RF distribution at CERN

FOSDEM 2026

Tristan Gingold

Agenda

- Quick introduction to accelerators

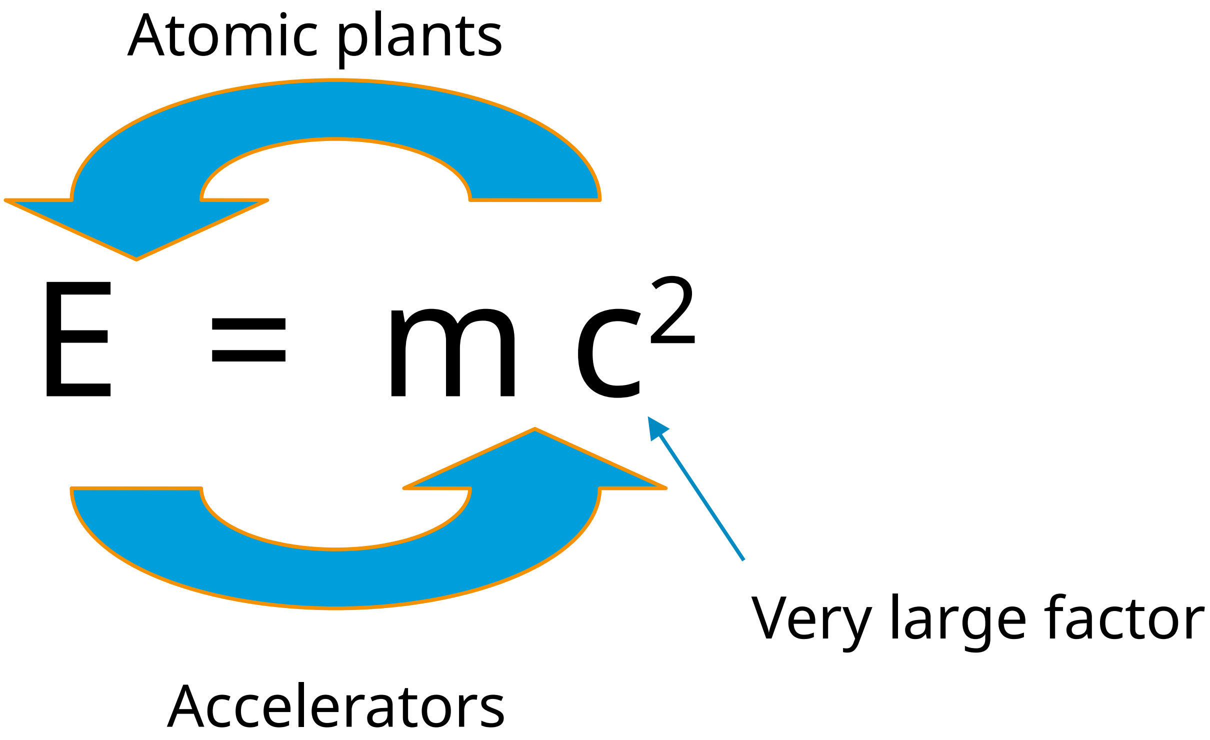
  Disclaimer: I am not a physicist
- Quick introduction to RF for accelerators

  Disclaimer: I am not an RF engineer
- Using White Rabbit for RF distribution

  … But I am a White Rabbit developer.

Particle Accelerators

Why particle accelerators ?



How to get energy ?

- You need a lot of energy (remember: c^2)
- Concentrated
- Einstein helps again!

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Kinetic energy

You need to accelerate

How to accelerate ?

But cannot give energy!

$$\vec{F} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

Nice factor!

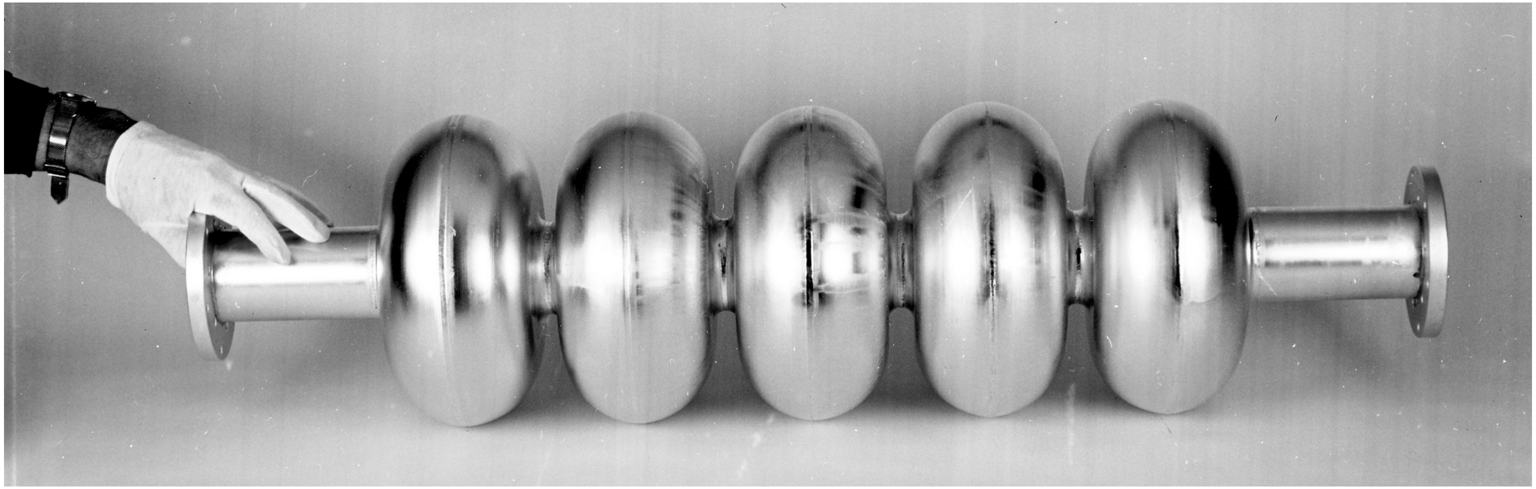
Some data:

Max electric field: 3MV/m (air breakthrough)

Max magnetic field: ~10T

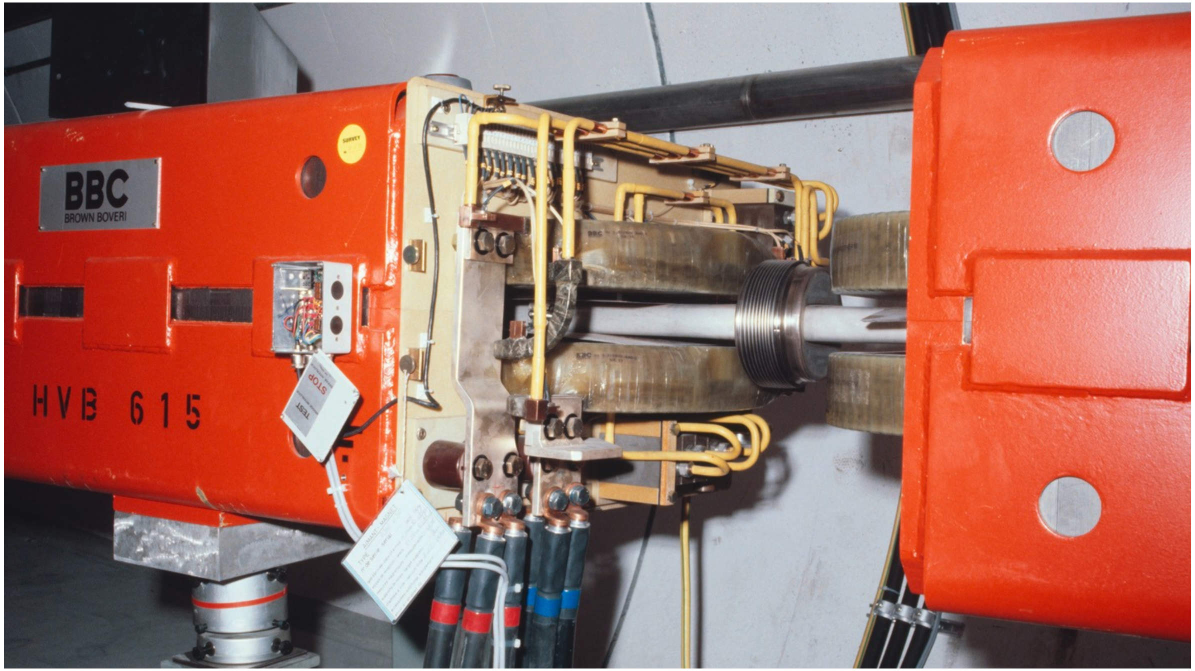
Building Blocks

RF cavities: accelerate particles with a E field



Building Blocks

Magnet: curve/stear, focus/defocus the beam using B fields



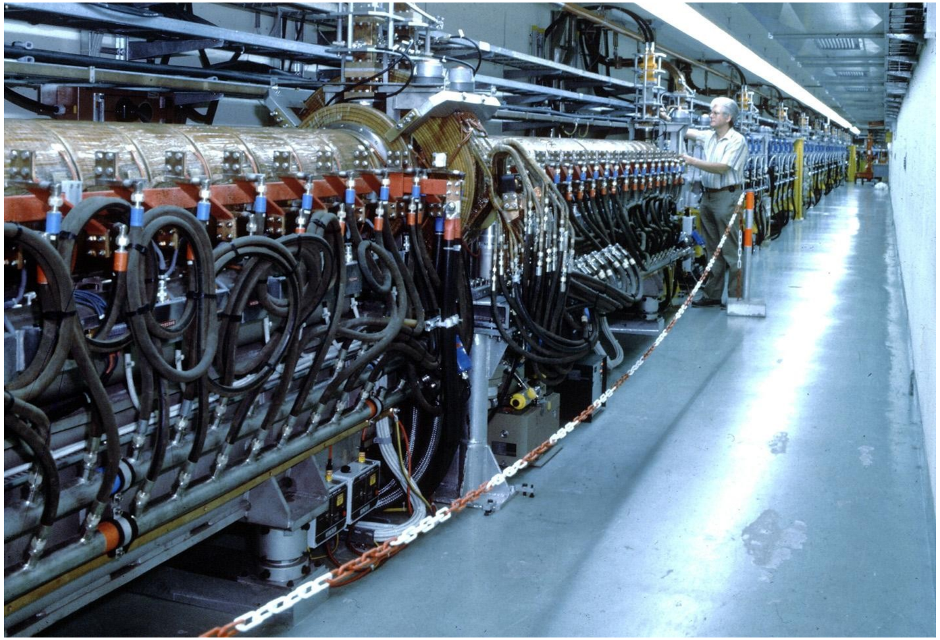
Topology: linear accelerator

Pros:

- Simpler
- Still used

Cons:

- Length
- Each element is seen once



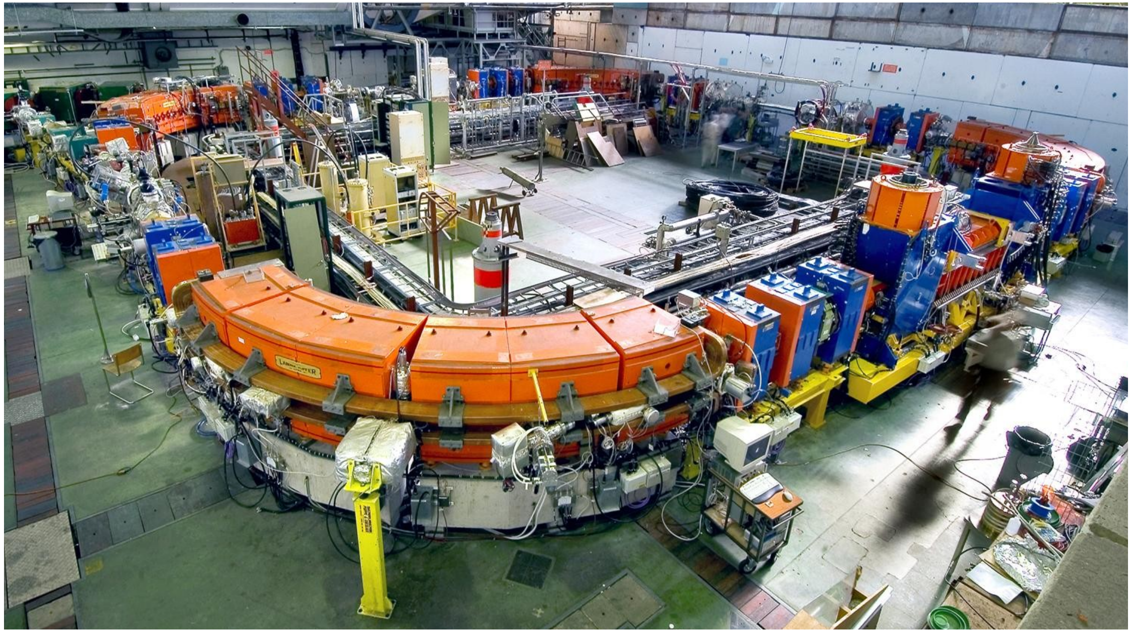
Topology: Circular Accelerator

Pros:

- Reuse elements
- Beam lifetime

Cons:

- More complex
- Synchrotron effect



Main challenge

The beam must stay within its chamber (a vacuum tube, ~5cm diameter)

The B field (which curves the beam) must be synchronized with the particles speed.

Hence the name synchrotron.

What to accelerate ?

- Electrons: elementary particular, but very light
- Protons: non-elementary, much heavier (~1800x)
- Ions: Even heavier

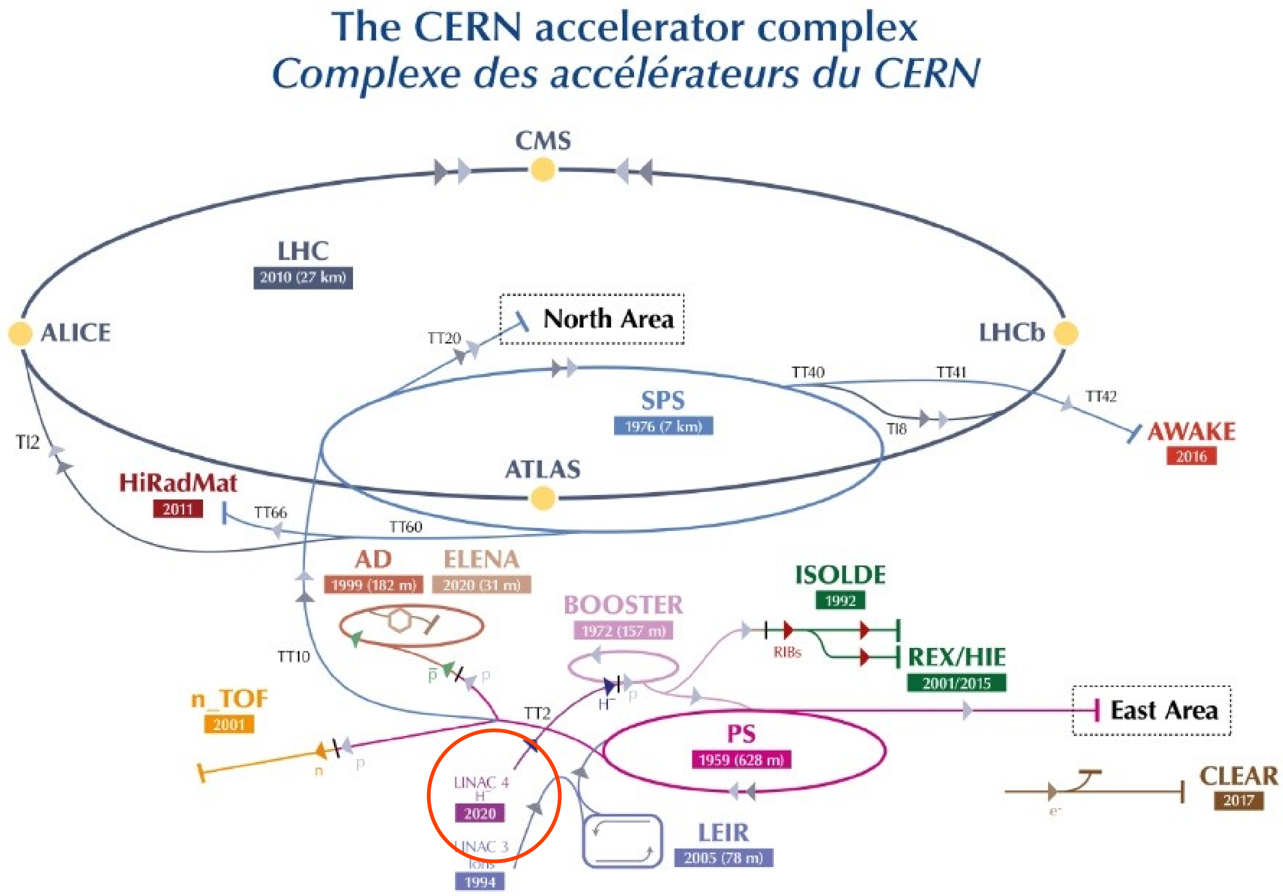
- Anti-particles: interesting for collisions, but need to be generated. Could be accelerated in the same chamber (as their charge is the opposite of their particles)

Other topics…

- Collisions, detectors
- Instruments: position, beam profile, intensity, …
- Injection/Ejection/kickers/septums…
- Magnet, supraconductive magnets
- Vacuum
- Safety/security…

- There are a lot of documents/presentations available online.

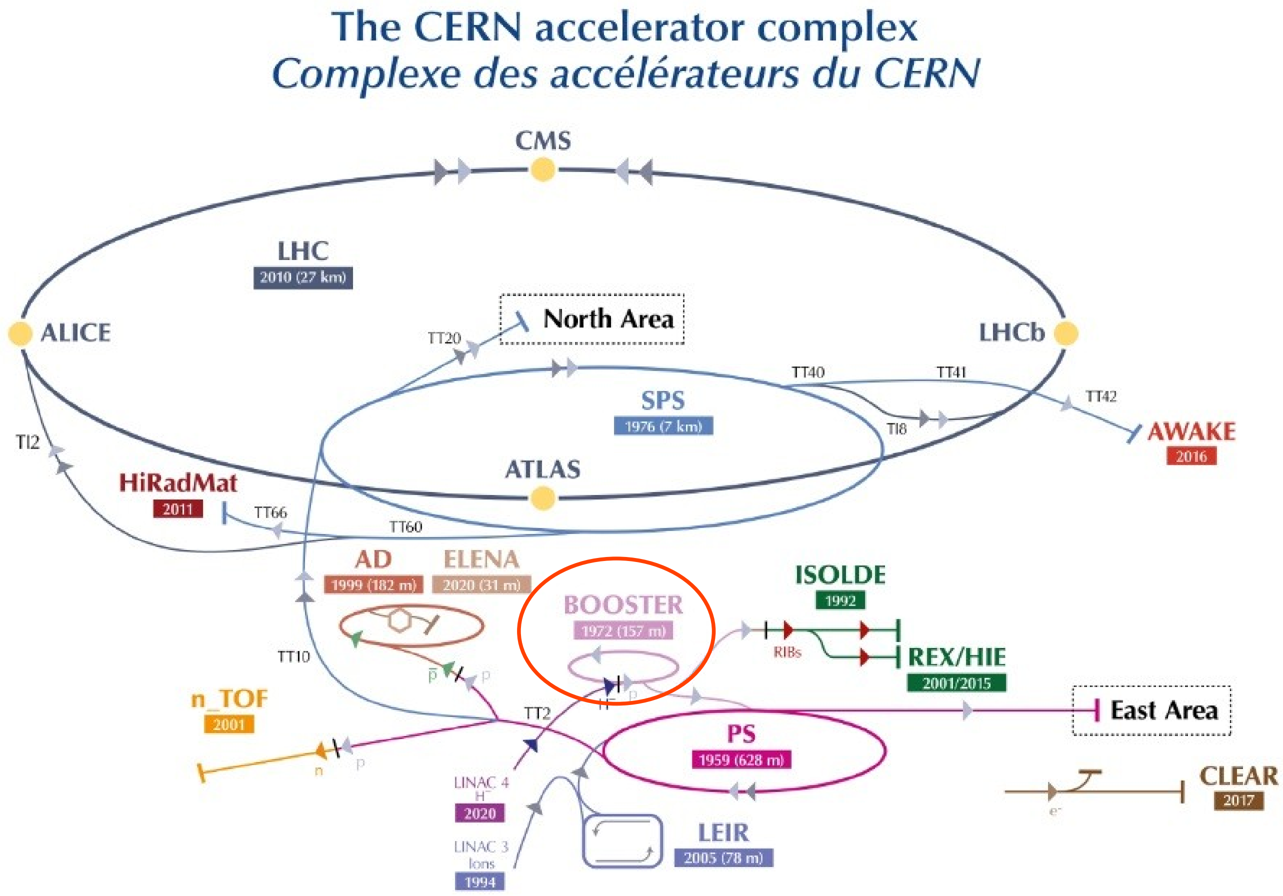
CERN accelerator complex



Linac 4
Source: a bottle of Hydrogen

To 160Mev
0.52c

CERN accelerator complex

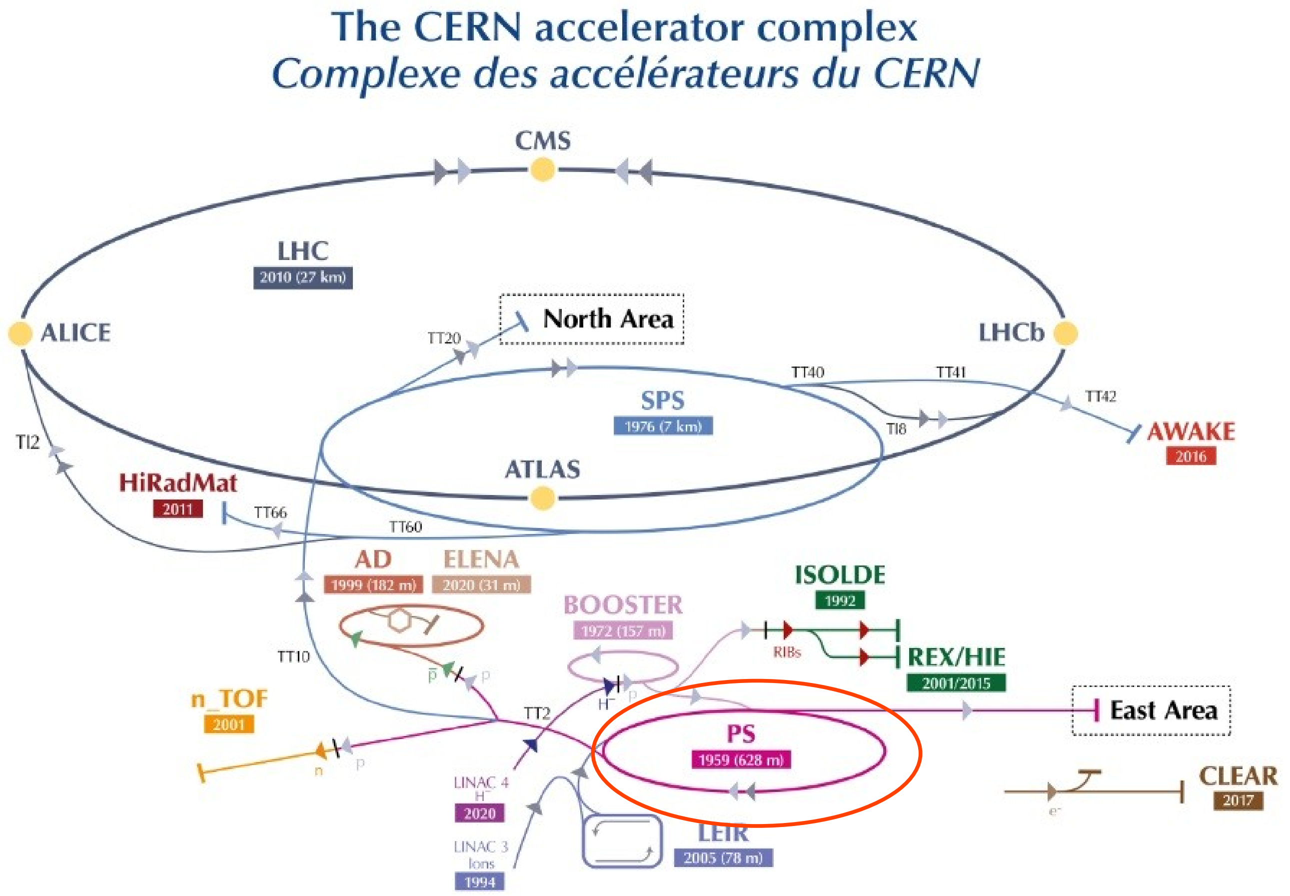


Booster

To 2GeV

0.95c

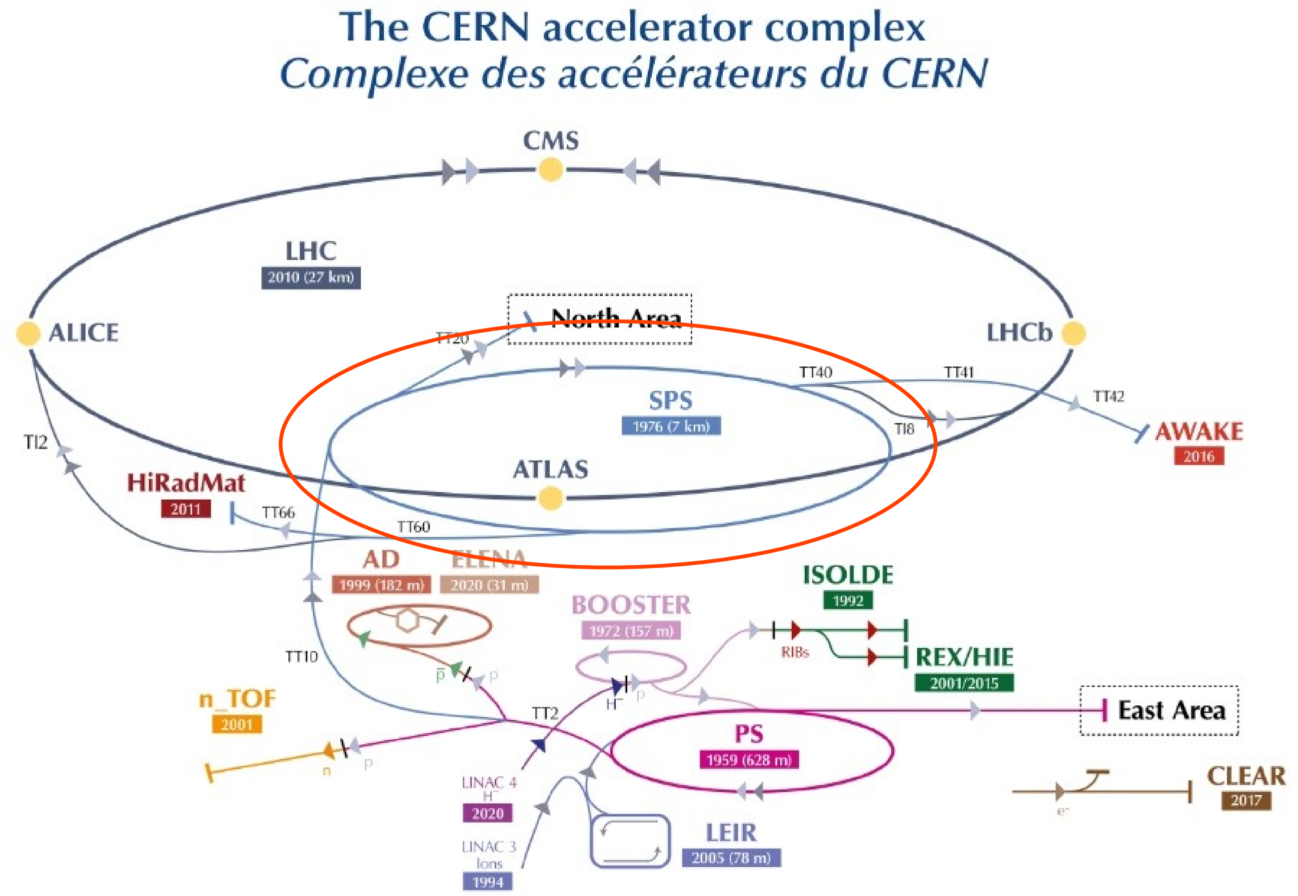
CERN accelerator complex



Proton-Synchrotron

To 26GeV
0.999c

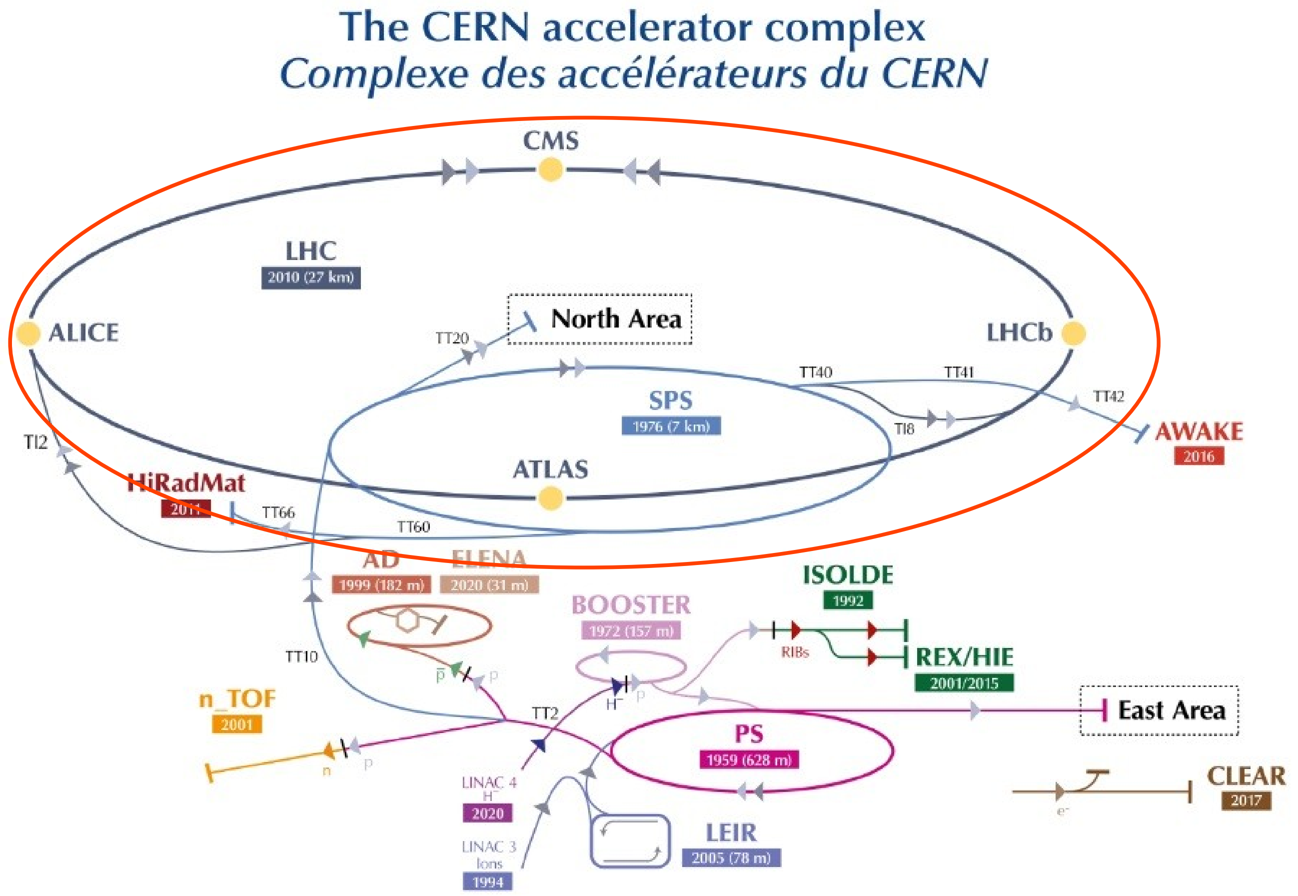
CERN accelerator complex



Super Proton-Synchrotron

To 450GeV, 0.999998c

CERN accelerator complex



Large Hadron Collider (LHC)

To 6.5TeV

0.999999991c

LHC

~5min to fill it

20min to reach the maximum speed/energy

Collisions for up to ~20h

Meanwhile, beam generated by previous accelerators is used for other experiments

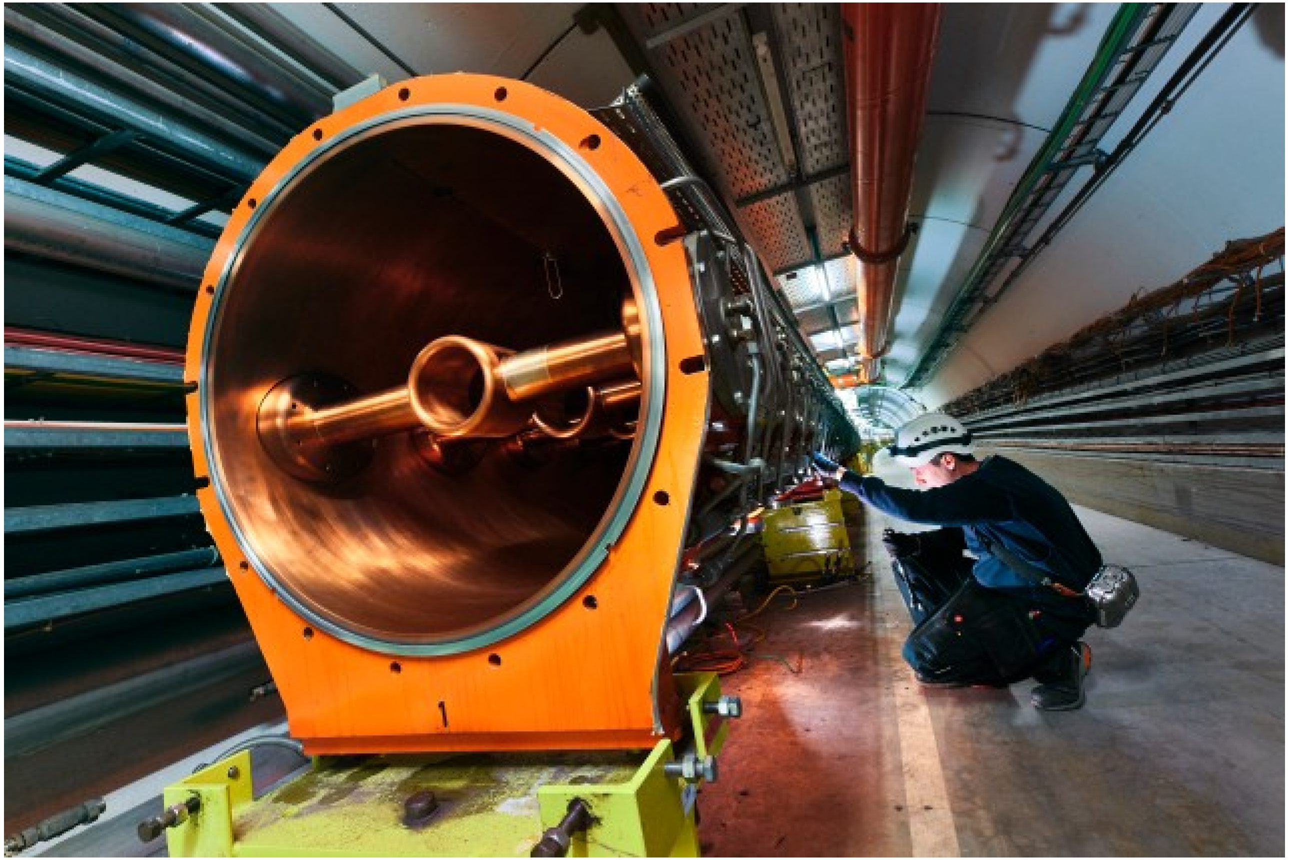
A very small proportion of the Linac4 output goes to LHC!

RF for accelerators

RF - Cavity

Beam passes through, and is accelerated by the RF waves

Here: Travelling Wave Cavity for SPS.



RF - Cavity

The shape of the cavity defines the RF frequency (resonant frequency).

From MHz to GHz.

Low frequency means large cavities (heavy, expensive), but high frequency means small cavities (tight tolerances, tiny cables).

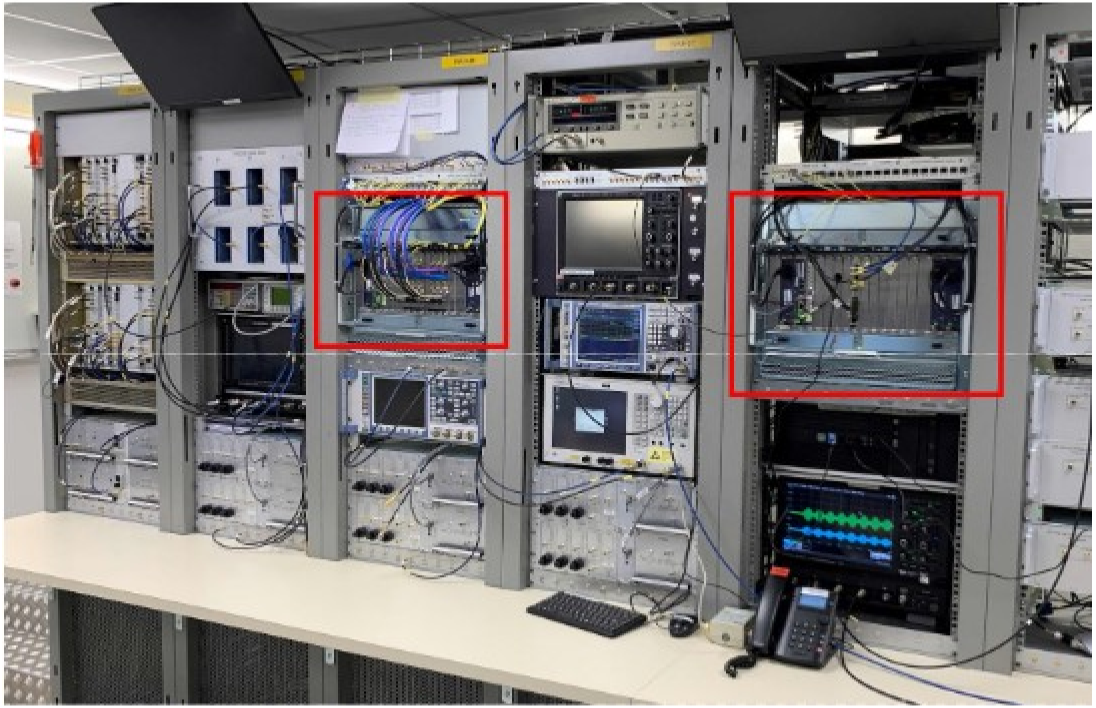
BW is important, as frequency increases when beam is accelerated.

PS: 3-10/13-20/40/80MHz, SPS: ~200MHz, LHC: ~400MHz

RF – Low-Level RF

Generation of RF signals.

Feedback loops using RF pick-up



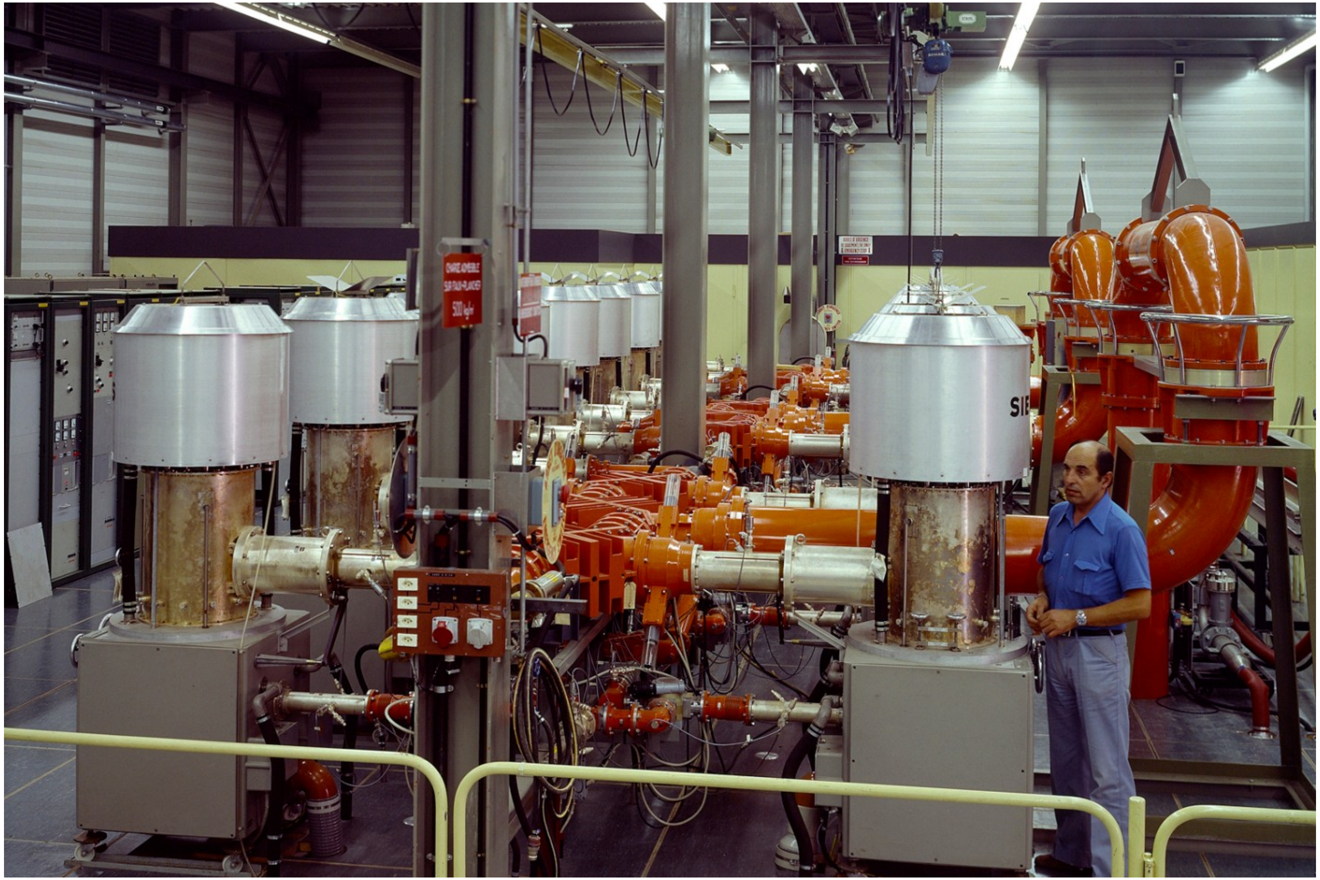
RF amplification

Remember:

High Energy Physics!

(SPS: ~5MW)

Coax, waveguides,
Water cooling

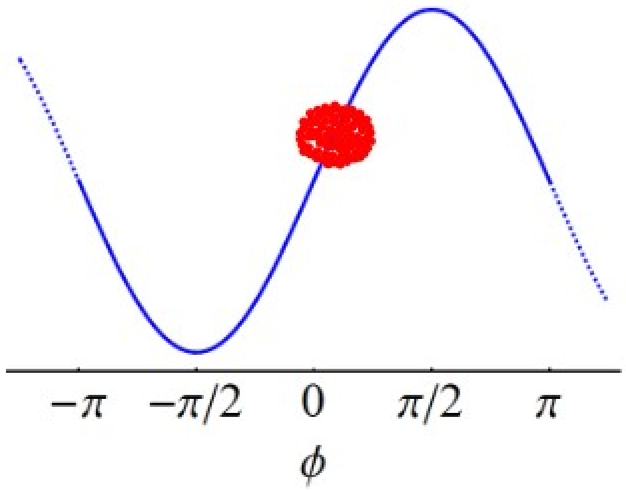


RF control

Amplitude, frequency and phase must be tightly controlled.

Otherwise, bunches (which compose the beam) may not be accelerated
Or non uniformaly…

And particles will leave the orbit.
Efficiency and safety issue!



White Rabbit

What is White Rabbit ?

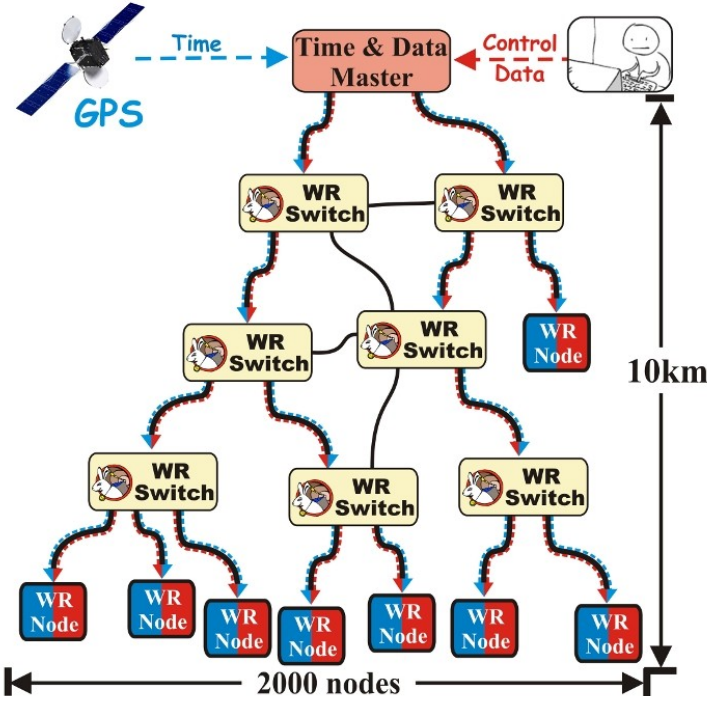
Time/frequency distribution over Ethernet.

Recover a clock (frequency) from Ethernet signal (like SyncE) and discipline a local oscillator.

Use enhanced PTP to measure propagation time through a link, and thus recover the phase.

Uses 1GbE over optical fibers.

Sub ns accuracy, ~50ps precision.



White Rabbit Ecosystem.

Developped mostly at CERN.

Open source

https://white-rabbit.web.cern.ch/

Main parts: switches, end-nodes

Standard fibers, standard SFPs

Switches available from private companies.

Grandmaster is synchronized on GPS and/or atomic clock

White Rabbit (WR) to distribute RF

White Rabbit for RF

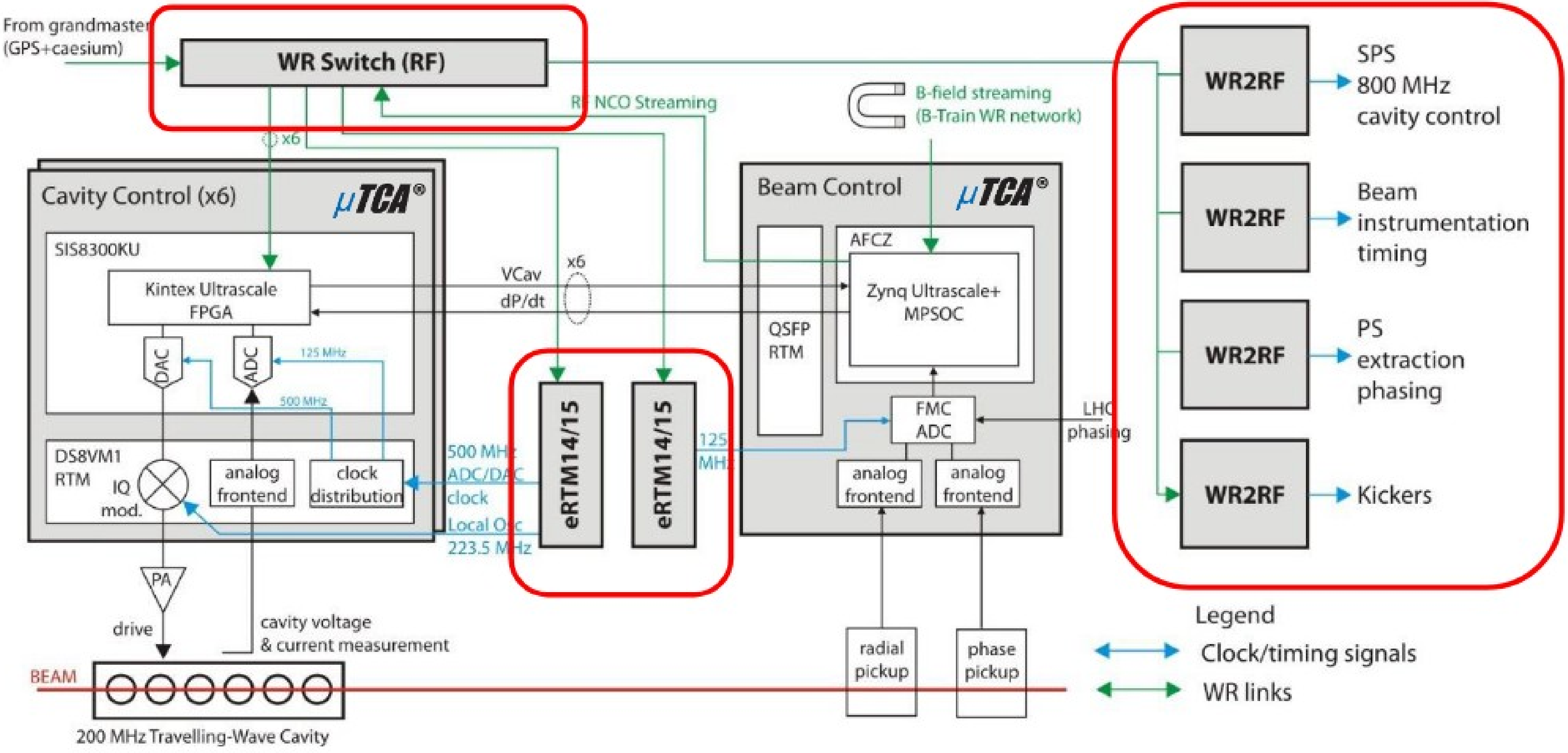
SPS RF system was renovated during 2019-2021.
The previous system was fully analog.

WR was chosen for the new system.

The requirements were:

- clock phase reproducibility: target < 13ps (1deg @ 200MHz)
- Phase noise: -130 dBc/Hz at 1 kHz (223 MHz)

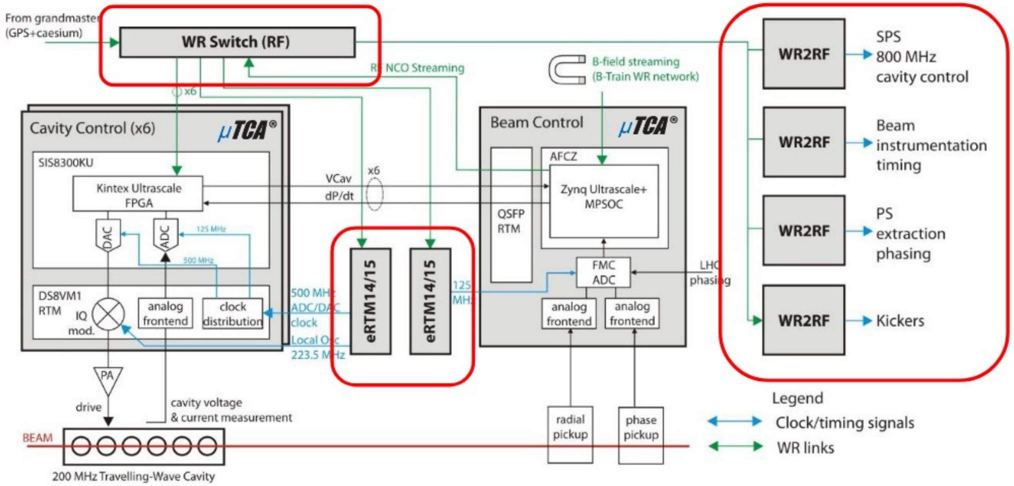
New SPS LLRF with WR



New SPS LLRF with WR

Distributed system:

- Several crates & remote boards



Digital system:

- ADC for feeback (pickups)
- DAC for RF generation
- Other inputs: B field, acceleration program
- Also output FTW (Frequency Tuning Word) to regenerate RF remotely

White Rabbit (WR) is used for communication, distribution and synchronisation

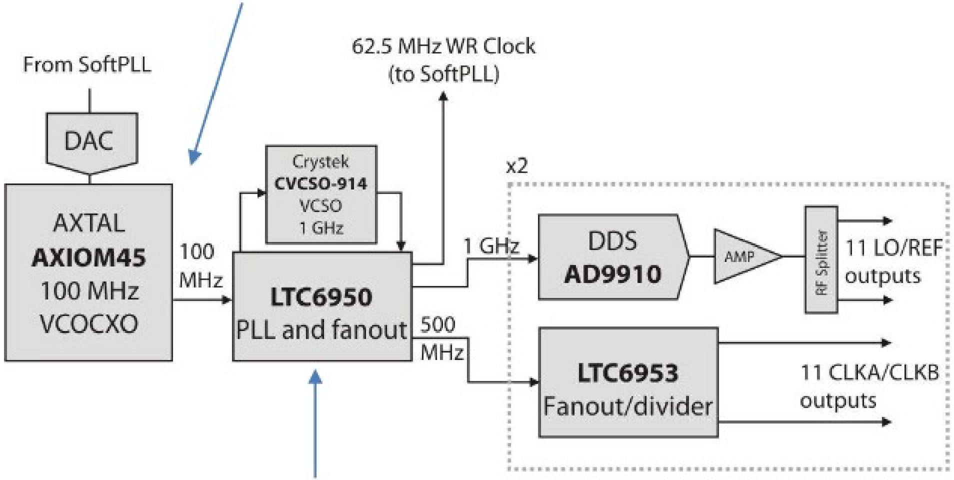
How To Generate Good Clocks ?

Good oscillators (OCXO)
Good electronics

Disciplined (by WR) to
GPS+atomic clock

Synchronized by WR

-100	dBc/Hz	@ 10 Hz
-135	dBc/Hz	@ 100 Hz
-162	dBc/Hz	@ 1 kHz
-172	dBc/Hz	@ 10 kHz
-175	dBc/Hz	@ 100 kHz



Phase Noise Typical:

1kHz	-110 dBc/Hz
10kHz	-139 dBc/Hz
100kHz	-160 dBc/Hz
1MHz	-170 dBc/Hz
10MHz	-174 dBc/Hz

How To Generate RF ?

LO (~213MHz) is generated by a DDS clocked at 1GHz

Mixed with IF (~13MHz), generated by the FPGA from the FTW.

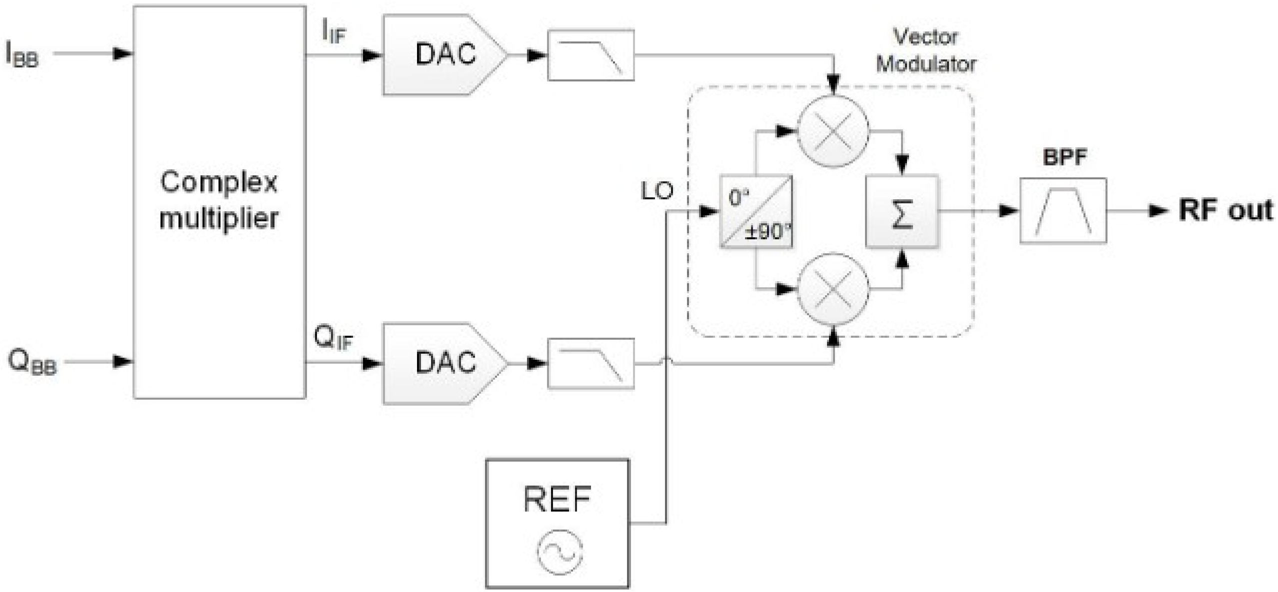


Fig16 – 200MHtz Cavity-Controller Vector modulator

Special command to reset the phase (DDS, NCOs…), granularity is 8ns.

And for LHC ?

Roughly the same system, but:

- Different frequency (400MHz), so different filters
- Lower phase noise requirements →
  - No more PLLs (too noisy)
  - Frequency multipliers instead
- No more phase reset, but resynchronization at any time
- Regenerated RF used by experiments
- Under development

References

- CERN:
  - https://www.home.cern/
- White Rabbit:
  - https://www.white-rabbit.tech/ (official)
  - https://gitlab.com/ohwr/project/white-rabbit/-/wikis/home
- LLRF:
  - https://indico.fnal.gov/event/16933/contributions/40752/attachments/25303/31476/LIU_SPS_LLRF_overview.pdf
  - https://indico.psi.ch/event/12911/contributions/38410/attachments/23033/40703/LLRF_2022_CERN_SPS_hagmann.pdf
  - https://indico.psi.ch/event/12911/contributions/38449/attachments/23038/40710/llrf_tom_16_9.pdf
- CERN Accelerator School (almost all the slides are available):
  - https://cas.web.cern.ch/previous-schools