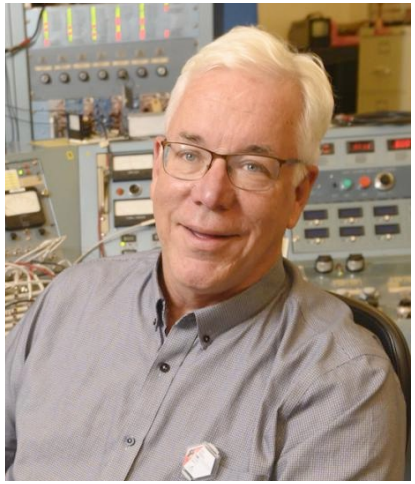
AF5: ACCELERATORS FOR PBC AND RARE PROCESSES



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Outline

- Goals of the AF5 Working Group
- Overview and Process
- Contributed LoIs
- Contributed White Papers
- Outline of Report
- PIP-II Opportunities
- Additional Accelerator Challenges
- Conclusions

AF5: Accelerators for PBC and Rare Processes

- AF5 Description:

  A number of fundamental physics questions require exploration of rare processes and what is called Physics Beyond Colliders (PBC). These are similar in spirit to those addressed by high-energy colliders, but require different types of beams and experiments. Modifications of existing accelerator complexes and future dedicated scientific infrastructure are considered for the next two decades through projects complementary to the LHC/HL-LHC and other possible future colliders.

- This efffort has greatly benefitted from the The Physics Beyond Collider study at CERN was set-up in 2016 and reported to the European Strategy for Particle Physics in 2019. Although it naturally had a CERN/European bent, it did attempt to evaluate things in a worldwide context. A couple of potentially interesting references follow.
  - Beyond the Standard Model Working Group Report https://arxiv.org/abs/1901.09966
  - Summary Report of Physics Beyond Colliders at CERN https://arxiv.org/abs/1902.00260

Scope of AF5

- Accelerator applications for rare processes and BSM physics:
  - rare processes: muons, taus, kaons, etc
  - dark matter/hidden sector experiments: beam dumps, etc
- Experiments that leverage HEP accelerator technology for non-accelerator experiments
  - Magnets
  - RF
  - Quantum sensors
- (Mostly) Excluded:
  - Things that are purely parasitic on other frontiers:
    - Colliders
    - Neutrino beam lines

Key Meetings and Workshops

- 6/22/20: AF5 Brainstorming Session
- 7/15/20: AF/EF/RP Cross-frontier Meeting
- 7/23/20: Muon-based and other beam-dump based dark matter/dark sector searches
- 9/23/21: Joint AF2/AF5/AF7/RP/NP Targetry Workshop
- 12/15/21: Booster Storage Ring Workshop
- 1/14/22: Muon Workshop
- Numerous Mu2e-II/Enigma workshops throughout

AF5 LoIs

- Tagged AF5:
  - Dark Sector, beam based, facility: 13
  - Dark Sector/axion, cosmic: 5
  - Dark Sector, beam based, parasitic: 4
  - Rare processes: 4
  - Technology: 4
  - EDM: 2
  - Nuclear: 1
  - Total: 33
- Additional LoIs that probably *should* have been tagged AF5
  - Dark Sector Studies at High Intensities: 19
  - Charged Lepton Flavor Violation 9
  - Dark Matter: Wave-like 6
  - Fundamental Physics in Small Experiments 4
  - BSM Neutrino Frontier 1
  - EF: BSM - More general explorations 1
  - Dark Matter: Particle-like 1
  - Total: 41
- Grand total 74

Role of AF5?

- Most of the topics that fall under this banner are already being addressed within the context of the of the appropriate physics group.
- We chose to focus on
  - Advertising capabilities of various facilities.
  - Experiments that require significant or unique accelerator development to achieve their physics goals.
  - Development of facilities to service multiple physics groups.
    - Emphasis on PIP-II opportunities
  - Identifying cross-cutting technology development

Apologies to Belle-II

- We realized until very recently that Belle-II kind of fell between the cracks
  - We thought they were under AF3
  - AF3 thought they were under AF5
- After some discussion, we agreed that we would summarize Belle-II needs and plans under AF5
  - Two white papers submitted to archive

AF05 Tagged White Papers

- A. Natochii, T. E. Browder, L. Cao, K. Kojima, D. Liventsev, et al. ”Beam background expectations for Belle II at SuperKEKB“, arXiv:2203.05731 [hep-ex] (pdf).
- M. Toups, R.G. Van de Water, Brian Batell, S.J. Brice, Patrick deNiverville, et al. ”PIP2-BD: GeV Proton Beam Dump at Fermilab's PIP-II Linac”, arXiv:2203.08079 [hep-ex] (pdf). (also under NF03, RF06)
- Matt Toups, R.G. Van de Water, Brian Batell, S.J. Brice, Patrick deNiverville, et al. ”SBN-BD: O(10 GeV) Proton Beam Dump at Fermilab's PIP-II Linac”, arXiv:2203.08102 [hep-ex] (pdf). (also under NF03, RF06)
- William Pellico, Chandra Bhat, Jeffrey Eldred, Carol Johnstone, et al. ”FNAL PIP-II Accumulator Ring“, arXiv:2203.07339 [physics.acc-ph] (pdf). (also relevant to AF02)
- R.G. Van de Water, S.G. Biedron, E.-C. Huang, A.J. Hurd, W.C. Louis, et al. ”LANSCE-PSR Short-Pulse Upgrade for Improved Dark Sector Particle Searches with the Coherent Captain Mills Experiment”, arXiv:2204.01860 [physics.ins-det] (pdf). (also under NF03, RF06)
- Swagato Banerjee, J. Michael Roney (for the US Belle II Group and the Belle II/SuperKEKB e- Polarization Upgrade Working Group). ”Upgrading SuperKEKB with a Polarized Electron Beam: Discovery Potential and Proposed Implementation”, pdf available here . (also under EF04, RF0)

Other Contributions Related to AF05

- RF02: Weak decays of strange and light quarks
  - E. Goudzovski, D. Redigolo, K. Tobioka, J. Zupan, et al., “New Physics Searches at Kaon and Hyperon Factories”, arXiv:2201.07805 [hep-ph] (pdf).
  - Nora Salone, Patrik Adlarson, Varvara Batozskaya, Andrzej Kupsc, Stefan Leupold, Jusak Tandean. ”Study of CP violation in hyperon decays at Super Charm-Tau Factories with a polarized electron beam“, arXiv:2203.03035 [hep-ph] (pdf).
  - Thomas Blum, Peter Boyle, Mattia Bruno, Norman Christ, Felix Erben, et al. ”Discovering new physics in rare kaon decays”, arXiv:2203.10998 [hep-lat] (pdf). (also under TF05, CompF02)
  - Jason Aebischer, Andrzej J. Buras, Jacky Kumar. ”On the Importance of Rare Kaon Decays“, arXiv:2203.09524 [hep-ph] (pdf).
  - The KOTO, LHCb, NA62/KLEVER Collaborations, and the US Kaon Interest Group. ”Searches for new physics with high-intensity kaon beams”, arXiv:2204.13394 [hep-ex] (pdf)

- RF03: Fundamental physics in small experiments (axions, EDMs, precision muon measurements)
  - W. Altmannshofer, H. Binney, E. Blucher, D. Bryman, L. Caminada, et al. (PIONEER Collaboration). ”Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays in the PIONEER experiment”, arXiv:2203.05505 [hep-ex] (pdf).
  - Ricardo Alarcon, Jim Alexander, Vassilis Anastassopoulos, Takatoshi Aoki, et al. ”Electric dipole moments and the search for new physics”, arXiv:2203.08103 [hep-ph] (pdf).

- RF05: Charged lepton flavor violation (electrons, muons, and taus)
  - K. Byrum, S. Corrodi, Y. Oksuzian, P. Winter, L. Xia, A. W. J. Edmonds, et al. ”Mu2e-II: Muon to electron conversion with PIP-II”, arXiv:2203.07569 [hep-ex] (pdf).
  - M. Aoki, R. B. Appleby, M. Aslaninejad, R. Barlow, R. H. Bernstein, C. Bloise, L. Calibbi, et al. ”A New Charged Lepton Flavor Violation Program at Fermilab”, arXiv:2203.08278 [hep-ex] (pdf).

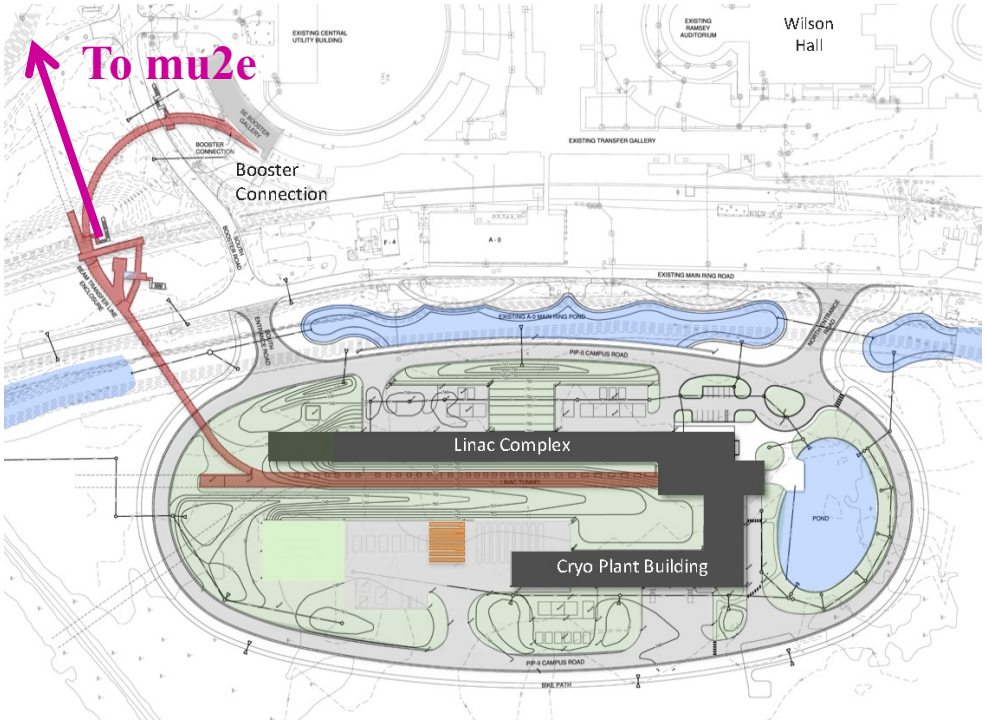
AF5 Report Outline

- Maximum exploitation of PIP-II
  - This has been most of the cross-cutting work in this area.
  - Mu2e-II and beyond
  - Booster compressor ring(s)
- Beam dump opportunities
  - Proton beam dumps
  - Electron beam dumps
  - Summary of facilities' capabilities
    - Largely summarized in Bob Zwaska's Report
- Other Opportunities and Their Challenges
  - Belle-II
  - EDM measurements
  - Rare Kaon experiments
  - Etc
- Synergistic opportunities with other WGs
  - Target development
  - RF
  - Magnet development

Role of PIP-II in Snowmass Planning

- PIP-II is the higher energy linac upgrade to the Fermilab Proton Source, from 400 to 800 MeV.
- The ostensible motivation for PIP-II is to increase the beam power to the high energy neutrino program (LBNF/DUNE), but that will only use a tiny fraction of the available neutrinos from PIP-II.
- There are many accelerator challenges facing the rare process community, but we consider PIP-II to be a particularly important opportunity for the Snowmass process to contribute to effectively planning the use of the additional beam power at 800 MeV.
- We consider this an important responsibility of the AF5 WG.

Review: PIP-II Scope Overview



800 MeV H– linac
- Up to 165 MHz bunches
- Up to 2 mA CW
- Up 1.6 MW

Upgraded Booster
- 20 Hz, 800 MeV injection
- New injection area

Upgraded Recycler & Main Injector
- RF in both rings

Protons for the High Energy Program
- .55 ms injection into Booster at 20 Hz
- Only ~1% of available beam!

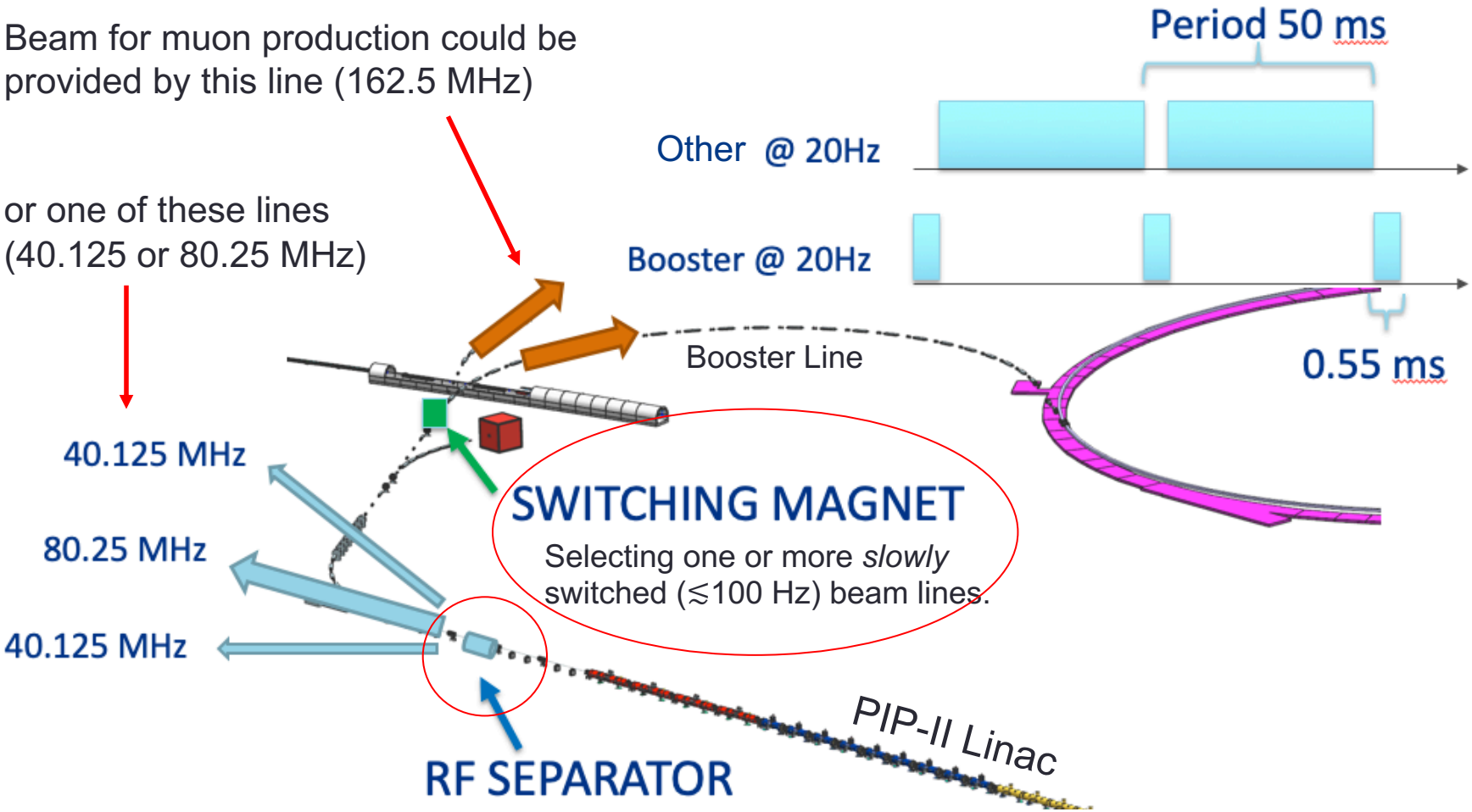
Additional beam
- Up to 1.6 MW
- All the beam to one experiment?
- 3-way beam split?

The PIP-II scope enables the accelerator complex to reach 1.2 MW proton beam on LBNF target, *but still leave most of the beam for other users!*

Beam Switching*

Beam for muon production could be provided by this line (162.5 MHz)

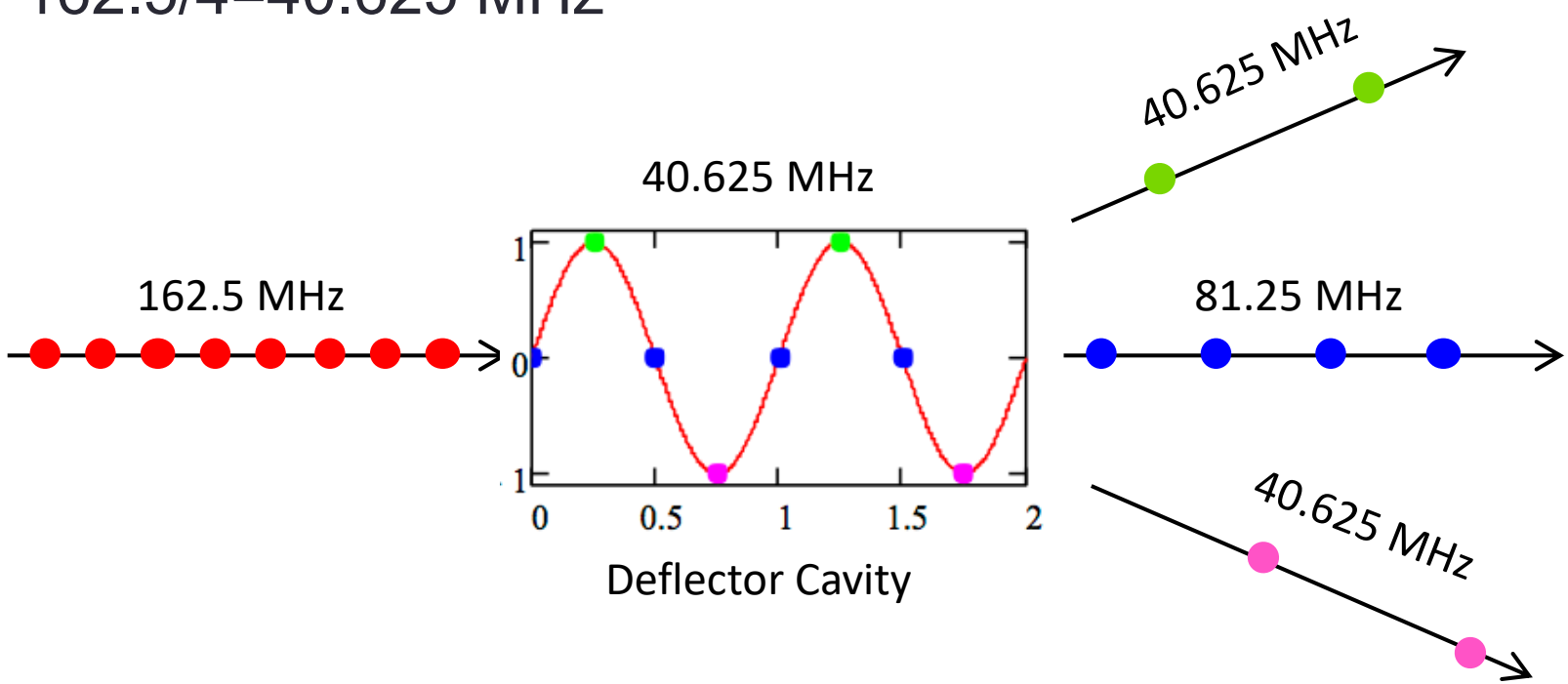
or one of these lines (40.125 or 80.25 MHz)



*Lia Merminga, CD-2 Refresh

RF Beam Splitting

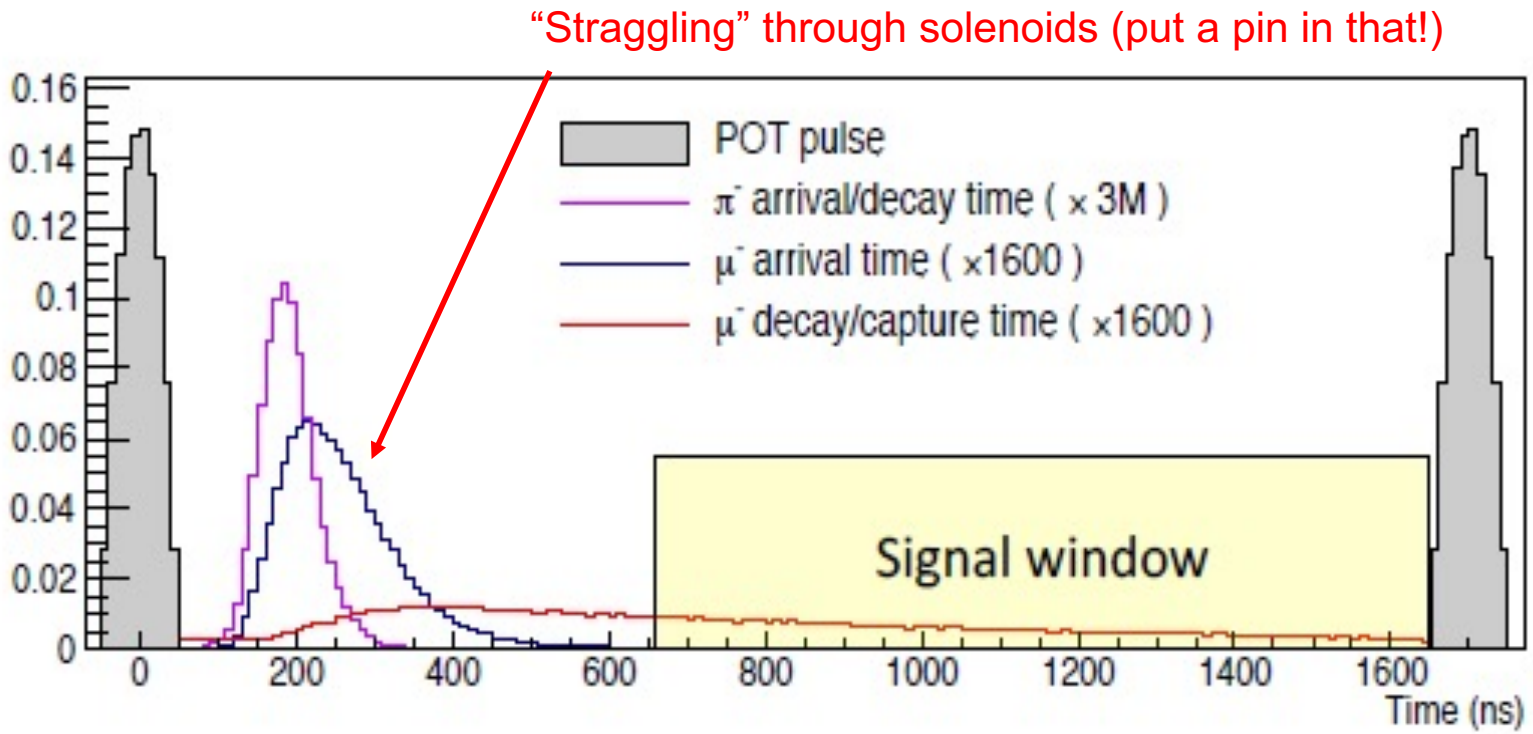
- The Beam will go through an RF deflector running at 162.5/4=40.625 MHz



- Individual beam lines are selected by choosing which bunches to populate.

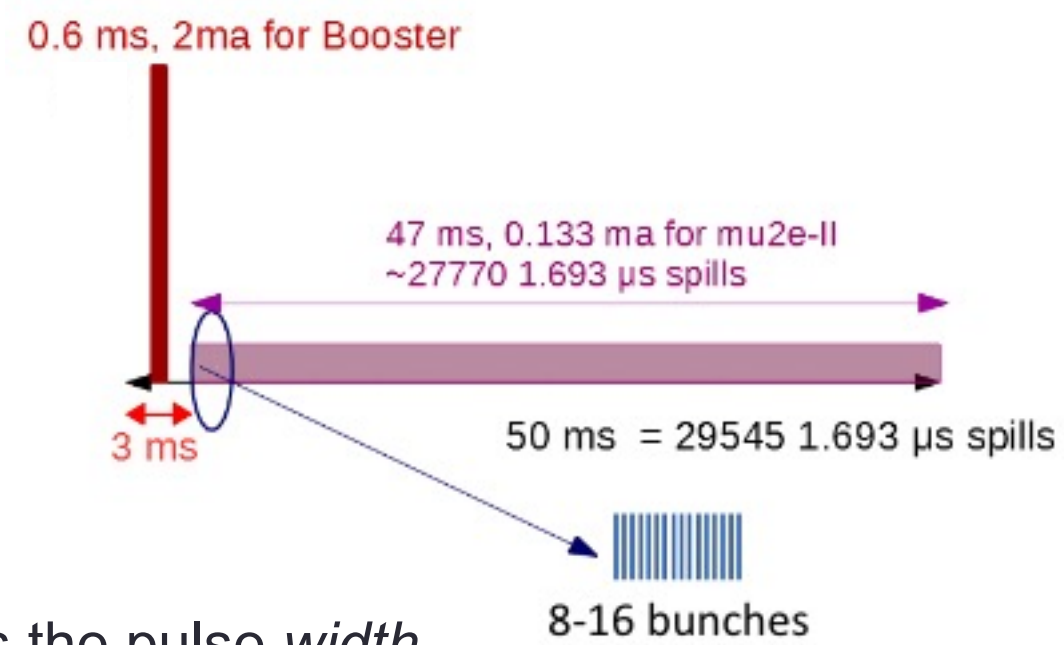
Example: Mu2e Beam Requirements

- The Mu2e experiment searches for the conversion to an electron of a muon that has been captured by an Aluminum nucleus.
- The most important backgrounds are prompt with respect to the proton that produces the muons.
- Solution: pulsed beam



Example: Mu2e-II Beam Formation

- Possible beam structure (100 kW):
  - 10 bunch burst @ 600 kHz
  - 1.4×10^8 protons/bunch
  - 600 kHz repetition rate
  - = 100 kW
  - 3% duty factor
  - 0.12 mA
  - These numbers are independent from the instantaneous bunch rate!
    - ie, which line we're in



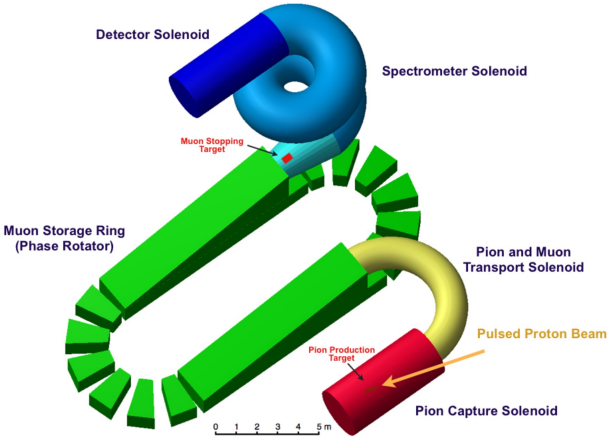
- The bunch rate only affects the pulse *width*
  - 162.5 MHz = 60 ns
  - 81.25 MHz = 120 ns
  - 40.625 MHz = 240 ns
- All of these numbers would double for 200 kW

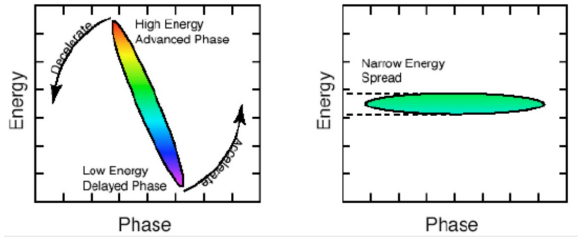
~275 162.5 MHz buckets

That's all that would be needed from the accelerator end!

Beyond Mu2e-II

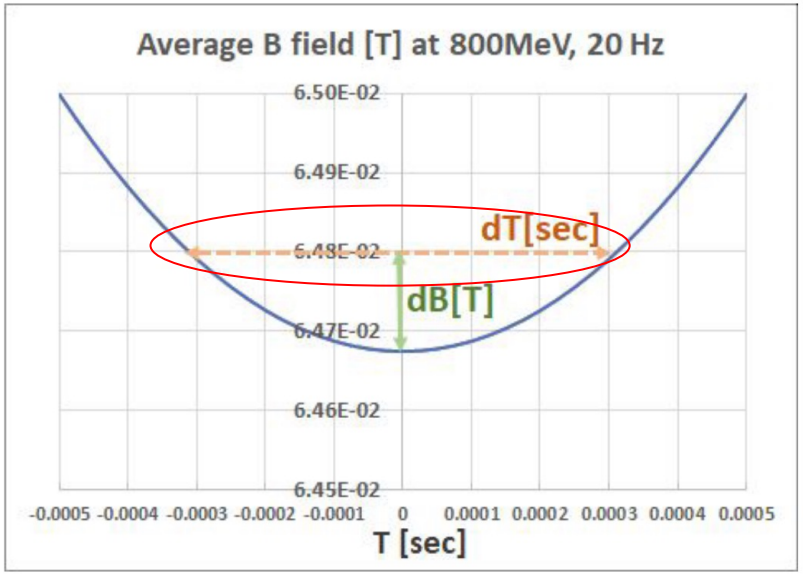
- To go beyond the Mu2e-II goals, or to go to heavier targets (shorter lifetimes), it's necessary to adopt another means to allow pions to decay to avoid "straggling"
- Solution: FFA





- Problem: cannot fill this ring directly from PIP-II beam
- Need a "compressor ring" to provide short, intense pulses at 100-1000 Hz.

Competing Priorities



- The neutrino program
  - The Booster magnets will run at a 20 Hz offset sine wave.
    - Initially, it will be flattened at the lower end during injection using the Booster corrector magnets.
  - Injecting more beam into the booster will require a longer injection pulse, going beyond the ability of the corrector magnets to flatten the field.
  - The Booster Storage Ring (BSR) would allow the protons to be pre-loaded, the way we preload protons in the Recycler for the Main Injector.
  - It therefore must be *at least the same circumference* as the Booster!
  - Might be other ways to solve this problem.
- Muons (and others?)
  - Want the shortest, most intense pulses we can get.
  - Space charge effects drive us to the *smallest possible* ring to achieve this.

PIP-II Discussions for Snowmass

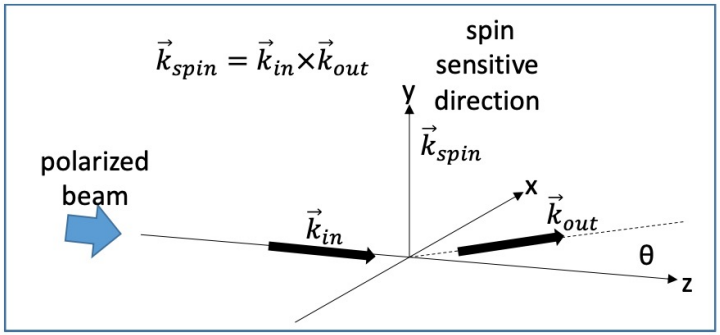
- Organize potential users
  - Limited success so far
- Compressor ring decisions
  - One? Two? Can the Booster loading needs be met in some other way?

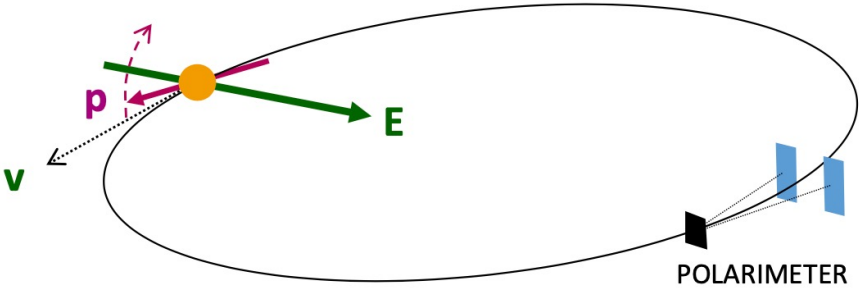
Other Accelerator-related RP Issues

- Beam Dump Experiments
  - Protons:
    - Issues largely align with needs of neutrino program
      - Beam intensity
      - Target R&D
  - Electrons
    - Possible opportunities for wakefield designs?
- EDM Measurements
  - These experiments typically involve unique storage ring designs, including electrostatic storage rings, which present very interesting accelerator physics problems.

Example: Proton EDM*

Storage ring Electric Dipole Moments





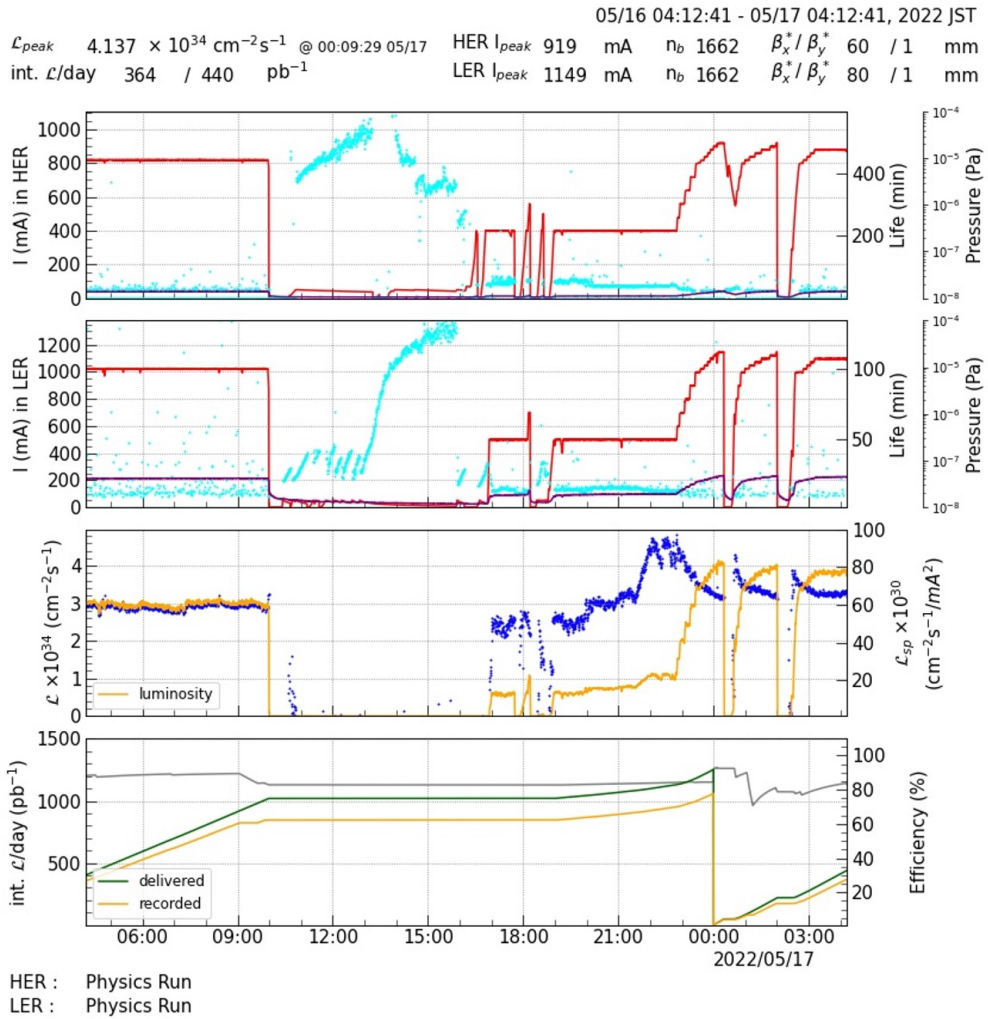
Frozen spin method:

- Spin aligned with the momentum vector
- E-field precesses EDM/spin vertically
- Monitoring the spin using a polarimeter

*see talk by Y. Semertzides, on Thursday

Belle-II

- SuperKEKB continues to push the boundaries of precision physics, and just broke the luminosity record.



May 16, 2022: SuperKEKB passed L=4 x 10^{34}/cm^2/sec. A new world record for accelerators.

This about 3 times higher than L_max(PEP-II/BaBar) with a factor of 5 lower product of beam currents. Nanobeams work !

Announcement from Belle-II KEKB*

- An ITF (International Task Force) has been formed to help improve SuperKEKB luminosity on the long term.
- There is collaboration now with a number of major accelerator labs.
- These include CERN (FCC-ee), IHEP, BINP, ESRF, BNL, SLAC.
- Early successes include ideas and suggestions for beam dynamics,
  optics and TMCI.
- The initial charge is to make a plan to go beyond 2 x 10^{35} and get
  to 6 x 10^{35}. But the ITF may discuss plans and R&D for even higher luminosity as soon as the initial problem is solved.
- This is an extremely helpful and fruitful development from KEK.
- Stay tuned.

*Tom Browder

Conclusions

- Lots of interesting physics out there!
- Very important to understand the capabilities of various labs and accelerators.
- Snowmass should seek a key role in planning for the PIP-II physics program at Fermilab.

BACKUP

Low energy hidden sector searches

- Motivated by the QCD axion as well as astrophysical hints, the low energy hidden sector is potentially accessible via number of sub-eV Axion/ALP search techniques. For example:
  - Helioscopes (e.g. BabyIAXO/IAXO)
  - Haloscopes using resonant cavities (e.g. ADMX) or other methods (e.g. MADMAX)
  - Light-shining-through-walls experiments (e.g. JURA, STAX)
- Many of these initiatives can profit from ongoing advances in accelerator technology e.g. high field superconducting magnets, superconducting RF.

Light Dark Matter searches

- Light Dark Matter searches in the MeV - GeV mass range target a parameter space of the Hidden Sector of special relevance to open questions in cosmology. Options include:
  - Direct detection WIMP searches (primarily addressed by the Cosmic Frontier).
  - Proton beam dump experiment: new proposals (e.g. BDF/SHiP), re-purposed existing experiments (e.g. NA62, MiniBooNE, SeaQuest)
  - Electron beam dump experiments: NA64, LDMX, BDX… Proposals could include use of novel use of existing facilities (LCLS-II, CEBAF, FAST/IOTA) or the development of new facilities.
  - Long lived particles at colliders (LHC, SuperKEKB)

Precision measurements and rare decays

- Precision measurements and rare decays can probe higher masses than accessible with LHC direct searches, via searches for the possible influence of the contribution of loop diagrams in a number of scenarios. For example:
  - Ultra-rare or forbidden decays/reactions:
    - Kaon sector (NA62, KOTO, KLEVER}
    - Lepton sector (TauFV, Mu3e, MEG,mu2e/mu2e-II)
  - Precision measurements:
    - Permanent EDM
      - in protons/deuterons (CPEDM)
      - in strange/charmed baryons (LHC-FT)
  - Anomalous magnetic moment of muon (g-2)

Technologies

- Use of existing accelerator technologies or accelerator technology under development for novel physics applications Technologies to be considered include:
  - High field magnets
    - e.g. axion and dark matter searches
  - Superconducting RF
    - e.g. axion searches
  - ERLs
  - Induction LINACs
    - e.g. rare muon processes
  - Quantum sensors, ultra-sensitive opto-mechanical force sensors (e.g. KWISP)
  - Carbon Nanotubes (CNT) (e.g. directional detection of DM candidates)
- Physics applications might include various types of axion/ALP searches (mentioned above), vacuum magnetic birefringence (VMB), exploration of Ultra-Light Dark Matter and Mid-Frequency Gravitational Waves (e.g. AION, MAGIS)

PIP-II Linac Beam Parameters

Parameter	Linac Output	Central Line	Side Lines	Comment
Energy [MeV]	800			
Max. Ave. Bunch Size	0.8×10^8			2 mA
Peak Bunch Size	2.0×10^8			5 mA
Bunch Frequency [MHz]	162.5	81.25	40.625	Maximum
Bunch Separation [ns]	6.2	12.3	24.6	Minimum

- Note:
  - Bunches can be arbitrarily populated, but bunch intensity cannot be changed quickly
  - During LBNF running, we will have to live with 1.4×10^8/bunch, as required by that program
    - 2mA into booster, painted (sparsified) into RF buckets