Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Evolution of accelerator timing: Mu2e → Mu2e-II

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Mu2e-II workshop @ Northwestern (https://indico.fnal.gov/event/17536/)

29-30 Aug 2018

Docdb-19876

Charge

- “Prepare some slides on how the experiment's timing system design, function, and relation to the accelerator timeline might evolve for Mu2e-II” - Ryan

First, summarize what we evolve from
(i.e., what we have for Mu2e)

Recall… Mu2e: macroscopic beam structure

- Sharing with NOvA defines macroscopic time structure

Mu2e-doc-2771

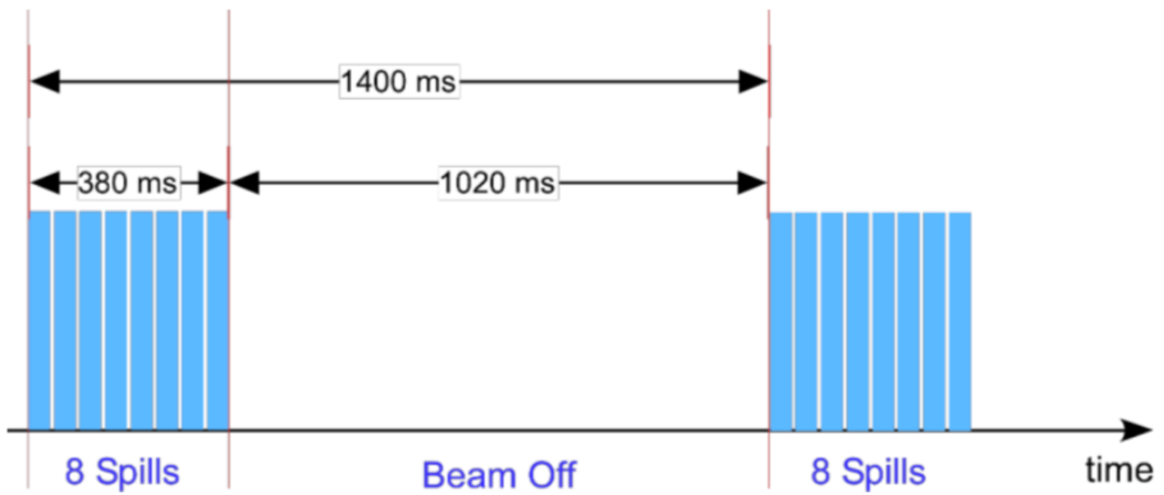
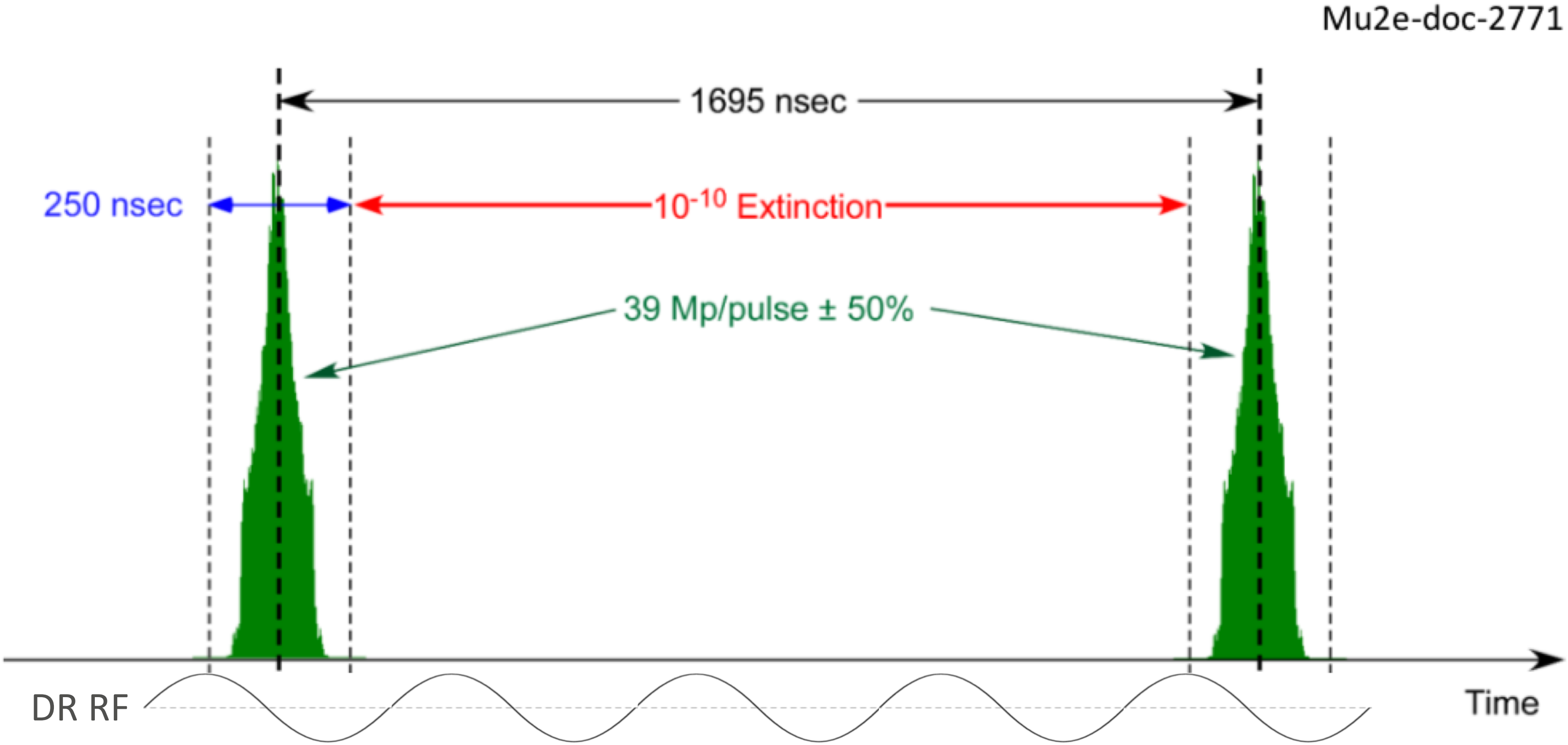


Figure 6: Macro-structure of the beam on the Mu2e proton target. For each spill the proton target will see a train of proton pulses lasting 43.1 msec followed by a 5 msec reset period with no beam. This is repeated eight times during each Main Injector cycle for a total beam on time of 380 msec. At the end of the eight spills beam to Mu2e is off for 1020 msec while the Recycler Ring is used for NOvA.

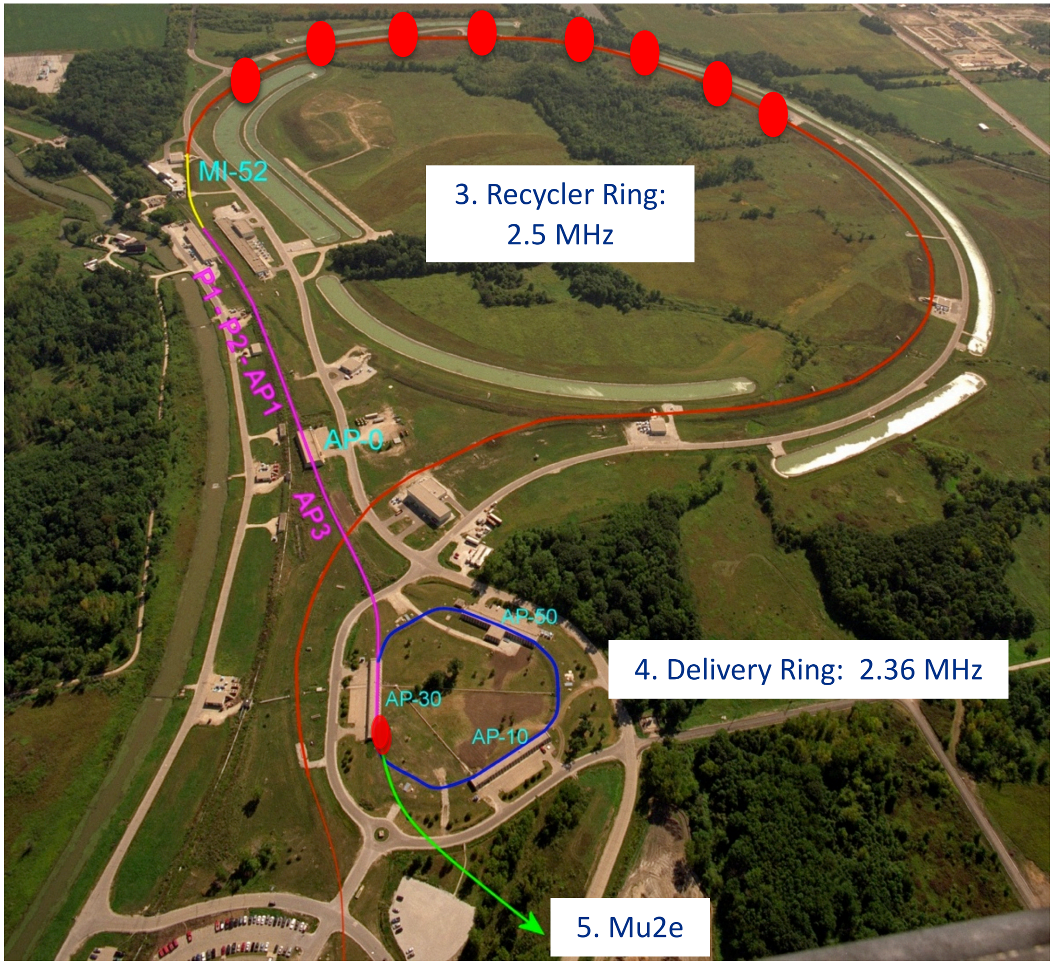
- 8 spills per Main Injector cycle
- Mu2e duty cycle (ON-spill/total) = (8 x 43.1ms) / 1.4s = 24.6%

Mu2e: microscopic beam structure and timing



- Microbunch timing defined by Delivery Ring RF = 2.36 MHz
- 8 GeV proton travel time around DR = 1695 ns (4x DR RF period)
- Microbunch ”contained” within ~½ the 2.36 MHz period (212 ns)

Recall: Delivery Ring RF phase shifts prior to spill

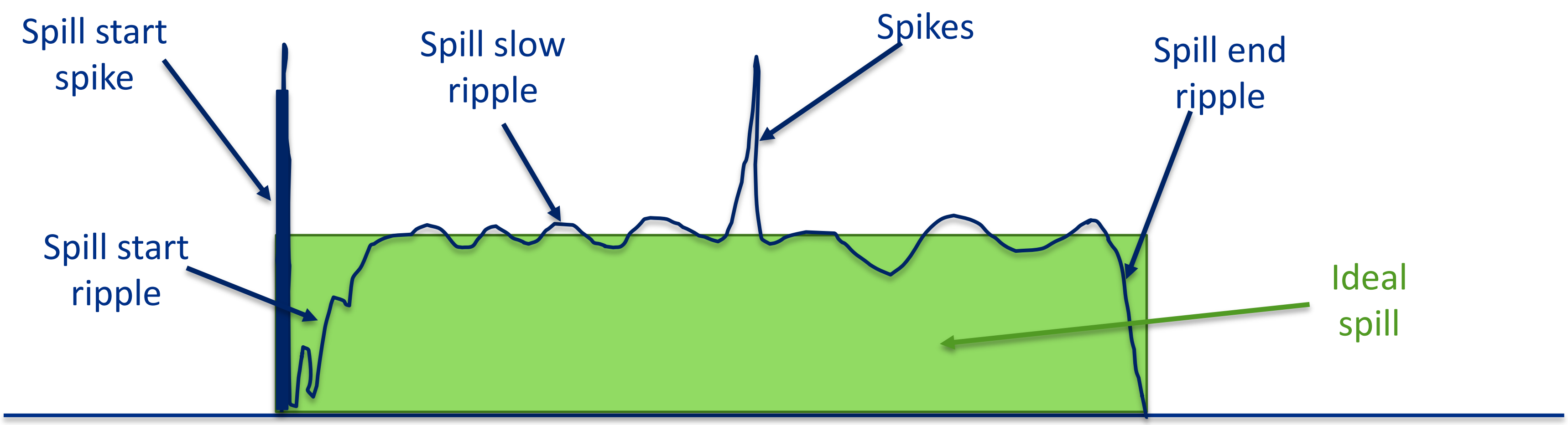


Step 1. LINAC, then into 2. Booster

- 2.5 MHz and 2.36 MHz are not harmonics
  - This means Recycler Ring RF and Delivery Ring RF are not locked (asynchronous)
- Just prior to beam transfer into Delivery Ring, the DR RF must be phase shifted so that the bunch lands in the DR bucket
  - Timing of microbunches **jumps** before each spill
- After the bunch has been transferred into the Delivery Ring, the DR RF does not shift
  - During spill, microbunches nicely spaced by 1695 ns

Docdb-19095

Mu2e: some (possible) features of spill variations



- Spill start spike: beam halo extracted
- Spill start ripple: modulation on extraction of tails of the beam
- Spill slow ripple: ~1kHz
- Spikes – fast induced modulations
- Spill end: beam phase space depleted, hard to regulate

Docdb-16190

Vladimir Nagaslaev

Mu2e timing architecture

- Mu2e has chosen a stable 40 MHz clock (system clock) from Clock Fan-Out (CFO) module
  - Mu2e system clock is not locked to the Delivery Ring clock → experiment and beam are asynchronous

- CFO receives electrical signal associated with microbunches (DR turn marker), which is used to tell us…
  - Microbunch timing with precision ~1 ns
  - Timing within spill

See docdb-19095 for details

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Following slides highlight some features of PIP-II, mostly focused on timing for Mu2e-II

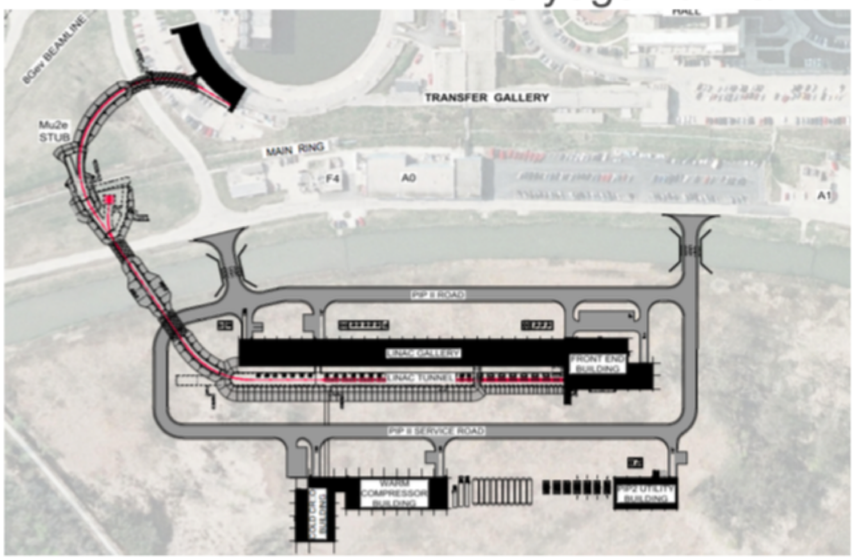
- Layout
- RF details
- Pulse timing
- Microbunch structure possibilities
- Expected variation pulse-to-pulse
- Macroscopic timing / duty factor

- Info in the following slides is pulled from Paul Derwent's talk at the Mu2e collaboration meeting March 2018 (docdb-16226), filled in by discussion with Paul 22 Aug 2018

Accelerator layout: direct shot LINAC → Mu2e-II

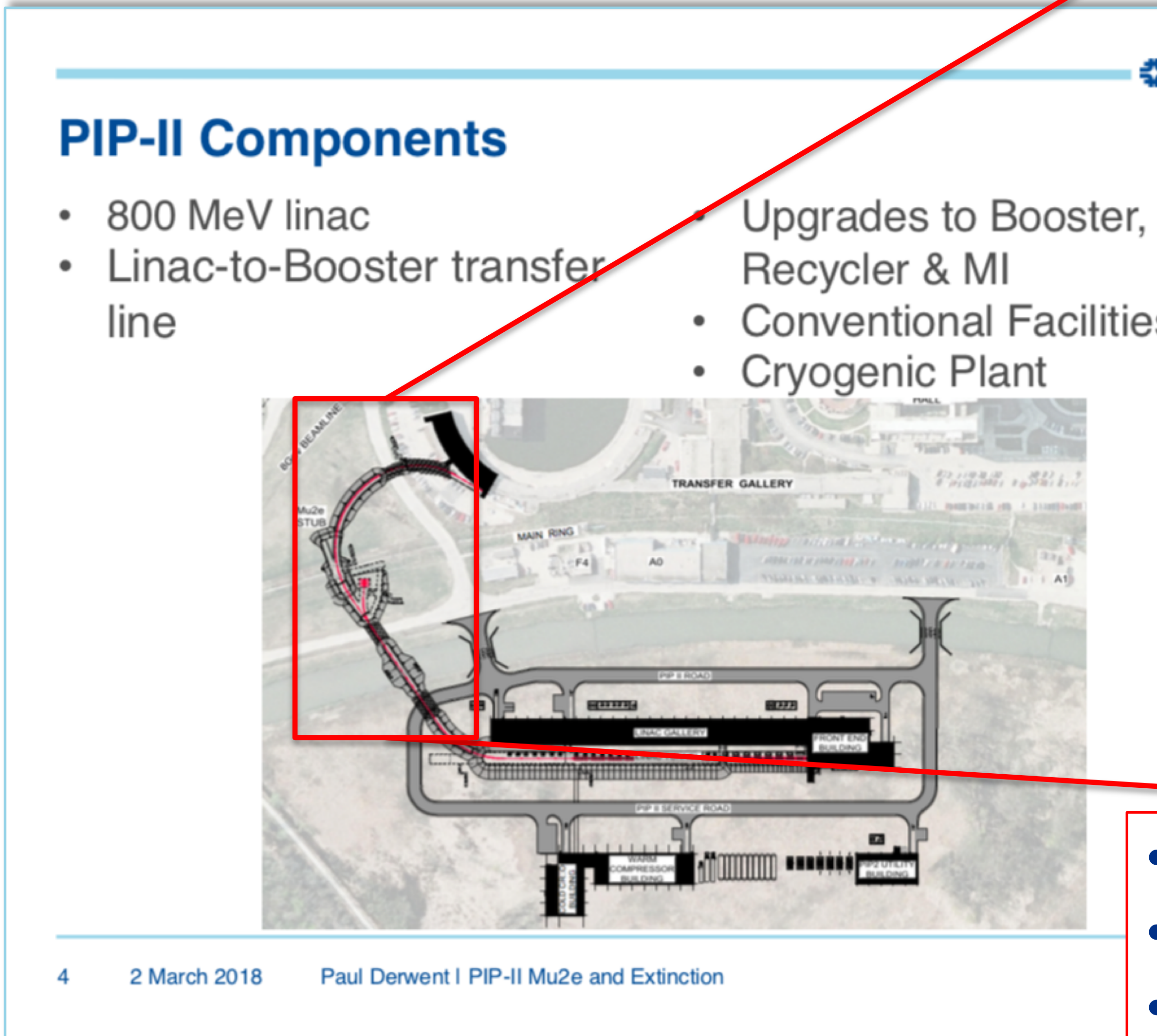
PIP-II Components

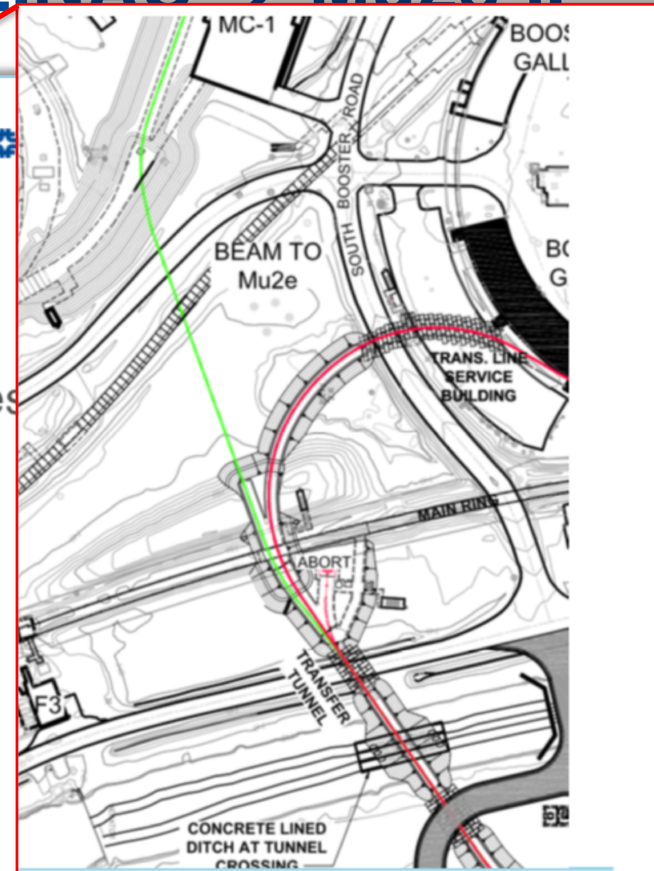
- 800 MeV linac
- Linac-to-Booster transfer line
- Upgrades to Booster, Recycler & MI
- Conventional Facilities
- Cryogenic Plant



- No Booster
- No Recycler Ring
- No Delivery Ring
- No slow extraction

Accelerator layout: direct shot LINAC → Mu2e-II





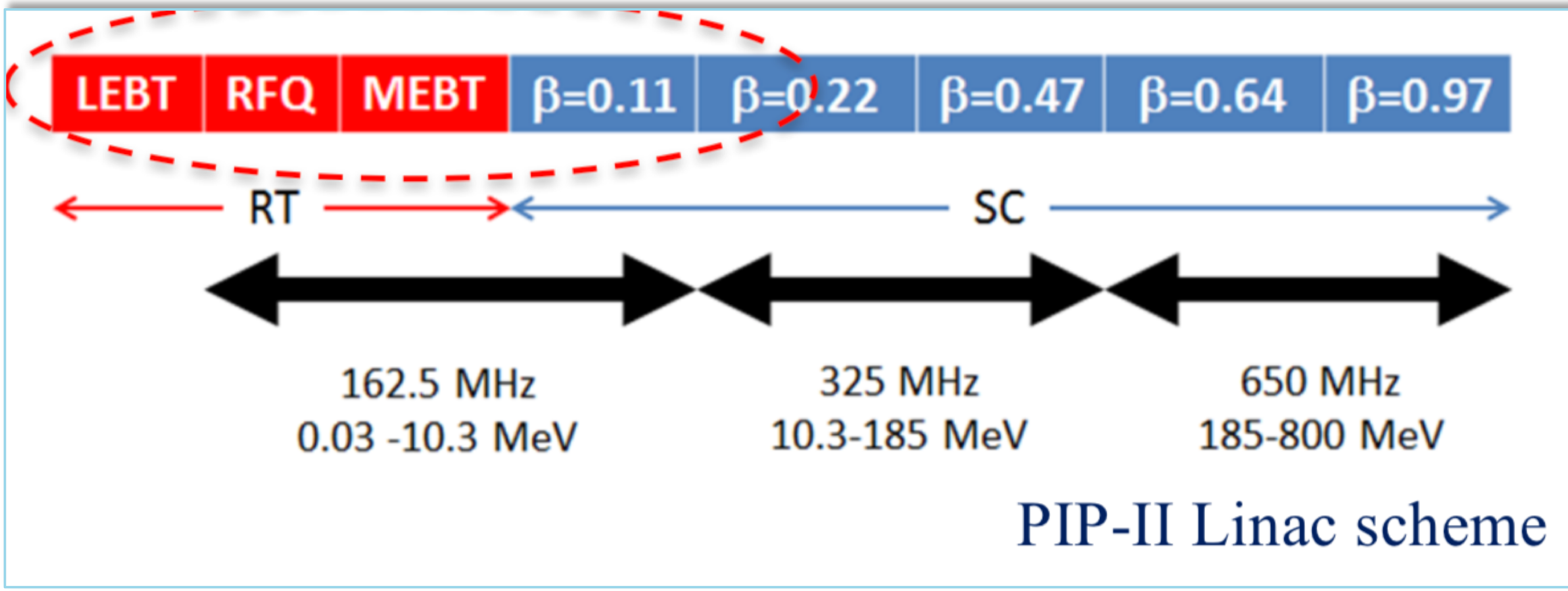
- No Booster
- No Recycler Ring
- No Delivery Ring
- No slow extraction

PIP-II RF details

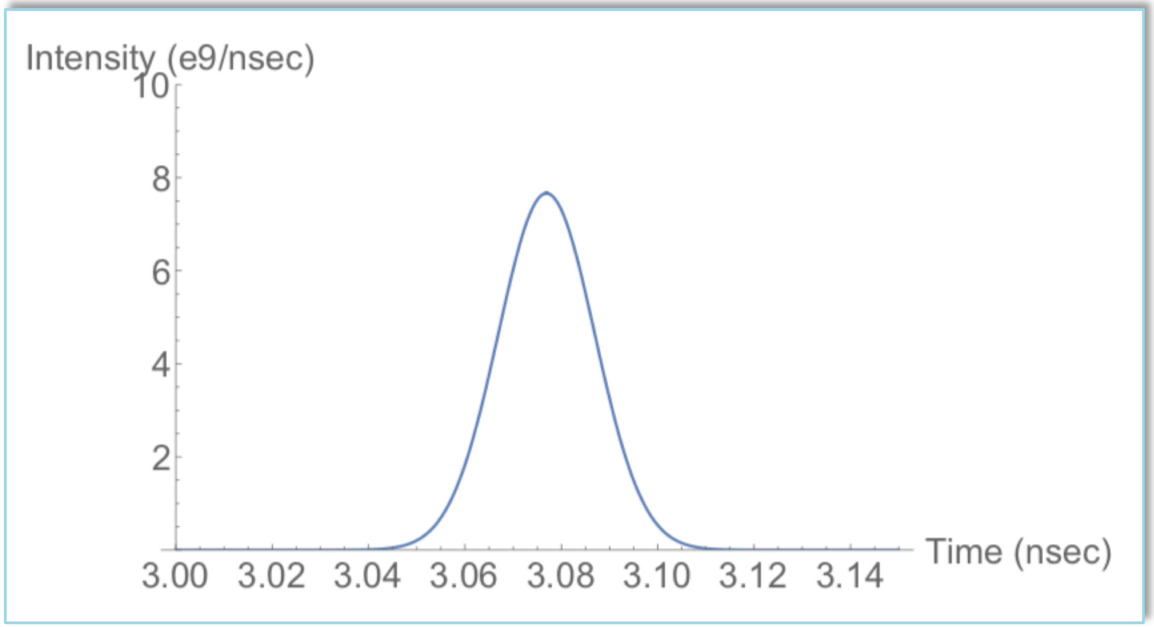
Time Structure for Mu2e

- Fundamental Time Structure set by 1st bunching device
  - 162.5 MHz Radio Frequency Quadrupole
  - 6.15385 nsec

162.5 MHz is a stable clock with no phase shifts, used to synchronize several RF cavities



Pulse timing



PIP-II delivers narrow pulses spaced by 6.15385 ns

A "chopper" has been developed to select which pulses to send to Mu2e

Timing of chopper matches 6.15385 ns:
1 ns ramp up, 4 ns ON, 1ns ramp down

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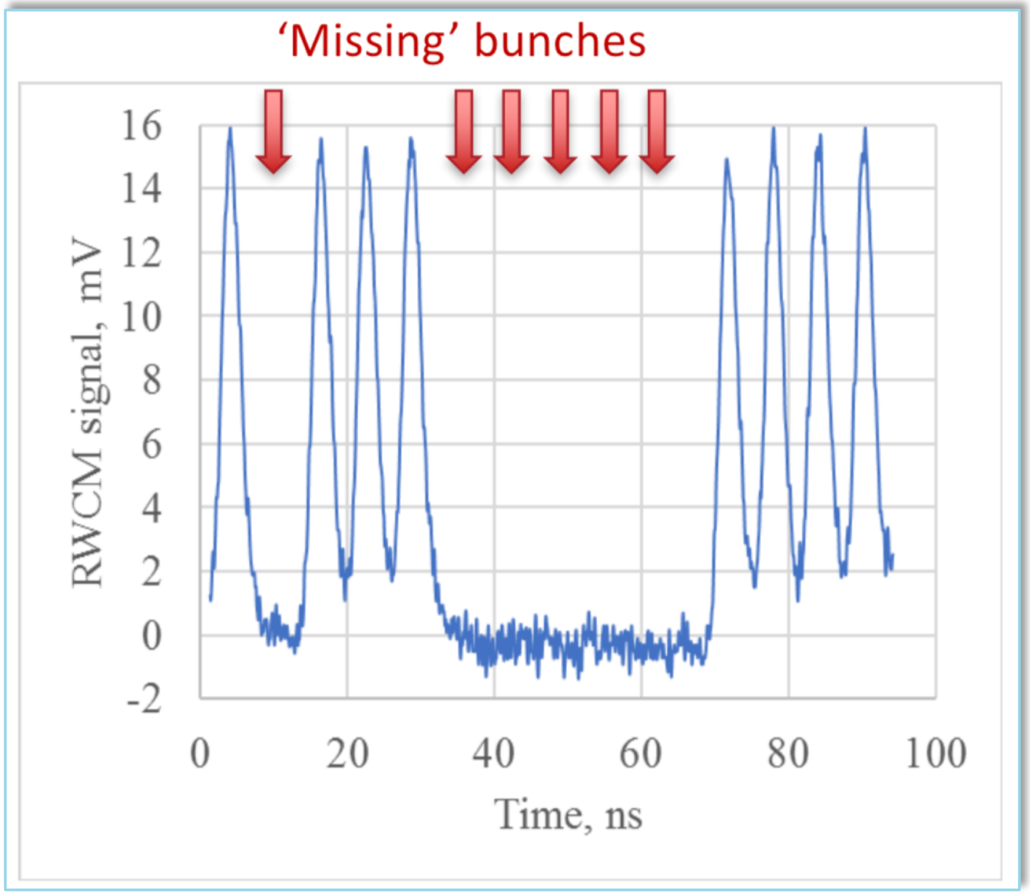
Pulse-to-pulse variation



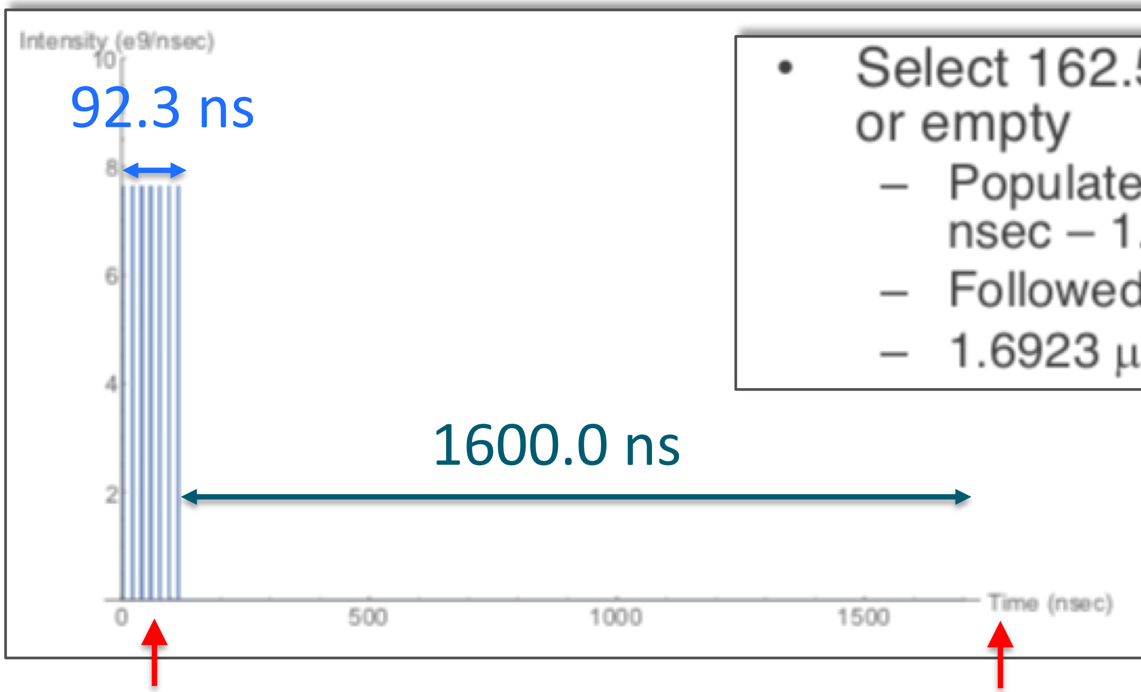
Pulses selected to send to Mu2e can be tuned as desired

PIP-II amplitude variation pulse-to-pulse likely less than 10%

Intensity per pulse driven by DUNE/LBNF program: limited by Booster RF power and time to ramp Booster RF

Example microbunch structure

- Recall: Mu2e microbunch = 4e7 protons in a ~250 ns wide pulse
- Mu2e-II microbunch = N pulses with spacing in units of 6.15 ns
  - Number of pulses and their spacing can be chosen/tuned depending on physics desires, target heating limitations, future operations of the complex, …



- Select 162.5 MHz bunches : populated or empty
  - Populate: 1 every 3 (18.5 nsec) for 100 nsec – 1.15e9 H^-
  - Followed by 259 'empty'
  - 1.6923 μsec pulse spacing

In this example, 1 microbunch = 6 pulses separated by 18.5ns (i.e., 3 x 6.15385ns), then 259 empty pulses (= 1600.0ns)

Macroscopic timing / duty factor

PIP-II macro-time structure driven by DUNE/SBN:

> 20 Hz Booster program: DUNE/SBN
> – 1.1% duty factor
> – Mu2e-II can use other 98% duty factor
> – 6.6e15 H^- / second
> – 85 kW

- During 1 period (50 ms) of DUNE/SBN cycle
  - 1 ms: fill Booster, change LINAC settings for Mu2e-II
  - 48.5 ms: ramp up Booster, transfer beam out of Booster, ramp down Booster
    - While ramping Booster, beam available for Mu2e-II
  - 0.5 ms: change LINAC settings for Booster
- Mu2e duty cycle = 48.5 / 50 = 97%

Summary of accelerator changes: Mu2e → Mu2e-II

- Duty factor
  - Mu2e : 29%
  - Mu2e-II: 97%
- Accelerator RF
  - Mu2e : 2.36 MHz (DR RF)
  - Mu2e-II: 162.5 MHz (6.15385 ns)
- Accelerator RF phase shift
  - Mu2e : yes (just prior to each spill)
  - Mu2e-II: no
- Microbunch structure
  - Mu2e : 3.9e7 protons in 250 ns wide pulse
  - Mu2e-II: N filled pulses spaced in 6.15ns steps (N and spacing tunable)
- Microbunch spacing
  - Mu2e : 1695 ns (4x DR RF period)
  - Mu2e-II: M empty pulses spaced in 6.15ns steps (M and spacing tunable)

First thoughts on TDAQ thoughts re: beam timing

- Given increase of duty cycle from 25% to 97%…
  - Pre-processing step with FPGA's? "Level-1+HLT" architecture?
  - When to collect cosmic rays?
  - When to perform calibrations?

- Given neither resonant extraction nor Delivery Ring…
  - Implications of smaller pulse-to-pulse variation? (no spill structure)
  - Work out new protocol to communicate "PIP-II beam to Mu2e" (i.e., replacement of DR turn marker)

- Given no phase shift of PIP-II RF…
  - Consider to lock Mu2e-II system clock to 162.5 MHz accelerator clock

- Given that PIP-II timing is based on pulses every 6.15 ns…
  - No action regarding structure within microbunch
  - Don't omit possibility to vary spacing between microbunches

Background slide

- Mu2e-II beam requirements, in prose

In prose, the expectations from Mu2e are…

- From Expression of Interest (arXiv:1802.02599):
  - "The proton pulses must be narrow, ideally < 100 ns base width… and ideally separated by a time which can be varied from 800 to 2000 ns. The microstructure of the beam (structure inside the < 100 ns-wide pulse) is not important… The fraction of the high frequency pulse train in the time line (macro duty-factor) should be as high as possible; optimally greater than 90%. Additionally, the pulse train should have minimal pulse-to-pulse variation throughout the train, optimally less than 10%"

- … and from 2018 presentation to FNAL PAC (docdb-18855):

> • PIP-II capable of meeting these requirements