Critical overview of RF equipment in the LHC injector chain

IEFC Workshop

Prepared by colleagues from BE-RF
presented by Erk Jensen

10th Feb. 2010

RF Issues overview

Machine	Short term	Medium term	Long term
Linac2	Vac. leak coupler – spare available	Linac 2 to be replaced by Linac 4	NA
Linac 3	Plasma source upgrade 18 GHz ongoing		Bertronix, LLRF upgrade, energy ramping/debunching
PSB	Lifetime RS 2012, C16 power supply, tomoscope, LLRF upgrade underway	C04 at the limit, transverse damper power upgrade, RF bypasses?, upgrade to 2 GeV: T.B.D, (new LLRF ...), outer rings already behave strangely ...	C02, C04, C16 to be renewed, upgrade LLRF all systems, upgrade transverse damper, all cables, ... → David McFarlane
LEIR	None	None	Lifetime Finemet® cores?
PS	RF bypasses, C10 tuning supply (Kempower), C10 control electronics, tomoscope, automated tuning C40	1-turn feedback (in the pipeline), renewal LLRF, C200 upgrade to be finished, transverse FB power upgrade, C40, C80: complete servo tuning (also for ions/protons)	Renew C10 drivers (and PA?), RF bypasses redesign, renewal LLRF, coupled bunch FB, all cables, ... → Ray Brown
SPS	800 MHz upgrade (power and LLRF) underway, BQM upgrade underway	SPS upgrade: review sectorization of TWC's, TWC impedance? new power station 200 MHz, ...	All power couplers, tetrodes long term supply, cables, ... → Nicolas Gilbert

PSB RF systems (for each ring)

Name	harmonic *h*	*f* range [MHz]	peak voltage	remarks:
C02	1	0.6 … 1.8	8 kV	acceleration
C04	2	1.2 … 3.9	8 kV	acceleration, bunch shaping
C16	8, 9	6 … 17	6 kV	controlled long. BU

+ transverse damper

Krusche, Paoluzzi: http://cern.ch/AccelConf/e98/PAPERS/TUP03H.PDF

Lifetime RS 2012 CL

- A total of 12 RS2012 are used in the PSB, 8 in the C04, 4 in the C16.
- We have a stock of (old) Siemens tubes, but for a number of years, Thales rebuilds them.
- The first two tubes by Thales showed a lifetime of only 15 kh, whereas the typical lifetime before was 30 kh.
- It is too early to call this an issue (not enough statistics), but we survey it and are in touch with Thales to straighten this out. M. Haase is reviving the PSB tubes test-stand. I expect this to become a **non-issue**.

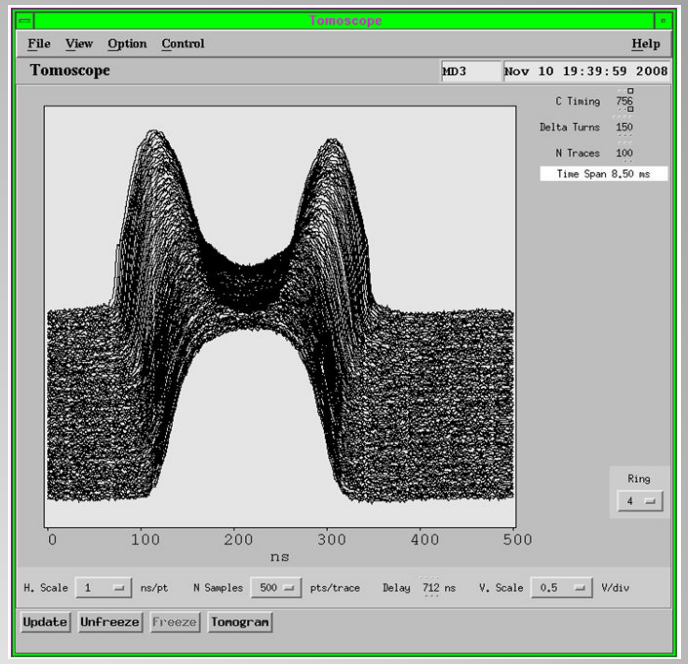
excerpt of PSB-C04 RS2012 inventory from last year:

Tube Nr.	Delivery date	Installed	Working Hours	Prospective removal	est. remaining lifetime
2912	17/10/1995	06/11/2001	29434	removed	
2913	17/10/1995	12/01/1996	36725	removed	
2940	17/04/1996	11/09/2000	29052	removed	
2941	17/04/1996	11/09/2000	29052	removed	
2952	05/06/1996	11/04/1997	36299	removed	
2953	05/06/1996	06/11/2001	29434	removed	
2955	05/06/1996	06/03/2005	30559	removed	
3143	07/09/1999	02/12/2004	25977	2010/2011	27.84%
3144	07/09/1999	02/12/2004	25977	2010/2011	27.84%
3193	25/09/2002	07/03/2006	13653	2012/2013	62.08%
3199	25/09/2002	07/03/2006	13653	2012/2013	62.08%
547827	20/12/2005	28/9/2006	12207	2013/2014	66.09%
547826	20/12/2005	03/07/2007	10315	2013/2014	71.35%
3209	04/02/2002	03/07/2007	10313	2013/2014	71.35%
3211	25/09/2002	03/07/2007	10313	2013/2014	71.35%

Thales tubes,
fail after 15000 h

Tomoscope

- The issue:
  - The Tomoscope is an important operational tool.
  - The present Tomoscope is based on special hw (scope), which is ageing – some channels started to drop out.
- Status:
  - Since PSB needs all 4 channels, a quick temporary fix was to swap the PS and PSB scopes.
  - We have now purchased a suitable (reconditioned) scope for a short-term solution.
  - RF, CO & FNAL*) (Hancock, Deghaye & McCrory) are looking at possible solutions to modernize the software (Java). OASIS scopes, as used in AD & LEIR, cannot be directly adopted due to lack of dynamic range.
  - To assure operation in the medium term, a second-hand scope of the old type will be purchased.



*): https://wikis.cern.ch/display/LAFS/Tomoscope

PSB C04 water cooling study

- The issue:
  - If the PSB is to pulse with 900 ms, the C04 becomes marginal – 600 ms is impossible without upgrade.
  - The conclusion was that even for 900 ms – for reliable operation – an upgrade to water cooling would become necessary
- Status:
  - This was not a priority and no study has been started.
  - The upgrade will however become necessary also in view of
    - the long-term consolidation and
    - the upgrade to 2 GeV extraction energy.

PSB C02 upgrade necessary?

- The issue:
  - **Beam loading: The current limitation of the C02 system … would indicate an intensity limit of 1.65 E13 per ring; or 6.6 E13 total.**
- Status: LLRF renovation progresses according to roadmap:
  - 2009*): Operational beams on ring 4 with current h/w + s/w.
  - 2010-11*): Ring 4 equipped with new h/w + s/w
  - 2012: All rings equipped with new h/w + s/w.
  - 2012-13: System commissioned for PSB-Linac2 operation.
  - 2014+: System re-commissioned with Linac4.

*) **Issue:** P resource problem signalled by MEA; reasons:

- LEIR took more resources than foreseen,
- some fundamental work had to be redone and couldn't be based 2003 BNL prototypes.

- The original question, whether PSB C02 needs upgrade for Linac4 or whether new digital LLRF system would suffice, will be addressed once the full potential of the new LLRF system can be evaluated.

See also: http://indico.cern.ch/materialDisplay.py?contribId=2&materialId=slides&confId=59488

PSB ⊥ damper upgrade

- The issue:
  - The transverse damper power is not sufficient for operation with Linac 4; roughly it should be quadrupled.
  - First MD's showed that 1E13 per ring is the limit of the transverse damper.
- Status:
  - MD's last year were not yet conclusive – it remains to determine the necessary bandwidth – MD's are scheduled in April '10.

PS RF systems

Name	harmonic *h*	count	*f* range [MHz]	peak voltage	remarks:
C10	7, 10, …, 21	10+1	2.7 … 10.01	1 … 20 kV	acceleration, RF "gymnastics"
C20	28, 42	1+1	13 or 20	15 kV	LHC 75 ns & 50 ns bunching
C40	84	1+1	40	3 … 350 kV	LHC bunching, bunch compression
C80	168	2+1	80	350 kV	LHC bunch compression
C200	420, 433	4+2	200	30 kV	re-bunching, controlled long. BU

+ transverse damper (2 x 6 kW)

PS RF Bypasses

- The issue:
  - On June 10th 2009, a vacuum leak developed in SS52, a 1 Ω resistor was found to be open, traces of arcing.
    Question: was the RF bypass damage cause or consequence?
- Status:
  - peak power on n-TOF 27 W peak, < 10 W average
  - The power/voltage specifications of the 1 Ω resistor are 50 W/300 V.
  - 40 % of the RF bypasses were measured and found OK. It looked OK!
  - However, during the shutdown, 3 more broken RF bypasses were found.
  - They were all of the "new" type.

  - Short term solution: all 24 "new" were replaced by "old" type bypasses.
  - It will be studied, what the problem with "new" type is.

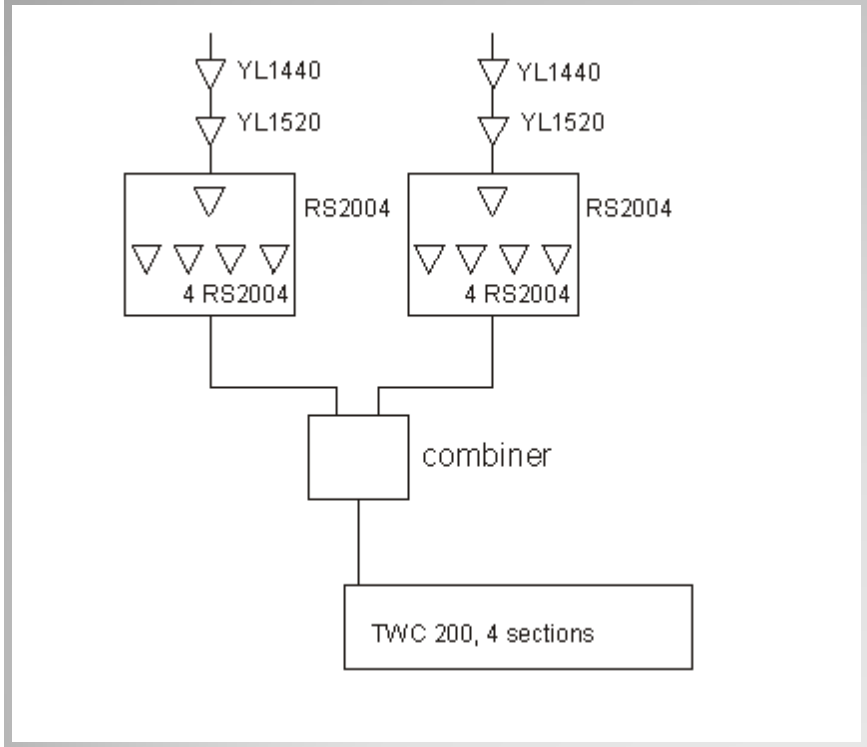
H. Damerau, J. Ferreira-Bento

PS 40 MHz: Automated tuning

- The issue:
  - The tuning of the 40 MHz cavity slowly drifts, also depending on # of LHC cycles and the beam current.
  - Automatic (slow) tuning was foreseen from the beginning, but never implemented.
  - The slow drift required frequent specialist interventions – just for the re-tuning.
- Status:
  - For one of the two cavities (78), a prototype solution has been implemented in June 09 and has since been running smoothly.
  - A missing module to adopt the same solution for cavity 77 was shipped from Naples. Both cavities should now be running with automated tuning.
  - This is a short-term solution; a long-term solution, which will be standard across different machines, will be studied by RF-CS. It will notably include the C80 and should solve the problem of different frequencies for ions and protons.

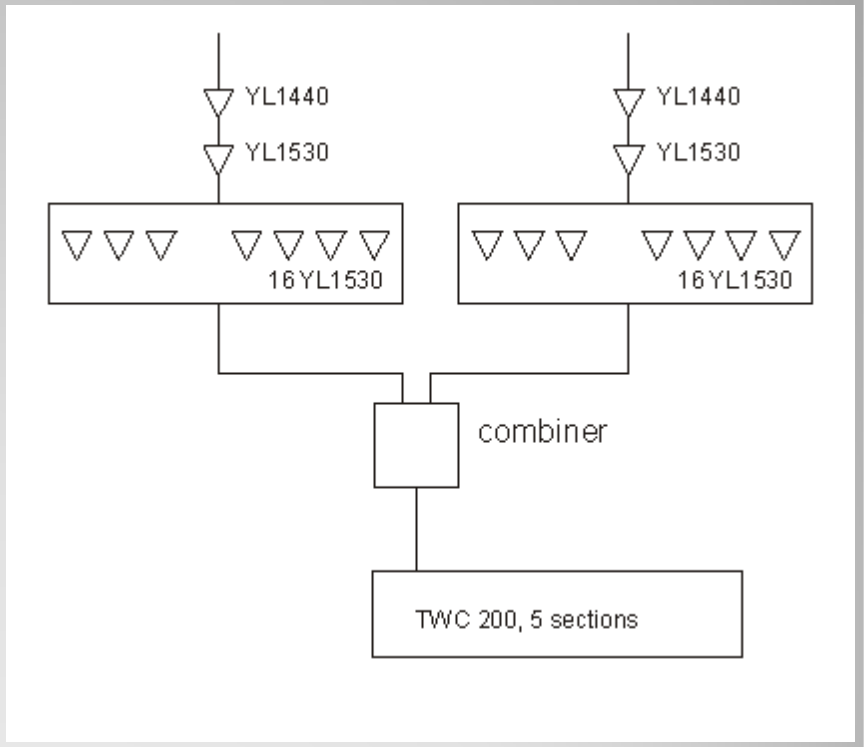
SPS RF systems – TWC 200 lines

Siemens, 2 TX per line, 2 lines



Total voltage (2 cavities): 4.1 MV w/o BL,
≈ 3.3 MV with nominal BL (1.15 10^{11} ppb).
With new tubes: 350 kW/TX

Philips, 2 TX per line, 2 lines



Total voltage (2 cavities): 5.5 MV w/o BL,
≈ 4.2 MV with nominal BL (1.15 10^{11} ppb).
With new tubes: 400 kW/TX

Stock of SPS high power tetrodes

- The issue(s):
  - Tubes are consumables!
  - Of some tubes (YL1530), we had a relatively large (but very old, hence of unknown value) stock of tubes.
  - This fact together with severe budget limitations had forced us over many years to buy less tubes per year than we consume.
  - Now the tube stock situation has become critical, just when CNGS (which is very demanding) started in full swing.
  - If we don't buy the correct number of tubes regularly, tube manufacturers may decide to stop making them!
  - For the RS2004, e.g., the lead time for the first 2 tubes is 6 months, then 1 additional month for every batch of 2 tubes.
  - We have frame contracts with the 2 tube manufacturers (Thales and Richardson) – negotiations for the extension/renewal have started.

Stock of SPS high power tetrodes

- Status:
  - Careful statistics done: With 6.25 kh yearly operation, we would need yearly column E, i.e. a budget of column K:
  - deviations from this to slowly approach I to J (NB: YL1530!)
  - These numbers (notably column D) are revised regularly.

					Orders over the last years:					
A	B	C	D	E	F	G	H	I	J	K
type	2009 price [kCHF]	# of sockets	average lifetime [kh]	yearly consumption	2007	2008	2009	stock Jan 2010	ideal stock	yearly need [kCHF]
RS2004	60.6	20	19	7	4	7	7	25	26	424
YL1530	11.1	68	27	16 *)	4	16	3	105	63	178
RS2048	11.9	36	12.5**)	18	8	8	12	60	72	214
YL1520	12.5	10	15.9	4	2	2	2	20	16	50
YL1440	5.1	14	15.8	6	2	3	8	27	22	31
TH561	10.9	4	11.1	2	1	2	2	8	9	22
				budget [kCHF]:	**426**	**779**	**659**			**919**

=ROUND(C*6.25/D,0)

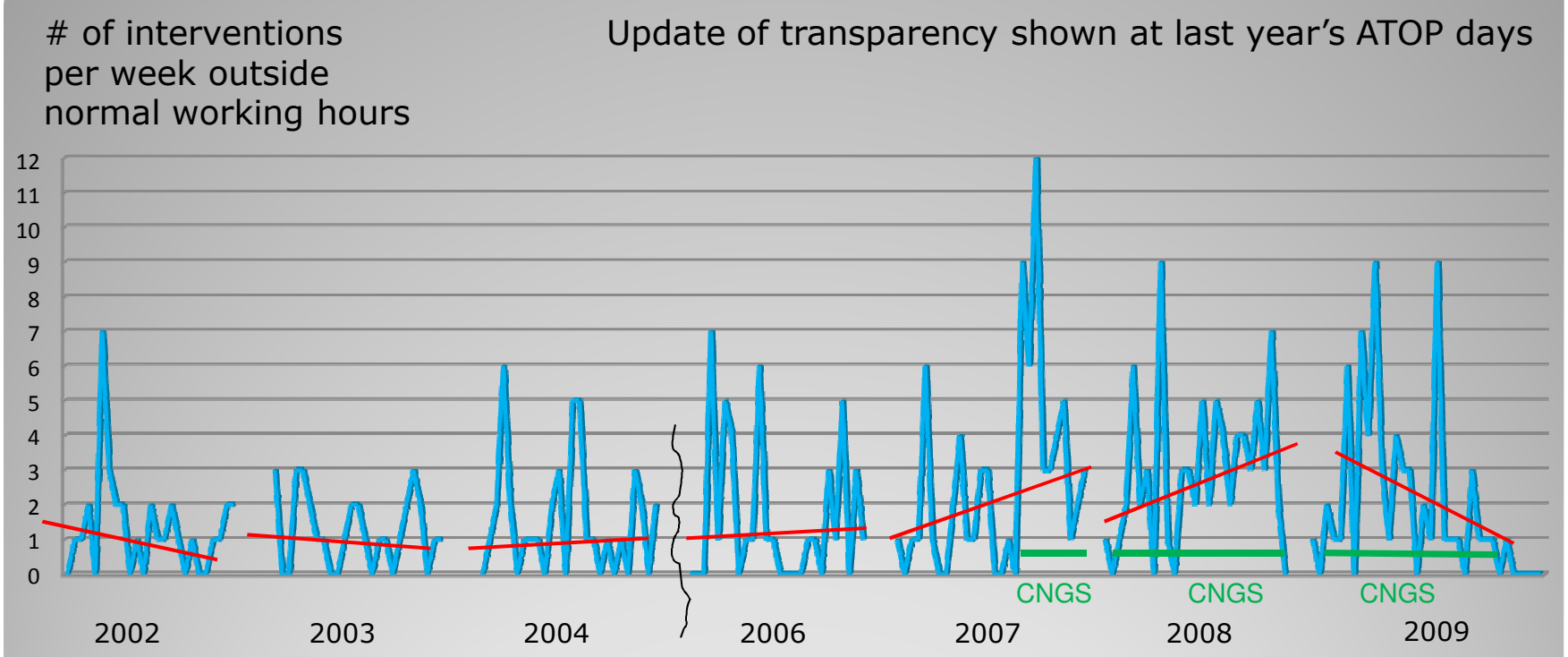
=ROUND(C*25/D,0)

=B*E, 2009 prices

*) before 2013: 5 per year, from 2013: 21 per year.

**) LHC ADT: no valid statistics yet.

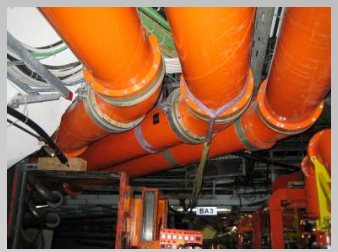
The need for correct yearly maintenance

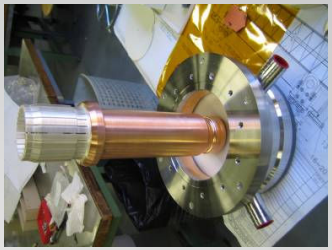


- From 2005, limited resources forced us to reduce some maintenance work.
- CNGS type beams result in more wear and thus reduce tube-lifetime (16! tubes broken in 2008!)
- Early 2009: memory effect – looked bad at first … BUT eventually – once the problems with HV supplies of TX3 and TX1 were fixed, 2009 was an excellent run – even with ions and CNGS …
- **But beware:** remember the effect of reduced maintenance! 2009/10 and 2010/11 will be minimum shutdowns ... expect some impact on the failure statistics!

SPS Power couplers

- Limits (cw, per line):
  - Amplifier: 750 kW (after combiner), limited by tubes & BW, BW-power-product & phase linearity recently upgraded (driver stages).
  - Spinner expansion lines: 750 kW
  - Couplers (upgraded 2000...2004) limit: >1.1 MW, tested "in series".

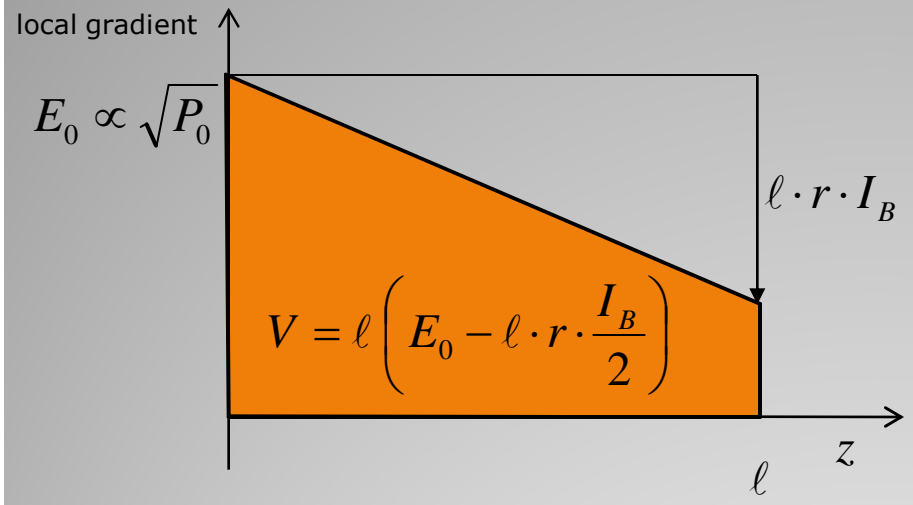




  - Coaxial line: 750 kW
  - Windows: 800 kW, 1.1 MW, tested "in series".
  - Connection coupler/cavity: 750 kW, tested 1 MW during only 10 minutes. Geometry not suitable for higher powers.

- The issues:
  - One possible conceptually easy upgrade would consist in connecting two lines to one cavity. In this case, the expansion lines, the windows and the connection coupler/cavity would become the bottlenecks.
  - The connection coupler-cavity is most critical, since in cannot be lab-tested but requires a test-cavity!
- Status:
  - ... not progressed due to other priorities

Beam loading in TWC200



special cases	I_B	V
no beam loading	0	$E_0\ \ell$
full beam loading	$\frac{E_0}{\ell\ r}$	$\frac{1}{2} E_0\ \ell$
total voltage = 0	$2\frac{E_0}{\ell\ r}$	0

Why more, shorter TW cavities help:

Total voltage of n cavities or total length $n\ \ell$: $n\ \ell \left(E_0 - \frac{n\ \ell}{n} \cdot r \cdot \frac{I_B}{2} \right)$

Total impedance: $\propto n\ \ell \cdot r$ (the same!!)

Beam current at which voltage is $\frac{1}{2} E_0\ n\ \ell$ (full beam loading): $I_B = n \frac{E_0}{n\ \ell\ r}$

the price to pay:

Total power required: $n\ P_0$

SPS RF systems – TWC 800

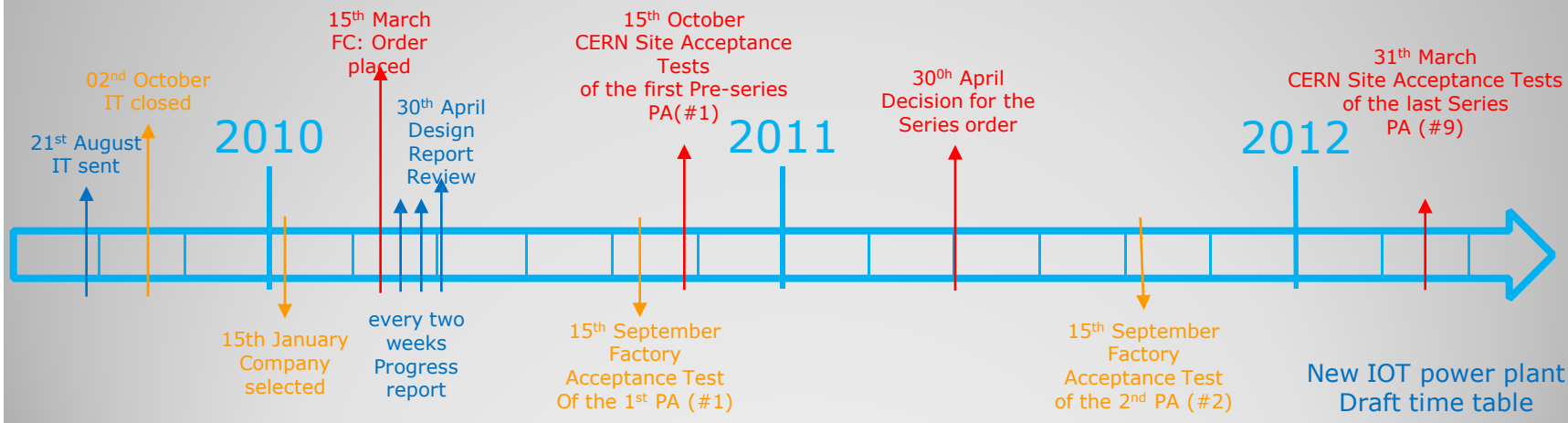
- System is essential at high intensity to cope with the dominant coupled bunch instability!
- This system is dying!
- "Valvo" klystrons (YK1198) are very old. These klystrons have not been built any more for decades! Of 16 existing tubes, 10 are broken, 6 are operational.
- Equally the transformers in their power supplies are at the end of their lifetime. The cavities are OK.
- We managed "just" (with a lot of personal commitment of some people) to supply the necessary 800 MHz voltage (700 kV) thru 2008 and 2009.

Renovation SPS 800 MHz system *I* (LL)

- The issue:
  - The 800 MHz system in the SPS is essential for maintaining stability above 1/5 of nominal intensity,
  - The existing beam control for the 800 MHz only controls the mean amplitude and phase of the voltage. However, it does not cater for changes along the batches for the voltage seen by the beam due to beam loading. An upgrade is required.
  - Needed to improve reliability and ease operation:
    - 1-turn feedback for induced voltage reduction at f_{rev} components,
    - feed-forward to deal with the fast leading edge.
- Status:
  - Work on feedback (-forward) systems has started as "White Paper" activity,
  - In addition to the original proposal, also the analog beam control for the 800 MHz will also be improved, using digital techniques where possible and useful.

Renovation SPS 800 MHz system *II* (HP)

- The issue:
  - System is necessary, but HP old & dying (10/16 klystrons broken)!
- Status:
  - Consolidation of existing system:
    - Power supplies fixed - now 2 systems running, 2 "hot spare" (waveguide switch).
    - Efforts with industry to repair the Valvo klystrons (CPI).
  - Tendering for new IOT-based 800 MHz systems:
    - IT-3624/BE: tenders received, company selected, peer review: 11/2/10



Summary RF equipment review

- The status of the RF equipment in the LHC injector chain has been reviewed.
- No "major" risks were identified.
- Main issues presently known and addressed:

  PSB C04 power limit, RS2012CL lifetime, tomoscope, PS RF bypasses, C10 tuning supply & control electronics, SPS TWC800 LL & HP upgrade.
- Upgrade scenarios have to be studied in more detail (PSB→ 2 GeV, SPS # of TWC200 cavities, power upgrade ...).
- After two "short" shutdowns in a row, expect larger failure rates!