Muon Collider: Proton Driver

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About ODU and me

- Old Dominion University (Norfolk, VA) is presently one of three US universities with a fully signed IMCC MoC
  - Our interests are in the MC Accelerator R&D: beam dynamics, cooling, SRF,…
  - Graduate student engagement through our DOE-funded accelerator traineeship program (VITA)

- I am presently at Jefferson Lab (EIC Principal Accelerator Scientist) and a Jefferson Lab professor at ODU
  - JLab is already collaborating with IMCC and was an important part of MAP; preparing to play a key role in a future US MC program (after the upcoming P5 report)

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Acknowledgements

- Many thanks to Mark Palmer (BNL) and Natalia Milos (ESS) for providing materials from previous (MAP) and on-going design studies (IMCC)

- Materials used in this talk:
  - “The Future Prospects of Muon Colliders and Neutrino Factories”, M. Boscolo, J.-P. Delahaye and M. Palmer, RAST 10, 189-214 (2019)

  - “Proton driver scenarios at CERN and Rutherford Appleton Laboratory”, J. W. G. Thomason, R. Garoby, S. Gilardoni, L. J. Jenner, and J. Pasternak, PRST AB 16, 054801 (2013)

  - MuCol EU Kick-off meeting, https://indico.cern.ch/event/1219912/ , Mar 28, 2023

  - MAP 2014 Spring Meeting, https://indico.fnal.gov/event/8326/

Introduction

- Several detailed studies have looked at MC Proton Drivers in the past.
  - Concepts based on SPL, Project X, ESS, PIP-II

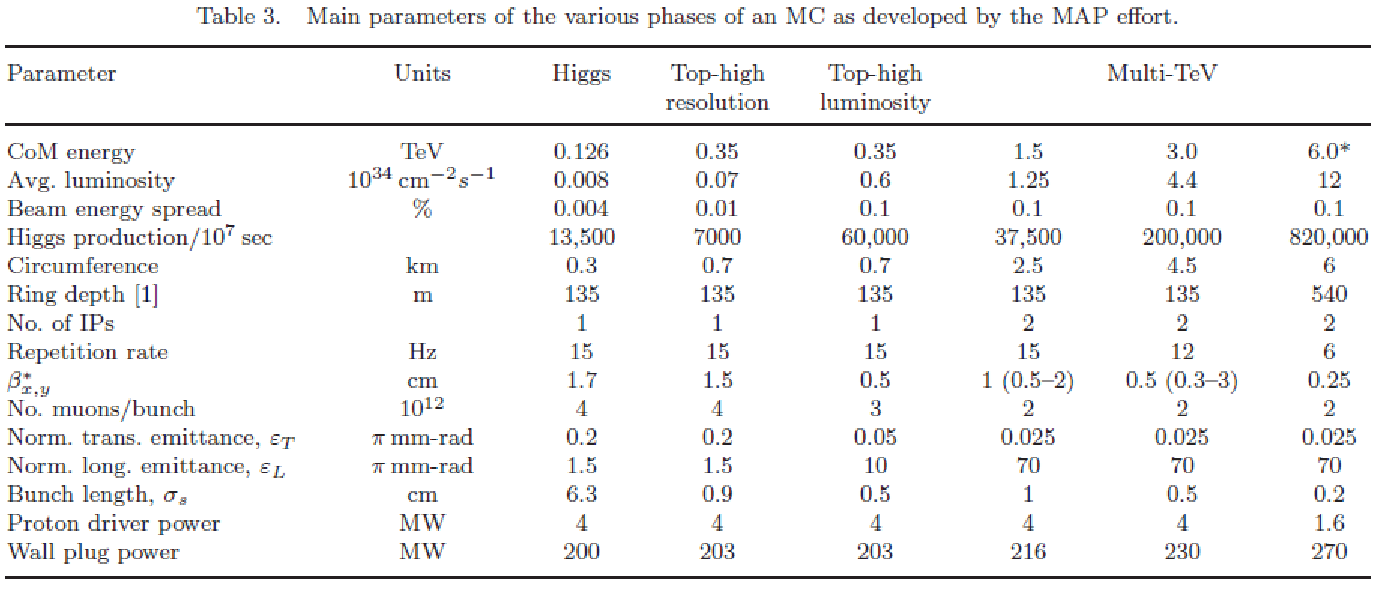


Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

Parameter	Units	Higgs	Top-high resolution	Top-high luminosity	Multi-TeV		
CoM energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. luminosity	10^{34} cm^{-2}s^{-1}	0.008	0.07	0.6	1.25	4.4	12
Beam energy spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs production/10^7 sec		13,500	7000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5–2)	0.5 (0.3–3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. trans. emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. long. emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton driver power	MW	4	4	4	4	4	1.6
Wall plug power	MW	200	203	203	216	230	270

*Accounts for off-site neutrino radiation

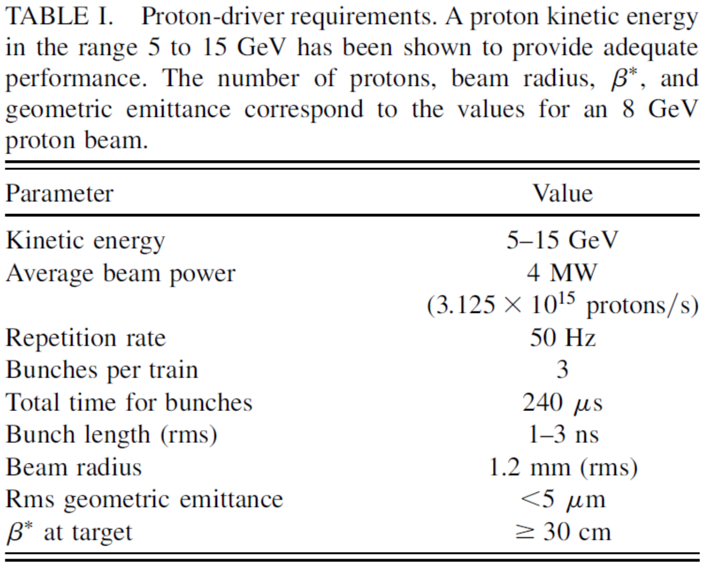


TABLE I. Proton-driver requirements. A proton kinetic energy in the range 5 to 15 GeV has been shown to provide adequate performance. The number of protons, beam radius, β^*, and geometric emittance correspond to the values for an 8 GeV proton beam.

Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW (3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	<5 μm
β^* at target	$\geq$ 30 cm

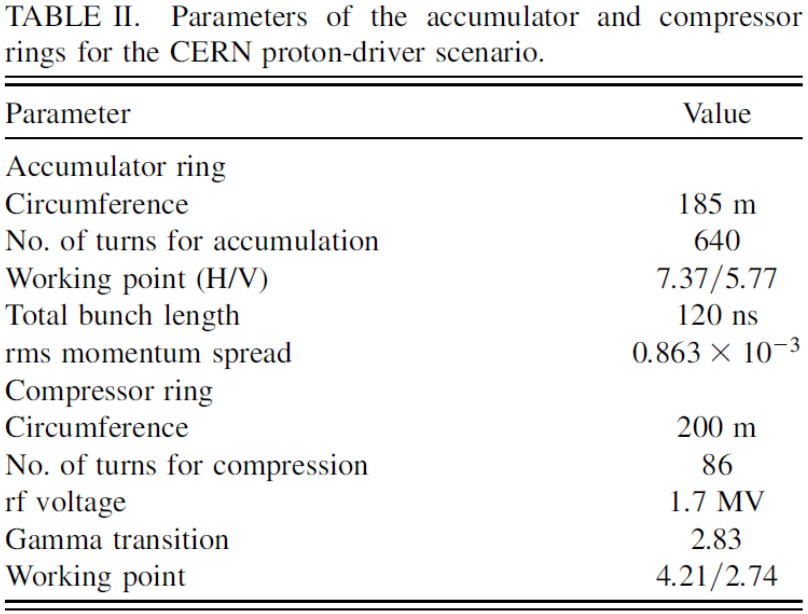


TABLE II. Parameters of the accumulator and compressor rings for the CERN proton-driver scenario.

Parameter	Value
Accumulator ring	
Circumference	185 m
No. of turns for accumulation	640
Working point (H/V)	7.37/5.77
Total bunch length	120 ns
rms momentum spread	0.863×10^{-3}
Compressor ring	
Circumference	200 m
No. of turns for compression	86
rf voltage	1.7 MV
Gamma transition	2.83
Working point	4.21/2.74

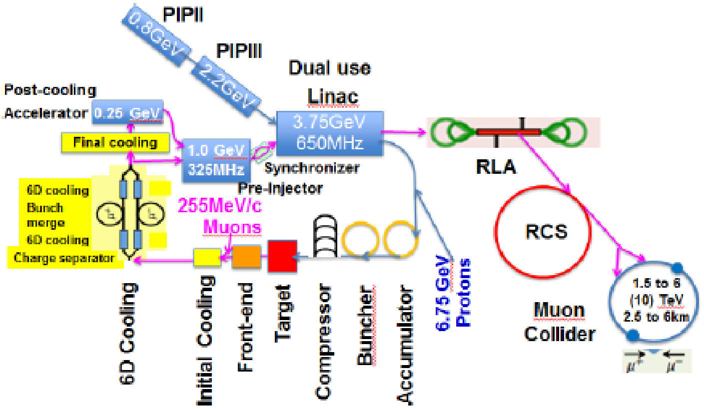
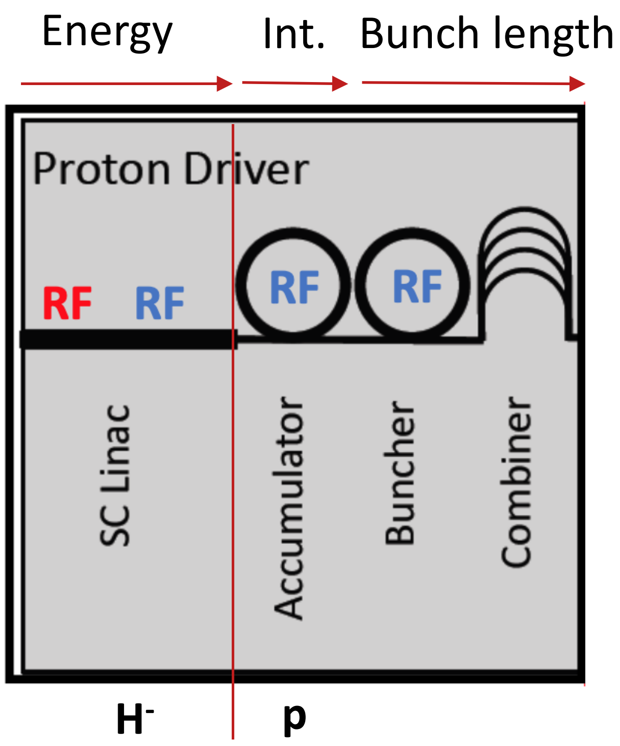


Fig. 13. Layout of a muon-based multi-TeV MC.

Proton Driver: Essential Elements

H- source and **accumulator and combiner complex**
10^{14}-10^{15} protons in ns-long bunch

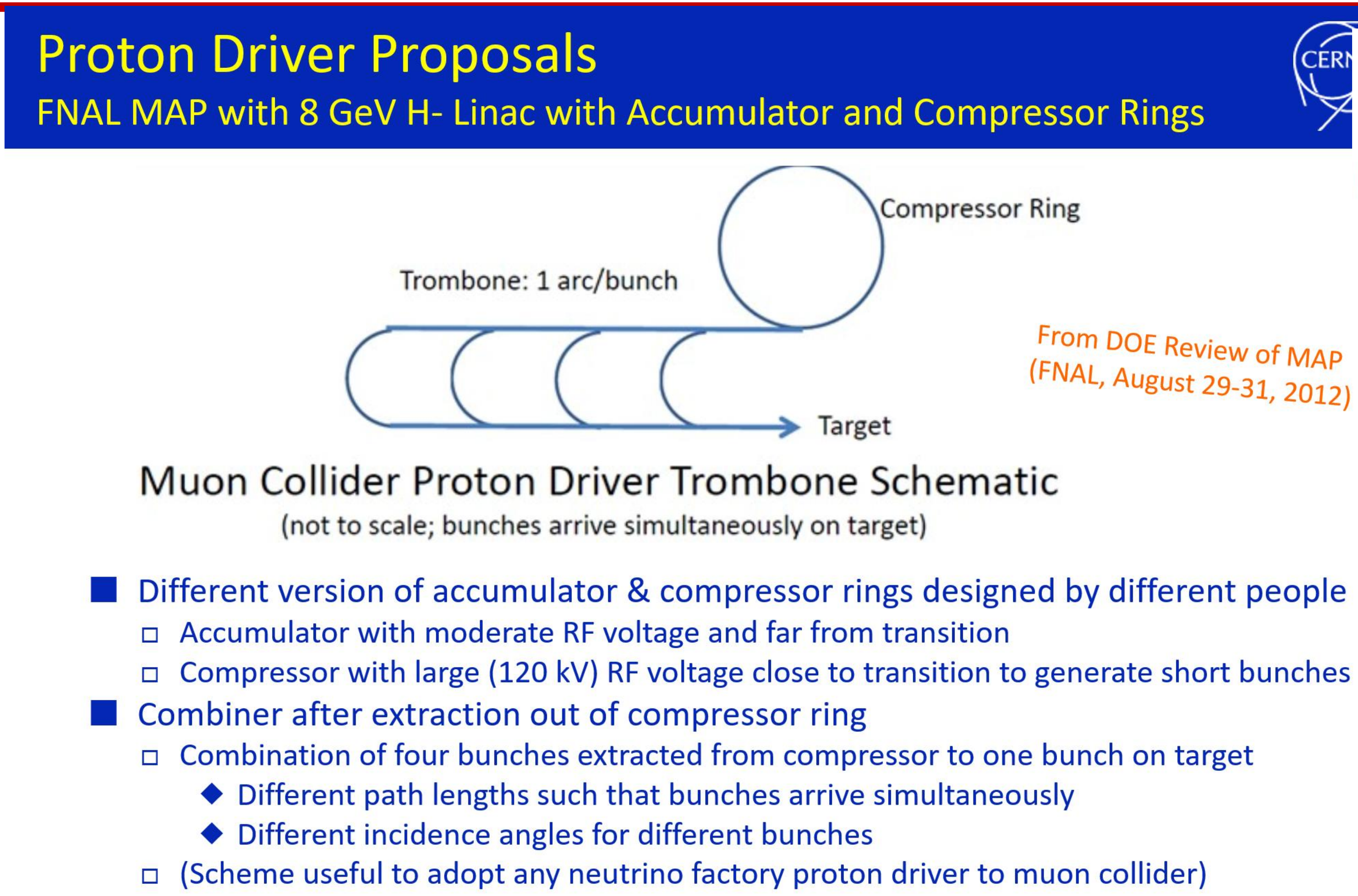
The concept is based on a Muon Collider with single (mu+ and mu-) colliding bunches



- H$^-$ source → high intensity
- ~10 GeV → Superconducting Linac (similar to SNS,ESS)
- Accumulator
- Buncher/Compressor
- Combiner → beam-to-target delivery system

- **Challenge:**
  High intensity short bunches @ low rep. rate

From the Muon Collider - Preparatory Meeting, CERN, 11th April 2019



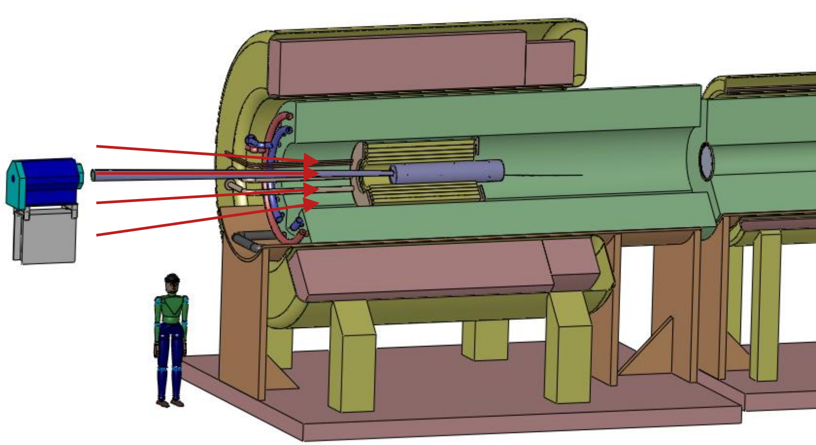
Proton Driver Proposals

FNAL MAP with 8 GeV H- Linac with Accumulator and Compressor Rings

Muon Collider Proton Driver Trombone Schematic

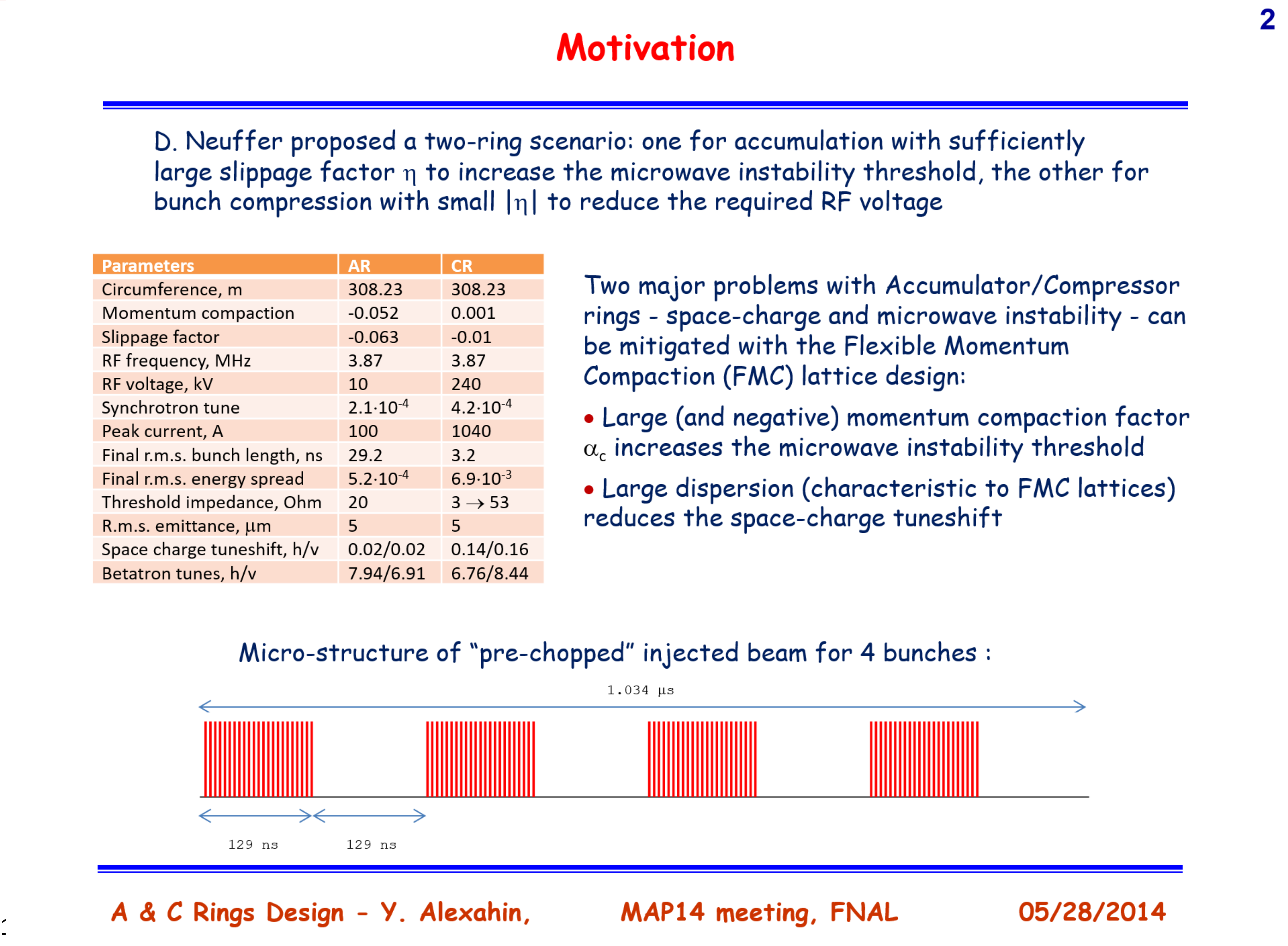
(not to scale; bunches arrive simultaneously on target)

- Different version of accumulator & compressor rings designed by different people
  - Accumulator with moderate RF voltage and far from transition
  - Compressor with large (120 kV) RF voltage close to transition to generate short bunches
- Combiner after extraction out of compressor ring
  - Combination of four bunches extracted from compressor to one bunch on target
    - Different path lengths such that bunches arrive simultaneously
    - Different incidence angles for different bunches
  - (Scheme useful to adopt any neutrino factory proton driver to muon collider)



C. Carli

Example of previous design studies (MAP)



Motivation

D. Neuffer proposed a two-ring scenario: one for accumulation with sufficiently large slippage factor η to increase the microwave instability threshold, the other for bunch compression with small $|\eta|$ to reduce the required RF voltage

Parameters	AR	CR
Circumference, m	308.23	308.23
Momentum compaction	-0.052	0.001
Slippage factor	-0.063	-0.01
RF frequency, MHz	3.87	3.87
RF voltage, kV	10	240
Synchrotron tune	$2.1\cdot10^{-4}$	$4.2\cdot10^{-4}$
Peak current, A	100	1040
Final r.m.s. bunch length, ns	29.2	3.2
Final r.m.s. energy spread	$5.2\cdot10^{-4}$	$6.9\cdot10^{-3}$
Threshold impedance, Ohm	20	3 → 53
R.m.s. emittance, µm	5	5
Space charge tuneshift, h/v	0.02/0.02	0.14/0.16
Betatron tunes, h/v	7.94/6.91	6.76/8.44

Two major problems with Accumulator/Compressor rings - space-charge and microwave instability - can be mitigated with the Flexible Momentum Compaction (FMC) lattice design:

- Large (and negative) momentum compaction factor α_c increases the microwave instability threshold
- Large dispersion (characteristic to FMC lattices) reduces the space-charge tuneshift

Micro-structure of "pre-chopped" injected beam for 4 bunches :

A & C Rings Design - Y. Alexahin, MAP14 meeting, FNAL 05/28/2014

Present IMCC Baseline parameters

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- Beam Power: 2 MW
- Rep. rate: 5 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns (rms)
- Beam Energy: 5 and 10 GeV
- Linac + 2 rings (initial design)

This talk

- Beam Power: 2 MW
- Rep. rate: 10 Hz
- Beam spot size: ~ 5 mm (1σ)
- Bunch length: 2 ns = 0.6 m (rms)
- Beam Energy: 8 GeV
- Linac + 2 rings (initial design)
  - Combine 4 bunches on target

What's important?

- Accumulator (accumulates 4 proton bunches):
  - Stripping injection and painting
  - Injection-related beam losses
  - Instabilities
    - Landau damping and feed-backs
  - Extraction kicker and septum magnet

$$P = 4N_b qEf_0 = 2\ \mathrm{MW}$$

- Buncher (rotates bunches by 90-degrees in the long phase-space):
  - Space-charge effects
  - Large energy spread (~1% rms)
  - Instabilities
    - Landau damping and feed-backs
  - Extraction kicker and septum magnet

$$\delta\nu \approx -\frac{3N_b r_p}{2\pi\beta\gamma^2\varepsilon_{n,rms}}\frac{C}{\sqrt{2\pi}\sigma_s} = -\underbrace{\frac{3r_p P}{4\sqrt{(2\pi)^3}\beta\gamma^2\sigma_s qEf_0}}_{\approx 2\times10^{-7}}\underbrace{\frac{C}{\varepsilon_{n,rms}}}_{???}$$

$$\delta\nu \approx -0.2$$ -- Conservative approach

Tension: larger beam emittance makes magnets, kickers, rf systems more expensive, a shorter circumference, C, leads to superconducting magnets (also more expensive)

SNS ring experience

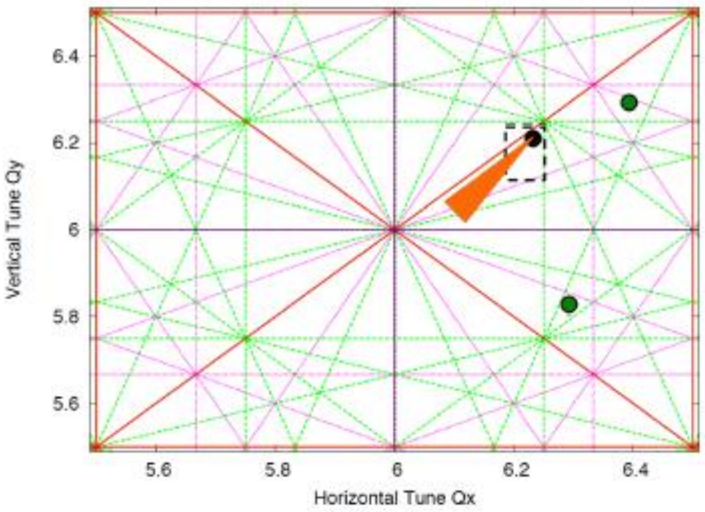
- SNS ring: 1.2 GeV, 1.4e14 at 60 Hz → 1.5 MW
- Single bunch ~1 us long
- Emittance (rms, norm): ~60 µm
  - Painting (non-gaussian)
- Fixed energy, storage for ~1000 turns (1 ms)
- Beam losses are acceptable for operations
  - Fully controlled by collimators
  - Relatively small space-charge tune shift (~0.2)

Feature	Cost	Payoff So Far
Large Aperture	$$$$	High
Injection Painting	$$$	High
Collimation	$$$	High
TiN coating	$$$	Unknown
2nd harmonic RF	$$	Medium+
Main sextupoles	$$	Low - None
Main octupoles	$$	None
Sextupole correctors	$	None
Octupole correctors	$	None
Clearing solenoids	$	None
Beam in gap kicker	$	None
Clearing electrodes	$	None

Vacuum chamber: stainless steel, 20 cm diam
Large aperture → high cost of magnets and other devices.

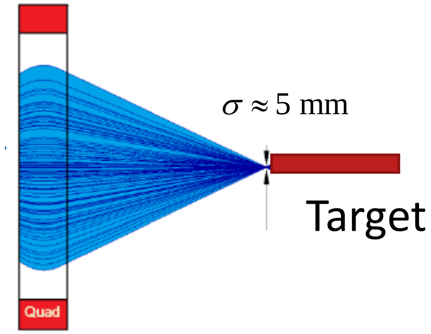
Courtesy of S. Cousineau (SNS)

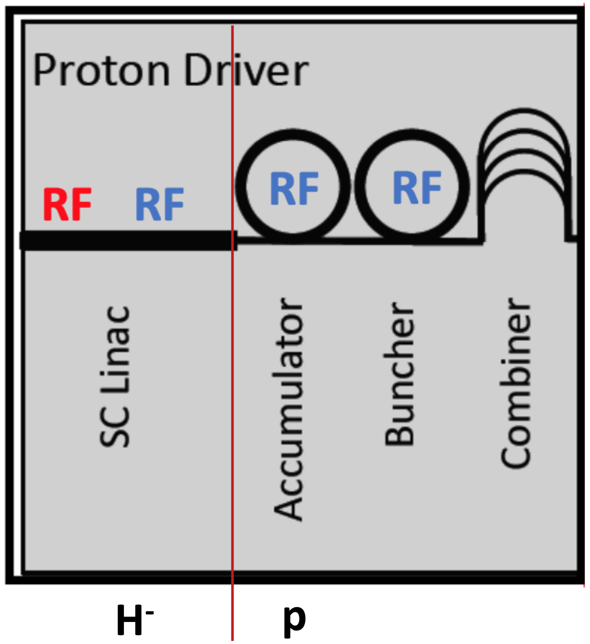
$$\delta\nu \approx -\frac{3N_b r_p B_F}{2\pi\beta\gamma^2\varepsilon_{n,rms}}$$



Start from beam-on-target considerations and proceed upstream

- Assume beta-function β_T on target: ~1 m
  - Combiner must accommodate large energy spread (~1 %)
- Assume a gaussian transverse beam distribution:
  - $$\boxed{\varepsilon_{n,rms} = \frac{\beta\gamma\sigma^2}{\beta_T} \approx \ 240\ \mu\text{m}}$$
  - This emittance is about 100 greater than the present Booster emittance
- We will assume that there are 4 proton bunches in the Buncher ring
  - These bunches are extracted in one turn and are combined on the target
- Beam intensity for 2 MW at 10 Hz (4 bunches)
  - $$\boxed{N_T \approx 1.6\times10^{14} \ \text{ or } \ N_b \approx 0.4\times10^{14} \ \text{per bunch}}$$





Discussion about beam emittance

- Large emittance means large beam size and, thus, a large vacuum chamber and magnets

$$\sigma_x = \sqrt{\frac{\beta_x \varepsilon_{n,rms}}{\beta\gamma} + \left(D_x \frac{\delta p}{p} \right)^2}$$

- Using SNS ($\beta\gamma \approx 1.8$) as our example (vacuum chamber diam 20 cm), we should limit the MC Proton Driver emittance to

$$\boxed{\varepsilon_{n,rms} \approx 100\ \mu\text{m}}$$

Space-charge tune shift

- SC tune shift $\delta\nu \approx -2\times10^{-7}\dfrac{C}{\varepsilon_{n,rms}}$ (this expression ignores the dispersive beam size)
  - Emittance: $\boxed{\varepsilon_{n,rms} \approx\ 100\ \mu\mathrm{m}}$
  - Dispersive beam size helps with reducing the effective tune shift and may be important

$$\delta\nu_x \sim \left\langle \frac{\beta_x}{\sigma_x\left(\sigma_x+\sigma_y\right)} \right\rangle_s \qquad \sigma_x = \sqrt{\frac{\beta_x\varepsilon_{n,rms}}{\beta\gamma}+\left(D_x\frac{\delta p}{p}\right)^2}$$

- We would like to limit the SC tune shift to ~0.2 at extraction from the Buncher
  - This gives us $C \approx 100\ \mathrm{m}$ -- Buncher circumference
  - Dispersion may help with space-charge but we must remember that the ring must have a large momentum acceptance (~few%)

- Thus, our first conclusion:
  - The Buncher ring should be about 100 m in circumference with 4 bunches

Buncher ring

- Typically, in a ring, about 60% of circumference is occupied by dipole magnets
    - 100-m ring -> 60 m of dipoles for a 8.9 GeV/c beam gives the magnetic field of 3 T

- Thus, such a Buncher ring is going to be based on SC magnets with a large aperture (~20-cm) and a low-frequency rf system, likely *h* = 4 (~10 MHz)
    - Higher frequency rf may not be compatible with a large aperture (~20 cm diam)

Accumulator ring

- The main purpose of the Accumulator ring is to convert a long (~1 ms) linac pulse of H- ions to 4 bunches of protons in a ring
  - Bunches should be ~6-m (20-ns) long (rms) with a small momentum spread (< 1E-3 rms) at extraction.
  - Space-charge effects are 10 times lower than the Buncher ring
- Ideally, the Accumulator ring should be the same circumference as the Buncher
  - However, this would also mean that the Accumulator would be based on 3-T SC magnets and it implies no ramping (not at 10 Hz anyway)
  - This would also mean that the Linac must be an 8-GeV linac
- Since the space-charge is 10 times smaller, one can envision room-temperature RCS-style magnets (~1-T max), and the Accumulator could be a 300-m ring
  - This scenario requires a separate analysis

Accumulator ring: challenges

- H- stripping at 8-GeV (foil or laser) is only ~96-98% efficient thus we will have to deal with 40-80 kW of beam losses
  - ~3000-turn injection
  - To compare: the total Fermilab Booster beam power is ~80 kW
- Large-aperture SC curved magnets with R = 10 m
  - Same for the Buncher ring
- Extraction kicker for a large aperture
  - Same for the Buncher ring

Linac

- Ideally, we would want an SNS-like linac, extended to 8 GeV
  - Deliver 1.6e14 protons in ~1 ms, or ~30 mA ave beam current during pulse
  - 3000-turns stripping injection

- It might be possible to adopt/adjust the PIP-II linac design but requires a detailed study
  - The present PIP-II linac current (2 mA) is too low for the MC Proton Driver

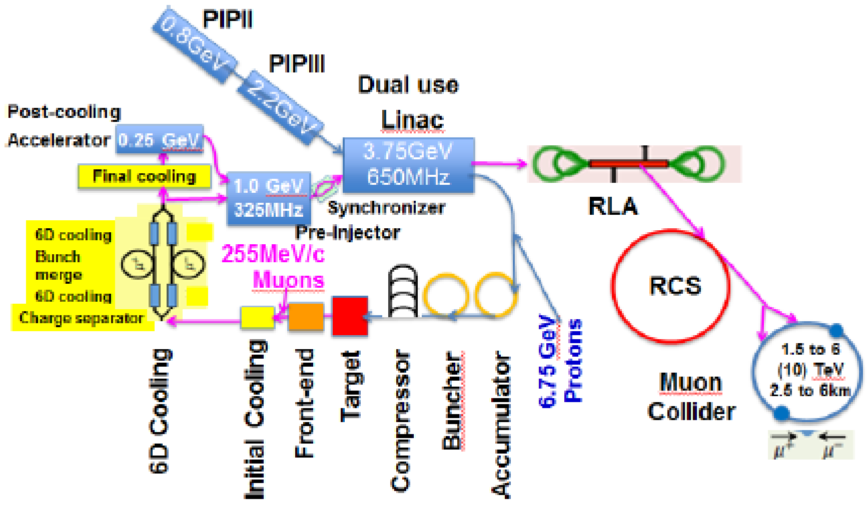


Fig. 13. Layout of a muon-based multi-TeV MC.

“The Future Prospects of Muon Colliders and Neutrino Factories”, M. Boscolo, J.-P. Delahaye and M. Palmer, RAST 10, 189-214 (2019)

Summary

- I believe it is possible (with work and resources) to design a Proton Driver, compatible with the Muon Collider requirements
- Much work has been done already by the MAP and IMCC teams
  - Much R&D is still needed and many physics challenges remain: optimal beam optics, beam dynamics, space-charge, instabilities, H- injection, loss mitigation
- None of the 6 Fermilab Booster replacement options (submitted to P5 as part of ACE) are optimized for an MC design or an MC Demonstrator
  - All 6 concepts were focused largely on how to achieve 2.4 MW for DUNE
- Main ingredients for a successful design:
  - High-current ~8-GeV H- linac
  - Two fixed-energy large-aperture (~100 m circumference) rings
    - Low-loss stripping injection
    - Large-aperture SC magnets (~3 T)
    - Low-frequency rf systems
    - High-field extraction septum magnets
    - High-field large-aperture extraction kickers
  - A 4-bunch combiner, delivering 4 bunches to the target