Experience with Recently Commissioned High-Power Proton Accelerators and Prospects for the Future

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• Israel Mardor (SARAF, Israel)
Applications of High-Power Proton Accelerators

**Particle Physics**
- Existing: FNAL NuMI (US), CNGS (CERN), J-PARC (Japan)
- Under Construction or Upgrade: FNAL MI/RR (US)
- Proposed: Project-X (US), SPL (CERN), MC/NF (US/Eur.)

**Nuclear Physics**
- Existing: RIKEN (Japan), TRIUMF (Canada),
- Under Construction or Upgrade: FRIB (US), FAIR (Germany), SPARAL2 (France), SARAF (Israel), PEFP (Korea)
- Proposed: EURISOL (Europe), SPES (Italy),

**Materials Science**
- Existing: SNS (US), SINQ (Switzerland), J-PARC (Japan), ISIS (UK), LANSCE (US)
- Under Construction or Upgrade: CSNS (China)
- Proposed: ESS (Europe), IFMIF (EU&Japan)

**Applications**
- Proposed: MYRRHA (Belgium), EUROTRANS (EU), TRASCO (Italy), ADS (China, India, Japan, Korea)
The Beam Power Landscape

The diagram illustrates the relationship between beam energy (GeV) and average beam current (mA) for various facilities. It differentiates between existing and planned facilities, with symbols indicating whether they are high power (SP) or low power (LP). The graph shows a range of facilities, such as IPHI, LEDA, IFMIF, and SPIRAL-2, plotted according to their beam power landscape characteristics.
Challenges for High Power Proton Accelerators

- Producing high-quality beams in the injector system (high brightness, low halo) at high duty factor
- Accelerating high beam currents to high energy
  - High-duty factor, high-power RF systems, structures and components; for RF efficiency and practicality, SCRF is the technology of choice
- Transporting high power beams while maintaining beamloss at a level where routine maintenance is possible (<1 Watt/m)
  - Acceleration of beams from keVs to GeVs with little emittance growth, and minimization of halo growth
  - Understanding and control of collective effects that have the potential to generate large-amplitude particles
  - Systems for stripping, collimation, low-loss extraction, machine protection
- Target systems capable of handling extreme power densities and extreme radiation environments (~ $10^5$ Rem/hr beam off)
Japan Proton Accelerator Research Complex (J-PARC)

- J-PARC is a multi-purpose proton accelerator facility to support user communities using secondary beams of neutrons, muons, hadrons, neutrinos, with plans for transmutation experiments.
J-PARC Tour

- 181 MeV Linac with 324 MHz RFQ, DTL, SDTL (30 mA, 0.5msec, 25 Hz)
- Space reserved for 400 MeV energy upgrade using 972 MHz Annular Coupled Structure
- 3 GeV Rapid-Cycling Synchrotron
- RCS serves the Materials/Life Sciences Facility
- 50 GeV Main Ring (30 GeV operation)
J-PARC Beam Power Performance and Plans

Power Capability

![Graph showing J-PARC Power Performance and Plans](image)

- **Previous Estimate Nov. 2003**
- **Present Estimate for 3 GeV**
- **Linac Energy Recovery**
- **300 kW 1 hour**
- **Training**
- **200 kW steady**
- **120 kW steady**
- **For short period**
- **115 kW steady**
- **Present Estimate for MR at 30 GeV**

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Courtesy T. Koseki, J-PARC
RCS Beam Power Delivered to the Materials and Life Science Facility

History of the proton power of MLF

- **Beam Power [kW]**
- **Availability [%]**
- **Cumulative power [MWh]**

Graph showing the history of beam power with specific dates and power levels.

- **20 kW**
- **210 kW**
- **120 kW**

Key dates and events:
- 2008/5/30 Day 1
- 2008/12/23 Starting User Program
- 2009/11/9 120 kW Operation
- 2010/11/26 200 kW Operation

Additional notes:
- Availability > 93%
- Various other power levels and availability notes.
Main Ring Performance

- Fast extraction: 135 kW routine operation at 30 GeV to the neutrino target with 3.2 sec cycle
  - Limited by losses and activation in injection and collimation regions
- Slow extraction: 3.6 kW routine at 30 GeV, extraction efficiency is 99.5% and duty factor is 17%.
  - 10 kW equivalent power demonstrated
  - Limited by extraction losses as intensity increases

Injection & Collimators

Beam loss power @ Injection < 200 W
J-PARC Performance Issues

- **Linac**
  - RFQ: conditioning/discharge issues; dramatic improvements recently with better H$_2$ pumping
  - Beam halo observed at high energy
  - Energy upgrade (recovery of design 400 MeV energy) essential for higher RCS power

- **3 GeV RCS**
  - Foil optimization: beamloss at injection and due to multiple foil passages
  - RF magnetic alloy (finemet) cores buckling issues; coating with low-viscosity epoxy mitigates
  - Beam power limited administratively by Hg target concern

- **MR**
  - Main Ring power supply: ripple limits Slow-Extraction power (100 kW design)
  - Transverse head-tail instability combatted with bunch-by-bunch feedback system
The Situation Following the Earthquake and Tsunami (S. Nagamiya)

- No Tsunami damage due to 10m design basis; damage due to earthquake
- Building generally OK due to many piles; roads and surrounding utilities suffered damage
- 10 cm water in linac tunnel; pumping underway; accelerator looks OK
- RCS: no significant visible damage; tests are needed to validate integrity of ceramic vacuum chamber
- MLF building looks OK due to substantial piles
- 30 cm drop in elevation of adjacent instrument buildings
- MR, hadron hall and neutrino hall OK
The Spallation Neutron Source

- The SNS at Oak Ridge National Laboratory is the world’s most powerful pulsed neutron source.
- The SNS construction project, a collaboration of six U.S. DOE laboratories, was completed in 2006, on-time and within budget at a cost of $1.4B.
SNS Accelerator Complex

Front-End: Produce a 1-msec long, chopped, H- beam

1 GeV LINAC

Accumulator Ring: Compress 1 msec long pulse to 700 nsec

- 402.5 MHz, 6% duty factor RFQ
- 402.5 MHz DTL (87 MeV)
- 805 MHz CCL (186 MeV)
- SC Linac w/ two 805 MHz cavity families
- 1 GeV Accumulator Ring
- Liquid Hg Target
SNS has Ramped-Up to 1 MW Beam Power and ~90% Availability

- Modulator Failures
- Ion Source Performance
- Foil and foil mounting failures
- Power $ Savings
Smooth Running…

Energy and Power on Target

- Minute Max Power10 (kW)
- Daily Energy MWhr (3.6GJ)

May/8 2010
May/9 2010
May/10 2010

Graph showing energy and power levels for May 8, 9, and 10, 2010, with data points and trend lines.
Emphasis is on Beam Availability
## Major Parameters Achieved vs. Designed

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design</th>
<th>Individually achieved</th>
<th>Highest production beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Power on Target (MW)</td>
<td>1.44</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Beam Energy (GeV)</td>
<td>1.0</td>
<td>1.01</td>
<td>0.93</td>
</tr>
<tr>
<td>Peak Beam current (mA)</td>
<td>38</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Beam Pulse Length (ms)</td>
<td>1000</td>
<td>1000</td>
<td>825</td>
</tr>
<tr>
<td>Repetition Rate (Hz)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Linac Beam Duty Factor (%)</td>
<td>6.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Beam intensity on Target (protons per pulse)</td>
<td>$1.5 \times 10^{14}$</td>
<td>$1.6 \times 10^{14}$</td>
<td>$1.1 \times 10^{14}$</td>
</tr>
<tr>
<td>SCL Cavities in Service</td>
<td>81</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>
Technical Issues

Ion Source
• lifetime and reproducibility

RFQ
• resonant frequency shift, resonant-frequency control at high duty factor

SC Cavity/CM Performance
• large variations in operating accelerating gradient; operating at less than design gradients in high-beta
• SC Cavity degradation with severe beamloss observed; recoverable with conditioning

SCL Beamloss
• unanticipated source of beamloss in SCL; doesn’t limit performance

Pulsed-power systems
• modulator reliability

Injection region/stripper foil
• very sensitive loss location; reworked several aspects of high power injection

Target lifetime
• cavitation induced damage observed; has not limited performance
Superconducting Linac activation is not increasing, despite significant increase in power and operational hours (A. Shishlo)

- Reduction in quadrupole focusing strength reduced losses
- Beam loss is not a limiting factor in SCL
Ring activation is primarily at the injection point, dominated by scattering losses from the foil.

Activation scales with fluence, close to expectations.

Losses are managed with optimization of injected beam, foil parameters, and foil geometry.

Courtesy J. Galambos, SNS
Ring Injection

- Ring circulating beam heating
- Injection spot (linac beam)
- Cut-corner to reduce circulating beam foil interactions

- “Cutting corners” to optimize the foil / linac beam shapes reduces scattering losses ~ 20%

Courtesy J. Galambos, SNS
Mercury Spallation Target Experience

- Cavitation induced damage has been a concern since early SNS design
- Two target change-outs have been performed, after ~7 d.p.a. each
- Post-irradiation examination has been performed
- Results reveal cavitation-induced pitting damage on Hg-facing surface
- Expectation is a strong non-linear dependence on pulse intensity
- Observed pitting damage is near stagnant flow region
- Not limiting beam power at present
- Mitigation efforts under study; simple change in Hg flow could mitigate

Courtesy B. Riemer, SNS
Progress at Soreq Applied Research Accelerator Facility (SARAF)

- The SARAF accelerator will be a 40 MeV, 5mA, CW proton/deuteron superconducting linac
- Phase I, now under commissioning, includes an ECR ion source, a 1.5 MeV/u 4-rod RFQ and a Prototype Superconducting Module (PSM) housing six 176 MHz HWRs and 3 solenoids
- Low duty cycle (10^{-4}) p/d accelerated up to 3.9 and 4.3 MeV
- CW 1 mA proton beams accelerated up to 3.5 MeV
- Duty factor for deuteron operation (which requires higher field and power dissipation) has been limited by a number of RFQ discharge/heating issues
Laying the Groundwork for Multi-MW Facilities: What Have We Learned?

1 W/m beamloss in a MW-class pulsed accelerator is achievable

- Space-charge limits in rings can be mitigated by phase-space painting
- Collective phenomena at high intensity are calculable, and results are believable
- Linac emittance growth is calculable and can be minimized in practice

But, …

- Multi-MW facilities need to predict, measure and control beam particle distributions at the part per million level to reach 1Watt/m beamloss requirements
- Prediction of beamloss is not to the point where an accelerator can be “engineered”
- Simulation capability is advanced, but incomplete knowledge of input distributions makes quantitative predictions at the ppm level impossible
- Beam instrumentation tends to focus on beam-core parameters. Lost particles are those that have reached large amplitudes, many-sigma beyond the core.
- Control of beamloss that cannot be predicted or measured demands that flexibility be built into the accelerator design!
Laying the Groundwork for Multi-MW Facilities: What Have We Learned?

- H- sources can provide low-emittance, high beam current at high duty factor
- High-duty factor/CW RFQs are difficult engineering challenges
- Superconducting linac technology works in a proton beam context: high-quality beams are obtained together with flexibility given by independently-powered SC system
  - But CW applications bring new challenges, like pushing quality factor of SC cavities
- Stripping of H- beams of ever-higher power becomes more and more difficult
- Liquid metal targets work at MW beam powers,
  - but extending beam power requires special measures to combat cavitation for short-pulse applications, or use of free-flowing liquid (MERIT experiment)
In Summary…

- The field of high-power proton accelerators has come a long way in the last decade, incorporating and demonstrating new technologies and approaches.
- These approaches show that MW-class proton beams can be generated, accelerated, handled and deposited.
- The stage is set for the next step in proton beam power by the next-generation Multi-MW accelerators:
  - Project-X (S. Nagaitsev)
  - European Spallation Source (S. Peggs)
  - MYRRHA
  - IFMIF

Thank You