ACHIEVEMENTS & NEW CHALLENGES FOR CERN'S DIGITAL LLRF FAMILY

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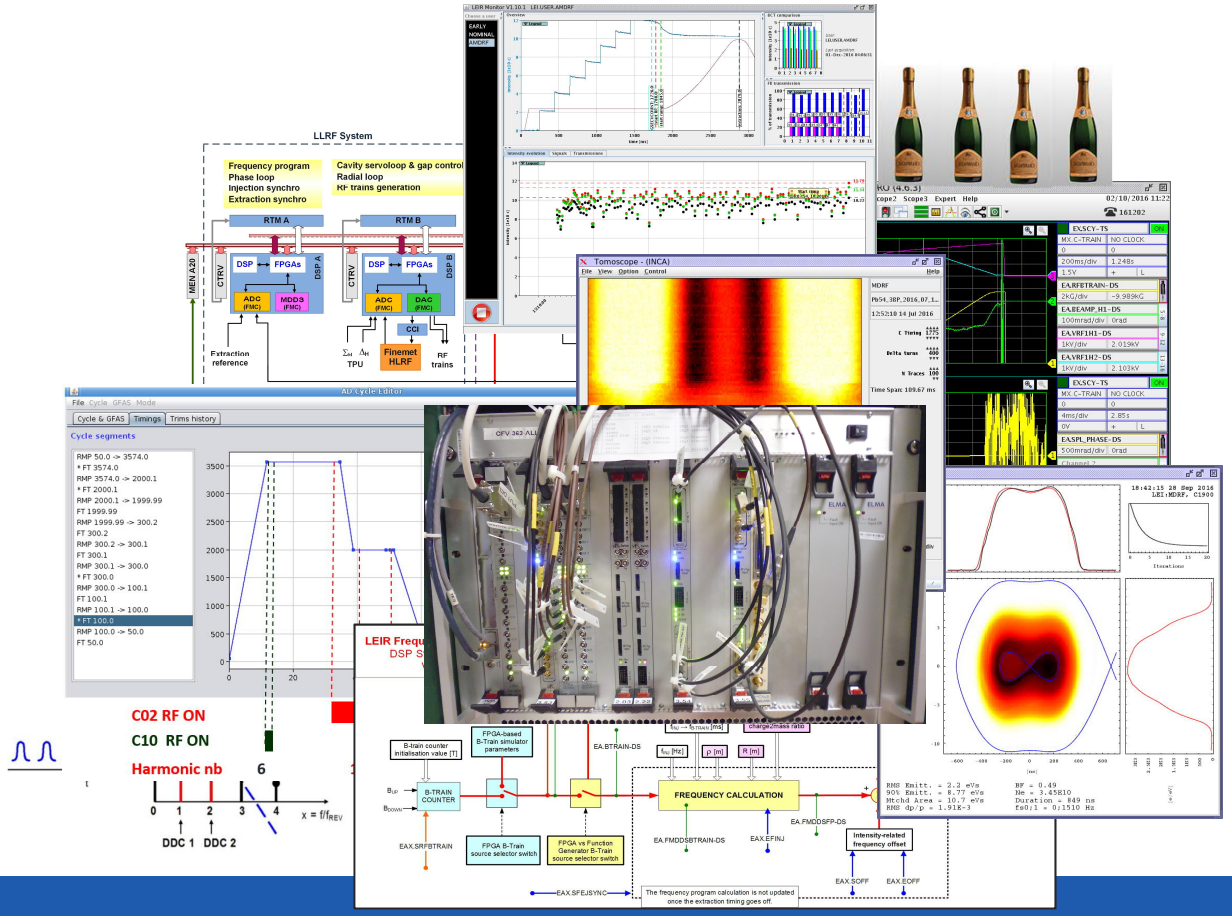
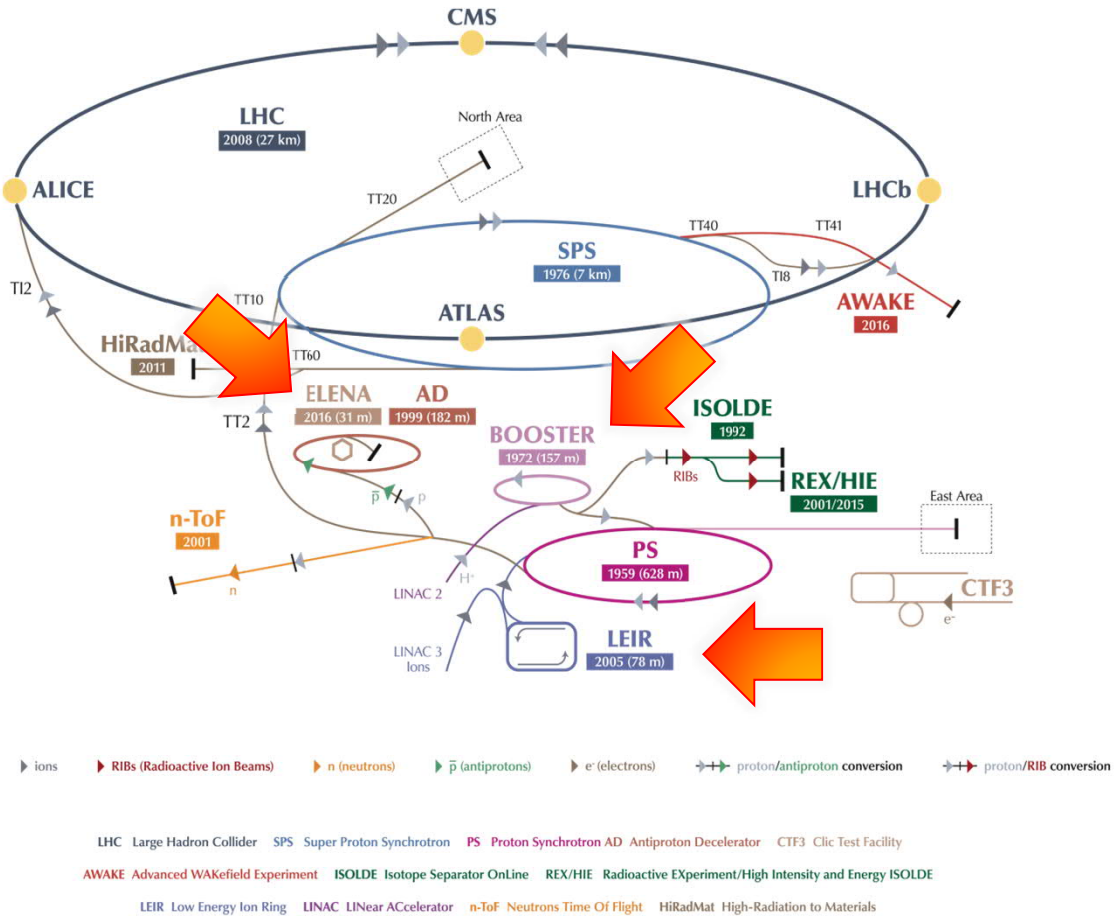


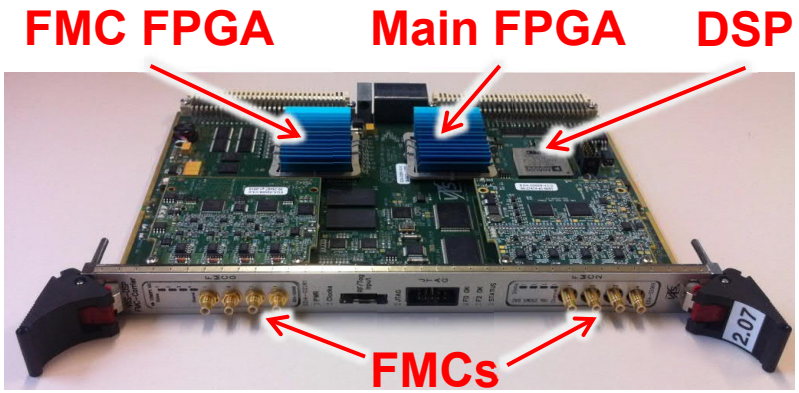
Outline

- **CERN VXS DLLRF overview**
- **LEIR DLLRF**
  - Overview
  - Selected achievements
- **PSB DLLRF**
  - Overview
  - Selected achievements
  - New challenges
- **ELENA DLLRF**
  - Overview
  - Selected achievements
  - New challenges
- **CONCLUSIONS**

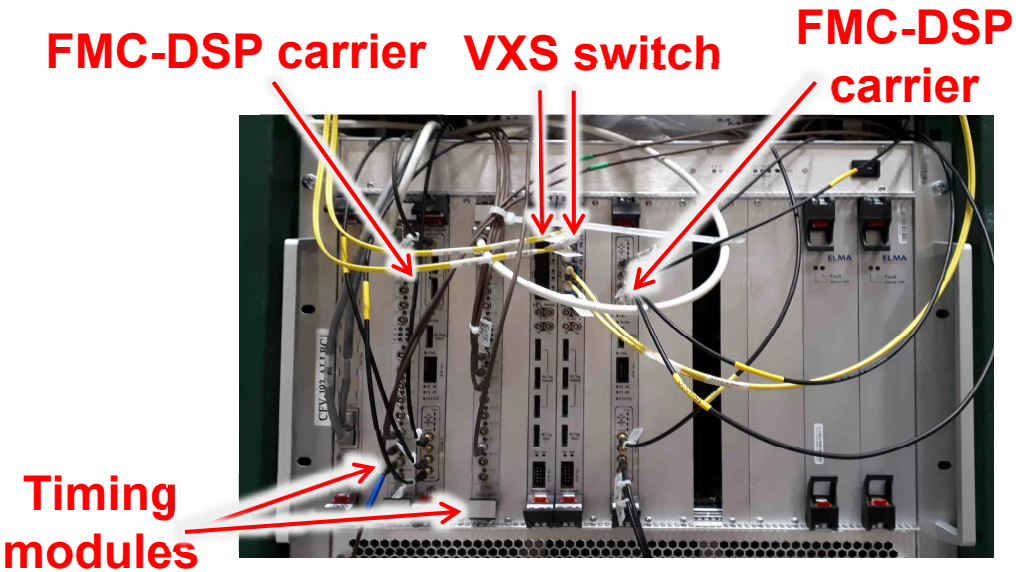


CERN VXS DLLRF overview

- **VXS** (a.k.a. 2nd generation) **DLLRF**: big RF group investment (manpower).
- Deployed on small CERN machines + medical machine (MedAustron).
- Used also for **longitudinal diagnostics** (**RF**) + **orbit systems** (**BI**).
- **Features**:
  - Direct RF sampling, baseband [I,Q] processing.
  - VXS crate, FMC-DSP carrier board, 3 HPC FMC types (function: MDDS, DDC, SDDS).
  - Initially clocked with sweeping clock. Now mostly fixed-frequency clock (→ J. Molendijk's talk @LLRF17).



FMC-DSP carrier board



ELENA LLRF system (2018 version)

VXS DLLRF deployment – past&future

When	What	Who
2014	**MedAustron** LLRF (sweeping clock)	MA+RF
	PSB 4 rings LLRF (sweeping clock)	RF
2016	**AD** orbit	BI
	LEIR LLRF upgrade to 2nd generation LLRF (sweeping clock)	RF
2017	**ELENA** orbit	BI
	ELENA LLRF (fixed frequency clock)	RF
2018	**LEIR** orbit	BI
	LEIR LLRF upgrade to fixed frequency clock	RF
	ELENA LLRF upgrade to include (some) longitudinal diagnostics	RF
2019	 **NOW – LS2** 	
2020	**PSB** LLRF upgrade to fixed frequency + Finemet control @16 h	RF
	ELENA LLRF upgrade to include full longitudinal diagnostics	RF
2021	**AD** LLRF & longitudinal diagnostics (fixed frequency clock)	RF
~2022	Beam loops implementation in **PS** LLRF (sweeping clock)	RF
≥ 2022	Start studies for 3rd generation LLRF system	RF

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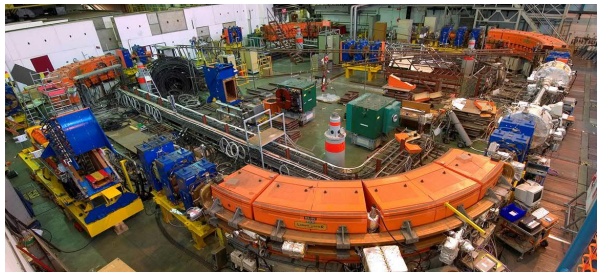

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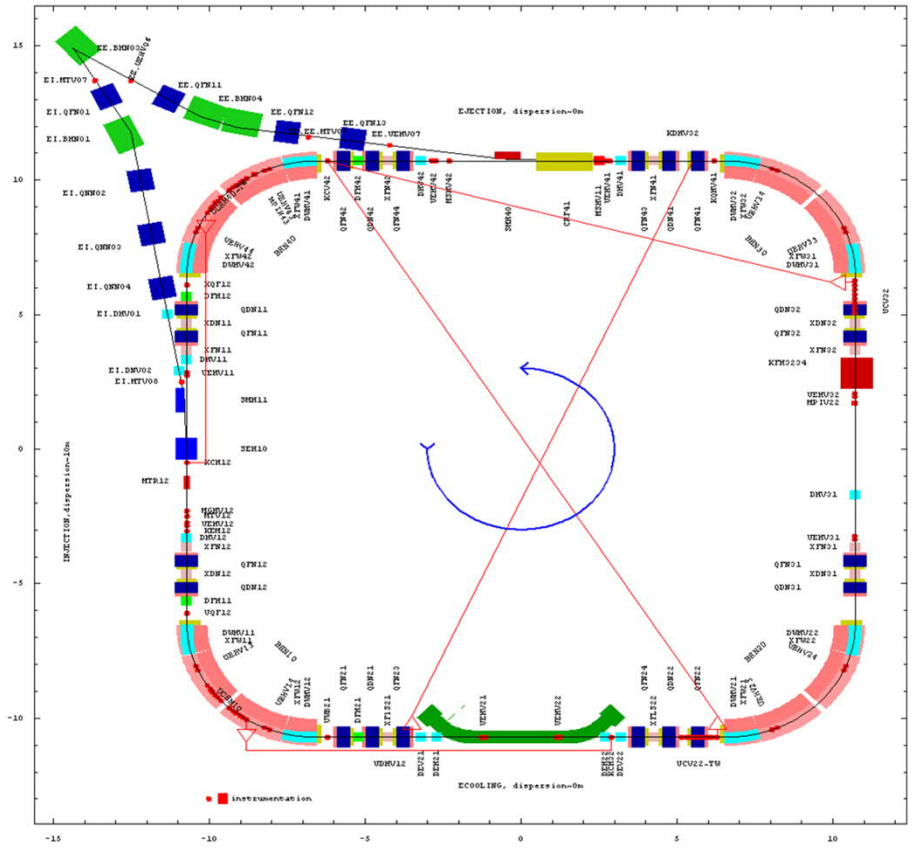
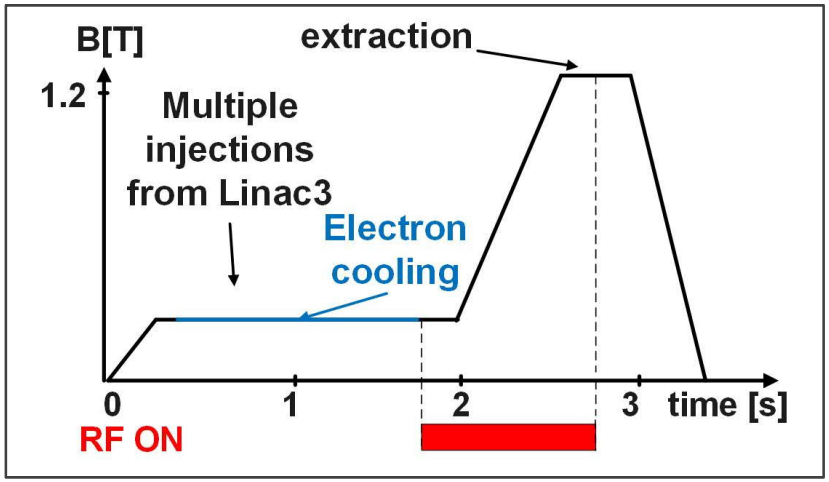
Low Energy Ion Ring



LEIR: the accelerator

Ion accumulator + accelerator, LHC injector.

- Ions: O^{4+}, Ar^{11+}, Xe^{39+}, Pb^{54+}
- Finemet-based HLRF (4 kV_P)



Typical NOMINAL cycle for Pb^{54+}

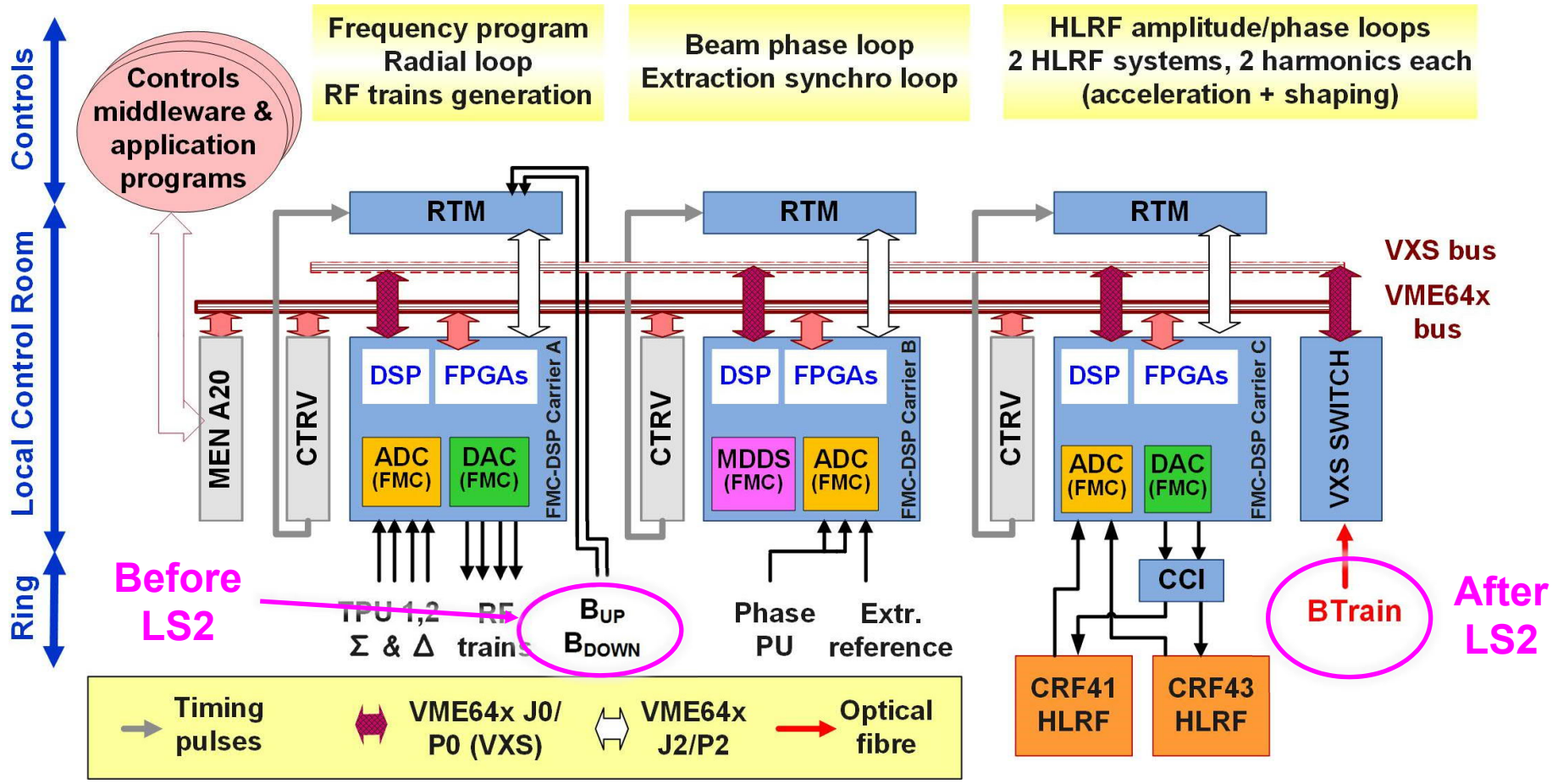
Parameter		Injection	Extraction
Revolution frequency, MHz		0.361	1.423
Energy, MeV/u		4.2	72.2
EARLY scheme	RF harmonic number		1
	Extracted intensity, Nb ions		2.5 E8
NOMINAL scheme	RF harmonic number		2+4, 3+6(*)
	Extracted intensity, Nb ions		10 E8
Circumference, m			78
Acceleration duration, s			~1

LEIR parameters for PB^{54+} ions in 2018.

- After LS2: new Btrain measurement/distribution system
- Possible future usage: biomedical research **BioLEIR** (not funded yet).

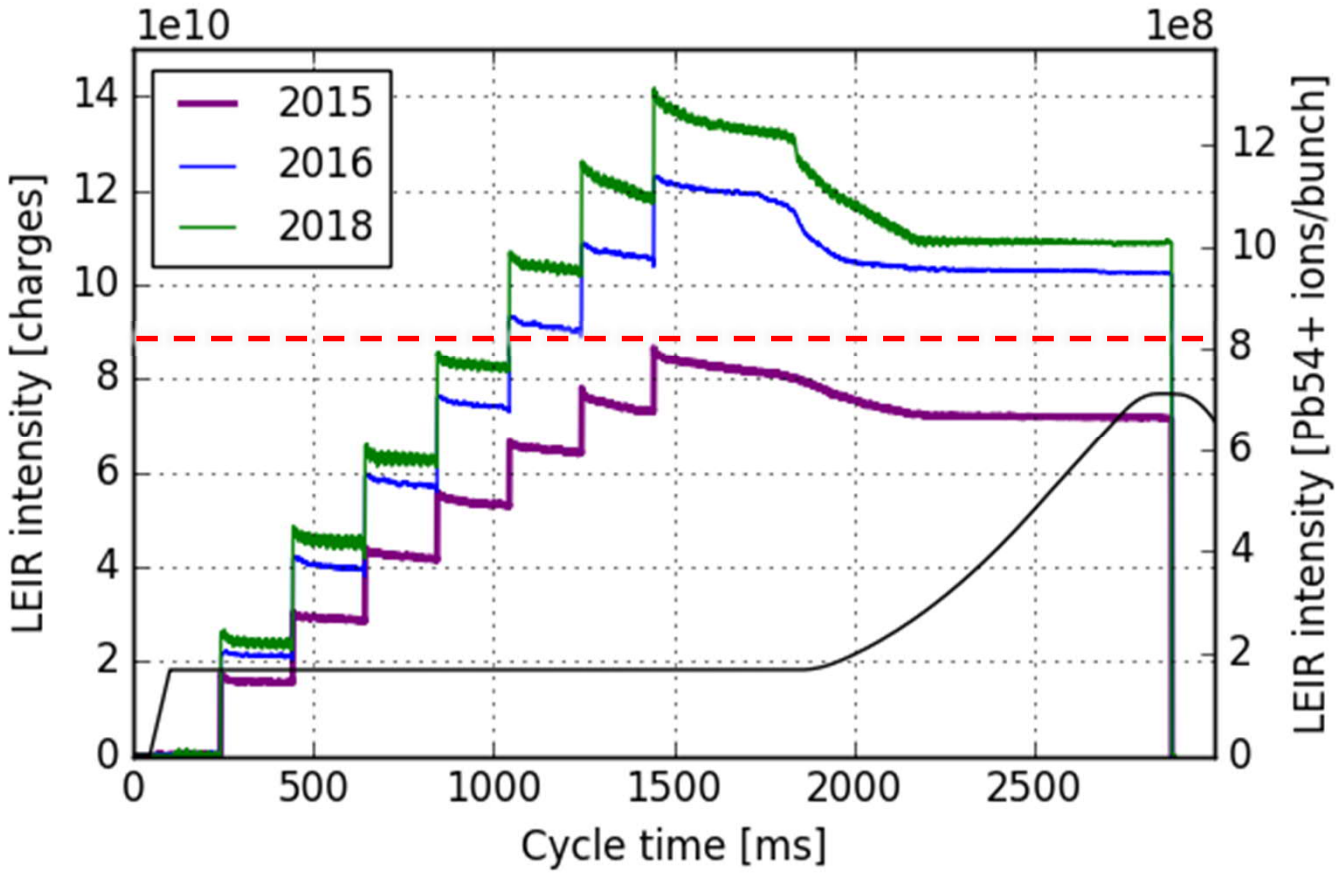
(*) **3+6 operation**: novel scheme to mitigate SPS slip-stacking problems, if any. It was possible thanks to the flexibility of LLRF + wideband Finemet HLRF systems.

LEIR: the DLLRF



- **Dual-harmonic operation on same cavity** (acceleration + bunch shaping).
- **Double-cavity operation** (MD mode)

LEIR achievement: Pb^{54+} intensity



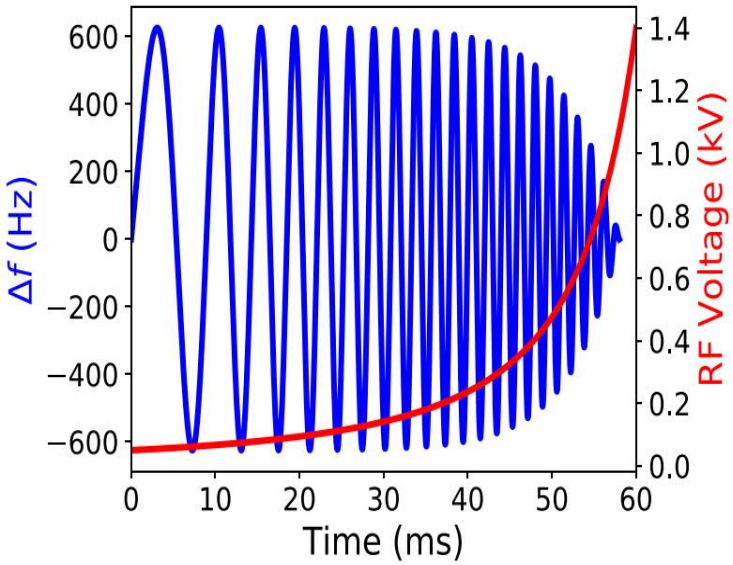
High Luminosity LHC (HL-LHC) specs for LEIR: 8.1 E8 ions/bunch

- **Exceptional progress** on extracted beam intensity over the last 3 years
- **LLRF instrumental to achieve this** result → next slide

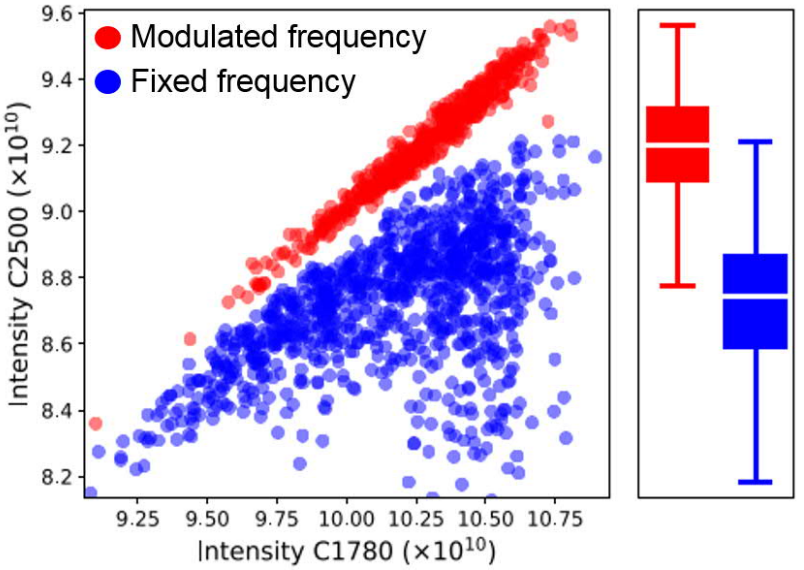
LEIR DLLRF achievement: freq. modulation

- Novel approach to capturing coasting ion beams: programmable RF frequency modulation @capture:
  - controlled blowup of longitudinal emittance
  - good reproducibility in longitudinal distribution

Improves beam transmission



Frequency modulation [blue] and voltage [red] at capture for a Pb^{54+} cycle.



Intensity before extraction vs. after capture with [red] and without [blue] modulated frequency capture.

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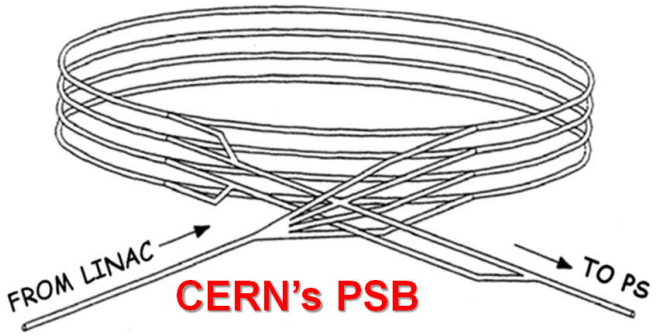
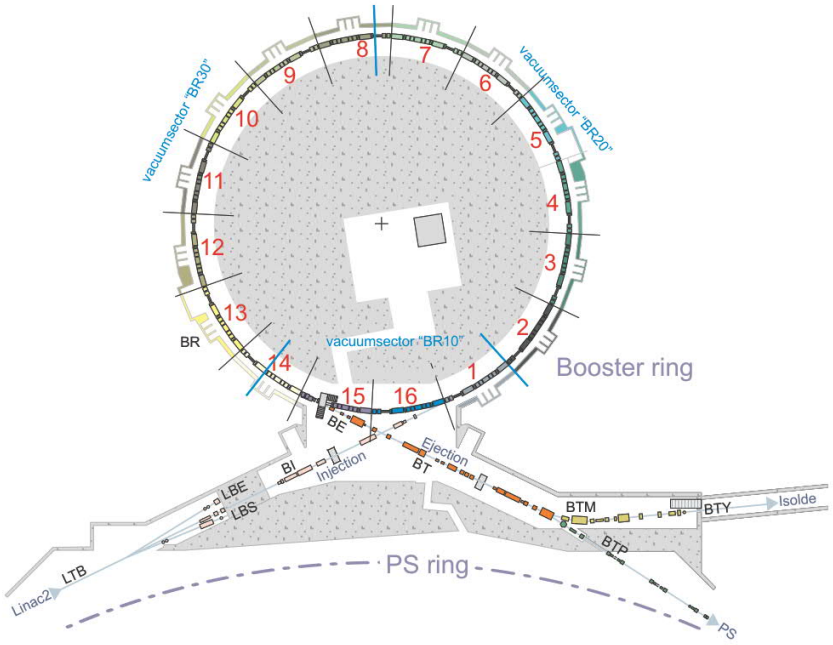
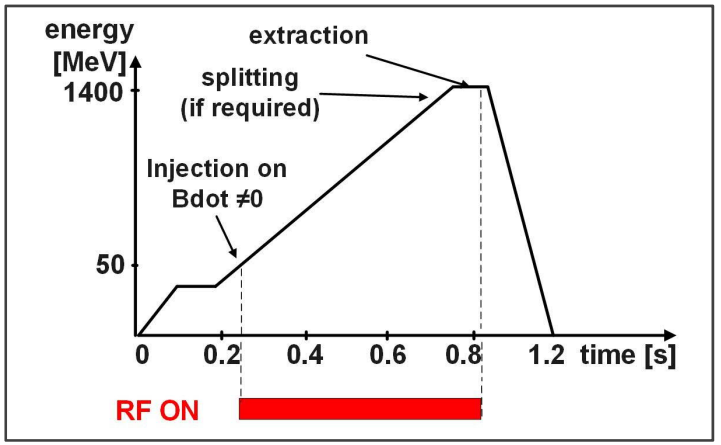


Proton Synchrotron Booster



PSB: the accelerator

- **Proton accelerator**, 4 superposed rings
- **LHC injector** + supplier to experimental zone.
- **Intensity/ring**: **5E9 p** @*h*=1 [LHCPROBE] to **1E13 p** @*h*=1 [ISOLDE].
  - Wide range of beam intensities/parameters.
  - Beam loading can be strong.



Pre-LS2 PSB typical cycle

- **Deep upgrades during LS2**:
  - Injection from Linac4 (long. painting).
  - Higher injection/extraction energies.
  - New Btrain system.
  - Finemet-based HLRF to replace pre-LS2 ferrite-based systems.
  - LLRF system will be upgraded to operate new Finemet HLRF.

	Energy	Revolution frequency
Injection	160 MeV	992 kHz
Extraction – a	1.4 GeV	1.748 MHz
Extraction – b	2 GeV	1.807 MHz
Circumference		157 m
Acceleration time		~600 ms

Post-LS2 PSB parameters

PSB DLLRF achievement: long. blowup

- New method deployed for controlled longitudinal blowup
- Operational (historical) method: high harmonic.
  - Single frequency sinusoidal modulation of high harmonic
  - Operational run also with Finemet test system (PSB Ring 4)
- New method: phase noise
  - "Random" phase modulation of main harmonic
  - Successful operational run in 2018
- After LS2 both methods will be used operationally

High harmonic

+ Easy to track changing f_s
+ Faster
- Requires control of high h
- Minimum of 5D parameter space

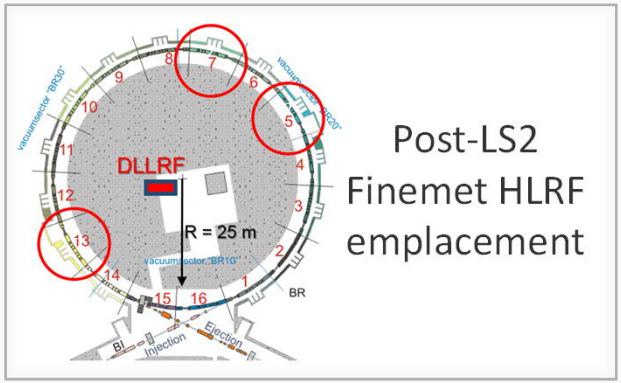
Phase noise

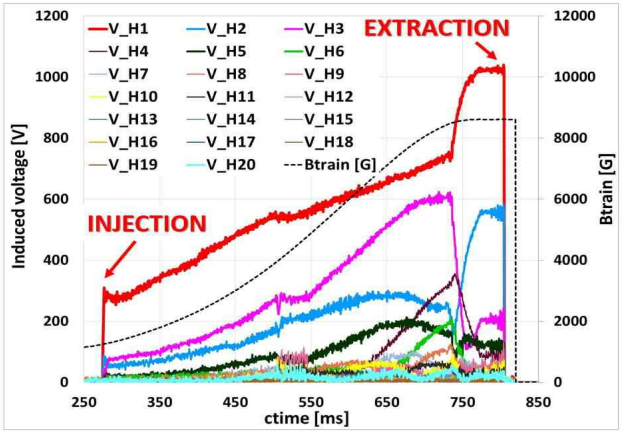
+ No need for high h control
+ Smaller parameter space
+ Targets specific synchrotron amplitudes
- Slower

PSB: post-LS2 DLLRF challenges

- Existing DLLRF systems to be profoundly upgraded for post-LS2 operation
  - Finemet HLRF test system in PSB Ring 4 since 2011
  - Several reliability runs carried out pre-LS2

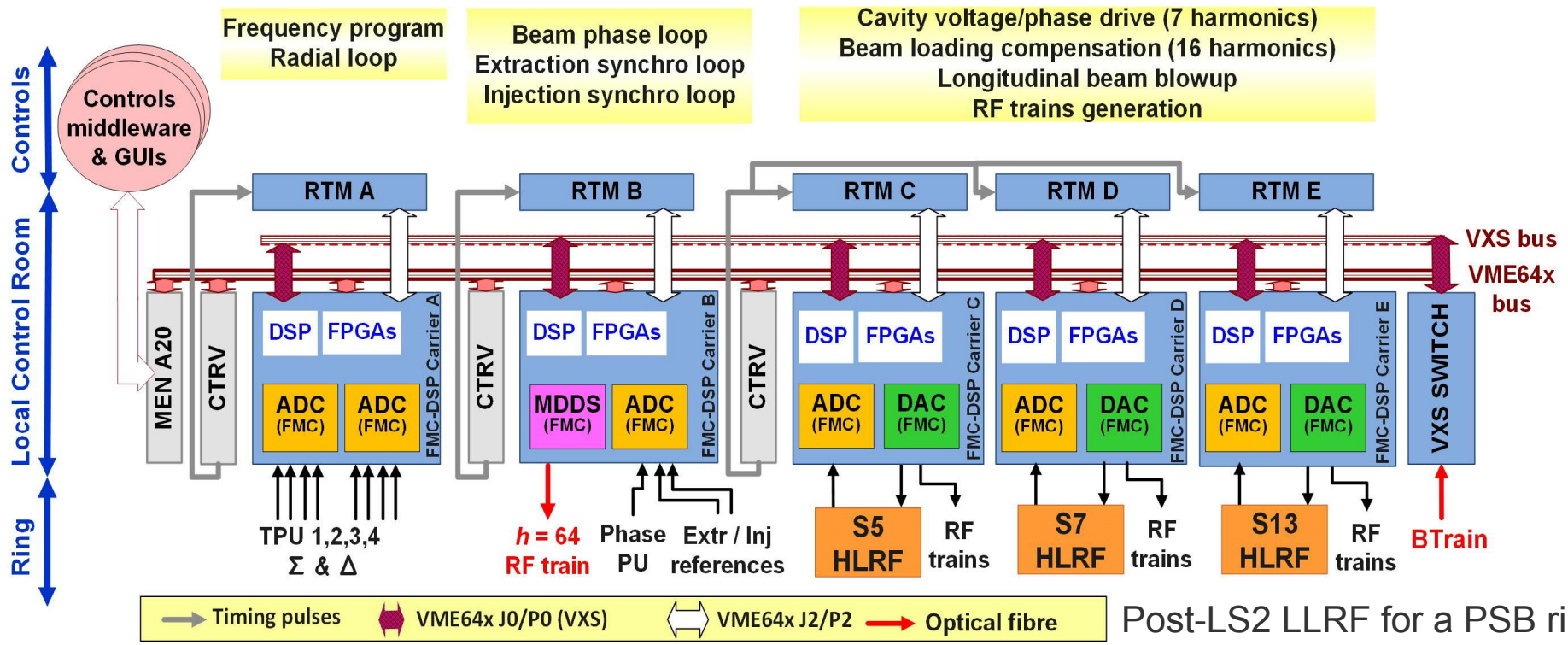
- **Distributed cavity concept**
  - **HLRF**: 3 systems/ring, 8 kV each, [1-20 MHz] BW.
  - **What**: voltage @same h balanced over the 3 HLRF systems. Wide frequency swing → challenging!
  - **Aim**: optimal power management + HLRF virtually never down.
  - **Cost**: higher LLRF complexity
- **Voltage control & beam loading compensation**
  - Beam loading compensation @16 h
  - Operation: voltage/phase control @4 h
  - MDs: additional voltage/phase control @3 h





Voltage induced @h = 1.. 20 by 800 E10 p beam

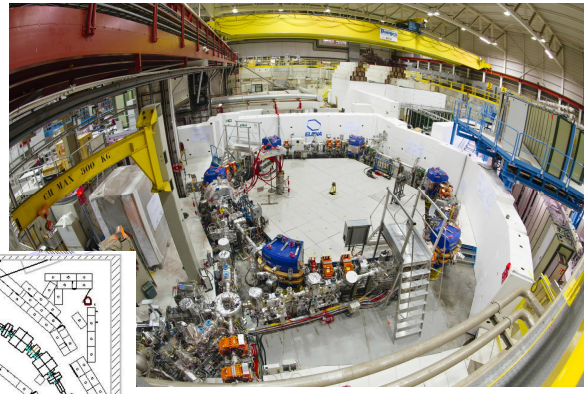
PSB: post-LS2 DLLRF

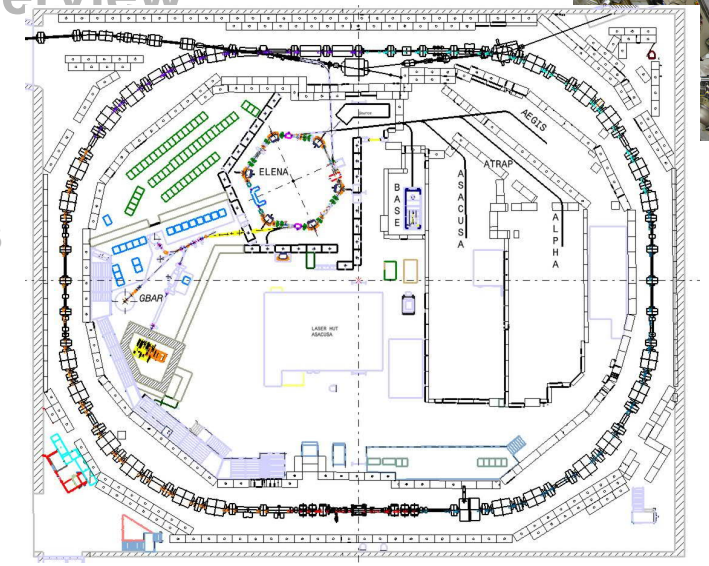


Post-LS2 LLRF for a PSB ring

- 5 FMC-DSP carrier boards vs. 3 boards for pre-LS2 system
- **Servoloops**: 16 h/cavity [in FPGA].
- Extended **longitudinal blowup capabilities** [in FPGA]
- **Rings synchronisation with Linac4**, injection into waiting bucket

Outline





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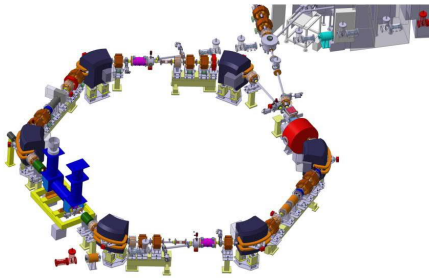
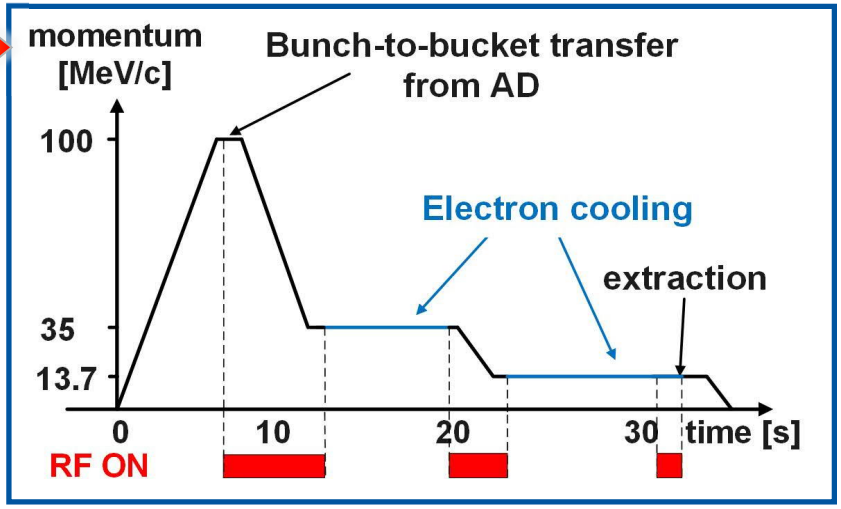
Extra Low ENergy Antiproton Ring



ELENA: the decelerator

- **Standard operation**: deceleration of antiprotons (pbars) from AD.
- **Setup**: acceleration/deceleration of H^- ions/protons from source.
- Under commissioning (started 12/2016).
  - Already provided slow pbars to GBAR
- Finemet-based HLRF (500 Vp)
- So far single harmonic operation
- Double harmonic operation
  - Aim: bunch shaping @extraction
  - It might help for space charge problems in the cycle, if any.
- Bunched-beam cooling or bunch rotation @extraction for shorter bunches



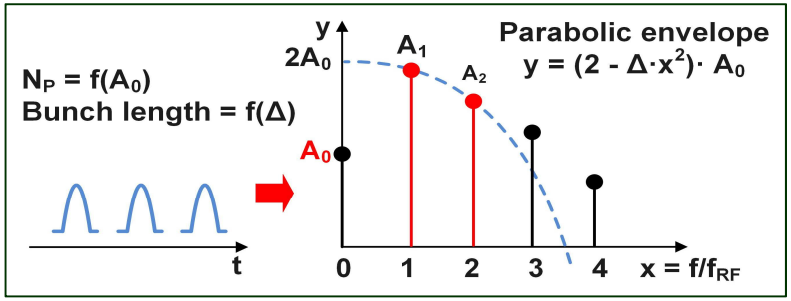
ELENA cycle in 2018 for pbar operation

Parameter	Injection	Extraction
Momentum, MeV/c	100	13.7
Magnetic field, mT	359.8	49.3
Revolution frequency, kHz	1044.9	144
Circumference, m		30.4

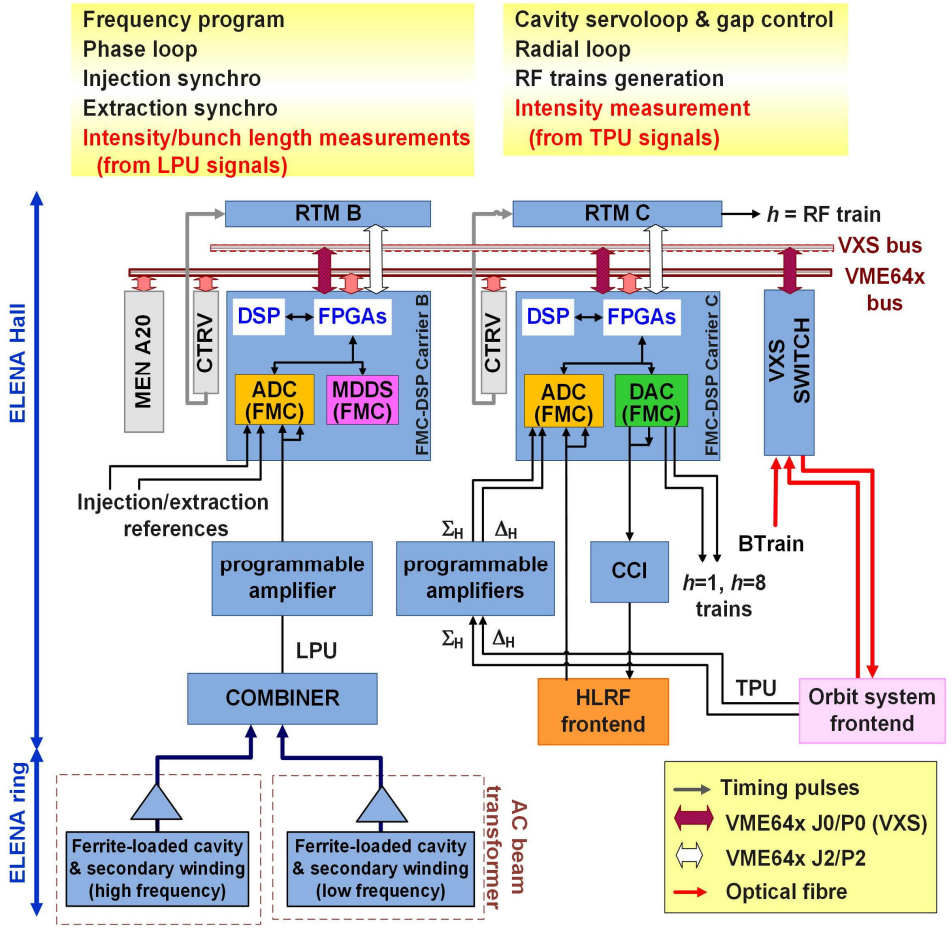
ELENA parameters for pbar operation

ELENA: DLLRF (2018 version)

- **RF segments**:
  - beam bunched / debunched several times in same cycle
  - → cavity gap relay opened/closed
- **Longitudinal diagnostics**
  - Part of RF workpackage
  - DC beam transformers do not work at ELENA's low intensity
  - Dedicated data treatment deployed in LLRF to measure bunched-beam intensity + bunch length.

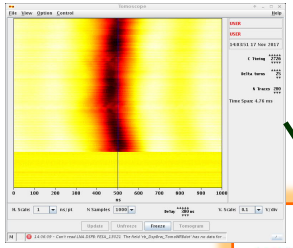


In-frequency bunched-beam data processing

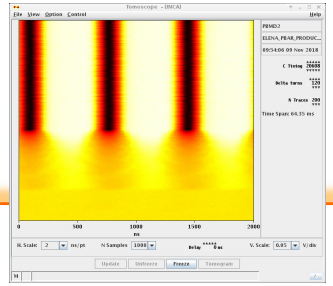


ELENA LLRF layout [2018 version]

ELENA DLLRF achievements with pbars



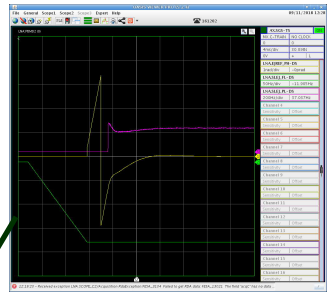
Bunch-to-bucket transfer

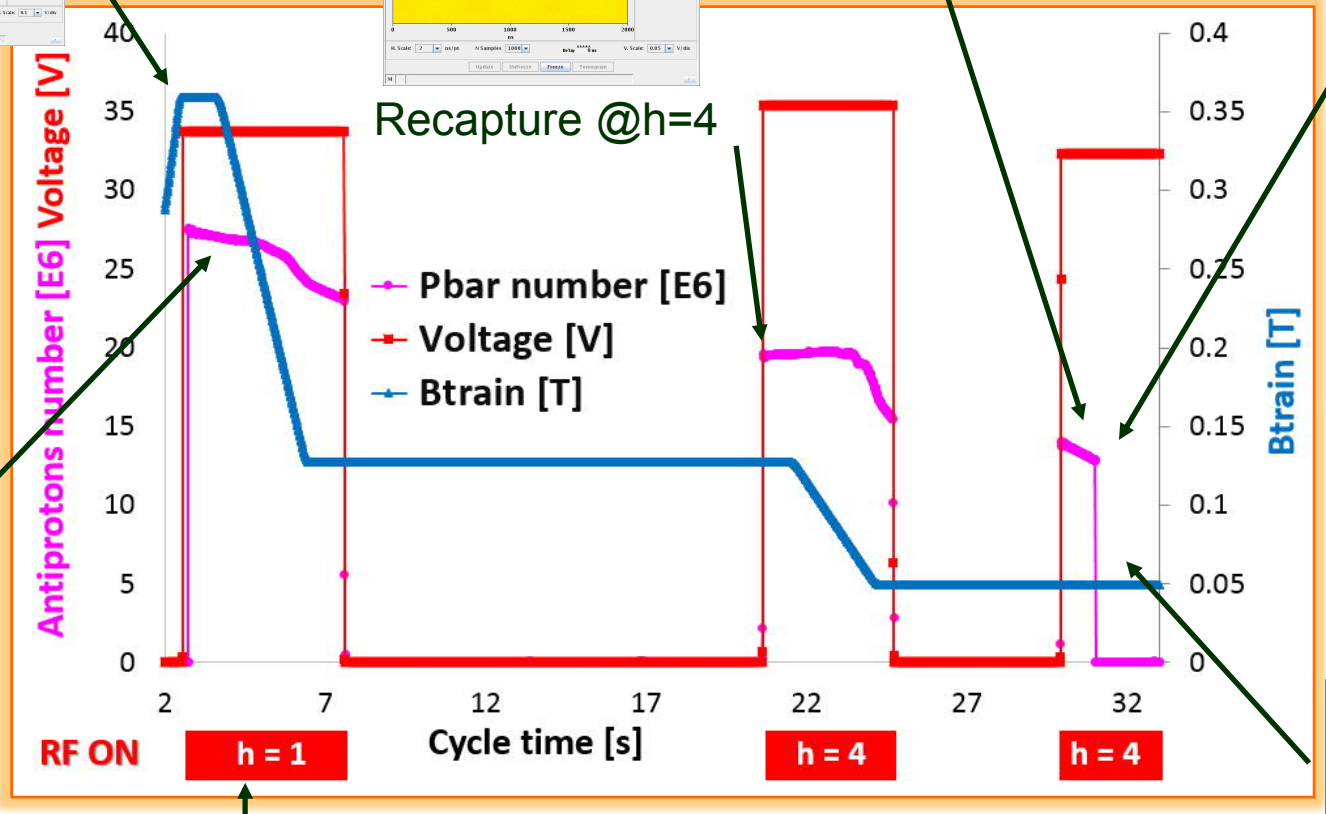


Recapture @h=4

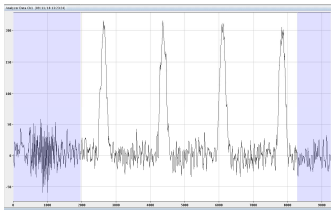
Bunched-beam cooling

Extraction synchro loop



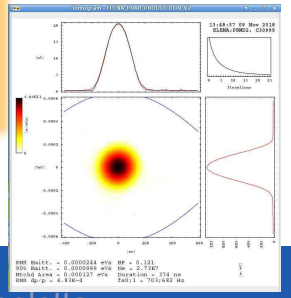


Beam intensity measured by LLRF



Four bunches in extraction line

RF segment

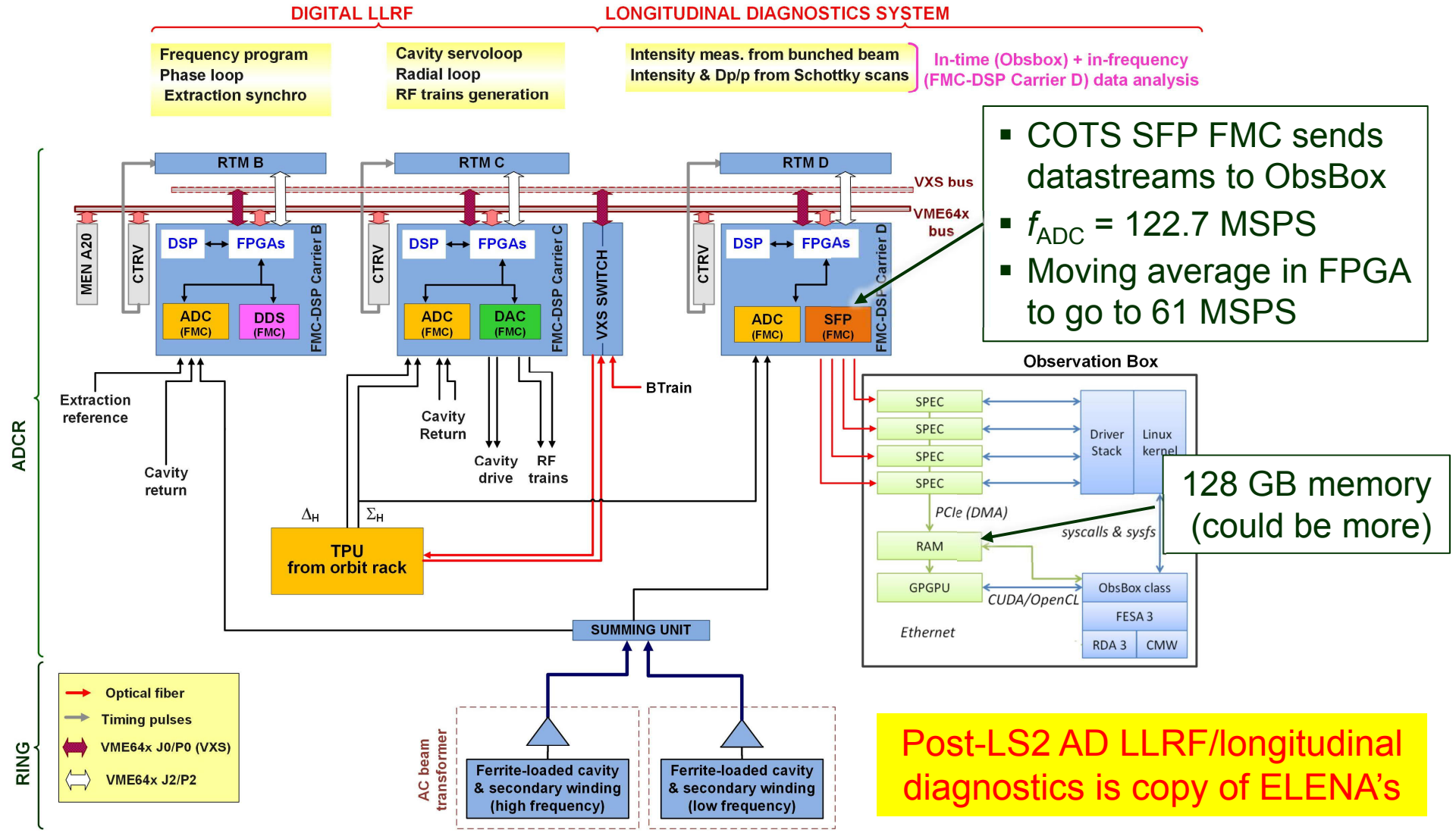


Tomogram before extraction

ELENA DLLRF new challenges

- Integration wit RF cycle editor (automatic control of main RF parameters)
- Longitudinal diagnostics will be expanded in 2020
  - Users: operators, RF experts + cooling experts
  - Dedicated FMC-DSP carrier hosting ADC + SFP FMCs
    - **In-frequency** data processing (**real-time**).
    - **Bunched** (intensity + bunch length, as in 2018) and **debunched** (intensity + Δp/p from Schottky scans) **beam** data processing.
    - Will pass to ObsBox averaged sampled data
  - Observation Box (ObsBox) sub-system
    - **In-time** data processing (**offline**).
    - Powerful standalone computer receiving input (raw data, f_{REV}, beam status) from FMC-DSP carrier over optical fibre.
- ELENA's LLRF + long. diag. to be deployed also in post-LS2 AD
- ObsBox useful to PSB, LEIR for real-time bunch length monitoring.

ELENA: LLRF + long. diag. system



- COTS SFP FMC sends datastreams to ObsBox
- f_{ADC} = 122.7 MSPS
- Moving average in FPGA to go to 61 MSPS

128 GB memory (could be more)

Post-LS2 AD LLRF/longitudinal diagnostics is copy of ELENA's

Conclusions

- **VXS DLLRF** (a.k.a. CERN 2nd generation DLLRF)
  - big investment (manpower) for RF group
  - it re-paid itself well.
- **Finemet HLRF favourite** (although very demanding) **companion**
- **LLRF + Finemet HLRF "ensemble" very flexible & upgradeable**
  - **Same building blocks** applied to **many machines**. **Synergy** of algorithms, firmware/software, experience and ideas.
  - Several features (ex: new operational harmonics, frequency modulation, noise generation scheme) added although not originally planned
  - **Machines operation substantially improved (performance + reliability)** by our DLLRF systems
  - **Happy (OP + physicists) users!**

Conclusions – cont'd

- **Longitudinal diagnostics capabilities** to be soon expanded
  - Essential for pbars machines (AD, ELENA)
  - ObxBox add-on very useful for other machines, too (bunch length meas).

- **Very demanding machines restart** after LS2
  - New (**AD**) or deeply upgraded (**PSB**) LLRF systems to be commissioned
  - ELENA commissioning (cont'd) and LEIR restart
  - After the post-LS2 restart marathon, we'll start studying the **3rd generation LLRF.**

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