Ionization Cooling for Muon Experiments

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The idea:
use the high-intensity muon source (frontend + initial cooling) designed by MAP for NF & MC for other experiments like the next generation mu2e

Possible experiments with cooled muons

There are a number of experiments that could benefit from using cooled muon beams:

- flavor violating $\mu \rightarrow e$ conversion in muonic atoms ("mu2e"),
- other charged lepton flavor violation experiments: $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$,
- muon electric dipole moment measurement,
- precision muon lifetime measurement,
- muonium to anti-muonium conversion

and many more, including experiments using neutrinos from muon decay (NuSTORM, NF).

From **Project X: Physics Opportunities**

Table IV-1: Summary of beam requirements for muon experiments.

Process	Time Structure	Capture or stop	Accepted muons	Muon KE
$\mu \rightarrow 3e$	continuous	stop	$O(10^{19})$	surface
$\mu \rightarrow e\gamma$	continuous	stop	$O(10^{19})$	surface
$\mu^- N \rightarrow e^- N$	pulsed	capture	$O(10^{19})$	≤ 50 MeV
$\mu^- N \rightarrow e^+ N(A, Z-2)$	pulsed	capture	$O(10^{19})$	≤ 50 MeV
$\mu^+ e^- \rightarrow \mu^- e^+$	pulsed	stop	$O(10^{13})$	surface

Surface beam = muons produced by pions stopped near a target surface $\Rightarrow$ nearly monoenergetic (p_μ=29MeV/c), 100% polarized

Mu2e experiment @ Fermilab

- ➢ **Parameters of μ→e**
  - ■ **Proton beam – 8GeV (~5ma)**
    - ● **$8 \cdot 10^{12}$/ 1.33s**
      - ■ **2 Booster batches/cycle**
    - ● **$6 \cdot 10^{19}$/ 10^7 s**
  - ■ **6 years (10^7 s)→ $3.6 \cdot 10^{20}$ p**
- ➢ **Form 4 bunches in Recycler**
  - ■ **extract one by one into Delivery Ring**
  - ■ **Slow extract into mu2e line**
  - ■ **0.0019 stopped μ/p**
    - ● **$6.7 \cdot 10^{17}$ μ / experiment**

Figure 4.3. The accelerator t...
represent Mu2e and NOvA p...
Recycler Ring occur in the fi...
the remaining twelve 15 Hz t...

Muon Campus Beam Lines

- M1 Line
- AP-0 Target Hall
- M2 Line
- M3 Line
- Delivery Ring
- Delivery Ring Abort Line
- M4 Line
- M5 Line
- MC-1 Experimental Hall
- Mu2e Target Hall
- Mu2e Detector Hall

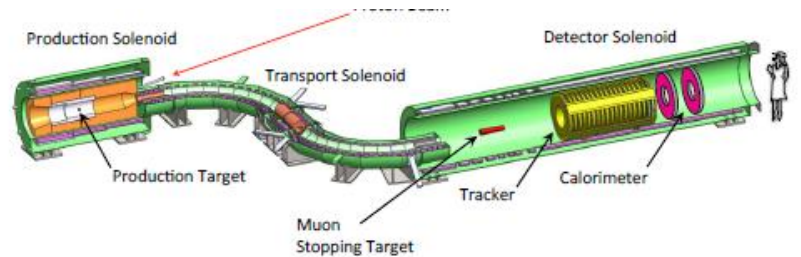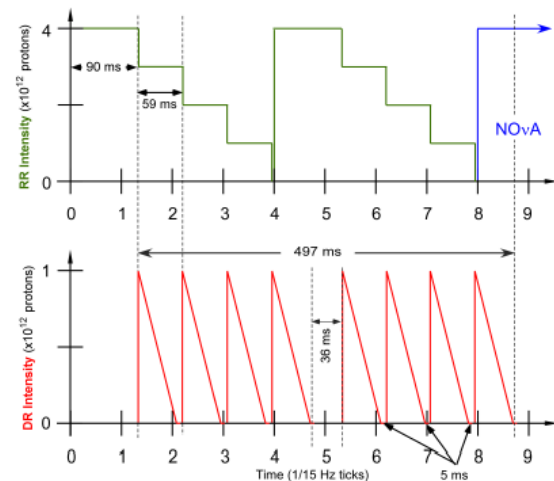Figure 4.6. Muon Campus beam lines

Figure 1.1. The Mu2e Detector. The cosmic ray veto that surrounds the Detector Solenoid is not shown.

Courtesy of D. Neuffer

Mu2e experiment @ Fermilab

➢ **Signal is monoenergetic**

- ▪ 105 MeV electron
- ▪ background is , μ decay in orbit
  - ● π capture, μ, π decay in flight, p-bar, e⁻, cosmic rays …
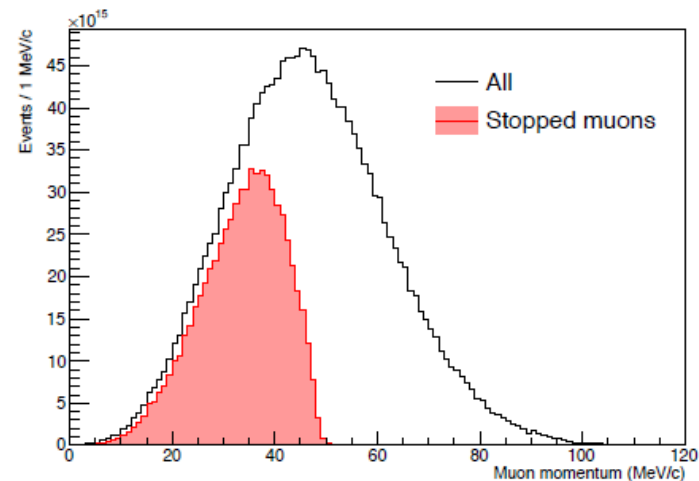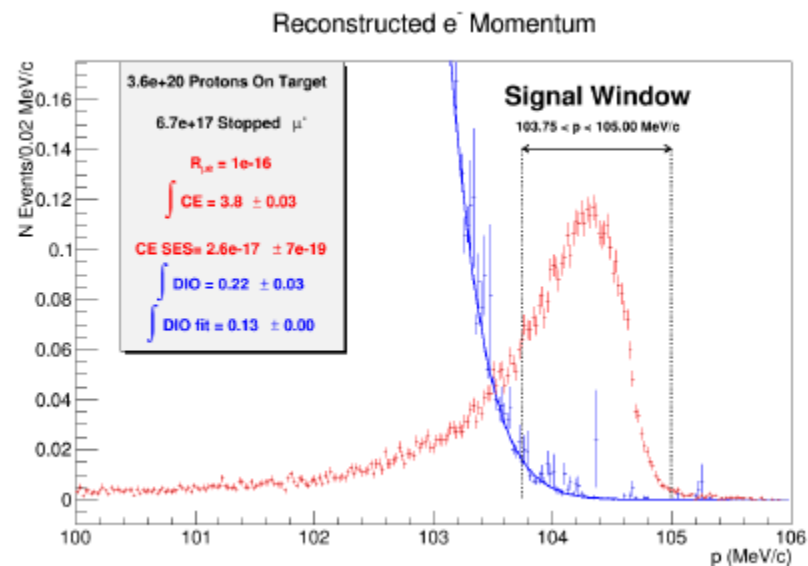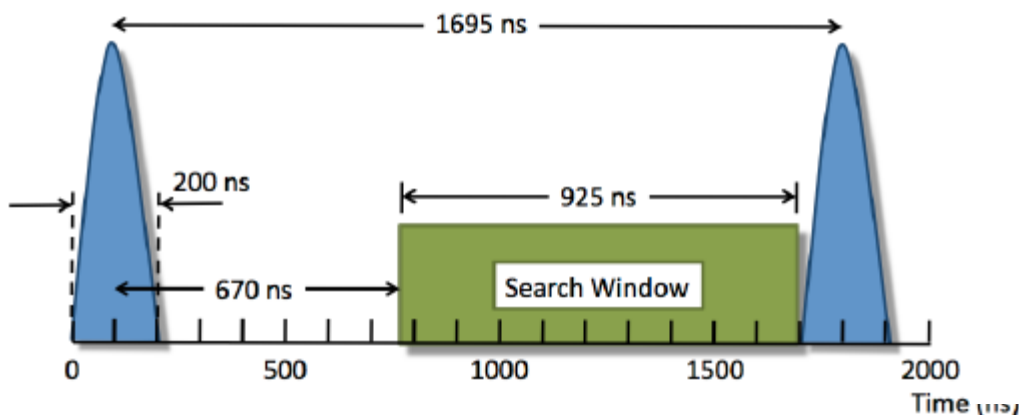 - ● 0.4 Background Events

Figure 2.7 Momentum distribution of muons delivered to the stopping target as well as the distribution of muons that stop in the target.

Courtesy of D. Neuffer

Goals of Next Stage

- ➢ **If result is zero ($<10^{-16}$)**
  - ▪ **Go to higher sensitivity**
    - • **more protons**
    - • **more muons**
  - ▪ **reduced background**

- ➢ **If result is nonzero ($\sim 10^{-14}$)**
  - ▪ **Go to higher sensitivity**
    - • **more protons**
    - • **more muons**
  - ▪ **Also explore Z-dependence**
    - • **Au (τ=77ns)**
      - ▪ **t < ~10ns bunching structure**
  - ▪ **Reduce background**
    - • **less decay in orbit**

- ➢ **More Muons**
  - ▪ **10^{10}/s $\rightarrow$?**
    - • **> 10^{12}/s**

- ➢ **Muon Collider Front End**
  - ▪ **up to ~10^{13}/s**
  - ▪ **cold beam; decelerate to 20 MeV/c**
  - ▪ **only μ's survive cooling; transport**

Mu2e experiment requirements

The goal: single event sensitivity ~ 10^{-19} with different target materials, from Al (Mu lifetime ~0.9 μs) to Au where Mu lifetime is only 77ns.

We look for a configuration that suits both Al and Au:

1. A flux of the order of 10^{12}muons/s.

2. There must be no muons with momentum > 76 MeV/c , since they could produce electrons at the conversion energy. Also the muons must be stopped in 400 microns or less of Al or the equivalent thickness of other material. This means that muons must have momentum < 20 MeV/c.

3. The width of the muon pulse should be much shorter than the Mu lifetime in the target material, 10ns seems adequate for both Al and Au

4. The time between muon pulses within a train must be long enough compared with the pulse width but should not exceed ~3 muon lifetimes in the target material.

5. There must be no pions and antiprotons. These are naturally removed with the use of a long cooling channel.

Emittance Requirements

Let us take p_{fin}=15MeV/c, σ_{pfin}=2MeV/c, σ_{tfin}=2ns so that muons at $\pm2.5\sigma$ lie within the specified ranges. Then

$$\varepsilon_{\|N} = \sigma_{pfin}\sigma_{zfin}/m_\mu = \sigma_{pfin}\sigma_{tfin}v_z/m_\mu = 1.6\,mm$$

If we want the beam size $\sigma_\perp$<5cm in a 1T solenoidal field ($\beta_\perp$=0.1m) then

$$\varepsilon_{\perp N} = \sigma_\perp^2/\beta_\perp \times p_{fin}/m_\mu \leq 3.5\,mm$$

Such emittances can be obtained with just HFOFO snake and longitudinal "shaving" (at the price of ~60% loss). Otherwise HCC must be included:

step	L (m)	$\varepsilon_{\perp N}$ (mm)	$\varepsilon_{\|N}$ (mm)	T (%)	$N_{\mu-}/N_p$
Front End	102	16	40	-	0.16
325 MHz HFOFO snake	130	2.7	7.2	70	0.11
Matching into HCC	12	3.3	7.7	72	0.08
325 MHz HCC	70	1.6	2.4	90	0.07
650 MHz HCC	120	0.8	1.2	80	0.06

Table: Parameters of the GH2-filled cooling channel, $N_{\mu-}$ being a sum over 20 best bunches. Production target in 15-20T solenoid is assumed.

Booster & Debuncher
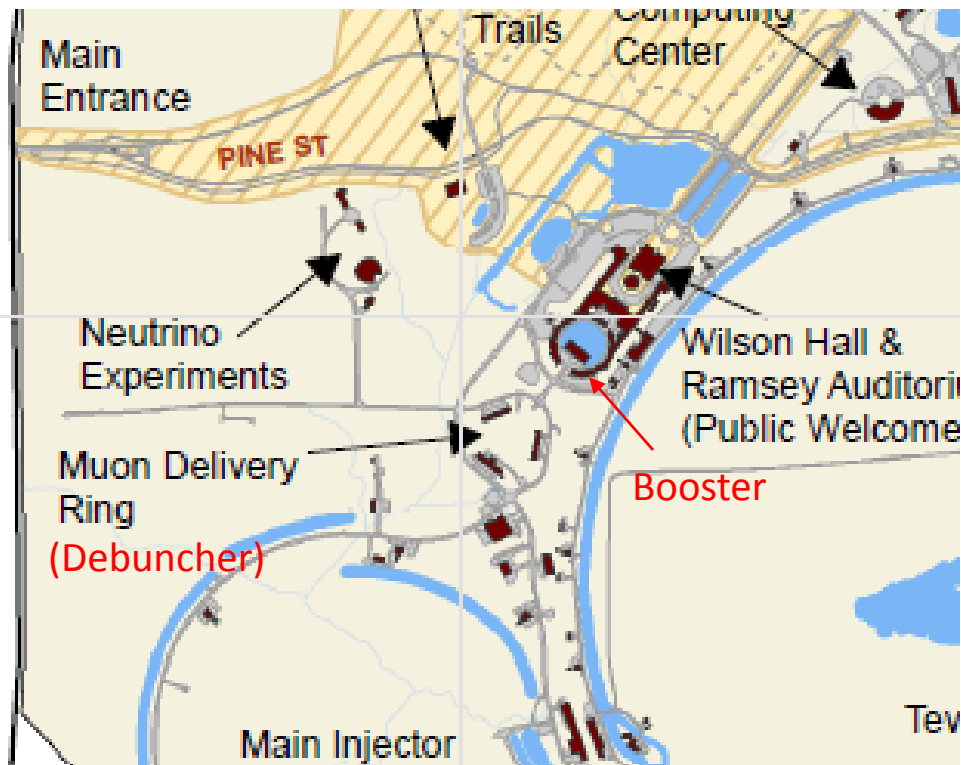
Debuncher (now "Muon delivery ring")

Circumference (m)	508
Rev. period (µs)	1.69
DRF-1 frequency (MHz)	53.1
Harmonic	90
DRF-1 voltage (MV)	5

Concept

- Use Booster as p-driver.

  $6 \cdot 10^{12}$ protons per batch at 15Hz $\Rightarrow 0.9 \cdot 10^{14}$ pps, P=115kW

- Store the batch (80 bunches) in Debuncher and dispense 1 bunch every other turn.

  Time spacing = 3.4 μs, total batch length on production target = 270 μs.

- Use the front end and the initial cooling channel of the same design as for NF/MC
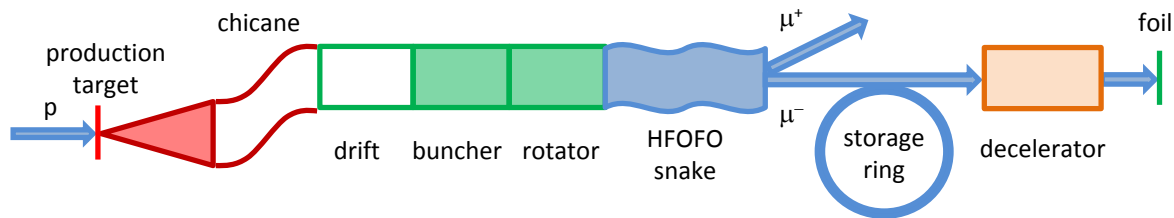
  B=15-20T on the target
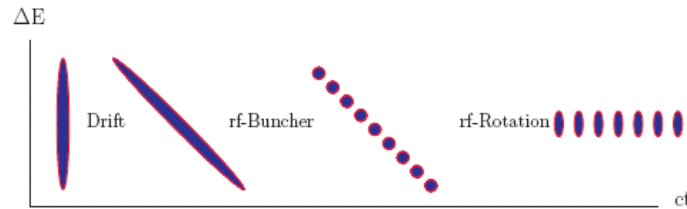
Front end concept.

2-3ns p-bunch produces > 100ns μ-bunch train or > 30 bunches spaced by 3.1ns at 325MHz

- Store 20 best μ-bunches in a ring and extract one-by-one at 3.4 μs/20=0.17 μs.

  1 Booster batch $\Rightarrow$ 1600 μ-bunches at 5.9MHz.

- Decelerate μ's in RF field (no more diffusion).

  Long. "shaving" can be performed in decelerator as well as in SR

Scheme

Schematic of the high-intensity muon source
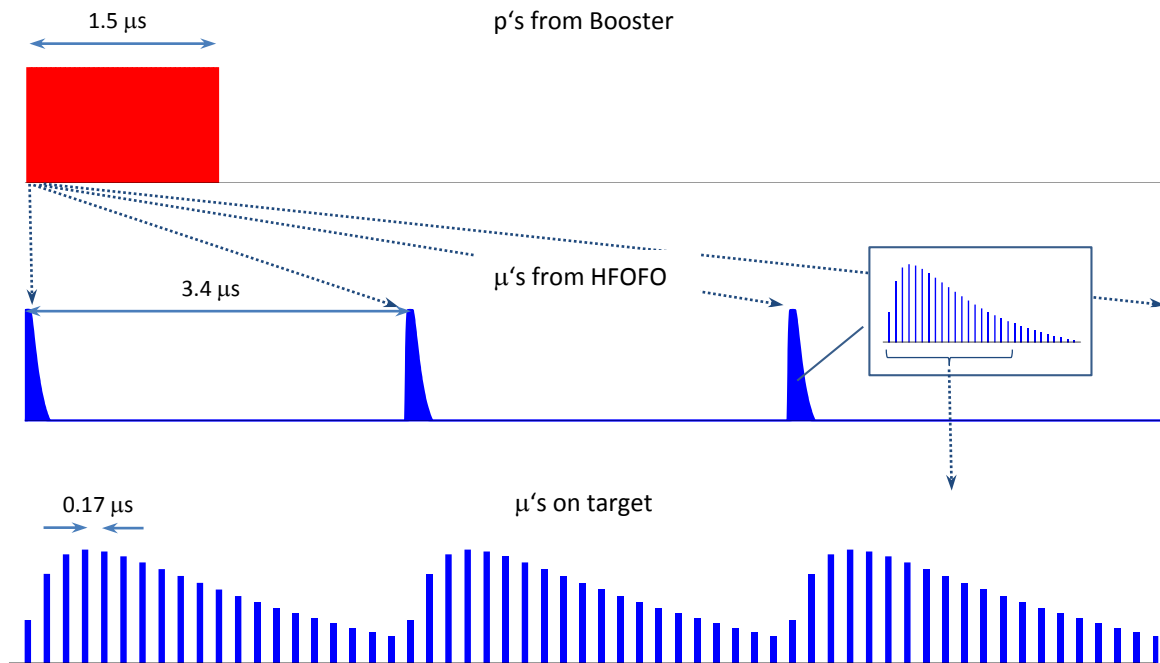
Time structure of the muon beam

Performance

Step	Efficiency	μ/s (10^{12})
Front End	0.16μ/p	14.4
Cooler	70%	10
Muon Storage Ring	71%	7.2
Longitudinal "shaving"	40%	2.9
Deceleration	90%	2.6

Overall efficiency of 0.03 μ/p should be compared with the mu2e expectation of 0.002μ/p.

Single event sensitivity of $5 \cdot 10^{-19}$ can be reached in 7 months for Al, assuming the product of acceptance and reconstruction efficiency is 10%.

It must be emphasized that the proposed muon source opens way for a variety of experiments including Neutrino Factory.

Plan of Action

• Preliminary concept of the detector to concretize the requirements to the beam

• Concept of the Decelerator (multi-frequency RF vs induction linac? Low-frequency high-gradient RF is needed)

• Study of the Front End options, e.g. initially low RF frequency (162.5MHz) with later transition to 325MHz – will allow lower B on the target.

• Optimization of the HFOFO channel to obtain lower emittance and – possibly – reduce final momentum.

• Layout on the Fermilab site: the possibility of using PIP-III linac (?) – together with accumulation and compression rings – should be envisioned as a path to NF

• Cost estimate!

An (unsuccessful) attempt was made to get funding from the Fermilab LDRD program. Among the reasons for negative decision:

"… Seems like an attempt to keep 6d ionization cooling going…

…Very expensive study of very expensive muon source (will be 4-10 more expensive that g-2 and mu2e combined)."

Cost Estimate Exercize a la Shiltsev

For linear machines

$$Cost \approx 2\sqrt{\frac{L}{10km}} + 10\sqrt{\frac{E}{1TeV}} + \sqrt{\frac{P}{100MW}}$$

- L_total ~ 300m

- With average gradient G=20MV/m the equivalent linac energy = G/2*L_total = 3GeV

- Power consumption? Let us take P=1MW (there is no HCC and final cooling)

Cost = 2*0.17 + 10*0.055 + 0.1 = $1B

I doubt this is a correct number, but anyway the cost will be high so the expenditure can be justified only if it is a step towards NF/MC

PRISM : Super-muon source
PRIME : μ-N→e-N Search with PRISM

- **Intensity** : 10^{11}-10^{12}μ±/sec, 100-1000Hz

- **Energy** : 20±0.5 MeV (=68 MeV/c)

- **Purity** : π contamination < 10^{-20}

Capture Solenoid

Matching Section Solenoid

R&Ds
2003.4-2009.3

Injection System

C-shaped FFAG Magnet

FFAG ring

RF Power Supply

RF Cavity
RF AMP

PRISM-FFAG

Functions of the Muon Storage Ring

- Makes momentum spread narrower,
  - improves the σ_E to 250keV
- Eliminates unwanted particle
  - long flight length
  - charge selection
  - momentum selection

Courtesy of D. Neuffer