The Cyclotron as the CW High Intensity Proton Accelerator at PSI

Thanks to the many colleagues at PSI for all information and slides
Paul Scherrer Institut

PSI-West

cyclotrons

PSI-East

SwissFEL
Mission

Science of matter and materials

Energy and environment

Life sciences

Development, construction, operation

Large scale research facilities

National and international users
Academia and industry
More than 2400 external users / year (44 beamlines)

Knowledge & expertise

Education

Technology transfer
Proton Accelerators

Cockcroft-Walton
870 keV, 10 mA

Ring Cyclotron
590 MeV, 2.4 mA

Injector 2
72 MeV, max 2.7 mA

1.4 MW
CW beam power

COMET cyclotron
proton therapy
PROSCAN
Users and Experimental Facilities

Spallation Neutron Source SINQ

Experimental Hall
2 targets: $S_\mu S$ and $\pi$

Ultra Cold Neutrons UCN

Isotope production
40 / 72 MeV, 100 $\mu$A
Contents

1. Cyclotron operation principle
2. Cyclotrons for 30-1000 MeV
3. PSI facility: high intensity at 590 MeV
   – High intensity issues
   – Operation
4. Applications
5. Perspectives: plans and ideas
Cyclotron operation principle
the first Cyclotron

invented by E.O. Lawrence,
constructed by M.S. Livingston
1931
Berkeley, California

Stanley Livingston (L) and Ernest Lawrence in front of
27-inch cyclotron (several MeV), Berkeley 1934.

credit:
Lawrence Berkeley Nat'l Lab
The 184-inch magnet at UCL runs the Dees at 1 or 2 MV and the 4,300-ton magnet e.g. 400 MeV He (1946)

590-MeV ring cyclotron (PSI)
Operation of the Cyclotron

4 RF Cavities
(0.9 MVp)
→ 186 turns
→ 590 MeV

Isochronicity:
At all radii (=all E) particles cross acceleration gap at same moment!

\[ T_{\text{circle}} = \frac{2\pi m}{qB} \]
Cyclotron types

- Non-uniform field
  - Constant RF Freq.
- Uniform field
  - Varying RF freq.

**Isochronous Cyclotron**
- Single pole with sectors
- Ring Cyclotron

**Synchrocyclotron**
- Single pole (dying out!)
- FFAG with sectors

**However:**

- CW-beam
- Pulsed beam

*However: new interest*
compact cyclotrons for isotope production: 10-30 MeV

Vertical orientation
proton therapy cyclotrons: 230 / 250 MeV

- IBA (1996), SHI
  250 Tons
  Isochronous Cyclotron

- Varian (2005)
  90 Tons
  Isochronous Cyclotron

- IBA (2018)
  60 Tons
  Synchrocyclotron

- MEVION (2013)
  17 Tons
  Synchrocyclotron

Superconducting Coils
Cyclotrons for 30-1000 MeV
> 30 MeV cyclotron

**Cyclotron works while:** \( T_{\text{circle}} \) independent from radius:

(particles move in pace with \( V_{\text{dee}} \))

BUT….

At high energy \( m=\gamma m_0 \) increases

- 10 MeV p: \( v/c=0.14 \) \( \Rightarrow \) \( m=1.01 \ m_0 \)
- 250 MeV p: \( v/c=0.61 \) \( \Rightarrow \) \( m=1.27 \ m_0 \)
- 590 MeV p: \( v/c=0.79 \) \( \Rightarrow \) \( m=1.63 \ m_0 \)

\[ Freq = \frac{1}{T_{\text{circle}}} \]

\[ V_{\text{dee}} \sim \]

\[ T_{\text{circle}} = \frac{2\pi.m}{q.B} \]
Synchro-Cyclotron

So: Problem = \( T_{\text{circle}} \) increases with radius.

**REMEDY 1:**

Decrease \( f_{RF} \) with \( 1/T_{\text{circle}} \) in time

= with \( r \) and extract

Repeat max 1000 x per sec
Beams for: ISOLDE, Nuclear physics, Medical applications, Astrophysics, ...
Synchro-cyclotron

2013: 250 MeV Synchro-cyclotron on a gantry

8.5 T, 250 MeV, 500 Hz
REMEDY 2:
Correct with B-field:

Increase $B$ with radius, ($= r \sim m$):

$$B(r) = \gamma(r) \cdot B_0$$

$$T_{\text{circle}} = \frac{2\pi m}{q B}$$
decrease pole gap + use trim coils

Trim coils mounted on the poles

Hillfield 590 MeV Ringzyklotron

\[ \gamma = 1.6 \]
\[ 2 \text{ T} \]

\[ \gamma = 1.1 \]
\[ 1.4 \text{ T} \]

\[ 2 \text{ T} \]

\[ 1.4 \text{ T} \]
\[ 1.5 \text{ T} \]

SM7
Vertical focusing

If $B$ decreases with radius:

$\Rightarrow$ Automatic vertical stability

... but isochronicity needs increasing $B$

If $B$ increases with radius:

$\Rightarrow$ NO vertical stability
Azimuthally Varying Field: AVF

If B-step is not crossed \( \perp \):  
\[ \Rightarrow \text{vertical force} \]
The PSI facility for high intensity proton beams of 590 MeV
PSI’s High intensity Cyclotrons for physics

- 72 MeV p
- 870 keV from Cockcroft-Walton
- Isotope prod.
- 590 MeV p
  2.4 mA (1.4 MW)

Ring cyclotron
ECR-Ion source

Electron cyclotron resonance ion source

- High reliability
- Small emittance
- **Stable beam 10 – 15 mA**
Injection of 870 keV protons into Injector II

Tank at 810 kV with 60 kV ECR

Cockroft Walton 810 kV DC

810 kV

870 keV 10 mA

Injector II cyclotron
Buncher: DC $\rightarrow$ Pulsen

- Frequency = 50 MHz
- DC Beam $\rightarrow$ pulsed Beam to be injected into Inj.-II
Injector II Cyclotron (1984)

- 4 Sector Magnets: 0.33 – 0.36 T
- 2 cavities 50 MHz: 450 kVp
- Beam energy: 72 MeV
- Number of turns: 81
- Max. beam current: 2.7 mA

In operation since 1984

Extraction Line
72 MeV Protons
2.7 mA (200 kW)
(after 81 turns)
Using collimators the beam is cleaned

10 $\rightarrow$ 2.4 mA, but:

- without halo
- short bunches

Beam injection into Inj.II

RF cavity 0.9 MeV/turn $\rightarrow$

81 turns = 71 MeV
Vortex or Spagetti effect in Inj.II

- Faster
- Slower

Same speed

→ too large radius: needs more time

→ too small radius: needs less time

→ larger radius

→ smaller radius
Vortex or Spagetti effect in Inj.II

Longitudinal Space Charge in Cyclotron

Simulation of a 1mA beam, circulating in Injector II at 3 MeV for 40 turns without acceleration.

The core stabilizes faster than the halos (calculations by Stefan Adam)

→ Automatic space charge compensation!
High intensity issues

Acceleration: $HV \rightarrow$ nr of turns

Space charge effects ($\rightarrow$ losses)

limited by reducing nr of turns:

- Faster process
- Larger radial distance between bunches
History of the Beam-Current

average voltage gain per turn [MV]

scaling law $I_{\text{max}} \propto N^{-3}$

losses $\propto [\text{turns}]^3 \propto [\text{charge density}] \times [\text{accel. time}] / [\text{turn separation}]$

(W.Joho)

higher RF voltage $\rightarrow$ lower nr of turns

since 2008

Cu cavities

~186 turns
RF Cavity in RING cycl.

50.7 MHz  $V_{\text{max}}=1.2\text{MV}$
$\rightarrow$ 400 kW/cav to beam

Now at $V = 850\text{ kV}$:
185 turns  $\rightarrow$ 2.4 mA

Goal: 165 turns  $\rightarrow$ 3 mA
High intensity issues

Extraction
Extraction from cyclotron

Cathode at -HV

Extracted beam

Septum

Last turns

\( \delta r \propto 1/r \)
Injection / extraction: Electrostatic Elements

Extraction Channel EEC
145 kV

Injection Channel EIC
130 kV

grounded tungsten stripes
Betratron oscillations

Important oscillations in cyclotrons:

Resonance at $V_r = Q_r = 1$:

- Effectively an orbit shift

→ Increase of turn separation

Extraction septum

Frequency $V_r = 1.5$:
Extraction with off-center orbits

without orbit oscillations: stepwidth from $E_k$-gain (PSI: 6 mm)

### Betatron oscillations

Betatron oscillations are excited to add a precession to the orbits, which increases the radial turn separation by a **factor 3**!

with orbit oscillations: extraction gap; up to $3 \times$ stepwidth possible (PSI: 18 mm)
High intensity issues

Operation is at limit of:

- damage due to **high power** (> 1MW)
- activation due to **beam losses**
High-Power Beams - Technical safety

beam hits material (e.g. steel vacuum chamber):

\[
\frac{\Delta T}{\Delta t} \approx \frac{P_0}{2 \pi \sigma_x \sigma_y \lambda \left[ \text{g/cm}^2 \right] c_p} = 250,000 \text{ K/sec}
\]

beam power
beam size
material specific interaction length
heat capacity
melts after 8 ms!

Damage at ring injection caused by 150 kW beam

→ fast and reliable interlock systems are necessary to avoid damage!
Component Activation of Ring Cyclotron

Activation level is limited such, that it allows for necessary service / repair work
+ local shielding
+ dedicated boxes for exchange of activated components
+ concentrate tasks in shutdown (3-4 mo.)
+detailed planning

→ typical personnel dose 50-300 μSv/mission

Activation map of Ring Cyclotron
(EEC = electrostatic ejection channel)

cool down times for service:
2.0 → 1.7 mA for 2h + 0 mA for 2h
In shut down: exchange of muon prod. target

Dose rate $\sim 1$ mSv/h in working area (after 3 months cooling)
Infrastructure – Exchange flasks

mobile and dedicated shielding devices for:
- targets
- electrostatic elements
- collimators
- septum magnets

exchange flasks: complicated and expensive
heavy, motors, instrumentation, SPS controls

<table>
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<th>Exchange flask for meson production</th>
<th>Electrostatic Extraction Element</th>
<th>Beam Collimators</th>
<th>Beam Splitter</th>
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<tr>
<td>Target E (4 cm graphite wheel)</td>
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</tbody>
</table>
Infrastructure – Hot Cell

view through lead-glass window: Meson production target wheel

Repair time usually < 2 days

irradiated SINQ spallation target, taken out of the cover
Segmented Collimators measuring the balance between scraped beam currents

**interlock**: when currents or asymmetry exceed margin
Diagnostics for Machine Protection

Beam loss monitors = System based on ca. 150 very fast (<100ms) devices (10 signals each):

**Ionisation chambers** as beam loss monitors

Simple and reliable devices

Losses outside margins generate interlock
Operation
Operational data wk. 26-52, 2018
Applications

of a 1.4 MW Beam (World Record!)

- most intensive Muon Beams $5 \cdot 10^8 \mu/s$
- Spallation-Neutron-Source $10^{14} \text{n/s}$
- Ultra Cold Neutron-Source
Muon and Neutron production

UCN $\rightarrow$ neutrons

SINQ $\rightarrow$ neutrons

E $\rightarrow$ Muons

M $\rightarrow$ UCN $\rightarrow$ neutrons
**Muon target-E\(\text{pais}\)** design

**TARGET CONE**
- Mean diameter: 450 mm
- Operating Temp.: 1700 K
- Irr. damage rate: 0.1 dpa/Ah
- Rotational Speed: 1 Turn/s
- **Target thickn:** 60 / 40 mm
- Beam loss: 18 / 12 %
- **Power depos.:** 30 / 20 kW/mA
Spallation Neutron Source SINQ
Much effort to **control defocusing**

→ **power density in SINQ**

Special fast beam-shape detection + fast interlocks
Plans and ideas

General Goal = Higher intensity

Accelerators

Targets

Upgrade; new possibilities
Upgrade Injector 2: RF cavities

New Resonators with strong field shifted to extraction Radius:

\[ R_{V=0} \]

\[ R_{V>0} \]
HiMB project: increases muon rate

More shearing incidence by slanting target orientation

Polarised Muons

30% more $\mu$

Proton beam

Graphit

Target E

$+ \text{ similar extension of target M: } 10^8/s \rightarrow 10^{10} \mu/\text{sec}$
Idea for a 10 MW driver

Superconducting sector magnets
→ more RF-cavities
→ higher E-gain/turn.

Now:
590 MeV, 2.4 mA = 1.4 MW

Idea:
1 GeV, 10 mA = 10 MW
Cyclotrons are still attractive!

- Commercial cyclotrons for isotope production and therapy
- Intense muon sources
- Intense neutron sources
- Energy amplifier concept (Rubbia)
- Transmutation of nuclear waste
High Intensity machines

DC beam

(Chart showing various accelerator projects with labels such as MYRRHA, ESS, SNS2, SNS10/2009, PX-Linac, HP-SPL (CERN), JPARC3 GeV, JPARC50 GeV, IPNS, and others, with axes for average current and beam energy, and different power levels indicated.)
Thank you for your attention
Metamorphosis

Wideroe’s linear accelerator

how to re-use the RF

\[ \frac{mv^2}{r} = Bqv \]

\[ v = \frac{2\pi r}{T_{\text{circle}}} \]

\[ T_{\text{circle}} = \frac{2\pi r}{v} = \frac{2\pi m}{Bqr} = \frac{2\pi m}{Bq} \]

"r cancels r ... don't you see what this means?"

The resonance condition does not depend on radius!“

(Lawrence to his PhD student Livingston, while bursting into his lab)
Hills-Valleys: Sectors

curved magnet poles keep vertical focusing with increasing E
New flat-top cavity in RING

**Flat-top** RF voltage by adding third harmonic of RF frequency (3x50=150 MHz) → longer pulse length

3.6 Grad=0.2 ns

60 Grad=3 ns

Since 2008: new RF cavities:
0.8→1.0 MV
Needs Higher V in flat top cav.

→ More protons per Bunch
**Target-M\textsuperscript{(ince)} design**

<table>
<thead>
<tr>
<th><strong>Target M:</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target thickness:</strong></td>
<td>5.2 mm</td>
</tr>
<tr>
<td><strong>Beam loss:</strong></td>
<td>1.6 %</td>
</tr>
<tr>
<td><strong>Power deposition:</strong></td>
<td>2.4 kW/mA</td>
</tr>
<tr>
<td><strong>Operating Temperature:</strong></td>
<td>1100 K</td>
</tr>
<tr>
<td><strong>Irradiation damage rate:</strong></td>
<td>0.12 dpa/Ah</td>
</tr>
<tr>
<td><strong>Rotational Speed:</strong></td>
<td>1 Turn/s</td>
</tr>
<tr>
<td><strong>Current limit:</strong></td>
<td>5 mA</td>
</tr>
<tr>
<td><strong>Usual life time:</strong></td>
<td>50000 h</td>
</tr>
<tr>
<td></td>
<td>$\Rightarrow$ 44 Ah $\sim$ 4 DPA</td>
</tr>
</tbody>
</table>
Muon beam line

The muon beams have a large emittance → big magnet (apertures)

(Photo: Paul Scherrer Institute/Markus Fischer)
Isotope Production IP2

- Splitted or direct beam
- Energy: 72 or 40 MeV
- Beam current: 100 $\mu$A (given by splitter position)

Electrostatic beam splitter

Carbon Degrader 40 MeV
Spallation neutron source SINQ

Lead target tubes

D$_2$O moderator

Principle of the Spallation Neutron Source SINQ

- Helium supply
- Helium refrigerator
- D$_2$ Compressor
- Cold helium (T < 23 K)
- Target cooling system
- Target plug
- D$_2$ Moderator
- Neutron beam tube
- Neutron beam port
- Neutron beam channel
- H$_2$O reflector
- D$_2$O moderator
- Beam shutter
- Sample
- Instrument
- Cooler
- Target block shielding (steel & concrete)
- Target block shielding
- Target block shielding

Marco Schippers, PSI, High Intensity beams from PSI cyclotrons
The PSI UCN source

DLC coated UCN storage vessel height 2.5 m, ~ 2 m³

heavy water moderator → thermal neutrons
3.6 m³ D₂O

pulsed 1.3 MW p-beam
600 MeV, 2.2 mA, 1% duty cycle

tank cryo-pump

UCN guides towards experimental areas 8.6m(S) / 6.9m(W)

cold UCN-converter ~30 dm³ solid D₂ at 5 K

spallation target (Pb/Zr) (~ 8 neutrons/proton)
Beam rotation system at SINQ

→ Reduce power/cm²

90 cm space in beam line for: magnet and monitor