Introduction:Project X, Neutrino factory and Muon Collider Requirements

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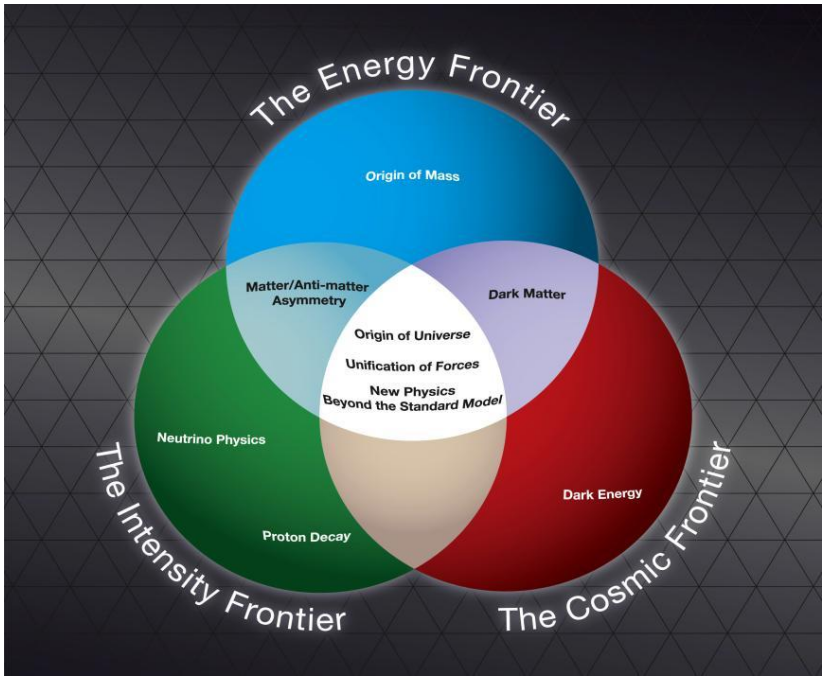
Fermilab Long Range Plan

- Project X will be the Intensity Frontier
- Neutrino Factory will push the Intensity Frontier farther by upgrading Project X
- Muon Collider, with an upgraded Project X, will become the Energy Frontier



Outline

- Project X design criteria
- Project X evolution & choices
- Neutrino Factory (NF) and Muon Collider (MC) requirements
- Simple match (on paper) Project X to NF/MC
- Implications of NF/MC requirements on connection to Project X
- Possible Project X upgrades

Project X Design Criteria

1. *A neutrino beam for long baseline neutrino oscillation experiments*
   - *2MW proton beam with energy between 60-120GeV*

Project X Design Criteria (1)

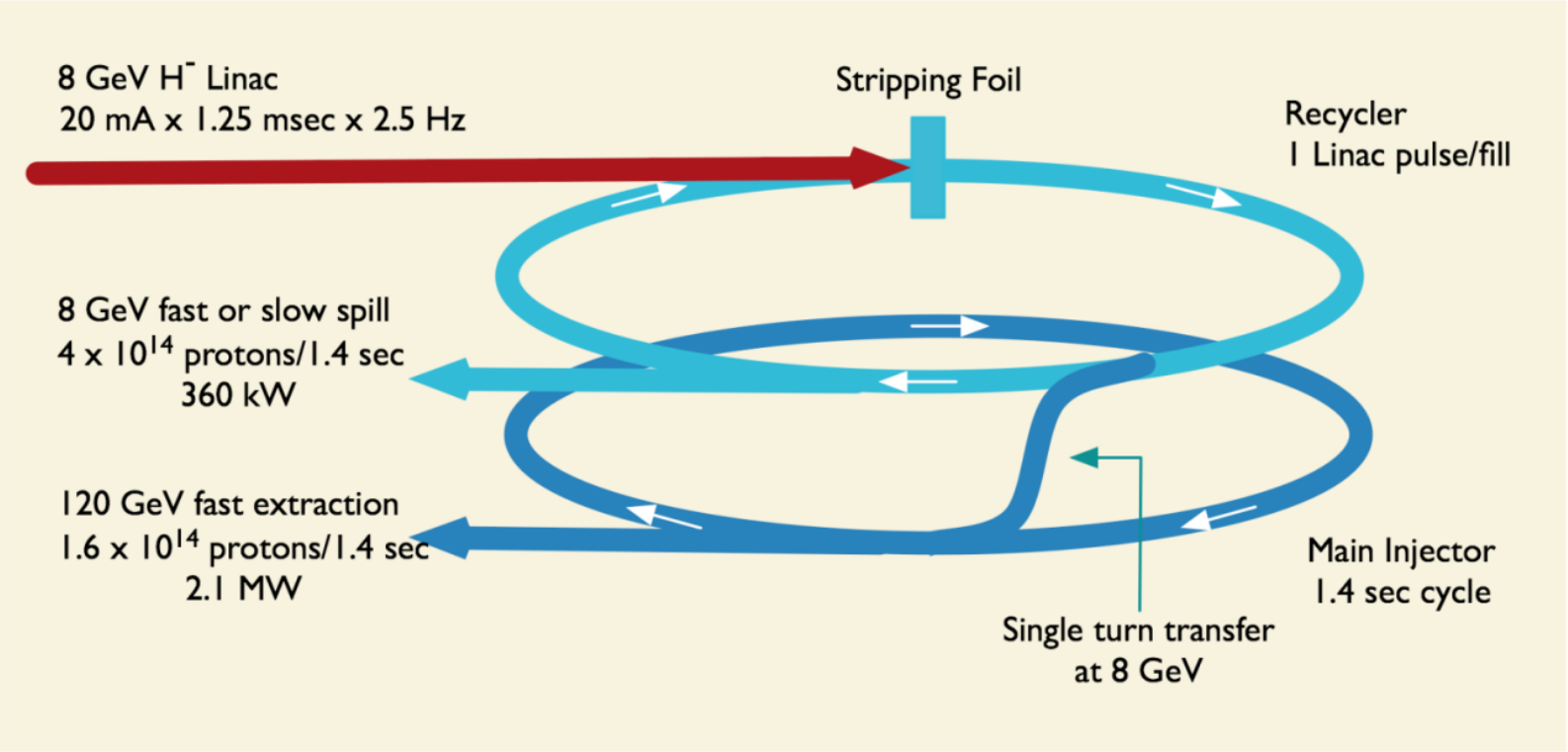
- Neutrino program with beam from Main Injector
  - Desiring 2MW means the following

Final Beam Energy (GeV)	MI Cycle Time (s)	Particles per MI Cycle (TP)	8 GeV Beam Power (KW)
60	0.6	125	267
120	1.33	139	133

  - Design Project X to deliver ~500KW so as to support other 8GeV experiments
  - Use Recycler as an 8 GeV accumulation ring

Project X Evolution (1)

- Initial Configuration
  - Pulsed 8GeV Linac aligned with ILC technologies
  - Suited for meeting neutrino requirement



Project X Design Criteria

1. A neutrino beam for long baseline neutrino oscillation experiments
   - 2MW proton beam with energy between 60-120GeV

2. *Kaon-and muon-based precision experiments running simultaneously with the neutrino program*

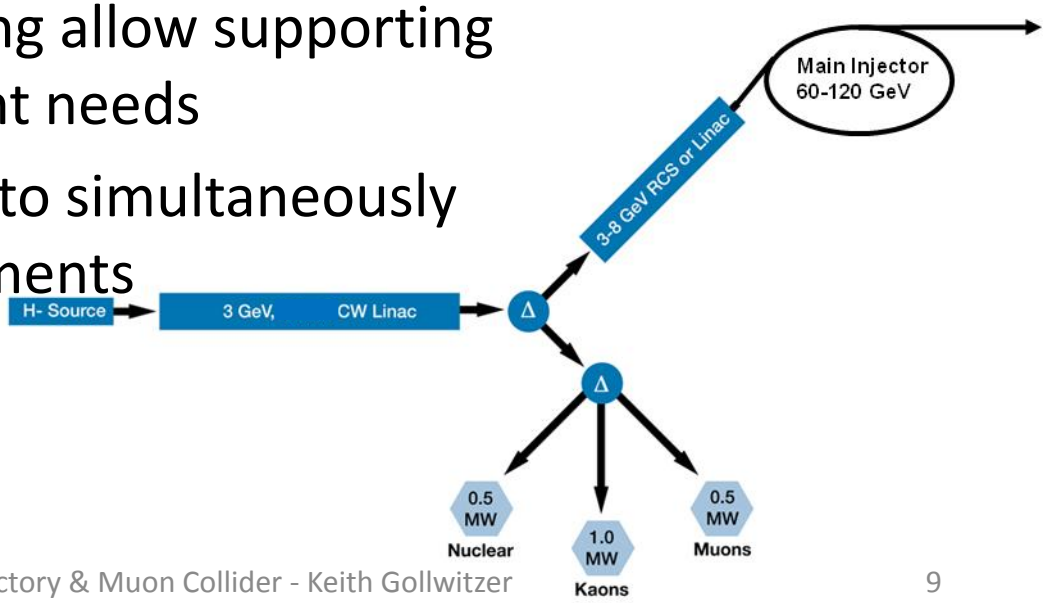
Project X Design Criteria (2)

- Non-neutrino experiments' desires

	Proton Energy (kinetic)	Beam Power	Beam Timing
Rare Muon decays	2-3 GeV	>500 kW	1 kHz – 160 MHz
(g-2) measurement	8 GeV	20-50 kW	30- 100 Hz.
Rare Kaon decays	2.6 – 4 GeV	>500 kW	20 – 160 MHz. (<50 psec pings)
Precision K^0 studies	2.6 – 3 GeV	> 100 mA (internal target)	20 – 160 MHz. (<50 psec pings)
Neutron and exotic nuclei EDMs	1.5-2.5 GeV	>500 kW	> 100 Hz

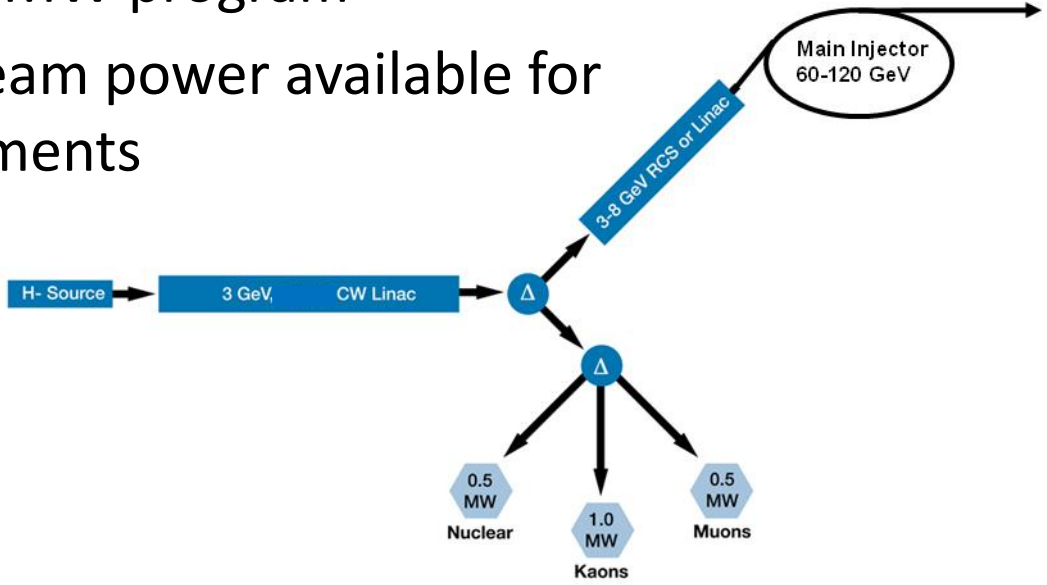
Project X Evolution (2)

- Second configuration
  - CW 3 GeV 1mA H^- Linac
    - Above Kaon production threshold
    - Produces low energy pions
    - Allows nuclear physics experiments
    - Low energy chopping allow supporting different experiment needs
    - Splitter/switchyard to simultaneously support the experiments

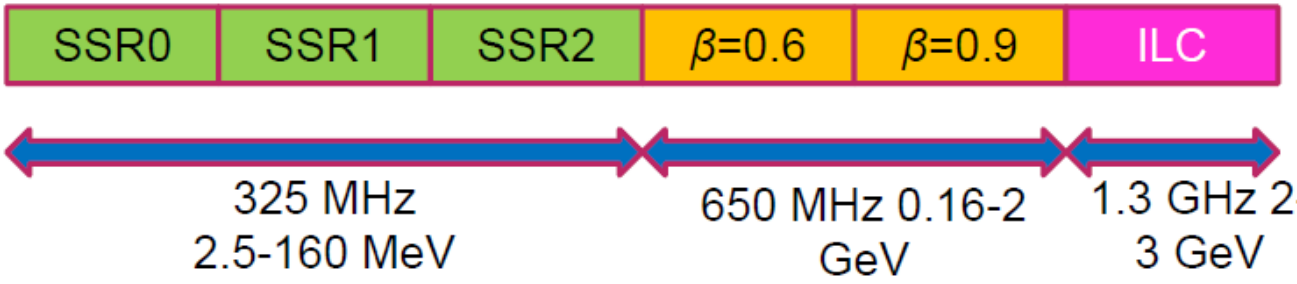


Project X Evolution (3)

- Second configuration
  - 3-8 GeV machine to fill RR/MI
    - 10Hz RCS (accumulation and acceleration)
    - Pulsed Linac (accumulation in Recycler)
    - Satisfies neutrino 2MW program
    - Additional 8GeV beam power available for other 8GeV experiments



Project X: Evolving 3GeV Linac



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	26 /26/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-32	18 /18/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	32-160	44 /24/ 4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-520	42 /21/ 7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	520-2000	96 /12/12	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	2000-3000	64 / 8/ 8	9-cell elliptical, quad

Project X: 8GeV Numbers

- 1mA CW Linac to feed RCS or pulsed Linac

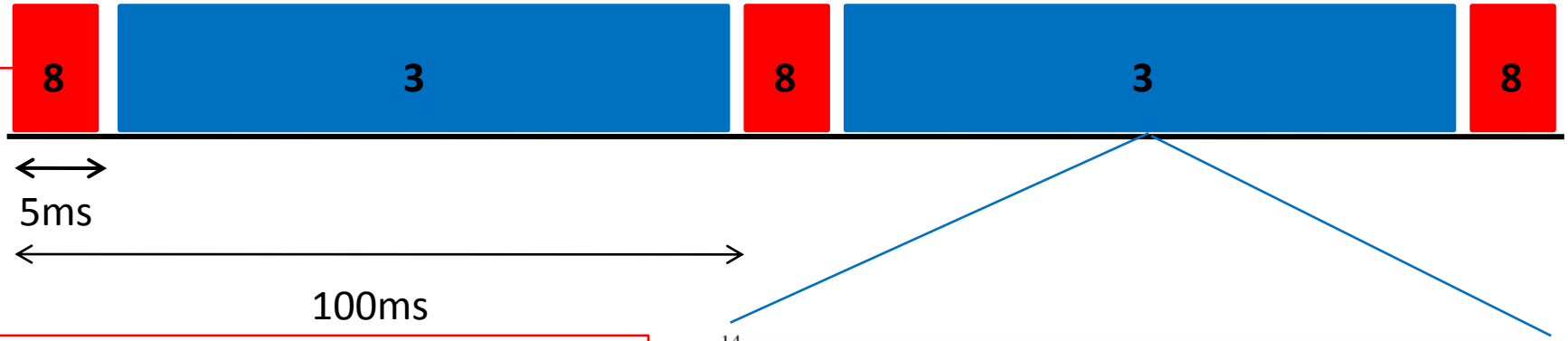
Final Beam Energy (GeV)	MI Cycle Time (s)	Particles per MI Cycle (TP)	8 GeV Beam Power (KW)	Accumulation Duty factor (%)
60	0.6	125	267	3.33
120	1.33	139	133	1.67

  - Design a system to deliver 300-400KW to satisfy neutrino program and any other 8GeV experiments
    - Accumulation duty factor of 3.75% to 5%

Accumulation/Stripping Duty Factor

- 400KW at 8GeV requires 50ms of accumulation/s
- Conventional Charge Exchange
  - Short Linac bursts so as to not overheat foil
    - Up to 5ms
  - While not injecting, accumulated beam is moved out of foil
  - Cooling rate of foil determines time between bursts
    - At least 10ms between bursts
- Laser
  - Burst length will be determined by laser capability

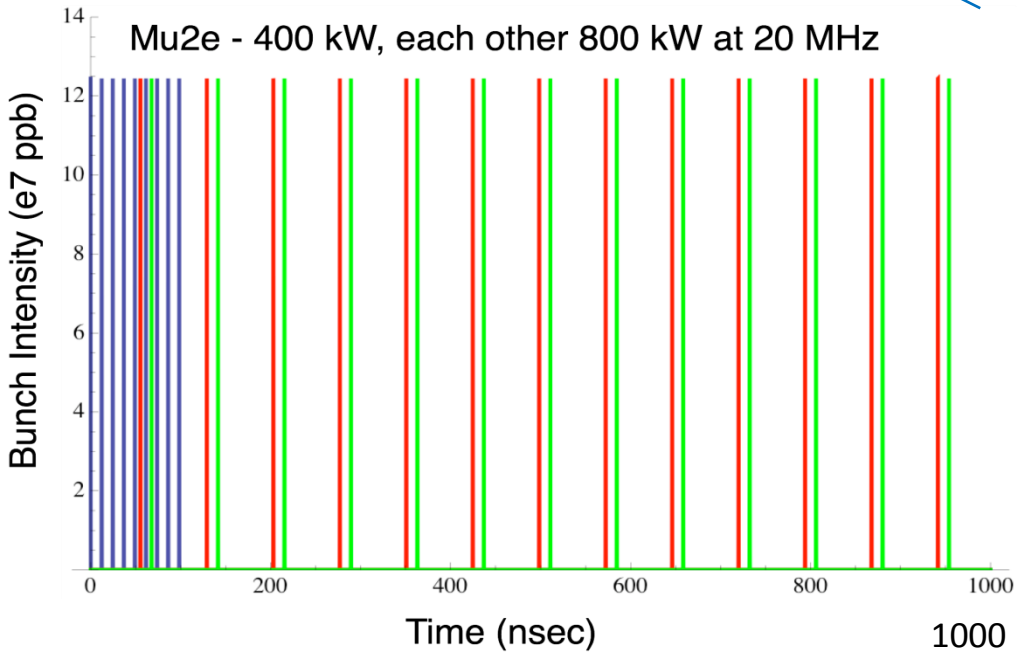
Simplified Project X Operation



5% 8GeV operation results in 400KW at 8GeV

Believe stripping foil will survive

Note that Linac beam is modulate to fill accumulation ring buckets



Project X: 3GeV Numbers

- Previously discussed numbers
  - 1mA beam current
  - 5% destined to 3-8GeV accelerator
- 3GeV program has access >2800KW
  - Assume finite time to switch 3GeV Linac output between switchyard and second accelerator
  - Previous slide showed example of 2MW program in 3GeV switchyard

RCS or Pulsed Linac

- Both support needs for Project X era
- Both have nearly the same cost
- Accumulation
  - Stripping inefficiency not much different between 3GeV in RCS and 8GeV in Recycler
  - Beam energy difference means larger beam power loss with pulsed Linac

Project X Design Criteria

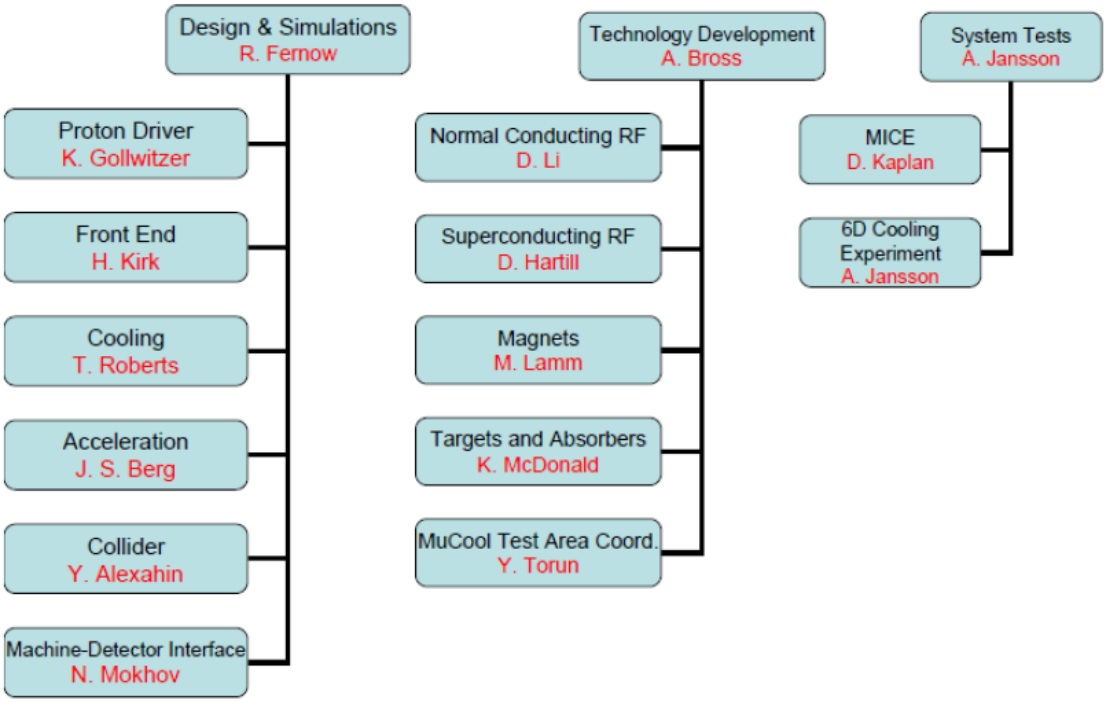
1. A neutrino beam for long baseline neutrino oscillation experiments
   - 2MW proton beam with energy between 60-120GeV

2. Kaon-and muon-based precision experiments running simultaneously with the neutrino program

3. *A path toward a muon source for a possible future neutrino factory, and, potentially, a muon collider at the Energy frontier*

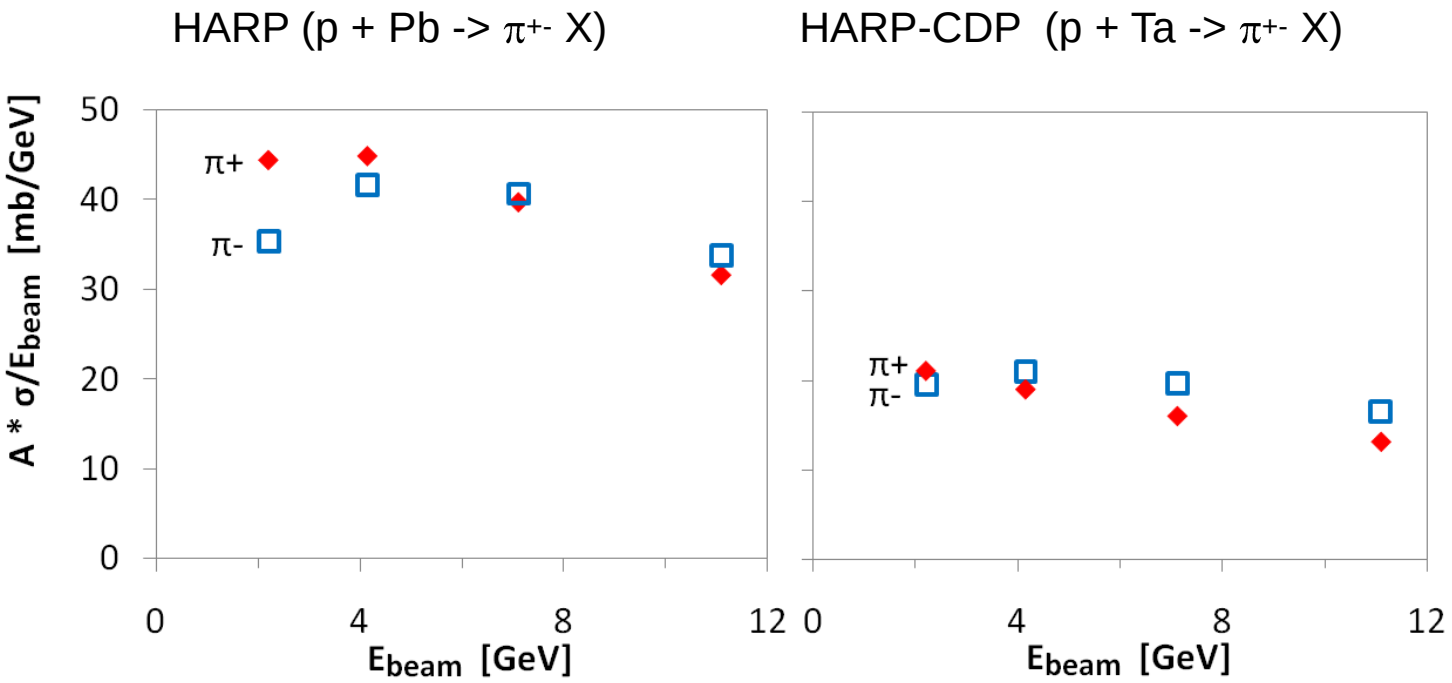
Muon Accelerator Program

- An interim organization is in place
  - Upcoming DOE review of 5yr proposal
  - Proton Driver task is to "consider additional effort needed to determine modifications to Project X"



10^{21} muons/year for Neutrino Factory and Muon Collider

- 4MW proton beam onto target
- Proton energy 5-15GeV
  - Most captured muons/W is ~8GeV



10^{21} muons/year for NF/MC (continued)

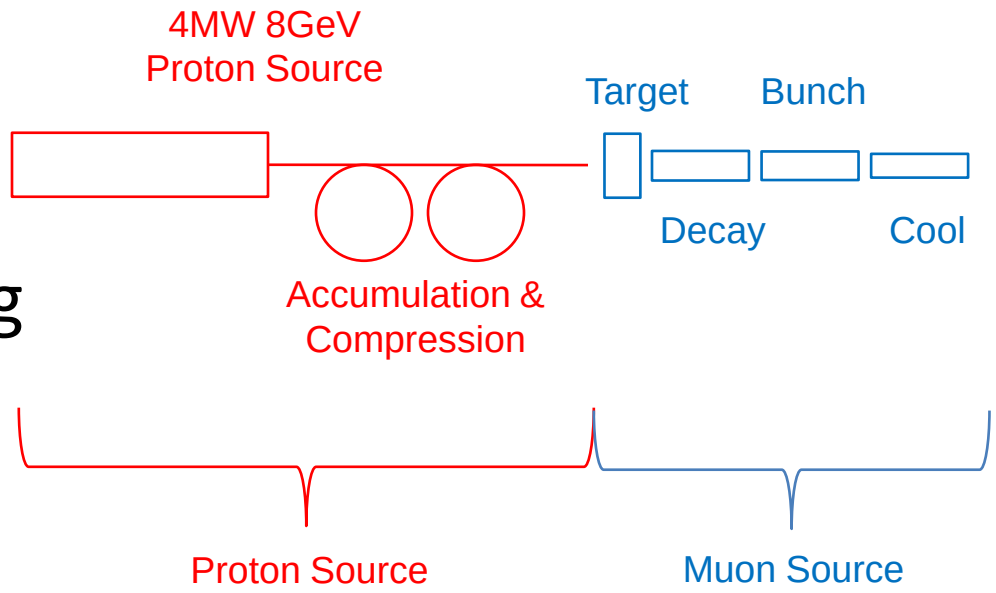
- Bunch Structure
  - 1-3ns rms bunch length
  - Neutrino factory
    - 3 bunch train in 320microseconds at 50-75Hz
  - Muon Collider
    - “Single” bunch at 15Hz
- Target
  - Liquid Hg-jet
    - 1cm transverse size
    - Proton beam to interact with 60cm at angle of 33mrad

RCS or Pulsed Linac (part 2)

- Support of future NF/MC complex?
  - 8GeV from 400KW to 4MW
    - 1.1×10^{19} proton/hr
  - If stay with 1mA CW Linac, require accumulation duty factor of 50%
    - Can stripping be done with foil or laser?
    - Need to increase rate of 3-8GeV machine.
      - RCS does not look favorable
        - » Need to spend 50% accumulating
        - » Need to increase repetition rate
      - Pulsed Linac becomes CW

A Basic Concept for 8GeV

- Proton Accumulation Ring
  - Considerations
    - Space Charge
    - Stripping
- Bunch Compressor Ring
  - Considerations
    - Forming 1-3ns bunches
    - NF: keeping short bunch length for many turns before 2nd and 3rd bunch extractions
    - MC: One bunch or delivery of several bunches at once to target

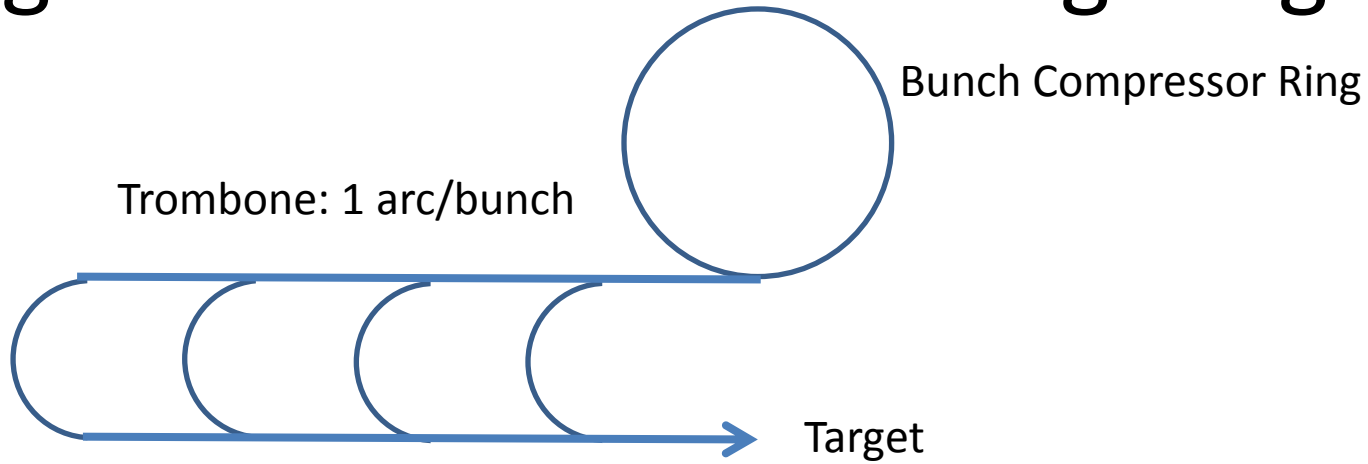


8GeV Ring Numbers

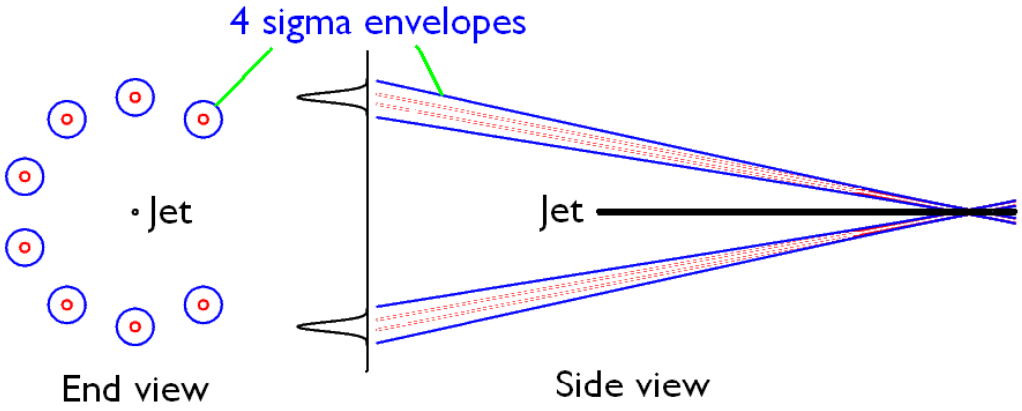
- 4MW at 8GeV
- Bunch in Proton Accumulation Ring
- Narrow bunches to 1-3ns in Bunch Compressor Ring

Facility	Cycle Frequency (Hz)	Bunches	Particles per Bunch (Tp)	Time between Bunch Extractions (μs)
NF	50	3	21	160
NF	75	3	14	160
MC	15	1	210	-
MC	15	8	26	Single Turn

MC: Single-turn Multi-Bunch Targeting



Muon Collider Proton Driver Trombone Schematic
(not to scale; bunches arrive simultaneously on target)



Each beam line provides different trajectory to target

Constraints due to Targetry (1)

- Transverse
  - Would like spot size smaller than target
    - σ_r = 0.25cm
  - Take β^* to be target length: 60cm
  - $\varepsilon_{95\%}$ = 62.5π mm-mrad
- Longitudinal
  - Bunch length of 1-3ns affects
    - Peak current
    - RF voltage
  - Assume 1% momentum spread at target

Constraints due to Targetry (2)

- Bunch Compressor Ring (BCR)
  - Nominal maximum lattice functions (β = 20m and D = 4m) implies dimensions of vacuum chamber for clean delivery of beam
    - $A_y \approx 5$cm
    - $A_x \approx 15$cm
  - Longitudinal instability at injection
- Space charge considerations for new rings
  - Small circumference requires strong magnets
    - Trade-off of beam tube size and dipole magnet strength

Possible Upgrade Paths

- 3-8GeV pulsed Linac convertible to CW
- Increase CW Linac beam current
- RCS to higher energy
- RCS rate increase
- Some combination of above