cyclotron
RF
systems
outline

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

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

\[
\frac{mv^2}{R} = qvB \quad R = \frac{mv}{Bq} \quad v_{orb} = \frac{Bq}{2\pi m}
\]
cyclotron basics

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

\[ \frac{mv^2}{R} = q\nu B \]

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

• 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: field index \( n = \varepsilon > 0 \)
  - \( Q_z, \nu_z > 0 \); marginal vertical stability
    - large beamsize \( \Rightarrow \text{bad transmission} \)
  - \( Q_r, \nu_r < 1 \); 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 + RF frequency modulation
  - vertical and phase stability
  - E. MacMillan, Phys. Rev. 68 (1945) 144
  - V. Veksler, Phys. Rev. 69 (1946) 244
- synchro-cyclotron è synchrotron è storage ring
  - workhorse high energy physics
- radially increasing field + azimuthal field modulation
  - vertical stability and isochronism
  - Thomas, Phys. Rev. 54 (1938) 580 and 588
- isochronous cyclotron
  - workhorse nuclear physics
synchrocyclotron

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

- frequency variation by variation of $C_R$
  - capacitance rotating in vacuum

- acceleration electrode $C_{Dee}$

- operational parameters
  - acceleration voltage $\sim 20$ kV
  - RF power 10 – 100 kW
  - self-oscillating
  - frequency swing $\sim 20\%$
    - Orsay 19 – 24 MHz
  - rep rate 100 - 400 Hz
synchrocyclotron

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

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operational parameters

- orbital frequency (non-relativistic) \( \nu_{\text{orb}} = 15.2 \frac{Q}{A} \bar{B} \) [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
  - research machines
    - multi-particle
    - multi-energy
    \( \approx \) large orbital frequency range
  - typical example SC AGOR-cyclotron @ KVI
    - particles protons – Pb
    - energy 190 – 5.5 MeV/nucleon
    - orbital frequency 30 - 6 MHz
operational parameters

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

![Graph showing operational parameters with different harmonic modes (h = 2, 3, 4) plotted against Q/A and E/A [MeV].](image_url)
operational parameters

- orbital and resonator frequency ranges incompatible
  - use different harmonic modes

- harmonic mode
  - 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

- capacitively loaded transmission line ($\lambda/4$ or $\lambda/2$)
- dual gap acceleration electrode
- 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 $\phi = \pi$
  $$\Delta E = -QV_0 \sin\left(h \alpha/2\right) \sin(\varphi)$$

- not all harmonic modes possible
  e.g. $\alpha = 60^\circ$ $\phi$ no acceleration for $h = 6$
resonator types

- single gap resonator
  - separated sector cyclotrons
  - used at PSI, RCNP and RIKEN
  - TE_{110} mode
resonator types

- single gap resonator
  - separated sector cyclotrons
  - used at PSI, RCNP and RIKEN SRC
  - $TE_{110}$ mode
resonator design: transmission line model

- traditional approach (used until ~10 years ago)
- validation on scale models
resonator design: transmission line model

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

![Diagram showing electric field distribution with labels for inflector housing, acceleration electrode, and voltage values 18 MV/m and 100 kV.]

courtesy Varian PT
resonator design: 3D simulations

- 75 MHz resonator for 400 MeV/nucleon $^{12}\text{C}$ 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

- 75 MHz resonator for 400 MeV/nucleon $^{12}\text{C}$ cyclotron IBA
frequency tuning transmission line resonator

\[ Z_0, l_L \quad C_D \quad Z_D = \frac{-1}{\omega C_D} \quad Z_L = Z_0 \tan\left(\frac{c\omega}{l_L}\right) \]

- 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
frequency tuning: single gap resonator

- basically two options
  - gap capacitance
  - chamber inductance
frequency tuning: single gap resonator

- basically two options
  - gap capacitance
  - chamber inductance

RCNP ring cyclotron

L

beam

C

Upper tuning panel

Accel. gap electrodes

Lower tuning panel

Tuning panels

\[ d \]

\[ 375 \text{ mm} \]
power coupling: capacitive

- simple mechanics
- also applicable for tuning control
- high voltage
  - insulator
  - discharge

Coupler capacitor under the Dee

LNS, Catania

Dee

matching
power coupling: inductive

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

AGOR, Groningen
RF controls

- controlled parameters
  - amplitude acceleration voltage
  - phase acceleration phase
    - 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

- error signal processing
  - 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 $<10^{-4}$
RF controls: phase

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

- bandwidth typ. 1 Hz

courtesy Peter Sigg, PSI
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

![Graph showing flattopping with higher harmonic](image)
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 μA 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 è perturbation
some examples: LNS SC cyclotron

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

è 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 è perturbation
  - minimize coupling capacitance
  - achievable value \(C_c \leq 10^{-3} \text{ pF}\)

![Graph showing response resonator 3 with resonator 1 excited.](image)

- Measurements AGOR

- Frequency [MHz]: 36.90, 36.95, 37.00, 37.05, 37.10
- Amplitude [dBc]: -110, -100, -90, -80, -70

- Response resonator 3
- Resonator 1 excited
- \(C_c = 1.1 \times 10^{-4} \text{ pF}\)
some examples: VARIAN PT cyclotron

- 250 MeV protons
- 4 coupled $\lambda/2$ resonators; 1 amplifier

courtesy Varian PT

[Diagram: Capacitive and inductive coupling between resonators]
some examples: 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
some examples: 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
- complex tuning control
  - 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: PET isotope production cyclotron

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