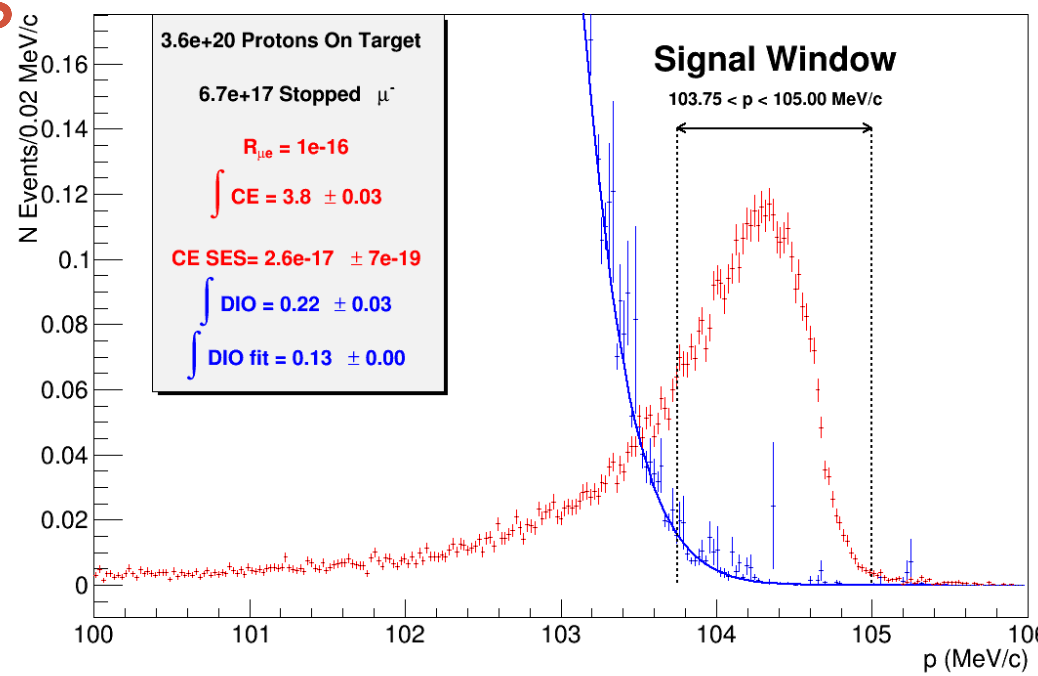
FFA FOR FUTURE MUON CONVERSION EXPERIMENT

Eric Prebys, UC Davis

Reminder: Mu2e Goals



- 3.2×10^{20} protons on target (3 years @ 8 kW)
- ~.4 background events
- Bottom line:
  - Single event sensitivity: $R_{\mu e}=3\times10^{-17}$
  - 90% C.L. (if no signal) : $R_{\mu e}<7\times10^{-17}$
  - Typical SUSY Signal: ~40 events or more

Four order of magnitude improvement over previous best experiment (SINDRUM-II)

After Mu2e

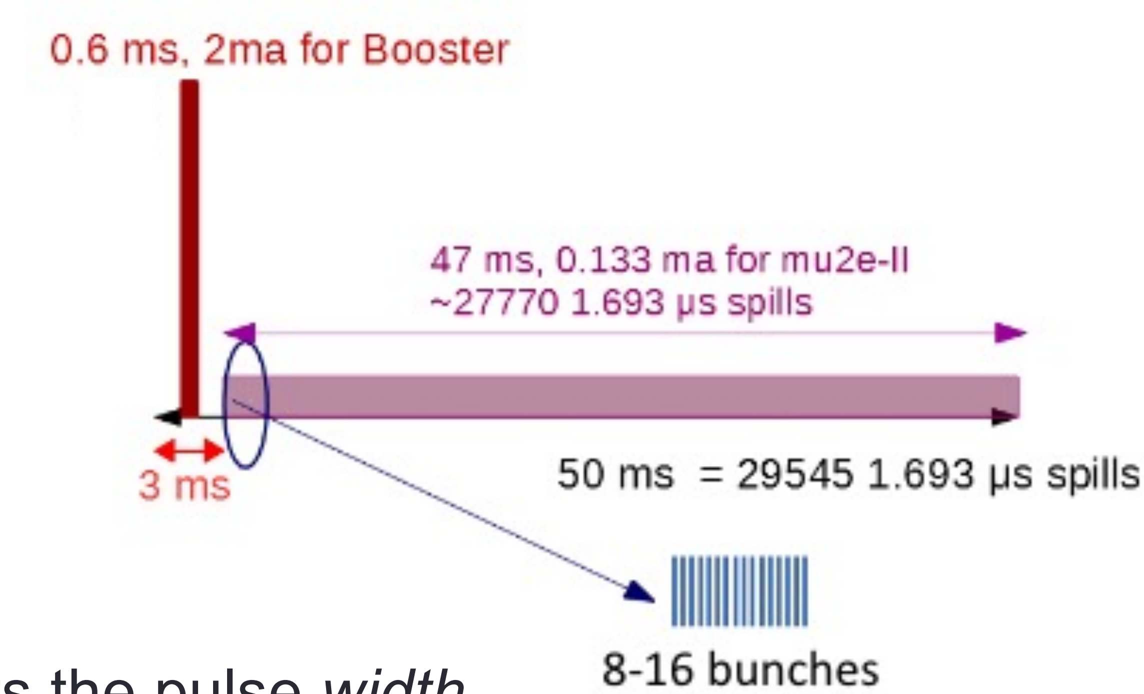
- Mu2e doesn't see signal?
  - Keep searching at higher sensitivity
  - Going to higher-Z targets will enhance conversion probability
- Mu2e sees signal?
  - More running to increase precision and study nature of signal.
  - Most important: dependence on the capture target!
- Common
  - More beam
  - Higher-Z targets

Potential Future Plans

- Mu2e-II
  - Redo the Mu2e experiment using beam directly from the PIP-II linac (8 GeV -> 800 MeV)
  - 8kW->100 kW
    - ~10 times the statistics
  - Unless the signal from Mu2e is large, we'll still be limited to aluminum or slightly heavier as a target.
  - I'll say very little about this.
- ACE Era
  - Goal: 1 MW at 800-2000 MeV (depending on PIP-II upgrades)
    - **Cannot** be done directly with PIP-II beam
  - Other significant issues going to higher statistics and heavier targets.
  - Let's talk about those…

Mu2e-II Beam Formation

- Possible beam structure (100 kW):
  - 10 bunch burst @ 600 kHz
  - $1.4x10^8$ 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

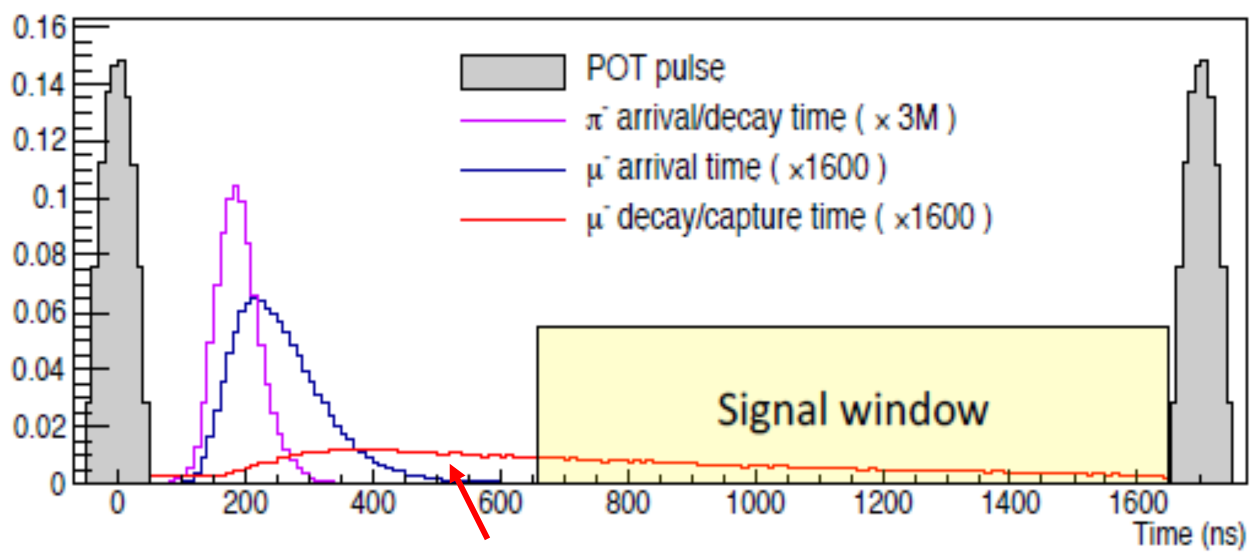
~275 162.5 MHz buckets

- All of these numbers would double for 200 kW

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

Target Nucleus Issue (same for Mu2e and Mu2e-II)

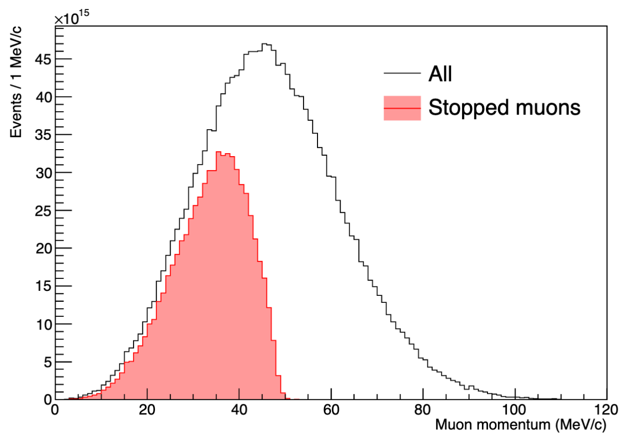
- We would like to go to higher Z nuclei either to enhance the rate if we don't see a signal or to study the A-dependence if we do;
- HOWEVER, heavier nuclei *dramatically shorten* the lifetime of the bound muons, which runs into problems with the long beam straggling time
    - Example: The probability of interaction for a gold nucleus would be enhanced by ~1.5-2 relative to aluminum, but the lifetime goes from 880 ns to only 73 ns!

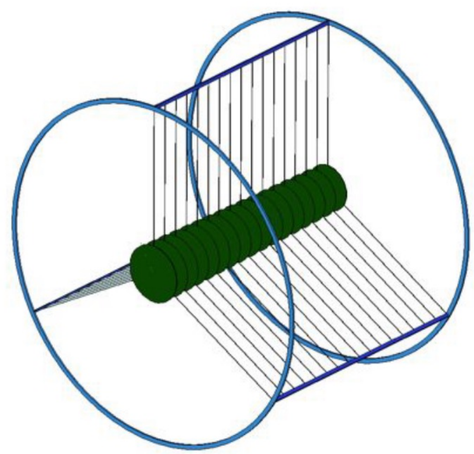


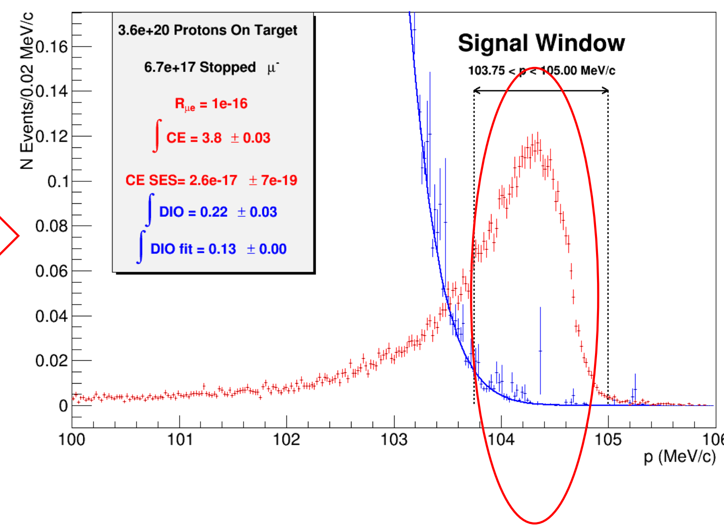
This curve would be dramatically shortened, so all the muons would decay away before the live window

Capture Target Issue

- Our tracking resolution is limited by scattering in our multi-layer capture target, which we need because of the muon energy distribution



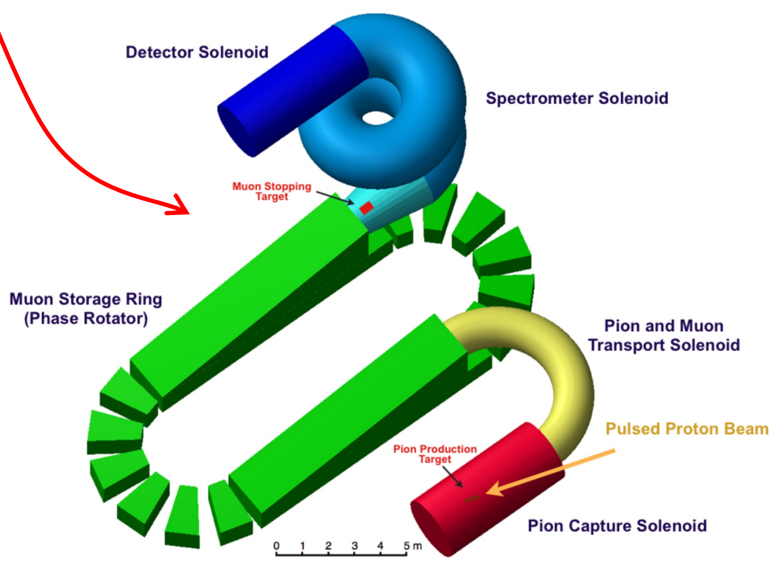


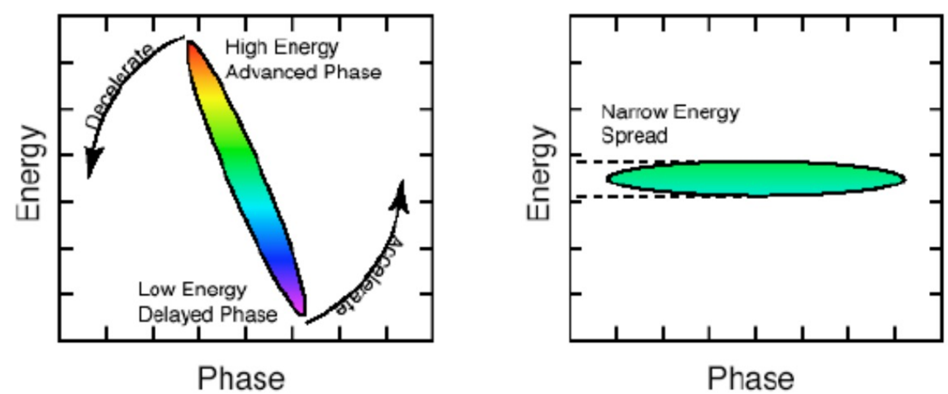


- To solve these problems we need:
  1. A different way for prompt backgrounds to die away
     - i.e. eliminate need for veto
  2. A source of muons with much narrower energy distributions.

Solution: FFA*

- This solution has been been developed for next generation of the competing COMET experiment at J-Parc
- Muons will be injected into an FFA for about ~6 turns
  - All the pions will decay away (eliminating the need for the veto)
  - The beam will be phase rotated to reduce the energy spread.





- Ultimately want 500-1000 kW!
- Unfortunately, can't feed this directly from PIP-II…

*J. Pasternak talk later in this workshop

PRISM parameters

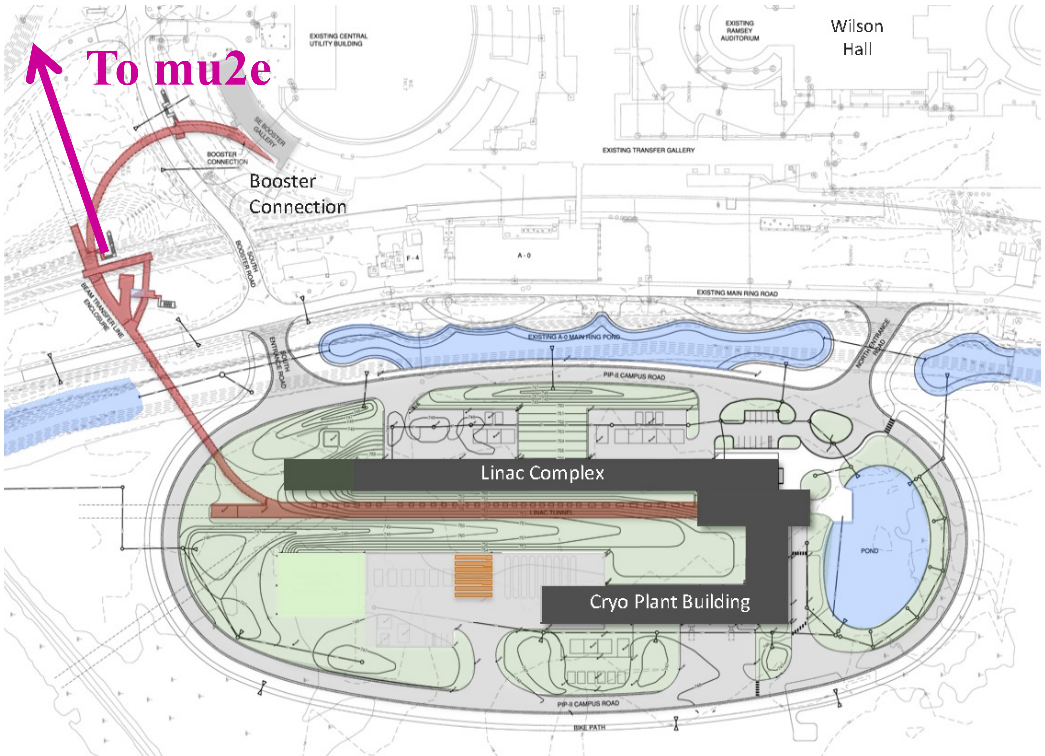
Parameter	Value
Target type	solid
Proton beam power	~1 MW
Proton beam energy	~ GeV
Proton bunch duration	~10 ns total
Pion capture field	10 -20 T
Momentum acceptance	±20 %
Reference μ^- momentum	40-68 MeV/c
Harmonic number	1
Minimal acceptance (H/V)	3.8/0.5 π cm rad or more…
RF voltage per turn	3-5.5 MV
RF frequency	3-6 MHz
Final momentum spread	±2%
Repetition rate	100 Hz-1 kHz

J. Pasternak

Would ideally like to lower this.

Induction linac, maybe?

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

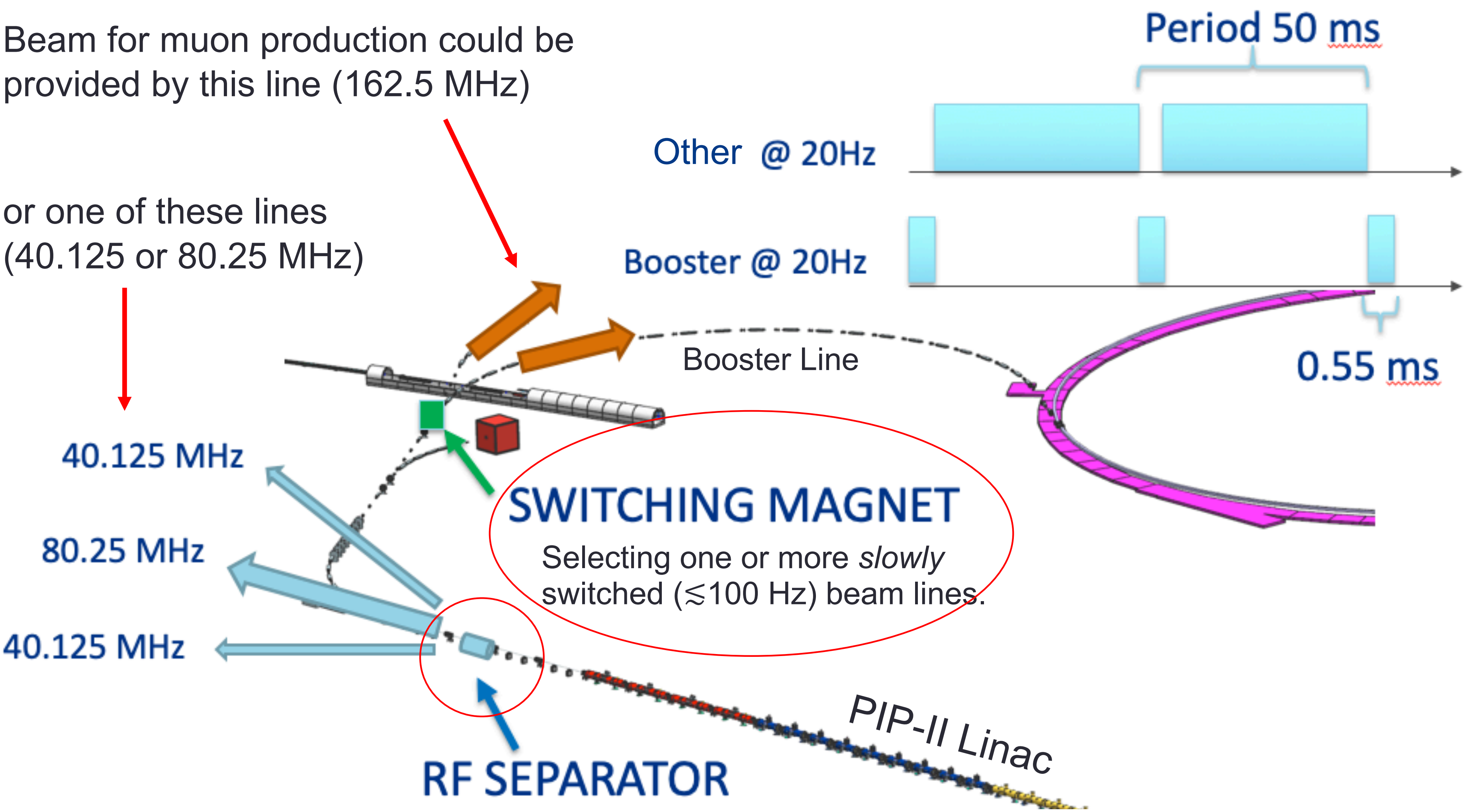
Upgraded Recycler & Main Injector
- RF in both rings

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!*

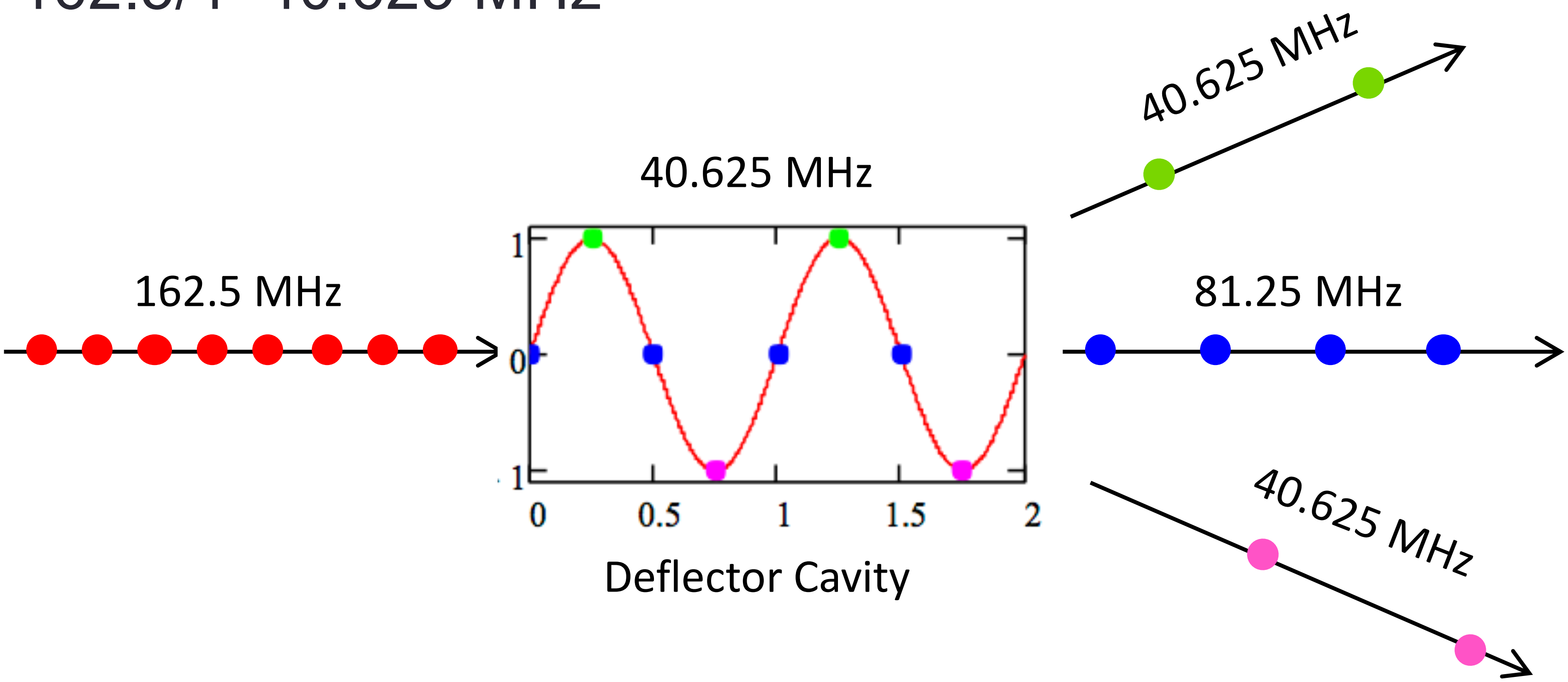
Beam Switching*



*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.

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

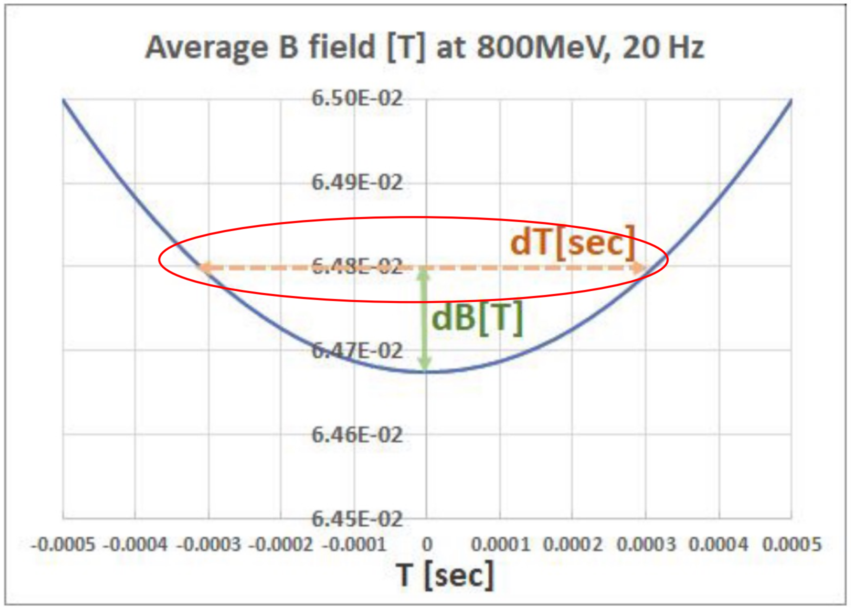
- Note:
  - Bunches can be arbitrarily populated, but bunch intensity cannot be changed quickly
  - During LBNF running, we will have to live with $1.4\text{x}10^8$/bunch, as required by that program
    - 2mA into booster, painted (sparsified) into RF buckets

Need for a Bunch Compressor

- In order to work, an FFA would need*
  - > 10^{12} protons/bunch
  - ~ 10 ns bunch length
  - 100-1000 Hz
- $10^{12} = 5000\mathrm{x}(2\mathrm{x}10^{8}) = 31\ \mu\mathrm{sec}$ ← 3000 times too long!
  - For these experiments, we need some sort of "bunch compressor" to accumulate beam into larger bunches, and then extract them to experiments.
- Two LoIs were submitted to Snowmass related to this:
  - E. Prebys, *et al*, "Letter of Interest: Bunch Compressor for the PIP-II Linac",(Green field, permanent magnet ring) https://www.snowmass21.org/docs/files/summaries/AF/SNOWMASS21-AF5_AF0-RF5_RF0_Prebys2-203.pdf
  - W. Pellico, *et al*, "FNAL Booster Storage Ring",(this workshop) https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-RF6_RF0_pellico-029.pdf

*See J. Pasternak Talk

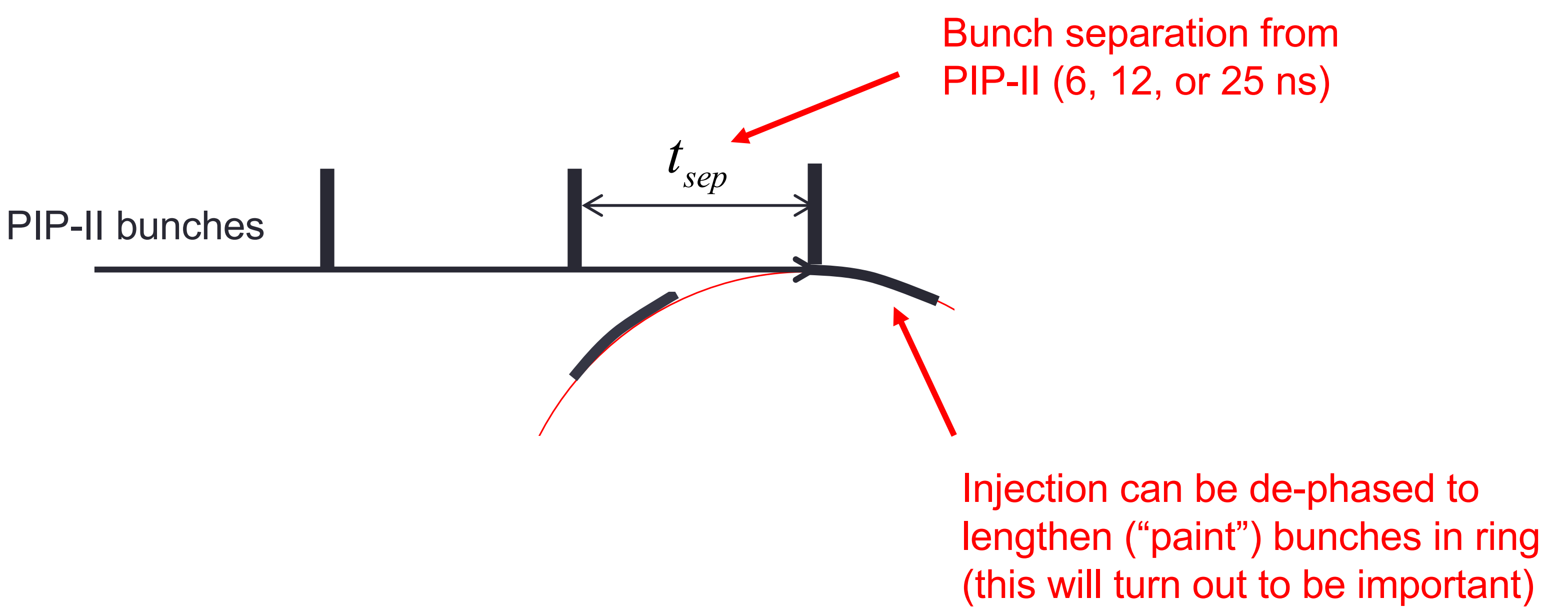
Competing Priorities



- 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.
  - As we will see, this will drive us toward the smallest possible ring circumference.

Filling a Compressor Ring

- H^- beam would be injected into the compressor ring over many turns using charge exchange injection.



Modes of Operation

- For Booster pre-loading
  - Fill ring continuously over many turns.
  - Transfer to Booster after accumulating enough protons
    - Still a very small fraction of the total time line.
- For FFA support
  - Continuously fill ring.
  - Time things so that individual bunches can be extracted as they fill up.
    - This would take a bit to explain, so you'll just have to trust me on it.
  - Bottom line: total power out = total beam power in
- Now, to understand beam stability issues…

All the Accelerator Physics U Need 2 Know

- Beam size in a *proton* accelerator is given by

Betatron lattice function. Typically 10s of meters in hadron machines

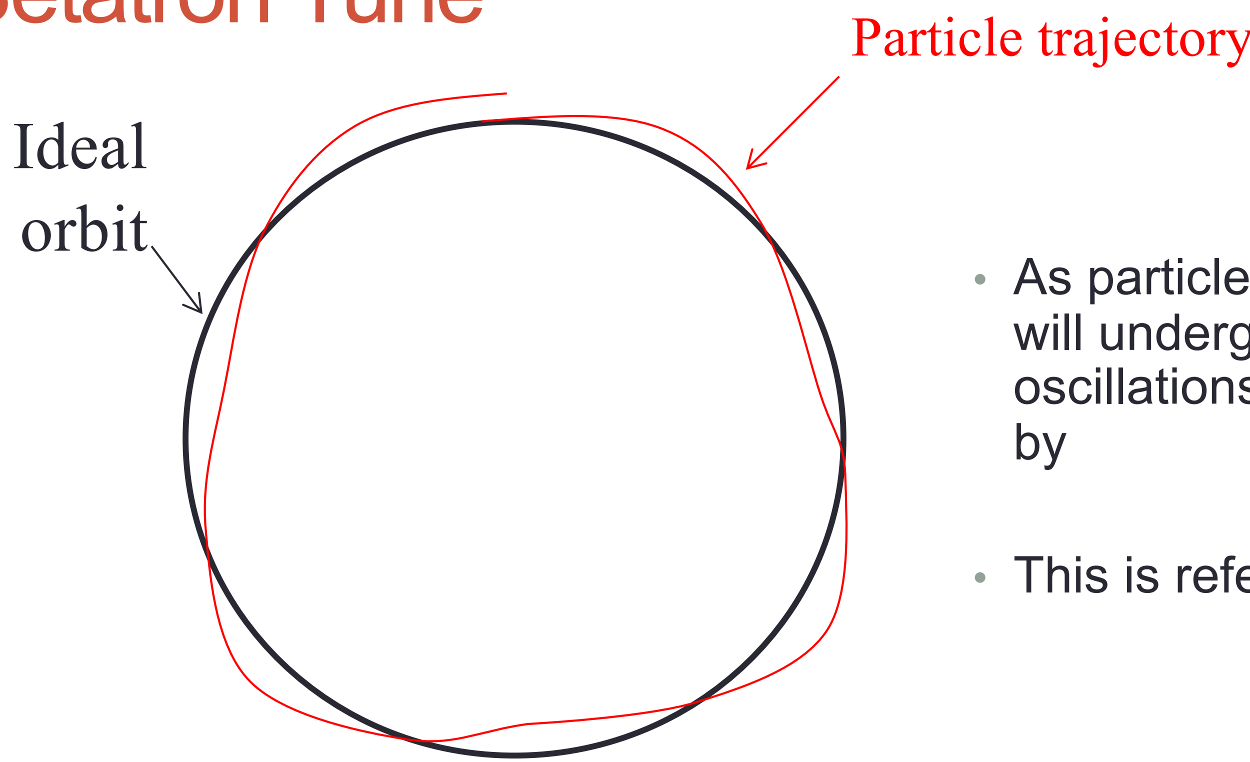
Position along nominal trajectory

Normalized emittance, related to area in transvers phase space. Limited to 2-3 π-mm-mr by Booster and Main Injector

$$\sigma(s) = \sqrt{\frac{\beta_\perp(s)\epsilon_N}{\beta\gamma}}$$

Standard Lorentz parameters

Betatron Tune



- As particles go around a ring, they will undergo a number of betatron oscillations ν (sometimes Q) given by
- This is referred to as the "tune"

- We can generally think of the tune in two parts:

Integer : magnet/aperture optimization → 6.7 ← Fraction: Beam Stability

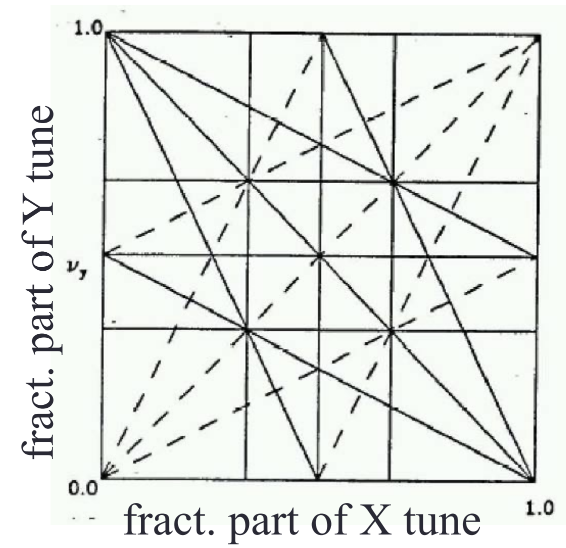
Tune, Stability, and the Tune Plane

- If the tune is an integer, or low order rational number, then the effect of any imperfection or perturbation will tend be reinforced on subsequent orbits.
- When we add the effects of coupling between the planes, we find this is also true for *combinations* of the tunes from both planes, so in general, we want to avoid

$$k_x \nu_x \pm k_y \nu_y = \text{integer} \Rightarrow \text{(resonant instability)}$$

"small" integers

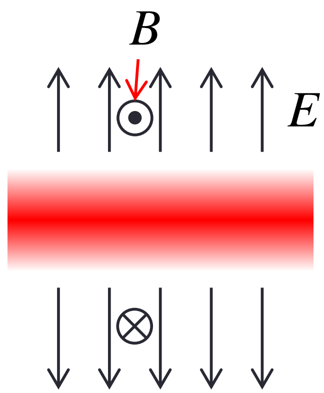
➔Avoid lines in the "tune plane"



- Many instabilities occur when something perturbs the tune of the beam, or part of the beam, until it falls onto a resonance, thus you will often hear effects characterized by the "tune shift" they produce.

Space Charge Tune Shift

- Consider the effect off space charge on the transverse distribution of the beam.



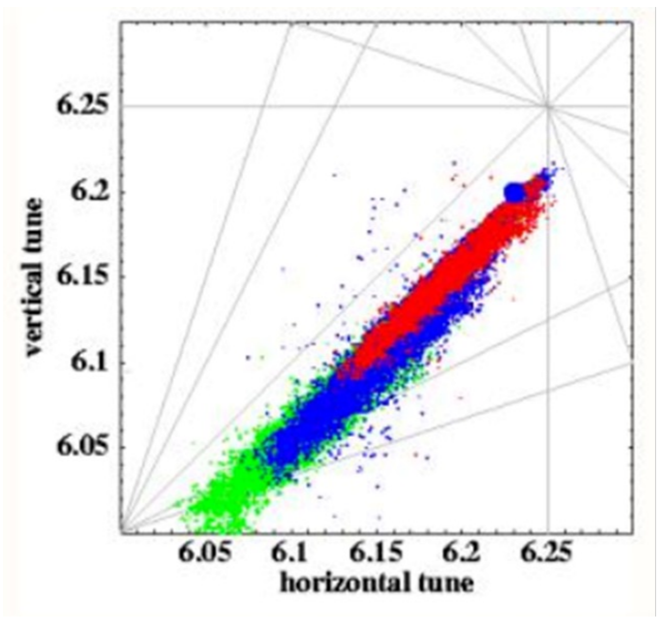
The electric field is repulsive, but the magnetic field is attractive.

The forces exactly cancel at β=1.

-> Space chage effects go down (quickly) with energy.

- Space charge tune shift limits the amount of beam that can be loaded into a synchrotron.

Example: SNS



Tune footprint in the SNS proton storage ring after 263, 526, and 1060 injection turns*

Ring Size and Space Charge Considerations

- Once we've fixed the injection energy, for a ring with multiple bunches, the space charge tune shift limit is given by

Peak Current/Average Current; Number of bunches; Bunch size; ~limit; Bunch length

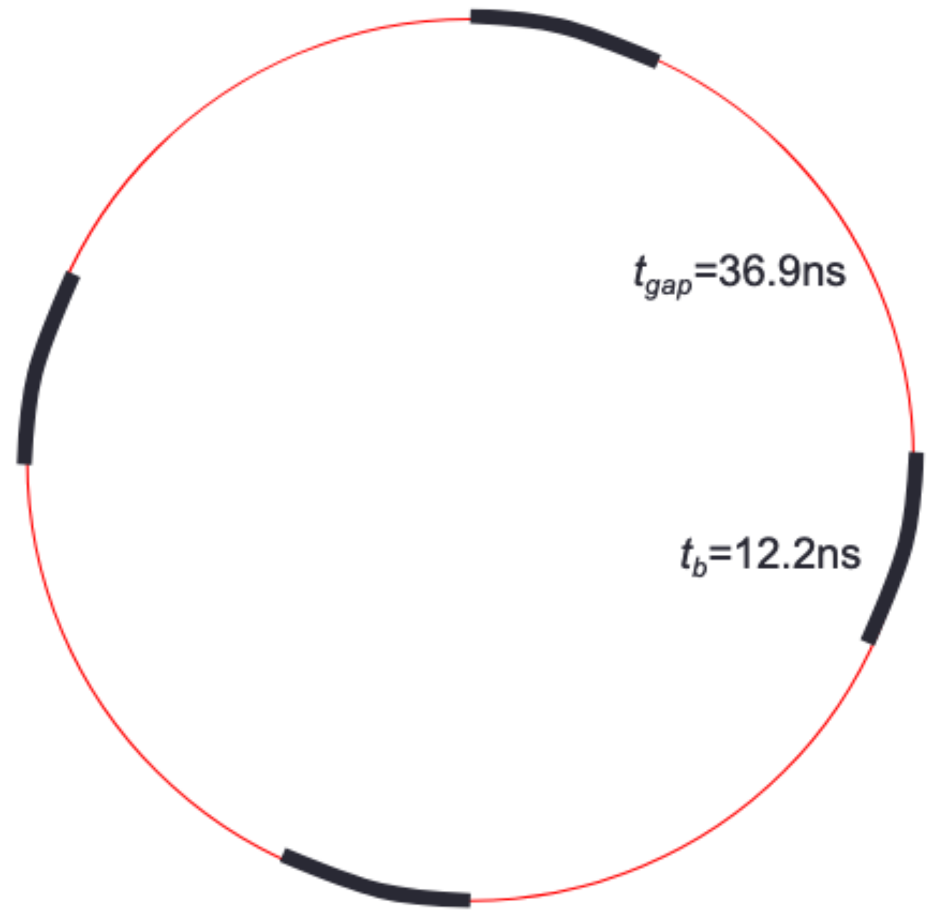
$$|\Delta\nu| = \frac{B n_b N_b r_0}{4\pi\beta\gamma^2\epsilon_N} \lessapprox .2 \rightarrow N_{b,\max} \propto \frac{\epsilon_N}{B n_b} = \frac{t_b}{\tau}\epsilon_N$$

Normalized emittance; period

- Maximize t_b → "paint" longitudinally
- Minimize τ → This is why we want the smallest ring.
- Maximize ϵ_N → "paint" transversely
  - No longer limited by MI aperture, but not without consequences

Strawman Parameters for Small Compressor Ring

- Circumference = 49.7m
- Number of bunches: 4
- Bunch frequency: 20.31 MHz
- Bunch length: 12.2 ns
- Gap length 36.9 ns
  - A kicker should be able to extract in this gap at ~100Hz
- Note! At this frequency, power is limited to 500 kW by the $2\text{x}10^8$ maximum bunch size!



Comparing Small Ring to BSR

- Assume extraction frequency = 100Hz, tune shift Δ_ν=.2

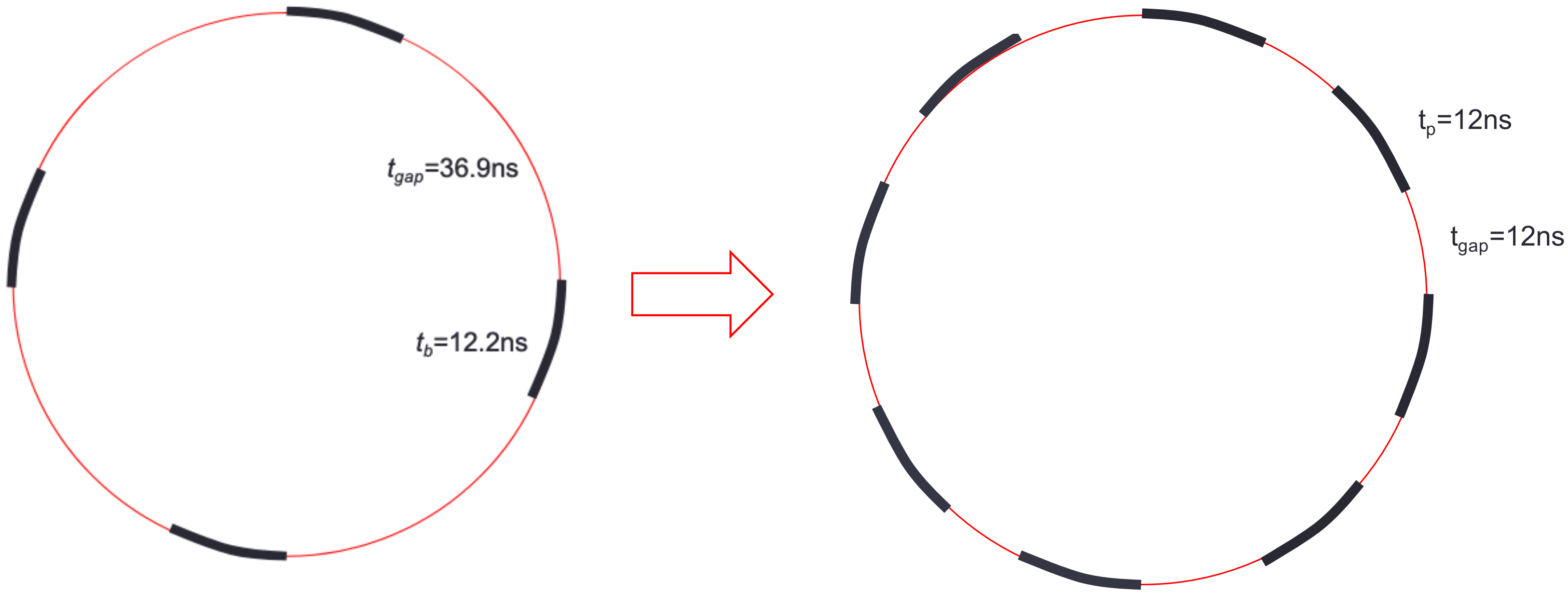
	C=50 m			C=500 m (BSR)		
Power [kW]	100	500	1000	100	500	1000
N_b [10^{12}]	7.8	39.1	78.1	7.8	39.1	78.1
ϵ_N [π-mm-mr]	27	134	267	267	1340	2670
radius ($\beta_\perp$ = 20m) [mm]	18.4	41.2	58.3	58.3	130.4	184.4

Magnet size and beam transport might be an issue

- But can we even get to 1MW?
  - Remember: at 20.31 MHz, power is limited to 500 kW by the $2x10^8$ bunch size

Going from 500 kW to 1 MW

- Must go from 20.31 MHz to 40.625 MHz



- Now need a 100 Hz kicker with a < 10 ns full rise and fall time
  - This is very hard
- Might be easier to go to two rings?

Challenges

- Aperture size
  - Magnets
  - Beam transport
- Injection
  - 500-1000 kW charge exchange injection is not trivial
- Extraction kicker
  - > 100 Hz would ease the space charge problem, but begins to get difficult

Summary

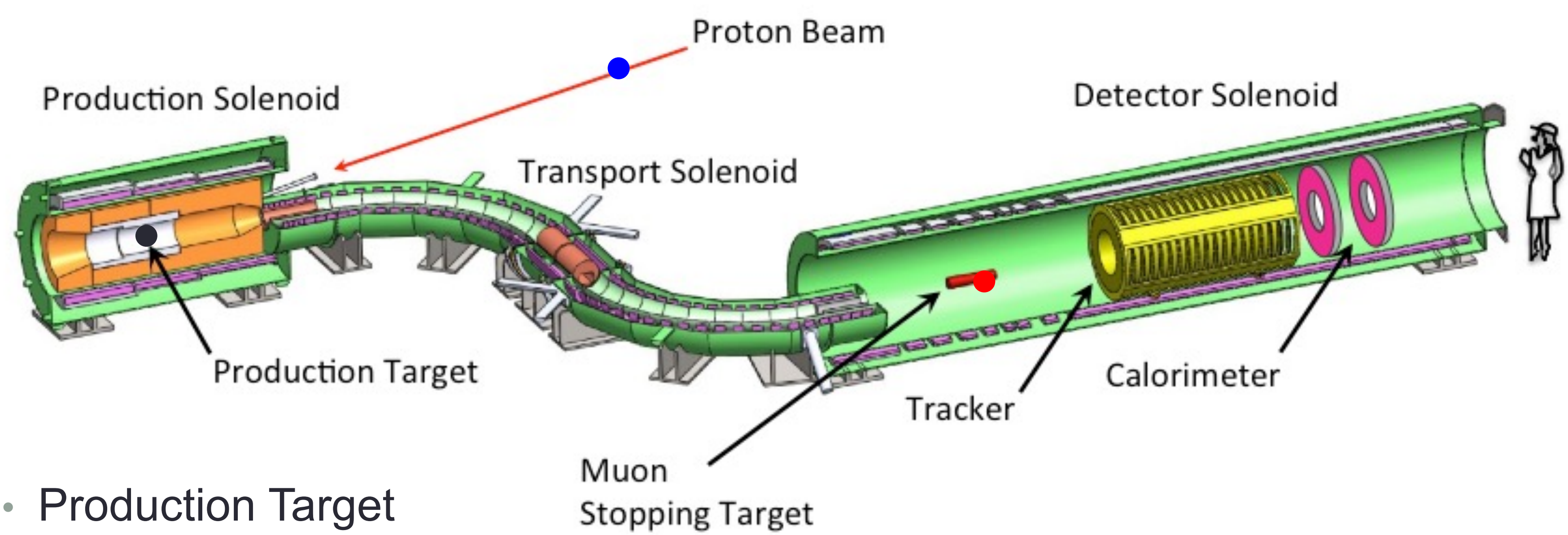
- Getting to a 1 MW beam with a pulse structure needed by an FFA is *extremely* challenging.
- The compressor ring needs for CLFV and LBNF are different
  - CLFV wants the smallest ring possible
  - LBNF needs a ring with the same circumference as the Booster
    - Might be another solution, e.g. energy vernier adjustment on PIP-II, a la Linac 4 at CERN?

BACKUP

Outline

- Review: the Mu2e experiment
- After Mu2e
  - Mu2e-II
  - Beyond Mu2e-II (The need for an FFA)
- Review: PIP-II
- Competing needs for a compressor
  - LBNF
  - CLFV
- Compressor parameters
- Challenges

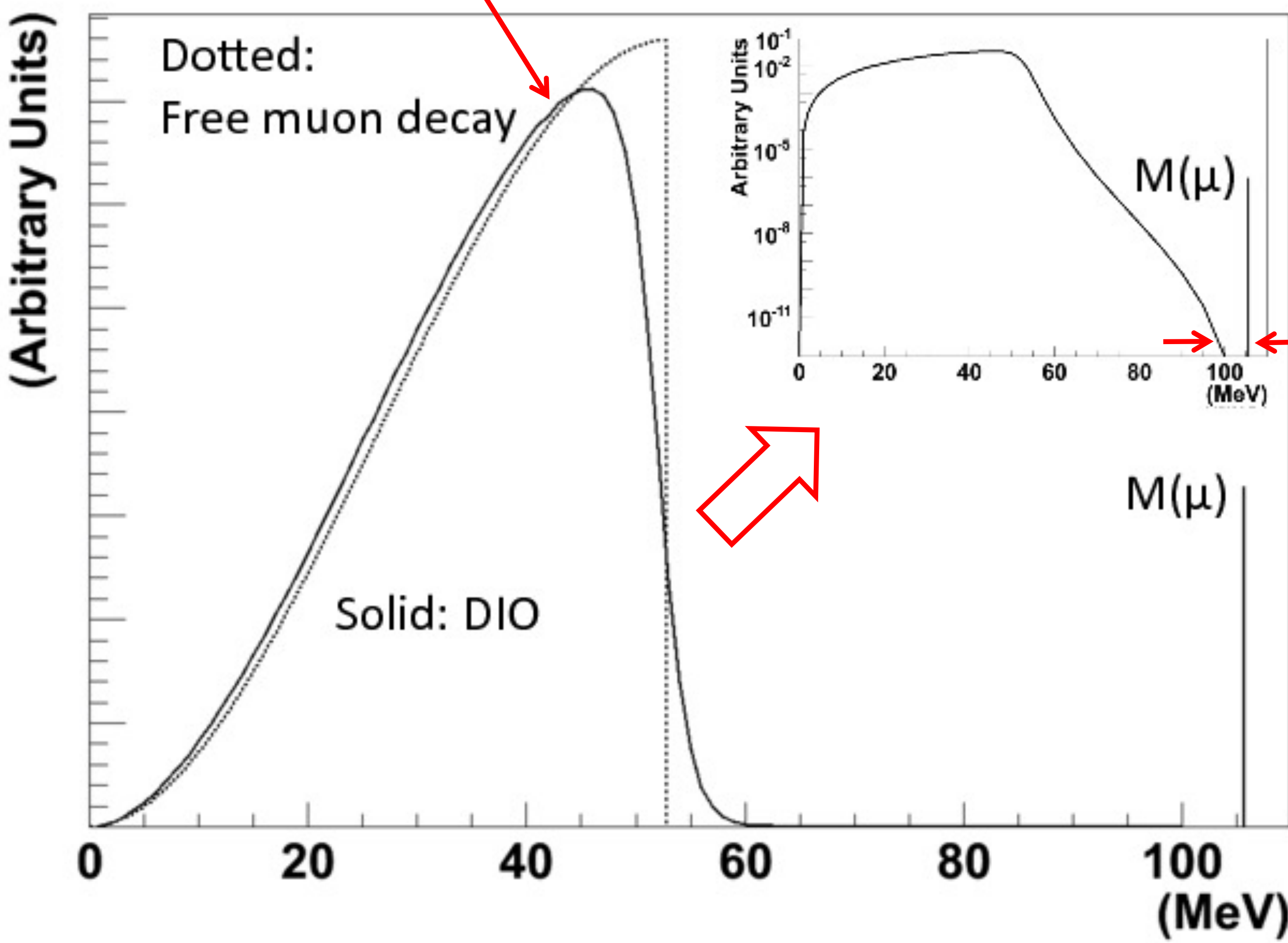
Reminder: the Mu2e Experiment



- Production Target
  - Proton beam strikes target, producing mostly pions
- Production Solenoid
  - Contains backwards pions/muons and reflects slow forward pions/muons
- Transport Solenoid
  - Selects low momentum, negative muons
- Capture Target, Detector, and Detector Solenoid
  - Capture muons on target and wait for them to decay
  - Detector blind to ordinary (Michel) decays, with $E \leq \frac{1}{2} m_\mu c^2$
  - Optimized for $E \sim m_\mu c^2$

Decay-in-orbit Spectrum Motivates Detector Specs

We want to be blind to this (acceptance)

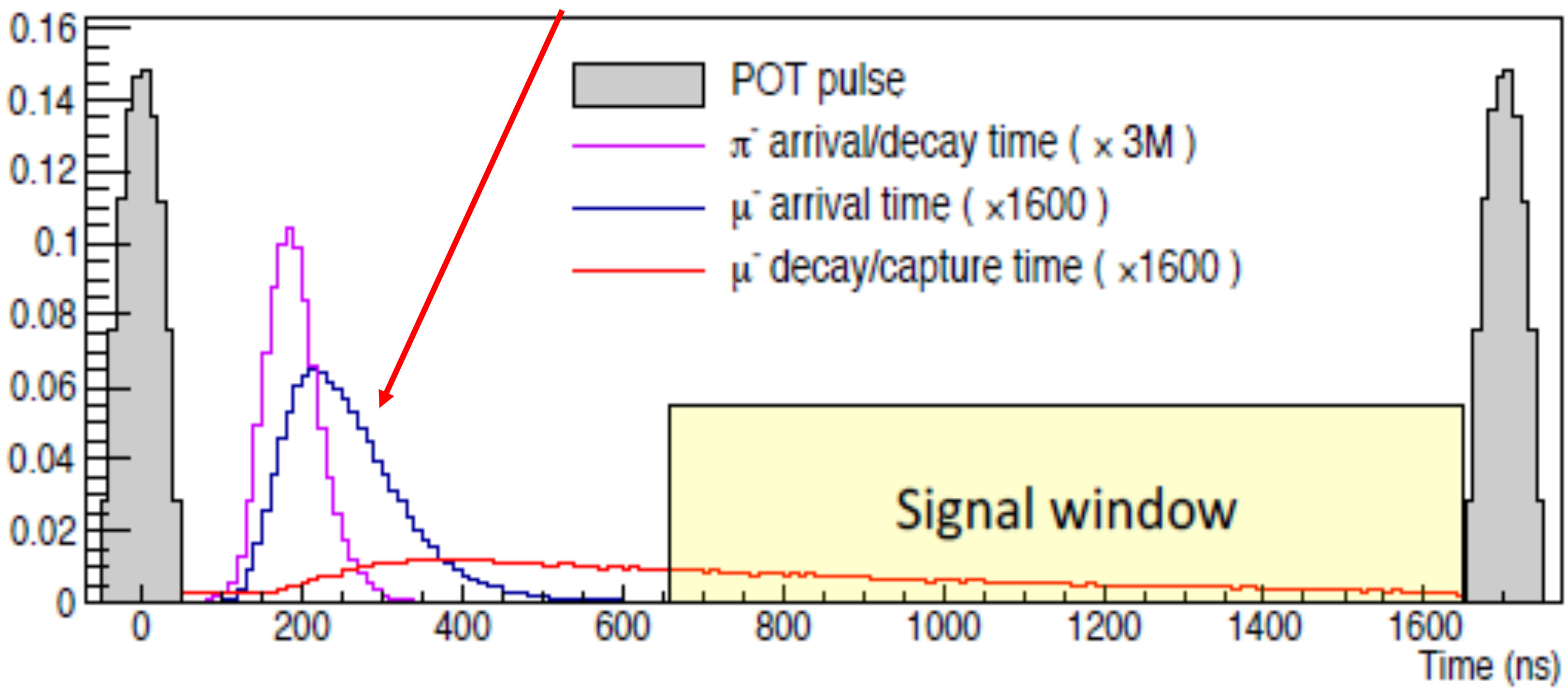


We must resolve this (target and tracker mass)

Beam Requirements

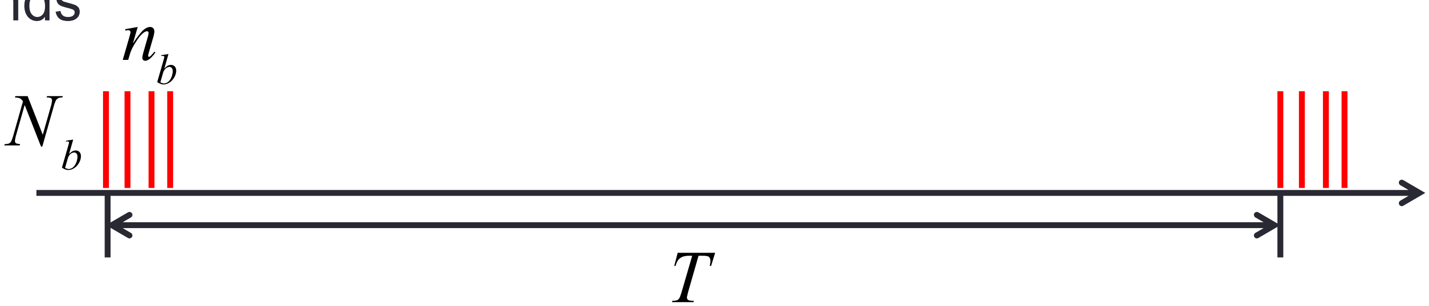
- Most backgrounds are prompt with respect to the arrival of the muons to the capture target
  - The most important are radiative decays due to residual pions!
- The previous best experiment was limited by the need to veto around the arrival of every charged particle.
- Solution: pulsed beam

“Straggling” through solenoids (put a pin in that!)



General: Calculating Beam Rate and Power

- Assume we have n_b bunches with N protons in each bunch every T seconds



$$\text{Rate [/s]} = \frac{n_b N_b}{T\ \text{[s]}}$$

$$\text{Current [mA]} = \left(\frac{N_b}{0.4\times10^8}\right)\left(\frac{n_b}{(T/6.2\text{ns})}\right)$$

$$\text{Power [kW]}=800\times(\text{Current [mA]})$$

- Reminder: Limits
  - $N_{b,max}$: 2x10[8] (5 mA peak)
  - Max. I_{ave}: 2 mA

$0.8\text{x}10^8$ @ 162.5 MHz = 1.6MW
$1.6\text{x}10^8$ @ 81.25 MHz = 1.6MW
$2.0\text{x}10^8$ @ 40.625 MHz = 1.0MW
$2.0\text{x}10^8$ @ 20.312 MHz = 0.5MW

This will be very important