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Accelerating Muons to TeV Scale

Energies on the Fermilab Site** Energies on the Fermilab Site

J. Scott Berg Brookhaven National Laboratory Fermilab APT Seminar

February 6, 2024

HOM @BrookhavenLab

Muon Collider Motivation Muon Collider Motivation
• Recent strengthening of interest in physics at the 10 TeV scale
• Would require ≈100 TeV CoM with protons
• Electrons Muon Collider Motivation
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• Electrons
• Would radiate too much in a ring **Muon Collider Motiva**
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• A linear collider is long and expens **uon Collider Motivation**

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• A linear collider is long and expensive, plus beamstr

S **Muon Collider Motivatio**
• Recent strengthening of interest in ph
• Would require \approx 100 TeV CoM with providency of the Muons of Muons and expensive, position So instead use muons of the Mudamental particles, all energy

- **uon Collider Motivation**
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Would require ≈100 TeV CoM with protons

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So instead u Frequent strengthening of interest in physics at the 10 TeV scanned Would require ≈100 TeV CoM with protons

Flectrons

• Would radiate too much in a ring

• A linear collider is long and expensive, plus beamstrahlung cha
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Muon Colliders and P5

- **Muon Colliders and

 From the draft report:

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extince for these aparaties (e.g. 44 uon Colliders and P5**

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• options for these energies (e.g., 100 TeV protons, 10 **Colliders and P5**
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10 TeV pCM muon collider at Fermi **ION Colliders and P5**
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• "we recommend targeted collider R&D to establish the feasibility of a

• The US pCM muon collider." Note they do *not* intend to close off other

options for these energies (e.g., 100 TeV protons,
	-
	- facilities within the next 10 years"
	- concert with the International Muon Collider Collaboration (IMCC)"

Muon Collider Facility Overview Muon Collider Facility Overview
• Proton driver creating high-power proton beam
• Front end: create pions at target, capture muons, convert to bunch train
• Cooling: reduce emittance, combine into one bunch **Muon Collider Facility Overview
• Proton driver creating high-power proton beam
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• Acceleration** Muon Collider Facility Overview
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• Acceleration: Muon Collider Facility Ov
• Proton driver creating high-power proton beam
• Front end: create pions at target, capture muons,
• Cooling: reduce emittance, combine into one bun
• Acceleration: increase energy
• Collider rin

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Target and Initial Capture

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• Proton beam (1–4 MW) hits target, and producing pions, decay to muons
• Pions produced with a large producing pions, decay to muons
- **Target and Initial Capture
• Proton beam (1–4 MW) hits target,
• Pions produced with a large
• Pions produced with a large
• angular and energy spread but a
• small spot size** angular and energy spread but a small spot size
- **Target and Initial Capture**

 Proton beam $(1-4 \text{ MW})$ hits target, moducing pions, decay to muons

 Pions produced with a large

angular and energy spread but a

small spot size

 Target is in a high field solenoid
 $(15–20$ T), which tapers down to a lower field to capture a large angular divergence

Capture of Bunch Train **Capture of Bunch Train
• Beam develops a time-energy correlation
• RF cavities form bunches
• Adjust RF frequencies to give bunches similar energies Capture of Bunch Train**
• Beam develops a time-energy correlation
• RF cavities form bunches
• Adjust RF frequencies to give bunches s **Capture of Bunch Trange Capture of Bunch Tranger**
• Beam develops a time-energy contract RF frequencies to give bunches
• Adjust RF frequencies to give bunch stars for both muon signs

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Ionization Cooling

- **ionization Cooling
• Lose transverse and longitudinal momentum
• Large angular divergence in absorber relative to** in absorber **initially and the control of the control**
	- multiple scattering: strong focusing, high field
-
- **Ionization Cooling

 Lose transverse and longitudinal momentum

 Large angular divergence in absorber relative to

 multiple scattering: strong focusing, high field

 Restore longitudinal momentum in RF cavity

 Dipo** transverse to longitudinal, cool longitudinally $\frac{1}{2}$ $\frac{$ • Lose transverse and longitudinal momentum

in absorber

• Large angular divergence in absorber relative to

multiple scattering: strong focusing, high field

• Restore longitudinal momentum in RF cavity

• Dipole field a
- and cool more

Acceleration to High Energy: Outline **Acceleration to High Energy: Outline**
• High-level factors driving accelerator design
• Pulsed synchrotrons (RCS)
• Fixed field alternating gradient accelerators (FFAs) **Acceleration to High Energy Section**
• High-level factors driving accelerator
• Pulsed synchrotrons (RCS)
• Fixed field alternating gradient accele **Acceleration to High Energy: Outline**
• High-level factors driving accelerator design
• Pulsed synchrotrons (RCS)
• Fixed field alternating gradient accelerators (FFAs)

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Ring Size

- **Ring Size**
• 50 TeV protons require a ring 10 times larger than 5 TeV muons:
• This is pretty much true for the collider ring. So a 10 TeV center of right? Well, sort of.
- **Ring Size**
• 50 TeV protons require a ring 10 times larger than 5 TeV muons:
right? Well, sort of.
• This is pretty much true for the collider ring. So a 10 TeV center of
mass collider ring fits comfortably on the Fermila mass collider ring fits comfortably on the Fermilab site; an equivalent proton collider would not. • 50 TeV protons require a ring 10 times larger than 5 TeV muons
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equiv **ing Size**

0 TeV protons require a ring 10 times larger than 5 TeV muons:

ght? Well, sort of.

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nass collider ring fits comfortably on the Fermilab sit **FORT ASSET AND THE ASSET AND THE SIS SPET AND THE SIS COLLIDET FING IS SPET AND THE SCOLLIDET FINGLE AND quivalent proton collider would not.** Coeleration is more com
- -
	- superconducting magnets in this time. But you could ramp iron-dominated magnets. But they won't get you fields above about 2 T.

Muon Decay in Acceleration **Muon Decay in Acceleration**
• Muon decays behaves logarithmically:
 $\frac{N_1}{N} = \left(\frac{E_1 + p_1 c}{\frac{E_1}{n}}\right)^{-\frac{mc^2}{Gct}}$

$$
\frac{N_1}{N_0} = \left(\frac{E_1 + p_1 c}{E_0 + p_0 c}\right)^{-\frac{mc^2}{Gc\tau}}
$$

- **Muon Decay in Acceleration**
• Muon decays behaves logarithmically:
 $\frac{N_1}{N_0} = \left(\frac{E_1 + p_1 c}{E_0 + p_0 c}\right)^{\frac{mc^2}{Gct}}$
• Average accelerating gradient G determines relation between
transmission factor and energy gain facto transmission factor and energy gain factor. Can't relax at high energy. **• In Map we specified 3.5 MV/m;** IMCC study is using 2.5 MV/m and even lower
- even lower

RF Cavities

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- **RF Cavities**
• Minimize RF for cost and efficiency
• Make many passes through same cavities
 ΔE 1 $\overline{\overline{B}}c\,\Delta E$ **RF Cavities**
• Minimize RF for cost and efficiency
• Make many passes through same cavities
 $n \sim \frac{\Delta E}{GL} \sim \frac{1}{2\pi} \frac{\overline{B}c}{G} \frac{\Delta E}{pc}$ **F Cavities**

linimize RF for cost and efficiency

lake many passes through same cavities
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• Minimize circumference of accelerating stages

• High fields in dipoles, large dipo **F Cavities**

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lake many passes through same cavities
 $n \sim \frac{\Delta E}{GL} \sim \frac{1}{2\pi} \frac{\bar{B}c \Delta E}{G pc}$

• Minimize circumference of accelerating stages

• High fields in dipoles, large dipole packing fra

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l \sim \frac{1}{GL} \sim \frac{1}{2\pi} \frac{1}{G} \frac{1}{\rho c}
$$

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Pulsed Synchrotrons

- **Pulsed Synchrotrons**
• Pulsed magnets need to be iron-dominated to change fields on a
• Iron dipoles will be limited to a bend field of 1.75 T **Pulsed Synchrotrons
Pulsed magnets need to be iron-dom
ms time scale
Iron dipoles will be limited to a bend
• 2.0 T if you use Fe-Co, but cobalt might Pulsed Synchrotrons**
• Pulsed magnets need to be iron-dominated to change fields on a
ms time scale
• Iron dipoles will be limited to a bend field of 1.75 T
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/ith *only* iron dipo • Pulsed magnets need to be iron-dominated to change field ms time scale
• Iron dipoles will be limited to a bend field of 1.75 T
• 2.0 T if you use Fe-Co, but cobalt might be a radiation problem
• With *only* iron dipole
- -
- Fermilab site
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Hybrid Dipoles

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- **Hybrid Dipoles**
• Need a higher average bend field with changing magnetic field
• Mix constant field superconducting magnets with iron magnets that
bend backward at low energy and forward at high energy **Hybrid Dipoles**
• Need a higher average bend field with changing magnetic field
• Mix constant field superconducting magnets with iron magnets that
• bend backward at low energy and forward at high energy
• More SC magnet bend backward at low energy and forward at high energy **Hybrid Dipoles**
• Need a higher average bend field with changing magnetic field
• Mix constant field superconducting magnets with iron magnets that
• More SC magnet: higher energy; more iron magnet: more range
• More SC m
-

Dipole Field and Circumference **Dipole Field and Circumference**
• What is the circumference from dipoles *only*?
• Starting point:
• Starting point:
 $\frac{q}{q}(B_2I_2+B_3J_4J_5)-\frac{q}{q}(B_2I_2-B_3J_4J_5)=2\pi$ **Dipole Field and Cir**
• What is the circumference from
• Starting point:
 $\frac{q}{p_+}(B_cL_c+B_WL_W)=\frac{1}{p_-}$ **Dipole Field and Cir**
• What is the circumference from
• Starting point:
 $\frac{q}{p_+}(B_cL_c + B_WL_W) = \frac{1}{q}$
• Circumference
 $L_c + L_W = \frac{\pi}{q} \left(\frac{p_+}{B_W}\right)$

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$$
\frac{q}{p_+}(B_{C}L_{C} + B_{W}L_{W}) = \frac{q}{p_-}(B_{C}L_{C} - B_{W}L_{W}) = 2\pi
$$

$$
L_C + L_W = \frac{\pi}{q} \left(\frac{p_+}{B_W} - \frac{p_-}{B_W} + \frac{p_+}{B_C} + \frac{p_-}{B_C} \right)
$$

• What is the circumference from dipoles *only*?

• Starting point:
 $\frac{q}{p_+}(B_C L_C + B_W L_W) = \frac{q}{p_-}(B_C L_C - B_W L_W) = 2\pi$

• Circumference
 $L_C + L_W = \frac{\pi}{q} \left(\frac{p_+}{B_W} - \frac{p_-}{B_W} + \frac{p_+}{B_C} + \frac{p_-}{B_C} \right)$

• Even for infinitely hi circumference for a given energy range: e.g., 2.5–5 TeV, 15 km

Dipole Field and Circumference

Dipole Field and Circumference
• Another point of view: average dipole field at high energy:
 $\frac{2B_CB_W}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$ $\mathcal{L}^{\mathbf{D}}W$ **ipole Field and Circumfer**

nother point of view: average dipole field a
 $\frac{2B_CB_W}{B_C + B_W - (B_C - B_W)(p_{-})}$

• With $p_{-} = p_{+}$, B_C as you would expect

• With $p_{-} = 0$, get $2B_CB_W/(B_C + B_W)$ (e.g., $B_W = 3.11$ T) **ipole Field and Circumference**

nother point of view: average dipole field at high energy:
 $\frac{B_C + B_W - (B_C - B_W)(p_-/p_+)}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$

• With $p_- = p_+, B_C$ as you would expect

• With $p_- = 0$, get $2B_CB_W/(B_C + B_W)$ (e.g., **ipole Field and Circumference**

nother point of view: average dipole field at high energ
 $\frac{2B_CB_W}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$

• With $p_- = p_+, B_C$ as you would expect

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• Another point of view: average dipole field at high energy:
 $\frac{2B_CB_W}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$

• With $p_- = p_+, B_C$ as you would expect

• With $p_- = 0$, get $2B_CB_W/(B_C + B_W)$ (e.g., $B_W = 1.75$ • Another point of view: average dipole field at high energy:
 $\frac{2B_CB_W}{B_C + B_W - (B_C - B_W)(p_-/p_+)}$

• With $p_- = p_+, B_C$ as you would expect

• With $p_- = 0$, get $\frac{2B_CB_W}{(B_C + B_W)}$ (e.g., $B_W = 1.75$ T, $B_C = 14$ T, get

3.11 T)

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\overline{B_C + B_W - (B_C - B_W)(p_-/p_+)}
$$

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- Add Quadrupoles
• Can't only have dipoles, need quadrupoles. What fraction of the
• Cassume iron quadrupoles pulsed to circumference do they require?
- Add Quadrupoles
• Can't only have dipoles, need quadrupoles.
• circumference do they require?
• Assume iron quadrupoles pulsed to
maximum 1.2 T pole tip, 50 aperture
plus 1 cm overhead, factor of 2 energy Add Quadrupoles

Can't only have dipoles, need quadrupoles. What fraction of

circumference do they require?

Assume iron quadrupoles pulsed to

maximum 1.2 T pole tip, 5σ aperture

plus 1 cm overhead, factor of 2 energy
 plus 1 cm overhead, factor of 2 energy $\frac{2}{3}$ **Add Quadrupoles**

Can't only have dipoles, need quadrupoles.

circumference do they require?

Assume iron quadrupoles pulsed to

maximum 1.2 T pole tip, 50 aperture

plus 1 cm overhead, factor of 2 energy

gain, 5 TeV max Add Quadrupoles

• Can't only have dipoles, need quadrupoles.

circumference do they require?

• Assume iron quadrupoles pulsed to

maximum 1.2 T pole tip, 5 σ aperture

plus 1 cm overhead, factor of 2 energy

gain, 5 Te
- End up with 9 m quadrupoles, and
20% quadrupole occupancy
 $\frac{20\%}{2}$ quadrupole occupancy

Kyle Capobianco-Hogan

warm

- Add Quadrupoles
• Instead, interleave superconducting and warm quadrupoles like
• Downside: need extra drifts between
• Downside: need extra drifts between with the dipoles odd Quadrupoles

extead, interleave superconducting and warm quad

ith the dipoles

• Downside: need extra drifts between

respects

se similar formulas to dipoles, assume Add Quadrupoles

• Instead, interleave superconducting and warm quadrupo

• Use similar formulas to dipoles, assume
 $^{12.5}$ T superconducting pole tip field

• Effective max pole tip field is 3.7 T **dd Quadrupoles**

extead, interleave superconducting and warm quality

ith the dipoles

• Downside: need extra drifts between

magnets

se similar formulas to dipoles, assume

2.5 T superconducting pole tip field

• Effect
	- magnets
- Use similar formulas to dipoles, assume $\frac{2}{3}$
12.5 T superconducting pole tip field AUC WURUTUPOIES

• Instead, interleave superconducting and

with the dipoles

• Downside: need extra drifts between

magnets

• Use similar formulas to dipoles, assume

12.5 T superconducting pole tip field

• Effective ma
	-
- 6% occupancy or so

Kyle Capobianco-Hogan

- Add Quadrupoles
• As cells get shorter, quadrupoles must get longer due to stronger
• But as cells get longer, occupancy
• But as cells get longer, occupancy focusing, thus higher occupancy fraction **dd Quadrupoles**

s cells get shorter, quadrupoles must get longer due t

ocusing, thus higher occupancy fraction

ut as cells get longer, occupancy

action goes down, but beam size

rows as well

• Quadrupoles start getti
- Add Quadrupoles

 As cells get shorter, quadrupoles must get longer

 Sut as cells get longer, occupancy

 Fut as cells get longer, occupancy

fraction goes down, but beam size

grows as well **fraction goes down, but beam size
grows as well
• Quadrupoles start getting longer at some** grows as well
	- point
- quadrupole length

Kyle Capobianco-Hogan

- Add Quadrupoles
• Now do things more carefully: put 50 cm drifts between magnets
• Minimum quad length at ~12% occupancy
• Quadrupole apertures growing rapidly
-
- Add Quadrupoles
• Now do things more carefully: put 50 cm drifts between m
• Minimum quad length at ~12% occupancy
• Quadrupole apertures growing rapidly Add Quadrupoles
• Now do things more carefully: put 50 cm drifts betwee
• Minimum quad length at ~12% occupancy
• Quadrupole apertures growing rapidly
• Roughly 90 m long cells for lower occupancy Add Quadrupoles
• Now do things more carefully: put 50 cr
• Minimum quad length at ~12% occupar
• Quadrupole apertures growing rapidly
• Froughly 90 m long cells
• 7 T dipole fields to reach 5 TeV
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Dipole Field and Energy Range

- **Dipole Field and Energy Range
• From before: factor of 2 energy gain, average bend field at high
• energy of 5.1 T, not 7 T. Choices:
• Factor of 2 accelerating from 1.75 TeV to 3.5 TeV** energy of 5.1 T, not 7 T. Choices: **ipole Field and Energy Range**
From before: factor of 2 energy gain, average bend field at high
nergy of 5.1 T, not 7 T. Choices:
• Factor of 2 accelerating from 1.75 TeV to 3.5 TeV
• Or accelerate from 3.6 TeV to 5 TeV
• ipole Field and Energy Range

rom before: factor of 2 energy gain, average bend field at

nergy of 5.1 T, not 7 T. Choices:

• Factor of 2 accelerating from 1.75 TeV to 3.5 TeV

• Or accelerate from 3.6 TeV to 5 TeV

• But **ipole Field and Energy Range**

rom before: factor of 2 energy gain, average bend field at high

nergy of 5.1 T, not 7 T. Choices:

• Factor of 2 accelerating from 1.75 TeV to 3.5 TeV

• Or accelerate from 3.6 TeV to 5 TeV **Dipole Field and Energy**
• From before: factor of 2 energy
• energy of 5.1 T, not 7 T. Choices
• Factor of 2 accelerating from 1.75
• Or accelerate from 3.6 TeV to 5 Te
• But with these lower energy range
better. Need to
	-
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	- better. Need to close the loop (work in progress).
-

Rough RF calculation **Rough RF calculation**
• Rough starting assumptions
• Low average gradient of 1 MV/m (90% transmi
• 25 MV/m real estate RF gradient (roughly ILC r **ough RF calculation**

• Low average gradient of 1 MV/m (90% transmission for a factor of 2)
• 25 MV/m real estate RF gradient (roughly ILC number)
• 45 degrees off-crest for the bucket **OUGh RF calculation**

buck starting assumptions

• Low average gradient of 1 MV/m (90% trans

• 25 MV/m real estate RF gradient (roughly IL

• 45 degrees off-crest for the bucket

• Careful with low average RF gradients:

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- **ough RF calculation**

equal to the sumptions

 Low average gradient of 1 MV/m (90% transmission for a factor of

 25 MV/m real estate RF gradient (roughly ILC number)

 45 degrees off-crest for the bucket

 Careful wi **ugh RF calculation**
gh starting assumptions
ow average gradient of 1 MV/m (90% transmission for a factor of 2)
5 MV/m real estate RF gradient (roughly ILC number)
5 degrees off-crest for the bucket
• Careful with low aver keeping the RF bucket large enough **Rough RF calculation**

• Rough starting assumptions

• Low average gradient of 1 MV/m (90% transmission fo

• 25 MV/m real estate RF gradient (roughly ILC number

• 45 degrees off-crest for the bucket

• Careful with low
-
-
- **FOUGH RF CAICUIATION**

 Rough starting assumptions

 Low average gradient of 1 MV/m (90% transmission for a factor of 2)

 25 MV/m real estate RF gradient (roughly ILC number)

 45 degrees off-crest for the bucket

 From Solution in the symple symple complex COV

• Low average gradient of 1 MV/m (90% transmission for a factor of 2)

• 25 MV/m real estate RF gradients: you spend a larger fraction of your voltage on

• Gareful with l ugh starting assumptions
Low average gradient of 1 MV/m (90%
25 MV/m real estate RF gradient (rough
45 degrees off-crest for the bucket
• Careful with low average RF gradients: you
keeping the RF bucket large enough
sult i

Additional RF Complications **Additional RF Complications
• Need several RF straights (CERN studies estimated 32)
• Synchronization between energy and dipole field
• Synchrotron tune is around 1; RF kick-drift pair must be below 0.16,**

- -
- **dditional RF Complications**
• eed several RF straights (CERN studies estimated 32)
• Synchronization between energy and dipole field
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preferably lower **dditional RF Complications**
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- Additional RF Complications

 Need several RF straights (CERN studies estimated 32)

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 Synchrotron tune is around 1; RF kick-drift pair must be below 0.16,

 Making magn **dditional RF Complications**

• Synchronization between energy and dipole field

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• Synchronization between energy and dipole field

• Synchrotron tune is around 1; RF kick-drift pair must be below 0.16,

preferably lowe
	-

Putting it all Together **utting it all Together**
• eed to put together designs with more factors cons
• Spaces between warm and cold dipoles
• Compute RF phase from required bucket area
• Add dispersion suppression between RF and arc

- **Putting it all Together
• Need to put together designs with more factors considered
• Spaces between warm and cold dipoles
• Compute RF phase from required bucket area utting it all Together**
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• Chromatic correction sex
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- **utting it all Together**

eed to put together designs with more factor

 Spaces between warm and cold dipoles

 Compute RF phase from required bucket area

 Add dispersion suppression between RF and arc

 Chromatic cor **Putting it all Together**
• Need to put together designs with more factors considered
• Spaces between warm and cold dipoles
• Compute RF phase from required bucket area
• Add dispersion suppression between RF and arc
• Ch together a design that takes all this into account self-consistently **IT COLOREM ANDIMERT AND AND SET AND AND SET AND AND SERVIDE CONDUCT:**
• Spaces between warm and cold dipoles
• Compute RF phase from required bucket area
• Add dispersion suppression between RF and arc
• Chromatic correct
	-

What is an FFA

- Fixed Field Alternating gradient accelerator
- What is an FFA
• Fixed Field Alternating gradient accelerator
• Large energy range (e.g., factor of 2) in a single beamline
• Magnet fields do not vary with time
• Alternating gradient focusing in compact cells for small o
-
- **What is an FFA**
• Fixed Field Alternating gradient accelerator
• Large energy range (e.g., factor of 2) in a single bea
• Magnet fields do not vary with time
• Alternating gradient focusing in compact cells for snexcursi **What is an FFA**
• Fixed Field Alternating gradient accelerator
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- **What is an FFA**

 Fixed Field Alternating gradient accelerate

 Large energy range (e.g., factor of 2) in a

 Magnet fields do not vary with time

 Alternating gradient focusing in compact c

excursion

 Motivation Motivation for muon acceleration: $\frac{2}{5}$
superconducting-only solution that $\frac{2}{5}$ $\frac{3}{5}$
will scale with magnet technology: will scale with magnet technology; $\overline{5}$ -3 overcome the limited field in iron $\frac{1}{\sqrt{2}}$

What is an FFA

-
- **What is an FFA**
• A single cell is duplicated around the ring
• Each cell has a long drift that can contain an RF cavity
• Also used for injection/extraction/etc.
	-
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• For muons: accelerate both signs, requires reflection sy **hat is an FFA**

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• For muons: accelerate both signs, requires reflection s consistent injection/extraction **What is an FFA**

• A single cell is duplicated around the ring

• Each cell has a long drift that can contain an RI

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• For muons: accelerate both signs, requires refle

consiste
- An FDF triplet with a long RF $\frac{2}{5}$ straight is the simplest solution

FFA to Accelerate to 5 TeV

- **FFA to Accelerate to 5 TeV
• Older study, parameters are inconsistent with pulsed synchrotron**
• 12% of circumference occupied by RF study **FFA to Accelerate to 5 TeV**
• Older study, parameters are inconsistent with pulsed synetudy
• 12% of circumference occupied by RF
• 50 cm between objects
• Ontimize to minimize the maximum field at the magnet of FFA to Accelerate to 5 T
• Older study, parameters are inconsiste
study
• 12% of circumference occupied by RF
• 50 cm between objects
• Optimize to minimize the maximum fie
• Defined so that 4.50 is at 2/3 of coil radiu **FFA to Accelerate to 5 TeV**
• Older study, parameters are inconsistent with pulsed synchrotron
• 12% of circumference occupied by RF
• 50 cm between objects
• Optimize to minimize the maximum field at the magnet coil
• De **FA to Accelerate to 5 TeV**
Poter study, parameters are inconsistent with pulsed study
2% of circumference occupied by RF
0 cm between objects
ptimize to minimize the maximum field at the magnet
• Defined so that 4.5σ is
-
-
- -

Sample Result **Sample Result
• Note tunes, orbits vary with energy
• Sample result for factor of 2 energy
• Just under 480 cells
• 4 m for RF (or injection/extraction)
• Ontimization for field Sample Result**
• Note tunes, orbits vary with energy
• Sample result for factor of 2 energy g
• Just under 480 cells
• 4 m for RF (or injection/extraction)
• Optimization for field
• F field is 12.4 T at outside
• D fiel

-
- **Sample Result**
• Note tunes, orbits vary with energy
• Sample result for factor of 2 energy gain
• Just under 480 cells • Sample result for factor of 2 energy gain **Sample Result**
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• D field is −5.3 T at ote tunes, orbits vary with energy
ample result for factor of 2 energy
ust under 480 cells
m for RF (or injection/extraction)
ptimization for field
field is 12.4 T at outside
ideal is -5.3 T at outside
• Reverse bend
-
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Field and Energy Range Field and Energy Range

• Assume maximum energy of 5 TeV

• Magnet field depends on minimum

• Plet bours field at seil, at 4.5 times **Field and Energy Range
• Assume maximum energy of 5 TeV
• Magnet field depends on minimum
• Plot shows field at coil, at 1.5 times
• beam radius, and field at beam**

-
- Magnet field depends on minimum
energy
-
- Assume maximum energy of 5 TeV

 Magnet field depends on minimum

energy

 Plot shows field at coil, at 1.5 times

beam radius, and field at beam

 Factor of 2 energy gain possible, but

high fields

 Limitations sim
- -
	-
-

Aperture

- **Aperture**
• For factor of 2, too large for Tesla
• 650 MHz probably possible cavities **Aperture**

• For factor of 2, too large for Tesla

cavities

• 650 MHz probably possible

• Reduced gradient may require longer

straight **perture**

or factor of 2, too large for Tesla

avities

50 MHz probably possible

• Reduced gradient may require longer

straight

C magnet apertures are also large
- - straight
-

Injection/Extraction **jection/Extraction**
his configuration (FDF) makes horizontal fa
• Beam near inner/outer edge of magnet
umber of straights for kickers to get separa
• For 0.2 T kickers, about 3 straights for extraction

- **Injection/Extraction**
• This configuration (FDF) makes horizontal favorable
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• Beam near inner/outer edge of magnet
umber of straights for kickers to get separation
• For 0.2 T kickers, about 3 straights for extraction
• Inject • Injection harder due to tune near 0.4. Reducing tune would lead to higher main magnet fields **injection/Extraction**
• This configuration (FDF) makes horizontal favorable
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 jection/Extraction
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• Inject Following Constants and the penetralism

this configuration (FDF) makes horizontal faver

• Beam near inner/outer edge of magnet

• For 0.2 T kickers, about 3 straights for extraction

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• Beam near inner/outer edge of magnet

umber of straights for kickers to get separation

• For 0.2 T kickers, about 3 straights for extraction

• Injection harder
- -
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	-

Acceleration

-
- **Acceleration
• Design is optimized for peak field
• Need to consider longitudinal dynamics
• One option is to shift RE phase Acceleration
• Design is optimized for peak field
• Need to consider longitudinal dynamics
• One option is to shift RF phase
• Without shifting phase, can do serpentine**
-
- **Acceleration**
• Design is optimized for peak field
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acceleration **Acceleration**

• Design is optimized for peak field

• Need to consider longitudinal dynamics

• One option is to shift RF phase

• Without shifting phase, can do serpentine

acceleration

• Requires designing for a more acceleration **cceleration**
• esign is optimized for peak field
• eed to consider longitudinal dynamics
• me option is to shift RF phase
• Vithout shifting phase, can do serpentine
• Requires designing for a more symmetric
• time of fli esign is optimized for peak field
eed to consider longitudinal dynamic
option is to shift RF phase
lithout shifting phase, can do serpent
cceleration
• Requires designing for a more symmetric
time of flight vs. energy
• Wi
	- time of flight vs. energy
	-

Further FFA Studies **Further FFA Studies
• This was just a first look
• Additional areas of study needed
• Look at longitudinal dynamics; do we needed Further FFA Studies**
• This was just a first look
• Additional areas of study needed
• Look at longitudinal dynamics; do we need to adjust th
• Look at DFD triplet **urther FFA Studies**
his was just a first look
dditional areas of study needed
• Look at longitudinal dynamics; do we need to adjust the lattice?
• Look at DFD triplet
• To what extent to nonlinear fields help? **urther FFA Studies**
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• Look at DFD triplet
• Need a concrete injection/extraction design
• Look at tap

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his was just a first look

dditional areas of study needed

• Look at longitudinal dynamics; do we need to adjust the lattice?

• Look at DFD triplet

• To what extent to nonlinear fields help?

• Nee

Pulsed Magnet Studies **Pulsed Magnet Stud**
• Iron response
• No good data on iron response at
saturation

-
- **ulsed Magnet Studies**
• No good data on iron response at high ramp rates and approaching
• No good data on iron response at high ramp rates and approaching
• Losses are important, but should also understand response saturation
	-
- **ulsed Magnet Studies**

on response

 No good data on iron response at high ramp rates and approaching

 Losses are important, but should also understand response

 Measure material response to single pulse for various **ulsed Magnet Studies**

on response

• No good data on iron response at high ramp rates and approaching

• Losses are important, but should also understand response

• Measure material response to single pulse for various maximum fields • Iron response
• No good data on iron response at high ramp rates and approximation
• Losses are important, but should also understand response
• Measure material response to single pulse for various ramp
maximum fields
•
	- **ulsed Magnet Studies**

	 No good data on iron response at high ramp rates and approaching

	 Losses are important, but should also understand response

	 Measure material response to single pulse for various ramp rates an pulse amplitudes and ramp rates
-

Collaboration with the IMCC **Collaboration with the IMCC**
• IMCC has contributed incredibly to the pulsed synchrotron design
• Extensive studies of power supply design
• Studies of many aspects of lattice design and beam dynamics **Collaboration with the IMCC**
• IMCC has contributed incredibly to the pulsed synchrotron
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• Studies of many aspects of lattice design and beam dynamical dynamics, coupled with pow **Collaboration with the IMCC**
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• Longitudinal dynamics, c **ollaboration with the IMCC**
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xtensive studies of power supply design
tudies of many aspects of lattice design and be.
• Longitudinal dynamics, coupled with power source lim
• **ollaboration with the**
MCC has contributed incredibly to
xtensive studies of power supply
tudies of many aspects of lattice of
• Longitudinal dynamics, coupled with propert of the number of RF stations
• Collective effect **ollaboration with the IN**

MCC has contributed incredibly to the p

xtensive studies of power supply desig

tudies of many aspects of lattice desig

• Longitudinal dynamics, coupled with power

• Impact of the number of R

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- IMCC has contributed incredibly to the pulsed syr
• Extensive studies of power supply design
• Studies of many aspects of lattice design and bea
• Longitudinal dynamics, coupled with power source limi
• Impact of the num
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Conclusions

- **Conclusions**
• The largest ring in a muon collider is the one that accelerates
beams to the highest energy
• Pulsed synchrotrons or FFAs both appear able to accelerate beams to the highest energy **Conclusions**
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• Pulsed synchrotrons or FFAs both appear able to accelerate
beams to similar energies near 5 TeV
• There is a tra
- beams to similar energies near 5 TeV
- **Conclusions**
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- **Conclusions**
• The largest ring in a muon collider is the one that accelerates
beams to the highest energy
• Pulsed synchrotrons or FFAs both appear able to accelerate
beams to similar energies near 5 TeV
• There is a tr some energy below 5 TeV, then later a second ring in the same tunnel to reach a higher energy

Acknowledgements

- **Acknowledgements
• David Neuffer proposed an acceleration scenario pointing out much of
• What you see here; there's just a bit more detail here
• I'm working with a Stony Brook University graduate student, Kyle** what you see here; there's just a bit more detail here
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Capobianco Capobianco-Hogan, on a scenario accelerating with pulsed synchrotrons on the Fermilab site; the plots came from his work Acknowledgements
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Capobianco-Ho
- studies
- pulsed synchroton
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