More Muon Cooling, Higher Luminosity

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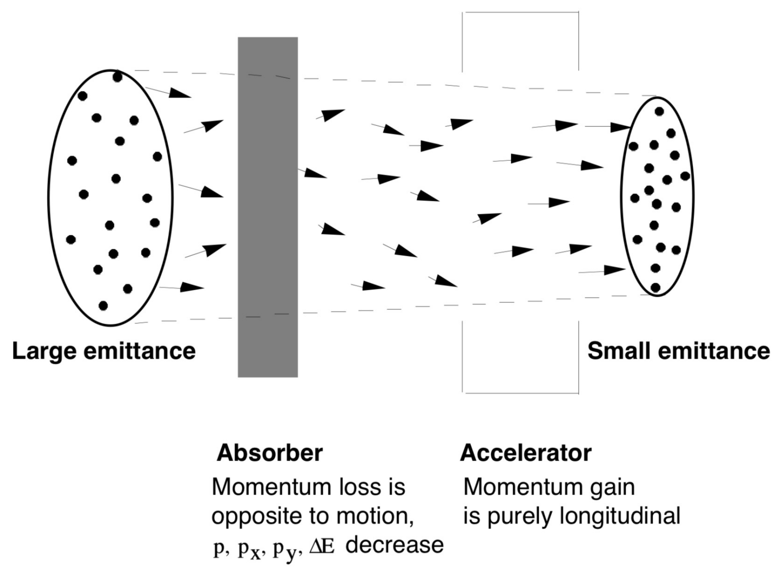
Transverse Muon Ionization Cooling

- **Transverse & longitudinal momentum is removed in absorber**
  Stronger focusing leads to larger p_t at the absorber
  RF replaces the longitudinal momentum
  Example: Lithium Hydride, 200 MeV/c, $g_t = 1$, $\beta^*_\perp = 1$ cm
  Calculate normalized equilibrium emittance to be 59 microns

$$\epsilon_{\perp,eq} \simeq \frac{\beta^*_\perp (13.6\,\mathrm{MeV})^2}{2 g_t\, \beta\, m_\mu c^2 L_R\, (dE/ds)}$$



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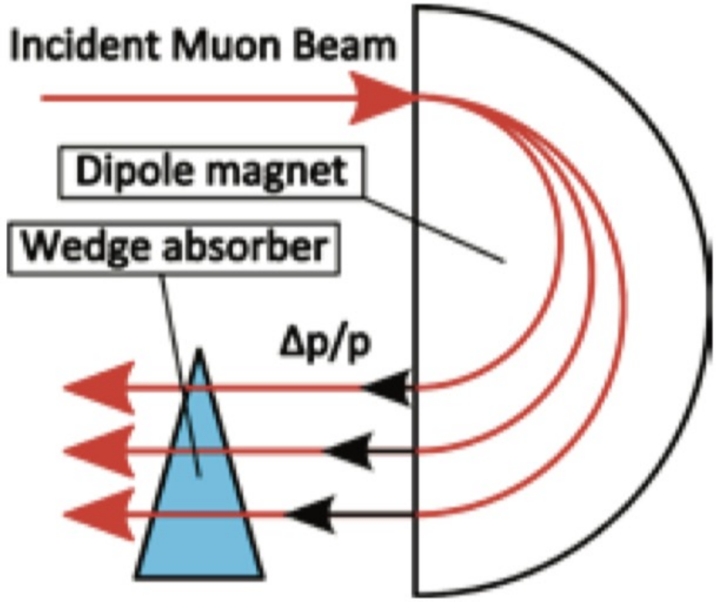
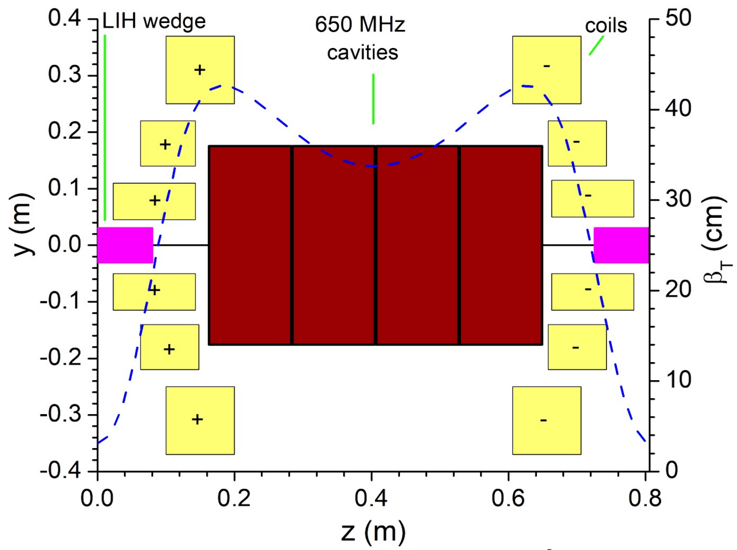
Longitudinal Muon Ionization Cooling



- **Muon Emittance Exchange**
  Introduce dispersion to spread muons at a wedge
  High momentum muons lose more energy
  Low momentum muons lose less energy
  Cost: transverse size of the beam gets bigger

Rectilinear Cooling Channel Status

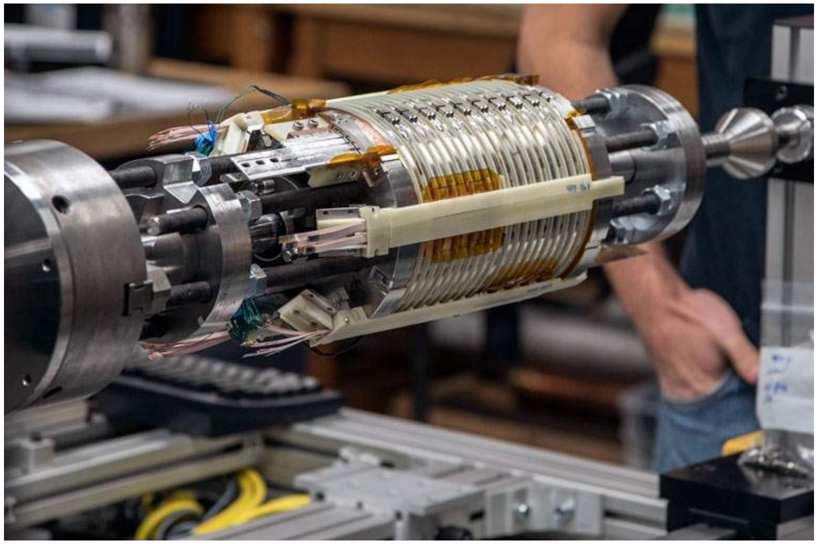
- **Channel is 969 m long with 826 cells. 6D cooling of 108 000**
  Diktys Stratakis and Bob Palmer, PRSTAB 18 (2015) 031003
  Witte, Stratakis, Berg, Palmer, Borgnolutti, IPAC14-WEPRI103



Rectilinear cell at the end in Stage B8 (14T maximum field coil)

- **Final xyz emittance equals (280, 280, 1570) microns**
  Luminosity is proportional to the square root of 6D emittance
  16x lower 6D emittance would lead to 4x higher luminosity
  Optimal high energy collider: (25, 25, 72000) microns
- **Is more cooling/reverse emittance exchange possible?**

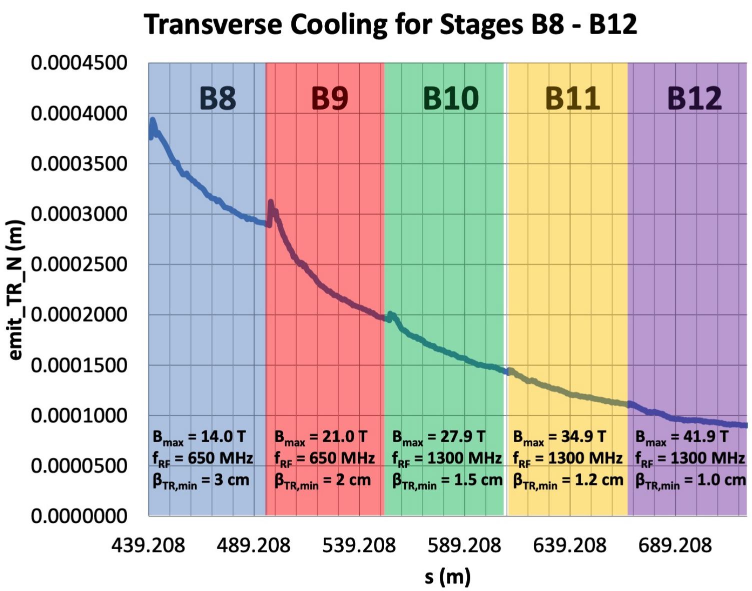
National High Magnetic Field Laboratory
Two Solenoids in Tallahassee, Florida

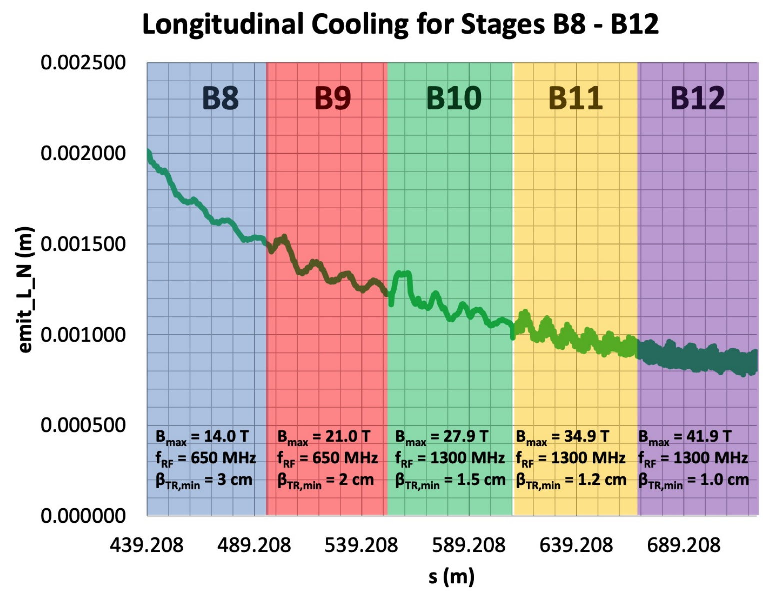


- 32 Tesla all superconducting solenoid
  Inner YBCO coils plus outer Nb_3Sn and NbTi coils
  IEEE Trans.Appl.Supercond. 22 (2012) 4300704

- 45.5 Tesla solenoid. 31.1 T resistive outsert
  14.4 T $(RE)Ba_2Cu_3O_{7-x}$ (REBCO, RE = Rare Earth) insert
  Superconducting coil: No insulation for safer quenching.
  Hahn...Larbalestier, Nature 570 (2019) 496 1260 amps/mm^2

Cooling with short 21, 28, 35, and 42 T solenoids





- **Add 57m long stages B9, B10, B11, and B12. Terry Hart 42T coil dimensions: ID, OD, Length = (3, 8, 4) cm**
  xyz emittance: (280, 280, 1570) to (90, 90, 850) microns
  6D emittance falls 18x. Collider luminosity rises 4x.
  Smaller transverse beams help final focus IP quads
  Transmission tuning is in progress

$$L = \frac{\gamma\, N^2 f_0\, (D\, C)}{4\pi \epsilon_{x,y}\, \beta^*}$$

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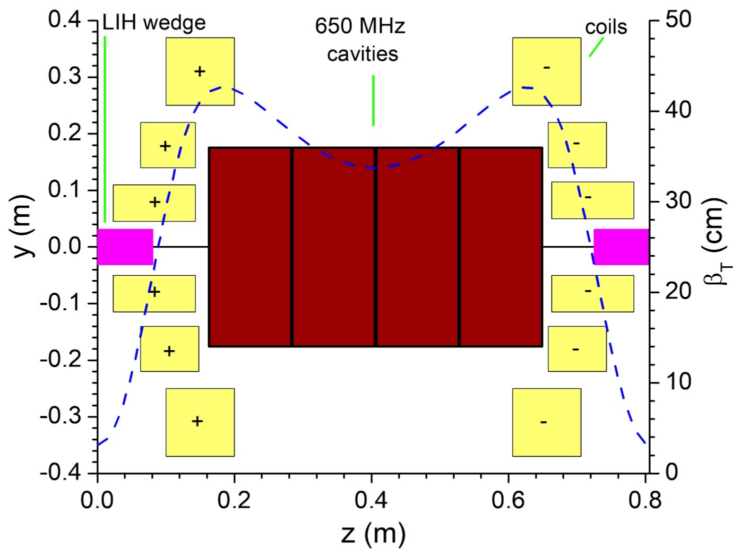
Kilograms of REBCO superconductor required

- Witte, Stratakis, Berg, Palmer, Borgnolutti, IPAC14-WEPRI103



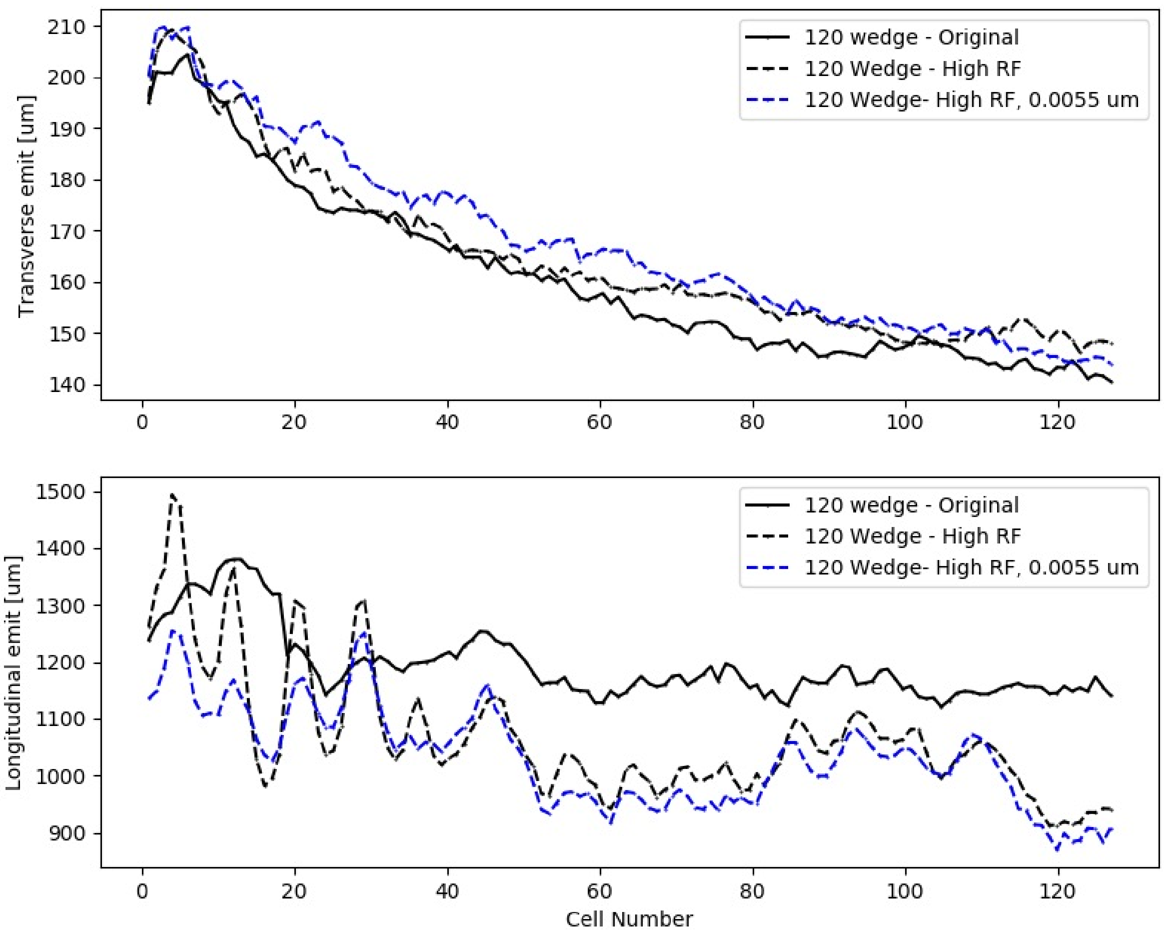
Rectilinear cell at the end in Stage B8 (14T maximum field coil)

- Inner B12 coil dimensions: ID, OD, Length = (3, 8, 4) cm.
  Middle/outer B12 coils are 19T Nb_3Sn for 40T inner coil
  Inner B12 coil volume = 173 cc. Mass = 1.4 kg
  1.4 kg x 366 half cells x 3 stages(B10, B11, B12) = 1500 kg
  Lance Cooley 2016 cost driver note. 1500 kg REBCO = $16M
  Gold would cost $90M for 1500 kg

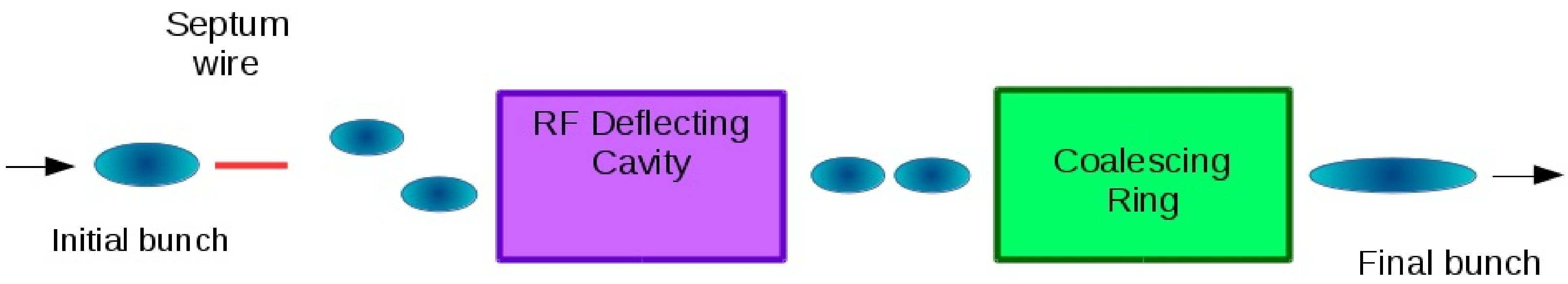
Further B10 Cooling Investigations. Rebecca Taylor

$$\epsilon_{L,eq} \simeq \frac{\beta_L m_e c^2 \beta\gamma^2 (2-\beta^2)}{4 g_L m_\mu c^2 \left[\ln\left[\frac{2 m_e c^2 \gamma^2 \beta^2}{I(Z)}\right] - \beta^2\right]} \qquad \beta_L = \sqrt{\frac{\lambda_{rf}\,\beta^3\,\gamma\,m_\mu c^2\,\alpha_p}{2\pi\, eV'\cos\phi_s}}$$

- **Raising RF from 28 to 50 MV/m improves ϵ_L and μ survival**



Reverse Emittance Exchange: High Energy Collider



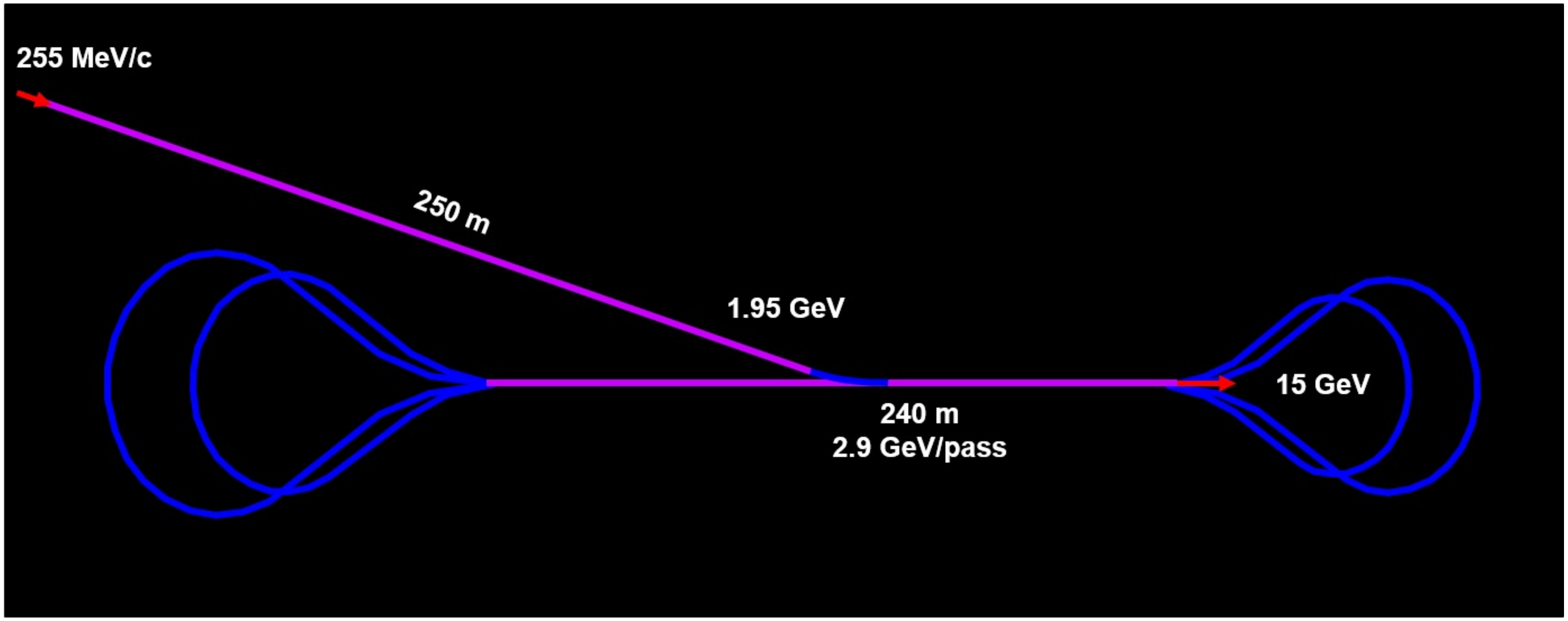
- **Use septa to split one $\epsilon_{xyz} = (90, 90, 850)$ micron bunch into 16 $\epsilon_{xyz} = (25, 25, 850)$ micron bunches.**
  Fermilab fixed target switchyard used 8 electrostatic septa
- **Use RF deflector cavities to form a 3.7 m long bunch train**
  Follow CLIC test experience
- **Snap bunch coalesce 16 bunches into one in a 21 GeV ring**
  Rotate over a quarter synchrotron period and then drift
  Capture in a short wavelength RF bucket
  87% longitudinal packing may be possible. Chandra Bhat
  Follow Tevatron experience
- **Don Summers, John Acosta et al., arXiv:1504.03972**
  Rol Johnson, Ankenbrandt, Bhat, Popovic, Bogacz, Derbenev, "Muon Bunch Coalescing," PAC07-THPMN095

Form 3.7m long train with RF deflector cavities

- **Combine 17 bunches into a 3.7 m long bunch train.**
  Use 10 RF Deflector Cavities because of their speed.
  Each cavity interleaves two or three bunch trains.
  Deflection is $\pm$4.5 mrad or zero at 300 MeV/c.
  The final train has a 231 mm bunch spacing.
  Accelerate with 1300 MHz RF cavities.

Tier	Number of Trains	No. RF Deflector Cavities	RF Frequency MHz	RF Wavelength	Output Spacing in Wavelengths	Output Bunch Spacing
1	$17 \to 6$	6	$(9/16)1300 = 731$	410 mm	9/4	923 mm
2	$6 \to 2$	3	$(3/8)1300 = 487$	616 mm	3/4	462 mm
3	$2 \to 1$	1	$(1/2)1300 = 650$	462 mm	1/2	231 mm

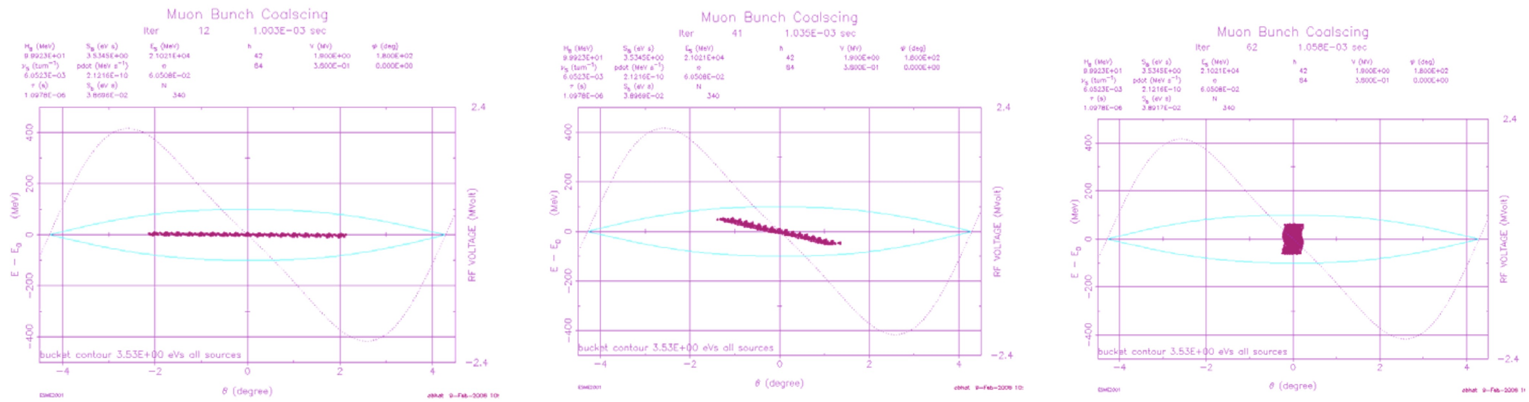
Accelerate the Bunch Train with a Dogbone



- **Linac plus 4.5 pass dogbone acceleration to 15 GeV. Alex Bogacz, JINST 13 (2018) P02002**

Snap Bunch Coalesce in a Ring after Dogbone

Inject **32 μS of Bunch Rotation** **Drift for 23 μS**



- **Snap bunch coalesce 16 bunches into one in a 21 GeV ring Rotate over a quarter synchrotron period and then drift Capture in a short wavelength RF bucket. Follow Tevatron. 87% longitudinal packing may be possible. Chandra Bhat Takes 55 μS. 13% muon decay loss**
- **Rol Johnson, Ankenbrandt, Bhat, Popovic, Bogacz, Derbenev, "Muon Bunch Coalescing," PAC07-THPMN095**

Summary

- **A prototype 32 T all superconducting solenoid runs in Florida**
  High field solenoids may be able to cool muons to $\epsilon_\perp = 90\,\mu$m
  Septa may be able to slice muon beams to get $\epsilon_\perp = 25\mu$m
  xyz emittance: $(90, 90, 850)\ \mu$m for s-channel Higgs factory
  xyz emittance: $(25, 25, 17000)\ \mu$m for high energy collider
  16x lower 6D emittance leads to 4x higher luminosity.