J-PARC H\(^-\) Ion Source and Space-Charge Neutralized LEBT for 100 mA High Energy and High Duty Factor LINACs

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Overview of the J-PARC Accelerators

400 MeV LINAC (25 Hz)
- Beam Pulse Width \( \leq 0.6\) ms
- Steady Operation \( I_H \leq 50\) mA
- Max \( I_H \) 0.6 ms & 60 mA on 8. July 2019
  *Ready for All Next 10 Year Plan

3 GeV RCS (25 Hz)
- Steady Operation
  - 0.54 MW for MLF
- Design Power Trial
  - 0.92 MW on 3. July 2019 for MLF

30 GeV MR (2.48 s Cycle)
- Steady Operation
  - 0.5 MW for Neutrino (FX)
  - 50 kW for Hadron (SX)
- Future Plans *linear increase
  - 2020~0.7 MW for Neutrino (1.32s Cy.)
  - 2028~1.3 MW for Neutrino (1.16s Cy.RF)
10.5 h Design Power Trial for MLF (0.92MW) on 3. July. 2019
Original Measures Devised for J-PARC H⁻ Ion Source

Cross-sectional view of J-PARC RF-Driven H⁻ Ion Source Test-Stand

High Brightness & RF power efficiency by (1) Thick PE(16mm-45°→1.5I⁻), (2) 50W-CW-30MHzRF igniter(17SCCMforϕPE=9mm→1.14I⁻), (3) TPE~70°C(0.84εnrmsx/y), (4) Slight H₂Os Feeding in Hydrogen Plasma(0.5εnrmsx/y & 0.67Divergence Angle).

<table>
<thead>
<tr>
<th>Source &amp; test-stand parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>CW 30 MHz RF pow.</td>
<td>50 W</td>
</tr>
<tr>
<td>2 MHz RF duty fact.</td>
<td>5%(1ms × 50 Hz)</td>
</tr>
<tr>
<td>2 MHz RF power</td>
<td>43.5~47 kW</td>
</tr>
<tr>
<td>Plasma elec. temperature (TPE)</td>
<td>70 °C</td>
</tr>
<tr>
<td>Terminal voltage Vₜ=Vₑ+Vₐ</td>
<td>62kV=12+50kV</td>
</tr>
<tr>
<td>Beam duty factor(BDF)</td>
<td>5 %,(1ms × 50Hz)</td>
</tr>
<tr>
<td>Test-stand 1st sec. vac. pump &amp; vac.press.(PᵥTS)</td>
<td>TMP1500 L/s &amp; 1.5 × 10⁻² Pa</td>
</tr>
<tr>
<td>Test-stand 2nd sec. vac. pump</td>
<td>TMP500 L/s</td>
</tr>
<tr>
<td>Solenoid magnet (SM) cur.</td>
<td>300 A (42000 AT)</td>
</tr>
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Test-stand 100mA Ope.
Macro Pulse Chopping with $W_H$- Mod. & RFQ Long. Acce.

(a) Terminal Voltage $V_T$

- $-30kV(V_{ADC}) \rightarrow -40kV(V_{ADC}+V_{EM})$
- $\rightarrow -52.5kV(V_{ADC}+V_{EM}+V_{AM}) \rightarrow -30kV(V_{ADC})$

(b) Plasma Production Forward & Reflected 2MHz RF

Voltages $V_{2MHzF}$ & $V_{2MHzR}$ and RFQ Tank Level $TL_{RFQ}$

(C) $I_{H-}@LEBT$, $I_{H-}@RFQ$ Exit, $I_{H-}@LINAC$ Exit

*Intermediate Chopper Period (812.5ns) Averaged $IH$- are plotted with white lines.

*Space Char. Neu. Satura. by 40 keV 0.1 ms $H^-$ beam

Succession to 52.5 keV $H^-$ beam

$\rightarrow I_{H-} & I_{H-} & I_{H-}$ Rapid Rise Time responding to $V_{AM}$

*High RFQ Transmission of 94.3% (67.9/72)

*0.07mA 40keV $H^-$ beam was detected with RFQ exit CT at downstream surface of QM1 with design $TL_{RFQ}$

$\rightarrow >> 0.07mA$ 40keV $H^-$ beam transmits through RFQ

*Low MEBT1 Transmission of 88.34% (60/67.9) due to space charge limited current of MEBT1
J-PARC LINAC 60 mA 1.5%(0.6ms × 25Hz) BDF Operation

Source & LEBT parameter

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<th>Parameter</th>
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<tbody>
<tr>
<td>CW 30 MHz RF power</td>
<td>50 W</td>
</tr>
<tr>
<td>2 MHz RF duty factor</td>
<td>1.75% (0.7 ms × 25 Hz)</td>
</tr>
<tr>
<td>2 MHz RF power</td>
<td>28kW</td>
</tr>
<tr>
<td>Plasma elec. temperature (TPE)</td>
<td>70℃</td>
</tr>
<tr>
<td>Terminal voltage (VT)</td>
<td>52.5 kV = (0or10+30+0or12.5) kV</td>
</tr>
<tr>
<td>Beam duty factor (BDF) by VAM</td>
<td>1.5% (0.6 ms × 25 Hz)</td>
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</tbody>
</table>

| Source & LEBT & LINAC Parameters for Presently Highest I_H- (60 mA) & BDF 1.5% (0.6ms × 25Hz) |

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>LEBT 1st sec. vac. pumps &amp; vac. press. (PV1)</td>
<td>TMP1500 × 2 L/s &amp; 5.8 × 10⁻³ Pa</td>
</tr>
<tr>
<td>LEBT 2nd sec. vac. Pumps &amp; vac. press. (PV2)</td>
<td>TMP1500+500 × 2 L/s &amp; 3.6 × 10⁻⁴ Pa</td>
</tr>
<tr>
<td>LEBT 3rd sec. vac. Pumps &amp; vac. press. (PV3)</td>
<td>CryoP3600 L/s &amp; 2.8 × 10⁻⁵ Pa</td>
</tr>
<tr>
<td>1st solenoid magnet (SM1) cur.</td>
<td>500 A (45000 AT)</td>
</tr>
<tr>
<td>2nd solenoid magnet (SM2) cur.</td>
<td>660 A (59400 AT)</td>
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<table>
<thead>
<tr>
<th>LINAC parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>RFQ vac. press. (PVR)</td>
<td>1.3 × 10⁻³ Pa</td>
</tr>
<tr>
<td>RFQ RF duty factor</td>
<td>1.8% (0.68 ms × 25 Hz)</td>
</tr>
<tr>
<td>Intermediate pulse / period</td>
<td>440 ns / 812.5 ns</td>
</tr>
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Effective $I_{H-}$ & $\eta$ (ratio of eff. $I_{H-}$ to $I_{H-}$) Estimation

$\rightarrow$ Constant Effective $I_{H-}$ & $\eta$ depends only on $P_{V1}$ or $P_{VTS}$

- Backward Traces with TRACE2D
  (L) from RFQ Entrance & Acceptance to GE Downstream Surface in J-PARC LEBT: $W_{H^-}$=52.5 keV
  $\rightarrow$ Effective $I_{H^-}$=25.1 mA ($\eta=34.9\%$ of 72 mA for $P_{V1}=5.8 \times 10^{-3}$ Pa) & Reversed Forward Trace: $W_{H^-}$=40 keV
  (R) from Emittance Monitors & Measured Emittances to GE Down. Surface in test-stand: $W_{H^-}$=56 or 50 keV
  $\rightarrow$ Effective $I_{H^-}$=22.6 mA ($\eta=28.3\%$ of 80 mA) or 19.3 mA ($\eta=29.2\%$ of 66 mA) * $\eta \sim 29\%$ for $P_{VTS}=1.5 \times 10^{-2}$ Pa
Emittance Improvements with Shortest Beam Extractor

Schematic of shortest beam extractor
1.9mm shorter than old one

Relationships between $V_E$ and $\varepsilon_{95\%nrmsx/y}$ measured with shortest beam extractor for conditions of $(WH-, IH-) = (50\,\text{keV}, 66\,\text{mA}), (56\,\text{keV}, 80\,\text{mA}), (62\,\text{keV}, 80\,\text{mA})$ and $(62\,\text{keV}, 100\,\text{mA})$.

Smallest $\varepsilon_{95\%nrmsx/y}$ measured with old beam extractor ($G_E=3.1\,\text{mm}$) are shown by black symbols.
Emittance Improvements with Shortest Beam Extracotor

100% beam H⁻ ion distribution (red dots), fitted normalized 1.5 \(\pi\) mm·mrad ellipses fitting 95% beam (blue line) and ellipse backward traced to GE downstream surface with TRACE2D (T2D) (red line) in horizontal (a) or vertical (c) phase-plane.

Relationships between \(\varepsilon_{nx/ny}\) and included beam fraction \(f_{bx/by}\) in 100% beam with ellipse fitting 95% beam (blue line), \(\varepsilon_{nx/ny}\) and included \(f_{bx/by}\) in common PARMTEQ (PQ) injection beam with \(\varepsilon_{nxrms/nyrms}\) of 0.25 \(\pi\) mm·mrad (red line) and \(\varepsilon_{nx/ny}\) and included \(f_{bx/by} \times 0.944/0.928\) in PQ beam (green line) in horizontal (c) or vertical (d) phase-plane for \(W_H\), \(I_H\) and \(V_E\) of 62 keV, 100 mA and 12 kV, respectively.
Rapid Beam Fluctuation Measurement in Pulse

Waveforms of $I_{\text{H}^-}$ measured by Faraday-cup with 50 $\Omega$ terminator and forward and reflected plasma production 2 MHz RF voltages ($V_{2\text{MHz}F}$ and $V_{2\text{MHz}R}$) in test-stand operation. (a) 1 ms pulses and (b) enlarged 0.007 ms pulse ends with falling time waveforms for persons being worried about rapid beam fluctuation in pulse.

Measured standard deviation including environmental noises, maximum and minimum values are 1 mA, 104.5 mA and 95.1 mA, which are almost same with J-PARC H$^-$ source driven with tungsten filament due to $V_{\text{PF}}$ fluctuation induced by plasma oscillation.

* Rapid beam fluctuation has no observable influence in LINAC & RCS acceleration.

* $\pm 0.1$ mA fluctuation of averaged beam feedbacked with $P_{2\text{MHz}}$ and $\pm 0.1$ mA tilt in pulse satisfy J-PARC requirements.
Conclusions

• Remarkable & Useful Space-Charge Neutralization of Constant Effective $I_{H^-} \& \eta$ (Effective $I_{H^-}/I_{H^-}$) Depends Only On Initial Worst $P_v$ ($P_{v1}$ or $P_{vTS}$) was Proven. Positive Ions Flows to Downstream with Better Vacuum Pressure Causes These Phenomena.

• Macro Pulse Chopping with $W_{H^-}$ Modulation & RFQ Longitudinal Acceptance Succeeded by 40 keV $H^-$ Ion Beam Space Charge Neutralization with <0.1 ms Rise Time and its Succession to 52.5 keV $H^-$ Ion Beam.

• Space-Charge Neutralization with Positive Ions Trapped in RFQ RF Field was also Observed by High Transmission of 94.3 % (67.9 mA of 72 mA) of J-PARC RFQ Designed for 50 mA Acceleration and No Unchopped Beam in Macro Pulse Chopping Disagreeing with J-PARC 30 mA RFQ Simulation. *It should Cause Low Transmission and Some Unchopped Beam in Macro Pulse Chopping, it Proton Beam was Accelerated.

• Significant Beam Loss from 67.9 mA to 60 mA Occurs in MEBT1 and Initial Part of Drift Tube LINAC 1 (DTL1) probably due to Emittance Blowup Caused by Space-Charge Limited Current. RFQ with Injection Energy Higher than 64 keV and Acceleration Energy Higher than about 4 MeV will be Necessary for 100 mA High Energy LINAC.

• All Transverse Emittances of $H^-$ Ion Beams with $(W_{H^-}, I_{H^-})$ of (50 keV, 66 mA), (56 keV, 80 mA) and (62 keV, 100 mA) in Test-Stand were Improved by about 8 % by Shortest Beam Extractor with Length 1.9 mm Shorter than Previous One. Emittance Growths in EE were Suppressed by 1.9 mm Shorter Length and Faster Acceleration.

Acknoledge : I appreciate excellent SNS internal antenna.
No challenge in J-PARC $\rightarrow$ I want to contribute other labo's challenging $H^-$ source.
H$_2$Os Feeder in H$_2$ Line

15µm-filter

H$_2$O~2cc reservoir for 1 year

stop valve 1

purge valve

stop valve 2

double needle valves both closed position

H$_2$ Line