Single Stage Cyclotron for an ADS demonstrator

P. Mandrillon and M. Conjat
AIMA-DEVELOPPEMENT
with the contribution of J. Mandrillon

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PSI - 1st multi-stages

Single turn Extraction

1st Single stage with Stripping Extraction of $H^-$

ICC 1975 in Zurich!
Beam Energy: in the 600 to 800 MeV protons to produce neutrons via spallation.
Beam Power: 5-10 MWatt.
Beam losses: internal losses < 200 Watt.
Reliability (beam trips)
Optimized Energy efficiency: $\eta = \frac{P_{\text{beam}}}{P_{\text{grid}}}$
Costs.
High intensity Cyclotrons: 
The lessons from the pioneers

PSI

1973

TRIUMF 1974 (1st 500 MeV beam)
1) PSI: Single turn extraction
Excellent agreement simulations/measures

> Increasing the separation $\delta$ between turns

$$\delta = \frac{R}{N\gamma(\gamma+1)/\nu_r^2}$$

> Reducing the number of turns $N$ with

High power new RF copper cavities.

[Y.J. Bi (PSI & Tsinghua Univ.), A. Adelmann]
The successful Werner Joho law!

\[ I_{\text{max}} \propto N^{-3} \]

Historical development of turn numbers in PSI Ring Cyclotron
2) The main causes of downtime of a multi-stages cyclotron

From M.Seidel PSI in 2009
The High-Tech injection/extraction electrostatic channels

$E_{\text{max}} = 90 \text{ KV/cm}$

injection element in Ring

Tungsten stripes
The injection/extraction devices of the multi-stages solution

The PSI 2 stages geometry: a 72 MeV Injector and the 590 MeV Booster ring. → various injection and extraction channels

- **EID**: Electrostatic deflector channel for 72 MeV Inj. II
- **EIC**: Electrostatic inflector channel for Ring machine
- **EEC**: Electrostatic extractor channel for Ring machine
Well known method (low energy cyclotrons):
Drawback: The relativistic electromagnetic stripping of H- (0.754 eV)
- For 520 MeV, Bmax in the sectors 6 kGauss - Large machine for 600 MeV
H₂⁺ acceleration and inwards extraction of H⁺ by stripping

L. Calabretta and D. Rifuggiatto
ECPM, Groeningen, 1997

Important advantages of H₂⁺ over H⁻:
- Reduced space charge at low energy
- High electron binding energy: 2.8 eV → High B
- 2 stripped protons/H₂⁺ with half momentum
- e⁻ thermal load per proton on the stripper: divided by 4

E.g. Trade driver proposal (ENEA - AIMA) to deliver 2mA-110 MeV protons by stripping of 1mA, 220 MeV H₂⁺
Other examples of high power Cyclotrons:
1995: Inspired by PSI the early proposal for driving the Energy Amplifier with a 1 GeV 3 stages Cyclotron

N. Fiétier and P. Mandrillon, Beam Dynamics and Space Charge aspects in the design of the accelerators for the Energy Amplifier, Proc. of the 14th ICC, Cape Town, 1995
800 MeV Superconducting Strong-Focusing Cyclotron
High current proton driver for ADS

Texas A&M University

- Two Stages Cyclotron: 100 MeV SF injector + 800 MeV SF booster.
- Stack of 3 Cyclotrons in //
- Booster: 12 Flux coupled stack of dipole magnet sectors
- 10 Superconducting 100 MHz RF cavities providing a 20 MeV Energy Gain/turn
- Large turn separation allowing to insert SF beam transport channels made of Panofsky Qpoles (G=6T/m)
The Daedalus two-stages H2+ 800 MeV/n Cyclotron

- Catania group Design: L. Calabretta et al., www.jacow.org, EPAC 2000, p. 918

Magnet: 6 Sectors superconducting coils (Riken type)
RF: 4 Single gap RF Cavities (PSI Type)+2 double gap cavities
Extraction: **stripping of H2+**
Single Stage Cyclotron Driver (S2CD™)
based on the Reverse valley B-field

Option A: 600 MeV-10 mA protons
Option B: 1600 MeV-5 mA H2+ → 800 MeV-10 mA protons
isochronism:
> positive radial gradient of $\langle B \rangle$
> strong vertical defocusing:
$$\Delta \nu_z^2 = -(\gamma^2-1) = - (d\langle B \rangle/dr)/\langle B \rangle$$
> edge and spiral focusing
$$\nu_z^2 = -(\gamma^2-1) + F^2(1+2 \tan^2 \zeta)$$
$$F^2 = \text{Field Flutter} = (\langle B^2 \rangle-\langle B \rangle^2)/\langle B \rangle^2$$
$$\zeta = \text{spiral angle of the sector}$$

2-A separated sector with reverse valley B:
$\rightarrow$ Stronger Flutter $\Rightarrow$ No Spiral needed
The reverse valley bends Cyclotron

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> edge and spiral focusing
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2-A separated sector with reverse valley B:
→ Stronger Flutter → No Spiral needed

Proton Extraction is more simple
- by stripping of H2+ > very short!
- by a bump, i.e. « Septum free extraction »
Single stage Cyclotrons Magnetic Fields

S2CD-600 MeV H+
With reverse Bv field

TRIUMF-520 MeV H-

B on the valley axis
The 600 MeV proton S2CD

> Large complex Coils: 1.1 MA turns/coil
  - $R_{\text{min}}$: 3.6 m $R_{\text{max}}$: 5.1m
  - Total length $\sim$48m
  - Superconducting coil: Section: 130 mm * 280 mm Current density 31 A/mm²
  - Water cooled Copper coil: Section 220* 470 mm Current density 10 A/mm²
Triple injection central region
Triple injection central region

Major advantage: low B-field in the central region

> 3 axial injections

\[ \Rightarrow \text{An injector cyclotron is not needed anymore!} \]
A single HV Platform for 3 Ion sources feeding 3 axial injections with spiral inflectors

Median plane

Vertical plane

$E_{\text{inj}} = 60 \text{ KeV}$
$E = 20 \text{ KV/cm}$
$k = 0.6$
$k' = -0.15$

The crowded Central region

The 60 KV platform
RF Delta double gap tapered walls cavities

- 6 cavities at 49 MHz (Option H+)
- 1000 KW beam power /cav + 350 KW losses /cav
- 2 RF coupling loop/window
- 2 amplifiers (electron tubes)/cavity
- Large stem allows to install pumping
The septum free Extraction (H+)

2 channels:

1st) Bump Channel: -2 kG to increase the -2 kG valley field

2nd) Foc. Channel: + 3T/m in the sector field.
H2+ Extraction

short trajectory, no focusing elements, no complexity

Initial condition:
5mm vertical amplitude @ 155MeV

Shorter trajectory if the stripping foil is located in a valley: leads to a smaller extracted beam
H2+ Extraction

short trajectory, no focusing elements, no complexity
The 1600 MeV H2+ option

> 6 straight hill sectors (14 tons)
> 12 small valley sectors

> Superconducting Coils
  - Rmin: 4.2m Rmax: 7.1m
  - Total length ~50m
  - Section: 160 mm * 310mm
  - Current density 55 A/mm²
Conclusions
Critical Issues of Single Stage designs

1- Large superconducting coils:
   - Mechanical design of a complex shape with bends
   - Possibility to use MgB2 for a cryo-free cooling system?
   => Tests and prototypes are needed

2- High power RF cavity design to handle 1.4 (H+) - 1.6 (H2+) Mwatt:
   - 2 RF Windows + 1 Amplifier/window
   - relation between cavity & extraction system

3- Multi Injection:
   - a single HV platform to house 3 ion sources is being investigated

4- H2+ acceleration:
   - interaction with residual gas: High vacuum is needed (cf. Daedalus)
   - Dissociation of the vibrational states producing high energy protons (according to experience, filament-based multicusp ion sources could be more relevant)
   - stripping foil lifetime: 500 mA.hours outstanding performance achieved at TRIUMF with oriented pyrolic Graphite (courtesy of Yuri Bylinskii)
• **Single stage accelerator**
  - Compact system - low construction budget and Low operational cost
  - Less components than traditional solutions → high reliability
  - No transport / no matching issues between stages

• **3 sources + axial injection lines**
  - redundancy
  - reliability
  - Intensity Flexibility:
    • 8 mA protons>4mA H2+: 2 Ion sources on + 1 Ion source in Stand-by
    • 12 mA protons>6mA H2+: 3 Ion sources on

• **Simplified Extraction system** : No Septum required
  - Increasing reliability
  - less activation => easier maintenance

A single stage 600MeV H+ or 1600 MeV H2+ cyclotron with Reverse Valley Field: a good candidate for an industrial ADS demonstrator.
Thank you for your attention