CHOICE OF RF FREQUENCY

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Abstract
A broad overview of effects and considerations that have a bearing for the accelerator environment is presented, and 'frequency' as a common input parameter. Aspects of beam dynamics, RF, and mechanical technology are briefly discussed to illustrate some contradictory requirements of accelerator design. While RF considerations are rarely a determining factor in that context, some trends can nevertheless be identified.

1 INTRODUCTION

In most situations the choice of RF frequency in an accelerator is determired by constraints that dictate a certain frequency or frequency band. This is particularly true for improvement programmes in existing machines. Rather than choices there are mostly contradicting trends in the choice of frequency, which will be discussed in what follows.

Most of the material presented is well known and has been published by other authors in internal reports or conference papers. In particular the scaling of cavity parameters vs frequency, cavity/beam interactions, properties of components, etc. have been the subject of extensive studies at CERN and elsewhere in the context of proposals for new machines.

This article does not pretend to present any new material, but intends to give a broad overview of a range of disjoint topics, with frequency as a common denominator.

2 REMINDER OF LONGITUDINAL PHASE SPACE PROPERTIES — RF VOLTAGE REQUIREMENTS

From a beam dynamics point of view the tendency is towards lower frequencies, as can be illustrated for the case of a synchrotron. It is assumed that the basic properties such as kinetic energy, transition energy, revolution frequency (f_{rev}) are frozen. The harmonic number h remains a free parameter and determines the operating frequency $h\cdot f_{\text{rev}}$.

For a *single* stationary full bucket, bucket half-height BHH and bucket area A scale as a function of RF voltage V and harmonic number h:

$$\begin{aligned} BHH &\propto V^{1/2}\cdot h^{-1/2} \qquad \text{resp.} \qquad & V &\propto BHH^2 h \\ A &\propto V^{1/2}\cdot h^{-3/2} & V &\propto A^2\cdot h^3 \ . \end{aligned}$$

Therefore, the RF voltage requirement increases linearly with the harmonic number for a given bucket *height*. Similary, the required voltage increases with the cube of the harmonic number, for a given bucket *area*. Figure 1 shows the bucket shape for different combinations of h and V.

If, however, the total longitudinal phase space area of the beam is distributed over h bunches, the required individual bucket area is reduced by a factor of h. In this case the required voltage for a given bunch area increases only linearly with the harmonic number.

The conditions are different if short bunch lengths are required. Suppose that a bunch of length σ_1, held by a voltage V_1, is adiabatically compressed to a bunch length σ_2. The required voltage V_2 in the central bucket region where the synchrotron frequency is constant is given by

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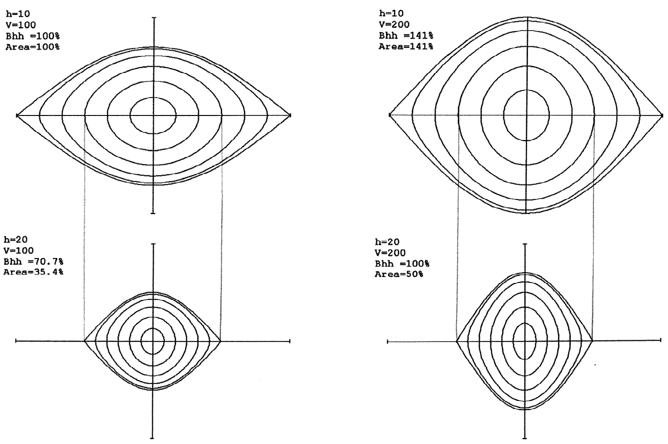

Fig. 1: Stationary bucket parameters for two different RF voltages (horizontal) and two different harmonic numbers (vertical)

$$V_2/V_1 \propto (\sigma_1/\sigma_2)^4/h \ .$$

The voltage requirement is reduced if high harmonic numbers are used, i.e. if the bucket is not unnecessarily wide. This consideration is, however, of a more theoretical nature since adiabatic bunch compression generally leads to prohibitively high RF voltages. Non-adiabatic methods like bunch rotation are then preferred.

2.1 Space charge

The usual figure of merit for evaluating space charge effects is the transverse tune shift ΔQ, which scales as $\Delta Q \propto 1/(\beta\gamma^2)$. The beam energy at the critical point, which is generally at the machine input, should therefore be as high as possible. Since the frequency in a synchrotron is proportional to β, there is a trend to extend the frequency range of the injector synchrotron to higher frequencies. While this will rarely lead to a different frequency band, it may be an important consideration for the improvement programmes of existing machines.

3 INFLUENCE OF THE TRANSVERSE PHASE SPACE — APERTURE

Frequency f and free-space wavelength λ are related by $\lambda = c_0/f$, therefore the two quantities may be used interchangeably for the argument. The electrical properties of of an RF structure with a given geometry are always determined in relation to the operating wavelength, hence dimensional constraints have a direct impact on the applicable wavelength or frequency. The cavity aperture plays a key role in this context.

Transverse phase space dynamics determine the beam size and the required aperture of the accelerating structure is determined by the radius of the good field region, i.e. the region around the beam axis where the RF accelerating field is sufficiently uniform for the application. The accelerating field tends to increase from the centre to the aperture radius and too large differences may lead to synchrotron–betatron coupling and other unwanted phenomena. Large beam tube radii and/or large good field regions consequently lead to large wavelengths, i.e. low frequencies, by essentially geometric considerations.

The trend wards to lower frequencies is enhanced by the transit time effect (see below). The gap width g should be as small as possible compared to the beam wavelength $\beta\lambda$. Therefore λ should preferably be large. In addition, large apertures increase the effective gap width, since the RF field extends deeper into the vacuum chamber than the geometric gap width. This is particularly true for buncher cavities at the low-energy end of an accelerator, where the relative velocity β is small but the transverse dimensions of the beam are large.

Transverse focusing elements are often an integral part of the RF structure that necessitate a compromise between longitudinal and transverse performance. Examples include the drift tubes holding the focusing quadrupoles in an Alvarez structure and the electrode design in an RFQ whose modulation depth determines the ratio between longitudinal and transverse electric field strength. In general these compromises set a lower limit to the operating wavelength in some proportion to the transverse beam emittance.

Conversely, if the frequency is given by other considerations, the influence of the aperture on the remaining machine parameters is of paramount interest (see below).

4 REMINDER OF THE BASIC RF CAVITY SCALING LAW

The properties of the intrinsic cavity can be fully described by three independent parameters obtained from the electromagnetic field pattern, namely resonant frequency, stored energy W, and power losses P. The resonant frequency f_{res}, is defined by the condition that the electric and magnetic stored energy are the same, each occurring only twice during a cycle, their sum being constant at any moment. W is obtained by integrating the electric or magnetic field energy over the volume. Similarly, P is obtained by integrating of the losses over the volume and the conducting surface. W and P are normalized for a gap voltage V (more precisely the integral of the electric field strength along a defined path, generally the beam axis). These three parameters may be converted to other parameters such as the Q-factor and are in a one-to-one relation with the well-known equivalent circuit of the three lumped elements r, L, and C connected in parallel with

$$\begin{array}{l} \omega_{\text{res}} = 2\pi\, c_0/\lambda_{\text{res}} = 2\pi f_{\text{res}} = 1/\sqrt{LC}, \quad W = V^2C/2, \\ \text{shunt impedance, CIRCUIT definition}\; r = V^2/(2P) \\ \text{characteristic impedance}\;\; X = \omega_{\text{res}}L = 1/(\omega_{\text{res}}C) = \sqrt{L/C} = r/Q \end{array}$$

Please note that for historical reasons the LINAC definition of the shunt impedance R (R upper case!) is still widely used. There the cavity voltage is considered as an RMS quantity, hence the required power P for a given intrinsic cavity voltage V is $P = V^2/R$. In the preferred CIRCUIT definition of r (r lower case!) the cavity voltage is realistically taken as the peak value of a sinusoidal waveform, which then leads to $P = V^2/(2r)$. It follows that $R = 2 \times r$.

Many definitions of the shunt impedance are based on the effective cavity voltage V_{eff} seen by the beam. It is different from the intrinsic cavity voltage V because the RF field changes during the transit by time of a particle through the gap region. This is conveniently expressed by the transit time factor $TTF = V_{\text{eff}}/V, T \le 1$. It depends on the ratio effective gap length g to beam wavelength $\beta\lambda$ and is approximatively given by

$$TTF \approx \frac{\sin\left(\pi\frac{g}{\beta\lambda}\right)}{\left(\pi\frac{g}{\beta\lambda}\right)} \;.$$

There are three scaling laws that permit complete determination of the electric parameters if all cavity dimensions are changed (blown up) by some factor in all dimensions:

- cavity dimensions/λ_{res} = constant,
- characteristic impedance r/Q = constant,
- Q-factor $\times$ skin depth/λ_{res} = constant.

For a given cavity wall material, the skin depth is proportional to $\sqrt{\lambda}$, therefore the Q-factor increases according to the third scaling law by the same proportion. If a given geometry such as a pill-box cavity is scaled for higher frequencies or lower wavelengths, the shunt impedance $R = Q \times r/Q$

decreases in proportion to $1/\sqrt{f}$. This basic tendency is enhanced by additional loss mechanisms at high frequency, in particular surface roughness, which increases the geometrical path length of the RF currents on the surface. It appears therefore that higher frequencies would be counterproductive as far as single-cavity performance is concerned.

5 SCALING OF CAVITY PARAMETERS PER UNIT LENGTH

The picture changes if assemblies of cavities are considered. Suppose that a certain RF voltage requirement V is distributed over n cavities of the same type. Then the individual cavity voltage becomes V/n, the individual power dissipation becomes $(V/n)^2/2r$, and the total power becomes $n(V/n)^2/(2r) = V^2/(2nr)$, i.e the power needed is reduced by a factor of n with respect to a single-cavity configuration.

It therefore makes sense to see how many cavities can be stacked per unit length l, in order to evaluate the performance of a cavity assembly rather than a single cavity, in other words to normalize the cavity parameters by axial length.

Commonly used parameters used in this context are

- R': effective shunt impedance (LINAC definition) per unit length
  $R' = R \times TTF^2/l = G^2/P'$,
- TTF: transit time factor, $G = V \times TTF/l$: gradient (effective voltage per unit length)
  P': power per unit length
  r': characteristic impedance per unit length, $r' = R'/Q$.

Figure 2 gives the characteristics of a travelling-wave structure at 29 GHz.

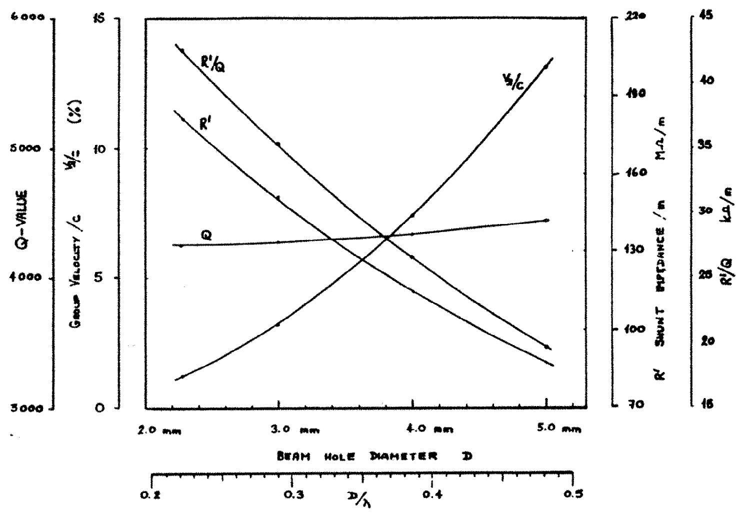

Fig. 2: R', R'/Q, Q, group velocity v_g/c as function of aperture. Reproduced from Ref. [1].

The curve for R' is approximately inversely proportional to the beam hole or aperture D normalized to the wavelength λ. This behaviour is confirmed by similar calculations at different wavelengths. It is therefore common practice to consider R' proportional to $1/(a\lambda)$ in general, or alternatively to take the quantity $R'a/\lambda$ as a figure of merit for comparisons.

A comparison of accelerating structures in different machines is given in Fig. 3.

It shows that $R'a/\lambda$ scales approximately as $\omega^{1/2}$. For cavity assemblies, the use of higher frequencies is therefore advantageous from the point of view of power consumption.

$$R' = r'Q \propto \omega^{1/2}(a/\lambda)^{-1}$$

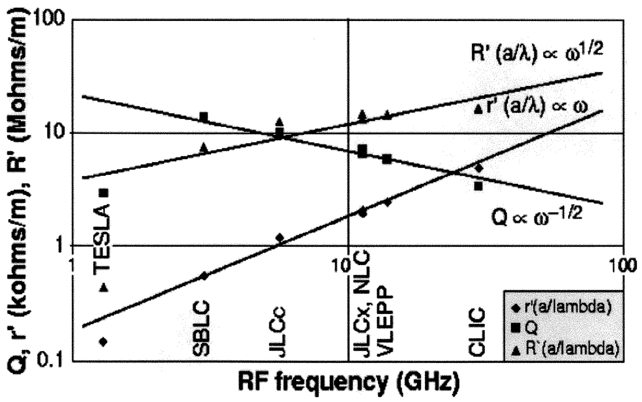

Fig. 3: Structure parameters of different machines vs frequency. Reproduced from J.-P. Delahaye et al., Ref. [2].

6 VOLTAGE HANDLING CAPABILITY

One of the most quoted figures of merit for the voltage handling capability of vacuum is the 'Kilpatrick criterion', published in *The Review of Scientific Instruments*, Vol 28, No. 10:

$$W \cdot E^2 \cdot e^{-\frac{1.75\cdot 10^5}{E}} = 1.8 \cdot 10^{14}$$

where W is the impact energy of an electron in [eV] and E is the local field strength in [V/m].

The physical mechanism behind this empirical formula consists of two parts: first the impact of an electron of kinetic energy W on the cavity surface, second the re-acceleration of the liberated secondary electrons by the local field strength E. For DC fields without local field enhancements, $W = E \cdot d$, where d is the distance between the electrodes. As the frequency increases, a transit time factor starts to act, resulting in $W < E \cdot d$; the same is true for local field enhancements.

To solve this implicit formula, the use of a numerical root finder is necessary. Under much simplified assumptions an often used approximation is

$$E \sim 25 \cdot f^{1/2} \ \ (E \text{ in MV/m},\ f \text{ in GHz})$$

The important fact is that *the voltage handling capabilty in vacuum increases at high frequencies*. This is the key argument for going to very high frequencies in proposals for linear accelerators/colliders at very high energies, where the necessary overall length of the accelerating structure for a given final energy becomes a determining cost factor.

The voltage handling capability is usually expressed as the net overall gradient in units of MV/m of a given configuration. It should be kept in mind that the internal cavity field strengths are higher by a factor of about two, partly due to a geometric factor (cavity length)/(gap length), partly due to local field enhancement on the edges of the gap.

The practical voltage limit is influenced by many factors such as vacuum condition, surface smoothness, surface deposits, and temperature. The Kilpatrick criterion is therefore considered more as a generally accepted figure of merit than a hard limit. It can be exceeded in practical designs by 'bravery factors' of about 1.5 (current in RFQ designs) or up to 2.5 (short pulses). It should also be mentioned that the Kilpatrick criterion is pessimistic at lower frequencies and corrections to the formula have been proposed.

One important factor is the RF pulse length. Experience shows that single-pulse voltage limits decrease with longer pulse duration. One possible mechanism for this effect is the heating of microscopic whiskers on the cavity surface that then act as thermal emitters, with time constants in the range of microseconds to milliseconds. On the other hand, the electric breakdown is statistical by nature and the ratio (pulse length)/(average time between sparks) determines the likelihood of a breakdown.

Increased voltage breakdown limits can only be exploited up to a certain point, then thermal effects become the limiting factor (see Fig. 4).

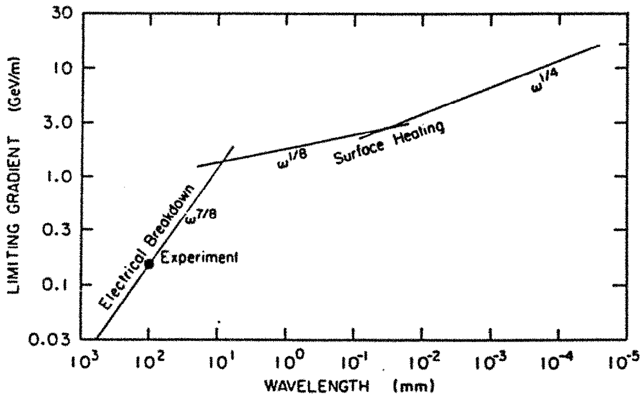

Fig. 4: Limitations on gradient as a function of wavelength due to electric field breakdown and surface heating in a SLAC-type disk-loaded structure. Reproduced from Ref. [3].

The average power density at the cavity surface increases with frequency due to the combined effects of reduced skin depth, reduced cavity dimensions and reduced shunt impedance. In addition, it is not sufficient to consider only the average power dissipation integrated over the pulse repetition time, but the thermal transient must also be taken into account. As the heat wave cannot be dissipated immediately from the outer layers to the inside of the walls, the surface attains dangerously high temperatures. Permanent damage such as roughening or cracking of the copper surface takes place above certain gradients.

7 WAKEFIELDS: ANOTHER LIMITING FACTOR TOWARDS HIGHER FREQUENCIES

Intense particle bunches create longitudinal and transverse wakefields, which dilute the time structure and/or may lead to transverse beam loss. For a given cavity geometry, the wakefield effects scale as ω^2, ω^3, or ω^4, depending on different simultaneous scaling of the beam parameters. Increasing the aperture reduces the transverse wakefield effect, as shown in Fig. 5.

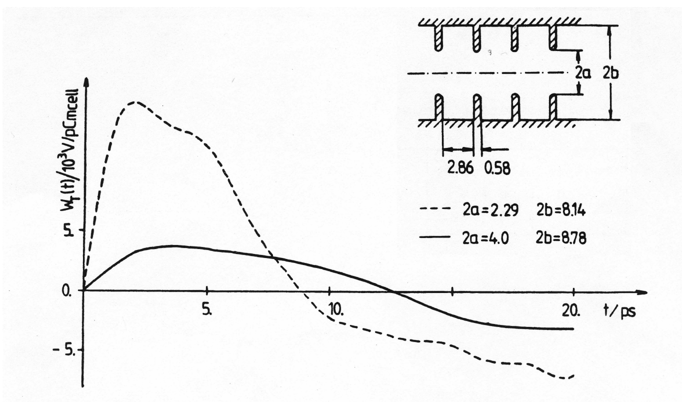

Fig. 5: Transverse wakefield for the structure given above. From Ref. [4]

Opening the aperture leads in turn to decreased shunt impedance and potentially other undesirable effects (increased group velocity, which in turn may lead to increased spark damage). The best overall compromise must take into account many contradictory requirements. This is the subject of very detailed ongoing studies in many laboratories, the details of which are beyond the scope of this article.

8 HARDWARE CONSIDERATIONS WITH LIMITED INFLUENCE ON THE CHOICE OF FREQUENCY

Under this heading there are two hardware-oriented issues, which demand different technical approaches, but which rarely play a determining role in the choice of frequency:

Superconductivity: Proof-of-principle SC cavities have been built to operate between about 80 MHz and 30 GHz, with plans to go to up to 80 GHz. Outside these rough limits, considerable R&D efforts may be necessary for new projects.

The superconducting material is mostly pure niobium, but niobium alloys and lead have also been used. The superconducting material may be either in bulk or applied in a thin sheet by sputtering or electrolysis. Simply stated, the dominant factor at high frequency is the achievement of low BCS resistance, which requires very low cryogenic temperatures. The dominant factor at low frequencies is the residual resistance of the SC conductor, which in turn requires special material properties (pure niobium is preferred). Another concern at low frequency is the large surface of the cavities, with associated difficulties with the rinsing, etc., which may lead to unusual cavity shapes.

Gradients of 44 MV/m have been attained at 1.3 GHz and the limit continues upward as more sophisticated methods of surface cleaning are developed and progress is made in materials science.

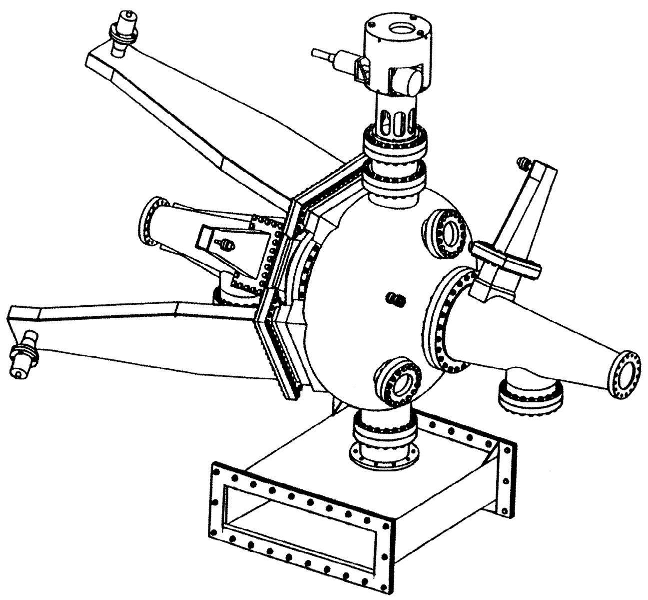

Fig. 6: Sketch of the DAΦNE RF cavity. From Ref. [5].

Higher-order-mode (HOM) damping: the operating frequency of a cavity is usually the fundamental mode at the lowest frequency, amongst a host of other unwanted resonances of higher order. To come close to the cavity designer's dream of a 'monochromatic' cavity, a either high-pass coupler, acting only on the HOMs, or a bandstop filter damping all frequencies except the fundamental, is necessary.

The technology to achieve this depends strongly on frequency, but solutions are known for all usual frequency ranges.

An example that fulfils an extreme requirement is shown in Fig. 6. The spectrum of ultrashort bunches in the DAΦNE and PEP machines extends to very high frequencies. Three waveguide couplers stretching out to the left in parallel to the beam line provide the necessary HOM damping and characterize the overall shape of the assembly.

9 RAPIDLY TUNABLE AND μ-LOADED CAVITIES

Certain applications require a rapid change of frequency. Examples include beam acceleration in rapidly cycling synchrotrons or longitudinal beam gymnastics with a change of orbit. Only a very limited range of a fixed-tuned cavity, the instantaneous (power) bandwidth, is directly usable for this purpose. Larger deviations require a dedicated fast tuning mechanism of some kind.

Slater's theorem relates the change in frequency ∂f to the corresponding change in cavity-stored energy ∂W for infinitesimally small changes:

$$\frac{\partial f}{f} = \frac{1}{2} \cdot \frac{\partial W}{W} \quad \text{or} \quad \Delta W \geq 2 \cdot W \cdot \frac{\Delta f}{f} \ .$$

This relation provides a first estimate of the total amount of stored cavity energy to be changed. For a frequency-agile cavity the overall stored energy W should therefore be kept as small as possible. The total necessary variation ΔW has a tendency to be much larger than the estimate from the above relation, since optimal power transfer from the generator to the cavity is difficult to achieve over the additional bandwidth.

The stored energy can be changed either capacitively or inductively. In practice, capacitive tuning can only be achieved by mechanical means since no static components are known to vary capacitance at high power. For inductive tuning, ferrites allow variation of their incremental permeability μ_{r} as a function a biasing magnetic field. However, their energy storage capability is rather limited, as shown in the following table

Material	Operating conditions	Stored energy/Volume [J/cm^3]
Vacuum	$E = 100$ kV/cm	440×10^{-6}
Ferrite	$B_{\mathrm{RF}} = 0.01$T, $\mu = 10$	4×10^{-6}

The active volume of an inductive tuner is therefore about two orders of magnitude larger than that of the capacitive counterpart.

9.1 Mechanically tuned cavities

Mechanically tuned cavities have the virtue of small size and low losses, but compromises between size and speed have to be made due to mechanical constraints. Therefore they are best suited to high frequency–slow speed applications. The concept of mechanically tuned resonators has gained a rather bad reputation, following negative experience with large rotatable capacitors. However, recent motion-control technology could bring a change.

9.2 Ferrite-tuned cavities

Ferrite-tuned cavities dominate the field of fast cycling machines. Ferrite cores, mostly of the nickel–zinc variety, can be arranged as integrating part of a cavity or as separate tuners. In either case provisions to apply the bias magnetic field have to be made using bias windings or external electromagnets with an iron core. The biasing magnetic field is oriented in parallel to the RF field. Tuning speed limits occur because of intrinsic ferrite effects flipping the microscopic magnetic domains, but also because of power supply limitations and eddy current effects in the tuner walls.

The product $\mu Q f$ is a figure of merit for ferrites. It attains 200×10^9 for low induction, but generally drops for practical RF amplitudes because of eddy currents. Therefore the core losses increase much faster than U_{RF}^2. The frequency swing obtainable in practice is determined by the obtainable μ-range, in other words the highest (unbiased) μ, since the lowest obtainable relative permeability for infinitely strong bias is 1.

The highest practical RF induction in a ferrite core is around 0.01 T or 100 G. Excessive losses, non-linear effects, instabilities, and thermal runaway may start above this approximative limit. This limit is responsible for the modest capability to store/shift energy. It also sets a practical limit for the lowest operating frequency at reasonable dimensions, since for a given geometry and induction limit the applicable RF voltage is directly proportional to the frequency. Since ferrite material is brittle, care must be taken in the design of the cooling system to avoid thermal gradients that typically lead to radial cracks in ferrite rings.

Within the constraints sketched above, ferrites are available for the use in frequency range of a few hundred kilohertz to a few hundred megahertz. The demand for ferrites for switched-mode power supplies at ever increasing frequencies has led to improved ferrites up to the MHz range with slightly higher saturation limits.

9.3 Orthogonally (transversely) biased ferrite tuners

Special ferrite compositions, in particular garnets originally intended for microwave applications, rely on a different mechanism to change permeability, namely on precession effects. These ferrites are characterized by very low losses at low permeability, but require very strong biasing fields oriented orthogonally to the RF field. These ferrites are an attractive alternative for applications above about 50 MHz.

9.4 Glaseous metal cores (FINEMET™, VITROVAC™)

In recent years a new type of material, consisting of amorphous and galseous metals, has found increased applications. It is obtained by special thermal treatment of the basic high-μ metal to suppress the crystalline structure. Thin metal bands are then wound together with insulating layers to form rings of appreciable diameters (50 cm and more). The result is a core with very high permeability that can be used up to 5–10 MHz, with saturation limit in the kilogauss range, however with much higher losses than ferrite cores.

Two big advantages can be gained in accelerating cavities with this material.

- The obtainable cavity gradient is more than one order of magnitude higher than in ferrite cavities, i.e. several hundred kV/m compared to about 10–20 kV/m, depending on frequency. This is a decisive feature for applications where the space in the accelerator is limited. Also fixed-tuned cavities for constant low frequency can be built to deliver high RF voltage with reasonably small dimensions.
- The cavity bandwidth is inherently very large. In addition the required tuning bias field is much smaller than with ferrite cavities. The tuning system for frequency-agile cavities is therefore drastically simplified. Due to the very large instantaneous bandwidth, the implementation of multi-harmonic accelerating waveforms instead of pure sinusoids is possible with a single cavity. This is an important factor for more sophisticated applications such as beam gymnastics using barrier buckets. Last, but not least, the low cavity shunt impedance reduces the risk of instabilities due to beam–cavity interaction.

The price to pay is the much higher RF power requirement. Compared to ferrites, the rings have better thermal conductivity combined with higher possible operating temperatures and reduced susceptability to thermal gradients. The increased injected power is therefore more easily dissipated by a cooling system.

10 MISCELLANEOUS TECHNOLOGICAL CONSIDERATIONS

10.1 Availability of RF amplifier equipment

There are mainly three overlapping frequency ranges that determine the choice of RF power equipment for the main line of accelerator applications.

Figure 7 resumes the situation. The figure dates from the 1970s, but it still reflects the basic physical limitations.

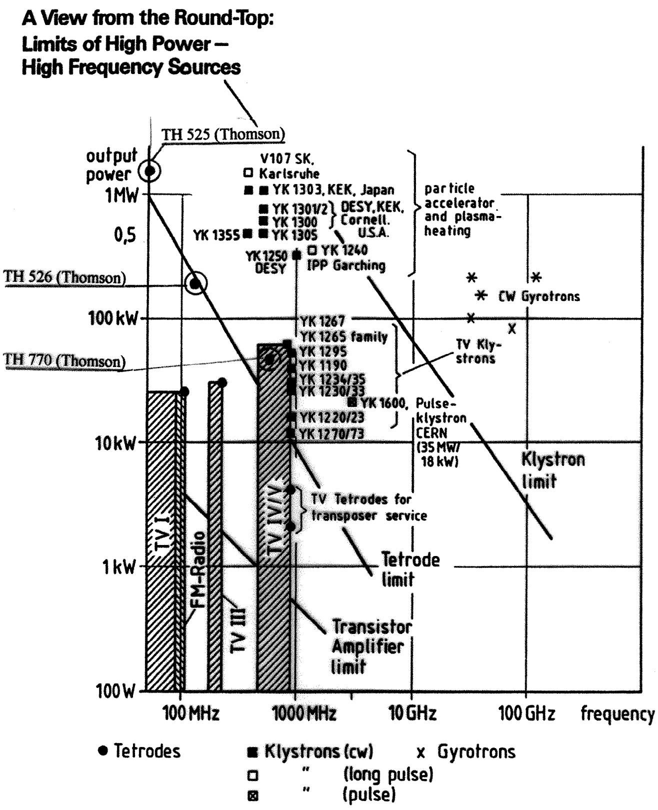

Fig. 7: Approximate limits of different RF amplifiers. From Ref.[6].

10.1.1 Up to ∼300 MHz: Electron tube technology

This is the oldest technology, used almost exclusively for communications, TV etc. until the 1950s. The amplification mechanism is based on the ideally powerless *density* modulation of an electron beam through a control grid. The RF structure thus obtained converts DC power to useful RF power. Continuous power outputs up to about 1 MW, or peak powers of about 5 MW can be obtained from single tubes.

At high frequencies, transit time effects appear that necessitate a reduction in the dimensions, which in turn leads to a reduction in power handling capabilities. In addition, the control of the electron beam density can no longer be achieved without power losses. Parasitic capacitive coupling reduces stability margins, forcing the use of such tubes in grounded grid configurations which additionally reduce the obtainable gain.

Practical amplifications are 10–20 dB per stage, with DC /AC efficiencies at 40–80%.

A large fraction of tube manufacturers has gone out of business in the last ten years, including the firm that originally created Fig. 7. This is a sign of the outmoded technology and a general trend in telecommunications towards higher frequencies.

10.1.2 ∼300 MHz to ∼10 GHz: Klystrons

Klystrons are the preferred power sources above about 300 MHz due to their large amplification and high power capabilities. Contrary to ‘gridded’ electron tubes, the electron beam is initially modulated in *velocity* (rather than density) by an RF cavity. The density structure ultimately required builds up after a well-defined drift length, where the faster electrons meet and overtake the slower ones. Passive RF cavities are situated at these spots to reinforce the velocity/density modulation. Each intermediate passive cavity adds about 10 dB of gain. An output cavity finally collects the resulting RF component. The required drift distances depend on the beam wavelength $\beta\lambda$, where β represents the relative velocity of the electron beam and λ the free-space RF wavelength. β is limited by the applicable beam accelerating voltage (300–400 kV), hence the required klystron length is almost directly proportional to the RF wavelength and the required gain. This sets a low-frequency limit for these devices.

The gain is usually 40–60 dB, the efficiency 40–65 %. The output power attains several megawatt CW and tens of megawatts for short pulses. The output cavity and output ceramic window are the main power limiting factors.

10.1.3 Above ∼10 GHz : Gyrotrons, two-beam accelerators

The Gyrotron principle is based on a tubular and gyrating electron beam. This allows for the use of higher-order azimuthal modes in the output cavity to circumvent the limitations of the fundamental-mode cavities used in klystrons. Gyrotrons are mainly used for plasma heating applications, e.g ECR particle sources.

In the context of TeV linear accelerators the principle of a two-beam accelerator was proposed for the Compact LInear Collider (CLIC) working at 30 GHz that is presently under study at CERN. The low-intensity, high-energy electron beam used for physics is driven by a high-intensity, low-energy proton beam running along the main structure in a separate beam pipe. Dedicated transfer structures extract the 30 GHz component from the tightly bunched drive beam and feed it to the accelerating structures. This concept minimizes the number of active elements in in the tunnel. Ingenious schemes are used for the compression and the time-wise distribution of the drive beam (see Ref. [7]).

10.1.4 Semiconductors for all frequencies

The rapid progress in semiconductor technology that started with the transistor has led to a large family of devices that cover practically all frequencies from DC to the optical range. RF semiconductors, which are inherently low-power devices due to their small dimensions, have nevertheless made large inroads in the medium-and high-power range due to power-combining techniques. A single amplifier or generator may be composed of dozens or hundreds of individual modules that may in turn consist of many basic cells.

In view of the continuing progress in this field, it is impossible to state precise limits. The present state of the art is represented by a multi-kilowatt pulsed amplifier at X-band (10 GHz).

10.1.5 Two exotic active elements for the microwave range

There are active elements in widespread use in general microwave applications, but they are seldom found in the accelerator world. Examples are the magnetron and the TWT. The former is mass produced for microwave ovens and similar appliances, extremely cheap and powerful, but lacking the necessary linearity and phase stability. The latter is a wideband device but this main advantage is of little importance for high-energy accelerators where high Q structures of moderate passband are normally used.

10.1.6 An emerging technology: Laser acceleration

Beam acceleration by femtosecond laser beams of extremely high instantaneous power has been achieved in recent years. Ultrahigh gradients over fractions of a millimetre have been demonstrated and "acceleration gradients a million times larger" compared to classical means seem possible [8].

10.2 Radio-frequency interference (RFI), electromagnetic compatibility (EMC)

The reduction of spurious emission from RF equipment was of minor concern in the past, since most RF amplifiers on the market were intended to operate close to the transmitting antennas designed to radiate the available power with maximum efficiency into the environment. Transmitter halls in accelerators were known as electrically noisy places, where low-power equipment had to be adequately protected. In other words, emphasis was put on reduction of equipment susceptability rather than reduction of emitted fields. This situation has gradually evolved, and the meeting of applicable international regulations limiting the maximally admissible field strength has become a serious issue.

Accelerators fall into the IMS (Industrial Medical Scientific) category. Inside closed areas the interference level may be very high, up to the (medical hazard) limit of 1V/m or 120 dbμV, provided that mutual agreement between transmitter and receiver can be achieved and the limiting values outside the closed area are met.

Emission to the outside world is regulated according to frequency bands and geographic location. There are industrial frequency bands where higher than normal emissions are tolerated. Inversely there are protected bands where special lower limits apply, e.g the different air traffic NAV bands (in particular 140–160 MHz), the hydrogen window at 1542 MHz or GPS in the same L-band. However, the ever changing technology, in particular the communications revolution, leads to varying regulations. As examples the 2.4 GHz band, formerly reserved for microwave ovens, is now widely used for Bluetooth and WiFi. The 27 MHz band, formerly reserved for wireless home telephones, is now reserved for industrial remote control.

As a general recommendation, the applicable RF interference regulations and possible local restrictions (e.g. in sensitive experimental areas) should be carefully identified and followed to avoid retrofitting of already installed equipment.

10.3 Dimensional constraints

While RF structures can be scaled over a wide frequency range, there are nevertheless soft limits on either side of the spectrum that determine the practical feasibility of a design.

10.3.1 Towards low frequencies

Towards low frequencies, the sheer size of the usual resonating structures becomes a limiting factor. Beam lines in accelerators usually run at heights of 1–1.5 m, and this is at the same time the maximum practical radius for a cavity. A pure pill-box type cavity of this radius resonates at 120.80 MHz. For any lower frequency some capacitive or inductive loading becomes necessary. *Inductive* loading can be achieved by the introduction of high-μ material (ferrites of amorphous metal, see above), whereas dimensional loading (coil) is excluded due to the necessity of transmitting the resonator voltage to the beam. *Capacitive* loading can be implemented by inclusion of materials of high dielectric constants such as ceramics, but these materials risk being destroyed by a single voltage breakdown. The usual way is to provide dimensional loading in the form of integrated capacitors, ranging from nose cones to large plates (see Fig. 8 for an extreme example).

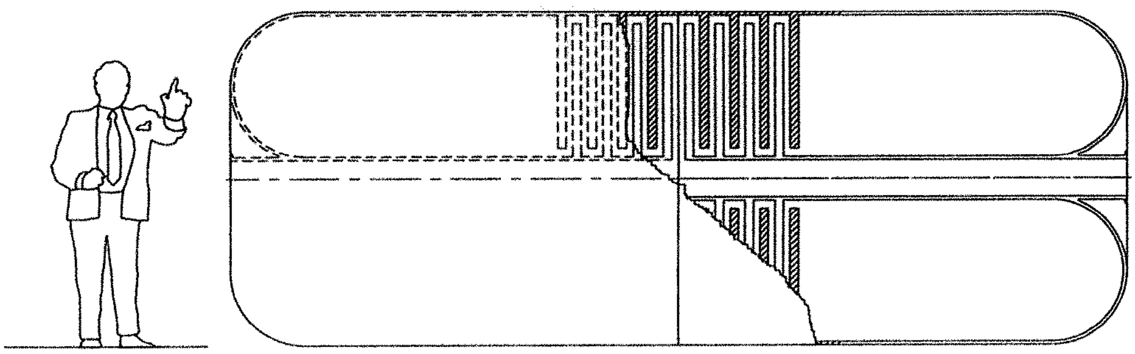

Fig. 8: Capacitively loaded high-power cavity for 500 kV gap voltage. From Ref. [9]

10.3.2 Towards high frequencies

Towards high frequencies, several phenomena come into play:

- Mechanical tolerance: structural tolerances become generally more critical for smaller dimensions of RF resonators at very high frequencies. In particular, careful alignment of the whole structure with reference to a nominal beam axis is mandatory to avoid the excitation of transverse deflecting modes. The "kick factor" $k_{1,}$ which characterizes this potentially lethal effect, scales as f^3 for a given ratio of aperture a to wavelength λ. Even if its impact is counteracted by larger aperture and other means, the required prealignment tolerances decrease with frequency. Figure 9 gives an idea of the tolerances required by different machines.
- Required surface finish: the well-known skin effect limits the penetration depth of RF fields into matter. At 10 GHz the skin depth in copper is $\sim 0.65\ \mu$m, i.e. of the order of optical wavelengths, and this scales as $f^{-1/2}$. If the surface roughness is of the same order as the skin depth, the effective path length for RF currents along the surface is increased and so are the losses. Mirror-like surface finish is therefore required for cavities working above the cm-wavelength range.
- Pumping performance: the molecular conductance C_{mp} per unit length of vacuum ducts of diameter d scales as

  $$C_{\mathrm{mp}} \propto d^3 \quad .$$

  Providing adequate vacuum quality becomes increasingly difficult with the smaller beam pipe diameters at very high frequencies.

11 MACHINE ENVIRONMENT: IMPACT OF PHYSICS REQUIREMENTS, NUMEROLOGY AND BUNCH TRANSFER SCHEMES

The determining factors for the choice of an RF frequency stem from the requirements of the physics experiments, together with the characteristics of existing machines in an accelerator chain that must be preserved.

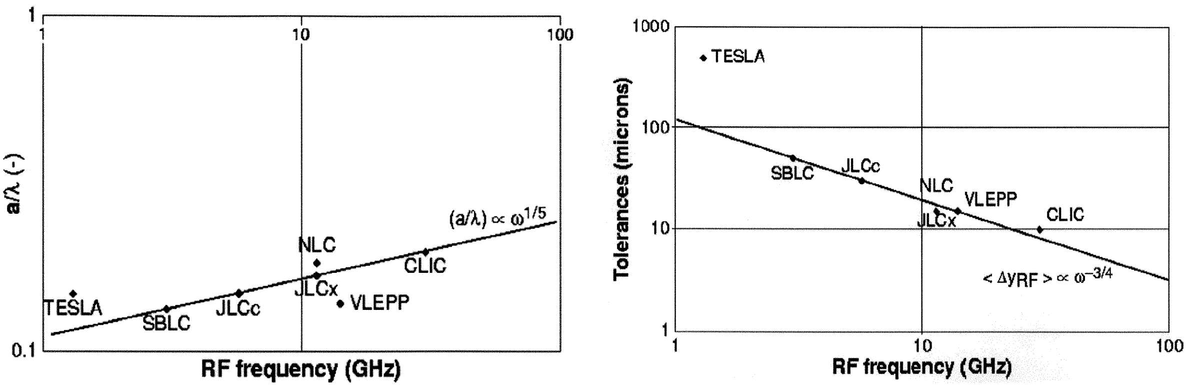

Fig. 9: Aperture and alignment tolerances in different machines

The influence of these parameters is best illustrated by the improvement programme of the PS and SPS synchrotrons at CERN for the LHC project [10]. The range of possible bunch spacings is primarily determined by luminosity requirements. This favours the concentration of the total number of available particles in a small number of bunches, leading to large bunch spacing. The characteristics of the particle detectors have also to be considered; their maximum data rate and dead time lead to another set of constraints. Within the basic acceptable range, a multiple of 5 ns must be taken to preserve the 200 MHz system of the SPS (5 ns bunch spacing). The value of $5 \times 5 = 25$ ns has finally been chosen.

Where to create the 40-MHz bunches that correspond to the 25 ns bunch spacing? In this case, it was decided to include 40 MHz and 80 MHz systems in the PS. The numerology, i.e. the ratio of the respective diameters of the three machines involved, allowed the approach of batch transfer of a number of bunches of the right spacing from in a single shot. The injection/ejection kicker rise times in the different machines determine the kicker gaps, i.e. the number of lost or missing bunches. In addition, the position of these missing bunches in the resulting bunch train has to obey certain criteria to avoid instabilities due to transient beam loading (Pacman effect). Under less favorable conditions, single bunch transfer may become necessary.

The luminosity requirements of the LHC demand a higher intensity than the four booster rings can provide in a single cycle. The PS can accept a total of eight high-intensity booster bunches (albeit at higher injection energy) and the most attractive solution was a two-batch filling scheme, whereby each batch of four bunches occupies one-half of the PS circumference. This scheme requires operating the Booster synchrotron at harmonic number $h = 1$ rather than at $h = 5$. Consequently the basic RF system was redesigned to work at one-fifth of the previous frequency.

12 CONCLUSION

Considerations of beam dynamics and accelerator physics are the key factors for the choice of RF frequency in accelerators. Questions arising from RF technology are secondary considerations. As a soft general statement it can be said that innovations in RF technology and the quest for higher beam energy push towards higher frequencies, whereas beam dynamics considerations tend to favour lower frequencies.

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