LLRF at CERN
Status and New Developments

Presented by W. Hofle

LLRF workshop 2017, Barcelona, 16th October 2017

Overview

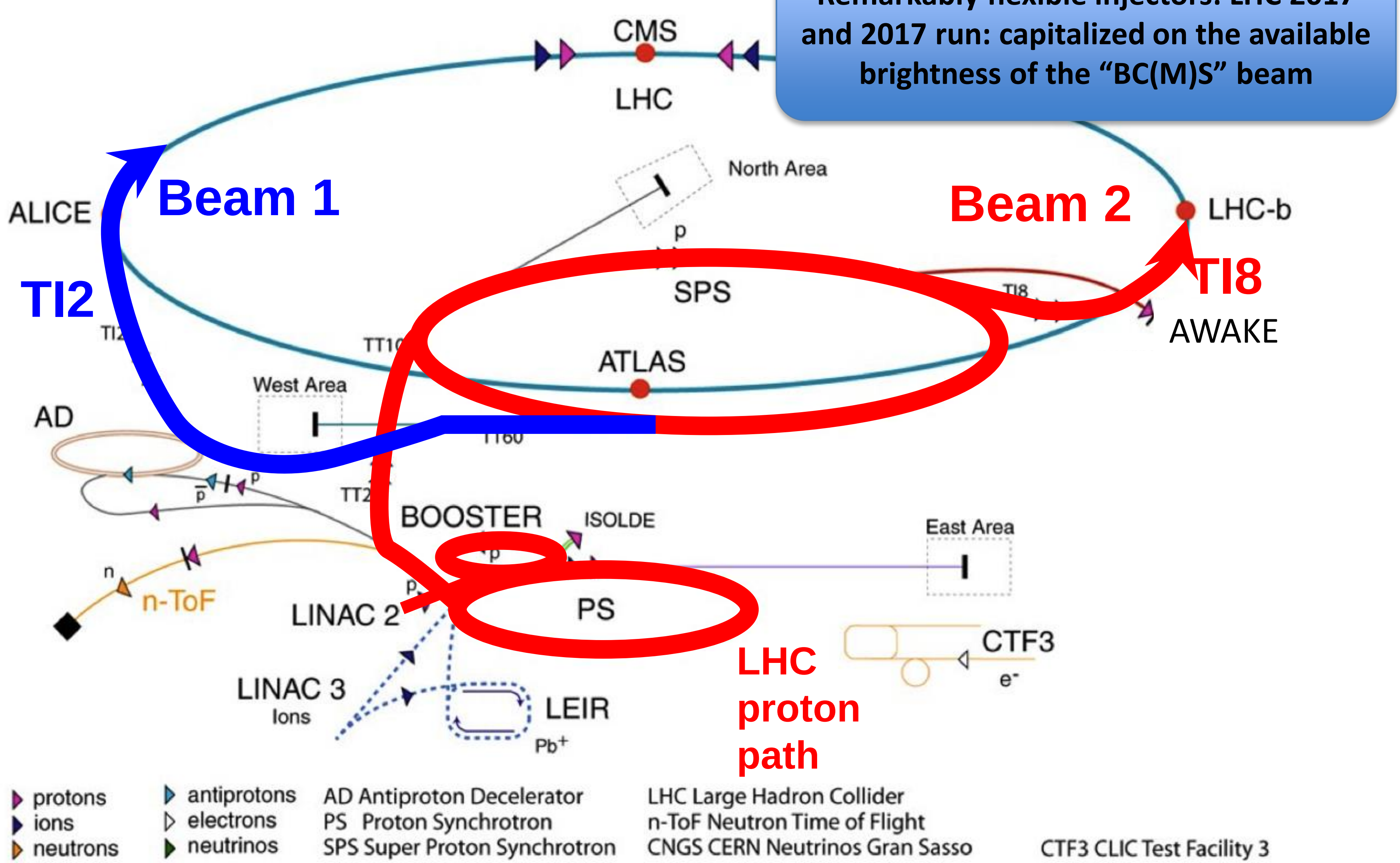
Contributions from CERN for

- **LHC**
- **LINAC4, LHC Injector Upgrade Project (LIU)**
- **AWAKE, FCCee**
- **ELENA, HIE-Isolde**

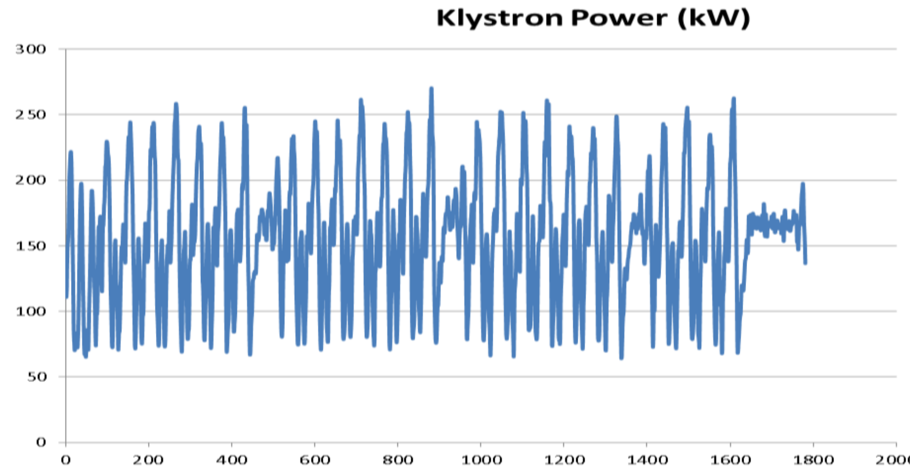
- **Summary and outlook**

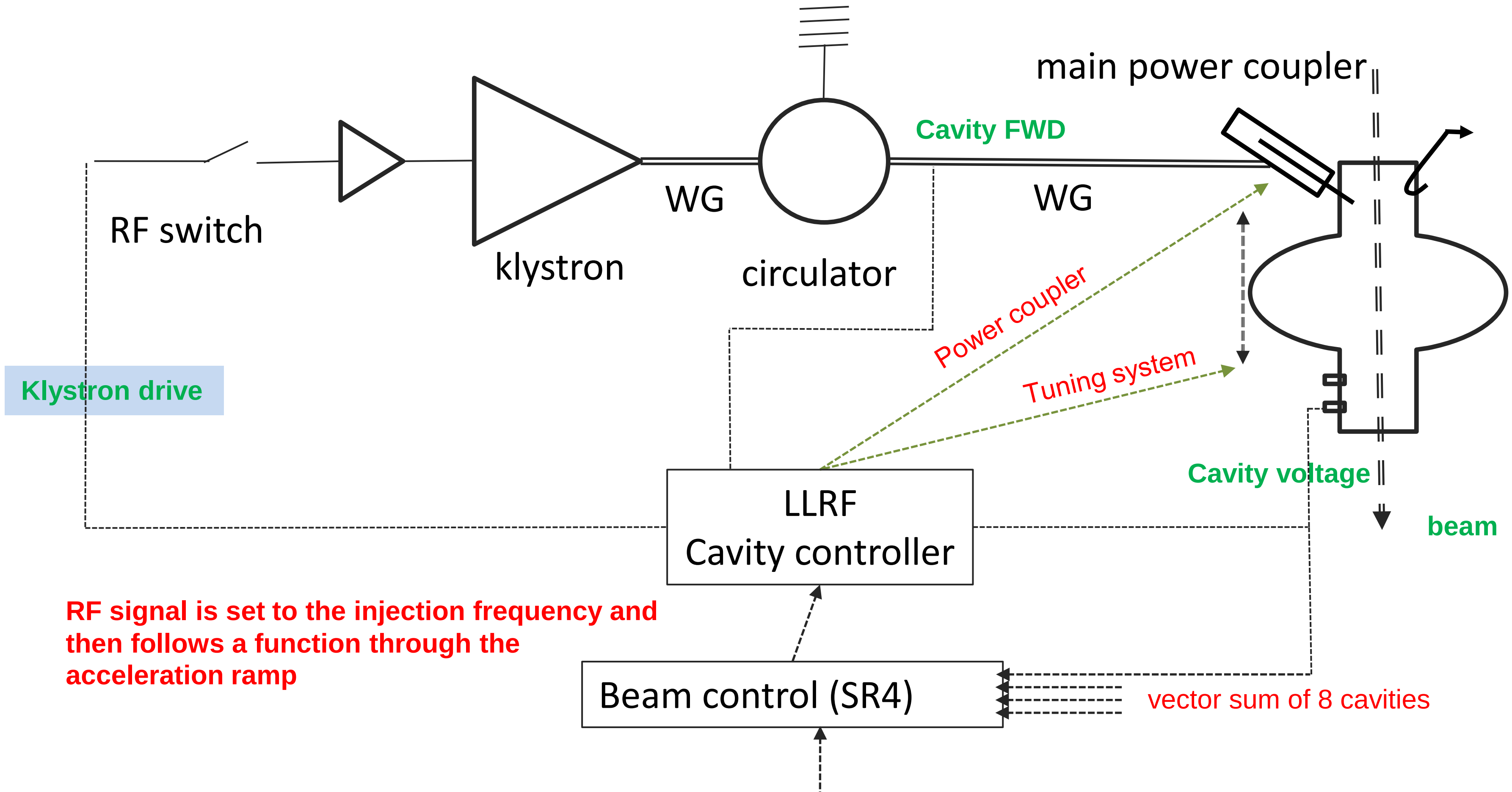
The accelerator complex

Remarkably flexible injectors: LHC 2017 and 2017 run: capitalized on the available brightness of the "BC(M)S" beam



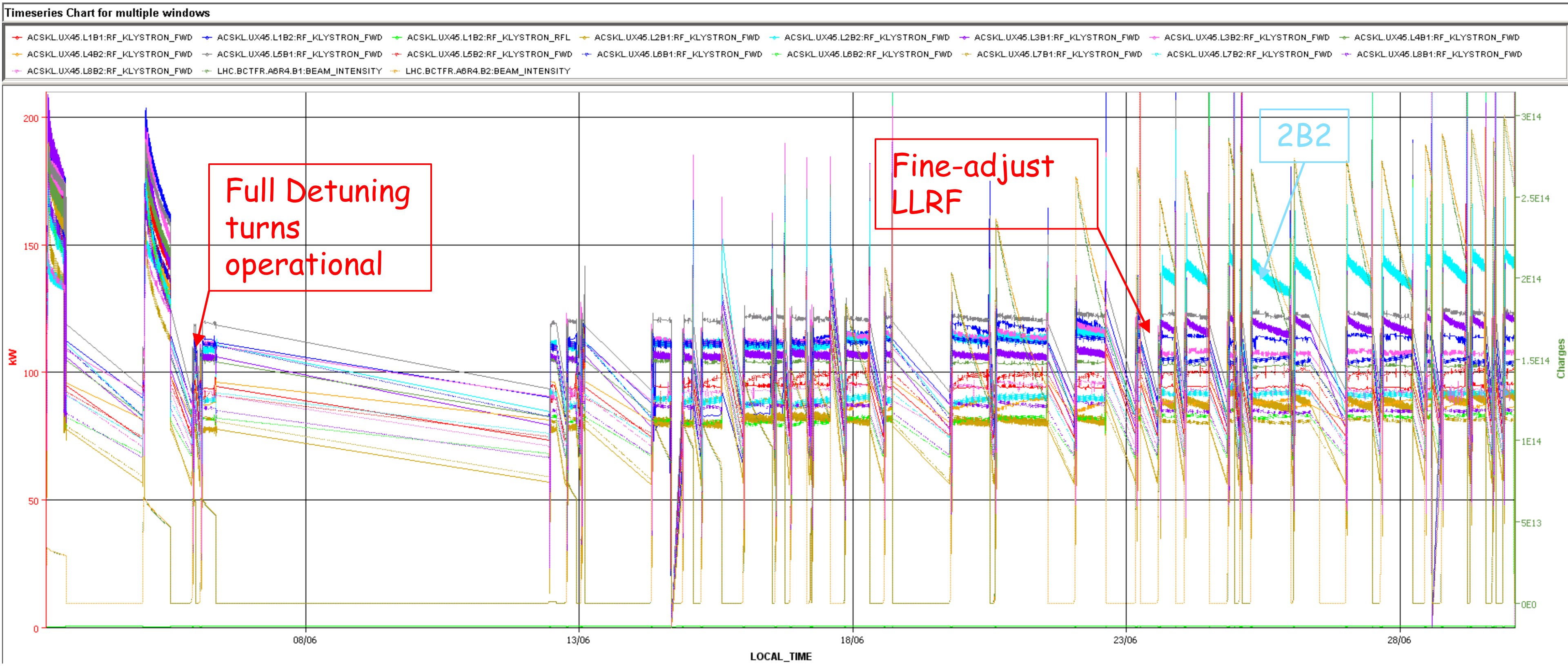
LHC LLRF system





RF signal is set to the injection frequency and then follows a function through the acceleration ramp

Reduction of required klystron power in LHC



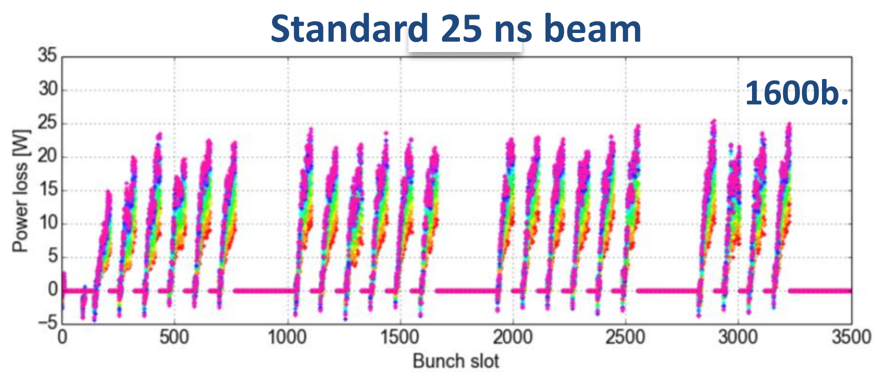
- Full Detuning switched ON June 4th, 2017 with 25 ns spaced bunches
- Above plot the power of all klystrons, plus beam intensity for all fills that made it to physics (injphys, preramp, …, stable), from June 3rd till now
- All klystron power below 120 kW (except 2B2, @ 140 kW)
- Currently running with > 1800 bunches 8b4e beam, luminosity levelled at 1.5 design value
- 36 fb^{-1} produced in 2017 (goal is 45 fb^{-1})

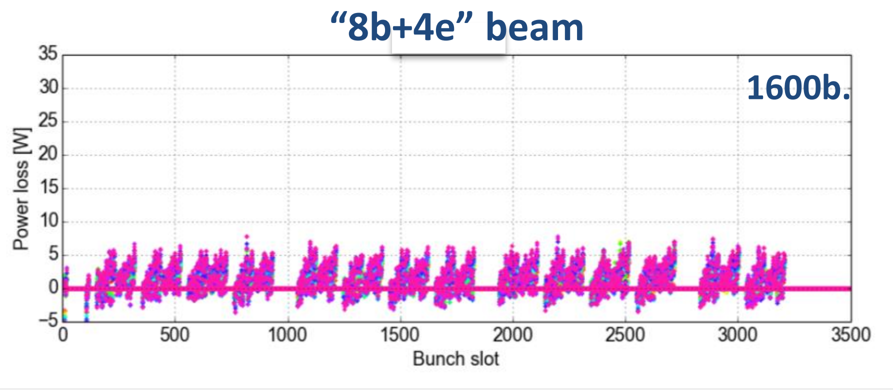
Talk by P. Baudrenghien

Electron cloud studies BCMS and 8b+4e

Motivation:

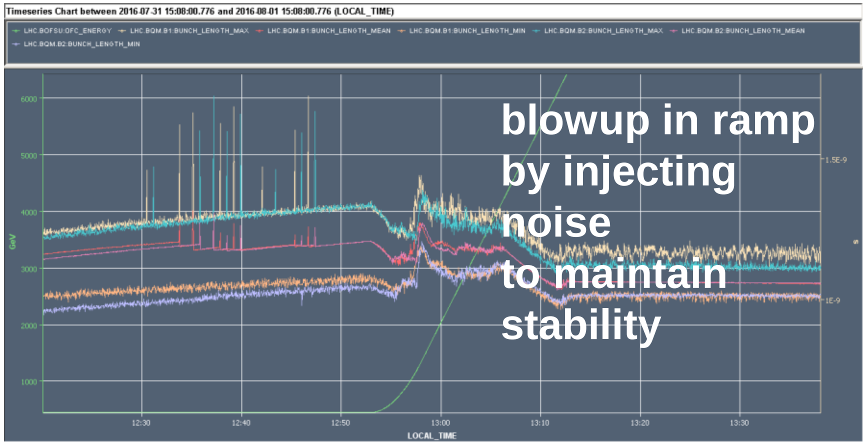
- **8b+4e scheme** is **fall-back scenario for HL-LHC** (in case e-cloud effects are too strong)
- Tests performed in the LHC in **2015** confirmed that the 8b+4e scheme can be used to **fully suppress the e-cloud** formation in the arcs, at the cost of **~30% less bunches**
- Used operationally as of fall 2017 as mitigation of the "16L2" issue (beam dumps by vacuum degradation from trapped gas on beam screen, being released by e-cloud heat load)





reduced e-cloud heat load

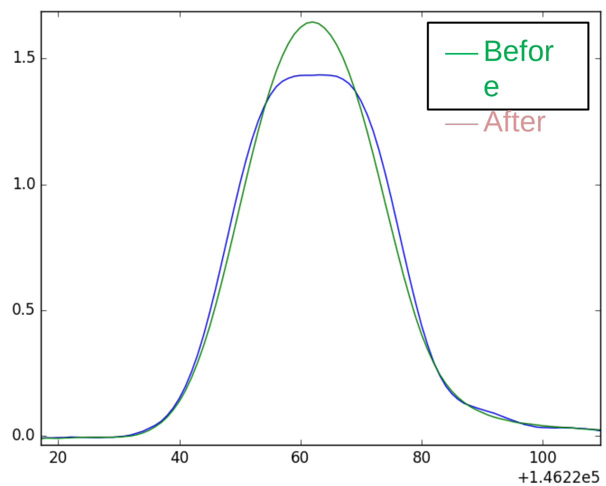
RF longitudinal blow-up in LHC



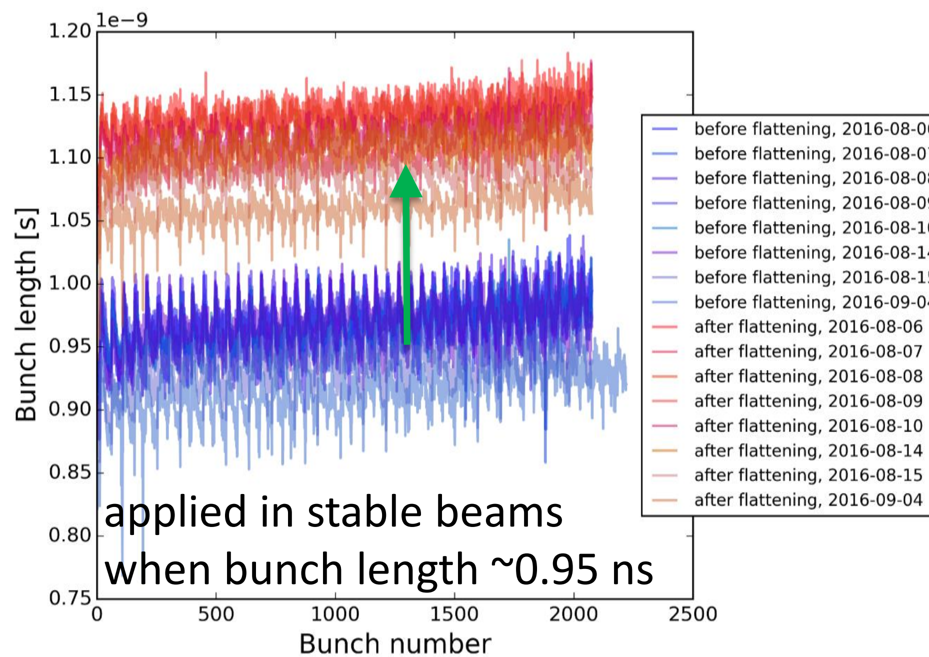
blowup in ramp by injecting noise to maintain stability

after (Fill 5151 in 2016) spread in bunch length 120-160 ps, reduced from 410 ps – 450 ps

Blow-up by RF modulation changes bunch shape (“flattening”) 6.8.16-4.9.16

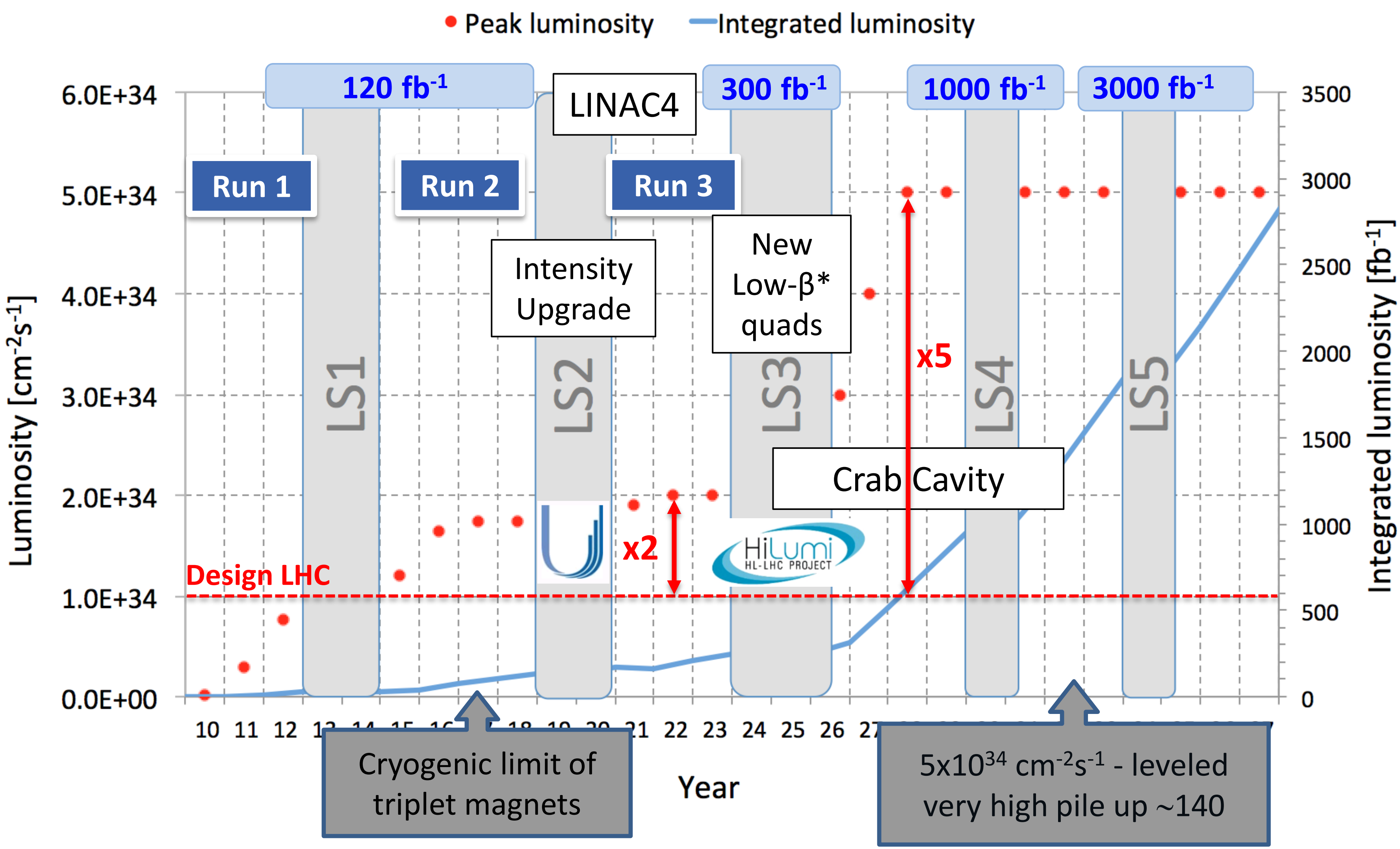


bunch lengthening at request of LHCb for reduction of pile-up density



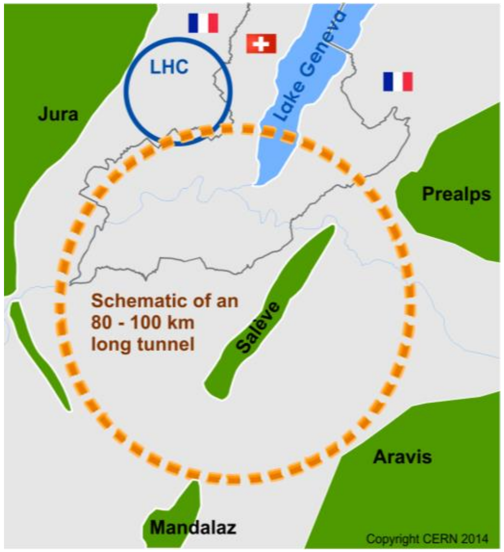
applied in stable beams when bunch length ~0.95 ns

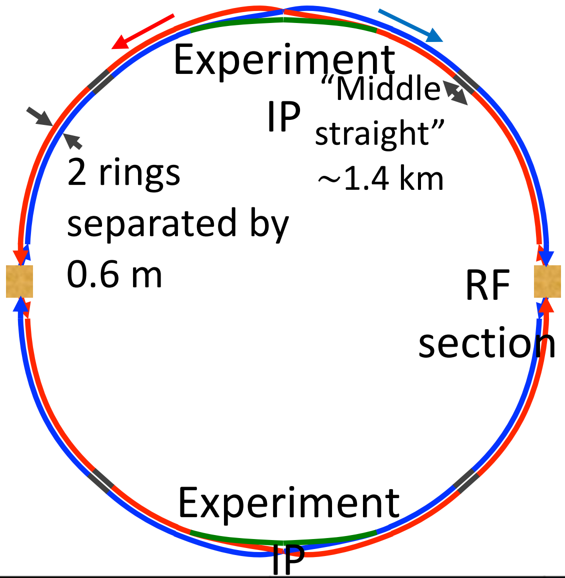
HL-LHC luminosity reach



100 fb^{-1} reached in first week of October 2017, target is 45 fb^{-1} in 2017

Beyond LHC: FCCee (~100 km tunnel)





	Z	W	H	$ttbar_1$	$ttbar_2$
Beam energy [GeV]	45.6	80	120	175	182.5
Beam current [mA]	1390	147	29	6.4	5.4
Number of bunches	16640	2000	393	48	48
Beam RF voltage [MV]	100	440	2000	9500	11000
400 MHz cavities	52 (1-cell)	52 (4-cell)	136 (4-cell)	104 (4-cell)	104 (4-cell)
800 MHz 5-cell cavities				296	376
Runtime [year]	4	1	3	1	3

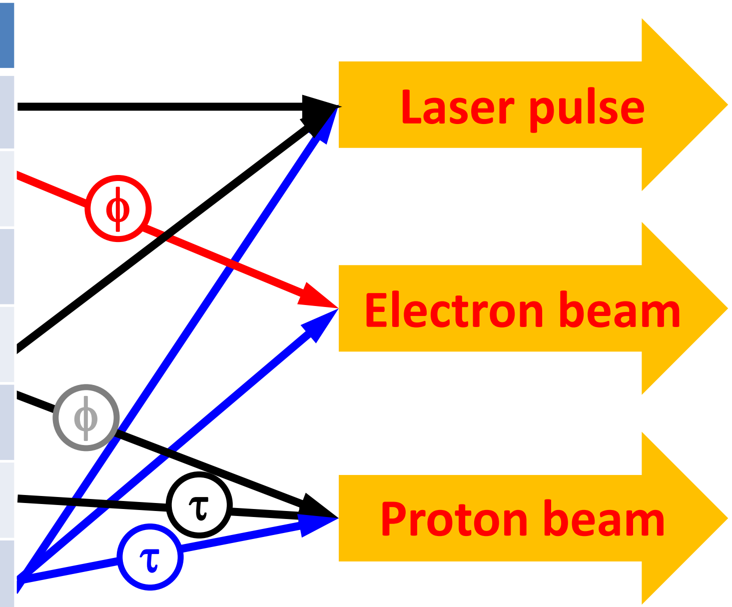
Poster: A. Butterworth

Challenging RF system for FCCee
while FCChh is for RF very similar to LHC

AWAKE: Synchronizing 3 Beams

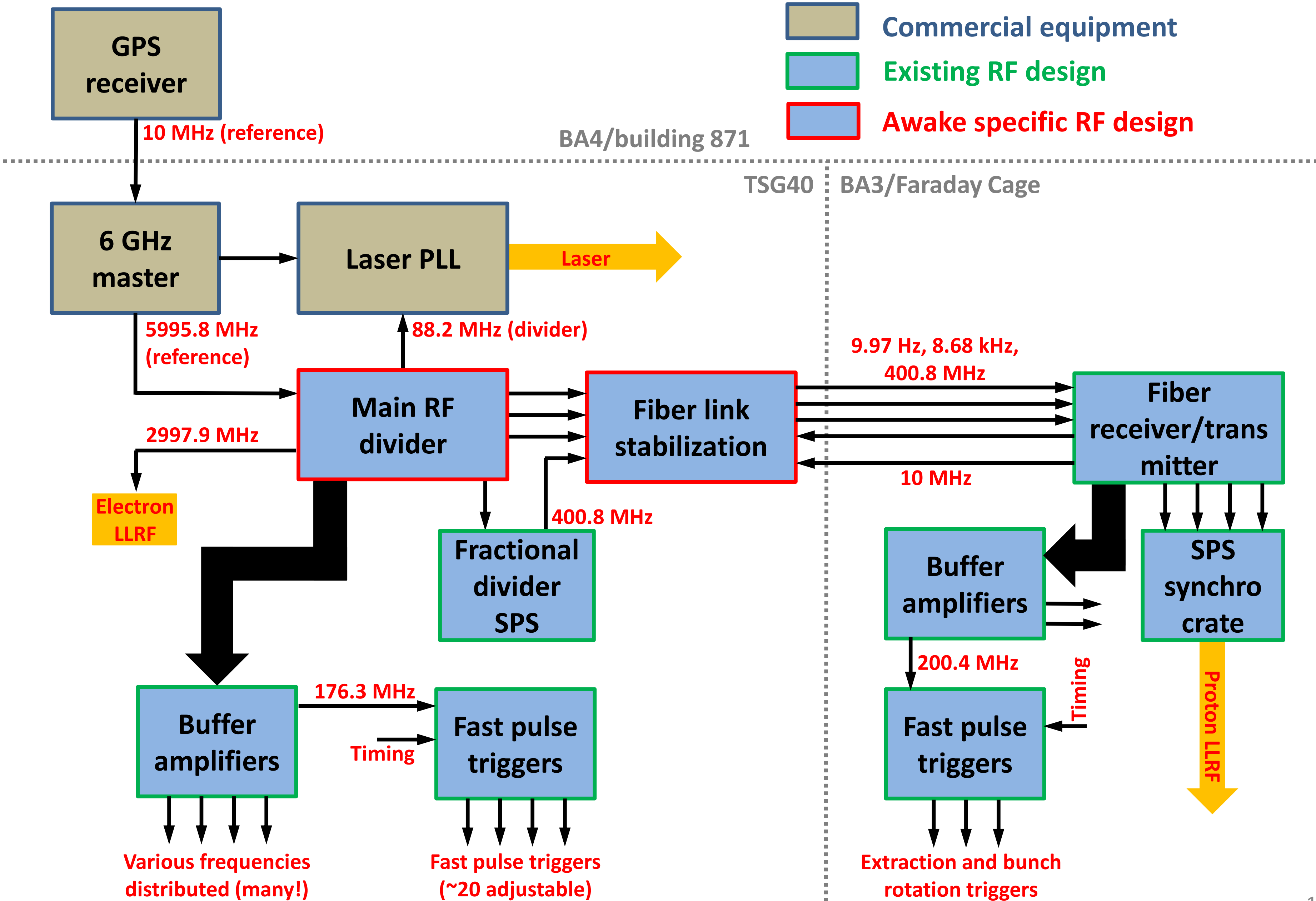
- Proton bunch driven, plasma wake field acceleration
  Synchronization and RF distribution must deliver **wide range of RF signals** for laser, electron and proton beams
- **Reference: signals (f_{ML}, f_{rep}) for laser**
- Signals for proton/electron beams and fast triggers **shifted**

Signal	Frequency	Ratio
Laser phase locked loop, f_{LPLL}	5.9958 GHz	1
Electron acceleration, $f_{RF,e}$	2.9979 GHz	$f_{LPLL}/2$
2×Laser mode-locker, $2f_{ML}$	176.347 MHz	$f_{RF,e}/17$
Laser mode-locker, f_{ML}	88.1735 MHz	$f_{RF,e}/34$
2×SPS RF system freq., $2f_{RF,SPS}$	400.8 MHz	$2f_{ML}$×25/11
Common frequency, f_c	8.68 kHz	$f_{ML}/10164$
Pulse repetition rate, f_{rep}	9.97 Hz	$f_c/870$



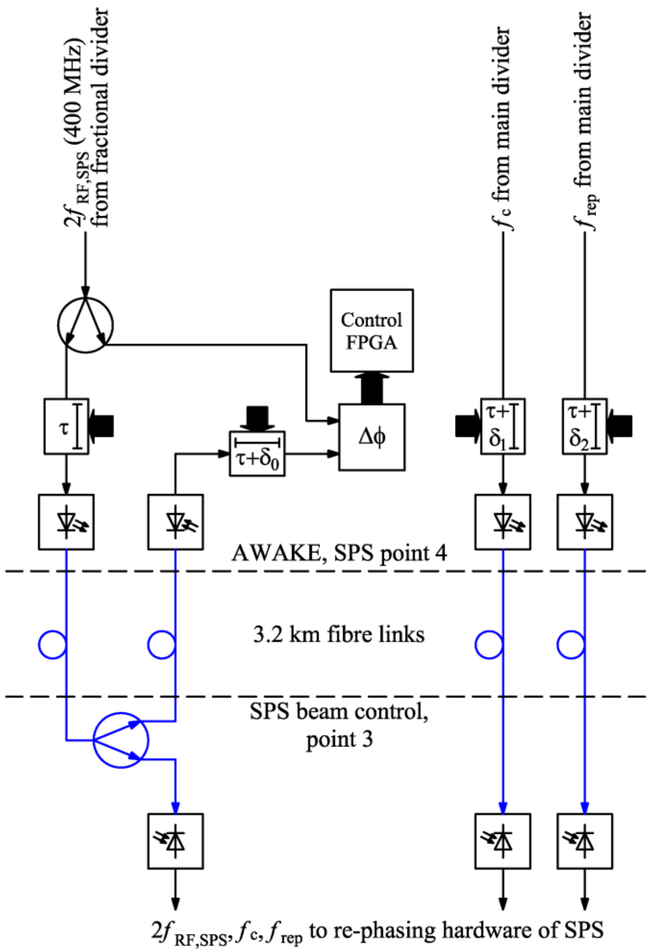
Simultaneous arrival of beams in AWAKE

Simplified overview synchronization and RF distribution

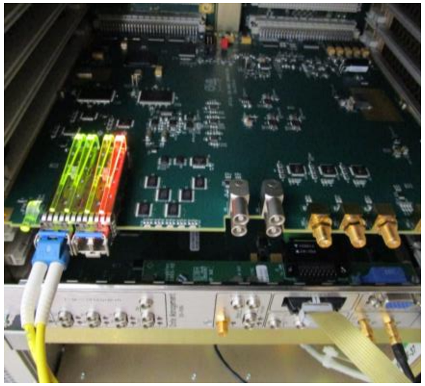


Fiber link stabilization

Simplified diagram



- **Prototype fully meets requirements**
- **Installed and commissioned**



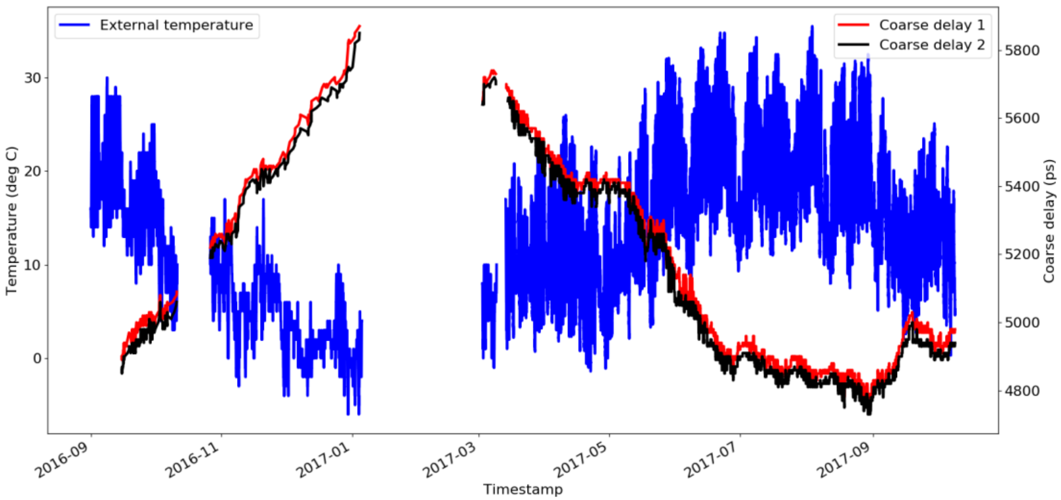
→ **synchronized proton beam extraction to AWAKE**

- **New logging of temperature and compensation delay for correlation**

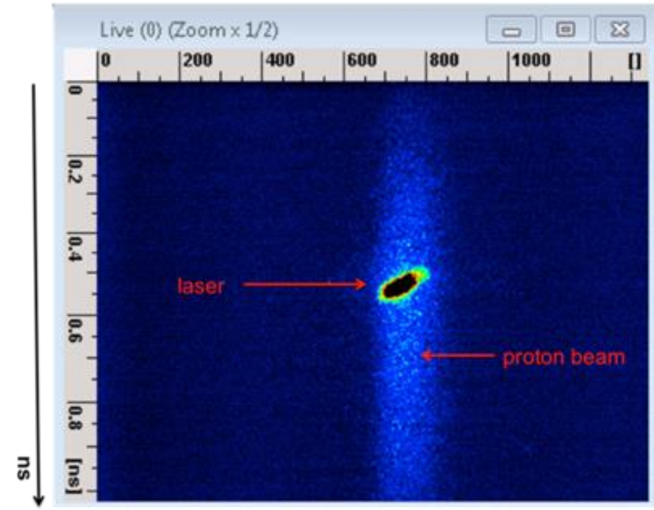
D. Barrientos, J. Molendijk, *Phase stabilization over a 3 km optical link with sub-picosecond precision for the AWAKE experiment*, submitted to IEEE Real Time Conf., 2016

Poster: D. Barrientos et al.

Phase-compensated optical link



Synchronization of the AWAKE proton and laser beams, 29.9.2016
Streak camera measurement with the BTV upstream the plasma cell



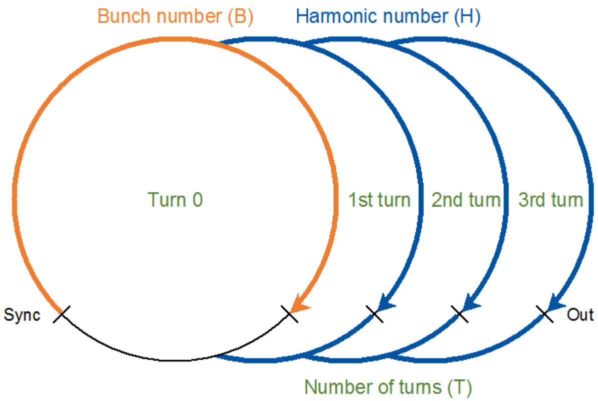
- Precise phase synchronization of proton beam and laser spot for the AWAKE experiment
- Operational since September 2016
- Performance tests show low phase noise and residual phase drift

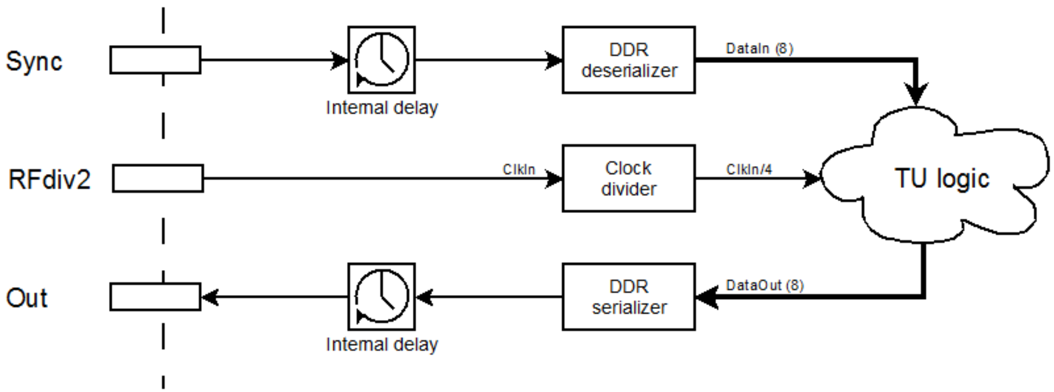
Test	Phase drift
Open loop	507.93 ps/°C
Optical splitter	22.72 ps/°C
WDM	0.61 ps/°C

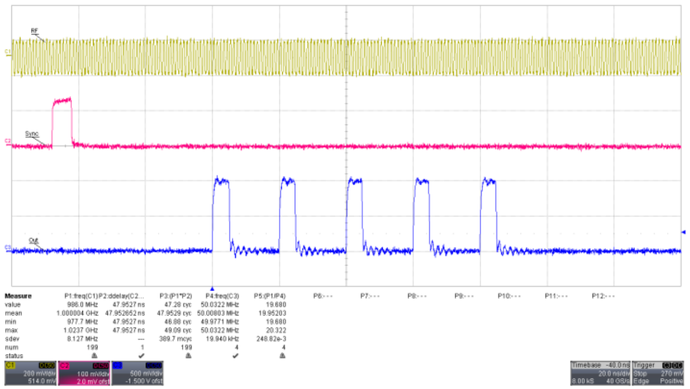
Poster: D. Barrientos

1 GHz Trigger Unit in FPGA

- Emulation of counters and state machine at 1 GHz in FPGA
- Flexible design: New modes of operation
- Applications throughout all CERN LLRF systems

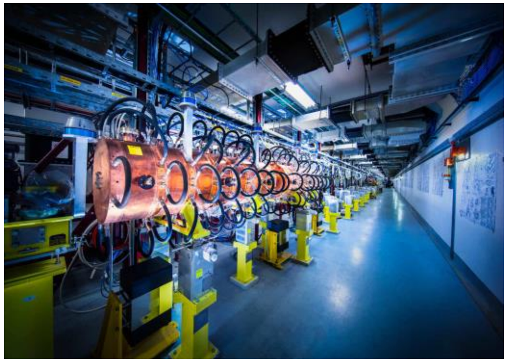


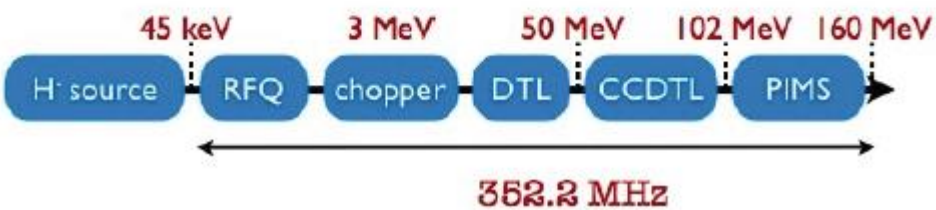




Poster: D. Barrientos

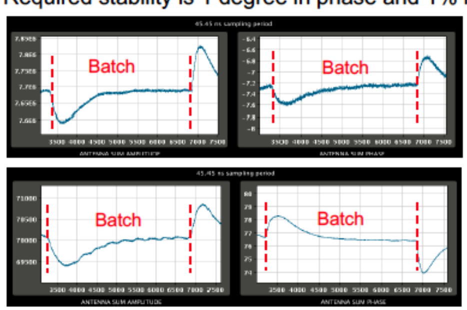
LINAC4 evolution: reliability run





Field Regulation Results

Results measured with a 160 μs long batch and beam current of 14 mA using the current PI controller. Required stability is 1 degree in phase and 1% in amplitude with a beam current of 40 mA.



CCDTL7 Voltage amplitude and phase. Uncompensated beam loading **-1.5% (amplitude), -0.3 deg (phase).**

Buncher1 Voltage amplitude and phase Uncompensated beam loading **-0.7% (amplitude), +2 deg (phase).**

Figure 6 – Linac4 field regulation results

Linac4 Beam Parameters Ion species	H-
Output energy	160 MeV
Bunch frequency	352.2 MHz
Max. rep. rate	2 Hz
Beam pulse Length	400 microsec
Mean pulse current	40 mA
Beam power	5.1 kW
N. particles per pulse	$1.0 \cdot 10^{14}$
N. particles per bunch	$1.14 \cdot 10^{9}$
Beam transverse emittance	0.4 πmm mrad (rms)

Poster: R. Borner

Paradigm change: from sweeping clock to fixed clock

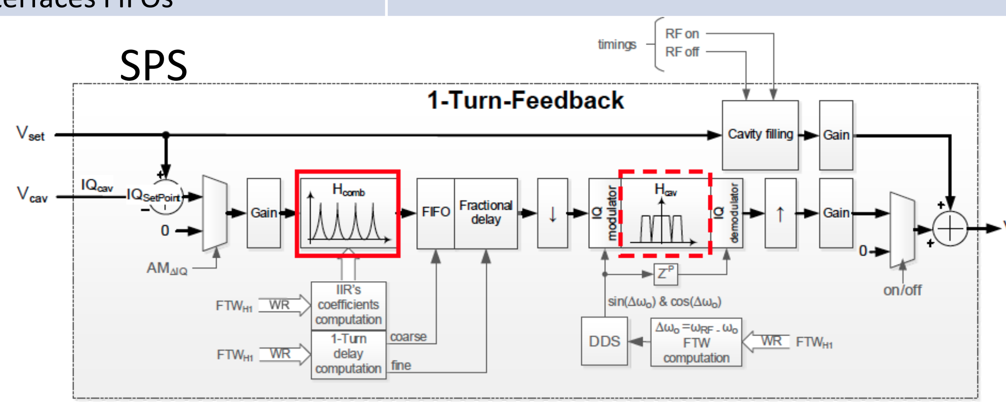
	Swept Clock	Fixed Clock
STABILITY OF THE FEEDBACK LOOPS	Variable sampling clock → Variable loop delay Compromise in Regulation Bandwidth and Feedback Stability	Fixed sampling clock → Fixed loop delay Optimal Regulation Bandwidth and Feedback Stability
PHASE JUMPS	RF as harmonic of clock → multiplexing required to cover wide RF range Phase Jumps when multiplexing	Simple DDS implementation can cover a wider range without interruption
ADC AND DAC	Complex analogue reconstruction filter Coherent signals fall in swept range Non optimal integrated noise	Fixed analogue reconstruction filters Coherent signals at fixed digital frequencies Optimized integrated noise
UP AND DOWN MIXING	Lower spectral purity of clock → DDS and IQ sensitive to jitter → Problem for heterodyne architectures	Non IQ sampling and Direct down conversion easier
TECHNOLOGY LIMITATIONS	PLLs tracking and locking Max dF/dt for DCM in FPGAs Non optimal PAR Synchronous digital logic design Clock domain synchronization Complex PAR constraints Serial interfaces FIFOs	PLLs and DCM readily usable Easy place and route Ease clock domain synchronization Ease use of serial interfaces and modern technologies

Three contributions:

Talks: J. Molendijk (ELENA)
J. Galindo (SPS LIU)

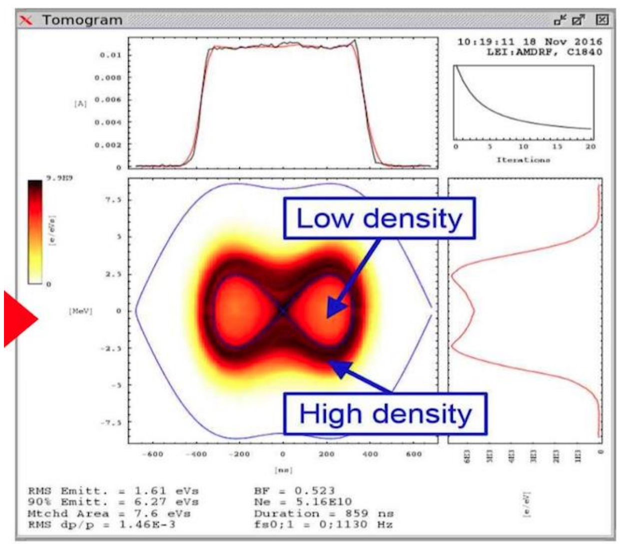
Poster: L. Schmid (SPS LIU)

SPS



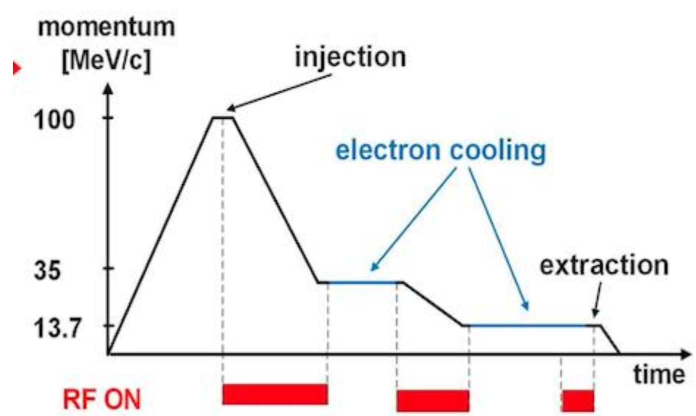
ELENA and PSB LLRF family

- VXS based LLRF system deployed for small synchrotrons at CERN
- 2016: LEIR intensity record with Pb ions
- PSB preparations for new finemet based RF system
- ELENA (anti-protons decelerator) with fixed frequency clocking



hollow bunches in LEIR

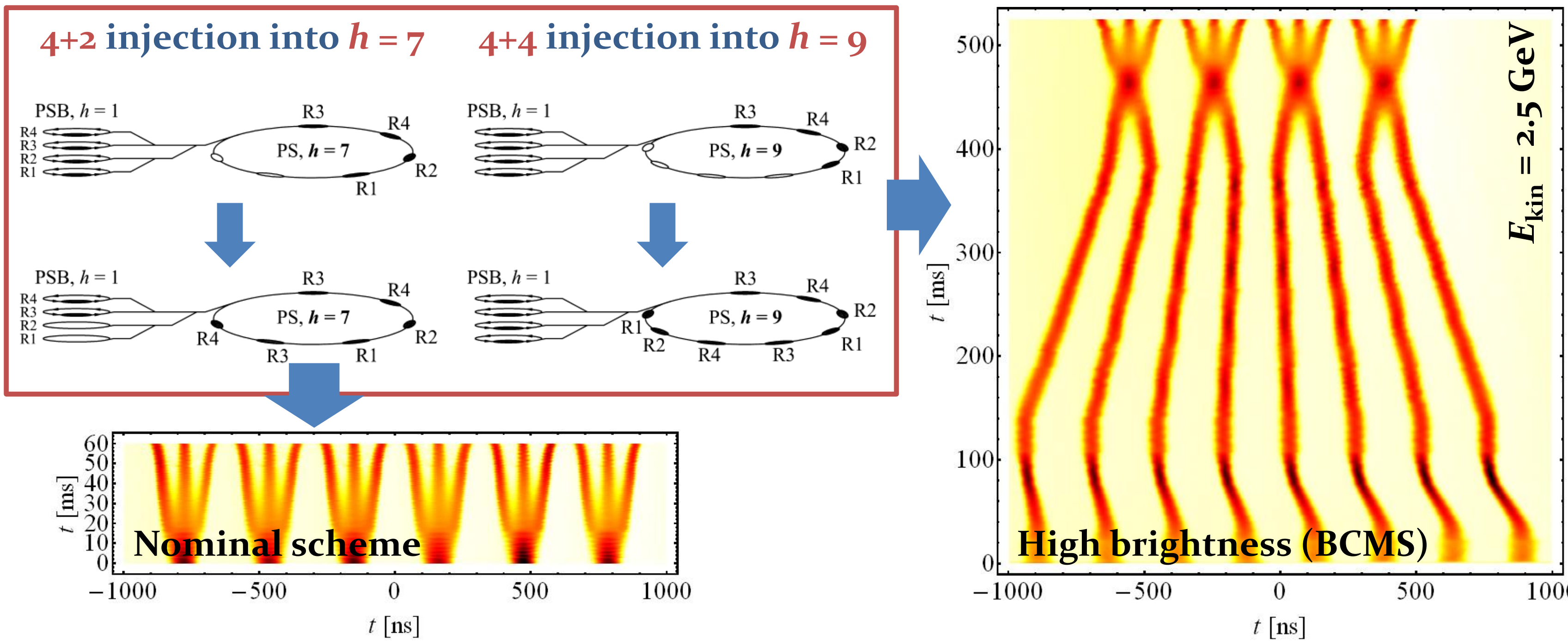
ELENA deceleration of anti-protons



Poster: M. E. Angoletta
Talk: J. Molendijk (fixed frequency sampling)

Key to LHC performance: LLRF schemes in CERN PS

- **Advanced RF manipulations for large variety of LHC type beams**
- **Different injection harmonics, many harmonics during cycle**



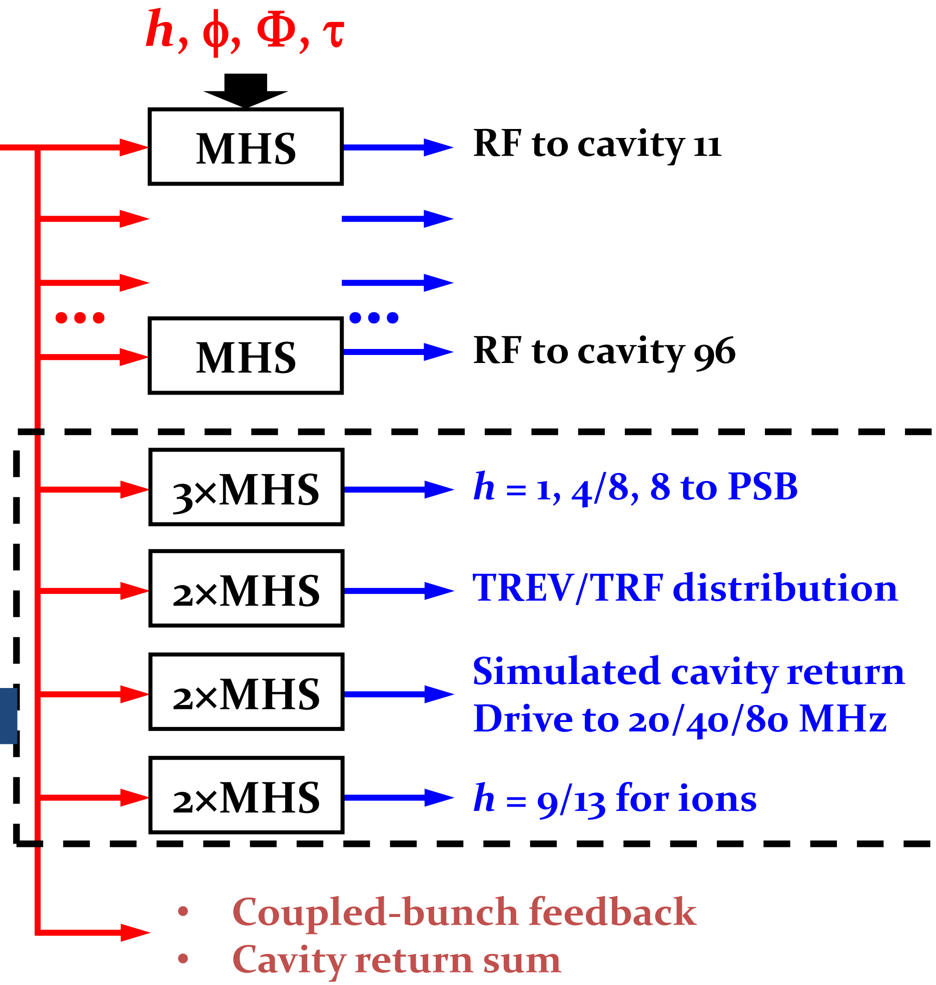
→ **Nominal scheme: 6 PSB bunches → 18 → 36 → 72**

→ **BCMS 25 ns: 8 PSB bunches → 4 → 12 → 24 → 48**

→ **2016: SPS delivers 2 x 48 to LHC; 2017 option: 3 x 48 BCMS versus 4 x 72 ?**

MHS system for PS LLRF upgrade (VME)

- **Multi-harmonic sources exchanged during EYETS 16/17**



- **MHS driving 10 MHz cavities integrated in cavity controller**
- **Separate MHS to generate beam control signals**

→ **Commissioned: 2017 start-up**

Poster: H. Damerau

SPS LIU: Evaluating use of µTCA

µTCA platform

The µTCA platform fits all requirements for the SPS LLRF upgrade. Since the LHC design, the LLRF systems have been developed on VME/VXS platforms for all CERN accelerators. Within the CERN Beams department, the decision has been taken to move away from VME for new projects. We are now prototyping the µTCA alternative as joint effort with the CERN Controls group.

DRTM_DS8VM1
(DESY, Struck Innov. Sys GmbH)

SIS8300-KU
(DESY, Struck Innov. Sys GmbH)

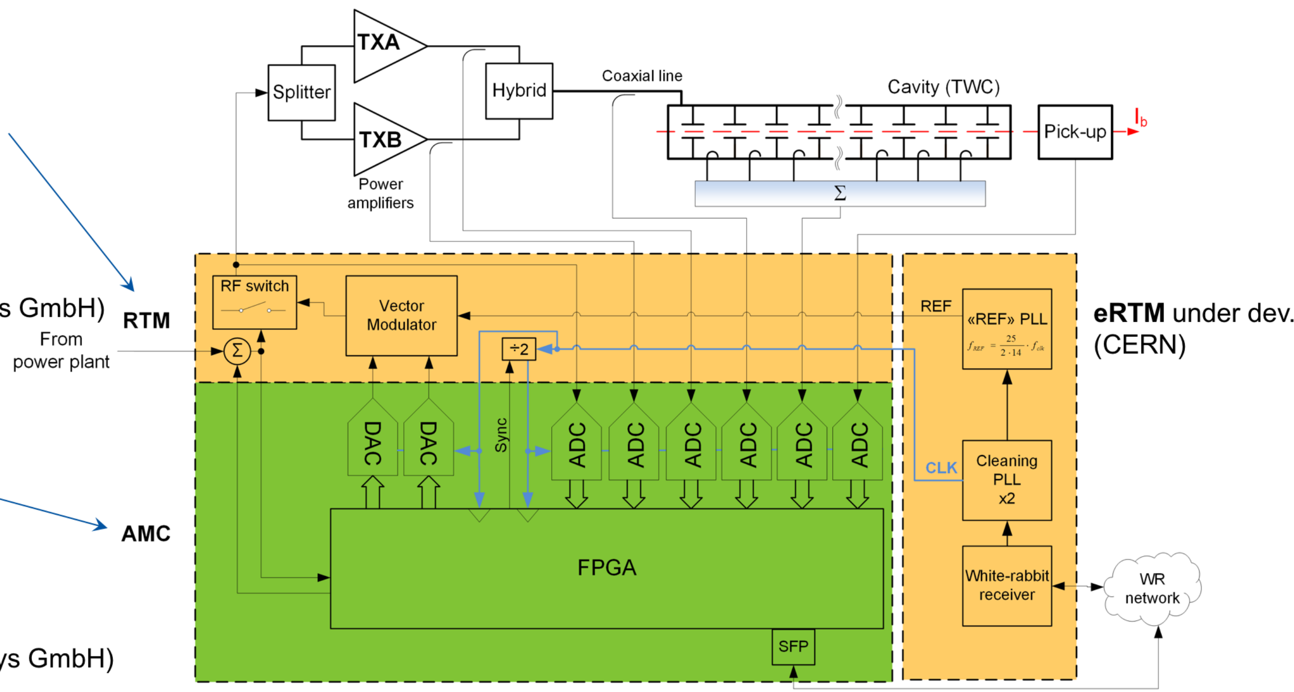


Figure 9 – SPS LLRF cavity controller on µTCA platform

Poster: G. Hagmann

Summary and outlook

- LHC VME LLRF systems being rolled out for applications in injectors: LINAC4, PS, SPS
- PSB LLRF family (VXS based) mature, being used in small CERN synchrotrons, ELENA, LEIR, PSB, ... AD
- Paradigm change with developments both for SPS and ELENA with fixed frequency sampling
- μTCA being tested for SPS 200 MHz LLRF and feedback upgrade as the baseline next generation standard
- Developments for ion post acceleration HIE-Isolde (D. Valuch et al.)
- Crab cavity LLRF developments for SPS (P. Baudrenghien et al.)