8 MeV H- CYCLOTRON TO CHARGE ELECTRON COOLING SYSTEM FOR HESR

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Abstract

- Compact Cyclotron to accelerate 
- $H^{-}$ ions to 8 MeV and current of 1 mA is considered as favourable source to charge high voltage terminal of Electron Cooling System for High Energy Storage Ring at GSI (HESR, Darmstadt).
- Different types of commercially available cyclotrons are being compared.
- Merit of original design and possible solutions are discussed.
Table 1. Selection of HESR Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference of central orbit, $C$</td>
<td>424.7 m</td>
</tr>
<tr>
<td>Antiproton energy</td>
<td>14 GeV</td>
</tr>
<tr>
<td>Moment. spread (coasting beam) 14 GeV $10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Beam emitt. (r.m.s. norm. before cooling) $0.7 \pi \text{ mm} \cdot \text{mrad}$</td>
<td></td>
</tr>
<tr>
<td>Betatron function amplitudes in cooling section 100 m (h and v)</td>
<td></td>
</tr>
<tr>
<td>Betatron function amplitudes at target 1.5 m (h and v)</td>
<td></td>
</tr>
<tr>
<td>Magnetic field in the cooling section</td>
<td>5 kGauss</td>
</tr>
<tr>
<td>The length of the cooling section</td>
<td>30 m</td>
</tr>
<tr>
<td>Electron cooling current</td>
<td>1 A</td>
</tr>
<tr>
<td>Number of stored antiprotons</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Maximum target thickness ($\text{H}_2 \text{ jet or pellets}$)</td>
<td>$5 \times 10^{15}$ \text{ atoms/cm}^2</td>
</tr>
<tr>
<td>Maximum luminosity</td>
<td>$3 \times 10^{32}$ \text{ cm}^{-2} \text{s}^{-1}$</td>
</tr>
</tbody>
</table>
Physics of electron cooling for HESR

- antiproton beam interact with
- inner target at HESR
- Antiproton scattering on target
- energy losses by the ionization process
- increasing of the energy spread by fluctuation of ionization losses
- Electrostatic Column chosen as high voltage device to accelerate e-beam

\[ E = 8 \text{ MeV}, \quad I = 10 \text{ A}, \quad \text{recuperation} = 10^{-4} \]
• Figure 8. Layout of high voltage cooler for HESR.
• 1 – transformation section
• E-beam passes from low-magnetic field of electrostatic column (500 Gs) to the high magnetic field of the cooler (5 kGs)
• 2 – electrostatic dipole corrections,
• 3 – energy analyzer of H⁻ beam for the voltage measurement;
• 4 – point of convergence of the pbar and electron beams;
• 5 – HESR triplets (TRIP_C1).
Electrostatic column

- length of column 12 m (10kV/cm)
- section adjustment
- variation of electrical and magnetic field
- magnetic field (500 G)
- power supply ( ~ 100 W)
- Choice of charging system
  - a) mechanical charging device like PELETRON or Van De Graff belt
  - b) H- cyclotron. Energy 10 MeV
  - c) electron linac to charge Column (huge radiation background)
  - d) series of independent charging devices
• e-beam extracted from e-gun located on top
• Cathode of the gun is immersed in the magnetic field
• e- beam is accelerated up to 8 MeV
• e- beam passes region of increased magnetic field
• from 0.5kG to 5 kG located at exit from Column
• e- beam is bent in the vertical and horizontal planes
• and is moved to the cooling section where E/S correction dipoles installed
• E/S Dipoles – to remove transverse motion excited
• in the bending section
• e- beam is returned to column (recuperation)
• decelerated and absorbed in the collector
• Collector in the head of the column
• Cyclotron is chosen to charge high voltage platform

• The H– beam is transported inside of the additional (third) accelerator tube to the top of E/S platform and is dumped in the head of the electrostatic column

• energy is analyzed by an energy analyzer device (3 on Figure 8)

• Signal from energy analyzer is used in the feedback circuit and as the reference point for the high voltage value
• INTRODUCTION

• Cyclotrons of 10 MeV ÷ 30 MeV energy range are in routine operation for isotope production and other medical applications.
• As for today the beam intensity from Cyclotrons is limited by extraction device.
• Cyclotrons at TRIUMF and PSI accelerate \( ^1H \)- and Protons up to 500 MeV and intensity of 400 mka to 2 mA.
• REVIEW OF COMMERCIAL CYCLOTRONS
  • (Choice of Prototype)

• 1. Proton Cyclotrons with internal beam
  • internal PIG Source - 2–3 mA of \( P \)
  • internal target inside Vacuum Chamber
  • Targets water cooled, tilted or spin
  • dissipate hit power up to 50 kW.
  • “CYCLONE14+” is an example
  • 14 “CYCLONE14+” -- “THERAGENICS”
  • (USA) - isotopes of Pd for brachy-therapy.
  • No Extraction devices.
  • Indicative price of “CYCLONE14+” 1.2 MEuro.
2. H- Cyclotrons with internal Ion Source

Low loss extraction by stripping of $H^-$ on foil.
- Single particle, fixed RF freq., chip and robust
- Variable Beam energy by radial motion of foil
- Beam stability is excellent
- Dissociation of negative ions at low level
- Examples of 3rd generation of cyclotrons
  - CYCLONE-10/5 and -18/9. (IBA, Belgium)
  - RDS-112 (CTI, USA).
  - Mini-Trace, Pet-trace (10,18 MeV) GE (USA)
  - 12 MeV Cyclotron (SUMITOMO, Japan)
  - CP42 - 200 mkA of H- beam (2nd generation)
- Price range is between 1.2 MUSD to 1.5 M Euro.
• CYCLONE-10/5 (18/9) etc. designed for PET isotopes only (C-11, N-13, O-15, F-18).
• Moderate Intensity - 70 mkA
• 4 fold symmetry magnetic structure
• 4 straight sectors and 4 deep valleys
• closed magnetic flux
• 8 holes in valleys for pumping, RF cavity
• support, flaps, diagnostics etc.
• 2 Dees in opposite valleys.
• Hill gap 50 mm
• Valleys Gap 600 mm
- H- Cold PIG Ion Source
- 2 Dees connected by strap
- RF harmonic = 2 (H-) =4 (D-)
- High Gas flow (3 sccm of H2)
- Moderate vacuum – 8.10-6 torr
- Beam transmission as function of vacuum
- Cyclotron was tuned for best transmission
- Reversed Polarity of Magnet -
- No losses of $P$ from 1 MeV to extraction
- Degradation of H- (1-18MeV) stripping losses
- Experimental data from different cyclotrons
H- beam distribution inside Cyclotron

stripping losses

Fraction of beam, %

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>6</td>
</tr>
<tr>
<td>8</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>12</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>16</td>
</tr>
<tr>
<td>18</td>
</tr>
<tr>
<td>20</td>
</tr>
</tbody>
</table>

1 - vacuum 10^-5 torr (C18)

2 - vacuum 5.10^-7 torr (TR18)
Transmission of H- beam in the Cyclotron stripping losses

TRANSMISSION = Ratio between extracted current and beam current at 1 MeV

Fraction of beam, %

Pressure in the Vacuum Chamber (10^-6 torr)

1, 2, 3, 4, 5 - data from C18/9
6 - data from C30
7, 8, 9 - data from TR18, TR30
Table 1. Beam Transmission versus Vacuum

<table>
<thead>
<tr>
<th>Vacuum</th>
<th>Energy</th>
<th>Transmission</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-5}$</td>
<td>1 MeV</td>
<td>100%</td>
<td>200 mkA</td>
</tr>
<tr>
<td>$2 \cdot 10^{-5}$</td>
<td>18 MeV</td>
<td>13%</td>
<td>20 mkA</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>18 MeV</td>
<td>37%</td>
<td>40 mkA</td>
</tr>
<tr>
<td>$8 \cdot 10^{-6}$</td>
<td>18 MeV</td>
<td>53%</td>
<td>55 mkA</td>
</tr>
<tr>
<td>$5 \cdot 10^{-6}$</td>
<td>30 MeV</td>
<td>75%</td>
<td>350 mkA</td>
</tr>
<tr>
<td>$3 \cdot 10^{-6}$</td>
<td>30 MeV</td>
<td>85%</td>
<td>350 mkA</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>18 MeV</td>
<td>92%</td>
<td>200 mkA</td>
</tr>
<tr>
<td>$3 \cdot 10^{-7}$</td>
<td>30 MeV</td>
<td>99%</td>
<td>1000 mkA</td>
</tr>
</tbody>
</table>
• C10/5 and C18/9 up to 200 mkA of H-ions at 1 MeV
• Extracted beam limited to 70 mkA - poor vacuum conditions
• PET Cyclotron employing internal Ion Source even with modified vacuum system not to many hope to reach designed value of 1 mA of extracted beam.
3. Self-extracted Cyclotron

- New method of beam extraction - Y. Jongen
- Prototype is operating at IBA.
- Gradient drops from $n>1$ to $n<-1$ at extraction
- Radial stability is lost
- Particles escape magnetic field.
- 6 mA of $P$ (internal PIG) accelerated to 14 MeV
- Extracted beam 2 mA
- Beam is spread out in radial direction
- 25% of Hallo between turns should be dumped
- Radiation background - very high
- Norm. emitt. $>10\pi \, mm \cdot mrad$ - unacceptable.
• 4. H- cyclotrons with external injection
  • possible prototype for 8 Mev H-
  • beam current 200 mkA up to 2 mA
  • external H- CUSP Ion Source.
  • TR18/9 (TRIUMF design) EBCO
  • Low emittance beam from CUSP
  • CUSP 3 electrode optics
  • Few versions of CUSP Source
  • 2 extraction ports (dual extraction)
  • 2 Targets at crossover points in the Yoke
• **MAGNET**

- Magnet in the Vertical plane.
- 4 Sectors Radial Ridge, straight.
- 8 holes in the valleys d=200 mm
- Hill Angle from 32 deg to 45 deg
- Bav = 1.2 T, Bh = 2 T, Bv = 0.5 T
- Hill Gap = 35 mm, Valley Gap = 200 mm
- R(sector)= 560 mm, R(pole) = 600 mm
- Height of magnet = 1080 mm
- Injection hole = 50 mm
- Weight of Magnet -- 25 tonnes
- Amp turns -- 85 kA* turns
- Main Magnet Power Supply -- 500 A, 48 V
- Stability of Main Magnet PS -- 10-5
• **RF System**
  - Dees = 2
  - Angular width of Dee = 45 deg
  - Amplitude of Dee voltage = 50 kV
  - RF freq = 73 MHz (H-), = 36 MHz (D-)
  - RF harmonic = 4
  - Axial gap in the Dee – 20 mm
  - Axial gap in the Puller -- 10 mm
  - \( \frac{dE}{dN} = 200 \) keV
  - 90 turns to reach 18 MeV
  - Power required -- 30 kW
  - RF voltage stability --- 10-4
  - RF frequency stability --- 10-7
• **Vacuum System**

• Cyclotron = \((3 \div 5) \cdot 10^{-7}\) torr (beam ON)
• ISIS = \(5 \cdot 10^{-7}\) torr (beam ON)
• Cryopump 4,500 l/s (vapour) 1,500 l/s (Air)
• ISIS - Cryopump and 2 TP (200 l/s each)
• Vacuum Chamber – aluminium cylinder isolated by pair of O-rings between magnet poles
• **Ion Source**
• Type -- H-, MULTICUSP
• Output current --
  • 5 mA - standard version
  • 15 mA - modified Source
  • 30 mA - high performance
• emittance (4RMS) --
  • $0.35\pi \ mm \cdot mrad$ - standard version
  • $0.5\pi \ mm \cdot mrad$ -- modified version
  • $0.7\pi \ mm \cdot mrad$ -- high performance
• injection energy (bias voltage) -- 25 kV (H-)
• 12.5 kV (D-)
• CUSP hole diameter = 8÷10 mm
• CUSP beam divergence = 15 - 25 mrad
• Arc current -- up to 60 A
• Arc voltage -- 100 V
• Beam parameters

• Beam transmission from Source to Inflector entrance (DC:DC injection line) –
  • 50% - through IBS Collimator of d= 20 mm
  • 8 mA out of 15 mA could be injected
  • 80% through IBS Collimator of 30 mm diameter

• Beam transmission (DC:CW) ratio of current in the injection line to the beam at 1 MeV probe (*RF Acceptance of Cyclotron*) -- Table 2.
Cyclotron Transmission vs emittance of injected beam

Ratio of CW:DC current, %

normalized emittance, Π mm.mrad

1 - beam hit Inflector plates
### T.2. Transmission (DC:CW) vs Emittance of Injected Beam

<table>
<thead>
<tr>
<th>Emittance</th>
<th>Transmission</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.2\pi$ mm*mrad</td>
<td>17 %</td>
<td></td>
</tr>
<tr>
<td>$0.3\pi$ mm*mrad</td>
<td>15 %</td>
<td></td>
</tr>
<tr>
<td>$0.4\pi$ mm*mrad</td>
<td>11 %</td>
<td></td>
</tr>
<tr>
<td>$0.5\pi$ mm*mrad</td>
<td>10 %</td>
<td></td>
</tr>
<tr>
<td>$0.7\pi$ mm*mrad</td>
<td>9 %</td>
<td></td>
</tr>
<tr>
<td>$0.8\pi$ mm*mrad</td>
<td>7 %</td>
<td>Beam hit plates of Inflector</td>
</tr>
</tbody>
</table>
• Nominal RF acceptance -- 10%
RF phase band accepted by Central Region
• 60 RF deg (original version)
  90 RF deg (modified Central Region)
• Pulse width = 2.5 nsec
• Radial betatron tune \( \nu_r = 1.06 \)
• Axial betatron tune \( \nu_z = 0.56 \)
• Circulating radial normalized emittance -
  - \( 1\pi \text{ mm* mrad} \)
• Circulating axial normalized emittance -
  - \( 0.5 \pi \text{ mm* mrad} \)
- Extraction radius = 500 mm
- $dR/dN = 2.5$ mm (18 MeV)
- Radial width of bunch -- 5÷6 mm
- $h1 \leq 2$ Gs
- $Ar \leq 1$ mm
- Extraction -- Multi-turn
- 3 turns paint stripping foil
- Single turn extraction -- not available
- Energy spread in the circulating beam = 100 keV
- Energy spread in the extracted beam = 200 keV
- Beam spot on stripping foil = 5 mm over 5 mm
### Table 3. High current cyclotrons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CYCLONE30 (IBA)</th>
<th>TR30 (TRIUMF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam current</td>
<td>350 mkA</td>
<td>1000 mkA</td>
</tr>
<tr>
<td>Energy (H- ions)</td>
<td>15-30 MeV</td>
<td>15-30 MeV</td>
</tr>
<tr>
<td>Extracted emittance (normalized $= \beta \gamma \epsilon$)</td>
<td>Radial $=10\pi$ Axial $=5\pi$</td>
<td>$2\pi$ $2\pi$</td>
</tr>
<tr>
<td>Energy spread</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Average field $B_{av}$</td>
<td>10 kGs</td>
<td>12 kGs</td>
</tr>
<tr>
<td>$B_{hill}$</td>
<td>17 kGs</td>
<td>19 kGs</td>
</tr>
<tr>
<td>$B_{vall}$</td>
<td>1.2 kGs</td>
<td>5.5 kGs</td>
</tr>
<tr>
<td>Circulating emittance</td>
<td>$5\pi \ mm.mr$</td>
<td>$1\pi \ mm.mr$</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Pole Radius</td>
<td>91 cm</td>
<td>76 cm</td>
</tr>
<tr>
<td>Hill gap</td>
<td>5 cm</td>
<td>4 cm</td>
</tr>
<tr>
<td>Valley gap</td>
<td>50 cm</td>
<td>18 cm</td>
</tr>
<tr>
<td>Sector angle</td>
<td>$54^0 \div 58^0$</td>
<td>$32^0 \div 45^0$</td>
</tr>
<tr>
<td>Coil power</td>
<td>7 kW</td>
<td>30 kW</td>
</tr>
<tr>
<td></td>
<td>65.5 MHz</td>
<td>74 MHz</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------</td>
<td>--------</td>
</tr>
<tr>
<td>RF frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Dees</td>
<td>2 ($h_{RF} = 4$)</td>
<td>2 ($h_{RF} = 4$)</td>
</tr>
<tr>
<td>RF voltage</td>
<td>50 kV</td>
<td>50 kV</td>
</tr>
<tr>
<td>Number of turns</td>
<td>180</td>
<td>150</td>
</tr>
<tr>
<td>Dee angular width</td>
<td>30°</td>
<td>45°</td>
</tr>
<tr>
<td>RF power</td>
<td>15 kW</td>
<td>35 kW</td>
</tr>
<tr>
<td>Ion Source</td>
<td>H- multi-CUSP</td>
<td>H- multi-CUSP</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td><strong>DC Output current from Source</strong></td>
<td>5 mA (2 mA injected)</td>
<td>10 – 15 mA</td>
</tr>
<tr>
<td><strong>Source emittance</strong></td>
<td>$0.8\pi$ mm·mrad</td>
<td>$0.37\pi$ mm·mrad</td>
</tr>
<tr>
<td><strong>Injection energy</strong></td>
<td>30 keV</td>
<td>25 keV</td>
</tr>
<tr>
<td><strong>Vacuum with beam</strong></td>
<td>$3\cdot 10^{-6}$ torr</td>
<td>$5\cdot 10^{-7}$ torr</td>
</tr>
<tr>
<td><strong>Vacuum system</strong></td>
<td>Cryo-Pump + Diffusion Pump</td>
<td>two Cryo-Pumps (4,500 L/sec each)</td>
</tr>
<tr>
<td><strong>RF Acceptance</strong></td>
<td>25% bnch on</td>
<td>8%-12% bnch off</td>
</tr>
<tr>
<td><strong>Beam losses Due to stripping</strong></td>
<td>20%</td>
<td>$\leq 1%$</td>
</tr>
</tbody>
</table>
• Vacuum Conditions in the 8 MeV H-cyclotron

• H- ions extracted. NO charge exchange.
• Electrostatic Deflector employed
• Positive DC voltage up to 50 kV applied
• If vacuum conditions poor
• In combination with axial magnetic field
• cold Penning discharge
• Threshold level of DC+ 20 kV at 10-6 torr
• Vacuum for 8 MeV H- Cyclotron

• $5 \cdot 10^{-8}$ torr should be satisfactory to avoid discharge

• **External injection** - mandatory

• Minimize gas load inside Cyclotron

• prevent DC+ discharge

• minimize stripping losses
• Beam parameters of H- 8 MeV

• preliminary estimations of beam parameters
• Based on semi-empirical formulas and
• Based on measurements - similar Cyclotrons
• RF acceptance of TR18, CYCLONE-30, TR30 etc. is 40÷60 RF if NO phase selection
• Large RF phase acceptance is positive feature
• for stripping extraction when number of turns
• to be extracted is not an issue and
• orbits are NOT separated
beam energy

\[ E \approx 48 B^2 R^2 (Z^2/A) \quad [\text{MeV, T, m}] \]

number of turns to reach energy \( E \)

\[ N = \frac{E}{2N_{\text{dee}} V_{\text{dee}} \sin (h_{RF} \Delta \theta_{\text{dee}}/2) \cos (\phi - \phi_0)} \]

phase advance per turn

\[ \Delta \phi = 2\pi (v_R - 1) \]

precession cycle to fill \( 2\pi/\Delta \phi \)

\[ N_R = (v_R - 1)^{-1} \approx 16 \]
Emittance increase due to precession

\[ \varepsilon = \varepsilon_0 \left( 1 + \frac{A_{coh}}{X_0} \right)^2 \]

\[ A_{coh} = \frac{R h_1}{2B (\nu_R - 1)} \]

beam size (incoherent amplitude)

\[ X_0 = \sqrt{\frac{R_{\infty} \varepsilon^n}{1000 \pi \gamma \nu_R}} \]

\[ R_{\infty} = \frac{c}{\omega} \]

beam size on foil

\[ W = \frac{dR}{dn} + X_0 \sin [2\pi \nu_R] \approx \frac{dR}{dn} + X_0 \left[ 2\pi (\nu_R - 1) \right] \]
radius gain per turn

\[
\frac{dR}{dn} = R_1 \left[ \sqrt{n} - \sqrt{(n-1)} \right] = (4.567 / B) \sqrt{(dE/dn)} \left[ \sqrt{n} - \sqrt{(n-1)} \right]
\]

\[
\frac{dR}{dn} = \frac{dE/dn}{dE/dr}
\]

2 \(\frac{1}{R}\) \(\frac{dR}{dn}\) = \(\frac{1}{E}\) \(\frac{dE}{dn}\)

\[
\frac{dE}{dr} = \beta \gamma^3 E_0 / R_\infty
\]
• TR18
• Central particle maximum energy gain
• accelerated in to final energy for 90 turns
• off-phase particles (10÷20 RF deg)
• 95 – 97 turns at radius of stripping foil
• \( \frac{dR}{dN} = 2.5 \text{ mm, } 2X_o = 4.4 \text{ mm} \)
• Multiturn extraction – few turns paint foil

• TR30
• Central particles 150 turns
• off-phased particles – 160-165 turns.
• radial Width of Beam is \( 2X_o=5 \text{ mm} \)
• (RF phase band \( \Delta \phi_{RF} \approx 40 \text{ RF deg} \))
• Radial emittance of H- circulating beam inside of TR13 (prototype of commercial TR18) was measured by B. Laxdal et al [10]

• Normalized area in radial phase space $\beta_y \varepsilon_r$ represents **Circulating Radial emittance** of the TR18 cyclotron

  • $\beta_y \varepsilon_r = 1\pi \text{ mm} \cdot \text{mr}$ (90% of beam current)
  • $\beta_y \varepsilon_r = 2\pi \text{ mm} \cdot \text{mr}$ (99% of beam current)

• Shadow method applied to measure emittance
• Different methods to Extract H- beam

• stripping extraction - efficiency close to 100% - 1 mA

• Protons accelerated in “self-consistent” mode
• No tails. Separated turns. 99.98%. 2 mA. PSI.

• Precession extraction. NO charge exchange.
• 80%-96%.
• No separation unless narrow Phase band – 3RF deg

• Extraction from isochronous radius. 50%-80%

• Self-extraction. 30% of dumped beam.
• IBA CYCLONE14+
Injected beam pulses

Repetition rate 1 MHz

More than $T_{rf}$

Injected beam pulses

$T_{pulse} = 1 \text{ mcsec}$

$T_{rf}$

Less than $T_{rf}$

Accelerated beam

$h_{rf} = 4$

$T_{pulse} = 1 \text{ mcsec}$

$T_{cyclotron}$

85%

2 nces

12%

3%

$T_{cyclotron}$
- Time structure of D- 9 MeV Pulsed beam
- Two-three peaks have been measured at
- TRD9 pulsed mode. One pulse of beam
- paint foil few times to be extracted.

- Intensity distribution (no collimation)
  - t1 : t2 : t3 = 50% : 40% : 10%
- Intensity distribution (collimated beam)
  - t1 : t2 : t3 = 85% : 12% : 3%
- 150 mkA of H- hit Septum if no separation
• Separation of turns in radial space
  • and
  • precession extraction
  • either
  • combination of two types
  • might be applied for
    • 8 MeV H- cyclotron
    • Septum might be shadowed
      • By narrow (1mm) foil
Precession and Flattop

- Precession improve extraction efficiency
- 98% extracted for $\Delta \phi \sim 3$ RF deg
- 80% extracted for $\Delta \phi \sim 20$ RF deg
- Position of precession maximum not stable unless flattop is applied
H- extraction at TRIUMF

- Precession employed for KAON H-definition study
- No turn separation
- Flattop voltage stabilize position of maximum beam density for wide
- RF phase band $\Delta \phi \sim 20$ RF deg
- 70mkA of 450 MeV H- beam extracted
- 10 mkA of H- intercepted by narrow
- (1 mm) foil, stripped and dumped
Table 6. Beam width and radius gain per turn

<table>
<thead>
<tr>
<th>$E_{MeV}$</th>
<th>$f_{orb}$ MHz</th>
<th>$B_{kGs}$</th>
<th>$\beta\gamma\varepsilon = \pi$ mm·mrad</th>
<th>$2X_0$ mm</th>
<th>$R_{extr}$ mm</th>
<th>$\frac{dE}{dN}$ keV</th>
<th>$N_{turn}$</th>
<th>$\frac{dR}{dN}$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>18</td>
<td>12</td>
<td>$1\pi$</td>
<td>2.8</td>
<td>500</td>
<td>2</td>
<td>200</td>
<td>90</td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>12</td>
<td>$2\pi$</td>
<td>4.2</td>
<td>430</td>
<td>2</td>
<td>200</td>
<td>65</td>
</tr>
</tbody>
</table>

$h_{RF} = 4 \quad R_\infty = 2607 \text{ mm}$
<table>
<thead>
<tr>
<th>$E_{MeV}$</th>
<th>$f_{orb}$ MHz</th>
<th>$B$ kGs</th>
<th>$\beta \gamma \varepsilon = \pi$ mm·mrad</th>
<th>$2X_0$ mm</th>
<th>$R_{extr}$ mm</th>
<th>$N_{Dee}$</th>
<th>$dE/dN$ keV</th>
<th>$N_{turn}$</th>
<th>$dR/dN$ mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>18</td>
<td>12</td>
<td>$1\pi$</td>
<td>3.2</td>
<td>340</td>
<td>2</td>
<td>200</td>
<td>40</td>
<td>4.3</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>10</td>
<td>$1\pi$</td>
<td>3.6</td>
<td>400</td>
<td>2</td>
<td>200</td>
<td>40</td>
<td>5.1</td>
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<tr>
<td>8</td>
<td>10.7</td>
<td>7</td>
<td>$1\pi$</td>
<td>4.2</td>
<td>570</td>
<td>2</td>
<td>200</td>
<td>40</td>
<td>7.2</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>12</td>
<td>$1.5\pi$</td>
<td>4</td>
<td>340</td>
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<td>40</td>
<td>4.3</td>
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<td>10.7</td>
<td>7</td>
<td>$1.5\pi$</td>
<td>5.2</td>
<td>570</td>
<td>2</td>
<td>200</td>
<td>40</td>
<td>7.2</td>
</tr>
</tbody>
</table>
• expected radial emittance for 8 MeV H-
cyclotron between $1.5\,\pi$ and $2\,\pi\,\text{mm}\cdot\text{mrad}$
• Radial Width of beam $\approx 5\,\text{mm}$ for narrow RF phase band ($\sim 5\,\text{RF deg}$)
• to separate turns at extraction
• Radius Gain per turn must be $> 7\,\text{mm}$
• Require reduced magnetic field of $B=7\,\text{kGs}$
• if 2 Dees being used
• to barely satisfy requirement
• of turn separation
<table>
<thead>
<tr>
<th>$E\text{ MeV}$</th>
<th>$f_{\text{orb}}\text{ MHz}$</th>
<th>$B\text{ kGs}$</th>
<th>$\beta\gamma\varepsilon=\pi\text{ mm·mrad}$</th>
<th>$2X_0\text{ mm}$</th>
<th>$R_{\text{extr}}\text{ mm}$</th>
<th>$N\text{ De}$</th>
<th>$dE/\text{dN}\text{ keV}$</th>
<th>$N\text{ tu}$</th>
<th>$dR/\text{dN}\text{ mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>18</td>
<td>12</td>
<td>1.5 $\pi$</td>
<td>4</td>
<td>340</td>
<td>4</td>
<td>400</td>
<td>20</td>
<td>8.5</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>10</td>
<td>1.5 $\pi$</td>
<td>4.4</td>
<td>400</td>
<td>4</td>
<td>400</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>10.7</td>
<td>7</td>
<td>1.5 $\pi$</td>
<td>5.2</td>
<td>570</td>
<td>4</td>
<td>400</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>8</td>
<td>18</td>
<td>12</td>
<td>2 $\pi$</td>
<td>4.6</td>
<td>340</td>
<td>4</td>
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<td>15</td>
<td>10</td>
<td>2 $\pi$</td>
<td>5</td>
<td>400</td>
<td>4</td>
<td>400</td>
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<td>10</td>
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<td>8</td>
<td>10.7</td>
<td>7</td>
<td>2 $\pi$</td>
<td>6</td>
<td>570</td>
<td>4</td>
<td>400</td>
<td>20</td>
<td>14</td>
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</tbody>
</table>
Ожидаемый профиль пучка при ускорении ионов Н- до 8 МэВ

Защитная фольга

4 Дуанта по 50 кВ,
поле 10 кГс

Септум Дефлектора

"Тень" от фольги

Выведенный пучок Н-

Интенсивность

380 мм

390 мм

400 мм

радиус, см
<table>
<thead>
<tr>
<th>RF $\phi^0$ deg</th>
<th>$dE/dN$ keV</th>
<th>$N_{\text{pee}}$</th>
<th>$E_N$ MeV</th>
<th>Rad $R_N$ mm</th>
<th>Rad $R_{N-1}$ mm</th>
<th>$dR/dn = R_N - R_{N-1}$ mm</th>
<th>$\delta R = R(0^0) - R(\phi^0)$ mm</th>
<th>$B$ kGs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^0$</td>
<td>200</td>
<td>2</td>
<td>8</td>
<td>404</td>
<td>399</td>
<td>5</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>$\pm 10^0$</td>
<td>197</td>
<td>2</td>
<td>7.9</td>
<td>401</td>
<td></td>
<td></td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>$\pm 15^0$</td>
<td>193</td>
<td>2</td>
<td>7.7</td>
<td>397</td>
<td></td>
<td></td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>$\pm 20^0$</td>
<td>188</td>
<td>2</td>
<td>7.5</td>
<td>392</td>
<td></td>
<td></td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>$0^0$</td>
<td>200</td>
<td>2</td>
<td>8</td>
<td>577</td>
<td>570</td>
<td>7</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>$\pm 10^0$</td>
<td>197</td>
<td>2</td>
<td>7.9</td>
<td>573</td>
<td></td>
<td></td>
<td>4</td>
<td>7</td>
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<tr>
<td>$\pm 15^0$</td>
<td>193</td>
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<td>7.7</td>
<td>567</td>
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<td></td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>$\pm 20^0$</td>
<td>188</td>
<td>2</td>
<td>7.5</td>
<td>560</td>
<td></td>
<td></td>
<td>17</td>
<td>7</td>
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</tbody>
</table>
• Dee voltage 50 kV optimum
• Commercial RF Power Supply might be purchased
• >50 kV problems - sparks, expensive RF equipment
• 2 Dees and B=10 kGs can NOT be used
  if one would like to separate turns
• Even Flattop can not guarantee turn separation
• for wide RF phase band of 40 RF deg
• 2 Dees and B=7 kGs NOT guarantee turn separation
  even for small RF phase band of ±10 deg
• Total width of beam pulse could reach 8 mm
• while expected turn separation is 7 mm
• Reducing of magnetic field to 7 kGs
  dimensions of Yoke grow to much
<table>
<thead>
<tr>
<th>( \text{RF degree} )</th>
<th>( dE/\text{d}N )</th>
<th>( N \text{ degree} )</th>
<th>( E_N )</th>
<th>( \text{Rad} R_N )</th>
<th>( \text{Rad} R_{N-1} )</th>
<th>( dR/\text{d}n = R_N-R_{N-1} )</th>
<th>( \delta R = R(0^\circ)-R(\varphi^\circ) )</th>
<th>( BkGs )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>400</td>
<td>4</td>
<td>8</td>
<td>404</td>
<td>394</td>
<td>10</td>
<td>--</td>
<td>10</td>
</tr>
<tr>
<td>±10°</td>
<td>394</td>
<td>4</td>
<td>7.9</td>
<td>401</td>
<td></td>
<td></td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>±15°</td>
<td>386</td>
<td>4</td>
<td>7.7</td>
<td>397</td>
<td></td>
<td></td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>±20°</td>
<td>376</td>
<td>4</td>
<td>7.5</td>
<td>392</td>
<td></td>
<td></td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>0°</td>
<td>400</td>
<td>4</td>
<td>8</td>
<td>577</td>
<td>562</td>
<td>14</td>
<td>--</td>
<td>7</td>
</tr>
<tr>
<td>±10°</td>
<td>394</td>
<td>4</td>
<td>7.9</td>
<td>573</td>
<td></td>
<td></td>
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<td>7</td>
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<td>±15°</td>
<td>386</td>
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<td>567</td>
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<td></td>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>±20°</td>
<td>376</td>
<td>4</td>
<td>7.5</td>
<td>560</td>
<td></td>
<td></td>
<td>17</td>
<td>7</td>
</tr>
</tbody>
</table>
• 4 Dees and B=10 kGs - solution for 8 MeV H-
• \( \frac{dR}{dN}=10 \text{ mm} \) and RF Acceptance \( 2\delta\phi=30 \text{ RF deg} \)
• create conditions for SINGLE turn extraction
• of high intensity beam up to 1 mA

• “Tails” between last circulating and
• extracted turns intercepted
• by foil, stripped and dumped
• Up to 5% of total beam (50 mkA, 400 W)
• should be dissipated
• Phase selection at 3rd and 10th turns helps
• limit tails to 1-2%
• and clean up separation between last turns
• **4 dees option**
  • flattop Voltage up to 15 kV
  • might be applied on second pair of Dees
  • phase band $2\delta\varphi=20$ RF deg
  • will be accelerated in single bunches
  • merit of flattop verified in experiment

• **Restrictions**
  • 2 E/S Deflectors must be installed
  • inside of Dees
  • DC+ voltage up to 50 kV to Deflector plates
  • Expected Energy spread of extracted beam
  • between 200 keV and 300 keV
### Table 8. Specifications for 8 MeV H- cyclotron

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam current</strong></td>
<td>1 mA (CW)</td>
</tr>
<tr>
<td><strong>Fraction of beam to be removed</strong></td>
<td>Less than 5%</td>
</tr>
<tr>
<td><strong>Energy (H- ions)</strong></td>
<td>4 ÷ 8 MeV</td>
</tr>
<tr>
<td><strong>Extracted emittance (normalized = βγε)</strong></td>
<td>Rad = 1.5π mm·mrad (95% of beam current) Axial = 1π mm·mrad</td>
</tr>
<tr>
<td><strong>Energy spread</strong></td>
<td>1%</td>
</tr>
<tr>
<td><strong>Magnet Geometry</strong></td>
<td>4 Sectors Radial Ridge, straight</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Average field $B_{av}$</td>
<td>10 kGs</td>
</tr>
<tr>
<td>Max field in the Hill $B_{hill}$</td>
<td>16 kGs</td>
</tr>
<tr>
<td>Min. field Valley $B_{vall}$</td>
<td>4 kGs</td>
</tr>
<tr>
<td>Pole Radius</td>
<td>450 mm</td>
</tr>
<tr>
<td>Hill gap</td>
<td>50 mm</td>
</tr>
<tr>
<td>Valley gap</td>
<td>250 mm</td>
</tr>
<tr>
<td>Sector angle</td>
<td>$40^0$</td>
</tr>
<tr>
<td>Coil power</td>
<td>20 kW</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>-----------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>RF frequency</td>
<td>61 MHz</td>
</tr>
<tr>
<td>Number of Dees (RF harmonic)</td>
<td>(4 \ (h_{RF} = 4))</td>
</tr>
<tr>
<td>Amplitude of RF voltage</td>
<td>50 kV</td>
</tr>
<tr>
<td>Energy gain per turn</td>
<td>400 keV</td>
</tr>
<tr>
<td>Number of turns</td>
<td>20</td>
</tr>
<tr>
<td>Dee angular width</td>
<td>45°</td>
</tr>
<tr>
<td>RF power Supply</td>
<td>One for 4 Dees. 30 kW</td>
</tr>
<tr>
<td>Ion Source</td>
<td>H- multi-CUSP</td>
</tr>
<tr>
<td>-----------</td>
<td>---------------</td>
</tr>
<tr>
<td>DC Output current from Source</td>
<td>20 mA</td>
</tr>
<tr>
<td>Source emittance (normalized= $\beta\gamma\varepsilon$)</td>
<td>$0.6\pi \text{ mm}\cdot\text{mrad} \ 4 \text{ RMS}$</td>
</tr>
<tr>
<td>H- Injection energy</td>
<td>50 keV</td>
</tr>
<tr>
<td>Injection Line</td>
<td>Einzel Lens + SSQQ</td>
</tr>
<tr>
<td>Buncher (crossover) Second – 60 cm Inflector</td>
<td>2 gaps, hole diameter =10 mm each gap = 3 mm</td>
</tr>
<tr>
<td>Inflector</td>
<td>Spiral, entrance gap = 10 mm Height $\approx 45$ mm</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----------------------------------------</td>
</tr>
<tr>
<td>Vacuum (with beam)</td>
<td>5·10^{-8} torr</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Vacuum system (Cyclotron)</td>
<td>2 CryoPumps (4,500 l/sec)</td>
</tr>
<tr>
<td></td>
<td>Inside Yoke holes</td>
</tr>
<tr>
<td></td>
<td>2 TPH2301 (2,000 l/sec)</td>
</tr>
<tr>
<td></td>
<td>Attached to Yoke holes</td>
</tr>
<tr>
<td>RF Acceptance (ratio of CW</td>
<td>10% Buncher OFF</td>
</tr>
<tr>
<td>current at 1 MeV to DC</td>
<td>16% Buncher ON</td>
</tr>
<tr>
<td>current in the injection line)</td>
<td></td>
</tr>
<tr>
<td>H- Beam losses inside cyclotron due to gas stripping</td>
<td>Less than 0.2%</td>
</tr>
</tbody>
</table>
| Extraction elements | 2 Deflectors  
|                     | Magnetic Channel  
|                     | Compensating channel  
<p>|                     | Protection foil (variable width) |
| Type of extraction | Single turn |
| Turn separation    | 10 mm |
| RF phase acceptance (no phase selection) | 60$^\circ$ RF |
| RF phase band accepted for Single turn extraction | 20$^\circ$ ÷ 30$^\circ$ RF |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width</td>
<td>1.2 nsec</td>
</tr>
<tr>
<td>Radial Width of bunch -</td>
<td></td>
</tr>
<tr>
<td>single turn</td>
<td>7 mm</td>
</tr>
<tr>
<td>Turn separation</td>
<td>10 mm</td>
</tr>
<tr>
<td>Imperfection First harmonic</td>
<td>Less than 2 Gs</td>
</tr>
<tr>
<td>Radial oscillations</td>
<td>≤ 1 mm</td>
</tr>
<tr>
<td>Phase collimators</td>
<td>Two</td>
</tr>
<tr>
<td>Variable width</td>
<td>3rd and 10th turns</td>
</tr>
<tr>
<td>Radial Probes</td>
<td>Two – in opposite Hills</td>
</tr>
</tbody>
</table>
• Alternative options
  • Precession extraction and Flattop
  • to separate turns of $2\Delta\varphi = 20$ RF deg
• 2 Dees and 2 Flattop cavities
• more complicated than high energy gain per turn
• special shape of magnetic field in the extraction
• region should be adjusted to each energy
• tuning of phase of second pair of cavities
• second power supply system
  • High Dee voltage
• 80 kV
• expensive PS
• spark problems may harm stable operation
• Schedule (preliminary)
  • Design
  • Computing magnet shape -- OPERA3D
  • Computing Inflector -- CASINO (TRIUMF)
  • Computing CR – CYCLONE3D (TRIUMF)
  • Monte-Carlo tracking - RF phase Acceptance
  • affects design of Central region and magnet
  • Computing –Extraction trajectories -- NSCL
  • Computing CUSP Ion Source Optics
  • Computing ISIS – PBO Lab-3D. Space Charge
• Design Magnet Yoke, Coil, Lifting system, Engineering Magnet - CAD–3D
• Design/Draft Central Region and Inflector
• Design/Draft Dees and RF cavities
• Design/Draft Vacuum Chamber
• and Vacuum system
• Design/Draft extraction system
• Design/Draft beam Line
• Design/Draft ISIS (Ion Source and Injection system)
• Design Cables and Connections
• Engineering
• Production, Purchasing
  • Yoke Oxycutting – ordering/production
  • Magnet Sectors -- production
  • Yoke, Lifting system -- production
  • RF System -- Production/Purchasing
  • ISIS elements -- Production/Purchasing
  • Vacuum System -- purchasing of elements
  • Vacuum Chamber -- production
  • Low emittance H- CUSP Ions Source - purchasing
  • Elements of extraction system – production/purchasing
  • Beam line elements -- production/purchasing
  • Magnet power Supply - purchasing
  • RF power Supply -- purchasing
  • ISIS power supplies -- purchasing
  • Beam line power supplies -- purchasing
  • Computer, Controllers -- PC, Allen-Bradley Industrial PLC Modules, Software - purchasing
• Mapping

• Assembling Mapping System
• Power Supply -- purchase, tests
• Mapping of magnet
• Corrections of shims
• Nickel plating of sectors
• Final mapping
• Magnet Acceptance
• Assembling
  • ISIS – Assy
  • Magnet and cablage – Assy
  • Vacuum Chamber, probes, elements – Assy
  • Vacuum System, Pumps, RF cavity - installation
  • Central Region and RF Dees, -- Assy
  • Extraction system - deflectors, magnetic channels, probes -- installation
  • Beam Line - Assy
  • RF power Supply -- Assy
  • Auxilliary Power supply systems -- Assy
  • Interface -- Assy
  • Computer, PLC controllers, cabotage - Assy
  • Wiring, cabling -- installation
- Tests
  - Ion Source acceptance, beam current, emittance
  - ISIS (low DC current, high DC current) -- beam transmission
  - Bunching, pulse structure
  - Vacuum - acceptance tests
  - RF system – tests of RF input transmission, Pillar tuning
  - Cold RF test -- raise of Dee voltage, training for sparks
  - Cold tests of extraction system – raise of positive voltage to nominal amplitude, sparks
  - Cyclotron Low current Beam tests – beam injection,
  - RF Acceptance, beam transmission, beam extraction
  - Cyclotron High current beam tests – beam injection,
  - RF Acceptance, beam transmission, beam extraction
  - Beam line tests -- transmission (low/high beam)
SUMMARY

- price and time required to design, build and test 8 MeV Cyclotron
- Private companies might deliver standard commercial cyclotron for isotope production after ONE year from signed Contract
- As good practice to run first beam in 1 year from Project starts
- few months is required to bring cyclotron into stable operation
- Price of commercial cyclotron is varying
- very basic modification of 10 MeV PET Cycl. ~ 1.2 MUSD
- more realistic - 3.5 MUSD. 30 MeV = 5 MUSD
Summary (continue)

• Systems and subsystems for 8 MeV - found on market
• policy of Private Companies to buy as many spare parts as possible rather than design it itself
• 8 MeV 1 mA H- Cyclotron might be designed based on
• Standard elements and equipment commercially available
• Original magnet and RF
• 8 MeV H- Estimated price = 1.5 - 2 MUSD
REFERENCES


• **W.Kleeven, S.Zaremba**, “Self-extracted Cyclotron”.
• XVI Cycl.Conf. 2001


