CRITICAL FEATURES OF RF SYSTEMS FOR LARGE CYCLOTRONS

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Summary

A brief review of RF systems for large cyclotrons is presented. Critical features of large resonators including theoritical studies, parasitic modes, mechanical and technological problems, vacuum and regulation systems are presented.

1. Introduction

Large RF systems have been built early in the history of cyclotrons especially with FM cyclotrons which could accelerate particules to large radii. Critical features of these systems were : possible parasitic oscillations, parasitic modes on the dee structure, sparking problems, multipactoring phenomena, mechanical vibration, movable fingers, with large RF current density, phase and voltage stability[1] ...!

Nothing has really changed in the critical features of isochronous or separated sector cyclotrons RF systems ...! Except that the voltage now required is greater, radially increasing to produce beam phase compression, voltage stability must be in the range of 10^{-5} and phase stability less than 0.1°!

With accelerated beams of 1mA to 2mA at 500 MeV new problems for the RF engineers are coming!

We must point out that the difficulties are quite different between fixed and variable frequency cyclotrons. Of course, these new specifications are possible by the simultaneous development of our knowledge and by the progress of computing techniques, electronical and mechanical components, pumping systems, manufacturing techniques and control ...

2. Review of Accelerating resonators

2.1. Compact isochronous cyclotrons

Due to the small magnetic gap aperture the frequency change can only be achieved by a volume variation of the "inductive" part of the resonator (Berkeley, Harwell, Grenoble, Dubna, Oakridge, Orsay . ...).

Various techniques have been used : movable shorts, movable panels, rotation panels ... depending on the frequency range (≃ 3 : 1) and mainly on the minimum frequency which determines the resonator volume. This volume can be reduced by using a high ratio of the external conductor to the internal conductor but the maximum current density in the shorting contacts has to be taken into account.

It's also very difficult to obtain an increasing radial voltage distribution (or at least flat) and various dee-to-line connections have been studied.

The maximum voltage which can be obtained is limited by the small electrical gaps and by the large surface with a high electric field.

2.2. Separated Sectors Cyclotrons

Resonators are normally in a "field-free" region, so various types of resonator and volume can be adapted to the new specifications which are :

- large voltage (> 1 MV/turn)
- accelerating voltage increasing with a positive gradient from the center to the extraction radius, to give a high beam pulse compression.

This point means that the inductive part of the resonator must be connected between the minimum and the maximum radius. With high frequency it's no longer possible to use only an inductive part placed on one side if we want to avoid a vertical electric field between the top and bottom parts on the dee. The necessity for a symmetrical inductance (λ/2) type increases again the resonator volume.
For variable energy machines (INDIANA, GANIL ...) the same problems as for compact cyclotrons exist. With fixed frequency machines (SIN) others types of resonators can be used on TM101 or TE101 modes. This is true also for flat-topping cavities which work at 3 times the cyclotron frequency.

3. Resonators computations and models

Before theoritical calculations it's necessary to study the whole parameters and think to possible solutions including :

- space and volume really usable
- for a fixed or variable frequency system : types of resonators which can be used for a given ratio of Vinj/Vext and techniques to change the frequency
- tolerances needed for the dee position and mechanical stability under vacuum of variable components,
- static and dynamic forces (flexion, water pressure, electromagnetic forces, thermal expansion ...)
- maximum current density in sliding contacts,
- possible parasitic modes, RF power, sensitivity to frequency shift, etc ...

One can have sometimes very special considerations such a superimposed mode (flat-topping).

3.1. Line equation

Line equation calculations are well adapted to low frequency resonators with complex shape[2]. Current distribution must be evaluated to determine the characteristic impedance of each section. With some experience the calculation of Q, Fr, Zs, V(n), I(n), Pj, can be done with a precision of a few percent. For high frequency this method becomes very inacurate or impracticable.

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3.2. Computer codes CAV2D - CAV3D

They are derived from revolution cavities codes : SUPERFISH, MESSYMESH and now can be used for three dimensional cavity or arbitrary shape[3]. Problems with 20000 points have already been calculated, with a precision of a few percent on the main parameters. These resonator computations, even if they don't give an absolute precision, are very useful to study the relative effects of parameters and parasitic modes.

3.3. Models measurements

If we need to increase the precision on current and voltage distributions, resonant frequency .. models measurements are necessary. The most difficult measurement is probably the voltage distribution for long accelerating gaps. New methods developped at SIN[4] and GSI[5] are quite fast and precise in comparaison to all others.
But still, there are some errors due to the field penetration and the real equivalent lenght of the resonator. Fig1. shows that the maximum voltage in a large dee aperture resonator could be far inside the dee gap. Measurements on the tip does not give a real idea of the voltage gain by the beam, especially if at some place (near extraction or injection radii) the dee aperture is smaller or closed. If a capacity divider is used in the tip region, the measured value will be different from the total beam voltage gain.

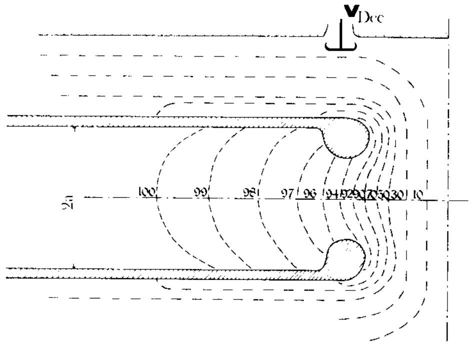

Fig.1 : Voltage in the tip region.

With such dee we will have other effects : a travelling probe going near the tip region will produce a resonant frequency shift and could be destroyed by large RF currents.

4. Parasitic modes

Two types of what we call parasitic modes can be observed : those which pertube the voltage distribution and stability (crossing modes) ; the others which create electromagnetic fields on special components ; beam probes, cryogenic panels, etc ... In the first group we have two subtypes modes : some are excited by an harmonic of the RF power generator, the others are excited by the beam itself.
Generally parasitic modes have a higher Q than the fundamental mode (Fig2. a,b).
For a fixed frequency cyclotron precise filters or resistive load can be used to reduce the level of the parasitic voltage without effects on the fundamental mode.
With FM or variable frequency cyclotron this is more difficult[6].

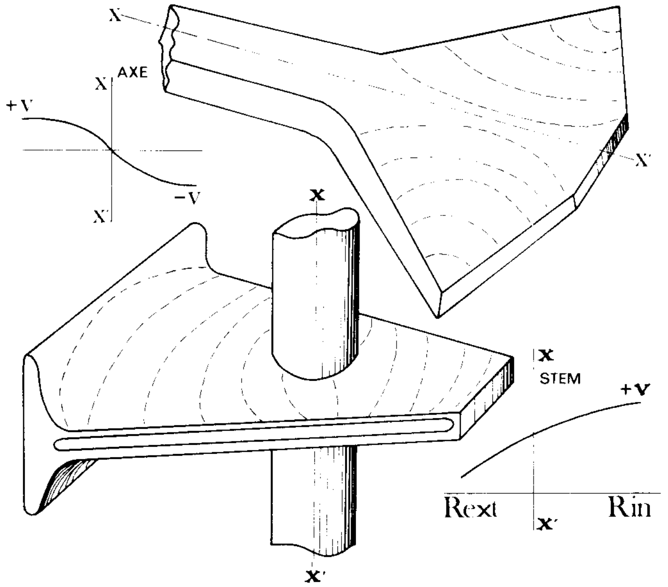

Fig.2 a,b : Crossing modes in "D" and "delta" shape electrodes.

At GANIL, for example, we have exactly Fp = 3Fo at 9.2 MHz (Fig3.).
Consequently, the input RF level of 3rd harmonic coming from the transmitter through the coupling loop must be lower than 65 db ($\Delta V/V \simeq 10^{-4}$). So the 3rd harmonic components must be well filtered in the plate circuit of the amplifier and we have to use the class A - B for the final stage which reduces the amplifier efficiency.

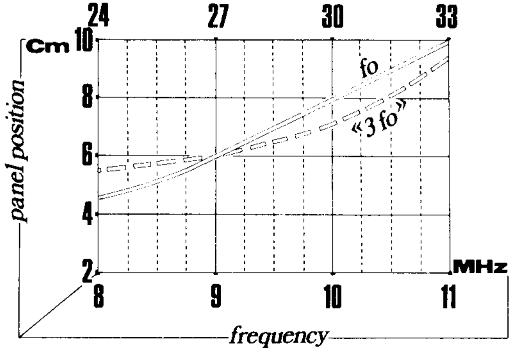

Fig.3 : Crossing mode on the GANIL's resonator.

On the TRIUMF RF system they want to use the parasitic mode $3\lambda/2$ to produce the flat-topping-voltage, feeded by a separated 3fo transmitter. Resonator tuning systems are of course more complicated because they must act independantly on each frequency.
Fig4. shows a parasitic mode on the second group : TM modes exist inside the electrode beam gap and in the vacuum chamber[8].
They are close to the working frequency and produce at some place enough electric field and current to pertube the beam or the heat the dee structure.

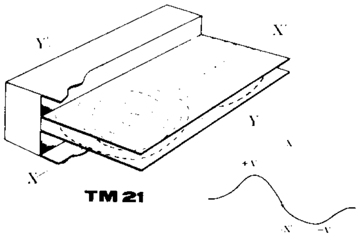

Fig.4 : TM 2.1 mode on the TRIUMF's resonator.

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5. Sparking problems

To determine the maximum electric field which can be applied on a RF electrode, everybody use the well-known Kilpatrick criterion :

$$f = 1.6.E^2 10^4.e^{-0.85/E}$$

where E is the maximum electric field on the electrode. During the last years[9] and especially for the RFQ resonators[10], a lot of new experiments have been done, using new pumping systems, cleaning processes ...

A great dispersion in the results shows that the criterion does not take into account all the parameters. The criterion itself must be (may be) redefined : for a linear accelerator with a very low duty cycle a spark per hour or less is not very important. For a cyclotron working in CW mode, with difficulties to go through the multipactor, a spark per hour means a lot lost beam time.

Fig5. shows the frequencies which have been tested at GANIL and corresponding dee voltage for a reasonable sparking rate. This is compared to the predicted Kilpatrick limit including mechanical tolerances. It means that for large surface, working in CW mode results are in good agrement with this criterion.

It has been shown that vacuum quality, cleaning process, low duty factor, no magnetic field can increase the maximum predicted electric field.

Surface oxydation, physisorbtion in the surface are very important in RF cavities at high electric field.

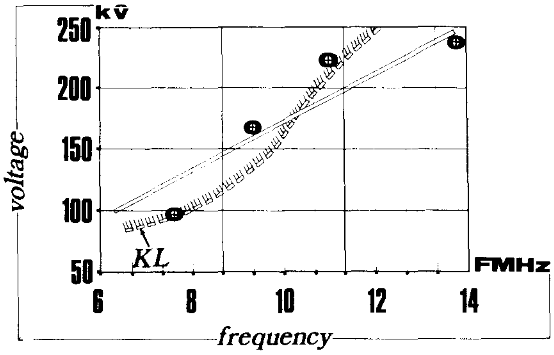

Fig.5 : Theoretical voltage at extraction radius (solid lines), Kilpatrick limit (dashed lines) and experimental values (circles).

6. Multipactor

Sparking problems and multipactor phenomena include the same parameters : preparation of electrode surfaces, work function of the material, secondary electron emission, outgasing rate ...

Now, with modern RF amplifiers, multipactor is not so serious that it was with self-oscillators. Nevertheless it seems that problems are more serious for aluminium cavity that for copper cavity and it's necessary to put some layer of carbon to suppress partially the second emission.

Other experiences[11] with aluminium cavities have shown that after few days at atmospheric pressure, it was not possible to run the cavity in CW mode : after a complete new cleaning process, using abrasive mineral powder, acid and de-ionised water and closing the cavity with wet surface, operation in CW was again possible. This phenomena has been observed also with copper when silicon oil diffusion pump was used : a thin layer of insulating material increases the secondary emission effect (MALTER effect).

7. Mechanical and technological problems

7.1. Mechanical calculations

The three-dimensional calculations using the finite elements method and including thermal field action and electromagnetic forces give a complete idea of the structure movement. Different vibrations modes can also be studied and particulary in regions where the sensitivity $\Delta f/\Delta d$ is important. Others parameters must be taken into account if a great precision positioning is needed : effect of unsymmetrical forces of the short-circuits contacts, movement of the structure support under vacuum ... etc. It is sometimes necessary to use an external mechanism which can correct (under vacuum) the electrode position.

When the frequency changes versus the displacement of the variable element (short-circuit, panels, ...) is greater than 0,5 MHz/cm it becomes very difficult to realize, even with modern techniques a sufficiently precise mechanism to have a given frequency : an important fine tuning system is then necessary.

If we want to keep the effects of external forces (electromagnetic, water vibrations ...) as low as possible on the phase movement, it's important to have the maximum structure stiffness. For cavities (SIN ..) it's not too difficult but for large structure (GANIL, TRIUMF) the stiffness of the dee structure might be as high as possible to keep the phase pertubations in the range of few degrees.

7.2. Materials

Interacting parameters in the choice of materials for large resonators are numerous : RF resistivity, outgasing rate, amagnetism, short "cooling" time after an irradiation, good mechanical and thermal properties, low secondary emission factor ...

Except for mechanical properties copper fits most of these parameters, but need to be supported by a rigid structure generally made of stainless steel.

Explosive method can be used to put a sheet of a few millimeters of copper on a thicker support (Aluminium or Stainless steel).

About the cooling time after an irradiation[12], Fig6. shows that after a long exposure time there is no real difference between Al, Cu or Fe. Using the spot or the electron bombardment welding technique no change can be observed in the stainless steel magnetic permeability which is about 1.003. With a TIG welding, procedures must be well defined and controled to keep the value below 1.01.

The cleaning process of various materials have been extensively studies at GANIL[13] and outgasing results are presented on the Fig7.

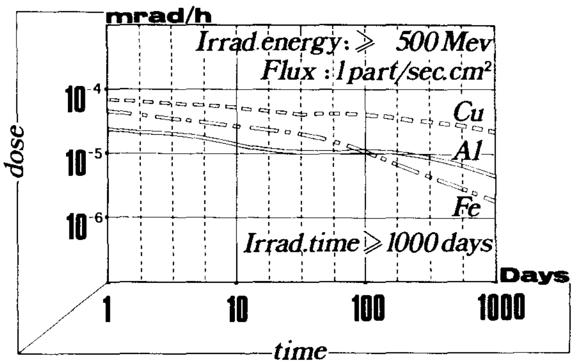

Fig.6 : Cooling time after a long irradiation for Cu, Al, Fe.

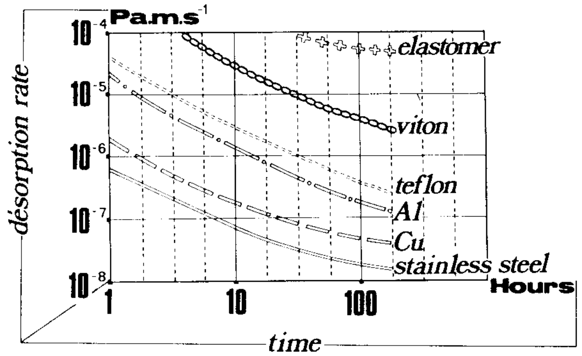

Fig.7 : Desorption rate of various materials.

This figure shows that between stainless Steel and Aluminium there is a factor 8 in the outgasing rate. Procedures to return to the air-pressure have also been studied[14]. We have observed a better outgasing on a stainless-steel chamber when dry air is used to fill up the tank, at least to 100 Torr (Fig8.) This proves that the forces to extract a molecule of water from a layer of gas molecules are less important than for a molecule of water on stainless-steel.

For other materials(Al, Cu, ...) it could be interesting to study the best gas to be used.

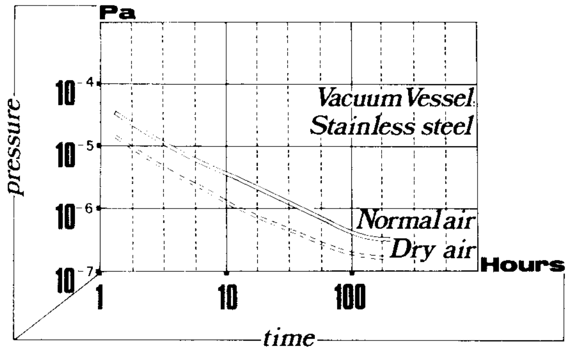

Fig.8 : Reduction on the pumping time using dry-air fill-up.

7.3. Contacts for movable shorts

If the sliding tuner is not operating continiously under power, high density current can be used probably more than 80 to 100 A/cm at 30 MHz. The mechanisms of these systems are complex and need an extra fine tuning system, so that temperature transient can be followed for a fixed frequency drive (or by the use of a self excited mode). With sliding contacts operating under RF power, studies have shown that the maximum current density is inversely proportional to the root square of the mechanical tolerances which can be accepted by the contact.

On a very clean copper surface friction problems under vacuum can also occur and generally a mixture of Ag (98%) and C (2%) is used. Fig9. shows the current density which have been tested at GANIL and the expected current at 60 MHz for a new type of sliding contacts.

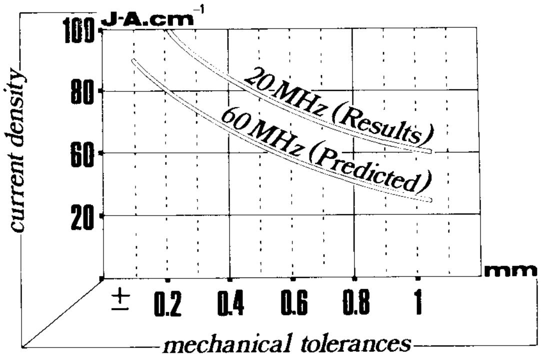

Fig.9 : Sliding contacts density vs mechanical tolerances, and frequency.

7.4. Water cooling system

In our system it's generally impossible to fixe the Reynolds number to have a non turbulent flow. Nevertheless it's important to keep the flow speed below 1m/s and to pay attention to pump vibrations. Geometrical RF structure must also be unsensitive to water pressure variation.

To keep the corrosion effect to a minimum it seems that the use of highly demineralized water (1 to 0.2 $\mu S.cm^{-1}$) with 20% of the total flow recycled over a mixed resin bed gives good results[15]. Under these conditions it is possible to have combinaison of Cu and Al circuits but with absolutely no galvanic contact between the two metals.

7.5. Fine tuning

With the use hydraulically driven dee tuning system, which combines the advantages of a high resolution (< 0,01mm), high speed (> 40mm/s), no blacklash, few and reliable electronical and mechanical components, additional trimmers are not necessary[16].

8. Regulation systems

8.1. Voltage stability

Critical features of the voltage regulator loop are : dividers stability, and when flattop RF systems or pull-push resonators are used, determination of the equivalent voltage which has to be regulated : the flattop voltage must follow the sum of the main resonator voltage, or this sum must be constant.

Capacitive dividers are more sensitive to mechanical movement (vibration, initial position ...) and thermal stability of componants. Due to their location, voltage pick-ups can be subject to spark or multipacting.

If the voltage distribution along the dee gaps is theoritically known the absolute calibration of the RF voltage can be obtain with an X-ray of about detector (GeLi) with a resolution 1 keV.

8.2. Phase regulations

Requirements for phase stability are generally in the range of 0.1° or less. Quality and long term stability of components are important. Digital phase detectors with thermal stabilization can reach a long term stability of 0.01° (or less)[17], with a constant sensitivity (≃ 50mV/°) over a variable frequency phase range, and eventually pulse frequencies. Connectors and cables must be first quality : with 100 meters and Δt of 20°C the phase shift can reach 0.1° with normal cable.

Phase stability of the beam, espacially with the use of high harmonic numbers is also strongly dependant on the magnetic stability :

$$\Delta\varphi \simeq 2\pi . h . N . \Delta B/B$$

with $h = 7$, $N = 100$, a variation of $\Delta B = 10^{-5}$ gives a phase beam variation of 2° !

So new feed-back loops using a beam phase detector and acting on the trim coils (SIN) or on the main magnet (GANIL) can give a good beam phase stability which is important when a cascade of cyclotrons is used.

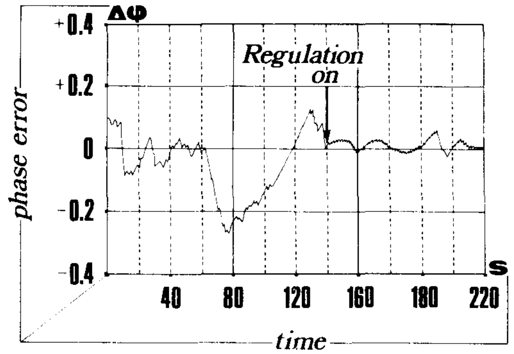

Fig.10 : Beam phase stability at SIN, with magnet regulation.

9. Conclusions

Progress of computing techniques in RF resonator calculations of arbitrary shape are extremely helpfull, but real problems are still in the mechanical and technological fields if guaranty of precise positioning, high voltage and high quality regulation systems are needed. Of course the cost of RF system including specific materials, various controles, cleaning process, modern welding techniques ... must be now an important components of the specifications !

As mentionned before [18] "A key factor for obtaining high beam intensity is the RF system" and experiments have to be carried out to solve the beam loading effects.

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