High power proton/deuteron accelerators

J-Luc Biarrotte (CNRS, IPN Orsay)
1. General overview

2. Elliptical-based SRF H linacs
3. Fully-SRF CW H/D linacs
4. Summary
High power H/D beams around the world

SRF-based high-power machines are to become more & more numerous
High power SRF linacs: NC to SC transition

- **NC/SC transition** ideally minimizes overall power consumption \( \sim \text{DC} \times (P_{\text{cav}} + P_{\text{beam}}) + P_{\text{cryo}} \)

- **For CW operation**, “SRF As Low As Reasonable Achievable” (i.e. down to the RFQ) has become the worldwide rule

SRF made feasible the production of very high power CW beams

-> most SRF present ion projects are CW
High power SRF linacs: RF structures

- QWRs
- HWRs & CHs
- Elliptical cavities
- Spoke cavities
- HI linacs
- D linacs
- H linacs (pulsed)
- H linacs (cw)

RF frequency (MHz)
Cavity beta

Non exhaustive plot!
The ones I will NOT talk about

- Heavy-ions high power linacs
  - SPIRAL-2, that will be the world first CW high power SC linac for p, d & A/q=3 ions
  - F-RIB
  - RAON

- Long-term planned SC upgrades of NC machines
  - J-PARC -> 400 MeV ACS upgrade in construction, upgrades using SRF foreseen (R&D might restart in 2014)
  - C-SNS -> 80 MeV DTL in construction, upgrade using SRF spoke cavities foreseen
  - KOMAC -> 100 MeV DTL in construction, 1 GeV upgrade using SRF foreseen

- “Far future” projects with low visibility and/or poor R&D activities (Eurisol, Indian-ADS...)
High power H/D SRF linacs

The ones I will talk about

- The present reference = SNS

- The “under construction” machines (or nearly)
  - ESS
  - SARAF
  - LIPAC (IFMIF demonstrator)
  - PXIE (Project X demonstrator)

- The other “under design” on-going projects (the major ones)
  - SPL
  - MYRRHA
  - C-ADS
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The SNS @ Oak Ridge

- SNS = the first high-energy SRF linac for H + the first MW-class one (pulsed but at relatively high DC: 6%)

Running well (availability >90%)

3 years to ramp the beam power up to 1 MW

3 MW upgrade plan (PUP)
  - 1.3 GeV upgrade
  - beam current upgrade
  - @ constant gradients

Replacement of DTL+CCL by SRF linac is considered

See S.H. Kim MOP007

See M.S. Champion MOP002
5MW mean power, pulsed at 4% DC

Design very similar to SNS, except that CCL is replaced by SRF spoke cavities

- Technological innovation
- "Optimus" 2 GeV new layout to reduce costs
  - Higher current (50 -> 62.5mA), same DC
  - Less cavities (-17 cryomodules)
  - Higher gradients (+11.25%): $E_{pk} = 45$ MV/m

Construction is about to start
First beam planned in 2019
4MW mean power, pulsed at 2% or 4% DC

Linac4 (= SPL front-end) is under construction

Linac4 connection to PS is planned in 2016

SPL status = R&D on $\beta=1$ cryomodule

Listen to O. Capatina FRIOB04
Beam losses & SC linac activation

- Activation is well contained in the SNS, but unpredicted beam losses have been observed.
- Losses recently explained by intra-beam stripping.
- Use H+ instead of H- if possible!! (losses /30)

SC linac has proven to be substantially more reliable than the NC linac despite the high number of RF stations & the complexity of cryogenics

- Less than 1 trip of the SC linac per day.
- Trips dominated by RF systems.
- Trips due to cavities are mainly due to errant beam hitting cavity surface (BLM trips from discharge/arching in warm linac).
- Cavity degradation is observed (usually recovered by thermal cycling).
- Multiple cryomodule repairs in house (coupler window leaks, He & vacuum leaks, tuner failures, HOM couplers...)

SCL system downtime breakdown

Cavity trip breakdown

Production Hours

- FY13 (Oct’12-May’13): 4683 hrs
- FY12: 5098 hrs
- FY11: 5437 hrs
Design constraint #1: Cavity gradients

- Cavity gradient is directly related to cost -> tendency to push the gradients
- SNS experiences a huge gradient variability -> needs for margins & operational flexibility !!

✓ Almost every SNS run, a few cavities have problems, resulting in lower $E_{\text{acc}}$ or turn-off -> linac retuning
✓ Achievable gradients are mainly limited by heating by electron activity at high duty factor (especially by induced collective limits)

<table>
<thead>
<tr>
<th>Facility</th>
<th>$\beta$</th>
<th>Gradient (MV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNS</td>
<td>0.61</td>
<td>10.2</td>
</tr>
<tr>
<td></td>
<td>0.81</td>
<td>15.8</td>
</tr>
<tr>
<td>SPL</td>
<td>1.0</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>19</td>
</tr>
<tr>
<td>ESS</td>
<td>0.65</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>0.86</td>
<td>20.0</td>
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<tr>
<td>ProjectX</td>
<td>0.61</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>17.0</td>
</tr>
<tr>
<td>MYRRHA nom</td>
<td>0.65</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>8.2</td>
</tr>
<tr>
<td>MYRRHA</td>
<td>0.5</td>
<td>8.2</td>
</tr>
<tr>
<td>SNS</td>
<td>0.81</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Ex. CM13 individual limits: 19.5, 15, 17, 14.5 MV/m
Ex. CM13 collective limits: 14.5, 15, 15, 10.5 MV/m
Design constraint #2: Power couplers

- The maximal power given by the power coupler to the cavity is a clear limit for linac designers, especially for pulsed high-current machines
  - SNS design limit: 550kW peak (48kW average), tested up to 2MW in test stand
  - SPL design limit: 1.0 MW peak (about 100kW average)
  - ESS design limit: 1.1MW peak (about 100kW average)

- Most of the high-power couplers design are very similar
  - Scaled from the original KEK 508 MHz coupler
  - Coaxial, single warm window, fixed coupling

- What about concentrating the R&D effort worldwide on a single design for all machines (1MW pulsed / 100kW CW)?
  - Would be then easier to push the limits towards higher powers (2MW...)

See R. Bonomi THP049

See E. Rampnoux THP065

See SNS, CEA, MYRRHA, FNAL, SPL, ESS, CARE-HIPPI Couplers
o **HOM couplers are not mandatory** (has become a general agreement)

- HOM voltages build-up is naturally damped (thanks to the high HOM frequency dispersion especially)
- Simple check that HOM are away from main machine lines (detuning/retuning can help if needed)
- **SNS HOM feedthroughs are being taken out**
- **No HOM couplers foreseen for ESS, Project X & MYRRHA cavities**

o **Tuners**

- Most of the slow mechanical tuners are based on the CEA Saclay design
- Contrary to SNS, **active detuning w/ piezo actuators are a necessity for ESS and SPL**, due to higher gradients and therefore higher Lorentz dynamic detunings

o **Cryomodules**

- Mostly from CEBAF-like or DESY-style concepts
- Innovative solutions are developed (e.g. SPL module)
- **Minimize static heat loads** is important for **pulsed machines**
- **For CW machines** -> the main concern is to **minimize dynamic heat loads** and therefore **maximise Qo**
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Challenges for CW high power SRF machines

- **Peak beam current is lower but mean beam current is usually higher**
  - SNS = 1mA, ESS = 2.5mA, MYRRHA = 4mA, C-ADS = 10 mA, IFMIF = 125mA !!
  - Beam loss mitigation and MPS management remain very high concerns
  - Reinforced by **SC structures at very low energies** (“soft” beam, small apertures, RFQ tails...)
  - Low peak beam current (except IFMIF) -> lowest RF coupling -> narrowest bandwidth -> management of microphonics is to be considered (a 2K bath helps!)

- **CW RF operation**
  - Dynamic heat loads dominates cryogenics -> Qo is an important cost driver
  - General agreement for **2K operation** down to 350 MHz spoke at least (Project-X, MYRRHA are even fully 2K)
  - Thermal issues on room-temperature elements (couplers, RFQ is non trivial !!!!)
  - Solid-state amplifiers when possible !!

- **SC cavities at the RFQ output** (or nearly)
  - Low-beta SRF (QWR, HWR, spoke...) is not yet very mature for high current beams: the only SC operating cavities with a high current beam are the HWR SARAF ones -> **technology demonstration is required**
  - High compactness is required for SC injectors due to beam dynamics constraints, but compromise is to be found vs operational ease, maintenance, beam diagnostics...
- 3MW H- beam power at 3GeV
- SRF from 2.1 MeV, 2K operation
- HWR, Spoke, Elliptical
- Main challenge = demonstration of the SRF injector

Listen to L. Ristori FRIOB02
Listen to S.S.Som FRIOB03
Front-end demonstrator PXIE is under construction (25 MeV, 1mA)

- Goal = validate Project X concept & eliminate technical risks (compact lattice layout)
- Beam operation planned between 2016 & 2018
- Cavities under fabrication

**Cavity Type**
- **HWR**
  - **Frequency**: 162.5 MHz
  - **Optimal β**: 0.112
  - **Effective Length**: 20.7 cm
  - **Aperture**: 33 mm
  - **$E_{\text{peak}}/E_{\text{acc}}$**: 4.7
  - **$B_{\text{peak}}/E_{\text{acc}}$**: 5.0 mT/(MV/m)
  - **$G$**: 48 Ω
  - **$R_{sh}/Q$**: 272 Ω

See P. Ostroumov MOP066

See A.I. Sukhanov MOP014
o Present operation performance

- 1mA CW protons at 4 MeV (2.1mA at 2 MeV)
- 4.8 MeV deuterons at 50% dc

o World first HWR operation with (high-current) beam !!

o Main present limitations of the (6 cav) PSM

- Simultaneous operation of all cavities at nominal field was not achieved for long period (despite efficient He processing)
- Heating of the power couplers (cold window)
- Microphonics management & piezo actuators degradation

o New plan for 40MeV upgrade by 2019 = contract w/ vendor
IFMIF and the LIPAC demonstrator

- **IFMIF** = 5MW D beam (40 MeV, 125mA CW)
- **LIPAC** demonstrator: 1.1MW (9 MeV, 125mA )
  - HWR concept similar to PXIE (but 4K)
  - First beam in 2016
- **First HWR prototype qualified (VC)**
- Additional challenge compared to SARAF/PXIE
  - -> 50 times more beam current !!!
  - Beam transport tuning, beam losses control...
  - 70kW CW per cavity !

Listen to N. Bazin THIOD03

See H. Jenhani THP056
2.4 MW cw proton beam @600 MeV

- Decision for construction 2015

Specific additional challenge = Reliability
(i.e. avoid beam interruptions)

- Redundant & compact injectors
(based on CH cavities)

- R&D on fast fault-recovery schemes
  - Compensate RF faults in main linac (<3sec)
  - Margins required on operation points
  - Fast piezo-based tuners

- R&D on main SRF components: CH, spokes, elliptical

See J-L. Biarrotte MOP018
See D. Mäder MOP065
See M. Bush THP003
See F. Bouly MOP057
Very ambitious ADS program
- Injectors by 2015
- ~1 GeV by 2022
- ~15 MW ADS by 2032

Same chosen reliability-oriented concepts as MYRRHA
- Redundant injector
- Fault tolerance in main linac

Based on FNAL/ILC frequency

Active R&D on SRF, especially the 2 front-ends @IMP & @IHEP
Chinese-ADS SRF activities

See S. He THP081

See P. Sha THP028

See H. Li THP022

See S. Jin THP017

See X. Chen THP050

See S.C. Huang THP015

See Z.Q. Li THP021
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Summary (personal view)

- High-power H/D accelerators have been made feasible thanks to SRF
- More & more SRF machines & projects, especially CW with SRF from RFQ on
- 2000-2030 will clearly be the “golden age” for SRF high-power linacs
  -> Enjoy! before new technologies appear (e.g. plasma acceleration)

- Present main R&D challenges
  - High gradients for pulsed machines (ESS, SPL)
  - Demonstration of SRF-based injectors is required (PXIE, SARAF, LIPAC)
  - Piezo-actuators base tuners become a necessity; reliability is to be improved

- Clear & high potential for synergies & collaborations
  - R&D on HWR and spoke cavities
  - Potential for common cavity and/or cryomodule designs (e.g. ESS/SPL/MYRRHA elliptical 0.65)
  - Potential for a common high-power coupler design to overtake the present 1MW pulsed limit
  - ADS R&D to improve reliability can be a potential benefit to all future projects
  - Solid-state amplifiers revolution
TY for your attention and…

➢...sorry for all possible mistakes & omissions...

➢...a warm thanks to all colleagues & friends for providing me useful information!

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