ADT and RF after LS1

Reported by A. Butterworth

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Outline

RF

Ph. Baudrenghien Evian 2014

- Upgrades done during LS1
  - What’s left to do
- Re-commissioning
- RF parameters (HW perspective)

D. Valuch Evian 2014

ADT

- Pre- during and post-LS1
- New features for Run II
- Diagnostics: “Observation box”
- Compatibility with new UPS

Replacement of faulty cavity module

Motivation:

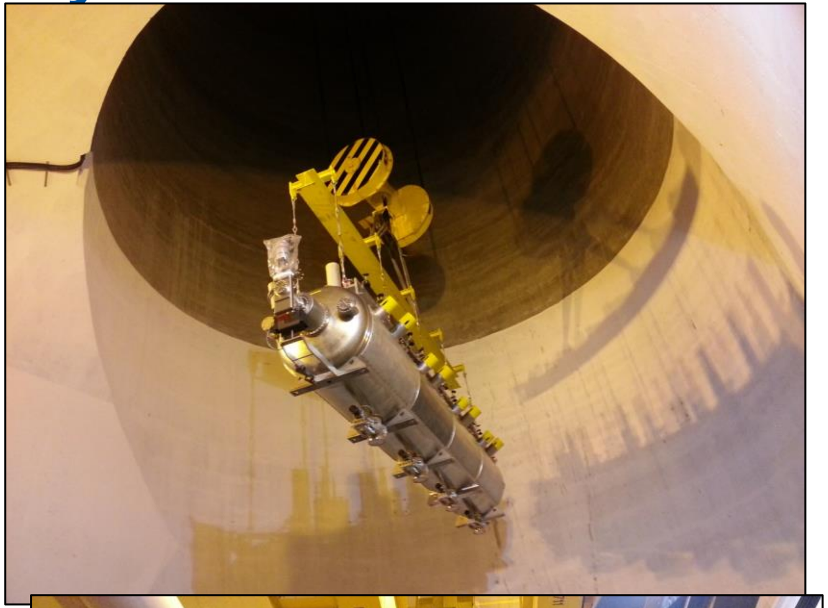
- C3B2 could not be operated reliably above 1.2 MV (cf. 2 MV nominal)

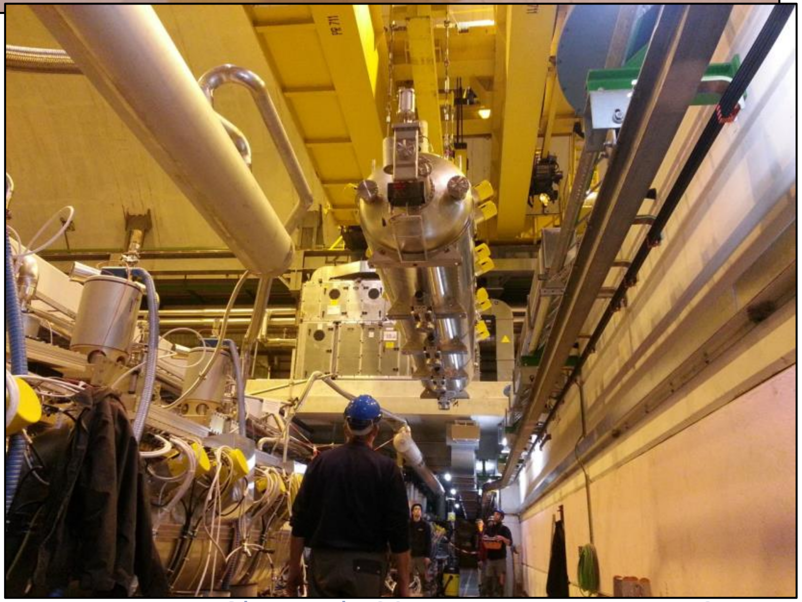
Status:

- *America* taken out and replaced by *Europa*

Recommissioning progress:

- preparing to restart the klystrons on waveguide short-circuits.
- tests dependent on the Cryo conditions sector 34 and 45
- no special issues anticipated with commissioning of Europa

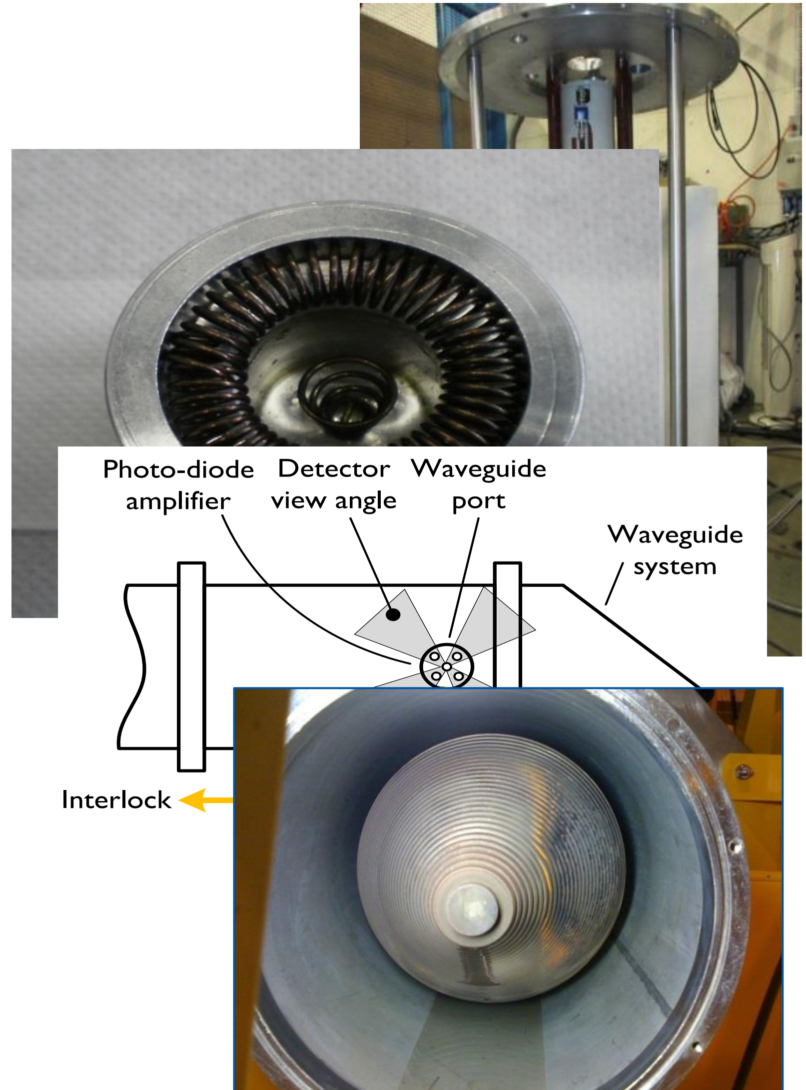




P. Maesen, G. Pechaud, M. Gourrage, M. Therasse, EN/HE
Photos courtesy of G. Pechaud and M. Gourragne

Upgrades for improved reliability

- Thyratron crowbars replaced by solid state thyristor stack design
- Klystron HV cable repairs: faulty spring contacts - connectors replaced
- Waveguide arc detectors: new design with immunity to radiation-induced spurious triggers
- Klystron collectors upgraded by Thales to handle design DC power of 500kW



Renovation of RF zone in SR4

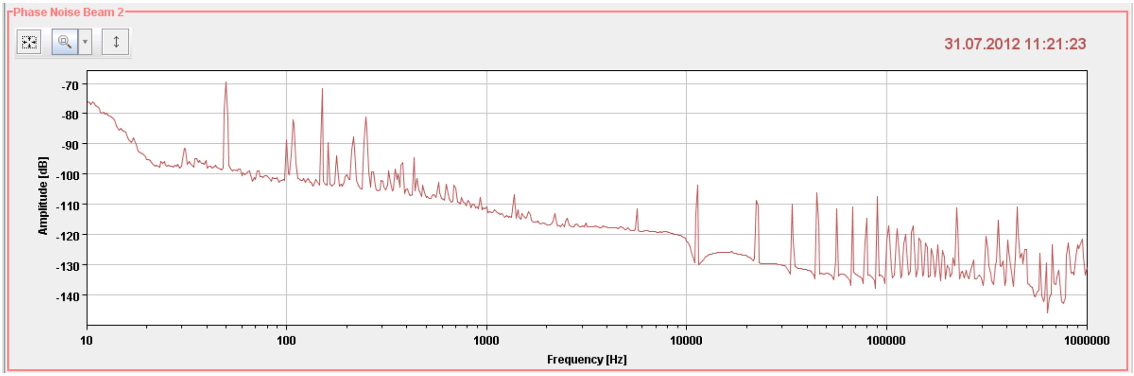
- Before LS1: RF zone was open & dependent on air conditioning of SR4 hall
- Electronic drifts experienced due to temperature and humidity variations

Renovation of RF zone in SR4

Now has roof and new air conditioning

RF noise monitoring

- On a few occasions, malfunctioning LLRF has resulted in severe RF noise, debunching and population of the abort gap



M. Jaussi
Th. Mastoridis

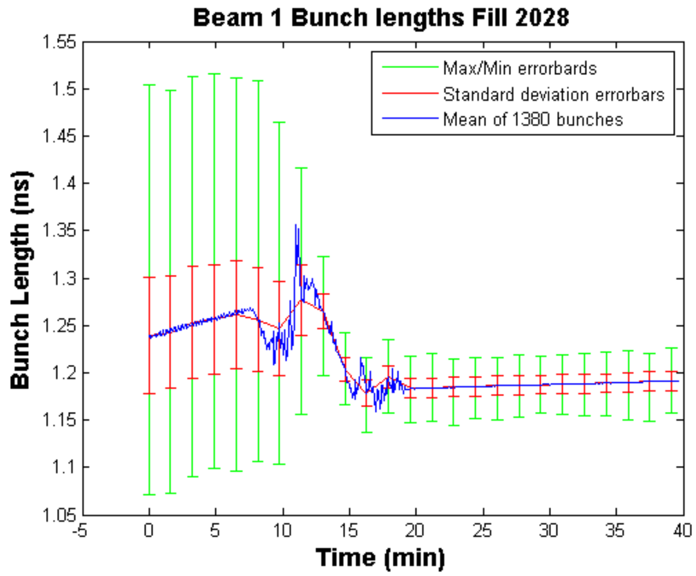
- Phase Noise Power Spectral Density (**sum of the 8 cavities**, each beam) display in CCC
  - compares to reference and generates audible warnings
- After LS1(mid 2015):
  - We will have a measurement of the amplitude and phase noise PSD for **each individual cavity**
  - implemented in custom-design VME module

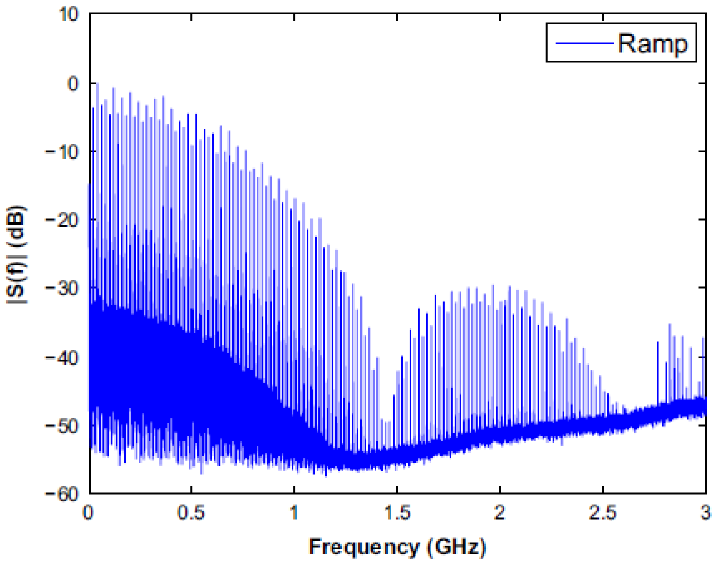
J. Noirjean

Shaping the longitudinal distribution with RF phase noise

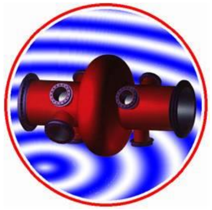
- Controlled injection of RF phase noise
  - increase longitudinal stability via blow-up
  - can be used to shape the bunch according to the noise spectrum
  - May be needed to compensate the synchrotron radiation damping at 6.5 TeV
- Many data available from Run1. Several observations are not understood
  - first goal: reproduce the run 1 blow-up measurements with the simulations
  - studies ongoing to find an optimum noise spectrum for a targeted bunch profile
- A simulation code is being implemented into PyHEADTAIL

H. Timko





New diagnostic: Bunch-by-bunch phase measurement



- The LLRF measures the phase of each bunch individually, then averages over the beam to correct the phase of the RF drive
- Individual bunch phase measurements have been used in the study of electron clouds. It gives information on the energy loss for each bunch

J.E. Muller

- May become extremely important if we suffer from longitudinal coupled-bunch instability with high intensity 25 ns operation
- Available in the custom-designed LLRF VME module but we had no means to provide large volumes of data

After LS1 (development ongoing)

- We will export a stream of single bunch phase measurements @ 40 MSPS, from the VME module to an external “observation box”
- See discussion later under ADT

Controls

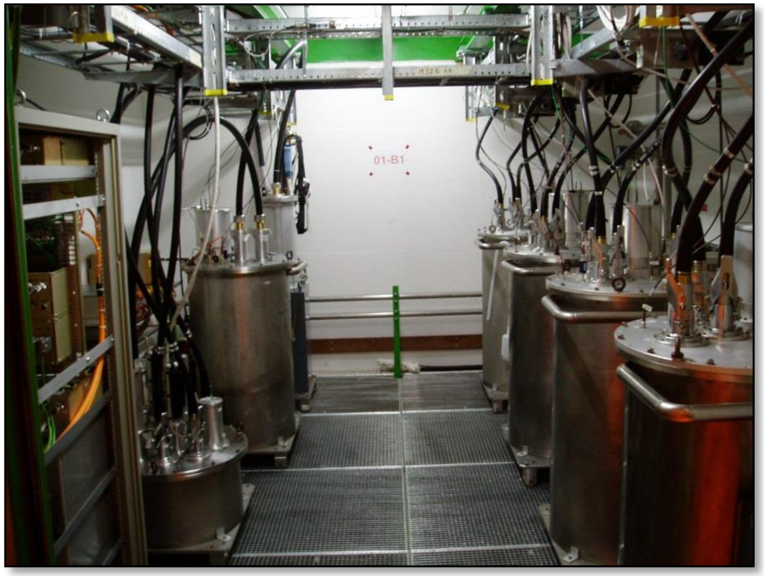
- Replacement of CPUs and move to Linux:
  - all RIO3 (LynxOS) being replaced by MEN A20 (Linux)
  - ~90% of FESA classes already migrated

- FESA upgrade:
  - will start up LHC with new ADT system in FESA3
  - other systems will remain on FESA 2.10
  - migrate to FESA3 during 2015 (technical stops and winter shutdown)

- Expert LabView applications:
  - either: will be progressively migrated to RDA 3 and LSA (by EN-ICE)
  - or: progressively re-implemented using another tool (Inspector?)
- Expert MATLAB applications for commissioning:
  - RDA communications will need migration to RDA3 or JAPC

RF re-commissioning

Step 1: Re-commission the High-Voltage

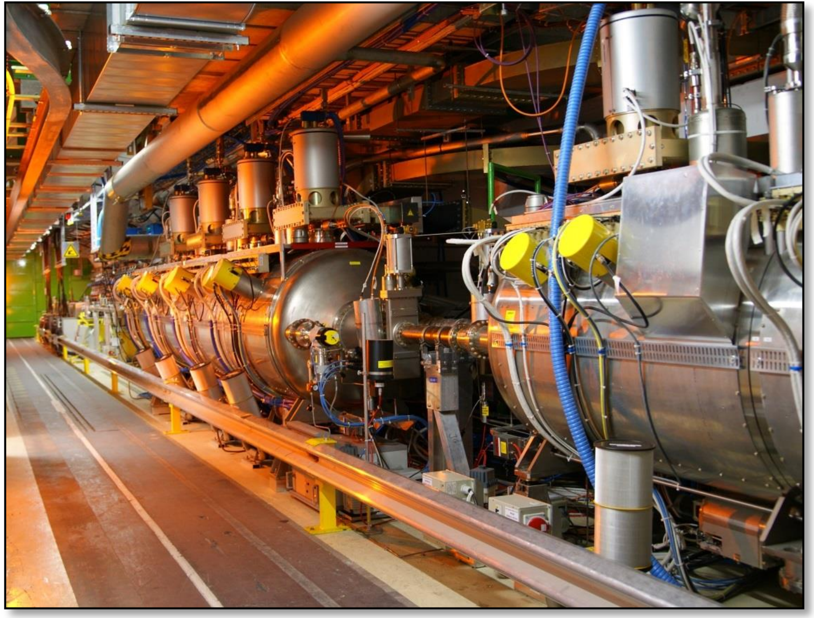


- Goal: re-commission the HV (50-60 kV) for the klystrons
- To be done: test of interlocks, commissioning the new crow-bars
- Start and duration: 2 weeks, starting in September
- Pre-conditions: general services (240/400 V), demineralized water, access to UX45 (incompatible with magnet ramping), 18 kV, power converters operational (including controls), controls software operational for the RF equipment in the HV bunkers (FESA, expert tools).

Step 2:
Re-commission the High-Power RF

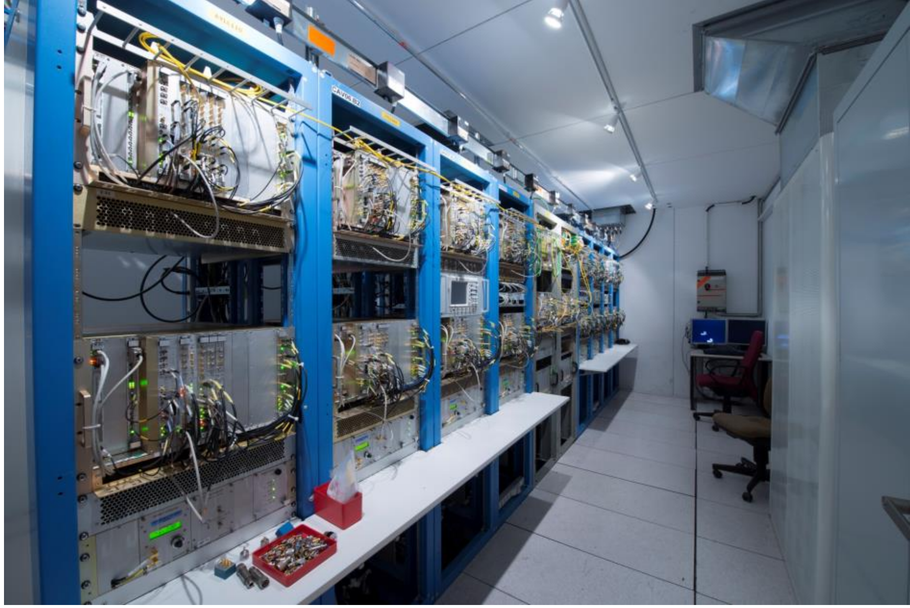
- Goal: re-commission the klystrons with waveguides on short-circuits. 8 new klystrons installed
- To be done: test of interlocks, commissioning the klystrons, calibrations
- Start and duration: 2 weeks, start in October
- Pre-conditions: in addition to the previous conditions, controls software operational for the High power equipment (FESA, expert tools), part of LLRF operational (SwLim module, RF drive interlock).

Step 3:
Re-commission the cavities



- Goal: re-commission the cavities. One new module (4 cavities) has been installed during LS1
- To be done: test of interlocks, conditioning of cavities, calibrations
- Start and duration: 3 weeks, cannot start before cryo ready (Nov.?)
- Pre-conditions: in addition to the previous conditions, cryo OK in sectors 34 and 45 (modules full and cold, stable conditions), RF zone closed (work may require occasional access to the tunnel), controls software operational for the cavities (FESA, expert tools), part of LLRF operational (conditioning mode), CCC RF-Control software operational (LSA-functions , RF Control application).

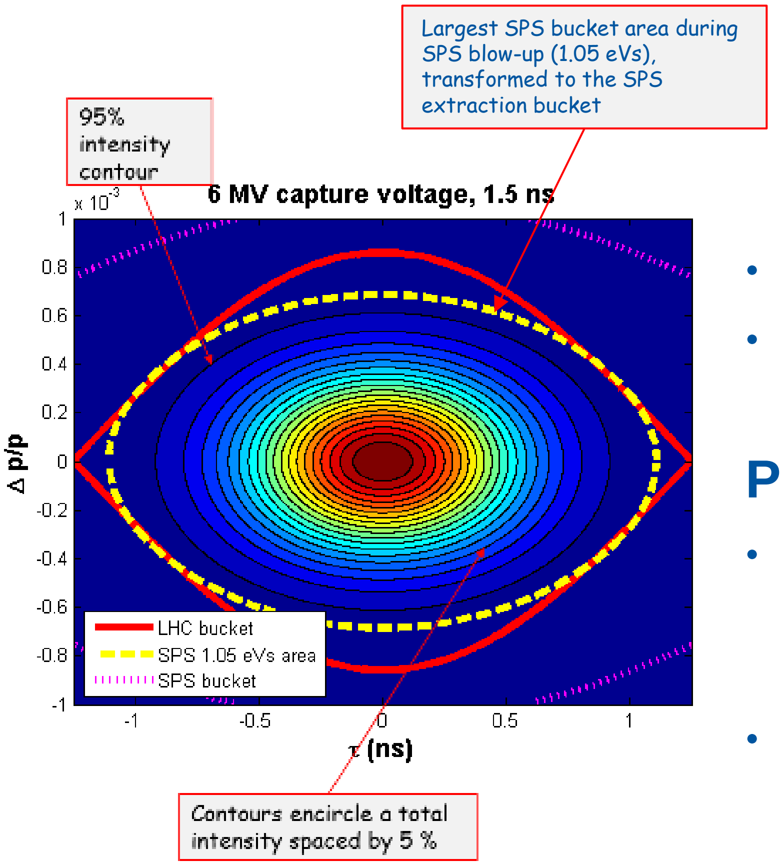
Step 4: Re-commission the LLRF



- Goal: re-commission the tuning and feedback loops
- To be done: calibration of cavity Q_L vs. coupler position, optimization of parameters for the LLRF
- Start and duration: 2-3 weeks, can start as soon as some cavities are conditioned to 2 MV
- Pre-conditions: in addition to the previous conditions, all controls software operational for the LLRF (FESA, expert tools).

RF parameters

Capture voltage



2012:

- SPS longitudinal emittance and bunch length from 2012 run (50 ns):

T. Bohl

SPS optics	Long. emittance mean	4s bunch length mean
Q26	0.5 eVs	1.45 ns
Q20	0.45 eVs	1.6 ns

- RF capture @ 6 MV → 1.24 eVs LHC bucket
- Measured capture losses below 0.5 %

Proposed for 2015:

- With 25 ns spacing, the bunch intensity will be lower (1.1E11 p vs. 1.4E11-1.65E11 p) but the total current higher (0.55A DC vs. 0.35 A DC).
- So we do not expect lower longitudinal emittances and bunch length from the SPS and propose to start with 6 MV capture voltage.

Flat-top voltage and power

- The cavity loaded Q can be optimized giving the minimal required power

$$P = \frac{V\, I_{rf,pk}}{8}$$

- Each LHC klystron can provide 300 kW RF (@ 8.8A, 58 kV)
- Keep 20% margin for regulation, limiting the theoretical power to 250 kW
- This sets the maximum voltage per cavity:

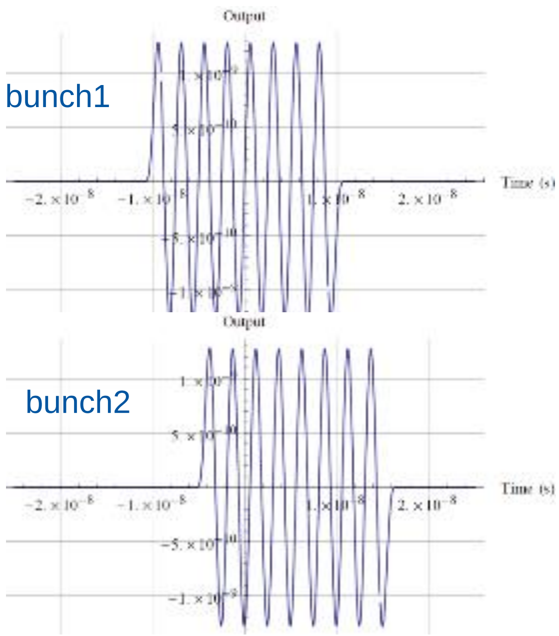
		Gaussian		Cosine^2		Point-like	
I_{DC}	Bunch length	$I_{rf,pk}$	V @ 250 kW (MV)	$I_{rf,pk}$	V @ 250 kW (MV)	$I_{rf,pk}$	V @ 250 kW (MV)
0.55 A DC	1ns 4σ	1.156	1.73	1.269	1.58	1.41	1.42
	1.25 ns 4σ	1.034	1.93	1.196	1.67	1.41	1.42
0.50 A DC	1ns 4σ	1.04	1.92	1.142	1.75	1.269	1.58
	1.25 ns 4σ	0.931	2.15	1.076	1.86	1.269	1.58

- With 8 cavities, taking the Cosine^2 profile and 1.25ns bunch length:
  - With 0.55 A DC, we can get 13.4 MV
  - With 0.5 A DC, we can get 14.9 MV

Bunch spacing: 25ns and 5+20ns

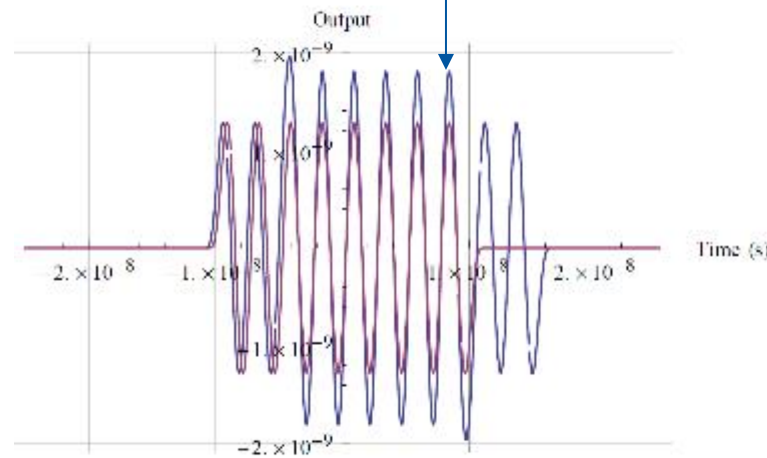
- The RF beam control was designed for 25 ns spacing
- With 5+20 ns spacing (scrubbing beams), the phase loop has to deal with 2 bunches passing in the same 25ns window:

Passage of a bunch in the PU generates a 20 ns long wavelet @ 400 MHz



Superposition of the 2 wavelets

Sample here



- The phase measurements, every 25 ns, will correctly average over the two bunches if the signal is sampled at the correct time. (LBOC Nov 26th,2013 for more)

Conclusions RF (1/2)

- **HLRF**. Large-scale modifications:
  - New cryomodule
  - new solid-state crowbars
  - klystrons upgraded for full DC power
  - All ready for start-up
- **RF voltage:**
  - Capture with 6 MV (as in 2011-2012)
  - The maximum RF voltage is 13.4 MV (0.55 A DC) and 14.9 MV (0.5 A DC), assuming cosine^2 profile, 1.25 ns base
  - Operation with 250 kW+ RF power requires the maximum 8.8A/58 kV klystron DC settings (these could be reduced during filling and preparation)

Conclusions RF (2/2)

- **Exotic bunch spacing:**
  - With a minor adjustment the RF will cope with the 5-20 ns bunch spacing
- **New diagnostics** are in preparation:
  - bunch-by-bunch phase measurement (hopefully available at start-up)
  - monitoring of the RF noise (second half 2015)
- The injection of RF phase noise is being implemented in the **PyHEADTAIL** simulation code.
  - The goal is to improve longitudinal blow-up and control bunch profile in physics.
- Initial commissioning is now underway

Transverse Damper

LHC Transverse Damper (ADT)

- Primarily designed for:
  - Damping of injection oscillations
  - Damping of oscillations driven by coupled bunch instability
  - Important role in preservation of the beam's transverse emittance

- Since the LHC start in 2008 it grew into (view from the CCC):

Injection oscillation damping

Injection cleaning

Abort gap cleaning

Transverse blow-up (used for loss maps)

Instabilities detection (with the damper PU)

Tune measurement

Slide: Delphine Jacquet, LHC Beam Operation Workshop, Evian 2012

ADT during LS1

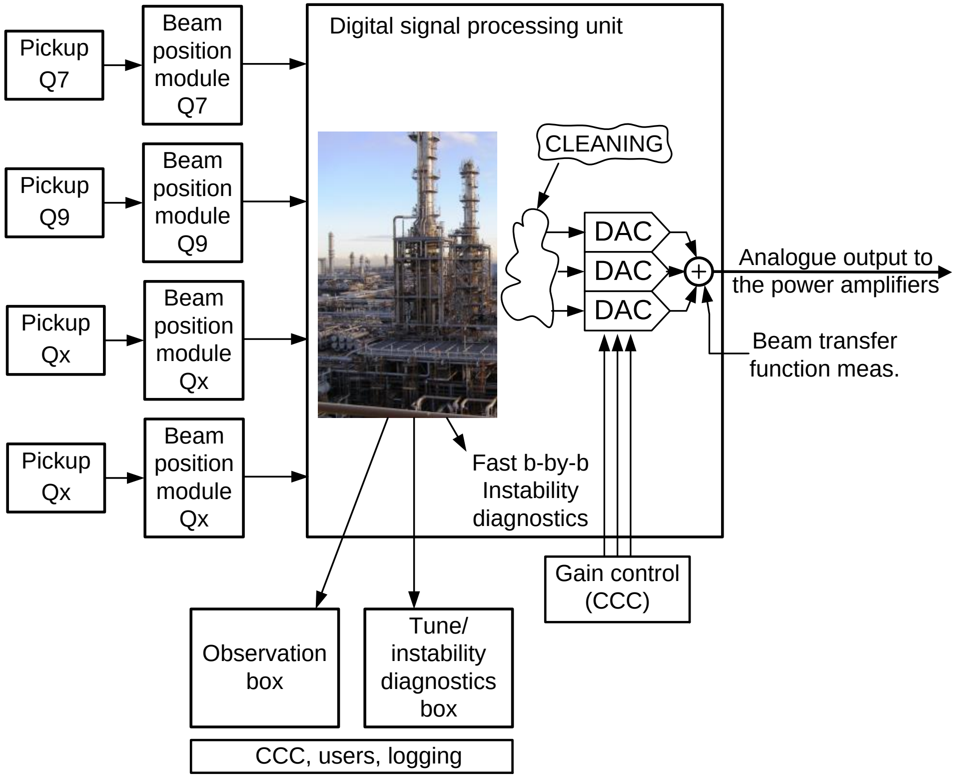
Coaxial cables replaced (pickups and surface-tunnel)
To reduce unwanted reflections from damaged cables
Smooth-walled cable for lower dispersion.

Tunnel work (coaxial cables, pickup-swap)

Damper Low-Level complete upgrade

ADT post-LS1 (main features)

- Combination of four pickups
- Implementation of all features added during run I
- More powerful digital signal processing
- Independent output DACs allow separate control for all features with high resolution -
  - Transverse feedback loop
  - Witness bunches
  - AG/IG cleaning, excitation
- High bandwidth links to external observation devices
  - "Observation Box"
  - LHC Instability Trigger system
- Detection of anti-symmetric intra-bunch motion
- Fast on-the-fly data analysis, detect oscillation patterns bunch-by-bunch and generate a trigger



Hardware status

- New ADT Low level RF hardware – synergy with the SPS damper upgrade works

- New digital “SPS damper everything” board
- SPS damper now being commissioned in BA2
- HW design will be reused for LHC
  - series production will be launched soon
- No showstoppers so far

New features for Run II

- Four pick-ups per beam, per plane, located at point 4
  - Q7-Q8 pickup swap with BPF system
  - All BPCRs existing, only question of connecting them to ADT

B1 horizontal	Q10L	Q9L	Q8L	Q7L	Q7R	Q8R	Q9R	Q10R
		β = 111 m		β = 106 m		β = 133 m		β = 153 m
		existing		existing		new		new

B1 vertical	Q10L	Q9L	Q8L		Q7R	Q8R	Q9R	Q10R
	β = 175 m		β = 155 m		β = 161 m		β = 142 m	
	new		new		existing		existing	

B2 horizontal	Q10L	Q9L	Q8L		Q7R	Q8R	Q9R	Q10R
	β = 158 m		β = 96 m		β = 150 m		β = 101 m	
	new		new		existing		existing	

B2 vertical	Q10L	Q9L	Q8L	Q7L	Q7R	Q8R	Q9R	Q10R
		β = 160 m		β = 167 m		β = 151 m		β = 180 m
		existing		existing		new		new

New features for Run II

- Estimated improvement in S/N (reference: 1 pick-up @ β =100 m)

$$\frac{S}{N} = 20\text{dB} \times \log_{10} \frac{\sum_{n=1}^{N} \sqrt{\beta_n / 100\text{m}}}{\sqrt{N}}$$

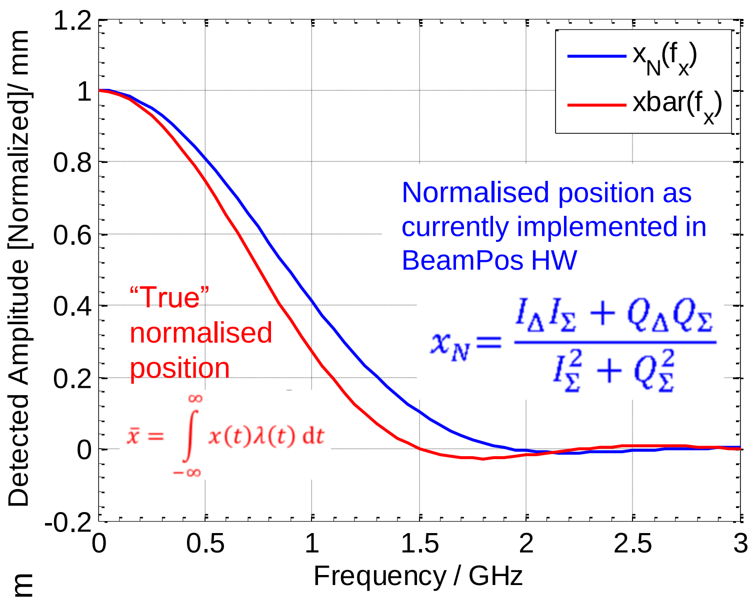
	Run 1 (2 PU) Q7,Q9	Run 2 (4 PU) Q7,Q9,Q10	After BI swap Q7,Q8,Q9,Q10	Run I → II dB (relative)
H.B1	3.8 dB	5.6 dB	7.0 dB	3.2
V.B1	4.2 dB	7.4 dB	8.0 dB	3.8
H.B2	4.4 dB	5.9 dB	8.0 dB	3.6
V.B2	4.9 dB	6.6 dB	8.2 dB	3.3

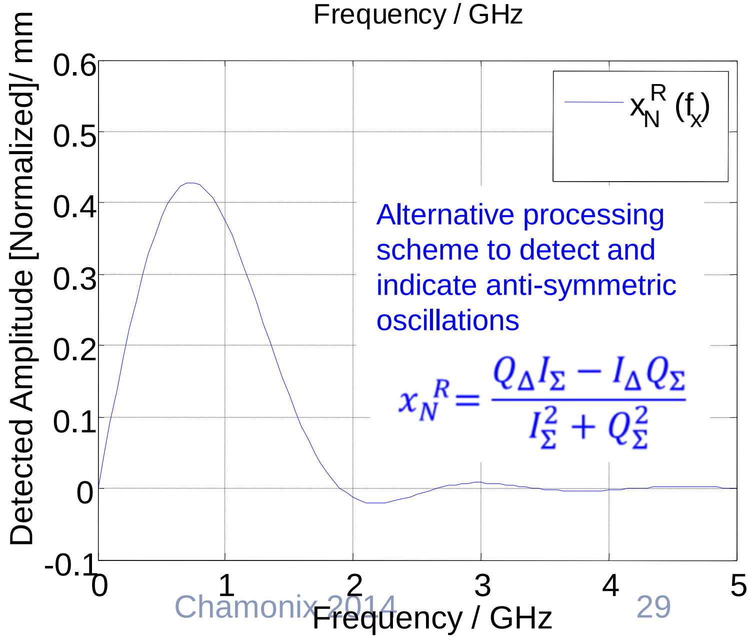
W. Hofle, G. Kotzian, D. Valuch: PU Choices for ADT - Plan for Run 2. LBOC 14.4.2014

Complementary data processing algorithm

- Current normalization scheme **sees only symmetric (even) oscillation** patterns (needed for the closed loop feedback)
- **Odd modes not visible to the damper**

- **New implementation** has additional algorithm which **can detect odd-mode** oscillations
- Cannot resolve original oscillation and absolute oscillation amplitude accurately
- **Can detect activity** and **distinguish between symmetric** and **asymmetric** (head-tail & higher order) **modes of every bunch → trigger!**





G. Kotzian, EDMS 1404633, presented at ABP-HSC meeting 22.01.2014

“Observation box”

- Make ADT and RF **bunch-by-bunch data** available to external applications
- **Streaming** over Gbit/s fibre links to an **external PC** (large memory & processing capabilites)
- Connected to **LHC instability trigger network**
- Data transmission and reception firmware
- Software implementation well advanced
- Application for bunch-by-bunch phase measurements

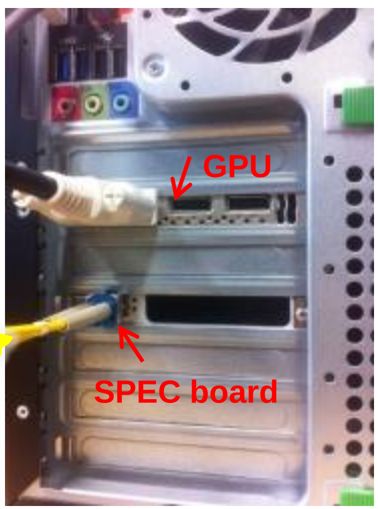
T. Levens, J. Molendijk

M. Ojeda

J. E. Muller, G-H. Hemelsoet

ADT Beam position module

Observation box receiver (PC)



Bunch by bunch data read out via PCIe

```
0x00000de3
0x0001c5bc
0x00000de4
0x00000de5
0x00000de6
0x00000de7
0x0001c5bc
0x00000de8
0x00000de9
0x00000dea
0x00000deb
0x0001c5bc
0x00040000
0x00000001
0x000150bc
0x000150bc
0x000150bc
0x000150bc
0x00000002
0x00000003
0x00000004
0x00000005
0x00000006
0x00000007
```

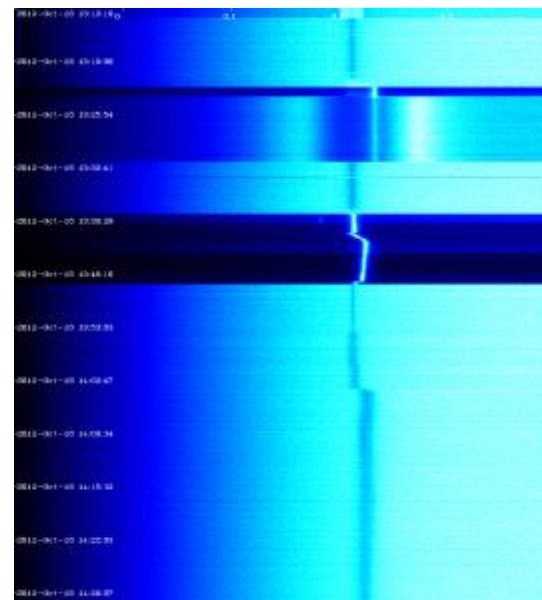
normally 1 comma per 5 words

← bunch #0+frev

4 comma burst on Frev marker

20ns !

Processed data (e.g. tune extraction)



Compatibility with new UPS

- ADT base-band signals (3kHz-20MHz) transmitted over coaxial lines from SR4 to the driver amplifiers in UX45
- Perturbed by ground currents from old UPS with switching frequency 5-8-16kHz (measurement campaign and fix in 2010)
- Newly installed UPS's produce very different noise spectra
- Some frequencies less prominent, some significantly stronger (40x)
- ADT team is in contact with EN/EL

A measurement campaign will be carried out in order to identify and quantify a possible perturbation of the ADT by the new UPS

ADT current status

- The new hardware is now ready for the SPS restart
- All major blocks successfully tested
- Commissioning ongoing
- New software (FESA3) makes commissioning process in SPS tedious
- Will learn from it for LHC

- Final work on the LHC ADT will begin once the SPS damper is fully operational:
- Series production of HW for LHC
- Sequences, functions, timings, high level procedures, dry runs, interaction with CCC, observation data, fixed displays...

Summary ADT (1/2)

- ADT undergoes a major upgrade during LS1 to improve flexibility and performance even further
  - Increase # of pickups, more powerful signal processing, dedicated signal paths for witness bunches or cleaning

- Synergy with the new SPS damper developments
  - Hardware currently being commissioned in SPS

- Algorithms for fast b-b-b symmetric/anti-symmetric (intra bunch) instability detection will be available

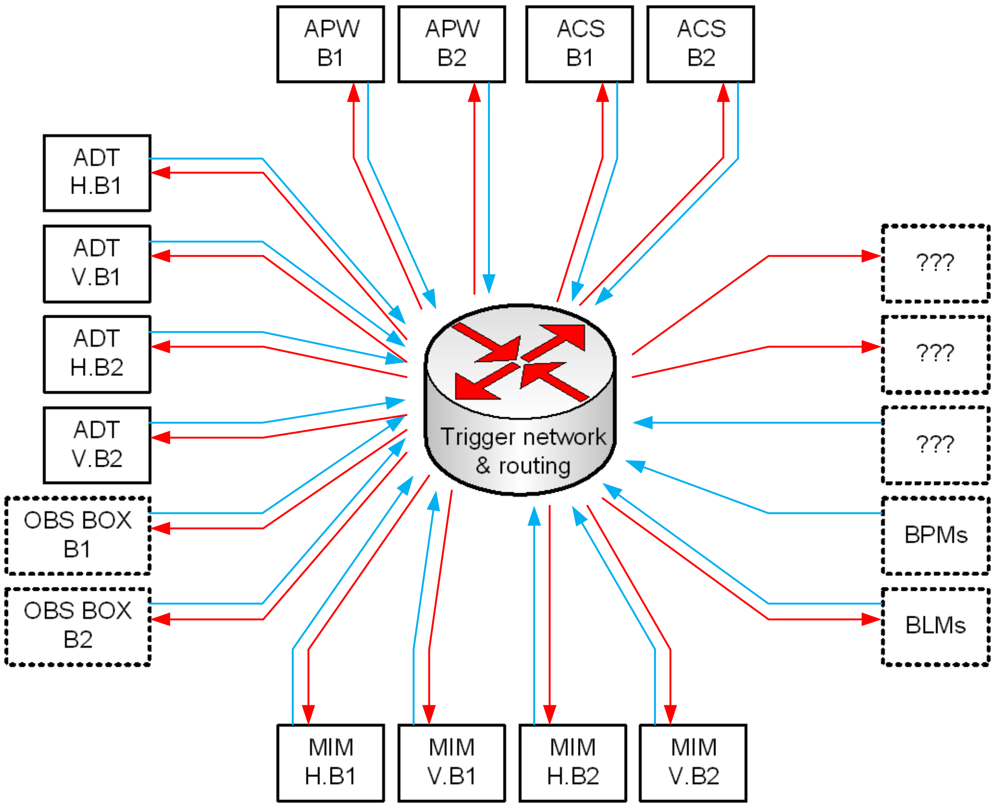
Summary ADT (2/2)

- Observation box
  - Bunch-by-bunch data storage for quasi-unlimited # of turns
  - Potential for sophisticated on the fly data analysis (instability, Q…)
  - Will be used also in the longitudinal plane
  - Connected to machine-wide instability trigger distribution network

- Compatibility with new UPS
  - A measurement campaign will be carried out in collaboration with EN/EL to quantify a possible perturbation

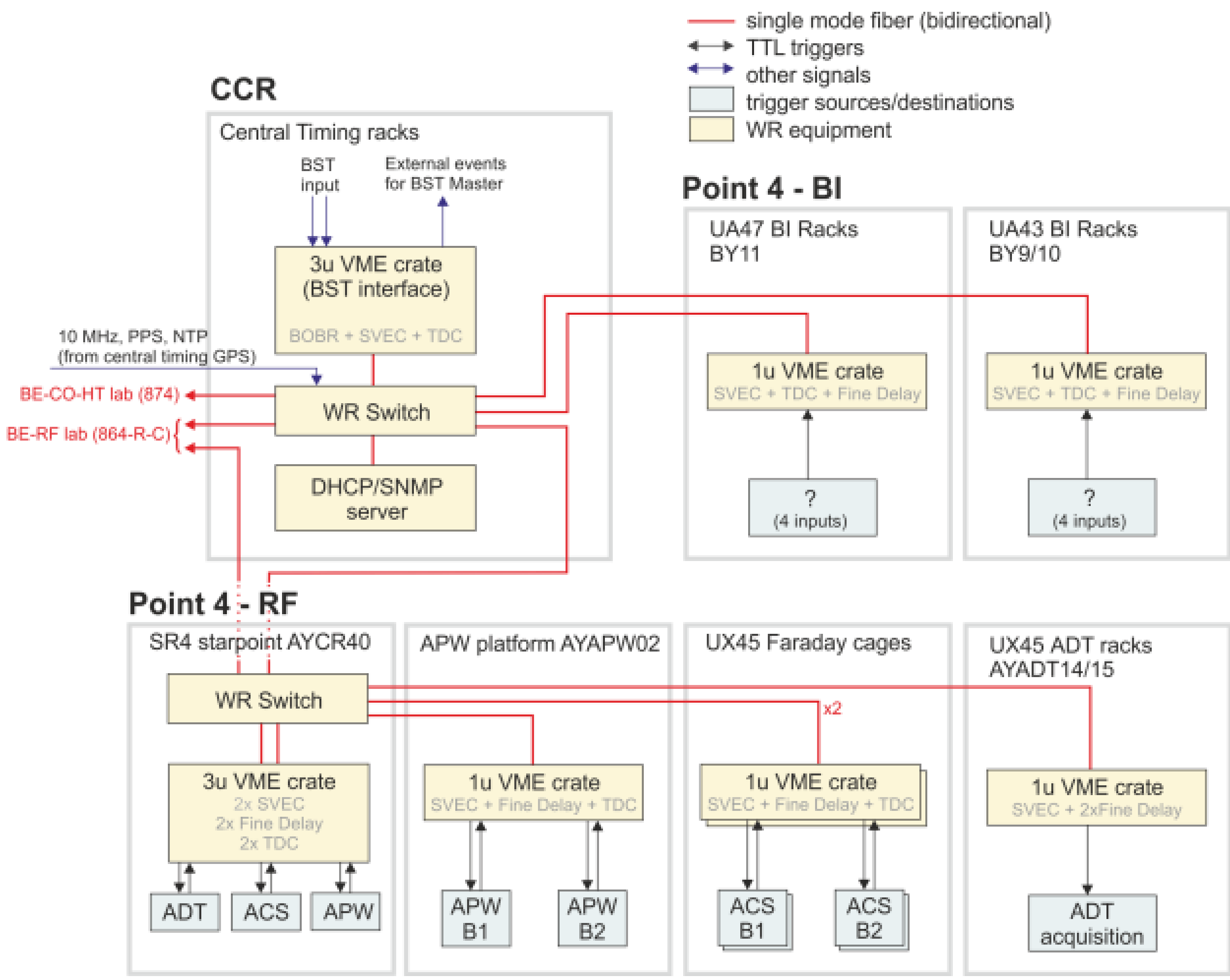
www.cern.ch

Instability trigger network functionality

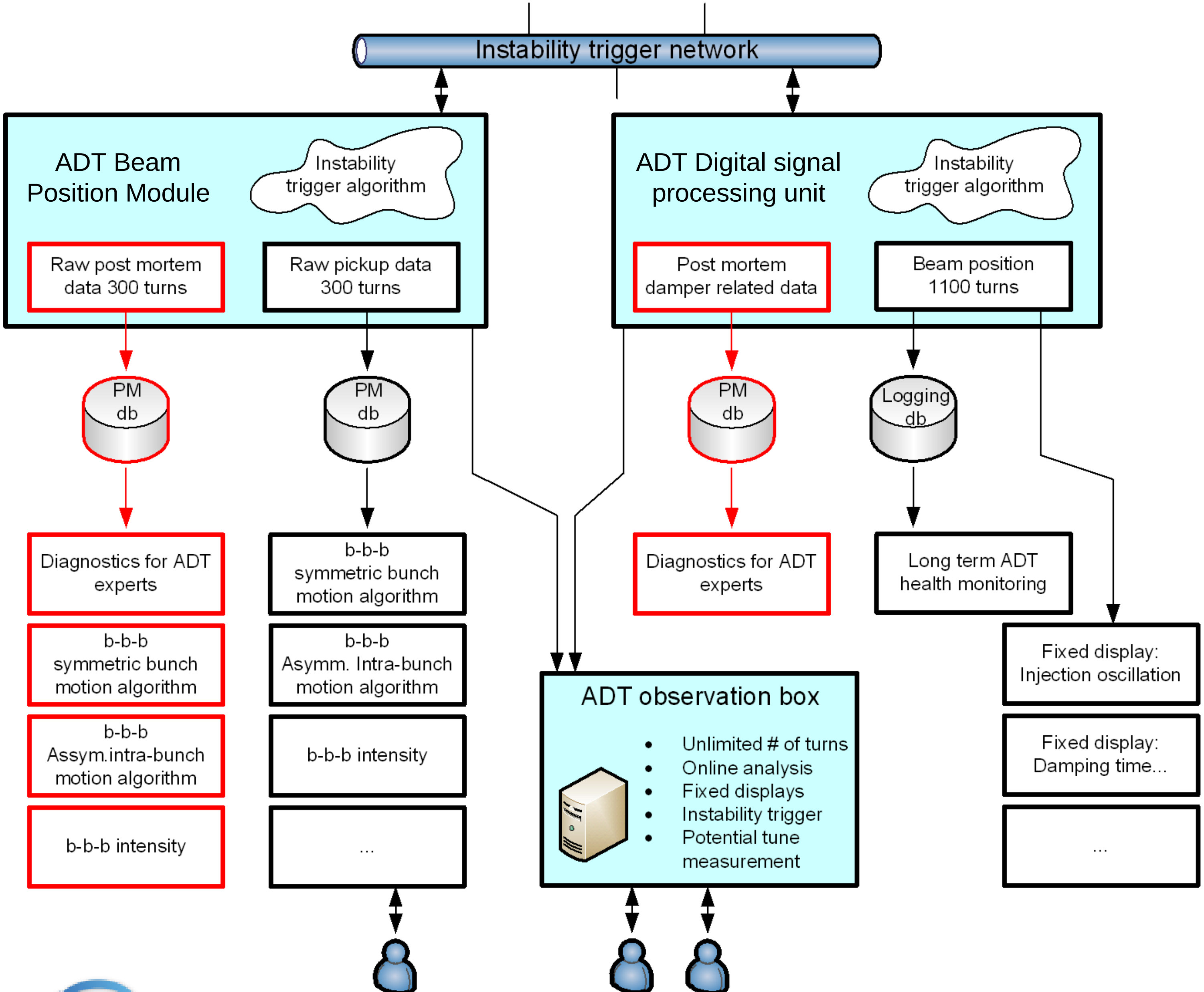


- A set of observation instruments can be located anywhere in the LHC or CCC
- Many of them can generate a trigger
- Many of them can receive trigger and freeze a data buffer

WR network architecture (initial configuration)

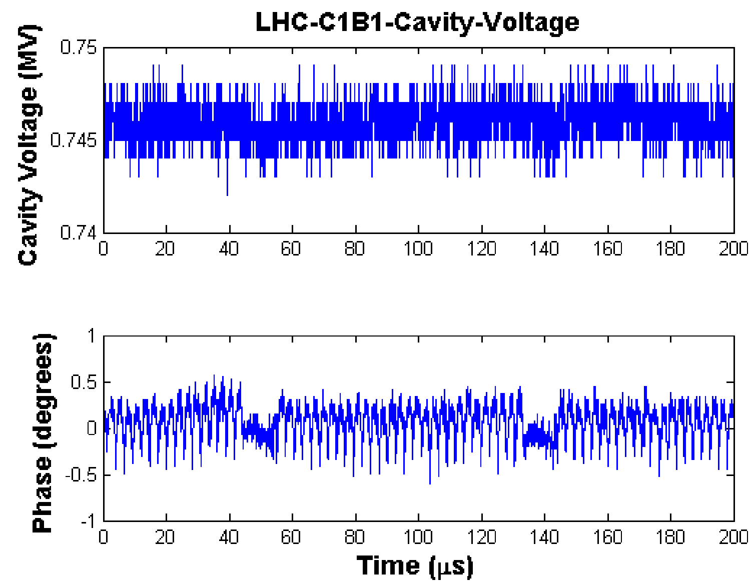


Post LS1 ADT summary

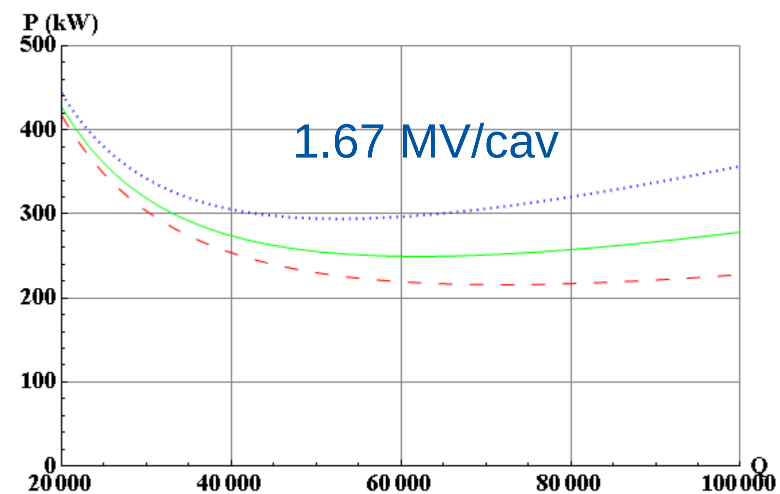


Required RF power

- We keep the voltage constant during beam and no-beam segment and detune the cavity so that the demanded klystron power is equal in both cases. That minimizes the peak demanded klystron power
- The power then depends on V, $I_{rf,pk}$ (RF component of beam current during beam segment) and cavity loaded Q_L
- We consider the nominal LHC beam: 1.1E11 p/bunch, 2808 bunches, 0.55 ADC. The RF component of beam current depends on the bunch length and profile



Opposite: Power versus QL for 1.67 MV/cav, 1.25 ns long bunches, cosine square (fb=0.837), gaussian (fb=0.715). Point-like bunches (fb=1)



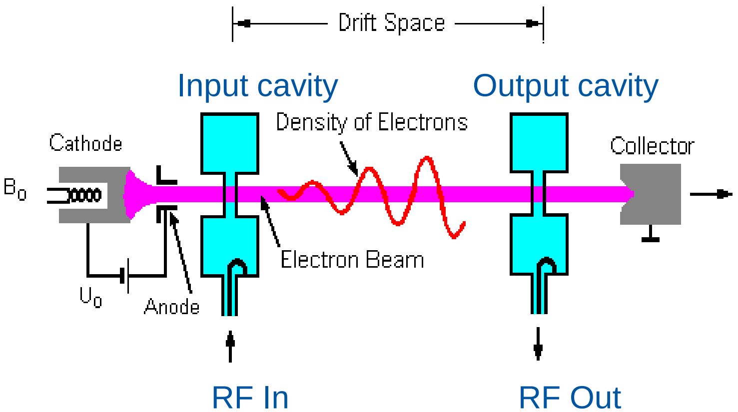
- We keep RF voltage constant during beam-on and gap.
- To keep power constant over one turn we must detune the cavity for the half-beam-intensity

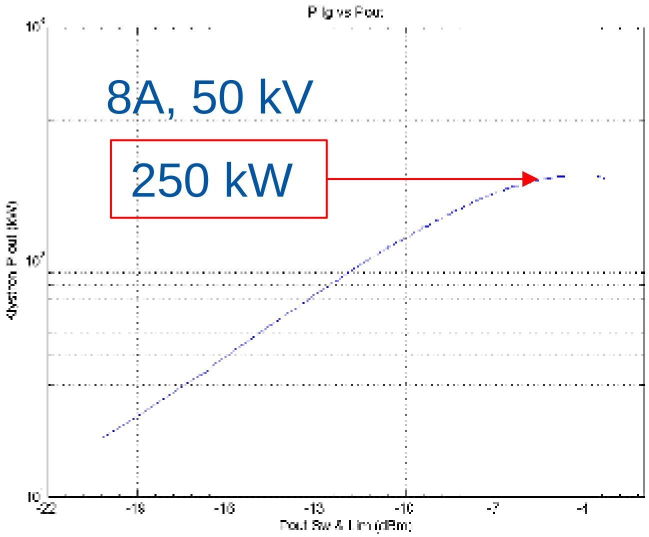
$$x_{opt} = \left[\frac{\Delta f}{f}\right]_{opt} = -\frac{1}{2} R/Q \frac{I_{DC}}{V_{acc}}$$

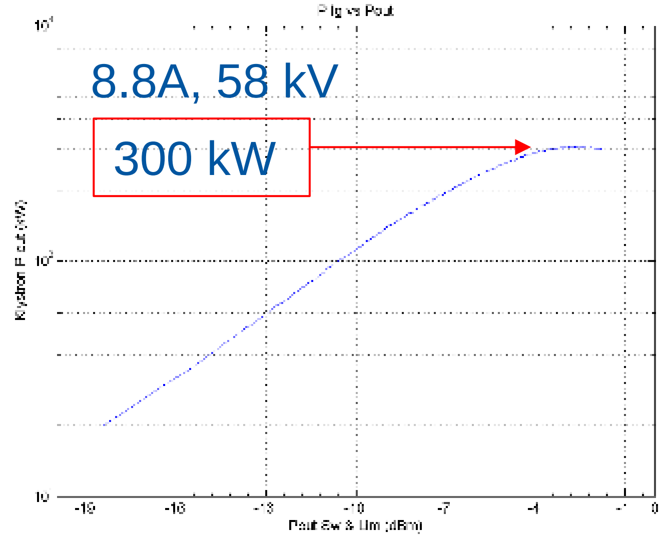
$$P(x) = \frac{1}{8} \frac{|V_{acc}|^2}{Q_L R/Q} + \frac{1}{2} Q_L R/Q \left| \frac{V_{acc}}{R/Q} x + I_{DC} \right|^2$$

- At injection:
  - 6 MV (Vacc=0.75 MV/cav) to minimize capture loss
  - Low Q_L favorable for fast damping of momentum/phase errors
  - For 0.6 A DC **nominal**
    - $Q_L = 20000$
    - Detuning -7.2 kHz
    - Klystron power 120 kW
- During physics:
  - Lifetime limited by intra-beam scattering. Emittance must be blown up to 1.5 eVs
  - 12 MV (Vacc=1.5 MV/cav)
  - For 0.4 A DC **2/3 nominal**
    - $Q_L \sim 60000$
    - Detuning -2.4 kHz
    - Klystron power 160 kW

- The power available from the LHC klystron can be changed by modifying its DC settings: Cathode Current and Anode Voltage



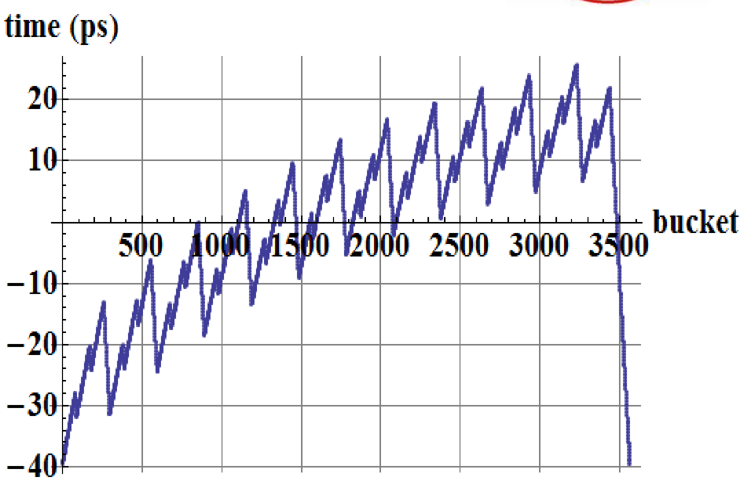




- We could operate the klystrons at low DC settings during filling where 120 kW are sufficient
- Move to high-power settings before start ramp. Procedure tested during run 1.

Other planned LLRF improvements

- A longitudinal damper, acting via the ACS cavities, would reduce the capture losses at injection. A first MD was conducted in 2013. Work will continue during and after LS1
- The RF voltage phase modulation along the beam batch will be essential in the HiLumi era (above ~0.6 A DC). Several MDs in 2012 have given good results. Incompatibility with the 1-T feedback must be understood. Work will continue after LS1



Modulation of the cavity phase by the transient beam loading in physics. 2835 bunches, 1.7 1011 p/bunch, 1.5 MV/cavity, QL=60k, full detuning (-7.8 kHz).