Radio Frequency Systems of the CERN Synchrotron Accelerators

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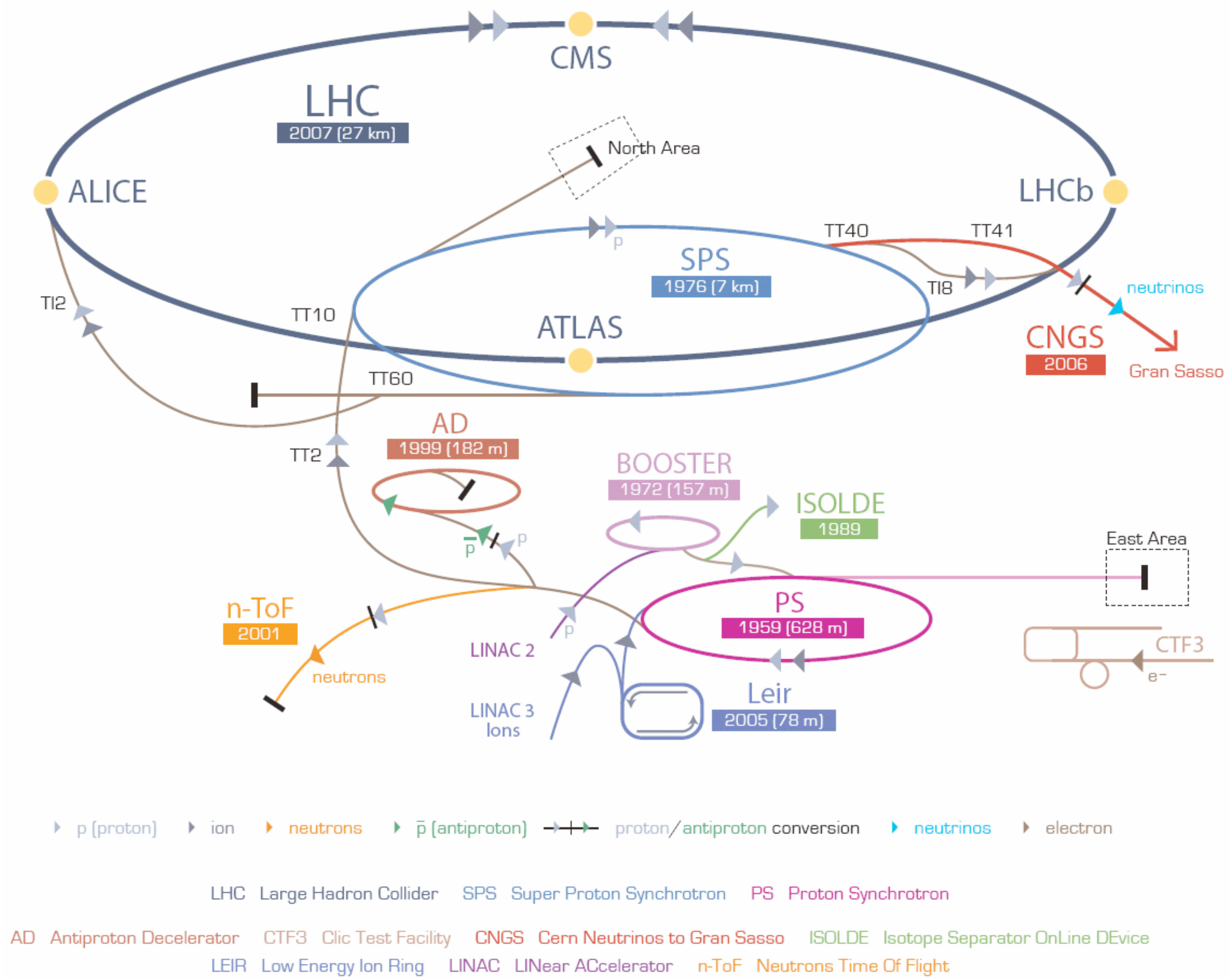
CERN

- CERN - European Organization for Nuclear Research
- One of the world’s largest and most respected centers for scientific research
- Founded in 1954
- 20 member states
- ~ 2500 employees
- ~ 2500 users from all around the world
- Annual budget ~ 1 billion CHF


Foto: CERN, http://cdsweb.cern.ch/collection/Photos

CERN

- CERN currently operates 10 particle accelerators
  - Linac 2 (p), Linac 3 (Pb ions)
  - PSB (Proton Synchrotron Booster) (p, Pb ions)
  - PS (Proton Synchrotron) (p, Pb ions)
  - AD (Antiproton Deccelerator)
  - LEIR (Low Energy Ion Ring) (Pb ions)
  - SPS (Super Proton Synchrotron) (p, Pb ions)
  - LHC (p, Pb ions)
  - CTF3 (CLIC test facility) (e-)
  - ISOLDE
  - Linac 4 under construction (H- ions)



Drawing: CERN, http://cdsweb.cern.ch/collection/Photos

CERN Radio Frequency Group

- RF group is responsible for all RF systems of all CERN accelerators
- Mandate:
  - Operation and maintenance of RF systems in all existing machines
  - Upgrades to RF systems in existing machines for future applications
  - Design and construction of systems for new approved machines
  - Research & development and design studies for future machines
  - RF parameters and longitudinal dynamics in present and future accelerators
  - Calculations and measurements relating to impedances and wake-fields in accelerator structures
  - Dissemination of RF expertise and knowledge inside and outside CERN.
- Together about 110 people in 6 sections

RF system in a particle accelerator

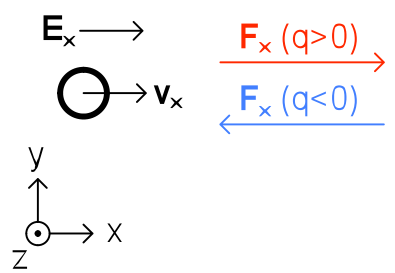
- RF systems are vital part of particle accelerators
- RF systems control momentum of the particles in the longitudinal plane
  - Acceleration
  - Keeping the beam circulating in form of bunches
- Control momentum in the transverse plane
  - Damping transverse oscillations, preserving the emmitance
  - Damping of certain types of instabilities
- Generate timing and synchronization for the whole complex
- RF systems are also used for beam diagnostics
  - Bunch profile, beam position, quality, machine tune measurement

Charged particle in an electromagnetic field

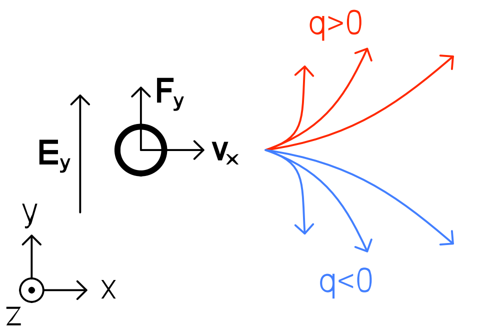
- *The force exerted on a charged particle q moving with velocity v through an electric field E and magnetic field B. The entire electromagnetic force F on the charged particle is called the Lorentz force (after the Dutch physicist Hendrik A. Lorentz)* [Encyclopædia Britannica]

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

Charged particle in an electromagnetic field

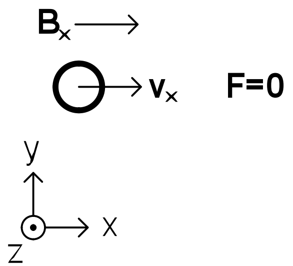


Electric field parallel with the particle's velocity vector. Particle is accelerated and gains energy.

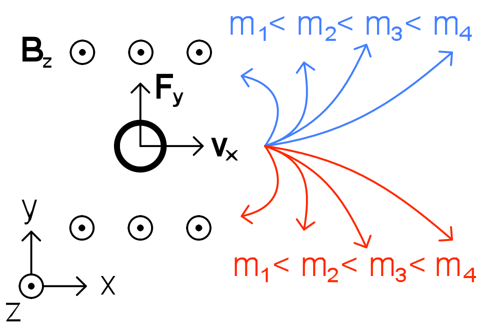


Electric field perpendicular to the velocity vector. The particle's trajectory is being bent and the particle is accelerated.

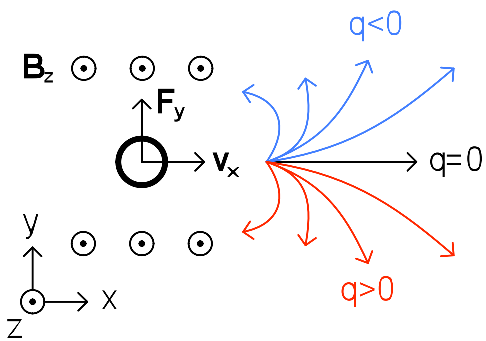
$$\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$$



Magnetic field parallel with the velocity vector. No force on the particle is developed.

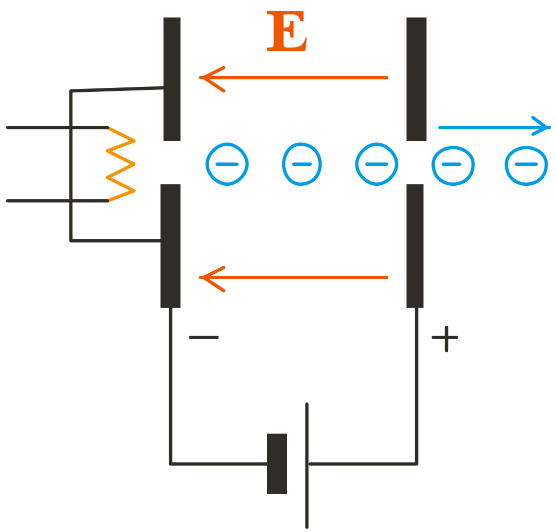


Magnetic field perpendicular to the velocity vector. The trajectory is being bent, however absolute value of the velocity vector is kept constant. Lighter particles are bent more than heavier ones.

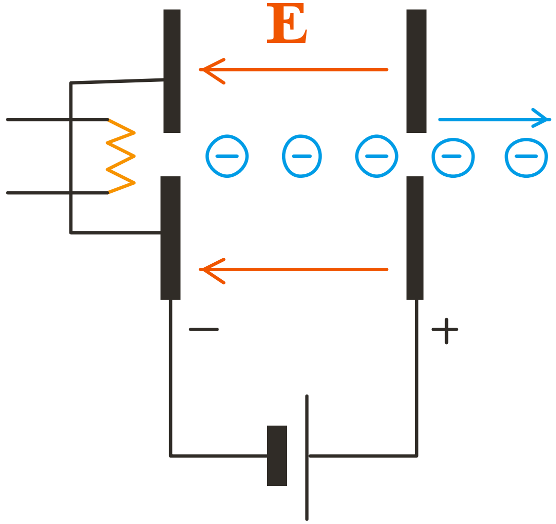


Magnetic field perpendicular to the velocity vector. The trajectory is being bent, however absolute value of the velocity vector is kept constant. Particles with higher charge are bent more.

Acceleration by DC voltage



Acceleration by DC voltage



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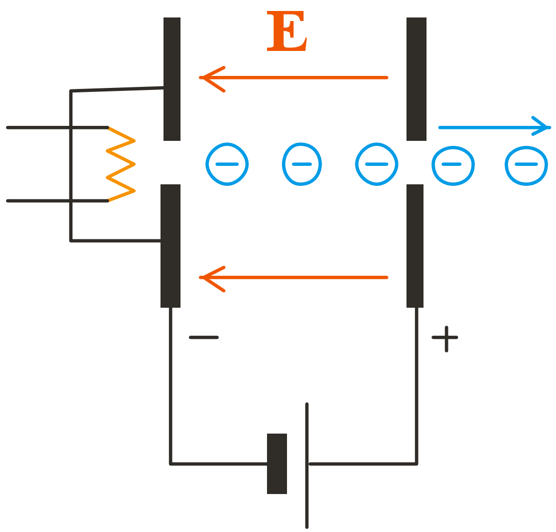
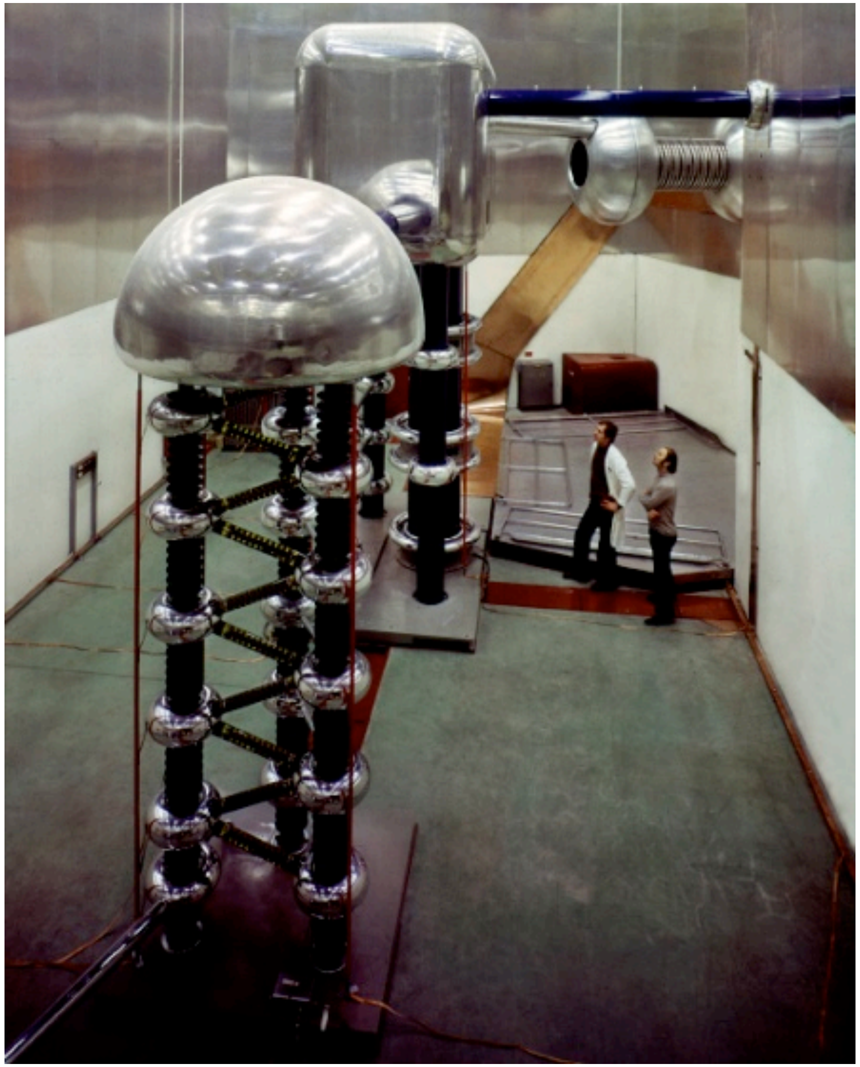
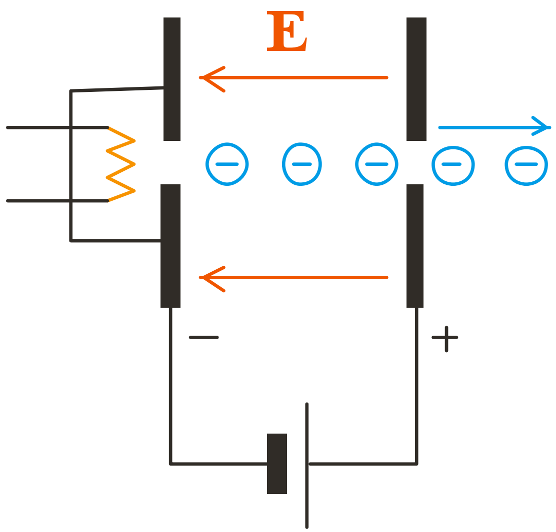




Acceleration by DC voltage



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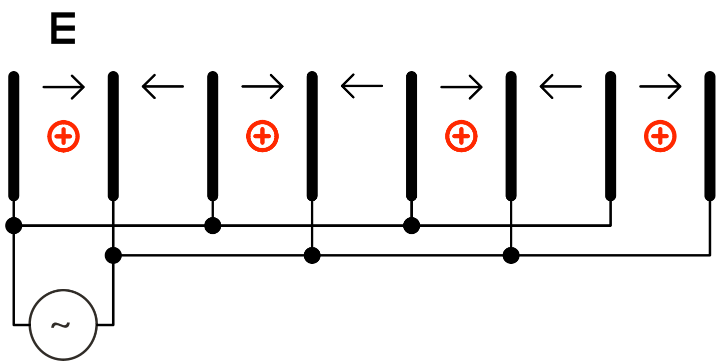
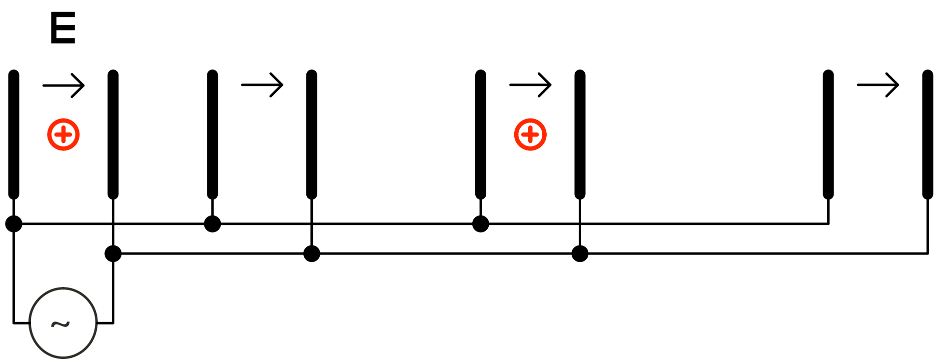
Acceleration by Alternating fields

- Phase of the electric field must be synchronous with the particle movement





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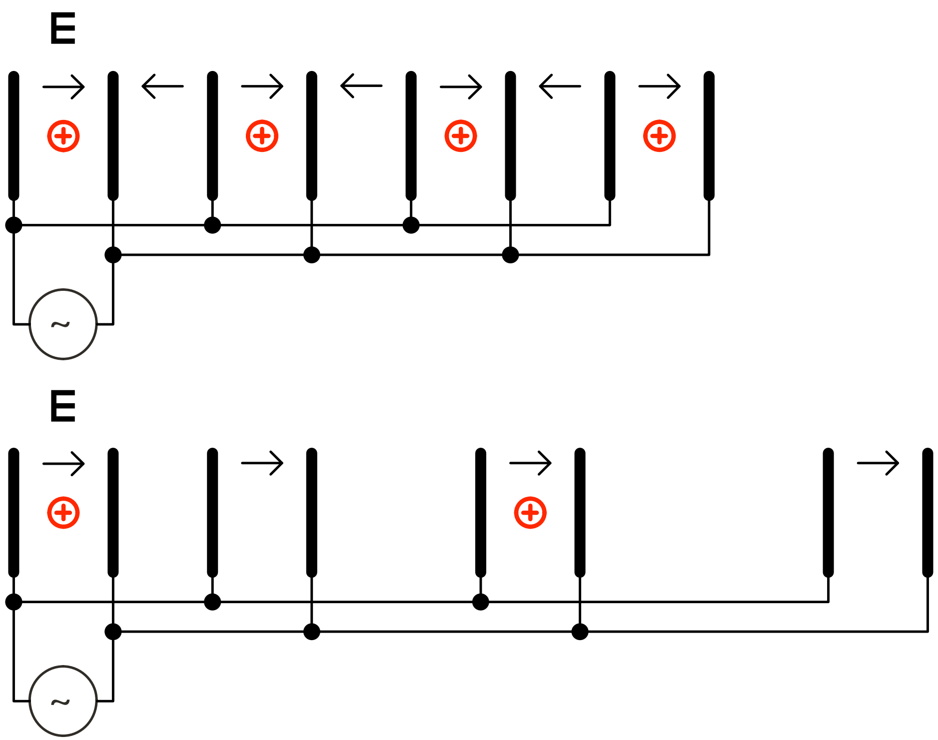
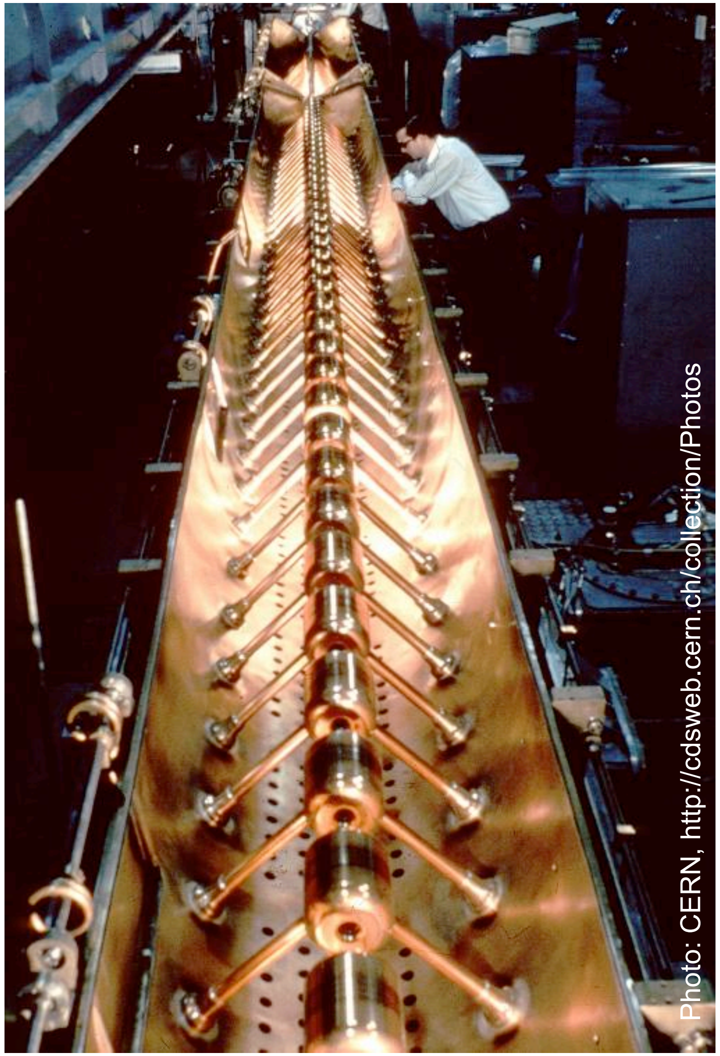
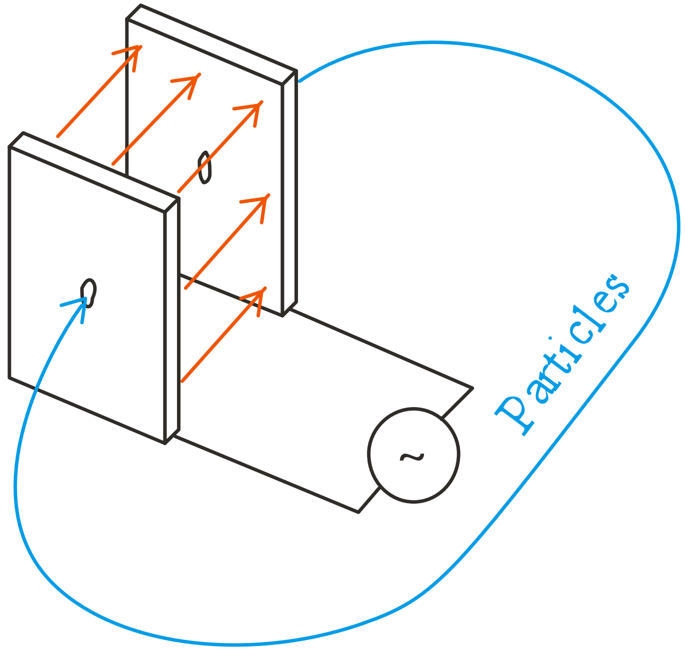




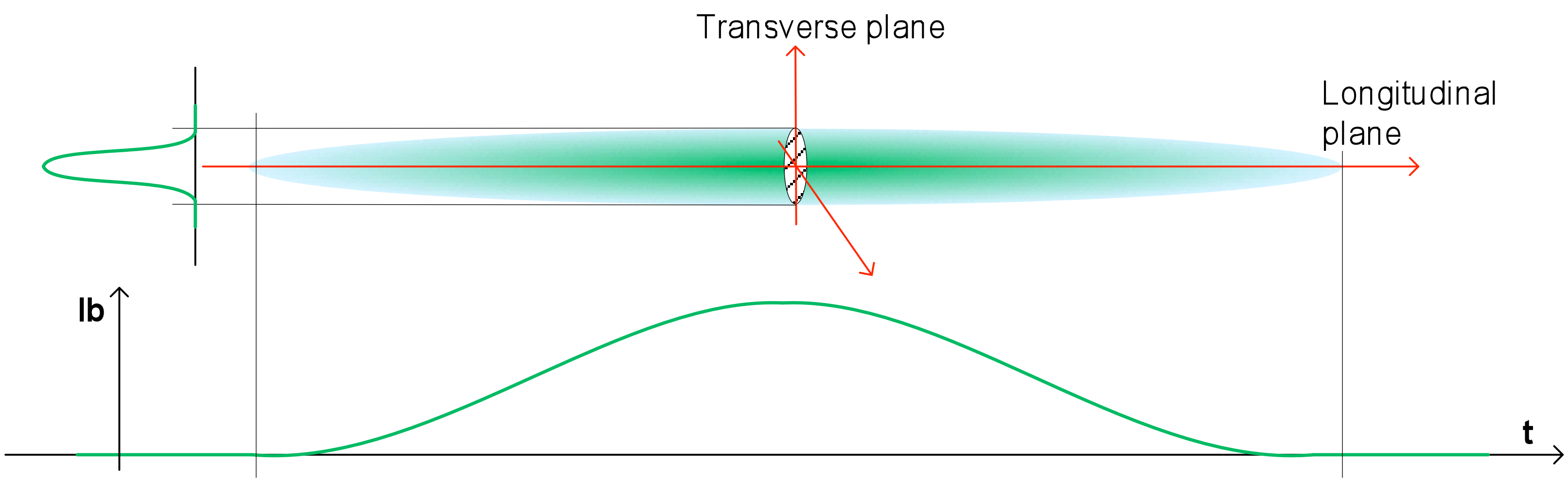
Acceleration by Alternating fields

- Accelerating structure can be re-used many times
- Use bending magnets to form a closed orbit trajectory



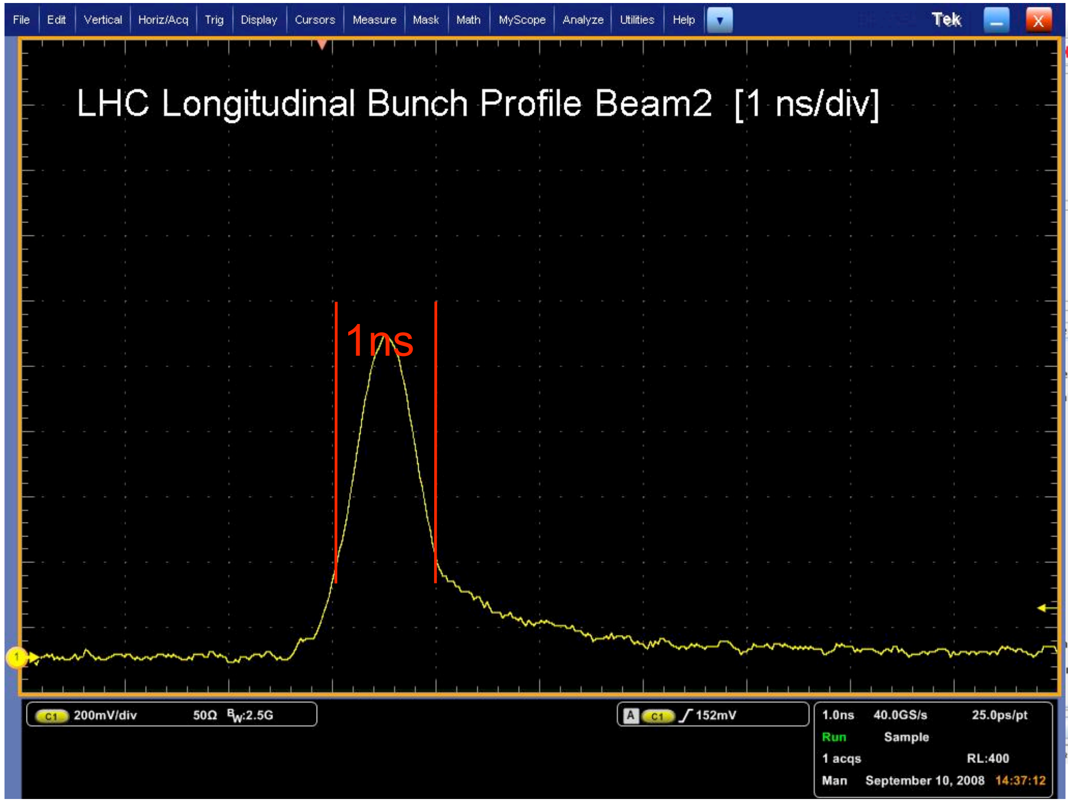
Acceleration by Alternating fields

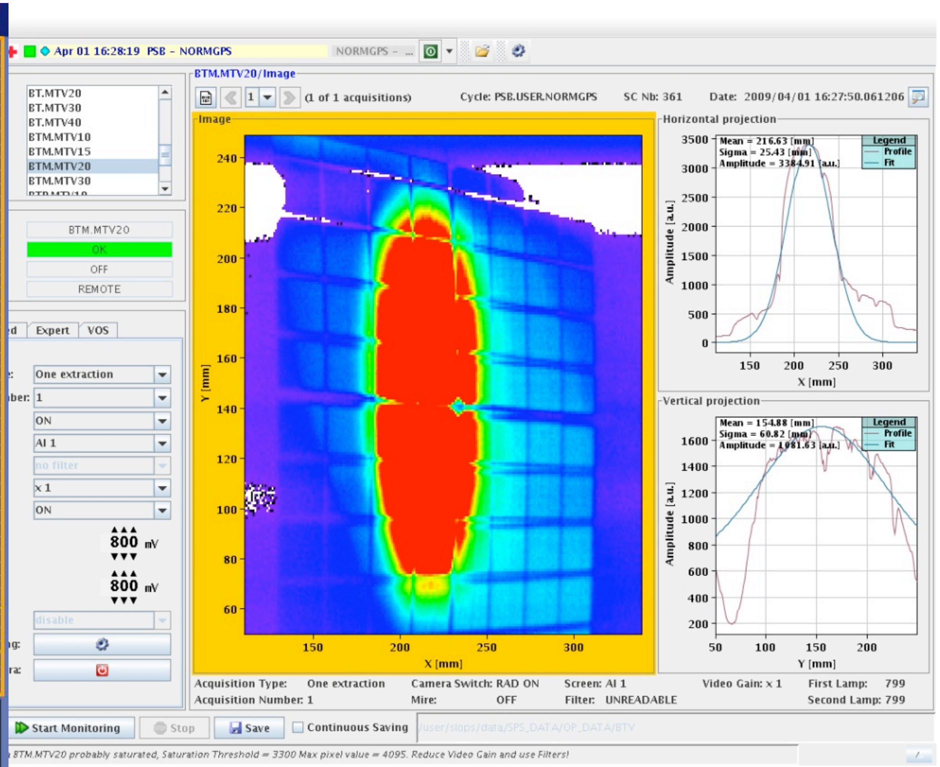
- If a beam of particles is accelerated by alternating fields it gets bunched.
- Bunch presents a “cloud” of particles, thin transversally (typ. μm-cm), and long longitudinally (typ. mm-m). Typically with Gaussian charge distribution in both planes.



Acceleration by Alternating fields

- Real bunch profiles:
  - Left: Longitudinal profile of the First LHC beam from 10.9.2008
  - Right: transverse profile of test beam measured in the PSB machine





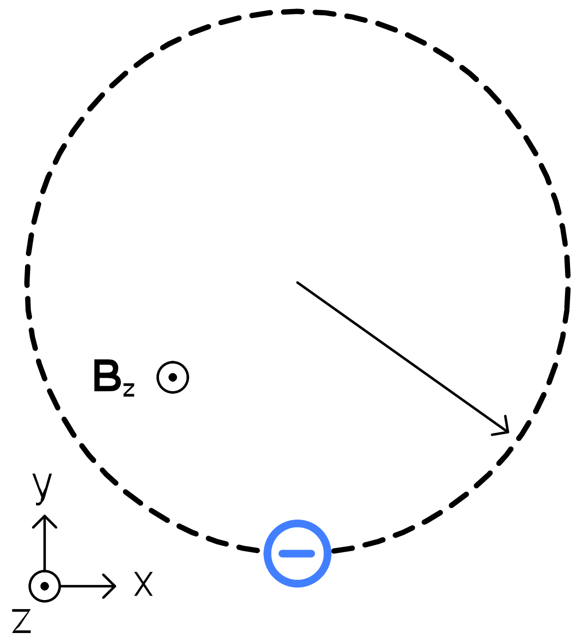
Synchrotron

- If the magnetic field strength is constant and energy (velocity) of the particle is constant it will move on a circular orbit

$$F_{centripetal} = F_{Lorentz}$$

$$\frac{mv^2}{r} = Bqv$$

$$\frac{v}{r} = \omega = \frac{Bq}{m}$$



Radius of motion of a particle with charge q, in a magnetic field B, mass m and velocity v:

$$r = \frac{mv}{Bq}$$

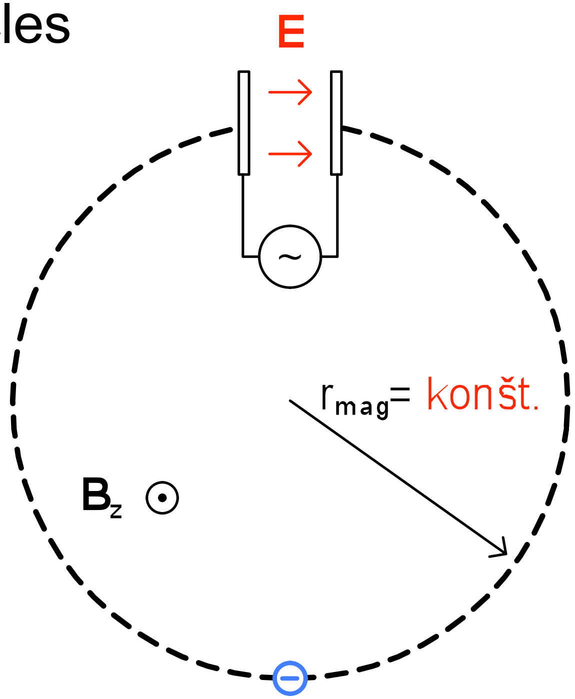
Examples of real machines:

SPS @ 450 GeV: r = 1100 m, B ~ 1.3T

LHC @ 7 TeV: r = 4297 m, B ~ 8.5 T

Synchrotron

- Now we must make sure that frequency and phase of the accelerating field is synchronous with the particles



Radius of motion of a charged particle in magnetic field:

$$r = \frac{mv}{Bq}$$

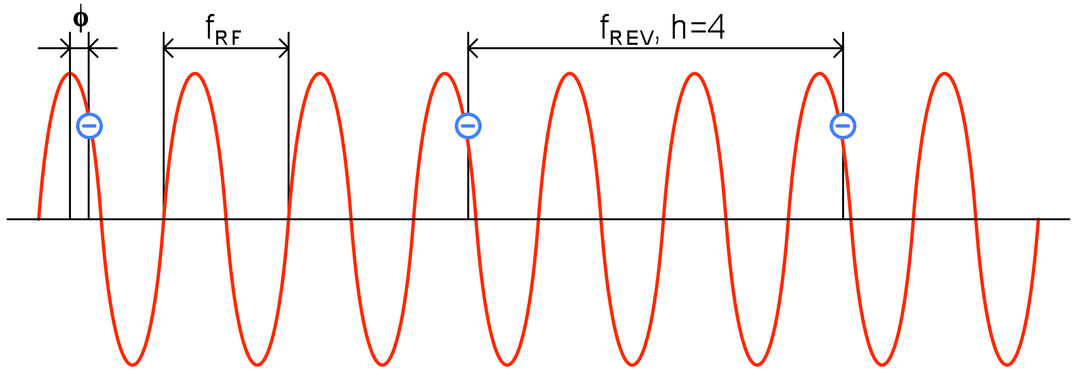
Revolution frequency of such a particle in an accelerator

$$f_{REV} = \frac{v}{2\pi r_{mag}} = \frac{Bq}{2\pi m}$$

To fulfill the synchronism condition, frequency of the RF field must be a harmonic of the revolution frequency*:

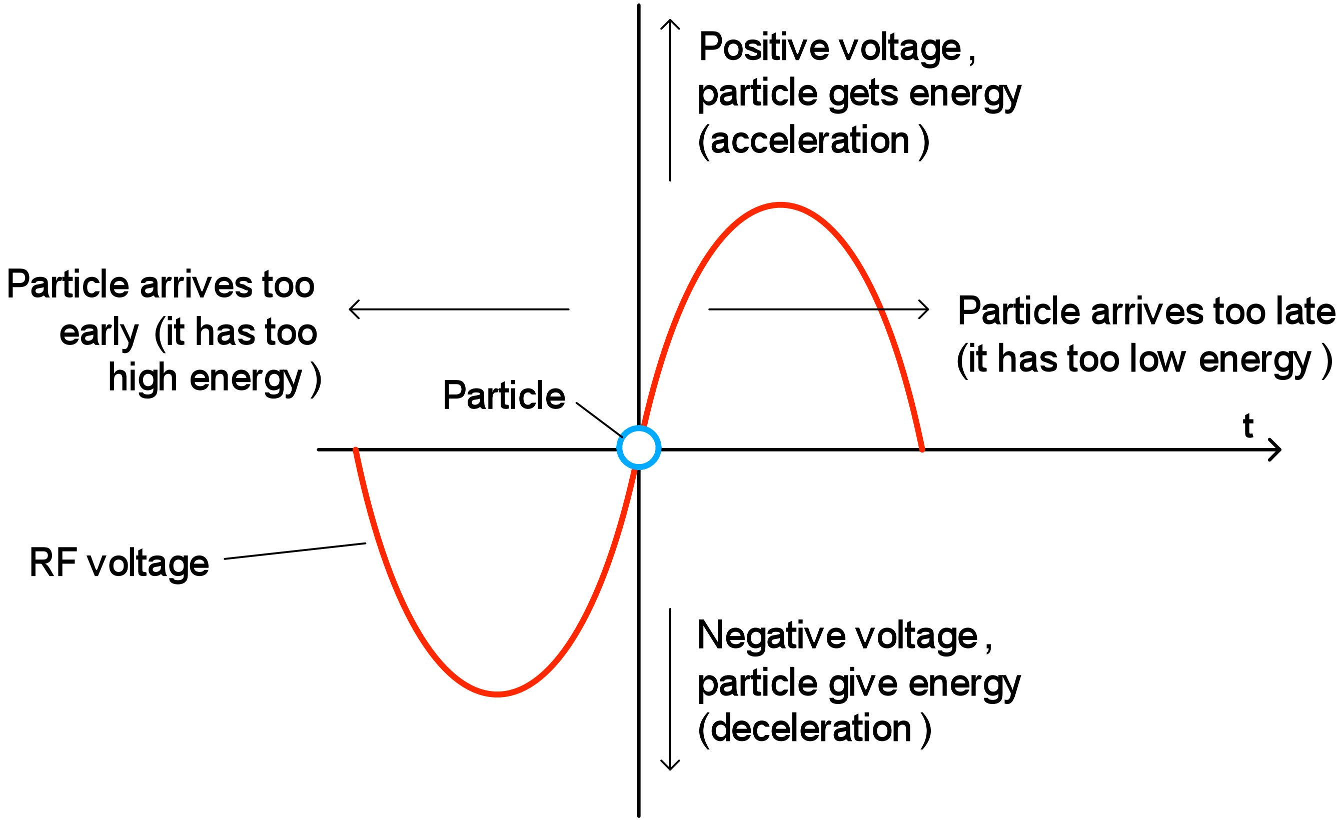
$$f_{RF} = h f_{REV}$$

* except of some special cases



Synchrotron motion and RF bucket

- The accelerating RF field creates an “RF bucket” which “traps” the particle
- Particle performs a synchrotron motion



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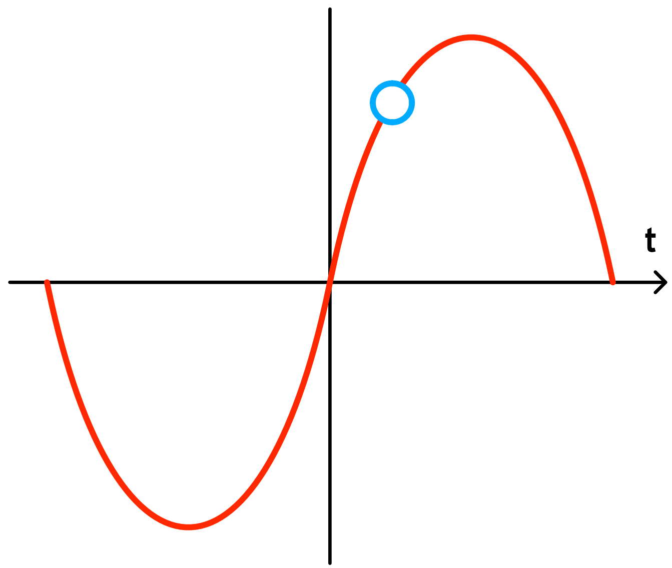

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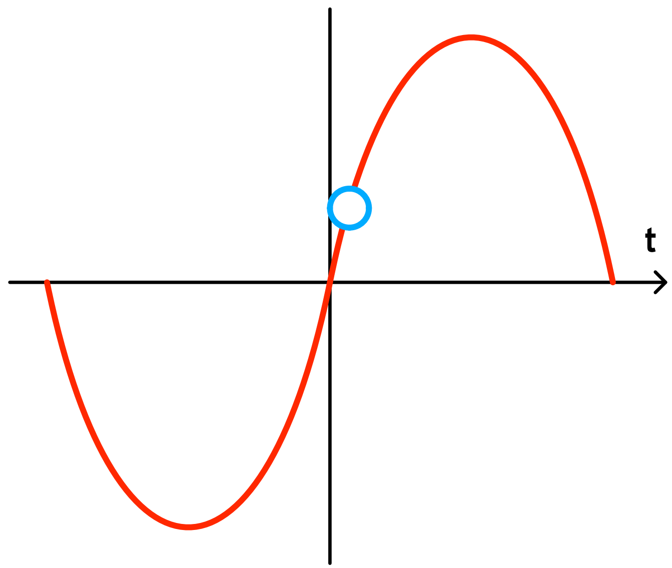

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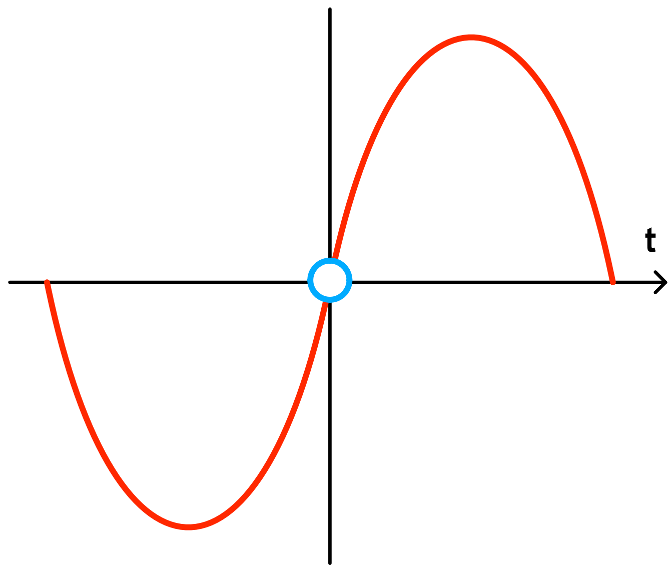

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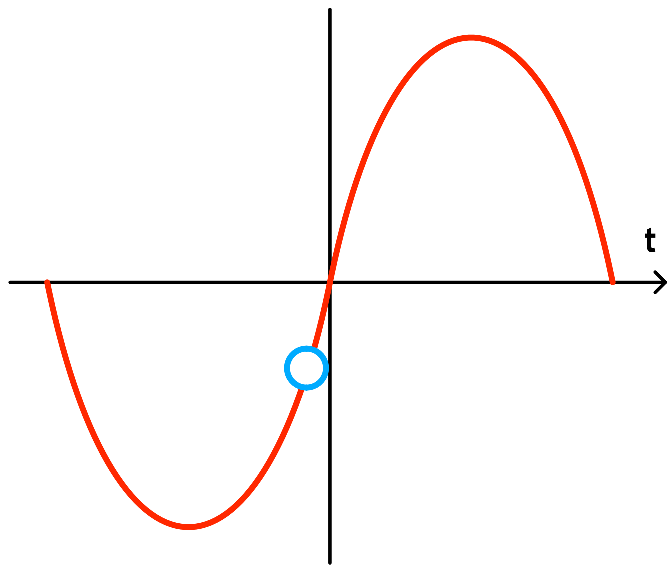

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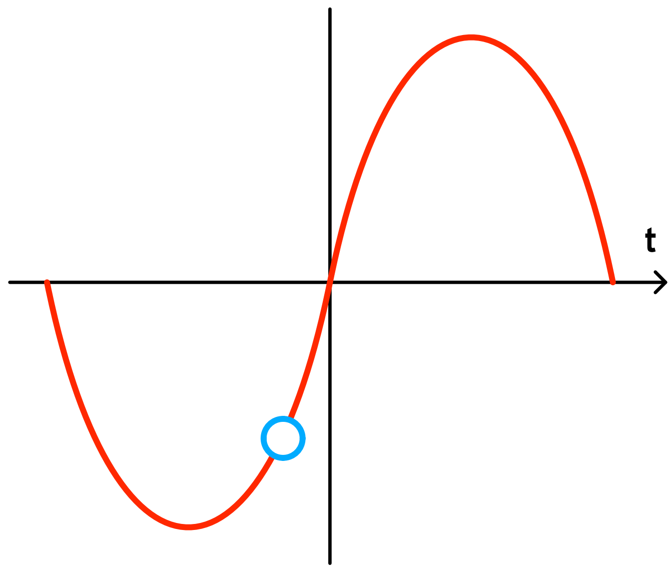

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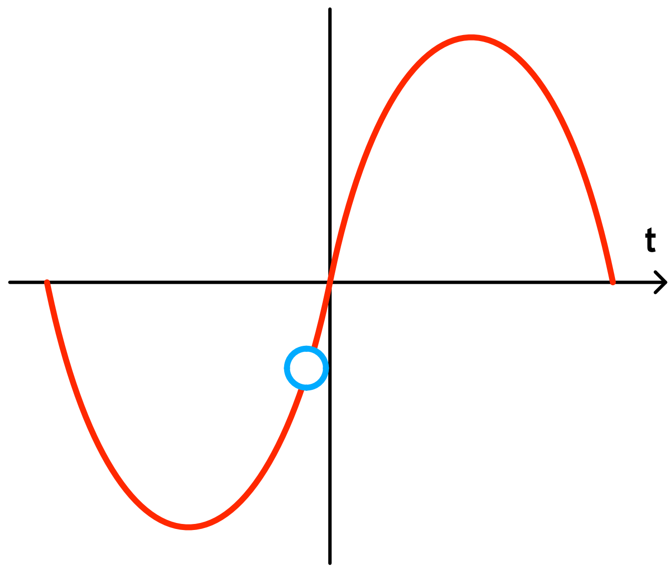

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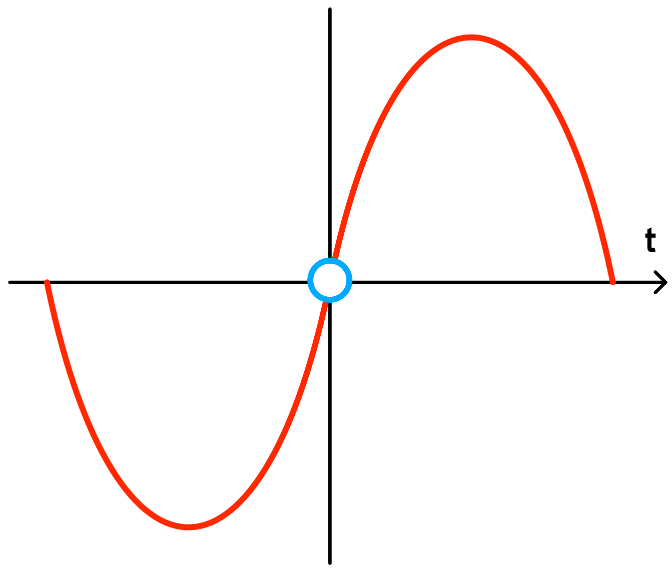

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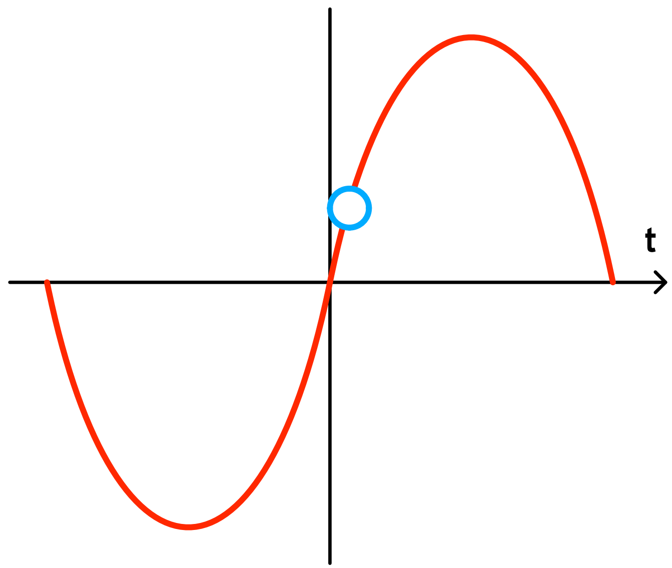

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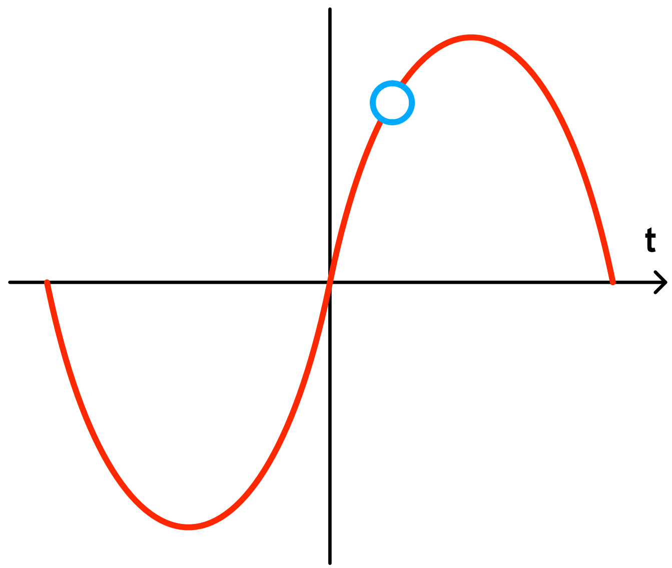
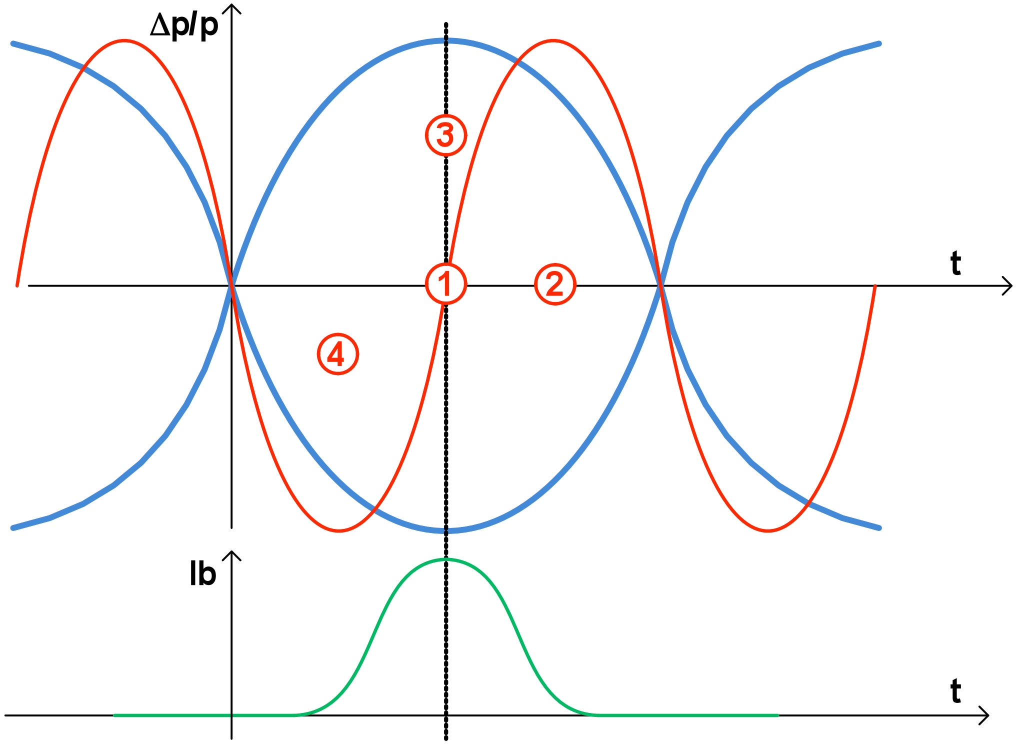


Synchrotron motion and RF bucket

- Synchrotron motion showed in a “phase space”



Particle 1:
Synchronous particle, arrives at correct time with correct energy. It gets no kick.

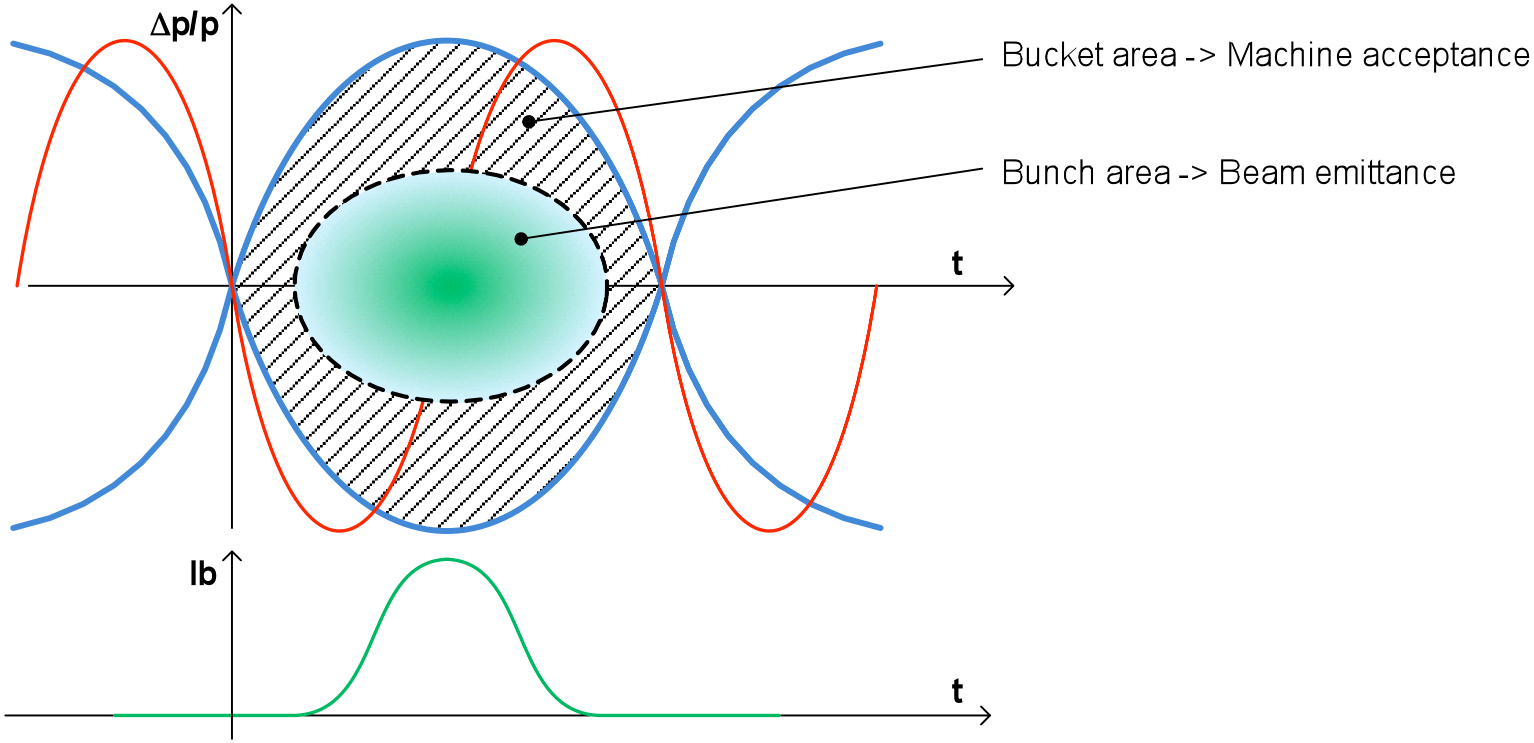
Particle 2:
Arrives with correct energy but too late, it will get a positive kick. Next turn will arrive earlier.

Particle 3:
Arrives with too high energy but at correct time. Next turn it will arrive too early. It gets no kick.

Particle 4:
Arrives too early. It gets negative kick. Next turn will arrive at correct time but with too low energy.

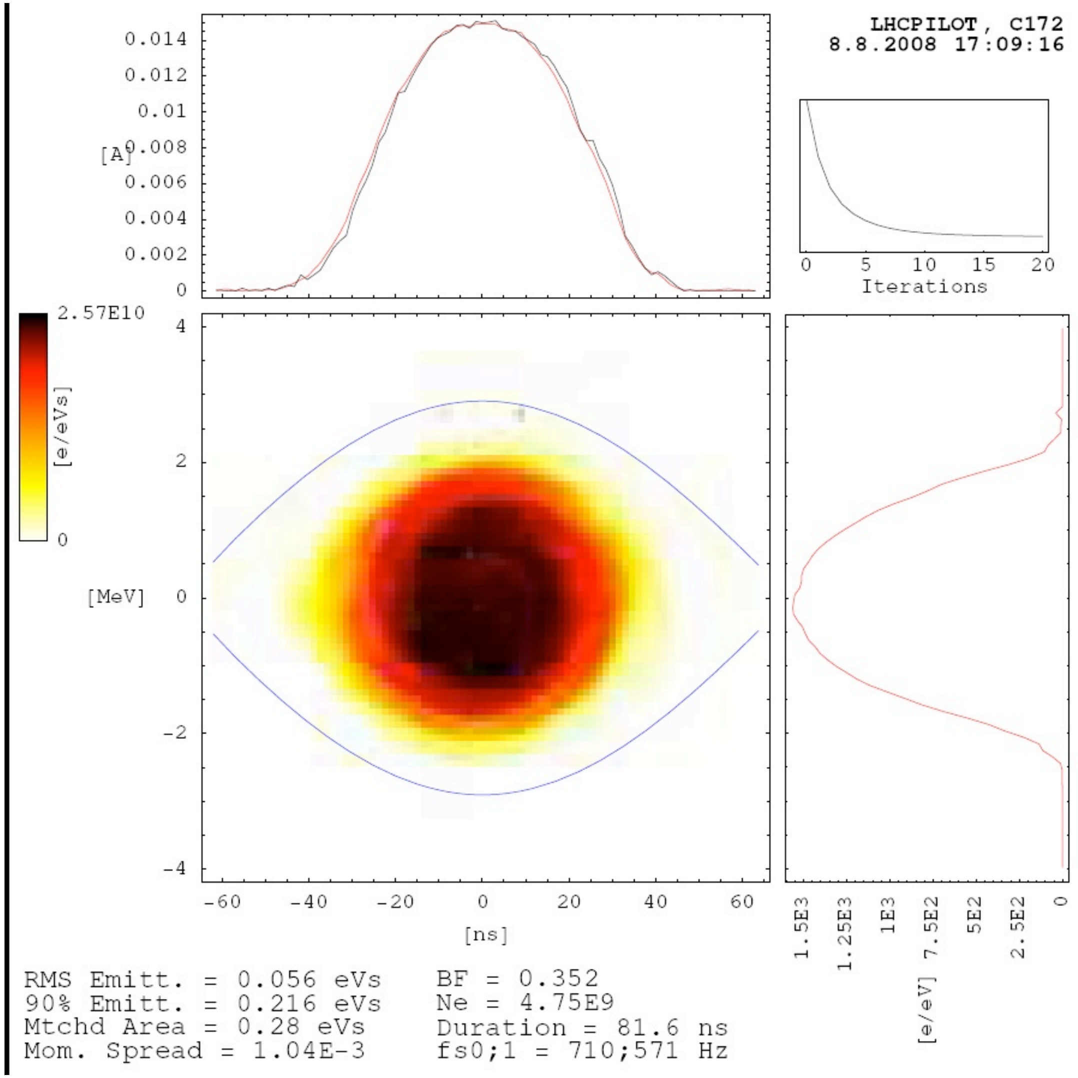
Synchrotron motion and RF bucket

- RF bucket filled with a bunch



Synchrotron motion and RF bucket

- Real LHC bunch measured by the Tomoscope in the PS machine



RF systems for synchrotrons – summary

- In the longitudinal plane, RF voltage creates the “RF buckets” which allow to
  - capture the injected beam
  - keep it bunched
  - provide the acceleration, deceleration
  - keep the beam circulating at a constant energy in storage rings

- The RF field must be synchronous with the circulating beam
  - RF frequency is (usually) harmonic number of the beam revolution frequency

Accelerating structures

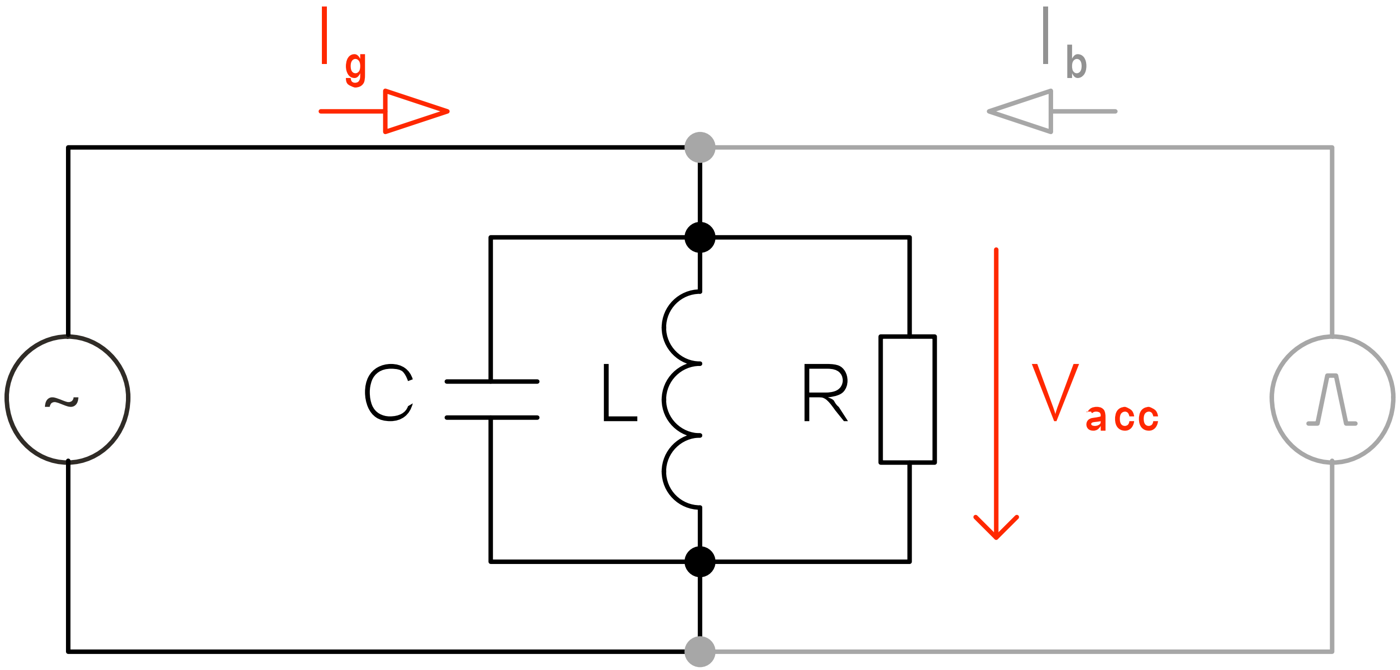
- The beam sees the RF voltage in the accelerating structures, generally called “RF cavities”

- Accelerating cavities
  - Lumped element
  - Travelling wave structures
  - Standing wave structures (microwave resonant cavities)
  - Other

- Technology
  - Normal conducting
  - Super conducting

Accelerating structures

- Resonance helps built up a high voltage voltage across the gap



RF system of the PSB and the PS machines

- Low energy beams are not yet relativistic:
  - Relative change of the velocity is high (PSB ~300%, PS ~10%)
  - Accelerating structures must follow the gradual increase of the velocity
  - Cavities must cope with large frequency spans

- Required RF voltages: typ. in kV range

- Required bandwidth: typ. > 2:1

- Typical structure: Tunable, lumped element resonant circuit (ferrite loaded cavity

- Power source: typ. tetrode amplifier, 5 - 25kW

RF system of the PSB and the PS

	Cavity	Count	Harmonic number	Freq. range (MHz)	Peak voltage (kV)
PSB	C02	1 per ring	1	0.6 - 1.8	8
	C04	1 per ring	2	1.2 - 3.9	8
	C16	1 per ring	8 - 24	6 -17	6
PS	C10	10+1	7 - 21	2.7 - 10	1 - 20
	C20	1+1	28, 42	13 or 20	15
	C40	1+1	84	40	3 - 350
	C80	2+1	168, 169	80	350
	C200	4+2	420 - 433	200	30

PSB RF system (details)

Table 1: Main parameters of PSB RF systems

Parameter \ System	C02	C04	C16
Frequency Range [MHz]	0.6 - 1.8	1.2 - 3.9	6.0 - 17.0
Quality Factor	6 - 28	90 - 190	60 - 80
Cav. Shunt Resist.[KOhm]	2.5	9	7
Nominal Gap Vrf [kVp]	8.0	8.0	6.0
Max. Gap Vrf [kVp]	10.0	9.0	8.0
Power Loss [kW]	13.0	3.0	2.5
Peak Power [kW]	50.0	20.0	10.0
CW Power [kW]	20.0	10.0	5.0
RF Feedback Gain [dB]	20	20 - 26	13 - 26
Ferrite Type (Philips)	4A11	4L2	4M2
Permeability at Remanence	~600	~200	~100
Tuning Bias [A* turn]	0 - 500	0 - 1800	0 - 3500
Power density [mW/cm^3]	64	31	58
Magn. RF Flux Dens.[mT]	4-12	3.2-9.4	1-3.2
Ferrite Ring Size [cm]	48x24x3	35x20x3	35x20x3
Total Ferrite Length [cm]	1500	1500	660

Source: THE NEW LOW FREQUENCY ACCELERATING SYSTEMS FOR THE CERN PS BOOSTER
A. Krusche, M. Paoluzzi, CERN, Geneva, Switzerland

PSB RF system (ferrite loaded cavity)

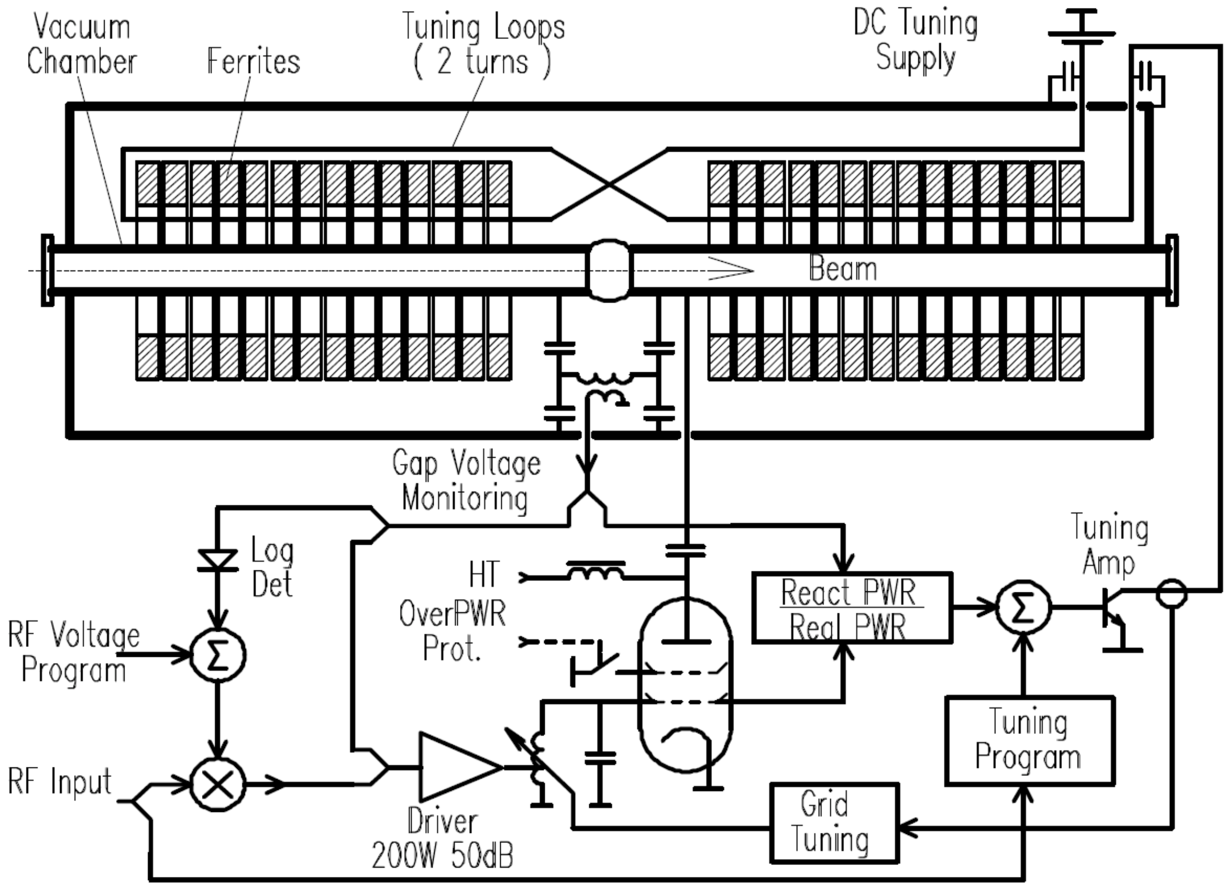


Figure 2: C02 system layout

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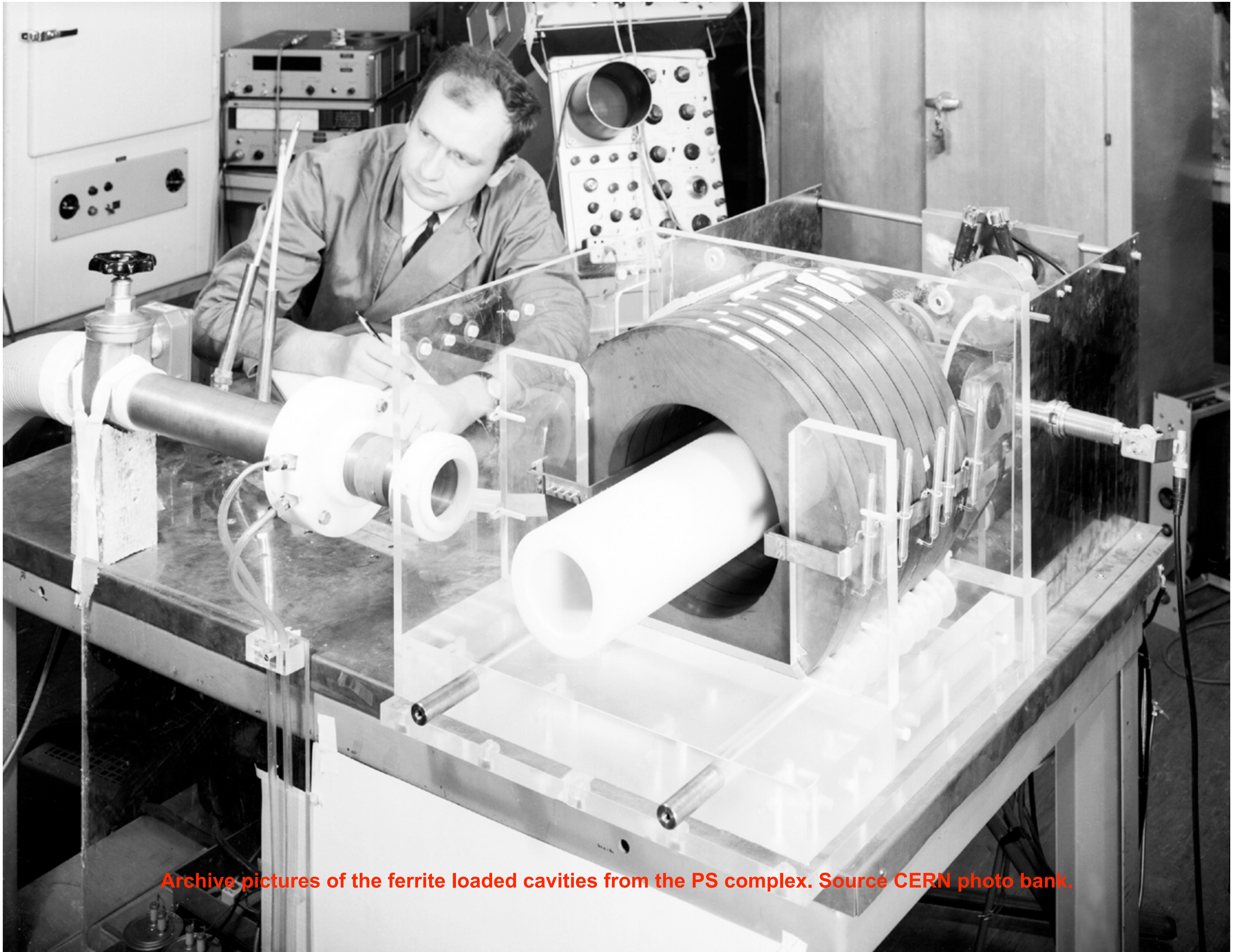
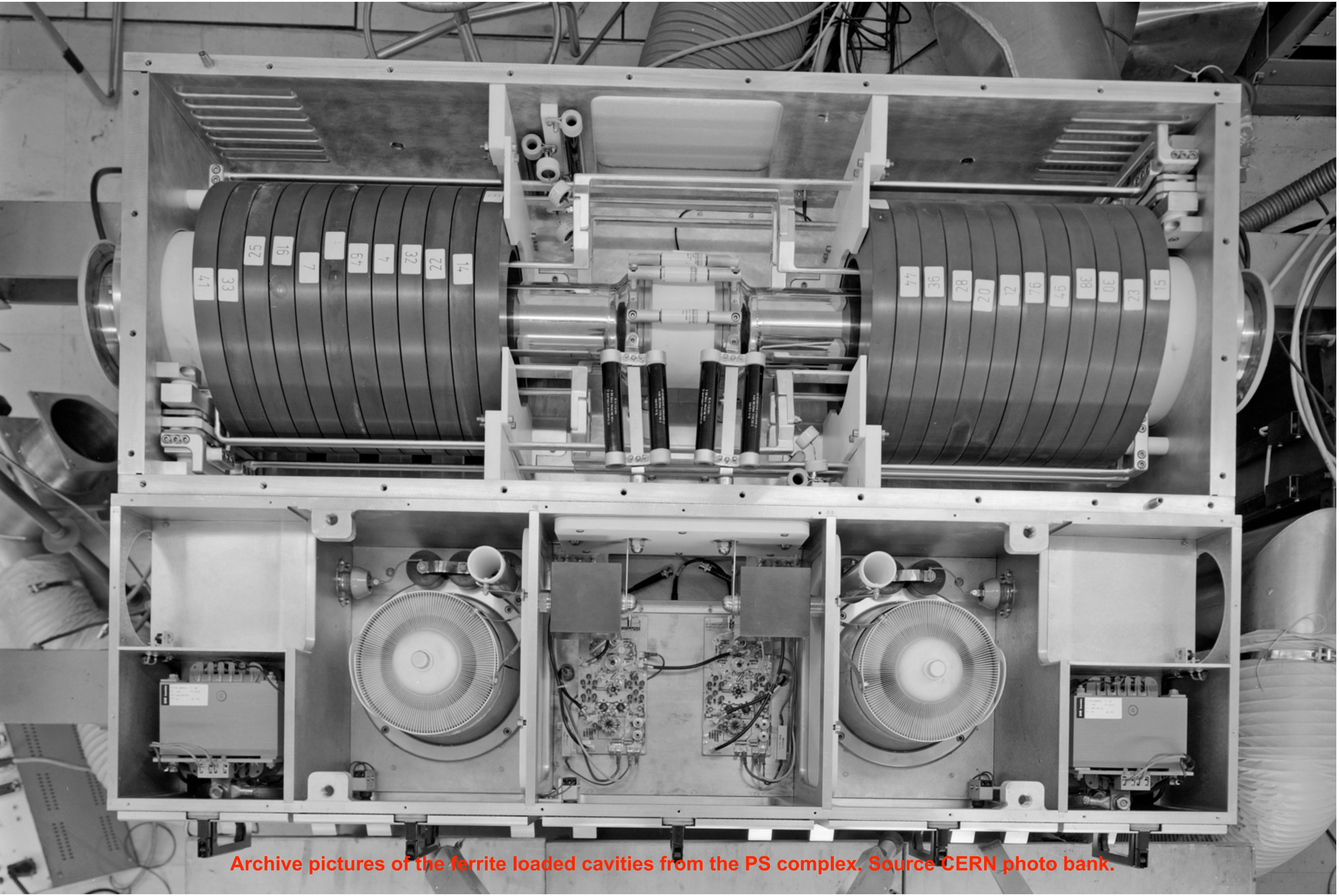
A. Krusche, M. Paoluzzi, CERN, Geneva, Switzerland



Archive pictures of the ferrite loaded cavities from the PS complex. Source CERN photo bank.



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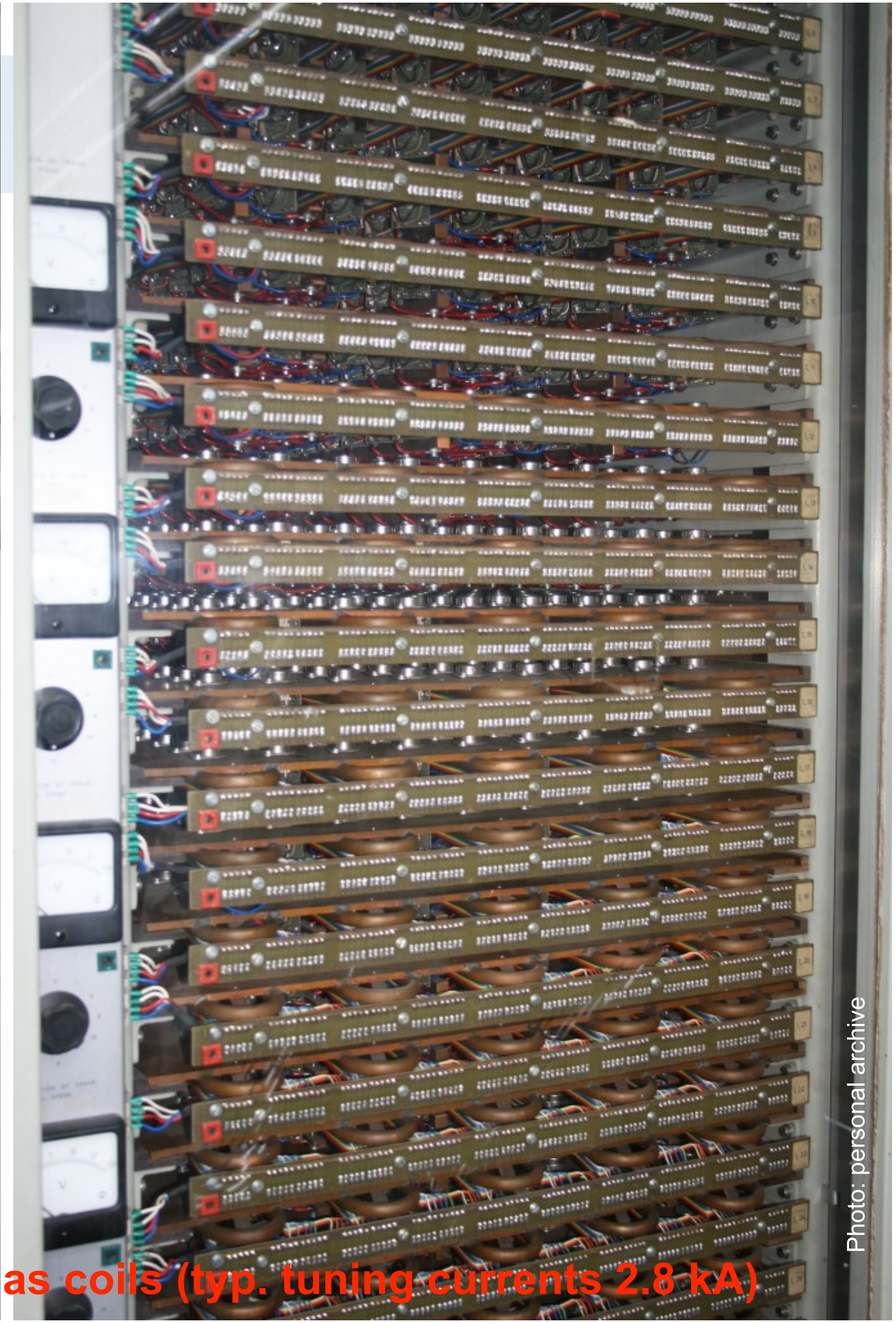
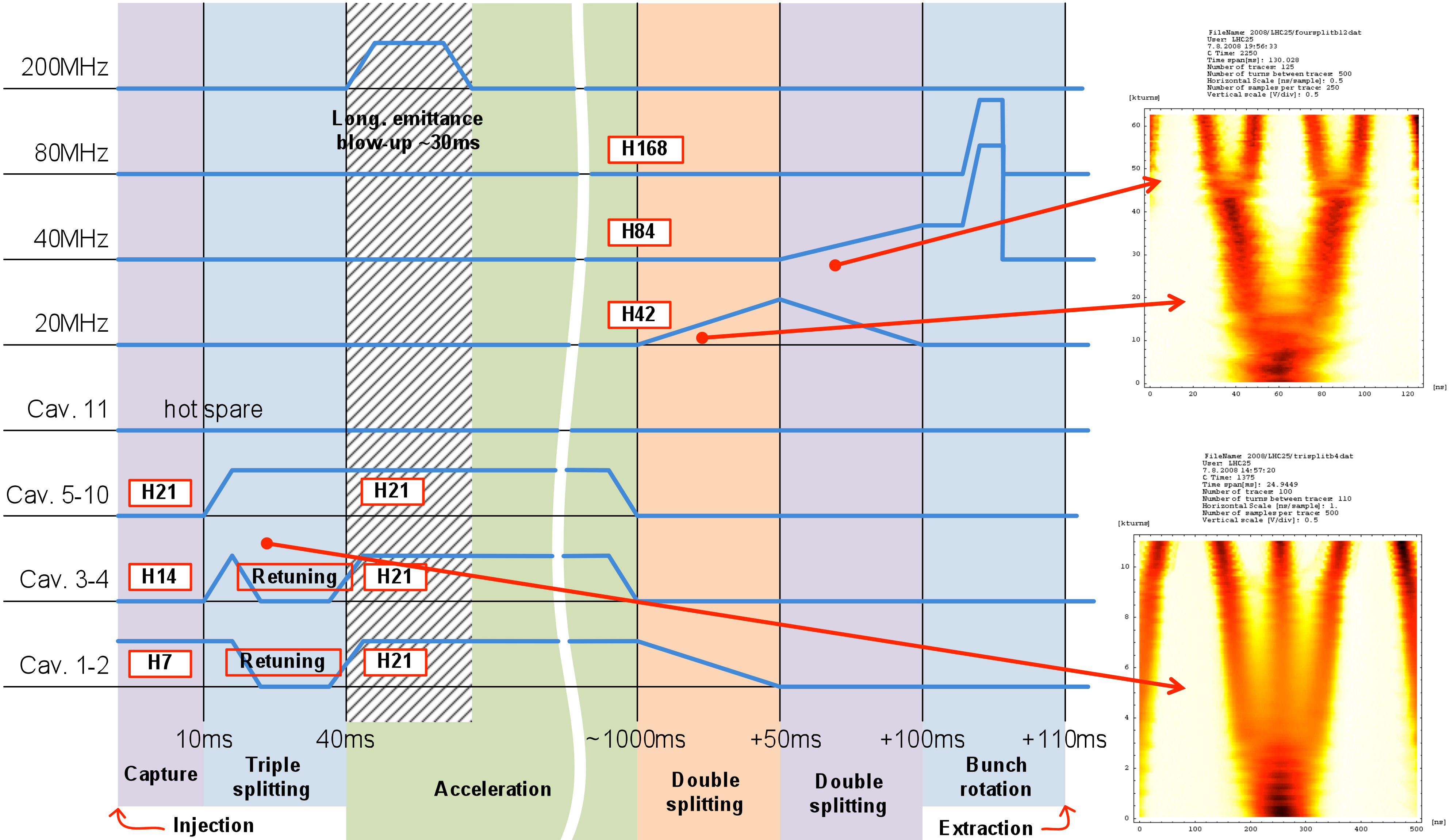


Linear current regulator for the ferrite bias coils (typ. tuning currents 2.8 kA)

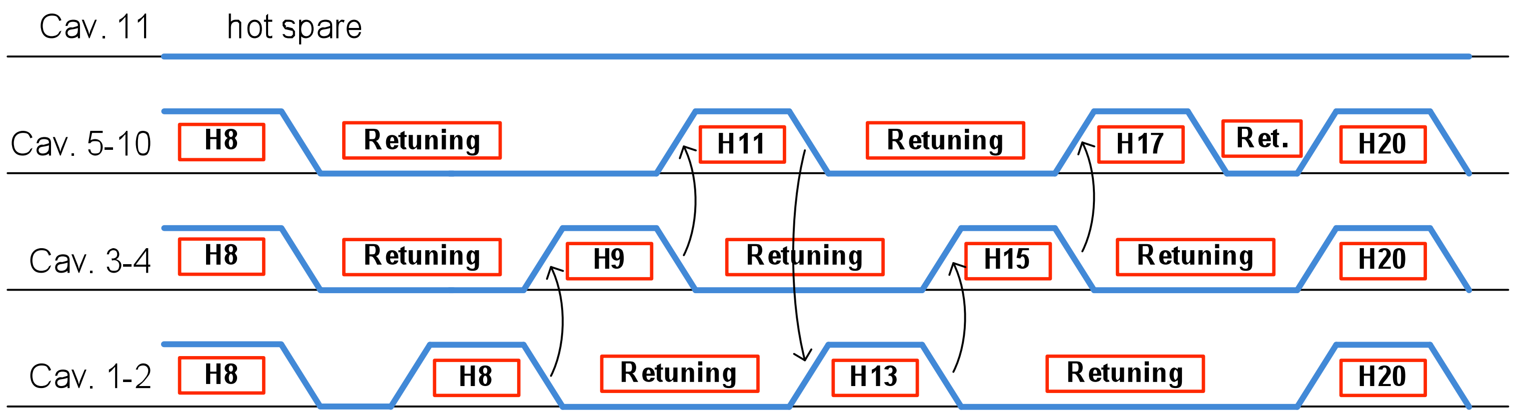
Photo: personal archive

Typical PS acceleration cycle (with LHC beam)



Typical PS acceleration cycle (AD beam)

- Cavities are tuned "on-fly" from H8 (~3.8 MHz) to H20 (~9.5 MHz) and the beam is handled subsequently by one after the other



RF system of the SPS and the LHC

- Larger synchrotrons accelerate already relativistic beams:
  - Relative change of the velocity is much smaller (SPS ~0.3%, LHC ~2.5ppm)

- Required RF voltages: typ. in MV range (10 vs. 16MV)

- Required bandwidth: very narrow

- Typical structures:
  - Travelling wave cavities (used in the SPS)
  - Standing wave superconducting cavities (LHC)

RF system of the SPS and the LHC

	Cavity	Count	Typ. harm. number	Freq. (MHz)	Band-width	Peak voltage (MV)
SPS	TWC 200 4 sections	2	4620	200.2	1.7 MHz	2.3
	TWC 200 5 sections	2	4620	200.2	1.4 MHz	2.8
	TWC 800	2	18480	800.8		0.7
LHC	ACS	8 per ring	35640	400.8	20 kHz @inj. 2 kHz @flat top	8 x 2

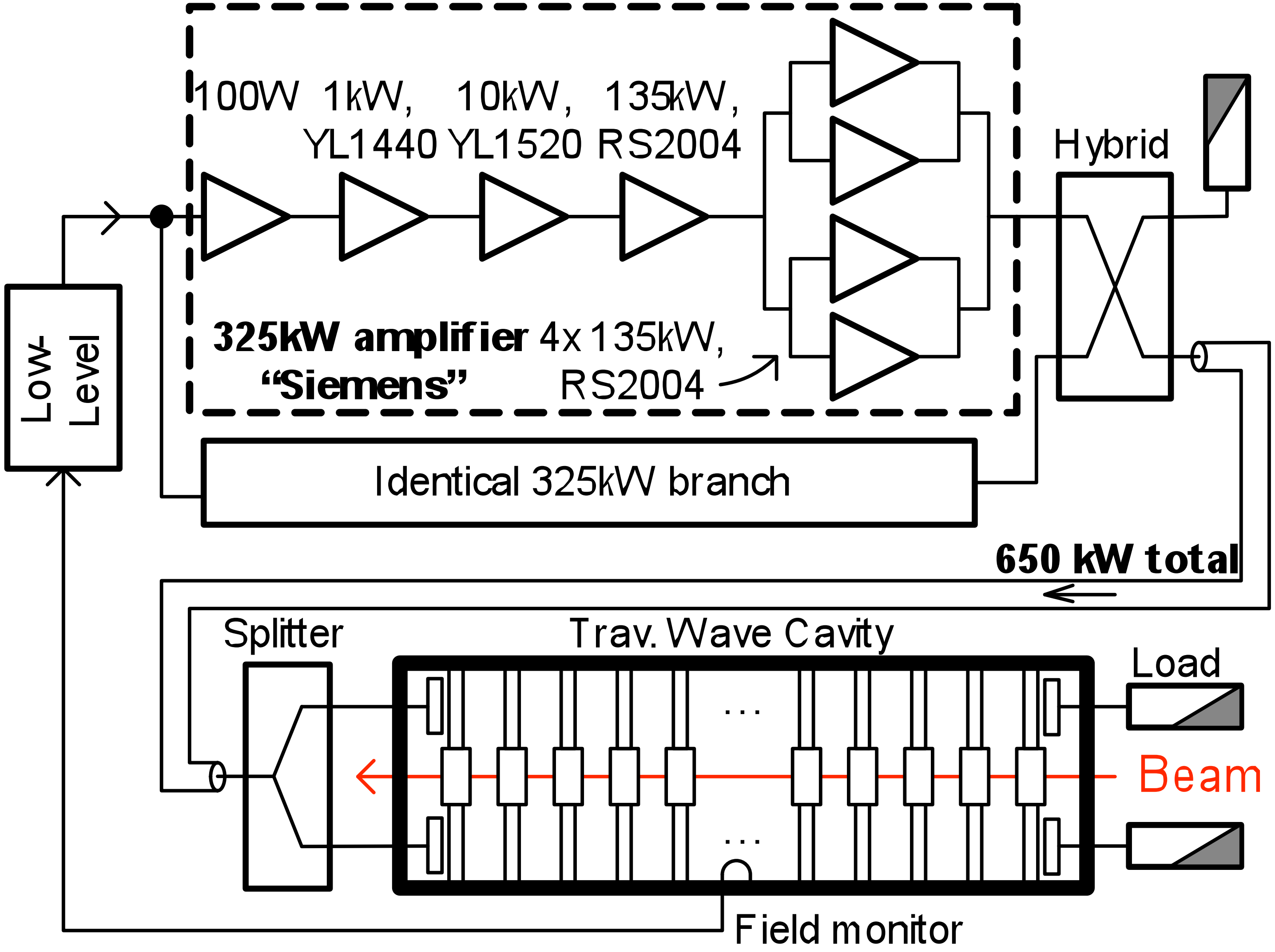
SPS RF system

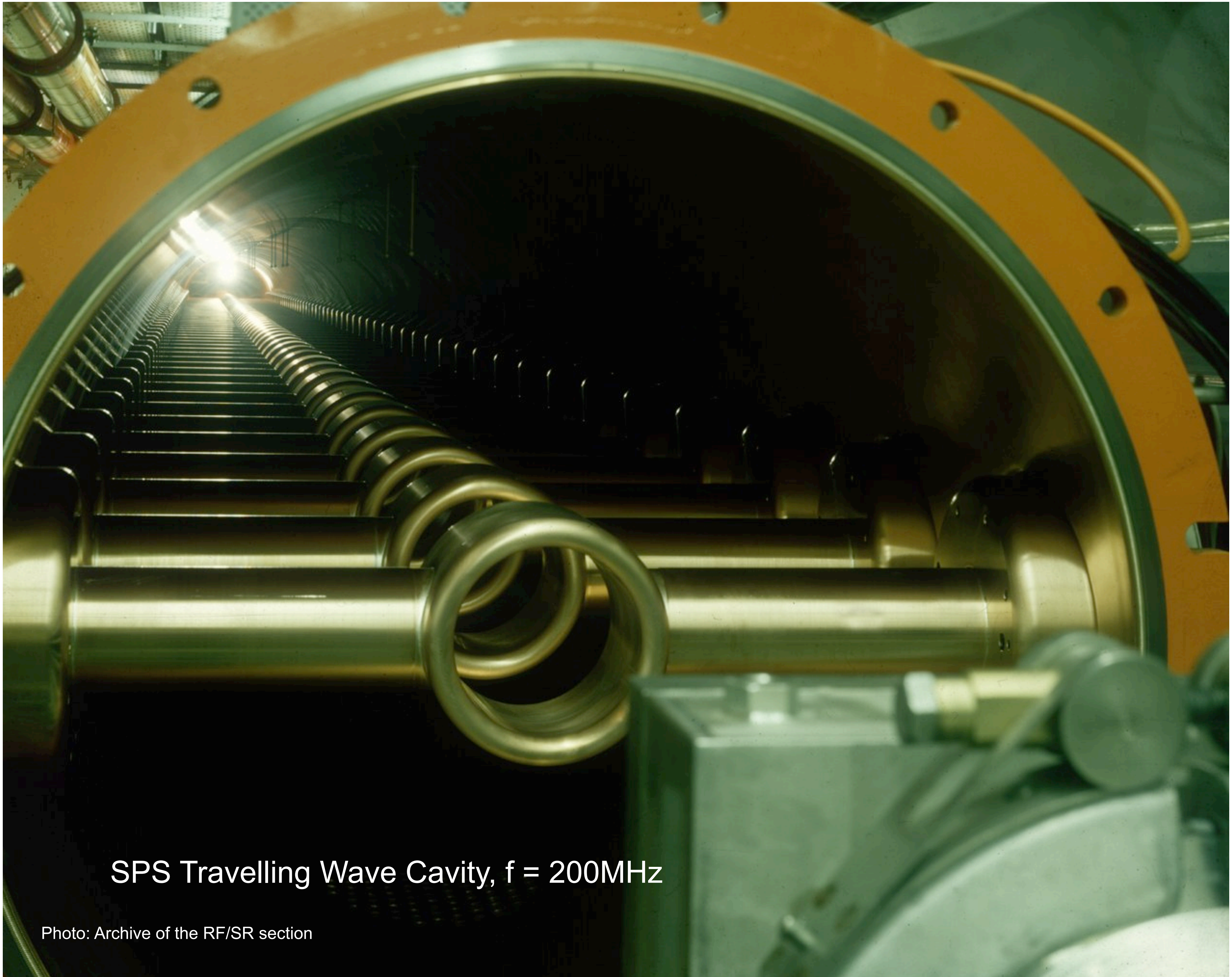
- Travelling wave cavities (~80m underground)
  - 2x 4 section cavity, BW 1.7MHz, delivers 2.3MV when driven by 700kW RF
  - 2x 5 section cavity, BW 1.4MHz, delivers 2.8MV when driven by 700kW RF
  - Cavity resonant frequency is fixed

- RF power amplifiers (surface)
  - 2x “Siemens” amplifier, 650kW CW each. Final stage 8x 135kW water cooled tetrodes RS2004 combined together
  - 2x “Philips” amplifier, 700kW CW each. Final stage 32x 35kW air cooled tetrodes YL1530 combined together

- Transmission line system
  - 50 Ohm coaxial lines, diameter 345mm, capable to transfer 700kW CW with only natural cooling

SPS RF system

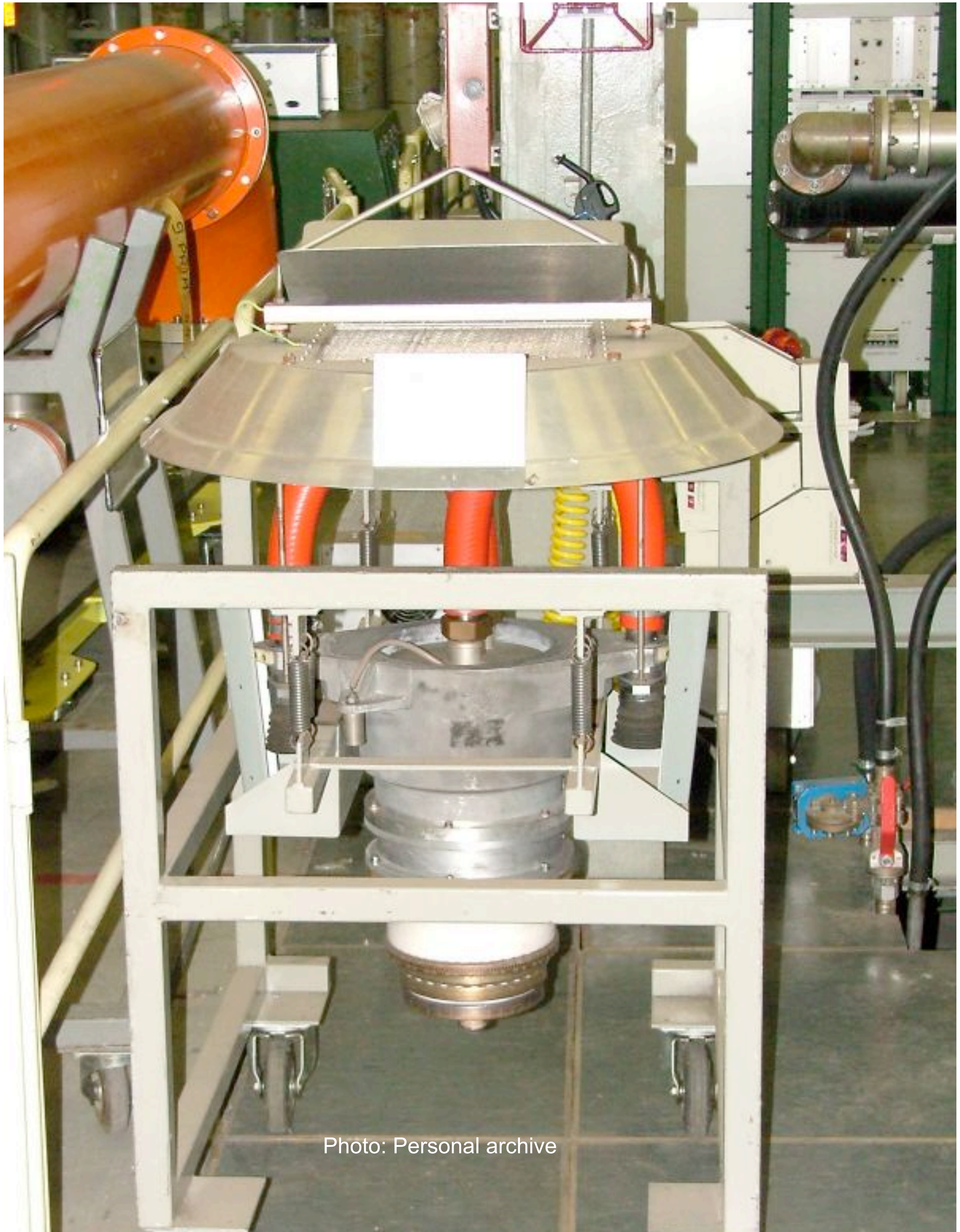


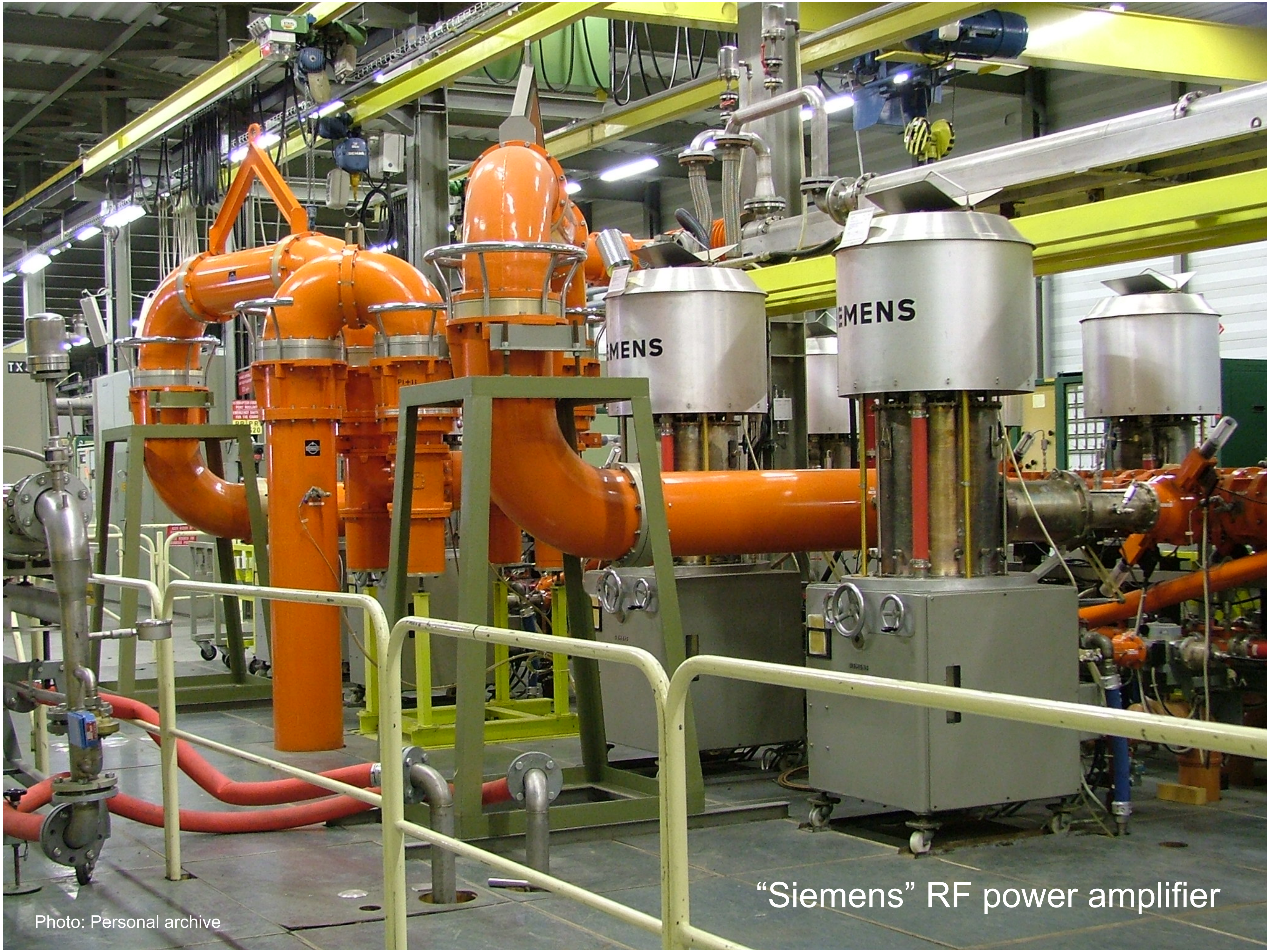

SPS Travelling Wave Cavity, f = 200MHz
Photo: Archive of the RF/SR section

SPS Travelling Wave Cavities integrated in the SPS tunnel

Photo: Personal archive

Tetrode RS2004





“Siemens” RF power amplifier

Photo: Personal archive

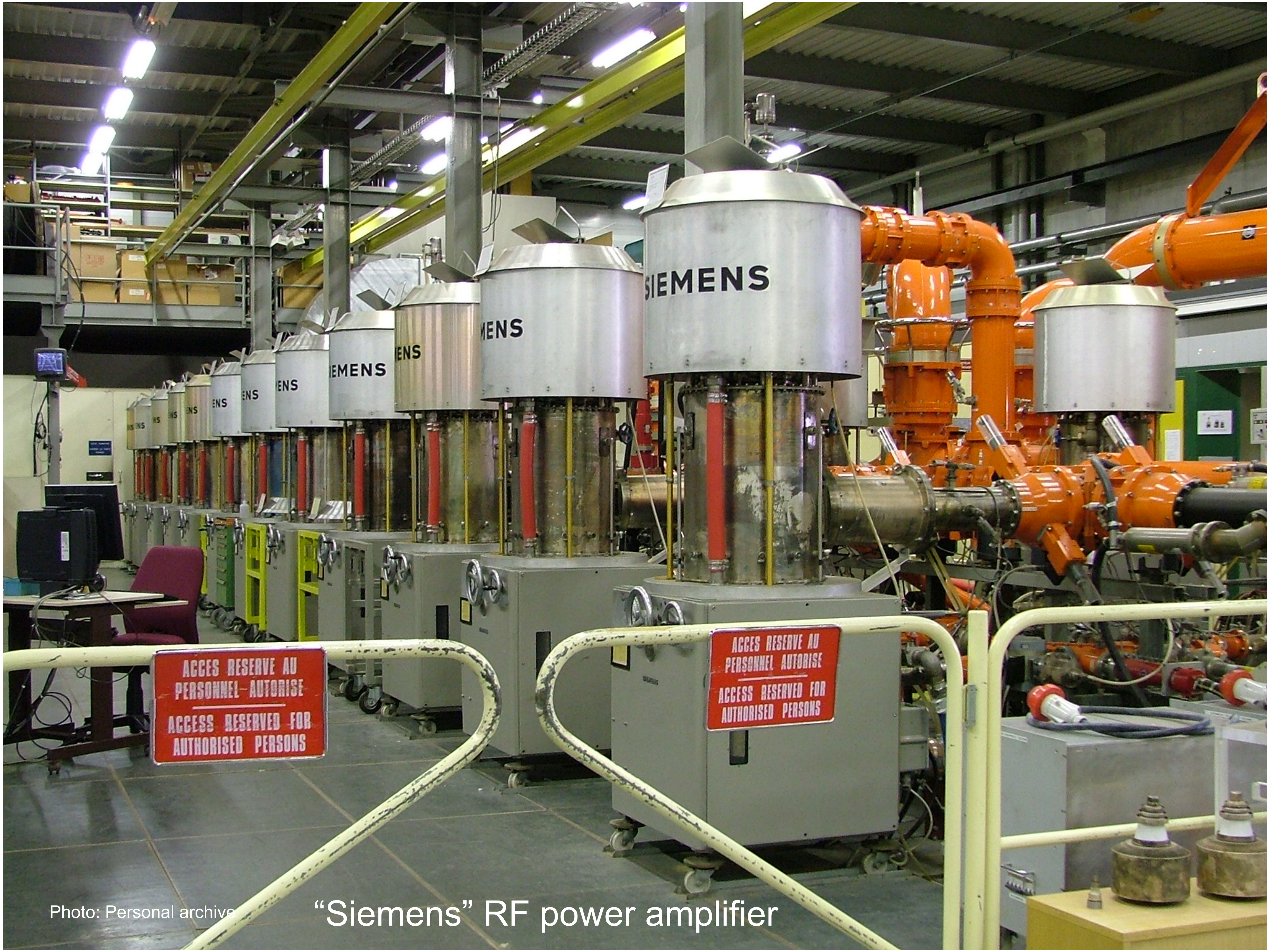
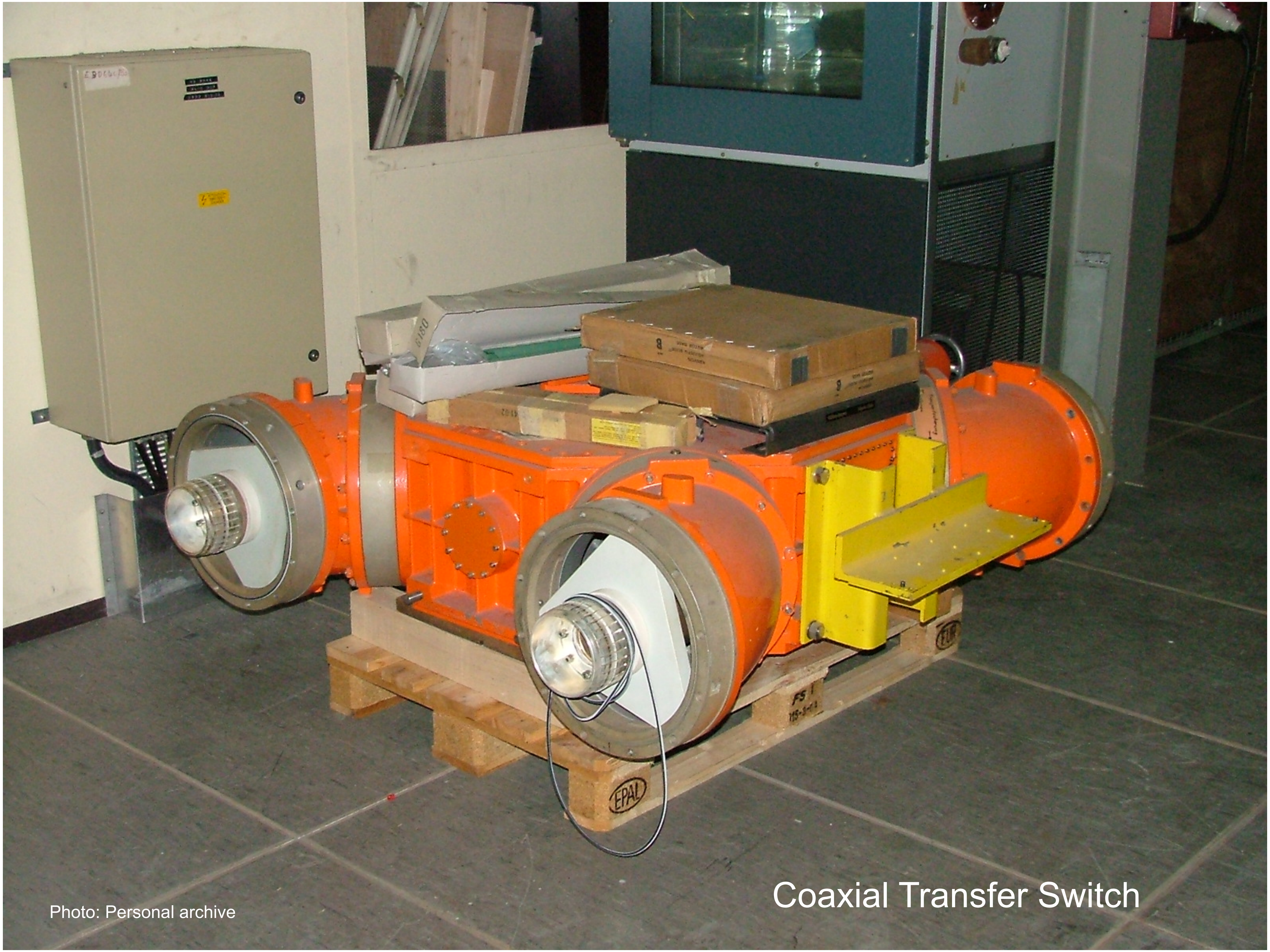


Photo: Personal archive

“Siemens” RF power amplifier

“Philips” RF power amplifier

Photo: Personal archive



Coaxial Transfer Switch

Photo: Personal archive

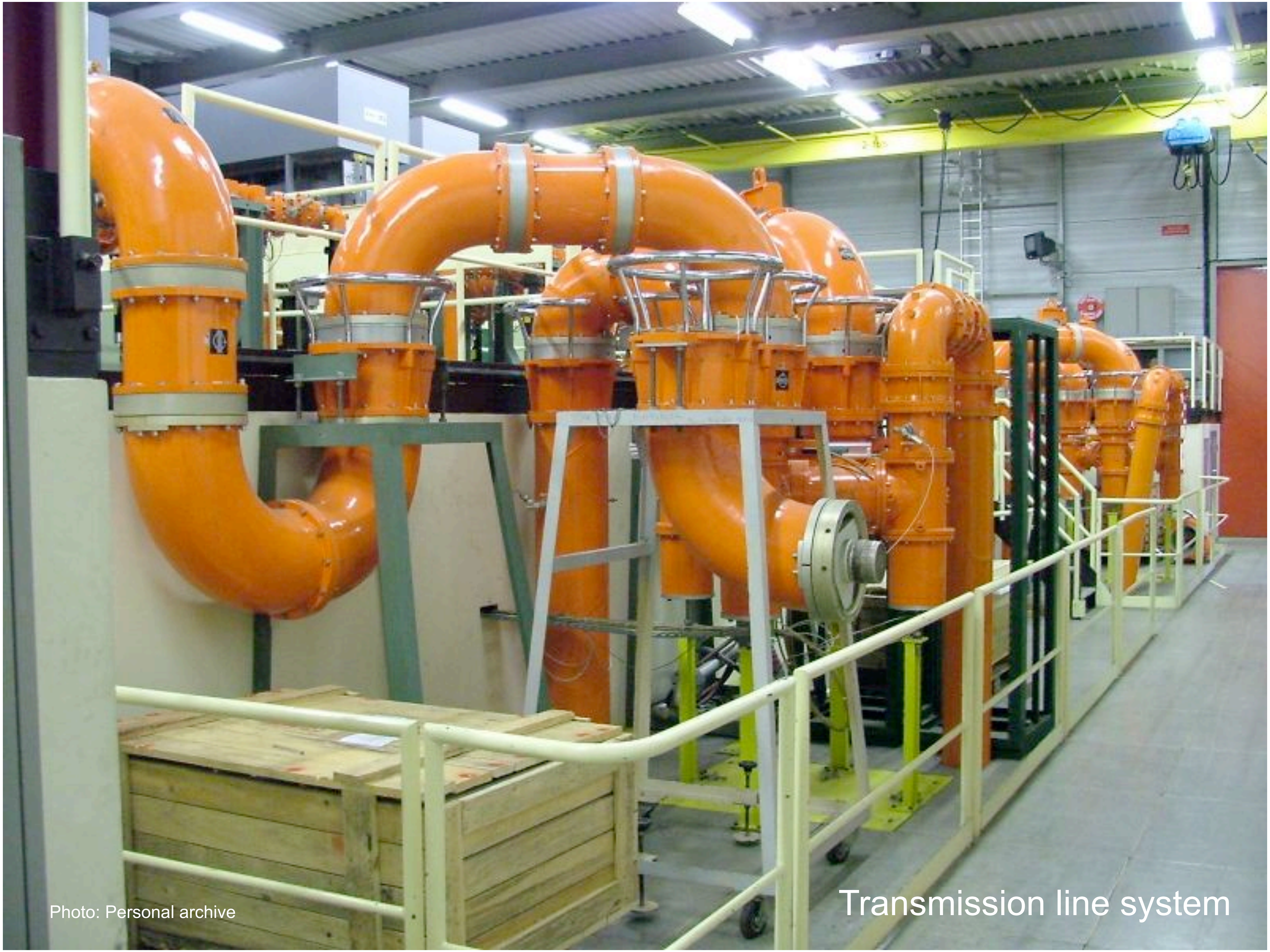


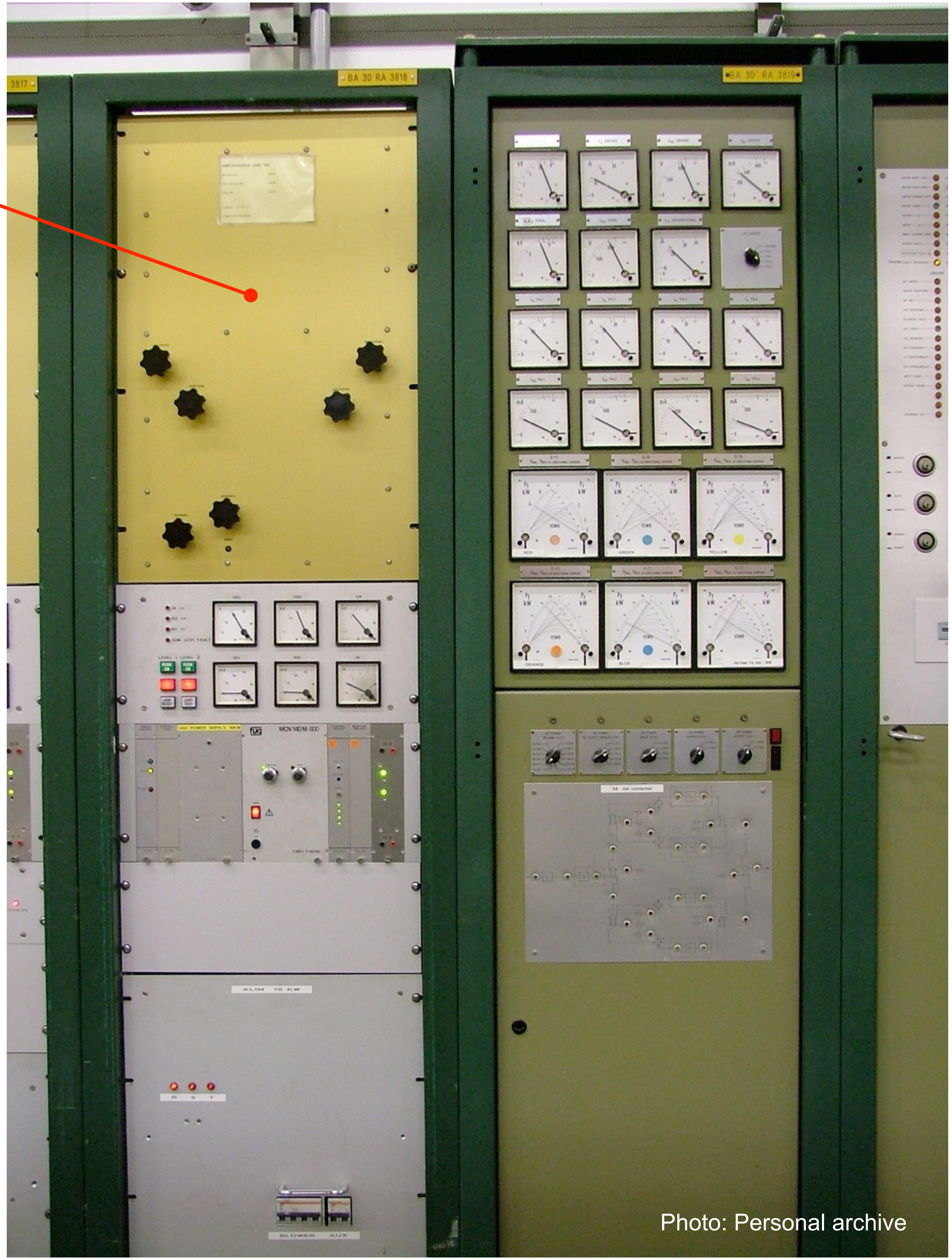
Photo: Personal archive

Transmission line system

Photo: Personal archive

Coaxial jumper

10kW pre-driver amplifier



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Final combiner power measurement

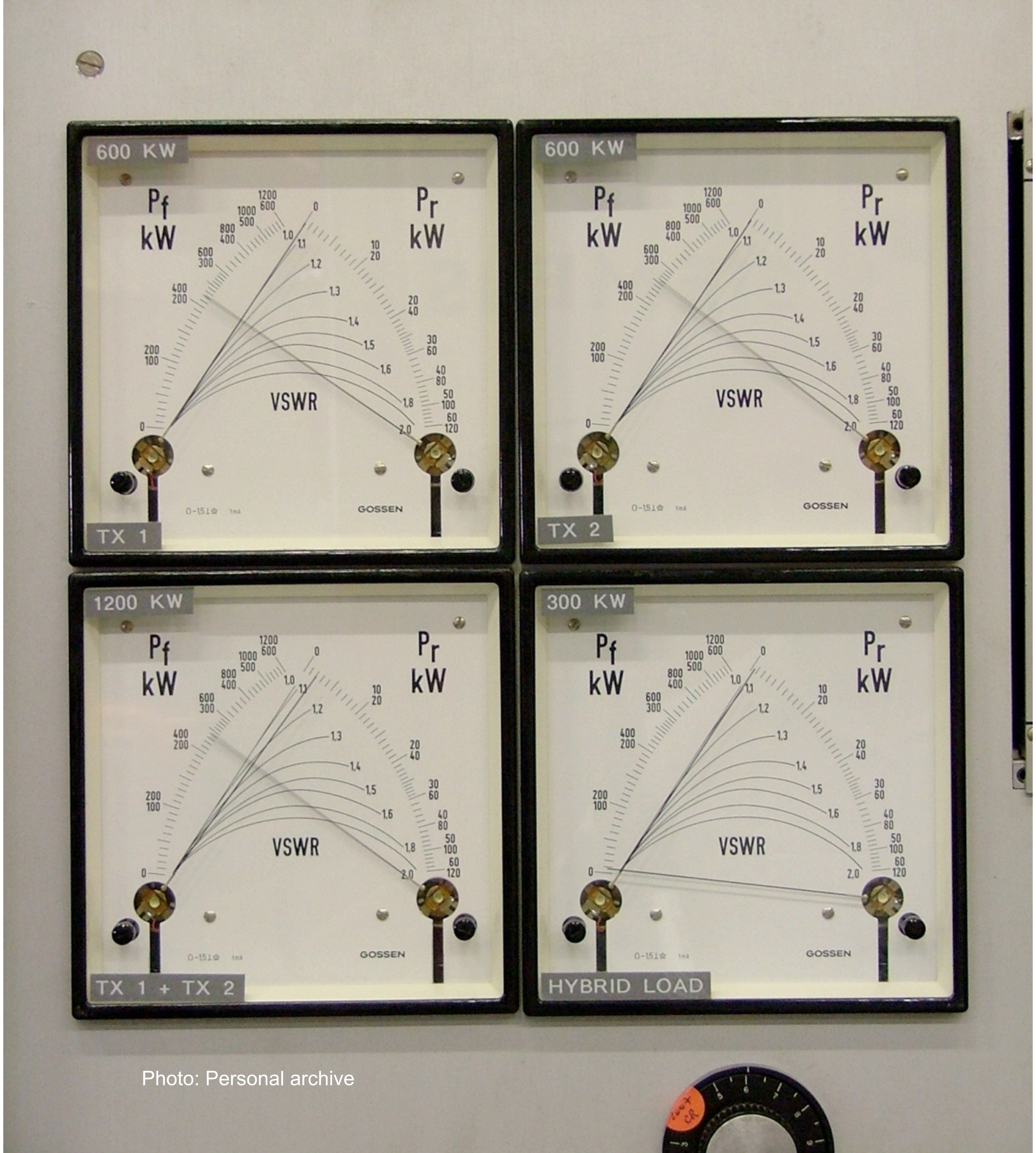
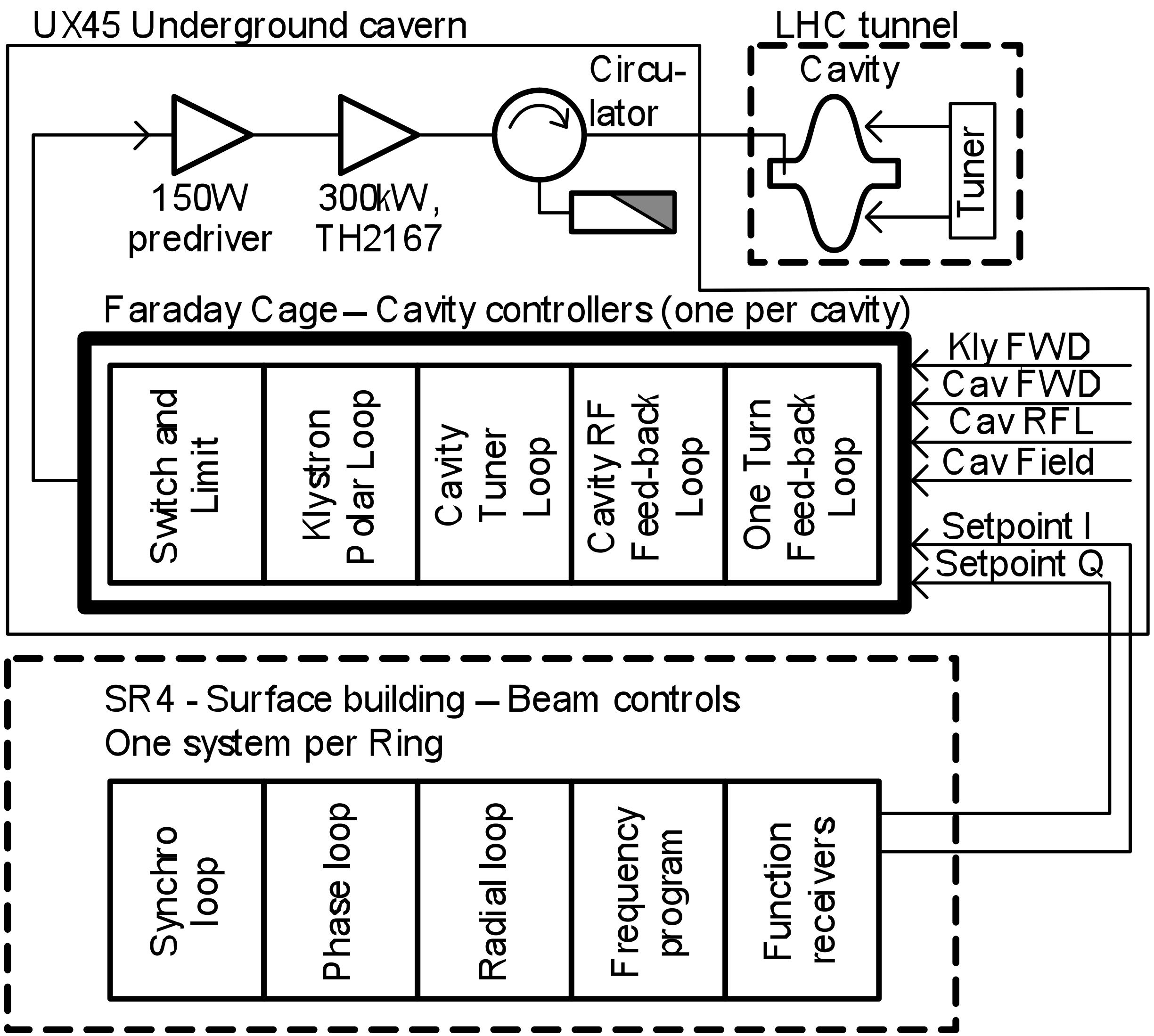


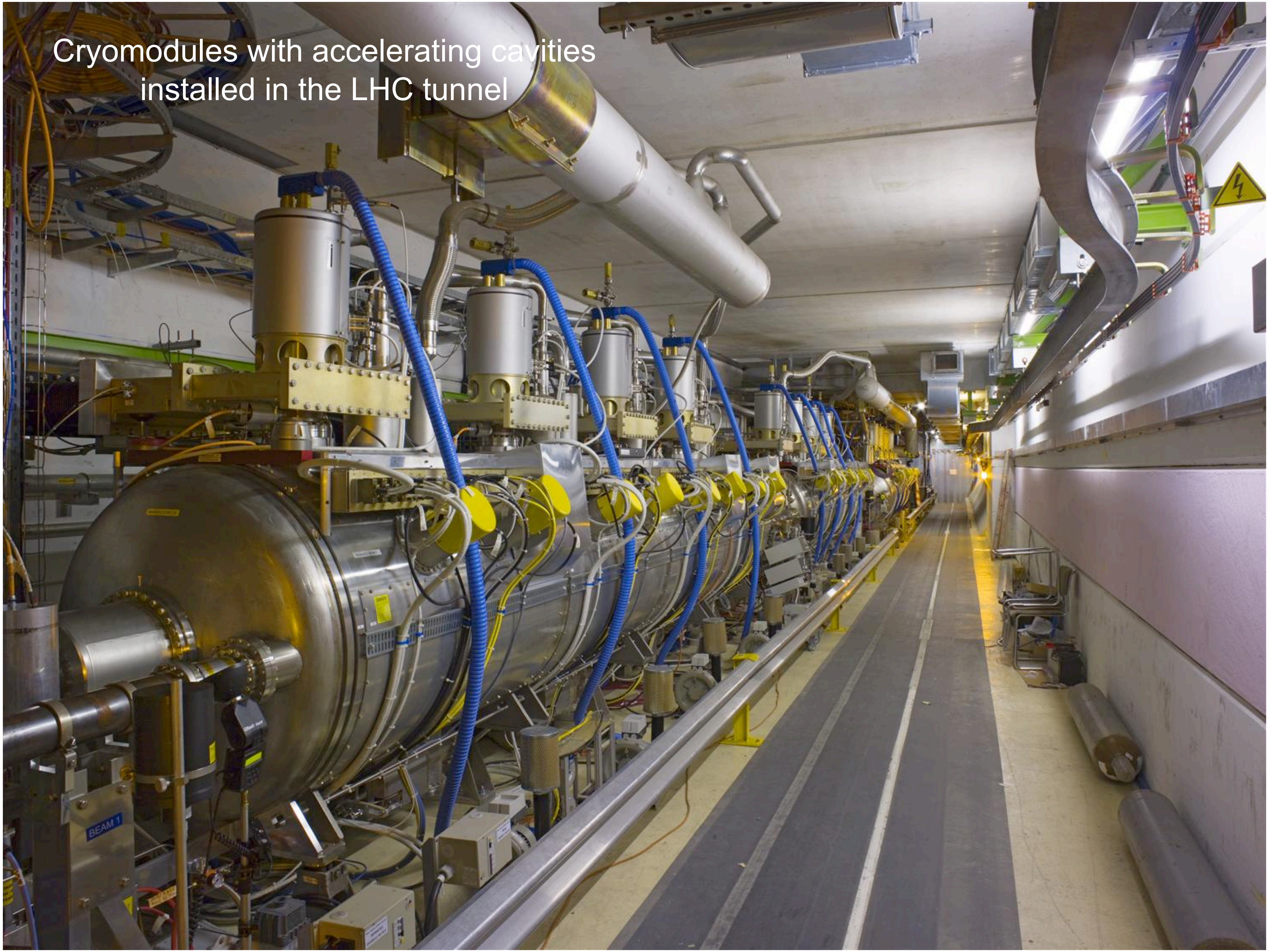
Photo: Personal archive

LHC RF system

- Superconducting standing wave cavities (in the machine tunnel)
  - 8x single cell cavity (per beam. Total 16 cavities). Delivers 2MV when driven by 300kW RF
  - Q_{ext} tunable from 10 000 to 200 000 by a movable main coupler
  - bandwidth ~20kHz (@ injection) ~2kHz (@ flat top)
  - Center frequency mechanically tunable in a range of 100kHz by a stepper motor
- RF power amplifiers (in the neighbour underground cavern)
  - 16x klystron 300kW CW, Thales TH2167
- Transmission line system
  - WR 2300 waveguides, half height, natural cooling

LHC RF system





Cryomodules with accelerating cavities installed in the LHC tunnel

LHC klystron TH2167

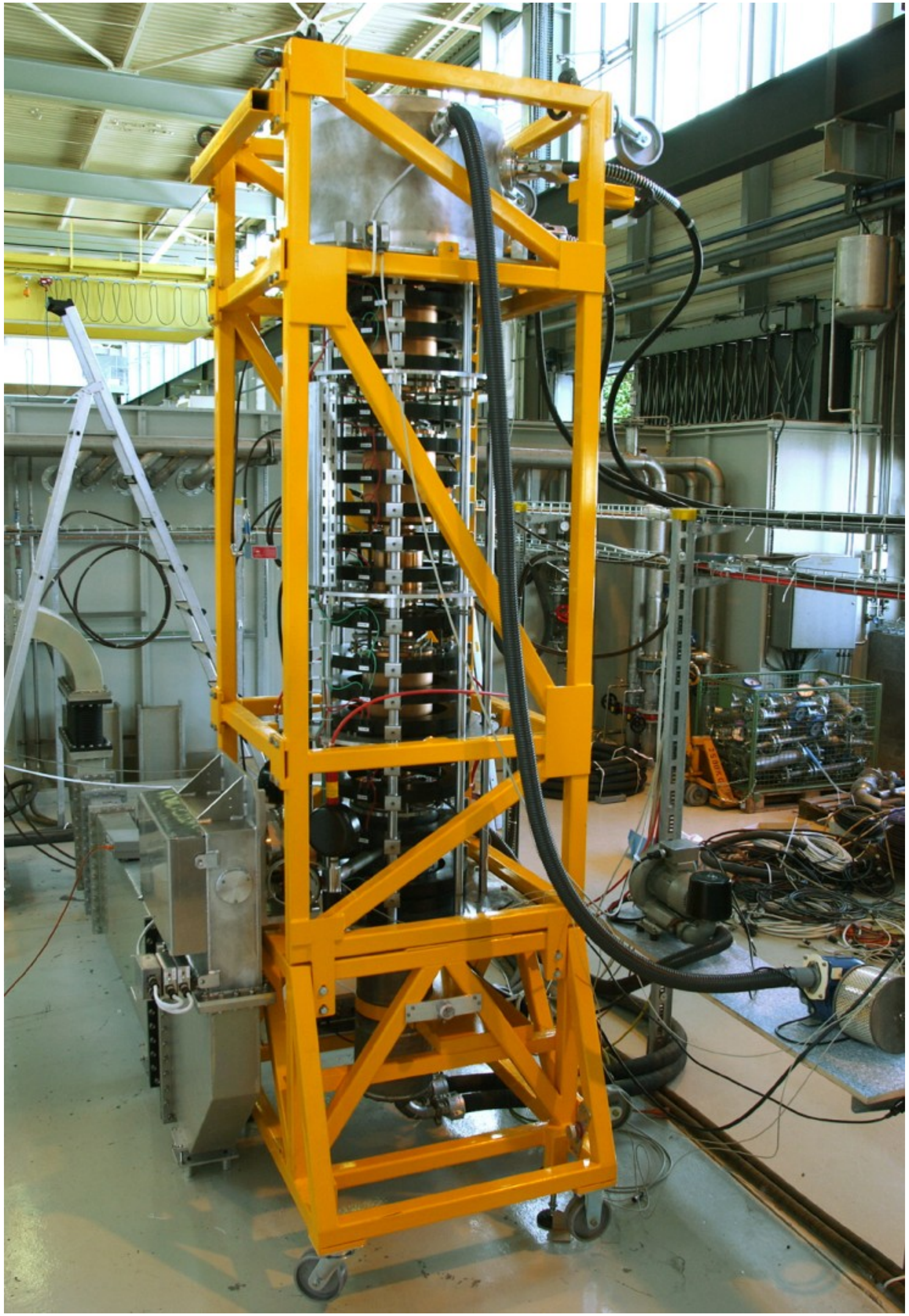


Photo: CERN, http://cdsweb.cern.ch/collection/Photos

LHC RF power plant

One unit contains:

- the 300kW klystron
- dry 300kW ferrite load
- ferrite circulator

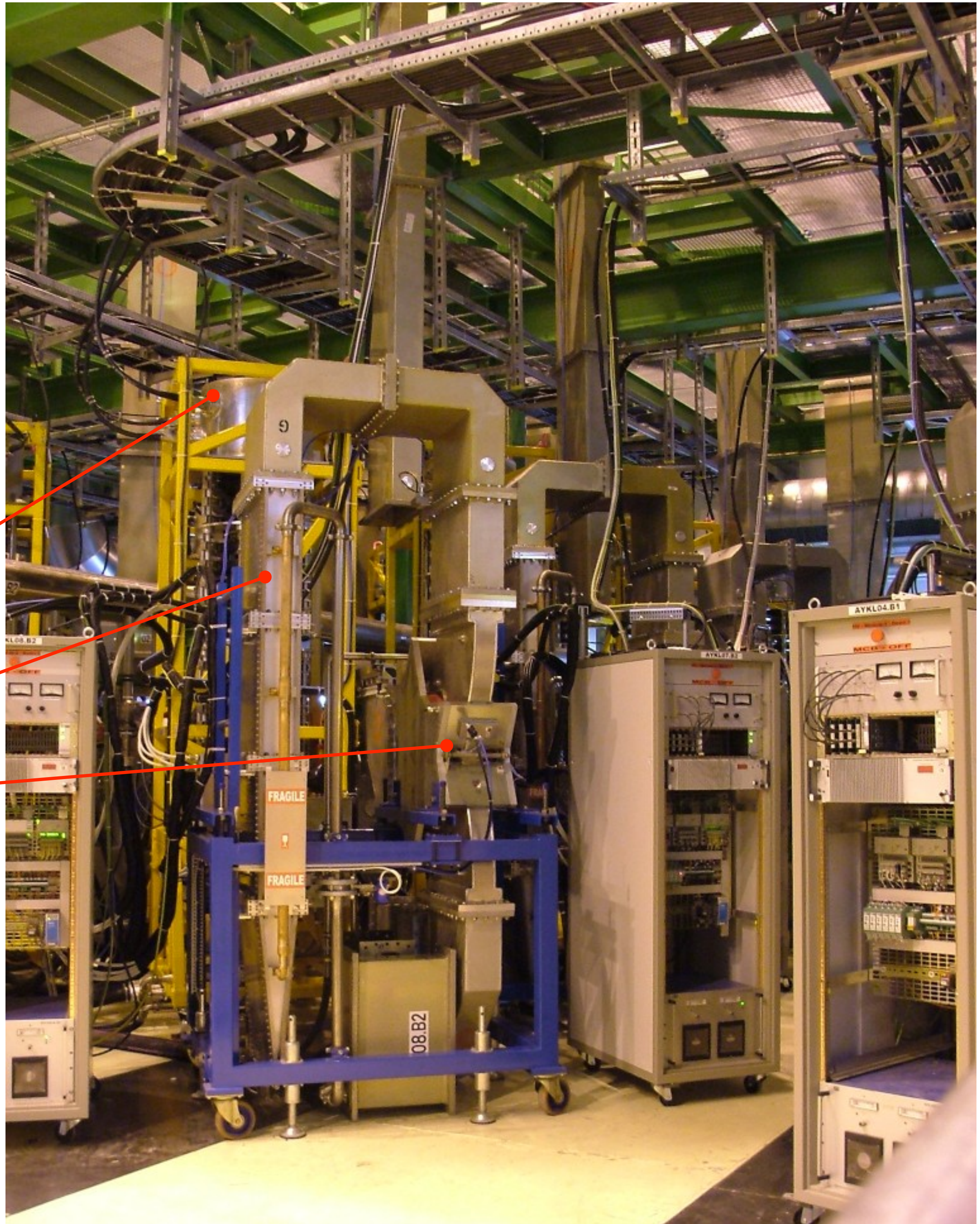
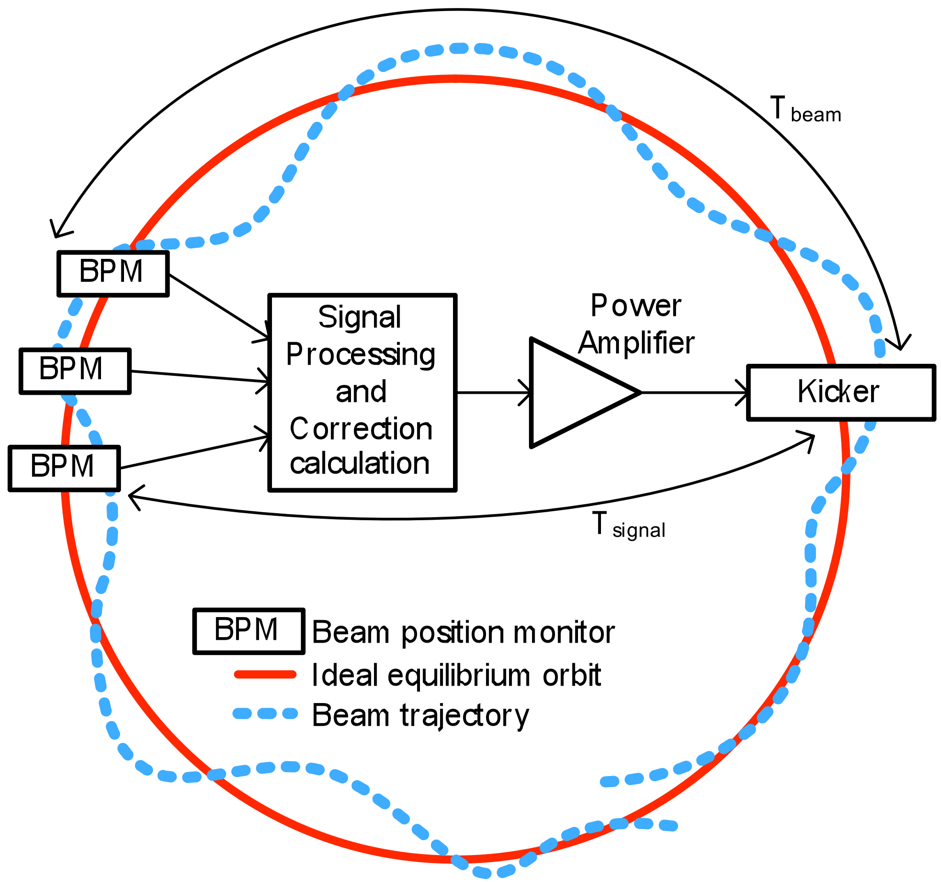


Photo: Personal archive


LHC RF power plant in the underground cavern
Photo: Personal archive

Transverse damping systems

- Transverse damping systems help to damp the transverse beam oscillations
  - Transverse injection errors
  - Damping of certain intensity related instabilities
- Electrostatic deflectors
  - Required deflector voltage ~kV
  - Typical bandwidth ones of kHz to tens of MHz
- Wideband tetrode amplifiers
  - LHC 3kHz – 20MHz



LHC transverse damper (power amplifiers and deflectors)

Photo: Personal archive

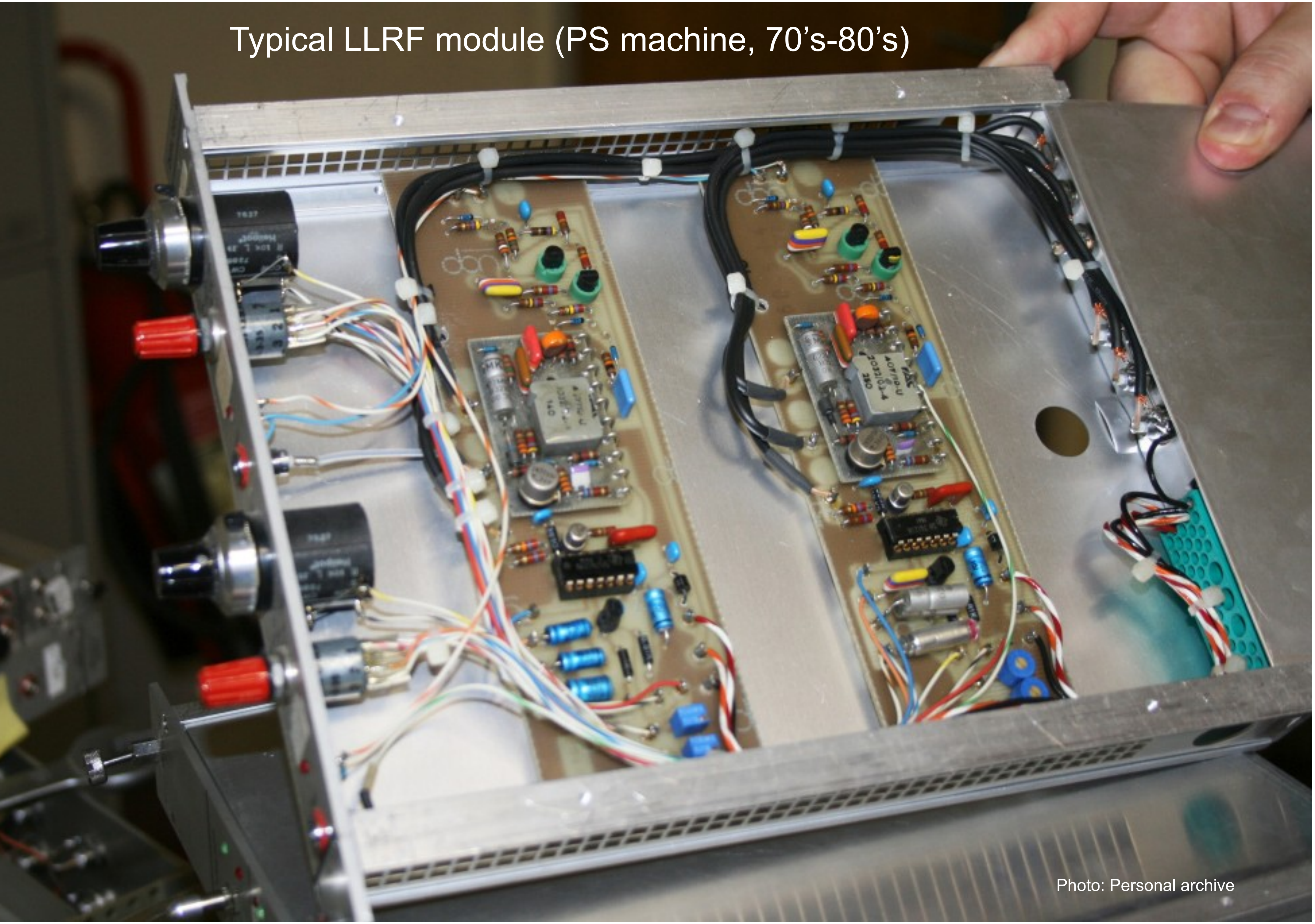
Low-Level and Feed-back systems

- Low-Level system: all feed back and other control loops in the system

- CERN accelerators accommodate a wide range of electronics
  - from purely analogue circuitry dating back to the 60’s
  - to state of the art remotely operated digital systems based on the most recent FPGA and DSP technology

- Running advanced control algorithms and signal processing techniques

Typical LLRF module (PS machine, 70's-80's)



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Typical LLRF module (SPS machine, 90's)

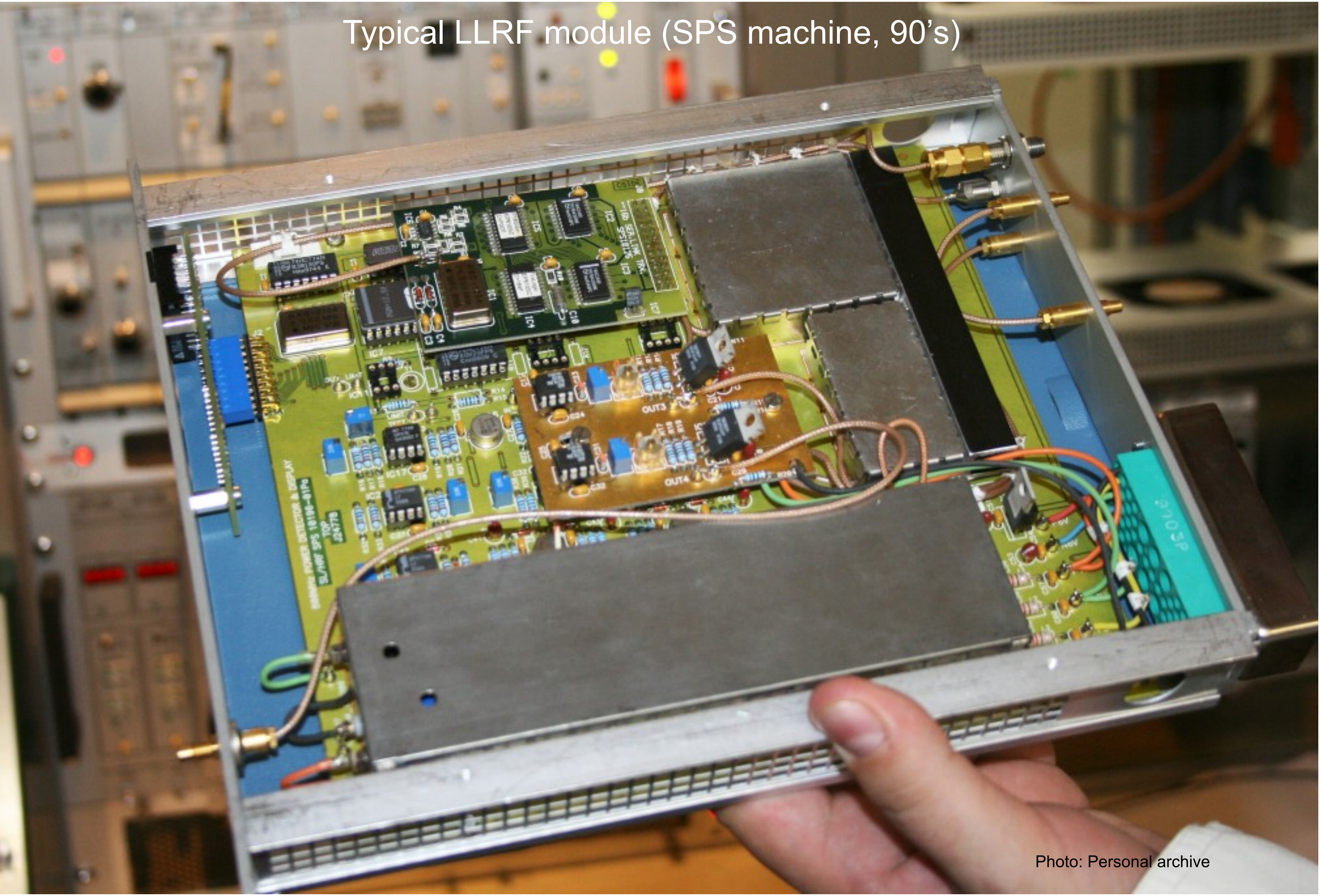

Photo: Personal archive

Typiccal LLRF module for the LHC (2006)

Left board: RF front-end

- 2 RF input channels
- Wideband analogue IQ demodulation

Right board: digital card

- remote controlled VME card
- 4x fast ADCs (100Msps/16bit)
- FPGA (Xilinx Virtex 4)
- 2x DAC (120Msps/14 bit)
- 4x proprietary 1Gbps serial link

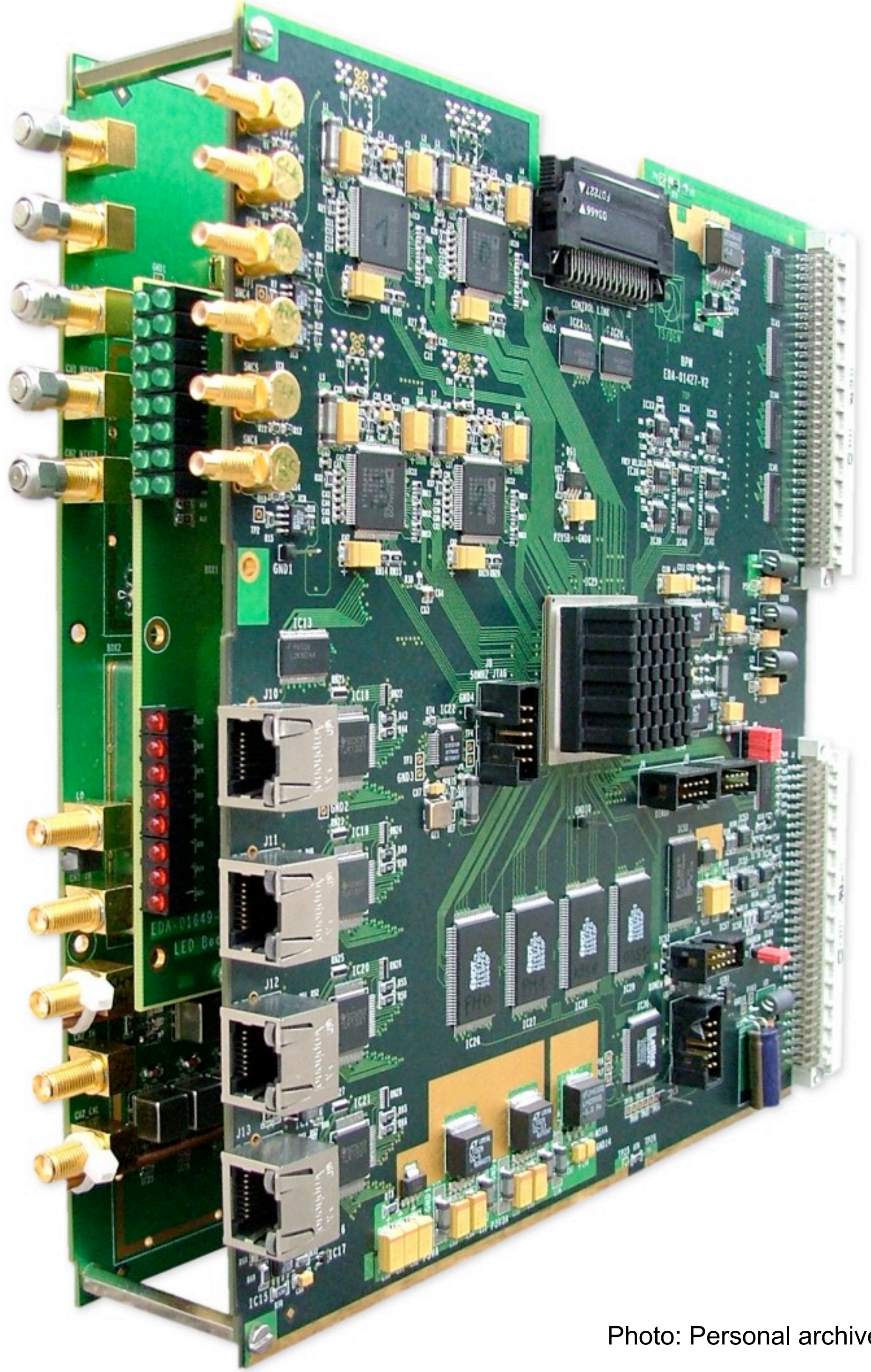

Photo: Personal archive


Photo: Personal archive
LLRF control room of the PS


Electronics for the PS tetrode amplifiers
Photo: Personal archive


Faraday cage SPS
Photo: Personal archive


Faraday cage SPS
Photo: Personal archive

Faraday cage LHC

Photo: Personal archive

Acknowledgements

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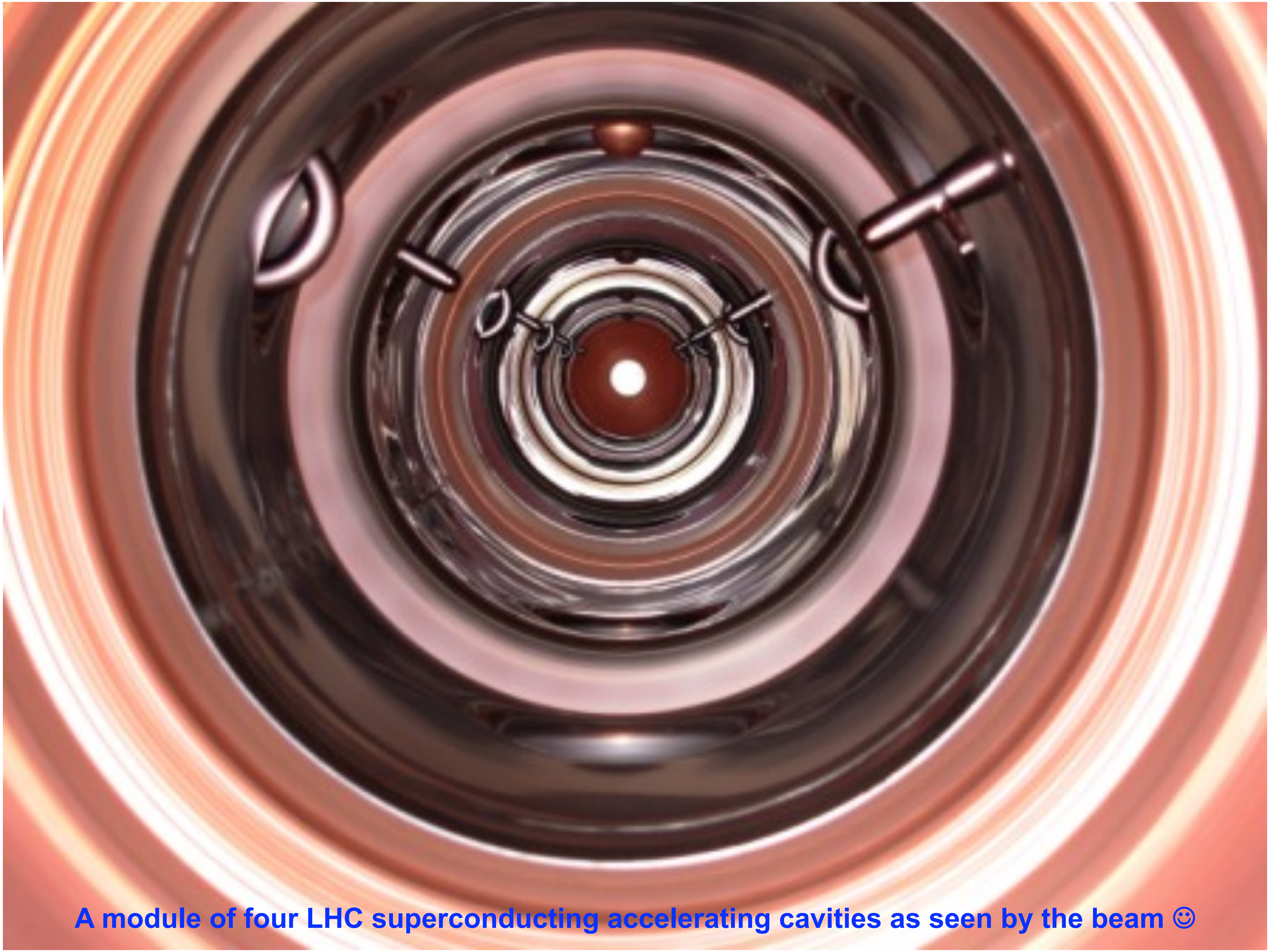

A module of four LHC superconducting accelerating cavities as seen by the beam ☺

Job opportunities at CERN

- CERN offers a wide range of job opportunities

- For students: Master, PhD
- Fellowships: Senior, Junior
- Staff positions

Job opportunities at CERN

- Technical Students:
- Are you an undergraduate student of a CERN Member State nationality in a technical field looking for a practical training period or a place to do your final project? CERN has a Technical Student programme that could interest you. If you have completed at least 18 months of your technical undergraduate studies, and your course requires a practical training period of 6 to 12 months, which you wish to spend at CERN, apply to the Technical Student Programme.

- Doctoral Students
- If you are or will be enrolled in the doctoral programme of a university in a Member State, and wish to spend 12 to 36 months of your thesis work at CERN, you may apply to the Doctoral Student Programme. This programme is open to students in scientific and technical fields, except theoretical and experimental particle physics. Candidates may already have a thesis subject defined with their home university OR they may be looking for a thesis subject. In the latter case, CERN proposes thesis descriptions which may then be discussed between the student, his/her home university and CERN.

Job opportunities at CERN

- Fellowship Programme

- The Senior Fellowship Programme, addressed to people with a Ph.D. or at least four years of experience after the degree which gives access to doctoral programmes. In both cases, a maximum of ten years of experience after the degree which gives access to doctoral programmes applies.

- The Junior Fellowship Programme, for holders of at least a Technical Engineer degree (or equivalent) and at most a M.Sc. degree (or equivalent) with not more than 4 years of experience.

Job opportunities at CERN

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