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Progress of Front End Design and FOFO Snake

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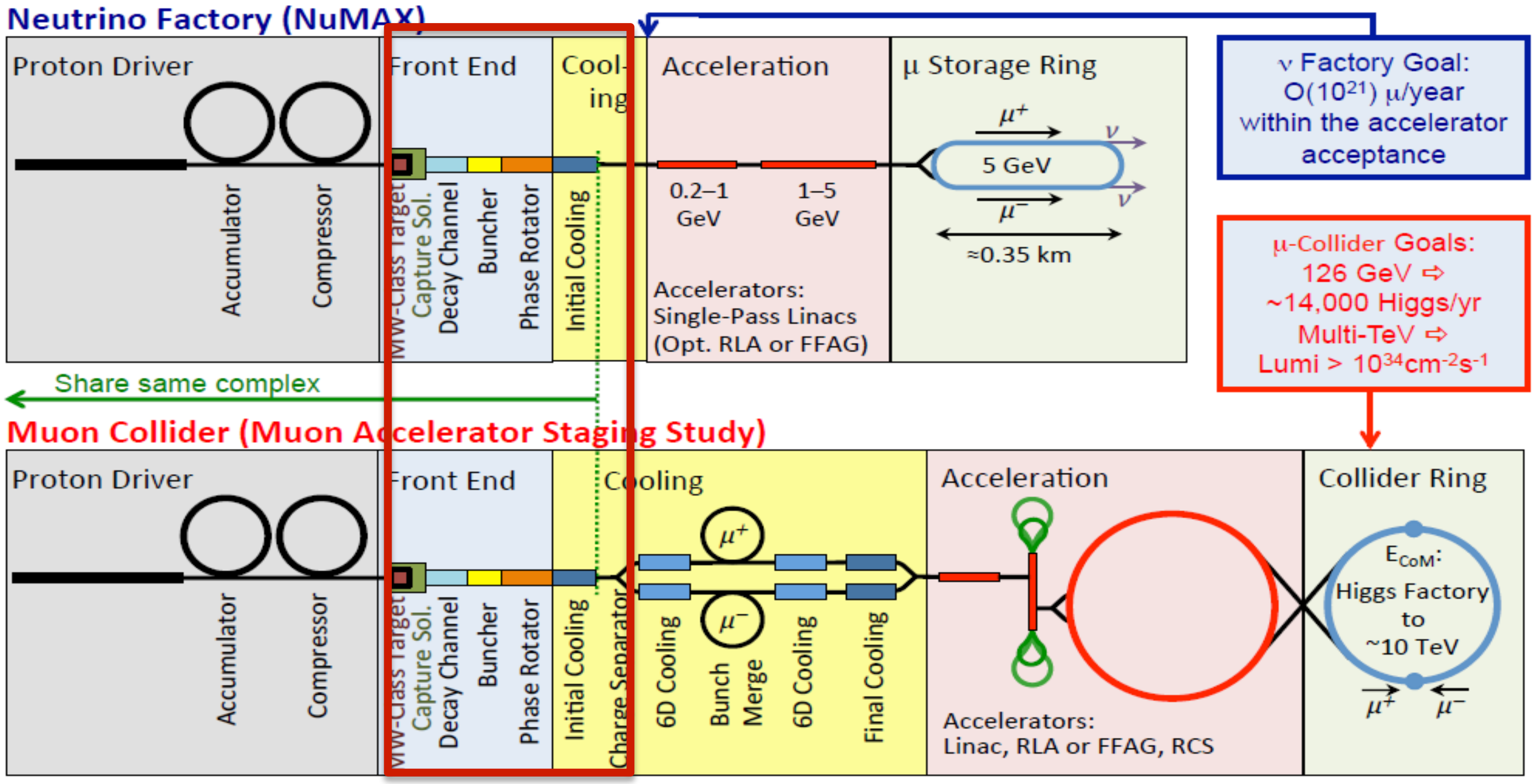
Outline

- **Front end design**
  - Baseline configuration
  - Buncher Phase Rotator
  - Cooler options
- **HFOFO “Snake” properties**
  - Design Concepts
  - Example (IBS)
  - Simulation
- **Variations**
  - cold muon source

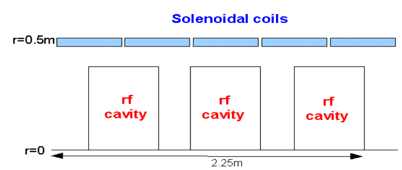
Front End and Initial Cooling

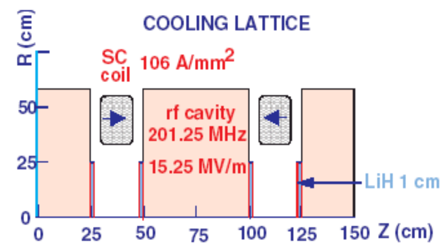


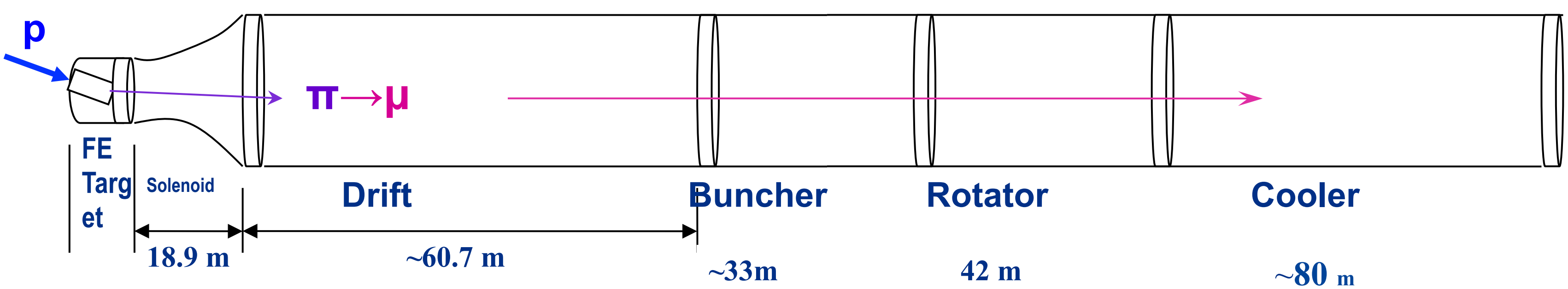
- **From target to end of initial cooling**
  - capture and bunch π→μ; initial cooling for downstream
  - captures & cools both signs (μ^+ and μ^-)
- **Same system can be used for both ν factory and μ^+-μ^- collider**

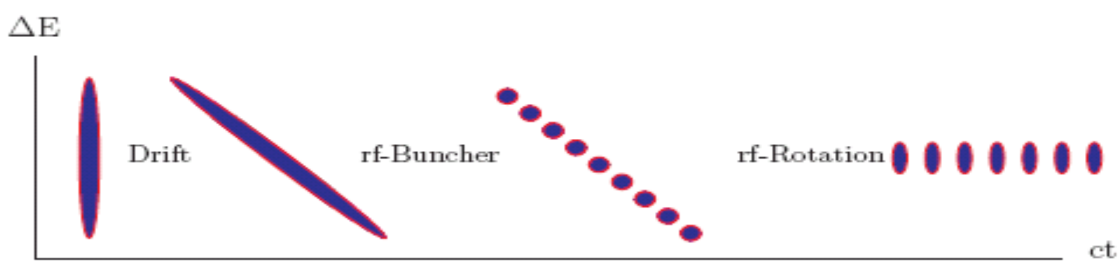
IDS Neutrino Factory Buncher and ϕ-E Rotator

- **Drift ($\pi \rightarrow \mu$)**
- **"Adiabatically" bunch beam first (weak 320 to 232 MHz rf)**
- **Φ-E rotate bunches – align bunches to ~equal energies**
  - 232 to 202 MHz, 12MV/m
- **Cool beam 201.25MHz**
- **Captures and Cools both μ^+ and μ^-**









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Buncher/Rotator Example

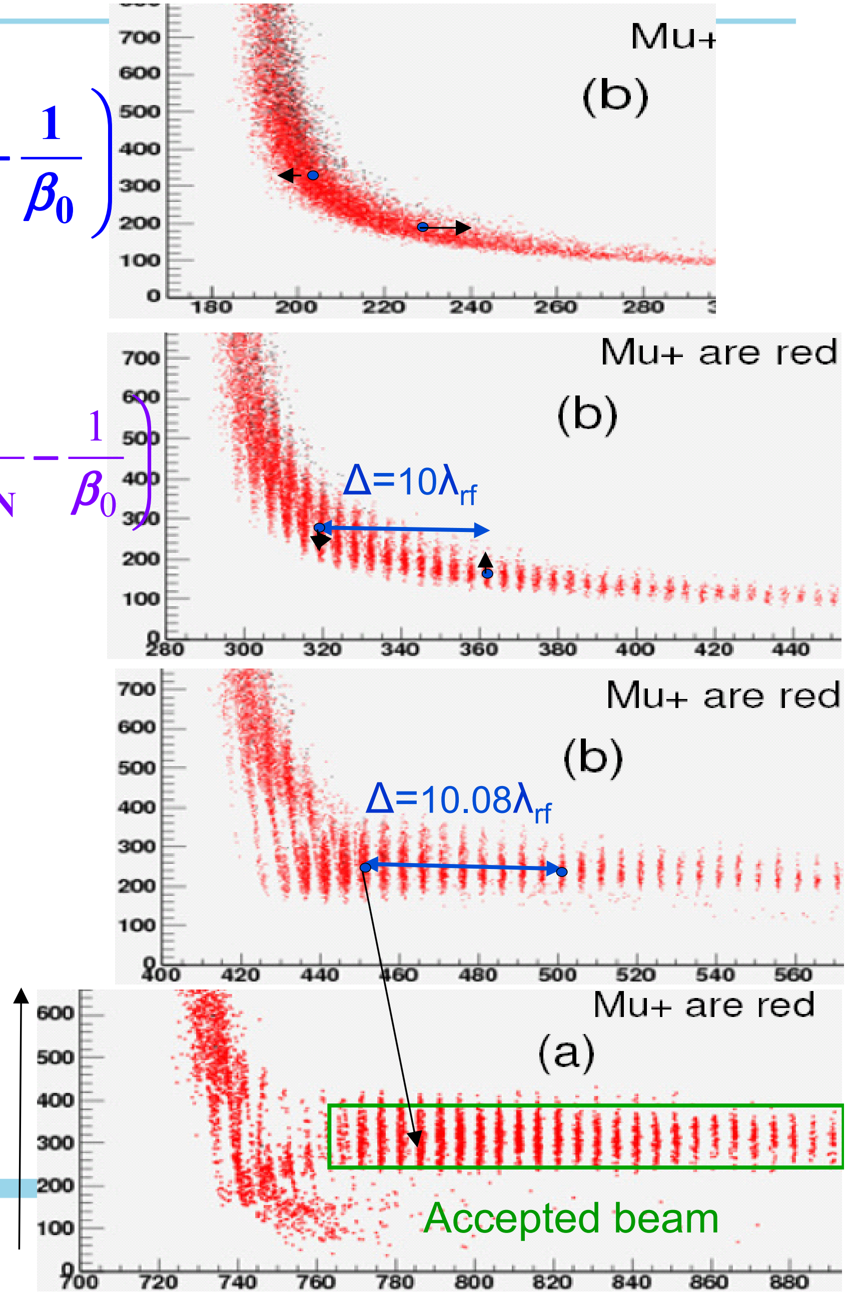
- **Drift** from target ~60m
  - π→μ
  - Beam lengthens

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

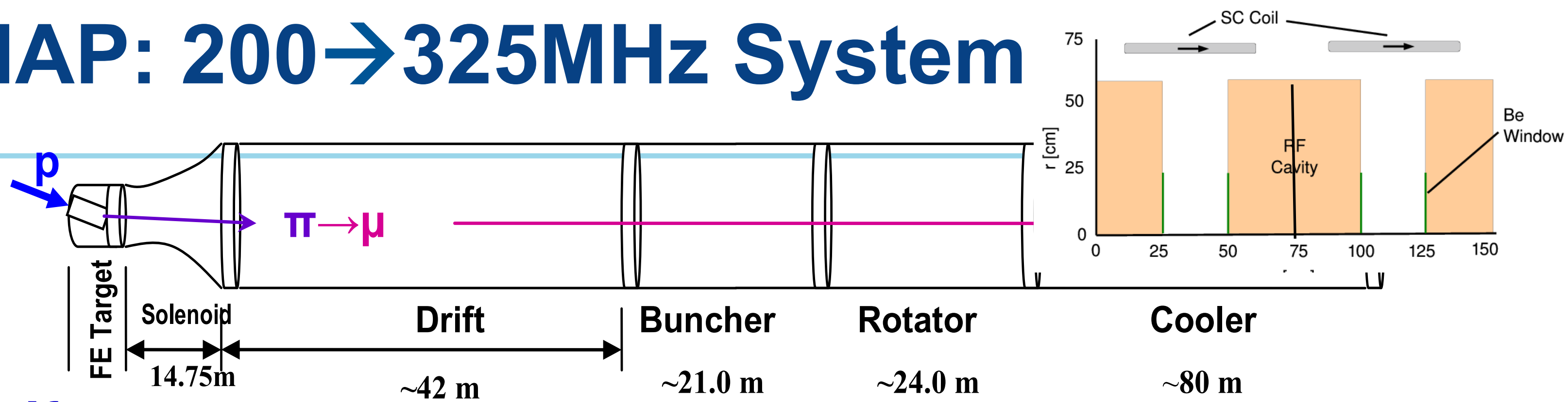
- **Buncher** (~30m)
  - **N=10, P_0=280MeV/c, P_N=154MeV/c**
  - **330 → 235 MHz**
  - **V'= 0 → 10 MV/m**

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

- **Rotator** (~35m)
  - **N=10.08 – accelerate/decelerate bunches**
  - **235 → 202 MHz,V'= 12 MV/m**
- **Cooler** (~80m)
  - **201.25 MHz, ASOL lattice**
  - **15MV/m in rf cavities**
  - **LiH or H_2 cooling**
- **Captures both μ^+ and μ^-**



MAP: 200→325MHz System



- **Drift**
  - 20T→ 2T
- **Buncher**
  - P_o=250MeV/c, P_N=154 MeV/c; N=12
  - V_{rf} : 0→ 15 MV/m
  - f_{RF} : 490→ 365MHz
- **Rotator**
  - **V_{rf} : 20MV/m**
  - f_{RF} : 364→ 326MHz
  - N=12.045
- **Cooler**
  - 245 MeV/c, 325 MHz, 25 MV/m
  - LiH absorbers

325 MHz – much more affordable than 200MHz

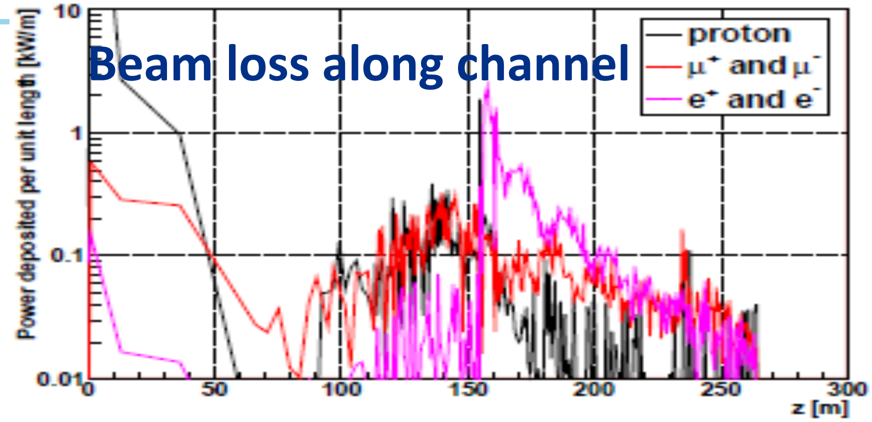
more compact, ~1/2 rf power

matches present/future power sources/ frequencies-ILC, PIPII

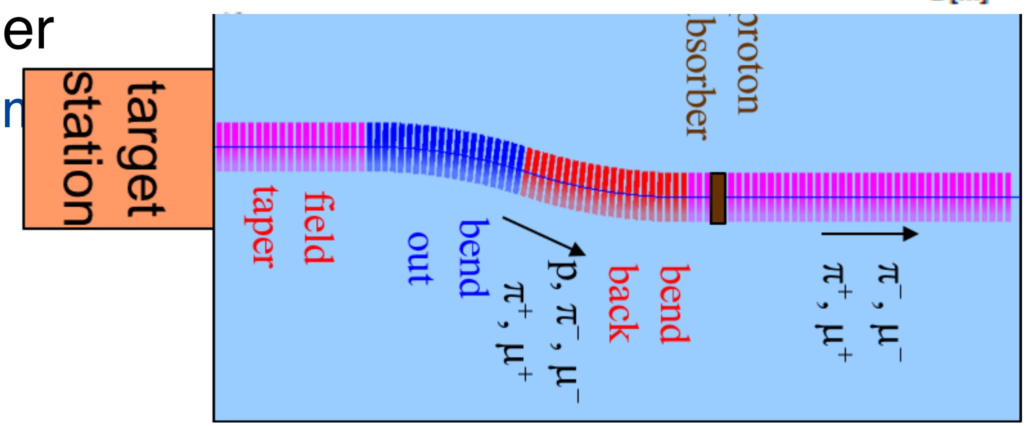
but more bunches in bunch train for collider (~12→~21)

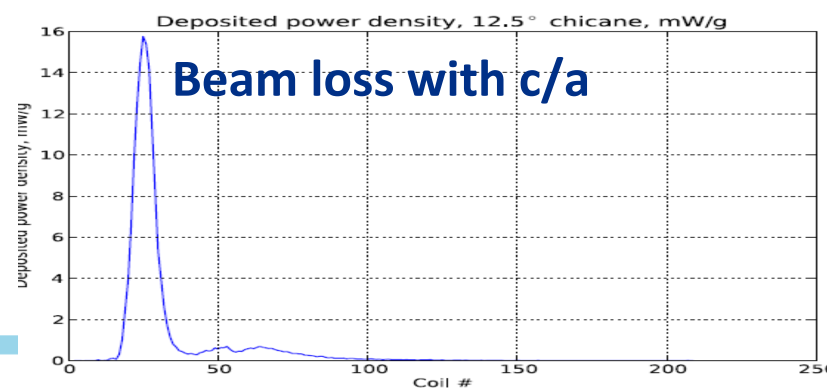
Problem: Beam Losses & Activation

- Beam Loss and Activation
  - 4MW p beam
  - 100 kW secondaries ..
    - ~**kW/m** losses in line



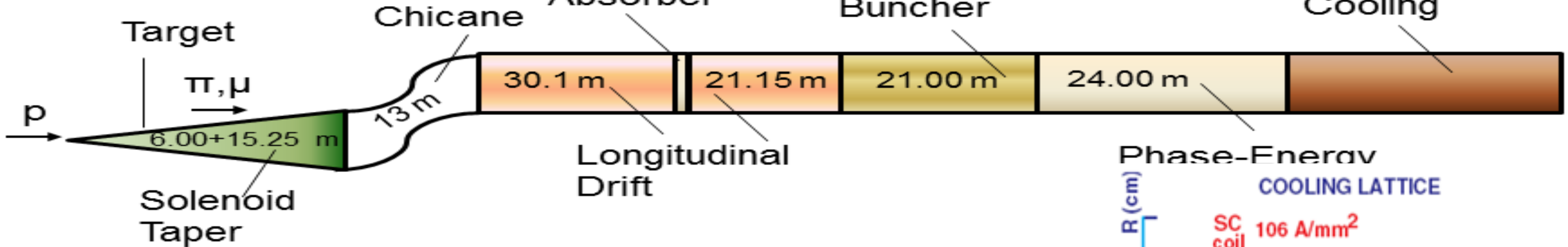
- Solution: Chicane and Absorber
  - Chicane: bend out ~15[illegible] 6.5m
  - bend back ~15[illegible] 6.5m
    - separates high-E particles
  - Absorber
  - ~10 cm Be
    - stops p, [illegible], K low-E [illegible]
- Localizes beam-related losses to before buncher/rf

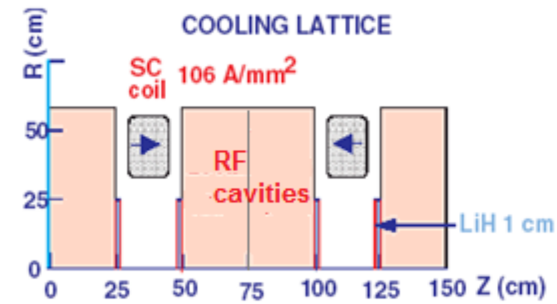




325 “Collider “ w Chicane/ Absorber

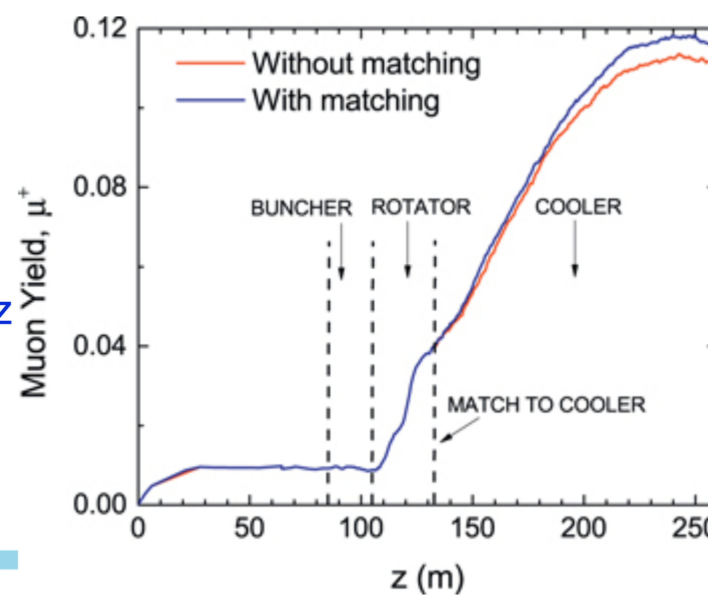
Chicane + Absorber



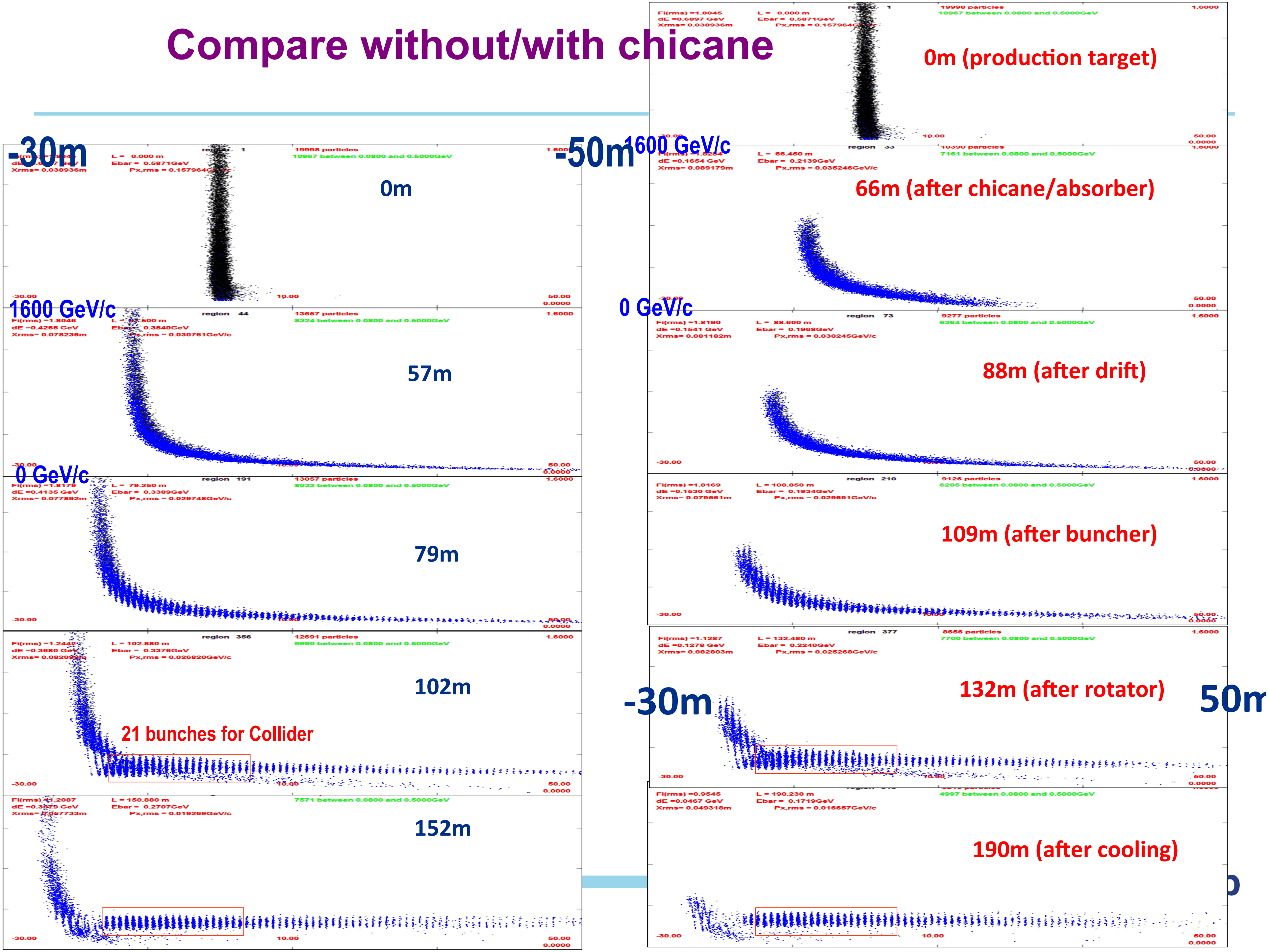


- **Add chicane**
  - 6.5m → +15°,6.5m -15°
- **Add 30 m drift after chicane to absorber**

  6.5m → +15°,6.5m -15°
- **Rematch**
  - particle 1-283 MeV/c→250
  - particle 2-194 MeV/c→154
  - Bunch (N=12) 0→15 MV/m :496→ 365 MHz
  - Rotate (N=12.045)– 20MV/m : 365 → 326.5 MHz
  - Cool -325MHz -25 MV/m
- **Obtain ~0.1 ⊠$^+$ and ⊠$^-$/p**

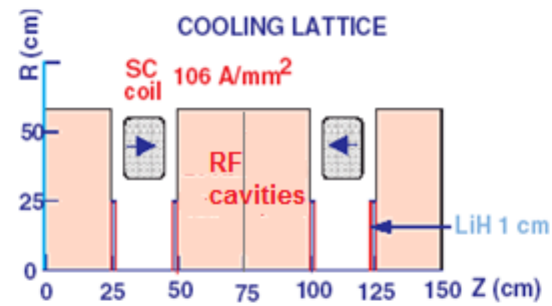


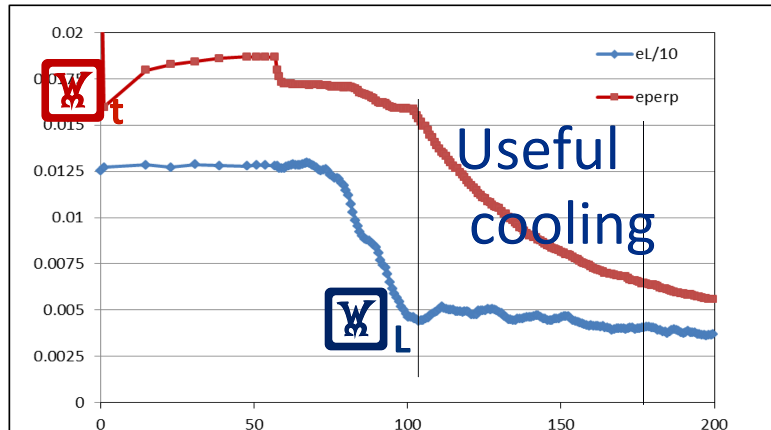
Compare without/with chicane

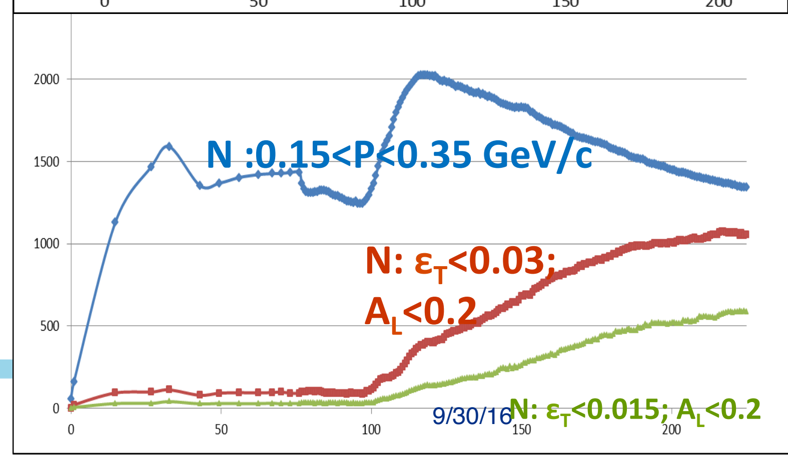


Cooling Section – "2-D" cooling only

- Baseline Initial cooling system
  - from IDS Neutrino Factory cooling
  - Consists of rf & LiH absorbers & Alternating Solenoid focusing
- Cools transverse emittance
  - ~ε_t : 0.016→0.0065 m
  - ε_L: 0.04→~0.03 m
    - no longitudinal cooling (scraping)
- ~0.1μ / 8GeV p within acceptance
    - most beam outside acceptance scraped away







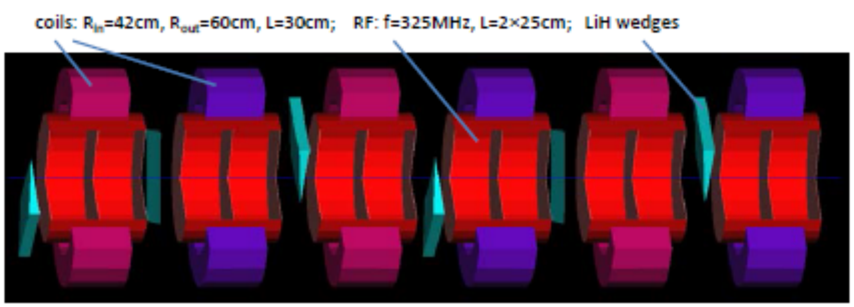
Vacuum rf or Gas-filled rf?

- Initial design was for vacuum rf within B = ~2T solenoids
  - rf gradient limited within magnetic fields (?)
    - gas-filled rf does not breakdown
      - (but has plasma loading effect)

- **Front end can have gas-filled rf**
  - **same performance as with vacuum rf**
    - **need a bit higher gradient to compensate energy loss in gas**
  - **With higher density gas and higher gradient**
    - **can have some cooling in buncher/rotator**
      - **better performance**
- **Would like to increase B $\rightarrow$3T**

“FOFO Snake” initial cooling [Y. Alexahin et al.]

- Motivation
  - Obtain front end 6-D cooling
  - equal cooling in x and y
    - cyclotron and drift modes
  - For both μ^+ and μ^-
    - Dispersion+wedge would only cool one sign …
      - (we thought …)



- Principles
  - Alternating solenoid cooling
  - resonance dispersion
    - tilts in solenoids

$$D_x = \frac{d\,x_{co}}{d\delta_p} \approx -\pi\, Q_x'\, x_{co} \cot(\pi Q_x)$$

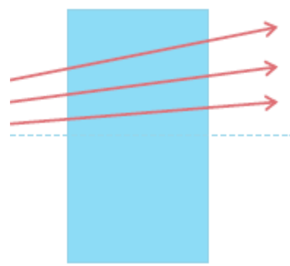
  - Longitudinal cooling from path length (E_μ)

Basic Principles of “FOFO Snake”

- **Alternating Solenoid field**
  - **Equal cooling of transverse modes**
    - **cyclotron/drift modes exchange at each flip**
- **Resonance Dispersion generation**
  - **solenoid tilts generate helical orbit/dispersion**
    - **x_{co} ~ 1/sin (πQ_x) ;**

$$D_x = \frac{d\,x_{co}}{d\delta_p} \approx -\pi\, Q_x'\ x_{co} \cot(\pi Q_x)$$

    - **larger compaction factor if tune ~ N+δ**
- **Longitudinal cooling in flat absorbers due to D'**
    - **path length (δ_p)**

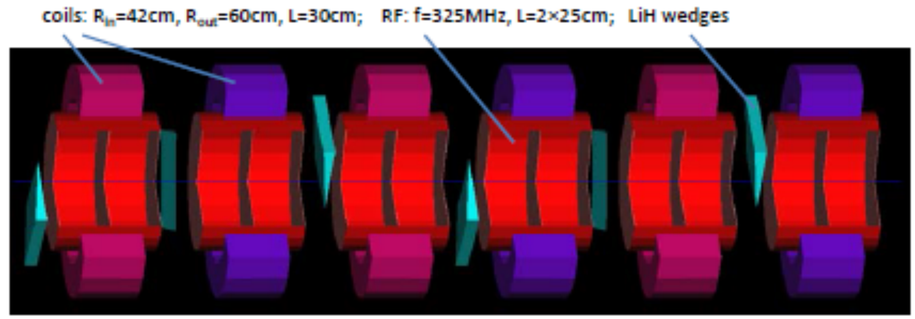


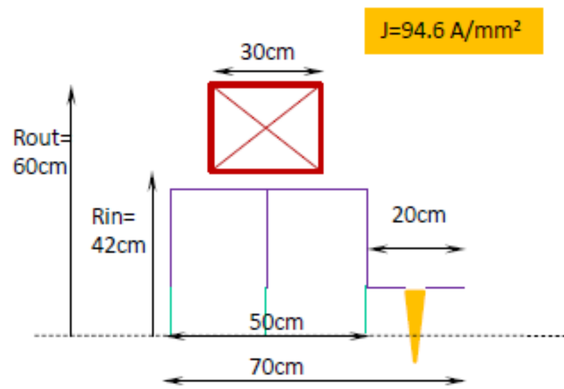
$$x = x_{co} + D_x \delta_p$$

    - **initially without wedge absorbers**

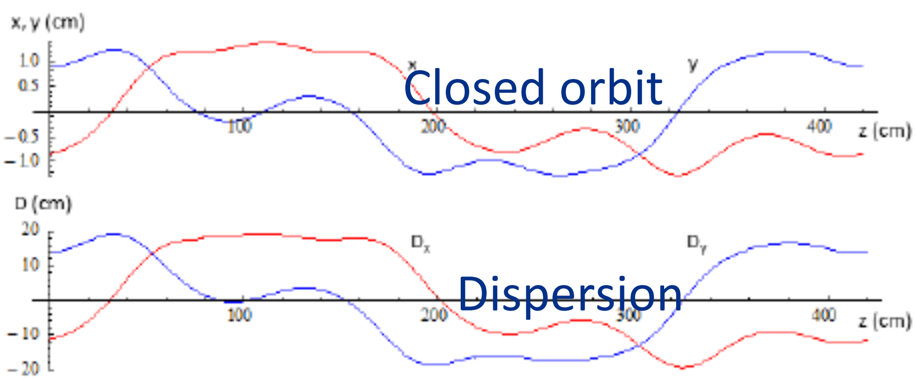
Baseline 325 Mhz cooler example

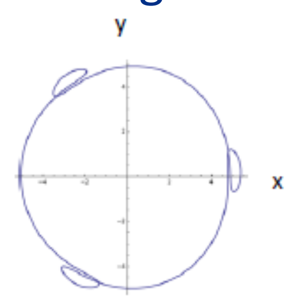
- 6 cell period
  - 4.2m, B_{max}=3.7T
    - β_t ~0.6m
  - 325MHz rf, 25 MV/m
  - 2.5 mrad Tilts
- Gas filled (1/5 Liquid H_2 density)
    - (slabs could also be used)
  - with LiH wedges





Single Cell





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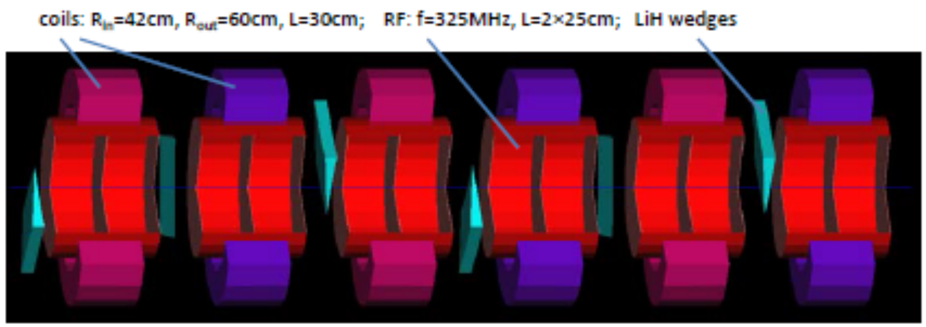
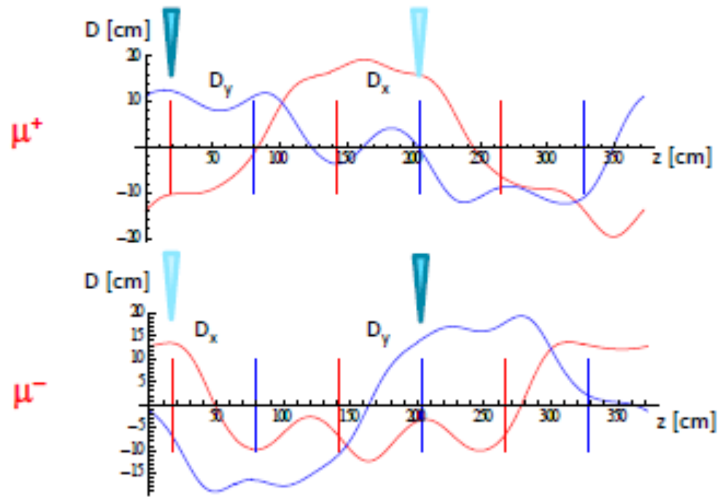
FODO snake properties

- 2.5 mrad tilts oriented at
- $\phi_k = \frac{4\pi}{3}, 0, \frac{2\pi}{3}, \frac{4\pi}{3}, 0, \frac{2\pi}{3}$ from vertical
- Wedges follow similar rotatior
  - Are placed to **cool both signs**: μ^+ and μ^-
- Eigen values, equilibrium ε

Mode	I	II	III
Tune	1.2271 + 0.0100 i	1.2375 + 0.0036 i	0.1886 + 0.0049 i
Emittance (mm)	2.28	6.13	1.93

  - not balanced in x, y – (add quad)
- Total cooling channel is **~30 cells (126 m)**





Dispersion and two vertical wedge absorbers: the left works for μ⁺ while the right works for μ⁻

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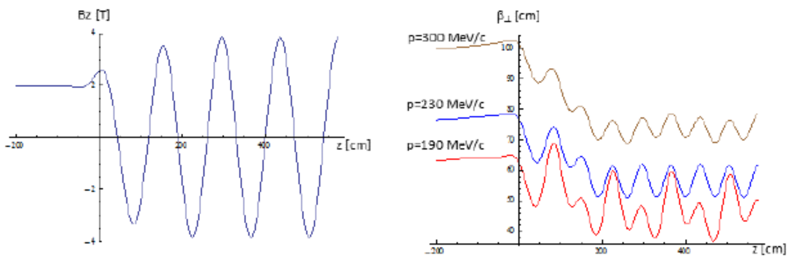
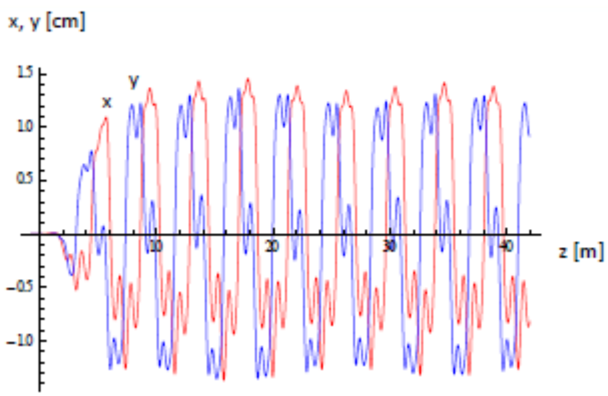
Matching from upstream Rotator

- Transverse Optics match
  - constant solenoid to ASOL

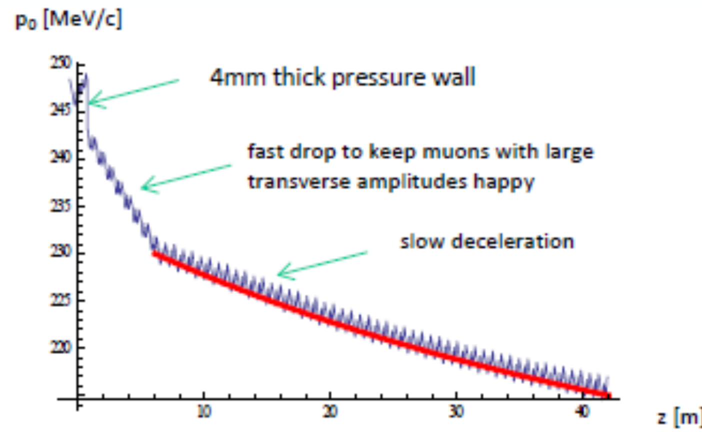


Magnetic field in the transition area (left) and β-function for constant momentum (right)

- Helical Orbit match
  - tilts of solenoids 3-9

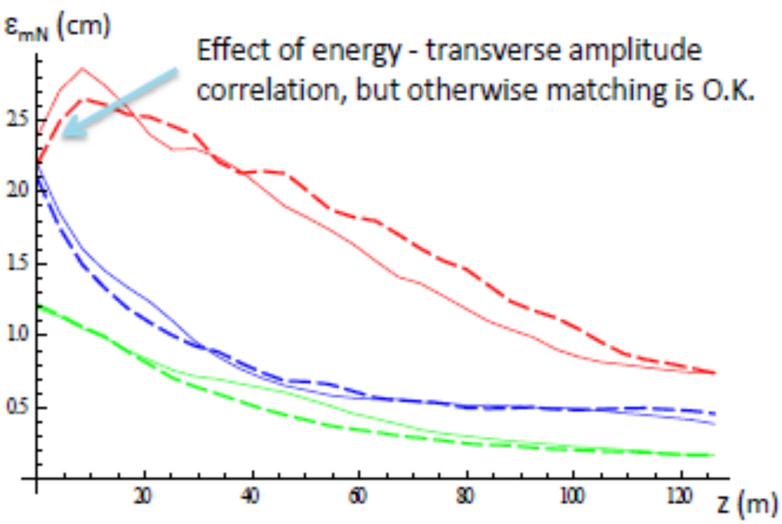


- Longitudinal momentum match
  - gradual deceleration

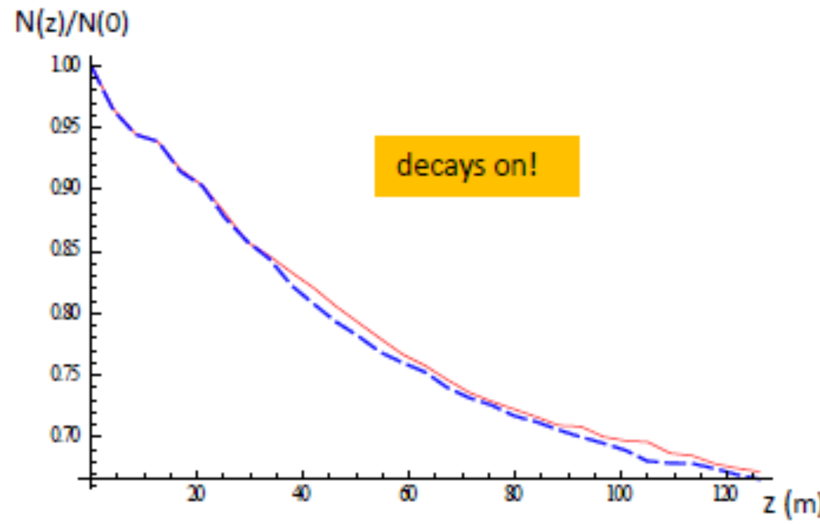


  - phases readjusted to compensate for amplitude/momentum correlation

Cooling & Transmission (G4BL)



Normalized emittances (cm) from Gaussian fit:
μ^+ - solid lines, μ^- - dashed lines.



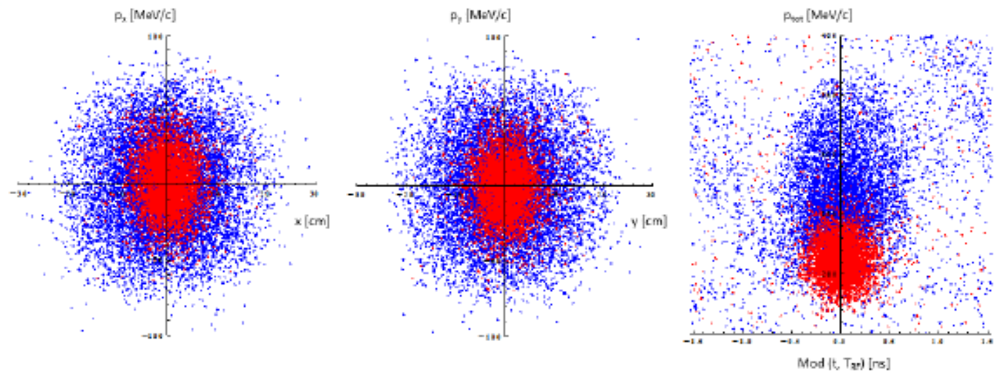
Transmission as a ratio of the number of muons in the Gaussian core: red solid line - μ^+, blue dashed line - μ^-.

Final/Initial values (Gaussian fit):

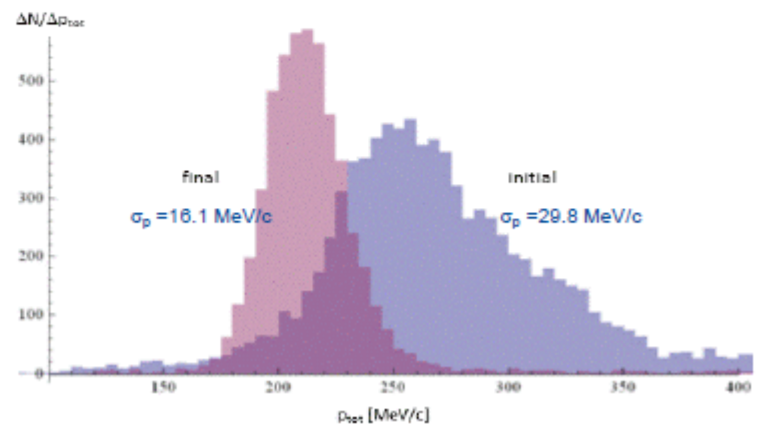
	$N^{(total)}$	$N^{(150<p<360)}$	$N^{(core)}$	$p^{(cnt)}$, MeV/c	ε_{mN}, cm			ε_{6D}, cm^3
μ^+	5378/11755	5167/7998	5010/7329	208.2/248.0	0.19/1.19	0.36/2.19	0.76/2.38	0.051/6.22
μ^-	5896/12396	5743/9020	5499/8248	207.7/248.8	0.16/1.22	0.46/2.10	0.72/2.19	0.051/5.59

Results and discussion

- **Beam phase space**
  - before (blue)
  - after (red)



- **Longitudinal distributions**
  - momentum spread reduced by factor of ~2



Comparison to 2-D cooling

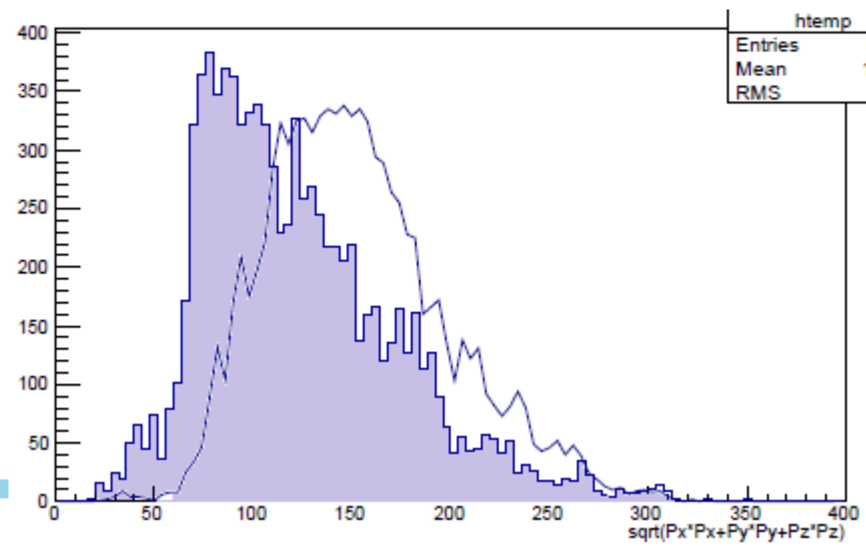
- Cools in 3-D
  - ε_1: 2.2→0.4 cm ;ε_2: 1.2→0.2 cm; **ε_L: 2.4→0.7 cm**
  - ε_t: 1.7 → 0.6 (2D)
- More Cooling (than 2-D baseline)
  - but longer channel & stronger focusing
    - up to 120m; B_{max} 2.8→ 3.7 T
- Initial Acceptance a bit less than 2-D cooling channel
  - ~10%
- Better match to downstream systems
  - from longitudinal cooling …

Front End with Helical FOFO cooler preferred

- **Smaller momentum spread bunches will fit into downstream components more easily**
  - **Acceleration transition 325→650 MHz can occur earlier**
    - **at ~1 GeV/c for nu-Factory → "NuMAX" scenario**
  - **Cooling transition 325→650 for collider sooner …**
  - **losses reduced; separation of μ^+ and μ^- easier …**
- **Deceleration to a lower energy muon beam (mu2e?) easier, with fewer losses**

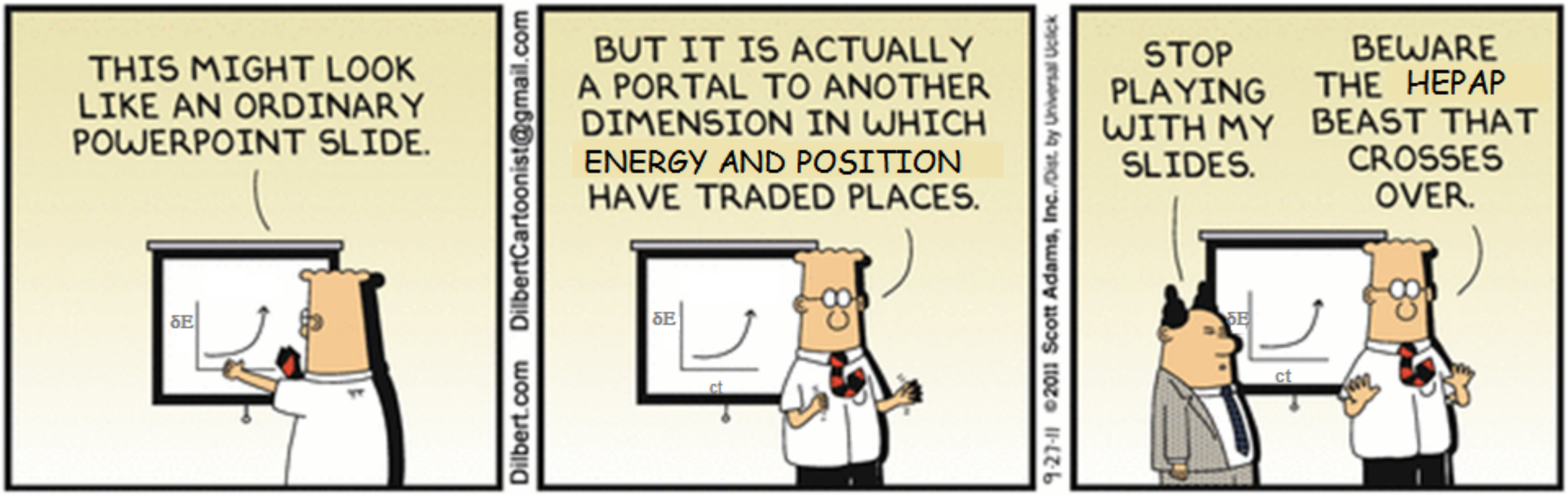
To Do

- **Write-up current status for JINST volume**
- **Variations / Improvements -- ?**
- **Scale back to low-energy applications**
  - smaller, lower field system capturing at 150 MeV/c
    - 50m →25m
    - → 100 MeV/c
    - ~0.05 μ/p



w. Y. Bao

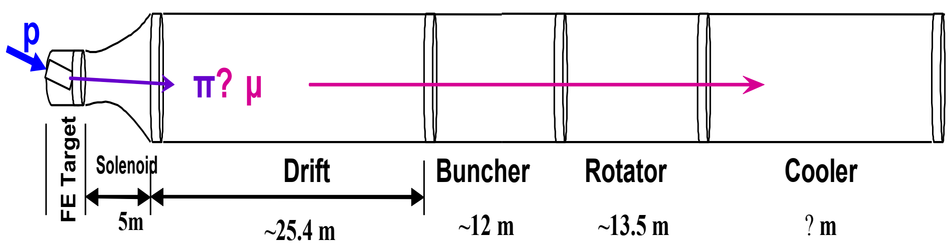
Summary


THIS MIGHT LOOK LIKE AN ORDINARY POWERPOINT SLIDE.
δE
Dilbert.com DilbertCartoonist@gmail.com
BUT IT IS ACTUALLY A PORTAL TO ANOTHER DIMENSION IN WHICH ENERGY AND POSITION HAVE TRADED PLACES.
δE
ct
9-27-11 ©2011 Scott Adams, Inc./Dist. by Universal Uclick
STOP PLAYING WITH MY SLIDES.
BEWARE THE HEPAP BEAST THAT CROSSES OVER.
ct

Backup slides

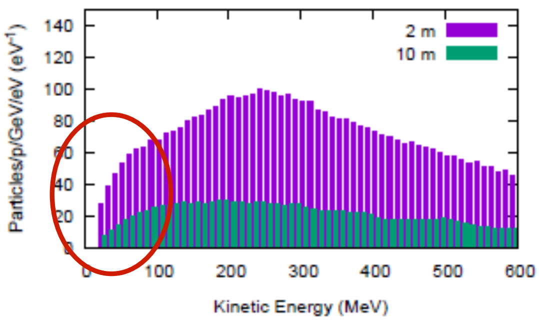
Low-E capture

- Capture at low momentum
  – prepare beam for low-E μ experiment
- Somewhat scaled back version of front end
  – 30.4m drift
  – shorter buncher /rotator
    - 12m / 13.5m
    - 0→15 MV/m, 15 MV/m
      – vacuum rf
  – B=2T

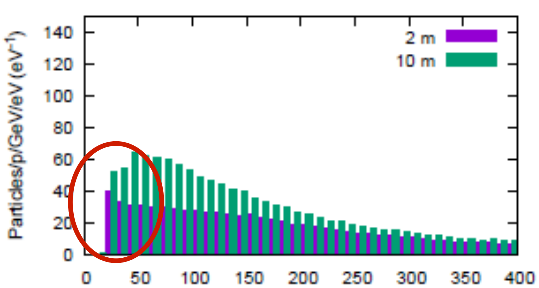


- Parameters
  – 150 MeV/c … 100 MeV/c reference particles
  – 77.8 // 39.8 MeV
- Bunch to 150 MeV/c
- Cooling at 2T (1-D cooling)

π^+



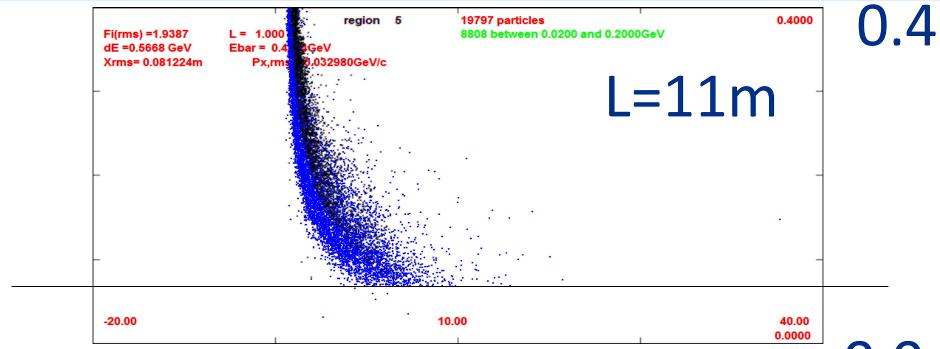
μ^+

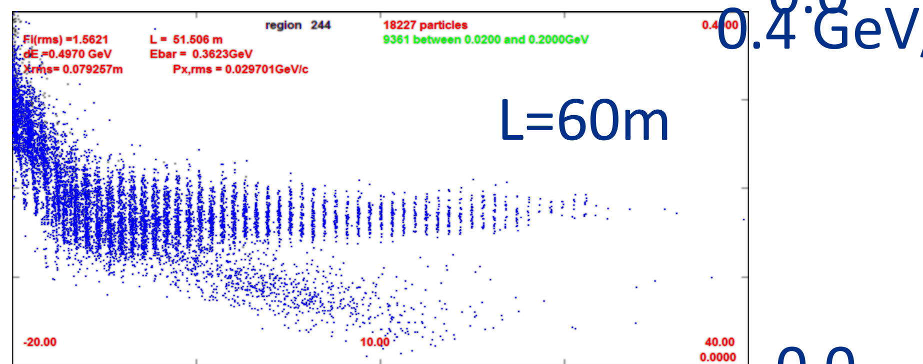


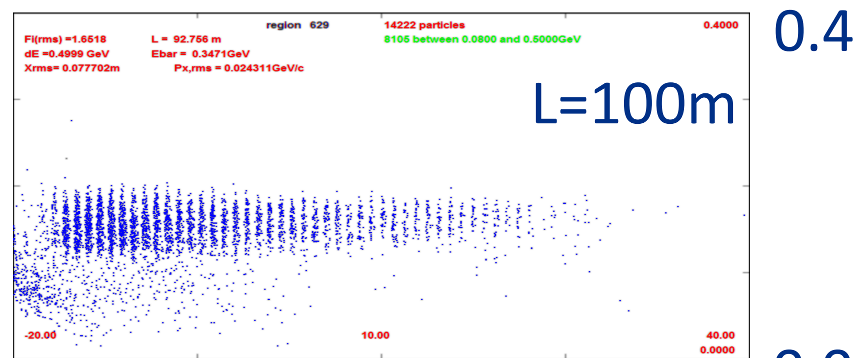
simulation of low-E buncher

- **Used Ding initial beam**
  - initial beam cut off at ~70 MeV/c
    - 21 MeV kinetic energy
  - bunch train formed

- **Cooling from 60m ➔ 100m**
  - longitudinal antidamping
    - g_L =~-0.5
  - B=2T , 2cm
  - more used to separate captured from uncaptured beam
  - ~0.05 μ/p within acceptance ??
    - not sure what acceptance criteria to use







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