Recirculation Optics for XFEL-O

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Introduction

• XFEL-O is an idea\textsuperscript{1} for a high-brightness x-ray source
  – Oscillator x-ray FEL using crystals as x-ray mirrors
• Requires high-quality beam
  – 7 GeV or higher
  – 0.1 micron normalized emittance
  – 0.02\% rms momentum spread
  – 20~40 pC in a 2 ps rms bunch
  – Few MHz bunch spacing
• A multi-pass linac may have cost advantages
  – Beam quality preservation is the main challenge
  – Complexity also a concern
• Design may be informative for multi-pass ERLs
• Designed and evaluated system using \textit{elegant}\textsuperscript{2}

\textsuperscript{2}M. Borland, APS LS-287, 2001; Y. Wang \textit{et al}., PAC07, 3444-3446.
System Schematic and Overview

Vertically-stacked TME-cell arcs

x/y emittance exchange

Vertically-stacked TME-cell arcs (100m average radius)

Vertically stacked TME-cell arcs

Vertical combiners

Vertical separators

550 MeV input beam

Horizontal injection dogleg

2.36 GeV/pass linac

10 GeV output beam

\(^{1}\text{M. Borland, Proc. PAC09, TU5RFP048, to be published.}\)
Design Sequence

- Match multi-pass linac optics for four beams
- Design emittance preserving arcs with same average radius for three beam energies
- Design x-y rotator and relay optics
- Match injection system to linac 1\textsuperscript{st} pass
- Match from linac to 1\textsuperscript{st} arc
- Match from 1\textsuperscript{st} arc to relay optics
- Reverse solutions to get to exit of 2\textsuperscript{nd} arc
- Match from arc to linac 2\textsuperscript{nd} pass
- Repeat for subsequent passes
- Match from final linac pass through extraction system
- In total, about 140 \textit{elegant} runs needed
  - Passing information between runs with SDDS files helps prevent errors and insanity
Linac Configuration

• Very similar to ERL@APS linac designs\(^1\)
  – 20 MV/m in 1-m-long, 1.3 GHz cavities
  – Doublet focusing

• Started with graded-gradient solution\(^2\):
  Set quadrupoles to give constant focal length for lowest energy beam

• Optimized all four passes simultaneously in two steps
  – Optimize common focal length, spacing to minimize the maximum beta functions
  – Refine, allowing all gradients and spacing to vary independently
  – Major goal is to reduce maximum beta functions
  – Initial lattice functions allowed to vary at each energy
    • Makes matching to upstream systems harder later on...

\(^1\)M. Borland et al., Proc AccApp'07, 196-203 (2007).
Linac Optics Solution

Graph showing the variation of $\beta_x$ and $\beta_y$ (in m) as a function of $s$ (in m) from 550 MeV to 10.00 GeV.

- 550 MeV to 2.91 GeV
- 2.91 GeV to 5.27 GeV
- 5.27 GeV to 7.63 GeV
- 7.63 GeV to 10.00 GeV
Arc Designs

• Emittance growth per pass scales like

\[ \frac{\gamma^5}{f^2 N_d^3 R} \]

where \( f \) is the dipole filling fraction, \( N_d \) is the number of cells, and \( R \) is the mean radius.

• To keep \( R \) small, need lots of cells for higher-energy arcs
  – Chose a mean radius of 100m

• Used TME cells for arcs
  – 2.9 GeV: 15 cells per 180 arc plus dispersion suppressors
  – 5.3 GeV: 31 cells per arc, plus suppressors
  – 7.6 GeV: 63 cells per arc, plus suppressors

• Dispersion suppressors use half-length, half-angle dipoles

• Sextupoles are included, but set at zero for now
Example of Arc Optics

![Graph showing the behavior of arc optics parameters over distance](image-url)
Injection

- Need to inject 550 MeV beam without perturbing recirculating beams
- Decided to use a horizontal chicane and septum
- Avoids having the 550 MeV beam go through strong vertical combiner dipole
- Keeps injector linac and main linac at same height

Beams from vertical combiner → Horizontal chicane → Beams to linac

- Beams: 550 MeV, 0.5T, 1.8T, 7.6 GeV, 2.9 GeV
- Horizontal bend (15.5 degrees)
Injection Optics

Initial lattice functions free to vary
Relay Optics and Emittance Exchange

- Beam is transported between arcs using triplet cells (“relay” optics)
- Optional x-y rotation allows exchanging emittances
  - Share emittance growth between x and y planes
  - Rotation module starts and ends at position of waists in the relay system
  - Require 4 skew quadrupoles to exchange emittances
  - 7 additional normal quads used for matching
  - Can be turned off easily due to incorporation of a relay triplet into the sequence of normal quads
Rotation Module Example ($\varepsilon_x = 2\varepsilon_y$)

Without rotation

With rotation
Vertical Separators (Combiners are Similar)

- Beam from linac must be fanned out into the arcs
- Used vertical doglegs with a common first dipole
- 10 GeV beam will also see this dipole

- Some magnet collisions evident
- Can stagger quads and sexts
- Consider multi-axis or off-axis yoke designs
- Use shielded tubes if needed
- Use septum for middle magnet of 10 GeV chicane

Geometry plot made with modified version of a script by A. Petrenko (FNAL).
Separator Optics (Combiners are Similar)

- Sextupoles needed to prevent emittance growth from chromatic aberrations
- Sextupole strengths, positions optimized by tracking
Full System Optics (Rotators Off)

$\beta_x (m)$

$\beta_y (m)$

$\eta_x (m)$

$\eta_y (m)$
Tracking Results (SR, Q=0, Rotation On)
Tracking Results (SR, Rotation On)
Conclusions

- Developed optics solution for a four-pass linac and recirculation system
- Realistic optics design with all components included
- Some element collisions, but looks solvable
- Less than 30% emittance growth in both planes
- No issues with CSR
- x-y rotators share emittance growth between planes
  - Requires low energy spread to avoid emittance growth
  - How will it work with errors, non-ideal beams?
- Is this cheaper than a straight linac?
  - ~250 bends, ~1200 quads, ~1100 sextupoles
- Perhaps a two-pass system is a good compromise
  - I.e., a single 5 GeV recirculation arc