RF measurements for particle accelerators

Modern particle Accelerators

for particle physics, material science, medical applications, …

RF devices

cavities, pick-ups, deflectors, quadrupoles …

Low Level RF systems

for beam handling, beam stability, RF gymnastics, …

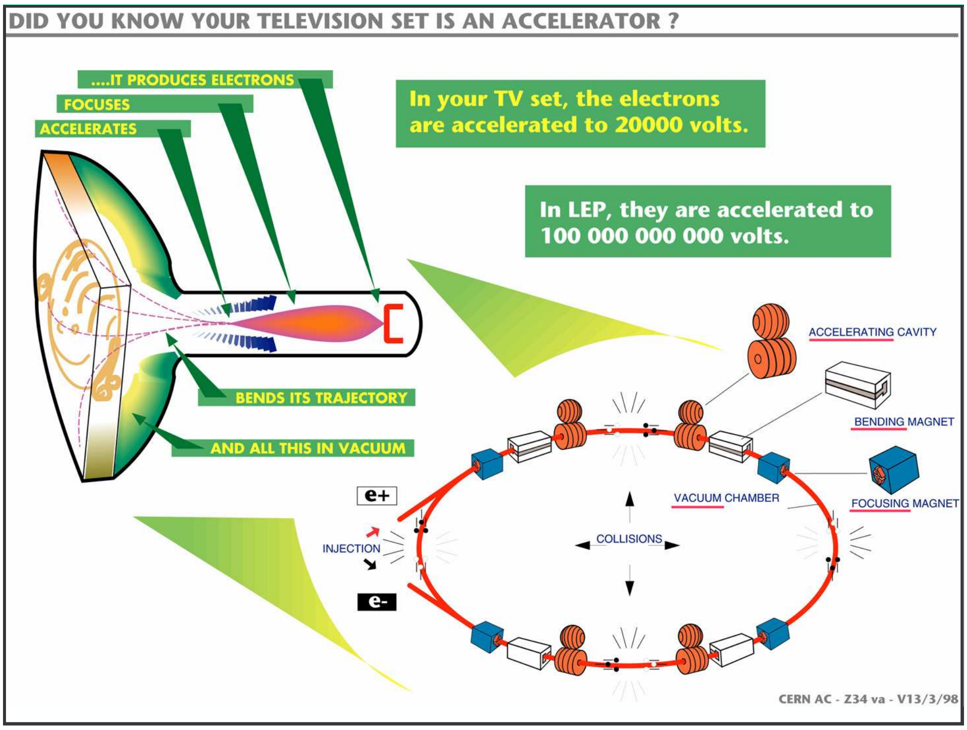
RF bench measurements

coaxial wire technique, device prototyping, …

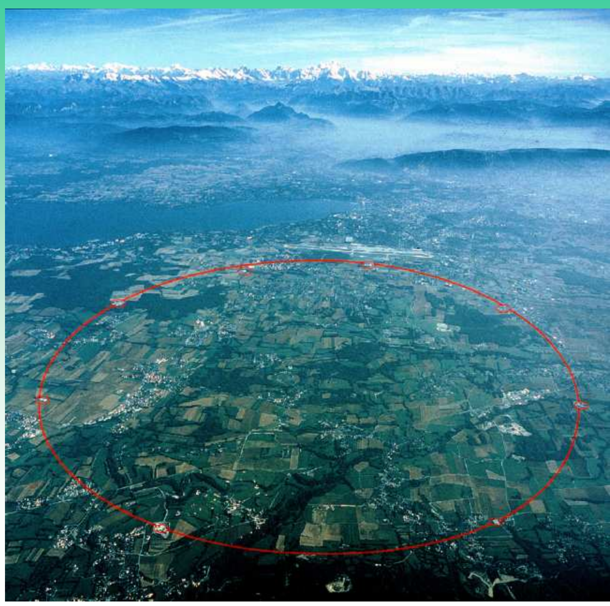
Acceleratori di particelle in funzione nel mondo (2003)*

Applicazione	Numero
Ricerca (alta energia, E > 1 GeV)	120
Ricerca (bassa energia, incluso biomedicina)	~1000
Sorgenti radiazione di sincrotrone	>100
Produzione radio-isotopi medici	~200
Radioterapia	>7500
Processi e ricerca industriale	~1500
Impiantazione ionica, trattamento superfici ed ingegneria dei materiali	>7000
Totale	**>17500**

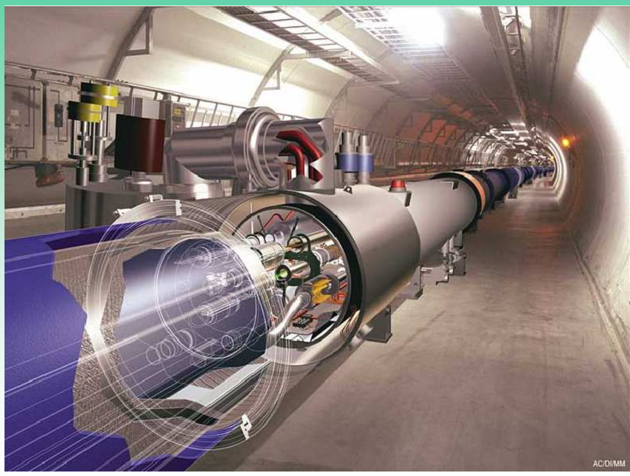
*U. Amaldi, G. Kraft, *Europhysics News*, Luglio/Agosto 2005



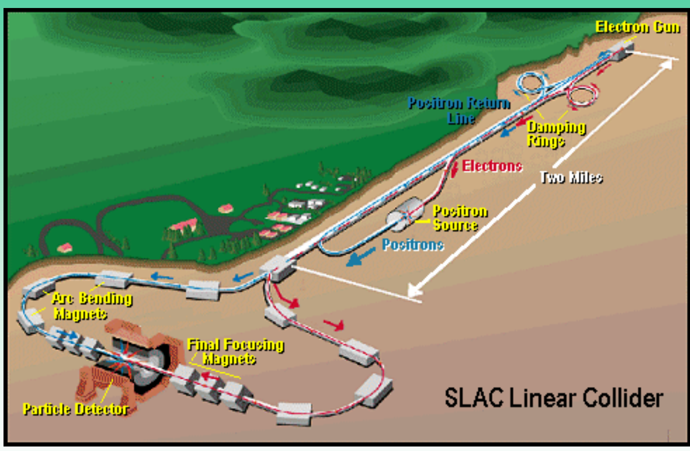
Large Hadron Collider



LHC: a superconducting machine



SLAC Linear collider



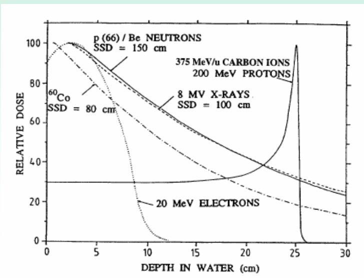
Light sources: … X-ray!!!

Medical accelerators

At INFN-Laboratori Nazionali del Sud (Catania), is working a **Superconducting Cyclotron** that after the installation of the axial injection produce proton beams at energy of 45-100 MeV. Nowadays this is the **unique functioning accelerator in Italy suitable for proton therapy applications.**

<u>Choroidal Melanoma</u>
85 - 90 % successfully treating with proton beams

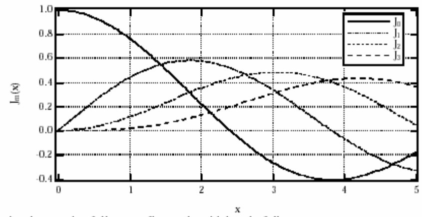
Age related <u>subfoveal macular degenerations</u> with subretinal neovascular membrane



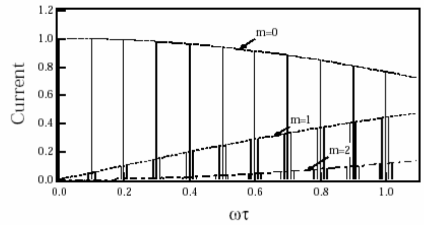
Single particle current spectrum

Synchrotron oscillation: single particle

The comb spectrum has added FM sidebands which are contained within Bessel function envelopes.



Rotation harmonics follow J_0, first order sidebands follow J1, etc.

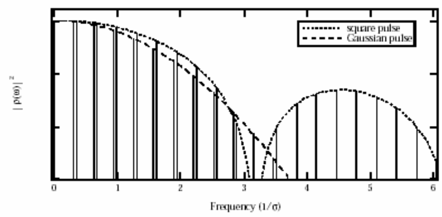


Note that the rotation harmonics disappear at the zeros of J0(ωτ).

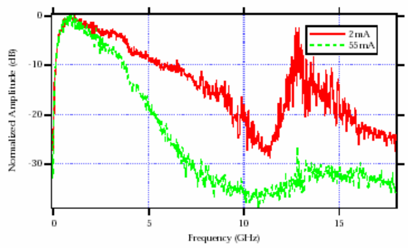
John Byrd, Stefano De Santis Derun Li, Bob Rimmer, Microwave Measurements Laboratory for Accelerators, USPAS, June 2003, Santa Barbara

Bunched beam spectrum: circular acc.

Bunched beam spectrum: circular acc.

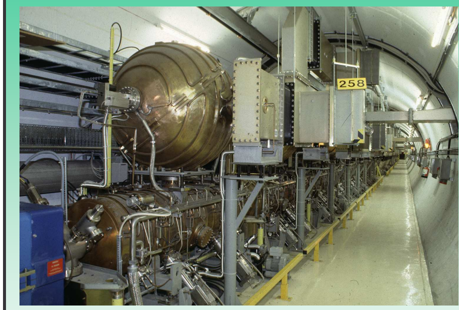


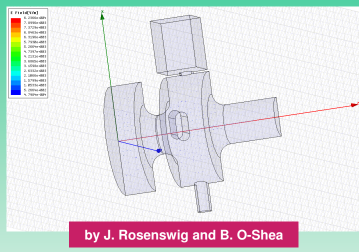
Below are some examples of broadband measurements on the ALS. The actual spectra is not Gaussian because of the frequency response of the button BPM used. The bunch has lengthened significantly at 55 mA shown by a narrowing of the frequency spectrum.

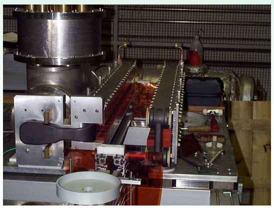


John Byrd, Stefano De Santis Derun Li, Bob Rimmer, Microwave Measurements Laboratory for Accelerators, USPAS, June 2003, Santa Barbara

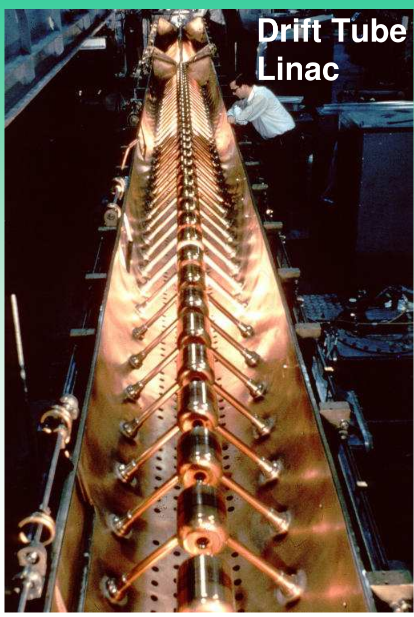
RF devices

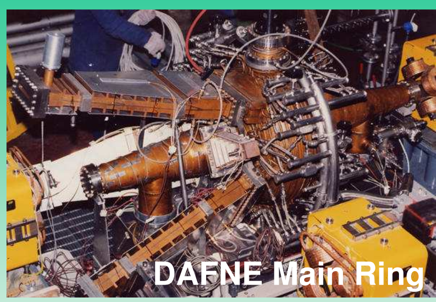


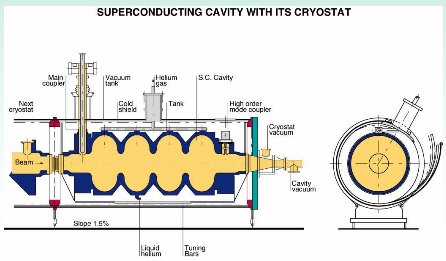




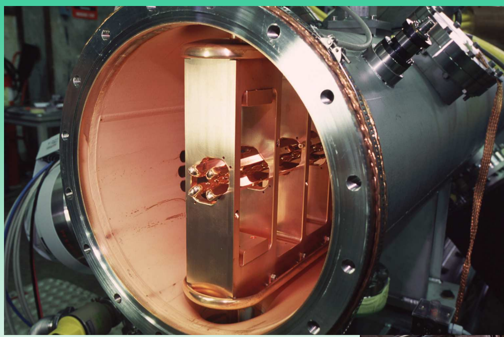
Accelerating/storage ring cavities



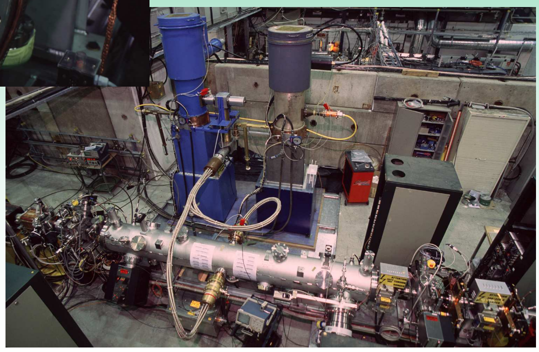




Radio Frequency quadrupoles: RFQ

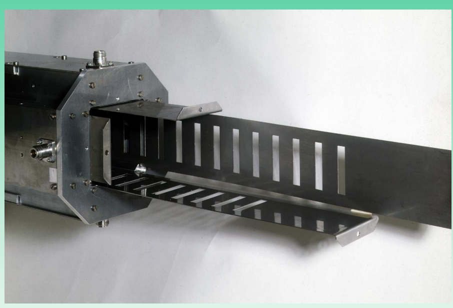


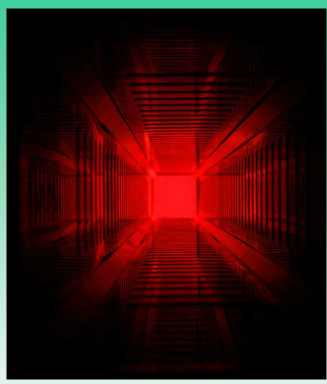
Radio Frequency Quadrupole Decelerator (RFQD) in ASACUSA beam line (AD machine)



Sometimes you need to decelerate particles as well …

RF kicker/pick-ups

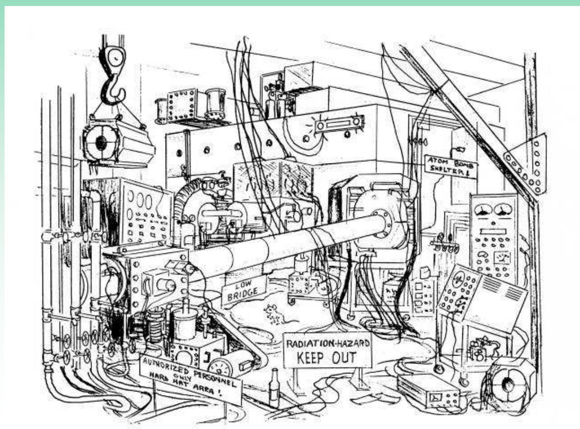




A "slotted transmission line" was used for both pickups and kickers of the stochastic cooling systems of the Antiproton Accumulator (AA). They served for the cooling of the high-density stack, in momentum and in both transverse planes. In the beginning in a single band, 1-2 GHz, later in 2 bands, 2-4 and 4-8 GHz.

Low level RF systems

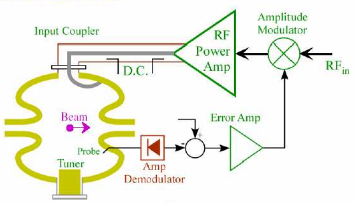
The low level RF system generates the signals driving the high power equipment and processes the information coming back from the various beam and hardware pick-ups. The method used to build the necessary low level functions are derived from telecommunication and radar domains. This field is prone to evolution of modern electronics.



Example of low level RF control (I)

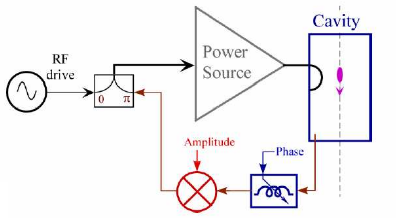
AMPLITUDE LOOP

The automatic regulation of the generator output level can be obtained by implementing amplitude loops. These are feedback systems which detect and correct variations of the level of the cavity voltage.
If the power amplifier is not fully saturated, the regulation can be obtained by controlling the RF level of the amplifier driving signal.
If the amplifier is saturated, the feedback has to act directly on the high voltage that sets the level of the saturated output power.



Beam Loading Compensation: The Direct RF Feedback

In the "direct RF feedback" configuration a sample of the cavity voltage is re-injected back and added to the RF drive. The effect of this loop is that of reducing the cavity impedance as seen by the beam by a factor equal to the open loop gain.

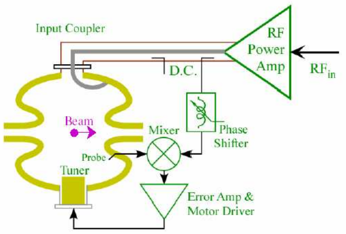


A. Gallo, Beam Loading and Low-level RF Control in Storage Rings, Lecture @ CAS 05

Example of low level RF control (II)

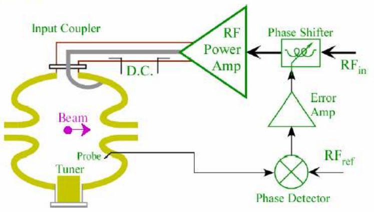
TUNING LOOP

The tuning loop restores automatically and continuously the cavity resonant frequency to compensate the beam reactive admittance. The loop controls the RF phase between the cavity voltage and the forward wave from the generator. Phase drifts are corrected by producing mechanical deformations of the cavity profile by means of dedicated devices (plungers, squeezers, ...). In fact the loop controls the phase of the transfer function:



PHASE LOOP

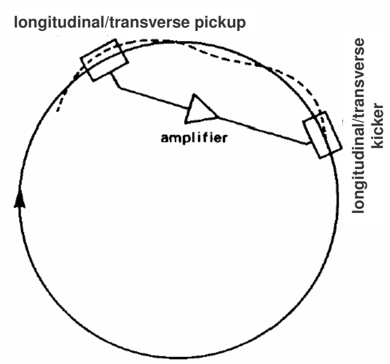
The cavity RF phase (or the power station RF phase) can be locked to the reference RF clock by another dedicated servo loop. The need for a phase loop is not strictly related to beam loading effects but more to ensure synchronization between different RF cavities or between RF voltage and other sub-systems of the accelerator (such as injection system, beam feedback systems, ...).



A. Gallo, Beam Loading and Low-level RF Control in Storage Rings, Lecture @ CAS 05

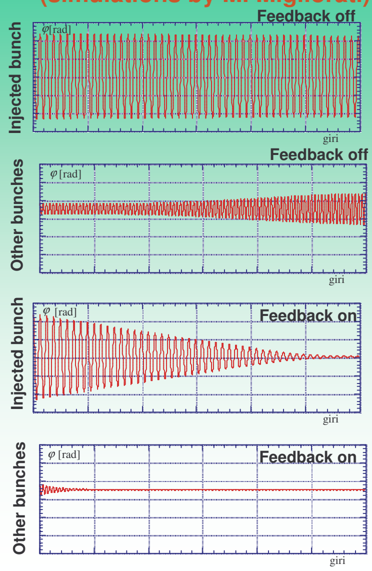
Feedback system for beam stability

Longitudinal and transverse feedback

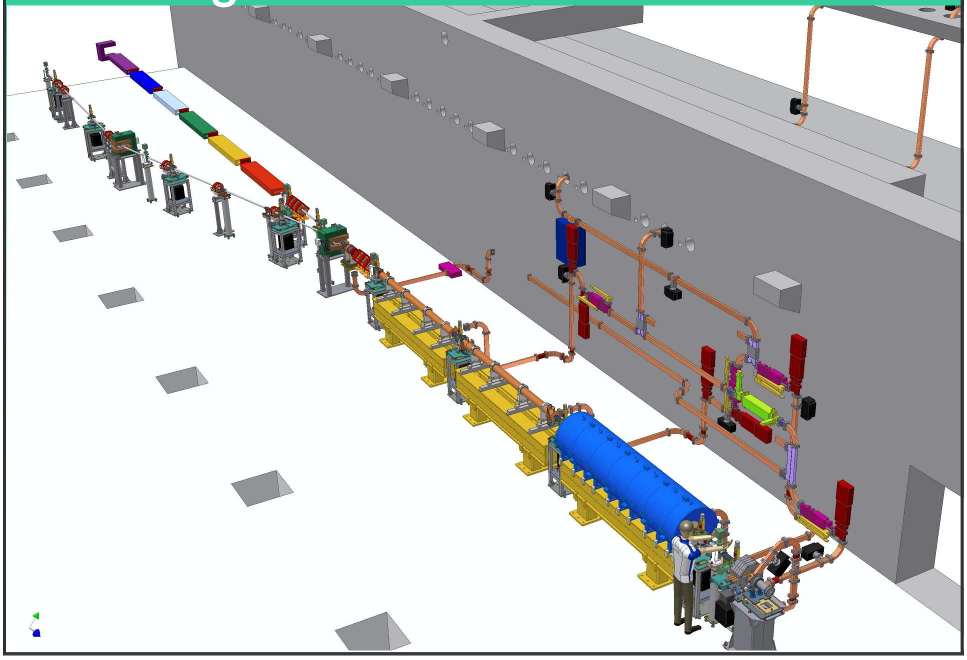


A famous example is the
STOCHASTIC COOLING for AntiProtons
(Nobel Prize 1984 to S. Van Der Meer, CERN).

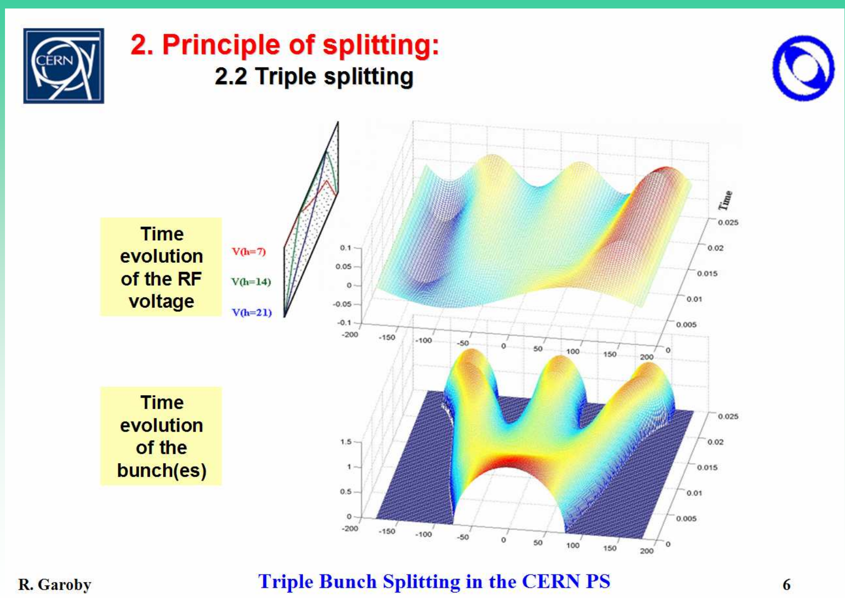
DAFNE longitudinal feedback (simulations by M. Migliorati)



Powering accelerator devices



RF gymnastics: bunch splitting (I)

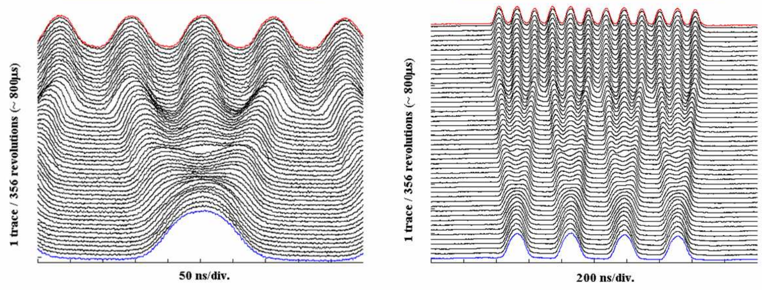


RF gymnastics: bunch splitting (II)

3. Experimental results:

3.1 Triple splitting at 1.4 GeV

Mountain-range display (1 PSB bunch)	Mountain-range display (4 PSB bunches)
T=1.4 GeV	T=1.4 GeV
1.5×10^{12} ppb	6×10^{12} ppp



RF gymnastics: bunch splitting (III)

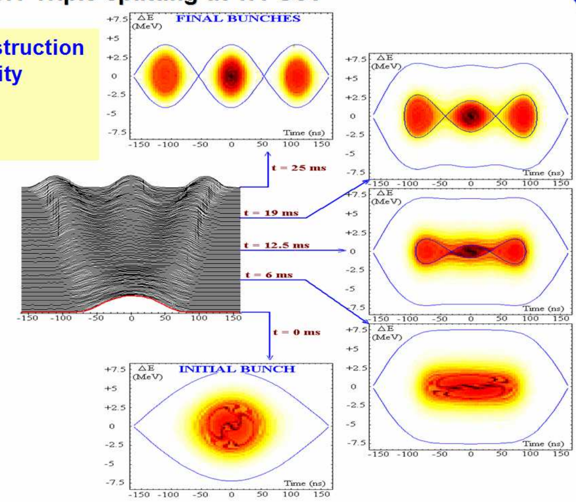
3. Experimental results:

3.1 Triple splitting at 1.4 GeV

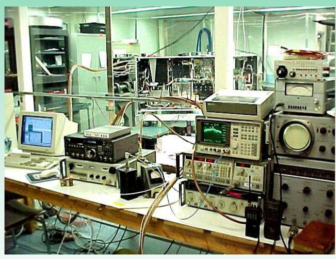
Tomographic reconstruction of phase plane density

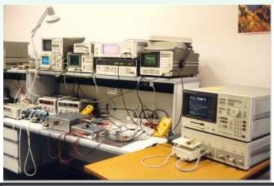
T=1.4 GeV

1.5×10^{12} ppb



RF bench measurements





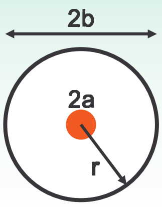
Field in the DUT with/without wire: a cylindrical waveguide (beam pipe)

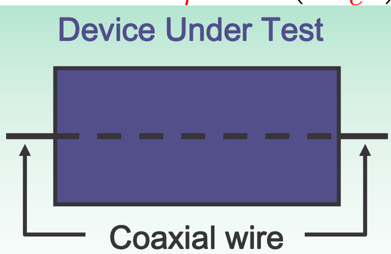
Ultra-relativistic beam field

$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = \frac{Z_0 q}{2\pi r} \exp\left(-j\frac{\omega}{c}z\right)$$

TEM mode coax waveguide

$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = Z_0 \frac{\text{const}}{r} \exp\left(-j\frac{\omega}{c}z\right)$$





Single wire centered/displaced
Two wires

A. Mostacci et al., RF coupling impedance measurements versus simulations, Care Workshop (2004).

Field in the DUT with/without wire: a cylindrical waveguide (beam pipe)

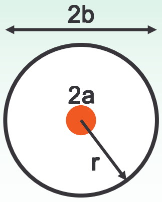
Ultra-relativistic beam field

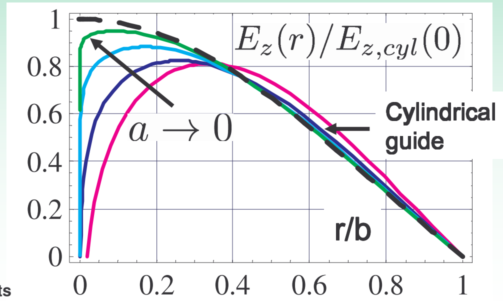
$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = \frac{Z_0 q}{2\pi r} \exp\left(-j\frac{\omega}{c}z\right)$$

TEM mode coax waveguide

$$E_r(r,\omega) = Z_0 H_\varphi(r,\omega) = Z_0 \frac{\text{const}}{r} \exp\left(-j\frac{\omega}{c}z\right)$$

TM01 mode in a coax waveguide (above cut-off)





A. Mostacci et al., RF coupling impedance measurements versus simulations, Care Workshop (2004).

EPA experiment: beam set-up

Goal of the experiment: to investigate the transmission properties of a coated ceramic chamber with the CERN EPA electron beam.

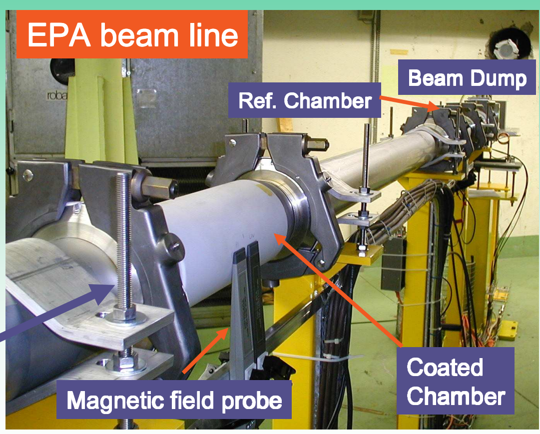
Titanium coating (1.5 µm)

Thickness << skin depth

DC resistance 1 Ohm

Reference chamber (non coated)

500 MeV electron bunch (7e10 particles, σ~ 1 ns)



EPA 1999: shielding properties

EPA 2000: effect of external shields

L. Vos et al., AB-Note-2003-002 MD

EPA experiment: bench set-up

The same ceramic chambers used in the beam experiment have been measured within a coaxial wire set-up, using the same magnetic field probes.

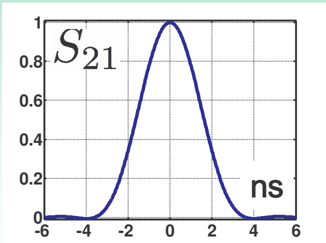
VNA with time domain option

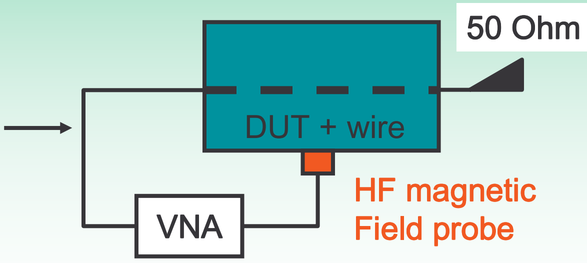
↓

Synthetic pulse (300 MHz BW)

wire diameter: 0.8 mm

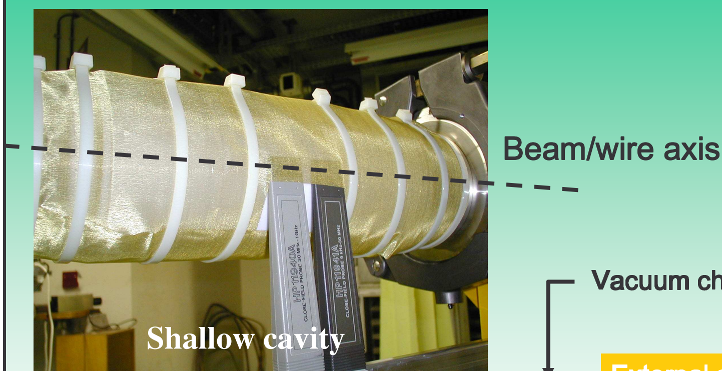
Matching resistors: 240 Ohm



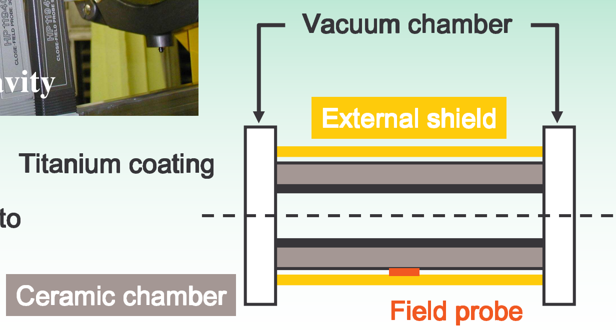


Just like in the early days of coaxial wire techniques (Sand and Rees,1974)

Bench vs beam measurement in EPA



The external shield is electrically connected to the vacuum chamber.



Bench vs beam measurement in EPA

The external shield carries image currents and field penetrates the thin resistive (titanium) layer if this external bypass is present.

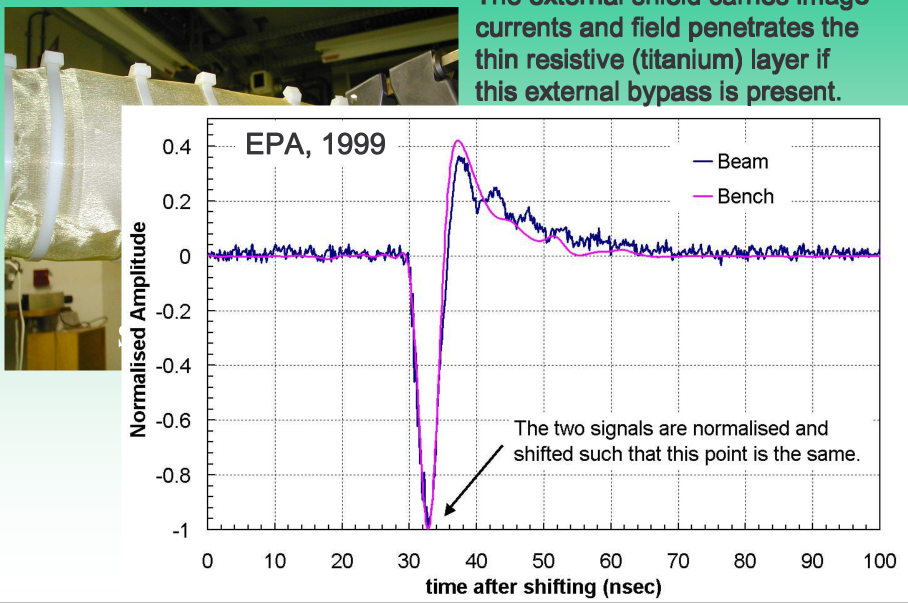
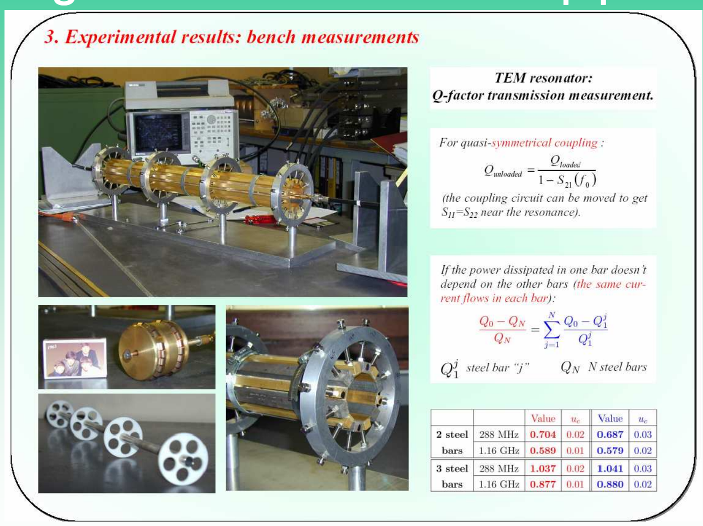


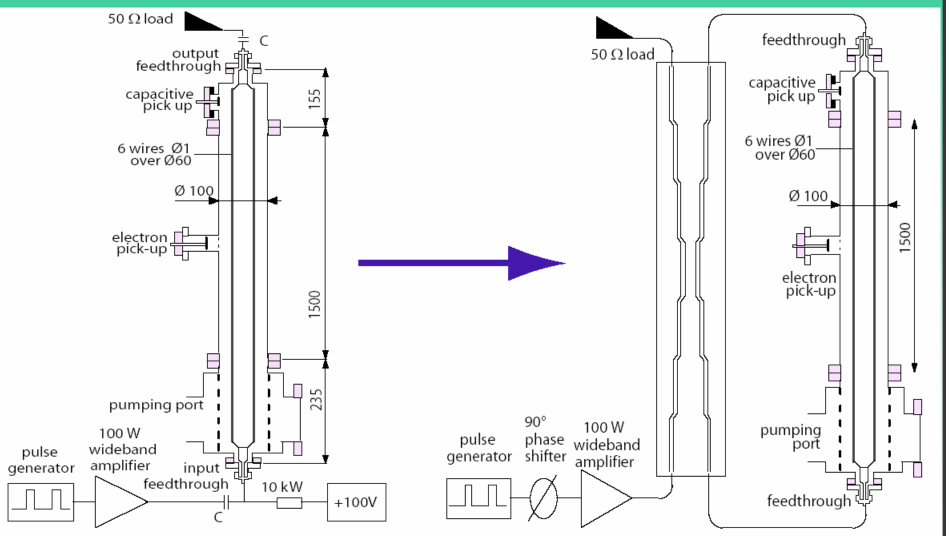
Image currents in azimuthally inhomogeneous metallic beam pipes



		Value	u_c	Value	u_c
2 steel bars	288 MHz	0.704	0.02	0.687	0.03
	1.16 GHz	0.589	0.01	0.579	0.02
3 steel bars	288 MHz	1.037	0.02	1.041	0.03
	1.16 GHz	0.877	0.01	0.880	0.02

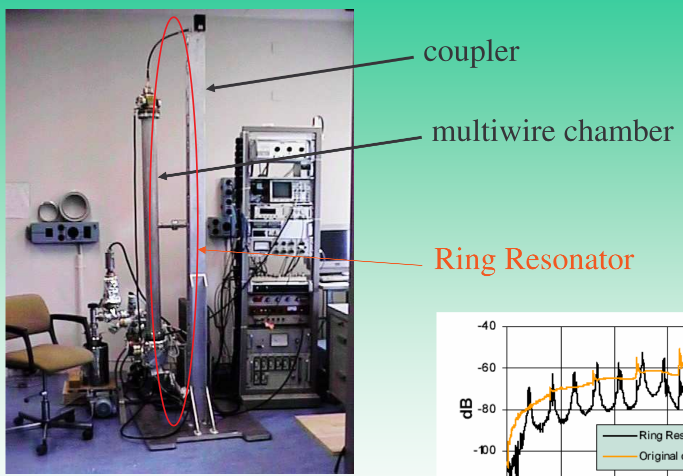
A. Mostacci, Image currents in azimuthally inhomogeneous metallic beam pipes Phys. Rev. ST Accel. Beams 8, 084402 (2005).

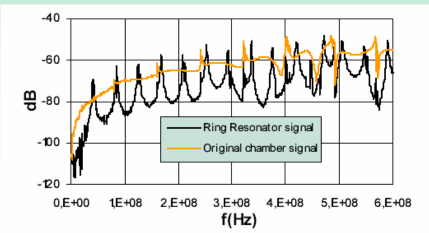
RF test bench for e-cloud studies (I)



U. Iriso, F. Caspers, J-M. Laurent and A. Mostacci, **Traveling wave resonant ring for electron cloud studies,** Phys. Rev. ST Accel. Beams 7, 073501 (2004)

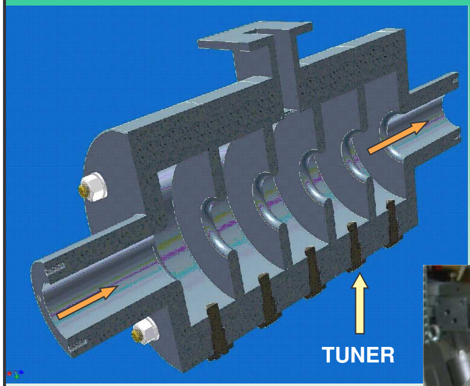
RF test bench for e-cloud studies (II)



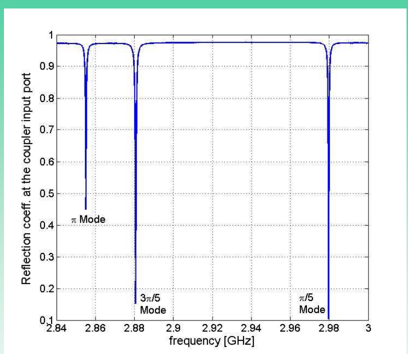


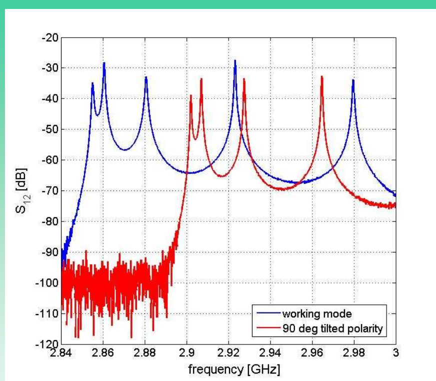
Amplitude of the signal seen in a button pick-up on the top of the chamber with the effect of the RR (black line) compared with the original chamber (orange line). Average gain of 6 db.

SPARC deflector

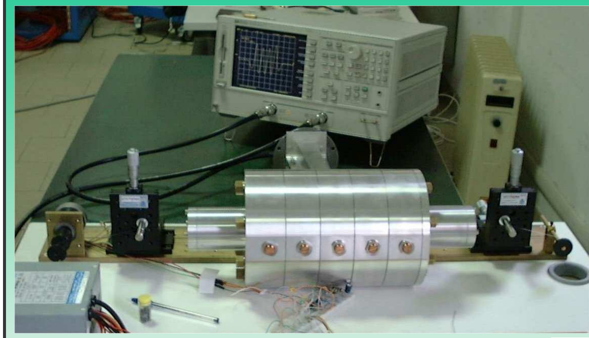


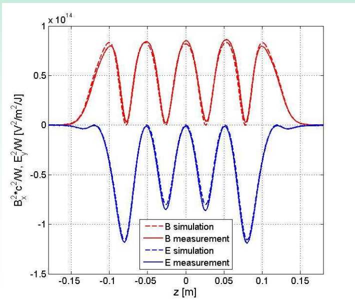
SPARC deflector: cavity properties

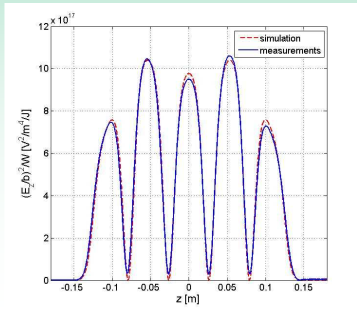




SPARC deflector: deflecting field







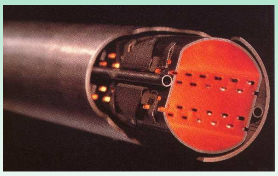
LHC reflectometer (waveguide TDR)

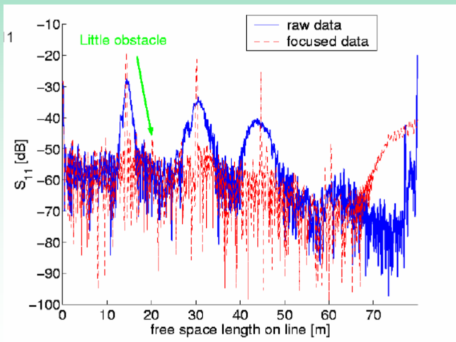
Problem: location of objects in the accelerator beam pipe

Possible solution using Time Domain Reflectometry

Also it was used at ESRF to locate discontinuities in their vacuum chamber during assembly (CERN-PS 92-30 AR)

Wave-guide TDR has been used more than 20 years ago to locate dents and deformations on long wave-guides in telecommunication towers from the ground to the antenna at the top.





T. Kroyer, Application of Waveguide Mode Diagnostics for Remote Sensing in Accelerator Beam Pipes, PhD thesis, CERN-Thesis-2005-61.

http://tkroyer.home.cern.ch/tkroyer/reflec/