100 MeV H⁻ Cyclotron Development and 800 MeV Proton Cyclotron Proposal

Tianjue Zhang
China Institute of Atomic Energy
Plan of Talk

1. Introduction
2. The Beam Commissioning of CYCIAE-100
3. High Power Cyclotron Facility Proposal
4. Other Cyclotron Development
In 1950’s, pioneering with hardship and building development basis

Research reactor and cyclotron

On June 13, 1958
Reactor reached criticality

On Sep. 27, 1958
cyclotron provided beams
Development of proton cyclotrons with high intensity at CIAE

2009 10MeV, 430μA
2012, 14MeV, 450μA
1994, 30MeV, 370μA
100MeV, 200-1000μA
230MeV, 1μA
800MeV, 3000μA

T. Zhang, NIM-B, 2011
Refer to IBA original design, CIAE redesigned and constructed a 30 MeV cyclotron CYCIAE-30 for medical isotopes production. 370 μA extracted beam was got at the end of 1994.

For the production of

- TI-201
- Pd-103
- F-18
- Ga-67
- Co-57
- Ge-68
- I-123
- In-111


370 μA proton beam was extracted from a 30 MeV compact H^- cyclotron CYCIAE-30 at the end of 1994.
Research Activities Related to Low Energy Accelerators in CIAE

China Institute of Atomic Energy
ICCA-2016, Sept 12–15, 2016, Zurich, Switzerland

100 MeV H- Cyclotron Development and 800MeV Proton Cyclotron Proposal

- **10MeV, 430μA**
- **First, Second Small Cyc**
- **PET Cyclotron, 14 MeV, 450 μA**

- **10th Small Cyc, under construction for BNCT**
- **3rd to 9th Small Cyclotron, 14 MeV, 100 μA to 400 μA, main parts for overseas**

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ICCA-2016, Sept 12–15, 2016, Zurich, Switzerland
As one of the main projects at CIAE, the **Beijing Radioactive Ion-beam Facility (BRIF)** will be used in fundamental and applied research such as neutron physics, nuclear structure, material and life sciences, medical isotope production.
Research Activities Related to Low Energy Accelerators in CIAE

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100 MeV H- Cyclotron Development and 800MeV Proton Cyclotron Proposal

First stage: 70MeV~100MeV, 200~500 µA: 20kW~50kW

Second stage: 30 MeV ~ 100 MeV, 1mA, 100kW.

General View of the 100 MeV Cyclotron

- CW mode, high current
- Energy variable;
- Dual beam extracted simultaneously;
- Low extraction beam losses

CYCIAE-100
Plan of Talk

1. Introduction

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First compact cyclotron with straight sector pole for energy beyond 70 MeV.

Whole field map is measured within vacuum for the first time, the final phase slope less than $\pm 10^\circ$.

Various technologies for high current compact H- cyclotron have been developed.

It is first time to develop a parallel computation code for multiphase bunch simulation, which is implemented in 6 international institutes to study space charge effects and multipacting effects.
Tolerance Control:
- Hill gap -- 0.05 mm,
- Pole edge -- 0.1 mm,
- Others

The installation, mapping and shimming of the main magnet system are finished by July, 2013
100 MeV H- Cyclotron Development and 800MeV Proton Cyclotron Proposal

Installation of RF, Vacuum, R-probes, extractors, central region, RF conditioning were finished by the end of 2013.
Beam Commissioning

- On December 18 of 2013, we got **320 μA** DC beam on an internal target. The transmission efficiency from the ion source to the exit of inflector is higher than **80%**.
On June 16, 2014, the internal target is moved to 1 MeV region and successfully got $10^9 \mu A$ beam with 20% RF duty cycle.

We gradually increased the duty cycle and reached CW mode operation.
Beam Commissioning

- On June 16, 2014, the internal target is moved to the 1 MeV region and successfully got $10^9 \mu A$ beam.
- July 4, 2014, we got the first 100 MeV proton beam extracted.
- We gradually increased the duty cycle and reached CW mode operation.

1 MeV
100 MeV

Stripping foil
Radial Probes

ICCA-2016, Sept 12–15, 2016, Zurich, Switzerland
Beam Commissioning

12 hours running test with extracted beam current $> 23 \mu A$, on July 25, 2014

- Inflector sparking
- Power supply failure

8hrs 50min
Beam Commissioning

ISOL system is driven by CYCIAE-100

Stripping foil

1.02μA

Transmission of ISOL beam line

FC1
1.01μA

FC2
1.00μA

FC3
0.99μA
ISOL system is driven by CYCIAE-100

100 MeV proton beam on CaO target
Production of $^{38}\text{K}^+$: $1\times10^6$ pps

The first RIB by BRIF, May 2015

The gamma spectra of $^{38}\text{K}$ after separator

Production of $^{38}\text{K}^+$: $1\times10^6$ pps

RIB To Tandem
From the first beam to mA

- Beam Development, 1000 hrs beam time
  - Re-Matching for the injection line
  - Improvement of the ion source
  - Addition of a buncher for beam injection
  - Optimization for LLRF control and power coupling
  - Water cool central region (in progress)
  - High power beam dump (in progress)

- Operation for Applications, 700 hrs beam time
  - RIB Production, 230 hrs
  - Radiation effects in electronics and biology, 150 hrs
  - Neutron physics, 120 hrs
  - Proton Radiography Experiment and others, 200 hrs
100 MeV H- Cyclotron Development and 800MeV

**From the first beam to mA**

- Matching for injection line:
- S-B-QQQ-S, 2.5m
- 8-10 mA, 40keV

In order to get mA level acceleration beam, several aspects are improved for the ion source, buncher system, beam loading of the RF system, space charge effects limit, beam matching from ion source to the central region, etc.

2016
Matching for injection line:
- S-B-QQQ-S, 2.5m
- 8-10 mA, 40keV

2016
From the first beam to mA
From the first beam to mA

- The multi-cusp ion source on the test stand:
  - 18 mA, 30 keV
  - \( \rightarrow \) 10 mA, 40 keV

The new extractor, ground electrode, new XY steeling
From the first beam to mA

- Non-intercepting 2-gap buncher
- Between the first solenoid and the triplet, ~1.1m away from the inflector.
- Gap=5 mm and D=0.5βγ instead of 1.5βγ at TRIUMF

LC matching circuit

Buncher driven by 600W amplifier

CTS model
From the first beam to mA

- The mA level beam is a heavy load for the RF system and may cause an open-loop condition for the Dee voltage regulation.

- To achieve an accurate amplitude control, the LLRF adopts a self-adaptation strategy to ensure the control loop is always closed, unless the power requirement exceeds 120% of nominal value.
From the first beam to mA

- The mA level beam is a heavy load for the RF system and may cause an open-loop condition for the Dee voltage regulation.

- To achieve an accurate amplitude control, the LLRF adopts a self-adaptation strategy to ensure the control loop is always closed, unless the power requirement exceeds 120% of nominal value.

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**LLRF Control**

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**Diagram:**

- The diagram shows a circuit with components labeled as follows:
  - **Ck:** Capacitor
  - **R:** Resistance
  - **L:** Inductance
  - **mA:** Milliampere
  - **400MHz:** Frequency
  - **44.8125MHz:** Frequency
  - **Data Bus:** Signal transmission path
  - **DDS:** Direct Digital Synthesizer
  - **ADC:** Analog-to-Digital Converter
  - **PID:** Proportional-Integral-Derivative controller
  - **0~1V:** Voltage range
  - **V_{dee}:** Voltage
  - **Amplitude Loop:** Feedback loop for controlling the amplitude of the signal
The tuner of the cavity consists of a fine capacitor and a coarse capacitor driven by two DC motors.

Based on the thermal situation after some operation of the cavities, the fine tuner was changed to a smaller one to achieve more precise tuning of the RF cavity. The residual tuning errors are reduced to less than 3 degrees for both cavities.
From the first beam to mA

Removable internal Target

- The removable target is put at the valley of main magnet, can be control to move in and out of the mid-plan.
- It is well water cool with secondary electron collection, which is not shown in the photo.
- The removable target was designed for 1.5kW beam power. It is installed in the central region of the machine (@ about 1 MeV) to stop the beam for low energy beam commissioning.
Research Activities Related to Low Energy Accelerators in CIAE

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100 MeV H- Cyclotron Development and 800MeV Proton Cyclotron Proposal

From the first beam to mA

In June, 2016, we got accelerated beam > mA

1073 μA
## From the first beam to mA

### In June, 2016, we got accelerated beam > mA

<table>
<thead>
<tr>
<th>Ion source (mA)</th>
<th>No Buncher (μA)</th>
<th>With Buncher (μA)</th>
<th>Bunching efficiency</th>
<th>Acceleration efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.33</td>
<td>100</td>
<td>201</td>
<td>2.01</td>
<td>15.1</td>
</tr>
<tr>
<td>1.91</td>
<td>145</td>
<td>310</td>
<td>2.14</td>
<td>16.2</td>
</tr>
<tr>
<td>3.25</td>
<td>201</td>
<td>399</td>
<td>1.99</td>
<td>12.3</td>
</tr>
<tr>
<td>4.27</td>
<td>258</td>
<td>490</td>
<td>1.90</td>
<td>11.5</td>
</tr>
<tr>
<td>4.71</td>
<td>410</td>
<td>633</td>
<td>1.54</td>
<td>13.4</td>
</tr>
<tr>
<td>6.43</td>
<td>542</td>
<td>740</td>
<td>1.37</td>
<td>11.5</td>
</tr>
<tr>
<td>8.69</td>
<td>610</td>
<td>950</td>
<td>1.56</td>
<td>10.9</td>
</tr>
<tr>
<td>9.52</td>
<td>636</td>
<td>1073</td>
<td>1.68</td>
<td>11.2</td>
</tr>
</tbody>
</table>
From the first beam to mA

In June, 2016, we got accelerated beam > mA

1 mA

RF sparking

Inflector sparking

mA Beam Acceleration

1135μA

1135.36 μA
From the first beam to mA

High Power Beam Dump

- For 100 MeV extracted beam
- 1 mA

Water cool Central region

Zurich, Switzerland
China Institute of Atomic Energy
From the first beam to mA

- **Beam Development, 1000 hrs beam time**
  - Re-Matching for the injection line
  - Improvement of the ion source
  - Addition of a buncher for beam injection
  - Optimization of LLRF control and power coupling
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- **Operation for Applications, 700 hrs beam time**
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Research Activities Related to Low Energy Accelerators in CIAE

China Institute of Atomic Energy
ICCA-2016, Sept 12–15, 2016, Zurich, Switzerland

100 MeV H- Cyclotron Development and 800 MeV Proton Cyclotron Proposal

- Re-Matching for the injection line
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Operation for Applications, 700 hrs beam time

- RIB Production, 230 hrs
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Beam Line for Isotope Production
Beam Line for ISOL System
Beam Line for Radiation effects in electronics and biology
Beam Line for Neutron physics
Beam Line for Proton Radiography Principle Experiment
Beam Line for 15/30 m Neutron Beam Line
Plan of Talk

1. Introduction
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Top proton beam power accelerators

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>800</td>
</tr>
<tr>
<td>Beam current (mA)</td>
<td>4</td>
</tr>
<tr>
<td>Bunch length (ns)</td>
<td>1.25</td>
</tr>
<tr>
<td>Particle per bunch</td>
<td>$7 \times 10^8$</td>
</tr>
<tr>
<td>Bunch interval (ns)</td>
<td>22.5</td>
</tr>
<tr>
<td>Beam power (MW)</td>
<td>3-4</td>
</tr>
</tbody>
</table>

CYCIAE-800
Beam parameters

Courtesy M. Seidel
## Staged Plan of the proposal

<table>
<thead>
<tr>
<th>Construction contents</th>
<th>Beam parameter</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stage one:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>■ Construction of CYCIAE-800</td>
<td>0.5 mA, 0.4 MW</td>
<td>1. nuclear data measurement, 2. single event effects</td>
</tr>
<tr>
<td>■ CYCIAE-100 of the BRIF project as the injector</td>
<td></td>
<td>3. radiation physics 4. Isotope production</td>
</tr>
<tr>
<td><strong>Stage two:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>■ A dedicated new injector, 100 MeV separated-sector cyclotron</td>
<td>2 mA, 1.6 MW</td>
<td>1. neutron science</td>
</tr>
<tr>
<td><strong>Stage three:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>■ Increase the beam power</td>
<td>5 mA, 4 MW</td>
<td></td>
</tr>
</tbody>
</table>
Since the year of 2009, we carried out conceptual study on this proposal:

- T.J. Zhang et al., *NIM-B*, 2011
- M. Li et al., *ICC2013*, 2013
- J. J. Yang et al., *IPAC2013*, 2013
- T. J. Zhang et al., *EMIS2015*, 2015
Proton Vs. $\text{H}_2^+$ (bachelor Vs. family of three)

<table>
<thead>
<tr>
<th></th>
<th>$\text{H}_2^+$ Superconducting</th>
<th>Proton Room Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>pro</td>
<td>a) Multi-turn stripping extraction; b) low RF voltage is OK; c) Smaller space charge effects</td>
<td>a) Mature technology at MW level (PSI, TRIUMF); b) Require low B field, warm magnet is OK; c) Good extraction beam quality; d) Low Vacuum is OK</td>
</tr>
<tr>
<td>con</td>
<td>a) Long-lived vibrational states $\rightarrow$ dissociate b) Require SC magnet c) Need high vacuum d) No construction experience at MW level</td>
<td>a) Require single-turn extraction; b) Require high RF voltage; c) Larger space charge effects; d) Need flat-top cavities and/or buncher</td>
</tr>
</tbody>
</table>

Our selection: proton

- Better quality of extracted beam
- Mature technology
- Lower engineering risk
Layout of the 800MeV cyclotron CYCIAE-800

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole number</td>
<td>9</td>
</tr>
<tr>
<td>Kinetic energy (MeV)</td>
<td>100-800</td>
</tr>
<tr>
<td>Magnetic rigidity (T·m)</td>
<td>1.48-4.88</td>
</tr>
<tr>
<td>Average orbit radius (m)</td>
<td>2.76-5.42</td>
</tr>
<tr>
<td>Cyclotron radius (m)</td>
<td>8.0</td>
</tr>
<tr>
<td>RF frequency (MHz)</td>
<td>44.37</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>6</td>
</tr>
<tr>
<td>Main cavity number</td>
<td>5</td>
</tr>
<tr>
<td>Flat-top cavity number</td>
<td>1 or 2</td>
</tr>
<tr>
<td>$Q_r/Q_z$ at extraction</td>
<td>1.55/1.40</td>
</tr>
<tr>
<td>$Q_r$ max/min</td>
<td>1.85/1.10</td>
</tr>
<tr>
<td>$Q_z$ max/min</td>
<td>1.40/1.05</td>
</tr>
<tr>
<td>dR/dn at extraction (mm)</td>
<td>7 (centering injection)</td>
</tr>
<tr>
<td>dR/dn max/min (mm)</td>
<td>35/6</td>
</tr>
</tbody>
</table>
Magnet Design


<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>sector number</td>
<td>9</td>
</tr>
<tr>
<td>spiral angle</td>
<td>0~50 °</td>
</tr>
<tr>
<td>sector width</td>
<td>13~17 °</td>
</tr>
<tr>
<td>sector radius</td>
<td>2.46~5.73 m</td>
</tr>
<tr>
<td>hill gap</td>
<td>90~54 mm</td>
</tr>
<tr>
<td>magnet diameter</td>
<td>16 m</td>
</tr>
<tr>
<td>magnet height</td>
<td>5.8 m</td>
</tr>
<tr>
<td>total stored energy</td>
<td>3.96 MJ</td>
</tr>
<tr>
<td>exciting current per pole</td>
<td>187 kA.turns</td>
</tr>
</tbody>
</table>
9 sectors, 380 ton per sector
Total: 3420 ton


100 MeV: 435 ton
**Beam Dynamic Design**

- **Orbit design**
  - Initial model
  - Optimized model
  - \( v_x = 2v_y \)
  - \( v_x = 1 \)
  - \( v_x = v_y \)

- **Phase slip**
  - Phase slipping (degree)
  - Turn number

- **Average field**
  - Average field (Tesla)
  - Turn separation (mm)

**References**

\[ \nu_r = 2\nu_z \] resonance in original structure

- The vertical beam trajectory in 50 turns for two particles with different initial offset: radially centered (left) and off-centered (right).

Structure Optimization: the magnet field flutter was enlarged by increasing the sector height by 12 cm and the spiral angle was increased by 10%.

Single turn extraction: *eccentric injection + half integral resonance*

Deflector parameter | value
--- | ---
Electrode gap (mm) | 16
Beading curvature (m) | 114
Effective length (mm) | 920
Voltage (kV) | 144
Field strength(kV/cm) | 90

*J. J. Yang et al., IPAC2013, 2013*
Space charge simulation by OPAL-CYCL code

The space-charge-limited beam current is increased from 1 mA to 3 mA by avoiding the crossing of $Q_r=1$ and $Q_r=2Q_z$ resonance. More work need to further increase beam current.

**Initial**

**Optimized**

- T. J. Zhang et al., EMIS2015, 2015
RF resonator design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonator number</td>
<td>6</td>
</tr>
<tr>
<td>Peak voltage (MV)</td>
<td>1.0</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>44.37</td>
</tr>
<tr>
<td>Length (m)</td>
<td>5.0</td>
</tr>
<tr>
<td>Height (m)</td>
<td>3.63</td>
</tr>
<tr>
<td>Inner radius (m)</td>
<td>1.9</td>
</tr>
<tr>
<td>Outer radius (m)</td>
<td>6.9</td>
</tr>
<tr>
<td>Resonator width (m)</td>
<td>0.4</td>
</tr>
<tr>
<td>Q factor</td>
<td>&gt;40000</td>
</tr>
<tr>
<td>Power dissipation (kW)</td>
<td>500</td>
</tr>
</tbody>
</table>

Graph showing voltage (kV) vs. radius (m)
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RF power supply

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Layout of the Injector

M. Li et al., ICC2013, 2013

**Magnet**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole type</td>
<td>straight sector</td>
</tr>
<tr>
<td>pole number</td>
<td>4</td>
</tr>
<tr>
<td>hill field (T)</td>
<td>1.15</td>
</tr>
<tr>
<td>average field (T)</td>
<td>0.36-0.41</td>
</tr>
<tr>
<td>pole radius (mm)</td>
<td>4134</td>
</tr>
<tr>
<td>Azimuth width (°)</td>
<td>22-30</td>
</tr>
<tr>
<td>hill gap (mm)</td>
<td>40</td>
</tr>
<tr>
<td>yoke inner radius (mm)</td>
<td>4300</td>
</tr>
<tr>
<td>yoke outer radius (mm)</td>
<td>6100</td>
</tr>
</tbody>
</table>

**Cavity**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>cavity number</td>
<td>2</td>
</tr>
<tr>
<td>cavity type</td>
<td>double-gap</td>
</tr>
<tr>
<td>outer radius (mm)</td>
<td>3900</td>
</tr>
<tr>
<td>Dee angle (°)</td>
<td>22.5</td>
</tr>
<tr>
<td>peak voltage (kV)</td>
<td>500</td>
</tr>
</tbody>
</table>
Space charge effects study

Fruitful collaboration with PSI on 590MeV, 1.4MW Ring cyclotron simulation and OPAL code development since the year of 2007

- J. J. Yang, A. Adelmann PRST-AB, 2010
- A. Adelmann, et al., OPAL user guide, 2008
- Y. J. Bi, A. Adelmann PRST-AB, 2011
- M. Seidel, et al., IPAC2011

FIG. 11. (Color) Top view of 1 mA bunch distributions at the turn 130 in the local frame $S_{\text{local}}$ at the 112° azimuthal position of turn 130 in the PSI ring cyclotron. The results are obtained from single bunch (left), seven bunches (middle), and nine bunches (right) simulations, respectively.
Plan of Talk

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## Design of a 1mA/14MeV Cyclotron CYCIAE-14B for BNCT

<table>
<thead>
<tr>
<th>Extracted Beam</th>
<th>H⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/Intensity</td>
<td>14 MeV / 1 mA</td>
</tr>
<tr>
<td>Ion Source</td>
<td>H⁻ , 10 mA</td>
</tr>
<tr>
<td>Radius of magnet pole</td>
<td>53 cm</td>
</tr>
<tr>
<td>B-field</td>
<td>2.0 kGs – 18.5 kGs</td>
</tr>
<tr>
<td>RF frequency</td>
<td>73.02 MHz</td>
</tr>
<tr>
<td>$V_{Dee}$</td>
<td>40-50 kV</td>
</tr>
<tr>
<td>Harmonics #</td>
<td>4</td>
</tr>
</tbody>
</table>
Proton Therapy Cyclotron CYCIAE-230

100 MeV H- Cyclotron Development and 800MeV Proton Cyclotron Proposal
Summary

- The beam commissioning on the CYCIAE-100 is in progress. We got the first 100 MeV proton beam on July 4, 2014, and the first RIB on May 4, 2015, 1mA acceleration in June, 2016. The 100 MeV cyclotron will be able to provide 200 μA proton beam as designed, even 1mA from the recent results.

- It is confirmed that a 3-4 MW cw proton machine, CYCIAE-800, should be feasible based on the existing technologies. We are eagerly expecting extensive international collaborations.

- At CIAE, a 14MeV/1mA and a 230 MeV cyclotrons for medical applications and proton irradiation are under construction as well.
Acknowledgement

We would like to extend our cordial gratitude to experts from **TRIUMF**, **PSI**, **INFN-LNS** and the international cyclotron community for their long-term support on the projects.
Welcome to visit Cyclotron Lab at CIAE, tjzhang@ciae.ac.cn