China ADS Linac R&D Progress

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On behalf of China ADS Linac team

Institute of Modern Physics (IMP), Chinese Academy of Sciences
Outline

- Brief introduction of China ADS Linac and R&D program
- R&D progress of China ADS Linac
  - 10 MeV Injector I and Injector II
  - Proton source and LEBT
  - Injector I RFQ and Injector II RFQ
  - Injector I Spoke012 and Injector II HWR010
  - Main Linac Cavity prototypes
  - Cryomodules for Injector I and Injector II
  - SRF Infrastructure
- Summary
China ADS Motivation

- Accelerator Driven System was proposed for
  - Nuclear Waste Transmutation – rapid development of NPP in China. 10% in 2030
  - Accelerator Driven Thorium Reactor (ADTR)
  - Isotopes Production … (ex. ISOL RIA)
China ADS Roadmap

2011  2016  2023  203x

1st Phase  2nd Phase  3rd Phase  4th Phase
R&D        CIADS        RESEARCH FACILITY        DEMO FACILITY

25MeV@3-10 mA  250MeV@10mA  1.5 GeV@10 mA

CIADS: INITIAL FACILITY
Configuration of China-ADS Linac

2nd Phase

CIADS: CW proton 250 MeV@10 mA

3rd Phase

ECR LEBT RFQ MEBT1 HWR or Spoke

MEBT2 10MeV

Spoke021 325MHz 32 cavities
Spoke040 325MHz 80 cavities
Elliptical 063 650MHz 32 cavities
Elliptical 082 650MHz 85 cavities

HEBT Target

Main Linac 1.5 GeV@10 mA
Challenges of ADS Linac

- Beam loss: Causes of beam loss, beam loss detection and control
- Beam trip and failure
- Rapid recovery after beam trip or failure
- High power beam commissioning and machine protection
- Fault-tolerance design and reliability-orientated design
- Operation with high reliability and high availability
- .....
10MeV injector – Different technology R&D

Injector I

Based on 325 MHz Spoke012

<table>
<thead>
<tr>
<th>Energy</th>
<th>35 KeV</th>
<th>3.2 MeV</th>
<th>5 MeV</th>
<th>10 MeV</th>
</tr>
</thead>
</table>

Injector II

Based on 162.5 MHz HWR010

<table>
<thead>
<tr>
<th>Energy</th>
<th>35 KeV</th>
<th>2.1 MeV</th>
<th>5 MeV</th>
<th>10 MeV</th>
</tr>
</thead>
</table>

IHEP/Beijing

IMP/Lanzhou
10 MeV injector I strategy — (IHEP)

1. ECRIS + LEBT + RFQ + MEBT + TCM2, 3.6 MeV
   - RFQ commissioning, validate CM design.
   - Ongoing, beam commissioning in 2014

2. ECRIS + LEBT + RFQ + MEBT + CM7
   - 5 MeV
   - Beam commissioning in March 2015

3. ECRIS + LEBT + RFQ + MEBT + 2xCM7 + HEBT
   - 10 MeV
10 MeV injector II strategy — step by step (IMP)

1. ECRIS + LEBT + 560keV RFQ prototype
   - Validate LIS+LEBT+RFQ design. Learn experiences.
   - Completed, 2013

2. ECRIS + LEBT + RFQ + MEBT + TCM1, 2.5 MeV
   - RFQ commissioning, validate CM design.
   - Ongoing, beam commissioning in Sept. 2014

3. ECRIS+LEBT+RFQ+MEBT+CM6, 5 MeV
   - Beam commissioning in March 2015

4. ECRIS + LEBT + RFQ + MEBT + 2xCM6 +HEBT
   - 10 MeV
The 1st phase: R&D goal (2016-2017)

- Build 20-25 MeV@3 mA CW proton SC linac to learn technology of intense beam SC linac
- R&D for 250 MeV@10 mA CIADS linac
- Study the challenging issues based on construction and operation of the 25 MeV@3 mA linac

HWR010, Spoke021

Build 20-25 MeV@3 mA CW proton SC linac to learn technology of intense beam SC linac
R&D for 250 MeV@10 mA CIADS linac
Study the challenging issues based on construction and operation of the 25 MeV@3 mA linac

HWR010, Spoke021

162.5 MHz
325 MHz

20-25 MeV@3 mA
Proton source and LEBT

Two proton sources for Injector I and Injector II by IMP

35keV@11.4 mA, 12 hours

35keV@14 mA

\[ \varepsilon_{n,\text{rms}} = 0.15 \, \pi \, \text{mm.mrad} \]
560keV 162.5MHz RFQ prototype at IMP

- August-Nov. 2013
- ECR-LEBT-560keV RFQ
- Beam commissioning
- CW 10.5 mA, 558 keV
- Transmission >90%

Signals on 2 FCTs, E=558keV

Signals on 2 DCCTs, η=91.7%
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>Proton</td>
</tr>
<tr>
<td>frequency [MHz]</td>
<td>162.5</td>
</tr>
<tr>
<td>Inter-vane voltage $V$ (kV)</td>
<td>65</td>
</tr>
<tr>
<td>Average bore radius $r_0$ (cm)</td>
<td>0.5731</td>
</tr>
<tr>
<td>Vane tip curvature (cm)</td>
<td>0.4298</td>
</tr>
<tr>
<td>$\rho / r_0$</td>
<td>0.75</td>
</tr>
<tr>
<td>Vane length / Total length (cm)</td>
<td>419.2 / 420.8</td>
</tr>
<tr>
<td>$m_{\text{max}}$</td>
<td>2.38</td>
</tr>
<tr>
<td>Number of cells</td>
<td>192 (including 2 T cell)</td>
</tr>
<tr>
<td>Maximum surface field (MV/m)</td>
<td>15.7791</td>
</tr>
<tr>
<td>Synchronous phase ($^\circ$)</td>
<td>from -90 to -22.7</td>
</tr>
<tr>
<td>$a_{\text{min}}$ (cm)</td>
<td>0.3158</td>
</tr>
<tr>
<td>Transverse acceptance (RMS, x/y, $\mu$m.mrad)</td>
<td>0.3/0.3</td>
</tr>
<tr>
<td>Input norm. RMS emittance (x/y, $\mu$m.mrad)</td>
<td>0.3/0.3</td>
</tr>
<tr>
<td>Output norm. RMS emittance (x/y/z, $\mu$m.mrad, keV.ns)</td>
<td>0.31/0.31/0.92</td>
</tr>
<tr>
<td>Overall beam transmission @ 0 / 15 mA</td>
<td>99.7% / 99.6%</td>
</tr>
</tbody>
</table>

*Collaboration IMP-LBNL*
48 sensing loop ports, Regularly spaced

80 Tuners
Equal spaced
20 per module

32 Pi-mode Rods
Equal space, 8 per module

Consists of four modules, each module is 1050mm long

2 RF input ports
Both in Module 2
One near side, one far side

8 vacuum ports
Not all are used

Injector II RFQ 162.5MHz
Structure design

Injector II RFQ 162.5MHz  4 fabrication tests

- Vane cutting tool test
- Full length vane fabrication test
- Braze clamp test
- Test module
Injector II RFQ 162.5MHz

Test fabrication at IMP/Lanzhou

Modulation measurement (by CMM): Max. error: 0.0107mm

Profile measurement (by CMM): Max. error: 0.0056mm

Fabrication

CMM measurement

Max. fabrication error: 0.0272mm

Brazing test was done in a hydrogen oven

Vacuum test

Size (inner surface) of test piece: 250 × 290 × 1050
Leakage rate: < 1 × 10⁻⁸ Pa·L/S.
Maximum deformation before and after brazing is 0.037 mm

A half length module was fabricated, comparison between test and simulation results was made

<table>
<thead>
<tr>
<th>Frequencies with tuners inserting 0mm</th>
<th>Simulation results</th>
<th>Measured results</th>
</tr>
</thead>
<tbody>
<tr>
<td>f₁ / MHz</td>
<td>164.339</td>
<td>163.930</td>
</tr>
<tr>
<td>f₂ / MHz</td>
<td>189.040</td>
<td>188.223</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequencies with tuners inserting 20mm</th>
<th>Simulation results</th>
<th>Measured results</th>
</tr>
</thead>
<tbody>
<tr>
<td>f₁ / MHz</td>
<td>165.769</td>
<td>165.349</td>
</tr>
<tr>
<td>f₂ / MHz</td>
<td>190.252</td>
<td>189.386</td>
</tr>
</tbody>
</table>
**Injector II RFQ 162.5MHz**

**Fabrication, brazing at IMP**

1. **Step 1**: Machining from segment
2. **Step 2**: Drilling cooling channel
3. **Step 3**: Fine machining
4. **Step 4**: Dimension measurement
5. **Step 5**: Cleaning before brazing
6. **Step 6**: Vane assembling
7. **Step 7**: RF cold measurement
8. **Step 8**: Fine machining
9. **Step 9**: Brazing in oven
10. **Step 10**: Vacuum detection
11. **Step 11**: End cutting
12. **Step 12**: Cavity assembling
High power coupler

Power split
Coupler
Phase shifter

RF power source and control system

3.9%  1%

Before tuning
After tuning

Field Flatness

0 600 1200 1800 2400 3000 3600 4200
RFQ length /mm
Injector II RFQ 162.5MHz

Diagnostics

Energy: BPM1, BPM3, TOF
Energy spread: slit2, dipole, FC3
Emittance: slit1+wire scanner
Beam current: DCCT2, ACCT2
Transmission: ACCT1, ACCT2
Injector II RFQ 162.5MHz Commissioning

- April 2014: assembling completed
- May-June 2014: RF training
- June 12, 400ms/1Hz pulsed beam 8mA
- June 21 CW 2.2mA @ 2.5 hours
- June 30 CW 10mA @ 4.5 hours
**Injector II RFQ 162.5MHz**  
**CW 2-10 mA beam commissioning**

**June 21, total 47 hours, 2mA@5.5 hours**

**June 30**  
10mA@4.5 hours

**July 4**  
6mA@5 hours

**July 18**  
10mA@2 hours
Yellow: LEBT ACCT; Voltage: 5.419V
Beam Current: 10.84mA
Blue: RFQ exit ACCT; Voltage: 2.625V
Beam Current: 10.50mA

**June 29, 5ms/1Hz, 10.5 mA**
97% transmission efficiency

Flight time between BPM1 and BPM3: 77.989 ns
Beam energy: 2.165MeV
Center energy: 2.145 MeV;  
Energy spread: 0.038 MeV (FWHM)
Beam: 10mA, 1Hz, 500us    Energy spread: 1.9%
Injector I RFQ 325MHz

Developed by IHEP independently

ADS injector I RFQ commissioning setup

Beam envelope evolutions along the LEBT, the RFQ, the movable beam DUMP line
RF source: E37705 600 kW 325 MHz klystron and 80 kV PSM power supply

- May 2014, assembling completed;
- July 21, 99.6% duty factor, 250kW;
- July 22, CW, 200kW
Injector I RFQ 325MHz  Pulsed beam commissioning

LEBT ACCT: 11.1mA

RFQ exit DCCT: 10.8mA

Transmission: 97%  (Duty factor 20%)
# Optimized design and key parameters

## Geometry Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>22</td>
</tr>
<tr>
<td>W</td>
<td>82</td>
</tr>
<tr>
<td>D</td>
<td>90</td>
</tr>
<tr>
<td>Factor</td>
<td>1.25</td>
</tr>
<tr>
<td>R1in</td>
<td>47</td>
</tr>
<tr>
<td>R2in</td>
<td>199</td>
</tr>
<tr>
<td>R1out</td>
<td>35</td>
</tr>
<tr>
<td>R2out</td>
<td>164</td>
</tr>
<tr>
<td>Lcav</td>
<td>180</td>
</tr>
<tr>
<td>Liris</td>
<td>73</td>
</tr>
<tr>
<td>R</td>
<td>234</td>
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</table>

## Parameter Values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>325 MHz</td>
</tr>
<tr>
<td>$G$</td>
<td>61 $\Omega$</td>
</tr>
<tr>
<td>$\frac{R}{Q_0}$</td>
<td>142 $\Omega$</td>
</tr>
<tr>
<td>$\frac{E_{\text{peak}}}{E_{\text{acc}}}$</td>
<td>4.5</td>
</tr>
<tr>
<td>$\frac{B_{\text{peak}}}{E_{\text{acc}}}$</td>
<td>6.4 mT/(MV/m)</td>
</tr>
</tbody>
</table>

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Injector I Spoke012  Fabrication by HIT
Injecto1 I Spoke012

Vertical test

Tested in Dec. 2012

✓ $Q_0 = 5.8 \times 10^8$ @6MV/m, 4K;
✓ $Q_0 = 3.4 \times 10^8$ @7MV/m, 4K
✓ Max. Eacc. >14.6MV/m

No quench but heavy MP and FE.

Bulk BCP 150 um
Annealing 750 C, 3 hours
Light BCP 30um
Baking 100 C, 48 hours
Injecto I Spoke012

Integration of Spoke012-2#

- $Q_0 = 8.5 \times 10^8$ @ 5MV/m, 4.2K;
- $Q_0 = 2.2 \times 10^8$ @ 6.5MV/m, 4.2K

Aug. 2013

$Q_0$ before aging
$Q_0$ after aging
Radiation before aging
Radiation after aging
5.23, 2014, 4 sets of Spoke012 (#3-6) fabrication, frequency and vacuum tests completed.

Other 7 sets of Spoke012 (#7-13) being fabricated.
### HWR010 Squeezed Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freq (MHz)</td>
<td>162.5</td>
</tr>
<tr>
<td>( \beta_{\text{opt}} )</td>
<td>0.101</td>
</tr>
<tr>
<td>( U_{\text{acc}} ) (MV)</td>
<td>0.78</td>
</tr>
<tr>
<td>( E_{\text{acc}} ) (MV/m)</td>
<td>4.5</td>
</tr>
<tr>
<td>( E_{\text{peak}} ) (MV/m)</td>
<td>25</td>
</tr>
<tr>
<td>( B_{\text{peak}} ) (mT)</td>
<td>50</td>
</tr>
<tr>
<td>( G = R_s Q_0 ) (( \Omega ))</td>
<td>28.5</td>
</tr>
</tbody>
</table>

### Optimized Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_{\text{in}} ) (mm)</td>
<td>40</td>
</tr>
<tr>
<td>( R_{\text{out}} ) (mm)</td>
<td>92</td>
</tr>
<tr>
<td>( L_{\text{iris}} ) (mm)</td>
<td>110</td>
</tr>
<tr>
<td>( T ) (mm)</td>
<td>45</td>
</tr>
<tr>
<td>( W ) (mm)</td>
<td>90</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>100</td>
</tr>
<tr>
<td>( D_2 )</td>
<td>300</td>
</tr>
<tr>
<td>( R_{\text{blend}2} )</td>
<td>15</td>
</tr>
</tbody>
</table>

\[ \text{B}_{\text{pk}}/E_{\text{acc}} \quad \text{E}_{\text{pk}}/E_{\text{acc}} \]

\[ R/Q_0 \quad G \]
Material
- OTIC, RRR>300, partly RRR>380

Drawing, machining and BCP
- Punching die, Al 7075
- Surface survey before every step of fabrication
- BCP (65%HNO₃:40%HF:85%H₃PO₄=1:1:2) 10um, resin by UPW, drying in cleanroom of class 100
- Polishing every seam and BCP 10um before EBW

E-beam welding
- EBW by two different parameters:
  - #01, #02;
  - #03, #04, #05.
Cryoperm shielding, < 20 mGs, at room temp. 
<7mT at 4 K, Rmag=0.8 nΩ

Rs of the #5 cavity is around 10 nΩ.
Rs of the #3 after 850 C baking is around 2 nΩ.

\[ Q_0 = 8.1 \times 10^8 \text{ @ } E_{\text{peak}} 25 \text{MV/m} \]
**Injector II HWR010**

**Ribs to df/dp**

- **df/dp**: 70Hz/mbar → **Goal**: <5 Hz/mbar
  - **<5Hz**: Ribs on one
  - **<1Hz**: Ribs on both

---

With ribs, at LN \( \frac{df}{dp} = 10 \text{Hz/mbar} \)

Without ribs, at LHe \( \frac{df}{dp} = 42 \text{Hz/mbar} \)
8 HWR010 cavities completed
Max. $B_{\text{peak}} = 107 \text{ mT} \quad @ \quad Q_0 = 4.0 \times 10^8$
Main Linac Spoke040-325MHz Fabrication
Main Linac Ellip082-650MHz

Fabrication
High Power Input Couplers for Injector I &II

Spoke012 cavity couplers were tested over 10 kW CW power and operated in horizontal test.

RFQ coupler’s windows tested up to 100 kW CW power.

HWR010 couplers was tested over 20 kW CW, and operated in horizontal test.
TCM1 was tested under 4.4 K condition for 3 times in 2014 so as to test cryogenic system, HWR010 performance, CM dynamic load, frequency tuner, HP coupler, df/dp, LLRF control system and so on.
Cryomodule Injector II

CM6 under fabrication

CM6-HWR010-162.5 MHz
Cryomodule prototype **TCM1** ready for beam commissioning

- ECRIS + LEBT + RFQ + MEBT + TCM1, 2.5 MeV
- RFQ commissioning, validate CM design.
- Ongoing, beam commissioning in Sept. 2014

Almost ready for beam commissioning at IMP/Lanzhou
Cryomodule Injector I

TCM2 Spoke012 prototype

CM7-Spoke012-325MHz

CM7 under fabrication
SRF Infrastructure  

BCP system at IMP

SRF chemistry lab

BCP device for components

BCP device for whole cavity

BCP acids mixing system
SRF Infrastructure

Clean room assembling and HPR
Summary

- R&D of China ADS linac is to build a 25MeV@3 mA CW proton SC linac which will be utilized to explore key technologies and challenges for 250 MeV@10 mA CIADS linac.

- It is planned: 25MeV@3 mA CW beam commissioning in the year 2016-2017. 10 MeV injector I and injector II beam commissioning by the end of 2015.

- Significant progress has been made for the R&D of China ADS linac. 2.1 MeV@162.5 MHz RFQ at IMP reached 10 mA CW proton beam. 3.2 MeV@325 MHz RFQ at IHEP reached 10 mA pulsed beam.

- It is demonstrated that HWR010 and Spoke012 have reached the designed performance and are qualified for 10 MeV injector I and injector II. Mass-productions are underway.

- CM6-HWR010 and CM6-Spoke012 for 5 MeV are under fabrication and will be started assembling soon.

- All SRF infrastructures for 25MeV@3 mA CW linac have been completed and already in operation.

- It remains a lot challenges for us to reach 5-10 MeV@3 mA SC linac stable operation!
Acknowledgement

Team of China ADS Linac does appreciate for all those collaborations, exchanges, discussions and recommendations from the colleagues at the following labs:

LBNL, ANL, Jlab, MSU/FRIB, FNAL, ORNL, TRIUMF, CEA/Saclay, IPN/Orsay, IAP/Frankfurt Univ., KEK…..

HIT, PKU, SINAP…..

All those progress would be impossible without your help!
Thank you for your attention!

谢谢！
## Injector II HWR010

### Mechanical analysis

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Simulation result</th>
<th>Test result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bared cavity</td>
<td>With He vessel</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>235.5 Hz</td>
<td>--</td>
</tr>
<tr>
<td>Pressure sensitivity</td>
<td>25.1</td>
<td>14.2</td>
</tr>
<tr>
<td>Helium fluctuation (+/-1.5mbar)</td>
<td>37.6</td>
<td>21.3</td>
</tr>
<tr>
<td>LFD coefficient</td>
<td>-4.66</td>
<td>--</td>
</tr>
</tbody>
</table>

- **Bandwidth**: 235.5 Hz
- **Pressure sensitivity**: 25.1 Hz/mbar
- **Helium fluctuation (+/-1.5mbar)**: 37.6 Hz
- **LFD coefficient**: -4.66 Hz/(MV/m)

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**Simulation result**

![Simulation result image](image1.png)

**Test result**

![Test result image](image2.png)

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**He vessel**

![He vessel image](image3.png)
HWR CM6设计完成

- 包含6个超导腔、6个超导螺线管和5个冷BPM等。
- 每个超导腔含有一个调谐器和一个耦合器。
- 工作温度为4.4K，工作压力为1.25bar。
- 6腔cryomodule总长度为4.12米。
- 采用2个G10 post支撑，便于准直调节
- 预冷和运行采用两种冷却回路
- 超导腔和磁体为同一液氦回路，同时冷却

<table>
<thead>
<tr>
<th>部件</th>
<th>漏热/个</th>
<th>数量</th>
<th>小计</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM静态漏热</td>
<td>40 W</td>
<td>1</td>
<td>40 W</td>
</tr>
<tr>
<td>HWR动态漏热</td>
<td>10 W</td>
<td>6</td>
<td>60 W</td>
</tr>
<tr>
<td>耦合器气冷负载</td>
<td>0.024 g/s</td>
<td>6</td>
<td>0.144 g/s</td>
</tr>
<tr>
<td>超导磁体电流引线</td>
<td>0.05 g/s</td>
<td>6</td>
<td>0.3 g/s</td>
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<tr>
<td>50K冷屏--气氦冷却</td>
<td>60 W</td>
<td>1</td>
<td>60 W</td>
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<tr>
<td>单个CM漏热总计</td>
<td>1</td>
<td>100W(4K)</td>
<td>1</td>
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</tbody>
</table>

6腔cryomodule漏热计算表

冷却管路系统

真空室：CM内部包括束流真空与绝热真空系统

冷屏结构及热分析

冷冷质量支撑及调节系统

预冷和运行采用两种冷却回路

超导腔和磁体为同一液氦回路，同时冷却

HWR CM6设计完成