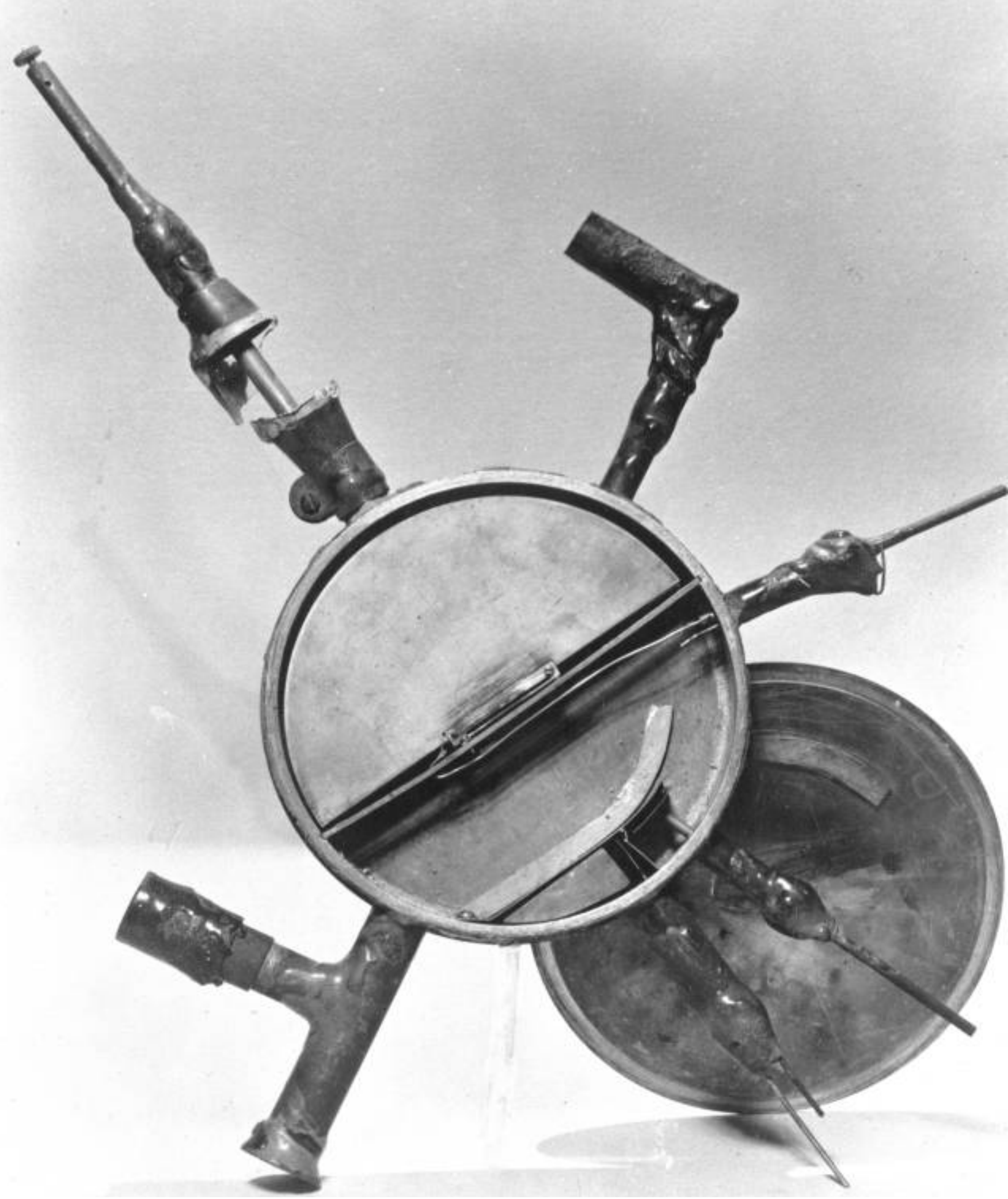
cyclotron

RF

systems



outline

- cyclotron basics
- resonator design techniques
  - transmission line
  - 3D finite element
- resonator tuning
- power coupling
- power generation
- RF control
- some specific examples

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cyclotron basics

- original observation: homogeneous magnetic field isochronous (Lawrence & Livingston 1931)

$$\frac{mv^2}{R} = qvB \qquad R = \frac{mv}{Bq} \qquad \nu_{orb} = \frac{Bq}{2\pi m}$$

centrifugal force — Lorentz force

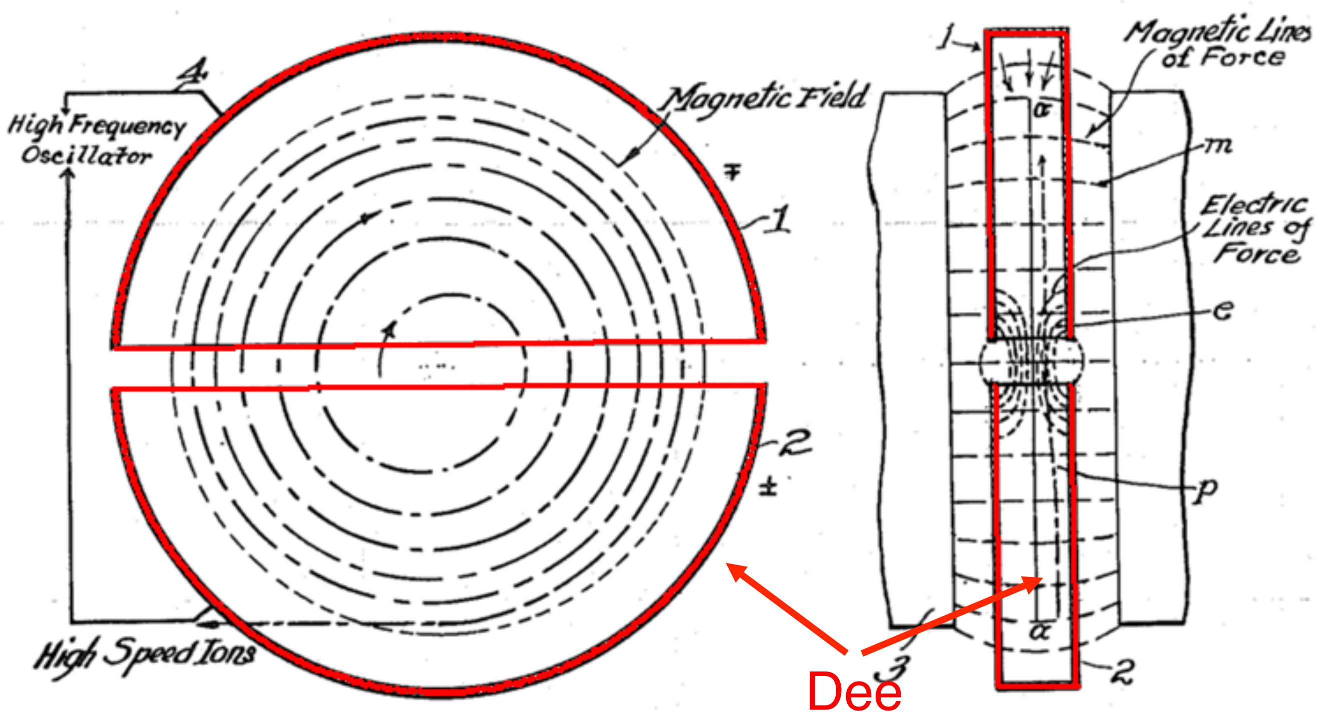
cyclotron basics

- original observation: homogeneous magnetic field isochronous (Lawrence & Livingston 1931)

$$\frac{mv^2}{R} = qvB \qquad R = \frac{mv}{Bq} \qquad \nu_{orb} = \frac{Bq}{2\pi m}$$

  - accelerate with RF electric field with $\nu_{RF} = h\ \nu_{orb}$ (h integer)

- drift tube linac “rolled up” in a magnetic field



U.S. Patent 1948384 -- Ernest O. Lawrence – Method and apparatus for the acceleration of ions.

why it should not work

- transverse optics
  - homogeneous field: fieldindex n = 0
    - Q_z, ν_z= 0; no vertical stability
    - ➡ linear growth of vertical beamsize
    - Q_r, ν_r= 1; resonance
    - ➡ no stable orbit due to imperfections
- longitudinal optics
  - isochronous: no longitudinal stability
  - relativistic mass increase
  - ➡ loss of synchronisation with accelerating voltage

why it works after all to some extent

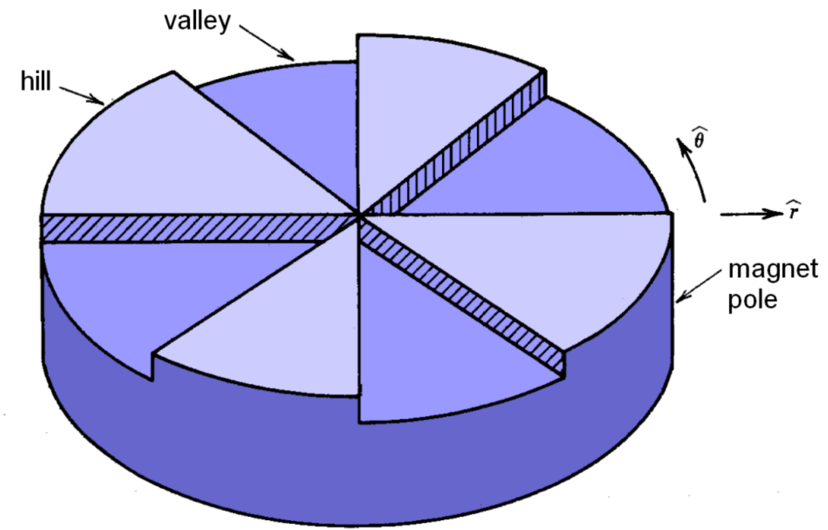
- fringe field effects: fieldindex $n = \varepsilon > 0$
  - Q_z, $\nu_z > 0$; marginal vertical stability
    ➡ large beamsize ➡ bad transmission
  - Q_r, $\nu_r < 1$; no resonance
  - “weak” focussing

- loss of synchronisation with accelerating voltage gradual
  ➡ acceleration possible over limited number of turns
  - maximum energy dependent on acceleration voltage
    50 keV acceleration voltage: 12 MeV protons
    Bethe and Rose, Phys. Rev. 52 (1937) 1254–1255

how to get it really working

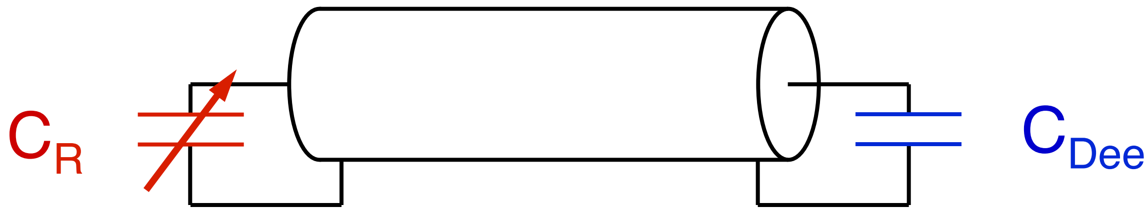
- radially decreasing field + modulation RF frequency
  - ➡ vertical and phase stability
    E. MacMillan, Phys. Rev. 68 (1945) 144
    V. Veksler, Phys. Rev. 69 (1946) 244
  - synchro-cyclotron ➡ synchrotron ➡ storage ring
    workhorse high energy physics; synchrotron radiation;
    carbon therapy

- radially increasing field + azimuthal field modulation
  - vertical stability and isochronism
  - Thomas, Phys. Rev. 54 (1938) 580 and 588
  - fixed RF frequency
  - isochronous cyclotron
    workhorse nuclear physics,
    isotope production,
    proton therapy

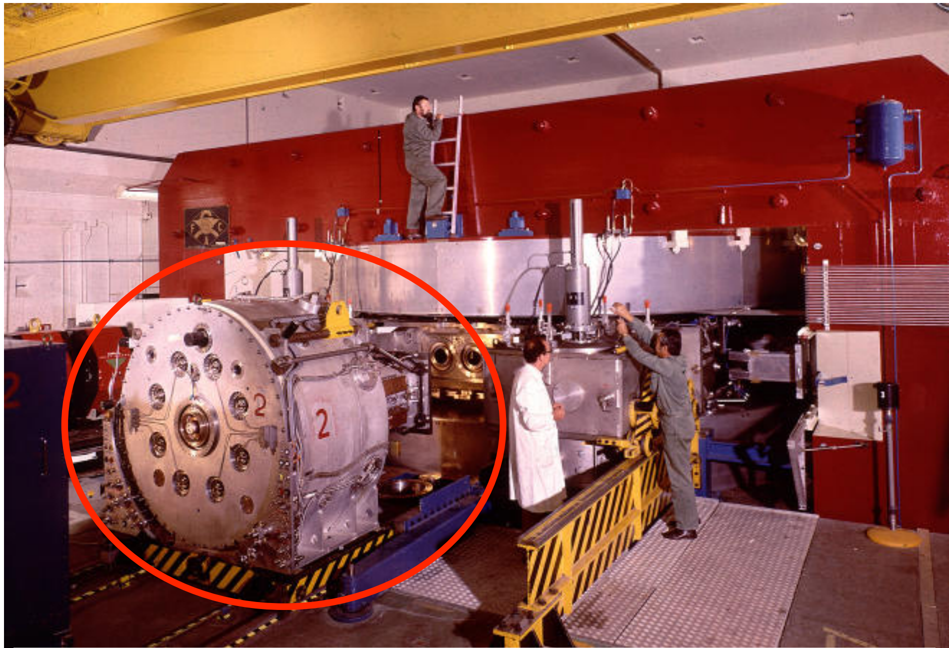


synchrocyclotron

- λ/2 transmission line with capacitive load on both ends

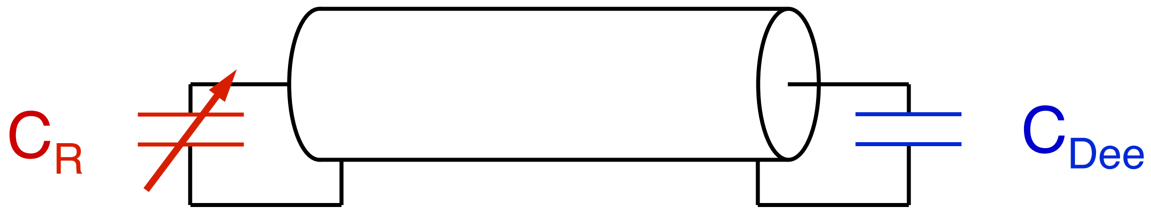


- frequency variation by variation of C_R
  - capacitance rotating in vacuum (RotCo)
  - electrode profile ➡ f(t)
- acceleration electrode C_{Dee}
- operational parameters
  - acceleration voltage ~20 kV
  - RF power 10 – 100 kW
  - rep rate 100 - 400 Hz
  - self-oscillating
  - frequency swing ~20 %


600 MeV synchrocyclotron CERN

synchrocyclotron

- $\lambda/2$ transmission line with capacitive load on both ends



- frequency variation by variation of C_R
  - capacitance rotating in vacuum (RotCo)
  - electrode profile ➡ f(t)
- acceleration electrode C_{Dee}
- operational parameters
  - acceleration voltage ~20 kV
  - RF power 10 – 100 kW
  - rep rate 100 - 400 Hz
  - self-oscillating
  - frequency swing ~20 %
    Orsay 19 – 24 MHz

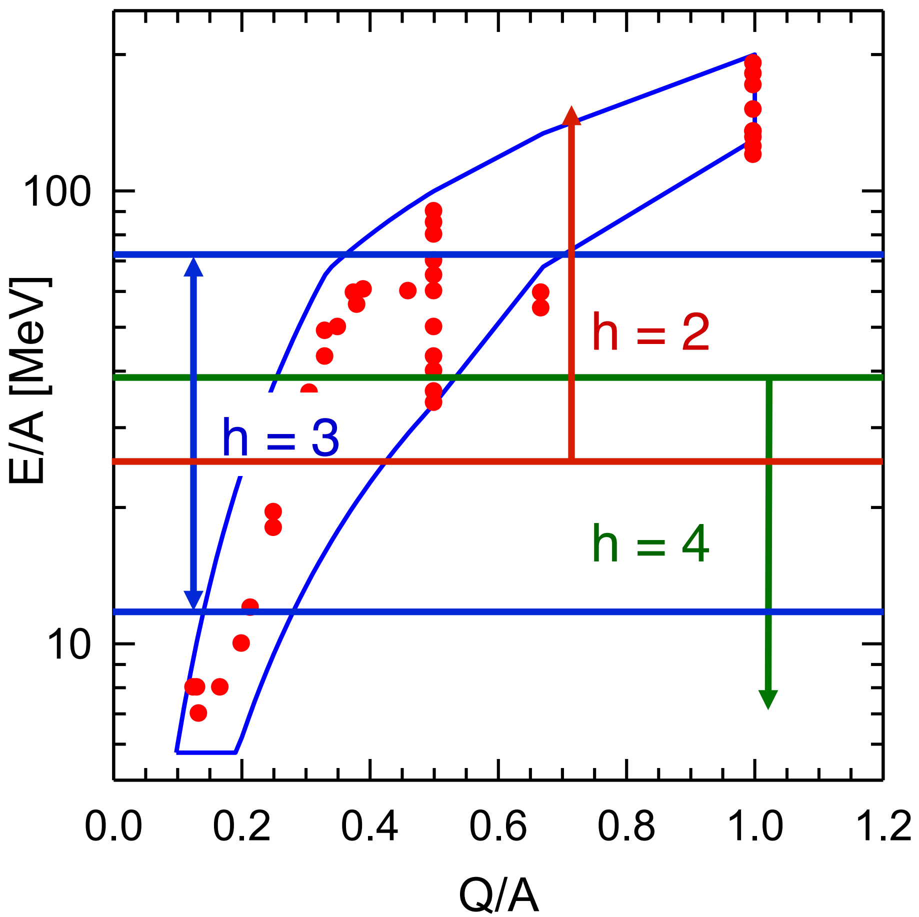
200 MeV synchrocyclotron Orsay

operational parameters

- orbital frequency (non-relativistic) $f_{orb} = 15.2 \frac{Q}{A} \bar{B}$ [MHz]
  - $\bar{B}$ average magnetic field along orbit [T]
  - Q/A charge-to-mass ratio ion
- typical values
  - compact RT cyclotrons 1 – 15 MHz
  - superconducting cyclotrons 6 – 35 MHz
  - separated sector cyclotrons 1 – 10 MHz
  - mostly research machines
    - multi-particle; multi-energy
    - ➡ large orbital frequency range
    - typical example SC AGOR-cyclotron @ KVI-CART
      - particles protons – Pb
      - energy 190 – 5 MeV/nucleon
      - orbital frequency 31 - 5.5 MHz

operational parameters

- orbital and resonator frequency ranges incompatible
  ➡ use different harmonic modes (example AGOR)
  different phasing of resonators

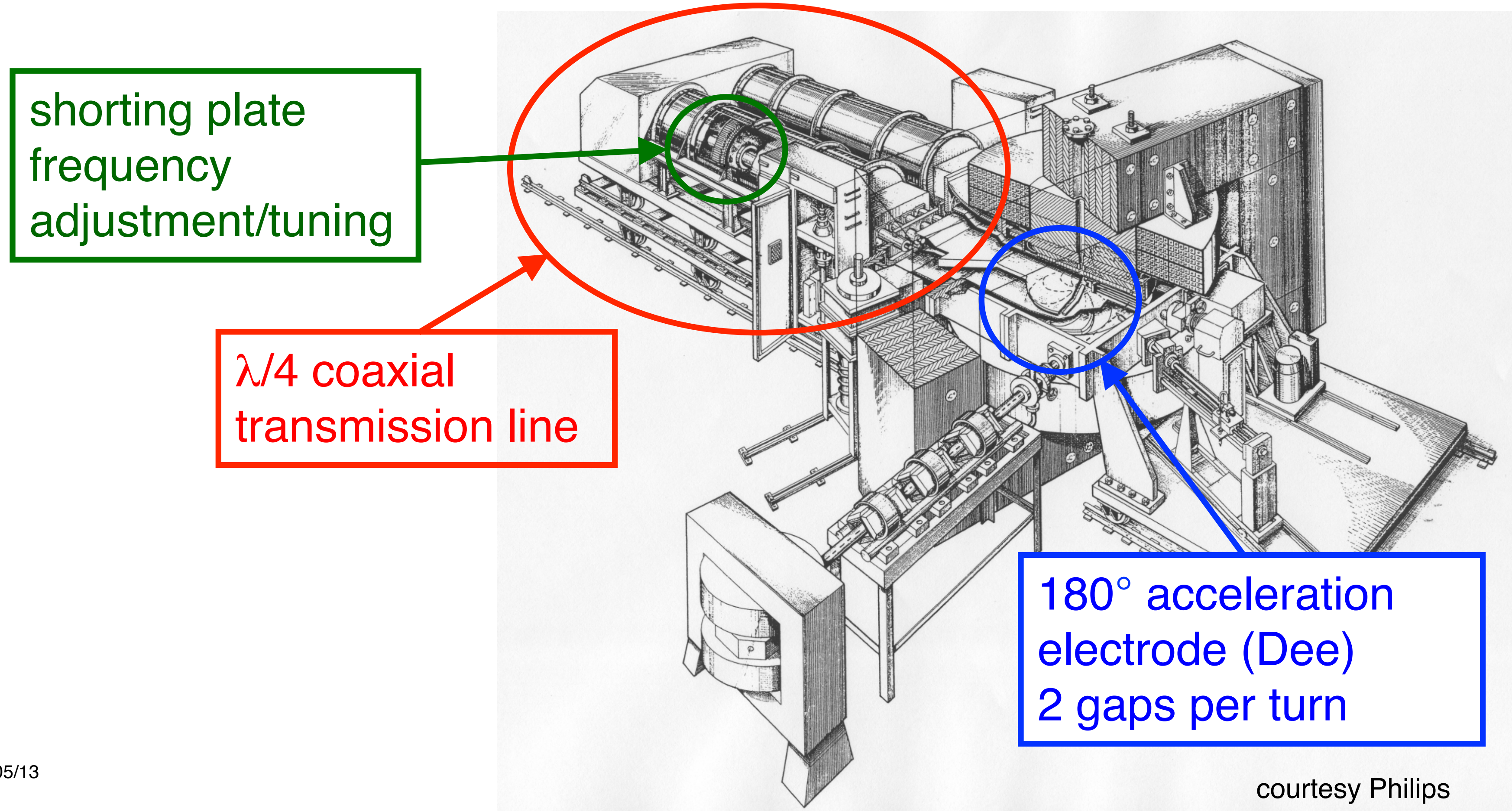


operational parameters

- orbital and resonator frequency ranges incompatible
  ➡ use different harmonic modes
- harmonic mode $h = f_{RF}/f_{orb}$
  - geometry acceleration electrode ➡ possible values
  - typical h = 1 – 6, max. 10
- acceleration voltage
  - typical V = 50 – 100 kV; max. 1000 kV
- RF power
  - typical P = 10 – 100 kW; max 400 kW (excl. beamloading)

resonator types

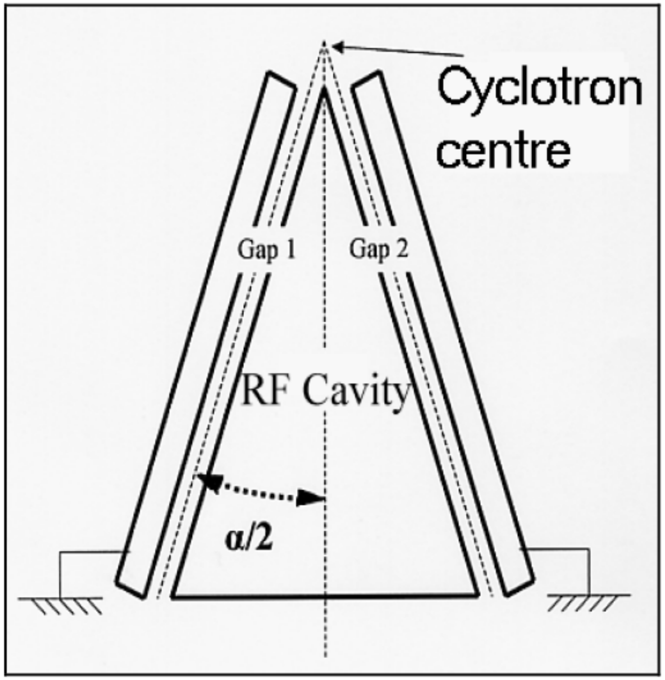
- transmission line (λ/4 or λ/2)
  - capacitively loaded by acceleration electrode(s)
  - TEM-mode
  - most common solution

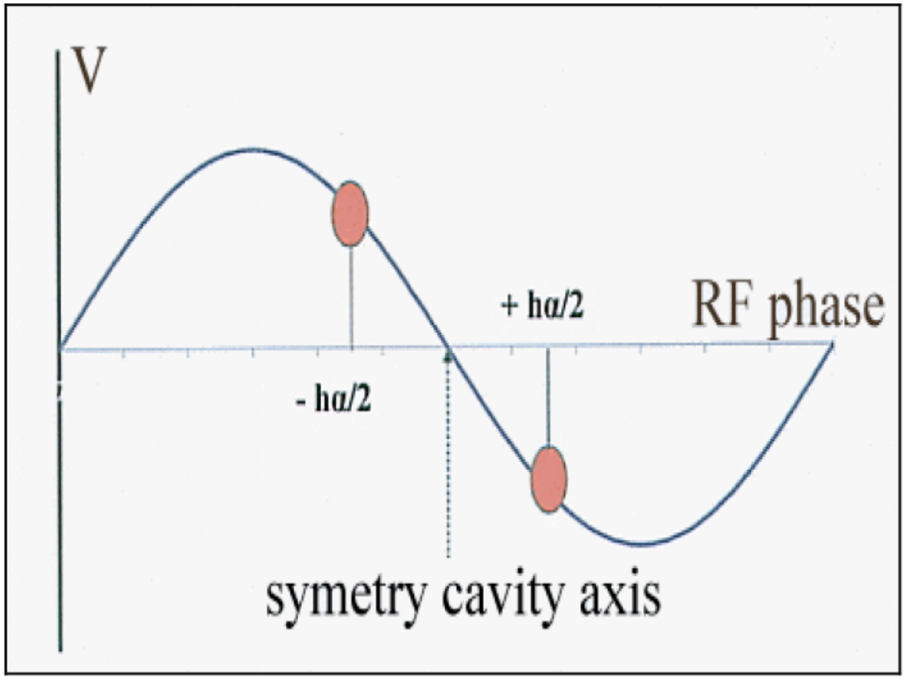


courtesy Philips

shape acceleration electrode vs. harmonic

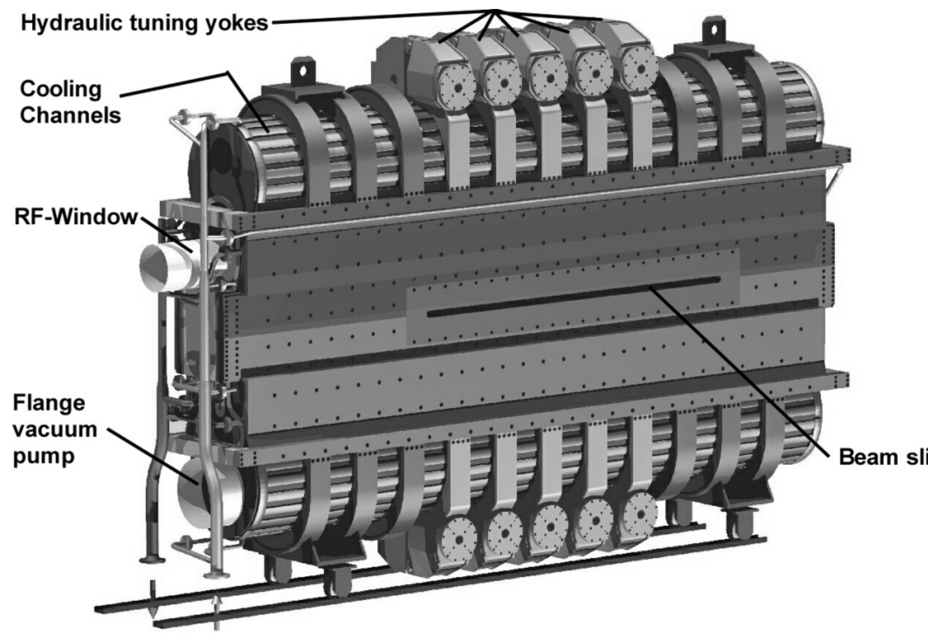
- highest acceleration: particle passes symmetry axis for $\varphi = \pi$
  $\Delta E = -QV_D \sin(h\alpha/2)\sin(\varphi)$
- not all harmonic modes possible
  e.g. $\alpha = 60°$ ➡ no acceleration for h = 6





resonator types

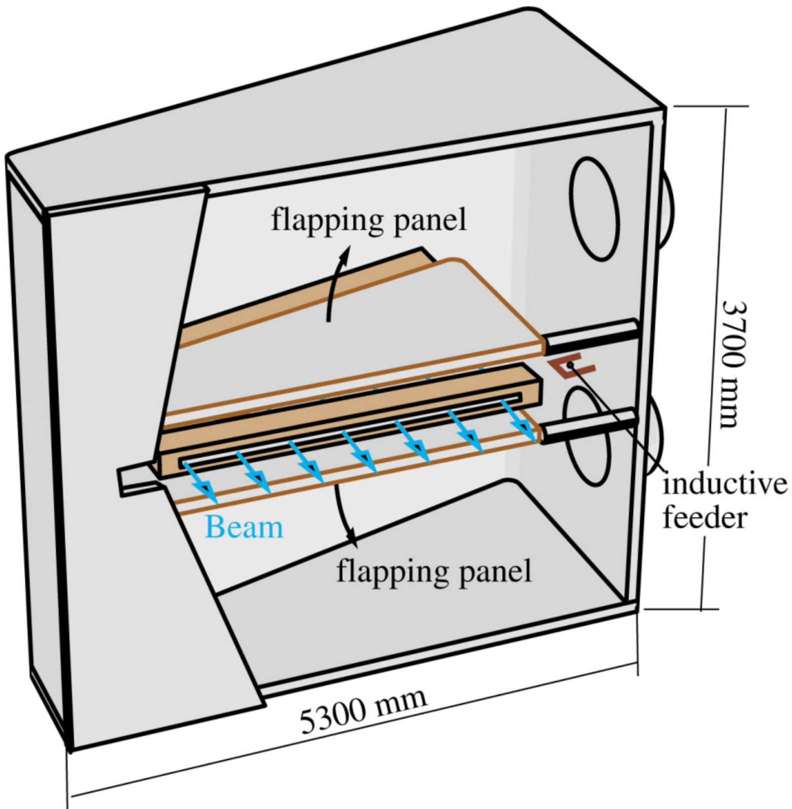
- single gap resonator
  - limited to separated sector cyclotrons
  - used at PSI, RCNP and RIKEN
  - TE110 mode

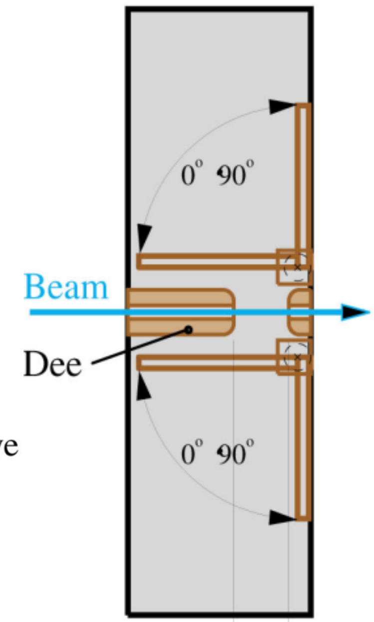


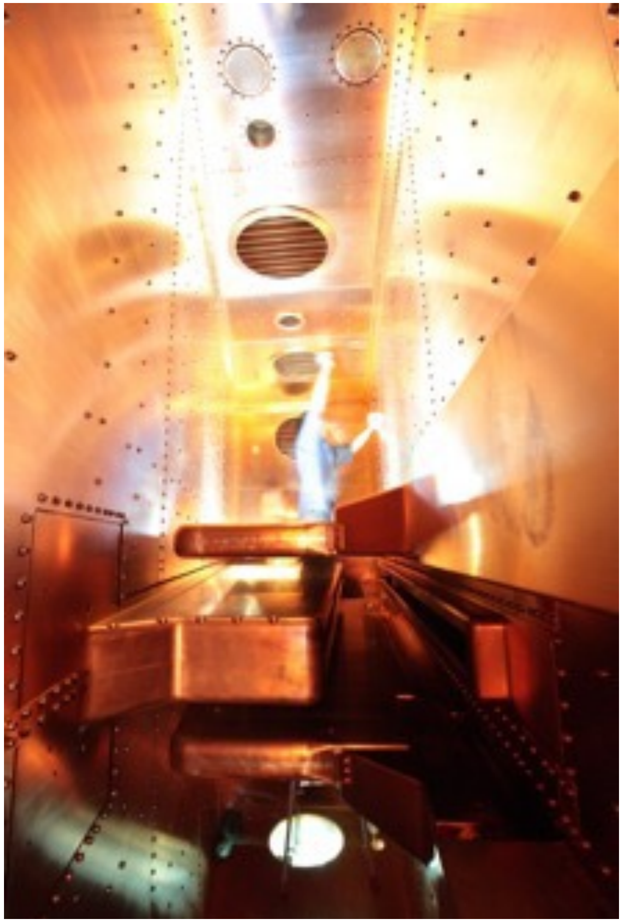
resonator types

- single gap resonator
    - separated sector cyclotrons
    - used at PSI, RCNP and RIKEN SRC
    - TE110 mode

SRC Single Gap Type Resonator

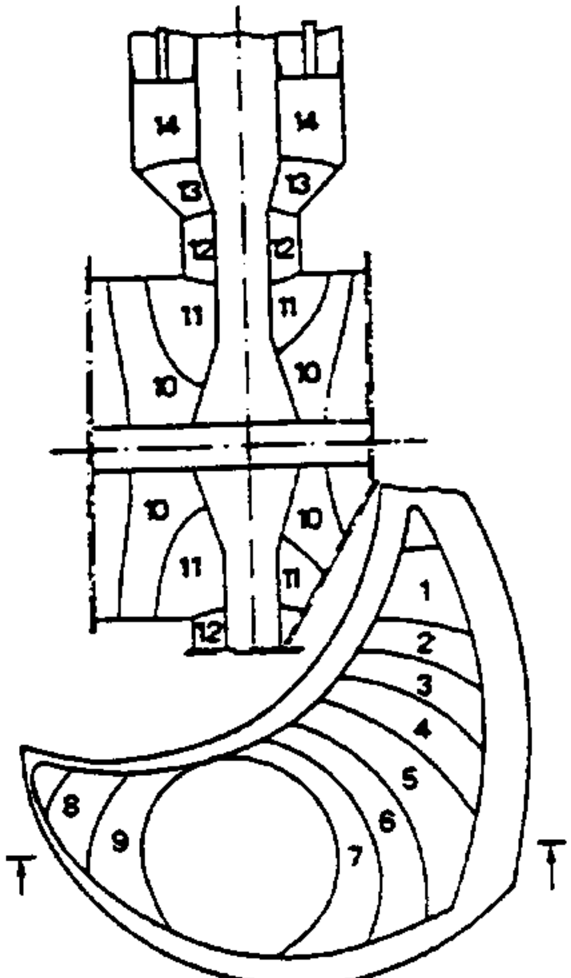


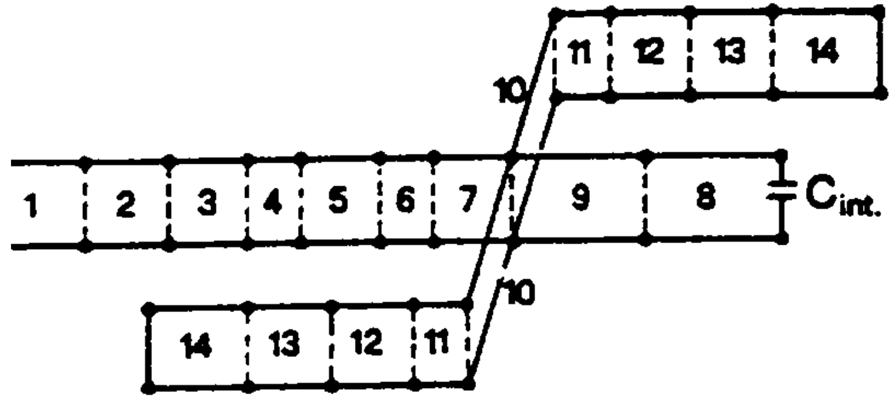


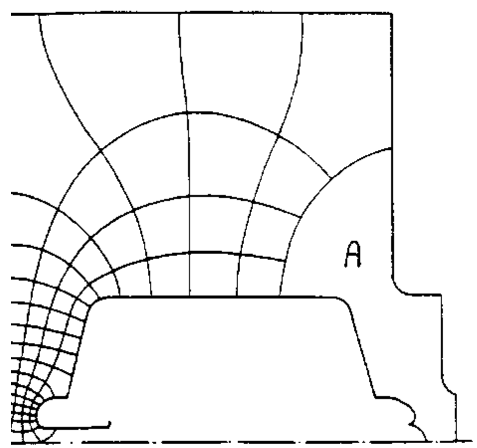


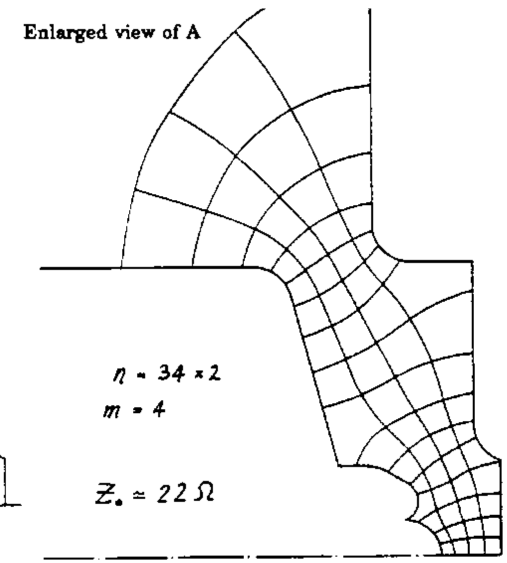
resonator design: transmission line model

- traditional approach (used until ~15 years ago)
  - validation on scale models







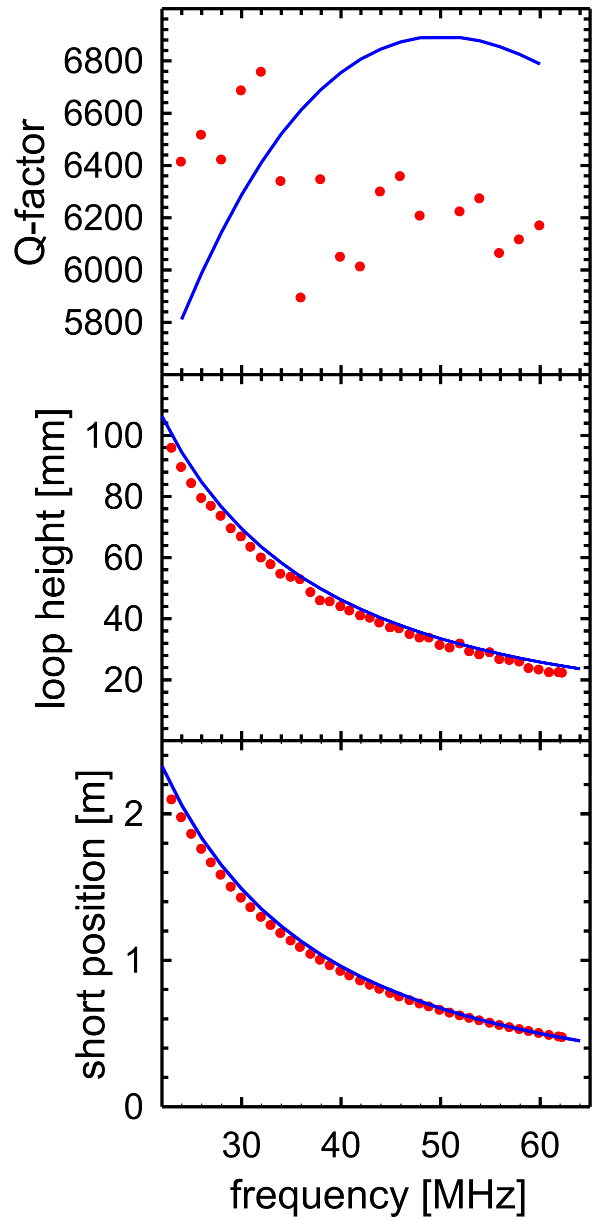


$$Z_c = Z_0 \frac{m}{n}; Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\,\Omega$$

resonator design: transmission line model

- design AGOR cavities
  - transmission line model
  - model measurements
  - results
    - Δ frequency < 1 MHz
      range 22 – 62 MHz
    - Δ loop height < 5 mm
      range 100 mm
    - Δ Q-factor/power < 10 %

- design accuracy sufficient for construction

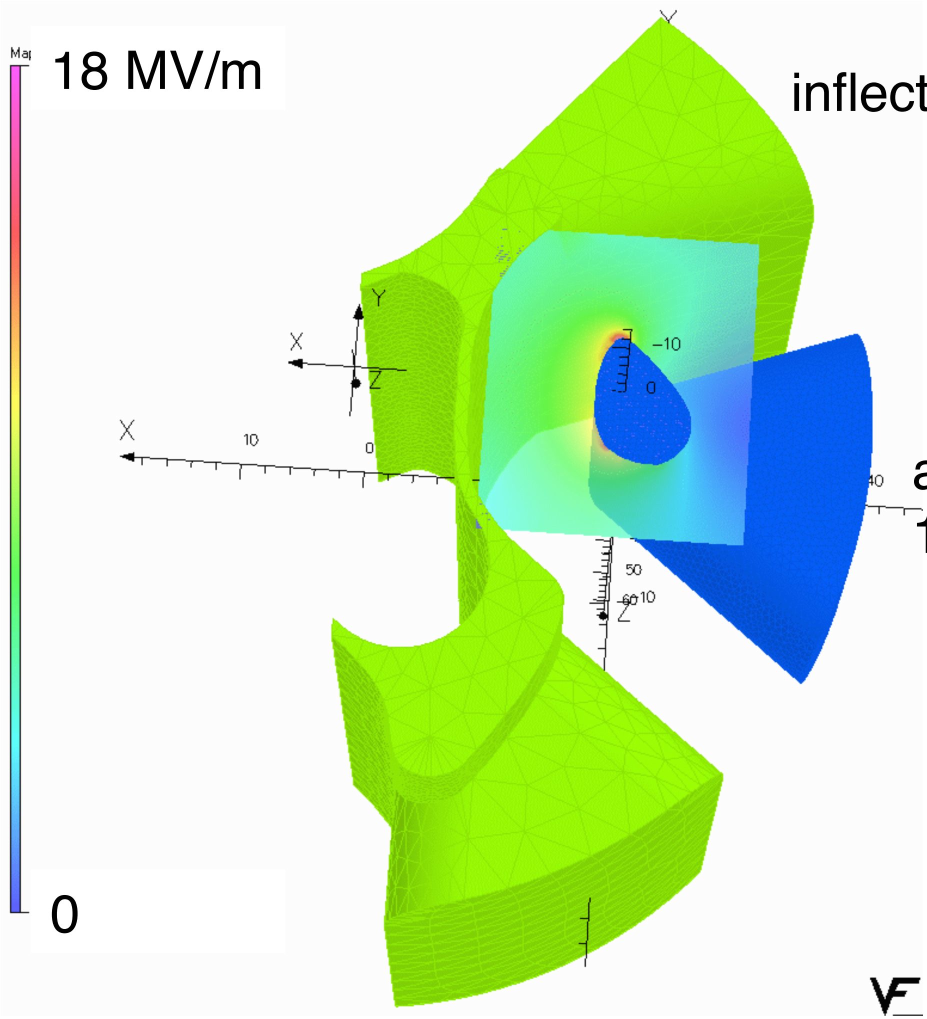


resonator design: 3D simulations

- recent trend; facilitated by computer and ICT revolution
- advantages
  - calculation of more complex resonator shapes
  - coupling with CAD-packages: input detailed geometry
  - detailed insight in current and voltage distribution
    - ➡better optimization of
      - cooling
      - peak fields (breakdown probability)
    - detailed maps RF-field for trajectory calculations
  - higher accuracy resonance parameters
  - coupling with thermal and mechanical simulations (deformation)
  - better insight in higher order modes
- disadvantages
  - less insight in critical parameters
  - initial stages design significantly slower
  - large computing power required

resonator design: 3D simulations

- optimization electric fields AGOR central region
  - reduce breakdown rate



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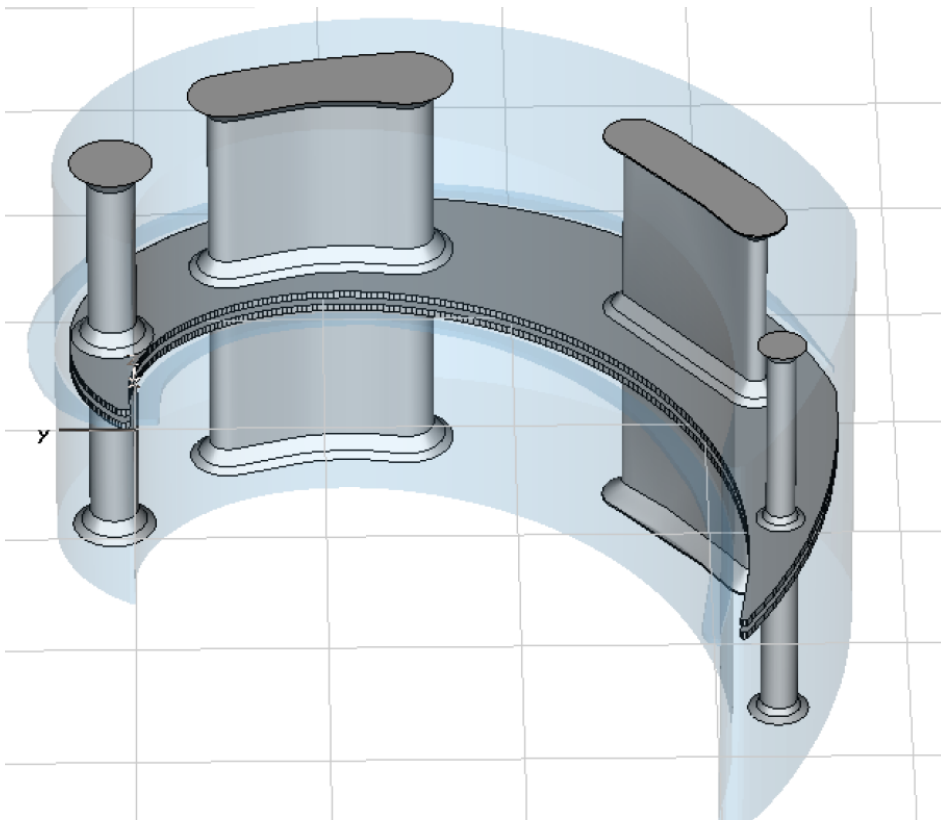
resonator design: 3D simulations

- 75 MHz resonator for 400 MeV/nucleon ^{12}C cyclotron IBA
- 4 parallel transmission line cavities
  - optimized voltage distribution
  - suppression higher order modes along Dee
  - mechanical stiffness



courtesy IBA, JINR

resonator design: 3D simulations

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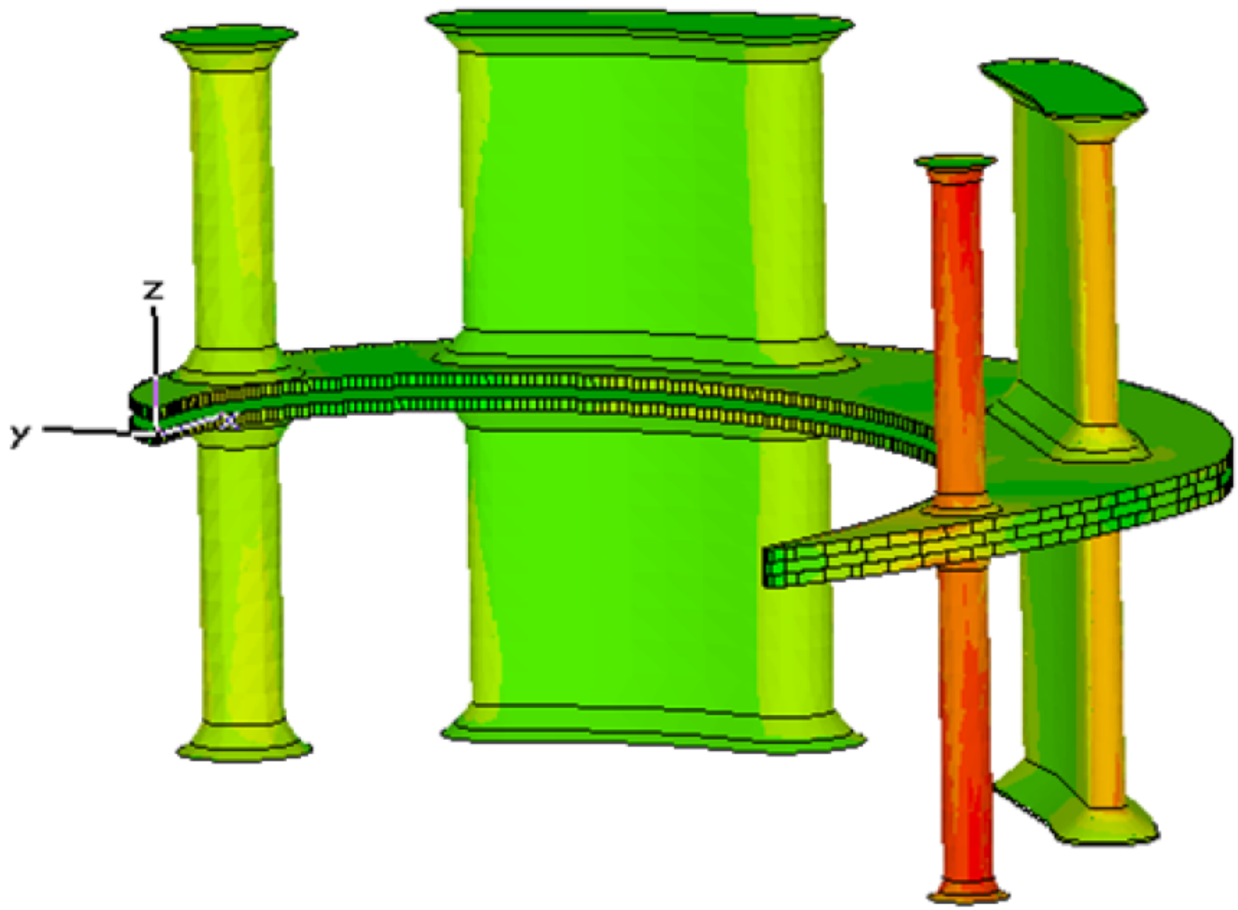
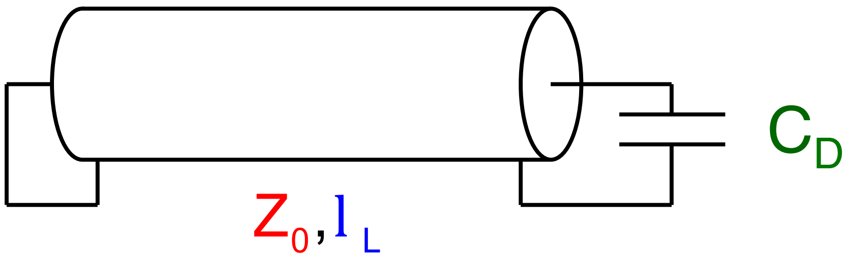


courtesy IBA, JINR

frequency tuning transmission line resonator



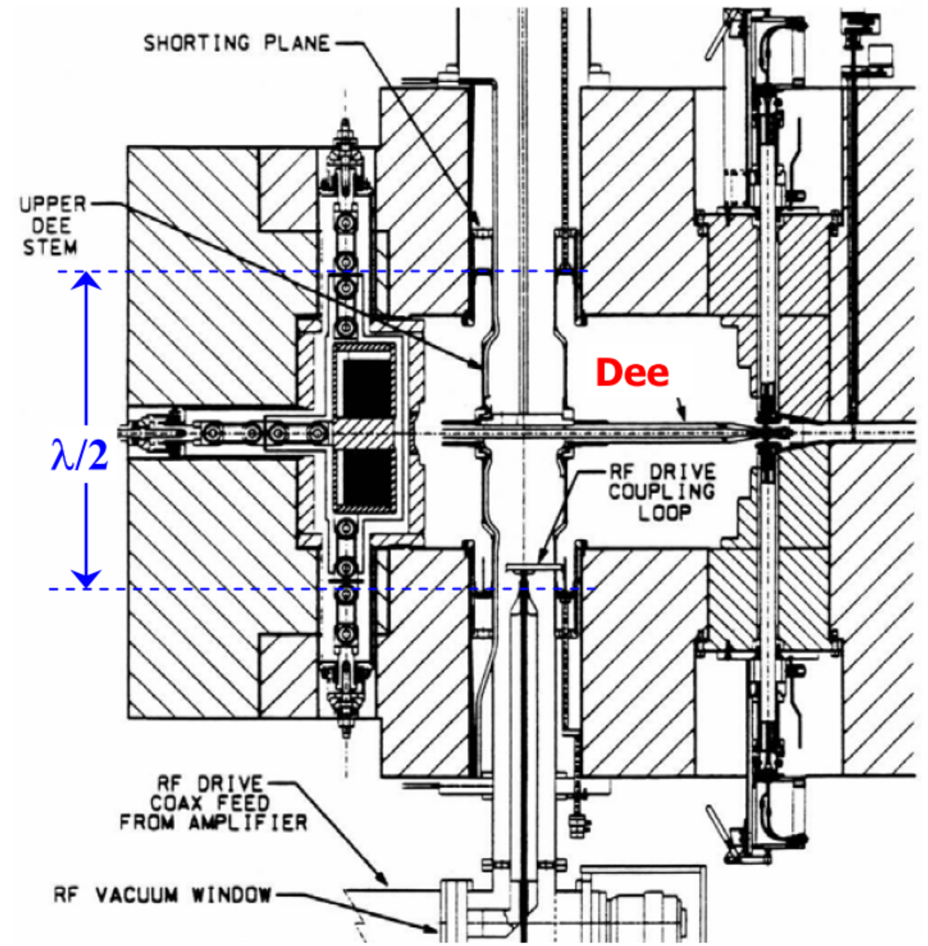
$$Z_D = \frac{-i}{\omega C_D} \qquad Z_L = iZ_0 \mathrm{tg}\left(\frac{\omega l_L}{c}\right)$$

- resonance condition $Z_D = -Z_L$
- transmission line resonators
  - length transmission line
    ➡mobile short
  - characteristic impedance transmission line
    ➡mobile panel, plunger
  - capacitance acceleration electrode
    ➡mobile panel
  - combination of techniques for coarse and fine tuning

frequency tuning: VARIAN PT cyclotron

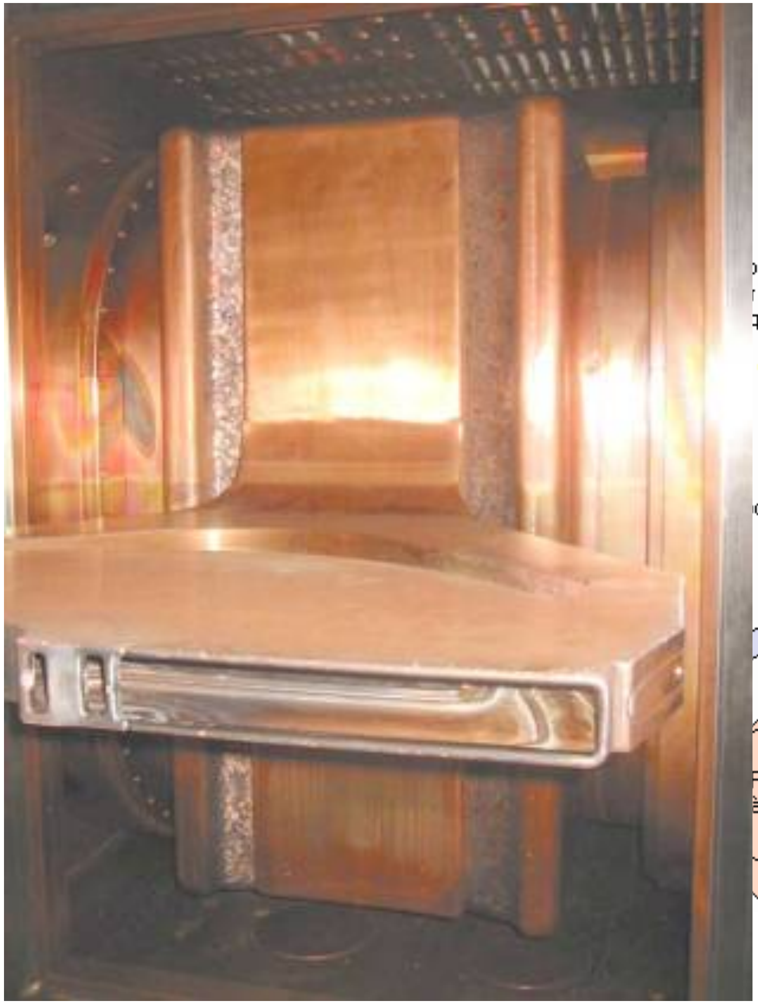
- frequency adjustment and tuning with sliding shorts
  - move both to retain symmetry
  - move under power

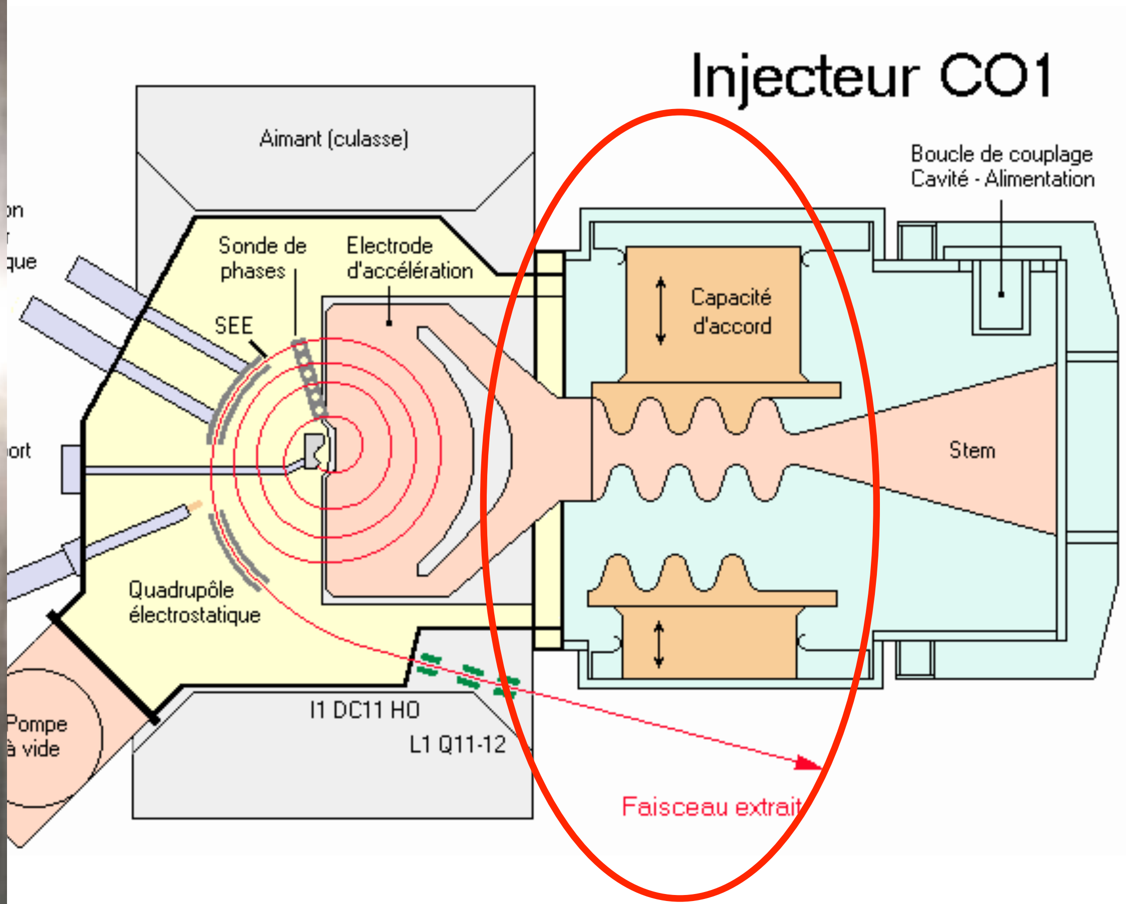
➡ high performance contacts
  - silver plated CuBe spring
  - carbon-silver contact grain
  - 50 A per contact at 60 MHz
  - development GANIL/AGOR



frequency tuning: GANIL injector cyclotron

- change characteristic impedance transmission line





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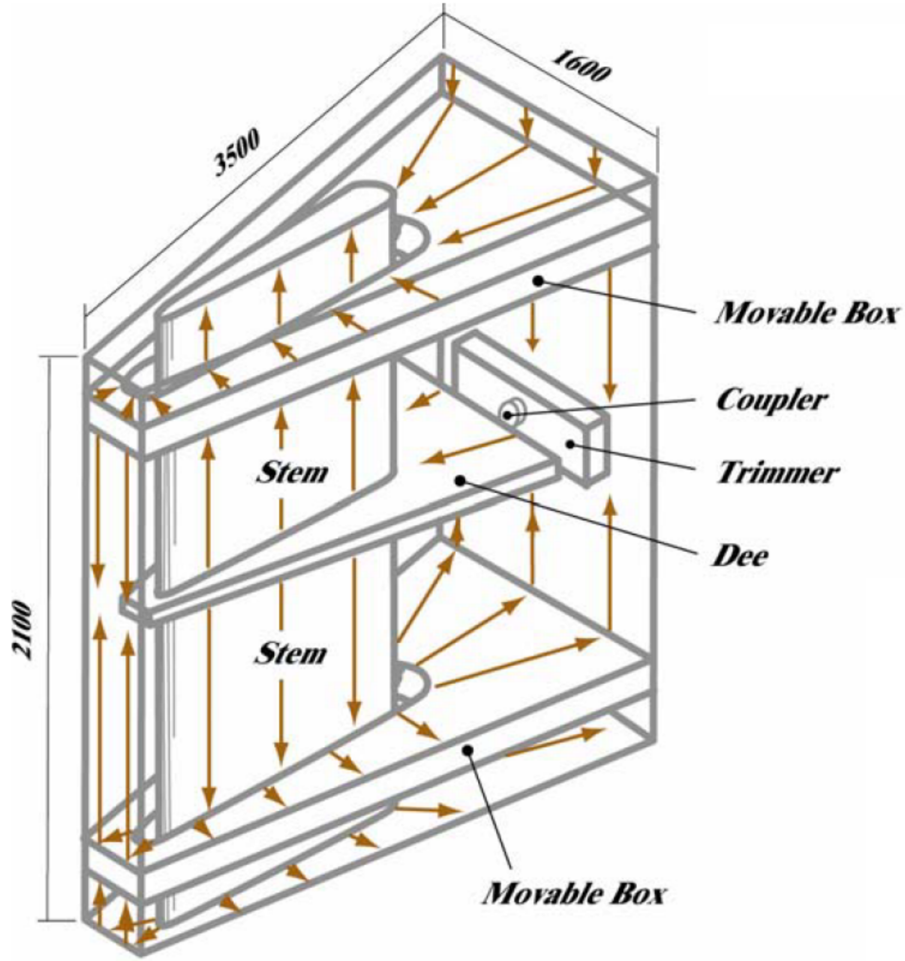
frequency tuning: RIKEN ring cyclotron

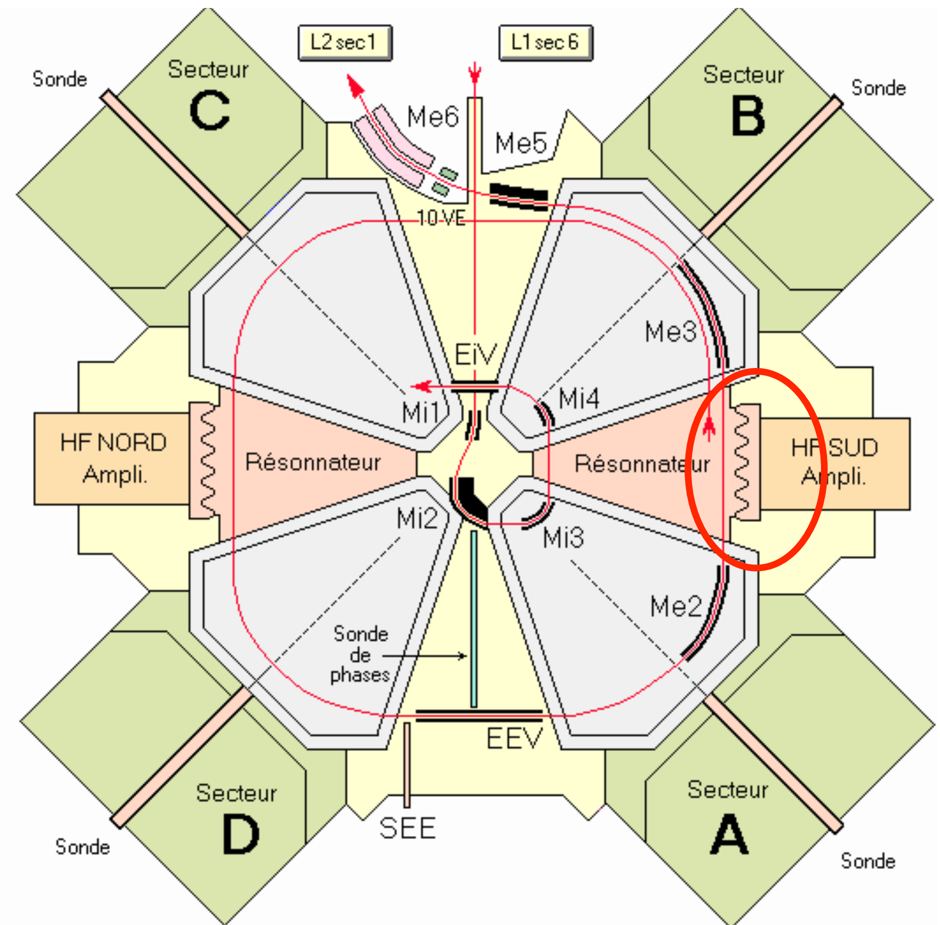
- change of characteristic impedance at different location
  - no high current density contacts on stem
  - box to median plane: more capitance ➡ lower frequency
  - box to outside: less inductance ➡ higher frequency

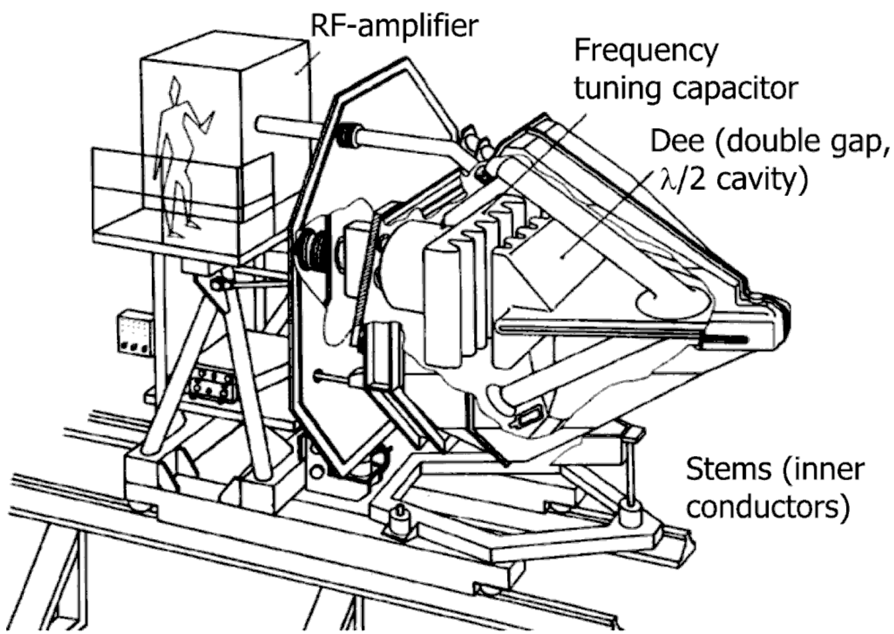


- resonator characteristics
  - 18 – 45 MHz
  - 300 kV @ 45 MHz
  - 150 kW @ 45 MHz

frequency tuning: GANIL main cyclotron

- change capacitance acceleration electrode





frequency tuning: GANIL main cyclotron

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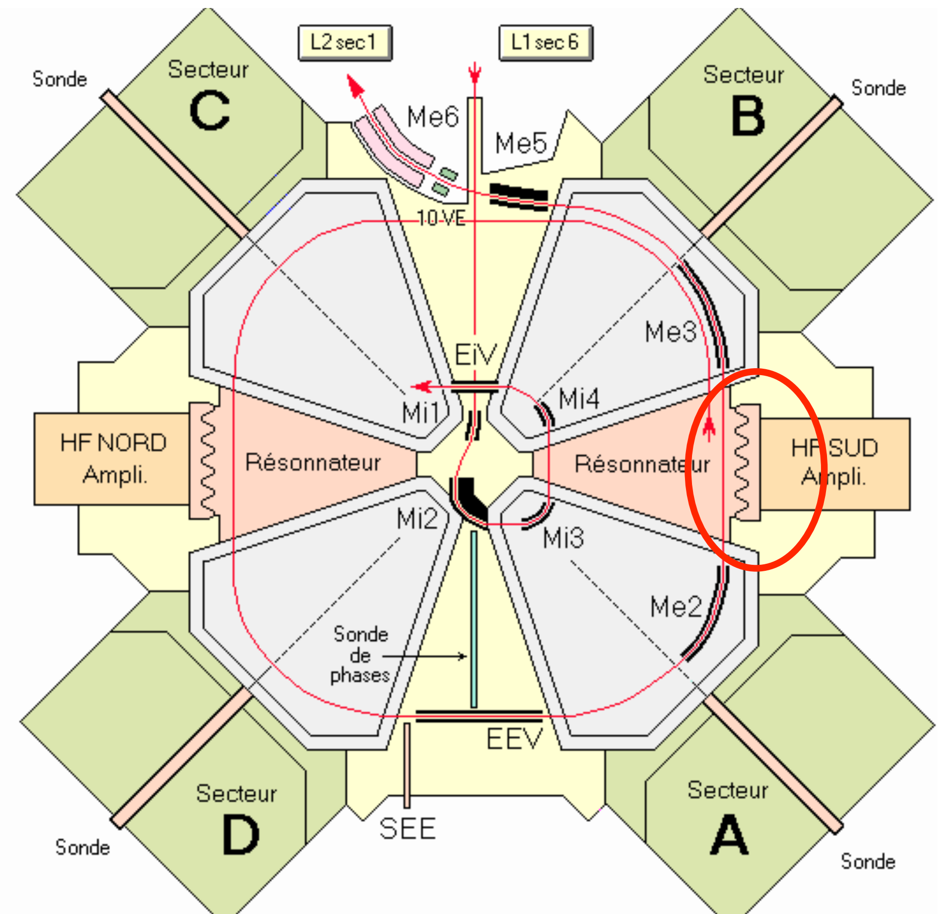
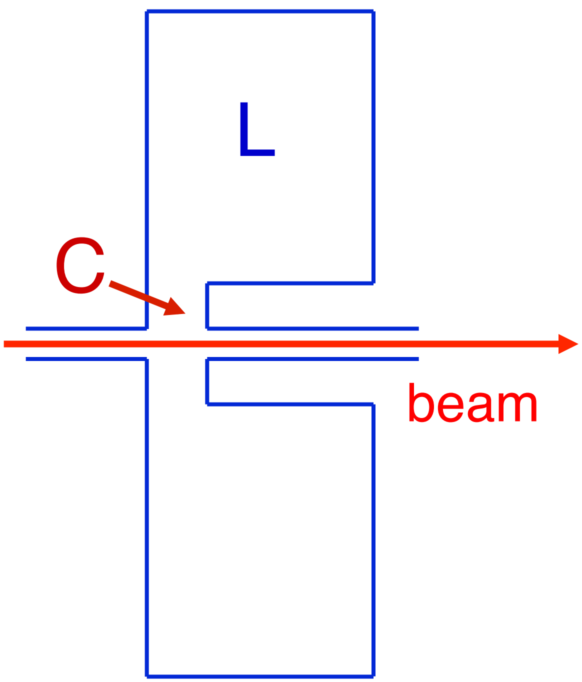


frequency tuning: single gap resonator

- basically two options
  - gap capacitance
  - chamber inductance

flapping panel



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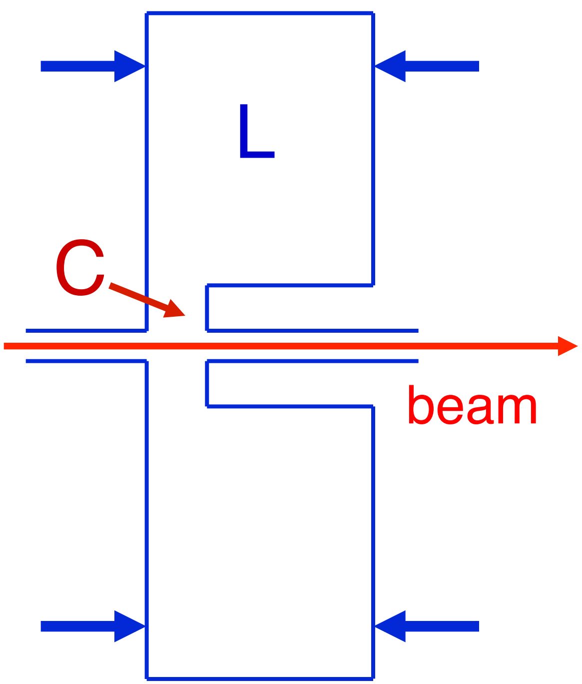

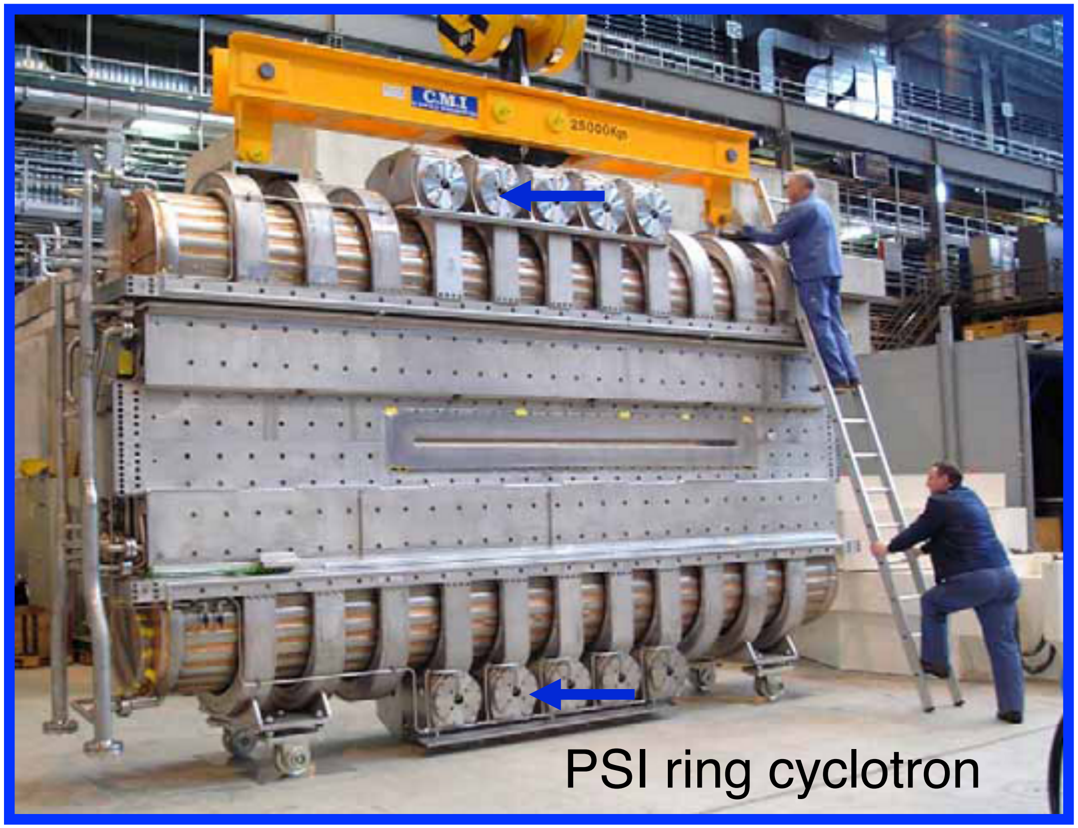

frequency tuning: single gap resonator

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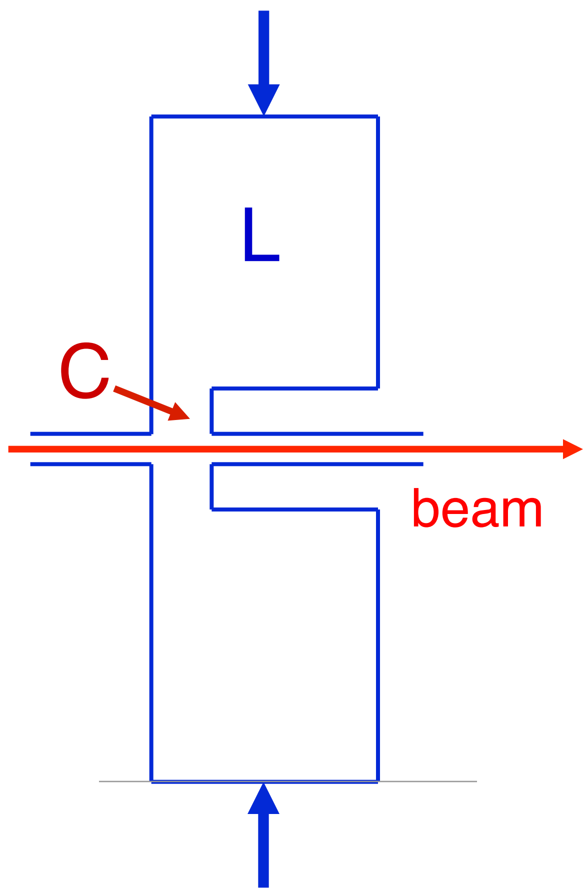
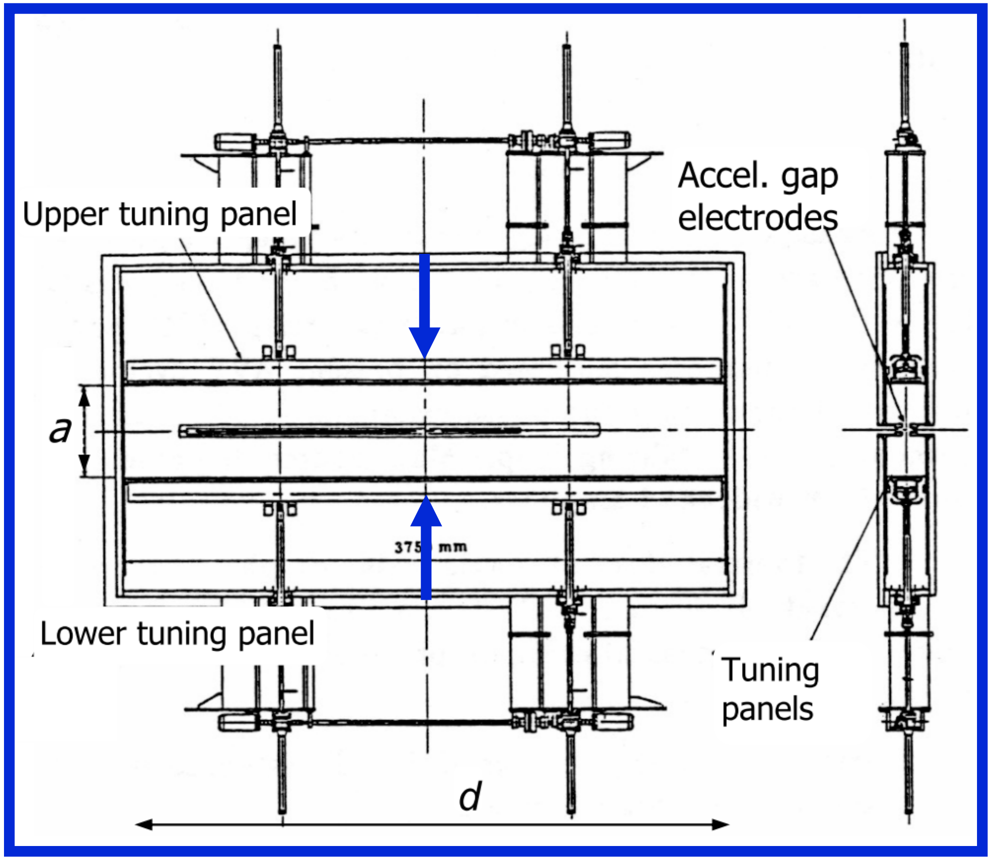
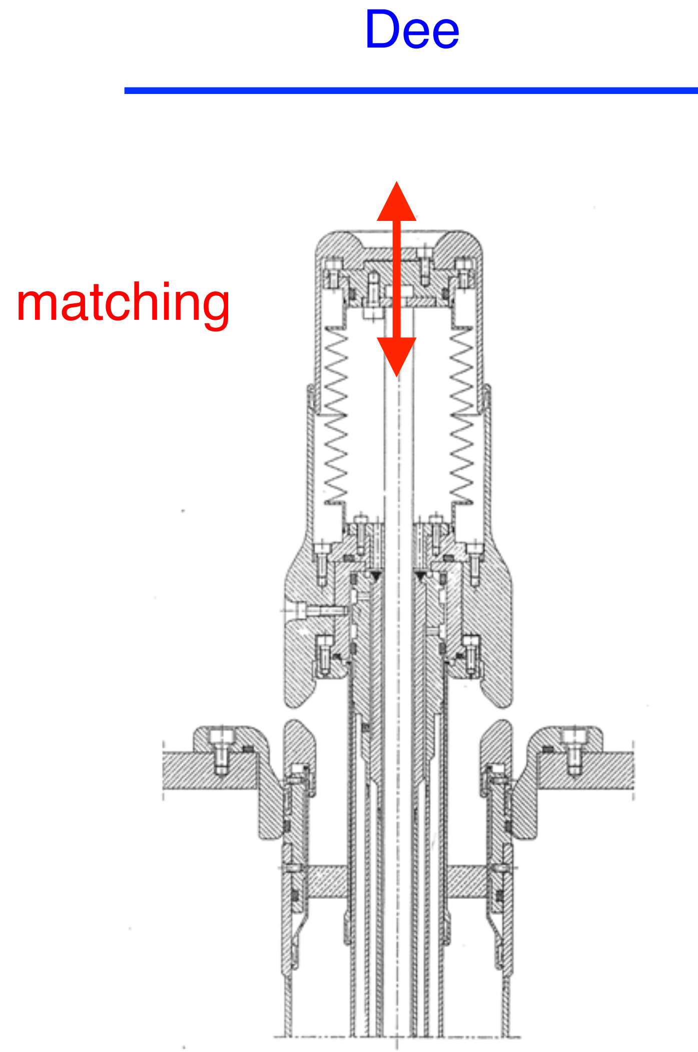


RCNP ring cyclotron



power coupling: capacitive

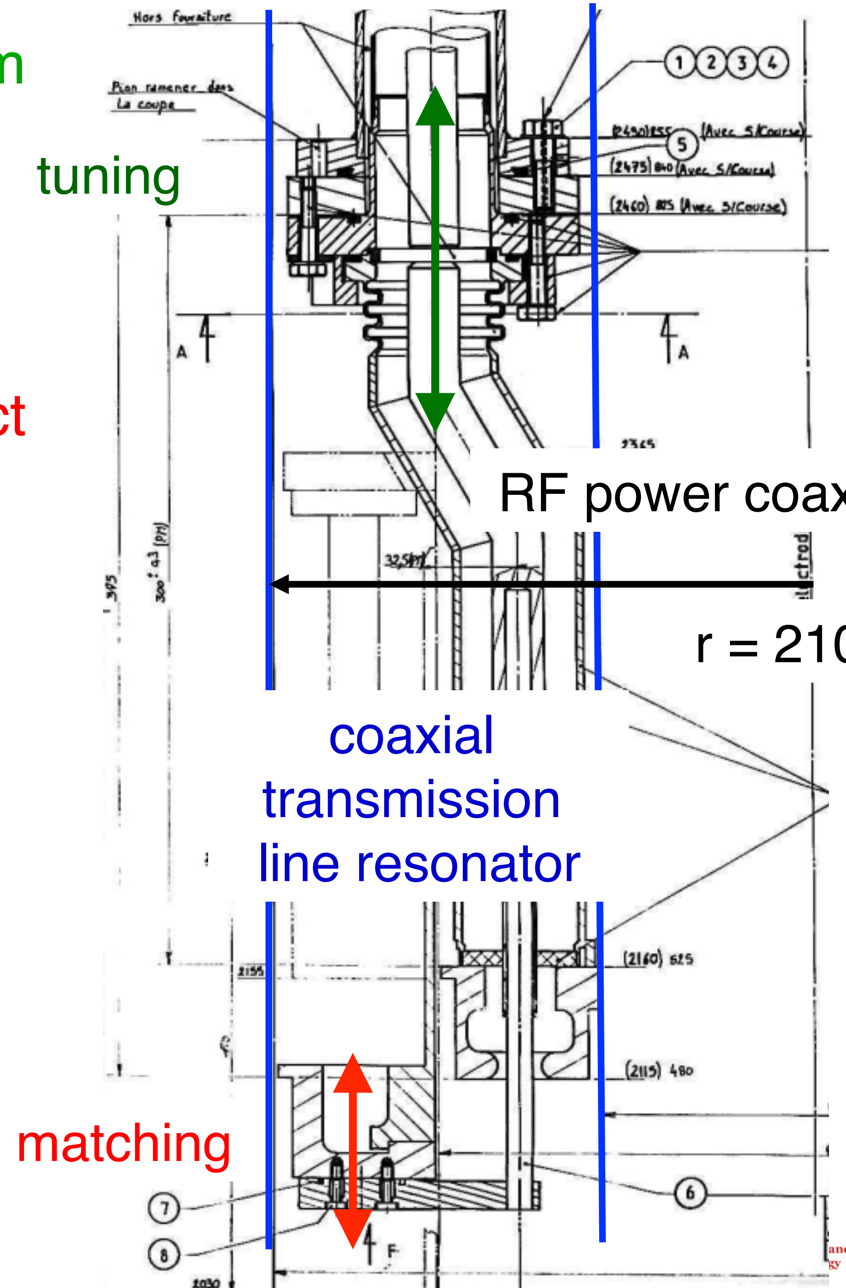
- ✓ simple mechanics
- ✓ also fine tuning control
- ✗ high voltage
  - ✗ insulator
  - ✗ discharge



power coupling: inductive

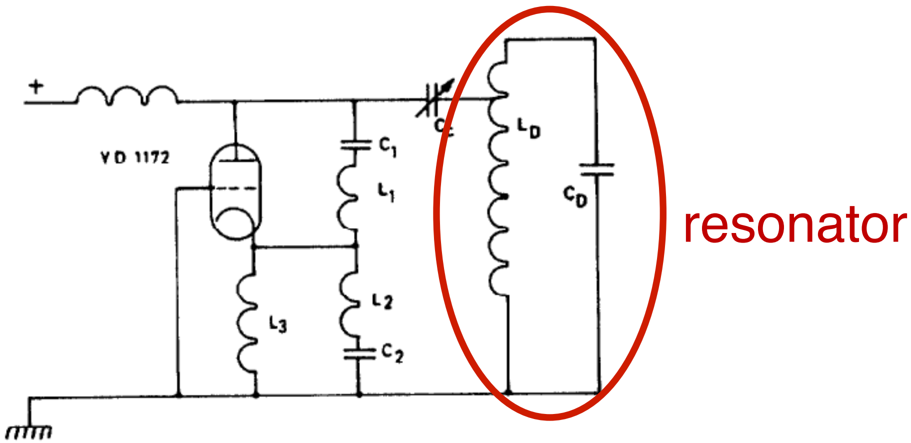
- ✓ low voltage ➡ insulator no problem
- ✗ multipactor
- ✗ variable frequency resonator: complex mechanics
- ✗ high current rotating/sliding contact


AGOR, Groningen



power generation

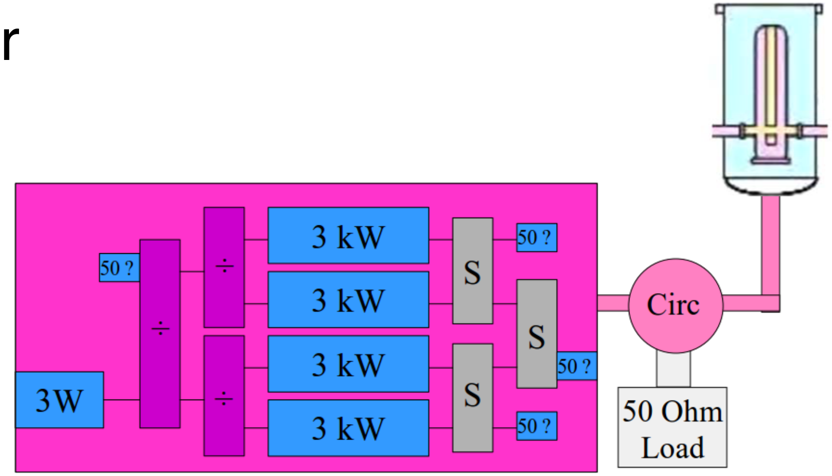
- synchrocyclotron: oscillator
  - resonator + RotCo ➡ resonance frequency
  - DC- bias needed to facilitate start-up (multi-pactor)



- isochronous cyclotron: amplifier
  - (broadband) solid state preamplifier
  - narrowband tube endstage (one or two stages)
    - tuned to required frequency
    - impedance matching (50 Ω line or directly to load)

power generation: new development

- modular parallel solid state amplifier
  - ✓ redundancy ➡ reliable
  - ✓ hot swappable
  - ✗ complex
  - ✗ low efficiency
  - ✗ reflected power (circulator)



SOLEIL RF power amplifiers 45 kW

RF controls

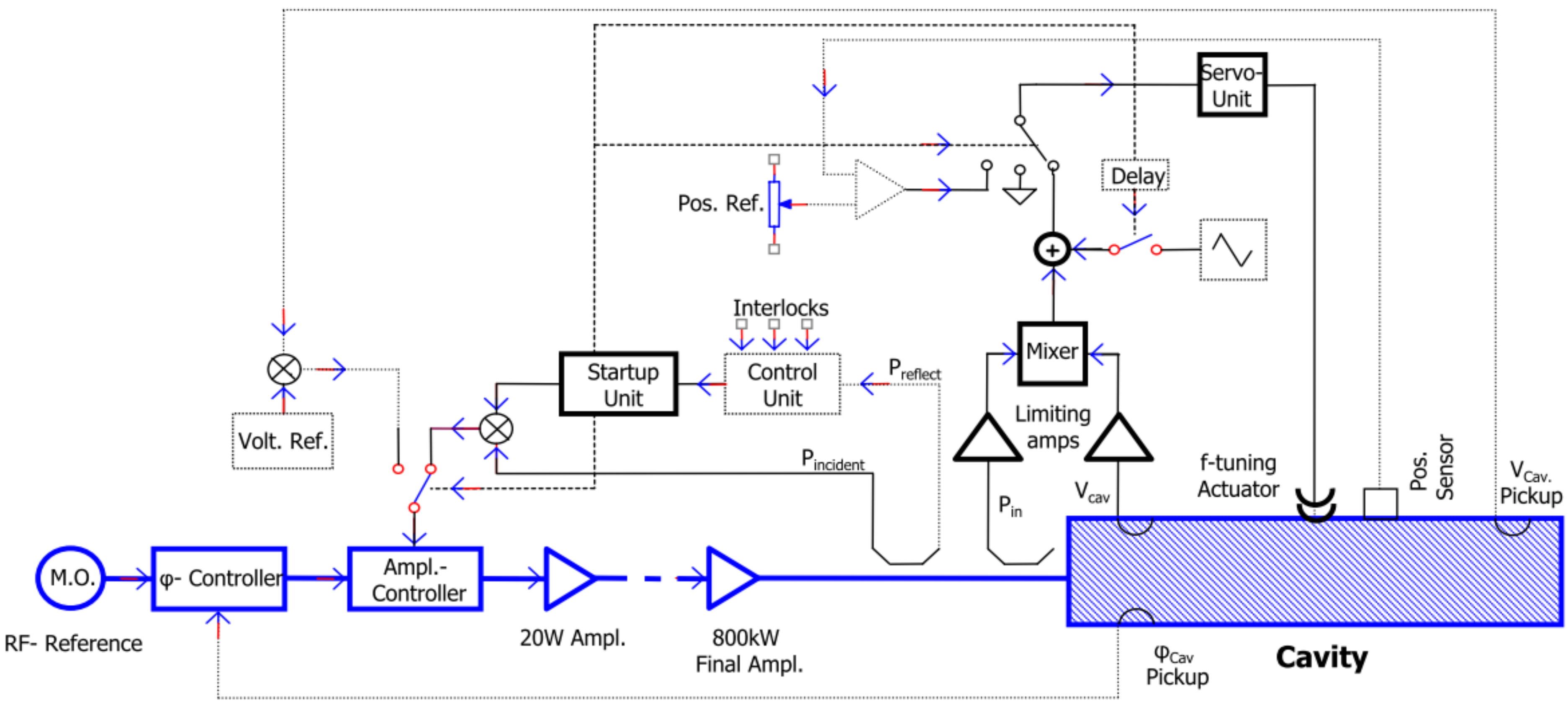
- controlled parameters
  - amplitude acceleration voltage
  - phase acceleration voltage
    - required when using several independent resonators
  - resonator tuning
  - high intensity: possibly matching (beam loading)

- measured parameters
  - amplitude acceleration voltage
  - phase acceleration voltage
  - phase incident wave – acceleration voltage
  - reflected power

RF controls: design issues

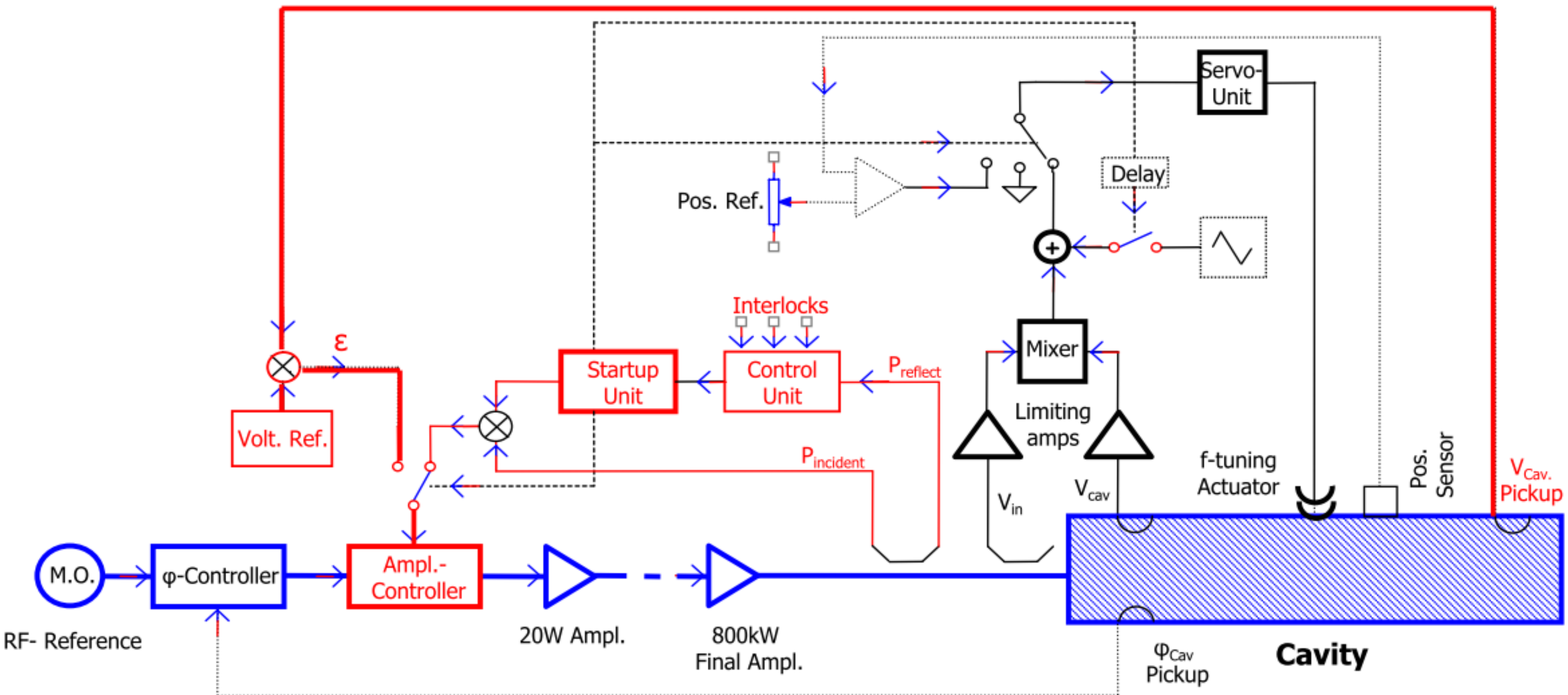
- pick-up probes
  - mechanical stability
- pick-up electronics
  - large amplitude and frequency range
- feedback loops
  - high gain for phase and amplitude stability
  - compensation resonator response
- grounds loop via RF circuitry

RF controls: overview



courtesy Peter Sigg, PSI

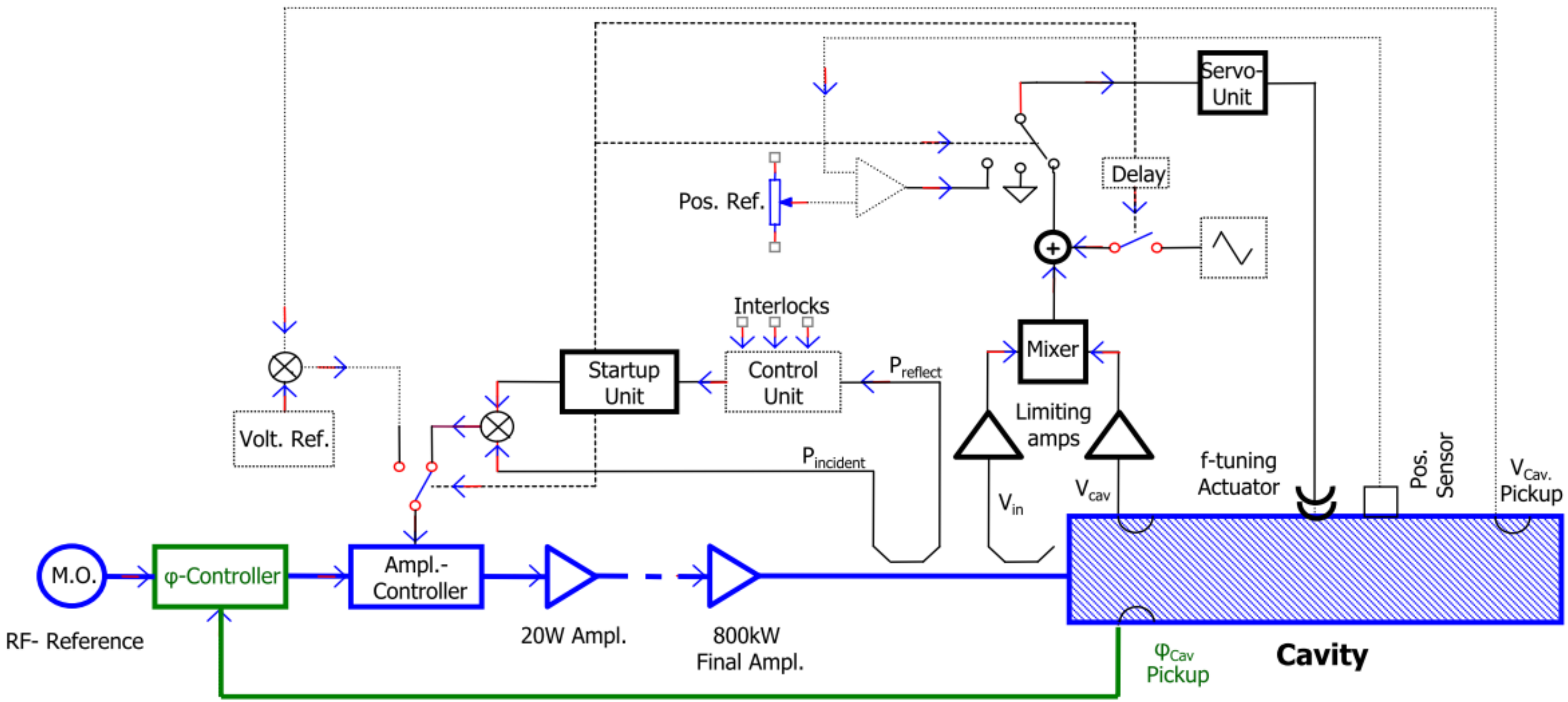
RF controls: amplitude



courtesy Peter Sigg, PSI

- power pulse at start-up to pass through multipactor region
- amplitude stability $<10^{-4}$

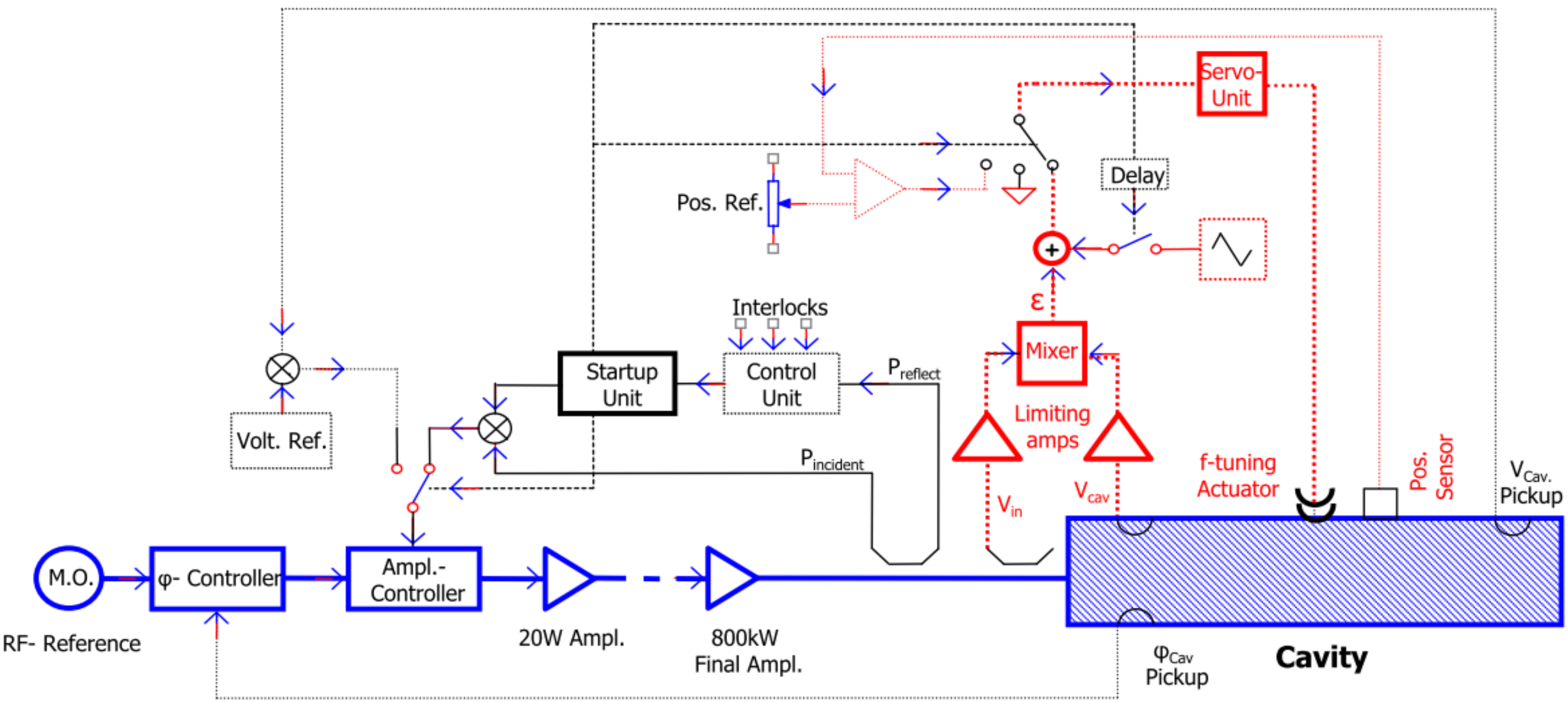
RF controls: phase



courtesy Peter Sigg, PSI

- essential for multi-resonator system
- phase stability <0.1°

RF controls: tuning

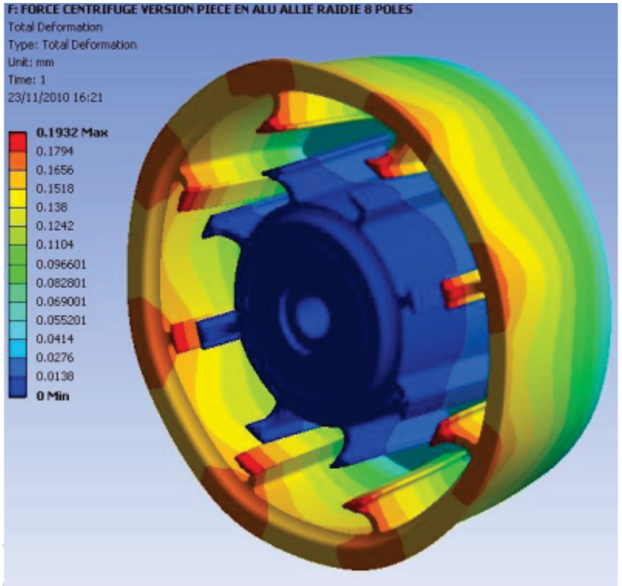


courtesy Peter Sigg, PSI

- bandwidth typ. 1 Hz

example: IBA S2C2 synchro-cyclotron

- 250 MeV protons
- $\lambda/2$ resonator; self-oscillating triode driven circuit
  - novel design RotCo
- frequency range 93 (injection)– 63 (extraction) MHz (h = 1)
- accelerating voltage 3 - 12 kV
  ➡ 40000 turns due to large phase width



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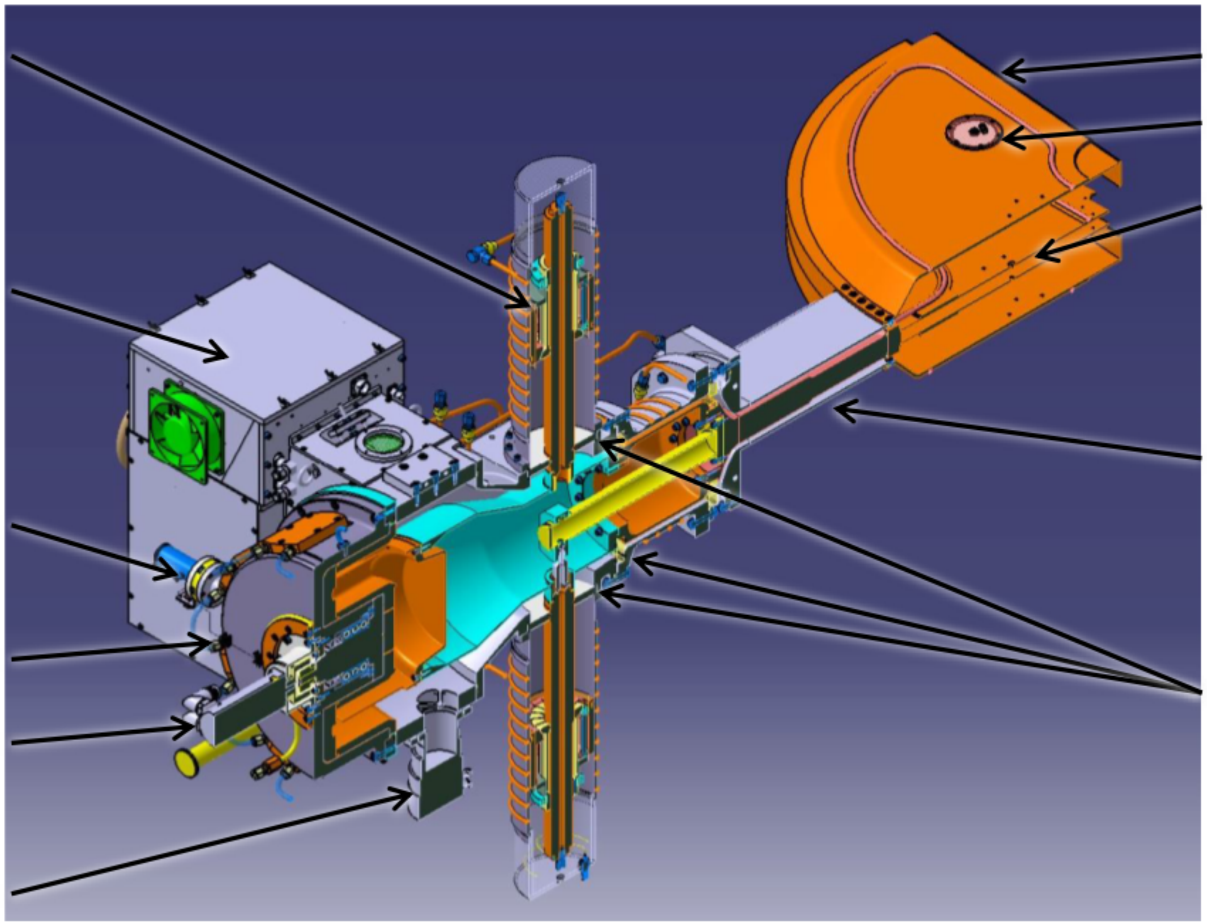
example: IBA S2C2 synchrocyclotron



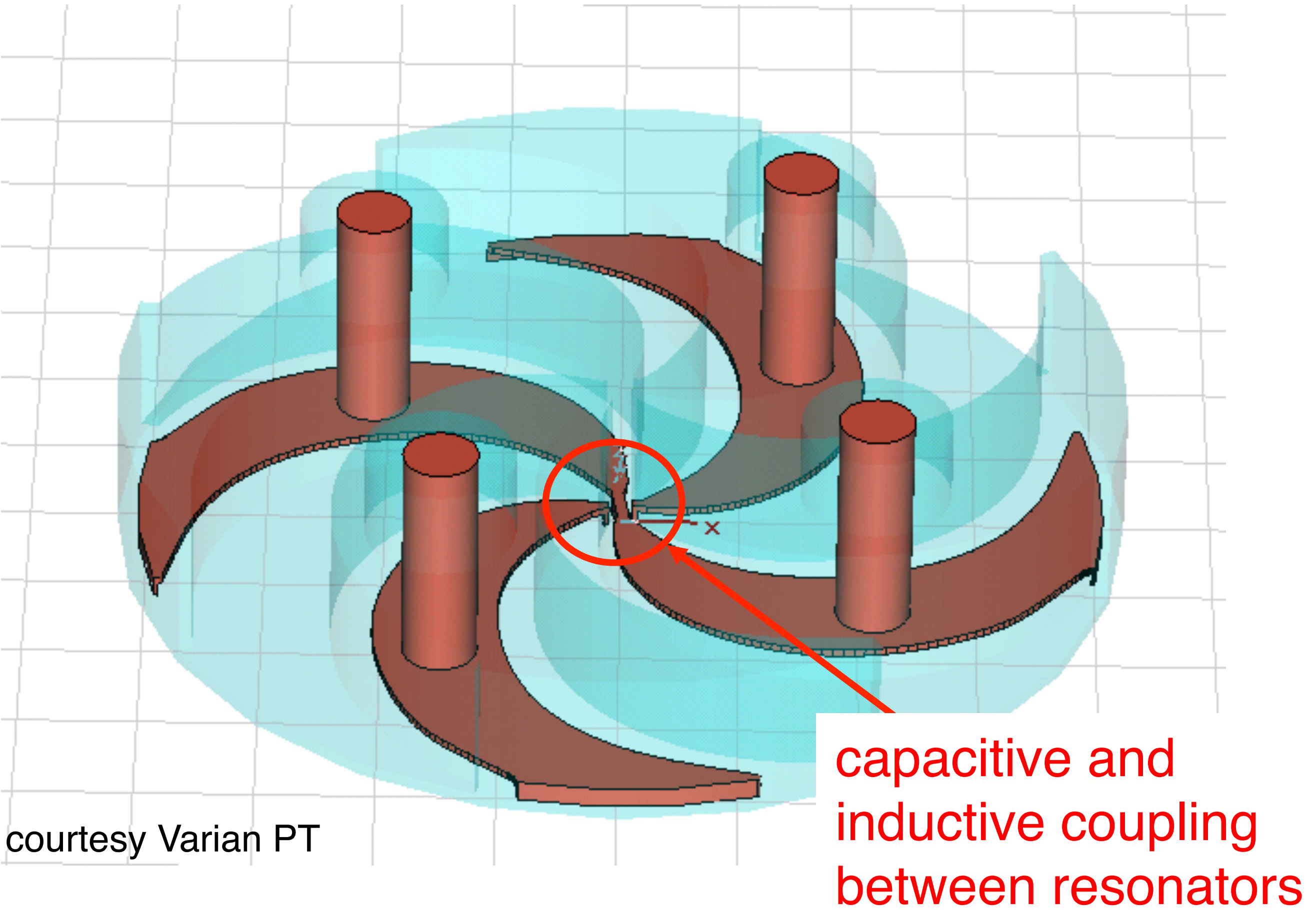
source: IBA

example: VARIAN PT cyclotron

- 250 MeV protons
- 4 coupled λ/2 resonators driven via one power coupler
  - 4 Eigenmodes; only three can be excited
  - push-pull mode at 72.4 MHz used (h = 2)
  - accelerating voltage 80 kV ➡ ~400 turns
  - RF power ~60 kW
- complex tuning control due to coupling
  - control parameters: 4 positions sliding short
  - error signals
    - phase drive power – resonator 1
    - 3 voltage ratios resonator 1 – resonator 2; 3 and 4
  - 4 x 4 transfer matrix not diagonal
    ➡ no independent servo loops

example: VARIAN PT cyclotron

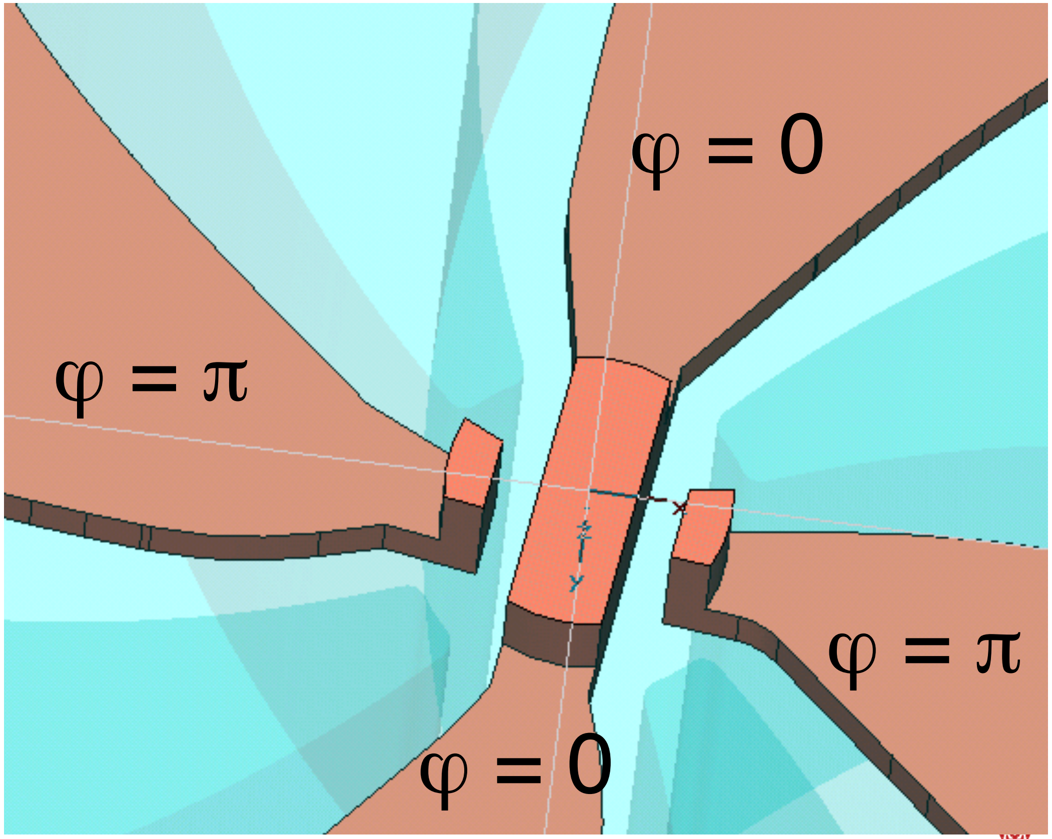
- 250 MeV protons
- 4 coupled λ/2 resonators; 1 amplifier



courtesy Varian PT

example: VARIAN PT cyclotron

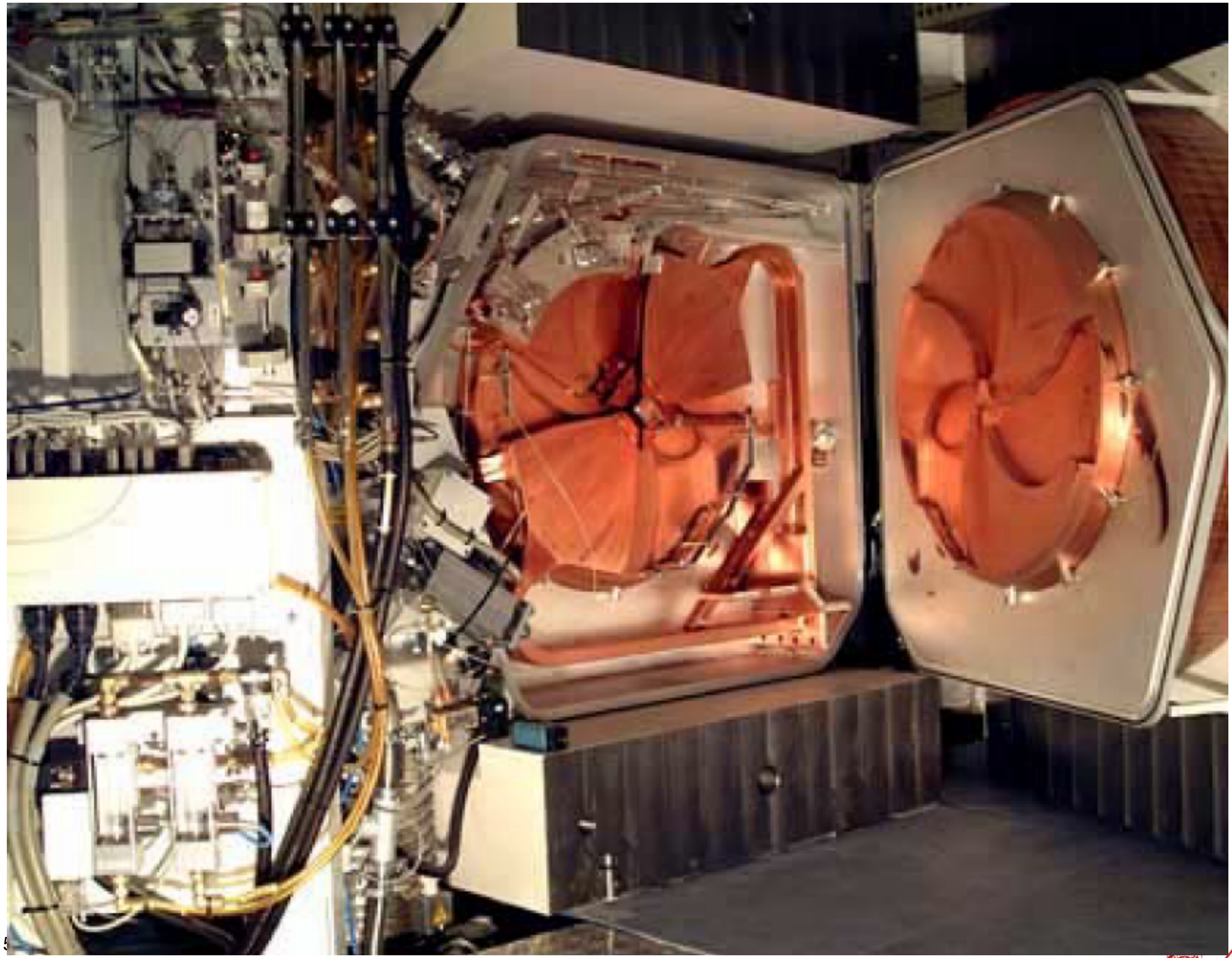
- 250 MeV protons
- 4 coupled $\lambda/2$ resonators driven via one power coupler
  - 4 Eigenmodes; only three can be excited
  - push-pull mode



courtesy Varian PT

example: PET isotope production cyclotron

- 2 MHz λ/4 resonators; π-mode for protons, 0-mode for deuterons



courtesy GE

acknowledgement

- Claude Bieth, GANIL
  for introducing me in the RF wonderland

- Antonio Caruso, LNS
  Marco di Giacomo, GANIL
  Peter Sigg, PSI
  John Vincent, NSCL
  IBA
  VARIAN PT
  for providing a lot of information

conclusions

- wide range of applications
  - isotope production
  - nuclear physics; radioactive beam production
  - meson factory; spallation neutron source
- wide range of beams and energies
  - protons up to uranium
  - 1.5 MeV/nucleon – 590 MeV/nucleon
- large dynamic range in intensity and beam power
  - <1 nA – 5 mA
  - <1 W – 1.3 MW
- compact cyclotrons, separated sector cyclotrons
- extraction radius 0.2 – 8 m

➡ large variety of RF systems

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SYNCHRO-CYCLOTRON

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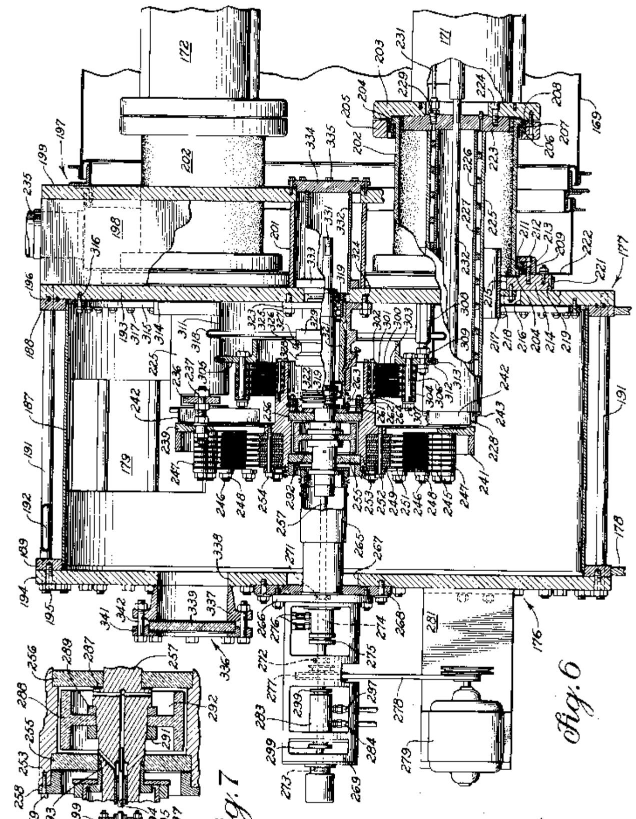

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SYNCHRO-CYCLOTRON

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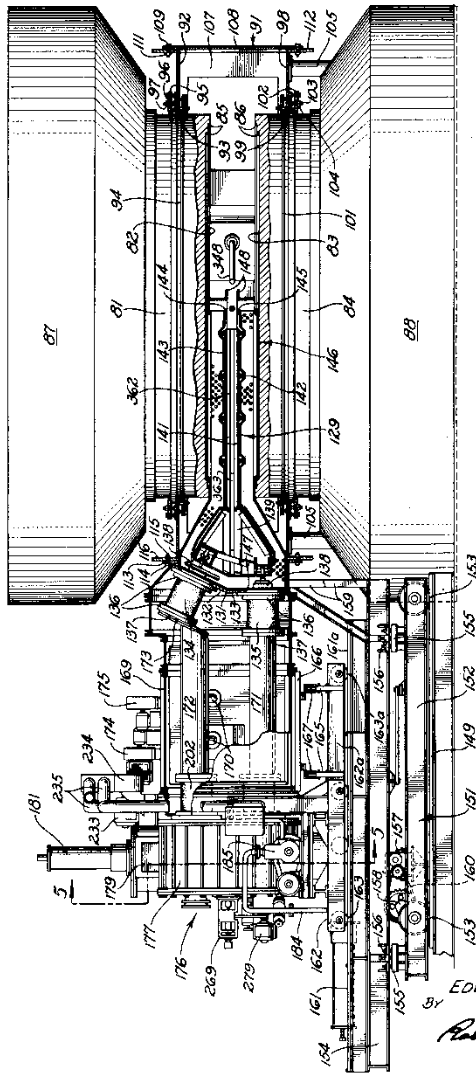

Fig. 4

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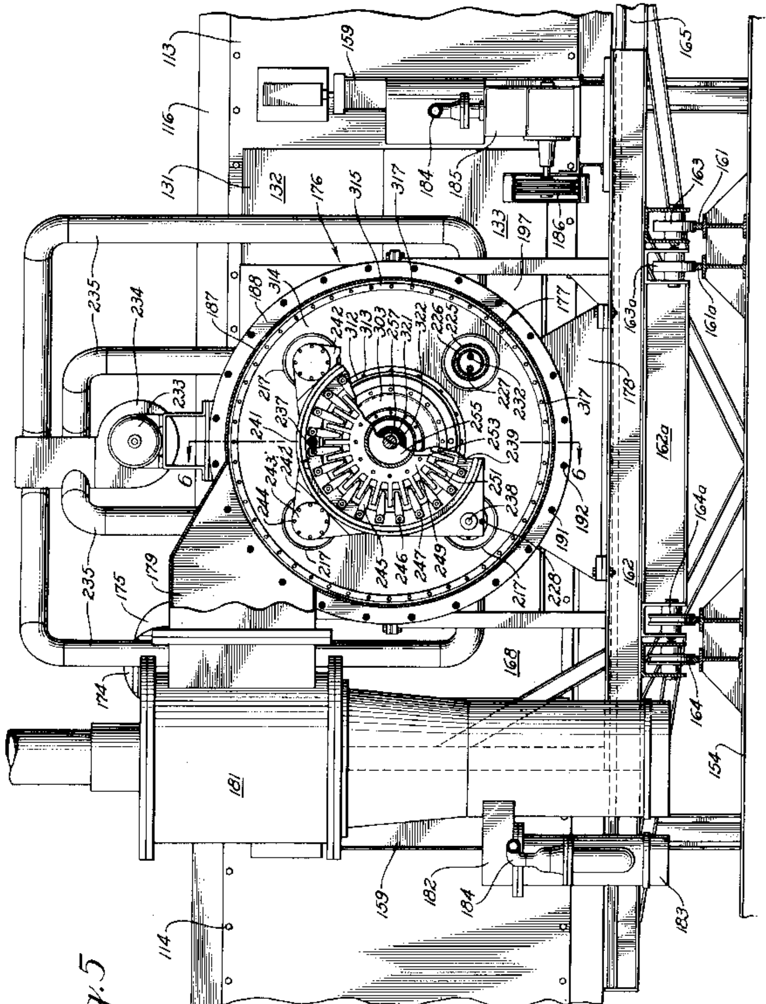

Fig. 5

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SYNCHRO-CYCLOTRON

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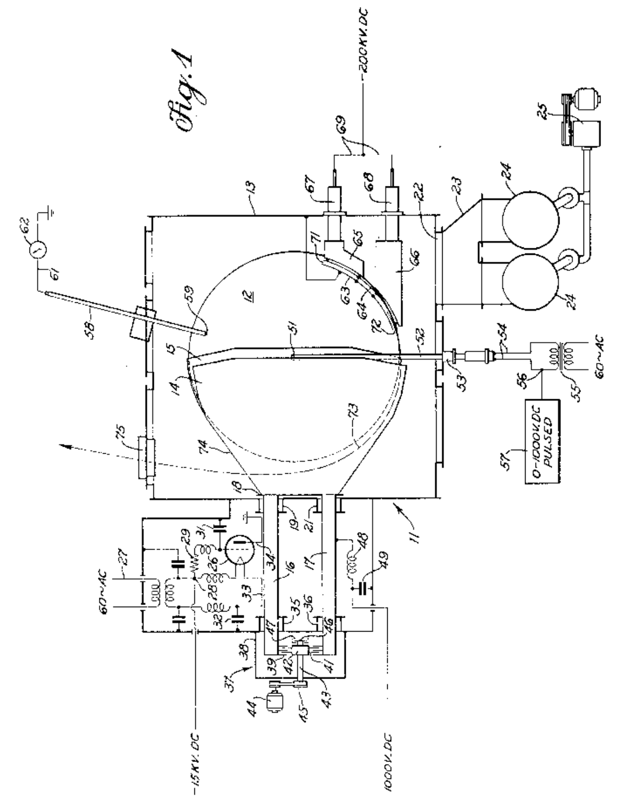

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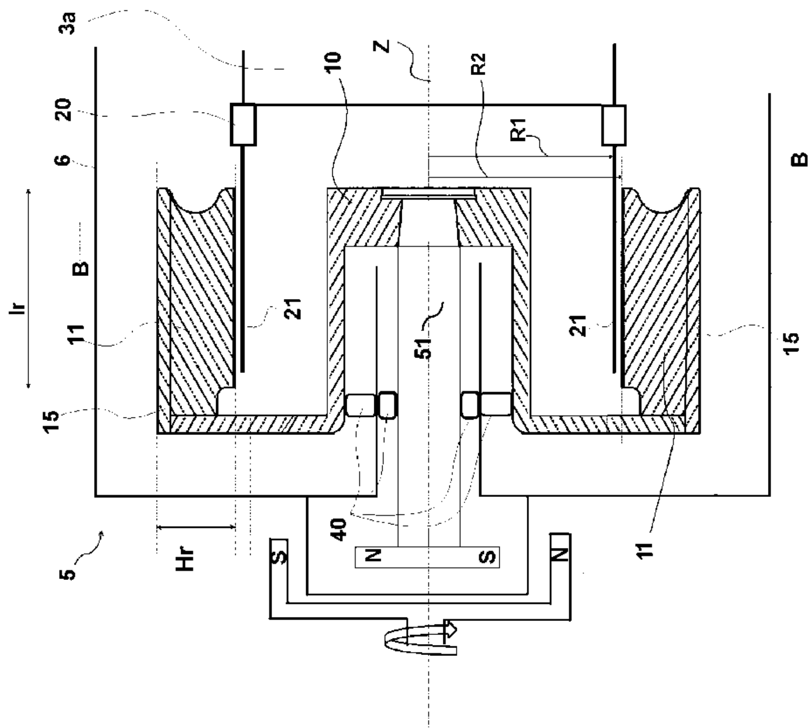


Fig. 4a

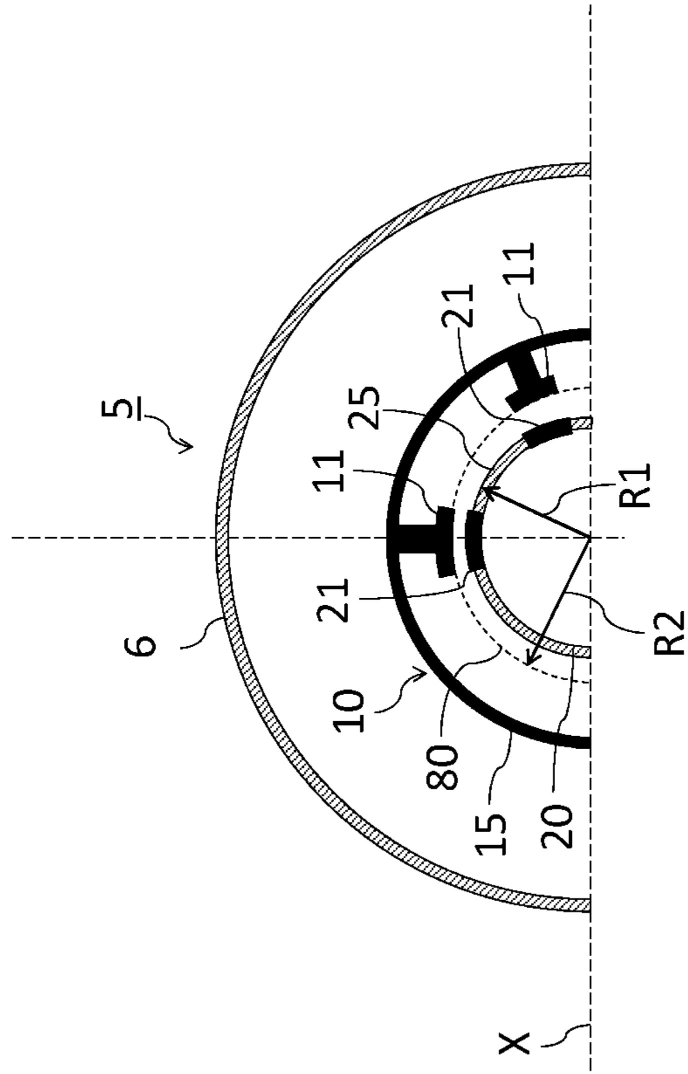


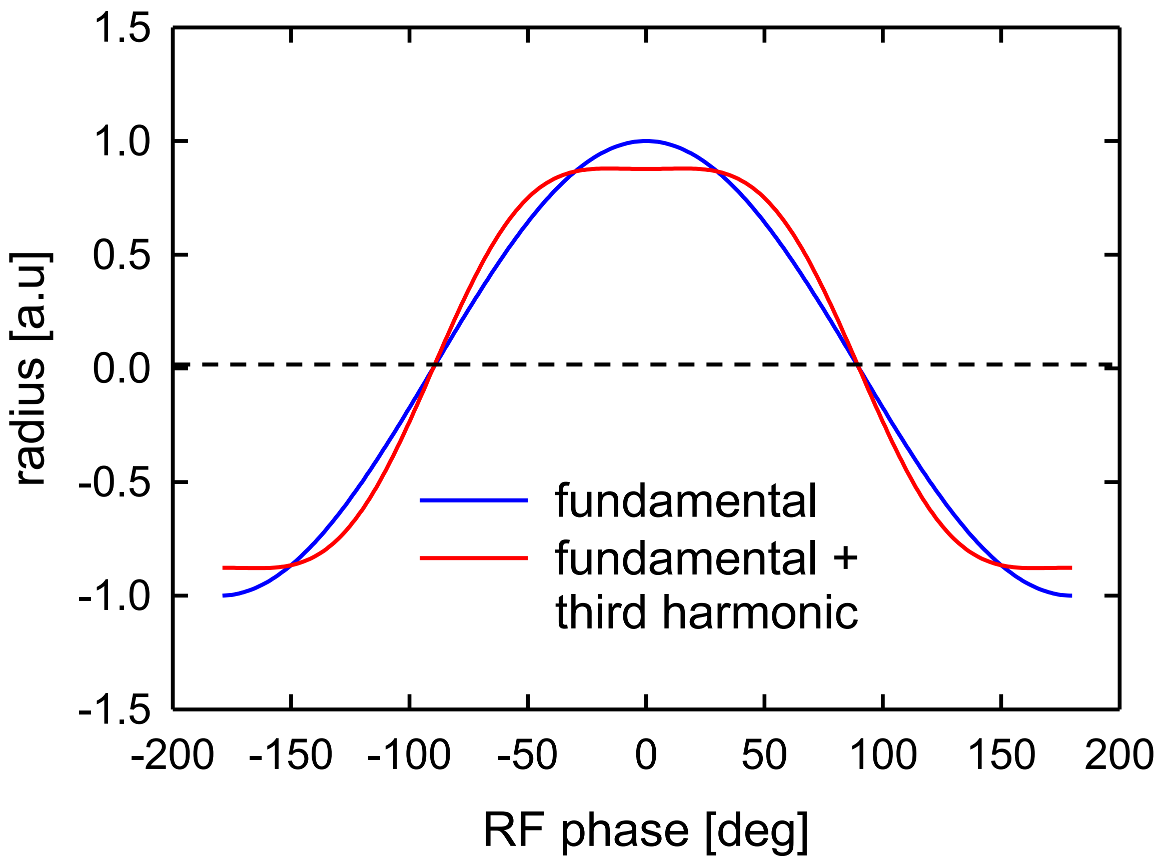
Fig. 4b

flattopping with higher harmonic

- cyclotron: no phase stability (always on transition)
  - $\Delta\varphi$ translates into ΔE
    - ➡radial bunch broadening, overlapping turns
    - increased by fieldimperfections: acceleration on slope
- add odd higher harmonic of RF voltage
  - ➡ reduced energyspread
  - ➡ compensate longitudinal space charge force
- flat topping resonator extracts power from beam
  - ➡ complex voltage and phase control @ high beam intensity

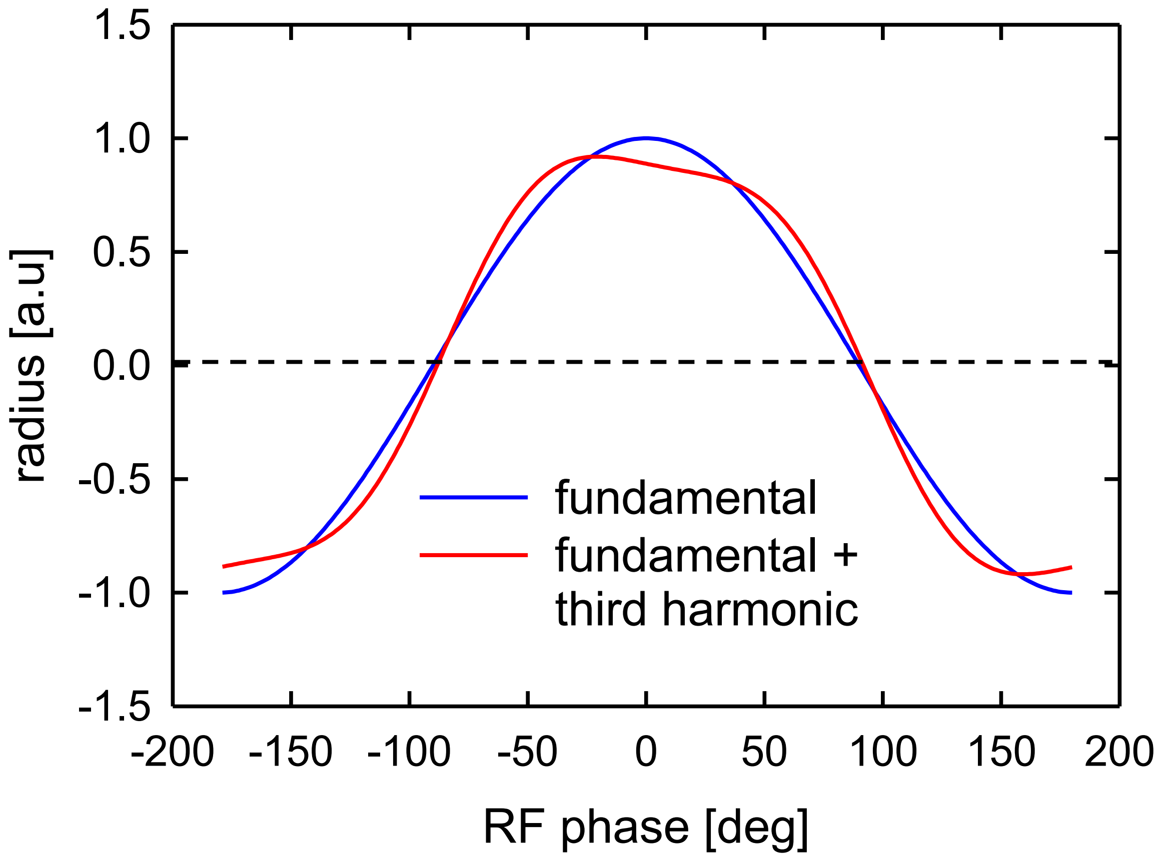
flattopping with higher harmonic

- accommodate larger bunchwidth and isochronism deviations



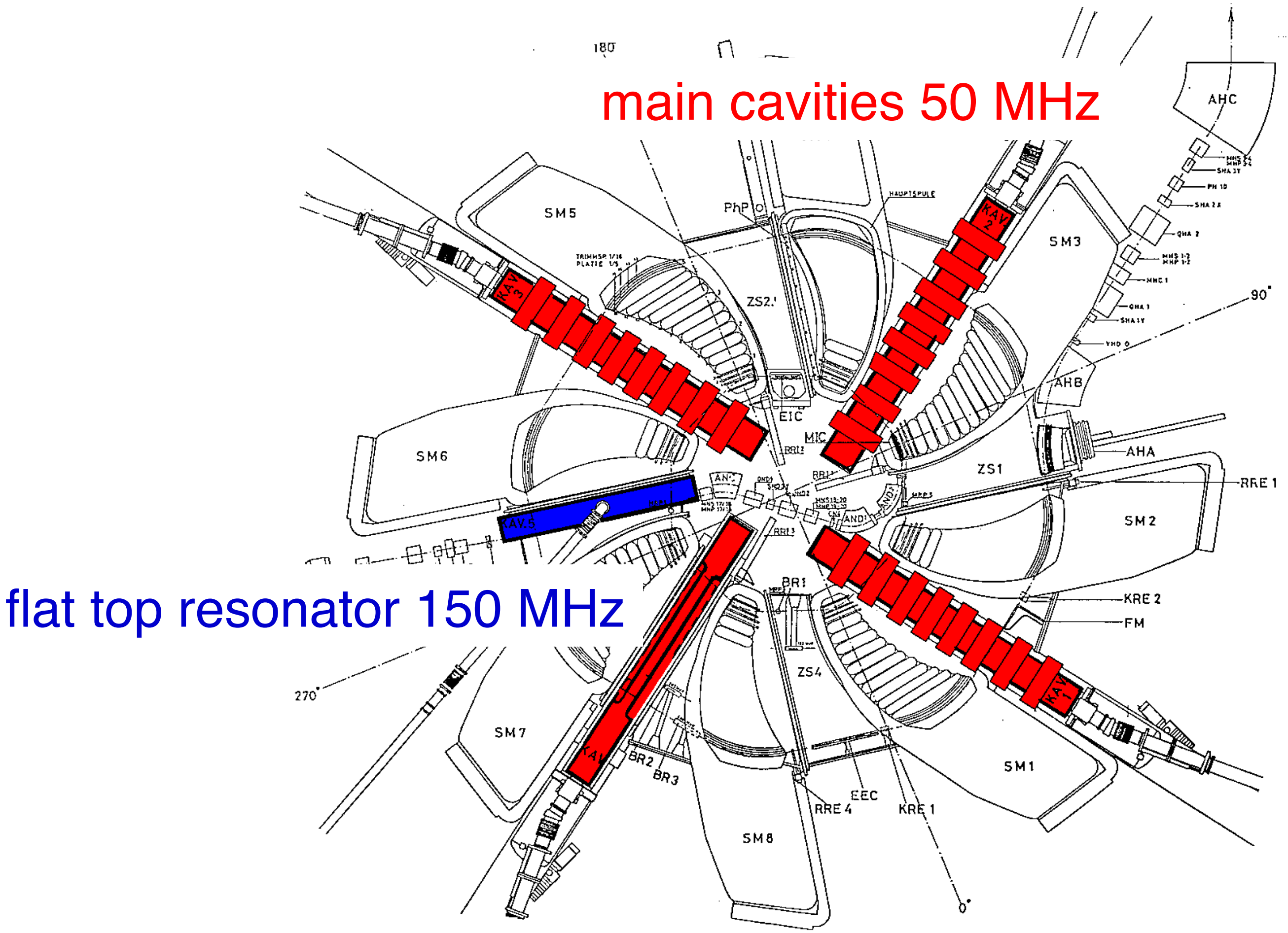
flattopping with higher harmonic

- accommodate larger bunchwidth and isochronism deviations
- compensate longitudinal phase space force
  - phase and amplitude intensity dependent



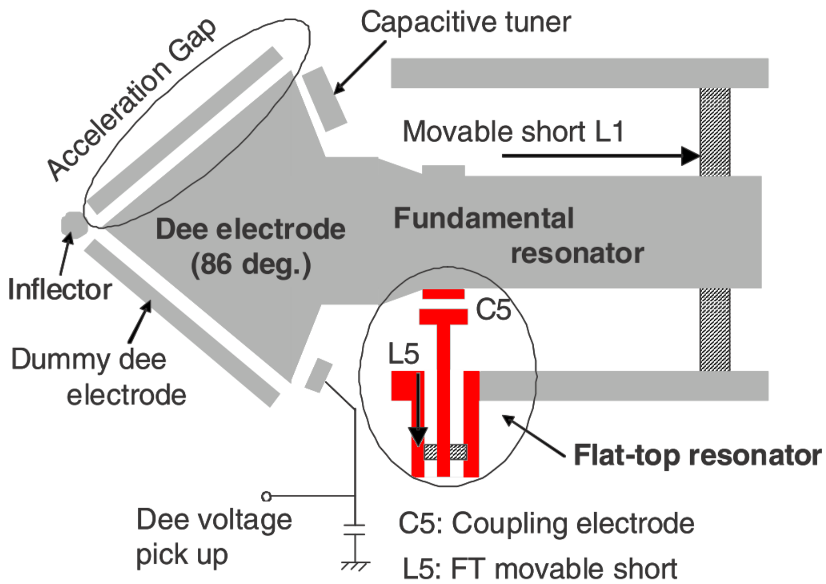
flattopping with higher harmonics

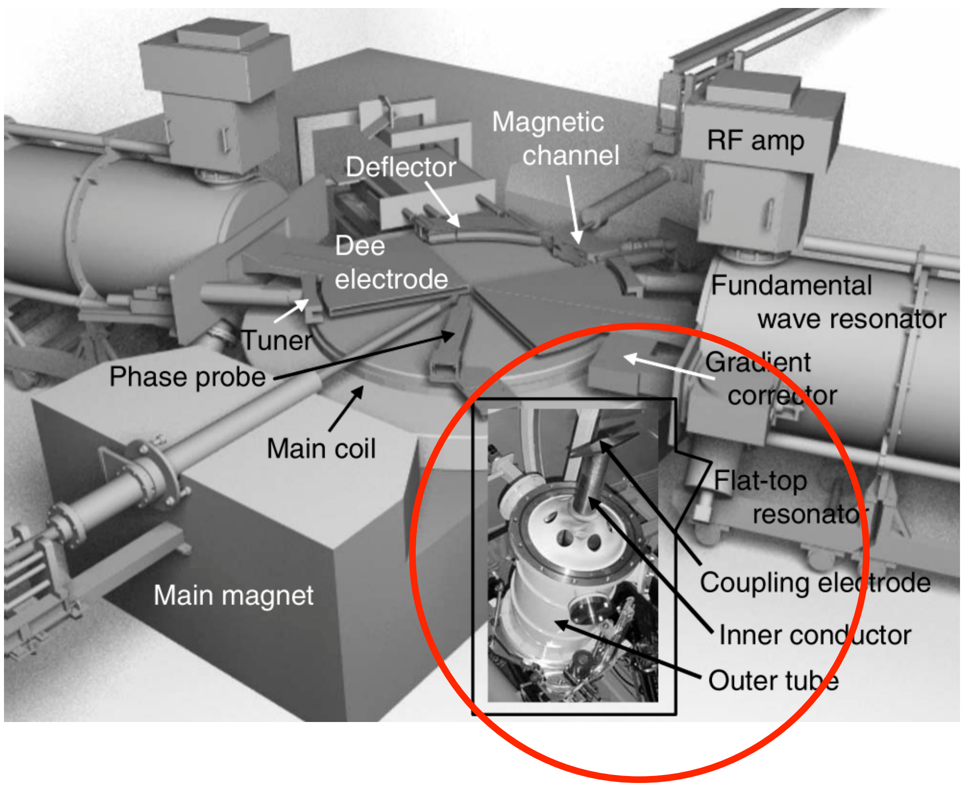
- PSI, RIKEN, RCNP: separate higher harmonic resonator



flattopping with higher harmonic

- JAERI AVF cyclotron: higher harmonic superimposed



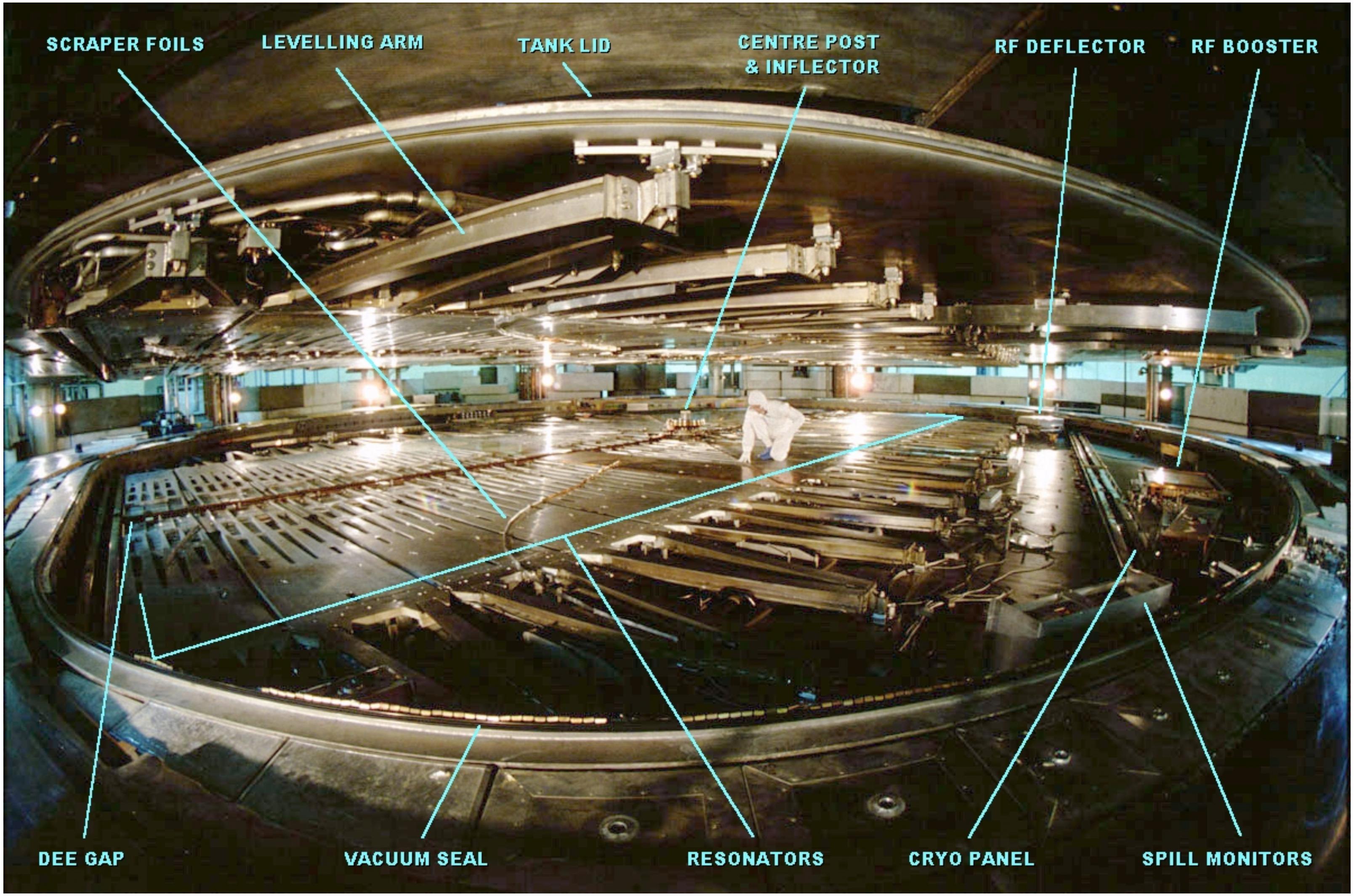


some examples: TRIUMF

- beam 200 μA 520 MeV H^-

some examples: TRIUMF

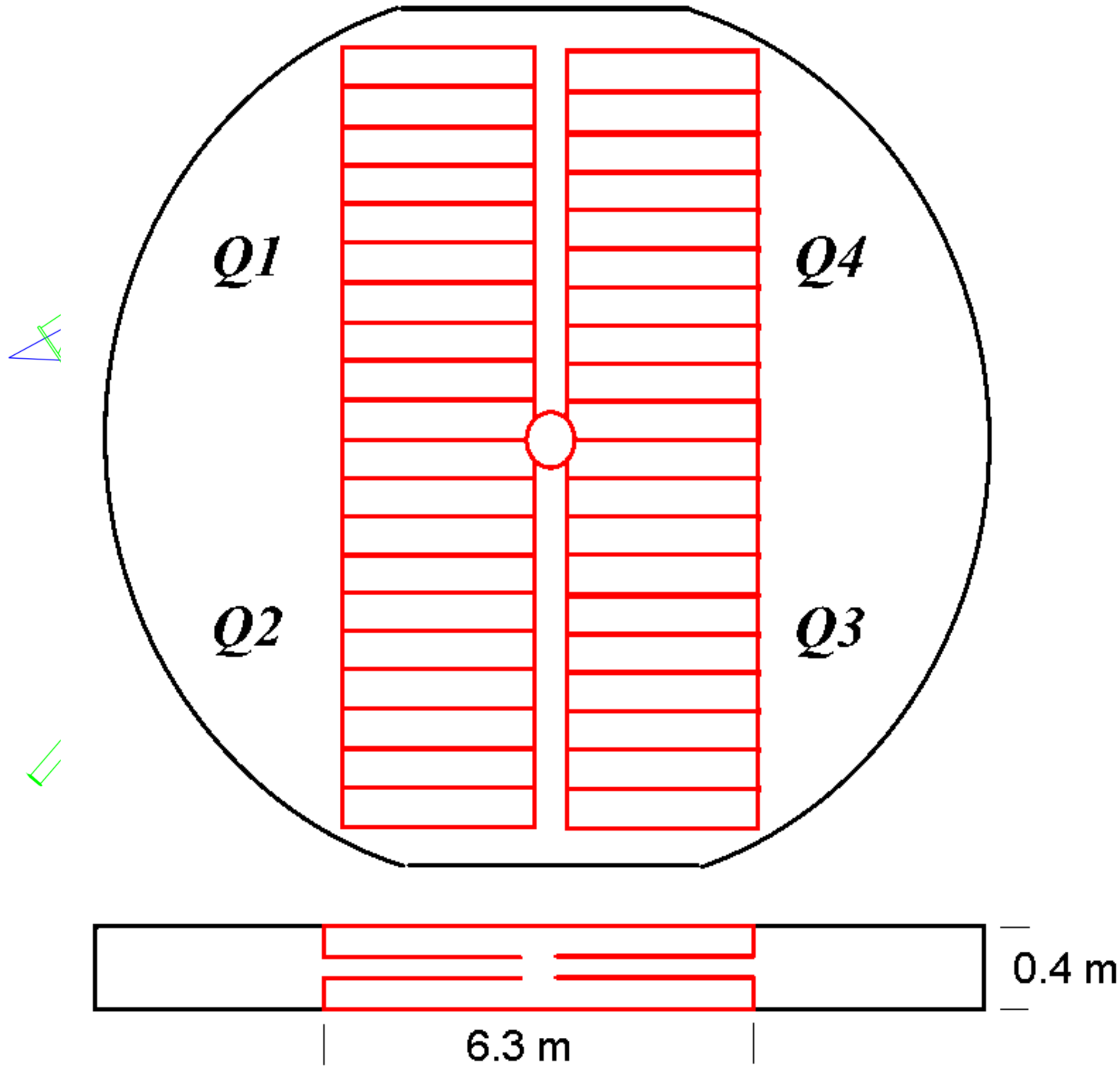
- beam 200 μA 520 MeV H^-



some examples: TRIUMF

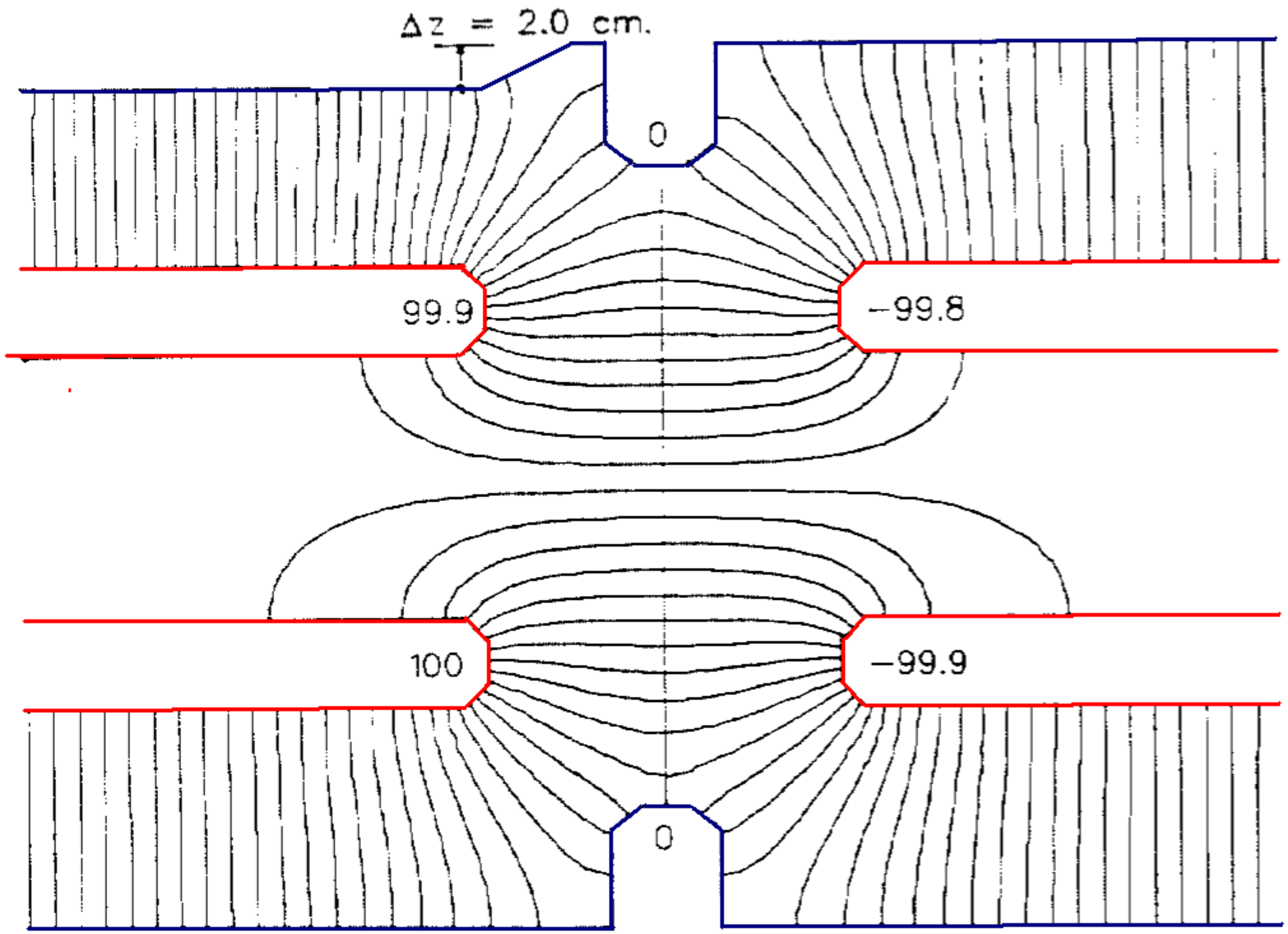
- 80 23 MHz $\lambda/4$ resonators
  - 2 x 20 above median plane
  - 2 x 20 below median plane
- excitation scheme
  - above – below inductive coupling; 0-mode
  - adjacent capacitive coupling; 0-mode
  - left – right capacitive coupling; π-mode
- inductive coupling; RF power 1.2 MW
- tuning by resonator deformation

some examples: TRIUMF



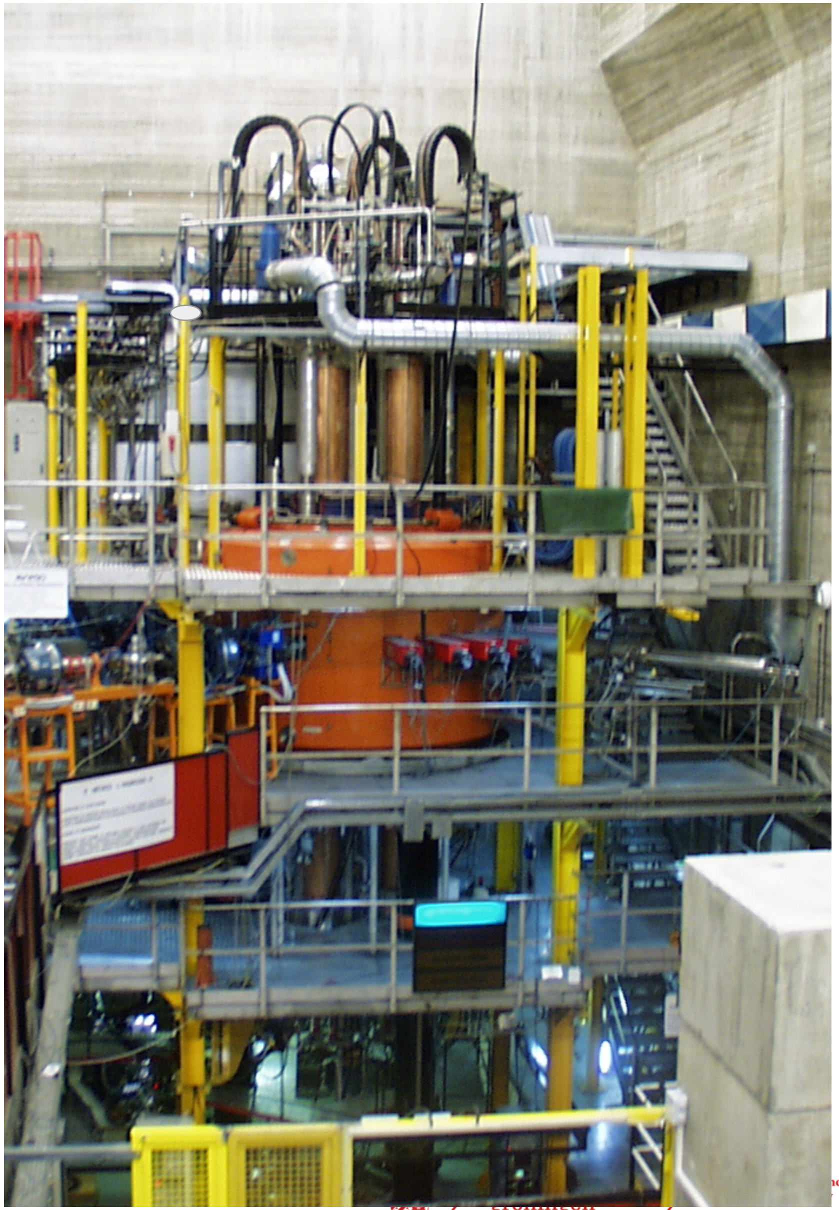
some examples: TRIUMF

- electric field distribution in accelerating gap



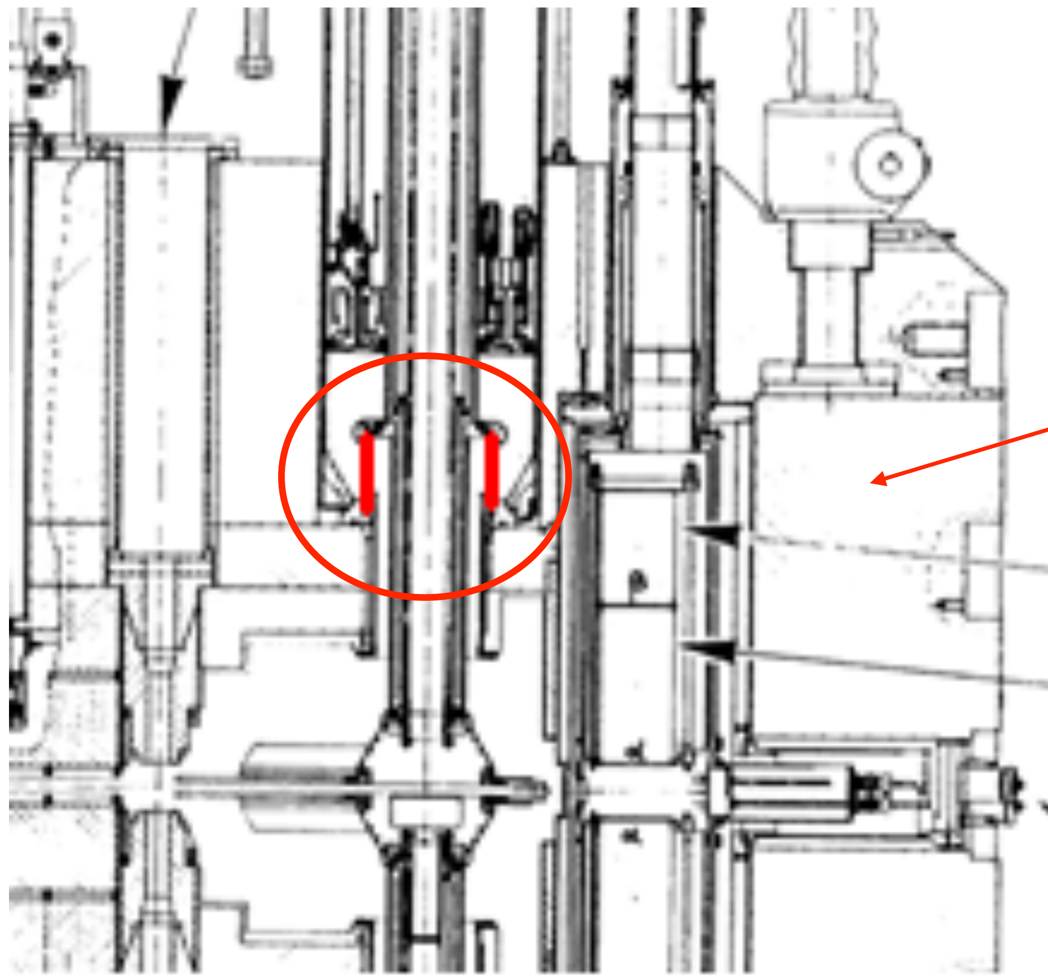
some examples: LNS SC cyclotron

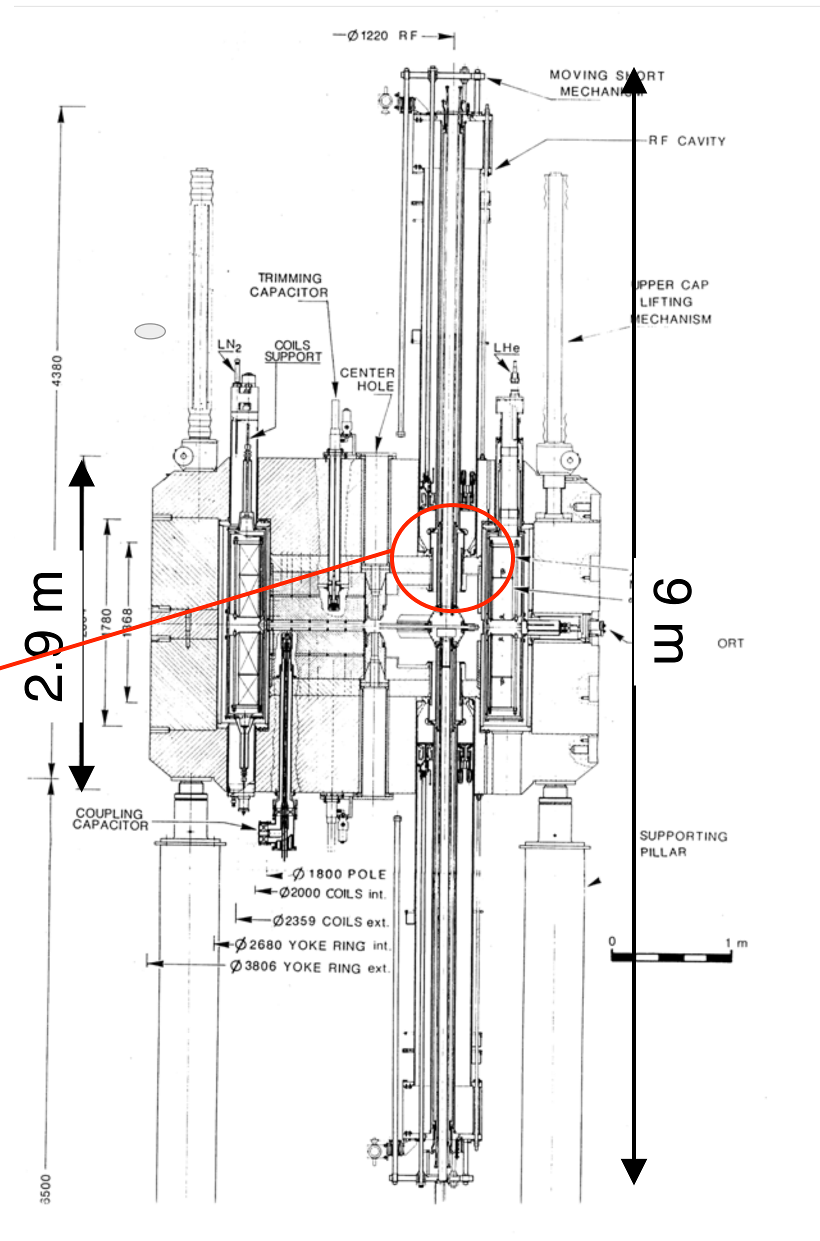
- three 15 – 48 MHz λ/2 resonators



some examples: LNS SC cyclotron

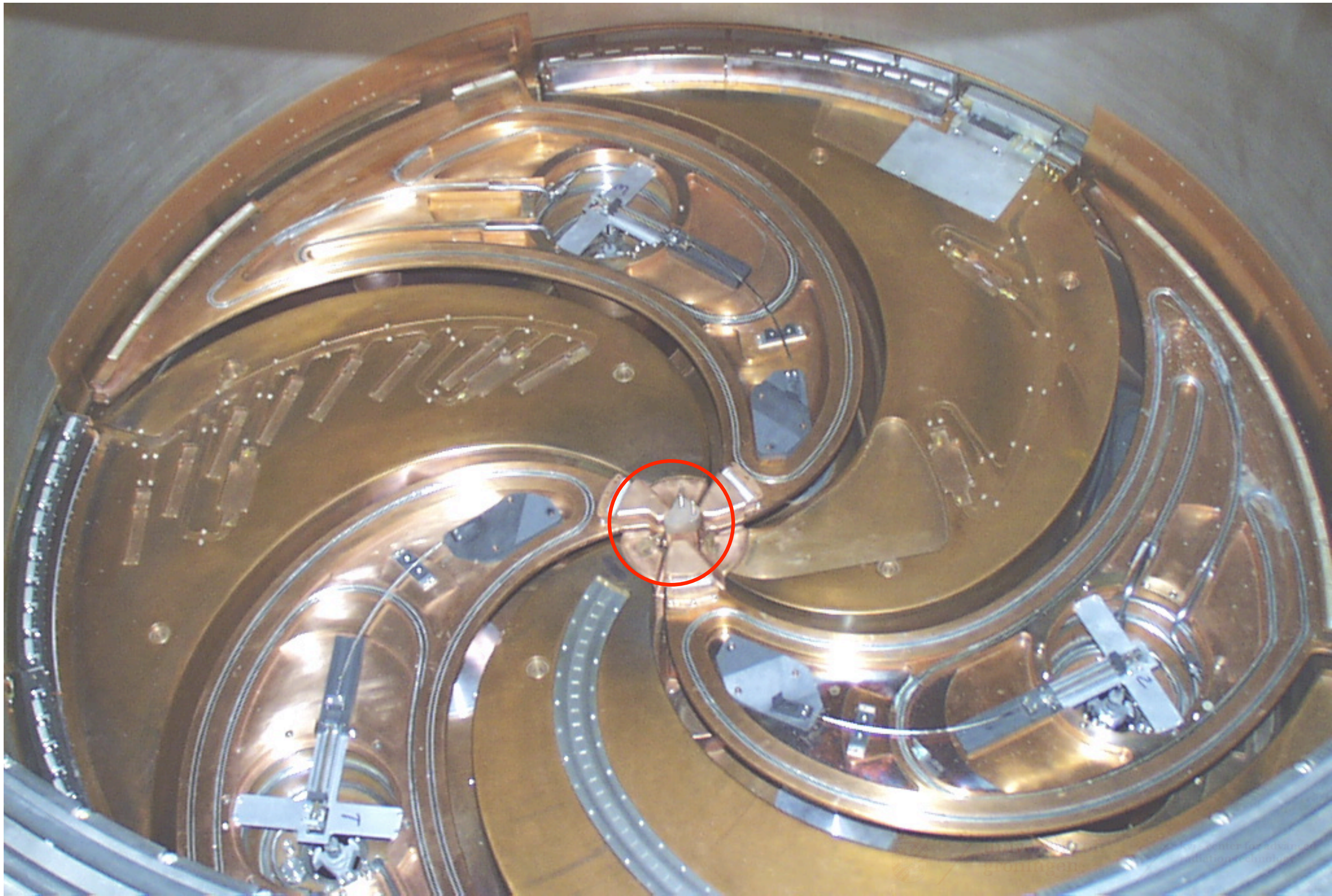
- three 15 – 48 MHz λ/2 resonators
  - vacuum feedthrough issue: E ll B





some examples: LNS SC cyclotron

- inter-resonator coupling in center
- not operating in Eigenmode
  - power transfer between resonators ➡ perturbation



some examples: LNS SC cyclotron

- inter-resonator coupling in center
- not operating in normal mode (h = 3)
  - power transfer between resonators ➡ perturbation
- some numbers
  - reactive power resonator — $P_R = 100$ MW
  - electrode voltage — $V_D = 100$ kV
  - operating frequency — $\nu = 40$ MHz
  - reactive power coupling — $1.75\ V^2 \omega C_c$

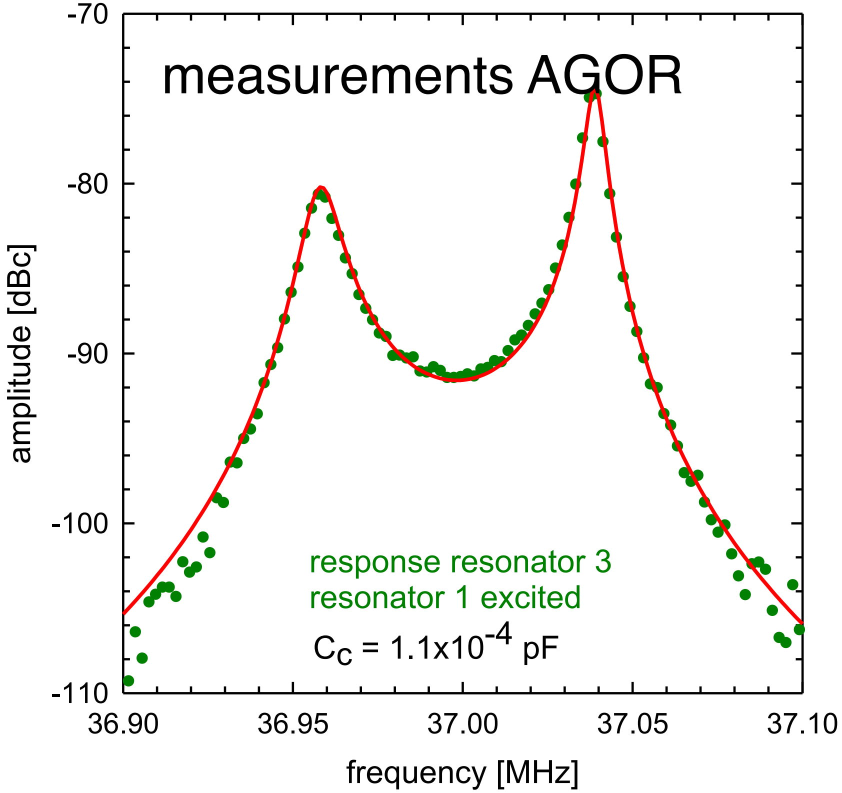
    4.4 MW/pF

  ➡ minimize coupling capacitance
  achievable value $C_c \leq 10^{-3}$ pF

some examples: LNS SC cyclotron

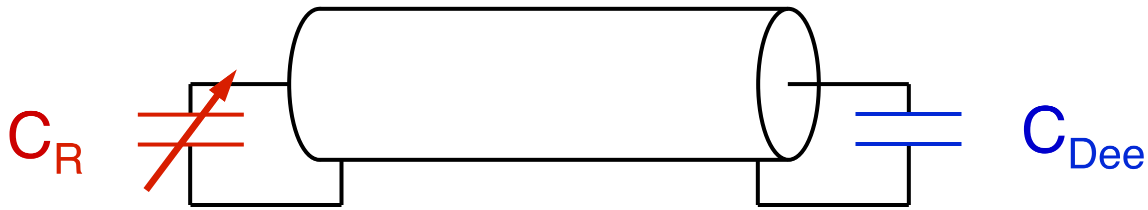
- inter-resonator coupling in center
- not operating in normal mode (h = 3)
  - power transfer between resonators ➡ perturbation

  ➡ minimize coupling capacitance
  achievable value $C_c \leq 10^{-3}$ pF



synchrocyclotron

- $\lambda/2$ transmission line with capacitive load on both ends



- frequency variation by variation of C_R
  - capacitance rotating in vacuum (RotCO)
- acceleration electrode C_{Dee}
- operational parameters
  - acceleration voltage ~20 kV
  - RF power 10 – 100 kW
  - rep rate 100 - 400 Hz
  - self-oscillating
  - frequency swing ~20 %
    Orsay 19 – 24 MHz

synchrocyclotron Liverpool