Complete Muon Cooling Channel Design & Simulations*

*Work supported in part by DOE STTR grant DE-SC 0007634.
Outline

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  • Tasks (The Challenge)
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*https://indico.fnal.gov/conferenceDisplay.py?confId=6437
Preliminaries

• Work reported here was supported under a phase I STTR grant with JLAB, Slava Derbenev subgrant PI.
• MuPlus, Inc. has been awarded a phase II STTR grant to complete the design.
  • Notification: March 4, 2013.
  • Start date: April 22, 2013.
• We had weekly meetings with attendance and/or input by:
  • Slava Derbenev, Vasily Morozov, Rol Johnson, Chuck Ankenbrandt, Dave Neuffer, Katsuya Yonehara, Jim Maloney, & Cary Yoshikawa
• All simulations were performed with G4beamline*.

Overview

The overarching goal is to design a complete cooling channel for a muon collider that is dual purpose.

1. Higgs Factory* (heavier $\mu$ mass benefits)
   - Production in s-channel in MC.
   - Direct measurement of the Higgs mass width of $\sim 4$ MeV/c$^2$.
2. Energy Frontier Machine
   - Obvious discovery enabler.
   - Utilize Higgs Factory investment.

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*Accelerators for a Higgs Factory: Linear vs. Circular (HF2012) https://indico.fnal.gov/conferenceDisplay.py?ovw=True&conflId=5775
Overview

- Small energy spread (~4 MeV/c²) for the s-channel Higgs Factory!
- No final cooling scheme (no emittance exchange).
HCC Overview

The Helical Cooling Channel (HCC):
- has a theory behind it*
- its concepts can be applied to a wide variety of beam dynamics
- has coil configurations and RF cavities that can generate the necessary fields

Phase I Highlights: Tasks (The Challenge)
(see 2/15/2013 MAP Friday meeting for details)

The primary phase I tasks were:
1. Extend the HCC theory to design matching sections between cooling segments.
2. Apply the matching section design between a pair of segments in an existing design to reduce/avoid emittance blowup, which will reduce particle losses and allow for a shorter channel.

Parameters of the 7 HCC cooling channel segments used by Yonehara [IPAC10, MOPD076]. All Z values (except for 0) refer to the end of a segment with segment number designated by unit value.

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Downstream Segment Without an Upstream Matching Section

- Green line: $e^{6D/10}$-NotMatched ($\text{mm}^3$)
- Purple line: $N(\text{wrt SegUpStreamEnd}) \times 10(10=100\%)$-NotMatched

z (m)

0 10 20 30 40 50 60 70 80 90

0 2 4 6 8 10 12

Cary Y. Yoshikawa
UCLA Higgs Workshop, March 22, 2013
Phase I Highlights: Results

- Developed a way to match longitudinal phase space over a short distance.
  - Key concept: Use of mixture of upstream and downstream RF cavities to manipulate effective slope of RF field, which controls longitudinal dynamics.

- Developed a way to match transverse phase space over a short distance.
  - Key concept: Recognize inherent long/trans coupling and enforce constant slip factor during transverse/radial matching.
Application of Matching Techniques

Matching Sections Between Upstream & Downstream Segments

Upstream Segment | Downstream Segment

Z(m)

long. match | transverse/radial match

eperp (mm) | elong (mm) | e6D (mm^3) | N(wrt SegUpStreamEnd)x10 (10=100%)
Phase I Highlights: Results

Downstream Segment With and Without an Upstream Matching Section

- e6D/10-Matched (mm³)
- N (wrt SegUpStreamEnd) x 10^(-10) - Matched
- e6D/10-NotMatched (mm³)
- N (wrt SegUpStreamEnd) x 10^(-10) - NotMatched
Phase I Highlights: Results

Downstream Segment With and Without an Upstream Matching Section

new channel length?
Phase I Highlights: Results

- Developed a way to match longitudinal phase space over a short distance.
- Developed a way to match transverse phase space over a short distance.
- A demonstrated example is a 5.25 m long matching section that is able to shorten a 90 m HCC segment to 40 m (45.25 m total) and achieve better performance!
  - Lower $\varepsilon_{6D}$
  - Higher particle survival rate
- These techniques are of general use and are not restricted to an HCC.
Phase II Plan

Major Technical Tasks Proposed

1. Redesign of HCC Segments and Matching Sections
   • cognizant of an extreme cooling scheme (EPIC)
2. Study Dynamics with Space Charge
3. Computational Tool Development (G4beamline enhancements)
Redesign of HCC Segments and Matching Sections

- The HCC segments will be redesigned from the start using particle tracks generated by the Neuffer front end to account for correlations generated in that subsystem. Matching in and out of straight sections will be developed.
- The HCC segments will follow three design guiding principles:
  1. The upstream segments will be optimized for acceptance.
     - A preliminary study showed that doubling the thickness of the Be windows on the RF cavities increased the $\epsilon_{6D}$ acceptance by 27%.
  2. The next set of segments will be optimized for maximal cooling rates to minimize the channel length. (Less decay and cost.)
  3. The last stage will make the beam as cold as possible by operating in a configuration with the lowest $\epsilon_{6D,\text{equil}}$ that potentially involves a lower momentum (higher $dE/dx$).
     - Higgs Factory version: will use wedge shaped RF windows to minimize $\epsilon_L$.
     - Energy Frontier version: will use flat RF windows to minimize $\epsilon_{6D}$.
     - These non-pressure bearing windows can be thought of replaceable inserts on the timescale of a transition from HF to EF.
- Each segment will be designed with analytic fields, followed by a design of coils that generate those fields as close as possible and a reevaluation utilizing coils.
- Be cognizant of possible downstream extreme cooling schemes (EPIC).
Optimization of Cooling Performance

- Balance between operating at:
  - Large cooling rates → minimizes channel length and decay losses.
  - Large energy loss rate → to achieve smallest $\epsilon_{\text{equiv}}$.

\[ \varepsilon_{N,T} \propto \frac{1}{ds} \]

Cooling is possible as long as $\Sigma_g > 0$, although it will be at a slower rate for smaller $\Sigma_g$.

We’ll strive for the lowest $\epsilon_{\text{equiv}}$ at the end of the channel.
Extreme Cooling Scheme: EPIC

Resonant dynamics: angular spread grows while beam size shrinks

The team is currently trying to find the best set of parameters to demonstrate PIC in the presence of full stochastic effects.
Study Dynamics with Space Charge

Must understand dynamics (especially longitudinal for a Higgs factory) of an intense bunch in a matter-dominated cooling channel.

- Identify relevant effects: space charge, charge screening in a dielectric medium, cavity loading, etc.
- Extend existing analytic and numerical tools to include these effects
- Explore space charge compensation and optimize the channel’s parameters
- Test and optimize the scheme in numerical simulations
Computational Tool Development  
(G4beamline enhancements)

G4beamline will be enhanced to support design and evaluation of the complete cooling channel. In particular, there will be:

- Faster computation of tracks
- Space charge computation improvements
- Parallelization improvements
- Additional physics processes
- Improved Emittance Calculation
  - ~incorporate vector potential
Summary

- We have a coherent plan spanning phase I and phase II SBIR/STTR’s to develop a Complete Cooling Channel for a Muon Collider.

- In phase I,
  - We have extended the HCC theory to match the beam dynamics longitudinally and transversely.
    - The underlying principles can be applied to other designs.
  - Application of our newly developed matching design to the most challenging transition achieved amazing results!
    - A 5.25 m long matching section is able to shorten a 90 m segment to 40 m (45.25 m total) and achieve better performance!
  - G4beamline was enhanced to support this effort and the larger community benefited (g-2).
    - Utilizing all improvements results in gain by a factor or 35,000!
Summary

- In phase II for which we have just received a grant, we will:
  - Redesign of HCC Segments and Matching Sections
  - Study Dynamics with Space Charge
  - Support Computational Tool Development (G4beamline enhancements)
- We are grateful to have been awarded the phase II grant and look forward to designing and simulating a complete cooling channel for a muon collider applicable to a Higgs Factory and Energy Frontier machine.
Back up
Performance Schedule (Tasks and Milestones)

Six months after start of funding:

- Segment and Matching Designs
  - A matching section out of the Neuffer front end and into an HCC segment that is similar to the first segment in the original design is completed.
  - Creation of criteria to determine end of a segment and need for the start of the next, most likely driven by cooling rate, is underway.

- Lowest Final Emittance
  - Study of optimal momentum to provide coldest beam underway.

- Space Charge, etc.
  - Identify effects determining the longitudinal dynamics.
  - Extend the analytic theory to take these effects into account.
  - Search the parameter space for the optimal longitudinal dynamics scenario.

- Computational Tool Development
  - G4beamline tracking efficiency improvements implemented.
  - G4beamline space-charge calculation able to handle a helical reference trajectory.
Twelve months after start of funding: (required for 2\textsuperscript{nd} year of funding)

- Segment and Matching Designs
  - Early segments that are maximized for acceptance are designed along with their matching sections.

- Lowest Final Emittance
  - Study of optimal momentum to provide coldest beam completed.

- Space Charge, etc.
  - Explore space charge compensation mechanisms.
  - Identify or develop numerical tools to simulate the longitudinal effects.

- Computational Tool Development
  - G4beamline space-charge calculations parallelized efficiently on Hopper at NERSC.
  - Improved Emittance Calculation
Eighteen months after start of funding:

- **Segment and Matching Designs**
  - Segments that are maximized for cooling rate are designed along with their matching sections.
  - If space charge permits, bunch merging and re-cooling would have commenced.

- **Space Charge, etc.**
  - Identify or develop numerical tools to simulate the longitudinal effects.

- **Computational Tool Development**
  - Additional physics processes incorporated into our simulations, as appropriate.
24 months after start of funding

- **Segment and Matching Designs**
  - Segment optimized for the coldest beam possible and its matching section is implemented into the HCC for both:
    - a Higgs Factory using shared wedge shaped RF windows.
    - an Energy Frontier machine using shared flat RF windows.
  - Matching section out of the HCC and into a straight channel that will accelerate the muons is completed.
  - Measure effect of tolerance of beam elements on performance.

- **Space Charge, etc.**
  - Optimize and finalize the longitudinal dynamics simulations.

- **Computational Tool Development**
  - Additional physics processes incorporated into our simulations, as appropriate.
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Downstream Segment Without an Upstream Matching Section

![Graph showing downstream segment without an upstream matching section with data points and lines representing e6D/10-NotMatched(mm^3) and N(wrt SegUpStreamEnd)x10(10=100%)-NotMatched.](image-url)
Phase I

The primary phase I tasks were:

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Matching Section Design

The new matching techniques will be illustrated via an application between segments 4 and 5.

In each plot, 37 particles were injected on reference trajectory with reference energy, separated in time by 10 degree increments with respect to full RF wavelength and propagated for 20 HCC periods ($\lambda_{HCC}$).

Seg 4
$\lambda_{HCC} = 0.8\text{ m}$
325 MHz

Seg 5
$\lambda_{HCC} = 0.5\text{ m}$
650 MHz
Matching Section Design

Matching will proceed in two steps, first longitudinally then radial/transverse.

- We match longitudinally first for practical reasons, so that the initial match will be to RF cavities that are small enough to fit into the subsequent smaller-aperture HCC.
- Segment 4a is an intermediate virtual channel introduced to facilitate the design of the matching section by defining the configuration at end of the longitudinal matching section and start of the transverse matching section.
  - Same $\lambda_{HCC}=0.8m$ as upstream Seg4 and same $f=650$ MHz as downstream Seg5.
  - “Virtual” => zero-length
- Longitudinal matching will proceed from segment 4 to 4a.
- Radial/transverse matching will proceed from segment 4a to 5.

Shown are synchrotron oscillations (a) in segment 4, (b) in virtual segment 4a, and (c) in segment 5.
Matching Section Design

Matching will proceed in two steps, first longitudinally followed by radial/transverse.

- We match longitudinally first for practical reasons, since the initial match will be to smaller RF cavities that must fit into the downstream smaller HCC.

Segment 4a is introduced as an intermediate virtual channel that borders the longitudinal and transverse matching sections.

- It has the same $\lambda_{HCC} = 0.8$ m as upstream Seg4 and $f=650$ MHz as downstream Seg5.

Quarter synchrotron oscillations

Cary Y. Yoshikawa
UCLA Higgs Workshop, March 22, 2013
The longitudinal matching concept is adapted from a method used to match rapidly between initial and final voltages $V_i$ and $V_f$ by jumping to an intermediate voltage $V_{\text{inter}} = \sqrt{V_i V_f}$ for a quarter synchrotron period.

Recall that the longitudinal dynamics is controlled by slope of accelerating voltage around the synchronous particle, which is proportional to both:
- Accelerating voltage
- RF frequency

The segments to be matched here have the same accelerating voltage, so we’ll use RF frequency to adjust the slope for matching.
Longitudinal Matching Design

- Rather than using cavities with an intermediate frequency $f_{\text{inter}} = \sqrt{f_i f_f}$, we used an appropriate mix of cavities running at the upstream and downstream frequencies*:
  - 59% of the upstream frequency (325 MHz) and
  - 41% of the downstream frequency (650 MHz).

In practice, we used a mix of 60%/40%.

Note that if higher gradients are allowed for higher frequencies, then voltage, frequency, and $\cos(\phi_s)$ should be adjusted to preserve the geometric mean of their product*:

$$V_{\text{int}} f_{\text{int}} \cos(\phi_{s,\text{int}}) = \sqrt{V_1 V_2 f_1 f_2 \cos(\phi_{s,1}) \cos(\phi_{s,2})}$$

*See backup slides for derivation.
Longitudinal Matching Design
1.25 m (quarter synchrotron oscillation)
Transverse Matching Design

- Recognizes the strong inherent coupling between the longitudinal and transverse dynamics in the HCC.
- The transverse matching proceeds by conserving the slip factor $\eta$.

\[
\eta = \frac{\sqrt{1 + \kappa^2}}{\gamma \beta^3} \left( \frac{\kappa^2}{1 + \kappa^2} \hat{D} - \frac{1}{\gamma^2} \right)
\]

where:

- $\gamma$ and $\beta$ are the usual relativistic parameters
- $\hat{D}$ is the dispersion factor: $\frac{p}{a} \frac{da}{dp}$ where “$p$” and “$a$” are the reference momentum and cylindrical radius, respectively.

- The value is near that for equal cooling decrements, but modified from 1.915 to 1.805 to take into account the slope of the rate of energy loss $dE/dx$ w.r.t $dp$ and to increase the acceptance.

- $\kappa$ is the pitch of the helical channel: $\frac{p_{\text{transverse}}}{p_{\text{longitudinal}}} = 2\pi a = 1$
Transverse Matching Design (cont.)

The B field dependence on $\lambda_{HCC}$ is $\sim 1/\lambda_{HCC}$:

$$b_z \propto b_\phi \propto \frac{db_\phi}{da} \propto \frac{1}{\lambda_{HCC}}$$

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Transverse Matching Design (cont.)

Radial matching from $\lambda_{HCC} = 0.8$ m to $\lambda_{HCC} = 0.5$ m is linear over a longitudinal distance of 4m (1 full synchrotron oscillation length).

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<th>$\sigma_x \sigma_{px}$ (mm-MeV/c)</th>
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<td>16.14</td>
<td>17.62</td>
<td>284.39</td>
<td>14.6</td>
<td>23.6</td>
<td>344.56</td>
</tr>
<tr>
<td>4</td>
<td>14.39</td>
<td>18.41</td>
<td>264.92</td>
<td>11.42</td>
<td>25.27</td>
<td>288.58</td>
</tr>
</tbody>
</table>

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Transverse Matching Design (cont.)

Radial matching from $\lambda_{HCC} = 0.8$ m to $\lambda_{HCC} = 0.5$ m is linear over a longitudinal distance of 4m (1 full synchrotron oscillation length).

<table>
<thead>
<tr>
<th>$z$ (m)</th>
<th>0</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_t$ (nsec)</td>
<td>0.1412</td>
<td>0.1329</td>
<td>0.1247</td>
</tr>
<tr>
<td>$\sigma_E$ (MeV)</td>
<td>7.3710</td>
<td>7.4730</td>
<td>7.3810</td>
</tr>
<tr>
<td>$\sigma_t \sigma_E$ (MeV-nsec)</td>
<td>1.0408</td>
<td>0.9932</td>
<td>0.9204</td>
</tr>
</tbody>
</table>
Results of application to the most difficult transition

Matching Sections Between Sections 4 and 5

- Longitudinal match
- Transverse/radial match

Graph showing various measurements (e.g., eperp(mm), elong(mm), e6D(mm^3), N(wrt Seg4End)x10(10=100%)) along Z(m) from 0 to 6.
Results of application to the most difficult transition
Segment 5 With and Without Upstream Matching Section

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Results of application to the most difficult transition

Segment 5 6-D Emittance With and Without Upstream Matching Section

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Results of application to the most difficult transition

Remarks on Consequences of Matching

- The unmatched Seg5 has emittance blow-up in the first ~5m and takes another ~45m to recover to $\varepsilon_{6D}$ at start of the channel.
- The unmatched Seg5 takes 57m to reach the $\varepsilon_{6D}$ at the start of the matched Seg5, which was achieved over 5.25m in the matching sections.
- A 5.25 m long matching section is able to shorten a 90 m HCC segment to 40 m (45.25 m total) and achieve better performance!
  - Lower $\varepsilon_{6D}$
  - Higher particle survival rate
- These techniques are of general use to channels of other designs!