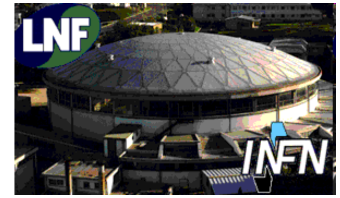
BULGARIAN ACADEMY of SCIENCES 1869

CAS CERN ACCELERATOR SCHOOL
INTRODUCTORY ACCELERATOR PHYSICS COURSE
VARNA, Bulgaria
Sept. 19 – Oct. 1, 2010



RF Systems

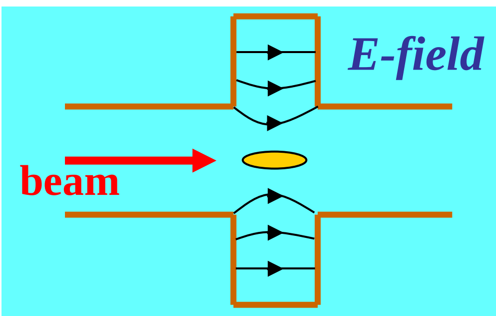
Alessandro Gallo, INFN – LNF, Frascati (Italy)

SUMMARY

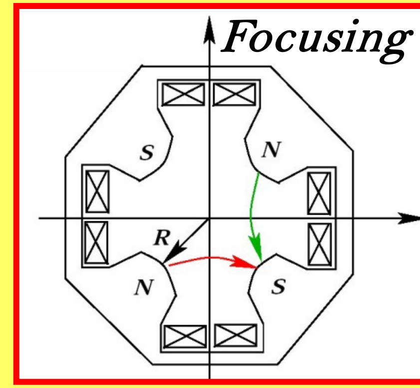
- **Introduction**
  - Definitions
  - RF system anatomy
- **RF Accelerating Structures**
  - Travelling wave, iris-loaded waveguides
  - Standing wave resonant cavities: basic theory and merit figures
  - External coupling to resonant cavities
  - Cavity tuning
- **RF Power Sources**
  - Solid State Amps
  - Grid Tubes (Tetrodes , IOTs, …)
  - Klystrons
  - Others
- **RF Power Distribution**
  - Waveguides and Transmission Lines
  - Hybrids, Couplers and Circulators
  - Pulse Compression
- **Beam Loading and LLRF**
  - Generator-Cavity-Beam model
  - LLRF definition and basic specs

What are RF Systems for in Particle Accelerators?

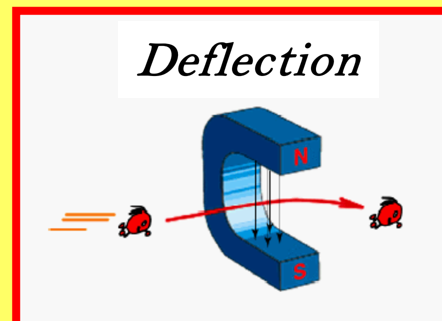
The motion of the charged particles in particle accelerators is governed by the Lorentz force:



$$\frac{d\vec{P}}{dt} = q\cdot\left(\boxed{\vec{E}} + \vec{v}\times\boxed{\vec{B}}\right)$$



B-field



Static magnetic field $\vec{B}(\vec{x})$ is used to model the beam trajectory and to focus the particle transverse motion (see Transverse Dynamics Lectures).

Longitudinal electric field $E_{//}$ is necessary to **accelerate** (≡ increase the energy) of charged particles. With the exception of pioneer electro-static accelerators, the **longitudinal E-field** component of **variable electromagnetic fields** $\vec{E}(\vec{r},t);\vec{B}(\vec{r},t)$ is always used for acceleration for practical reasons.

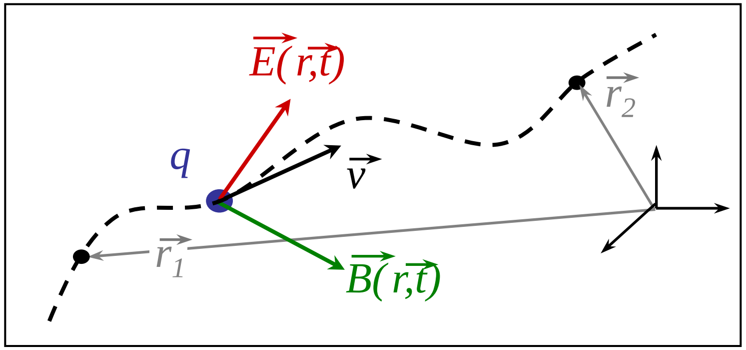
What are RF Systems for in Particle Accelerators? (cont'd)

The elementary energy gain of a charge subject to the Lorentz force is:

$$dW = v\,dp = \vec{v}\cdot d\vec{p} = \vec{v}\cdot\left[q\left(\vec{E}+\vec{v}\times\vec{B}\right)\right]dt = q\,\vec{E}\cdot d\vec{r}$$

The energy gained by a charged particle with motion law $\vec{r}(t)$ interacting with a variable electric field along a portion of its trajectory is given by:

$$\Delta W_{21} = q\int_{\vec{r}_1}^{\vec{r}_2}\vec{E}\left(\vec{r}(t),t\right)\cdot d\vec{r} = \underbrace{q\int_{z_1}^{z_2}E_z\left(z(t),t\right)dz}_{straight\ line\ trajectory}$$



DEFINITION:

The **RADIOFREQUENCY (RF) SYSTEMS** are the hardware complexes devoted to the generation of the accelerating E-fields.

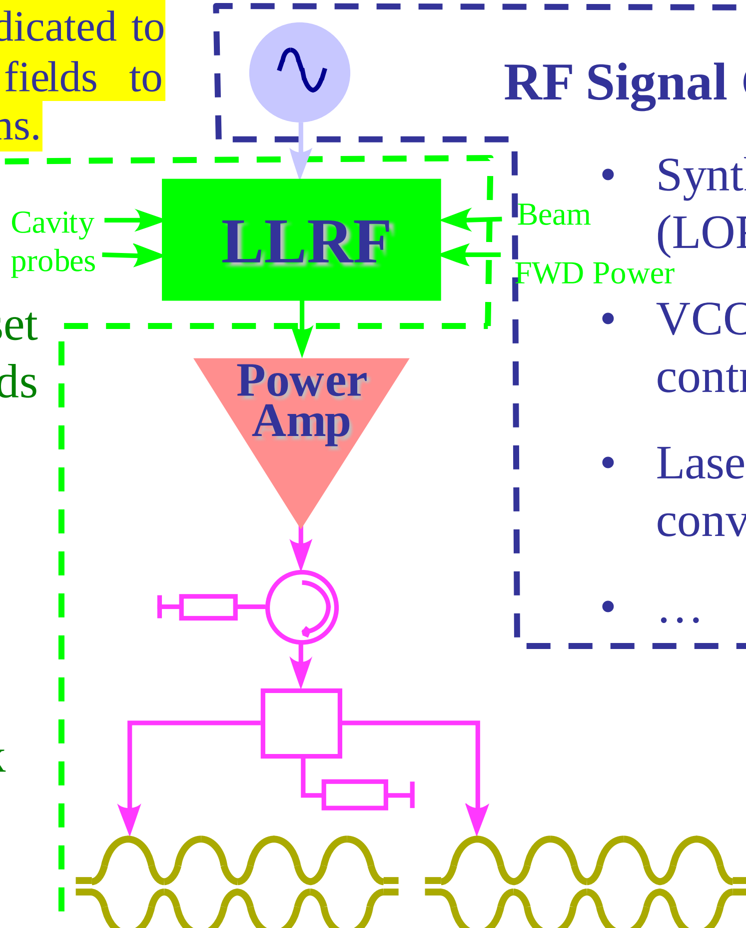
They have been mainly developed in the **RADIO WAVE REGION** of the e.m. spectrum, because of both physics (synchronization with the revolution frequencies of synchrotrons and cyclotrons) and technical (availability of power sources) motivations.

RF Systems: Basic Definitions and Anatomy

The RF systems in particle accelerators are the hardware complexes dedicated to the generation of the e.m. fields to accelerate charged particle beams.

RF Signal Generation

- Synthesized oscillators (LORAN stabilized)
- VCOs (driven by low-level controls)
- Laser-to-voltage reference converters
- …

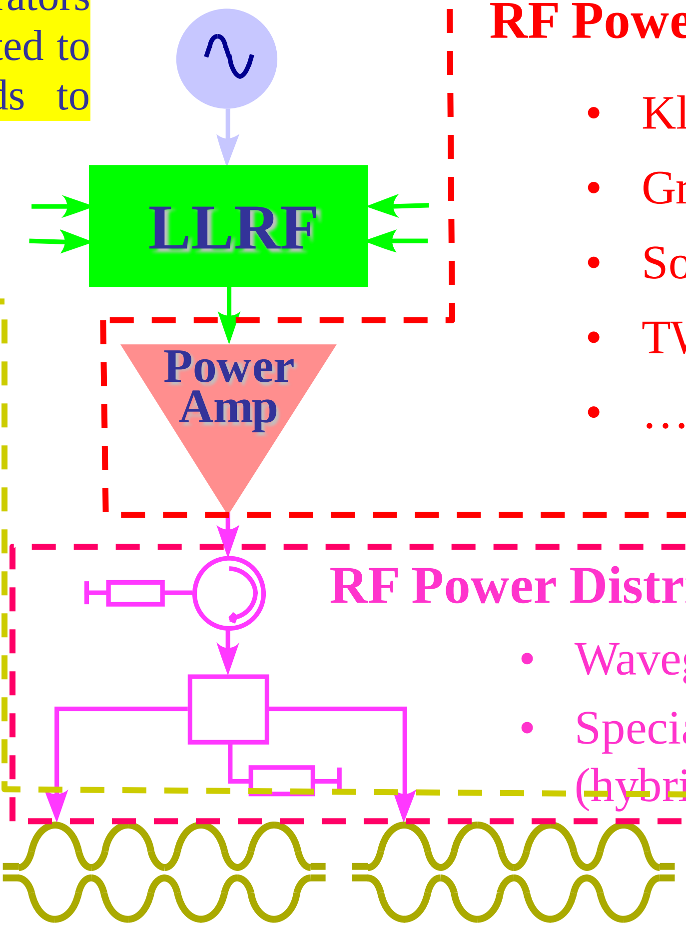


Low-level RF control

- Amplitude and phase set of the accelerating fields
- Tuning control of the accelerating structures
- Beam loading compensation
- RF and beam feedback systems
- …

RF Systems: Basic Definitions and Anatomy

The RF systems in particle accelerators are the hardware complexes dedicated to the generation of the e.m. fields to accelerate charged particle beams.



RF Power Generation

- Klystrons
- Grid Tubes
- Solid State Amps
- TWTs
- …

Accelerating Structures

- Resonant Cavities
  - Single or multi-cell
  - Room-temperature or Superconducting
- Travelling wave sections
- RF Deflectors (either SW or TW)

RF Power Distribution

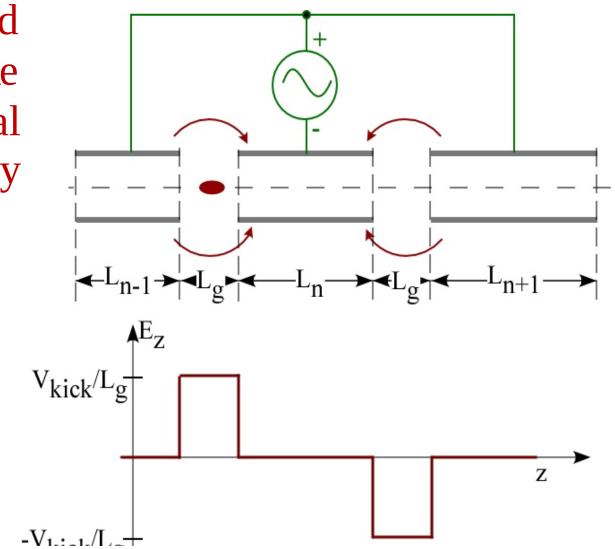
- Waveguide network
- Special Components (hybrids, circulators, …)

More on RF Systems

- Actual RF system frequencies in particle accelerators span from ≈10 MHz to 30 GHz and beyond;
- Depending on the characteristics of the beam RF systems can operate either continuously (CW) or in pulsed regime;
- Facility total RF powers up to ≈ 100 MW rms and ≈ 10 GW pulsed (up to ≈ 2 MW rms and ≈ 100 MW pulsed per station);
- Lot of science and technology involved (electromagnetism, HV, vacuum, cryogenics and superconductivity, electronics, computing, material and surface physics, cooling, …);
- Accelerations for energy increase (toward final energy, as in linacs, synchrotrons, cyclotrons, …) or for energy restoring (around nominal energy, as in storage rings …);
- RF accelerating fields also provide particle capture and longitudinal focusing (see Longitudinal Dynamics lectures);
- In some cases, through different mechanisms, accelerating fields also influence the beam transverse equilibrium distributions (adiabatic damping in linacs, radiation damping in lepton synchrotrons and storage rings …).

RF Accelerating structures

The Wideröe Drift Tube Linac is an historical and didactical example of acceleration based on variable fields. The beam is accelerated while crossing the gap between equipotential drift tubes. The length of the tubes has to match the beam velocity in order to cross each gap in phase with the accelerating field:



$$\frac{L_n}{v_n} = \frac{T_{RF}}{2} \rightarrow \begin{cases} L_n = \frac{1}{2} v_n T_{RF} = \frac{1}{2} \beta_n \lambda_{RF} \\ < \Delta U >_{ave} = q V_{kick} / L_n = 2 q V_{kick} / \beta_n \lambda_{RF} \end{cases}$$

There are two main consequences from the previous conditions:

1. The tube equipotentiality requires $\lambda_{RF} >> L_n \rightarrow \beta_n << 1$, which only applies for non-relativistic beams. To efficiently accelerate relativistic beams distributed fields have to be used.
2. Average gradients are inversely proportional to the RF wavelengths. The use of high RF frequencies increases the acceleration efficiency.

The natural evolution of the drift tubes was represented by high frequency, field distributed structures like resonant RF cavities and disk-loaded waveguides.

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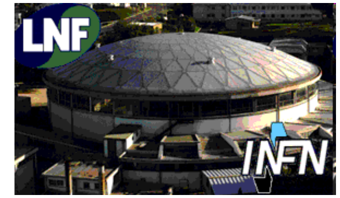

RF Systems

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Travelling Wave (TW) RF Accelerating Structures

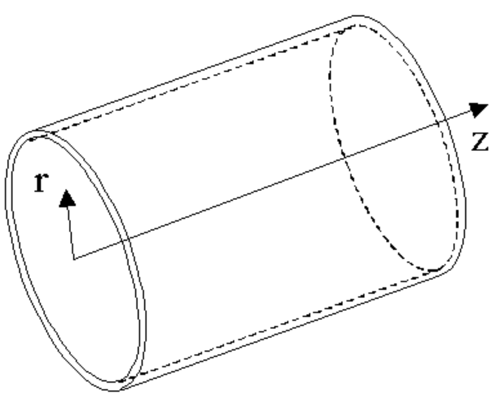
Already in the “Longitudinal Dynamics” lectures by Joel Le Duff

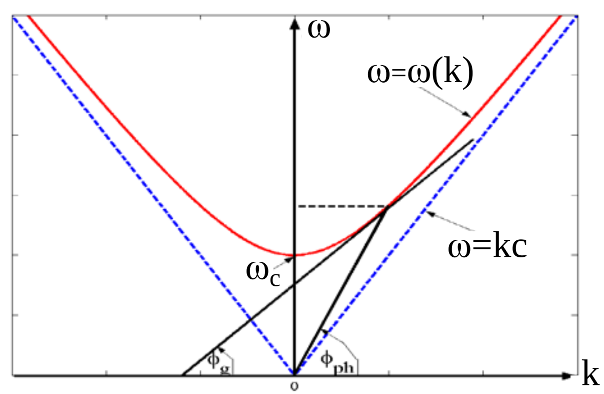
RF Acc. Structures: TW iris-loaded waveguides

According to Maxwell equations an e.m. wave travelling along a **transverse uniform guide** has always a phase $\boldsymbol{v_{ph}}$ velocity larger than the light speed $\boldsymbol{c}$ and **can not be synchronous** with a particle beam.

$$\vec{E}(x,y,z,t)=\sum_n \underbrace{\vec{E}_n(x,y)}_{\text{waveguide modes}} e^{j[\omega t-\underbrace{k_n(\omega)}_{\text{mode propagation constant}}z]}$$

$$k_n(\omega)=\sqrt{\left(\frac{\omega}{c}\right)^2 \underbrace{-k_{c_n}^2}_{\text{mode wavenumber cut-off}}}<\frac{\omega}{c} \rightarrow \begin{cases} v_{ph}=\dfrac{\omega}{k}>c \\ v_g=\dfrac{d\omega}{dk}<c \end{cases}$$



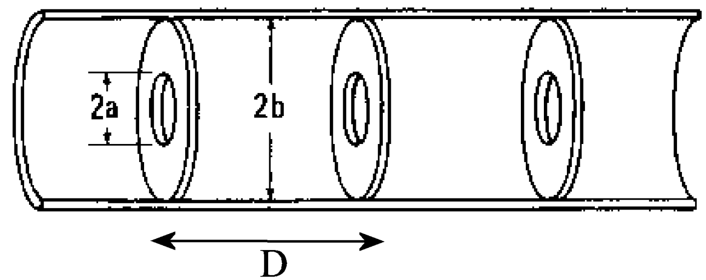


The ω(k) function is the so-called **dispersion curve** of the guide mode.

- The wave phase velocity v_{ph} at the operation frequency ω is equal to *tan*(ϕ_{ph});
- Modes propagate only if $\omega>\omega_c$ ($\omega_c=k_c \cdot c$ = ***mode cut-off*** frequency);
- The wave group velocity v_g at the operation frequency ω is equal to *tan*(ϕ_g);
- Negative k in the plot correspond to waves travelling toward negative-z.

RF Acc. Structures: TW iris-loaded waveguides

To "slow-down" the phase velocity of the guided wave periodic structures, also called "iris loaded", are used. According to the Floquet theorem, the field in the structure is that of a special wave travelling within a spatial periodic profile, with the same spatial period D of the structure. The periodic field profile can be Fourier expanded in a series of spatial harmonics with different phase velocity according to:



$$\vec{E}(x,y,z,t) = \sum_n \vec{E}_n(x,y,z)\, e^{j[\omega t - k_n(\omega) z]}$$

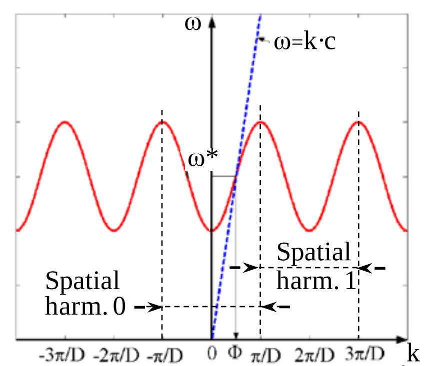
$$\vec{E}_n(x,y,z+D) = \vec{E}_n(x,y,z)$$

$$\vec{E}_n(x,y,z) = \sum_{i=-\infty}^{+\infty} \vec{E}_{n,i}(x,y)\, e^{-j\frac{2\pi i}{D} z}$$

$$\vec{E}(x,y,z,t) = \sum_{n,i} \vec{E}_{n,i}(x,y)\, e^{j\left[\omega t - \left(k_n + \frac{2\pi i}{D}\right) z\right]}$$

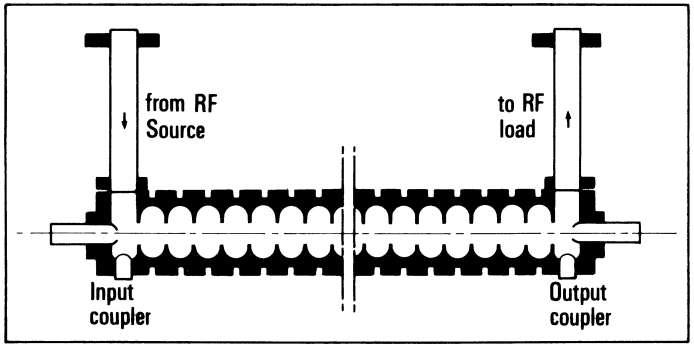
An iris loaded structure typical dispersion curve is plotted aside. In this case:

a) The plot is periodic in k, with a period of $2\pi/D$;
b) Every plot period is the dispersion curve of a particular spatial harmonic;
c) By design, at a ***certain excitation frequency*** $\boldsymbol{\omega^*}$ the fundamental spatial harmonic can be made ***synchronous with the beam***;
d) The high order spatial harmonics (i=1,2,3,...) are not synchronous and do not accelerate the beam over long distances.



RF Acc. Structures: TW iris-loaded waveguides

The most famous TW structure is the iris loaded accelerating waveguide developed at the "Stanford Linear Accelerator Center" (SLAC). It is an S-band structure (f = 2856 MHz) composed by 86 accelerating cells, with input/output couplers, capable of delivering accelerating fields up to 30MV/m.



Other details in the "Introduction to Linacs" lectures by Maurizio Vretenar!

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Standing Wave (SW)

RF Accelerating Structures:

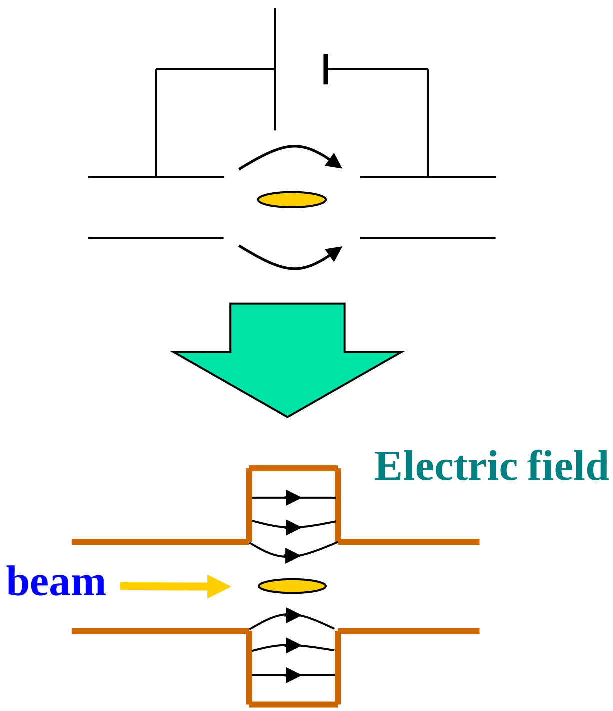
Resonant Cavities

Already in the "Longitudinal Dynamics" lectures by Joel Le Duff
Much more in the "RF cavities" lecture by Erk Jensen!

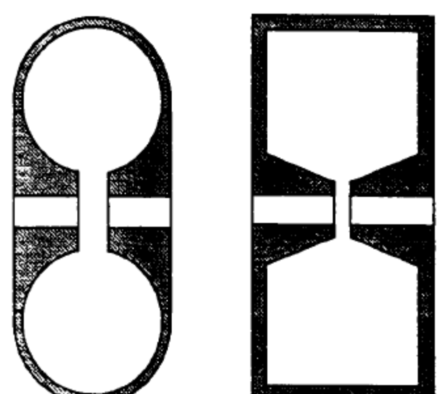
RF Accelerating structures: Resonant Cavities

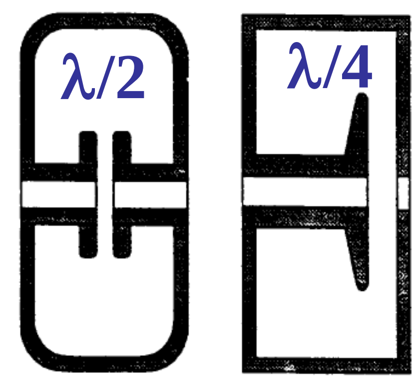
High frequency accelerating fields synchronized with the beam motion are obtained by exciting metallic structures properly designed. In this case the structure physical dimensions are comparable with the e.m. field wavelength, and the exact spatial and temporal field profiles have to be computed (analytically or numerically) by solving the Maxwell equations with the proper boundary conditions.

Resonant cavities are (almost) closed volumes were the e.m fields can only exists in the form of particular spatial conformations (resonant modes) rigidly oscillating at some characteristics frequencies (Standing Waves).



Reentrant or nose-cone cavities





Disk-loaded or coaxial cavities

Modes of a Resonant Cavity: General Problem

The resonant cavity modes are solutions of the homogeneous Maxwell equations inside closed volumes surrounded by perfectly conducting walls. The mathematical problem has the following formal expression:

Homogeneous Maxwell Equations
+ perfect metallic boundaries

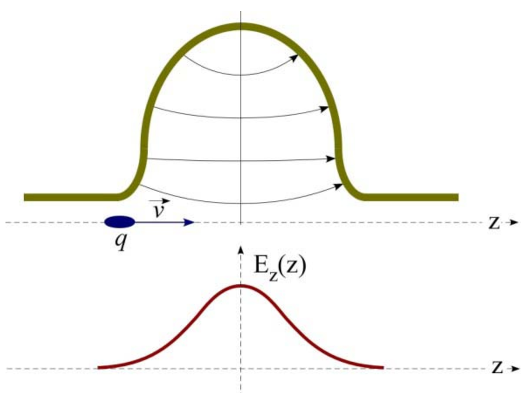
$$\left\{\begin{array}{l} \textit{Wave equation} \\ \textit{Field solenoidality} \\ \textit{Perfect boundary} \end{array}\right. \rightarrow \left\{\begin{array}{l} \nabla^2 \vec{E}(\vec{r},t) = \varepsilon\mu \dfrac{\partial^2}{\partial t^2}\vec{E}(\vec{r},t) \\ \vec{\nabla}\cdot\vec{E}(\vec{r},t) = 0 \\ \vec{n}\times\vec{E}(\vec{r},t) = 0 \end{array}\right. \xrightarrow[\textit{Phasors}]{} \left\{\begin{array}{l} \nabla^2 \vec{E}(\vec{r}) = -k^2\,\vec{E}(\vec{r}) \\ \vec{\nabla}\cdot\vec{E}(\vec{r}) = 0 \\ \vec{n}\times\vec{E}(\vec{r}) = 0 \end{array}\right.$$

According to the theory of linear operators, the solution is represented by a discrete set of eigen-functions $\vec{E}_n(\vec{r})$ and their associated eigenvalues $k_n = \omega_n / c$. The magnetic field eigenfunctions $\vec{B}_n(\vec{r})$ can be obtained from the Maxwell 3rd equation: $\vec{\nabla}\times\vec{E} = -\dfrac{\partial\vec{B}}{\partial t} \xrightarrow[\textit{phasors}]{} \vec{\nabla}\times\vec{E}_n(\vec{r}) = -j\omega_n\vec{B}_n(\vec{r})$

The $\vec{E}_n(\vec{r})$ functions are the cavity modes, each one resonating at a certain specific frequency ω_n. The eigen-functions are also a linear independent base, so that the actual fields $\vec{E}(\vec{r},t)$, $\vec{B}(\vec{r},t)$ can always be represented as a linear superposition of the cavity modes: $\vec{E}(\vec{r},t) = \sum_n a_n\vec{E}_n(\vec{r})\,e^{j\omega_n t}$; $\vec{B}(\vec{r},t) = \sum_n a_n\vec{B}_n(\vec{r})\,e^{j\omega_n t}$

Energy Gain

Cavities are normally designed to exploit the field of a **particular resonant mode** to accelerate the beam (accelerating mode). The lowest frequency mode (**fundamental mode**) is generally used for this task.



Let's consider a charge q travelling at constant speed v along a cavity gap on the reference frame z-axis. Assume that only the accelerating mode $\vec{E}_a(r,\varphi,z)$ is excited. The longitudinal E-field on the axis is:

$$E_z(z,t) = \Re e\left[\vec{E}_a(r=0,z)\cdot\hat{z}\,e^{j\omega_a t}\right] = \Re e\left[E_z(z)e^{j\omega_a t}\right]$$

Being the charge eq. of motion $z = v(t - t_0)$, the energy gain for a single gap transit is:

$$\Delta U = q\int_{-L/2}^{L/2}\Re e\left[E_z(z)e^{j\omega_a(z/v - t_0)}\right]dz = q\,\Re e\left[e^{-j\varphi_0}\int_{-L/2}^{L/2}E_z(z)e^{j\omega_a z/v}dz\right] \quad with \;\; \varphi_0 = \omega_a t_0$$

The **maximum energy gain** ΔU_{max} is obtained at the **optimal** value of the **injection phase** φ_0:

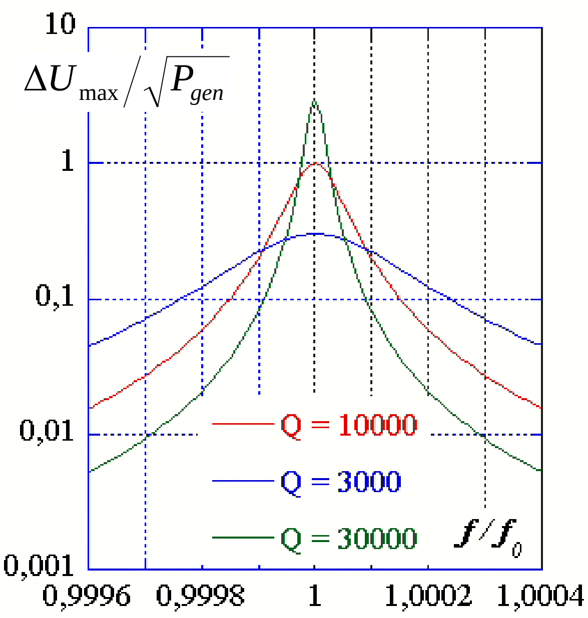
$$\Delta U_{max} = qV_{max} = q\left|\int_{-L/2}^{L/2}E_z(z)e^{j\omega_a z/v}dz\right| \xrightarrow[E_z(z)=even\ function]{} = q\int_{-L/2}^{L/2}E_z(z)\cos(\omega_a z/v)\,dz$$

Cavity Loss – *Q* factor

Real cavities are ***lossy***. ***Surface currents dissipate energy***, so that a certain amount of RF power must be provided from the outside to keep the accelerating field at the desired level. If the external excitation is turned off, fields inside the cavity ***decay exponentially*** with a time constant τ_n characteristic of any given mode.

In frequency domain, the dissipation makes the modes resonating ***not only at the eigenvalue frequency*** ω_n but in a ***frequency band*** of width $\Delta\omega_n$ around ω_n. Both the bandwidth $\Delta\omega_n$ and the decay time τ_n are related to the ***quality factor*** Q of the mode defined as:

$$Q = \omega_n \frac{U}{P} \quad \rightarrow \begin{cases} \tau_n = 2Q/\omega_n \\ \Delta\omega_n\big|_{3dB} = \omega_n/Q \end{cases}$$



where U and P are the e.m. energy stored in the mode and the corresponding power dissipation on the walls.

General expressions for U and P are:

$$U = \int_{Vol} \left(\frac{1}{4}\varepsilon \left|\vec{E}\right|^2 + \frac{1}{4}\mu \left|\vec{H}\right|^2 \right) d\tau; \quad P = \frac{1}{2} R_s \int_{Surf.} H_{tan}^2 \, d\Sigma \quad with \quad R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\omega\mu_0}{2\sigma}}$$

Cavity Loss – Superconductivity

Superconductivity is a very well-known physical phenomenon that is widely used in RF for particle accelerators.

Surface resistance is ***reduced*** by ***orders of magnitude*** (5 typically) in superconducting (SC) cavities, which are then very suitable when large gradients have to be sustained continuously or in a high duty-cycle regime.

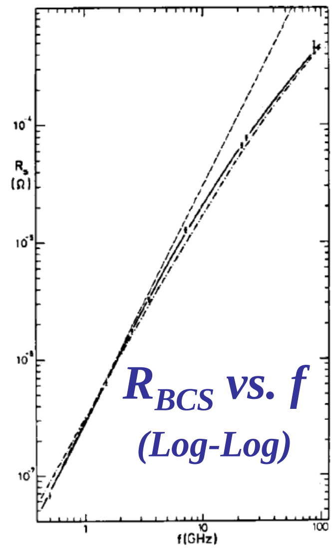
Surface resistance $R_S = R_{BCS} + R_{res}$

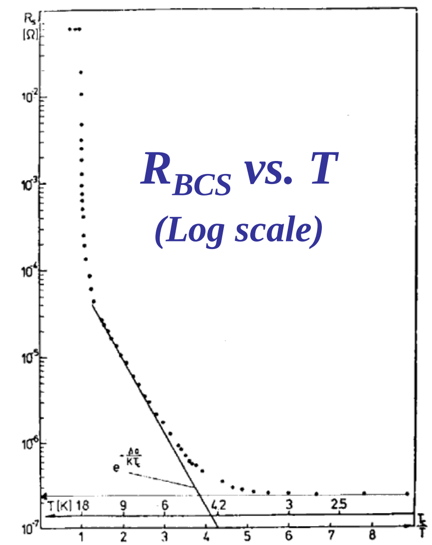
$$R_{BCS} = A \frac{1}{T} \omega^2 \exp\left(-\frac{\Delta(T)}{kT}\right) \qquad T \leqslant \frac{T_c}{2}$$

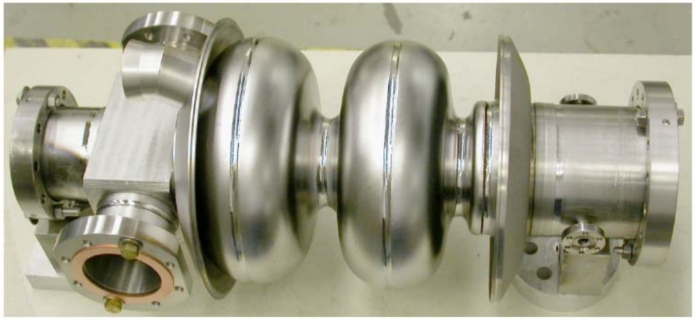
k the Boltzmann constant

A is a material parameter,

$\Delta(T)$ is the energy gap of the superconducting material







1.3 GHz, 2-cell cavity for Cornell ERL injector.

Shunt impedance

One of the most important parameter to characterize the cavity accelerating modes is the shunt impedance R defined as:

$$R = \frac{V^2}{2P} = \frac{1}{R_s} \frac{\left| \int E_z(z) e^{j\omega z/v} dz \right|^2}{\int_{Surf.} H_{tan}^2 d\sigma}$$

Frequency and material conductivity

Mode field configuration

The shunt impedance is the parameter that qualifies the efficiency of an accelerating mode. The higher the value, the larger the attainable accelerating voltage for a given power expenditure.

Another very useful parameter is the ratio between shunt impedance and quality factor :

$$\left(\frac{R}{Q}\right) = \frac{V^2}{2P}\,\frac{P}{\omega U} = \frac{1}{2\omega}\,\frac{\left| \int_{traject.} E_z(z) e^{j\omega z/v} dz \right|^2}{\int_{Vol.} \left(\frac{1}{4}\varepsilon \left|\vec{E}\right|^2 + \frac{1}{4}\mu \left|\vec{H}\right|^2 \right) d\tau}$$

The ***(R/Q)*** is a pure geometric qualification factor. In fact, for a given mode it is straightforward that the ***(R/Q)*** does not depend on the cavity wall conductivity, and its value is preserved if homothetic expansions of a given geometry are considered.

The *(R/Q)* is a qualification parameter of the cavity geometrical design.

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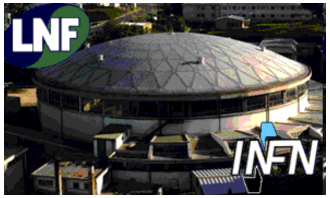


A.Gallo: RF Systems

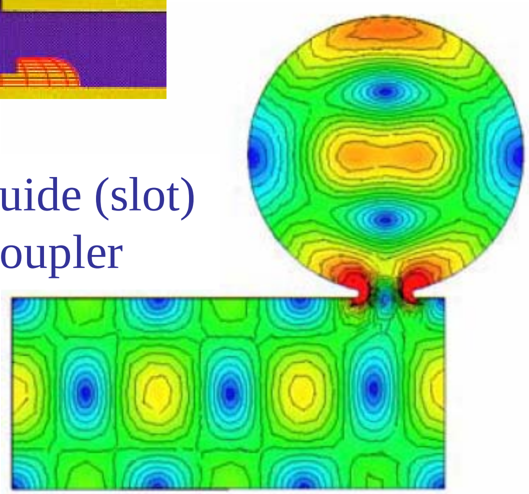
Merit Figures

PARAMETER	DEFINITION	FREQUENCY SCALING	TYPICAL VALUES
Quality factor Q Ratio between energy stored U and energy dissipated per cycle U_{loss}. Defines the resonance bandwidth and the field decay time.	$Q = \omega \frac{U}{P} = 2\pi \frac{U}{U_{loss}}$	$Q \div \frac{1}{R_s} \div \begin{cases} f^{-1/2} \; (NC) \\ f^{-2} \; (SC) \end{cases}$ $\left[Q \div e^{\Delta(T)/kT} \quad (SC) \right]$	$\begin{cases} 10^4 \div 10^5 \; (NC) \\ 10^9 \div 10^{10} \; (SC) \end{cases}$
Shunt Impedance R Square of the accelerating voltage V normalized to the RF power P dissipated to sustain the field.	$R = \frac{V^2}{2P}$	$R \div \frac{1}{R_s} \div \begin{cases} f^{-1/2} \; (NC) \\ f^{-2} \; (SC) \end{cases}$	single cell: $\begin{cases} 1 \div 5 \, M\Omega \; (NC) \\ 100 \div 500 \, G\Omega \; (SC) \end{cases}$
Shunt Impedance per unit length Z Square of the accelerating voltage V normalized to the RF power P and cavity gap length L.	$Z = \frac{R}{L} = \frac{V^2}{2PL}$	$Z \div \frac{1}{R_s L} \div \begin{cases} f^{1/2} \; (NC) \\ f^{-3/2} \; (SC) \end{cases}$	$\begin{cases} 2 \div 20 \, M\Omega/m \; (NC) \\ 0.1 \div 5 \, T\Omega/m \; (SC) \end{cases}$
Geometric factor (R/Q) Geometric factor qualifying the accelerating cavity shape regardless to frequency and wall conductivity.	$(R/Q) = \frac{V^2}{2PQ} = \frac{V^2}{2\omega U}$	$(R/Q) \div f^0$!!!	single cell: $50 \div 100 \, \Omega$

Input-Output coupling

Real cavities are never completely closed volumes. At the least, apertures for beam transit (beam tubes) are required, as well as RF input couplers to feed the cavity, and RF output couplers to probe the field inside. The RF couplers can be of different types:

Magnetic (loop) input coupler



Waveguide (slot) input coupler

- Electric couplers (Antennas): the inner of a coaxial line connected from the outside couples to the cavity mode E-field;
- Magnetic couplers (Loops): the cavity mode B-field couples to a loop connecting inner and outer conductors of a coaxial line.
- Waveguide couplers: the cavity mode fields are coupled to an external waveguide of proper shape and cut-off through a hole or a slot in the cavity walls

Coupling and loading parameters of a cavity

The coupling strength of a port can be measured as the amount of power P_{out} extracted form the cavity through the port itself for a given level of the mode fields inside. This leads to the definitions of the ***external-Q*** (Q_{ext}) (in analogy with the definition of the resonance quality factor Q) and coupling coefficient β of a coupler according to :

$$Q_{ext} = \omega \frac{U}{P_{out}}; \qquad \beta = \frac{Q_0}{Q_{ext}} = \frac{P_{out}}{P_{walls}}$$

where Q_0 is the usual quality factor of the resonant mode, related only to the dissipation P_{walls} on the cavity walls.

The extra-power flow through the cavity couplers, in addition to the power loss in the walls, may significantly change the characteristics of the resonance. This effect is known as "cavity loading". The loaded cavity Q-factor Q_L is lowered by the power coupled out through the ports and result to be:

$$Q_L = \omega \frac{U}{P_{Tot}} = \omega \frac{U}{P_{walls} + \sum P_{out_n}} \rightarrow \frac{1}{Q_L} = \frac{P_{walls}}{\omega U} + \sum \frac{P_{out_n}}{\omega U} \rightarrow \begin{cases} \dfrac{1}{Q_L} = \dfrac{1}{Q_0} + \sum \dfrac{1}{Q_{ext_n}} \\[2ex] \dfrac{1}{Q_L} = \dfrac{1 + \sum \beta_n}{Q_0} \end{cases}$$

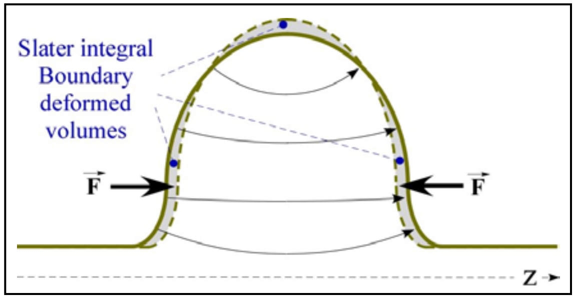
Tuning

The cavity resonant frequencies need to be continuously controlled during operation. Actual frequencies are affected by thermal drifts and, in case of superconducting cavities, by pressure variations in the cryogenic bath.

Storage ring cavities have to be largely detuned during beam injection to compensate the beam loading. Synchrotron cavity frequencies have to follow beam velocity increase associated to the energy ramping.

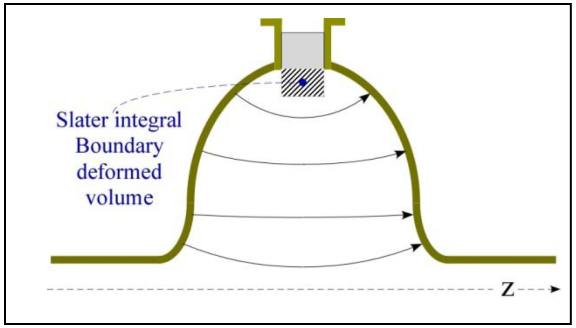
The frequency control is normally obtained through small deformations of the cavity boundaries. The Slater theorem can be used to compute the resonant frequency change, according to:

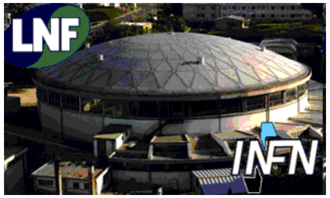
$$\frac{\Delta\omega}{\omega_0} = \frac{\int_{\Delta V}\left(\mu H^2 - \varepsilon E^2\right)d\tau}{\int_V\left(\mu H^2 + \varepsilon E^2\right)d\tau} = \frac{\Delta U_H - \Delta U_E}{U}$$



Cavity tuning is normally actuated through:

- Cooling fluid temperature control (linac TW or SW sections);
- Structure pushing/stretching by application of axial forces (SC and multi-cell cavities);
- Variable penetration of tuning plungers in the cavities volume (room-temperature, single cell cavities under heavy beam-loading).





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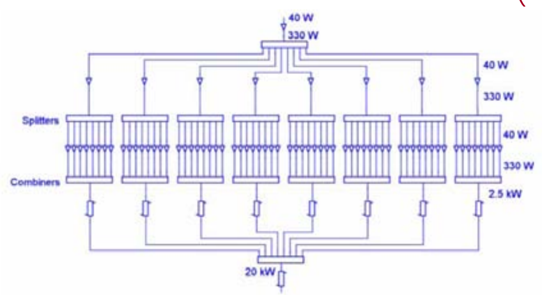
RF Power Sources

RF Power Sources: Solid State Amplifiers

Various technologies available:

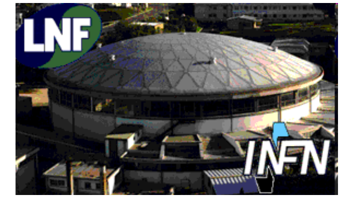
- Silicon bipolar transistors
- silicon LDMOS
- GaAsFET,
- Static Induction Transistors (SITs)



The power required is obtained by operating numerous transistors in parallel.

352 MHz, 190 kW solid state amplifier for the SOLEIL RF System

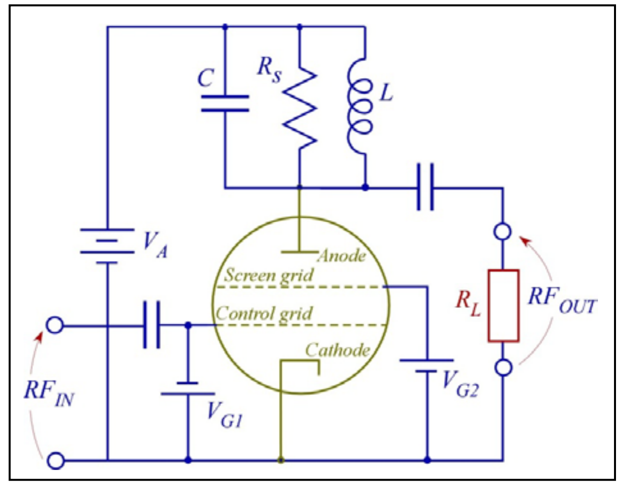
RF Source	Frequency / Bandwidth	Max Power	Class of operation / Efficiency	Features	Drawbacks
Solid State	**dc ÷ 10 GHz** / **Large** (up to multi-octave)	0.5 kW/pallet 200 kW/plant	A, AB $\eta \leq 40$ %	▪ Simplicity ▪ Modularity ▪ No HV	▪ Large dc currents ▪ Combiner Losses



RF Power Sources: Tetrodes (*Grid Tubes*)

Tetrodes are long-time, well established grid tubes RF sources.

- Evolution of Triodes;
- Widely used in industry, TV and communications;
- Electrons in the tube are produced by thermo-ionic effect at the cathode;
- Intensity of the captured current at the Anode electrode is modulated by the Control grid potential;
- Screen grid increases RF isolation between electrodes.



RF performance

Operating example (in cavity TH 18528)

	CW	Long pulses	
Frequency	345	40	MHz
Output power	60	80	kW
Pulse duration	cw	2	sec
Anode voltage	10.5	12	kV
Anode current	7.7	7.7	A

RF Source	Frequency / Bandwidth	Max Power	Class of operation / Efficiency	Features	Drawbacks
Tetrodes	**50 ÷ 1000 MHz / few %**	200 kW/tube	A, AB, B, C $\eta \le 70$ %	▪ Simplicity ▪ Low cost	▪ HV ▪ Transit-time limited

RF Power Sources: Inductive Output Tubes

Inductive Output Tubes (IOTs) are grid tubes (also known as “klystrodes”) commercially available since ’80s. They combine some design aspects of tetrodes and klystrons:

- Anode grounded and separated from collector;
- Tube beam current intensity modulated by the RF on the grid. RF input circuit is a resonant line;
- Short accelerating gap to reduce transit-time, beam emerging from a hole in the anode;
- RF output extracted from a tuned cavity between anode and collector decelerating the bunched beam;
- High efficiency, widely used in TV and communications.

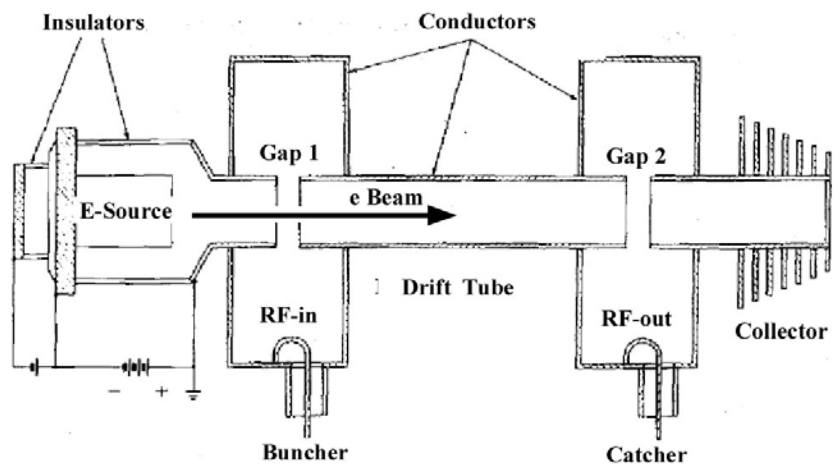
150 kW CW RF Amp for ELETTRA SLS (Trieste) 2×80 kW IOTs

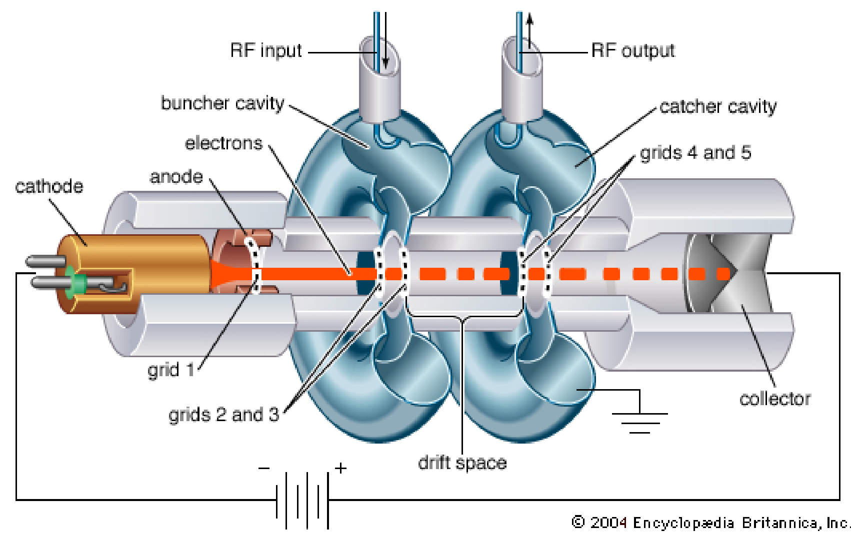
RF Source	Frequency / Bandwidth	Max Power	Class of operation / Efficiency	Features	Drawbacks
Inductive Output Tubes (IOTs)	**100÷ 2000 MHz / few %**	500 kW/ tube	B, C $\eta \leq 80$ %	▪ Efficient ▪ Reliable ▪ Cheap	▪ HV ▪ Power limited (@ high freq.)

RF Power Sources: Klystrons *(Velocity Modulation Tubes)*

The klystron has been invented in late '30s by Hansen and Varian Bros.

- Based on the velocity modulation concept;
- After being accelerated to a non-relativistic energy in an electrostatic field, a thermo-ionic beam is velocity-modulated crossing the gap of an RF cavity (buncher) excited by the RF input signal.
- Velocity modulation turns into density modulation after the beam has travelled a drift space. RF power output is extracted from a tuned output cavity (catcher) excited by the bunched beam.
- Other passive cavities are generally placed between buncher and catcher to enhance the bunching process.
- Beam particle transverse motion is focused all over the fly by solenoidal magnetic fields.
- Operation as oscillator is possible by feeding back an RF signal from catcher to buncher.





RF Power Sources: Examples of klystrons

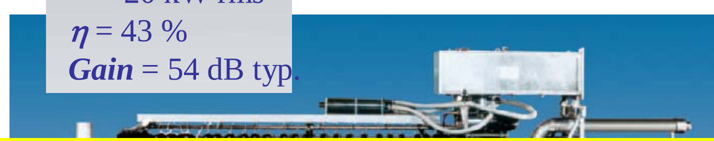
The klystron is the most widely diffused RF source in particle accelerators. A large variety of tubes exists for different applications, spanning wide ranges of frequency and output power, as well as different duty cycles. Principal tube categories are:

- High power CW tubes (up to 2 MW), for synchrotron, storage rings and CW linacs;
- Very high peak power (up to 100 MW) tubes for low duty-cycle machines (1÷4 μs, 100 Hz rep rate), such as S-band, C-band (and proposed X-band) normal-conducting linacs;
- High peak power (up to 10 MW) tubes for high duty cycle machines (1 ms, 10 Hz rep rate), such as SC linacs for FEL radiation production or for future linear colliders. Multi-beam klystrons have been developed for this task.

TH 2132
S-band
Klystron
f = 2998.5 MHz
P = 45 MW pk / 20 kW rms
η = 43 %
Gain = 54 dB typ.

NLC Klystron
f = 11.4 GHz
V_0 = 490 kV
I_0 = 260 A
P = 75 MW pk
η = 55 %

MBK
for TESLA
f = 1300 MHz
V_0 = 115 kV
I_0 = 133 A
P = 9.8 MW peak
η = 64 %
Beams = 6



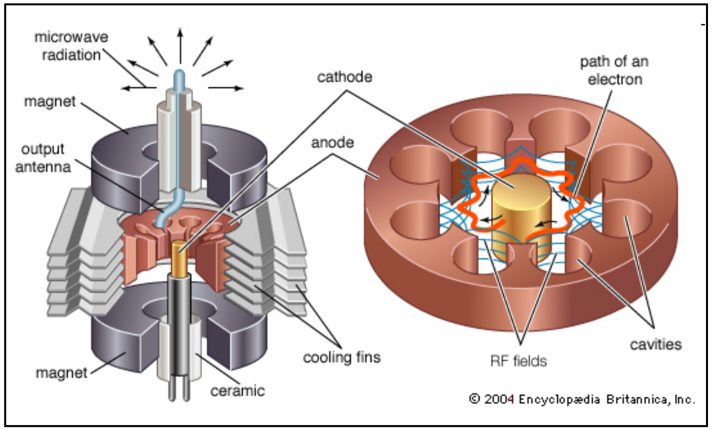
TH 2089 Klystron
for LEP
f = 352 MHz
P = 1.3 MW CW
η = 65 %
Gain = 40 dB min.

RF Source	Frequency / Bandwidth	Max Power	Efficiency	Features	Drawbacks
Klystrons	**0.3÷ 30 GHz / ≈1 %**	≈2 MW rms ≈100 MW peak	η =40÷60 %	▪ High power ▪ High gain	▪ HV ▪ Efficiency

RF Power Sources (*Others*):

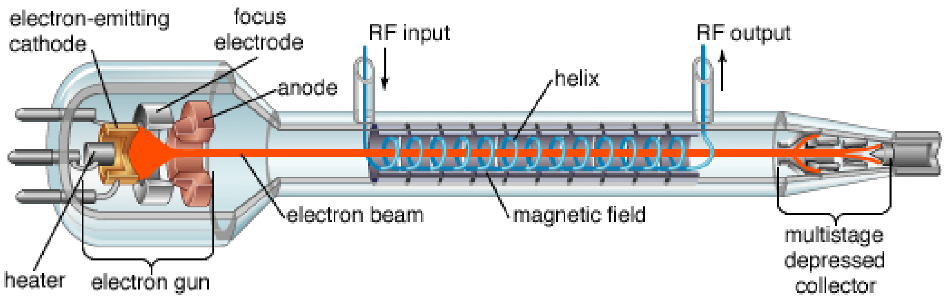
Magnetrons and Travelling Wave Tubes (TWTs)

In a Magnetron the cathode and anode have a coaxial structure, and a longitudinal static magnetic field (perpendicular to the radial DC electric field) is applied . The cylindrical anode structure contains a number of equally spaced cavity resonators and electrons are constrained by the combined effect of a radial electrostatic field and an axial magnetic field. The output power is coupled out from one of the cavities connected to a load through a waveguide. Magnetrons are oscillators providing output power up to 1 MW.



Magnetron Sketch

Helix Travelling Wave Tube Sketch



Helix Travelling Wave Tubes are widely used μ-wave amplifiers.

Amplification is due to a continuous bunching of a thermo-ionic electron beam interacting with an RF filed travelling along an helix line which allows the energy transfer from the beam to the line. Typical gains are 40 to 60 dB while DC-to-RF conversion efficiency up to ≈ 75 %.

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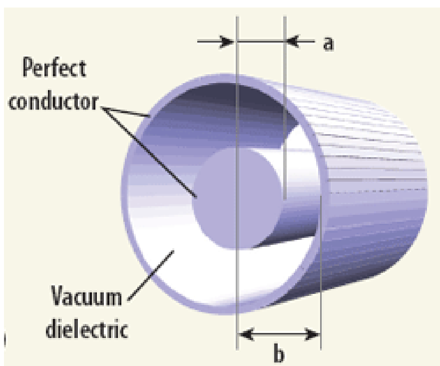
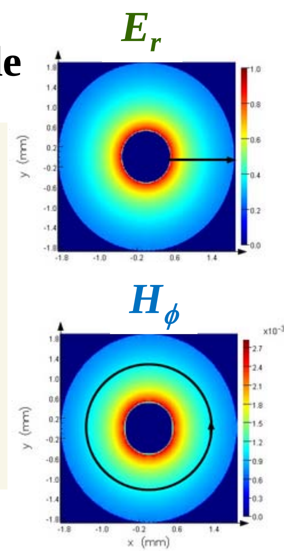
RF Power Distribution

Transmission Lines and Waveguides

In most cases RF Power is transferred from sources to the accelerating structure through a network of **coaxial transmission lines** or **rigid rectangular waveguides**.

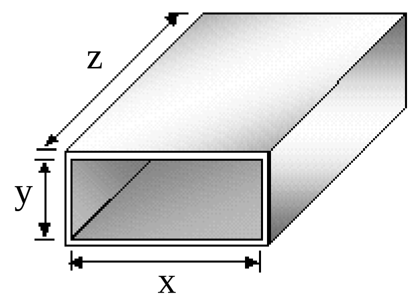
Coaxial Line TEM mode

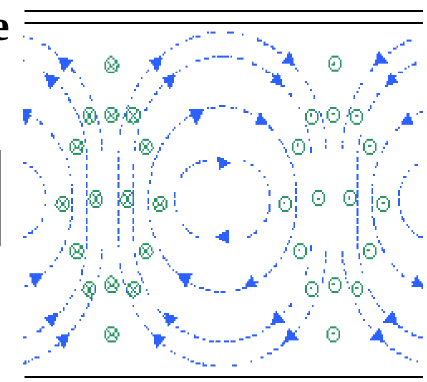


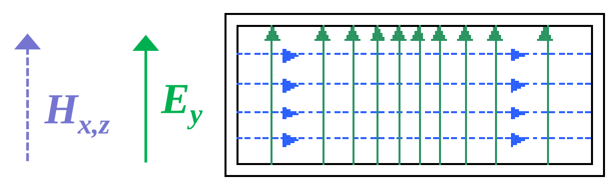


- No cut-off (usable from dc)
- No dispersion
- $E_r(r) \div H_\phi(r) \div 1/r$
- $Z_0 = V/I = 1/(2\pi)\cdot(\mu/\varepsilon)^{1/2} \cdot ln(b/a)$
- Large attenuation
- Difficult to cool

Rectangular Waveguide TE_{10} mode





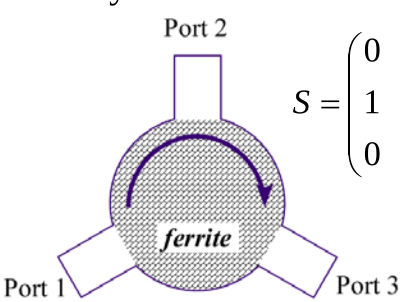


- Dispersive
- Only $\lambda < \lambda_c$, $\lambda_c = 2x$ (cut-off wavelength)
- Low attenuation
- Easy to cool
- Suitable at high frequency, high power

Special Components in the WG Networks

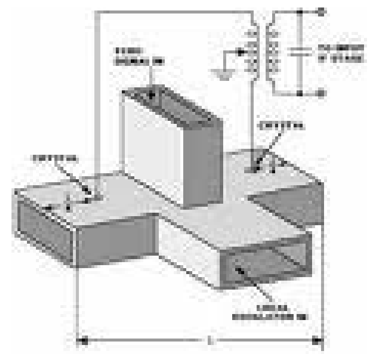
CIRCULATORS

Circulators are **non-reciprocal 3-ports** (typically) devices based on the peculiar properties of the ferrite materials. They are interposed between the RF power sources and the cavities to convey the reflected power on dummy loads.



$$S = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

HYBRID JUNCTIONS / POWER SPILTTERS

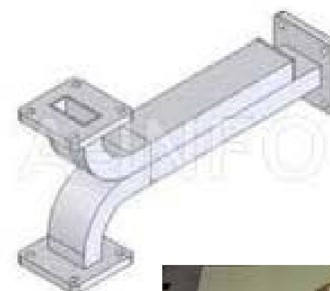


The "magic-T", a particular 180° hybrid

Hybrid junctions and RF splitters are used to feed various accelerating structures from a single RF power source. Phase relation among ports depends upon the chosen splitting technique.

DIRECTIONAL COUPLERS

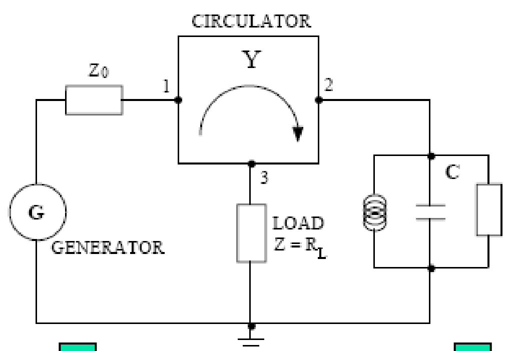
Directional Couplers are quadrature hybrids with unequal coupling coefficients. They are mainly used to sample the fields in the waveguides for control and diagnostic purposes.

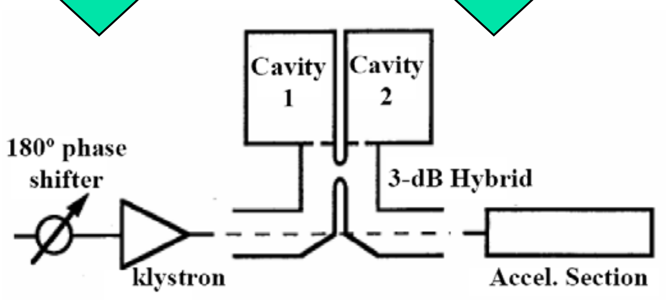


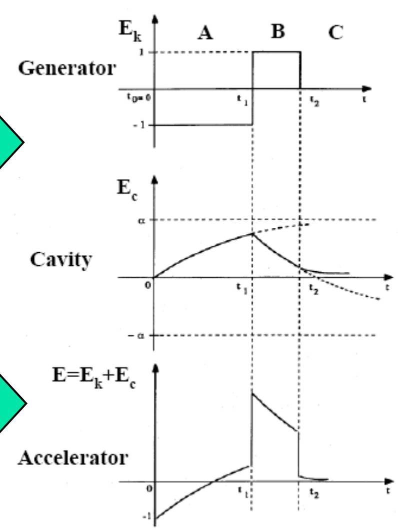
RF Power Sources: Pulse Compression (SLED)

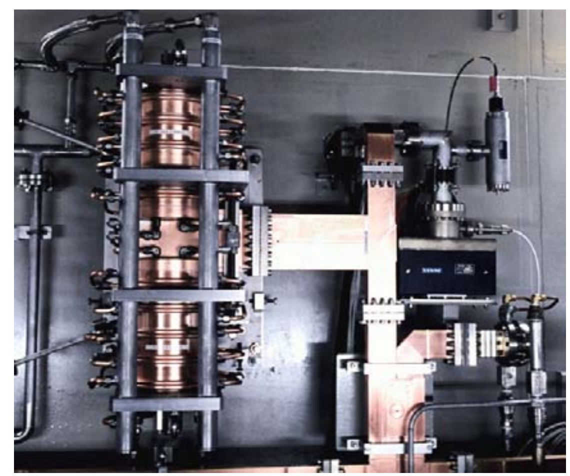
The Stanford Linac Energy Doubling (SLED) is a system developed to compress RF pulses in order to increase the peak power (and the available accelerating gradients) for a given total pulse energy. This is obtained by capturing the pulsed power reflected by a high-Q cavity properly excited by the RF generator (typically a klystron). In fact the wave reflected by an overcoupled cavity ($\beta \approx 5$) peaks at the end of the RF pulse to about twice the incident wave level (with opposite polarity).

By playing with this, and properly tailoring the incident wave, accelerating gradients integrated over a small portion of the original pulse duration are almost doubled.









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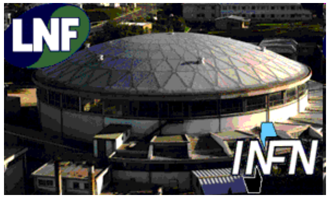

RF Systems

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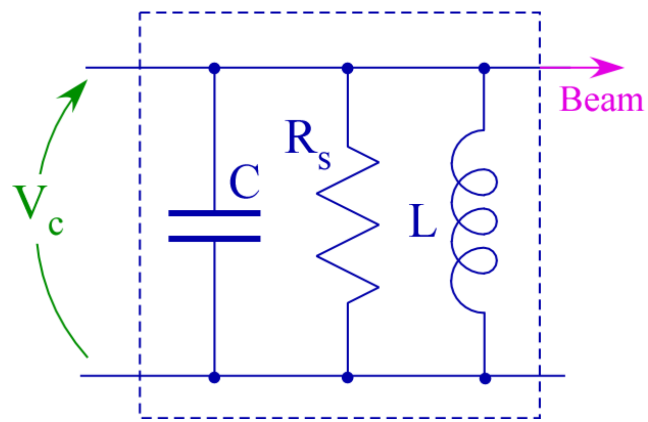
Beam Loading and

Low Level RF (LLRF)

THE CAVITY RLC MODEL

The beam-cavity interaction can be conveniently described by introducing the resonator RLC model. According to this model, the cavity fundamental mode interacts with the beam current just like a parallel RLC lumped resonator. The relations between the RLC model parameters and the mode field integrals ω_{cav} (mode angular resonant frequency), V_c (maximum voltage gain for a particle travelling along the cavity gap for a given field level), U (energy stored in the mode), P_d (average power dissipated on the cavity walls) and Q (mode quality factor), are given by:

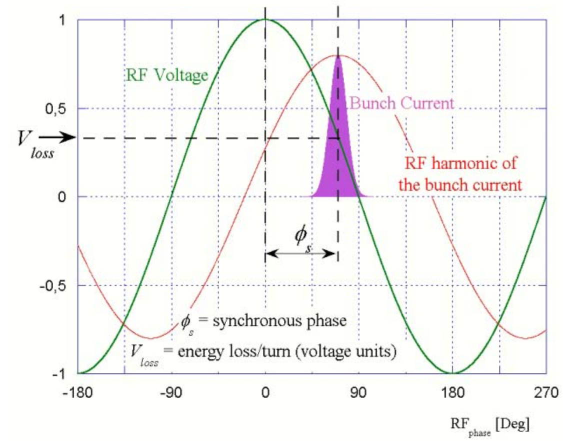
Mode field integrals	Cavity RLC model	RLC parameters
$V_c = \left\lvert \int_{gap} E_z(z)\, e^{j\omega_{cav}\frac{z}{\beta c}} dz \right\rvert$ $P_d = \frac{1}{2}\int_S R_{surf} H_t^2 d\sigma$ $U = \frac{1}{4}\int_V (\varepsilon E^2 + \mu H^2) d\tau$ $Q = \frac{\omega_{cav} U}{P_d}; \quad R/Q = \frac{V_c^2}{2\omega_{cav} U}$	 Note: we assume that positive voltages accelerate the beam, which is therefore modelled as a current generator discharging the cavity	$R_s = \frac{V_c^2}{2P_d}$ $C = \frac{1}{\omega_{cav}\, R/Q}$ $L = \frac{1}{\omega_{cav}^2 C} = \frac{R/Q}{\omega_r}$

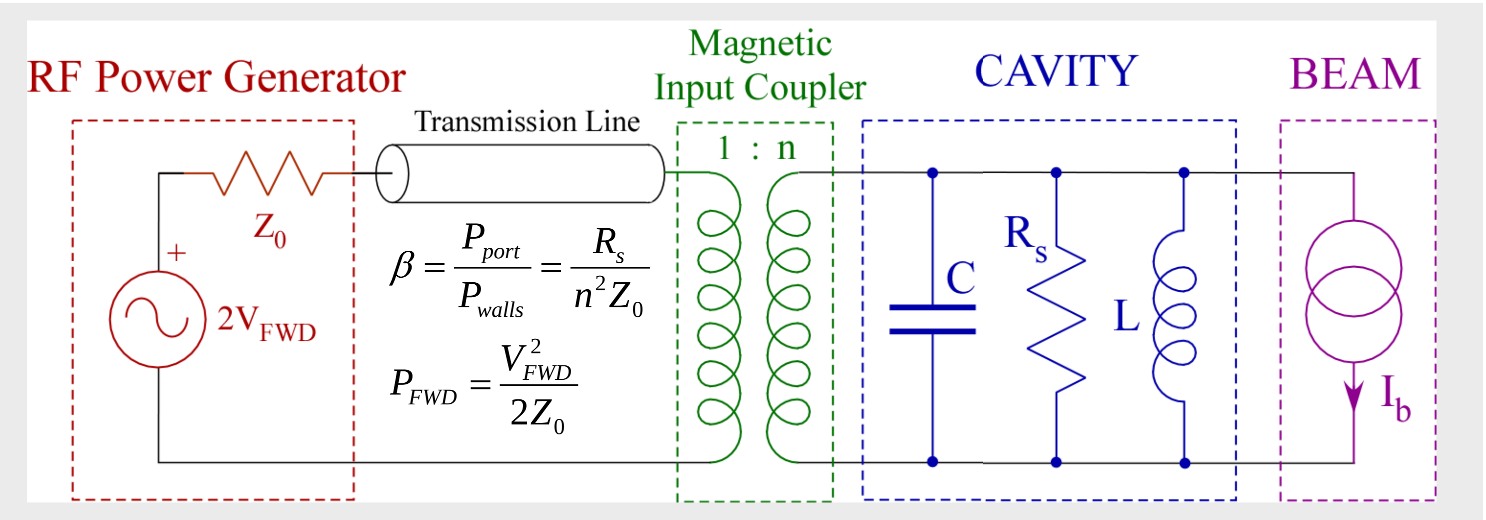
Generator - Cavity - Beam model: Beam loading

The cumulative contribution of many bunch passages depends essentially on the RF harmonic of the beam spectrum.

The static beam loading problem consists in computing:

- the overall **contribution** of the **beam** to the **accelerating voltage**;
- the **RF generator power** needed to refurnish both cavity and beam;
- the **optimal values** of **cavity detuning** and **cavity-to-generator coupling** to minimize the power request to the generator.





Generator - Cavity - Beam model: Beam loading

The reflection coefficient ρ on the RF power transmission line according to the system model is given by:

$$\rho = \frac{\boxed{\beta - 1 - \frac{R_s I_b}{V_c}\cos\phi_s} - jR_s \boxed{\left(\frac{\delta}{R/Q} + \frac{I_b}{V_c}\sin\phi_s\right)}}{\beta + 1 + \frac{R_s I_b}{V_c}\cos\phi_s + jR_s\left(\frac{\delta}{R/Q} + \frac{I_b}{V_c}\sin\phi_s\right)}$$

Zero for optimal coupling factor

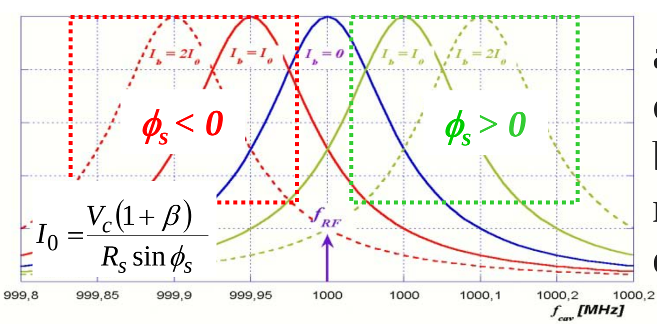
Zero for optimal cavity detuning

Being the detuning parameter δ defined as:

$$\delta = \frac{\omega_{RF}}{\omega_{cav}} - \frac{\omega_{cav}}{\omega_{RF}} \approx 2\frac{\Delta\omega_{RF-cav}}{\omega_{RF}}$$

minimizing the power reflection requires an optimal cavity detuning given by:

$$\delta = -\frac{I_b\, R/Q}{V_c}\sin(\phi_s) \;\; \Rightarrow \;\; \Delta\omega_{RF-cav} = -\omega_{RF}\frac{I_b\, R/Q}{2V_c}\sin(\phi_s)$$



acceleration off-crest of a large beam current may require large cavity detuning !

Complete minimization of the power reflection requires also an optimal value of the input coupling coefficient β:

$$\beta_{opt} = 1 + \frac{I_b R_s}{V_c}\cos(\phi_s) = 1 + \frac{P_{beam}}{P_{cav}}$$

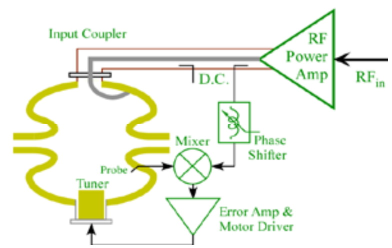
$$P_{FWD} = \frac{1}{2}\frac{V_c^2}{R_s} + \frac{1}{2} I_b V_c \cos(\phi_s) = P_{cav} + P_{beam}$$

Low-level RF Control (LLRF)

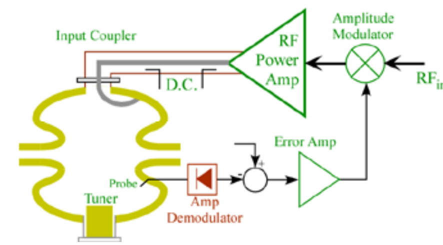
The Low-level RF is the hardware section pre-forming the RF signal before being amplified to fed the accelerating structures.

The LLRF system consists in a number of integrated controllers of various topologies (servo loops, beam feedback loops, feed-forward schemes) that accomplish several tasks such as:

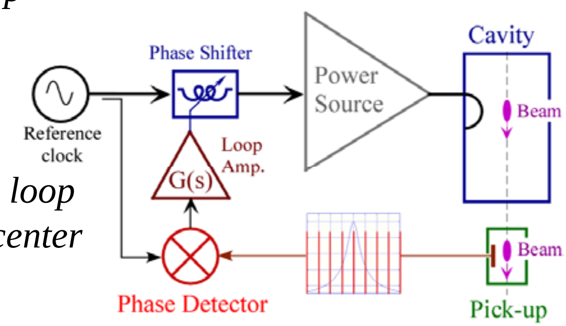
- automatic cavity tuning, compensating thermal drifts and beam loading variations;
- automatic RF level control, to follow beam loading variation in Storage Rings (SRs) or to stabilize the beam energy in linacs;
- automatic RF phase control, to stabilize the bunch timing (SRs, linacs) and energy (linacs);
- suppression of beam instabilities arising from the interaction with the cavity accelerating mode in SRs, obtained through a combination of feedback loops (beam phase loop, direct RF feedback loop, comb loop, …) and/or beam feed-forward compensations;



Automatic tuning loop



Automatic RF level control



Beam phase loop (beam barycenter feedback)

- Revolution frequency tracking, RF phase jump and all related controls during transition energy crossing in synchrotrons (RF gymnastics);
- adaptive feedback and/or feed-forward systems to compensate transient effects in pulsed regime or due to beam gaps;
- …

An example: PEP-II (SLAC B-factory) LLRF

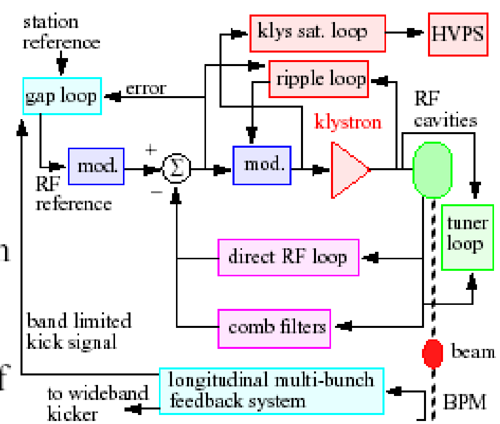
Tuner loops - standard tuning for minimum reflected power

Klystron operating point support

- Ripple loop adjusts a complex modulator to maintain constant gain and phase shift through the klystron/modulator system.
- Klystron saturation loops maintain constant saturation headroom

Direct feedback loop (analog)

- Causes the station to follow the RF reference adding regulation of the cavity voltage
- Extends the beam-loading Robinson stability limit
- Lowers the effective fundamental impedance seen by the beam



Loop technology legend

Magenta - EPICS loop
Green - digital
Red - analog

Comb filter (digital)

- Adds narrow gain peaks at synchrotron sidebands to further reduce the residual impedance

Gap feedback loop (digital)

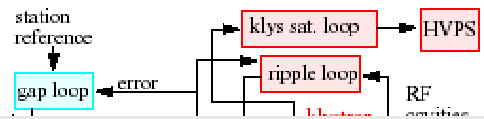
- Removes revolution harmonics from the feedback error signal to avoid saturating the klystron on gap synchronous phase transients

Longitudinal feedback uses RF as low-frequency “woofer” kicker

An example: PEP-II (SLAC B-factory) LLRF

Tuner loops - standard tuning for minimum reflected power

Klystron operating point support



- In the last decades the LLRF controls have progressively evolved from fully analog electronics systems (as they were in CERN PS pioneeristic age) to more and more digital electronics based systems, exploiting the great potentiality of DSP (first) and FPGA (now) controllers.

- Extends the beam-loading Robinson stability limit
- Lowers the effective fundamental impedance seen by the beam

Loop technology legend

Magenta - EPICS loop

- In modern machines LLRF is becoming more and more complex task (a science in itself!) requiring a combination of different expertise such as RF, electronics and computational engineering.

- Removes revolution harmonics from the feedback error signal to avoid saturating the klystron on gap synchronous phase transients

Longitudinal feedback uses RF as low-frequency "woofer" kicker