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

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Outline

- Introduction
  - IDS ν-Factory
    - (International Design Study)
  - Front end
    - bunch, rotate and cool
- Baseline method
  - Constraints
  - "adiabatic buncher"
  - φ-E rotate, cool
- IDS example
  - variations
  - Latest versions
- ν-Factory→μ^+-μ^- Collider
  - shorter buncher/rotator
- rf problems
  - options
- Discussion

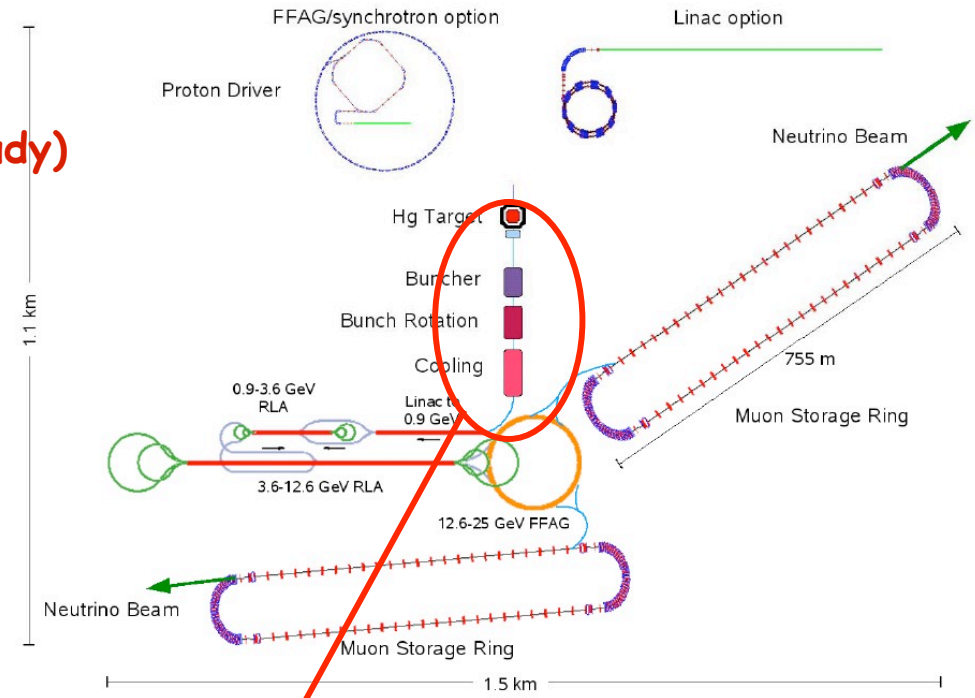
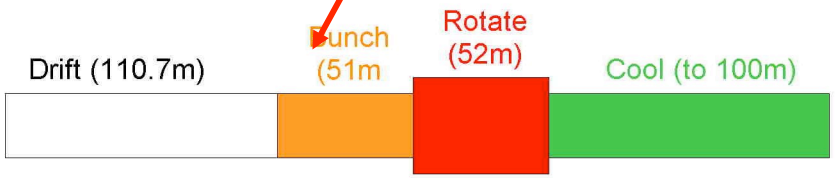


Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.



Neutrino Factory - IDS

- **International Design Study** K. Long, WE6RFP067
  - 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**

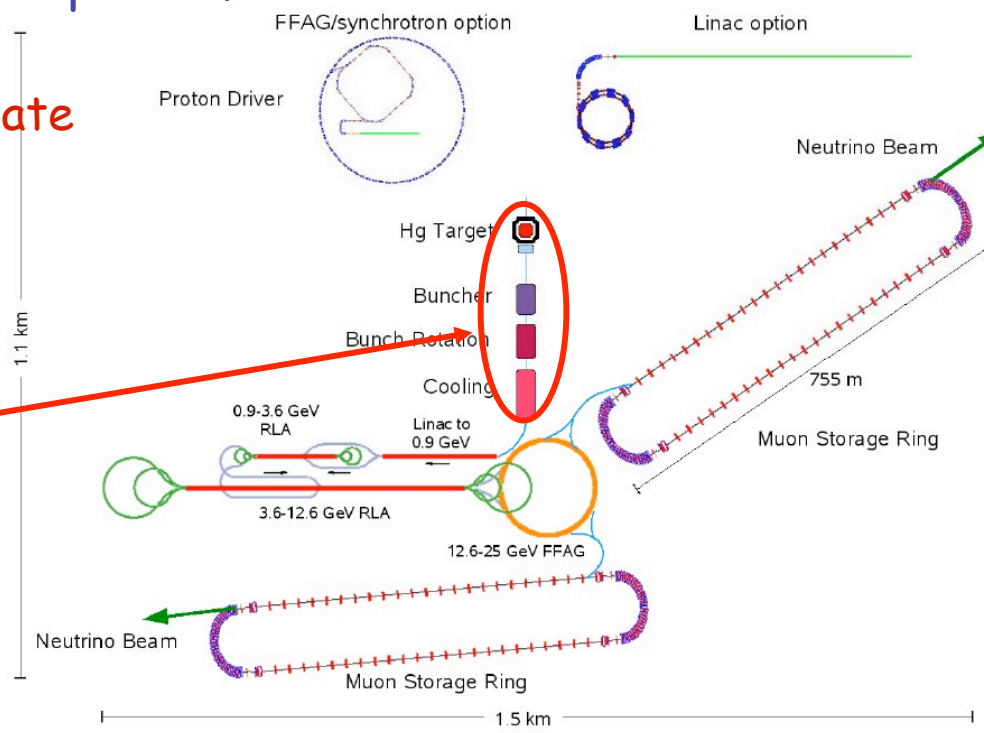


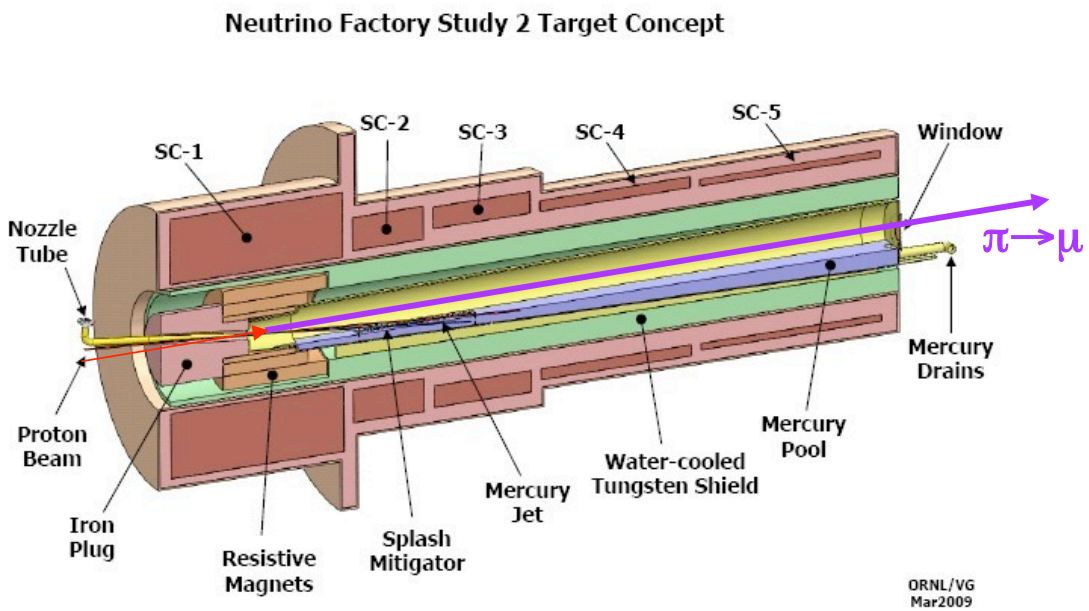
Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.

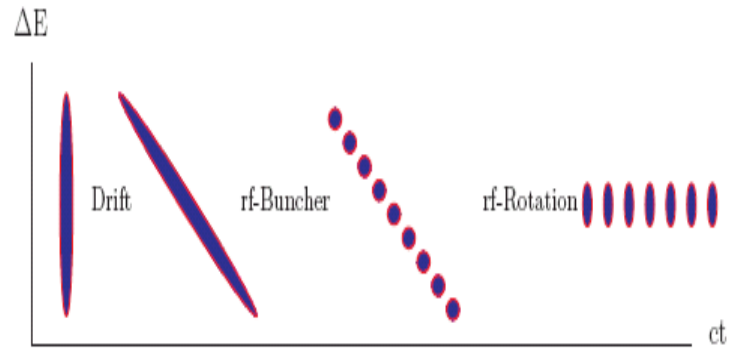
International Scoping Study

J. S. Berg et al., "Accelerator Concept for Future Neutrino Facilities", RAL-TR-2007-23, submitted to JINST (2008).

Solenoid lens capture

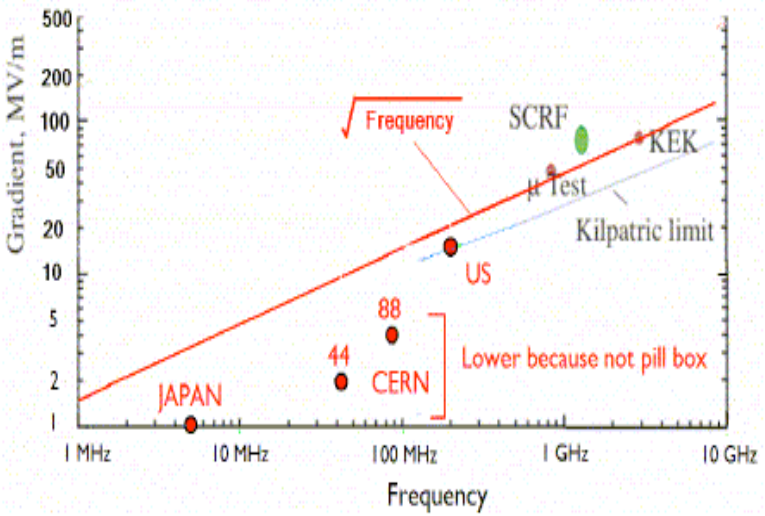
- Target is immersed in high field solenoid
- Particles are trapped in Larmor orbits
  - B= 20T -> ~2T
  - Particles with $p_\perp < 0.3\, B_{sol} R_{sol}/2 = 0.225$GeV/c are trapped
  - $\pi \rightarrow \mu$
  - Focuses both + and – particles
  - **Drift, Bunch and phase-energy rotation**

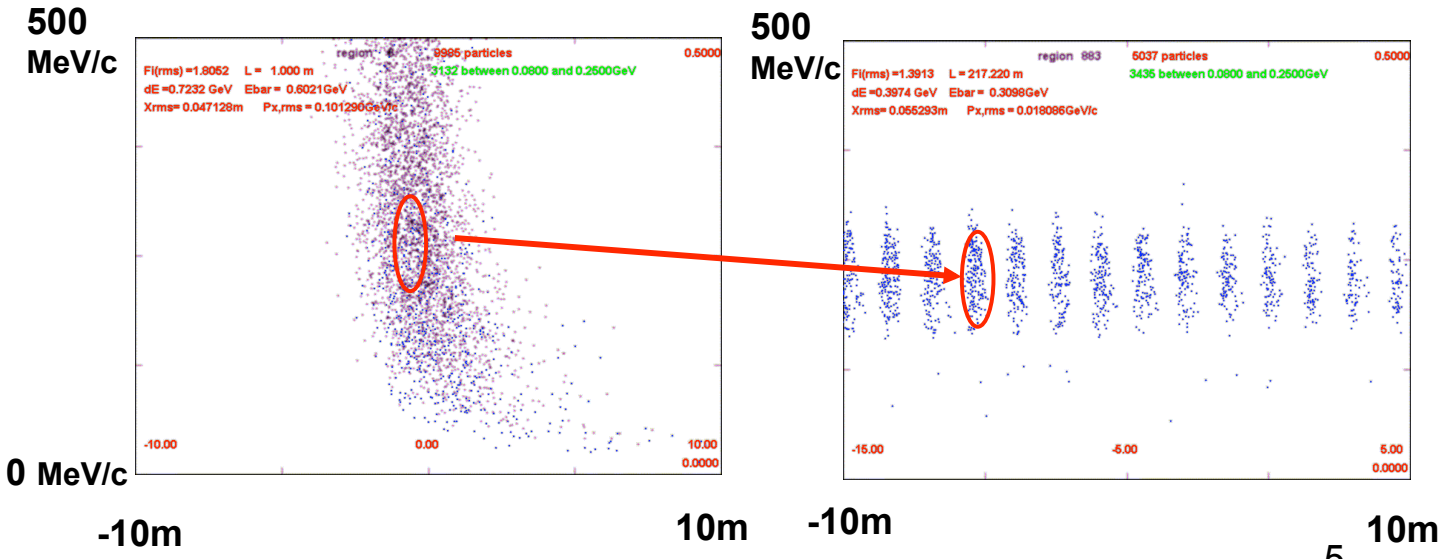




Target to Cooling/Acceleration match

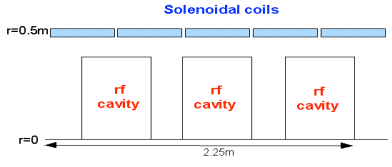
- Longitudinal capture, acceleration, and cooli
  - **requires high gradient: V' >~10 MV/m**
    - **f > ~200MHz ??**
  - **Initial beam is ~1m bunch, δP ~ 500 MeV/c**
  - **For cooling/acceleration need:**
    - **P =~200MeV/c, δP/P ~10%, 0.3m bunches**

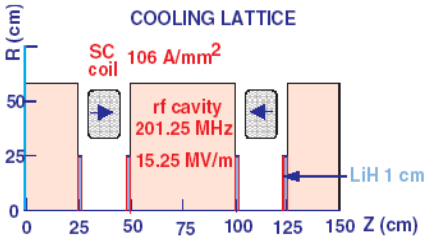


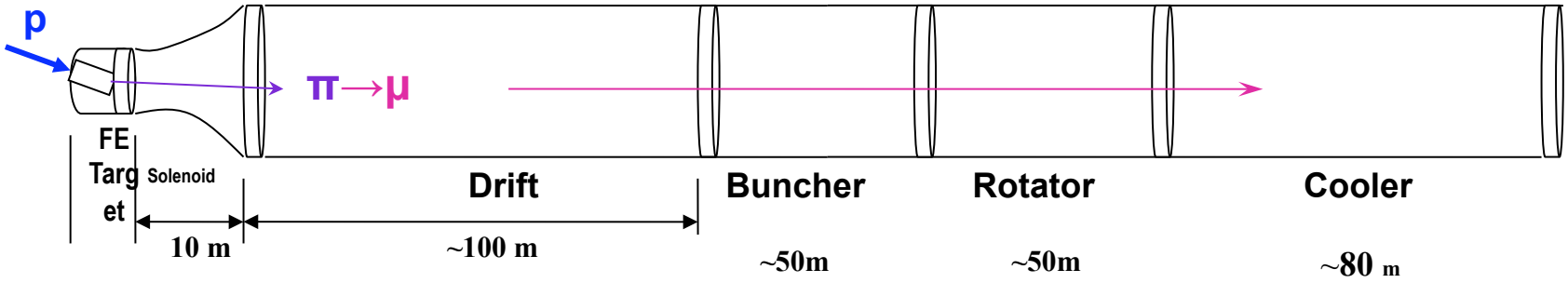


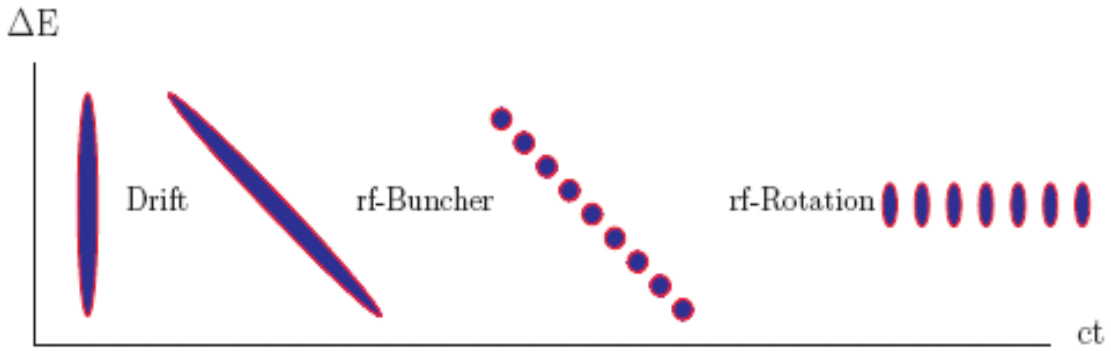
High-frequency Buncher and φ-E Rotator

- Drift (π→μ)
- "Adiabatically" bunch beam first (weak 320 to 240 MHz rf)
- Φ-E rotate bunches – align bunches to ~equal energies
  - 240to 202 MHz, 12MV/m
- Cool beam 201.25MHz





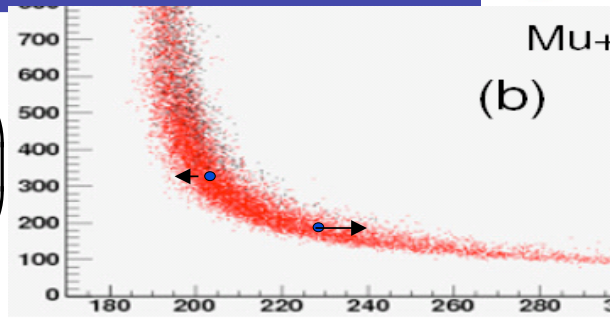




N_B= 10 example

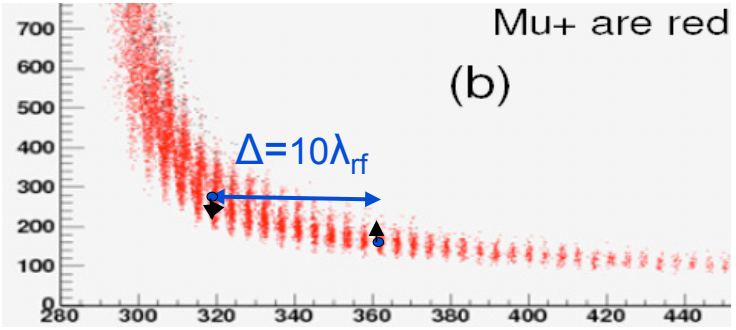
- **Drift from target ~60m**
  - Beam lengthens

$$\delta(ct_i) = L\left(\frac{1}{\beta_i} - \frac{1}{\beta_0}\right)$$

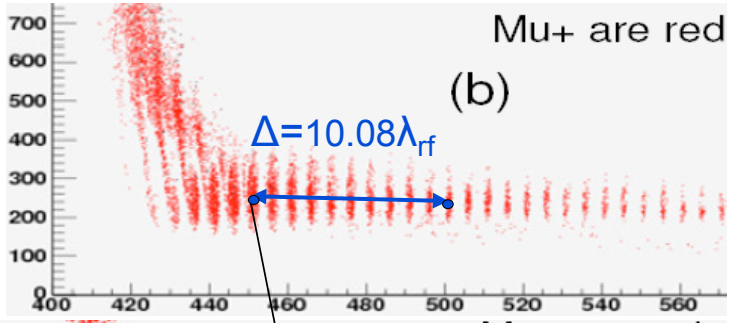


- **Buncher (~30m)**
  - N=10
  - P_0=280MeV/c, P_N=154MeV/c
  - 330 → 235 MHz
  - V'= 0→10 MV/m

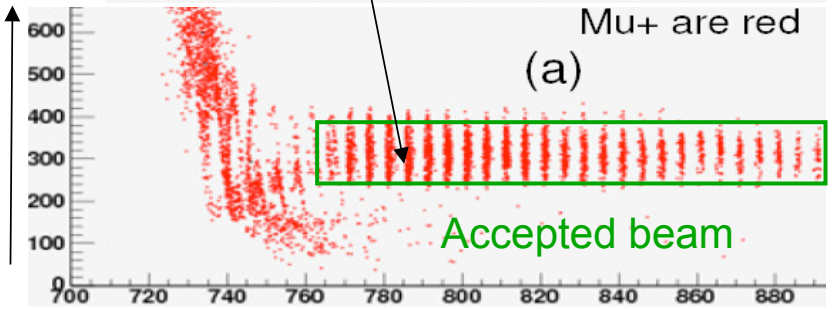
$$\lambda_{rf}(L) = \frac{\delta ct_{0N}}{N} = \frac{L}{N}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$$



- **Rotator (~35m)**
  - N=10.08 – continue to bunch
    - accelerate/decelerate bunches
  - 235 → 202 MHz,V'= 10 MV/m



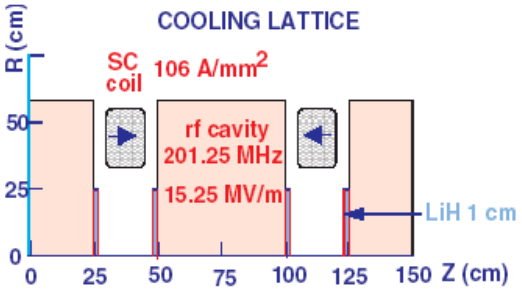
- **Cooler (~80m)**
  - 201.25 MHz, ASOL lattice
  - 15MV/m in rf cavities
  - LiH or H_2 cooling



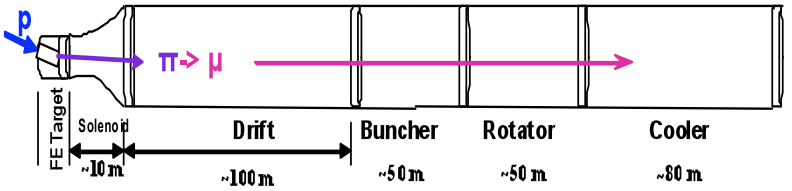
- **Captures both μ^+ and μ^-**

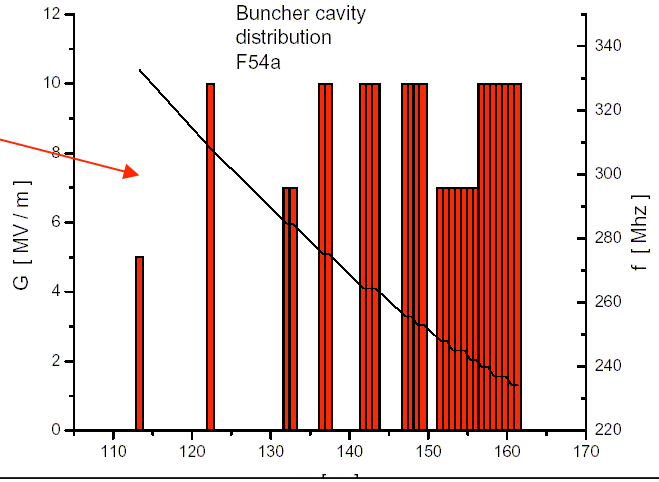
Details of ISS implementation

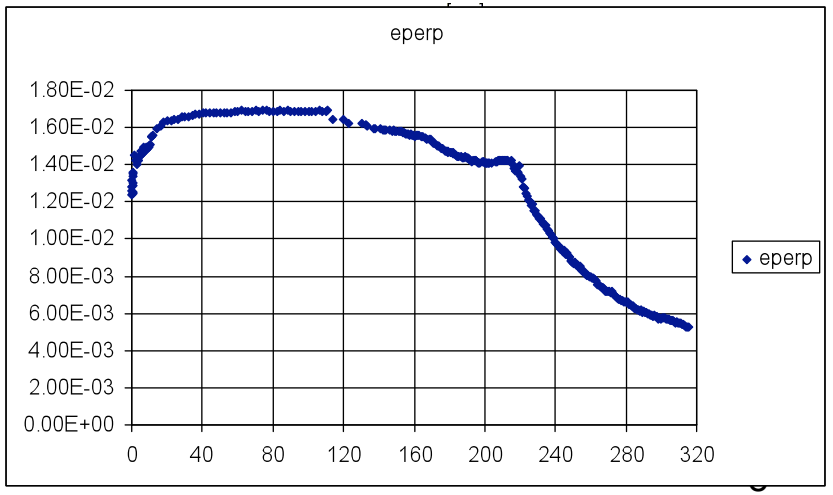
- **Drift –110.7m**
- **Bunch –51m**
  - P_0=280 , P_{18}=154MeV/c δN_V = 18
  - 12 rf freq. (5 to 10 MV/m)
  - 330 MHz → 230MHz
- **ϕ-E Rotate – 54m**
- 15 rf freq. 230→ 202 MHz
  - δN_V = 18.032
  - 12MV/m
- **Match and cool (80m)**
  - $\varepsilon_{x,y}$: 0.018→0.006m



- **Captures both** μ⁺ and μ⁻
  - ~0.1 μ/(10 GeV p)

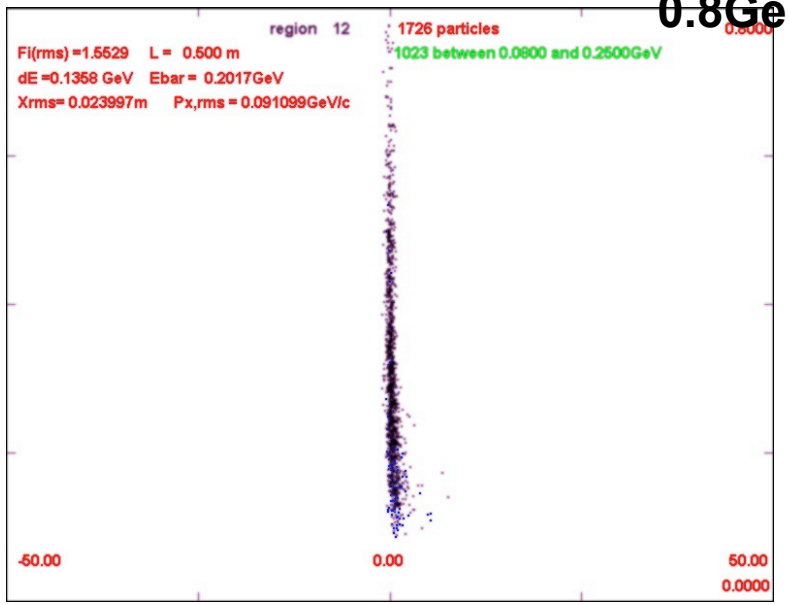






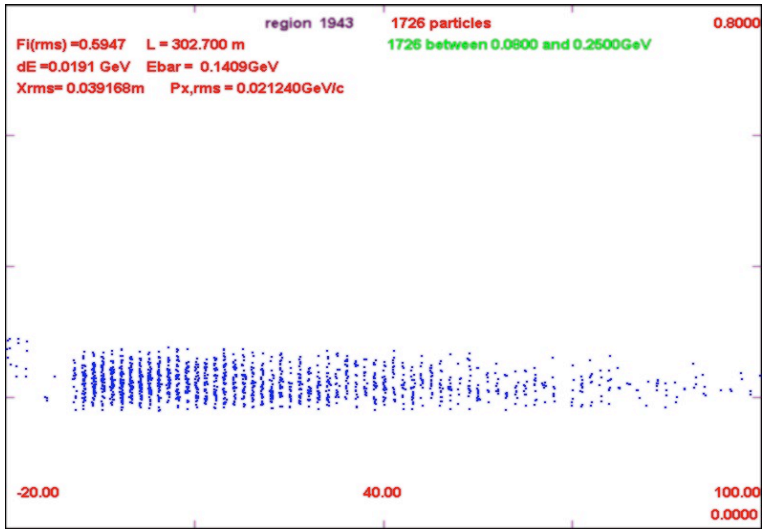
ISS Study Beam acceptance

- **Method captures large initial longitudinal phase space**
  - with relatively small dilution
- **Initial Beam**
  - $P_{\pi\rightarrow\mu}$ 75 to ~600 MeV/c,
    - ΔP=±250MeV/c
  - σ_{bunch} = ~1m rms
- **Captured beam**
  - 50+ bunches (~80m long)
- **Accepted bunches are**
  - ΔP = ±20MeV/c
  - σ_{bunch} = ~0.3m
- 0.2 μ^+/24GeV p
  both μ^+ and μ^-



0.8GeV/c

0



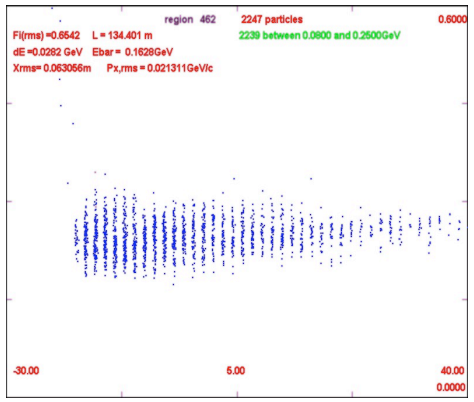
0m

100m

Shorter Bunch train example N=10

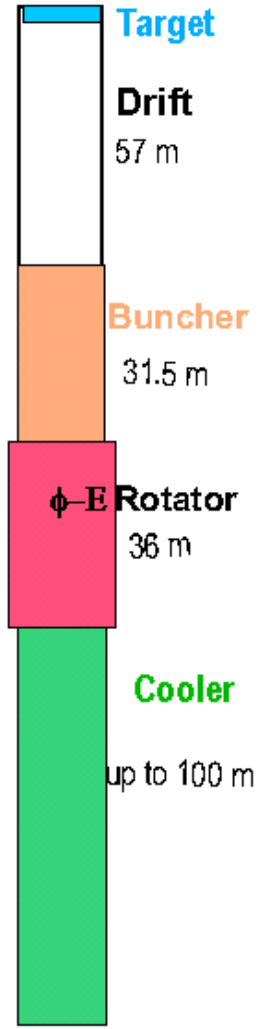
- **Reduce drift, buncher, rotator to get shorter bunch train:**
  - 217m ⇒ 125m
  - 57m drift, 31m buncher, 36m rotator
  - Rf voltages up to 15MV/m (×2/3)

- Obtains ~0.08 μ/p_{8GeV} in ref. acceptance
  - similar to ISS baseline
- 80+ m bunchtrain reduced to < 50m
  - ΔN: 18 -> 10

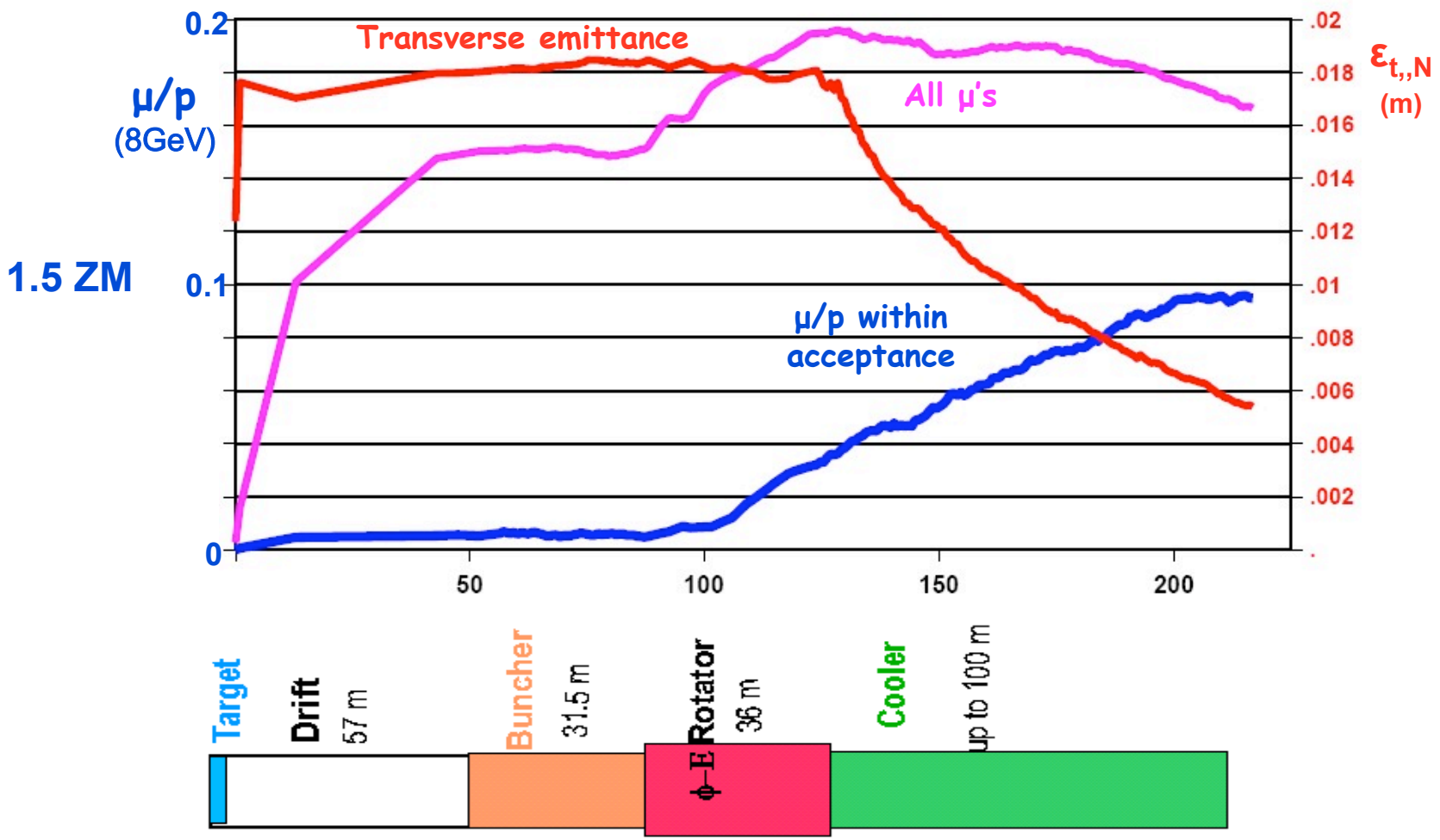


600MeV/c

-30 40m



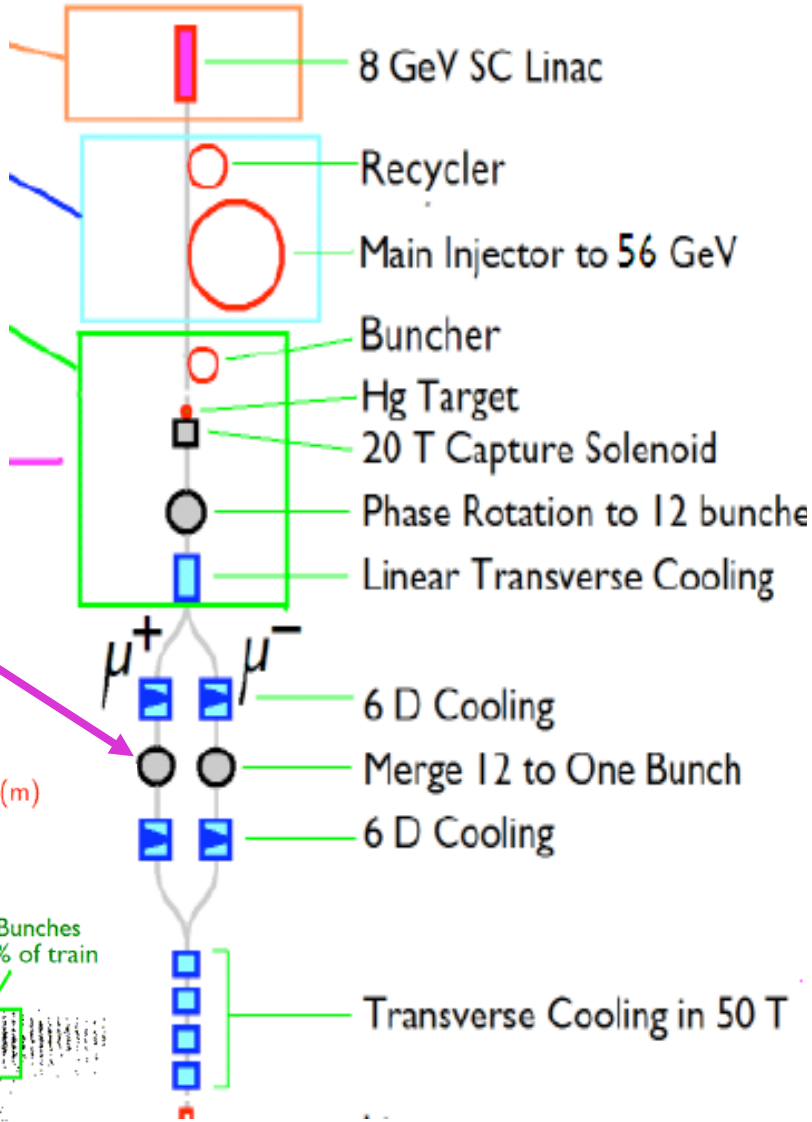
Simulation Results: N_B = 10, H_2 cooling

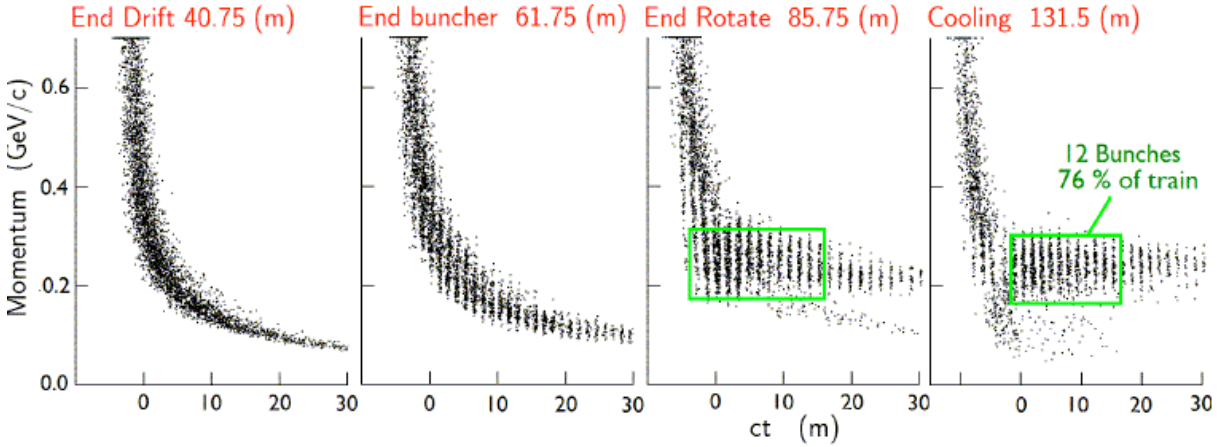


Adapt to Collider (2009 scenario)

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

R. Palmer, TU1GRI03



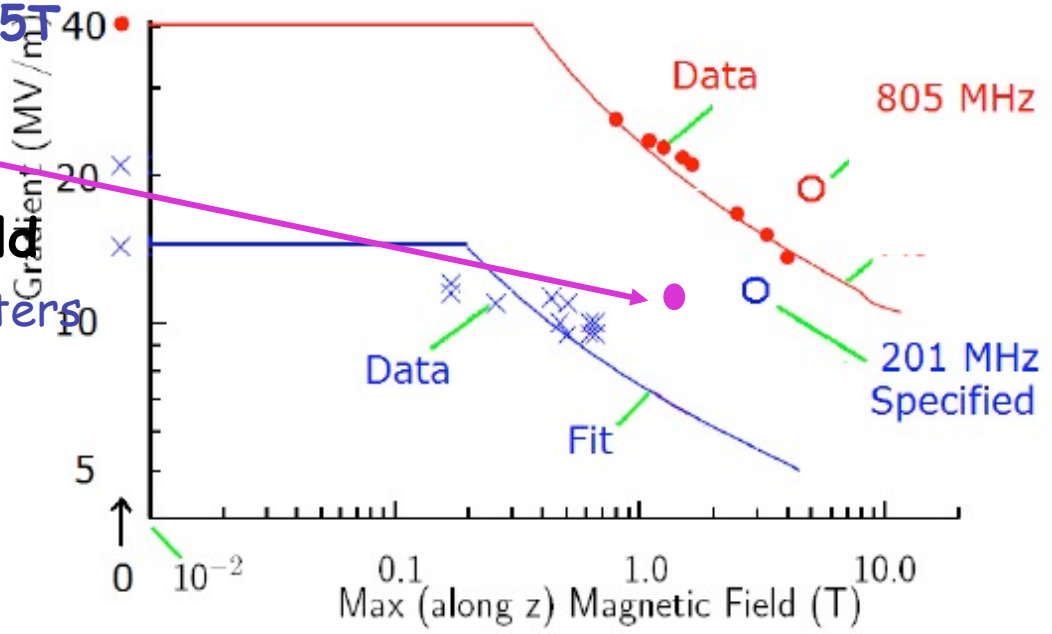


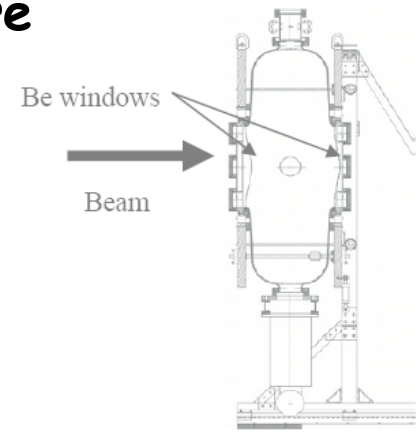
Rf in magnetic fields?

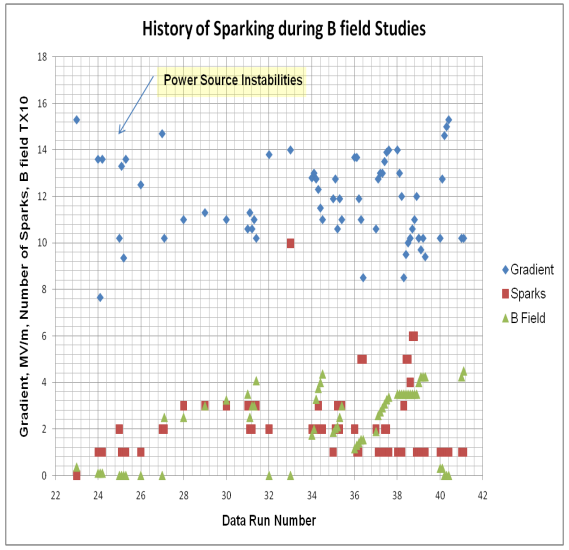
- **Baseline:** V'= 12MV/m in B=1.75T

- **Experiments show reduced gradients within magnetic field**
  - not quite at front end parameters
  - first test cavity
- **May require changes in our parameters …**
  - $V'_{max} \propto (f_{rf})^{1/2}$???

- **Future experiments will explore these limits**
  - D. Huang et al - TU5PFP032

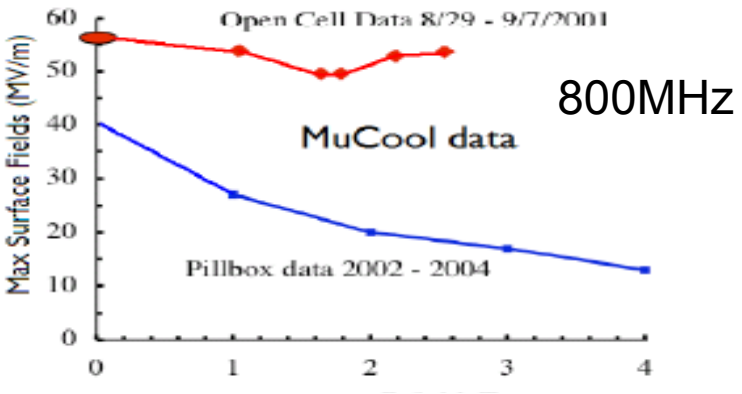


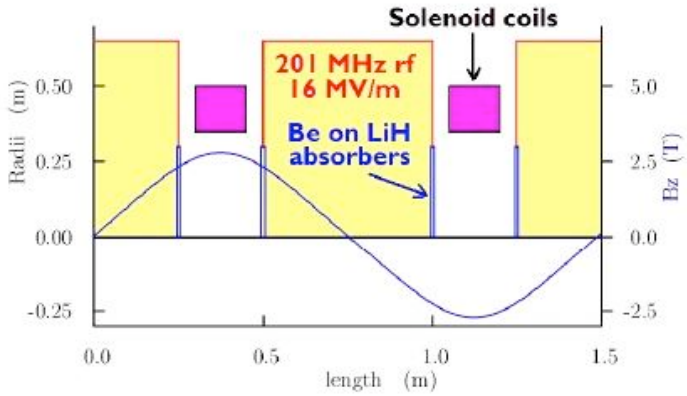


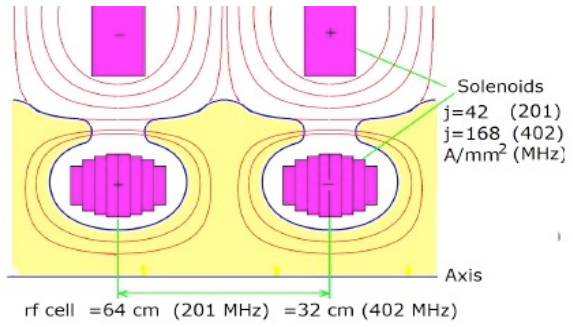


Front end rf options

- **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

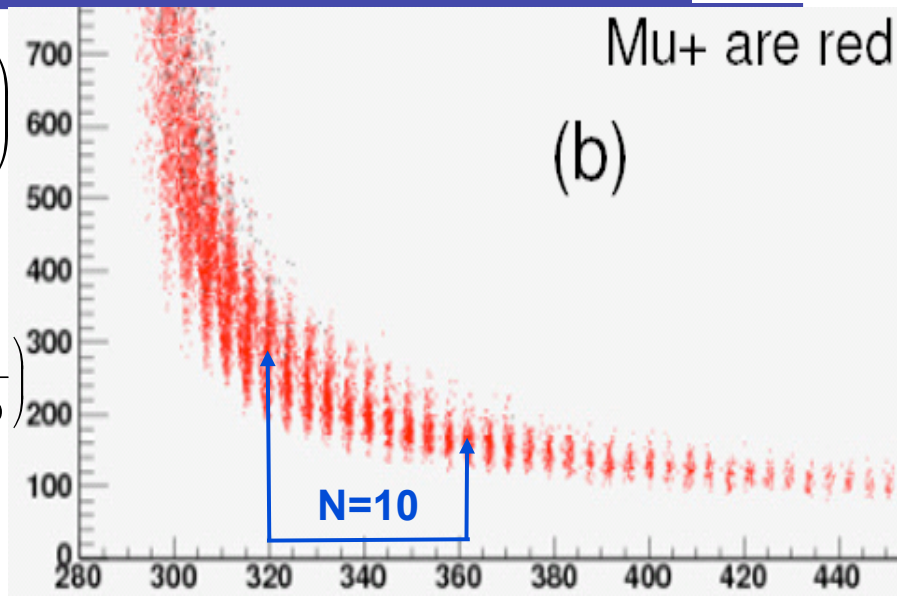
- **High frequency (bunch, phase rotate, cooler) is well suited to neutrino factory scenarios**
  - Study 2B/IDS designs
  - Produces trains of μ^+ and μ^- bunches for acceleration and storage (~ 80m trains)
  - Latest versions provide shorter trains (30 to 50m)
- **Can use high-frequency capture to obtain bunch train for ν-Factory → μ^+-μ^- collider**
  - (~10 to 14 bunches long at 200MHz)
  - Recombine after cooling for collider mode
- **Questions**
  - **~12 MV/m** at **B ≅ 2T** and **f ≅ 200MHz** OK?
  - Is ~12 bunches OK for Collider scenario?

Supplemental Slides

Need to develop best design for IDS

Adiabatic Buncher; φ-E rotation

- **Beam first drifts**
  - -beam lengthens $\delta(ct_i) = L\left(\frac{1}{\beta_i} - \frac{1}{\beta_0}\right)$
- **Buncher:** Set rf phase to be zero **for reference particles**
  - Spacing is N λ_{rf} $\lambda_{rf}(L) = \frac{\delta ct_{0N}}{N} = \frac{L}{N}\left(\frac{1}{\beta_N} - \frac{1}{\beta_0}\right)$
  - $\Rightarrow \lambda_{rf}$ 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** μ^+ and μ^-