Abstract
The following chapter is an extension and complement of the chapter titled: 'CYCLOTRON CAVITIES', written by C. Pagani (University of Milano and INFN, Milano, I). It will deal with cavity concepts deviating from conventional cyclotron cavities (Dees) treated in the previous lecture, which are mostly based on a $\lambda/4$ or $\lambda/2$ coaxial resonator design. Cavities differing from that design usually can only be employed in separated sector cyclotrons (SSC or SOC), because such designs provide more space for the RF cavities.

1. INTRODUCTION
As has been noted by C. Pagani’s in his paper on cyclotron cavities [1], cyclotrons have been around for quite a while and have evolved into numerous different types - for a large variety of applications. Cyclotrons started out as purely experimental machines, used in nuclear- and atomic physics, later in applied physics, but by now, also include such exotic 'species' as high energy heavy ion accelerators for research (radioactive beams), high power proton cyclotrons (HPPA’), used for neutron spallation sources and, in the future, possibly for applications like accelerator driven nuclear systems (ADS) for transmutation [2] or in energy amplifiers [3]. With respect to high power accelerators, it should be pointed out that one of the operational accelerators with the highest beam power output in the world - about 1MW - happens to be a cyclotron [4]. About 80 of these individually designed machines are in operation at the present time. Some other types of cyclotrons, designed especially for medical applications, (like radio-isotope production, as well as particle beam radiotherapy), are available as commercial units, and have reached a very high level of reliability, expressed in availability rates in excess of 95%. At present, there are approx. 130 commercial cyclotrons in operation worldwide.

For future applications of cyclotrons, availability and reliability become even more important issues. If one analyses reliability data, it becomes obvious that RF systems at present account for approx. 1/3 of all unscheduled beam interruptions in a cyclotron (PSI) [6] as well as in a linac (LANL) [5]. Therefore, designing RF systems and cavities for cyclotrons now will also have to take into account such things as: cavity voltage spark rate, repairability and maintainability. These aspects become paramount if cyclotrons are to be used in ADS systems; for example for radioactive waste transmutation [2]. There, only a dozen or so unscheduled beam interruptions per year seem to be tolerable at the moment, but this 'trip tolerance number' seems to depend heavily on the duration of the beam trips. The PSI two-stage facility at present produces about 20 beam trips per day, of > 1 min. duration. However, all RF systems together are responsible for less than one trip/day!

Since cyclotrons are inherently compact and can be designed for a relatively high efficiency rate (beam power/AC-grid power), they promise to become economical alternatives in future HPPA applications. Such machines would almost inevitably be of the SSC design and will require acceleration cavities capable of very high acceleration voltages (>1MV$\text{peak}$). The cavities tend to be rather large, and thus will operate at relatively low frequencies (in the range of ~ 20 to 170 MHz), but in return, will yield high Q- and R$_p$-values. The following sections will introduce some of the aspects and practical considerations in the design of acceleration cavities for such cyclotrons.
2. SPECIAL CONDITIONS FOR HIGH BEAM POWER CYCLOTRON RF SYSTEMS

When accelerating high (mA) beam currents in cyclotrons to higher energies, new problems arise, and ask for solutions. To reach higher beam energies (say: > 120 MeV) at high beam currents, multi-stage cyclotron arrangements are usually employed, with the final (high power) cyclotron stage being of ‘pure’ separated sector design, of the type usually called a ‘ring cyclotron’ (see Fig. 1). These machines do have sufficient space available in the center to make a different type of RF cavity design feasible; the ‘single gap cavity’. Such cavities are basically waveguides, operating in fundamental mode, with a sinusoidal voltage distribution along the acceleration gap. An extension of this ring cyclotron concept can employ superconducting magnet sectors (RIKEN, RIBF) [8], or even include superconducting magnets and cavities, like the TRITRON machine [9].

Generally, the required low extraction losses (< 0.02 %) will call for single turn extraction, that is: high energy gain per turn plus very limited beam phase acceptance (a few degrees) at injection.

To improve the phase acceptance range in a final cyclotron stage, systems with one or more flat-topping cavities and beam-power absorption devices will have to be included in such a design. Flat-topping, that is: adding a third harmonic cavity (operating 180° out of phase - in the deceleration mode) widens the phase acceptance angle for the particle bunches to approx. 25°.

In acceleration cavities, beam power compared to cavity losses, is no longer negligible; the load impedance of the cavity varies widely as a function of the beam load, and either variable couplers for impedance matching, or final power amplifiers that can handle the load variation have to be designed. In the PSI ring cyclotron cavities, for example, beam power is now at the same level as cavity losses; that is: about 300 kW (CW) for each.

In the case of flat-topping cavities, the beam loading effect is even more pronounced: the beam actually deposits energy in the cavity (since the particle bunches are 180° out of phase), acting like a second generator on the cavity, in parallel to the final amplifier. This power can exceed the wall losses in the cavity, that is: in order to maintain the very stringent cavity voltage- and phase control, the amplifier has to either go into an absorbing mode, or an additional load (variable or fixed) has to be connected to the cavity to absorb the excess power [10]. This is one way to reduce the Q-value of the cavity, and of course requires largely overrated RF- final amplifiers [11].

It is preferable for large SSC’s - because of the activation caused by high beam intensity and energy - require that all amplifiers be removed from the accelerator vault. This requires long, tuned transmission lines (l = n+λ) between final amplifiers and cavities, but in turn, allows easy amplifier access and repair, and therefore drastically increases maintainability and availability of the RF system. Ultimately, this concept reduces the amount of activated material (nuclear waste) produced.
3. TYPES OF SEPARATED SECTOR CYCLOTRON (SSC) CAVITIES

3.1 Tools for electromagnetic cavity design

The evolution of cavity design programs and experience gathered with some of these codes has been discussed in Ref. [12]. Lectures on 'Cavity construction techniques' by W. Wünsch and 'Cavity design procedures' have been presented earlier in this course, so only a few remarks about applications of such tools with respect to SSC cavities are needed.

Most conventional RF resonators in today's classical cyclotrons have been designed using iterative methods with, for example, transmission line element models combined with network simulation techniques (SPICE, etc.), and then building and measuring (scaled) models [1]. For second order optimization of critical regions (e.g.: vacuum feed-through of resonator, couplers or tuning devices) and comparison to model measurements, 2D codes (SUPERFISH, URMEL, etc.) could be used, due to cylindrical nature of many of such elements. Only very simple geometries, like for example the PSI-ring cyclotron cavity, have ever been designed using purely analytical methods- the field equations for a simple box in $H_{101}$ mode. (comp. Eq.1)

As soon as more demanding cavity shapes are involved, however, 3D programs (or extensive model building:) are the only way to optimize cavity designs for:
- maximum shunt impedance ($R_p$) at the fundamental mode; and therefore, minimal RF- power losses,
- surface current distribution for cooling system layout,
- multipactor suppression by choice of a suitable geometry, (besides proper choice of surface material or -coating, of course)
- optimal damping of parasitic modes.

3.2 Classes of SSC cavity designs

The different cavity designs are depending on the specifications and geometric layout of a cyclotron, and can therefore be grouped and differentiated by the electromagnetic- and geometrical properties:

- Frequency range required:
  a) Fixed frequency cavities, used for example in fixed energy proton accelerators, e.g. for spallation neutron sources and ADS. Such designs tend to be simpler and therefore cheaper.
  b) Variable energy (and variable particle type) machines: they require cavities with a wide frequency tuning range, in many cases exceeding a frequency ratio of 2:1, and also operate at varying acceleration voltages.

- Single-gap- and double gap cavities

- Cavities can further be separated into: normal conducting and superconducting cavities; up until today however, only one superconducting cavity design has been demonstrated to work in an actual cyclotron, and it differs radically from other well known designs. [9]

3.3 Single-gap vs. double-gap cavity design

SSC-cavities can be separated into:

3.3.1 Double gap ($\lambda/4$ or $\lambda/2$ transmission line type) resonators, also called 'delta' resonators

They are suitable for applications where a special radial voltage profile (along the acceleration gaps) is desired. Large radial- and vertical dimensions of the resonator are possible (for higher energy cyclotron applications); and to obtain high $R_p$ values (with minimal RF power demand for maximum acceleration voltage), the resonator can be made wide at outer radii (piece-of-pie shape).
If the coaxial part of the resonator is not of a simple, cylindrical shape (like in superconducting cyclotrons of the Milan [1] or NSCL [1] design), which can be successfully optimized by 2D geometry codes, but rather look like the GANIL- or PSI injector cyclotron RF cavities, an optimal stem design (possibly multiple stems) will be nontrivial, several iterations of modeling might be needed, and are best carried out with advanced 3D RF design tools, like for example, MAFIA. [12]

![Double gap cyclotron cavity (PSI injector)](image)

**Fig. 2:** Typical λ/2 double-gap cavity; capacitive fine tuning (T) and capacitive power coupler (P)

Practical experience indicate that the peak RF voltage (< 400 kV, per gap) and \( R_p \) obtainable in a large, double gap design will still be somewhat lower than in optimized single gap cavities. An advantage worth mentioning: the fact that a double gap cavity has an inner conductor (coaxial design) means that it is possible to choose between capacitive- and inductive power coupling.

### 3.3.2 Single gap, waveguide-type resonators.

This is a much rarer design, and it has several features which are different from ‘conventional’ double gap cavities. For the simplest, box-shaped design (like the old PSI ring cyclotron cavity) an analytical solution for the electromagnetic field distribution does exist (\( H_{101} = \text{TE}_{110} \) mode):

\[
E_y = E_0 \cdot \sin \frac{\pi \cdot x}{a} \cdot \sin \frac{\pi \cdot z}{d} \\
H_x = -j \cdot \frac{E_0}{z} \cdot \frac{\lambda}{2 \cdot d} \cdot \sin \frac{\pi \cdot x}{a} \cdot \cos \frac{\pi \cdot z}{d} \\
H_z = j \cdot \frac{E_0}{z} \cdot \frac{\lambda}{2 \cdot a} \cdot \cos \frac{\pi \cdot x}{a} \cdot \sin \frac{\pi \cdot z}{d}
\]  

(1)

Fig. 3:Cavity shape and frame of reference
and, for the wavelength $\lambda$ at the fundamental frequency $f_{101}$, we have:

\[
\lambda_{101} = \sqrt{\frac{2}{\frac{1}{a^2} + \frac{1}{d^2}}}; \quad \text{and;} \quad f_{101} = \frac{c}{\lambda_{101}} = \frac{c}{2} \sqrt{\frac{1}{a^2} + \frac{1}{d^2}}.
\]

(2)

It becomes clear that the width of the cavity has no influence on the fundamental resonance frequency, so a single gap cavity can be made very narrow in the beam plane dimension, where space restrictions are the most severe. It is advantageous to make the cavity narrow along the acceleration gap; and it is preferable to internal electrodes, because such electrodes inevitably increase RF losses (lower the achievable $R_p$).

Characteristically, higher Q-values are obtainable than with conventional transmission line/dee designs, where acceleration voltages rarely exceed 200 kV and Q-values stay below $= 20'000$. For comparison: the existing PSI cavities: (to be replaced by a more efficient design in the future), have a $Q_0 = 32'000$; with $R_p = 1 \text{ M}\Omega$, and operate at $V_{\text{peak}} = 780 \text{ kV}$.

Useful particularly at high RF-voltage and beam power levels, yet another advantage can be designed into a waveguide-type cavity: less sensitivity to higher order modes. The ratio between length and height of a cavity should be chosen such that the higher order modes of such a cavity will not coincide with the higher harmonics of the fundamental frequency, so they will not get excited by such harmonic frequency components coming from the final amplifier. This fact also has some consequences for the final amplifier stability. Since the higher harmonics get reflected back into the amplifier, some harmonic component absorption scheme might have to be employed in the transmission line between amplifier and cavity.

With the obtainable high $R_p$ value, very high acceleration voltages (for cyclotrons) are possible; the new (fixed frequency) RF cavity for the PSI ring cyclotron for example, is designed for a peak RF voltage of $> 1 \text{ MV}_{\text{p}}$, with a shunt impedance $R_p = 1.8 \text{ M}\Omega$ [13]. Unfortunately, this voltage is not available across the full acceleration gap; it has a sinusoidal distribution (in the fundamental $H_{101}$ mode). This implies that single gap cavities need some space to extend into the center region of the machine - past the innermost particle radius - to present some acceleration voltage at such a minimal radius.

![Acceleration voltage distribution in 'box' type cavity; accel. gap along 'Z'-axis](image)

Fig. : Acceleration voltage distribution in 'box' type cavity; accel. gap along 'Z'-axis

A general conclusion is therefore that single gap cavities are probably best suited for larger ring cyclotron designs, (final stage in multistage accelerator), and that double gap cavities are probably better suited for smaller first stages or lower energy cyclotrons.

There are working (or planned) examples of all cavity designs mentioned, here is a list of a few representative types:
### Table 1

Some representative acceleration cavity types in operating cyclotrons of the SSC type

(Note: RT= room temperature, normal conducting; SC= superconducting; SS= separated sector machine)

<table>
<thead>
<tr>
<th>Type of resonator:</th>
<th>Operating frequency</th>
<th>Typical $Q_0$-value</th>
<th>Name of lab/machine; special features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Double gap,</strong> $\lambda/4$ resonator; RT</td>
<td>variable (2-60 MHz)</td>
<td>2'000 - 8'000</td>
<td>Numerous 'classical' cyclotrons, (with 'Dees') $\rightarrow$ 'moveable short'- or 'panel' tuning system</td>
</tr>
<tr>
<td><strong>Double gap,</strong> $\lambda/2$ resonator; RT</td>
<td>6 - 14 MHz</td>
<td>6'500 - 14'000</td>
<td>GANIL/SSC; SS-machine, RT-magnets $\rightarrow$ 'capacitive' tuning system</td>
</tr>
<tr>
<td><strong>Double gap,</strong> $\lambda/2$ resonator; RT</td>
<td>fixed (51 MHz)</td>
<td>28'000 (Al)</td>
<td>PSI/Injector II; SS-machine, RT-magnets</td>
</tr>
<tr>
<td><strong>Double gap,</strong> $\lambda/2$ resonator; RT</td>
<td>18 - 38 MHz</td>
<td>14'000 - 16'000</td>
<td>RIKEN/RRC; SS-machine, RT-magnets, $\rightarrow$ 'box' tuning system</td>
</tr>
<tr>
<td><strong>Single gap resonator:</strong> RT</td>
<td>30 - 52 MHz</td>
<td>18'000 - 25'000</td>
<td>RCNP/Ring Cyclotron; $\rightarrow$ 'flap' tuning system</td>
</tr>
<tr>
<td><strong>Single gap resonator:</strong> RT</td>
<td>fixed (51 MHz)</td>
<td>32'000 (Al) 48'000 (Cu)</td>
<td>PSI/Ring Cyclotron; very high voltage &amp; load</td>
</tr>
<tr>
<td><strong>Single gap resonator:</strong> SC !!</td>
<td>fixed (170 MHz)</td>
<td>$&gt; 10^8$ (!)</td>
<td>TRITRON; fully SC, (incl. magnets)</td>
</tr>
<tr>
<td><strong>Under construction:</strong></td>
<td>18 - 38 MHz</td>
<td>25'000 - 34'000</td>
<td>RIKEN/RIBF/SRC; with SC magnets $\rightarrow$ 'flap' tuning system</td>
</tr>
</tbody>
</table>

### 3.4 Mechanical engineering and design features for cavities

A room temperature cavity of either double- or single-gap design can be constructed as either an integrated cavity or as a 'conventional' cavity, where a separate RF resonator is mounted inside a vacuum chamber - the 'separate boxes' design. A superconducting cavity will always be of the 'separate boxes' design!

An 'integrated cavity design' means that the cavity structure (the resonator) serves a double function as a vacuum chamber with RF properties; the cavity wall generally consists of just one layer. The inner surface of a vacuum tank has to satisfy the conditions for an RF resonator; that is: geometry and surface conductivity are givens. On the outside, the dissipated RF power plus the atmospheric load forces have to be taken care of. Contrarily, a conventional cavity, which I call of 'separate boxes' design (in lack of an generally accepted term for this type of resonator) is built such that a complete RF cavity - including it's cooling system, power couplers, tuning elements and probes (pick-ups) - sits inside a vacuum vessel; the cavity walls will therefore always be double-layered, but with clearly separated functions. The inner box - the actual RF cavity - typically is being made of copper, with cooling lines attached to its outer surface, to take up the thermal load of the RF losses, while the outer wall acts only a vacuum chamber, designed to withstand the atmospheric pressure. This vacuum chamber is typically made of stainless steel, or aluminum.

If one tries to list advantages and disadvantages of the two types of cavity constructions, it becomes clear that such a list applies to single gap as well as double gap cavity designs. The only difference may be cooling: in a single gap cavity, all cooling takes place on outside walls, since there is no inner conductor.
Tools: Especially for the case of integrated cavities, the application of 3D finite element analysis and design tools becomes unavoidable for optimal design procedures. One of the biggest problems using such design tools is that most codes have been developed for either electromagnetic field computations or for mechanical engineering purposes, and - if at all - the capability to handle ‘the other part’ has been an add-on, so going back and forth between the two modeling systems is often unnecessarily cumbersome, a lot of manual mesh adapting and manipulation usually is required.

Ultimately, for the next generation of large cyclotron cavities, mechanical constraints, material properties and limits imposed by different manufacturing technologies (and costs!) will play a decisive role in the choice of the final design, which may not be the maximum ‘electrical’ performance but an optimized version with respect to both electromagnetic- and mechanical engineering considerations.

<table>
<thead>
<tr>
<th>Integrated RF-Cavity</th>
<th>Separate RF-Cavity in Vacuum Tank</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ADVANTAGES:</strong></td>
<td></td>
</tr>
<tr>
<td>Vacuum surface (pumping!) is only 1/3rd of separate RF cavity in vacuum tank design</td>
<td>Electrical characteristics (inner shape) and cooling functions can be separated from the vacuum tank design: → heat removal (with thermal effects) can be optimized, independent of the vacuum tank loads</td>
</tr>
<tr>
<td>RF power couplers, tuners and pick-ups are simpler; only one wall: → ease of maintenance</td>
<td>Manufacturing of components easier (&amp; cheaper) than integrated design</td>
</tr>
<tr>
<td>Most effective use of volume between magnets, available for actual RF cavity</td>
<td>A double gap cavity can be made of two shells, separated at median plane: → smaller units, cheaper</td>
</tr>
<tr>
<td>If designed without electrodes, the cavity is empty: → high $Q_0$, simple el. design</td>
<td></td>
</tr>
</tbody>
</table>

| **DISADVANTAGES**    |                                   |
| Complex mech. design; RF- and mechanical design are combined, because thermal effects and vacuum loads cannot be treated separately | More components (RF cavity & cooling, pick-ups and tuning) are inside vacuum chamber: maintenance more complicated and time-consuming |
| Manufacturing of cavity more demanding and complex: → more expensive (?) |                                   |

| **TYPICAL EXAMPLES**  |                                   |
| Double gap design:     | PSI, ring cyclotron               |
|                        | RIKEN RIBF; RRC, acceleration cavities |
| Single gap design:     | PSI, injector cyclotron           |
|                        | RIKEN RIBF; SRC,IRC accel. & flattop cavities |
|                        | TRITRON; superconducting !        |

4. FREQUENCY TUNING SYSTEMS

4.1 Fixed frequency cavities

Since fixed frequency cavities only need fine tuning for the one operating frequency, their design is much simpler, and usually the reliability is better. According to several operators of RF systems with variable frequency range, (like Ref. [16], and private communication), the coarse (wide range) tuning systems have a relatively high failure rate (unscheduled maintenance and repair) due to their technical complexity. Fine tuning devices - usually plungers or capacitive trimmers - have to carry much less current than the moveable shorts or flapping panels that are used for large frequency variations.
For applications like in ADS systems, which will demand very high reliability and availability at reasonable costs, fixed frequency systems are probably an optimal solution.

In the case of big, box-shaped, integrated cavities like the ones employed in the PSI ring cyclotron (see Fig. 5), the fine tuning can be done by hydraulically squeezing the side-walls of the cavity about the median plane; by a maximum displacement in the beam plane of about 5 mm per side (corresponding to less than 2% of the gap width). This generates a $\Delta f/f_0 = 0.4\%$, ($\Delta f = 200$ kHz), sufficient to correct atmospheric pressure changes and thermal effects acting on the cavity side-walls. The new cavity under construction at PSI will use a hydraulic system with limited tuning range but fast response time, and additionally a slower, thermal expansion control system, also acting on the mechanical support structure of the cavity, to handle slower, larger resonance frequency drifts [13].

![Image](image.png)

Fig. 5: Cross-section through a PSI ring cyclotron cavity, old (existing) and new design

4.2 Variable frequency cavities

4.2.1 Double gap, coaxial type cavities

If a cavity is designed with a $\lambda/2$ or $\lambda/4$ coaxial structure, large frequency tuning ranges are most often achieved by:

a) moveable (sliding) shorting plane at the inductive end of the resonator; or by:

b) using a fixed short, and vary the characteristic impedance $Z_l$ of the current end section of a transmission line, thereby changing the effective length; or, alternatively, (obtaining the same effect) by changing the impedance at the capacitive end of the resonator.

c) Finally, one can use moveable sections of (lower) characteristic impedance inside the coaxial lines, thus again varying the effective length of the resonator.
Examples of systems of type a) are numerous, and employed for instance in superconducting magnet cyclotrons, like the Milano (Catania, INFN) design, (Ref. [1], p. 520), or the NSCL machines.

The type b) design is also widespread, an example is the Texas A&M cyclotron, also shown in Ref. [1], on p. 503. The impedance variation is obtained by moving panels, which, in effect, change the volume (and \(Z_0\)) of the end section if a coaxial resonator. GANIL [17] employs a different strategy: the frequency tuning is performed at the capacitive, high voltage end (the 'Dee') of a \(\lambda/2\) cavity. The first case has to overcome problems of high current loads in panel hinges, while tuning at the 'Dee-end' requires careful design to guarantee the voltage holding capacity (sparking).

The type c) design finally is successfully employed in \(\lambda/2\)-cavities in the RIKEN ring cyclotron (RRC), [14]. There, it is called the 'moveable box' frequency tuning (Fig. 6). This box is galvanically connected only to the outer conductor surface via sliding contacts; the main advantage stems from the fact that the circumference path along the outer conductor is much longer, therefore the current density (in A/cm) for the sliding contacts is much lower than if the contact were made to the inner conductor. Also, cooling of the outer the shell of a resonator is usually easier than of the inner conductor.

4.2.2 Single gap, waveguide-type cavities

Such cavities are usually designed for even higher \(Q_0\)-values and higher acceleration voltages than their coaxial counterparts, and, due to the lack of internal parts (no inner conductor), the technical possibilities for frequency tuning over a wide range are somewhat more limited. Since the resonance frequency of such a 'box' is usually defined by two key dimensions - the height \(a\) and the length \(d\) in Fig. 3 - and the dimension along the acceleration gap should remain constant, varying the height by symmetrically moving top and bottom walls is the obvious way to obtain the frequency variation. This method is employed in the flat-top cavity design of the RCNP ring cyclotron [16]; as well as in the two cyclotrons (IRC- and RRC) of the future RIKEN RIBF, also for flat-topping [8].

For even higher voltage levels - for accelerating cavities - a different approach for resonance frequency variation was chosen: the 'moveable flap' design [8][16]. This concept achieves respectable acceleration voltages (up to 500 kV\(_p\) @ 38 MHz). Critical components are, as one would expect, the hinges, they have to carry the panel currents to the cavity wall. Such cavity tuning systems, by the way, can no longer be calculated in closed form, or with simple numerical models. Only full use of advanced 3D codes will allow optimized designs, together with careful measurements on scale models [8].
5. POWER COUPLING INTO CAVITIES

5.1 Inductive couplers

As mentioned before, inductive coupling is the only practical way to feed RF power into a waveguide-type cavity, since there is no inner conductor to efficiently use capacitive coupling. Basically, the inductive couplers and are similar in all RF cavities, and have already been treated in this course.

A analytical approach to determine the loop area $A$ of an inductive coupler for $50 \Omega$ input impedance, (coupling into a box shaped cavity in the median plane) is usually very unreliable (off by at least a factor of 2, or more), but gives a rough lower limit:

\[
A \approx d K Z_l R_f \cdot \frac{1}{\omega \cdot \mu_0}; \quad (3)
\]

under idealized conditions, (loop wire dia. ~ 0, homogeneous field distribution, etc with $d =$ length of cavity, $K$ a geometry-dependent factor, $Z_l = 50 \, \Omega$, and $R_f =$ surface resistance of cavity material.

However, it is relatively easy to get good experimental data: one takes a simple wire loop and varies the shape and size until the desired matching impedance (usually $\geq 50 \, \Omega$) is reached, for example by measuring $S_{11}$ with the help of a network analyzer. When high beam loads are expected, the input impedance of a cavity can be set to be as high as $75 \, \Omega$, such that optimal impedance match (to $50 \, \Omega$) is obtained at high beam load levels.

This way, variable coupling loop installations can be avoided, because they are mechanically complex designs and therefore potential sources of RF system failures at very high power levels. Variable size loops are unavoidable in variable frequency cavities, as for example in the RIKEN RABF resonators [8]

Only recently, with the availability of 3D codes with time domain modules, has it become possible to model the coupling loop region in a cavity more accurately; at the same time, such methods also permit optimized vacuum window designs in RF power couplers [15]. We at PSI are at present in the process of optimizing coupling loops using 'MAFIA' modeling, in the hope of extending the present operating power of $> 650 \, \text{kW} @ 51 \, \text{MHz}$ up to $1 \, \text{MW (CW)}$ for the new PSI ring cyclotron cavities in the future.
5.2 Capacitive couplers

Capacitive coupling is widely used in double gap, coaxial type resonators, because the inner conductor presents an ideal opportunity to couple via a capacitance to the high voltage end (typically the 'Dee structure'); and be independent of geometry changes at the inductive end of the resonator especially if that end is used for frequency tuning. Matching the cavity to a 50 $\Omega$ transmission line with a suitable capacity usually presents no special problem; a further advantage can be that a variable capacity (= variable distance of the coupler to the 'Dee') is usually easier to design and operate reliably that a variable area (usually by rotation) inductive coupling loop.

A further advantage - compared to an inductive coupler - may also turn out to be that a capacitive coupler can be biased with a DC voltage, to suppress multipacting in the coupling region and around the ceramic window of such a coupling device.

6. ACKNOWLEDGEMENTS AND CONCLUSION

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Cyclotron cavity design is still a very exciting field, open for new ideas and concepts, especially in view of the new (numerical) design tools that recently have become available (although not necessarily more affordable). Completely new fields for cyclotron application - like ADS with HPPA's, compact SC medical cyclotrons, or even fully superconducting cyclotrons (including the RF cavities !) - will ask for up to now unknown ease of operation as well as utmost reliability - and practically no more RF sparking !

This will call for more and intensified studies of discharge- and voltage breakdown mechanisms and multipacting phenomena in cavities. Ultimately, these investigations will hopefully lead to a drastic reduction in the number of beam interruptions in cyclotrons caused by RF systems. At the same time, machines will have to be designed, with higher efficiency (also a new aspect in cyclotron design), and further improved reliability and reduced operational costs: cyclotrons will be measured by the same criteria applied to other 'high-tech' industrial products!
7. REFERENCES

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