High-power Targets

LINAC 2004

Lūbeck, Germany

August 19, 2004
Intense Secondary Beams

New physics opportunities are generating world wide interest in the development of new intense secondary beam.

- Neutron Sources
  - European Spallation Source
  - US Spallation Neutron Source
  - Japanese Neutron Source
- Kaons
  - RSVP at BNL
  - CKM at FNAL
- Muons
  - MECO and g-2 at BNL
  - SINDRUM at PSI
  - EDM at JPARC
  - Muon Collider
- Neutrinos
  - Superbeams
  - Neutrino Factories
Multi-MW New Proton Machines

SNS at 1.2 MW → 2.0 MW
JPARC 0.7 MW → 4.0 MW
FNAL 0.4 MW → 1.2 MW → 2.0 MW
BNL 0.14 MW → 1.0 MW → 4.0 MW

AGS Upgrade to 1 MW

High Intensity Source plus RFQ

200 MeV Drift Tube Linac

200 MeV 400 MeV 800 MeV 1.2 GeV
Superconducting Linacs

BOoster

To Target Station

AGS
1.2 GeV → 28 GeV
0.4 s cycle time (2.5 Hz)

To RHIC

0.2 s 0.2 s

Harold G. Kirk
High-power Targetry Workshop  
Ronkonkoma, Long Island Sept. 2003

Over 40 attendees from:  

<table>
<thead>
<tr>
<th>Facilities Represented</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argonne</td>
</tr>
<tr>
<td>Brookhaven</td>
</tr>
<tr>
<td>CERN</td>
</tr>
<tr>
<td>Fermilab</td>
</tr>
<tr>
<td>FZ-Julich</td>
</tr>
<tr>
<td>KEK</td>
</tr>
<tr>
<td>Los Alamos</td>
</tr>
<tr>
<td>Michigan State</td>
</tr>
<tr>
<td>Oak Ridge</td>
</tr>
<tr>
<td>Princeton</td>
</tr>
<tr>
<td>PSI-Zurich</td>
</tr>
<tr>
<td>Rutherford Lab</td>
</tr>
<tr>
<td>SLAC</td>
</tr>
<tr>
<td>AGS</td>
</tr>
<tr>
<td>ESS</td>
</tr>
<tr>
<td>EURISOL</td>
</tr>
<tr>
<td>IFMIF</td>
</tr>
<tr>
<td>ISIS</td>
</tr>
<tr>
<td>JPARC</td>
</tr>
<tr>
<td>LANCE</td>
</tr>
<tr>
<td>Neutrino Factory</td>
</tr>
<tr>
<td>NUMI</td>
</tr>
<tr>
<td>NLC</td>
</tr>
<tr>
<td>RIA</td>
</tr>
<tr>
<td>SINQ</td>
</tr>
<tr>
<td>SNS</td>
</tr>
</tbody>
</table>

Harold G. Kirk
High-power Targetry Challenges

High-average power and high-peak power issues

- Thermal management
  - Target melting
  - Target vaporization

- Radiation
  - Radiation protection
  - Radioactivity inventory
  - Remote handling

- Thermal shock
  - Beam-induced pressure waves

- Material properties
Thermal Management

T1 target at JPARC
Kaon Production
Rotating Ni Disks
Water Cooled
590 J/g

Neutron Spallation Target at LANL
Lance p beam 0.8 GeV 0.8 MW
Stainless Steel Claded Tungsten
Water Cooled 100 W/g

Harold G. Kirk
Harold G. Kirk

Neutrino Horns

CERN 2.2 GeV 4MW SPL Proton Beam on an Hg target

BNL 28 GeV 1MW Proton Beam on a Carbon-Carbon target

Harold G. Kirk
Prototype of T2K Neutrino Target

Prototype design for He cooling pipe is in progress.

Inner Pipe
- $t=2.0\text{mm Graphite}$  
- or $t=0.3\text{mm Ti (Ti-6Al-4V)}$

Outer Pipe
- $t=0.3\text{mm Ti-6Al-4V}$

Graphite Cap

Exit  

Entrance of He
CERN ISOLDE Solid Targets

BEFORE
PS-Booster 1-1.4 GeV  0.005 MW
Various targets/materials

AFTER

Tantalum Target

Harold G. Kirk
A Rotating Solid Target

Schematic of a rotating tantalum target

rotating toroid

toroid magnetically levitated and driven by linear motors

proton beam

toroid at 2300 K radiates heat to water-cooled surroundings

solenoid magnet

Roger Bennett, RAL
Granular Solid Target

Advantages for a granular approach

- Reduced sample volume results in reduced sample thermal gradient
- Large surface/volume ratio leads to better heat removal
- Better liquid or gas conduction through the target
- Simpler stationary solid target approach
- Could utilize high-Z target material
Liquid Metal Targets—PbBi Eutectic

MEGAPIE Project at PSI
0.59 GeV proton beam
1 MW beam power
Goals:
- Demonstrate feasibility
- One year service life
- Irradiation in 2005
The SNS Mercury Target

SNS Target Configuration

- Target Container
- Cooling Channels
- Mercury Main Flow
- Stainless Steel Target Container
- Proton Beam

BROOKHAVEN NATIONAL LABORATORY

Harold G. Kirk
Target Region Within Core Vessel

- Target Module with jumpers
- Target Inflatable seal
- Core Vessel water cooled shielding
- Core Vessel Multi-channel neutron guide flange
- Outer Reflector Plug
- Moderators
ESS team has been pursuing the Bubble injection solution. SNS team has focused on Kolsterizing (nitriding) of the surface solution. SNS team feels that the Kolsterized surface mitigates the pitting to a level to make it marginally acceptable. Further R&D is being pursued.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Normalized Erosion*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas layer near surface</td>
<td>0.06</td>
</tr>
<tr>
<td>Bubble Injection</td>
<td>0.25</td>
</tr>
<tr>
<td>Kolsterized surface</td>
<td>0.0008</td>
</tr>
<tr>
<td>1/2 Reference Power</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* Erosion relative to reference (2.5 MW) case
Radiation Management
The JPARC Kaon Target

Concrete shield block

Service space:
2m(W) × 1m(H)

Iron shield

Concrete shield

Beam

Water pump

T1 container

~18m

~10m
The Neutrino Factory Target

Component Lifetime

<table>
<thead>
<tr>
<th>Component</th>
<th>Radius (cm)</th>
<th>Dose/yr (Grays/2 x 10^7 s)</th>
<th>Max allowed Dose (Grays)</th>
<th>1 MW Life (years)</th>
<th>4 MW Life (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner shielding</td>
<td>7.5</td>
<td>5 x 10^-10</td>
<td>10^{12}</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Hg containment</td>
<td>18</td>
<td>10^3</td>
<td>10^{11}</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>Hollow conductor coil</td>
<td>18</td>
<td>10^5</td>
<td>10^{11}</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Superconducting coil</td>
<td>65</td>
<td>6 x 10^6</td>
<td>10^6</td>
<td>16</td>
<td>4</td>
</tr>
</tbody>
</table>

Harold G. Kirk
High-peak Power Issues

When the energy deposition time frame is on the order of or less than the energy deposition dimensions divided by the speed of sound then pressure waves generation can be an important issue.

\[
\text{Time frame} = \frac{\text{beam spot size}}{\text{speed of sound}}
\]

Illustration

\[
\text{Time frame} = \frac{1\text{cm}}{5 \times 10^3 \text{ m/s}} = 2 \mu\text{s}
\]
CERN ISOLDE Hg Target Tests

Proton beam 5.5 TP per Bunch.
Pressure Wave Amplitude

\[ \text{Stress} = Y \alpha_T \frac{U}{C_V} \]

Where \( Y \) = Material modulus
\( \alpha_T \) = Coefficient of Thermal Expansion
\( U \) = Energy deposition
\( C_V \) = Material heat capacity

When the pressure wave amplitude exceeds material tensile strength then target rupture can occur. This limit is material dependant.
E951: Graphite & Carbon-Carbon Targets

Key Material Properties

<table>
<thead>
<tr>
<th></th>
<th>ATJ</th>
<th>CC X/U</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$, GPa</td>
<td>10</td>
<td>54/5.3</td>
</tr>
<tr>
<td>$\alpha_T$, $10^{-6}/^\circ$K</td>
<td>2.5</td>
<td>~0</td>
</tr>
<tr>
<td>Tensile Strength, MPa</td>
<td>15</td>
<td>182/44</td>
</tr>
</tbody>
</table>
BNL E951 Target Experiment
24 GeV 3.0 e12 proton pulse on Carbon-Carbon and ATJ graphite targets
Recorded strain induced by proton pulse

E951: Strain Gauge Measurements

24 GeV, 3 x 10^{12} protons/pulse

Harold G. Kirk
Laser-vibrometer studies of surface-movement at CERN

Ta cylinder (l = 100 mm, d = 10 mm), proton beam 2 mm horizontally off-axis, 4 bunches, 32 TP

Pb cylinder (l = 100 mm, d = 10 mm), proton beam 2 mm horizontally off-axis, 1 bunch, 8 TP

v(t) signal (0 to 6 ms)

FFT(v) (0 to 2 MHz)

Time resolution of 4 PSB bunches

fewer and lower frequency modes than in Ta

v(t) detail (10 µs)

reflection

v(t) signal (0 to 6 ms)

FFT(v)
Target Material Examples

Peter Thieberger, BNL
Consider the case of a 16 TP, 3ns, 24 GeV proton pulses

Beam Induced Stress
Material Yield Strength
Super-invar Irradiation at BNL

The cylindrical samples of super-invar.

The target basket after irradiation.

Dilatometer in Hot cell.

Results of coefficient of thermal expansion measurements.

Harold G. Kirk
Achieving Intense Muon Beams

Maximize Pion/Muon Production

- Soft-pion Production
- High Z materials
- High Magnetic Field

Meson Production - 16 GeV $p + W$

dN/dKE (1/GeV/interacting proton)

Pion Kinetic Energy, GeV

Harold G. Kirk
E951 Hg Jet Tests

- 1cm diameter Hg Jet
- 24 GeV 4 TP Proton Beam
- No Magnetic Field

Proton Beam

Mercury Jet

$t = 0 \text{ ms}$
$t = 0.75 \text{ ms}$
$t = 2 \text{ ms}$
$t = 7 \text{ ms}$
$t = 18 \text{ ms}$
CERN/Grenoble Hg Jet Tests

- 4 mm diameter Hg Jet
- \( v = 12 \text{ m/s} \)
- 0, 10, 20T Magnetic Field
- No Proton Beam

A. Fabich, J. Lettry
Nufact’02

Harold G. Kirk
Key Initial Hg Jet Results

- Hg jet dispersal proportional to beam intensity (10 m/s for 4 TP 24 GeV beam)
- Hg jet dispersal velocities ~ ½ times that of “confined thimble” target
- Hg dispersal is largely transverse to the jet axis -- longitudinal propagation of pressure waves is suppressed
- Visible manifestation of jet dispersal delayed 40 µs
- The Hg jet is stabilized by the 20 T magnetic field
Bringing it all Together

We wish to perform a proof-of-principle test which will include:

- A high-power intense proton beam (16 to 32 TP per pulse)
- A high (> 15T) solenoidal field
- A high (> 10m/s) velocity Hg jet
- A ~1cm diameter Hg jet

Experimental goals include:

- Studies of 1cm diameter jet entering a 15T solenoid magnet
- Studies of the Hg jet dispersal provoked by an intense pulse of a proton beam in a high solenoidal field
- Studies of the influence of entry angle on jet performance
- Confirm Neutrino Factory/Muon Collider Targetry concept
Simulations at BNL (Samulyak)

Gaussian energy deposition profile Peaked at 100 J/g. Times run from 0 to 124 µs.

Jet dispersal at t=100 µs with magnetic Field varying from B=0 to 10T
A High-power Target Test at CERN

CERN-INTC-2003-033
INTC-I-049
26 April 2004

A Proposal to
the ISOLDE and Neutron Time-of-Flight Experiments
Committee

Studies of a Target System for
a 4-MW, 24-GeV Proton Beam

J. Roger J. Bennett1, Luca Bruno2, Chris J. Densham1, Paul V. Drumm1,
T. Robert Edgecock1, Tony A. Gabriel3, John R. Haines3, Helmut Haseroth2,
Yoshinari Hayato4, Steven J. Kuhn5, Jacques Lettry2, Changguo Lu6, Hans Ludewig5,
Harold G. Kirk5, Kirk T. McDonald6, Robert B. Palmer6, Yarema Prykarpatskyy5,
Nicholas Simos5, Roman V. Samulyak5, Peter H. Thieberger5, Koji Yoshimura4

Spokespersons: H.G. Kirk, K.T. McDonald
Local Contact: H. Haseroth

Proposal submitted April 26, 2004
Proposed Target Test Site at CERN
High Field Pulsed Solenoid

- 70° K Operation
- 15 T with 4.5 MW Pulsed Power
- 15 cm warm bore
- 1 m long beam pipe

Peter Titus, MIT

BROOKHAVEN
NATIONAL LABORATORY

Harold G. Kirk
Layout of the Experiment
PS Extracted Beam Profile

Beam Profile

500 ns

250 to 1500 ns

Pump

Probe

Scintillator Profile

Harold G. Kirk
Conclusions

- New physics opportunities are establishing the case for the development of new high-power proton drivers.
- High-power targets are necessary for the exploitation of these new machines.
- Target systems have been developed for the initial 1MW class machines, but are as yet unproven.
- No convincing solution exists as yet for the envisioned 4 MW class machines.
- A world wide R&D effort is under way to develop new high-power targets and BNL is part of that effort.