MAP –muon source from protons

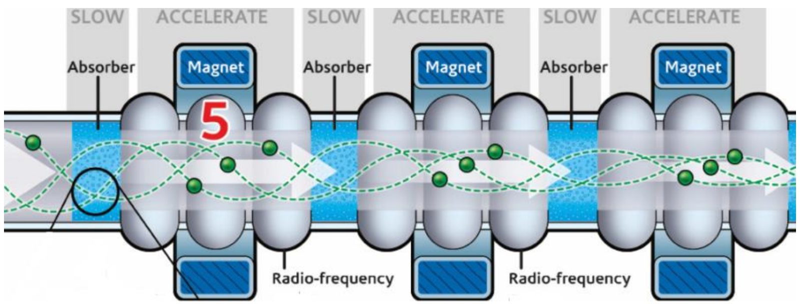
March 2020

Introduction

- **Muon-based Accelerator Physics**
- MAP muon source – and options
  - Proton source
  - Targetry
  - $\pi \rightarrow \mu$ collection
  - Cooling
  - Acceleration
  - Storage rings
- Muon based neutrinos
  - "nuSTORM"–Muon storage ring for neutrinos "neutrino factory"
- Future experiments and directions
  - Current experiments (g-2, mu2e, ..
  - Future experiments (Mu2e-II, mueγ, …)

Demonstration of Cooling by the Muon Ionization Cooling Experiment– Nature 57, p. 53 (2020)

- Early concept (1983)
  - D. N., Part. Acc. 14, 75
- Updated graphics:



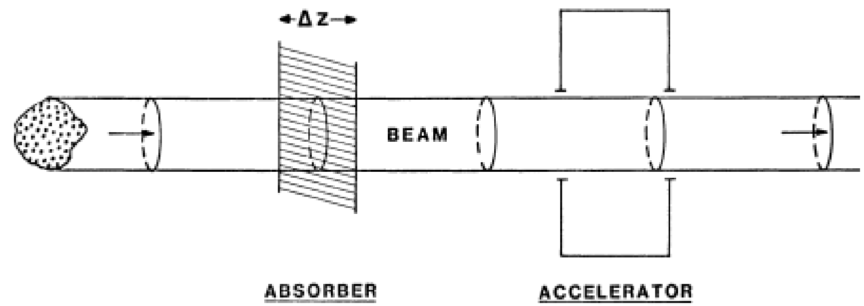
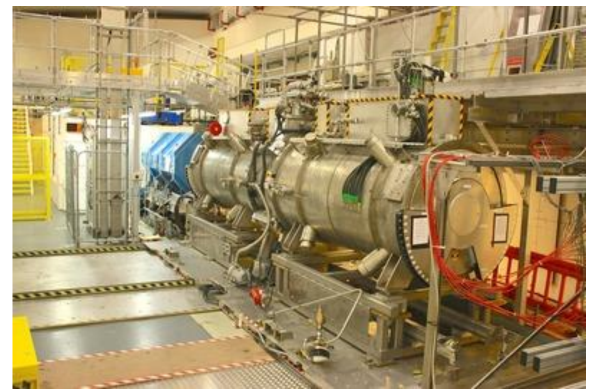
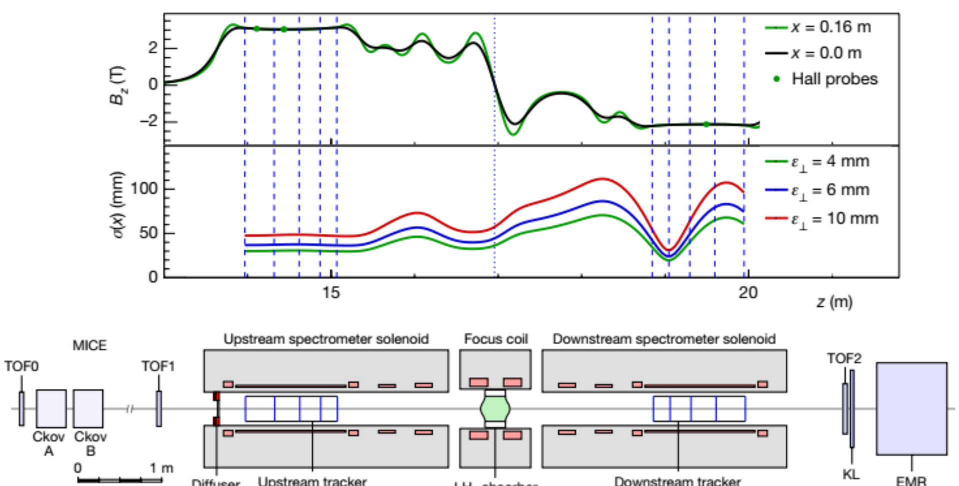
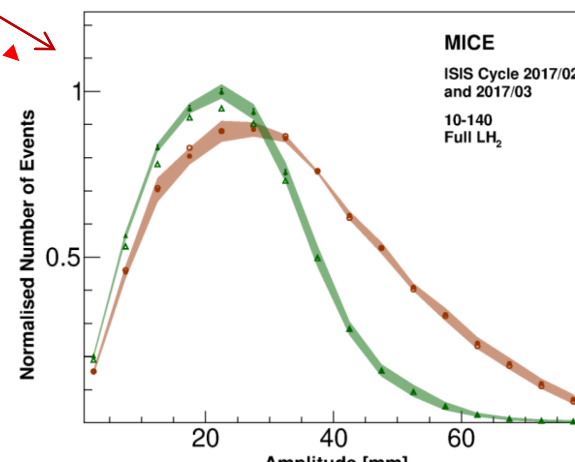


FIGURE 1 Sketch of "ionization cooling" principle



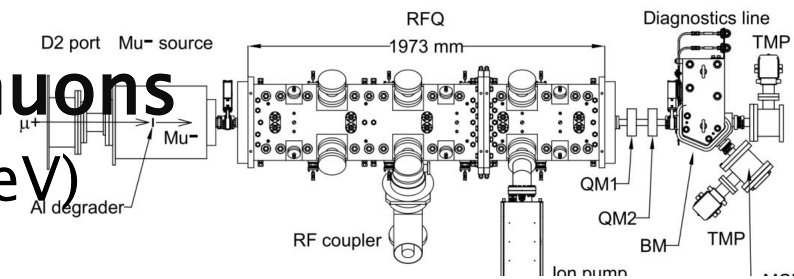
- Experimental Result (2020)





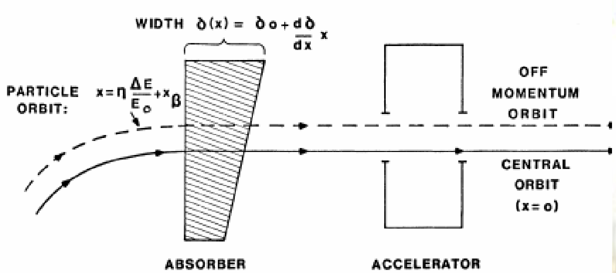
Recent Research

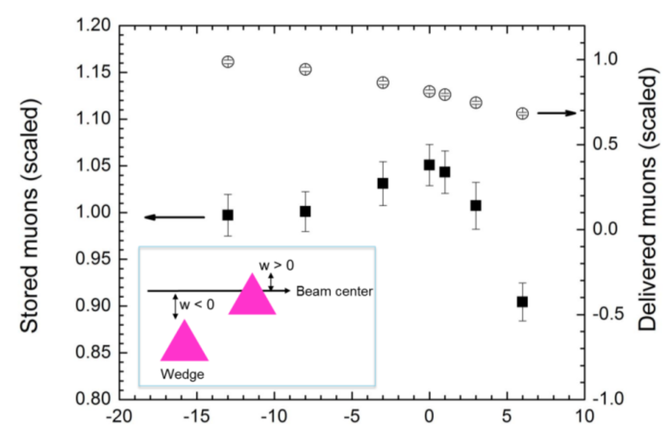
- **First rf acceleration of muons**
  - JPARC – MUSE rfq (5→ 89keV)
  - 324 MHz
  - Phys. Rev. Accel. Beams **21**, 050101 (2018)



➢ **First use of muon cooling to improve**

- **operational intensity** (g-2 exp, D. Stratakis et al., 2019-LDRD)
  - B_4C or poly wedge
  - Increases useful μ's by 8%, reduces background by ~30%

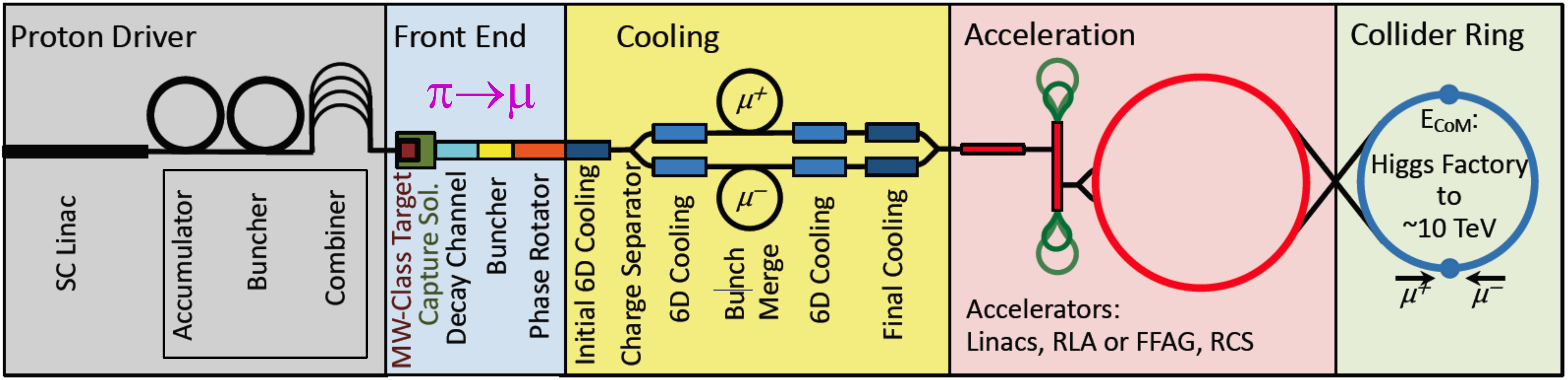




MAP Program

- **MAP** developed ~detailed designs for $\mu^+\!-\!\mu^-$ colliders
  - Almost complete "feasibility study"
    - down-selecting
    - Not cheap …
  - In serious danger of succeeding …
    - Too ambitious, too risky for P5
- Go through MAP design
  - Discuss variants and potential improvements

Muon Colliders: MAP Scenario Overview



Proton Driver

Short, intense proton bunches

4 **MW power**

MAP: 8 GeV Linac →

PIP-II + PIP-III RCS
Could be better

Target

Produce pions
Collect and cool muons from pion decay

Cooling

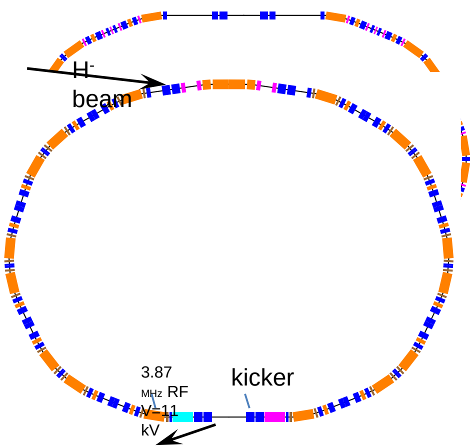
Single pass →
Ring coolers,
Improve final cooling
PIC cooling ??

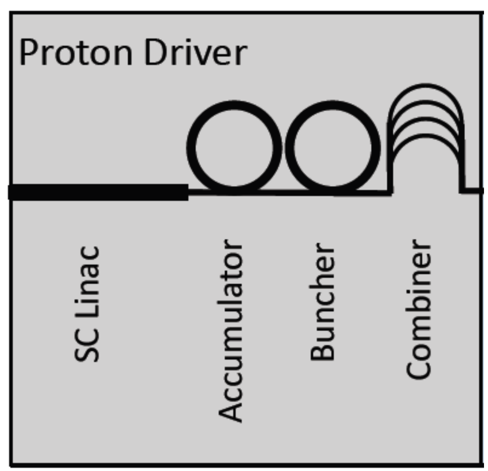
Acceleration to collision energy

Collider
rings for 0.125,1.5,3, 6 TeV designed

MAP Proton Driver

- **8 GeV Linac -4MW 15 Hz**
  - matches Project X
- **Inject into ring 1**
  - Accumulate–4bunches
- **Bunch to <3ns in ring 2**
- **Extract into 4 transport lines on to target, using Combiner**



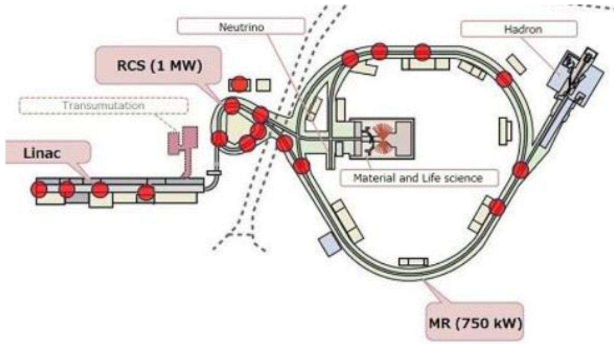


- **Problems:**
- **8 GeV energy too small ?**
  - Space charge too large
  - 3 extra transport lines onto target ?
  - 2 Rings ???
  - Lower power may be better …

Other proton driver Solutions

- **Rapid-cycling synchrotron or FFAG**
  - Low-harmonic naturally obtains intense bunches
  - Compression to <~1m possible
  - FFAG could be better than RCS

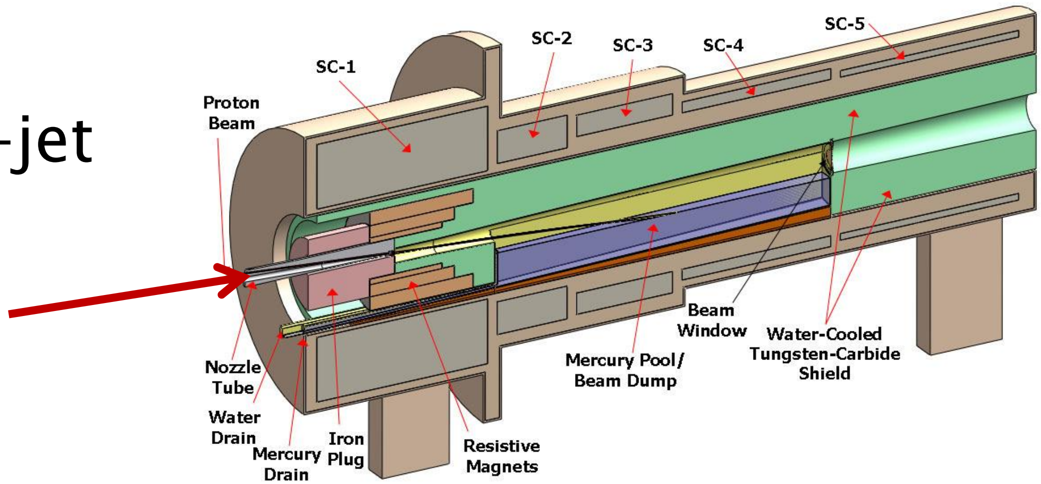
- **Examples**
  - JPARC 3 GeV RCS (25 Hz, 2 bunches, 1MW
  - JPARC MI, 30 GeV~1Hz, 8 bunches 0.75 → 1+ MW



  - CERN PS
    - 1.2 Hz, 8 bunches 0.17 MW

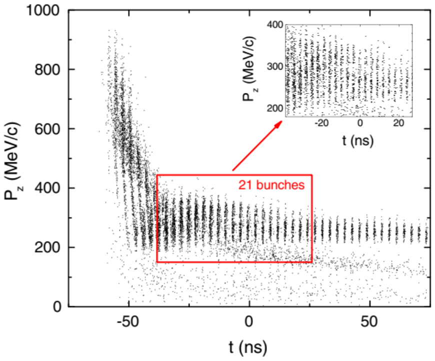
Targetry system

- Baseline puts short p
- bunches on mercury-jet target
- In ~20 T solenoid
  - 20→~2T taper
- Captures both signs
- Other targets
  - Hg leaks …



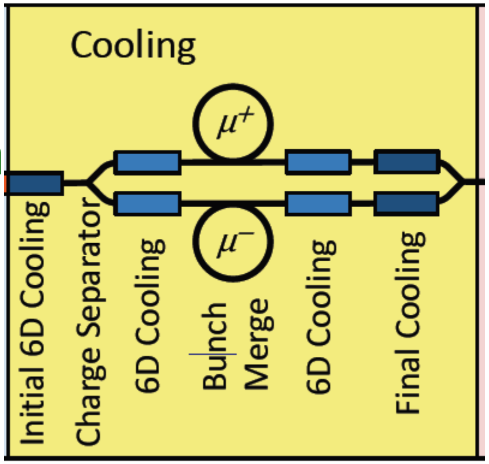
Bunching and phase rotation system

- Takes a short p bunch off target
  - 450→325 MHz
  - **Forms into string of 325 MHz bunches (21)**
- Initially Considered induction linac
  - → 1bunch
- Also 350→200 Mhz
  - ~12 bunches
  - Neutrino Factory



Cooling Systems

- **Baseline Cooling system is absorbers +rf within solenoids**
  - Much of the cooling is actually used for bunch combination



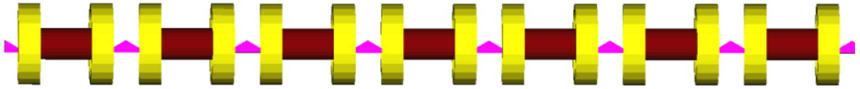
- **Could it be improved??**

It's too long

  - ~1km linac, ~250 cells

Inefficient – cooling rate g_{eff} <0.2

Cools only to ~0.0002 m



Final cooling needs improvement …

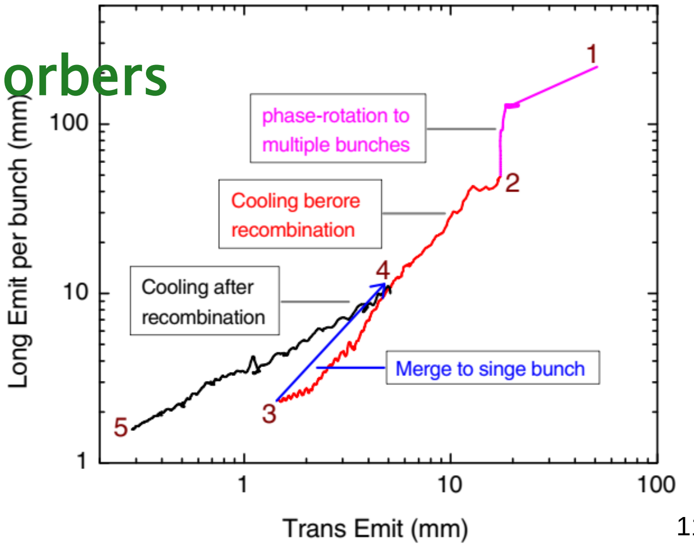
- **Options:**

Ring coolers ?? to reuse cooling rf, absorbers

Helical or PIC cooling (Derbenev) ?

Li lens or Quad or plasma Lenses?

Rf choices



Bunch Merge

- **Baseline Cooling system has a**
- **21 → 1 bunch merging system**
  - Includes 7 trombones

  - Alternative rf based system could be used
    - DN & C . Yoshikawa

  - Cooling follows

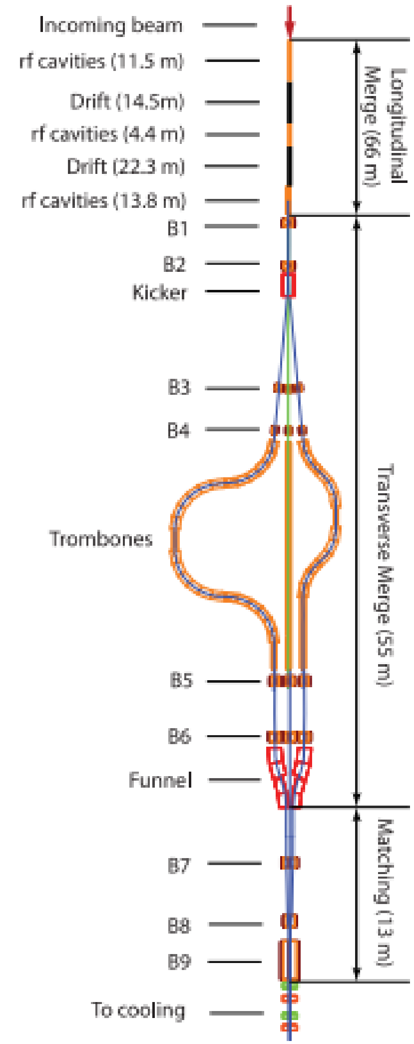
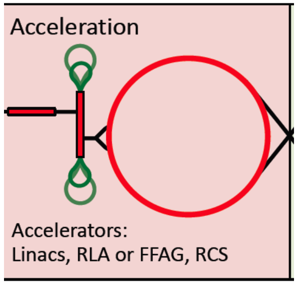
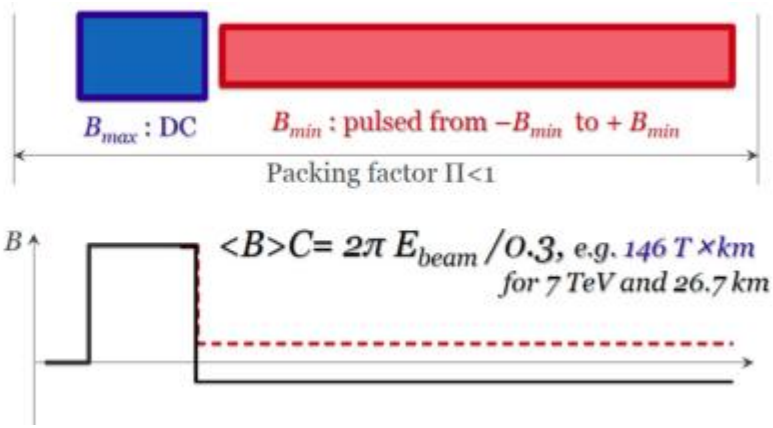


FIG. 3. Merge scheme.

Acceleration Systems

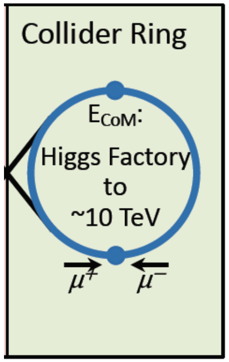
- **Linac to ~GeV, RLA to 100 GeV**
  - **At high energy RLA is expensive**
- **Baseline high energy version is hybrid RCS**
  - ±2 T + 8 T SC
    - **Awkward lattice structure with large energy-dependent orbit**
      - Cycling is easy for E > TeV





- **FFAG lattices ?**
  - **Super conducting with coil placementt determining field profiles**
    - Many turns of acceleration within same magnet
  - **Vertical FFAG ?- S. Brooks**

Collider Rings



- **Some excellent lattice designs**
  - 1.5, 3, 6 TeV
  - Muon Decay background mitigation not fully solved

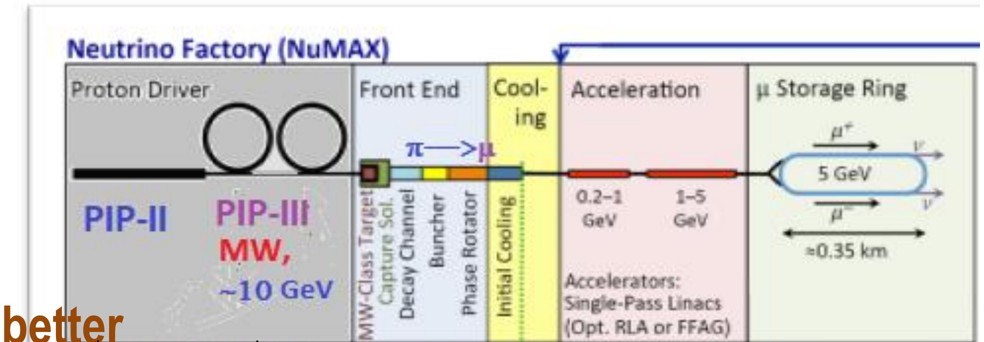
- **For very high energy radiation damping will help**
  - 50+ TeV?

Neutrino Factory

Start with low-energy muon bunches

- ϕ-E rotation and cooling

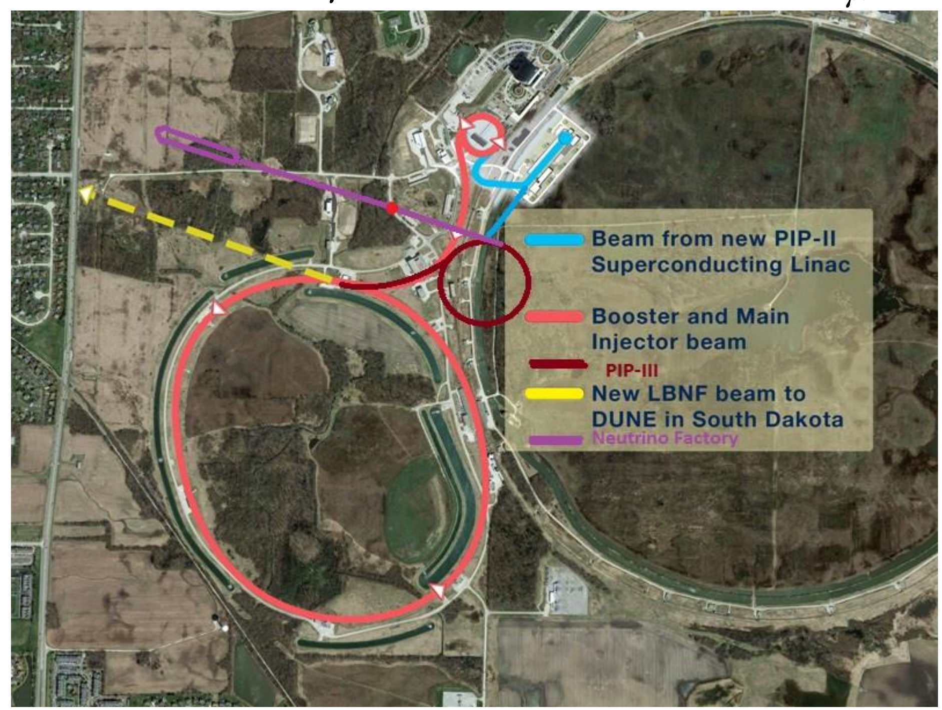
Accelerate to X GeV and store



ν-beams from μ decay provide better quality beam

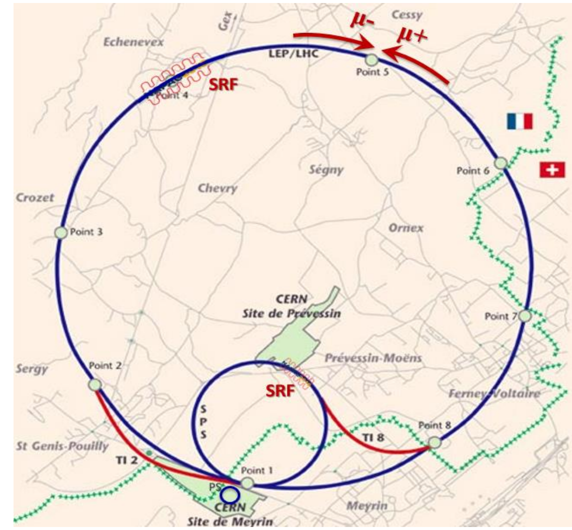
- Adds well-defined ν_e beam

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$



High Energy to 14 TeV at LHC

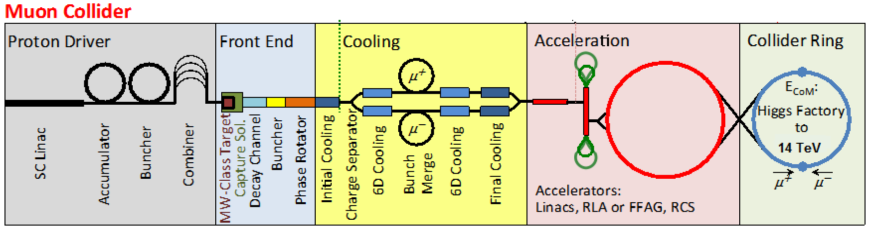
- $\mu^+\mu^-$ site-filler in LHC tunnel
- **muon source:**
  - CERN PS-based proton source + cooling
  - MAP 8GeV 2MW p + cooling
  - threshold 45 GeV e^+ ring + e^- production
    - LEMMA- Boscolo et al. -no cooling
  - Separate collider ring preferred

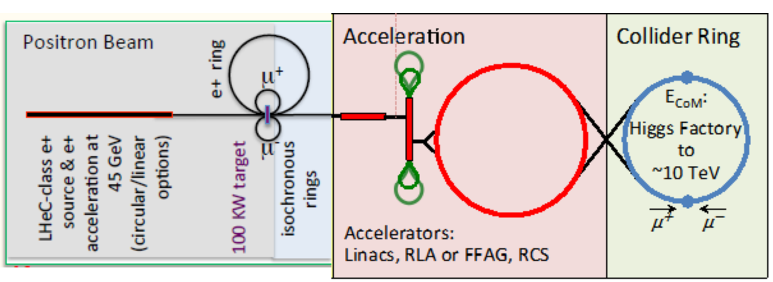


Shiltsev & Neuffer, IPAC 18

Parameter	"PS"	"MAP"	"LEMC"
Avg. luminosity	$1.2\cdot10^{33}$	$3.3\cdot10^{35}$	$2.4\cdot10^{32}$
Beam δE/E	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2\cdot10^{11}$	$2\cdot10^{12}$	4.5×10^{7}
n_b	1	1	1
$\epsilon_{t,N}$ mm-mrad	25	25	0.04
β^*, mm	1	1	0.2
σ^*(IR), μm	0.6	0.6	0.011
Bunch length, mm	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$6\cdot10^{12}$	$2\cdot10^{14}$	$3\cdot10^{13}$
Driver beam power	0.17MW	1.6MW	40 MW
Acceleration, GeV	1-3.5, 3.5-7 RCS	1-3.5, 3.5-7 RCS	40 GV, RLA 20 turn
N rad. (unmitigated)	0.08	1.5	0.015 mSv/yr

Muon Collider





3 Laws of Beam Physics

1. **Beam Phase Space cannot decrease**
   - Liouville's theorem cannot be violated

2. **Beam Phase Space increases**
   - bunch combination is inefficient

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3. **Break the 1st Law wherever possible**
   1. radiation damping
   2. **stochastic cooling- van der Meer …Thorndahl**
   3. electron cooling
   4. ionization cooling –"muon cooling"
   5. charge-exchange injection
   6. "stochastic injection" ($\pi \rightarrow \mu$ decay)
   7. ??