Precooling with Gas in the “Front-End”

In collaboration with:

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Introduction

- Muons, Inc.:
  - High-Pressure Gas-Filled RF Cavities
  - Helical 6D Cooling Channel (HCC)

- Challenges:
  - Breakdown suppression
  - High Gradients within high magnetic fields
  - High Gradients at low frequency
  - Radiation limits
Motivation

- What else can we do?
  - Capture beam into RF early
  - Capture large fraction of beam with RF
  - RF phase rotation over short distance
  - Simultaneous precooling

- What problems can we face?
  - Pion interaction with gas
  - Pion decay within RF buckets
Plan

- Simple comparison:
  - Neutrino Factory-like baseline (No RF or Gas)
  - Neutrino Factory-like baseline w/ HP Gas (100 atm)
    \[ \lambda_l = 59.4 \, \text{m} \]
  - 201.25 MHz RF w/ HP Gas
  - “Back-of-the-envelop” Phase Rotation
    (i.e., “Phase Rotation by Dummies”)
Production

- 80 cm long, 1 cm radius Carbon Target
- 1 MW / 8 GeV protons
- 20 T capture solenoid
- 100 mrad tilt angle
- 7.5 cm radius beam pipe
Adiabatic Matching

- Adiabatically decrease field strength to 5 T
- Increase beam pipe radius to 15 cm (*matches HCC*)
- Short matching section (5 m)
Initial Distribution

Energy Spectrum

Time Distribution

- 74% Pions / 26% Muons
- 0.14 $\pi$ / 0.05 $\mu$ per POT
Baseline Examples

- Neutrino Factory-like Decay Channel:
  - 50 m of 5 T solenoid
  - No RF cavities
  - No HP gas

- Immediate Capture into RF cavities:
  - 50 m of 5 T solenoid
  - 201.25 MHz / 50 MV/m / 20 cm RF cavities
  - No HP gas
**HP Gas Examples**

- Neutrino Factory-like Decay Channel with gas:
  - 50 m of 5 T solenoid
  - *No RF cavities*
  - 100 atm / Room Temp. GH₂

- Immediate Capture into RF cavities with gas:
  - 50 m of 5 T solenoid
  - 201.25 MHz / 50 MV/m / 20 cm RF cavities
  - 100 atm / Room Temp GH₂
What are the losses due to RF?

Muon Transmission

![Graph showing Muon Transmission](image-url)

- **Normalized Number of Positive Muons**
- **Distance down Channel [m]**

**Legend:**
- Vacuum
- Vacuum RF
What are the losses due to gas?

Muon Transmission

![Graph showing normalized number of positive muons vs distance down channel in meters with 'Vacuum' and 'HPG' lines]
And if we do everything at once?

Muon Transmission

![Graph](image_url)

- Normalized Number of Positive Muons vs. Distance down Channel [m]
- Lines represent different conditions:
  - Vacuum
  - Vacuum + RF
  - HPG
  - HPG + RF
Do we see any cooling?

Muon Transverse Emittance

![Graph showing transverse emittance vs. distance down channel in meters.](image)
Is it worth writing home about?

Transverse “Merit Factors”
Phase Rotation

- What do we need to phase rotate initial beam?
  - Large gradient (50 MV/m)
  - Low frequency (50 MHz)
  - HPG (100 atm / Room Temp.)

- New problems:
  - Large gradient $\rightarrow$ Large energy spread
  - Large energy spread $\rightarrow$ Large tune spread?

\[ Q_s \sim V^{\frac{1}{2}} E^{-\frac{1}{2}} \]
Initial Beam

Longitudinal Phase Space
This should to be fun…

- The beam is not ideal for rotation…
  - Enormous energy spread
  - Still a fairly long time spread
  - Strong correlation between energy and time
- But wait…
  - Use the gas to lower the energy via dE/dx loss
  - Move low energy particles up with RF
  - Use reference momentum lower than peak
Well, that’s something!

Muon Transmission in the 200-300 MeV/c Momentum Range
Final Beam (after 2 m)

Longitudinal Phase Space

- X-axis: Time of Flight [s]
- Y-axis: Momentum [MeV/c]
Put it all together

- Phase rotation:
  - 50 MHz / 50 MV/m / 0.2 m RF cavities
  - 2 m of transport

- Dump it into RF:
  - 201.25 MHz / 50 MV/m / 0.2 m RF cavities
  - 48 m of transport
Transmission…

Muon Transmission

Normalized Number of Positive Muons

Distance down Channel [m]

Transmission…

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Cooling…

Muon Transverse Emittance

![Graph showing transverse emittance over distance down the channel.

Distance down Channel [m]

- Vacuum
- Vacuum RF
- HPG
- HPG RF
- HPG RF with Rotation

Transverse Emittance [m radian]
Merit...

Transverse “Merit Factors”

Normalized Transmission * Emittance vs. Distance down Channel [m]
Summary

- **HP Gas:**
  - Losses are significant, but…
  - Losses may be manageable

- **Phase rotation:**
  - Difficult, but…
  - Interesting / Useful / Possible?

- Lot’s of room for improvement!