Cyclotrons and superconducting linacs as high intensity driver accelerators

Mike Seidel, PSI

International Conference on Cyclotrons and their Applications
Zürich, Sep 16
Outline

• Proton Drivers and their Applications
• Specific technology aspects of cyclotrons and superconducting linacs
  – parameter reach (power/energy)
  – technology, complexity
  – energy efficiency
  – reliability/trip statistics
  – economy, size/cost
• Conclusion and Remarks
  – Pro’s and Con’s on Linear vs. Circular
Applications and Requirements for Proton Driver Accelerators

**proton drivers** are needed to generate **secondary radiation**, typically: **neutrons, muons, neutrinos**

**applications are:**

ADS, particle physics- and solid state physics research

- **energy:** ADS, Neutron Sources around 0.8..2GeV, others up to ~100GeV
- **power:** 1...15MW; ADS: $P_{\text{therm}} = P_{\text{beam}} \times G/(1-k)$
- **beam losses:** $\approx 1W/m$; PSI: 100W at critical location
- **reliability:** ADS: 0.01...0.1 trips per day(!)
- **efficiency:** as best as possible, $\eta=P_{\text{beam}}/P_{\text{grid}} = 20...50$
- **cost:** as low as possible; ADS: compare nuclear power plant: O(5B€)
optimum p-energy for neutron production?

![Graph showing n-production per particle and energy]

- Flat maximum around 1.1-1.2 GeV

# Proton Drivers – Concepts & Applications

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Muons</th>
<th>Neutrons</th>
<th>ADS</th>
<th>RIB’s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclotron</td>
<td>Daeðalus$^1$</td>
<td>PSI-HIPA TRIUMF</td>
<td>PSI-HIPA CIAE</td>
<td>AIMA$^2$ TAMU-800$^3$</td>
</tr>
<tr>
<td>RCS</td>
<td>J-PARC</td>
<td>J-PARC ISIS CSNS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FFAG</td>
<td></td>
<td></td>
<td>KURRI +ongoing studies$^4$</td>
<td></td>
</tr>
<tr>
<td>s.c. Linac</td>
<td>PIP II $^5$</td>
<td>PIP II $^5$</td>
<td>SNS ESS ISNS$^6$</td>
<td>ADSS$^7$ CIADS$^8$</td>
</tr>
</tbody>
</table>

1 Decay-at-Rest Experiment for $\delta cp$ studies At the Laboratory for Underground Science, MIT/INFN-Cat. et al
2 Accelerators for Industrial & med. Applications, reverse bend cyclotron, AIMA company
3 Cyclotron 800MeV, flux coupled stacked magnets, s.c. cavities, strong focusing channels, Texas A&M Univ.
4 FFAG studies, e.g. STFC
5 SRF linac, Proton Improvement Plan-II (PIP-II), Fermilab, Batavia
6 Indian Spallation Neutron Source, Raja Ramanna Centre of Advanced Technology, Indore, India
7 Accelerator Driven Sub-critical System at Bhaba Atomic Research Centre (BARC), Mumbai, India
8 China Initiative Accelerator Driven System, Huizhou, Guangdong Prov. & IMP, Lanzhou, China
intensity forefront today:
- SNS Linac: 1.4MW pulsed
- PSI cyclotron: 1.4MW CW
- J-PARC RCS: 0.5MW...1MW pulsed
Superconducting Linac

+ low RF losses (high Q) → effective energy transfer
+ large aperture (5..10cm) → low beam losses
+ strong focusing using quadrupole lattice → very high intensity possible
+ very high energy possible by adding length

- significant cryo losses at low T → limits overall energy efficiency
- each structure passed only once by beam → poor economy
- lengthy machine & building; complex and expensive technology
superconducting RF technology

**Advantages of s.c. technology:**
- tremendous progress over two decades! (DESY & TESLA collab.)
- CW operation possible, small RF losses (beware cryo efficiency)
- efficient power transfer; no overhead power for structures / couplers
- promising outlook for future dev.: high Q, high Tc materials, e.g.

*High Q₀ Development, A.Grassellino (FNAL), IPAC15*

s.c. resonators have extremely high Q, e.g. 2E10@1.3GHz (E-XFEL)

**at this Q a church bell would ring for 2 years(!)**
High fields generate a pressure on the cavity walls; due to the narrow resonance at high Q the frequency shift is significant.

\[ \Delta f \propto E^2 \]

Example SNS high beta cavity without and with detuning compensation [Delayen et al]
energy efficiency of s.c. Linacs

• contrary to s.c. coils, s.c. resonators are not loss free, losses are described by the surface resistance \( R_s \) with two components \( R_{BCS}, R_{res} \) (G geometry constant, ca. 300\( \Omega \)):

\[
R_s = R_{BCS}(T) + R_{res}(H_{ext}) \quad Q_0 = \frac{\omega U}{P_{dissip}} = \frac{G}{R_s}
\]

• the relation between dissipated power and voltage is given through \((R/Q)\):

\[
\left( \frac{R}{Q} \right) = \frac{U_a^2}{P_{dissip} Q}
\]

• cooling power at room temperature is much higher due to Carnot efficiency

\[
P_{cryo} = \frac{P_{cold}}{\eta_c \eta_p} \approx 700P_{dissip}@2K
\]
energetic efficiency of s.c. Linacs

Hypothetical example for 1GeV Linac, simplified: 100% single s.c. cavity type:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_f$</td>
<td>1 GeV</td>
</tr>
<tr>
<td>$U_a$ per cavity (1m)</td>
<td>15 MeV</td>
</tr>
<tr>
<td>(R/Q)</td>
<td>$10^{20} \Omega$</td>
</tr>
<tr>
<td>$Q$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$P_{\text{dissip}}$</td>
<td>$22W + 5W(\text{static})$</td>
</tr>
<tr>
<td>CoP (2K)</td>
<td>700</td>
</tr>
<tr>
<td>$P_{\text{cryo}}$</td>
<td>$18.9kW$</td>
</tr>
<tr>
<td>$\eta_{\text{RF}}$</td>
<td>55%</td>
</tr>
<tr>
<td>$\eta_{\text{tot}}(1mA, P_{\text{beam}} = 1MW)$</td>
<td>32%</td>
</tr>
<tr>
<td>$\eta_{\text{tot}}(5mA, P_{\text{beam}} = 5MW)$</td>
<td>48%</td>
</tr>
</tbody>
</table>

Comment: pulsed linacs have much lower efficiency
S.c.Linac: Parameter Examples

parameters* for high-\(\beta\) part of proton linac:

<table>
<thead>
<tr>
<th>facility</th>
<th>(E_{\text{range}}) [MeV]</th>
<th>(P_{\text{beam}}) [MW]</th>
<th>avg Grad. [MV/m]</th>
<th>Freq [MHz]</th>
<th>(n_{\text{cav}})</th>
<th>length [m]</th>
<th>(P_{\text{coupler}}) [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS</td>
<td>382-974</td>
<td>1.4</td>
<td>12,3</td>
<td>805</td>
<td>48</td>
<td>90</td>
<td>18</td>
</tr>
<tr>
<td>ESS</td>
<td>561-2000</td>
<td>5.0</td>
<td>19,0</td>
<td>704</td>
<td>84</td>
<td>177</td>
<td>43</td>
</tr>
<tr>
<td>CADS</td>
<td>367-1500</td>
<td>15.0</td>
<td>10,4</td>
<td>650</td>
<td>85</td>
<td>(\approx200)</td>
<td>135</td>
</tr>
</tbody>
</table>

* taken from conf. papers, subject to adjustments

note: **these gradients** are moderate as compared to the electron linacs at 1.3GHz (20kW per coupler)
s.c. linac RF coupler

example: TESLA design, courtesy: W.D. Möller (DESY)

type: coaxial (antenna),
two ceramic windows, intermittend vacuum,
Conditioning critical

cavity
limitation for s.c. linacs: power per coupler

→ high beam power at moderate energy is difficult due to limited power transfer per coupler

\[ P_{\text{tot}} = n \times P_{\text{coupl}} \]

CW values achieved in tests at CERN: courtesy E. Montesino

→ established operating values are low today, e.g. SNS, E-XFEL
tuning experience in SNS Linac @ 1MW

Mike Plum, ORNL, HB2012:
empirically optimized for low losses, linac and transport lines

→ beam core optics is obviously mis-matched, presumably beam tails
  “feel”deviating optics and are better transported in this case
→ also at PSI (cyclotron) we rely much on empirical tuning 😊
## Summary s.c. linacs – specific aspects

<table>
<thead>
<tr>
<th></th>
<th>comment</th>
<th>performance</th>
<th>economy</th>
<th>technical challenge</th>
<th>outlook</th>
</tr>
</thead>
<tbody>
<tr>
<td>high Q</td>
<td>low loss, but at low T, Lorentz force detuning</td>
<td>good</td>
<td>good</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>advanced cavity material</td>
<td>extremely pure Nb (energy!), advanced surface treatment</td>
<td>bad</td>
<td></td>
<td>yes</td>
<td>sputtering, coating</td>
</tr>
<tr>
<td>cooling efficiency</td>
<td>Cop(2K) ≈ 700(!)</td>
<td>bad</td>
<td></td>
<td></td>
<td>high Q, high Tc mats.</td>
</tr>
<tr>
<td>crucial coupler</td>
<td>for high current high power transfer required- bottleneck</td>
<td>bad</td>
<td>bad</td>
<td>yes</td>
<td>good CERN Results</td>
</tr>
<tr>
<td>multiple cav. per klystron</td>
<td>regulation problem, lowest cav. limits performance</td>
<td>bad</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Isochronous Separated Sector Cyclotron

+ multiple acceleration with same resonators $\rightarrow$ economy
+ continuous wave acceleration naturally possible
+ relatively compact layout
+ good energy efficiency
- extraction critical $\rightarrow$ energy limitation (less severe for stripping extraction)
- relatively weak focusing $\rightarrow$ intensity limitation
- large radial orbit variation $\rightarrow$ wide vacuum chamber and magnets (forces!)

PSI Ring cyclotron:
- 590MeV, 1.4MW
- diameter 15m, 186 turns
- extraction septum
- RF: Grid-to-beam: 32%
cyclotron technology: resonators

- $f = 50.6 \text{MHz}$; $Q_0 = 4.8 \times 10^4$; $U_{\text{max}} = 1.2 \text{MV}$ (presently 0.85 MV)
- Transfer of up to $\frac{1}{2} \text{ A}, 400 \text{ kW}$ power to the beam per cavity
- Wall Plug to Beam Efficiency (RF Systems): 32%

hydraulic tuning

new

beam(s)

loop coupler @ 50MHz
cyclotron technology: sector magnets

cyclotron magnets typically cover a wide radial range → magnets are heavy and bulky, thus costly

PSI sector magnet

- iron weight: 250 tons
- coil weight: 28 tons
- Field: 2.1T
- orbit radius: 2.1…4.5 m
- spiral angle: 35 deg

Riken SRC sector magnet

- weight: 800 tons
- Field: 3.8T, 5000A
- orbit radius: 3.6…5.4m

field map
cyclotron extraction

for clean extraction of protons a large turn separation is of utmost importance

general scaling at extraction:

\[ \Delta R(R_{\text{extr}}) = \frac{U_t}{m_0 c^2 (\gamma^2 - 1)} \frac{R_{\text{extr}}}{\gamma} \]

desirable:
- limited energy (< 1GeV)
- high energy gain \(U_t\)
- large radius \(R_{\text{extr}}\)

scaling during acceleration:

\[ \frac{dR}{dn_t} \approx \frac{U_t}{m_0 c^2 \beta^2} \frac{R}{\beta^2} \rightarrow \Delta R(R) \propto \frac{1}{R} \]

illustration: stepwidth vs. radius in cyclotrons of different sizes;
100MeV inj \(\rightarrow\) 800MeV extr
cyclotron extraction PSI
- tedious tuning

red: tracking simulation [OPAL]
black: measurement

dynamic range:
factor 2.000 in particle density

position of extraction septum
d=50µm

[Y.Bi et al]
Charge exchange extraction schemes

accelerate H⁻ or H₂⁺ to extract protons

extraction by charge exchange in foil
eg.: H⁻ → H⁺
     H₂⁺ → 2H⁺

binding energies

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H⁻</td>
<td>H₂⁺</td>
</tr>
<tr>
<td>0.75eV</td>
<td>15eV</td>
</tr>
</tbody>
</table>

stripped electrons may deposit energy in the foil, 1/2000 of beam power

Comments:
- H⁻: significant probability for unwanted loss of electron; Lorentz dissociation: B-field low, scattering: vacuum 10⁻⁸mbar
- H₂⁺: unfavorable charge to mass ratio (economy); complex extraction path or reverse bend needed
- e⁻ may be deposited in foil
Cyclotron Intensity limitations: space charge

Longitudinal space charge → transverse tails → losses at extraction [Joho 1981]

\[
\Delta U_{sc} = \frac{8}{3} e I_p Z_0 \ln \left( \frac{4w}{a} \right) \cdot \frac{n_{\max}^2}{\beta_{\max}} \approx 2.800 \Omega \cdot e I_p \cdot \frac{n_{\max}^2}{\beta_{\max}}
\]

\[
\frac{1}{\Delta R_{extr}} \propto n_{\max}
\]

→ Attainable current scales as Voltage\(^3\)

Transverse space charge → reduces focusing, tune shift

\[
\ddot{y} + \left( \omega_c^2 \nu_0^2 - \frac{n_v e^2}{\epsilon_0 m_0 \gamma^3} \right) y = 0
\]

\[
\Delta \nu_y \approx -\sqrt{2\pi} \frac{r_p R}{e \beta_c \nu_0 \sigma_z} \frac{m_0 c^2}{U_t} \cdot I_{\text{avg}}
\]

→ This limit is for cyclotrons more severe than for Linacs
High intensity cyclotrons: Studies

- $\text{H}_2^+ \text{ AIMA Cyclotron w reverse bend, multiple 60keV injection [P.Mandrillon et al]}
- $\text{H}_2^+ \text{ Daedalus cyclotron [neutrino source, L.Calabretta et al]}
- \text{TAMU: s.c. magnet, stacked cyclotron w strong focusing [P.McIntyre et al]}

\begin{center}
\includegraphics[width=\textwidth]{diagram.png}
\end{center}
reliability, today's performance

→ Today at least 3 orders of magnitude missing, for both acc.types
reliability, concepts

proposed solution: **redundancy** and automatic readjustments; in Linac: cavity failure is compensated by redistribution of lost energy gain; with cyclic accelerator or injector: use more than one accelerator

![Diagram showing two cavities with a fault between them](image)

**numerical example:**
tube: MTBF=5000h; MTTR=8h
- Linac with 80 tubes, accepting 0 fault:
  \[ \text{MTBF}_{\text{eff}} = 62h \]
- Linac with 80 tubes, accepting 1 fault (\(k=1\)):
  \[ \text{MTBF}_{\text{eff}} = 1.074h \]
- Linac with 80 tubes, accepting 2 faults:
  \[ \text{MTBF}_{\text{eff}} = 26.067h \]
- Cyclotron with 4 tubes, accepting 0 faults:
  \[ \text{MTBF}_{\text{eff}} = 1.250h \]

**binomial distribution,**
\[ B_p = \text{incomplete Beta Function} \]
\[
P_{\text{eff}} = \sum_{m=k}^{n} \binom{n}{m} p^m (1 - p)^{n-k} = B_p(k, n - k + 1)
\]
facility size

cyclotron facility shielding, e.g. d=3m, 2x23mx23mx11m: 12.400m³ concrete
linac facility shielding, e.g. d=3m, 8x8x200 + 23mx23mx11m: 25.800m³ concrete

- cyclotrons should have an advantage in view of building size and shielding volume
- the lengthy character of the linac tunnel implies more restrictions on the choice of the construction site
about cost

cost estimates for new projects need detailed studies, thus focus on numbers for existing machines to give an impression on the possible cost range

example SNS, courtesy: N. Holtkamp [2006, USD]:

<table>
<thead>
<tr>
<th>Description</th>
<th>Accelerator</th>
<th>MCHF [1975/78]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Support</td>
<td>75.6</td>
<td></td>
</tr>
<tr>
<td>Front End Systems</td>
<td>20.8</td>
<td>20.8</td>
</tr>
<tr>
<td>Linac Systems</td>
<td>311.0</td>
<td>311.0</td>
</tr>
<tr>
<td>Ring &amp; Transfer System</td>
<td>146.6</td>
<td>146.6</td>
</tr>
<tr>
<td>Target Systems</td>
<td>108.2</td>
<td></td>
</tr>
<tr>
<td>Instrument Systems</td>
<td>63.3</td>
<td></td>
</tr>
<tr>
<td>Conventional Facilities</td>
<td>378.9</td>
<td></td>
</tr>
<tr>
<td>Integrated Control System</td>
<td>58.5</td>
<td>58.5</td>
</tr>
<tr>
<td>BAC</td>
<td>1,162.9</td>
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<tr>
<td>Contingency</td>
<td>29.8</td>
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<tr>
<td>TEC</td>
<td>1,192.7</td>
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<tr>
<td>R&amp;D</td>
<td>99.9</td>
<td>79.9</td>
</tr>
<tr>
<td>Pre-Operations</td>
<td>119.1</td>
<td>95.3</td>
</tr>
<tr>
<td>TPC</td>
<td>1,411.7</td>
<td></td>
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</tbody>
</table>

inflation 06-16 USA: $≈+22% → 870M$

example PSI-HIPA, courtesy: U. Schryber [1995]:

<table>
<thead>
<tr>
<th>Description</th>
<th>MCHF [1975/78]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring Cyclotron</td>
<td>31.1</td>
</tr>
<tr>
<td>Injector II Cycl. + CW</td>
<td>22.5</td>
</tr>
<tr>
<td>Buildings + Infrastructure</td>
<td>51.5</td>
</tr>
<tr>
<td>Sum accelerator:</td>
<td>53.6</td>
</tr>
<tr>
<td>+ inflation factor* 2016 (+120%):</td>
<td>120MCHF</td>
</tr>
</tbody>
</table>

*not reliable
### Summary – p-Driver Accelerators

<table>
<thead>
<tr>
<th></th>
<th>Isochronous Cyclotron</th>
<th>S.C. Linac</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter Reach</strong></td>
<td>-</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>- $E_k \approx 1\text{GeV}$, diminishing turn separation</td>
<td>- large aperture $\rightarrow$ intensity</td>
</tr>
<tr>
<td></td>
<td>- focusing limit, $\approx 5\text{MW?}$</td>
<td>- strong focusing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- unlimited energy</td>
</tr>
<tr>
<td><strong>Reliability</strong></td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>- simplicity, but..</td>
<td>- redundancy possible, but ..</td>
</tr>
<tr>
<td></td>
<td>- tedious tuning, extraction</td>
<td>- otherwise complex system</td>
</tr>
<tr>
<td><strong>Economy</strong></td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>- comparably compact</td>
<td>- many expensive cavities, cryogenics, energy consum.</td>
</tr>
<tr>
<td></td>
<td>- classic technology</td>
<td>- lengthy building</td>
</tr>
<tr>
<td></td>
<td>- huge magnets</td>
<td></td>
</tr>
<tr>
<td><strong>Outlook</strong></td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td></td>
<td>- new concepts are discussed, community comparably weak</td>
<td>- high Tc development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- high Q treatments</td>
</tr>
</tbody>
</table>

**Subjective:** in community less cyclotron expertise than linac expertise $\rightarrow$ bias on choice of technology
thank you for the attention!