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
cyclotron basics

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

\[
\frac{mv^2}{R} = qvB \quad R = \frac{mv}{Bq} \quad \nu_{\text{orb}} = \frac{Bq}{2\pi m}
\]

centrifugal force  Lorentz force
cyclootron basics

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

\[
\frac{mv^2}{R} = qvB \quad R = \frac{mv}{Bq} \quad \nu_{\text{orb}} = \frac{Bq}{2\pi m}
\]

• accelerate with RF electric field with \( \nu_{\text{RF}} = h \nu_{\text{orb}} \) (h integer)

• drift tube linac “rolled up” in a magnetic field
why it should not work

• transverse optics
  • homogeneous field: fieldindex $n = 0$
    • $Q_z, \nu_z = 0$; no vertical stability
      ➔ linear growth of vertical beamsize
    • $Q_r, \nu_r = 1$; 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

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

\[ C_R \quad \equiv \quad C_{\text{Dee}} \]

• frequency variation by variation of $C_R$
  • capacitance rotating in vacuum (RotCo)
  • electrode profile $\Rightarrow f(t)$

• acceleration electrode $C_{\text{Dee}}$

• operational parameters
  • acceleration voltage $\sim 20$ kV
  • RF power 10 – 100 kW
  • rep rate 100 - 400 Hz
  • self-oscillating
  • frequency swing $\sim 20\%$

600 MeV synchrocyclotron CERN
• $\lambda/2$ transmission line with capacitive load on both ends

\[
\begin{array}{c}
C_R \quad \Rightarrow \quad C_{\text{Dee}}
\end{array}
\]

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  Orsay 19 – 24 MHz

200 MeV synchrocyclotron Orsay

used for proton therapy 1990 - 2010
operational parameters

- orbital frequency (non-relativistic) \( f_{orb} = 15.2 \frac{Q}{A} \overline{B} \) [MHz]
  - \( \overline{B} \) 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
• orbital and resonator frequency ranges incompatible
  ➔ use different harmonic modes (example AGOR)
  different phasing of resonators
orbital and resonator frequency ranges incompatible ➔ use different harmonic modes

• harmonic mode $h = \frac{f_{\text{RF}}}{f_{\text{orb}}}$
  • 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 ($\lambda/4$ or $\lambda/2$)
  - capacitively loaded by acceleration electrode(s)
  - TEM-mode
  - most common solution

shorting plate
frequency
adjustment/tuning

$\lambda/4$ coaxial
transmission line

180° acceleration
electrode (Dee)
2 gaps per turn
courtesy Philips
shape acceleration electrode vs. harmonic

- highest acceleration: particle passes symmetry axis for $\varphi = \pi$
  $$\Delta E = -Q V_d \sin(h \alpha/2) \sin(\varphi)$$

- not all harmonic modes possible
e.g. $\alpha = 60^\circ \Rightarrow$ 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
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
    - $\Delta$ frequency $< 1 \text{ MHz}$
      - range 22 – 62 MHz
    - $\Delta$ loop height $< 5 \text{ mm}$
      - range 100 mm
    - $\Delta$ 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
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
resonator design: 3D simulations

- 75 MHz resonator for 400 MeV/nucleon $^{12}$C cyclotron IBA

courtesy IBA, JINR
frequency tuning transmission line resonator

\[ Z_D = \frac{-i}{\omega C_D} \quad Z_L = i Z_0 \tan \left( \frac{\omega l}{c} \right) \]

- 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
frequency tuning: RIKEN ring cyclotron

• change of characteristic impedance at different location
  • no high current density contacts on stem
  • box to median plane: more capacitance ➔ 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

- change capacitance acceleration electrode
frequency tuning: single gap resonator

- basically two options
  - gap capacitance
  - chamber inductance

flapping panel
frequency tuning: single gap resonator

• basically two options
  • gap capacitance
  • chamber inductance

[Diagram showing a resonator with labels L and C]
frequency tuning: single gap resonator

- basically two options
  - gap capacitance
  - chamber inductance

RCNP ring cyclotron
power coupling: capacitive

✔ simple mechanics
✔ also fine tuning control
✘ high voltage
✘ insulator
✘ discharge

Coupler capacitor under the Dee

LNS, Catania
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 swappabble
  ✗ 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

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

courtesy Peter Sigg, PSI
RF controls: phase

- essential for multi-resonator system
- phase stability $<0.1^\circ$
RF controls: tuning

- 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
example: IBA S2C2 synchrocyclotron

Adjustable stub
Oscillator
Pyrometer
Rotco
Servo motor
Turbo pump

Liner
RF pick-up
Dee
Line through cryostat
Vacuum feedthrough

source: IBA
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 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 $\lambda/2$ resonators; 1 amplifier

![Diagram of VARIAN PT cyclotron](image.png)

courtesy Varian PT

capacitive and inductive coupling between resonators
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
example: PET isotope production cyclotron

- 2 MHz $\lambda/4$ resonators; $\pi$-mode for protons, 0-mode for deuterons
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  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
flattopping with higher harmonic

- cyclotron: no phase stability (always on transition)
  - $\Delta \phi$ translates into $\Delta E$
    - radial bunch broadening, overlapping turns
  - increased by field imperfections: 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

main cavities 50 MHz

flat top resonator 150 MHz
flattopping with higher harmonic

- JAERI AVF cyclotron: higher harmonic superimposed
some examples: TRIUMF

- beam 200 $\mu$A 520 MeV H$^-$
some examples: TRIUMF

- beam 200 $\mu$A 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; $\pi$-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 $\lambda/2$ resonators
some examples: LNS SC cyclotron

- three 15 – 48 MHz $\lambda/2$ resonators
- vacuum feedthrough
  issue: $E \parallel B$
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 \(\Rightarrow\) 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

\(\Rightarrow\) 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 $C_c \leq 10^{-3}\, \text{pF}$
synchrocyclotron

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