Summary: After LS1 ….before LS2

M.Pojer and R.Schmidt

After LS1 the energy will be about 6.5 TeV

The physics potential of LHC is determined by the integrated luminosity useful for the experiments, and not only by the **peak luminosity**

The integrated luminosity is determined by the peak luminosity, the luminosity decay and the efficiency of operation (**availability**)

Presentations

Peak luminosity

- Performance potential of the injectors after LS1, Heiko Damerau
- Performance reach of LHC after LS1, Werner Herr

Availability

- Magnet powering with zero downtime - a dream? Markus Zerlauth
- Beam systems without failures – what can be done? Matteo Solfaroli and Jan Uythoven
- Will we still see SEEs? Marco Calviani
- UFOs – will they take over? Tobias Baer
- Quenches: will there be any? Arjan Verweij

Performance potential of the injectors after LS1, Heiko Damerau

- Upgrade of the injector complex to be finished after LS2
  - PS Booster, for injection into the PS at 2 GeV (instead of 1.4 GeV) after LS2
- Upgrade of PSB to 2 GeV required to overcome space charge limit in PS
- LINAC4 with H- injection into PSB at 160 MeV, possibly end of 2015
- The full performance of LINAC4 requires H-injection into PSB, without this **LINAC4 can deliver only beams resulting in 50% of the luminosity**
- Even if LINAC4 is connected to the PSB, almost no gain from the higher brightness from the PSB due to space charge limitations in the PS at 1.4 GeV. The gain comes with the transfer energy to 2 GeV.
- In case LINAC2 breaks down…
  - Emergency connection of LINAC4 in 2 months operating with 50 MeV, but accepting reduced performance
- Connection of LINAC4 with H- injection, requires 7 months
- **Might be better continue to use LINAC2 until LS2**…

Possible improvements before LS2

- RF manipulations increase brightness from the injectors, but batches will have less bunches (slightly reducing the number of bunches in LHC)
  - Several options of bunch manipulations… promising very low transverse emittances …then one can increase intensity by merging bunches….
- Longitudinal coupled bunch instabilities require feedback, limitations to about $1.9 \cdot 10^{11}$. Feedback system planned for 2015
- Can the low emittance be transported to LHC….?
  - Scrubbing in SPS should help to suppress electron cloud effects for very low emittance beams... this takes time, possibly to be done before LHC starts operating
  - Q20 optics in the SPS
- Filling time will increase, optimum filling is important (such as dedicated LHC filling), to gain time and to reduce emittance growth in LHC at injection energy

Performance reach h = 7 or 9 → … → 21

First PS studies in 2012		50 ns high int.	25 ns low $\varepsilon_x/\varepsilon_y$	25 ns ultra-bright
PS injection	Bunch intensity	$0.6 \cdot 10^{12}$ ppb	$0.8 \cdot 10^{12}$ ppb	$0.65 \cdot 10^{12}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.0 µm	1.2 µm	1.0 µm
	Vert. tune spread, ΔQ_y	-0.21	-0.24/-0.26	-0.26
PS ejection	Bunch intensity	$1.90 \cdot 10^{11}$ ppb	$1.27 \cdot 10^{11}$ ppb	$1.54 \cdot 10^{11}$ ppb
	Emittance, $\beta\gamma\varepsilon$	1.1 µm	1.3 µm	1.1 µm
	Bunches per batch	18/24	36/**48**	32
Brightness limit PSB		X	X/-	X
Space charge limit PS			-/X	X
Coupled-bunch limit PS		X		
SPS ejection	Bunch intensity	**Beyond SPS reach**	$1.15 \cdot 10^{11}$ ppb	**Beyond SPS reach**
	Emittance, $\beta\gamma\varepsilon$		1.4 µm	
Relative intensity/luminosity in LHC		(1.0/1.8)	**1.3/1.3**	(1.63/2.38)

(expected performance)

Example for parameters

More than present luminosity with 25 ns and slightly higher total current

H. Damerau, Chamonix 2012, 09/02/2012

Performance reach of LHC after LS1, Werner Herr

- Assumptions: E = 6.5 TeV, emittances can be preserved
- Not yet limited by head-on beam-beam effects. We know that we can collide high intensity bunches
- Long-range beam-beam effects are more relevant than head-on beam-beam effects and reduce the dynamic aperture. The dependence on intensity is unknown, extrapolations are not obvious
- A beam separation of 10-12 sigma is required, but depends on beam parameters (here 10 sigma are assumed)
- Required for optimising the luminosity
  - Small emittances, beam sizes
  - Sufficient bunch intensity
  - Sufficient number of bunches
  - Sufficient long range separation
  - Possibly luminosity levelling
- Three scenarios: pessimistic, realistic, optimistic

…already above nominal luminosity

Possible options:

→ Assumptions: $\beta^* = 0.5$ m at 7.0 TeV, separation 10 σ

	Δt/nb*)	ϵ_n (μm)	Nb (10^{11})	$\mathcal{L}_{peak}$ (10^{34})	α (μrad)	PU	ξ
●	50/1404	2.0	1.4	1.35	±120	61	0.008
●	25/2808	3.0	1.2	1.30	±150	30	0.005
●	50/1404	2.0	1.7	1.90	±120	87	0.009
●	25/2520	1.3	0.7	1.00	±100	23	0.006
●	25/2592	1.4	1.15	2.30	±120	63	0.009

Will take time!

nb*): needs adjustment for exact filling scheme !!

Integrated luminosity of up to 70 fb^{-1}

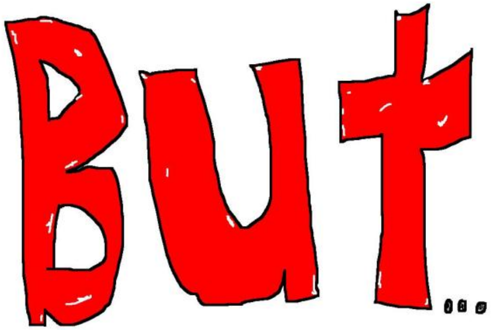
…further optimisation and tests

Further improvements

- Unequal beta functions (0.5 m and 0.3 m, similar to SppbarS collider with 0.6 m and 0.15 m)
- 2 · nominal luminosity could be a target
- 4 · nominal luminosity could be a (very ambitious) target
- Exact filling scheme makes small changes
- Emittance preservation very important
- Luminosity levelling with high luminosity is always an option
- Tests in 2012
  - scaling of long range beam-beam effects with intensity
  - impact of noise on beam-beam effects

Comment: a reduction of the dynamic aperture due to beam-beam effects to, say, 5 sigma, is not necessarily a disadvantage

Magnet powering with zero downtime - a dream?
Markus Zerlauth



Magnet powering with zero downtime - a dream? Markus Zerlauth

- The LHC magnet powering system is very complex, we have about 6 years of experience with its operation
- This includes power converters, quench protection, cryogenics, powering interlocks and electrical distribution
- 50% of all premature beam dumps are due to a failure in the magnet powering system that includes several 10-thousand interlocks protecting the machine from an energy stored in the magnets of 10 GJoule (7 TeV)
- Potential gains by increased availability: about 35 days luminosity operation
- Number of faults depends on intensity and integrated luminosity (much less faults during ions run)
- Failures dominated by SEE, R2E work will lead to large improvements
- All equipment groups are undertaking serious efforts to further enhance the availability (see presentation by R.Denz and L.Tavian)

…walk through the systems

Power converters: **many** improvements already **applied during** 2011

- **Fault states to warning states**, FGC lite rad tolerant + diagnostics module
- Weak auxiliary power **supplies in 60A converters** to be changed during LS1
- Study of **redundant power supplies for 600A** (two power modules providing redundancy with one FGC)

QPS

- More monitoring is required, many other mitigations are proposed, improved handling of thresholds is planned **alongside other operational diagnostic tools** (see presentation by R.Denz)

Cryogenics

- Possibly implementation of redundant PLCs for **cryo controls** during LS1
- Consider increase of time-out for loss of cryo-maintain from 30 s to 2-3 min
- Long-term availability depends also on upgrades and spare strategy (see presentation by L.Tavian)

…walk through the systems, comments

Powering interlocks (one false trigger/year expected, in 6 years no HW fault)

- With the relocation of the PLCs (SEE) there should be very little failures
- Can we reduce circuits that request to dump the beams in case of failure, possibly with a circuit – by circuit configuration?

Electrical distribution

- Minor perturbations can be survived but FMCM triggers, in particular for D1 (warm magnet close to insertion 1 and 5) and others warm magnets
- Possible improvement of active filter to be tested during HWC. Option after LS1: installation of **switched mode converter type** that **is** less sensitive

General remarks

- After LS1 less failures due to R2E activities
- Expect ~30% less beam dumps in 2012, after LS1 further down by 25-30% (however, the systems will operate with higher power, to be seen)
- Critical systems could be done in 2oo3 logics
- Proposal: create a **Working Group on Availability** across systems

Beam systems without failures – what can be done? Matteo Solfaroli and Jan Uythoven

- Details on each beam dump were worked out (see slides)
- At 450 GeV there were 38 high intensity beam dumps during 2011
  - Mainly due to beam losses and bad trajectories
- During the energy ramp in 2011 only 15 beam dumps (40 in 2010)
- When operating at 3.5 TeV, 107 beam dumps both for 2010 and 2011
- 450 GeV – many improvements planned to reduce the number of dumps
  - See talk by C.Bracco
- During the energy ramp, 40% beam dumps by RF
  - In Summer 2011 all RF interlocks were connected to the Beam Interlock System since the beam intensity increased, leading to an increased number of dumps to protect the RF system from the beams
- Improvements are underway
  - Below a beam current of 50%, some failures will not lead to a beam dump
  - The number of beam dumps from the RF system should decrease by 50% for 2012, after LS1 it should be further reduced by 20%

…systems overview

- **Vacuum system**
  - No fundamental issues
  - After LS1 other effects with 25 ns are expected
- **Beam monitoring** (BGIs): operational error and failure of equipment…
- **Injection and extraction**: most failures due to power converters, should be improved
  - A slightly enlarged current tracking window for the MKB is proposed
- **Collimators:** several SEE but there is no fundamental issues
  - New PXI chassis with higher availability will be available after LS1
  - The position of the collimator jaws will be tighter, but buttons to measure the beam position in collimator jaws will help to improve the measurement
- **Operation:** beam dumps due to mistakes: significant improvement, during 2011 only 3 beam dumps, all in non-standard operation…

…comments

In general, less beam dumps from beam related systems than from systems for magnets powering

- RF: improvement on the way (see talk E. Jensen)
- BLM thresholds will decrease and are closer to noise
- Other systems: only a few beam dumps, but needs to be watched

- Depending on the required effort, even to avoid a single beam dump per year might be of interest
- Effect of integrated radiation (radiation dose) and aging to be watched

Will we still see SEEs? Marco Calviani

- **R2E Objective MTBF>1 week** after LS1, for high luminosity operation
- Some improvement expected for 2012, lot of work during this Xmas stop
- During LS1 additional shielding will be installed and complete relocation of critical systems is planned
- However, for the tunnel (and somewhat in RRs): no shielding, no relocation, in particular critical in dispersion suppressors
  - Most critical is electronics in the tunnel: QPS, 60 A power converters, cryogenics and beam instrumentation
- Predictions difficult: number of SEE number depends on several factors, failure cross-section, beam losses, vacuum pressure (for 25ns bunch spacing)
  - Pressure in arcs => next slide
- How to improve knowledge: follow 2012, radiation test campaigns, improve radiation monitoring

..walk through the systems

- **Power converters**: in total 1700, solution is long term R&D
  - Radiation tolerant power converters (or part of the converters) and relocation of power converters (requires R&D effort)
  - HW rad tolerant R&D is needed (FGClite, tests planned. Complete redesign of 600A converters and more)
  - Big improvement after LS1, for 60 A but some uncertainty. Radiation testing before installation is mandatory
  - Superconducting links: available for LS2, final solution could be an hybrid
  - Review in 2012/13
- **QPS:** certain systems will always remain in tunnel and critical areas,
  - Radiation tolerant system to be installed in LS1. Failure estimation requires radiation testing
  - Some equipment: relocation in LS1
- **EN/EL - CRYO**: should be ok

Radiation level evolution

- Tunnel areas – no shielding/relocation possible

	Areas	High-Energy Hadron Fluence (/year) 2011	>LS1 (nominal)	Ultimate
Tunnel	DS (P1/5)	1.00E+10	1.50E+11	6.00E+11
Tunnel	DS (3/7)	1.00E+09	1.50E+10	6.00E+10
Tunnel	DS (other)	3.00E+08	1.40E+10	1.80E+10
Tunnel	ARC	2.00E+08	9.00E+09	1.20E+10

	Areas	High-Energy Hadron Fluence (/year) 2011	>LS1 (nominal)	Ultimate
Investigated	UA23 (maze)	3.40E+06	2.00E+07	2.90E+07
Investigated	UA87 (maze)	1.00E+06	6.00E+06	8.40E+06
Investigated	UJ23	2.00E+05	9.00E+05	1.20E+06
Investigated	UJ87	5.00E+05	2.30E+06	3.00E+06
Investigated	UX45	2.50E+06	1.50E+07	2.10E+07
Investigated	UX65	1.00E+06	6.00E+06	8.40E+06
Investigated	REs (entry!)	5.00E+05	2.30E+07	3.00E+07

- Dominated by leakage (luminosity or collimation)
- Beam-gas dominated
  - Large uncertainty due to 25ns operation vac pressure
  - Large number of exposed equipment → potentially more failures
- Beam-gas pressure (25ns operation)
  - PLCs most sensitive equipment

Engineering Department

Power converters failures post-LS1

Failures on 60A not necessarily lead to beam dump!

failure per year			
converter	2011	2012	>LS1
LHC60A-8V	4	10 .. 30	60 .. 200
LHC120A-10V	1	2 .. 3	10 .. 30
LHC600A-10V	7	7 .. 10	1 .. 15
LHC4-6-8kA-8V	1	1 .. 3	1 ..45

I would be more optimistic

Thurel, TE/EPC + MCWG/R2E team

- 2012:
  - Shielding improvemen
  - Digital filter improver
- **Post-LS1**:
  - Assumes EPC solved
  - Reduction of failure r LS1 years (*not include*

Uncertainties:

- Rad-failure cross-sections!
- Radiation levels in the ARC

→ FGClite critical for R2E

→ PC patches for AC-DC

→ Radiation testing before installation required

…comments

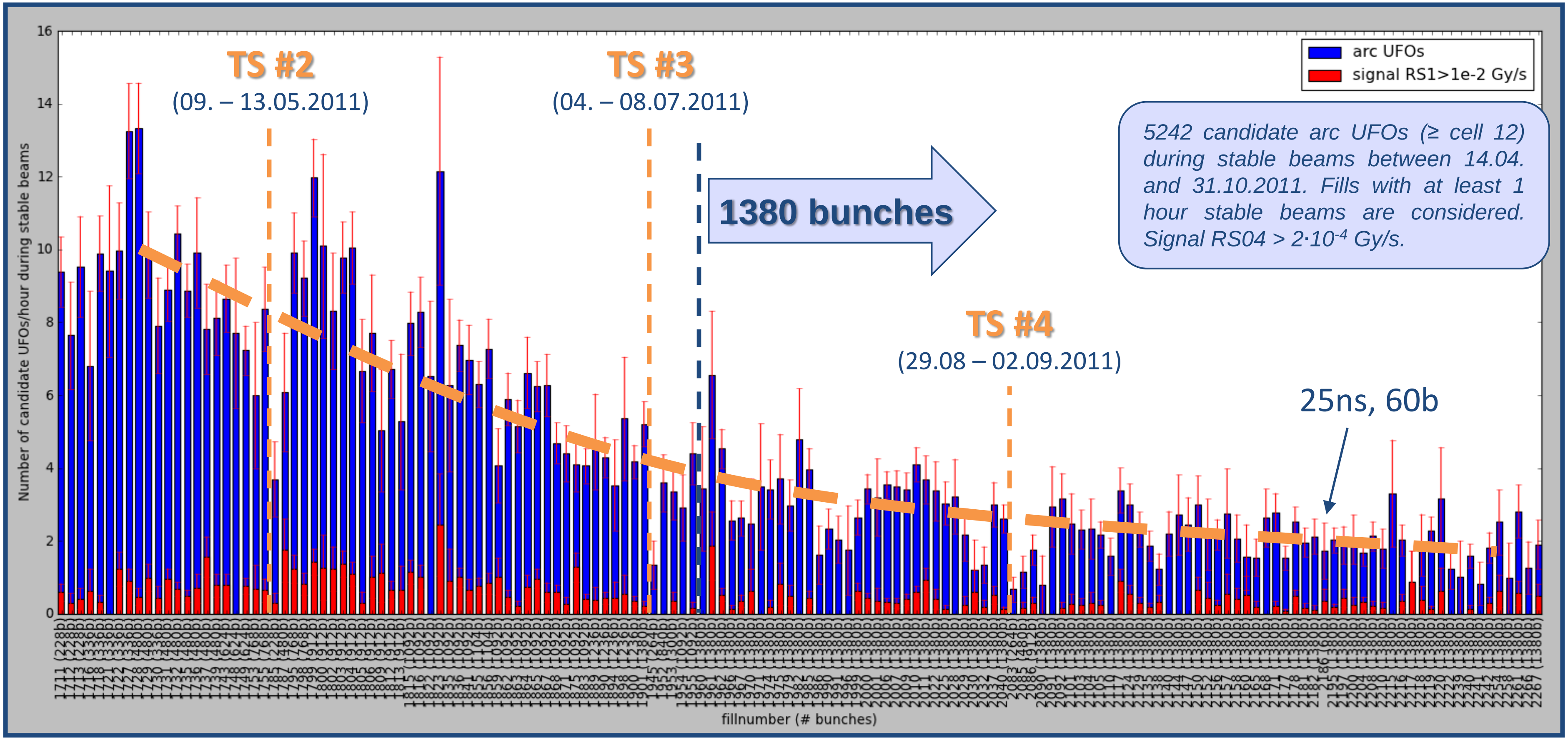
- Scrubbing run for operation with 25 ns beams is very important and should allow to reduce to pressure to a level similar to todays pressure
- The collimation settings this year will be tighter, but the behaviour of integrated losses should not change (function of intensity)

Still SEE after LS1, but MTBF > 1 week should be ok, needs continuous effort

UFOs – will they take over? Tobias Baer

- In 2010, 35 beam dumps due to UFOs, dust (?) particles in LHC beam
- In 2011, 16000 UFOs, but only a few beam dumps (increase of BLM thresholds)
- UFOs all around LHC, rate decreases during the year by factor of 5
- Many UFOs at the injection kicker magnet (MKI) UFOs
  - 11 dumps in 2011, 8 at 3.5 TeV, no conditioning observed
  - Occur after injection (0.5h), some very fast (too fast for gravitational fields)
  - At MKI, minimum size of 40 um from FLUKA
  - Lab measurements, dynamics of particles has been modelled
  - Lab studies of MKI, opened, many particles on the filter, 1-100 mu
  - Typically Al2O3, come from ceramic tubes
  - MKI metallisation => rise time and power deposition, not obvious
- Many UFOs for the short 25 ns run were observed, and multiple events (12 UFOs at the same location within 20 s)

UFO rate 2011



Decrease of UFO rate from ≈10 UFOs/hour to ≈2 UFOs/hour.

… expectation and proposals

- Energy dependence: signal at 6.5 TeV about factor of 3 higher, rate might be similar
- **For 6.5 TeV: 81 beam dumps expected for arc, 27 for MKI**
  - Assuming 50 ns and conservative BLM thresholds, with 25 ns bunch trains the number could be higher
- This year improve understanding: add BLMs, FLUKA simulations, bunch-by-bunch diagnostics, 25ns operation, MKI UFO MD, possible shaker device

Would UFOs quench a magnet? …if not, we do not care. Tests can address this question (such as a **wire scanner test**)

Proposal for 2012: BLM thresholds in "good" sectors

- Increase BLM thresholds by factor 3.3
- In case of a quench, reduce thresholds
- In case of beam dumps, increase the BLM thresholds

Quenches: will there be any? Arjan Verweij

- **Quenches** are **part of normal operation**, although possibly avoid them (due to efficiency and downtime)
- There are **several mechanisms for quenches** (beam induced, false triggers, ramp down, ..)
- At 7 TeV: increased time for getting beam back, about 10 h
- Quenches at 760A can be “quenchinos”, not expected above 3.5 TeV
- **Main dipole training quenches**: propose **to limit number of quenches to 50-100 during the first training after LS1**, since there is a small damage risk for each quench (for RB order of 10^{-4})
- **Quenches due to beam loss are fuzzy…**
  - Uncertainty due to position of beam losses and quench mechanisms, time scales of beam losses, …
  - Studies of quench thresholds in the Lab are not easy to perform, and difficult to extrapolate to LHC

Difference 3.5 TeV ⇔ 6.5-7 TeV

At 6.5-7 TeV the SC magnets run much closer to the critical surface (J_C,B_C,T_C) while at the same time exposed to higher beam losses.

Example: main dipole	3.5 TeV	6.5 TeV	7 TeV
I	5900 A	11000 A	11850 A
I / I_C at B_{peak}	13%	44 %	55%
$B_{central}$	4.2 T	7.7	8.3
Stored energy	1.7 MJ	6 MJ	7 MJ
Splice heating for R=0.6 nΩ	20 mW	73 mW	85 mW
Joule heating at 10 K at B_{peak}	44 W/cm^3	230 W/cm^3	280 W/cm^3
dI/dt at FPA	-120 A/s (τ=50 s)	-110 A/s (τ=100 s)	-120 A/s (τ=100 s)
T_C	6.8 K	4.1 K	3.5 K
T_{margin}	4.9 K	2.2 K	1.6 K
Enthalpy (1.9 K to T_C) at B_{peak}	**16 mJ/cm^3**	**3.1 mJ/cm^3**	**1.9 mJ/cm^3**

<400 mW/cm^3 at 760 A

…proposals

- Before LS1: being very cautious with quenching dipole magnets
- After LS1: consolidation of splices (improved interconnects) and CSCM tests (demonstrate functioning of the correct current by-pass with diode), less worries in case of quench
- **Proposal:** BLM thresholds to be set to quench threshold, then increase / decrease the threshold when gaining experience to find optimum between number of quenches and number of beam dumps
- Other mechanisms to quench (such as fast ramp-down) are not expected at RB and RQ, but for other magnets this is very common
- First part of quenches expected during hardware commissioning, after that period hopefully only (few) quenches due to beam losses
- Expect few de-training and beam loss induced quenches…

Final remarks

- Peak luminosity after LS1 (…not in the first year) could **exceed nominal luminosity by a factor of 2**
- Being optimistic and pushing some parameters, even a **factor of 4 is not excluded** (this would take time…)
- **Availability is a concern**, but it is very reassuring to see that **all teams are working improvements**
  - LHC HL requires more than 7 hours stable beams per fill – not there yet
- After **consolidation of splices AND of testing the circuits with the CSCM** we should be less afraid about quenching a magnet…..
- In my view, **UFOs and beam induced quenches** are the most important risk for efficient operation at 6.5…7 TeV – we should be prepared
- Suggestion: **Workshop on beam induced quenches** in autumn, with all players, to come to a coherent view

Thanks to all speakers

…do not want to be killed by UFOs

……not all quenches are dangerous