RF FOR CYCLOTRONS (I)

Introduction

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RF FOR CYCLOTRONS (II)

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What is a cyclotron ?

It is a ***circular particle accelerator***, based on the following concept:

$\mathbf{F}_{mag} = q\,\mathbf{v} \times \mathbf{B}$ is the magnetic force acting on a charged particle, moving inside a magnetostatic field **B**; with q = particle charge; and

$\mathbf{F}_{cent} = -\,(m\,v^2/r)\,\mathbf{n}$ is the centripetal force, where m equals the particle mass, and **n** is $\perp$ to the trajectory.

These forces equalized, yield $\boxed{\frac{q|B|}{m} = \frac{v}{r} = \omega_p = \omega_{rf}}$; the *resonance condition* for a closed orbit.

$\Rightarrow$ ***For a given particle and energy, the RF frequency is fixed and constant.***

At particle energies higher than a few MeV, however, $m = m_0$ no longer holds, and so, to compensate for the increasing mass (causing loss of isochronism), **B** is increased with radius. This, however, results in axial defocussing. To compensate for that effect, the so-called '*flutter*' is introduced. It consists of adding a suitable azimutal modulation to the magnetic field, to compensate for the axial defocussing effect of the radially increasing **B**.

Such a machine is called an *'Azimutally Varying Field Isochronous Cyclotron',* or AVF isochronous cyclotron.

What are the Main Components of a Cyclotron ?

(and where is the RF system?)

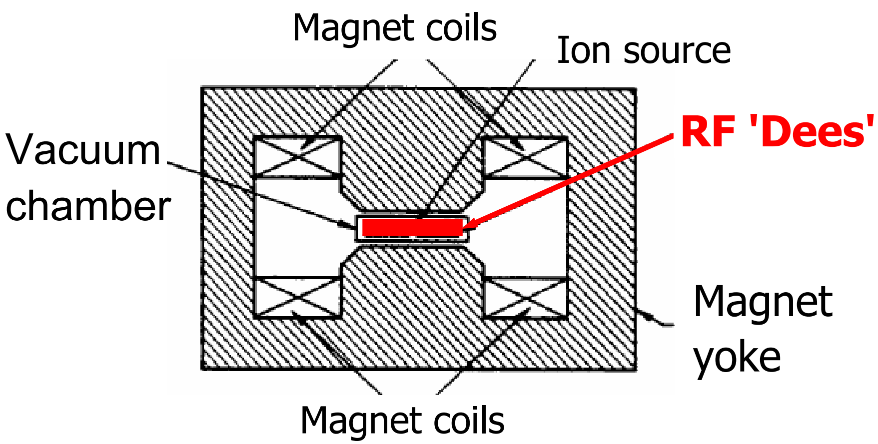


Fig. 1: Cross section through a 'classical' cyclotron

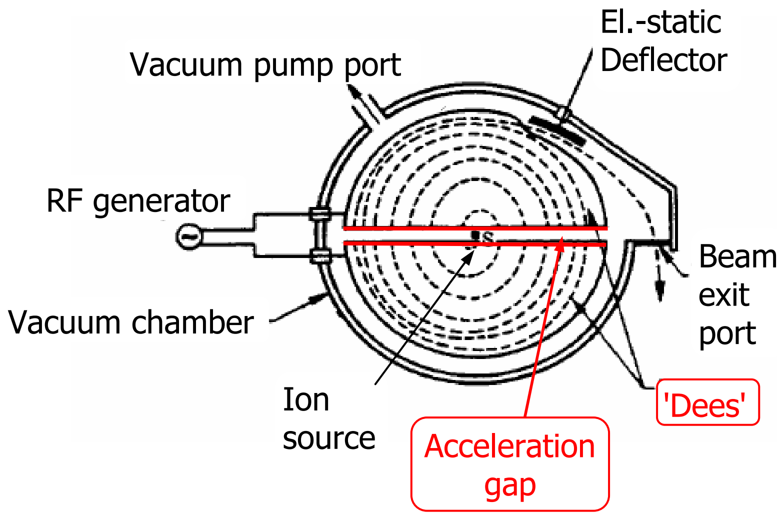
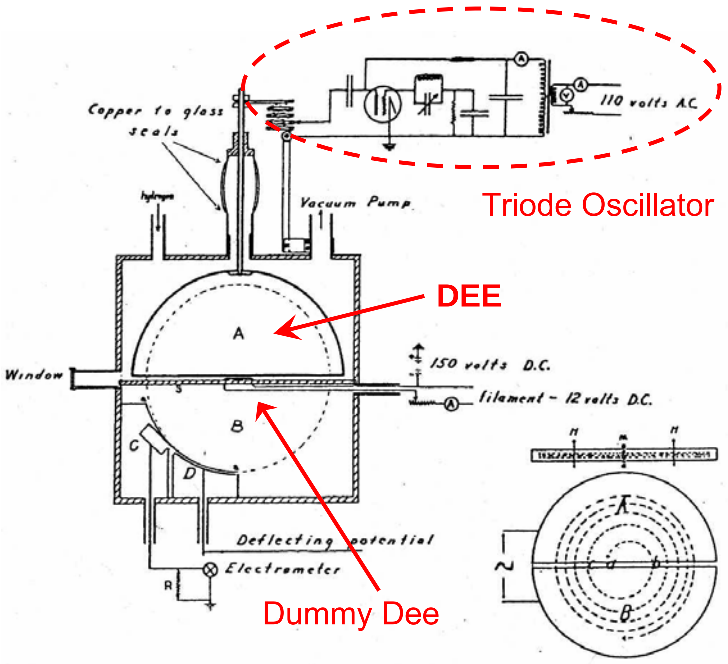


Fig. 2: A simplified plan view of a cyclotron, showing most essential components

Over 200 cyclotrons have been built, to accelerate almost every type of particle; from protons to uranium, to energies from a few MeV to 1 GeV.
Recently, the range has been extended to include radioactive particles, as well.

How it all started . .



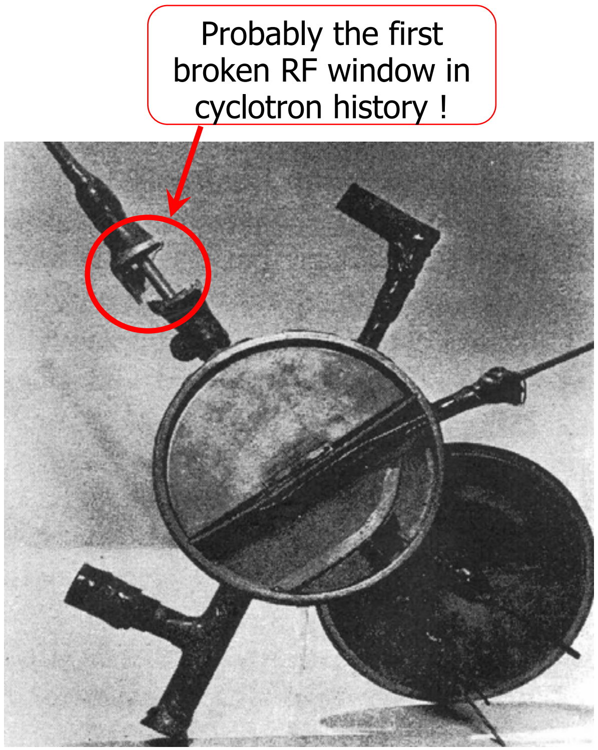
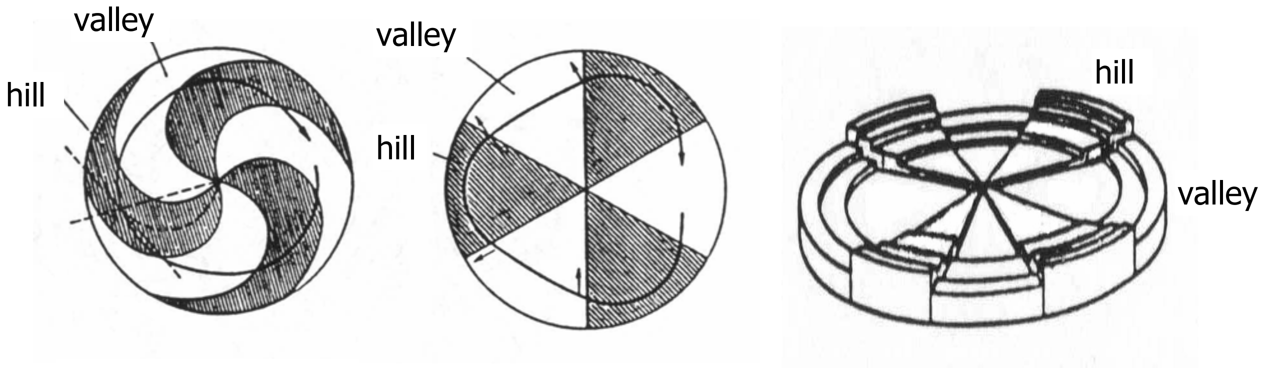


Fig . 3 : Schematic and remnants of the first cyclotron (1930); by Lawrence and Livingston

Pole Shapes, Effects on RF System Design



Three spiral sectors | Three triangular sectors | View of pole face; four sectors

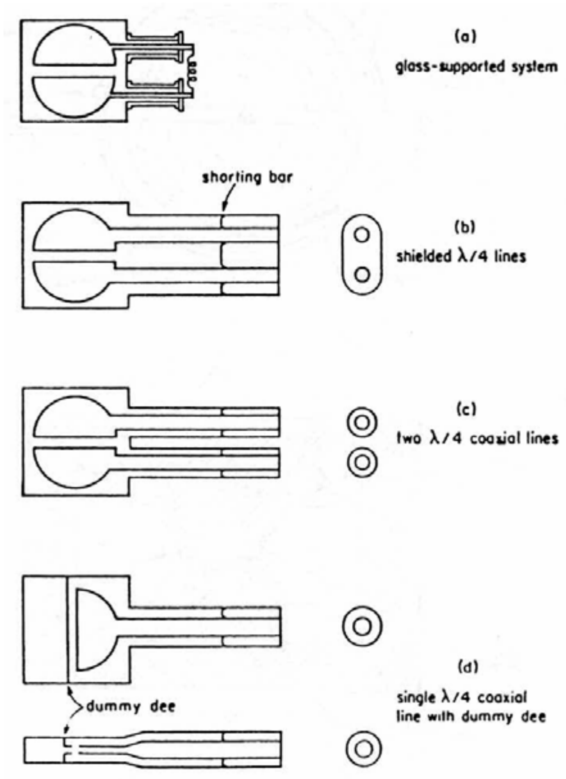
Fig. 4: Different pole shapes (for 'flutter') for AVF isochronous cyclotrons

The choice of the pole shape and the number of sectors have a great impact on the available space for RF systems. Dees, and possibly stems and liners have to fit into the gaps and/or valley sections.

In order to reach a high Q-value (and therefore low losses) for a desired Dee voltage, RF designers would like to have a maximum of space available. (Ideal: ⇒ Separated sector cyclotron!)

'Classical' λ/4 cyclotron resonators and Dees; plan view and cross-section

The original cyclotron had electrodes resembling the letter '**D**', and this name stuck, even though the original shape is now only rarely used. In all classical cyclotrons, the ***Dees are (capacitive) electrodes***, inserted into the magnet gap, usually in the 'valley' of the pole plates. A shorted coaxial part (the inductive end) extends to the outside of the magnet yoke, thus completing the structures to λ/4 resonators.



Dee with glass feed-trough and external inductor for tuning of the resonance frequency (antique!)

Two λ/4 lines, with one moveable shorting plate, for frequency tuning

Two separate coaxial λ/4 lines, moveable shorts for frequency tuning

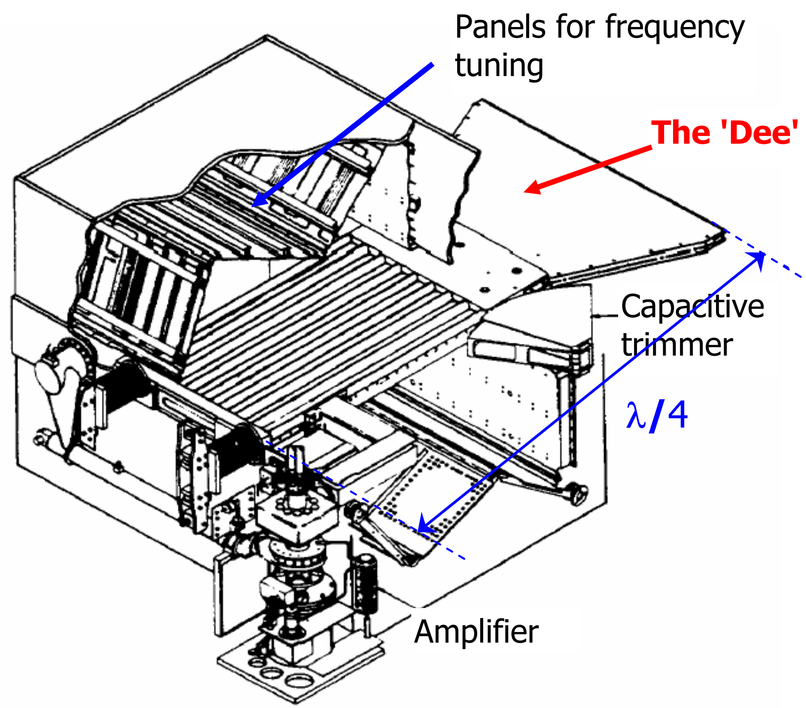
Single λ/4 coaxial line with a 'Dummy Dee'; moveable short for frequency tuning

Side view

Fig. 5: Different types of λ/4 - coaxial cyclotron resonators, plan view and cross-section

Examples of Cyclotron RF Designs:

Numerous variations are possible: (besides the 'classical' solution; Fig. 6)
- *More than one Dee* (2 - 4), to increase the energy gain per turn. (Fig. 7)
- Each Dee connected to an upper and lower coaxial $\lambda/4$ -section, to form a *vertical $\lambda/2$ resonator* (Fig. 7)
- *Two Dees,* coupled directly or capacitively in the center, forming a *horizontal $\lambda/2$ resonator*



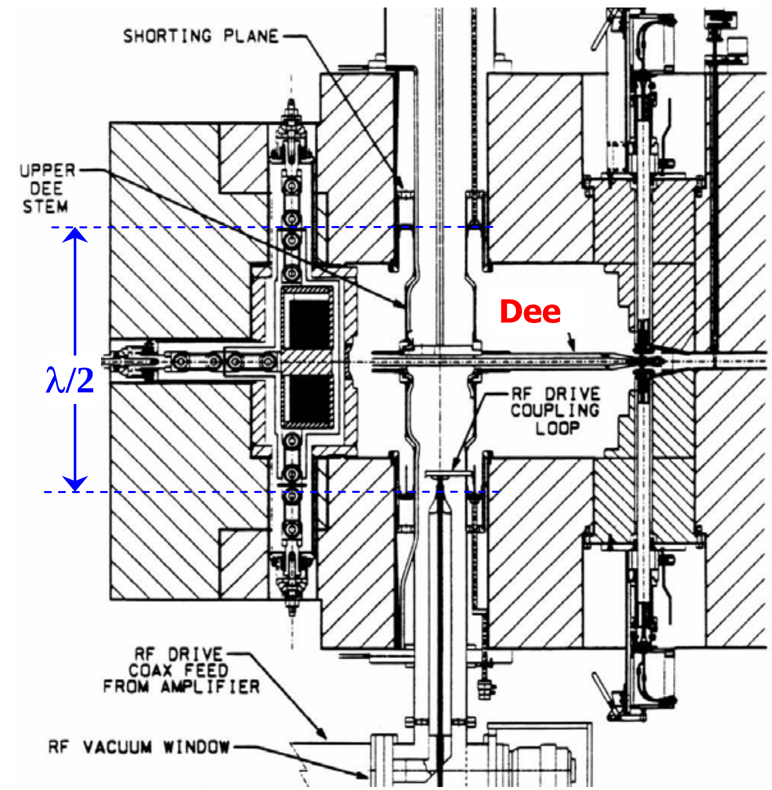


Fig 6: 'Classical' cyclotron with one $\lambda/4$ Dee (coaxial resonator), and panel tuning (Texas A & M University)

Fig. 7: A more recent design: the NSCL superconducting cyclotron. It uses three Dees with a $\lambda/2$ coaxial resonator design, vertically protruding through magnet and vacuum chamber.

Design and Modelling of RF Structures for Cyclotrons

Transmission Line Models

Classical design methods, developed long before big computers and 3D codes were available, are based on the ***transmission line*** approach.

An ideal (no losses) coaxial transmission line is divided into segments of constant characteristic impedance Z_k, connected together to form topologies used in network analysis. Some computer codes (like SPICE) for network analysis became available a long time ago and were used for network analysis.
Refined codes - developed especially for this type of RF design - allow the use of lossy transmission lines (e.g.: 'WAC', developed by J. Vincent at NSCL)

Experience with these methods, including model building and measurement, is quite good, with some experience, the key parameters (f_o , Q_o , R_p {RF losses}) can be determined to about 5% accuracy.

The real problem with applying the transmission line design lies in an accurate determination of the ***effective length*** l_k and ***characteristic impedance*** Z_{0k} of each of the k coaxial transmission line segments used in the network model.

Assumption: Model elements of the sections have the following (ideal) properties:
- **Quasi-planar propagation surface** (choose sections accordingly); and:
- **pure TEM - mode** (correct if each section is defined with constant Z_o)

The following page illustrates how to determine the two crucial parameters, l_k and Z_{ok}:

1. *Effective line length l_k of the k^{th} transmission line segment*

The length of the k^{th} element can be found with reasonable accuracy by determining the average current path between the internal- and external conductors.

2. *Characteristic impedance Z_{ok} of the k^{th} transmission line segment*

Two methods to obtain approximate values for Z_o are at hand:

a) Zo can be calculated by using any ***electrostatic code*** to compute the capacitance per unit length C', of each transmission line section: $Z_0 = \frac{1}{c \cdot C'}$ (Ω) ; with c = speed of light in vacuum.

b) Another way to obtain the characteristic impedance of transmission line segments is the method of ***'square plotting'*** ; it relies on the fact that in a plane wave travelling along a transmission line in vacuum (or air), **E** and **H** are always perpendicular ($\perp$).

Their relation is: $\frac{|\mathrm{E}|}{|\mathrm{H}|} = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377(\Omega)$

This allows graphical tracing of electrical field lines (coinciding with those of the electrostatic field) and equi-potentials (corresponding to the field lines of **H**) by trial and error; all that is required is that the lines always intersect at right angles and form curvilinear squares. Each square generated this way will always contribute with an impedance of 377 Ω.

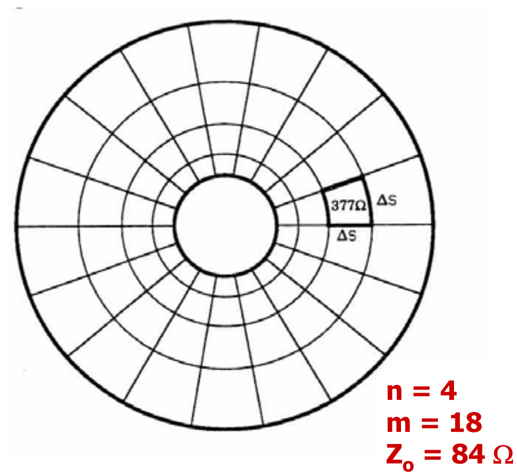
This leads to: $Z_0 = 377\frac{n}{m}$ (Ω), with:

n = number of squares ***in series*** between any two adjacent ***electric field lines,***

m = number of squares ***in parallel*** between any two adjacent ***equipotentials.***

Examples:

Here are two examples of curvilinear square plots, one of a simple, cylindrical coaxial line, the other of a more complicated shape.



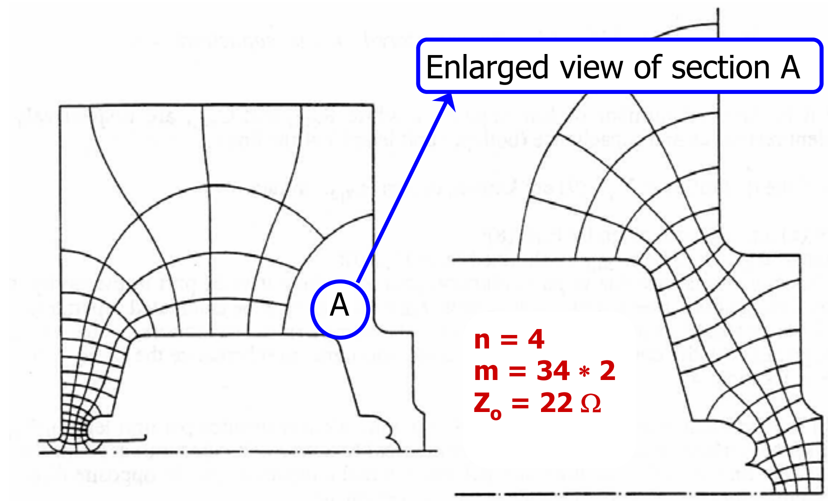


Fig. 8: 'Curvilinear squares' plot, simple cylindrical coax line

Fig. 9: A complex shaped coaxial line

Actual Model:

To illustrate the method, we show a basic model, derived for computer simulation of an actual cavity design (Milan cyclotron, Fig. 8).

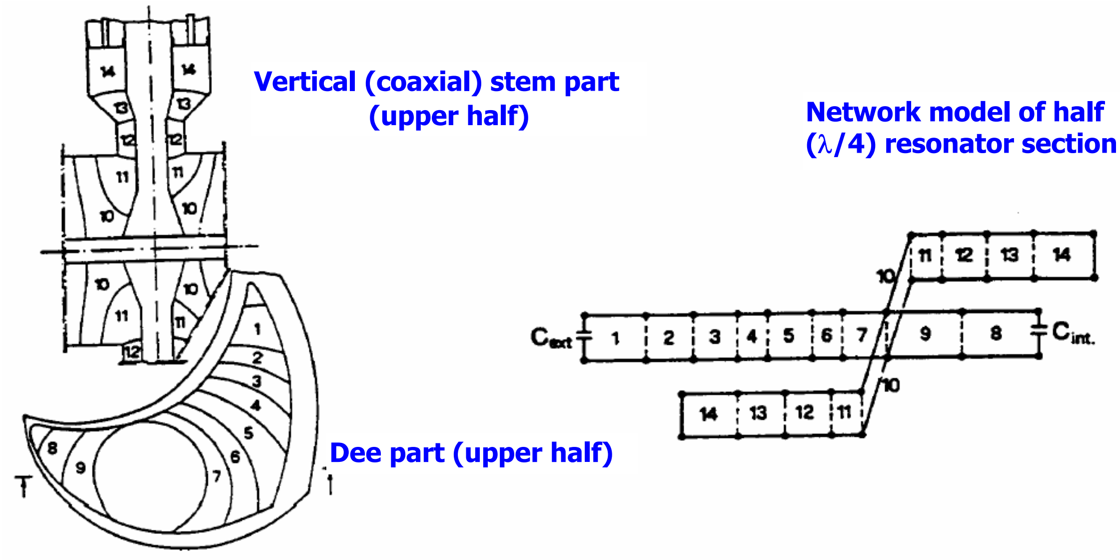


Fig. 10: A λ/2 Dee- and coaxial resonator model, using transmission line techniques

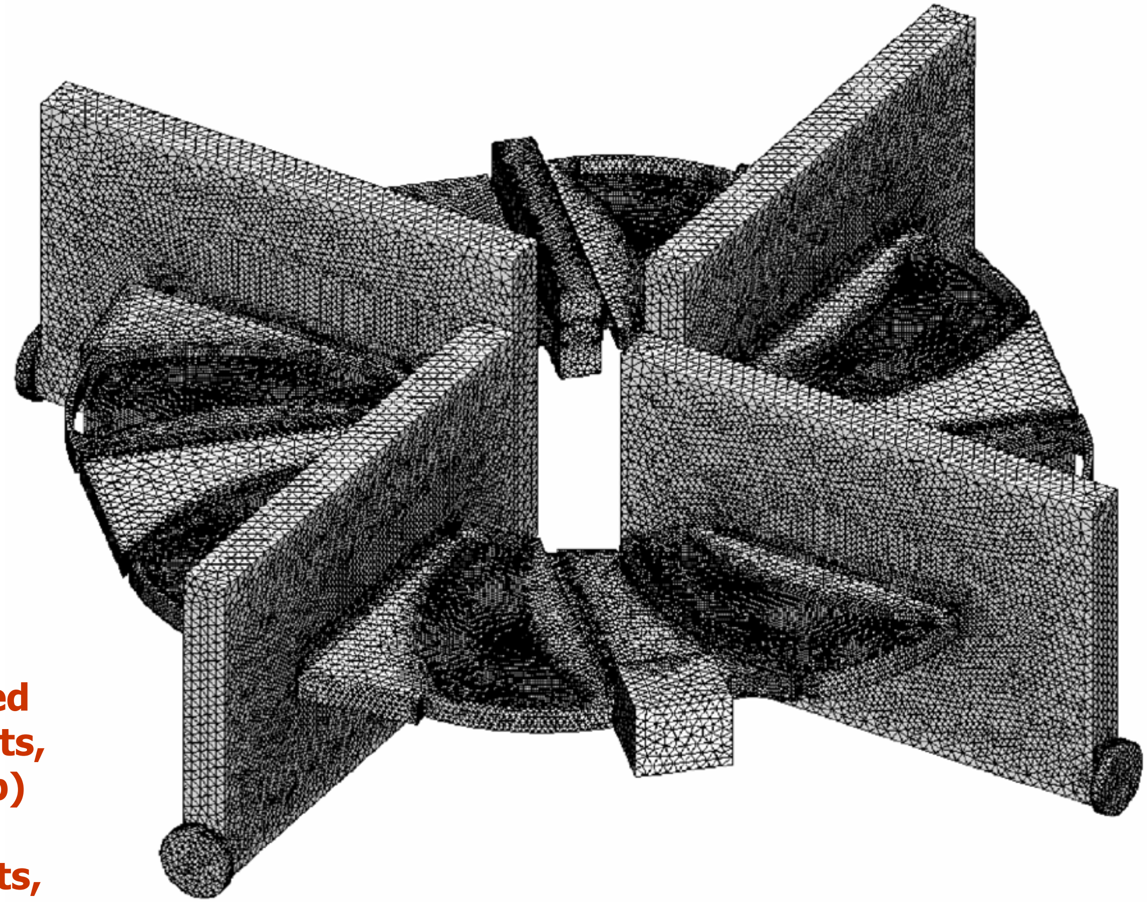
Note: Electromagnetic 3D code simulation for a sufficiently accurate description of a geometry as shown in Fig. 7 has been estimated to require some 10 million mesh points (*constant* grid size); far beyond reach for such codes when the transmission line models were first used.

3D Electromagnetic Field Modeling

- Recently, computers became powerful enough to permit 3D electromagnetic field modeling of complex shapes (like Dees!) with large numbers of mesh points (> 1M tetrahedral elements, 2nd order elements). Simulation tools (MWS, HFSS) have also been greatly refined and improved.
- Example: a typical calculation of eigenmodes with 'Omega3P' (SLAC), solving for 20 modes, takes 45min., with 32 CPUs on an IBM-SP4. Total memory requirement: approx. 120 GB.
- This way, parasitic cyclotron modes can be numerically confirmed.
- Beam-cavity interactions can also be investigated, the excitation of higher order modes in cavities and vacuum chambers can be analyzed and verified.
- Previously, *integrated cavity* design (vacuum chamber and cavity as one unit) was rather tedious, because the effects of mechanical forces and thermal effects on the RF geometry were very difficult to predict with reasonable accuracy. (see cavity design procedure, p. 19 ff)
- Today, mechanical cavity design can be performed using *FEA* (*finite element analysis*) simulation. The RF geometry data (from modal simulation) is transferred into a thermal- and structural model (mech. simulation method, e.g. ANSYS), taking into account atmospheric pressure and thermal effects.

  This procedure yields a **deformed** RF geometry, which represents the **operating** geometry.

An Example of 3D Electromagnetic Field Modeling of Complex Shapes - the PSI Separated Sector Cyclotron with RF Cavities and Vacuum Chamber



- **Mesh of RF cavities and vacuum chamber, created with tetrahedral elements, using CUBIT (Sandia Lab)**
- **1.2 M 2nd order elements, 6.9 M degrees of freedom**

Fig. 11: 3D field model of the PSI separated sector rf system and vacuum chamber

Another Example of Large Scale Electromagnetic Modeling of a 'Classical' Cyclotron: The PSI 4 Sector 250 MeV_P Medical Cyclotron built by ACCEL GmbH

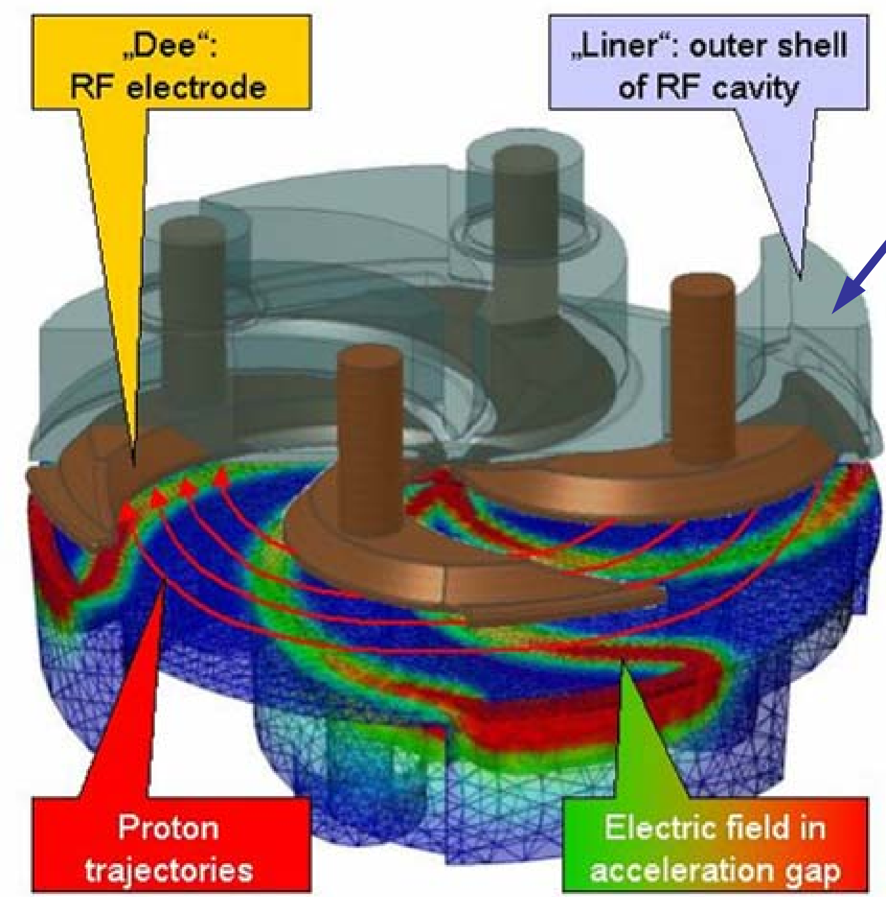
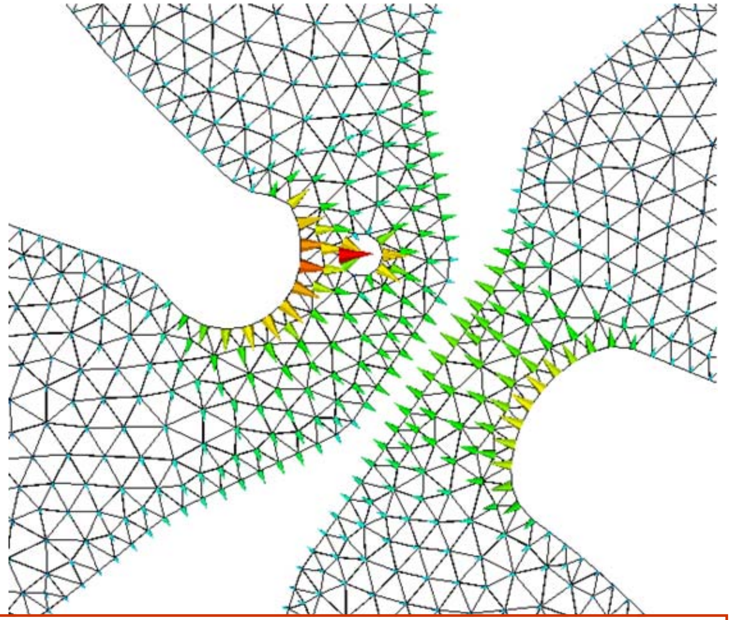


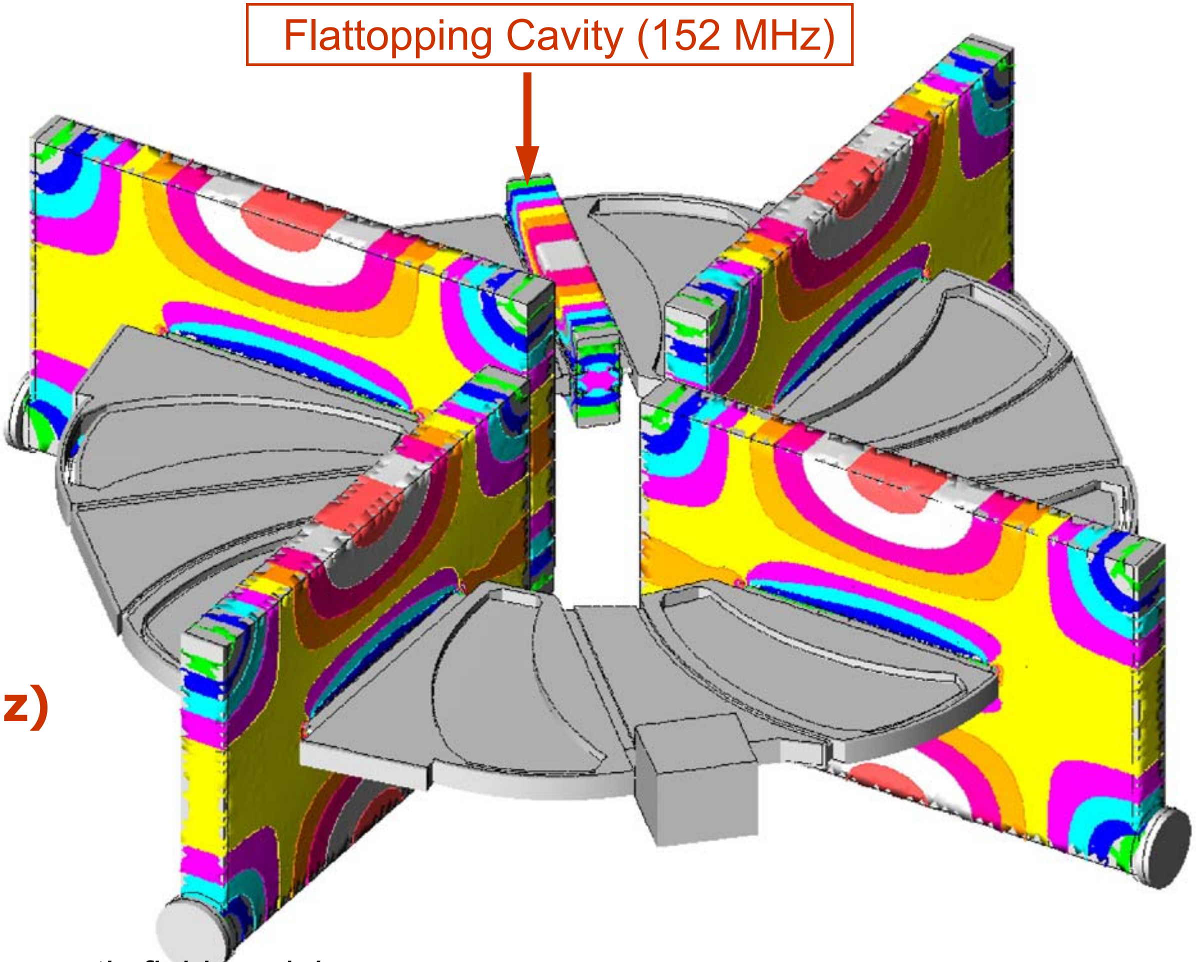
Fig. 12: Cyclotron electromagnetic field model

Electromagnetic field model; shown are:
- *Upper half: structure of Dees & liners*
- *Lower half:* ***mesh, E-field in gaps***



Field model of center region:
Mesh and E-field gradients in median plane

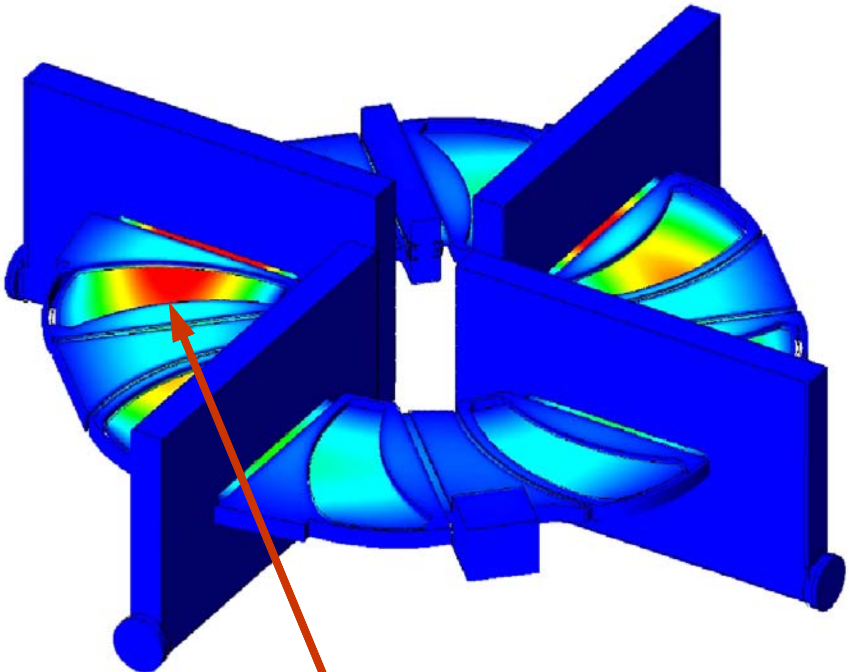
Results of the Electromagnetic Simulation: the PSI Separated Sector Cyclotron's *Fundamental Acceleration Cavity Modes*



Shown are the fundamental frequency (51 MHz) cavity modes for the H- field

Fig. 13: Cyclotron electromagnetic field model

. . and some of the Parasitic Cyclotron Modes:



E-field of **simulated** 54 MHz mode

Measured spectrum
(Network analyzer data)

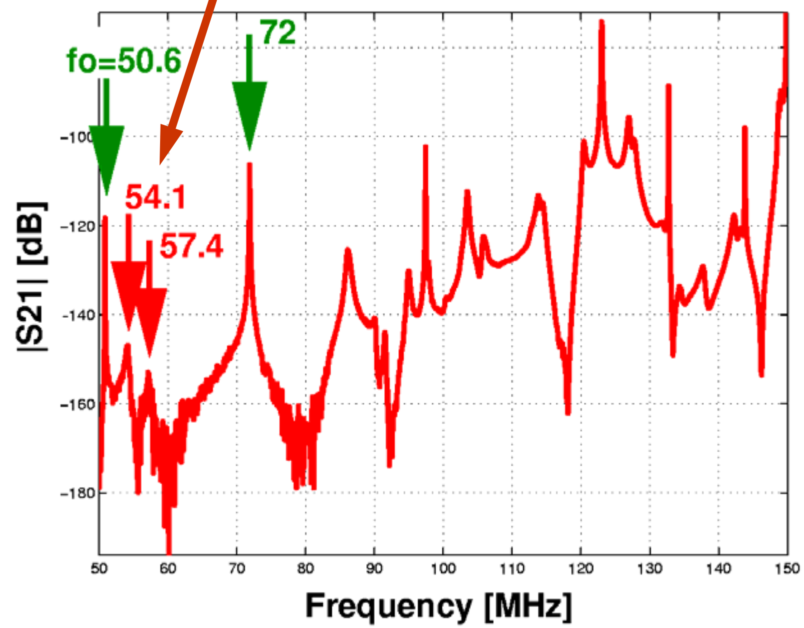


Fig. 14: Parasitic cyclotron modes

These Results allow a Field-Particle Interaction Simulation:

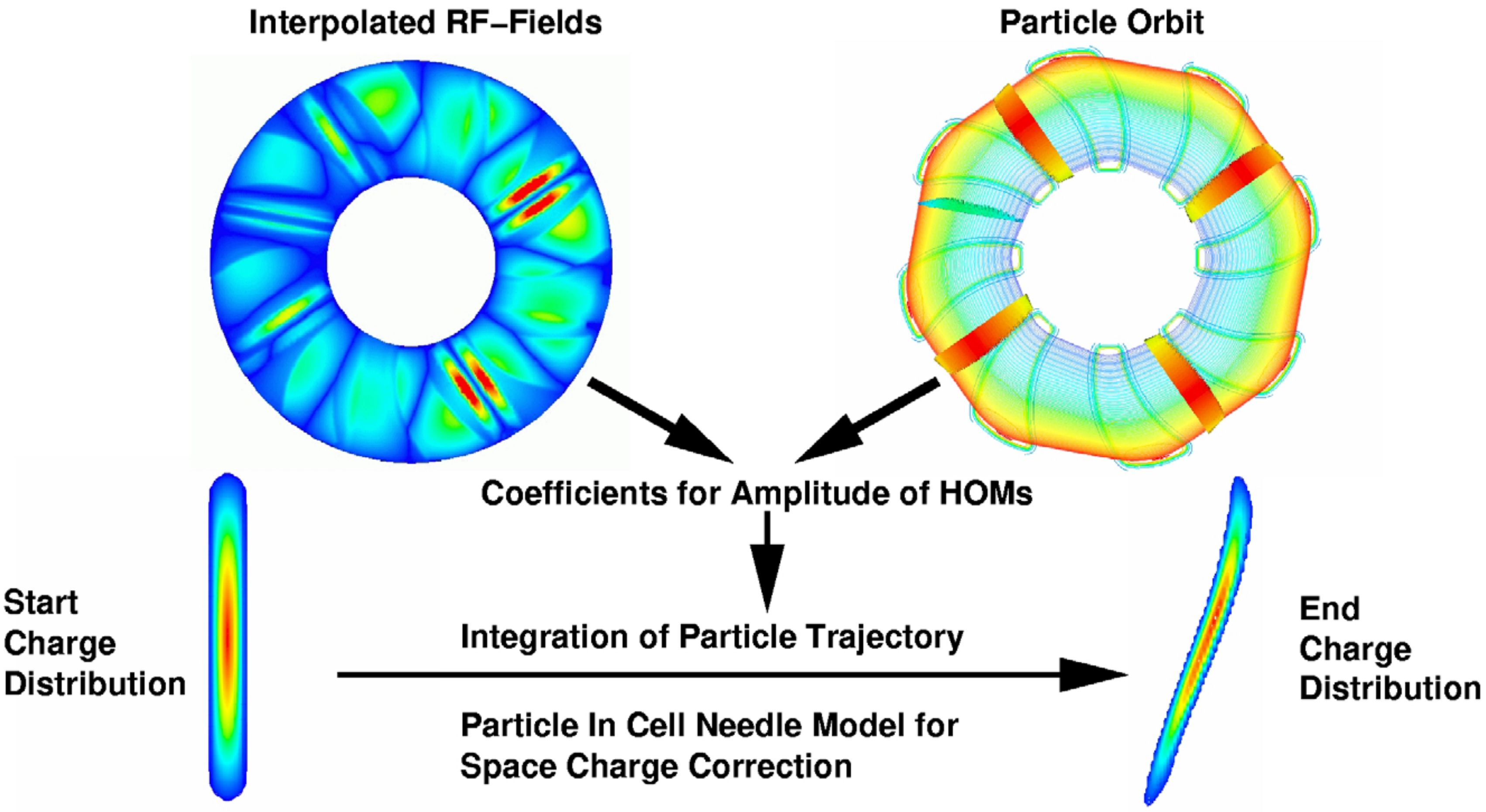


Fig. 15: Effect of beam induced fields on bunch charge distribution

Mechanical Engineering Design of an Integrated Cavity

Illustrated on a 50 MHz Cyclotron Cavity Replacement for the PSI Ring Cyclotron

- ***We use: FEA–Simulation (ANSYS) to answer the following questions:***

  - **Inner** dimensions of the cavity under **vacuum** ⇒ **resonance frequency**
  - Frequency drift (thermal, atmospheric pressure)
  - Temperature distribution
  - Frequency tuning range
  - Effect of manufacturing tolerances

?

- ***Applying Sequential Coupled Field Analysis, we arrive at crucial values for:***

  - **Inner** dimensions of the cavity in **air** ⇒ essential for **manufacturing!**
  - Frequency drift (tuning system)
  - H- and E- field distribution ⇒ acceleration gap voltage profile
  - Resonance frequency in air
  - Q-value

!

The Cavity Design Procedure in Some Detail:

Sequential Coupled Field Analysis

RF- Simulation (Modal)
- undeformed RF-Geometry

→
- H- and E- Field
- Resonance Frequency
- Q-Value

↓

Thermal Simulation
- heat flux
- forced convection (cooling)
- natural convection/ambient temperature)

→
- Temperature Distribution

↓

Structural Simulation
- results from thermal simulation
- atmospheric pressure
- hydraulic tuning forces

→
- Deformation
- Stress Factors

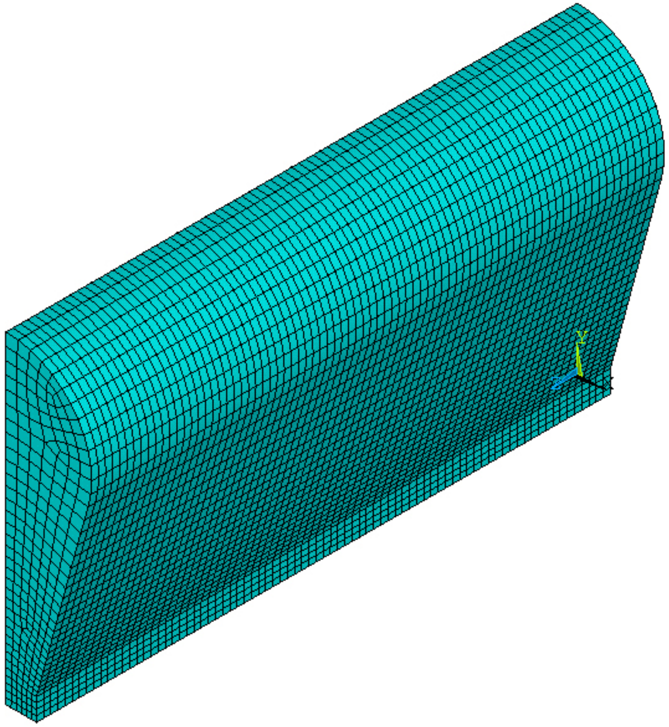
↓

RF- Simulation (Modal)
- deformed RF-Geometry

→
- **Frequency Drift**
- H- and E- Field
- Resonance Frequency
- Q- Value

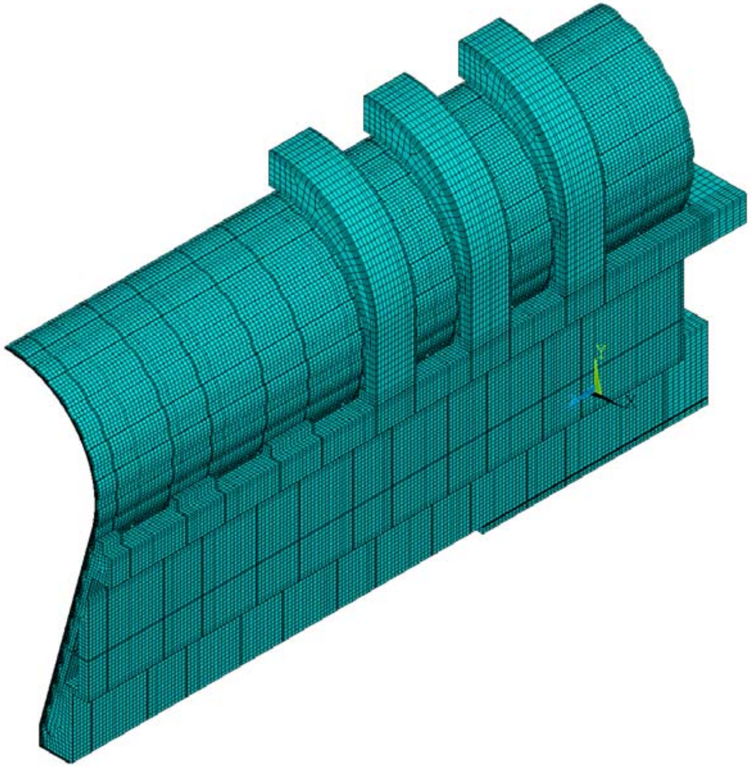
Illustration of these Steps on the 1/8th Sector Cavity Model:

1. RF-Model



20 Node Brick Element (HF120)
85'423 Nodes
18'954 Elements

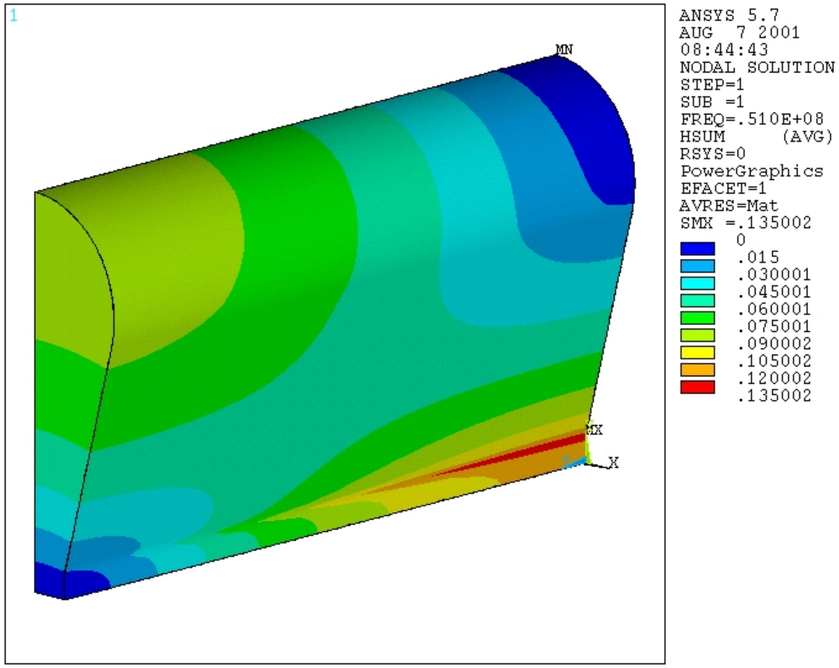
2. Mechanical/Thermal Model



8 Node Brick Element (Solid45/Solid70)
334'205 Nodes
292'484 Elements

Fig. 16: Cavity models

3. From the Magnetic Field Distribution to the Heat Flux Distribution..



H- field distribution

Temperature Distribution

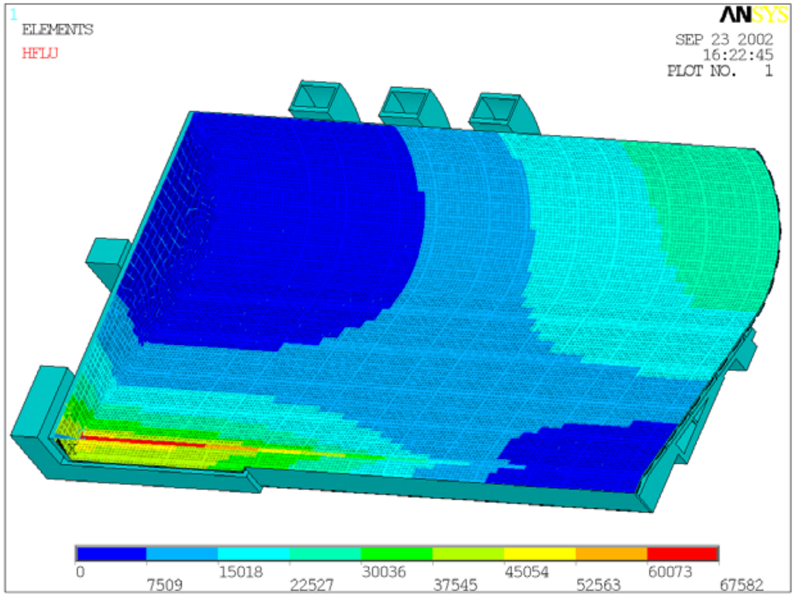
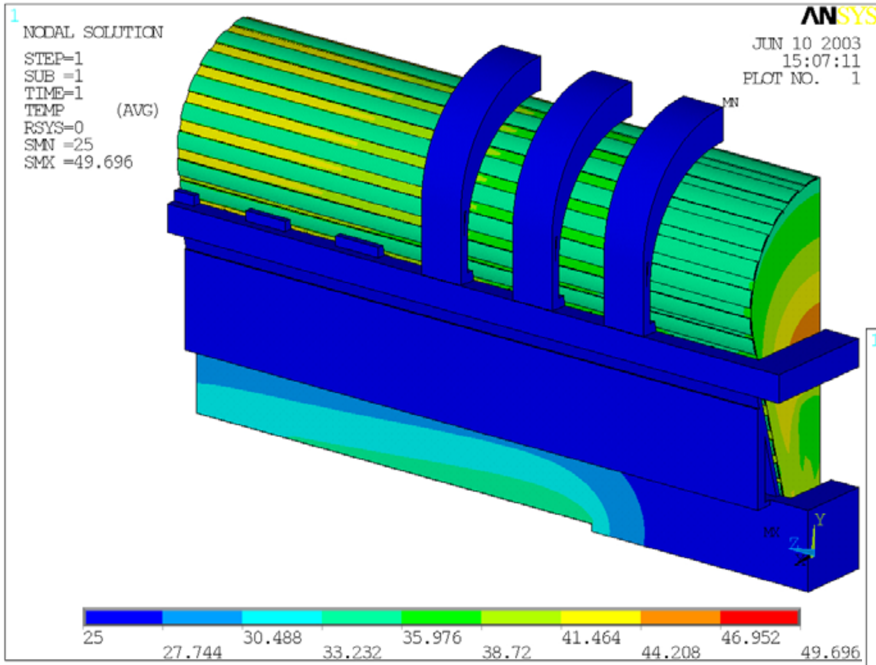


Fig. 17: Field- & temperature distribution on cavity

.. and to the Temperature Distribution at 500 kW RF Power



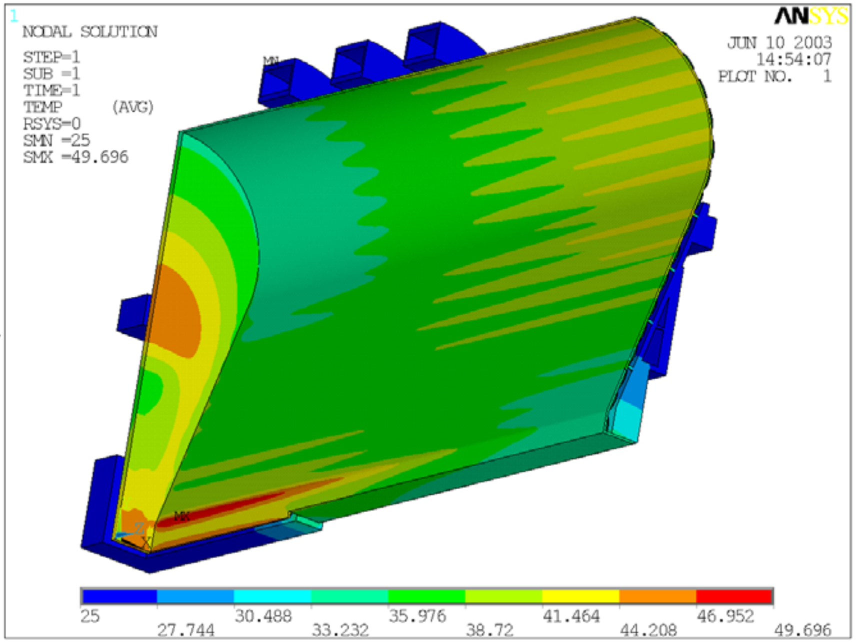
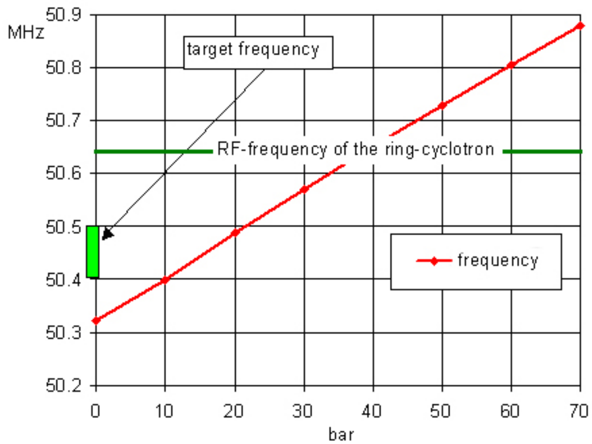
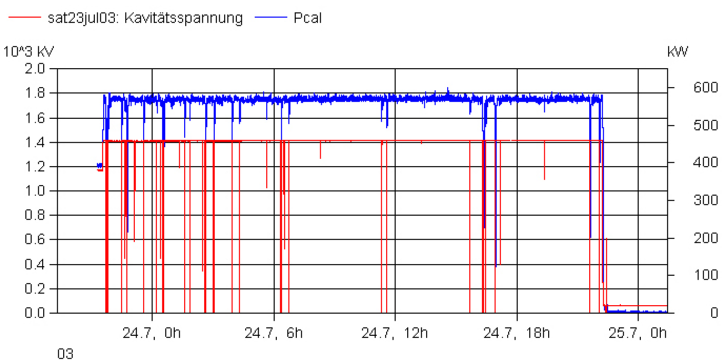


Fig. 18: Cavity model: temperature distribution

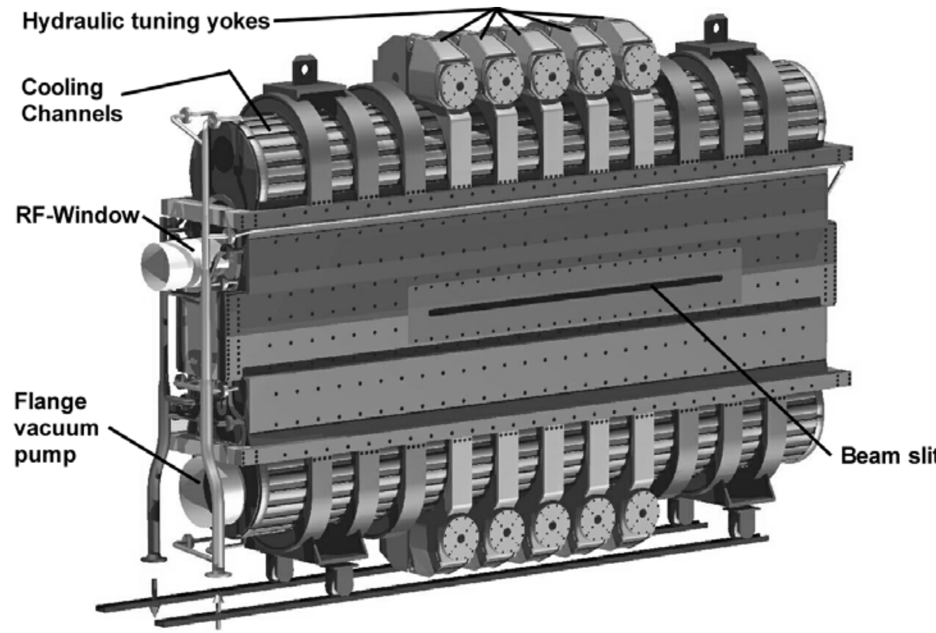
Final result: the new PSI cavity



Frequency tuning range: predicted and measured



Cavity commissioning test results: voltage and power



Resonance frequency		*Q-value*	
Calculated	*Measured*	*Calculated*	*Measured*
51.040 MHz	*50.993 MHz*	*46054*	*45090*

Fig. 19: The 50 MHz, 1.4 MV ring cyclotron cavity

RF Structures for Separated Sector Cyclotrons (SSC)

Higher energy levels, and/or higher beam power ask for a different approach to cyclotron design:

Take the cyclotron apart: Separate sectors for RF cavities and magnets → SSC

- **New challenges for cyclotrons; existing and new machines:**
- Higher energy: 1 GeV or higher; with multitude of particles and charge states
  → Radioactive beam facilities, e.g.: RIBF, at RIKEN (J)
- High beam currents: > 3 mA (p), CW; → (PSI upgrade);
- Very high beam power: > 1MW, for neutron spallation sources: (PSI at present: 1.2MW)
  → MYRRHA project; and in the future: HPPA's for ADS, like for transmutation or energy amplifier projects
- Superconducting magnets (RIKEN, RIBF), and even superconducting cavities (TRITRON)!

Consequences for RF systems:

- *Very high cavity acceleration voltages:* from several 100 kV increase to >1 MV: → high Q_o , low wall losses (high R_p)
- *Very high power RF amplifiers* are required (→ 1 MW_{RF})
- *Control systems* demand very high amplitude- & phase stability under variable load conditions (stability!)
- *Beam loading* no longer negligible, load matching difficult (strongly varying load!)
- *Power couplers* become critical components; > 600 kW (CW) per coupler
- *Flat-topping* systems are needed, they are even more demanding, because of (inverse) beam loading effects
- *Increased reliability:* → Much shorter unscheduled down-times required
  → Improved maintainability and repairability
  → Significant reduction in the number of cavity sparks and very fast recovery from such events (beam trips)
  ⇒ Goal: from 1 trip/day to 10 trips/year for ADS applications!

Classes of separate sector cyclotron (SSC) cavity designs:

Cavity designs in general depend on the specifications and geometric layout of a cyclotron, therefore designs are differentiated by their electromagnetic- and geometrical properties:

- Operating frequency:
  - *Fixed frequency* cavities:
    fixed energy proton accelerators, e.g. for spallation neutron sources and ADS.
    Such designs tend to be simpler and therefore cheaper.
  - *Variable frequency*: variable energy (and variable particle type) machines:
    they require cavities with a wide frequency tuning range, (frequency ratio: > 2:1), and operate at different acceleration voltages.

- Single-gap- and double gap cavities

- 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. → TRITRON !

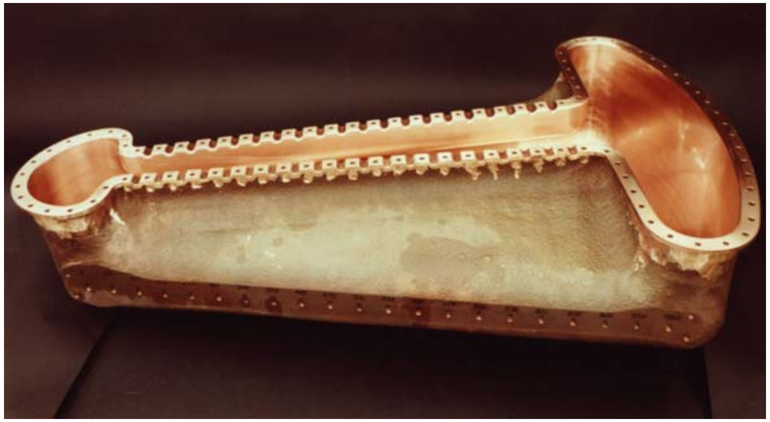
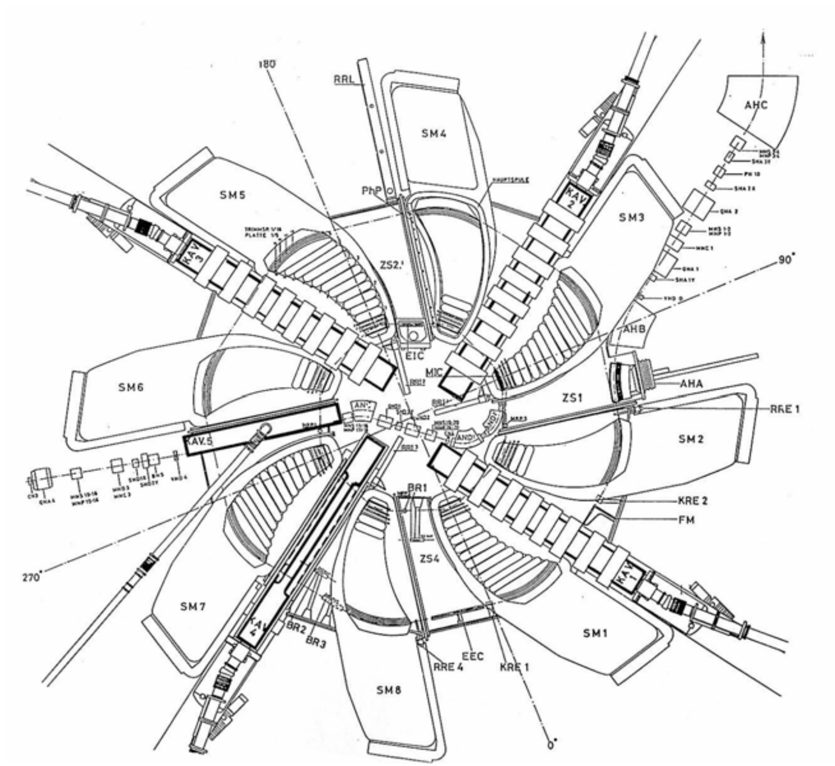


*Fig 20: Half shell of the **TRITRON superconducting RF cavity**; note that there are no beam slits, but rather 20 holes per side for the 20 beam orbits !*

An example of a separate sector cyclotron: the PSI ring cyclotron



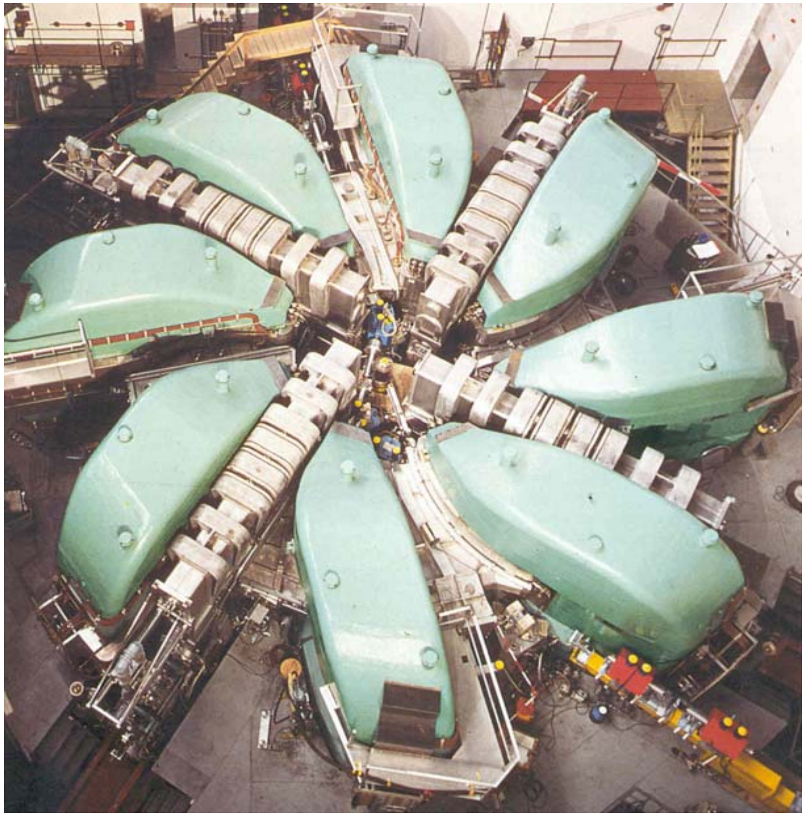
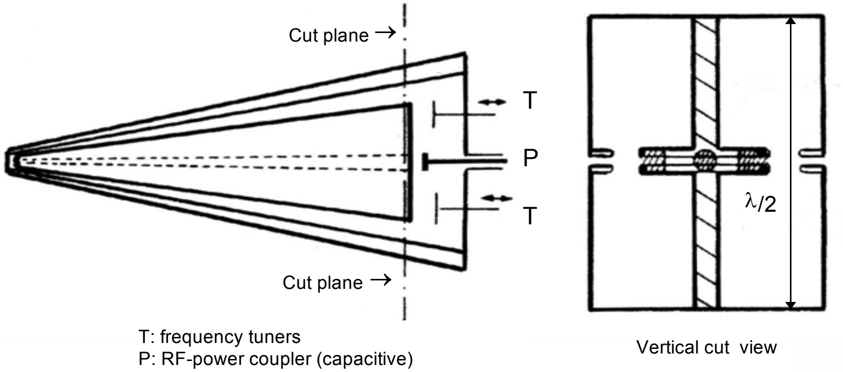


Fig. 21: A typical 'Separated Sector Cyclotron' (SSC), median plane view (left), and photo (right). Shown is the PSI 590 MeV (p) ring cyclotron, with 8 sector magnets and 4 accelerating cavities

The Double Gap (λ/2 Transmission Line Type) Resonator



2 Examples:

Fig. 22: Simple sketch of a λ/2 double gap cavity, fixed frequency (PSI injector cyclotron).

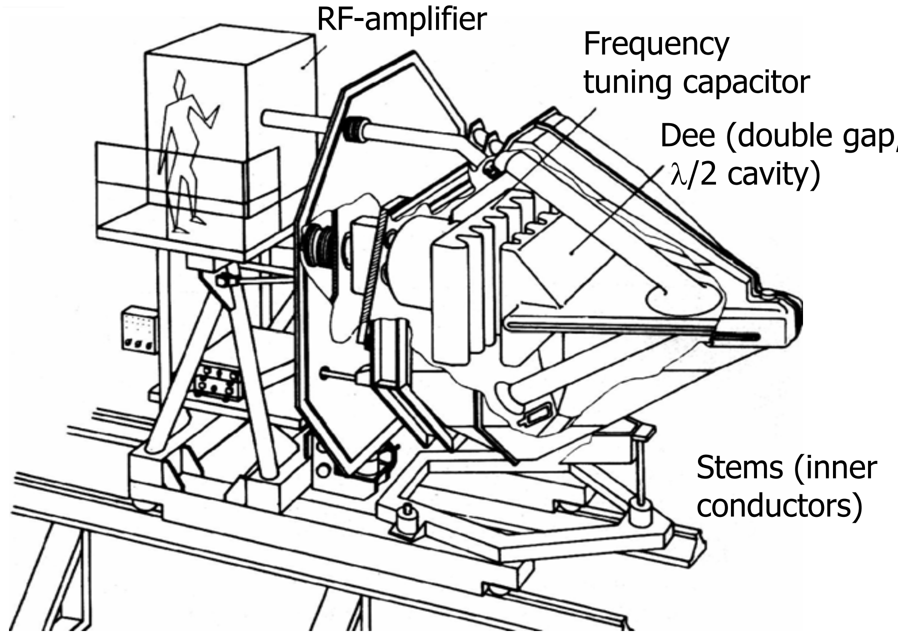


*Fig 23: A 'real' **double gap cavity;** coaxial, λ/2 design, variable frequency, with capacitive tuning (GANIL)*

The Structure of a GANIL Double Gap λ/2 Resonator:

Schematic drawing from the previous page –
illustration of physical details

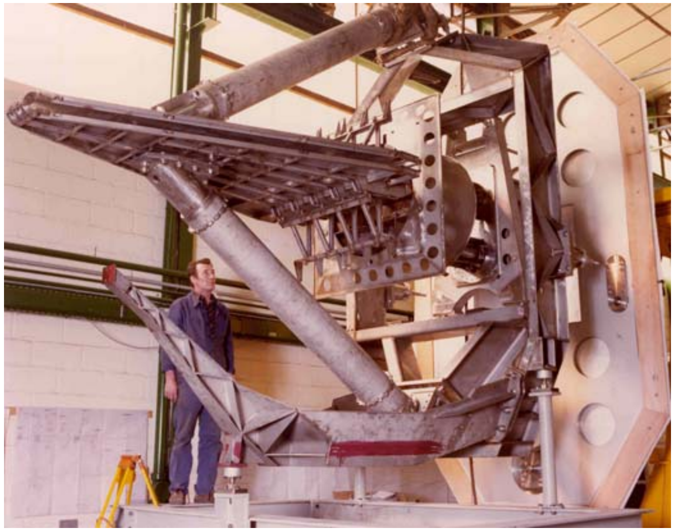


Fig. 24: Stainless steel support frame, beam plane is visible

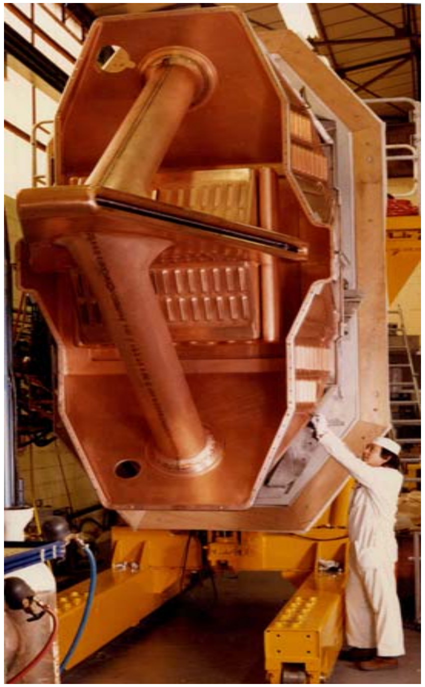


Fig. 25: Copper skinned inner conductors with 'Dee' (inner electrode)

Fig. 26: Outer shell of resonator, with support frame and beam slit

The Single Gap Cavity *(compare Fig. 19, the new PSI Cavity)*

In the simplest version it is a box (waveguide), operating in the fundamental mode H_{101}:

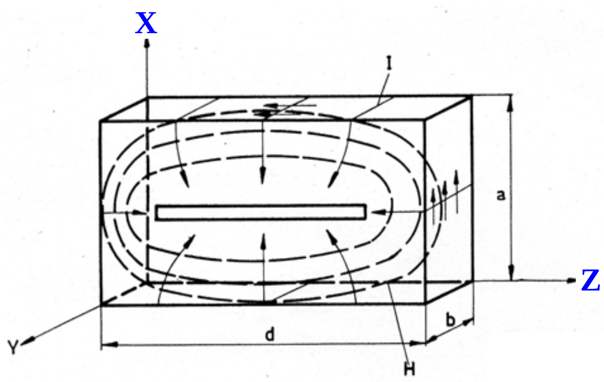
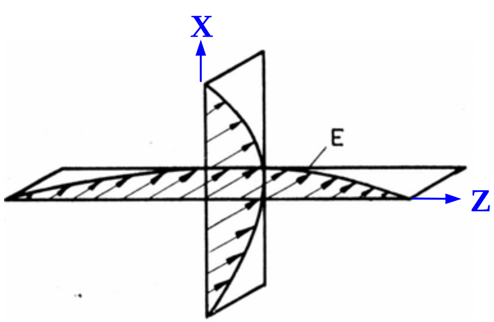


Fig . 27: Single gap cavity, simple box shape and voltage distribution



Properties: For the fundamental mode, we have:

$$\lambda_{101} = \frac{2}{\sqrt[2]{\frac{1}{a^2} + \frac{1}{d^2}}} ; and: f_{101} = \frac{c}{\lambda_{101}} = \frac{c}{2} \cdot \sqrt[2]{\frac{1}{a^2} + \frac{1}{d^2}}$$

Advantage:

a box cavity can be made less sensitive to higher harmonics: choose the ratio of *a* to *d* such that some ***higher order modes do not coincide with the higher harmonics*** of the fundamental mode !
Higher Q_o- and R_p values are obtainable than in coaxial $\lambda/2$ resonators, therefore higher acceleration voltages can be reached

Disadvantage:

single gap cavities are best used in 'ring cyclotrons' because acceleration voltage is sinusoidally distributed; that is: not available across the full radial dimension of the cavity (see Fig. 27)

Tuning the cavities

For fixed frequency cavities, keeping them tuned to the resonance is comparatively simple (see Fig. 19, the PSI ring cyclotron cavity).

Wide range tuning systems for cyclotrons with variable frequency however, are quite demanding: depending on the type of resonator, different strategies have to be used:

Double gap, coaxial type cavities ($\lambda/2$ or $\lambda/4$)

1. A **moveable (sliding) shorting plane** at each inductive end of the resonator; (see Fig. 5; Fig. 7 shows the solution for the NSCL superconducting cyclotron)
2. using a fixed short, **vary the characteristic impedance Z_l** of the current end section of a transmission line, thus changing the effective length; Fig. 6)
3. alternatively, (to obtain the same effect): change the impedance at the capacitive end of the resonator with a **variable capacity** (the GANIL design, Fig. 23).
4. Finally, one can use **moveable sections of (lower) characteristic impedance** inside the coaxial lines, thus again varying the effective length of the resonator. (see Fig. 28)

Tuning a double gap, coaxial type cavity (λ/2)

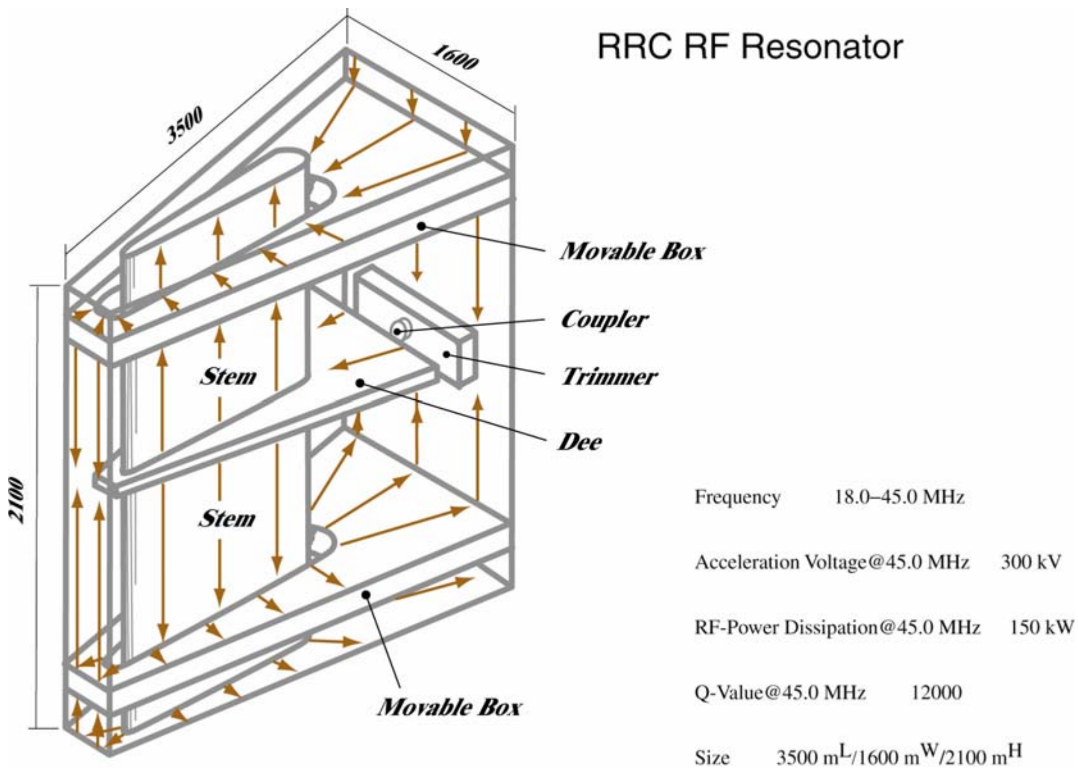


Fig. 28: A λ/2 double gap cavity, frequency variation and vertical symmetry is achieved with 'moveable boxes' (RIKEN) (includes a trimmer for fine tuning)

Tuning single gap, waveguide-type cavities

Such cavities are designed for high Q_0-values and higher acceleration voltages.

Due to the lack of internal parts (no inner conductor), technical possibilities for frequency tuning over a wide range are more limited.

Sliding Shorts

The resonance frequency of such a 'box' is usually defined by two key dimensions - the height ***a*** and the length ***d*** (comp. Fig. 27) The dimension ***d*** (along the acceleration gap) should remain constant, varying the height ***a*** by symmetrically ***moving top-*** and ***bottom walls*** is an obvious way to obtain the frequency variation. This method is employed in the flat-top cavity design of the RCNP ring cyclotron as well as in the two cyclotrons (IRC- and RRC) of the RIKEN RIBF, there the concept is used for flat-topping cavities.

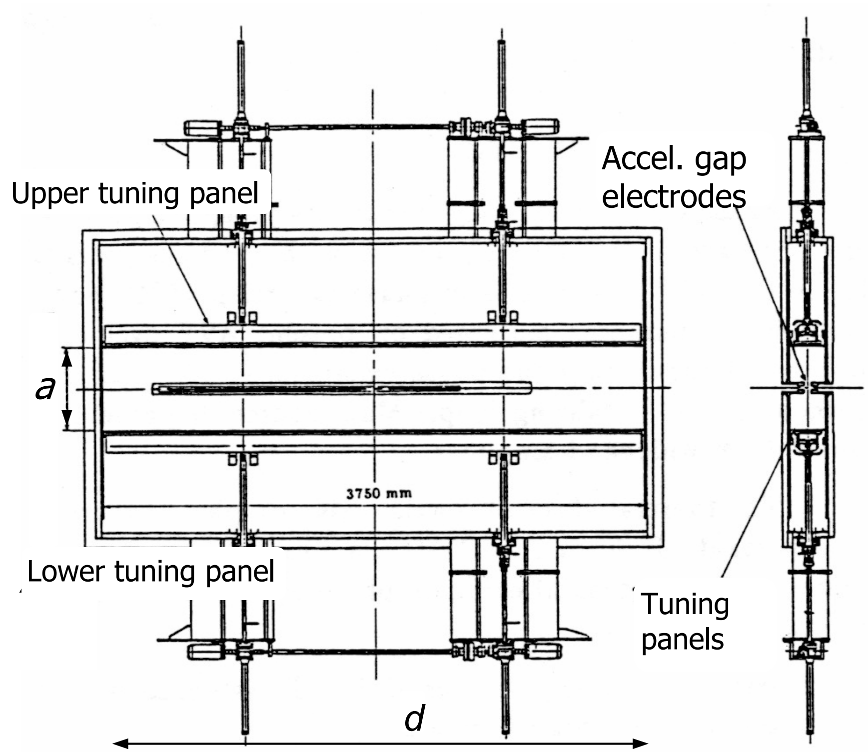
For even higher voltage levels – used for accelerating cavities - a different approach for resonance frequency variation can be chosen:

'Flapping Panels'

The ***'moveable (rotating) flap'*** (a.k.a. 'flapping panel') design. This concept achieves respectable acceleration voltages (up to 500 kVp @ 38 MHz in the RIKEN SRC cavity). Critical components are the hinges; they have to carry the panel currents to the cavity wall. (see Fig. 30) Such cavities, with their tuning systems, 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.

Illustration of two different tuning systems:

Sliding shorts



'Flapping panels'

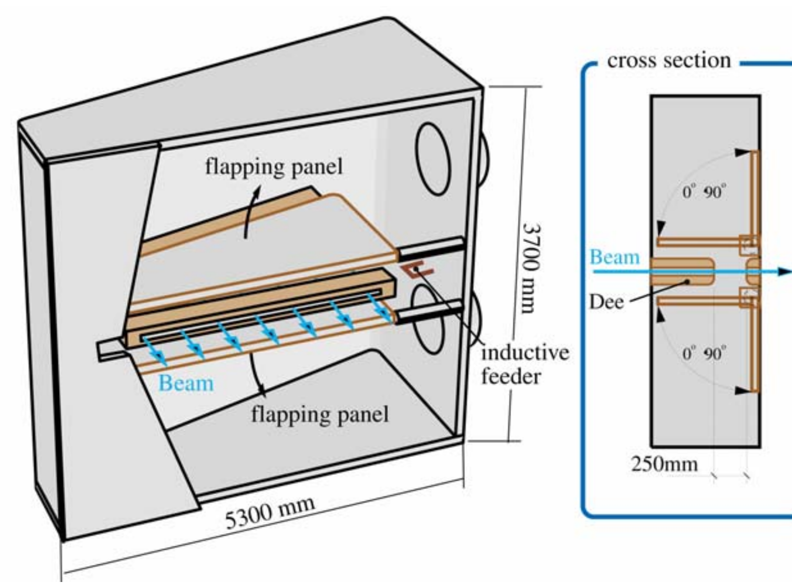


Fig. 29: The flat-top cavity of the RCNP cyclotron, with sliding upper- and lower walls: the 'tuning panels'

Fig. 30: View of SRC cavity and tuning system with moveable flaps ('flapping panels')

RF Power Amplifiers

Characteristics, Requirements, Concepts

- **Operation mode**: mostly CW, pulsing can be used for start-up (to overcome multipacting in cavities)
- **Operating frequencies**: from ≈ 2 MHz to ≈ 200 MHz
  - Variable frequency amplifiers: → extensive *remote controlled tuning* circuitry required!

    Frequency range: if possible choose in *commercial broadcasting domain* (e.g. short wave range, ≈ 6 - 26 MHz; or low TV or FM broadcasting range. *(Simplification: no high power modulators required!)*

    Advantages:
    - 'Off-the-shelf' amplifier chains available at reasonable conditions (costs, delivery time)
    - Wide power range available (several 100 kW is no problem)
    - Automatic (remote controlled) frequency tuning is usually included.
    - High reliability; long term availability of spare parts is often guaranteed.
  - Fixed operating frequency power amps:
    - First, also look at *commercial amps* (TV, FM broadcasting)
    - Alternatively, have amplifiers custom built (very few manufacturers!) or acquire ability to design and build yourself, especially if you require 'exotic' frequencies or very high power (knowledge base will be useful for improving and modifying later)
- **Amplifying** (active) **components:**
  - Driver stages: solid state designs, used up to 10 kW
  - Final stages: power tetrodes for communication: air- or water cooled, metal-ceramic constructions.

    Reliable (>18'000 hrs operation time if properly protected). Gain: ≈ 13 dB in grounded grid configuration.

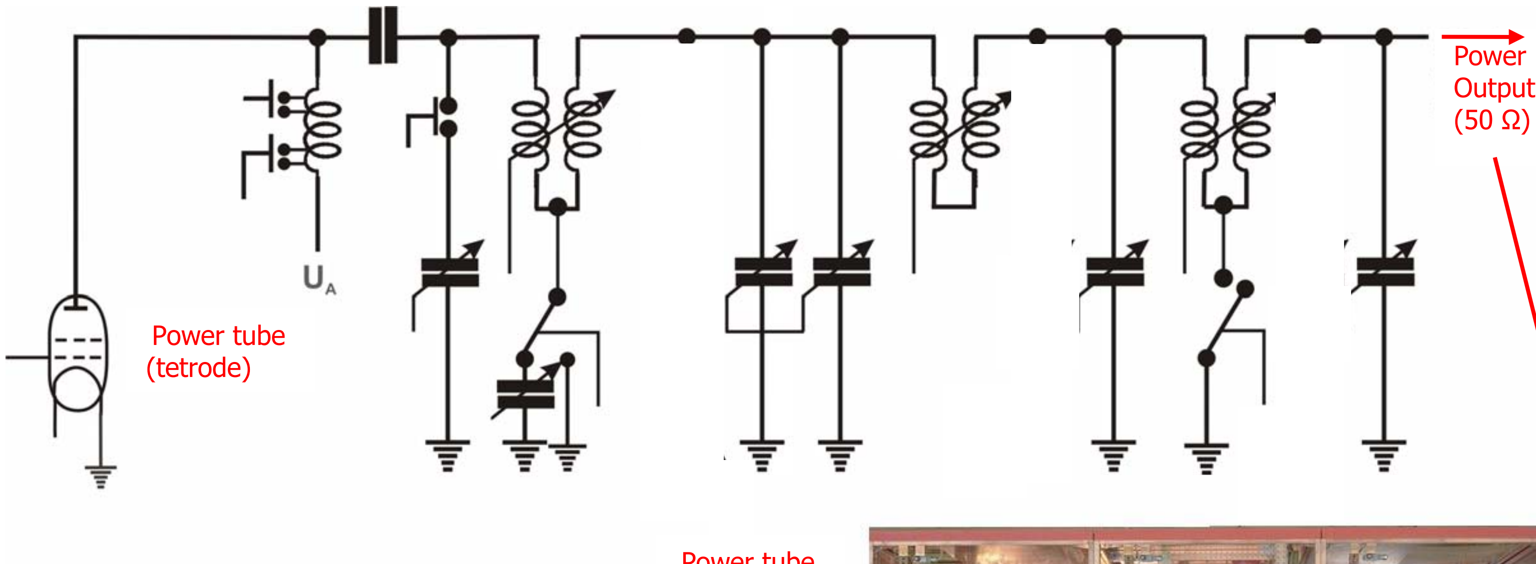
    Robust: → sparking in cavities or Dees does not damage tube with proper protection measures.

    High efficiency (60-70 %, defined on wide-band 50 Ω load)

Important: When specifying the required output power of final stage amplifier, sufficient reserve (≈ 30%) should be included, to provide the regulation range for the amplitude control system (cavity voltage); and ageing!

Types of Power Amplifiers:

a) Discrete components, grounded cathode configuration



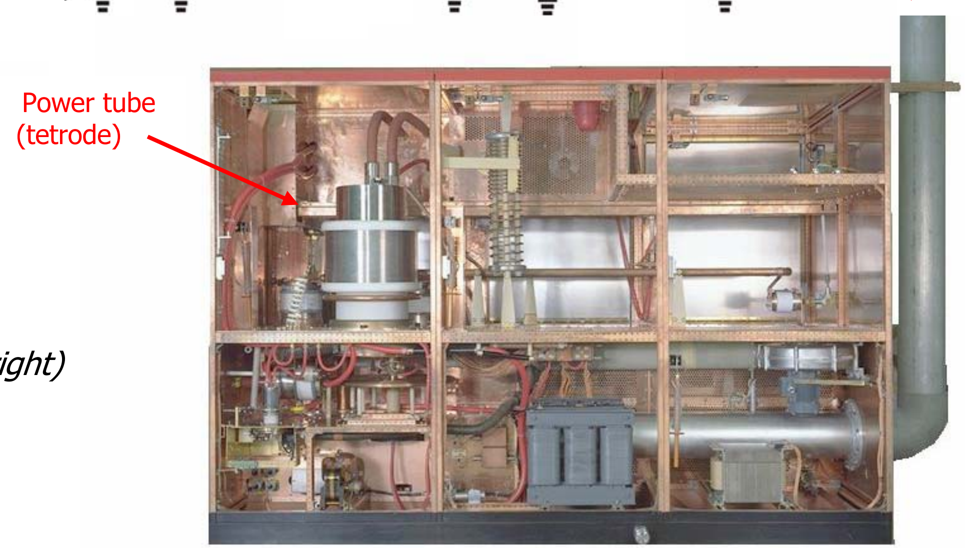
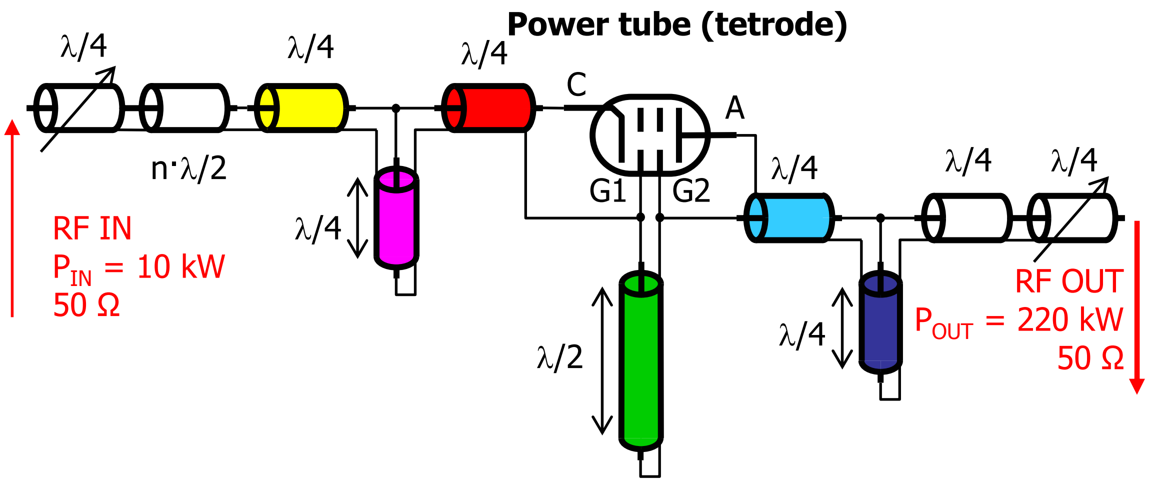


Fig. 31: Commercial short wave transmitter,
4 – 26 MHz, 500 kW RF output power
Simplified block diagram, (top) and
picture of open final amplifier cabinet (right)
(THALES, model TSW 2500)

Types of Power Amplifiers (cont.)

b) Coaxial design, grounded grid configuration



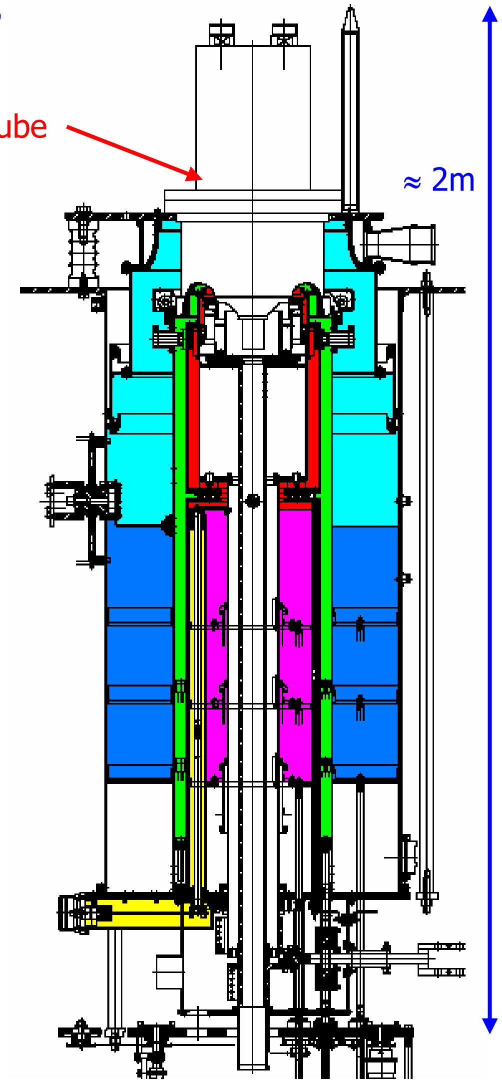


Fig. 32: Schematic diagram (simplified) and cross-sectional view of PSI's new 150 MHz/220 kW power amplifier (The colors in both images match, that is: represent identical components)

Cyclotron RF Control Systems

Some basic facts and prerequisites

The key control circuits in a cyclotron RF system are:

- **Amplitude** (= cavity/Dee-voltage) **control system**. It includes the pulsing/ramping circuitry (if required), and also the RF-, cyclotron- and safety interlock access ports. Typical stability values that can be obtained are: $V_{noisepp}/V_{ResDC} < 2 \cdot 10^{-4}$ pp
- **Frequency tuning system** (might be split into coarse- and fine tuning) Different actuators can be used; the most popular types are:

  - Stepping motors (with or without gears), suitable if control element (e.g. trimmer) is not continuously moving (e.g. coarse tuning)
  - Hydraulic actuators are used when fast, continuous corrections are required, or in case of heavy mechanical load (large mass, or vacuum forces)

- **Phase control system** – required only if cyclotron consists of more than one independent amplifier/Dee system and/or is used in a multistage configuration (more than one accelerator connected in series). Phase noise (peak-peak) can be held $< 0.05\,^{0}$ pp

Cyclotron RF Control Systems:

Block Diagram of a typical (generic) RF Control System

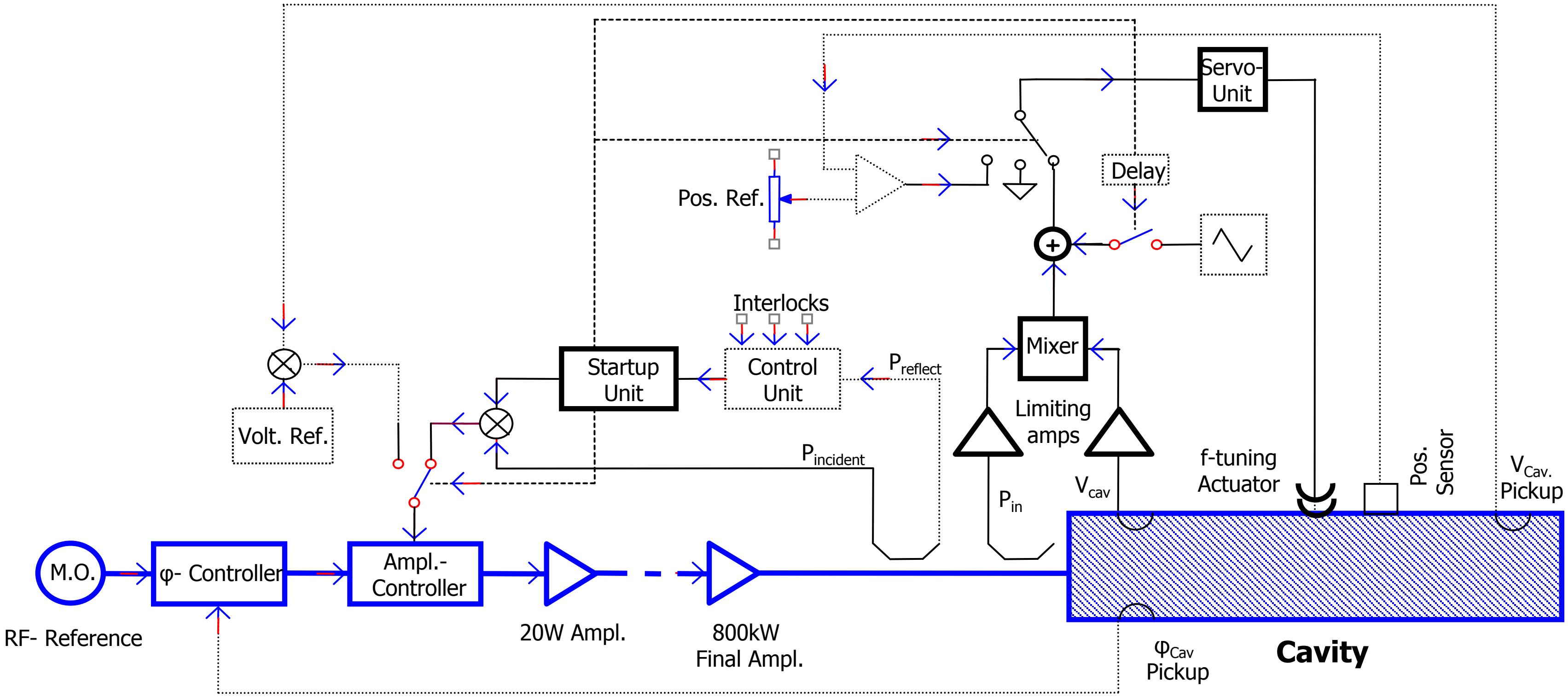


Fig. 33: Block diagram of a typical RF control system, showing the main RF signal path, the amplitude (A) control loop, the phase (φ) control loop, and the resonance frequency tuning loop

Block Diagram of Amplitude (A) Control Loop

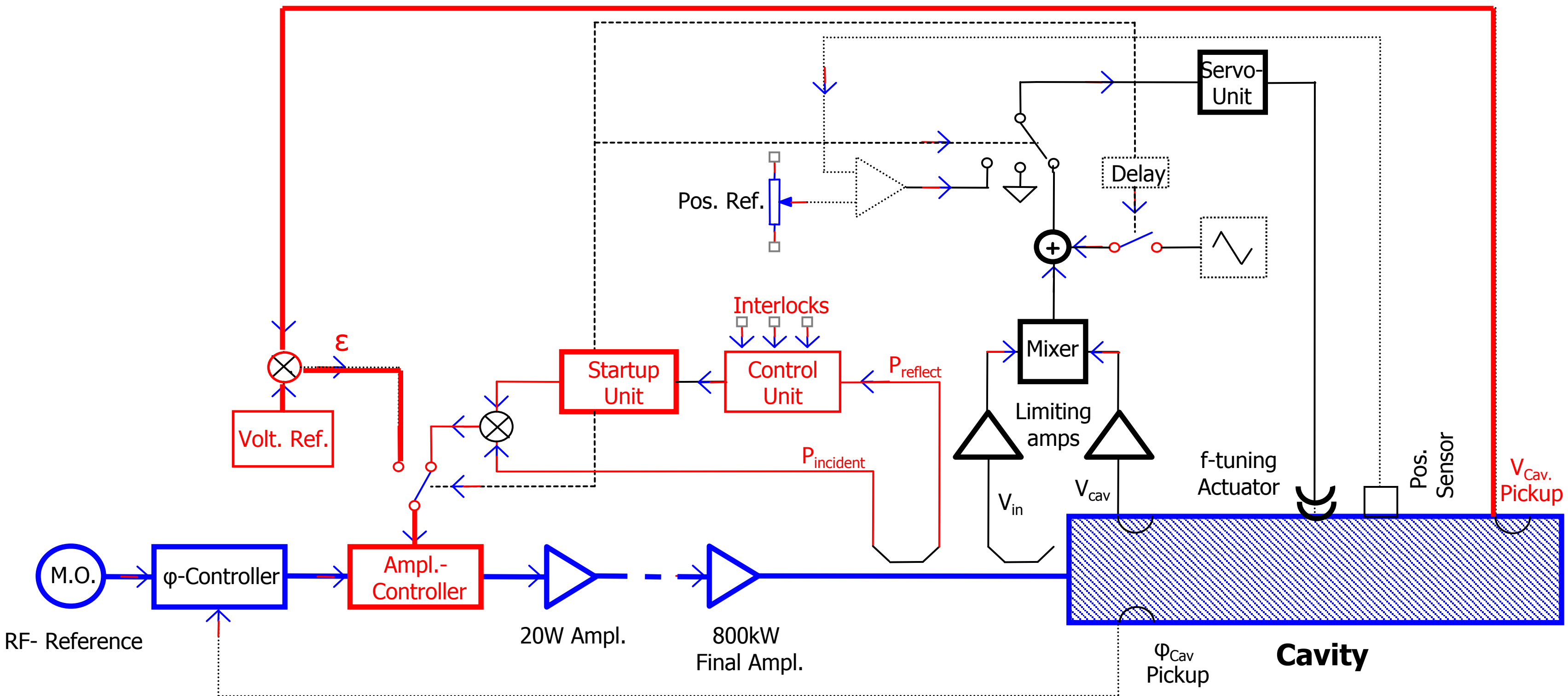


Fig. 34: Block diagram of the ***amplitude (A) control loop****, with pulsing/startup- and interlock control circuitry*

Block Diagram of the Phase (φ) Control Loop

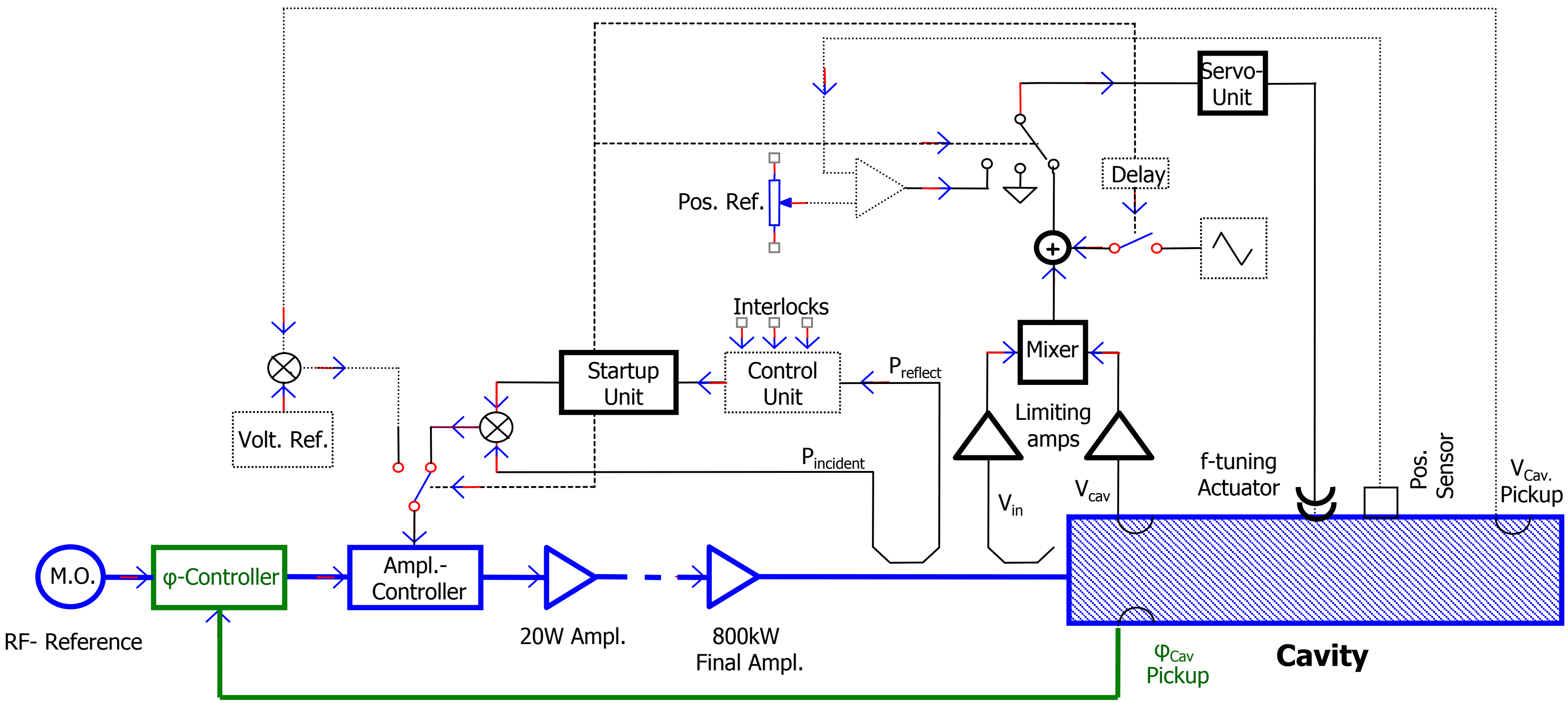


Fig. 35: Block diagram of the ***phase (φ) control loop***

Block Diagram of the Resonance Frequency Tuning Control System

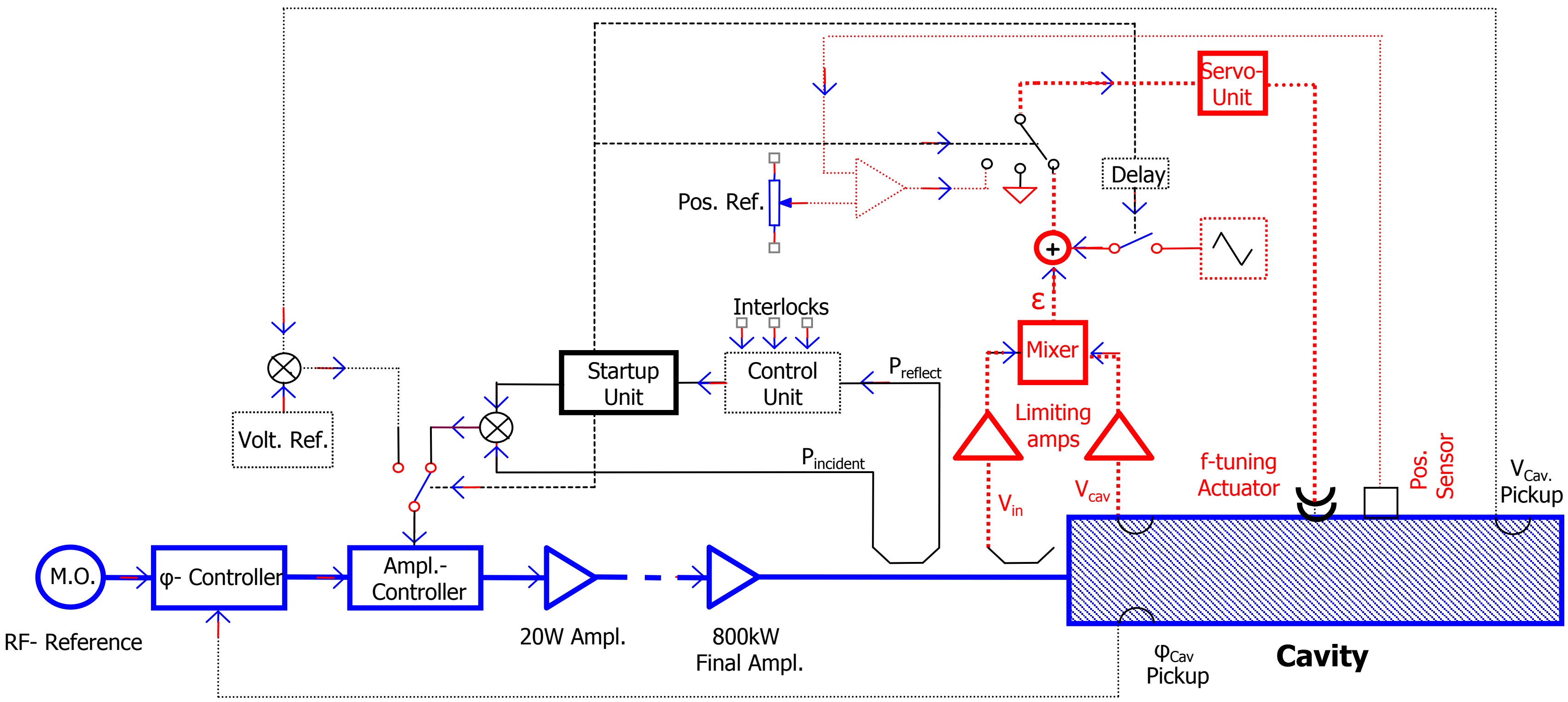


Fig. 36: Block diagram of a ***resonance frequency tuning loop***

A few Notes on Cyclotron RF Control Systems

Cavity voltage turn-on procedures:

After limiting amplifiers with dynamic ranges of up to 60 dB became available, it was possible to tune resonators at very low power levels (below multipacting levels!), 'punch' rapidly through the multipacting regions, and continue to ramp to the required cavity operating voltage. Such a control signal is shown below.

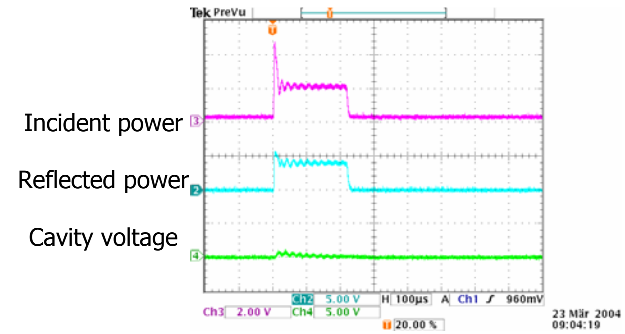
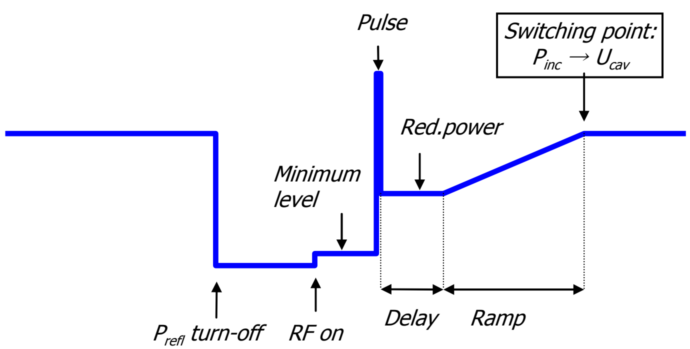


Fig. 38: RF signals in a 200 μs pulse: off resonance (above) , and on resonance (below) Duty cycle: ≈ 1%.



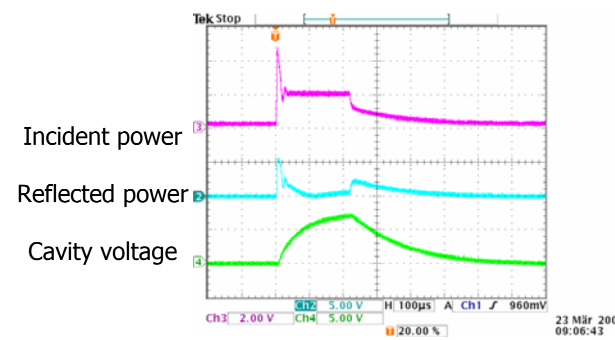


Fig. 37: Turn-on procedure of cyclotron cavity voltage, with pulsing and ramping

A few Notes on Cyclotron RF Control Systems (cont.)

Control loop optimisation, ground loops

When control loops are designed, gain- & bandwidth- optimisation is usually carried out according to the rules for small signal (linear!) control theory. This is legitimate – contrary to transmitter design, we usually do not want any modulation at all! Often though, the theoretically possible suppression of the distortion, hum and noise cannot be reached. Mostly, this is due to ground loops – the concept is usually considered only when most of the hardware is already in place. Below is an illustration of the effect: shown are the frequency spectra of the demodulated cavity amplitude signal. The same concept applies to all other high bandwidth control loops, of course.

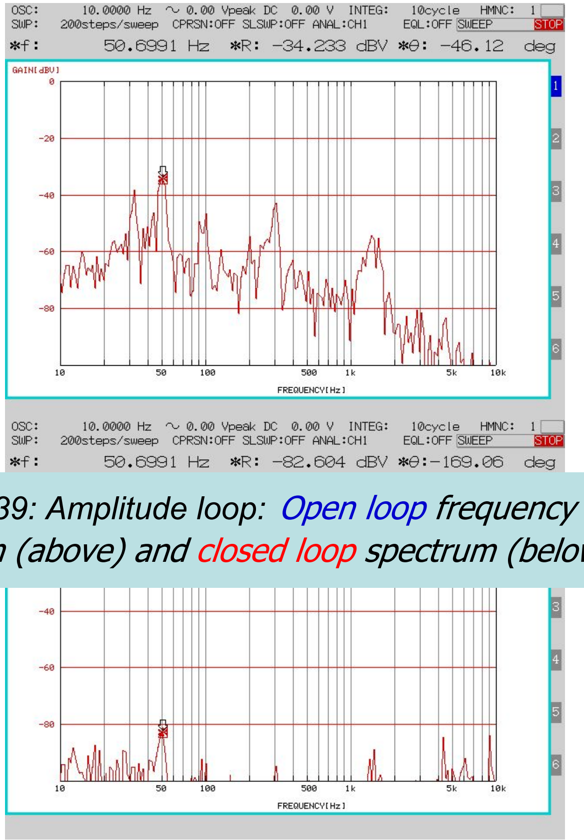


Fig. 39: Amplitude loop: Open loop frequency spectrum (above) and closed loop spectrum (below).

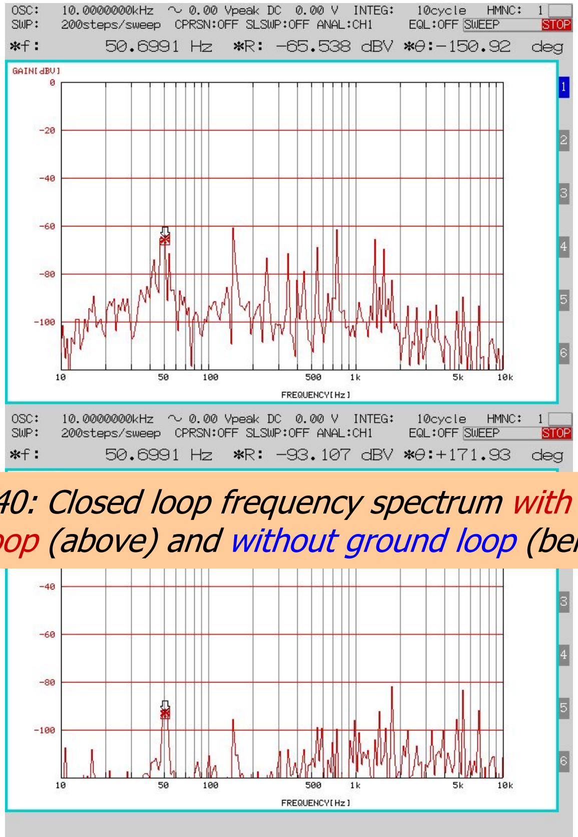


Fig. 40: Closed loop frequency spectrum with ground loop (above) and without ground loop (below)

Outlook:

In future applications of cyclotrons, availability and reliability become very important issues. Issues like cavity voltage spark rate, repairability and maintainability become of paramount importance.

The reduction of the amount of activated material (nuclear waste) produced when cyclotrons reach the end of their lifecycle has to be designed into new machines from the beginning. (⇒ remove as much equipment as possible from cyclotron vaults!)

The newer fields for cyclotron applications, like compact SC medical cyclotrons, ADS; or new concepts, like 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 break-down mechanisms as well as multipacting phenomena in cavities.

Machines will have to be designed with higher efficiency (also a new aspect in cyclotron design), and reduced operational costs: cyclotrons will be measured by the same criteria applied to other 'high-tech' industrial products.
(Note: this is already the case in commercial cyclotrons !)

Acknowledgements

My thanks go to all my colleagues for letting me use their pictures and documentation, to illustrate the many interesting ways to build cyclotrons!