Conceptual Design Review of the Magnet Circuits for the HL-LHC:

- 21-23 March, 2016 -

Review Report

presented by

Akira Yamamoto

on behalf of the Review Panel members

Guram Chlachidze (Fermilab), Arnaud Devred (ITER), Chen-Yu Gung (ITER),
Rudiger Schmidt (CERN), Davide Tommasini (CERN),
Akira Yamamoto (KEK and CERN, Chair), and Markus Zerlaunth (CERN, Sc. Secretary)

Reported at HL-LHC Technical Coordination Committee, 31 March, 2016

Review Panel Members

Review Panel Members:
- Guram Chlachidze (Fermilab)
- Arnaud Devred (ITER)
- Chen-Yu Gung (ITER, through remote contribution)
- Rudiger Schmidt (CERN)
- Davide Tommasini (CERN)
- Akira Yamamoto (CERN and KEK, Chair)
- Markus Zerlaunth (CERN, Sc. Secretary)

Link person:
- Felix Rodriguez Mateos (CERN)

Administrative Secretaries
- Cecile Noel and Julia Cachet (CERN)

Background of the Review

- The High Luminosity LHC (HL-LHC) Project requires changing or modifying numerous magnet circuits in the High Luminosity insertions (Point 1 and Point 5) of the collider.
- The higher peak field, higher current and larger magnetic energy, as well as the necessity to displace the power converter far from radiation areas, with use of superconducting links, make the system more complex and technically very challenging.
- "*Mr. HL-LHC Circuit*", Felix Rodriguez Mateos, has been appointed to steer the optimization and ensure consistency of the whole system.

Charge and Goal of the Review

- Examine the baseline choices and open variants with respect to the following aspects :
  - Circuit Topology
  - Magnet and Circuit Protection
  - Circuit Integration
  - Operation
  - Voltage Withstand Levels
  - Plan and Schedule

Some Notes

- The review panel is expected:
  - to review the conceptual "design" of the HL-LHC magnet circuit, and
  - to advise/recommend "a clear view" for the circuit system design prioritized for further design studies and demonstration/realization plans.

The review not to cover R&D works and/or the production program.

Review Agenda and Schedule

3/21	Subjects	*Convener*/Speaker
8:30	**Closed Session**	***A. Yamamoto***
9:00	***Session 1: Setting the scene and cold powering***	***L. Rossi***
9:00	Welcome and scope of the review	Lucio Rossi
9:10	The HL-LHC magnets: status report	Ezio Todesco
9:40	HL-LHC circuits: global vie and open questions	Felix Rodriguez Mateos
	(Break ?)	
10:40	Integration of powering and protection systems	Paolo Fessia
11:20	SC links	Amalia Ballarino
12:00	Bus bars	Herve Prin
12:30	*Lunch Break*	

Review Agenda and Schedule

3/21	Subjects	*Convener*/Speaker
13:30	*Session 2: Protection of circuits & instrum.*	*Luca Bottura*
13:30	The principle of he CLIQ systems	Emmanuele Ravaioli
13:45	The 11 T dipole magnet and protection	Susanna Izquierdo-Bermudez
14:05	The 11 T dipole circuit(s)	Samer Yammine
14:25	The inner triplet magnets and protection	Giorgio Ambrosio
14:45	The inner triplet circuit	Emmanuele Ravaioli
15:05	D1	Tatsushi Nakamoto
	D2	Pasquale Fabbricatore
15:35	D1 & D2 circuit aspects	Felix Rodriguez-Mateos
16:20	Triplet orbit correctors	Fernando Toral
16:50	Triplet high-order correctors	Giovanni Volpini
17:20	Matching section correctors	Gijs De-Rijk
17:50	**Closed Session**	**Akira Yamamoto**

Review Agenda and Schedule

3/22	Subjects	*Convener*/Speaker
8:30	***Session 3: Systems***	***Andrzej Siemko***
8:30	Operation requirements	Massimo Giovannozzi
9:10	Power converters: operational aspects	Jean-Paul Burnet
9:50	Quench detection	Jens Steckert
11:00	CLIQ & HDS units	Knud Dahlerup-Petersen
11:30	Warm cabling, cooling and ventilation	Laurent Jean Tavian
12:00	*Lunch Break*	
13:30	***Session 4: Elqa, MP3 and String***	***Ezio Todesco***
13;30	Electrical qualit assurance	Felix Rodriguez-Mateos
14:00	Diagnostics and analysis: the point of view of MP3	Arjan Verweij
14:30	Inner triplet string	Luca Bottura
15:00	*Break*	
15:30	Documentation plan	Reiner Denz
16:10	Roadmap for decisions	Daniel Wollmann
16:40	**Closed session (followed by working dinner)**	***Akira Yamamoto***

Review Agenda and Schedule

3/23	Subjects	*Convener*/Speaker
8:30	**Panel Closed Session**	***Akira Yamamoto***
12:30	Review Panel Lunch	*L. Rossi*
14:00	**Panel Closed Session**	***Akira Yamamoto***
16:00	**Close-out by Panel**	**Akira Yamamoto**
17:00	Adjourn	

Finding and Comment/Recommendation

- We present our finding, comment/recommendation with a different way from the original one, as follows:

  - **General Comment**
  - **11 T Dipole circuit and protection**
  - **Inner triplet circuit and protection**
  - **D1 and D2 circuit protection**
  - **Technical subjects commonly discussed**
  - **Summary and acknowledgment**

General Comment

- We have been much impressed with considerable amount of excellent works performed and reported in a comprehensive manner.

11 T Dipole: Circuit

- Finding
  - Baseline: Main circuit in series w/ MB
  - Compensation inevitably required to compensate different magnet characteristics by using correctors or trim-PC.

- Comment/**Recommendation**
  - The operational mode with trims/correctors should be further investigated, including failure modes.
    - Trims may introduce some risk on the main dipoles circuit.

  - Even in case trims not considered, we still recommend to provide CLs for trim-current.
  - The option of global correction together with the optimization of the transfer function should be investigated in detail.

11 T Dipole: Protection

- Finding:
  - Combination of QPHT and Diode is the baseline.
  - CLIQ is not considered for 11 T dipole protection.
  - It is proposed to use variable quench detection threshold and/or validation delay-time.

- Comment/Recommendation
  - We support the baseline protection.

  - Improving the reliability of QPHT strips and the connection of the lead-wires to the strips is mandatory.
  - Develop and validate strategy for the variable detection threshold and/or validation delay-time, taking into account high dependability of the system.
  - Detailed risk analysis including critical failure modes (eg, trim-PCs) on the circuit is recommended.

Inner Triplet: Circuit

- **Finding**
  - Base-line: 2 main PCs with 2 trim PCs.
  - A new proposal : Single main PC with 3 trim PCs.

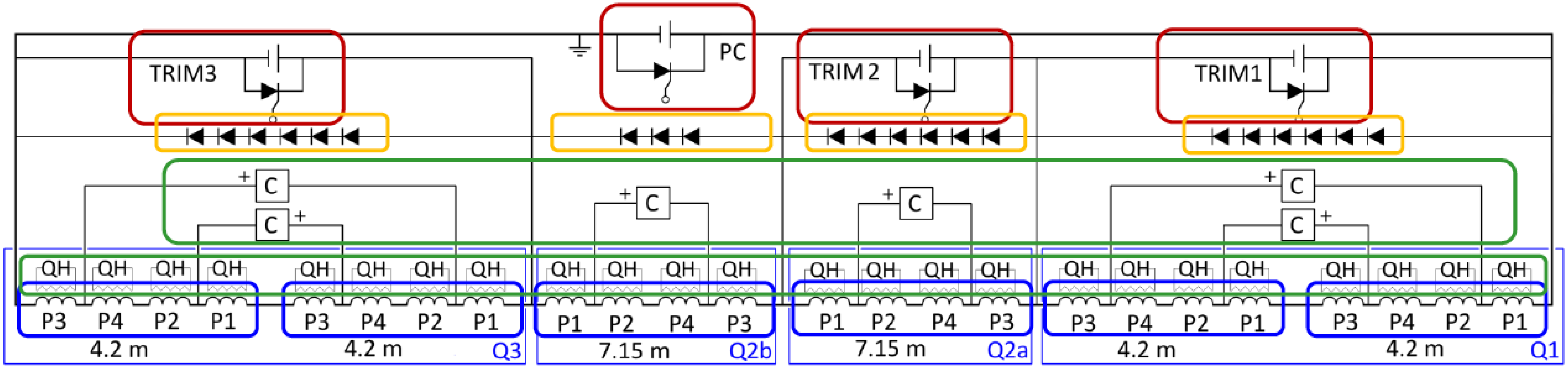
- **Comment**
  - We support the new proposal.
    - Advantages for beam dynamics (with reducing tune variation)
    - Saving CLs in main circuit
  - We understand positive experience with the current inner triplet operation in series with an extra-ordinal trim scheme.

Powering and Quench protection system

We support the new proposal !

POWERING SYSTEM
1 main power supply (2-quadrant)
3 trim power supplies

Parallel Diodes



MAGNETS
4x 4.2 m QXF (LARP)
2x 7.15 m QXF (CERN)

PROTECTION SYSTEM
CLIQ system + Quench Heater system

Inner Triplet : Protection

- **Finding**
  - Outer QPHT + CLIQ is proposed as a baseline redundant system.
  - Inner/Inter-layer QPHT technology is still under investigation.

- **Comment/Recommendation**
  - A lot of work has been integrated.
  - **Risk analysis** should be digested
    - so as to extract salient information for most critical failure modes;
  - **A summary table** should be assembled to compare basic options:
    - Outer quench heaters only, with and without quench back,
    - Outer quench heaters with CLIQ,
    - Outer and Inner quench heaters, with and without quench back;
  - **CLIQ** needs to be further and more thoroughly investigated,
    - in particular regarding long-time reliability when applied to Nb_3Sn coils
  - **R&D on inner QPHT** should be continued,
    - in particular to prevent degradation due to bubbling;

D1 and D2: Circuit

- **Finding**
  - Baseline: two independent PCs,
  - No strong request from beam optics for series operation,
  - No significant cost saving for series circuit.

- **Comment**
  - We support the baseline choice.

D1 and D2: Protection

- **Finding**
  - QPHTs provide sufficient protection
  - Increase of redundancy was recently implemented with additional QPHTs.

- **Comment/Recommendation**
  - We support the baseline with no CLIQ protection.
  - QPHT analysis needs to be refined
    - in particular, for D2.

Correctors

- **Finding**
  - Triplet orbit-correctors MCBXF presently protected by QPHTs. External energy extraction was discarded.
  - Design of most HO correctors will be changed to lower the operating current. Only the quadrupole corrector MCQSX is proposed to keep the present baseline current of 180 A.
  - Protection of HO correctors is passive with a fixed limit on the PC output voltage and by a crowbar.

- **Comment/Recommendation**
  - We support the proposal for MCQSX to keep the operating current at 180A.
  - We recommend to reconsider Energy Extraction (EE) for MCBXF:
    - additional R&D required to select the best option between EE or QPHT.

Protection: General

- **Comment/Recommendation:**
  - Integrated approach did not appear to have been systematically applied for all circuits including magnets, leads, links, and bus-bars.
  - In comparison with LHC, there are several novel and challenging technologies including Nb_3Sn magnets, Superconducting Links, CLIQ, and high-current 2-quadrant PCs.
  - We recommend close and regular interaction (communication)
    - between various experts, possibly by setting-up of a dedicated working group (or using existing structure) on circuit integration and protection.

CLIQ : General

- **Finding**
  - The principle has been established.
  - CLIQ is proposed for the protection for the inner triplet quadrupoles in combination with QPHTs.

- **Comment/Recommendation**
  - The implementation of CLIQ is encouraged for the inner triplet quadrupoles.

  - CLIQ technology with long Nb_3Sn magnets needs to be demonstrated.
  - The effect of AC currents in the circuit shall be fully analyzed
    - eg, perturbations to the SC link protection.

Superconducting Link (SL)

- **Finding**
  - The baseline is composed of MgB_2 cables connected to flexible HTS cables without LTS links.
  - These enable operation at gaseous helium at <~20 K. The length will be about 100 m.
  - The proposed cable assembly includes several different circuits.
- **Comment/Recommendation**
  - The integration of flexible HTS cable requires additional R&D effort which would not be needed if the link would be based on a LTS or a conventional cable.
  - More emphasis should be put in circuit development including exploration of an option capable of sustaining the controlled magnet ramp down (with a time constant level of 10^3 sec.),
    - although most of the effort had been put in successfully developing and MgB_2 cable with focusing on a relatively shorter time constant of several sec. sufficiently sustaining for safe magnet discharge,
  - Development plan needs to be established for the joints between SL (HTS/ MgB_2 and MgB_2/NbTi).
  - A comprehensive quench protection system has to be developed and demonstrated for the circuit, including instrumentation.
  - Systematic study of cross-talk between the difference circuits for different failure scenarios (eg. Quench of main magnets) should be carried out.
  - SL circuit should be demonstrated during the Phase 1 string test.

High-pot/Voltage Qualification

- Finding
  - It is proposed to use a reference temperature/pressure per magnet based on worst case voltage scenario (eg, 75K, 1 bar, in helium)
  - Test voltages in air or gaseous helium are derived from this reference value by applying so called scaling factor.
  - The strategy for the test in liquid helium is still under discussion.

- Comment/Recommendation
  - The proposed approach of such a reference voltage per magnet is interesting.
  - More experience is needed to finalize the strategy, in particular for the scaling factor and the safety margins.

Risk Analysis and Mitigation

- Comment/Recommendation
  - Keep things simple & standardized + with accurate and correct diagnostic data! Every complication will multiply efforts for operability and event analysis throughout many years of operation.
  - Quantitative analysis of dependability of entire protection scheme should be carried out.
  - We recommend to re-assess how to implement redundancy including majority voting (eg, 2 oo 3).

String

- Finding
  - 2 phase string is proposed.
  - The string test will come relatively late.

- Comment/Recommendation
  - We strongly support the string test in 2 phases.

  - Establish a clear test program and objectives for each of the phases.
  - Implement all effort to realize the phase 1, as early as possible.
  - Fallback options in case of unavailability or delays from some of the components should be worked out (D1, CP, power converters), as early experience will be important input to many WP.
  - Ultimate equipment safety test should be included.

Plan and Schedule, Documentation

- Finding
  - Schedule is very tight,
  - Civil engineering will be frozen soon.

- Comment/Recommendation
  - Proper resource loaded schedule should be developed,
    - in particular for the string, considering concurrent activities such as LS2.
  - Critical activities should be identified.
  - Suitable resources should be allocated to cover critical activities.

Summary and Acknowledgment

This conceptual design review has been properly organized in timely manner for the efficient proceeding the HL-LHC construction program, specially for some common technology.

We would thank all members of HL-LHC and circuit group for their much effort to prepare for the review and to progress the project. Special thanks for your warmest hospitality during the review works.


Many thanks for everybody !!

Appendix

- Summary slides for individual presentation, provided by Markus Zerlauth

Introduction – Lucio Rossi

- HL-LHC approved in May 2013 by EU strategy update
- C&S review in 2015 has allowed CERN to fully finance the project
- Magnet circuits are described in the CDR and by now in the TDR-V0 (planned for release in ~ one year)
- Baseline has been re-discussed this year to optimize for cost and performance (including ancillary equipment) after the C&S review
- New baseline has to be frozen soon to allow new costing and planning in view of C&S review 2 in October 2016
- Charge to review: Examine the baseline choices and open variants and comment on readiness of circuit and soundness of the technical choices

Status of HL-LHC Magnets – Ezio Todesco

- 11T: Replace an integrated 120Tm of standard dipole with 2x5.5m 11T dipoles to make space for additional COLL required for beam intensities larger than nominal
- Nb3Sn, 11.5T peak field, first Nb3Sn magnet in an accelerator, in series with dipole chain (protection), trim used to compensate different saturation path
- Two short models successfully built, tested and assembled in double aperture, long magnet is main next challenge
- IR magnets: reduce beta* by factor of four in LS3, two sides around IR1/5 + spares (at least 2 spares / magnet)
- Triplet magnet also feature 11.5T peak field (by chance similarities with 11T), but 7m long
- Protection with outer layer quench heaters and/or CLIQ to create redundancy and decrease hot spot temperature – 100mV at high field is a must, 10ms validation time
- Current 16.5kA, ~140/20mH, 8MJ per 7m long magnet
- D2: Challenging magnet due to strong cross-talk between apertures (dealt with asymmetry in coil structure), hence issue with field quality, similar current and inductance (single circuit option under study). However difference of ~ 2% in transfer function (due to different way of saturation). Could be dealt with trim or stronger orbit correctors

Status of HL-LHC Magnets – Ezio Todesco (2)

- Q4: required to match beta function of triplet with arc – need independently powered apertures. 3.8m long
- Orbit correctors MCBXFA/B, for space optimization adopted nested option, additional corrector wrt to current LHC to increase flexibility . Mechanical lock to avoid effects of torque between magnets, 1.5kA and 20-50mH, 0.2MJ (small)
- Higher order corrector package: 9 different magnet types, current 180A, effort of re-design to eventually use 120A
- D2 orbit correctors: First canted design in accelerator, details see later
- Two WP3 magnets successfully tested, sextupole corrector and short triplet model, very good result for QXF (as tests done in 4.5K bath)
- Discussion:
  - Akira: 100mV threshold is a must - what does it mean: Ezio: We cannot exceed this detection thresholds, otherwise the detection time & peak temperature might be too high.
  - Davide: If a D1 and D2 are individually powered, do we still need H&V correctors in triplet: Massimo: Have to keep separate the 2 main functions, i.e. the ring functions and the correction of the orbit (alignment of triplet magnets, crossing angle and global orbit) i.e. D1 and D2 are for ring geometry -> Conclusion: There is no advantage of removing the corrector at Q3 as here the space is not as critical anymore, however length of triplet orbit corrector maybe re-discussed (Rudiger/Oliver)
  - Guram: Inner layer QH will be tested for 11T: Frederic: Plan to fabricate a model with QH this year. Implanted already in between 2 coils but never tested. Guram: If we consider this for magnets we should test this asap.

HL-LHC circuits: Global view and open questions – Felix Rodriguez Mateos

- Within the scope of this conceptual review
  - The powering schemes to fulfill the requirements with respect to beam operation at a conceptual level (this is a CDR)
  - The instrumentation and protection means foreseen in the magnets
  - The protection means foreseen at circuit level
  - The integration aspects of the foreseen hardware in compatibility with the infrastructure
  - The appropriateness of the proposed utilities and infrastructure (cabling, cooling & ventilation)
  - The strategy for the electrical quality assurance of circuit components
- Studies required for optimization extend to protection, compatibility, dependability (recommend that this is part of each components design from early phase), simplicity, saving
- To come later: electrodynamics aspects in sc link, compatibility of CLIQ wrt to design of sc link, feedback from individual component tests & manufacturing (magnet/link/leads) will be of paramount importance

HL-LHC circuits: Global view and open questions – Felix Rodriguez Mateos (2)

- Summary of proposed main changes
  - It is proposed to reduce the number of main inner triplet circuits from 2 to 1 per IP side. This has implications that will be discussed later in several talks (E. Ravaioli, J.P. Burnet)
    - This circuit will have no energy extraction system
    - 2-quadrant converter is required
    - Three trim circuits are required
  - It is proposed to remove energy extraction systems from the closed-orbit dipole correctors of the inner triplet
  - It is proposed that the super-ferric magnets get low voltage extraction within the crowbars of the converter (compatible with the PC limits)
  - Only exception is the quadrupole corrector for which a standard 0.7Ohm/600A extraction system can be envisaged
  - D2-Q4 orbit correctors would not require quench heaters
  - Q5 orbit correctors would not require quench heaters
- Discussion:
  - Guram: Is the TDR V0 available? Markus has distributed to all reviewers
  - Rudiger: Will we have a an overview of the different converter types used?
  - Akira: Is the new proposed topology for the triplet similar to the current one? Yes for topology, but currently 2 high current converters. To be followed up in more detail!
  - Akira: More reasonable to put in series and have a trim?! Felix: Not proposed but will be presented
  - Ezio: D1/D2 trim due to different magnets, for triplet because magnet production will not be ideal

Integration of powering and protection system – Paolo Fessia

- Trim for 11T would be 600A
- Double decker: 1 new UR tunnel, 2 UA, then big US/UW and PX
  - Main issue is with excavation partially during operation -> test with shaker between 4-100Hz
  - If excitation frequencies match mechanical structures of machine, vibration will effect the beam
  - Mitigation: Bring big shaft far away from most sensitive part (triplet) and optimize planning (shaft in 2018, major underground excavation during LS2)
  - Constraint: Envelope of underground structure has been fixed 26/02/2016, drawings now handled by contractor for final design – modifications up to 2019 possible but much more expensive – What is the risk if the schedule slips further?!
- Cryogenic distribution + CC powering + powering: through shaft and then distribution downstairs. Asymmetry for cc powering an issue?! 1 free duct from each UA down to the machine for instrumentation and cabling
- Powering system symmetrically arranged between two sides
- Several modifications wrt to baseline already in integration (1 triplet converter, smaller corrector ratings,…)
- Quench Heaters: Would populate the UL(557) where current R2e relocated equipment has been placed + RRs.

Integration of powering and protection system – Paolo Fessia (2)

- Example of installation constraints: sc link
- Discussion:
  - Guram: space installation for 11T converter and trim to be confirmed
  - Oliver: Feasibility of installation of sc link will be studied? Amalia: there should be time to do validation test at room temperature, i.e. check as well electrical integrity?
  - Davide: Service tunnels seem extremely crowded?! Do we still have the choice of discussing option of 2 power converters in terms of space? What about accessibility of equipment for maintenance?!
  - Rudiger: Already some decisions taken that are not in the baseline – volume is one thing, but what are really the compromises already taken?! Paolo: Mostly volume, but also shaft diameter has been reduced to 10.5m, still should be able to bring down all equipment without modification
  - Markus: Connectivity of nc cables to DFB? Circuit separator (already discussed for LHC) to avoid forces on CL?!
  - Davide: Who is working on the connectivity of the sc link and DFB (Amalia will come back to that)
  - Ezio: Contingency in rack space considered? Paolo: Yes taken into account, but no big margins (pushed by project)
  - Rudiger: People can access during beam operation and HWC – how do you deal with safety issue (helium release) – Paolo: RF gallery blocked, eventual safety exit down to LHC
  - Akira: Did RP people already agree to this proposal? Paolo: Simulations done for worst case: 2mSv/person, operational case much less. Air: doors to decay air + overpressure
  - JP: Limitation of space: Design is based on the use of sc links, hence EPC will have to change the design of the power supply (due to the higher power/voltage)

SC Links – A.Ballarino

- SC link is component of cold powering system (new system, relying on new sc material)
- Optimization done in 2015 to reduce total conducted current, resulting in a total of ~ 70kA . Total for HL-LHC is transport of 2x500kA with 344 leads and sc cables
- 8 cold powering systems in total, with two major types (DFX and DFM)
- Everything designed for electrical withstand of 1-1.5 kV in nominal operating conditions (includes protection scenarios)?
- CLIQ would be fed by its own system
- In case of quench, discharge would have to happen with time constants of 3-6 seconds (with CLIQ/heaters even much faster)
- Launched procurement of 80km of wire (units lengths >= 500m), first large procurement, already 60km at CERN, 20km to be delivered by end of April 2016, next step is to make cable
- Cable expected to have diameter of 65mm, 11kg/m, then integrated into flexible line (4 subsequent shields/enclosures) – few spare wires foreseen in cable
- Discussion:
  - Rudiger: Each HTS link it's own cryogenic enclosure and VAC, i.e. 344 flexible lines with 44 per box?! Complexity and cryogenic/vac distribution to be studied in more detail, What about safety?
  - Arnaud: Why not using MgB2 up to the bottom of the CL? Amalia: not as mechanically stable as HTS, ease of connectivity

SC Links – A.Ballarino (2)

- 100mV detection threshold as baseline, 15 MIITS as quench capital before detection
- SC link assembly: bending radius of >=1.5m, diameter < 300mm
- Protection should also include the splices/joints between MgB2/NbTi, needs for sc leads ~ 1 - 5mV with integration times of 100ms
- Program and schedule: Till beg 2018 construction and test of prototype (80m long sc link, horizontal test in SM18 triplets and later MS) called phase 1; 2018-2021 series production (phase 2); 2021-2023 test and validation of series production (phase 3) -> See slides
- Discussion:
  - Arnaud: R&D on joints between MgB2 and HTS joints – Amalia: Well aware that this is critical point, setting up team to look at cooling and quality of joints
  - Protection of sc link and HTS connection to lead is separate (confirmed by Amalia)
  - Voltage measurement growing during a quench along a length of ~ 10m – does noise grow along the length of the cable? Amalia: Being looked at
  - Davide: If forced to increase detection threshold to 200mV, what would be the implications? Amalia: No final answer, would have to re-work the configuration of cable in terms of stabilization part
  - Laurent: What about the link between the DFB and the standalone magnets (Q4, Q5, Q6), no details yet!
  - Oliver: What will be transported into the tunnel? Amalia: Ready made cryostat , but surely has t be leak tested once installed,…

SC Links – A.Ballarino (3)

- Discussion (ctd):
  - Rudiger: Voltage taps, where and how integrated?! Amalia: Not yet studied in detail, but to be brought up in IFS box
  - Akira: In sc link we always need to minimize joints , would appreciate more detailed information? Ezio: Indeed additional element, will we have a reliability study?!
  - Markus: When will we have a prototype of the flexible lead. Amalia: For end of year with 2x 20kA leads with flexible connection, then later on a full set for IT connections. Leads could still be integrated in different cryostat as well.
  - Guram: Protection of MgB2/NbTi joint part of link protection?
  - Guram: Spare as well for MS? Amalia: Yes will be there as well
  - Akira: What is the real advantage of using MgB2 for link or Nb-Ti? Amalia: With MgB2 full line cooled with gas, simplified cryostat, probably no need of additional screen, more temperature margin (up to 20K instead of 6K). Akira: when using gas, cooling is more difficult , however Amalia replied that MgB2 enables a big temperature margin
  - Paolo: Also a safety issue to avoid liquid helium. R. van Weelderen – no big difference in terms of used liquid (as both are super-critical He)
  - Paolo: What would be the overhead if we put the same cable in both sc links? To be studied…

Busbar integration in the cold masses – H.Prin

- Discussion on internal vs external splices being studied – final proposal is combination of both options, with the 18kA busbars being internal, all other ones external
- 3 options for the D2: all connected on QQS side , or intermediate
- Q4 similar to standalone in all aspects
- Q10 with MS: Design almost completed, perfectly feasible using external busbars from Line N
- 11T dipole: Internal connections as for present dipole, foresee change of screwed connection
- Connection cryostat to integrate collimators for ion physics debris in IP2
- Need detailed electrical scheme to agree on baseline, proposal made based on proven techniques for splices,… internal/external splices is compromise between feasibility and total number of splices until a 18kA cable has been developed.

Busbar integration in the cold masses – H.Prin

- Discussion
  - Akira: D1 is one of the simplest magnets as directly connected to DFBX interconnect. Herve, simple to connect, however the passing busbars are the concern
  - Davide: Many ideas but a number of options still open – is there a specific issue for which the review should provide an answer? Herve: Bringing most of busbars external brings additional complications, Additional Q4 busbars (today feeding the D2) which will become the Q5 – what to do with these busbars
  - Ezio: Routing of orbit corrector busbar has to go through the Q2?

CLIQ System – E.Ravaioli

- CLIQ provides effective heat deposition wrt to conventional technology based on thermal diffusion
- Fast and homogeneous quench initiation
- Lower hot-spot temperature
- Disadvantages
  - Requires additional current leads
  - Energy deposited very homogenously in the coil
  - CLIQ connected directly to main circuit
- CLIQ configuration, much dependent on position of CLIQ unit
- Discussion
  - Guram: CLIQ proposed for redundancy, ca the system hence be optimized to work both for low and high current? Emmanuele: System could be optimized for both, but if dimensioned for high current it will also work for low current, even if more energy than required is deposited.

CLIQ System – E.Ravaioli (2)

- Discussion (ctd)
  - Akira: How to design redundancy of connection into the magnet, is it needed? Emmanuele: Very low likelihood that this connection can fail, as it is done in a very similar way as the normal internal magnet splices. Lucio: CLIQ connection much more robust than thin wire to QH
  - Davide: Do we want to study and implement both options if we believe that one of them is sufficient for protection? Emmanuele: CLIQ will deposit more energy I the inner layer and mid plane, QH will quench the outer part, so the combination of the two allows to reduce the hot-spot temperature
  - Amalia: System not yet fully studied for propagation on AC signals in the system (i.e. that it perturbs the rest of the system)
  - Rudiger: Redundancy does not necessarily mean that both systems are operational in parallel, but rather that CLIQ could take over in case of QH failures

11T dipole protection - Susana Izquierdo

- 11T has around twice the stored energy / m3
- In Nb3Sn, voltage spikes at low field are typically observed due to flux jumps
- Baseline is 100mV/10ms – important to keep, as each 10ms in addition will mean 40K additional in hot spot
- Each coil is protected with 2 quench heater circuits on the outer coil radius (HF & LF), magnet is self protecting up to 1.5kA
- Baseline protection scheme, using 31 voltage taps/coil in short model, for prototype also additional tap between inner and outer layer
- For series magnet, each coil will have four voltage taps for internal splices and 8 channel comparison for symmetric QD
- Each aperture is protected with 4 QH circuits, 2 heaters per coil only in the outer layer
- QHDS charging voltage 900V, using 150A instead of 80A, reducing heater firing delay from 5ms to 1ms
- Proposal of putting in series HF and low field heaters , with draw back un unequal voltage distributions in case of heater failure

11T dipole protection - Susana Izquierdo (2)

- HV in case of heater firing (with failing heaters) define limits of worst case scenarios
- Discussion
  - Davide: Between flux jumps and CLIQ the electromagnetic environment seems challenging -> Reiner: Will be discussed tomorrow
  - Rudiger: Flux jumps: Length will also make a possible impact , any studies done to simulate how this scales with length? Susanne: Not yet

11T dipole circuit- Samer Yammine

- Current dipole circuits, 154MB, 15.7H, 1mOhm of R_tot, 2 x 70mOhm EE
- Main issue is coupling between main circuit and trim circuit with 4 quadrants
- Trim voltage is limited to minimize impact in case of instability (+-5V)
- From controls point of view the two circuits can be considered decoupled (very minor cross-talk)
- Current dependent interlock (not dump in case in Stable Beams)
- Proposal is for 100mOhm of serial resistance through choice of cabling and positioning of the trim power converter
- Discussion
  - Manuele: Seemingly the failures induce current oscillations , was it studied what kind of voltage oscillations this implies? Lorenzo: This was studied at the beginning of the transients, showing the potential triggering of some iQPS crates during the transients, but simulation are very sensitive to the input parameters (which are in additional evolving in the tunnel). Worst case failure might be intermittent failure where 1.2 – 1.3 kV can be reached
  - Bernhard: Study also shows that without the 11T some iQPS might trigger, so not as bad as such
  - Rudiger: What about having two diodes in series over the two 11T halfs?
  - Davide: Do we have other options? Samer: Power 11T individually – Can we live without the trim? Gianluigi: Not desirable as using corrector strength, 1 slide to be presented tomorrow

D1 protection aspects and instrumentation – T. Nakamoto

- 150mm aperture, 35Tm, 75% operating point, NbTi LHC MB outer cable
- 135W in total, radiation does > 25MGy
- Initial concept of the quench protection was a 75mOhm dump resistor w/o heaters, until May 2015
- After C&S review in march 2015, baseline was changed to protection by heaters w/o dump resistor
- July 2015m tentative heater design was adopted for the 1st model based on the experience of the MQXA
- Protection with standard LHC heaters, 2 heater circuits in magnet with 4 heater circuits in the magnet
- Heater tests planned for the 1st 2m model from 500A (injection) to 12kA (collision) + some tests at ultimate current
- CERN proposed inclusion of additional heaters in HF region, difficulty of increased length for magnet test at KEK, CERN also proposed extension of SC lead at mid-point for possible implementation of CLIQ in future
- Difficult to place the QD voltage taps for asymmetric quenches in the D1
- Discussion
  - Davide: Protection scheme may depend if the D1 and D2 are powered in series
  - Felix/Bernhard: Should not change the protection scheme for individual magnet
  - Ezio/Luca: Common problem to all NbTi magnets, seems to be a problem with a magnet brand, will deserve dedicated discussion

IT magnets and protection – G. Ambrosio

- MQXF foresees protection with heaters and CLIQ, in these slides showing failure scenario of non-working CLIQ
- Quench protection plan: No EE, 6 CLIQ units, LF heaters only as backup
- Planning for 4 V-taps per coil, 2 VT per lead around Nb3Sn-NbTi splice
- 6 independent heater strips (outside stainless steal with copper plating, inner layer Zig-Zag, reducing copper between heaters pads to maximize heat extraciton
- HQ02 quenched many times, including many high temperature quenches (up to 400-500K) without heater failures
- Heaters have been design and optimized by collaboration between CERN, LBNL and Tampere University
- Without EE the MQXF magnets need active protection also at low current (<=1kA)
- Plan is to keep hot spot temperature below 350K in normal conditions
- Only with No CLIQ and no IL heaters (hence only OL) the hot spot temperature stays below 347K
- Similar result for peak voltages, have to avoid half coild failure, only OL or 1 coil failure
- Conclusion: QH protected the MQXF magnets and provide redundancy to CLIQ system
- Heater design can be adjusted to protect MQXF at low current
- Exploring option of keeping some heater strips disconnected and used as back-up

IT magnets and protection – G. Ambrosio (2)

- Discussion:
  - Davide: If we have already OH and CLIQ, why still IL?
  - Ezio: When simulations were initially started, situation looked more worrying, hence all options were explored (IL, OL, intra layer and CLIQ). May look like we are overdoing it?!
  - Guram/Rudiger: Need to define how this redundancy is used? Do we always install and connect everything or do we keep it on standby?

IT circuit – E. Ravaioli

- Warm diodes preferred over parallel resistors in order to avoid bypass current
- What happens if polarity is wrong? Only voltage distribution or also efficiency of protection?
- Discussion:
  - Davide: Is plot in page 9 the total voltage including the voltage of the local developed quench? Emmanuele: Yes
  - Davide: On what subject would you like to have some feedback? Emmanuele: Ideally on the level of required redundancy, as we have options not to connect certain heater strips
  - Torun: What if the heater turn on time is delayed: Emmanuele, not of primary concern, as one would need several 10s of ms before the build up voltages become too important.
  - Akira: Doubling of triggering part is also important. Emmanuele: Indeed one could consider keeping the triggering of CLIQ and heaters independent, but one has to keep availability in mind. Reiner: Foreseen at the level of the trigger generation as well
  - Rudiger: We have experience in quantitative modelling, should be done properly for such a complex system
  - Emmanuele: Current mitigations are special connector per polarity, and possibility to discharge at 50V
  - Akira: Diodes will not get energy of the magnets, but only takes the difference of the magnets during extraction (for a few 100ms) -> Do we need water cooled diodes, maybe better not to use if not needed?

IT circuit – E. Ravaioli (2)

- Discussion (ctd):
  - Arnaud: What would be the proposal without CLIQ? Emmanuele: Still one supply with OH. Might need an overview table.
  - Guram: Page 14: Suggested scheme for QH configuration is contradictory to 11T proposal. Emmanuele: 11T is a dipole, triplet is a quadrupole -> Could be analyzed more thoroughly
  - Rudiger: Quench back – do we always take it into account? Is it the same mechanism as CLIQ or not?
  - Emmanuele: From protection point of view the two options are similar
  - Oliver: Motivation of single circuit with 2 quadrant power supply is also a motivation
  - Davide: We should be prudent to add a novel technology of protection – what is the real added value: Emmanuele: Hot spot temperature + possible redundancy
  - Arnaud: Question of risk is to be addressed and benefits of solution have to be clearly weighed against the additional complexity (additional leads, …)
  - Ezio: One importnat point is as well the likelyhood of the magnets to quench in the String. How is interlocking and protection being done: Indeed we currently intend to quench all magnets
  - Giorgio: Main argument is possibility for redundancy
  - Rudiger: Size of lead is around 10mm2 of copper, with 2 per magnet -> Rudiger: When do we have to decide on the integration of CLIQ, during magnet design?!
  - Paolo: CLIQ unit will be installed in new gallery, hence preventive maintenance possible
  - Andrzej: Remember that IL have a impact on heat transfer on main channel
  - Davide: If we decie to put CLIQ and the heaters, then why also the inner layer heaters (as they also represent a risk of shorts to ground,...). Do we believe that only with OL heaters are not sufficient?

D2 protection aspects and instrumentation – P. Fabbricatore

- 35Tm, 105mm aperture, 140m from IP, 70m from D1, 188mm beam beam separation at cold
- Magnet is design in collaboration between CERN and INFN (called MAGIX)
- 4.5T magnet of 7.78 m, working at 35% of load line
- Main challenge with cross-talk between apertures
  - Mitigation: Asymmetric coil, yoke has a window and is slightly elliptical, single power supply for the two apertures
- Protection
  - Currently considered as a standalone magnet, D2 is a heater protected magnets
  - Same heater design as LHC dipole, 900V, 122A
  - Very similar scheme as for 11T, 8 circuits formed by 2 heaters each (4 per aperture)
  - Detection threshold 100mV, after 58ms the QHs have quenched the 8 blocks with maximum delta T of 220K for quenched turn
  - Peak voltage to ground is 2kV, but has to be reviewed because of pessimistic assumptions, with 2 QH circuits off one may reach 350K
- Construction of 1.5m short model might start end of this year
- Discussion
  - Guram: Using 4 out of 8 QH circuits only. Answer: All heaters will be wired and ready for use, however the 4 HF heaters would be enough
  - Felix: How did you achieve 2kV? Akira: Not realistic as always both sides will quench, not only one side. Answer: Yes, probably well below 1kV

Discussion on D1-D2 circuit configuration – F. Rodriguez

- Alternative powering of D1 and D2, using a single power converter per side and IP
- Circuits protection wise decoupled due to use of diodes, warm busbar bridge in gallery and rather short
- Currently no proposal to change the baseline
- Discussion
  - Loss of flexibility for commissioning
  - Rudiger: What is the driver of this idea: Felix: Cost saving for power converter, Lucio: Missing comparison , also missing e.g. comparison of reliability?

Triplet orbit correctors– F. Toral

- MCBXFB, nested corrector, and high requirement for radiation resistance (28MGy), nominal current <2.5kA (as cable geometry is fixed due to use of existing cable)
- Slight difference between long and short magnet, low working point to gain margin and mechanical stability for to variable field vector (magnetic field depends as well on powering of 2nd nested magnet)
- Protection strategy
  - Nested dipoles are in quadrature, hence no mutual inductance, high self-inductance due to small cable and large aperture
  - Simplest would be crowbar extraction, EE system has high cost, quench heater assembly is challenging because of complicated support structure of nested magnets
- SQUID code used for quench simulation (CIEMAT). Assuming a maximum crowbar voltage of 50V (0.03Ohm), hot spot temperatures would reach >350K for the long magnet, quench heaters seem necessary. A priori not needed for short one, but due to connection via sc link this might still be advisable
  - Final decision still pending, but seems likely that ongoing short prototype will be equipped with heaters
  - Detection thresholds 100mV and 10ms
- Protection with heaters much relaxed, somewhat higher voltages (700V wrt to 500V), but hot spot temperatures limited to 120K
- Orbit corrector not a high field magnet but nevertheless challenging design
- Quench simulations to be compared to upcoming measurements

Triplet orbit correctors– F. Toral (2)

- Discussion
  - Davide: Should high cost of the switch be the driving factor of the decision? Ezio: Recent C&S review brought a big change in baseline, removing the EE systems in most circuits. For this current level the risk has to be balanced with the additional development (Felix/Rudiger: Mostly a resource issue rather than a technical issue). Andrzej: Would not withdraw the solution of a switch at this moment in time, as resource investments are similar. Ezio agrees to complete the assessment and then decide
  - Daniel: Space reservation has been kept for the time being if finally EE is retained
  - Fernando: Simulations with EE were done, 0.3 Ohm was a sufficient value
  - Bernhard: Comment in placement of quench heaters. Fernando: Indeed the simulations shown with QH only take into account firing the QH on one of the magnet – Magnet is still protected even if only half of QH circuits would fail
  - Akira: What is the point of view of the project? Felix: QH have proven reliability, switches represent high effort in term of maintenance
  - Guram: 4 heater strips per coil, 8 per magnet : A lot of redundancy
  - Paolo: Do we really need to impregnate the heaters with the coil? Might give more flexibility for assembly if we have problems with heaters? Fernando: to be discussed in more detail
  - Jens: Instrumentation should foresee mid point to facilitate protection

Triplet higher order correctors– G. Volpini

- All magnets currently foreseen with a nominal current <200A, magnetic length between 100-800mm, apart from MQSX very small stored energy
- First sextupole successfully tested last month @ LASA, no training quench up to nominal and even tested up to short sample limit at 4.2K
- Operating current currently chosen on the basis of the wire available
- Request to reduce current to <=120A to comply with existing power converter, i.e. to 105A to keep margin for ultimate
- No QH foreseen (only spot heaters for prototype test), quench studies performed with QLASA
- Issue with reduced nominal current is high number of turns, and hence higher voltages to ground in case of quenches – still feasible but more challenging for design and construction
- Simulations and experimental results are sometimes different, still more work required to understand the differences -> Do we need to understand differences across tools?
- Prototype status: Sextupole tested, octupole and decapole in executive design, dodecapole and quadrupole in conceptual design
- For quadrupole would prefer to stay with 182A: Possible for EPC, but more cost & space efficient to use smaller power converter modules
- Case of quench in sc link, magnet energy might be dumped in

Triplet higher order correctors– G. Volpini (2)

- Discussion
  - Rudiger: lost 3 circuit in point 2 during injection event, should we increase in view of HL the understanding of this event?
  - Different quench codes: Bernhard: WP7 will provided independent validation of each problem with different code, as long as experimental results confirm simulations we can be confident with simulations

Operation requirements – M. Giovanozzi (2)

- Request for LHC, tune ripple requested to be <10E-4 for beta_max of 4.5km
- HL-LHC, beta_max may reach 217km for round optics, 43km for flat optics -> new regime to be explored
- Try to reach beta* error (important for performance reach), should have a tune ripple in the order of < 1 E-5
- Two control regime to be considered, I control for f<0.1Hz, V control for >. 0.1Hz
- Series powering has advantage in terms of total tune ripple (factor 2-2.5 wrt to current powering baseline), assumption of Class 1 power converter (+-1ppm)
- 300 and 600Hz frequencies are most significant for degradation of dynamic aperture (DA)
- D1-D2 powering: Class 1 power supplies required, which makes added tunes shift negligible even for independent circuits (still factor 10 below triplet)
- ABP wants to separate geometry and orbit correction, but no big performance advantage for single circuits
- IPQs: Q4 situation relaxed through recent baseline change of magnet (lower current, higher inductance), still request for Class 1 converter
  - High beta options not retained for HL-LCH era, therefore 3 lead scheme seems also suitable for HL-LHC – for ABP even single converter with trim would be valid (2kA trim would be sufficient), but would have to be validated against all optics variants
- Power converter type for Q5 and Q6 remains to be defined (ripple study)
- 11T: Main difference in transfer function is at 3.5TeV, hence highest trim current at this value

Operation requirements – M. Giovanozzi (2)

- The difference in TF generates a bump of 2 cm, either solved with local correction (trim) or global correction with several magnets (loosing 5 sigma of aperture, and about 40-80% of corrector strength, and a bump of around 1.5mm will develop during the ramp, including collimation region). This option should be developed in more detail
- Operation for L=5E34: Pre-squeeze time currently estimated to 826s, Q5 circuits are the slowest, global ramp-down chart shown, all circuits should (and currently do) stay within the ramp down of the main dipoles
- Discussion
  - Akira: D1D2 LR means a connection across the IP, eventually requiring a sc link
  - Davide: What is the difference in terms of cost of a class 1 and class 2 converter? -> Next talk, Miguel: Input to simulations are baseline parameters, actual performance is different and might be a better (especially for Class2)
  - Oliver: Analysis of all failure studies done, e.g. D1 vs FMCM? Markus: Will come in WP7 and less critical due to sc magnets
  - Luca: How much of current corrector strength is used in this region? Massimo: Could work out a solution using > correctors and limit to 50% for a given circuit, but then additional correctors need to be interlocked
  - Arjan: 1ppm current does not always mean 1ppm in field – is this considered? Massimo: For simulations we use 1:1, clearly pessimistic, currently not better measurements available
  - Rudiger: Coll in 11T critical during ramp? Massimo: Tbc with Stefano, but normally open

Power converter and operational aspects – J.P. Burnet

- New HL-LHC triplet requires a doubling of the DC current delivered to the current LHC triplet (from 230kA to 460kA)
- Present triplet is most complex powering scheme, due to coupled controls requiring a special electronics 'decoupling matrix'
- Not trivial to have a 1ppm control for nested circuits – current triplet works perfectly but MTTR + time for fault finding much higher than standalone circuit
- Circuit layout optimization needs to take into account beam optics, tune shift, squeeze and ramp down time and magnet protection
- Impact of sc link
  - Different to current LHC, feedbox will be very close to converter, dividing by a factor of 5 the cable resistance – with current baseline the ramp down time is getting too important, hence a new generation of 2Q converters is required
  - With 2Q converter, the ramp down can be actively controlled at -14A/s by applying a negative voltage , main topic will be energy management (could use e.g. batteries for intermediate energy storage)
- D1-D2 in series: Estimate no saving, but just more manpower and complexity

Power converter and operational aspects – J.P. Burnet (2)

- Discussion
  - Lucio: inner triplet is more complex than HL-LHC, as the new triplet is much more similar in terms of main magnet design and the trims are much smaller
  - Oliver: Ramp down without beam. So why care about precision: JP: Yes but then when re-starting the magnetic history will be very different
  - Davide: 11T option: what is the difference in terms of cost and effort: JP: problem much smaller as big decoupling between the trim and main magnet (hence no decoupling matrix needed), hence no pbm to add a trim to the 11T
  - Knud: Energy efficiency is becoming a priority for CERN, hence 2Q converters are the right direction
  - Paolo: What about 1 PC and trim for Q4-Q6. JP: If using the trim, we will have two magnets of same size as the trim and main circuit will influence each other, hence again decoupling matrix + additional complexity required. Lucio: Everything should be looked at objectively based on the new baseline for Q4
  - Hugues: In case of internal power converter failure, how do we decrease the current for these high inductance circuits?
  - Akira: Why is the triplet so different from D1-D2. JP: If connection is done in the warm part then the effort is comparable
  - Amalia: short DC cable impacts, what about extra resistors instead of nc cables

Matching section correctors – G. De Rijk

- Integrated field 5 Tm, current <=600A, possibly 5.5 Tm, magnetic length of 1.92m, aperture 105mm, beam distance 188/194mm, 75kJ/aperture, self protecting magnets with Cu/sc ~ 3
- Correctors have to adapt to the differences in yoke between the Q4-Q6 magnets
- Busbar connections (external needed due to winding of winding with rectangular cable in 6 layers)
- Sc wire for demonstrator will be LHC wire No3, however Cu/Sc ratio not enough for self-protection (final wire will have to be different)
- Aim of hotspot temperature is to have it well below 250K in case of quench
- Discussion
  - Ezio: Canted magnet will be a prima in a an accelerator. Due to low field this is an interesting option, other big advantage is simplicity of design and cost of production
  - Guram: Cable is single (no spliced on the outside)
  - Davide: Circuit wise any issues or everything is clear? Gijs: Fully self-protecting magnet makes circuit design much more easy
  - Rob Van Weelderen: Not advisable to go through the lower heat exchanger tube, as D2 will have a high heat load already, so cross-section may be required for heat exchange

Quench Detection – J. Steckert

- QD challenge is to find a small resistive voltage in a large inductive signal, need to compensate inductive voltage and suppress noise
- Importance of appropriate instrumentation to achieve good compensation
- Sc link protection:
  - 100mV with 3s evaluation time (margin to filter noise)
  - Splice monitoring needs to be discussed and clarified
- Improvement of controls system (bandwidth, logging rate, remote firmware update)
- SM18 as important test bed for final units
- Discussion
  - Guram: No backup options mentioned, what if main system fails? Jens: No backup but redundancy can be studied.
  - Guram: Location of electronics at similar distance of current system? Jens: Currently around 100m of distance, will be similar to current system
  - Rudiger: Voltage taps are essential for the correct protection, exchange has to be efficiently done between magnet and protection people.
  - Reiner: is taking place, recently done for 11T
  - Bernhard: Is there an estimate on the effect on flux jumps and potential requirements to increase detection threshold? Jens: Hard to predict, already currently we have IPQs which behave very differently…

CLIQ & QHDS – K. Dahlerup Pedersen

- Current QHDS is a robust but non-redundant design (redundancy by multiplication of circuits and selection, i.e. crossing), failure rate only 2 per mille/year (i.e. 10-12 cases/year)
- Longevity of super capacitors to be further investigated
- Upgrade of trigger board would gain 2-3ms in terms of turn-on time
- CLIQ comes with certain safety measures due to high stored energy and voltage
- CLIQ is redundant to a large extent, including the triggering circuit; redundancy of trigger source (from QD system to be clarified).
- First generation of CERN-made, industrial quality units have successfully passed type testing on dummy and real sc loads
- 2oo3 units are currently at Fermilab
- 2nd generation will feature multiple charging levels and five different capacitances, will be first version with full redundancy of the trigger application (from input to output including doubling of the thyristors)
- Discussion
  - Guram: If one can control the load for QHDS and CLIQ . Andrzej: Currently we do not have a real online monitoring system, however every discharge is now automatically analyzed to detect pre-cursors. Luca: indeed we recently opened a magnet where the heater circuit was shorted with the magnet at the level of the omega, apparently discharging into the magnet

CLIQ & QHDS – K. Dahlerup Pedersen (2)

- Discussion
  - Jens: Trigger for CLIQ is active low? In case of power cut we would discharge the CLIQ system? Knud: Indeed but inly for test system
  - Ezio: Both QHDS and CLIQ have energy storage, for QHDS it is in the order of kJ, for CLIQ some 10s of kJ.
  - Ezio: There is no big difference between a QHDS and CLIQ. Knud/Felix: Prototype probably a factor of 5for prototype in terms of price, but not expected for series production. A QHDS is around 3kCHF, for the first prototypes of CLIQ it was 15kCHF
  - Davide: Study already done to route the CLIQ wires safely out of the cold-mass? Herve: All CLIQ cables were on the top line of the cold mass, routing them up to the DFX and get them out at this level. Option would be to do this at each cryostat (using conduction cooled leads for which we currently do not have the space)
  - Akira: Should do a reliability study of the CLIQ system, also assess e.g. pre-series production experience. Andrzej: indeed this is planned for SM18, where 30 units have been foreseen
  - Davide: Can all CLIQ units be placed in the gallery. Yes: If placed in the gallery far away, but cross-section has to be adapted, but could be consequent. To be worked out.

DC cabling – L. Tavian

- Sufficient elevation between connection on DFHM/DFHX and cable trays has to be foreseen
- 18kA currently foreseen with 2x1300mm2
- All cables with fully halogen free hoses
- Fixation system for cables separated from leads?
- Some 500kW of resistive losses in DC cabling for IP1 and IP5, 580kW for ultimate and 740kW for rated
- Air cooling capacity from 38 to 43kW depending on operating conditions
- Discussion
  - Additional validation tbd before final choice of DC cable cross-section, i.e. compatibility with total voltage from converter for resistive voltage drop and boost voltage (driving didt)

ELQA and HV withstand – F. Rodriguez Mateos

- HVWL working group active since last year
- Based on LHC experience, aim is to engineer a common strategy for HL-LHC circuit components
- Worst case (for realistic failure cases) voltages to ground in QXF are 520V, peak turn-to-turn are 50V
- Testing magnet at 75K, 1 bar to 2x520V + 500V = 1540V should guarantee soundness of electric system for all operating conditions
- For LHC all main magnets were tested at 5kV in dry air BEFORE testing
- Worst case voltages for 11T dipole: teat at 75K and 1b at 3400V, pragmatically 5kV in dry air (confirmed by similar worst case voltage of original LHC dipole = 1.3kV)
- In conclusion, more detailed studies needed per magnet to assess the p & T conditions at which the maximum voltages will occur
- Discussion
  - Felix: In LHC we divided voltage by factor of 5, arriving at 600V, similar strategy might have to be applied
  - Davide: Definition of factors appears elegant and accurate. Important to understand what we test, as the 75K, 1 b means we are exploring problems of ground faults, but not far distances.

ELQA and HV withstand – F. Rodriguez Mateos (2)

- Discussion
  - Approach however does not fully hold, as only e.g. for the QFX we can fully follow the proposed test voltages. For 11T in air the theoretically required test voltage is >12kV, but was proposed to 5kV for practical reason (as the 11T will be integrated into the LHC main circuit) -> consequences are that we have a slightly higher risk for the 11T magnets
  - Davide: Assumption of 520V is coming from the assumption of having CLIQ
  - Davide: Need to define what we use as insulation for QFX magnet, Mica was very successfully used in many magnets in Booster,.. never revealing any problems of insulation
  - Amalia: All other elements in the circuit need to be tested as well – feed-through, busbars,… hence we need to be sure that industry can also test at the same level
  - Rudiger: After shutdown we test again at warm, and at 75K, 1 bar?! Ideally yes, the same conditions should be re-tested if this is possible (certainly in IT, difficult for 11T)
  - Akira: test in dry air does not replace test at 75K as the conditions are different – most representative test is with whole magnet circuit in nominal configuration and conditions
  - Lucio: At some point we have to be pragmatic, as we are already at the limit of technology. Significant as absolute voltage level is also observation of leakage current

MP3 – A. Verweij

- LHC Magnet Circuits, Powering and Performance Panel
- Simplicity of operation and protection schemes should not underestimated, i.e. favor self-protected magnets, simple bridge comparison, separate D1-D2 powering, 3 lead powering
- Experience from LHC
  - Protection of busbar and main magnets should be separated (for correctors can be combined)
  - Splices and joints can be combined with the magnet or busbar
  - FPA in circuit should not trip other circuits due to mutual coupling, especially in sc link
  - Each circuit should have a complete documentation (approved by WPs)
  - V-taps should be fully redundant
  - Sampling frequency of data logging at least 5 Hz
  - QD should be flux-jump insensitive, current dependent QD thresholds and one controller per circuit
- 11T has to comply to ELQA tests at 2.1kV and not impose more stringent requirements on remaining circuit, should not quench or trip during an exp decay from nominal current
- D2 protection a bit easier due to two apertures against half aperture protection for D1
- Inner triplet: no QD/monitoring of individual splices
- QH: Use the same type as in the LHC as much as possible, measure both current and voltage to have early fault detection

MP3 – A. Verweij (2)

- If CLIQ is used, measure the current decay with at least 5kHz and voltage over CLIQ capacitors
- DCCTs for QD with f>5kHz
- Time synchronization of diagnostics across all systems, with accurate data
- Discussion
  - Guram: 11T commissioning at nominal current + 100A. Arjan: For margin in operation
  - Guram: Is there R&D ongoing for MgB2 material? Amalia: Proposed individual protection of each wire/cable in the link is foreseen, but needs to be covered by the QD system
  - Davide: What is the real added value of the individual taps for diagnostics? Protection is always guaranteed by global QD? Arjan: Yes, but for more granular diagnostics it might be beneficial
  - Jens: Might be good for QD to consider the QD taps between upper and lower as the flux jumps seem to be less important there. Arjan: Agrees that more iterations are required

String 3 – L. Bottura

- IT String is part of WP16 for IT String and Commissioning – aiming at a full integral test of the equipment from Q1 till D1 including the DFX, in conditions as similar as possible to the operational ones, including magnet powering and protection
- Timeline: Based on production plan only after 2020, hence eventually 2 phases, 1st phase with prototype magnets and link, then final components in 2nd phase
- LHC had String 1 between 94-98 (6 cool downs, 172 quenches) and String 2 from 2000-2004, focusing on powering and cryogenic sand accelerator relevant operation
- Schedule: Q1 and Q2 prototype will come early, a D1 and CP prototype end of 2019, which could then compose a partial string (without Q3); power converters not yet available, hence interest to place DFX close to current power converters of test benches -> Is there an interest of further reduced string configuration to allow advancing by another year (e.g. without D1)?
- Projected use of current liquefier requires adding an additional 35g/s liquefier for the time of the IT String
- No issue from EN/EL, only infrastructure work; water cooling undergoing an upgrade
- Test result currently foreseen in final configuration in 2022
- Questions to committee: Is the IT String the right test (at the right tie) to validate the integrated system powering and protection? Are there parts of the IT String that are missing or redundant? What tests and instruments are mandatory/desirable to achieve the declared objective

String 3 – L. Bottura (2)

- Discussion:
  - Akira: Final validation tests for String of worst case failures (e.g. power cuts, missing QHs,…)
  - Rudiger: Effects of flux jumps should be better understood well before the IT String, e.g. already during magnet tests
  - Oliver: Vibration studies / mechanical stability to be tested as well on the String, e.g. mechanical alignment system, reinforced feet to damp eigenmodes
  - Ezio: Very important to test as much as possibel early on, important the latest for 2020, but has to be weighed against ressources (and test program on string ahs to be limited, pusing a maximum to individual magnets)

Documentation Plan – R. Denz

- Proper documentation is a fundamental part of any project and should be regarded as a deliverable of its own
- Timely delivery is essential
- Document plan presented
- Current review is expected to validate baseline choices, some R&D already done, hence time to harvest information and compile the ‘Protection R&D documentation’
- Discussion:
  - Lucio: Protection R&D document is a dynamic document that will be updated with current findings
  - Rudiger: Documentation goes across teams, groups,.. someone will have to feel responsible

Roadmap for decisions – D. Wollmann

- First milestone is reservation for civil engineering
- Updated baseline for HL circuits taking into account all relevant constraints
- Very tight schedule, 2.5 years until LS2 and 3.5 years installation of triplet string
- Update of circuit baseline urgently required to derive the detailed parameters, protection needs and failure cases