Acceleration: Important Topics for Future Studies

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Introduction

- Theme of this talk: describe
  - What we've learned about muon acceleration
  - What I think the next topics to study should be, if
    - Someone be interested in muon acceleration,
    - Some funding becomes available, or
    - There is time to do some work during our last gasps…
- Acceleration should not be a question of feasibility: it is a question of cost control and performance
  - Maximize RF passes
  - Maintain sufficient average RF gradient
  - Limit emittance growth and non-decay losses

Introduction

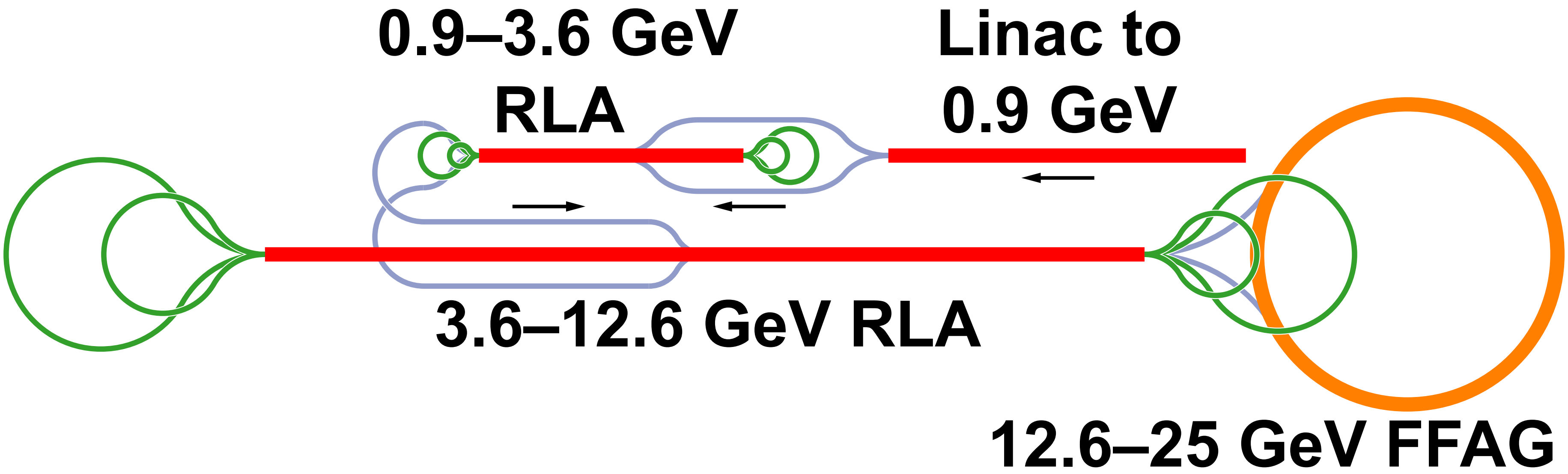
- Talk outline
  - Accomplishments under MAP
  - Next questions to answer (for future generations?)
    - Design and simulation studies
    - Key hardware questions

Accomplishments under MAP

- Neutrino factory acceleration scenarios
  - IDS-NF
  - NuMAX
- FFAGs
- Longitudinal emittance growth in RLAs
- Pulsed synchrotron lattices
- Pulsed magnet R&D

IDS-NF Acceleration

- Began wanting a muon beam energy of 25 GeV
- Linac, 2 RLAs, and an FFAG: maximizing RF passes for cost-effectiveness

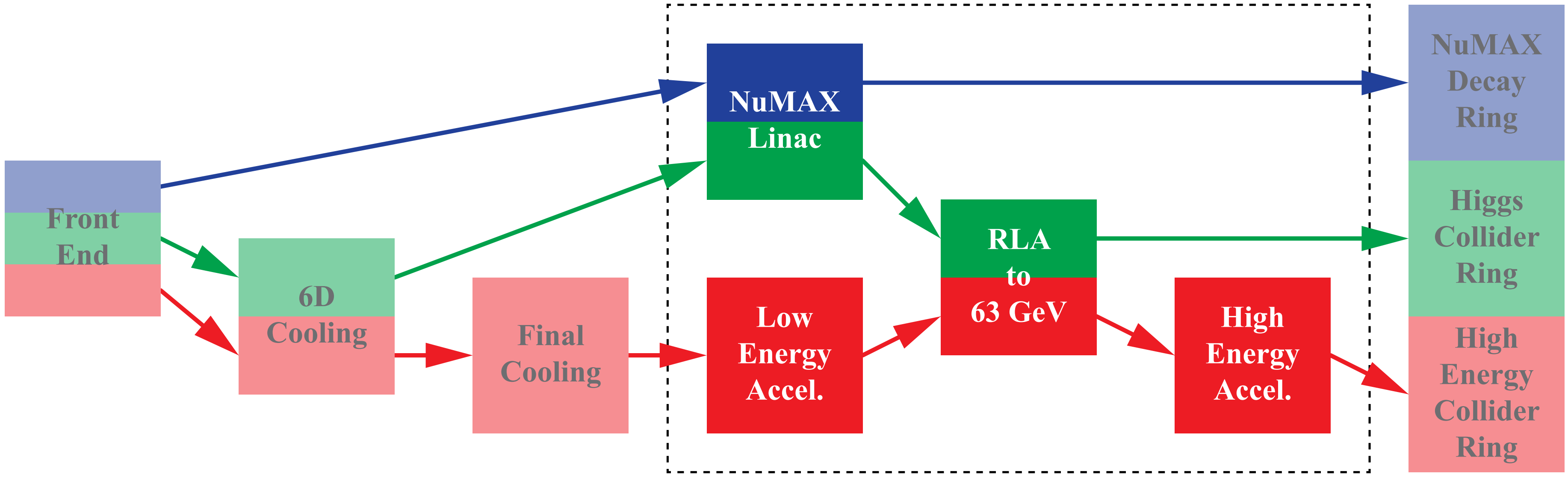


IDS-NF Acceleration

- Rethinking of RLA design principles. In particular:
  - Arcs grow with momentum to avoid need for chromatic corrections
  - Better handling of arc crossings
- RLA switchyards proved challenging
- Then θ_{13} became large, and the ideal muon beam energy went down to 10 GeV
  - An FFAG to 10 GeV did not appear to be cost-effective
  - Switched to a linac and two RLAs

MAP Acceleration Scenario

- Outline of a Fermilab-based acceleration scenario:



NuMAX

- Fermilab to SURF distance dictates 5 GeV muons
- Idea to share the high energy linac section between protons and muons
- Just heard about the details on that

FFAGs

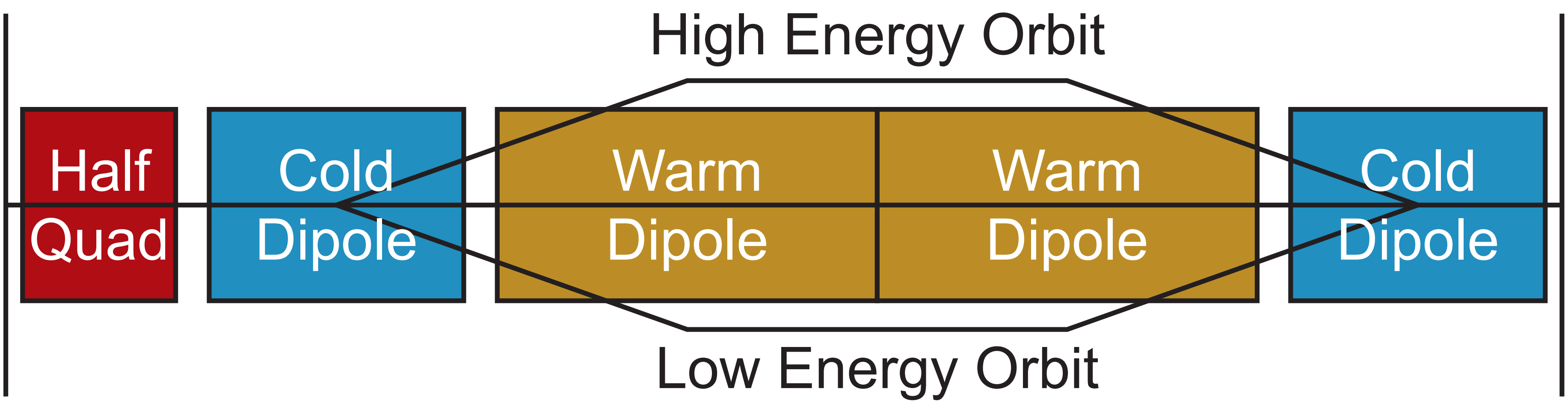
- Looked into FFAGs for high energy colliders
- Large longitudinal emittances require large circumferences
- For higher energies, did not appear to offer a cost advantage over pulsed synchrotrons
- At lower energies, also did not appear to be advantageous, based on assumptions about RLA designs

Longitudinal Emittance in RLAs

- Specified an RLA from 5 to 63 GeV
- Beam loading limited the linac passes in RLAs
- FFAG designs had looked at longitudinal emittance preservation, but RLAs had not
- Longitudinal (HE collider) emittance preservation:
  - Long arcs with many cells
  - Significant beta matching from linac to arcs
- Suggests a reconsideration of design
  - Split into two stages
  - Racetrack design
  - Both will increase switchyard crowding
  - FFAGs aren't looking as bad as they used to…

Hybrid Synchrotron Lattices

- Hybrid synchrotrons (mixed pulsed and superconducting dipoles) ideal for rapid acceleration at high energies
- Came up with a lattice for a hybrid synchrotron
- Gave a rough estimate of parameters
  - In particular, dispersion size is a significant contribution to aperture



Hybrid Synchrotron Lattices

- Identified needed changes to lattice
  - More acceleration steps, otherwise energy out of sync with magnet fields
  - Time of flight correction: likely requires orbit motion in quadrupoles
  - Chromaticity correction
- Described a better cell structure to meet requirements

Cell: FL2/2 | RF | DL | RF | FL1 | RF | DE | B | F | B | D | B | F | B | D/2

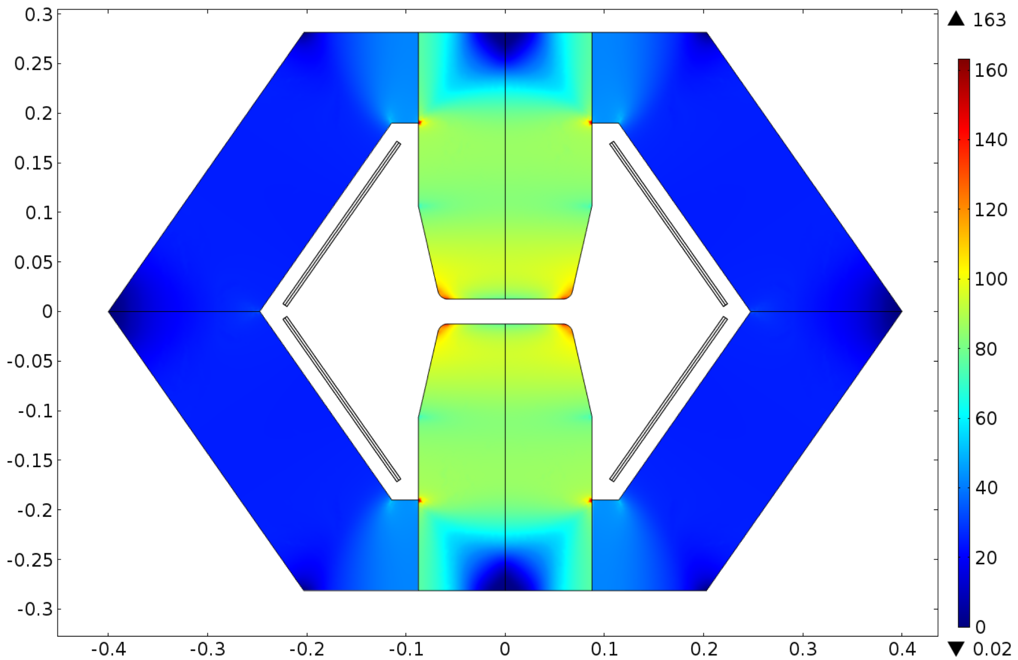
Arc: D/2 | SD1 | B | | F | SF | B | SD2 | D | SD2 | B | SF | F | | B | SD1 | D/2

Pulsed Magnets

- Don Summers built and tested a pulsed magnet with grain-oriented steel
  - Two designs, second improved by adding mitred joints
  - Reached 1.8 T at 1.4 kHz
  - Saw some field quality issues
  - Takeaway: the concept works
- Identified issues with grain-oriented steel
  - Does not converge in simulations
    - Some indications that this problem can be addressed
  - Field quality sensitive to assembly tolerances
    - Field lines (therefore errors) pinned along grains
    - Possible cause for field quality issues in experiment

Pulsed Magnets

- Holger Witte: two-material pulsed magnet design
  - Low-loss material in back yoke
  - High saturation material for pole
  - Takeaway: pulsed magnet designs possible with non-oriented materials and acceptable losses



Next Steps: Design/Simulation

- Designs to limit longitudinal emittance growth
- Hybrid pulsed synchrotron lattice
- RLA switchyards
- Sextupole-corrected FFAG lattices
- Integrated final “cooling” and initial acceleration
- Complete acceleration scenario
- Collective effects

Longitudinal Emittance Growth

- Implement RLA design modifications to reduce longitudinal emittance growth
  - Examine high-level design modifications (racetrack, more stages)
  - Design transverse matching in arcs
  - Check estimates against tracking
- Examine longitudinal growth in linacs
  - IDS-NF tracking results showed apparent emittance growth
  - Results were also inconsistent in details between tracking codes
  - Determine how to design to keep emittance growth within limits

Hybrid Pulsed Synchrotrons

- Implement time of flight and chromatically corrected lattice cell
- Find good lattice parameters and understand parametric dependence
  - In general will favor shorter cells, more cold/warm dipole alternations
  - Synchrotron bucket match important: impacts aperture
  - At some point overhead (drifts, quads) takes over
- Check dynamic aperture/emittance growth
  - Mismatch from discrete energy jumps vs. continuously ramped magents
  - Impact of chromatic correction sextupoles

RLA Switchyards

- Large emittances and energy spreads: many magnets needed in RLA switchyards
- IDS-NF RLAs never resolved interferences
  - Expect this to be soluble
  - Requires closing the loop between lattice design and (rough) engineering
- Longitudinal emittance growth concerns may lead to more crowded switchyards

Sextupole-Corrected FFAG

- Colliders: comparison of RLAs and FFAGs based on overly optimistic RLA designs
  - Controlling longitudinal emittance growth considered for FFAGs, but not for RLAs
  - Comparison should be revisited once RLAs have been updated
- Potentially get better efficiency out of FFAGs with sextupole corrections
  - Make the FFAG more isochronous
  - Works poorly for neutrino factory emittances: dynamic aperture
  - Should work better for collider emittances

“Final Cooling” + Acceleration

- No precise plan on how to get from end of “6D cooling” to collider emittances
- Where you end up defines initial acceleration
- Likely to be some common RF technology
- Some scenarios involve acceleration and a later emittance exchange
- Goals
  - Starting with a “final cooling” scenario, design a corresponding acceleration scenario, taking beam to a handoff point where “standard” acceleration can be used
  - Inform comparisons between solutions, in terms of cost and performance

Complete Acceleration Scenario

- Begin with what above studies tell us about scaling and relative “cost” of subsystems
  - Want a good idea of system scale vs. parameters
  - Understand good choices for machine parameters (e.g., energy range, when to switch technology)
  - Beam dynamics considerations impact these choices
- Put together a complete system as a reference point for study

Collective Effects

- Large single-bunch charge, large impedance from RF
  - Extract a significant fraction of the cavity stored energy in a single pass
- Mitigated by the relatively small number of turns
  - In pulsed synchrotrons, also mitigate with chromaticity correction, strong synchrotron oscillations
  - These mitigations probably not available in earlier stages
- There is also the head-on beam-beam
- Collective effects need to be simulated, quantified

Next Steps: Hardware

- Power supplies for pulsed magnets
- SCRF input couplers
- Pulsed magnet testing

Pulsed Magnet Power Supplies

- Pulsed synchrotrons are the preferred technology for high energy acceleration
  - The magnet technology appears straightforward
  - Can we power magnets with sufficiently control?
- Questions to answer:
  - To what extent can we control the current ramp?
  - What is the pulse-to-pulse reproducability?
  - What will be the lifetime?
  - What are the scale limitations?
  - What is the efficiency (could dominate power usage)?
- Do we need to build something?
- This will be a significant undertaking.

SCRF Input Couplers

- Later acceleration stages: top off RF
- Requires significant input power (approaching MW level per cavity)
- Can require fewer cells per cavity (harming real-estate gradient) if this input power limits us

Pulsed Magnet Testing

- I believe we have sufficient evidence that pulsed magnets are feasible
- Incomplete understanding of some details
  - In particular: how does the material respond to excitation when field changes rapidly?
- Can over-engineer magnets to make details less important
  - This has a cost in terms of power consumption, power supply requirements

Pulsed Magnet Testing

- Want to "close the loop"
  - Measure materials sufficiently to input into simulation
  - Construct a magnet with some sensitivity to these details
  - Simulate the same magnet; verify experimental behavior matches: current/voltage/field vs. time

Summary

- We've learned a lot about the important aspects of acceleration design for a muon accelerator, despite a low level of effort
- The driving consideration is cost control, primarily through multi-turn acceleration, not feasibility per se
- I've identified what I think are the next set of questions to address, should anyone be able to and wish to work on this
    - A bit of this may even get addressed before we're done