    => potential to prepare the SPS for supplying the beam required for the SLHC,
  - Higher injection energy in the SPS + higher intensity and brightness

    => easier handling of high intensity. Potential to increase the intensity per pulse.

  First step towards the SPL:
  - Linac4 will provide beam for commissioning LPSPL + PS2 without disturbing physics.

- **Benefits for users of the LPSPL and PS2**

  More than 50 % of the LPSPL pulses will be available (not needed by PS2)

  => New nuclear physics experiments – extension of ISOLDE (if no EURISOL)…

  Upgraded characteristics of the PS2 beam wrt the PS (energy and flux)

Stage 2': SPL

Upgrade the LPSPL into an SPL (multi- MW beam power at 2-5 GeV):

- 50 Hz rate with upgraded infrastructure (electricity, water, cryo-plants, …)
- 40 mA beam current by doubling the number of klystrons in the superconducting part)

Possible users

- **EURISOL (2nd generation ISOL-type RIB facility)**

=> special deflection system(s) out of the SPL into a transfer line

=> new experimental facility with capability to receive 5 MW beam power

=> potential of supplying b-unstable isotopes to a b-beam facility…

- **Neutrino factory**

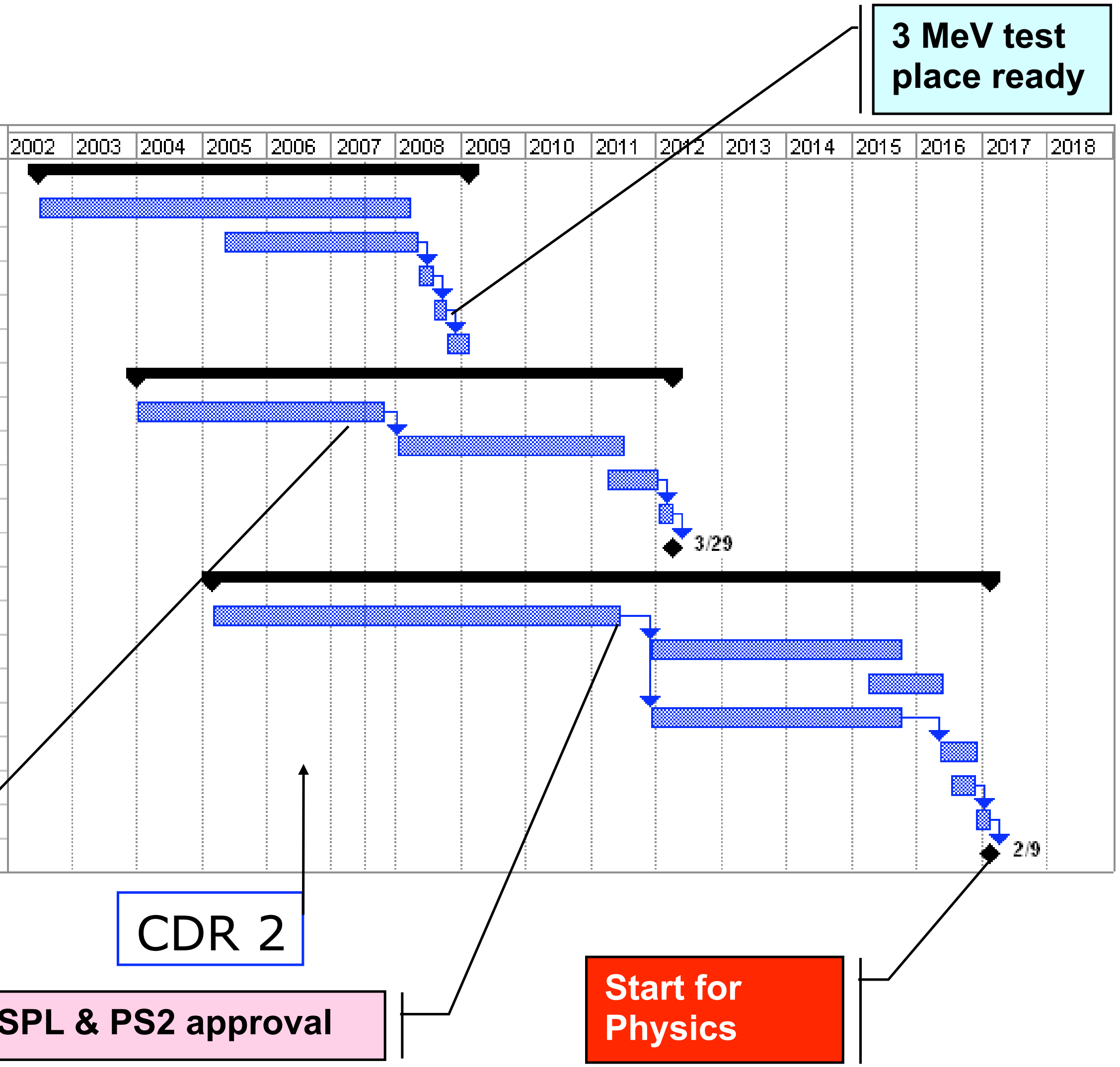
=> energy upgrade to 5 GeV (+70 m of sc accelerating structures)

=> 2 fixed energy rings for protons (accumulator & compressor)

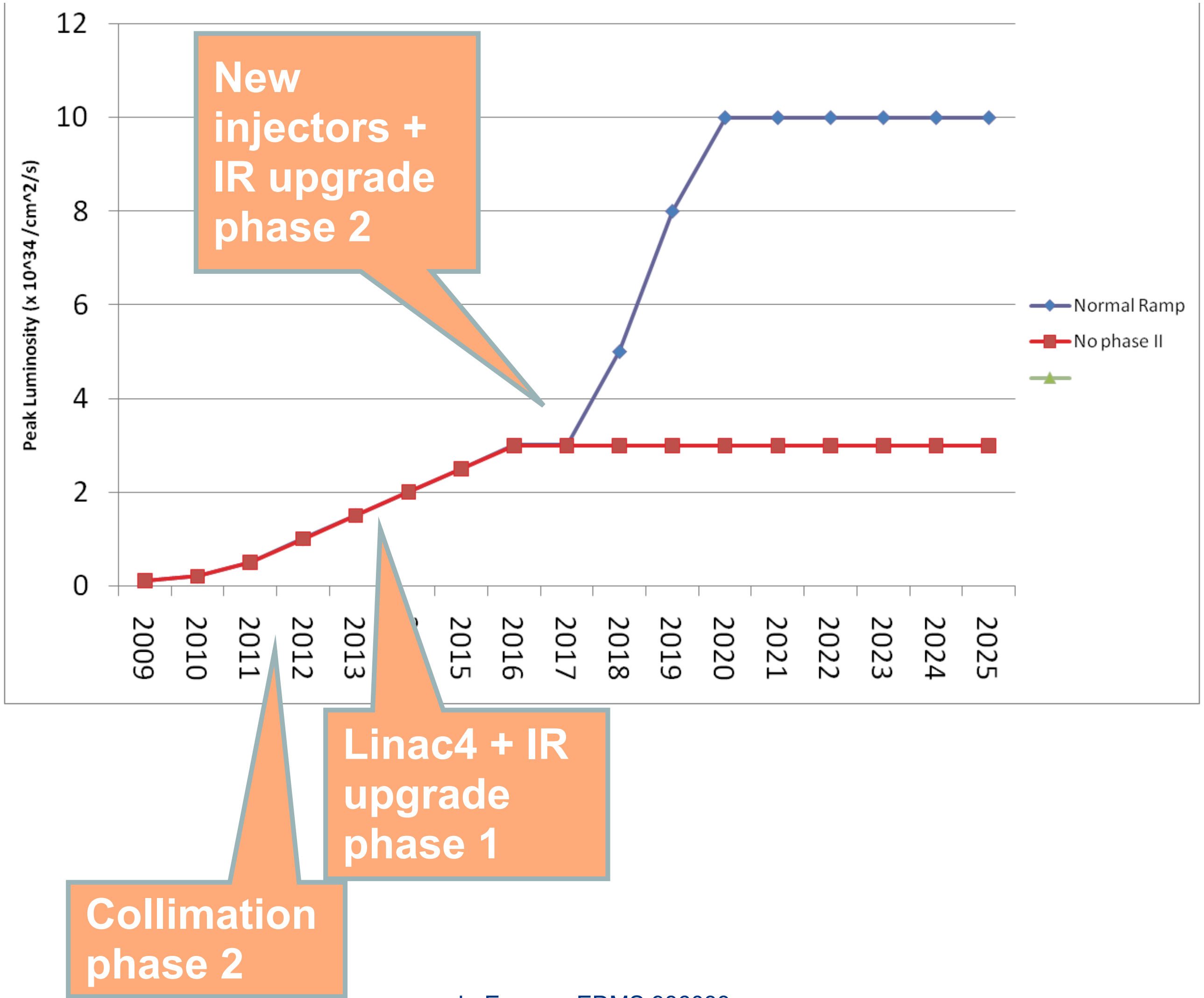
=> accelerator complex with target, m capture-cooling-acceleration (20-50 GeV) and storage

Planning …

ID	Task Name
1	**3 MeV Front End**
2	Design and construction
3	CERN Installation
4	Commissioning w/o beam
5	IPHI RFQ Installation
6	Commissioning and operation
7	**LINAC4**
8	Design refinement
9	Construction
10	Linac commissioning
11	Linac + PSB commissioning
12	Start for physics
13	**SPL + PS2**
14	Design refinement
15	SPL Construction
16	SPL beam commissioning
17	PS2 construction
18	PS2 beam commissioning
19	SPS modification
20	SPS beam commissioning
21	Start operation for physics



Peak luminosity…



Integrated luminosity…