Muon Capture for a Neutrino Factory (IDS) or a Muon Collider

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Introduction

- **IDS ν-Factory**
  - (International Design Study)
- **Front end**
  - bunch, rotate and cool

Baseline method

- **Constraints**
- “adiabatic buncher”
- $\phi$-E rotate, cool

IDS example

- variations
- Latest versions

ν-Factory→μ$^+$-μ$^-$ Collider

- shorter buncher/rotator

rf problems

- options

Discussion
Neutrino Factory - IDS

International Design Study

- deliver Reference Design Report of a Neutrino Factory
  - detailed, with cost estimate

Neutrino Factory

- Proton Driver
  - 4MW, 50 Hz, ~10GeV p

- Target, Capture, Cool
  - $\pi \rightarrow \mu$, bunch, cool

- Acceleration
  - linac, RLAs, FFAG

- Storage/Decay rings
  - 2 baselines (~4000, ~7500km)

- Detectors
  - 50 kT detectors

- $>10^{21}$ µ-decays /SS /year

International Scoping Study

Solenoid lens capture

- **Target is immersed in high field solenoid**
- **Particles are trapped in Larmor orbits**
  - $B = 20T \rightarrow \sim 2T$
  - Particles with $p_{\perp} < 0.3 \frac{B_{\text{sol}} R_{\text{sol}}}{2} = 0.225 \text{GeV/c}$ are trapped
  - $\pi \rightarrow \mu$
  - Focuses both + and - particles
  - **Drift, Bunch and phase-energy rotation**
- Longitudinal capture, acceleration, and cooling:
  - Requires high gradient: $V' > \sim 10$ MV/m
    - $f > \sim 200$ MHz ??
  - Initial beam is $\sim 1$ m bunch, $\delta P \sim 500$ MeV/c
  - For cooling/acceleration need:
    - $P = \sim 200$ MeV/c, $\delta P/P \sim 10\%$, 0.3 m bunches
Drift ($\pi \rightarrow \mu$)  
“Adiabatically” bunch beam first (weak 320 to 240 MHz rf)  
$\Phi-E$ rotate bunches – align bunches to ~equal energies  
- 240 to 202 MHz, 12MV/m  
Cool beam 201.25MHz
$N_B = 10$ example

- **Drift from target ~60m**
  - Beam lengthens
  \[
  \delta (ct_i) = L \left( \frac{1}{\beta_i} - \frac{1}{\beta_0} \right)
  \]

- **Buncher (~30m)**
  - $N=10$
  - $P_0=280\text{MeV/c}$, $P_N=154\text{MeV/c}$
  - $330 \rightarrow 235 \text{ MHz}$
  - $V' = 0 \rightarrow 10 \text{ MV/m}$

- **Rotator (~35m)**
  - $N=10.08$ – continue to bunch
    - accelerate/decelerate bunches
  - $235 \rightarrow 202 \text{ MHz}, V' = 10 \text{ MV/m}$

- **Cooler (~80m)**
  - $201.25 \text{ MHz}$, ASOL lattice
  - $15\text{MV/m}$ in rf cavities
  - LiH or $\text{H}_2$ cooling
  - Captures both $\mu^+$ and $\mu^-$
Details of ISS implementation

- Drift -110.7m
- Bunch -51m
  - $P_0=280$, $P_{18}=154\text{MeV/c}$ $\delta N_V = 18$
  - 12 rf freq. (5 to 10 MV/m)
  - 330 MHz $\rightarrow$ 230MHz
- $\phi$-E Rotate - 54m
- 15 rf freq. 230 $\rightarrow$ 202 MHz
  - $\delta N_V = 18.032$
  - 12MV/m
- Match and cool (80m)
  - $\varepsilon_{x,y}$: 0.018 $\rightarrow$ 0.006m
- Captures both $\mu^+$ and $\mu^-$
  - $\sim 0.1$ $\mu/(10 \text{ GeV p})$
ISS Study Beam acceptance

- Method captures large initial longitudinal phase space
  - with relatively small dilution
- Initial Beam
  - $P_{\pi \rightarrow \mu}$ 75 to $\sim 600$ MeV/c,
    - $\Delta P = \pm 250$ MeV/c
  - $\sigma_{\text{bunch}} = \sim 1$ m rms
- Captured beam
  - 50+ bunches ($\sim 80$ m long)
- Accepted bunches are
  - $\Delta P = \pm 20$ MeV/c
  - $\sigma_{\text{bunch}} = \sim 0.3$ m
- 0.2 $\mu^+/24$GeV p
  - both $\mu^+$ and $\mu^-$
Shorter Bunch train example N=10

- Reduce drift, buncher, rotator to get shorter bunch train:
  - 217m $\Rightarrow$ 125m
  - 57m drift, 31m buncher, 36m rotator
  - Rf voltages up to 15MV/m ($\times 2/3$)

- Obtains $\sim 0.08 \, \mu/p_{8\text{GeV}}$ in ref. acceptance
  - similar to ISS baseline

- 80+ m bunch train reduced to < 50m
  - $\Delta N$: 18 $\rightarrow$ 10
Simulation Results: $N_B = 10$, $H_2$ cooling

Transverse emittance

$\mu/p$ (8GeV)

$1.5$ ZM
Adapt to Collider (2009 scenario)

- Need small number of bunches
  - High intensity
- Start with ν-factory front end
  - Use both $\mu^+$ and $\mu^-$ bunch trains
- Cool and recombine
  - $12 \rightarrow 1$ bunch
  - $N_B = 7$ parameters

R. Palmer, TU1GRI03
Baseline: \( V' = 12 \text{MV/m in B=1.75T} \)

- Experiments show reduced gradients within magnetic field:
  - not quite at front end parameters
  - first test cavity

- May require changes in our parameters ...
  - \( V'_{\text{max}} \propto (f_{\text{rf}})^{1/2} \) ???

- Future experiments will explore these limits
  - D. Huang et al - TU5PFP032
Front end rf options

- **Lower-Gradient baseline**
  - 4 to 8MV/m ?
  - longer system

- **Cavity changes**
  - Open cell rf?
  - coatings/materials? Be, Al, ALD

- **Gas-filled cavities ?**
  - Suppresses breakdown
  - electrons/ions ?

- **Focusing Variants**
  - Lower B-field across cavities
  - "alternating solenoid"

- "magnetically insulated" cavity
  - fields similar to alternating solenoid
  - Beam dynamics OK
Conclusions

- High frequency (bunch, phase rotate, cooler) is well suited to neutrino factory scenarios
  - Study 2B/IDS designs
  - Produces trains of $\mu^+$ and $\mu^-$ bunches for acceleration and storage (~ 80m trains)
  - Latest versions provide shorter trains (30 to 50m)

- Can use high-frequency capture to obtain bunch train for $\nu$-Factory $\rightarrow \mu^+-\mu^-$ collider
  - (~10 to 14 bunches long at 200MHz )
  - Recombine after cooling for collider mode

- Questions
  - $\sim$12 MV/m at $B \approx 2T$ and $f \approx 200$MHz OK?
  - Is $\sim$12 bunches OK for Collider scenario?
Supplemental Slides
Need to develop best design for IDS

I made some improvements to your drawings and sent them for fabrication.

But don’t worry – I left your name on them so you’ll get all of the credit.

You don’t handle good news very well.

GAAA!!!

WAAAA!!!

Shoot me!
Shoot me!
Shoot me!
Adiabatic Buncher: $\varphi$-E rotation

- **Beam first drifts**
  - beam lengthens $\delta(c t_i) = L \left( \frac{1}{\beta_1} - \frac{1}{\beta_0} \right)$

- **Buncher**: Set rf phase to be zero for reference particles
  - Spacing is $N \lambda_{rf}$, $\lambda_{rf}(L) = \frac{\delta c t_{0N}}{N} = \frac{L}{N} \left( \frac{1}{\beta_N} - \frac{1}{\beta_0} \right)$
  - $\Rightarrow \lambda_{rf}$ increases
  - gradually increase rf gradient

- **Rotator**: rephase rf so that higher energy bunches accelerate, low energy bunches decelerate
  - Finish when bunch energies are aligned in $E$
  - match to 210 MeV/c, 201.25 MHz

- **Cooler**: Cool with absorbers +rf
  - Captures both $\mu^+$ and $\mu^-$