Availability in view of operation at 7 TeV
…and in general

R.Schmidt

Chamonix 2016

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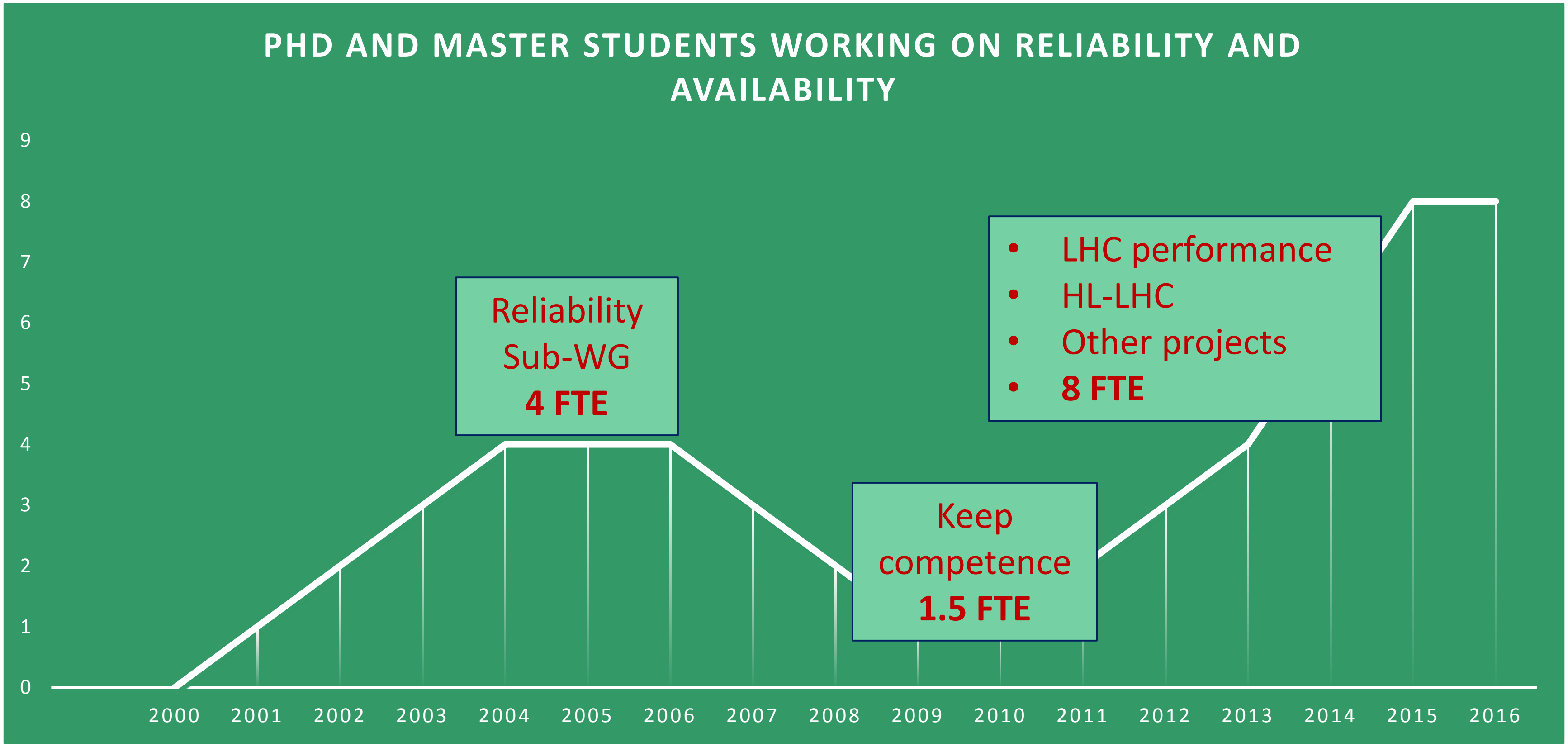
Where do we come from….

- Availability has always been discussed for accelerator operation, at CERN and elsewhere
- Got particular attention when discussing the complex LHC machine protection systems: worries to dump the beam frequently, e.g. if one out of 4000 BLMs has a fault
- Reliability and availability have been taken into account in the design of Machine Protection System
  - Demonstrate reliability, e.g. protection function – when something goes wrong, are we protected?
  - Demonstrate availability, e.g. will the systems allow the LHC to operate efficiently?
  - Coordination of this effort across groups: Sub-Working Group of Machine Protection WG on reliability in 2004 / 2005 (chaired by J.Uythoven)

Resources working on reliability and availability



- The numbers in this figure are somewhat proportional to the effort invested into reliability and availability
- Reliability and availability are closely linked: same methods, same models

Where do we go to…

Operation at 6.5 TeV

- This year and next year(s) collect maximum integrated luminosity

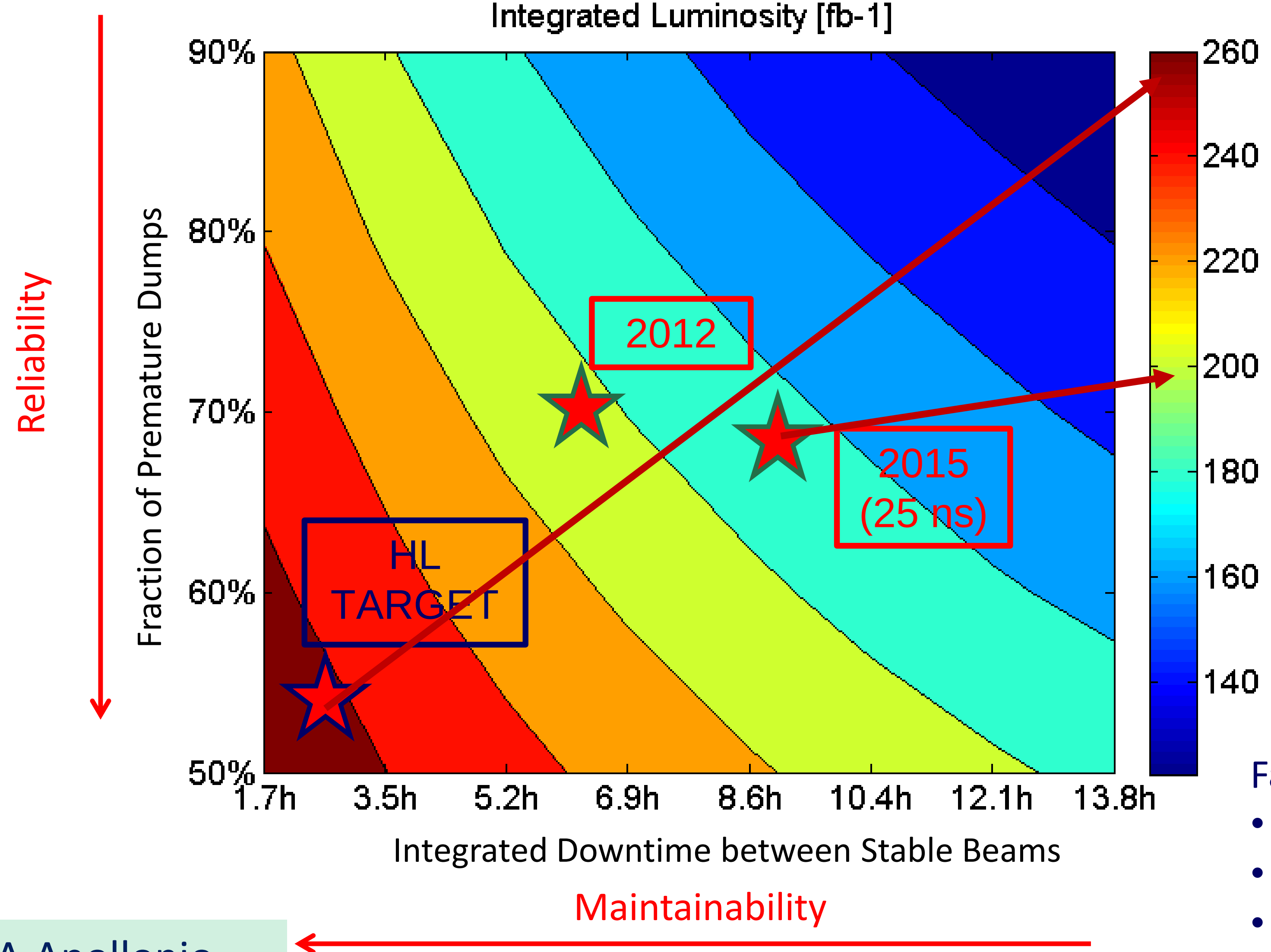
Operation at 7 TeV, the nominal energy of LHC

- Would be of interest to go to this energy, or even higher
- Possibly an intermediate step between 6.5 TeV and 7 TeV

High Luminosity LHC – Game Changer

- Before HL-LHC: to maximise integrated luminosity - maximise peak luminosity
- With HL-LHC: peak luminosity is limited - maximise time in stable beams (already today for LHCb)
    - Might come even before HL-LHC

Sensitivity Analysis: HL-LHC



Extension of running by several years for same target $\int L \cdot dt$

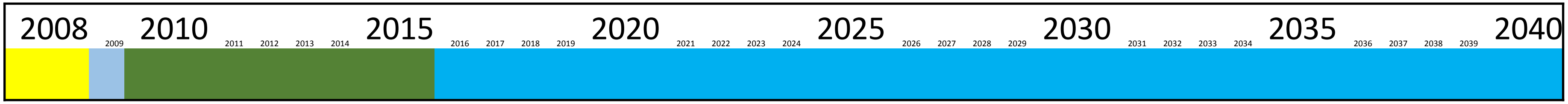
Fault time:

- Diagnostics
- Logistics
- Repair

A.Apollonio

Increasing availability – long term view

- For such complex machine, the availability of LHC today is already remarkably good
- The LHC is a "young" machine, and will be operated for many more years



- Increasing availability is possible by many small steps (no miracles are expected)
- Small improvements contribute to higher availability when integrated over many years
- Improvements that are difficult and costly: might still be worth it, needs to be quantified - side effects to be considered

$\int L \cdot dt$: maximise time for beam operation

- Maximum number of days for physics operation
  - For 2016: 152 days are planned for proton physics and 24 for ion physics (176 out of 365), less than for other accelerators
- Increasing the number of operating hours with beam with a maturing accelerator?
  - Shorter shut-downs or less shut-downs?
  - Very short technical stop over Christmas? Compatible with injectors?
  - Reduced time for “Hardware and Beam Commissioning”?
  - Reduced time for “Intensity ramp-up”?
  - Special runs take time and interrupt smooth operation…..
- Conceivable with an improved knowledge of LHC and stable running
- Not for today and no compromise on protection – but there are a number of ideas that should be considered
- Some hardware and software changes and further automation

7 TeV

Preparation for beam operation at 7 TeV

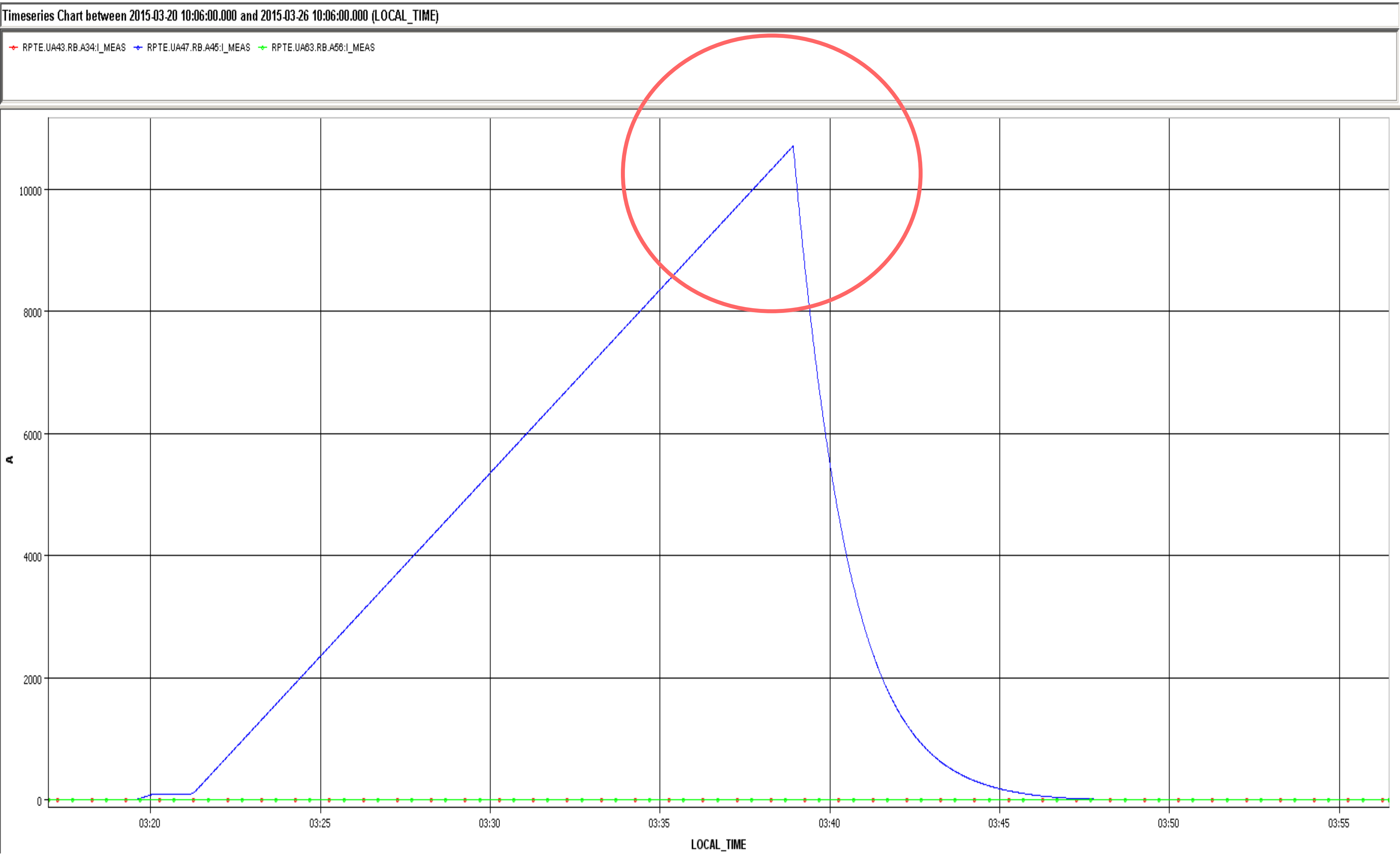
- Dipole magnet training takes time – reduction of time for physics
  - Assume number of training quenches (estimated to 400…700)
  - Recovery from one training quench takes about 12 hours (for more magnets quenching in the same cryo-cell, significant increase of time, for quenches in other cryo-cells, little increase) - two quenches per day per sector, if not too many secondary quenches in the same cell

- There is a (small) risk of damage during extensive training, although the damage is expected to be far less than in 2008

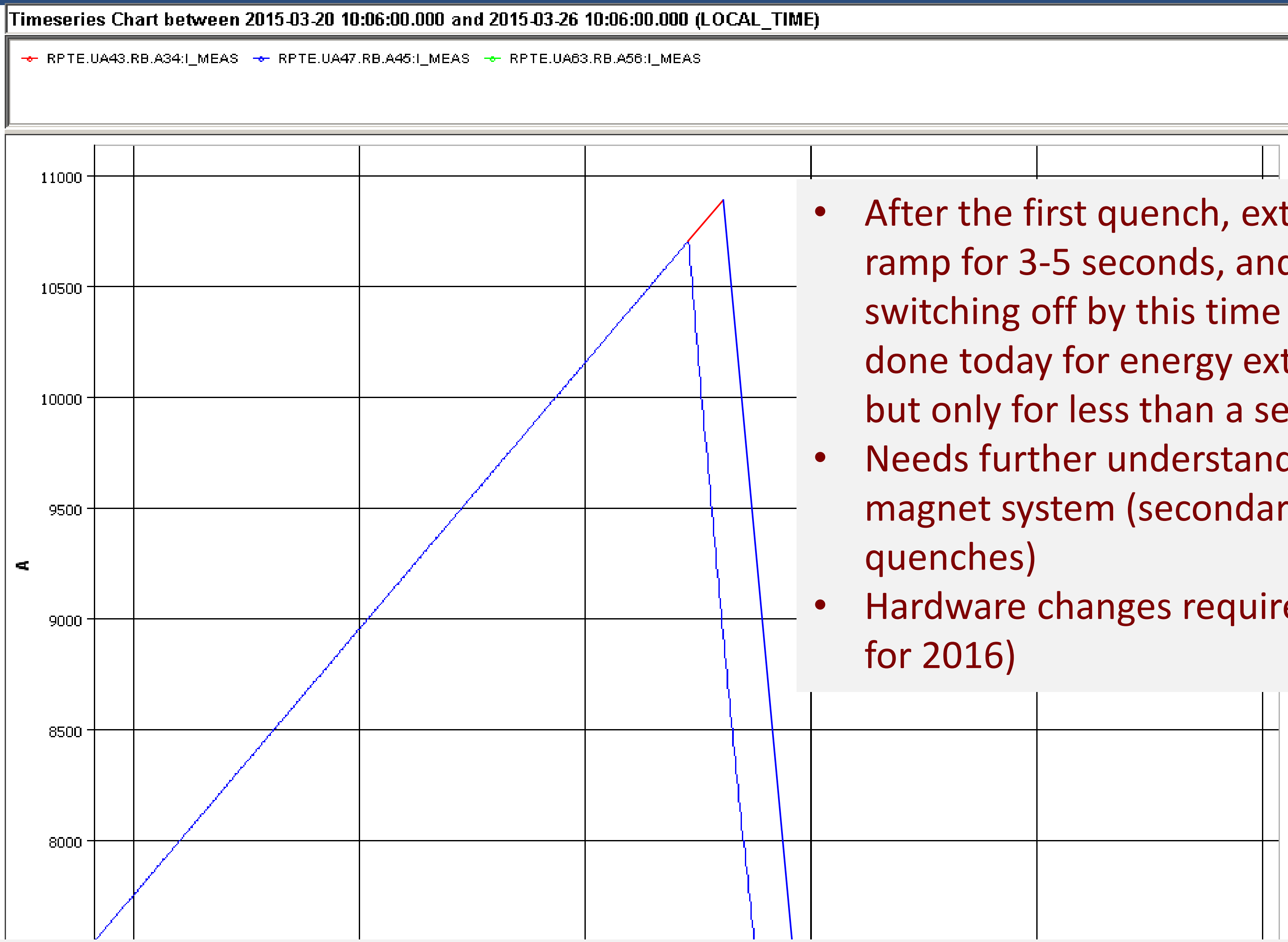
- Number of spontaneous quenches at flat-top might increase
  - Very difficult to estimate, needs experience

- Speeding up of training campaign (already discussed in 2007)

Typical training quench, sector 45, to 10700 A



Training more than one magnet



- After the first quench, extend ramp for 3-5 seconds, and delay switching off by this time (already done today for energy extraction, but only for less than a second)
- Needs further understanding of magnet system (secondary quenches)
- Hardware changes required (not for 2016)

- Estimation for length training of campaign (depends on several factors) – one to two months
- Using strategy for multiple training – possible reduced by a factor of two

Maximise time with colliding beams (stable beams)

- During scheduled time for physics, higher fraction of time in stable beams
  - Reduced number of faults resulting in beam dumps allows to optimise fill length – requires to increase the availability of systems
  - Reduce time from “End-of-fill (beam dump)” to “Start stable beams”
  - Faster ramp-up and ramp-down (can we increase dI/dt for the main dipoles from 10 A/s to 11 A/s or to 12 A/s?)
  - Less pre-cycles or shorter pre-cycles (being discussed, see M.Solfaroli)
  - Reduce number of tunnel accesses by automation (faults that required an access today: can remote reset or redundancy be implemented?)
  - Reconsider conditions for access (if access with a limited magnet current is possible, pre-cycles could be avoided)
  - Instead of switching-off a sector after a trip without a quench, consider powering down to injection current and not to zero current

Availability for systems in beam operation

	Systems	Impact of 7 TeV operation on availability
1	Injector complex	
2	Injection systems	
3	Beam injection	
4	Access system	
5	Machine Interlock Systems	
6	Accelerator Controls	
7	Technical services (electricity supplies, ..)	
8	Beam Instrumentation	
9	Transverse damper	
10	Magnet protection system (QPS)	
11	Experiments	
12	Vacuum	
13	RF	
14	Cooling and ventilation	
15	Collimation	
16	Beam Dumping System	
17	Power converters	
18	Cryogenics	
19	Beam Losses (incl. UFOs)	
20	Beam induced quenches (UFOs)	
21	Magnet circuits	

No change

Potentially worse

Expected to become worse

Availability for beam operation at 7 TeV

- Total length of cycle will slightly increase due to higher current of 900 A => 90 s per ramp
- UFOs are more likely to dump the beams and quench magnets
- Extraction kicker magnets – higher risk of asynchronous beam dump – mitigation by new switches after LS2 (see C.Bracco)
- Cryogenics operates closer to the limits, no major effect expected
  - Recovery for quench at higher current will (slightly) increase, order of one hour/quench
- Effects of powering with higher currents did not (yet?) show adverse effects – no additional reduction in availability expected
- Interlock levels were set, some of them years ago – to be iterated
  - MPP (Machine Protection Panel) and MP3 (Magnet Powering & Protection Panel) + Groups (VAC, ABT, RF, …)

Prediction for UFOs (B.Auchmann)

- No accurate prediction of UFO rate as a function of energy
  - The reference run at 2.54 TeV would indicate that rates increase with energy; but there is not enough data for an extrapolation.
- To find an estimate on trends…..
  - use UFO data from 2015 at 6.5 TeV
  - assume that the UFO dynamics remains roughly the same (same average number of inelastic collisions per interaction at 6.5 and 7 TeV)
  - scaling of quench levels from 6.5 to 7 TeV –the energy deposition to quench a magnet is less (-25%)
  - energy deposition into magnets per inelastic collision increases (+12%)
- During 2016 operation we will get more accurate info on number of UFOs
- The number of potential quenches appears to roughly double at 7 TeV compared to 6.5 TeV – **No Showstopper**

Expectations for Luminosity at 7 TeV (G.Arduini)

- Higher energy – smaller beam sizes due to smaller emittance, allowing for a slightly lower beta function
  - Collimators should remain the same in mm, keep impedance constant
  - Small reduction of the beta* (e.g. from 40 cm to 37 cm) could be achieved due to the reduction of the emittance
  - Peak luminosity increase of about 10% with respect to 6.5 TeV
- Radiation damping slightly increased, but more burn-off
  - No or only slightly longer luminosity lifetime
- Beam instabilities: no significant change, possibly slightly more delicate
  - Beam more rigid, octupole magnets less efficient (smaller beam size + higher energy)
  - No major problems expected

For the colleagues from the accelerator physics group (BE-ABP) to work out a detailed prediction

Availability in general

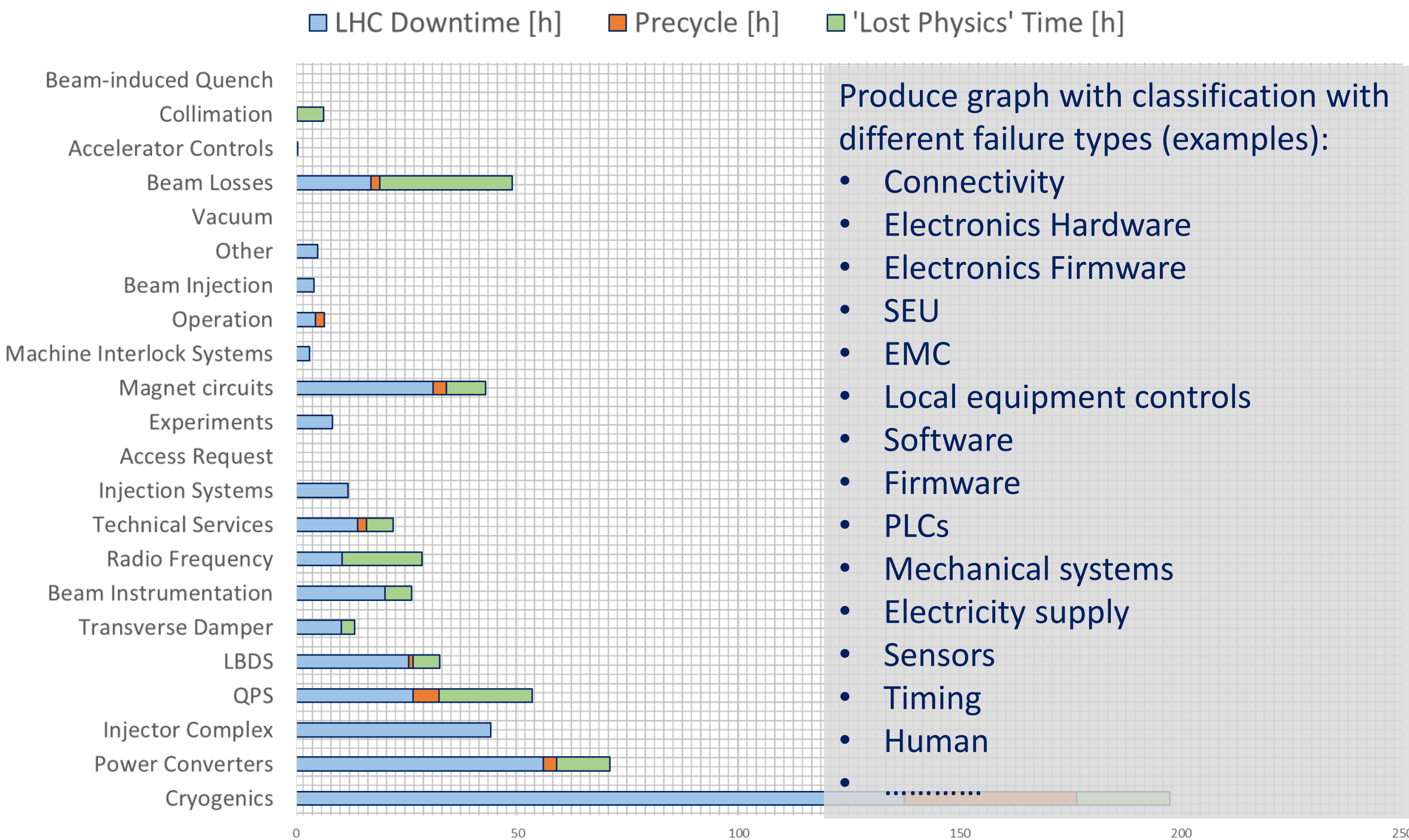
Understanding factors detrimental for availability

- Understanding of faults: Accelerator Fault Tracking – excellent progress
  - Extend the use of AFT to equipment and to injector complex

- Needs resources
  - Controls aspects – for development of tools
  - Analysis of events – following up faults appearing during operation
  - Coordination – between different activities

- **Availability Working Group** to follow up this effort

Proposal for an additional classification



Produce graph with classification with different failure types (examples):

- Connectivity
- Electronics Hardware
- Electronics Firmware
- SEU
- EMC
- Local equipment controls
- Software
- Firmware
- PLCs
- Mechanical systems
- Electricity supply
- Sensors
- Timing
- Human
- ……….

Additional classification

	(Only part of the matrix is shown)	Connec-tivity	Power supplies (small)	Electronics hardware	Electronics firmware	SEU	EMC	Local equipment controls	etc
1	Injector complex								
2	Injection systems								
4	Access system								
5	Machine Interlock Systems								
6	Accelerator Controls								
7	Other technical services (electricity supplies, ..)								
8	Other systems								
8	Beam Instrumentation								
9	etc								

- A classification of typical failure types is required to find adequate mitigations
- It helps to collaborate between groups to exchange information and to work on common weaknesses and mitigations
- Has been done for Single Event Upsets, with large success (excellent collaboration across groups)
- Can be extended to other failure categories

The wider picture

- Tools, methods and competencies do not depend on the specific accelerator
- The competence on availability modelling is not a core competence at CERN

Availability culture

- We succeeded to establish a “Safety Culture” for LHC
  - Has always been there for personnel safety, now also established for protection of equipment

No session at Chamonix !

- We need to further work on the “Availability Culture”
  - Awareness
  - Using same vocabulary across teams
  - Communication between teams
  - Training
  - Better information on reliability of equipment and components – databases

- Catalogue for the reliability of equipment
  - Excellent progress for radiation tolerant electronics

Other accelerators and installations

- FCC (availability is a fundamental concern for such complex accelerator)
- CLIC (chapter on availability in CLIC Technical Report, similar complexity as FCC)
- LINAC4 (will be used as injector after Long Shutdown 2)
- MYRRHA (ADS-Accelerator Driven Spallation study in Belgium)
  - LINAC4 will be used as benchmark for availability models
  - Funding (to CERN) within EU Project (H2020 Grant Agreement 662186)
- ITER
  - An interlock system based on majority voting (for fault tolerance and allowing regular re-testing) was built by the CERN team and was successfully used for the first ITER current lead test campaign in China
  - Experience gained on high available systems (2 out of 3 voting)

Collaboration with other institutes

University of Stuttgart

- Collaboration with CERN since about 4 years, with several Master theses and PhD theses

Tampere University

- Three PhD theses under way (two located at Tampere, one at CERN)

Empresario Agrupados

- Spanish Company, industrial consulting services, especially in the nuclear energy field, addressing reliability and availability of MYRRHA and LINAC4

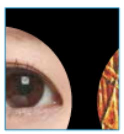
Delft University

- Studies on availability of LHC cryogenics within a PhD thesis

Report on CERN, and in particular on the collaboration on availability and reliability in the **University Stuttgart's Magazine**

FORSCHUNG LEBEN

(v.l.) Volker Schramm, Tobias Griesemer und Miriam Blumenschein, Studierende des IMA, am CERN in Genf.



WISSENSCHAFT INTERNATIONAL

Mit deutscher Zuverlässigkeit

Stuttgarter Team analysiert Schutzeinrichtungen am Europäischen Kernforschungszentrum CERN

Universität Stuttgart

Ereignis aus dem Jahre 2008 gewesen sein. Damals kam es am LHC zu einem Unfall mit fatalen Folgen, wenn auch zum Glück nur materiellen Schäden. An jenem 19. September 2008, nur neun Tage nach der Inbetriebnahme des LHC, versagte eine Schweißnaht, wodurch ein Tank mit flüssigem Helium explodierte. Die Explosion verschob einen 30 Tonnen schweren Magneten um einen halben Meter und der supraleitende Magnet erwärmte sich rasch – zu rasch. Die erforderlichen Reparaturen dauerten mehr als ein Jahr.

PERSONELLE VERBINDUNGEN

„Gemeinsam mit den beiden CERN-Arbeitsgruppen Machine Protection und Availability verbessern wir die Sicherheit und Verfügbarkeit des LHC", sagt Bertsche. „Die Methoden sind dabei dieselben, die wir auch für kommerzielle Maschinen oder Fahrzeuge anwenden." Die Kooperation schlägt sich auch personell nieder: Drei Studierende des IMA arbeiten derzeit in Genf, eine Doktorandin des CERN in Stuttgart. Eine weitere Doktorandenstelle will Bertsche noch schaffen. „Das CERN ist ja sehr international ausgerichtet, diese Atmosphäre und die dortigen Möglichkeiten schätzen unsere Studierenden sehr", hat Bertsche festgestellt. Dr. Peter Zeiler, Bereichsleiter am Stuttgarter IMA, illustriert, welche Früchte die Kooperation trägt. „Einer unserer Studierenden hat das Schutzsystem der LHC-Energieversorgung untersucht, um zu sehen, wo es Lücken in der Redundanz gibt." Betriebskritische Systeme wie die Energieversorgung sind doppelt ausgelegt, damit ein Ausfall einer Komponente keine direkten Folgen für den LHC-Betrieb hat. Im Schutzsystem sind mehr als 100.000 Platinen verbaut. „Die Ergebnisse der Analyse haben die CERN-Leute nun in der letzten Wartungsphase des LHC aufgegriffen und umgesetzt", so Zeiler. Ein anderer Student untersuchte im Labor experimentell Methoden, mit denen sich ermitteln lässt, wie robust Speicherbausteine von Computern angesichts der Strahlung im Tunnel sind: „Wenn die Protonen im LHC aufeinanderprallen, entstehen ja sehr energiereiche Teilchen, die in elektronischen Komponenten Bit-Fehler erzeugen können", erklärt Zeiler. Aus Kostengründen kommen am LHC zum Beispiel in der Auswerteelektronik oft keine strahlungsgehärteten Bauteile zum Einsatz, daher liefern solche Untersuchungen des IMA wertvolle Erkenntnisse für die Zuverlässigkeit gewöhnlicher Speicher. In einem weiteren Forschungsprojekt wollen CERN und IMA die Verfügbarkeit des LHC steigern, denn je mehr Messzeit für die Experimente zur Verfügung steht, desto zuverlässiger werden letztlich die physikalischen Ergebnisse sein, die die „Weltmaschine" liefert. Derzeit liegt ihre Verfügbarkeit nur bei 35 Prozent, gut 70 Prozent wären theoretisch möglich, wenn man Instandhaltungszeiten berücksichtigt.

Michael Vogel

Proposal for EUCARD under discussion

- Develop a coordinated approach towards coherent RAMS standards in the accelerator community

- IMA at University of Stuttgart involved as a beneficiary

- Trainings for staff, students, associated member of personnel on the essential practices of RAMS (Reliability, Availability, Maintainability, Safety)

- First ‘Test Training’ at CERN in February 2016 (not yet covered by EUCARD) – profiting for developing a regular training course
  - Organised with IMA Stuttgart, assistance by University Tampere

A.Apollonio and J.Gutleber

Conclusions and Proposals

a) 7 TeV

b) Availability

Operation at 7 TeV

- Operation during 2016 at 7 TeV would decrease the integrated luminosity significantly
- Experience the magnet system is required to make a realistic prediction for integrated luminosity, taken into account the time required for training
- From 2016, a more realistic prediction for UFOs at 7 TeV is expected (about two times more quenches compared to 6.5 TeV)

- There will be a significant investment before starting up with 7 TeV, the subsequent run at 7 TeV should be sufficiently long
- Particle Physics Input is required to set the priorities, and to define when 7 TeV operation is required

If magnet system operates reliably at 7 TeV, a gain of integrated luminosity is expected for a sufficiently long operational period

Proposal for the preparation of 7 TeV operation

- At the start of the extended end-of-year technical stop in 2016, train the dipole magnets in one or two sectors to(wards) a value for 7 TeV + 100 or 200 A
  - This will provide information on the number of training quenches required to go to 7 TeV
  - Possibly later, training after warm-up of one sector would allow to assess effect of repetitive thermal cycles (B.Auchmann)
- Operate the magnet system in this sector for some time in order to understand the probability for spontaneous quenches at flat top (must be compatible with scheduling)
- Investigate the option of accelerated quenching

Availability

Forum for discussion between equipment groups, controls and operation (mainly LHC)

- Availability Working Group: after a year of finalising the AFT tool and collecting data, this year should AWG…
  - a) conclude from analysing the data and provide guidelines for improvements
  - b) specify further extensions of the AFT

Forum for detailed and intense discussions on availability and reliability among experts (on models, software tools, analysis) is proposed (not limited to LHC, includes FCC, CLIC, LINAC4, …)

- Team on availability modelling to be created
  - (Brief) mandate should be written

Availability

- The first training session on availability and reliability will be evaluated, the curriculum will be adapted, and other training sessions should be organised

- Up to today, most of the work on availability was done by students and fellows, supervised part-time by non-experts – needs continuity

- To keep the overview of all activities, to ensure coherence and to prevent competing activities is challenging

A Staff position for an expert on accelerator availability is required