Introduction to High Power Proton Accelerators

W.T. WENG

BROOKHAVEN NATIONAL LABORATORY

OCPA-AS( N1 )
MiYun, Beijing
July 31, 2010
Outline

1. Two Examples

2. Issues of high intensity beam acceleration

3. Proposals and designs of future facilities with megawatt beam power

4. Pros and cons of Linac, Linac-AR, RCS, Cyclotron, and FFAG
Two Examples

Why starting with examples?

1. I am most familiar with the works I did

2. To show how to apply the general principles and theories you have learned to actual accelerator design and construction

3. To introduce few concepts and world activities of high power proton accelerators
Example 1: Booster Project and AGS Upgrade

Booster was constructed in 1987 – 1990 to

- Increase proton intensity in the AGS
- Raise polarized proton intensity in both AGS and RHIC
- Raise heavy ion mass and intensity in the AGS and RHIC
Gold Ion Collisions in RHIC

Beam Energy = 100 GeV/u
$L_{\text{ave}}$ per IR = $2 \times 10^{26}$ cm$^{-2}$ sec$^{-1}$

RHIC

9 GeV/u
$Q = +79$

AGS

1 MeV/u
$Q = +32$

BOOSTER

TANDEMS
Space Charge Tune Shift in Ring

\[ \Delta Q = \frac{3 \, r_p \, N}{2\pi \, \beta \, \gamma^2 \, \epsilon_N \, B_f} < 0.25 \]  

Where:

- \( r_p \) : Classical proton radius
- \( N \) : Total number of proton
- \( \epsilon_N \) : Normalized emittance
- \( B_f \) : Bunching factor

Limited tune spread to avoid resonance loss of beam.
Space charge effect of injection energy

The Booster can raise the AGS injection energy from

\[ E = 200 \text{ MeV} \quad \text{with} \quad \beta \gamma^2 = 0.83 \quad \text{to} \]

\[ E = 1.5 \text{ GeV} \quad \text{with} \quad \beta \gamma^2 = 6.23 \]

Everything being equal, a factor of about seven increase is possible
BNL AGS kept highest intensity record for synchrotron since 1995
That for an AR were kept by ISR and SNS.
AGS Intensity History

![Graph showing AGS intensity history with key milestones labeled: 6 Booster cycles, AGS transition energy jump, Rf beam loading comp., Booster, H⁻ injection, 200 MeV linac. The graph plots proton intensity per pulse on the y-axis and fiscal year on the x-axis.]
Technologies developed for high intensity beams:

- Low loss charge exchange injection (AGS, SNS, …)
- High current ion source
- Boosters (CERN, FNAL, AGS, KEK, …)
- Rapid cycling synchrotron (FNAL, ISIS, …)
- Pulsed and CW RFQs (LEDA, AGS, SNS,..)
- Super-conducting Linac (SNS, …)
- Transition energy jump or avoidance (CERN, AGS, J-Parc, …)
- Beam loading compensation and 2\textsuperscript{nd} harmonic cavity (AGS, ISIS, …)
- Electron cloud cures (PSR, SNS…)
- Beam Collimation (SNS,
- Damping of collective instability (AGS, SNS, ..)
H⁻ injection into the Booster

Injected:
23 × 10^{12} ppb
1.3 eVs

Circulating:
17 × 10^{12} ppb
3.0 eVs

- 90 mA H⁻ magnetron source, about 100 turns accumulation
- High B dot gives effective longitudinal phase space painting.
- Injection period is approx. equal to synchrotron period.
AGS High Intensity Performance

- 6 single bunch transfers from Booster
- Peak intensity reached: $72 \times 10^{12}$ ppp
- Bunch area: 3 eVs at injection
  10 eVs at extraction
- Intensity for FEB ops: $60 \times 10^{12}$ ppp
- Strong space charge effects
during accumulation and energy
transition in AGS
- 2nd order transition energy jump
limits available momentum aperture.
- Chromatic mismatch at transition
causes emittance dilution
Example 2: The Spallation Neutron Source

The SNS is a short-pulse neutron source, driven by a 1.4 MW proton accelerator.

SNS will be the world’s leading facility for neutron scattering research with peak neutron flux ~20–100x ILL, Grenoble.

SNS is funded through DOE-BES at a cost of 1.4 B$.

The Project is a collaboration of six US DOE laboratories.

SNS will be 8x ISIS, the world’s leading pulsed source.

Stepping stone to other high power facilities.
Evolution of the performance of neutron sources

Effective thermal neutron flux \( n/cm^2-s \)

- Chadwick
- Berkeley 37-inch cyclotron
- 350 mCi Ra-Be source
- CP-1
- CP-2
- MTR
- NRU
- HFIR
- HFBR
- ILL
- ISIS
- SNS
- FRM-II
- ZINP-P

Steady State Sources
Pulsed Sources

Evolution of Neutron Sources

1. Reactors, 1940 –
2. ISIS/RAL 1980 ---
3. LAMF/LANL, 1980 ---
4. IPNS/ANL, 1985 -- 2005
5. ANS/ORNL(R&D), 1985 ---1996, followed by SNS
   LANL, ANL, BNL, ..
Power of a Proton Beam

\[ P(MW) = E_k(Gev) \times I_{ave}(Amp) \quad (2) \]

\[ I_{ave} = \frac{N_e}{\tau} = 1.5 \times 10^{14} \times 1.6 \times 10^{-14} \times 60 \]
\[ = 1.4 \text{ mA} \]

\[ P_{SNS} = 1.0 \times 1.4 = 1.4 \text{ MW} \]

High power accelerator needs both high intensity and high repetition rate
Neutron Yield

\[ n = 0.1 \times (A + 20) \times E \text{ (Gev)} \]  \hspace{1cm} (3)
\[ \approx 20 \]

For SNS mercury target at 1 Gev

\[ N_n = n \times N_p = 0.1 \times (A + 20) \times P \]  \hspace{1cm} (4)

Means that total neutron flux is proportional to total proton beam power
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

2.5 MeV

1000 MeV

Chopper system makes gaps

mini-pulse

1 ms macropulse

Liquid Hg Target
Accumulator Ring and Transport Lines

- Designed and built by Brookhaven National Lab
- Accumulates 1-msec long beam pulse by multi-turn charge exchange injection
  - Circum 248 m
  - Energy 1 GeV
  - Accum turns 1060
  - Final Intensity $1.5 \times 10^{14}$
  - Current 26 A

[Diagram of the Accumulator Ring and Transport Lines with labeled sections for Injection, Extraction, Collimation, RF, HEBT, and Target.]

[Image of the Accumulator Ring facility with equipment and machinery.]
1 MW Beam Power Achieved!

Neutron facility achieves 1-megawatt power

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**1021.3 kW on Target**

**Beam to Target**

*Graph showing power on target vs. beam to target.*

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**Dream delivered: SNS pushes past one megawatt**

*Stuart Henderson said he was ready to get some sleep. Whether he meant for the first time since April 28, 2006, he didn’t say. But the director of the Research Accelerator Division was obviously relieved.*

The Spallation Neutron Source, which is supported by Stuart’s division, on September 18 became the first spallation neutron source to break the one-megawatt barrier. SNS is now the most powerful spallation neutron source in the world, topping the continuous-beam SINDY at the Swen Institute in Switzerland, which currently runs at 900 kilowatts.

Much as the day the SNS was first turned on in April 2006, the milestone came with a control-room whoop as the power reading on the instrument panel rolled over to seven figures.

The SNS was ramping up for its latest operational run following a maintenance shutdown that included the installation of a broad new target module to replace the original target, which outlasted most expectations of service life.

“After a long time in the making and the dream of a lot of people to make a megawatt-class pulsed spallation neutron source, and today we’ve finally delivered on that dream,” said Stuart just after the deed was done.

*See MEGAWATT, page 9*
Beamloss: SNS Residual Activation after 1 MW Operation (Hot Spots)

All numbers are mRem/hr at 1 ft.
• We plan to double the SNS beam power by
  – Increasing beam energy with 9 additional cryomodules (SNS Power Upgrade Project)
  – Increasing peak current from the source (Operational improvements)
  – modifying injection and extraction regions to accommodate higher beam energy (all other power supplies support 1.3 GeV operation)

• Anticipate PUP “CD-2” Approval (Baseline) in 2011; Construction Timeline 2012-2017

• Active R&D: Laser-stripping, target cavitation damage mitigation, electron-proton instability damping, source development, ...

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic Energy</td>
<td>1.0 GeV</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td>Beam Power</td>
<td>1.44 MW</td>
<td>3.0 MW</td>
</tr>
<tr>
<td>Linac Beam Duty Factor</td>
<td>6%</td>
<td>6%</td>
</tr>
<tr>
<td>Peak Linac Current</td>
<td>38 mA</td>
<td>59 mA</td>
</tr>
<tr>
<td>SRF Cavities</td>
<td>81</td>
<td>117</td>
</tr>
<tr>
<td>Ring Bunch Intensity</td>
<td>$1.5 \times 10^{14}$</td>
<td>$2.5 \times 10^{14}$</td>
</tr>
<tr>
<td>Ring Space Charge Tune Spread</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>
3. Possible Applications of HPPA

Nuclear waste transmutation and accelerator driven sub-critical reactors:

- CW or high DF to minimize mechanical shock
- E: 1 – 10 GeV (minimize power deposition in window, fully absorb beam in reactor)

Production of intense secondary beams:

- Neutrons: DF: CW - 10^{-4}, E: 0.5 - 10 GeV (neutron production ~ prop. to beam power)
- Kaons: DF ~ 0.5 (minimize pile-up in detector), E: > 20 GeV
- Neutrino super-beam: DF: ~ 10^{-5}(suppress background), E: > 1 GeV (depends on neutrino beam requirements)
- Muons for neutrino factory: DF: ~ 10^{-5} (pulsed cooling channel), E: > 10 GeV (for 5MW, $I_{\text{peak}} > 50\text{A}$)
- Muons for muon collider: DF: ~ 10^{-7} (maximize luminosity), E: ~ 20 – 30 GeV (for 5MW, $I_{\text{peak}} = 1.7 – 2.5\text{ kA}$)
High Power Proton Accelerators

Upgrade Plan

plot: selected accelerators, average beam current vs. energy, power $\propto$ current

- PSI$_{upgr}$
- SNS
- SNS$^{10/2009}$
- PX-Linac
- HP-SPL (CERN)
- JPARC$^3_{GeV}$
- JPARC$^{50}_{GeV}$

P = 1MW
P = 100kW
P = 10MW

$E_\gamma$ [GeV]
Design options for high power facilities

<table>
<thead>
<tr>
<th>design:</th>
<th>issues/challenges:</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW or high DF:</td>
<td>Cyclotron + p source, E ≤ 1 GeV</td>
</tr>
<tr>
<td>SC Linac + p source</td>
<td>CW front end (RFQ, DTL)</td>
</tr>
<tr>
<td>Low DF:</td>
<td>Linac + accum. ring, E ≤ 5 (8?) GeV (H⁻ stripping)</td>
</tr>
<tr>
<td>Linac + RCS</td>
<td>Rep. rate &lt; 100 Hz, P_{RCS}/P_{Linac} ≤ 10</td>
</tr>
<tr>
<td>Linac + FFAG</td>
<td>Rep. rate ≤ 1 kHz, P_{RSC}/P_{FFAG} ≤ 3</td>
</tr>
<tr>
<td>Linac + n × RCS</td>
<td>For high energy</td>
</tr>
<tr>
<td></td>
<td>Bunch-to-bucket transfers</td>
</tr>
<tr>
<td></td>
<td>High gradient, low frequency rf</td>
</tr>
</tbody>
</table>
Achieved: 590 MeV, 2 mA, 1.2 MW
Upgrade: 590 MeV, 3 mA, 1.8 MW
Possible: 1000 MeV, 10 mA, 10 MW

[M. Humbel (PSI)]

Space charge current limit scales with third power of rf voltage.

Space charge limit scales with $V^3$ scaling law.
PSI Ring Cyclotron

Magnetic Magnets: 1 T

Magnet weight: ~250 tons

Accelerator Cavities: 850 kV (1.2 MV)

Flat-Top Resonator: 150 MHz

Injection coil circuits: 15

Accelerator frequency: 50.63 MHz

Resonant number: 6

Cylindrical beam energy: 72 → 590 MeV

Beam current max.: 2.2 mA

Injection orbit radius: 4.5 m

Inner diameter: 15 m

Relative Losses @ 2mA: ~ 1.2 x 10^-4

Transmitted power: 0.26-0.39 MW/Res.

M. Seidel, HIPA 2009, Fermilab
Grid to Beam Power Conversion Efficiency

for industrial application, transmutation etc., the aspect of **efficient usage of grid power** is very important

**PSI**: $\sim$10MW Grid $\rightarrow$ 1.3MW Beam

$$P_{\text{grid}}(I) \approx (8.0 \pm 0.5)\text{MW} + 0.81\text{MW} \cdot I[\text{mA}]$$

contains many loads not needed for ADS!

▶ differential measurement of electrical power vs. beam power (total PSI power shown)

$\frac{dP}{dI} = 0.8 \text{ MW/mA}$

M. Seidel, HIPA 2009, Fermilab
Particle losses along the accelerator

<table>
<thead>
<tr>
<th>Accelerator Section</th>
<th>kin. energy [MeV]</th>
<th>max. loss [μA]</th>
<th>typ. loss [μA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injector II, extraction</td>
<td>72</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>collimator FX5 (shielded)</td>
<td>72</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>transport channel II (35m)</td>
<td>72</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Ring Cyc., Injection</td>
<td>72</td>
<td>2</td>
<td>0.3</td>
</tr>
<tr>
<td>Ring Cyc., Extraction</td>
<td>590</td>
<td>2</td>
<td>~0.4</td>
</tr>
<tr>
<td>transport channel III</td>
<td>590</td>
<td>0.1</td>
<td>0.02 (est)</td>
</tr>
<tr>
<td>target E+M (shielded)</td>
<td>590</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>transport channel IV</td>
<td>575</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>SINQ target (shielded)</td>
<td>575</td>
<td>70%</td>
<td>70%</td>
</tr>
</tbody>
</table>

acceptable for service:

\~ 2 \cdot 10^{-4} \text{ relative losses per location (at 590 MeV)}
Parameter Set for a 10 MW Cyclotron
[1997, Th. Stammbach et al]

<table>
<thead>
<tr>
<th>parameters</th>
<th>1 GeV Ring</th>
<th>PSI Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1000 MeV</td>
<td>590 MeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>120 MeV</td>
<td>72 MeV</td>
</tr>
<tr>
<td>Magnets</td>
<td>12 ($B_{max} = 2.1$ T)</td>
<td>8 ($B_{max} = 1.1$ T)</td>
</tr>
<tr>
<td>Cavities</td>
<td>8 (1000 kV)</td>
<td>4 (800 kV)</td>
</tr>
<tr>
<td>Frequency</td>
<td>44.2 MHz</td>
<td>50.63 MHz</td>
</tr>
<tr>
<td>Flat tops</td>
<td>2 (650 kV)</td>
<td>1 (460 kV)</td>
</tr>
<tr>
<td>Injection radius</td>
<td>2.9 m</td>
<td>2.1 m</td>
</tr>
<tr>
<td>Extraction radius</td>
<td>5700 mm</td>
<td>4462 mm</td>
</tr>
<tr>
<td>Number of turns</td>
<td>140</td>
<td>186</td>
</tr>
<tr>
<td>Energy gain at extraction</td>
<td>6.3 MeV</td>
<td>2.4 MeV</td>
</tr>
<tr>
<td>$\frac{dE}{d\phi}$</td>
<td>11 mm</td>
<td>5.7 mm</td>
</tr>
<tr>
<td>Turn separation</td>
<td>7 s</td>
<td>7 s</td>
</tr>
<tr>
<td>Space charge limit</td>
<td>10 mA</td>
<td>2.2 mA (3.0 MV/turn)</td>
</tr>
<tr>
<td>Beam power</td>
<td>10 MW</td>
<td>1.3 MW</td>
</tr>
</tbody>
</table>
Several proposals, but no existing facility
Issues: CW front end (RFQ, DTL), operating efficiency of SC cavities/rf system

Low Energy Demonstration Accelerator (LEDA):
6.7 MeV, 100 mA CW (0.7 MW)
Successful demonstration of CW front-end
Bench-marking of halo simulation codes

High Intensity Proton Injector (IPHI, CEA) [R. Ferdinand]
3.0 MeV, 100 mA CW (0.3 MW)
First beam in 2006, to be used for SPL (CERN)

International Fusion Materials Irradiation Facility (IFMIF):
2 x 125 mA D⁺, 5 MeV (RFQ), 40 MeV (DTL) (2 x 0.6 MW, 2 x 5 MW)
Start 2009 (?)
Waste Storage Times

Products are longer lived (~30 years half life) than actinides (~10^5 years). Actinide waste needs storage for geological periods of time - Yucca mountain solution. EA produces actinide waste so the storage time is reduced.
The Conceptual design

Diagram showing the flow of materials and processes:
- Accelerator Complex
- Beam
- Energy Amplifier
- Fuel Discharge
- Fuel Loading
- Reprocessing (Partition)
- Actinides
- Fission Fragments
- Fuel fabrication
- Waste Packaging (Vitrification)
- Fresh Thorium Supply
- To Secular Repository

Power Generation (675 MW)
- Generator
- Turbine
- Condenser
- Heat exchanger

Spent fuel
- Reprocessing Complex (every 5 years)

Figure 1.1
Advantages of the EA:

Safety margin with different systems (fraction of delayed neutrons) as compared with that of an Energy Amplifier.

October 19, 2009
Rajendran Raja, AHIPA09, WG4 talk
Example of a 10 MW beam (Project X?); very close to the power of standard EA unit defined by C. Rubbia.

\[ \text{OUTPUT} \]

- 517 MWₑ
- 540 MWₑ
- 23 MWₑ
- 10 MW

**Project X**

\[ \text{Electrical Energy Converter} \]

\[ (\eta_{el} \sim 45\%) \]

\[ 1200 \text{ MW} \]

\[ \text{(Energy Amplifier)} \]

\[ k = 0.98 \]

\[ G = G_0 / (1-k) \]
SINQ and LANSCE experiences show 1 or 2 orders of frequency reduction might be necessary to meet the criteria.

Three strategies for reduction:
1. Reduction of the beam trip duration down to 1 sec.
2. Reduction of frequency for relatively long beam trip
3. Mitigation of the criteria by design consideration and detailed transient analysis.

Detailed analysis on the causes of the beam trips is underway to explore the realistic solutions for Strategy-1 and 2.
Nuclear and Particle Experimental Facility

Materials and Life Science Experimental Facility

Nuclear Transmutation

Linac (350m)

3 GeV Synchrotron (25 Hz, 1MW)

50 GeV Synchrotron (0.75 MW)

Neutrino to Kamiokande

J-PARC = Japan Proton Accelerator Research Complex
2.2 GeV, 1.8 mA, 4 MW, 50 Hz [R. Garoby (CERN)]

After Linac: DF: 8.2 %, $I_{\text{peak}} = 22$ mA (H$^-$)

After accumulator: DF: $\sim 10^{-4}$, $I_{\text{peak}} \sim 18$ A

After compressor: DF: $\sim 2 \times 10^{-5}$, $I_{\text{peak}} \sim 90$ A

Solid Nb super-conducting 704 MHz cavities

New Design

5.0 GeV

G $\sim 20$ MeV/m
1. Acceleration in a single machine

A linac is largely accepted as the best accelerator at least up to a few hundreds of MeV. Accelerating up to the final energy in a linac avoids beam transfers and guarantees very low beam loss in the accelerator itself.

2. Safe and proven set-up

There is no doubt that an sc linac can be built to reliably deliver multi-MW of beam power up to 4-8 GeV. Proof of existence is given by SNS.

3. “Easy” ring(s)

A synchrotron is needed to transform the long linac pulse (nx100 μs) into a small number of short bunches. It can however be simplified wrt an RCS and it is credible because of:
- no space charge
- no need to accelerate ( CW power supply and magnets, ordinary vacuum chamber, simpler RF system, no capture loss…)
- no time for instabilities to develop.
### Specifications (from ISS report)

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<thead>
<tr>
<th>Parameter</th>
<th>Basic value</th>
<th>Range</th>
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</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>10</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Burst repetition rate [Hz]</td>
<td>50</td>
<td>?</td>
</tr>
<tr>
<td>Number of bunches per burst (n)</td>
<td>4</td>
<td>1 – 6 ?</td>
</tr>
<tr>
<td>Total duration of the burst [µs]</td>
<td>~ 50</td>
<td>40 - 60</td>
</tr>
<tr>
<td>Time interval between bunches [µs] (t_{int})</td>
<td>16</td>
<td>~ 50/(n-1)</td>
</tr>
<tr>
<td>Bunch length [ns]</td>
<td>2</td>
<td>1 - 3</td>
</tr>
</tbody>
</table>

SPL-based 5 GeV – 4 MW proton drivers have been designed [SPL + 2 fixed energy rings (accumulator & compressor)] which meet these requirements.
SPL-based proton driver: principle

Beam accumulation
- Accumulator ring
  - Charge exchange injection
  - \( \sim n \times 100 \mu s \) accumulation time
  - Isochronous \((\eta = 0)\): beam frozen longitudinally to preserve \( \Delta p/p \)
  - No RF \((\Rightarrow \text{minimum impedance})\)
  - 1-6 bunches of \( \sim 120 \) ns length

Bunch compression
- Compressor ring
  - Large RF voltage (large stored energy & minimum RF power)
    \((\Rightarrow \text{bunch rotation on stored energy})\)
  - Large slippage factor \( \eta \) \(\Rightarrow\) rapid phase rotation in few \(x 10 \mu s\),
  - \(\sim 2 \) ns rms bunch length \(\at\) extraction to the target
    \((\Rightarrow \text{moderate } \Delta Q \text{ because of dispersion})\)

Synchronization between rings
- Ratio of circumferences guaranteeing correct positioning of successive bunches inside the compressor without energy change in any ring
Generation of 6 bunches

Accumulation
Duration = 400 µs

Compression

$\text{SPL beam}$
[42 bunches - 21 gaps]  

$\text{Accumulator}$
[120 ns pulses - 60 ns gaps]

$\text{Compressor}$
[120 ns bunch - $V(h=3) = 4$ MV]

$\text{Target}$
[2 ns bunches - 6 times]

Scenario for 6 bunches:
- $t = 0$ µs
- $t = 12$ µs
- $t = 24$ µs
- $t = 36$ µs
- etc. until $t = 96$ µs
<table>
<thead>
<tr>
<th><strong>SPL for proton driver</strong></th>
<th><strong>Output beam</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
<td><strong>Values</strong></td>
</tr>
<tr>
<td>Kinetic beam energy</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Average current during the burst</td>
<td>40 mA</td>
</tr>
<tr>
<td>Beam power</td>
<td>4 MW</td>
</tr>
<tr>
<td></td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th><strong>Accumulator</strong></th>
<th><strong>Compressor</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameters</strong></td>
<td><strong>Values</strong></td>
</tr>
<tr>
<td>Circumference</td>
<td>318.5 m</td>
</tr>
<tr>
<td>Transition gamma</td>
<td>6.33</td>
</tr>
<tr>
<td>RF voltage</td>
<td>-</td>
</tr>
<tr>
<td>Harmonics number</td>
<td>-</td>
</tr>
<tr>
<td>No. of arc cells</td>
<td>24</td>
</tr>
<tr>
<td>Super periodicity</td>
<td>2</td>
</tr>
<tr>
<td>Nominal transverse tune</td>
<td>7.77/7.67</td>
</tr>
<tr>
<td>No. of turns for accum.</td>
<td>400</td>
</tr>
<tr>
<td>Maximum no. of bunches</td>
<td>6</td>
</tr>
<tr>
<td>Main quadrupole</td>
<td></td>
</tr>
<tr>
<td>Bore radius</td>
<td>56 mm</td>
</tr>
<tr>
<td>Field gradient</td>
<td>5.5 T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>1.2 m</td>
</tr>
<tr>
<td>Main bending</td>
<td></td>
</tr>
<tr>
<td>Full gap</td>
<td>103 mm</td>
</tr>
<tr>
<td>Full width</td>
<td>162 mm</td>
</tr>
<tr>
<td>Field strength</td>
<td>1.7 T</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>1.5 m</td>
</tr>
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</table>
IT IS CLEAR THAT

there is no show-stopper for a multi-MW proton driver based on a 5 GeV SPL delivering 6 or even 3 proton bunches of ~2 ns rms length on target at 50 Hz.

reducing to a single bunch is probably not impossible, but much more challenging.

HOWEVER

the accumulator and compressor rings remain to be designed in detail (RF system, minimization of beam losses, design of collimation and collimators, H0 & unstripped H- beam dump, …).

R & D on H- stripping and charge exchange injection is mandatory. Laser-based stripping deserves study and experimental tests.

if high beam power and accumulator/compressor rings are implemented as upgrades, the corresponding needs have to be foreseen when initially building the superconducting linac.
pulse duration, \(N_b\) = number of bunches per pulse, \(\tau_b\) = final compressed bunch length.

<table>
<thead>
<tr>
<th>Power (MW)</th>
<th>Type</th>
<th>Energy (GeV)</th>
<th>Frequency (Hz)</th>
<th>Protons per pulse (\times 10^{13})</th>
<th>(\tau_p) ((\mu s))</th>
<th>(N_b)</th>
<th>(\tau_b) (ns)</th>
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<tbody>
<tr>
<td>1</td>
<td>Synch</td>
<td>28</td>
<td>2.5</td>
<td>9</td>
<td>720</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Synch</td>
<td>28</td>
<td>5</td>
<td>18</td>
<td>720</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Synch</td>
<td>40</td>
<td>5</td>
<td>12.5</td>
<td>720</td>
<td>24</td>
<td>3</td>
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<tr>
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<td>6</td>
</tr>
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<td>50</td>
<td>10</td>
<td>1.4</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
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<td>50</td>
<td>8.3</td>
<td>1.6</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
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<td>50</td>
<td>5</td>
<td>2.3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
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<td>(10^4)</td>
<td>0.06</td>
<td>0.4</td>
<td>10</td>
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<td></td>
<td>0.06</td>
<td>0.5</td>
<td>10</td>
<td>10</td>
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</table>
FNAL SCL Proton Driver Proposal

Super-conducting linac: 8.0 GeV, 0.25 mA, 2 MW, 10 Hz  [B. Foster (FNAL)]

After Linac: DF: 0.9 %, $I_{peak} = 28$ mA ($H^-$)

After MI (accumulator): DF: $\sim 6 \times 10^{-5}$, $I_{peak} \sim 5$ A

After MI (acceleration): 120 GeV, 2 MW, 0.7 Hz, DF: $\sim 4 \times 10^{-6}$, $I_{peak} \sim 5$ A

1.3 GHz Tesla cavities, stripping of $H^-$ (all fields < 600 G )
Option 4: a 3-GeV CW linac with a 650 MHz intermediate system, based on 5-cell cavities.

SSR0 SSR1 SSR2 $\beta=0.6$ $\beta=0.9$ ILC

325 MHz, 2.5-160 MeV 650 MHz, 0.16-2 GeV 1.3 GHz
2-3 GeV

Note: 650 MHz, $\beta=0.9$, 5-cell cavities are same physical length as 1300 MHz, $\beta=1.0$, 9-cell cavities
total number of cavities in each configuration:
C-2v1.0: 316 cavities (to 3 GeV)
C-2v2.0: 250 cavities (less if $\beta=0.95$)

Total linac length is reduced by $\sim 20\%$ (for 3 GeV)
  - Or, 3 GeV linac (option 4) is $\sim 20\%$ longer than the 2 GeV linac in IC-2v1.0

Early analysis of cost trade-offs indicate that 1300 MHz cavity becomes more cost effective than 650 MHz somewhere in the range of 2 GeV

Development of IC-2v2.0 (option 4) will allow us to explore issues related to introduction of a third frequency, and variations on the 300 MHz cavity shape
Primary parameters

5 MW long pulse source (upgrade to 7.5 MW?)

≤ 2 ms pulses

≤ 20 Hz

Protons (H+)

Low losses! 1 W/m

High reliability, >95%
Summary
Beam power efficiency

Beam power efficiency is an issue for high intensity accelerator.

\[
BPE = \frac{\text{beam power} \ (E \times I_{\text{beam}})}{\text{total operational power}}
\]

- BPE > 30% for \( P_b > 10 \text{MW} \), otherwise
  - Environment problem: CO2
  - ADSR becomes nonsense; Creating nuclear wastes more than treating!

- Superconducting magnet
  - High temperature SC is very attractive.
Comparative Advantages of RCS vs LAR

- Lower Beam Current
- Lower Injection Energy
- Higher Injection Beam Loss is allowed.
  (If one increases the beam energy by a factor of 7.5 times, the allowed beam loss during the injection is 7.5 times as high as that for AR with the same beam power.)
- Perhaps immune against the e-p instability?
- SNS debate in 1999 BNL(LAR) design or ANL(RCS) design?
RCS Challenges

- Lower injection energy in turn implies higher space charge effect.
- Large aperture magnets are required, giving rise to large fringing fields.
- Ceramics vacuum chamber with RF shield to avoid the eddy current effect.
- Stranded coil to overcome the eddy current effect on the magnet coils.
- Injection to make large aperture beam and its extraction are hard to manage.
- Precise magnet field tacking is necessary for each family of magnets.
- Powerful RF accelerating system for rapid acceleration.
Main challenges for future Multi-MW facilities

- **Beam Loss and collimation**
  - Maintainability requires losses $\sim 1 \text{ W/m}$
  - For 1 km/10MW facility: total losses of 1 kW or $10^{-4}$ at top energy
  - Since losses are not evenly distributed, lower values may be required at some locations

- **Power Consumption Efficiency**
  - Efficiency = (beam power)/(wall plug AC power)
  - Present facilities have typically low efficiency (few %)
  - Need new technologies for efficient beam power production

- **Design and Performance of High Power Production Targets and secondary beams**

- **Reliability and Availability for Users, especially for commercial power production**
Conclusions

- Multi-MW facilities are being planned with DF from CW to \(10^{-6}\)
- Designs for a CW facility with few MW beam power are mature, either by SPL or Cyclotron
- Several excellent and detailed designs for Multi-MW low DF facilities exist. The designs will benefit from the operational experience of recent projects (SNS, J-PARC).
- FFAG is not suitable for high intensity, but can provide high power through high rep rate (\(100\) to \(\sim\) KHz)
- Active R&D needed to improve performance, increase reliability, and reduce cost
- China is entering the field at a critical time for both technological advancement and industrial competitiveness.
References


2. “Upgrading the SNS Compressor Ring to 3 MW”, W. T. Weng, .et. Al., EPAC2002

Exercies

1. Changing one parameter at a time, how to raise SNS proton beam power from 1.0 MW to 2.0 MW by varying
   a. Beam energy
   b. Beam intensity
   c. Beam rep-rate

2. What is the best combination (realistic and cost-effective), by varying all possible parameters to reach 2 MW?

3. Compare the relative advantages of LAR and RCS design of CSNS design, in terms of
   a. Accelerator performance limitation
   b. Required changes of power supply, RF, and Vacuum
   c. Cost and reliability