The Very High Intensity Future

Jie Wei

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Outline

- Introduction
- Key technologies
- Accelerator physics challenges
- Future perspectives
- Acknowledgements
Accelerator Beam-power Frontier

- High energy, nuclear physics ($\nu$, K factories)
  - $1 \sim 400$ GeV proton
  - Linac + Synchrotron

- Material, life science, (SNS) accelerator-driven subcritical systems (ADS)
  - $0.5 \sim 3$ GeV proton
  - Cyclotron, linac, rapid cycling synchrotron, accumulator

- Rare isotope beams (RIB)
  - $0.01 \sim 1$ GeV/u heavy ion
  - Linac, cyclotron, synchrotron

- Material irradiation; isotope
  - $\sim 0.02$ GeV/u deuteron; linac
Historical Records of Beam Power

- **Proton CW**
  - LANSCE: ~ MW since 1980
  - PSI: ~ MW since 1995

- **Proton pulsed**
  - ISIS: ~ 0.1 MW since 1985
  - AGS ~ 0.1 MW since 1994

- **Heavy ions**
  - RIKEN, ATLAS, NSCL up to 7 kW

- ~100 MW R&D
  - LEDA 0.7 MW 2000
SNS: 1.4 MW Pulsed Proton on Target
Planned Linac Energy Increase to 1.3 GeV for ~ 2.8 MW
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Planned Linac Energy Increase to 1.3 GeV for ~ 2.8 MW
J-PARC: Marching Towards 1 MW Goal
Recovered from Earthquake; Commissioned 400 MeV Linac
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Recovered from Earthquake; Commissioned 400 MeV Linac
Developed as a National User Facility for Basic & Applied Research by Proton Engineering Frontier Project (2002-2012)
- Structure: 50 keV Injector, 3 MeV RFQ, 20 MeV DTL-I, MEBT, 100 MeV DTL-II
- RF Frequency: 350 MHz, Beam extractions: 20 MeV or 100 MeV

Commissioned & Started beam service in July 2013 with 2 beamlines
- Utilized in Bio-life, Materials, Energy-environment, Space, Nano, Isotopes, Basic Science, & Industrial applications

### Key Parameters

<table>
<thead>
<tr>
<th></th>
<th>20 MeV</th>
<th>100 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output energy (MeV)</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Peak beam current (mA)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Beam duty (%)</td>
<td>24</td>
<td>8</td>
</tr>
<tr>
<td>Avg. beam current (mA)</td>
<td>4.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Pulse length (ms)</td>
<td>2</td>
<td>1.33</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>Avg. beam power (kW)</td>
<td>96</td>
<td>160</td>
</tr>
</tbody>
</table>
Accelerator Operation in 2013

- Operation: 2,290 hours
- Beam on: 432.7 hours
- Availability: 82%
- Operation Conditions:
  - Energy: 20 & 100 MeV
  - Beam power: 1 kW

User Service in 2013 by 2 Beamlines (TR23 & TR103): from July 22 – December 20, 2013

Beam Service Statistics

Institution

937 Services

R&D Fields

937 Services
RIKEN: CW Beam from d to U
Cyclotron-based Facility with Cutting Edge Developments

Mode 1 (Light: d, He, O, ..)
Mode 2 (Medium: Ca, Kr, Zn, ..)
Mode 3 (Heavy: Xe, U)

Courtesy: RIKEN / O. Kamigaito
RIKEN: CW Beam from d to U
Cyclotron-based Facility with Cutting Edge Developments

RILAC2 (2011~)

Mode 2 (Medium: Ca, Kr, Zn, ..)
Mode 1 (Light: d, He, O, ..)
Mode 3 (Heavy: Xe, U)

RIKEN: CW Beam from d to U
Cyclotron-based Facility with Cutting Edge Developments

Courtesy: RIKEN / O. Kamigaito
Accelerator Baseline Configuration

**Particles**

<table>
<thead>
<tr>
<th>Particles</th>
<th>H⁺</th>
<th>(^3\text{He}^2⁺</th>
<th>D⁺</th>
<th>Ions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q/A</td>
<td>1</td>
<td>2/3</td>
<td>1/2</td>
<td>1/3</td>
</tr>
<tr>
<td>I (mA) max.</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>(W_o) max. (MeV/A)</td>
<td>33</td>
<td>24</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>CW max. beam power (KW)</td>
<td>165</td>
<td>180</td>
<td>200</td>
<td>44</td>
</tr>
</tbody>
</table>

Total length: 65 m (without HEBT)

- Slow (LEBT) and Fast Chopper (MEBT)
- RFQ (1/1, 1/2, 1/3) & 3 re-bunchers
- 12 QWR beta 0.07 (12 cryomodules)
- 14 QWR beta 0.12 (7 cryomodules)
- 1.1 kW Helium Liquifier (4.5 K)
- Room Temperature Quadrupoles
- Solid State RF amplifiers (up to 20 KW)

6.5 MV/m max \(E_{acc} = \frac{V_{acc}}{(\beta \lambda)}\) with \(V_{acc} = \int E(z)e^{\omega z/c} dz\).
Accelerator Baseline Configuration

Heavy ion source (A/q=6) and RFQ - optional upgrade

Leaves source (A/q=3)

1mA

ECRIS

d^+, H^+, He

1mA

5mA

RFQ (88MHz)

MEBT line

QWR 88MHz

(\(\beta = 0.07\))

QWR 88MHz

(\(\beta = 0.12\))

SC Linac

0.75 MeV/n

0.75 MeV/n

d^+ : 20 MeV/n
HI : 14.5 MeV/n

Neutron For Science

20 MeV/n

14.5 MeV/n

RIBs production

SPIRAL2

driver accelerator

6.5 MV/m max

\(E_{acc} = \frac{V_{acc}}{(\beta_{opt} \lambda)}\)

with

\(V_{acc} = \int E_z(z) e^{i\omega z}/c dz\)

Total length: 65 m (without HEBT)

Slow (LEBT) and Fast Chopper (MEBT)

RFQ (1/1, 1/2, 1/3) & 3 re-boosters

12 QWR beta 0.07 (12 cryomodules)

14 QWR beta 0.12 (7 cryomodules)

1.1 kW Helium Liquifier

(4.5 K)

Room Temperature Quadrupoles

Solid State RF amplifiers (up to 20 KW)

165

180

200

44

48

1.1 kW

165

180

200

44

48

1.1 kW
FRIB: Goal 400 kW CW p to U
Ground Broken in March 2014
FRIB: Goal 400 kW CW p to U
Ground Broken in March 2014
FRIB: Goal 400 kW CW p to U
Ground Broken in March 2014
CADS: Goal 15 – 30 MW CW Proton

Injector II
ECR 162.5MHz
RFQ 162.5MHz

dc B

SC-HWR
SC-CH

162.5MHz

MEBT2 10MeV

Spoke021, 37.1m
42Cavity/7CM
Spoke040, 58.2m
64Cavity/8CM
Elliptical 063, 16m
34Cavity/8CM

Main Linac

Spoke021
325MHz
28 cavities
Spoke040
325MHz
72 cavities
Elliptical 063
650MHz
28 cavities
Elliptical 082
650 MHz
85 cavities

MEBT1

1.5 GeV @ 10 - 20 mA proton beam

HEBT
Target

Inj. 10 MeV
35 keV
2.1 MeV

MEBT2 10 MeV
35 keV
3.2 MeV

MEBT1

RFQ 325.0MHz

Spoke 325MHz

34 MeV
178 MeV
367 MeV
1500 MeV

ECR 162.5MHz
RFQ 162.5MHz

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

J. Wei, IPAC’14, MOYBA01, Slide 18
Key Technology Examples

- Superconducting RF
- Integrated Cryogenics
- Loss Detection and Machine Protection
- Collimation
- Ion Source
- RFQ
- Charge Stripping
- Target
- Radiation-resistant Magnets, Handling
- Rapid Cycling Synchrotron Technology
- Accumulator Technology
- Site Specific Complications
Superconducting RF
SNS: the First Hadron Linac Extensively Using SRF (JLab)
Superconducting RF
SNS: Actual Accelerating Gradient Largely as Designed

![Graph showing Eacc (MV/m) vs. Cavity number for Medium and High beta regions. The design gradient and average operating gradient are indicated. CM19 and CM12 are marked under repair.]

Courtesy: SNS / S. Kim
Superconducting RF
FRIB: CW Linac Extending SRF to Low Energy (500 keV/u)

- Resonators (2 K) and magnets (at 4.5 K) supported from the bottom to facilitate alignment
- Cryogenic headers suspended from the top for vibration isolation
Superconducting RF
FRIB Subsystems: Resonators, Couplers, Tuner, Mechanical Damper, Solenoids, BPMs, Shieldings

Quantities do not include 4 spare cryomodules and 17 spare cavities.

QWR Coupler
HWR Coupler
HWR Tuner
QWR & HWR Cavities
Cold BPM

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

J. Wei, IPAC’14, MOYBA01, Slide 23
Cost significant: cryogenics systems accounts for ~ 20% linac cost.

An integrated design of the cryogenic refrigeration, distribution, and cryomodule systems is key to efficient SRF operations.

- Ganni cycle: floating pressure process
- Distribution lines segmented
- Cryomodules connected with U-tubes: maintenance
- 4-2 K heat exchangers housed inside cryomodules
Low-energy ions has low detection sensitivity & high impact
Must mitigate both acute & chronic beam loss (by beam inhibition)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
<th>Detection</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPS</td>
<td>~ 35  μs</td>
<td>LLRF controller; Dipole current monitor; Differential BCM; Ion chamber monitor; Halo monitor ring; Fast neutron detector; Differential BPM</td>
<td>LEBT bend electrostatic deflector</td>
</tr>
<tr>
<td>RPS</td>
<td>~ 100 ms</td>
<td>Vacuum status; Cryomodule status; Non-dipole PS; Quench signal</td>
<td>As above; ECR source HV</td>
</tr>
<tr>
<td></td>
<td>&gt; 1 s</td>
<td>Thermo-sensor; Cryo. heater power</td>
<td>As above</td>
</tr>
</tbody>
</table>
Beam Collimation
Halo & Beam Loss Control; Charge Selection

- Ring: 3D phase space collimation; multi-stage in transverse direction
  - SNS: dedicated collimation straight section
- Linac & transport: often combines with charge stripping
  - Heavy ion linac: charge selector
Ion Source
Sources for High Intensity/Duty Ions and for Pulsed H⁻

- ECR source for high intensity (CW), high charge state beams
- Higher RF frequency and magnetic field (~28 GHz; RF power ~15 kW)
- SC sextupole & solenoid state-of-the-art SC technology

Cesium-seeded, volume production sources are most promising for high current, long pulse, low emittance H⁻ beams

LBNL VENUS ECR ion source test result

Courtesy: LBNL

Courtesy: ORNL / LBNL / SNS
RFQ
Extending LEDA Technology to Heavy Ions

- LEDA RFQ holds the power record accelerating 100 mA CW proton beam to 6.7 MeV (4-vane, variable voltage profile)
- Challenging mechanical / cooling design and fabrication process
- RFQ with trapezoidal vane modulation built/tested at ANL
- RFQs developed worldwide
- Heavy ion RFQ: low frequency, large dimension
Charge Stripping: Heavy Ion
He Gas stripper for U @ 11 MeV/u; Plasma Window Test

Large beam aperture: > φ 10 mm
8 order pressure reduction: 7,000 Pa => 10^{-5} Pa
5 stage differential pumping: 21 pumps
He circulating volume: 300 m³/day

Plasma window successfully tested at BNL
To ease the challenge of differential pumping
Liquid lithium film established with controllable thickness and uniformity
- Liquid lithium film moving at ~50 m/s speed to remove deposited heat
- Controlling uniformity to ~10% within beam spot area

Beam power tests on liquid lithium film successfully performed at ANL
- The film sustained ~200% of FRIB maximum power density deposition

Charge Stripping: Heavy Ion
Liquid Lithium Film Tested with LEDA Source at ANL

Liquid lithium film flowing at high speed (~50 m/s) intercepting a proton beam of about 60 kV at ANL. The test produced power deposition densities similar to the FRIB uranium beams.
Target
Stationary, Rotating and Liquid Targets

- Target is often the bottleneck to high power applications
  - Neutron production targets: absorbs most beam power to an enlarged area
  - RIB target (FRIB): ~25% power onto 1 mm
  - High energy targets: < 5% power absorbed
- Non-stationary targets more often used
  - Liquid:
    - SNS, J-PARC: Hg
    - SARAF, IFMIF: Li
    - MYRRHA: PbBe
  - Rotating
    - FRIB ...

FRIB rotating multi-slice graphite target
30 cm diameter, 5000 rpm
60 MW/cm³ if stationary
Radiation-resistant Magnets, Handling

- High radiation area near the target, collimator, beam dump require special attention

SNS RTBT mineral insulated radiation hardened magnets
Courtesy SNS / BNL

Remote vacuum clamps
Courtesy SNS / BNL

Remote water fitting
Courtesy SNS / BNL

High Temperature Superconducting warm iron quadruple for use behind FRiB production target.
Courtesy FRiB / BNL
Rapid Cycling Synchrotron Technology
J-PARC Advanced RCS Technology Pioneered by ISIS/AGS

- Large beam chamber aperture
- Accurate magnet tracking
- Limit the uncontrolled beam loss below 1%

J-PARC RCS dipole and vacuum chamber
Courtesy J-PARC

Wideband RF cavity with water-cooled magnetic alloy

Ceramic vacuum chamber with RF shielding & TiN coating

brazed aluminum coil

Proton Synchrotron RF System

FRIB
Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University
Accumulator Technology
SNS Advanced Accumulator Technology Pioneered by PSR

- Large beam chamber aperture
- Electron cloud mitigation
- Impedance reduction (kickers)
- Nonlinear magnetic corrections

SNS accumulator arc half cell under installation
Courtesy ORNL / SNS / BNL

Ring arc half cells installed in tunnel
Folder linac with 2\textsuperscript{nd} order achromat bends for wide momentum acceptance

Beam loss at high energy interferes with loss detection of low-energy beams

Hazard analysis upon beam faults complicated; installation and commissioning interlaced

Vibration mitigation: linac service/utility area and cryogenics area are near the accelerator tunnel housing cryomodules
Design Challenge Examples

- Beam Loss Control
- Space Charge
- Coupling Impedance
- Instabilities
- Multiple Charge State Acceleration
- Electron Cloud
Hands-on maintenance:
- Proton: uncontrolled beam losses kept below ~ 1 W/m (activation ~ 1 mSv/h; 30 cm from surface; 4 h after machine shut down)
- Heavy ion: ~ 1 W/m (less stringent in activation but more demanding in machine protection; similar cryogenic heat load considerations)

Personnel protection: commissioning, operation & fault conditions

<table>
<thead>
<tr>
<th>Type and location</th>
<th>Energy [MeV/u]</th>
<th>Peak power</th>
<th>Duty factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncontrolled loss</td>
<td>0 – 200</td>
<td>~1 W/m</td>
<td>100%</td>
</tr>
<tr>
<td>Controlled loss:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge selector</td>
<td>12 – 20</td>
<td>42 kW</td>
<td>100%</td>
</tr>
<tr>
<td>Charge stripper</td>
<td>12 – 20</td>
<td>~1 kW</td>
<td>100%</td>
</tr>
<tr>
<td>Collimators</td>
<td>0 – 200</td>
<td>~1 kW</td>
<td>100%</td>
</tr>
<tr>
<td>Dump FS1-a</td>
<td>12 – 20</td>
<td>42 kW</td>
<td>0.03%</td>
</tr>
<tr>
<td>Dump FS1-b</td>
<td>12 – 20</td>
<td>12 kW</td>
<td>5%</td>
</tr>
<tr>
<td>Dump FS2</td>
<td>15 – 160</td>
<td>300 kW</td>
<td>0.03%</td>
</tr>
<tr>
<td>Dump BDS</td>
<td>150 – 300</td>
<td>400 kW</td>
<td>0.03%</td>
</tr>
</tbody>
</table>
Space Charge
Performance Limiting for Low-energy Linac and Rings

- Linac: halo generated through core-halo parametric resonance; resonances between transverse longitudinal motion
- Ring: resonances & halo excited by lattice nonlinearity in the presence of space charge induced tune spread

Tune footprint along the four IFMIF cryomodules superimposed to the Hofmann chart

Vertical emittance growth due to space charge in SNS ring. Courtesy A. Fedotov et al
Coupling Impedances Control
Instability Control with Design Mitigation & Feedback

SNS ring injection kicker with double coating
Courtesy: SNS / BNL

SNS ring extraction kicker optimization
Courtesy: D. Davino et al

SNS ring extraction kicker pulse forming network
Courtesy: SNS / BNL

J-PARC MR transverse bunch-by-bunch feedback in a narrowband mode
Courtesy: O. Konstantinova et al

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**TABLE V.** Estimated beam coupling impedance of the SNS accumulator ring at frequency below 10 MHz. The beam revolution frequency is 1.058 MHz. The leading impedance source contributing to possible instability is the extraction kicker modules located inside the beam vacuum pipe (Sec. IV.C.2).

<table>
<thead>
<tr>
<th>Device/Mechanism</th>
<th>$Z_\parallel/n$ (Ω)</th>
<th>$Z_\perp$ (kΩ/m)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space charge</td>
<td>$-j196$</td>
<td>$j(-5.8+0.45)\times10^3$</td>
<td>incoherent and coherent part</td>
</tr>
<tr>
<td>Extraction kicker</td>
<td>$0.6n+j50$</td>
<td>$33+j125$</td>
<td>25 Ω termination at PFN</td>
</tr>
<tr>
<td>Injection kicker &amp; pipe</td>
<td>$0.5/n$</td>
<td>$17.5$</td>
<td>pipe coated; lowest tune at 200 Hz</td>
</tr>
<tr>
<td>Injection foil assembly</td>
<td>$j0.05$</td>
<td>$j4.5$</td>
<td>MAFIA modeling</td>
</tr>
<tr>
<td>rf cavity</td>
<td>$0.9$ (resonance peak)</td>
<td>$18$</td>
<td>to be damped</td>
</tr>
<tr>
<td>Resistive wall</td>
<td>$(j+1)0.71$ at $\omega_0$</td>
<td>$(j+1)8.5$ at $\omega_0$</td>
<td></td>
</tr>
<tr>
<td>Broadband beam position monitor</td>
<td>$j4$</td>
<td>$j18$</td>
<td>unscreened</td>
</tr>
<tr>
<td>Broadband bellows</td>
<td>$j1.1$</td>
<td>$j7$</td>
<td>tapered 1-to-3 ratio</td>
</tr>
<tr>
<td>Broadband steps</td>
<td>$j1.9$</td>
<td>$j16$</td>
<td>screened</td>
</tr>
<tr>
<td>Broadband ports</td>
<td>$j0.49$</td>
<td>$j4.4$</td>
<td>unscreened</td>
</tr>
<tr>
<td>Broadband valves</td>
<td>$j0.15$</td>
<td>$j1.4$</td>
<td></td>
</tr>
<tr>
<td>Broadband collimator</td>
<td>$j0.22$</td>
<td>$j2.0$</td>
<td></td>
</tr>
</tbody>
</table>
Electron Cloud
Performance Limiting for PSR But Not Yet for the SNS Ring

Preventive measures are effective in the SNS ring suppressing electron generation and enhancing Landau damping.

BPM $\Delta V$ signal

CM42 (4.2 $\mu$C) (Circulating Beam Current)

Instability observed at the Proton Storage Ring
Courtesy: LANL / R. Macek

SNS ring extraction kicker with patterned TiN coating
Courtesy: SNS / BNL
Multiple Charge State Acceleration
Demanded for Heavy Ions to Achieve High Power on Target

- Simultaneous acceleration of multiple charge state needed due to the broad charge spectrum upon stripping
- Challenges in optics design, diagnostics, fault recovery

Five charge states of the uranium beam designed to overlap at the FRIB target.
Future Perspective

- Accelerator projects at the high-intensity frontier are flourishing worldwide with demands from science to applications.

- Efforts worldwide are readying the technologies and designs meeting the requirements of user facilities with high reliability, availability, maintainability, tunability, and upgradability.

- Heavy ion machines are join the crowd towards MW power level.

- For protons applications, we speculate to reach multi MW beam power using cyclotrons, synchrotrons or accumulators, and up to 100 MW with SRF linacs.
Growth of Accelerator Beam Power

- **Proton CW**
  - ADS (APT) linac-based: aiming at 10 ~ 100 MW proton based on LANSCE, LEDA
  - ADS cyclotron-based: aiming at ~ 2.4 MW based on PSI experience

- **Proton pulsed**
  - SNS, J-PARC/RCS advanced PSR, ISIS, AGS power records x10 to MW level

- **Heavy ions**
  - FRIB, SPIRAL2… linac-based aiming at ~ 400 kW to advance existing records by ~ 2 orders-of-magnitude
Other operating or proposed projects include LEDA, PSR, HIAF, RAON, CPHS and those proposed at CERN (SPL, LAGUNA-LBNO, SHIP) and RAL
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