Why cyclotrons for isotope production?

- **Cost-effective** machines for achieving:
  - required energies (<100 MeV) and
  - high currents (< 1000 µA)
  - Constant particle revolution frequency in a uniform magnetic field =>
    same accelerating structure used multiple times

- **Compact** =>
  - magnet and RF integrated into one system
  - Single stage => no injector accelerator needed

- **Moderate magnetic fields up to 1 to 2 Tesla**

- **Simple RF system:**
  - Constant RF-frequency (10-100 MHz) => CW operation
  - Moderate voltages (10-100 kVolt)

- **Relative easy injection** (internal ion source or axial injection)

- **Simple extraction** (stripping for H⁻ ions)
Major milestones in cyclotron development (1)

1. Classical cyclotron (Lawrence)
   • Uniform magnetic field => loss of isochronism due to relativistic mass increase => energy limited
   • CW but weak focusing => low currents

2. Synchro-cyclotron (McMillan-Veksler)
   • B(r) decreasing but time varying RF frequency => high energies achievable
   • Pulsed operation and weak focusing => very low currents

3. The isochronous AVF cyclotron (Thomas focusing)
   • Azimuthally varying magnetic fields with hills and valleys
   • Allows both isochronism and vertical stability
   • CW-operation, high energies and high currents
   • Radial sectors => edge-focusing
   • Spiral sectors => alternating focusing

Major milestones in cyclotron development (2)

4. The separate sector cyclotron (Willax)
   • No more valleys => hills constructed from separate magnets
   • More space for accelerating cavities and injection elements
   • Example PSI-cyclotron at Villingen-Switzerland
   • Very high energy (590 MeV) and very high current (2 mA) => 1 MWatt

5. H⁻ cyclotron (Triumf)
   • Easy extraction of H⁻ by stripping
   • Low magnetic (center 3 kG) field because of electromagnetic stripping
   • Triumf is largest cyclotron in the world (17 m pole diameter)

6. Superconducting cyclotron: Fraser/Chalk River/Blosser/MSU
   • High magnetic field (up to 5 Tesla) => high energies at compact design

7. Superconducting synchrocyclotrons (Antaya-Wu-Blosser)
   • Very high magnetic fields (9 Tesla)
   • Very compact => cost reduction => future proton therapy machines?
Commercial cyclotron vendors

- **IBA**, Belgium
- **GE**, USA
- **SUMITOMO**, Japan
- **ABT**, USA
- **SIEMENS**, Germany
- **Best**, Canada
- **Advanced Cyclotron Systems, Inc.**, Canada

Market and suppliers of 30 MeV cyclotrons

<table>
<thead>
<tr>
<th>Name</th>
<th>country</th>
<th>30 MeV beam</th>
<th>Year of Op.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBA Cyclone 30</td>
<td>Belgium</td>
<td>400 - 800 - 1200 μA</td>
<td>1986 / 2010</td>
</tr>
<tr>
<td>SHI HM-30</td>
<td>Japan</td>
<td>1 mA (BNCT)</td>
<td>2009</td>
</tr>
<tr>
<td>MCC 30/15</td>
<td>Russia (Efremov inst.)</td>
<td>100 μA</td>
<td>2010</td>
</tr>
<tr>
<td>Kirams-30</td>
<td>Korea (university based)</td>
<td>500 μA</td>
<td>2007</td>
</tr>
</tbody>
</table>
**IBA Cyclone-30 for production of SPECT isotopes**

First IBA machine
30 MeV - 500 µA
1986

Cyclotron used by all radiopharmaceutical producers:
Nordion, Mallinckrodt, Cis-bio, Amersham...

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**IBA medical cyclotrons: some general features**

- Deep-valley magnetic structure
  - Strong azimuthal variation of B ⇒ Strong focussing
  - Small gap requiring low power dissipation
- 4-fold symmetry
  - Two accelerating structures (dees) in two valleys ⇒
  - Very compact; two other valleys for pumping, ESD....
- Acceleration of negative ions (H⁻ or D⁻) ⇒
  - Stripping =>very easy using thin carbon foil
  - 100% extraction efficiency
- Injection from internal PIG-source (PET-isotopes) or with a spiral inflector (SPECT => cyclone 30)
Deep-valley Cyclotron Magnet Design

Extraction of the beam from the cyclotron

Extraction is always a major concern in cyclotrons => how to get the beam out of the magnetic field

1. No extraction at all => place an internal target
2. Stripping extraction (H-cyclotrons)
3. Extraction with an electrostatic deflector (ESD)
   • Proton therapy cyclotrons
4. Self-extraction => suitable shaping of the magnetic field
5. Regenerative extraction => synchrocyclotron

Some examples will be shown later
Extraction by stripping (Cyclone 30)

- Stripper foil removes the two electrons of the H⁺ ion
- Orbit curvature changes sign after stripping foil
- Simple => high extraction yield and little internal activation
- Energy variation by moving stripper position
- All energies go to one crossover point by proper foil azimuthal position
- Place combination magnet at crossover
- Ideal solution for industrial cyclotrons

Extraction by stripping: carbon stripping foil

Simpler than this is not possible
Extraction by stripping (Cyclone-18/9)

- Fixed foil position => constant energy but
- Multiple extraction ports around the machine
- Dual beam capability

An Internal Ion Source

- Some advantages
  - Simple and cheap: No injection line needed
  - Compact: two ion sources can be placed simultaneously
  - Cost considerations are essential in this market

- Some limitations
  - Moderate beam intensities
  - Simple ion species (H⁺, H⁻, deuterons, He-3, He-4)
  - Gas-leak directly into the cyclotron (stripping of negative ions)

- Carefull CR design is needed in order to obtain good centering and focusing
**Cold Cathode PIG Ion Source => how does it work**

- Electron emission due to high initial electrical potential on the cathodes
- Electron confinement due to the magnetic field along the anode axis
- Electrons produced by thermionic emission and ionic bombardment
  - Start-up: 3 kV to strike an arc
  - Operating point 100V
- Cathodes heated by the plasma (100 V is enough to pull an outer e- off the gas atoms)

**Chimney cathodes and puller**

Chimney: copper-tungsten ⇒ good heat properties; machinable
Cathodes: tantallum ⇒ high electron emission (low workfunction)
The cyclotron central region with an internal source

Two ion sources can be placed symmetrically

Compact Deep-valley Cyclotron Design
3D EM and beam-dynamics simulations

3D E-field calculations

Orbit calculations

Essential in cyclotron design

3D B-field calculations

External Ion Source => Axial Injection

- External ion source => beam injection along the vertical axis
- Bend from vertical to horizontal with an electrostatic inflector
- Higher currents can be achieved
- More different ion species can be injected
- Better cyclotron vacuum (less stripping losses for H⁻)
- Injection line needed with buncher, lenses, diagnostics, pumping…
Ion source: considerations for axial injection

- H\(^+\) is a very fragile ion => ion source requires careful design and optimization to get good performance
- Multicusp volume ion source with special 3D magnetic field shape (permanent magnets) to maximize plasma-confinement
- A separate zone of lower plasma temperature is made with magnetic filter, where H\(^+\) can be formed and stabilized
- Multiple extraction electrodes for beam divergence adjustment
- High current: 15 mA
- Good emittance: 100 \(\pi\) mm-mrad (4-rms) at 30 keV

Considerations for the injection line

- Good vacuum to minimize stripping losses (H\(^+\))
- Differential pumping to separate ion source vacuum from beam line
- Source is DC but Cyclotron is RF => matching needed
  - Bunching to increase injection efficiency
- Focusing: small beam spot at the entrance of the inflector => space charge effects
- Steering: good alignment of beam spot on inflector
- Beam diagnostics needed
- Compact (short) design to reduce stripping and space charge
  - Install several elements in the return yoke
An example of an injection line and ion source

C30-HC achieved 1.2 mA extracted beam with this injection line

Automized Magnetic Field Mapping

- Move Hall-probe on a 2D polar grid to obtain a full fieldmap in the median plane of the cyclotron
- Analyse the magnetic field on equilibrium orbits in order to evaluate isochronism
- Shim the hill sectors of the iron in order to improve the isochronism (reduce RF phase slip)

Precise mapping and iron pole shimming is needed in order to isochronize the magnetic field
A family of cyclotrons for isotope production

<table>
<thead>
<tr>
<th>PET</th>
<th>PET+SPECT</th>
<th>Multi-purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 units</td>
<td>160 units</td>
<td>2 units</td>
</tr>
<tr>
<td>C10/5</td>
<td>C18/9</td>
<td>C30-family</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C70</td>
</tr>
</tbody>
</table>

Baby-cyclotron 11 MeV

- 11 MeV proton.. limited capacity for PET
- H⁺ (proton only) - 120 µA ~ 1300 watts
- Usually hospital based 18F- 11C system

External shielding for neutrons and gammas
Medium energy Cyclone 18

- 18 MeV proton (9 MeV deuteron) or TWIN proton
- H⁻ (proton) 150 µA ~ 2700 watts
- D⁻ (deuteron) 50 µA
- Access to common PET
  - 18F
  - 11C
  - 13N
  - 15O
- And new RI
  - 64Cu, 89Zr, 124I, ...
  - Also 123I solid tgt

Cyclone 18+ for Pd-103 production (Brachytherapy)

- Large doses, lower cross-section require high current operation: example
- 18 MeV p @ 2mA on internal target
- 14 cyclotrons in the same factory
- 30 kW of beam with 100 kW of electrical power ⇒ 30 % accelerator efficiency

&[103Rd(p,n)_{103}^{103}Pd]

80% of the RF power is for beam acceleration; 20 % for building the accelerating field
The C14SE self-extraction cyclotron for 103-Pd

- Accelerate high intensity 14 MeV protons
- Good vacuum not required
  - Internal ion source
  - Less expensive pumping
- High current protons
  - ESD not possible
  - Extraction completely from magnetic design
  - IBA patented
- The ion source reached 15 mA on internal beam stop.
- Extracted beam intensities reached 1.4 mA
- On target reached 0.8 mA

IBA recently made a study for a dual extraction SE cyclotron as a candidate for Tc-99 production

The C70 cyclotron for Arronax

- Multi-purpose isotope production cyclotron
- Routine PET and SPECT
- Radio-chemistry research
- Therapeutic isotopes
  - $^{211}$At, alpha emitters
  - $^{67}$Cu, $^{177}$Lu, beta emitters
  - Pulsed alpha (research)

<table>
<thead>
<tr>
<th>Accelerated Beam</th>
<th>RF mode</th>
<th>Extraction</th>
<th>Extracted Energy (MeV)</th>
<th>Beam Intensity (µA)</th>
<th>Exit Ports</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$^+$</td>
<td>2</td>
<td>stripping</td>
<td>H$^+$</td>
<td>30–70</td>
<td>750</td>
</tr>
<tr>
<td>D$^-$</td>
<td>4</td>
<td>stripping</td>
<td>D$^+$</td>
<td>15–35</td>
<td>50</td>
</tr>
<tr>
<td>$^4$He$^{2+}$</td>
<td>4</td>
<td>ESD</td>
<td>$^4$He$^{2+}$</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>HH</td>
<td>4</td>
<td>ESD</td>
<td>HH</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>
C70 multiple particles => additional complexity

- Particles with different charge sign
  - B-field must be inversed between + and – particles
  - Two different types of ion sources (multicusp vs ECR)
- Particles with different q/m ratio (1/1 and 1/2)
  - Isochronous field shape not the same for both types
  - Central region geometry not the same for both types
  - Harmonic mode of acceleration not the same types
- Different methods of extraction needed
  - Stripping for H⁻ and D⁻
  - ESD for α and H₂⁺
- High intensity H⁻ requires very good vacuum

C70 => additional complexity of magnetic field

- Centering coils
- Extraction coils
- Isochronization coils
C70 => additional complexity of central region

Horizontal deflector at exit of the inflector needed to place different both particle types on the equilibrium orbit (orbit centering)

Illustration of the C70 dual extraction system

- Stripping extraction for negative particles
- ESD for α-particle
- Two opposite exit ports
- Simultaneous dual beam capability for H- and D-
- Variable energy for H- and D-
- External switching magnet to direct different energies and particle into the beam lines
The C70 multiple particle cyclotron

Injection line with two ion sources on top
Two beam exit ports at opposite angles
Two stripper probes at opposite angles

The C70 electrostatic deflector (ESD)

Water-cooled pre-septum adjustable
Septum 2nd part (copper)
Septum first part (tungsten) allowing heat expansion
The ESD if you don’t do it right

α - beam 5kWatt
extraction efficiency 90%
500 Watt on thin septum

C70 at Arronax => a versatile RI production site

Six different vaults for routine RI production,
development and research
A typical RI Production beam line

- Wobbler for beam spreading on target
- Quadrupole doublet for beam transport/focusing
- 4-finger collimator
- Diagnostics (Faraday cup and viewer)
- Solid target station with remote handling and water cooling
- Rabbit system for automatic transport of the irradiated target to the hot cells

Hot-cells are needed for the remote handling of irradiated target material

- 15 cm lead shielding
A simpler version of the Cyclone 70 => proton only
Zevacor Molecular USA

- H-minus only => optimized for high intensity 35-70 MeV; 750 µA
- Simpler magnet: isochronism for proton only
  - Compensation coils not needed => simplifies magnet considerably
- Simpler extraction => stripping
- Simpler injection => only one ion source
- Prototype currently being mapped at IBA

3D Tosca finite element design of the magnetic structure

Cyclone 70 proton only

- Accelerate H- at harmonic 4 => less turn, lower losses
- Re-optimization of the RF

CST 3D finite element modeling of the accelerating structure coupled to the final RF amplifier
Vacuum stripping in a high intensity H⁻ cyclotron

- H⁻ interacting with rest-gas may lose its electron
- Neutral H-atom moves on straight line and hits vacuum chamber wall
- Extra out-gassing on the walls induced by the beam
- May lead to an avalanche effect
  - Vacuum deteriorates with current => more stripping losses => more outgassing
  - Max extracted current is limited by vacuum
- How to reduce stripping losses
  - Better base vacuum => more pumping
  - Less outgassing => local cooling of vacuum chamber walls
  - More efficient acceleration => less turns in the machine
- Choose optimum harmonic mode of acceleration H
  - 4-fold symmetric cyclotron => dee-angle 45° => H=4

The C30XP cyclotron

- Very similar to the C70 (multi-purpose, multiparticle) but 30 MeV instead of 70 MeV
- Most important difference is the RF-system
  - Can operate in two modes with frequencies that exactly differ with a factor 2 (dual frequency)
  - Allows to accelerate all four particles at the same optimum harmonic mode H=4
  - Minimum turns => minimum stripping losses
- Also much simpler isochronous system for different particles => iron inserts (flaps) that can be moved up and down (this method can not be used at 70 MeV)
Dual frequency RF system

- Coaxial cavity made up of two resonating volumes which are coupled by a capacity.
- Low frequency mode is the quarter wave ($\lambda/4$) mode.
- High frequency mode as the $3\lambda/4$ mode.
- By proper dimensioning of the structure, the condition of frequency-doubling is obtained.

Dual band IMPA + FPA
66 and 33 MHz on the same cavities
Without any moving RF parts

Cyclone® 30 XP: proton-deuteron-alpha
- Based on the successful Cyclone® 30; eXtra Particles

Proton (H- accelerated)
16 - 30 MeV, 350 µA
2 exits, H+ (proton)

Deuteron (D- accelerated)
9 - 15 MeV, 50 µA
2 exits, D+ (deuteron)

Alpha (He2+ accelerated)
30 MeV, 50 µAe
1 common exit with H+
Electrostatic deflector

Prototype installed in Julich and waiting for berm license

Ref: ECPM 2012; Cyclone 30 multiparticles status
Beam lines and targets

- Cyclone 30 with Solid target high current + PET system

Target technologies
1. Liquid targets
2. Solid targets
3. Gas-targets

18F target development => liquid target

IBA new Conical shaped $^{18}$O water targets

$^{18}$O(p,n)$^{18}$F

Enriched H$_2^{18}$O
150 $\mu$A, 4ml => 18 Ci $^{18}$F
High pressure (50 bar)
He-window cooling
Water cooling
Solid target irradiation

**Avoid melting/evaporation**

<table>
<thead>
<tr>
<th>Element</th>
<th>Density (g cm⁻³)</th>
<th>Melting point (°C)</th>
<th>Thermal conductivity (W cm⁻¹ K⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>8.96</td>
<td>1083</td>
<td>4.03</td>
</tr>
<tr>
<td>Thallium</td>
<td>11.65</td>
<td>303</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Solid target: $^{203}$Tl(p,3n)$^{201}$Pb $\rightarrow$ $^{201}$Tl
$^{123}\text{I}$ production using $^{124}\text{Xe}$ gas target

- High power target
- High yield and ultrapure $^{123}\text{I}$
- Closed-loop and full recovery of $^{124}\text{Xe}$ (liquid $\text{N}_2$)

$^{124}\text{Xe}(p,pn)^{123}\text{Xe} \Rightarrow ^{123}\text{I}$

1. Target
2. $\text{Xe}^{124}$
3. $30$ min production
   - $\text{Xe}^{124}$
   - $\text{Xe}^{123}$
4. $\text{I}^{123}$
5. $\text{H}_2\text{O}$

Kipros 120 (200) – ZAG Zyklotron