Outline

• Introduction
• Multi-GeV recirculating superconducting proton linac
• Beam dynamics design/simulation of a double pass proton linac
• Effects of overtaking collision in the CW double pass proton linac
• Field error sensitivity
• Conclusions and future work
High Power GeV Superconducting Proton Linac Can Have Many Applications in Science and Industry

- Accelerator driven tritium production
- Driver for spallation neutron sources
- Driver for high energy physics studies
- Accelerator driven nuclear energy production
- ...
Accelerator Production of Tritium

Superconducting Linac:
- Significant power savings and lower operating and capital cost
- Allow much larger aperture at high energies
- Permits greater operational flexibility

Accelerator Driven Spallation Neutron Sources

Front End: Produces a 1-ms-long, chopped, low-energy $^1$H$^-$ beam

Linac: Accelerates the beam to 1 GeV

Accumulator ring: Compresses a 1-ms-long pulse to 700 ns

$^1$H$^-$ stripped to

Beam sent to target


Table 1: ESS Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012 Baseline</th>
<th>2013 Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion species</td>
<td>Proton</td>
<td>Proton</td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>Beam power [MW]</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Beam current [mA]</td>
<td>50</td>
<td>62.5</td>
</tr>
<tr>
<td>Beam pulse [ms]</td>
<td>2.86</td>
<td>2.86</td>
</tr>
<tr>
<td>Duty cycle [%]</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 1: Block layout of the ESS baseline linac 2013, OptimusPlus (not to scale). Warm colored boxes represent the normal conducting components and cold color boxes the superconducting sections.

M. Eshraqi et al., 2014.
Accelerator Driver for High Energy Physics Applications

Figure III-1: The Project X Linacs

Accelerator Driven System for Nuclear Energy Production


But **Superconducting Proton Linac is Expensive**...

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**Linac vs. RCS Revisited**

- Project X was a fairly mature, linac-based proposal that would produce high power at 60-120 GeV, while supporting a broad program at lower energies
  - It was judged to be **too expensive**.
- The current charge is to find the most cost effective way to *achieve the physics goals of DUNE*
  - Currently no explicit mandate for a low energy program
- Unless there’s a huge breakthrough in SRF technology, an RCS is the best way to do this, HOWEVER
- The charge says the final recommendation “may include alternatives”
  - The alternative will almost certainly be a linac-based option.
  - Reduced costs and/or changing physics priorities may well make that the ultimate frontrunner.

- Eric Prebys at 2015 Fermilab workshop

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**A Potential Lower Cost Solution: Recirculating Proton Linac**
Recirculating Electron Linac has been built and under operation (e.g. JLAB Recirculating Electron Linac)

But there is no recirculating proton linac in the world...
Significant Differences between Proton Linac and Electron Linac

- Electron velocity approaches to speed of light over a few MeVs
- Acceleration efficiency (transit time factor) independent of energy
- Typical electron linac consists of a single type of RF cavity (C band or S band or SC or ...)

- Proton velocity varies during the process of acceleration up to GeV
- Acceleration efficiency depends on the proton energy
- Typical proton linac consists of many type of RF cavities with different geometries (DTL, CCL, CCDTL, SC,...)

recirculating linac uses a single type of RF cavity for multiple energy beam
A Reasonable Proton Energy Bandwidth Can Be Achieved with Appropriate Choice of RF Cavity Structure

\[ \Delta E_c = qVT \cos(\phi) \]

\[ T_0(\beta) = \frac{2\beta}{\pi n} \left( \frac{\sin(\pi n(\beta - \beta_G)/(2\beta))}{\beta - \beta_G} - (-1)^n \frac{\sin(\pi n(\beta + \beta_G)/(2\beta))}{\beta + \beta_G} \right) \]

- A single type of cavity can cover a range of proton energy with appropriate cell numbers
- A multi-GeV recirculating proton linac could be realized with multiple energy sections
The Total Number of RF Cavities Can Be Optimized w.r.p the Cavity Geometry Beta and Transition Energy

Energy Averaged Transit Time Factor:

\[ T(\beta_G) = \frac{m c^2}{\Delta E_{max}} \int_{\beta_{in}}^{\beta_{out}} \frac{T(\beta, \beta_G) \beta}{(1 - \beta^2)^{3/2}} d\beta \]

Maximum Energy Gain in Two Sections:

\[ \Delta E_{1,2_{max}} = qV_1N_1T_1 + qV_2N_2T_2 \]

Two sections, \( E_{in} = 150 \text{ MeV}, E_{out} = 2 \text{ GeV}, V_1 = V_2 = 13 \text{ MV} \)
A Multi-Section Multi-GeV Recirculating Proton Linac (~a factor of 5 reduction of superconducting cavities)

- Total number of superconducting cavities: 494 -> 107
- Shorten the distance of straight accelerating section

Fermilab 650 MHz 5 cell superconducting cavity (CW): $E_{acc} \geq 15MV/m$

Relative RF Acceleration Phase Changes in Multiple Beam Passes

\[ \Delta E_1 = V_1 T_1 \cos(\omega t + \phi_1) \quad \Delta E_2 = V_2 T_2 \cos(\omega t + \phi_2) \]

Phase slippage with proton energy:

\[ \delta \phi = \omega \frac{D}{V} \rightarrow \text{distance between RF1 and RF2} \]
\[ \delta \phi = \omega \frac{D}{V} \rightarrow \text{proton velocity after RF1} \]

Possible solutions:
• Fast adjustment of RF cavity driven phase versus energy
• Fast adjustment of RF cavity frequency versus energy
• Use of synchronous acceleration condition:

\[ t_i^m - t_i^n = \pm k T_{rf}, \quad k = 0, 1, 2, 3, \ldots \]
Synchronous Condition Can be Met with Variable Separation of Cavities in the Two Pass Section

No need to adjust RF cavity phase/frequency during the two pass acceleration

Proton Kinetic Energy vs. Distance

Separation Distance vs. Cavity Number
Phase Shifter Can be Used for Multiple Proton Beam Passes

Parameters:

\[ B, E, l_1, l_2 \]

\[ P = BR \]
\[ R = \frac{l_1}{\sin \alpha} = \frac{P}{B} \]
\[ \alpha = \arcsin\left(\frac{Bl_1}{P}\right) \]

Path equation:

\[ \text{path} = 2 + 4 \arcsin\left(\frac{Bl_1}{P}\right) \cdot \frac{P}{B} + 2 \frac{l_2}{\sqrt{1 - \left(\frac{Bl_1}{P}\right)^2}} \]
Beam Dynamics Design/Simulation of the Double Pass Section

### On-Axis Field Distribution of the RF Cavity and Other Parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch current</td>
<td>20, 40 mA</td>
</tr>
<tr>
<td>Normalized transverse emittance</td>
<td>0.23 mm mrad</td>
</tr>
<tr>
<td>Normalized longitudinal emittance</td>
<td>3.0° MeV</td>
</tr>
<tr>
<td>Radio frequency</td>
<td>650 MHz</td>
</tr>
<tr>
<td>Radio-frequency geometric beta $\beta_G$</td>
<td>0.63</td>
</tr>
<tr>
<td>Accelerating gradient</td>
<td>14 MV/m</td>
</tr>
<tr>
<td>Radio-frequency phase</td>
<td>$-30^\circ$</td>
</tr>
</tbody>
</table>

![On-axis field profile of the SC cavity and the buncher cavity](image-url)
Non-Periodic Lattice Design by Optimizing the Envelope Oscillation and Emittance Growth w.r.p Quadrupole Settings

- Alternative phase focusing is used to enhance the transverse focusing for the 1st four cavities
- Integrate the Differential Evolution optimizer with self-consistent beam-dynamics simulation using the IMPACT(Z) code.
- Maintain smooth envelope oscillation evolution.
- Control emittance growth.

\[
\text{cost} = w_\sigma \sum_{i=0}^{N} \sum_{j=x,y} (\sigma_j(i) - \sigma)^{p_\sigma} \\
+ w_\epsilon \sum_{j=x,y,z} (\epsilon_j(L) - \epsilon_j(0))^{p_\epsilon}
\]
Berkeley Lab Accelerator Simulation Toolkit

Detailed modeling of:
• beams, plasmas, laser-plasma inter., linacs, rings, injectors, plasma accelerators, traps, ...

Using state-of-the-art codes:
• BEAMBEAM3D, IMPACT, INF&RNO, POSINST, WARP.

With original advanced algorithms:
• boosted frame, IGF, laser envelope, SEY, AMR, relativ. particle pusher, symplectic space-charge model, EM spectral Circ, ...

http://blast.lbl.gov

- Key Features include:
  - Time-dependent and position dependent
  - Serial and massive parallelization
  - Detailed 3D RF accelerating and focusing model, dipole, solenoid, multipole, ...
  - Multiple charge states, multiple bunches
  - 3D space-charge effects
  - Structure + resistive wall wakefields
  - Coherent synchrotron radiation (CSR)
  - Incoherent synchrotron radiation (ISR)
  - Gas ionization
  - Photo-electron emission
  - Machine errors and steering
- Can be used to model beam dynamics in:
  - Photoinjectors
  - Ion beam formation and extraction
  - RF linacs

J. Qiang et al., PRAB 20, 054402, 2017.
FFT based Green function method:
- Standard Green function: low aspect ratio beam
- Shifted Green function: separated particle and field domain
- Integrated Green function: large aspect ratio beam
- Non-uniform grid Green function: 2D radial non-uniform beam

Fully open boundary conditions

Spectral-finite difference method:
- 2D open boundary
  - Transverse regular pipe with longitudinal open

Multigrid spectral-finite difference method:
- Transverse irregular pipe
Reasonably Smooth Envelope Oscillation Evolution and Small Emittance Growth in the 1st Pass

Graph showing the evolution of envelope oscillation (σ_{x,y}) and normalized emittance (ε/norm.) over the first pass.
Smooth Envelope Oscillation Evolution and Small Emittance Growth in the 2nd Pass
Reasonable RMS Sizes and Emittance Evolution in the 1\textsuperscript{st} Arc
Reasonable RMS Sizes and Emittance Evolution in the 2nd Arc

\[ \sigma_{x,y} \text{ (mm)} \]

\[ \Delta \varepsilon/\varepsilon \]

X

Y

\[ \text{norm. } \varepsilon \text{ (mm mrad)} \]

z (m)
Reasonable Transverse RMS Sizes and Emittances Evolution through the Double Pass Proton Linac from S-2-E Simulation

\[ \sigma_{x,y} \text{ (mm)} \]

\[ \Delta \epsilon/\epsilon \text{ (mm mrad)} \]

\[ z \text{ (m)} \]
Reasonable Longitudinal RMS Size and Emittance Evolution through the Double Pass Proton Linac from the S-2-E Simulation
Effects of Overtaking Collision in CW Double Pass Proton Linac

Injector frequency 162.5 MHz, SC frequency 650 MHz, 10 collisions

Simulation of the Overtaking Collision Effects Using the IMPACT-T Code Including Space-Charge Forces of Both Energy Bunches

- Convert the particle distributions from Z to T.
- Calculate the space-charge forces from itself and the space-charge forces from the other energy bunch.
- Advance protons with both space-charge forces and external forces.

**computation domain**
RMS Sizes Evolution w/o Collision through the 1st Cavity
RMS Emittances Evolution w/o Collision through the 1<sup>st</sup> Cavity
RMS Sizes Evolution w/o Collision through the Double Pass Linac
RMS Emittances Evolution w/o Collision through the Double Pass Linac
Mismatch Factor Evolution of No-Collision and Two-Bunch Collision through the Double Pass Linac

\[ M = \sqrt{1 + \frac{\Delta + \sqrt{\Delta(\Delta + 4)}}{2}} - 1 \]

\[ \Delta = (\Delta_x)^2 - \Delta_y \]
Similar Phase Space Distributions at the Exit of the Linac w/o Collisions

less than 20% differences in all Twiss parameters
# Effects of Random Field Errors in the Double Pass Proton Linac

<table>
<thead>
<tr>
<th>Cavity</th>
<th>Static Errors</th>
<th>Dynamic Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase</td>
<td>± 1°</td>
<td>± 0.5°</td>
</tr>
<tr>
<td>Amplitude</td>
<td>± 1%</td>
<td>± 0.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Quad</th>
<th>Static Errors</th>
<th>Dynamic Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>gradient</td>
<td>± 0.5%</td>
<td>± 0.05%</td>
</tr>
</tbody>
</table>
Horizontal RMS Size Evolution with 100 Set of Random Errors

Final RMS Size:
- Reference: 2.17 mm
- With Errors Avg: 2.37 mm
- Growth: 9.2%
Vertical RMS Size Evolution with 100 Set of Random Errors

Final RMS Size:
- Reference: 2.48 mm
- With Errors Avg: 2.65 mm
- Growth: 6.9%
Longitudinal RMS Size Evolution with 100 Set of Random Errors

Final RMS Size:
- Reference: 1.2 degree
- With Errors avg: 1.29 degree
- Growth: 7.5%
Conclusions and Future Work

• A multi-GeV multi-section recirculating superconducting proton linac can substantially save the accelerator construction and operation costs.
• Beam dynamics simulation in the two-pass section demonstrates the simultaneously accelerating and focusing of two energy beams.
• Overtaking collisional effect between the low energy bunch and the high energy bunch is small and would not preclude the CW operation of the accelerator.
• Field sensitive study suggests that the accelerator would be insensitive to these errors.

➢ Beam steering with misalignment errors
➢ Design of multiple pass phase shifter
➢ Design of multiple pass arcs
➢ Failure mode study

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Thank You!