NuFact08 Summer School- Ionization Cooling

David Neuffer

Fermilab

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Outline

- **ν-Factory and $\mu^+ - \mu^-$ Collider:**
- **Ionization Cooling**
  - Cooling description
  - Heating – Longitudinal Cooling
  - Emittance Exchange - Partition Numbers
  - Solenoidal focusing
  - Helical Cooler-PIC-REMEX
  - Low-Energy Cooling
- **Cooling Scenarios**
- **Other Applications**
  - **Nuclear physics, stopped μ's**
- **Experimental Studies**
  - **Mice**
  - **Mucool**
  - **Muons, Inc.…**
  - **MCTF**

References

- A. N. Skrinsky and V.V. Parkhomchuk, Sov. J. Nucl. Phys. **12**, 3(1981).
- D. Neuffer, Particle Accelerators **14**, 75 (1983)
- D. Neuffer, "$\mu^+\mu^-$ Colliders", CERN report 99-12 (1999).
- **D. Neuffer, "Introduction to Muon Cooling", NIM A532, p. 26 (2004).**
- Y. Derbenev and R. Johnson, Phys. Rev. ST A. B. 8, E041002 (2005);

- **Simulation tools**
  - R. Fernow, **ICOOL** http://pubweb.bnl.gov/users/fernow/www/icool/readme.html
  - T. Roberts, G4BeamLine (Muons, Inc.) http://www.muonsinc.com/
- **Collaboration Efforts**
  - Muon Collaboration: http://www.cap.bnl.gov/mumu/mu_home_page.html
  - Muon Collider Task Force: https://mctf.fnal.gov/
  - **MICE** Collaboration: http://hep04.phys.iit.edu/cooldemo/
  - UKNF group (RAL)

Cooling Requirements

- **Beam from target** has

  $\varepsilon_{\perp,rms} \cong 2\times10^{-2}$ **m-rad;** $\varepsilon_{\parallel,rms} \cong$ **1m**

  - **Δx=~0.1m**×20 MeV/c; **Δz=~1m**×δE = 100MeV;

- **μ-Storage Ring ν-Factory**
  - Goal is to collect maximum number of μ^+ and/or μ^- that fit within accelerator / storage ring acceptances
  - Transverse cooling by ~10× is sufficient
  - $\varepsilon_{\perp,rms} \cong$ 0.006 to 0.002m-rad; $\varepsilon_{\parallel,rms} \cong$ 0.06 m-rad/bunch

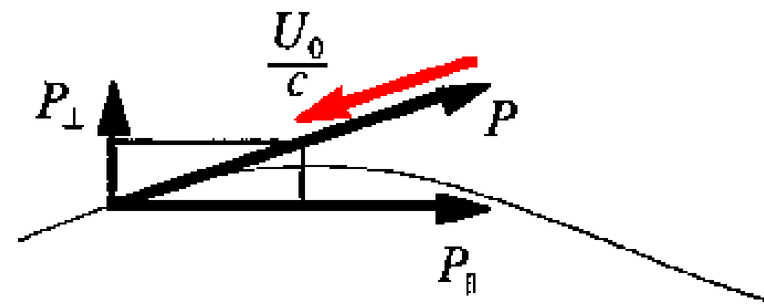
- μ^+–μ^- **Collider**
  - Goal is maximal cooling of maximum number of **both** μ^+ AND μ^-; high luminosity needed.
  - Cooling by > ~100× in each of ε_x, ε_y, ε_z is required
  - $\varepsilon_{\perp,rms} \cong$ 0.5 to 0.025×10^{-4}m-rad; $\varepsilon_{\parallel,rms} \cong$ 0.04 m-rad

Ionization Cooling-general principle

Transverse cooling:

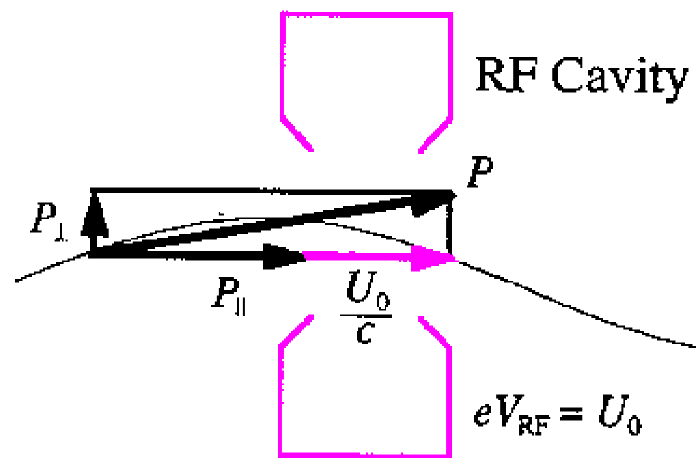
- Particle loses momentum P($\perp$ and $\parallel$) in material

$$P_x \rightarrow P_x \left[1 - \frac{dP}{ds} \frac{\Delta s}{P} \right]$$



- Particle regains $P_{\parallel}$ (only) in RF

$$\varepsilon_{\perp} \rightarrow \varepsilon_{\perp} \left[1 - \frac{dP}{ds} \frac{\Delta s}{P} \right]$$



- Multiple Scattering in material increases rms emittance:

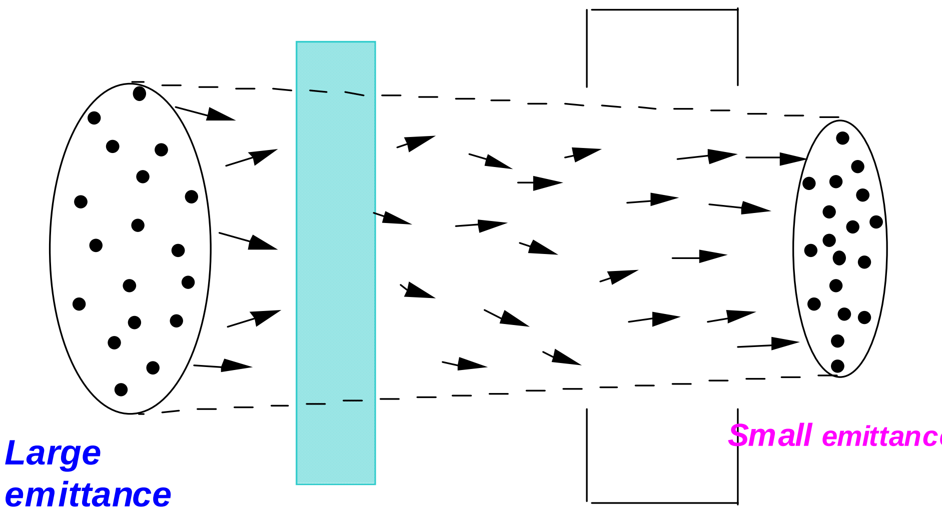
$$\Delta \varepsilon_{\perp,N} = \beta\gamma \frac{\langle x^2 \rangle}{2\,\varepsilon_{\perp}} \left(\Delta \langle \theta_x^2 \rangle \right) = \beta\gamma \frac{\beta_{\perp}}{2} \left(\frac{E_s^{\;2}}{(\beta c p)^2 L_R} \right) \Delta z$$

Ionization Cooling Principle

Loss of transverse momentum in absorber:

$$p_x \to p_x\left[1-\frac{dp}{ds}\frac{\Delta s}{p}\right]$$

$$\varepsilon_{\perp,N} \to \varepsilon_{\perp,N}\left[1-\frac{dp}{ds}\frac{\Delta s}{p}\right]$$



Absorber

Momentum loss is opposite to motion, p, p_x, p_y, ΔE decrease

Accelerator

Momentum gain is purely longitudinal

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{P_\mu}\frac{dP_\mu}{ds}\varepsilon_N + \frac{\beta\gamma\beta_\perp}{2}\frac{d\langle\theta_{rms}^2\rangle}{ds}$$

$$= -\frac{1}{\beta^2 E_\mu}\frac{dE_\mu}{ds}\varepsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

Heating by multiple scattering

Combining Cooling and Heating:

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\langle\theta_{rms}{}^2\rangle}{ds}$$

- Low-Z absorbers (H_2, Li, Be, …) to reduce multiple scattering
- High Gradient RF
  - To cool before μ-decay (2.2γ μs)
  - To keep beam bunched
- Strong-Focusing at absorbers
  - To keep multiple scattering
  - less than beam divergence …

⇒ Quad focusing ?

⇒ Li lens focusing ?

⇒ Solenoid focusing?

$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$

Transverse cooling limits

- **Transverse Cooling – equilibrium emittance**

$$\varepsilon_{N,eq} = \frac{\beta_\perp E_s^2}{2\beta m_\mu c^2 L_R \frac{dE_\mu}{ds}}$$

equilibrium scattering angle

$$\sigma_\theta = \sqrt{\frac{E_s^2}{2\beta^2 \gamma m_\mu c^2 L_R \frac{dE_\mu}{ds}}}$$

Material Properties for Ionization Cooling

Material	Symbol	Z, A	Density gm/cm³	dE/ds (min.) MeV/cm	L_R Cm	L_R dE/ds MeV	$\sigma_\theta \cdot \beta\gamma^{1/2}$	$g_x \beta \varepsilon_N/\beta_\perp$ mm-mrad/cm
Hydrogen	H_2	1, 1	0.071	0.292	865	252.6	0.061	**37**
Lithium	Li	3, 7	0.534	0.848	155	130.8	0.084	**71**
Lith. H	LiH	3+, 7+	0.9	1.34	102	137	0.0824	**68**
Beryllium	Be	4, 9	1.848	2.98	35.3	105.2	0.094	**88**
Carbon	C	6, 12	2.265	4.032	18.8	75.8	0.110	122
Aluminum	Al	13, 27	2.70	4.37	8.9	38.9	0.154	238
Copper	Cu	29,63.5	8.96	12.90	1.43	18.45	0.224	503
Tungsten	W	74, 184	19.3	22.1	0.35	7.73	0.346	1200

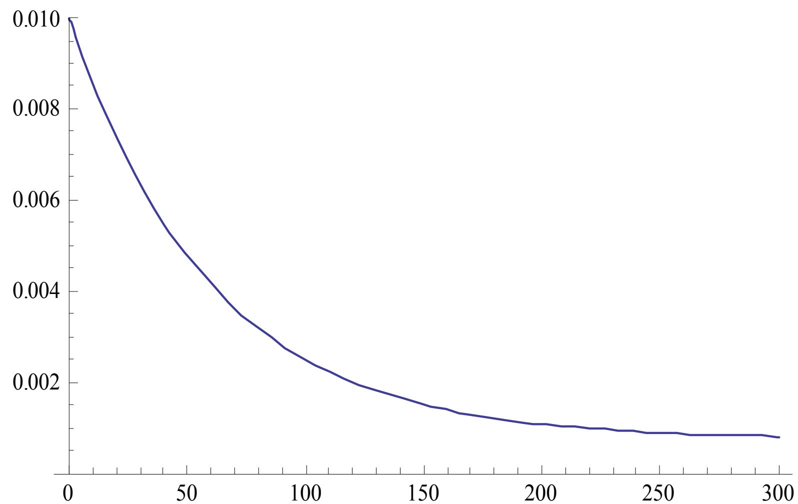
- Want materials with small multiple scattering (large L_R), but relatively large dE/ds, density (ρ)
- Want small $\beta_\perp$ at absorbers => strong focusing
- - equilibrium emittances ($/\beta_\perp$) smallest for low-Z materials

Problem

- Plug in some sample values for the cooling equations; solve for ε_t equilibrium and $\varepsilon_t(s)$
  - try dE/ds = 5 MeV/m, p =300 MeV/c,
  - $\beta_\perp$ =0.1m, Li absorbers

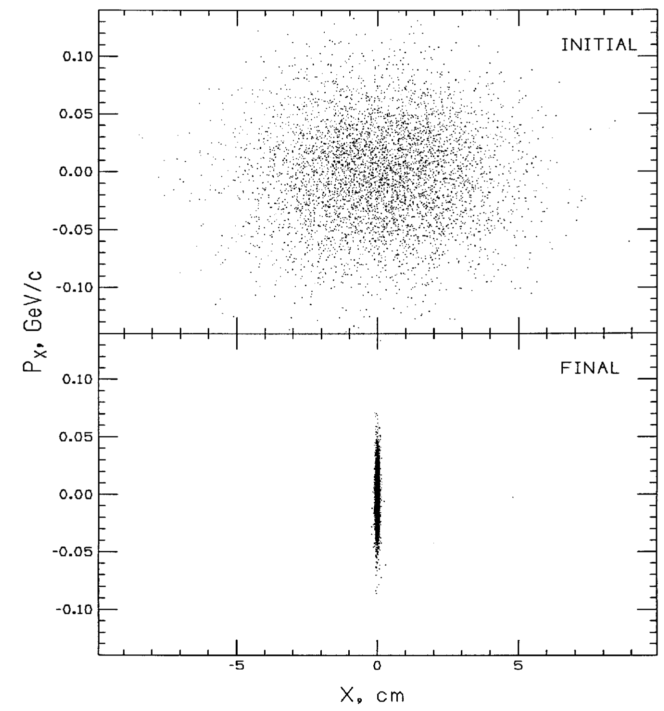
$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\left\langle \theta_{rms}{}^2 \right\rangle}{ds}$$

$$\frac{d\left\langle \theta_{rms}^2 \right\rangle}{ds} = \frac{f\ E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$



Ionization Cooling difficulties

- Must focus to very small $\beta_\perp$
  - $\beta_\perp$: 1m $\rightarrow$ ~1mm
- Intrinsic scattering of beam is large
  - θ_{rms} > ~0.1 radians
- Intrinsic momentum spread is large
  - σ_P/P > ~0.03
- Cooling must occur within muon lifetime
  - $\tau_\mu = 2.2\gamma$ μs or $L_\mu = 660\ \beta\gamma$ m pathlength
- Does not (directly) cool longitudinally



Longitudinal "Cooling"

$$\frac{dE}{ds} = 4\pi N_A \rho r_e^2 m_e c^2 \frac{Z}{A}\left[\frac{1}{\beta^2}\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right) - 1 - \frac{\delta}{2\beta^2}\right]$$

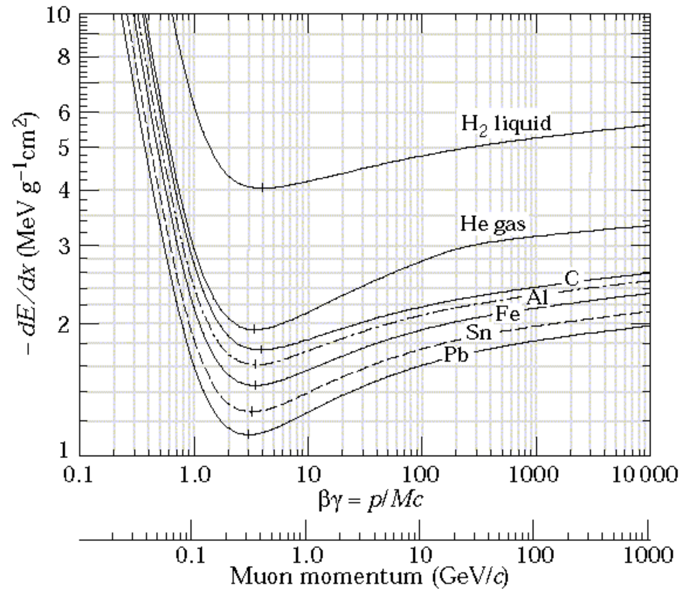
- **Energy cooling occurs if the derivative :**

$$\partial(dE/ds)/\partial E = g_L (dp/ds)/p > 0$$

$$g_L = -\frac{2}{\gamma^2} + 2\frac{(1-\frac{\beta^2}{\gamma^2})}{\left(\ln\left[\frac{2m_e c^2\beta^2\gamma^2}{I(Z)}\right] - \beta^2\right)}$$

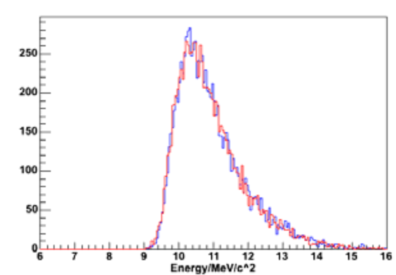
- $g_L(E)$ is negative for $E < \sim 0.2$ GeV and only weakly positive for $E > \sim 0.2$ GeV

⇒ **Ionization cooling does not effectively cool longitudinally**



Energy straggling increases energy spread

$$\frac{d\left\langle \Delta E_{rms}^{\;2}\right\rangle}{ds} \cong 4\pi\left(r_e m_e c^2\right)^2 n_e \gamma^2\left(1 - \frac{\beta^2}{2}\right)$$



"Emittance exchange" enables longitudinal cooling:

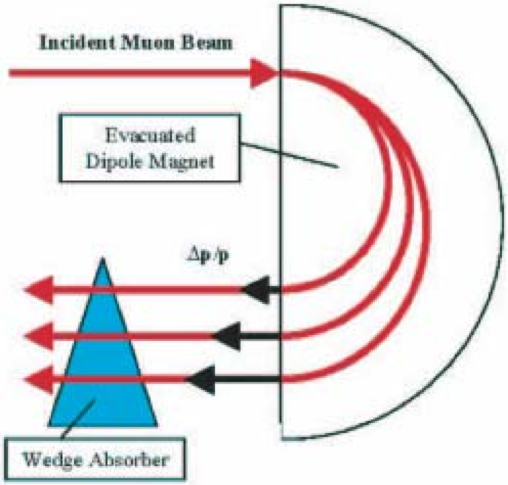


Figure 1. Use of a Wedge Absorber for Emittance Exchange

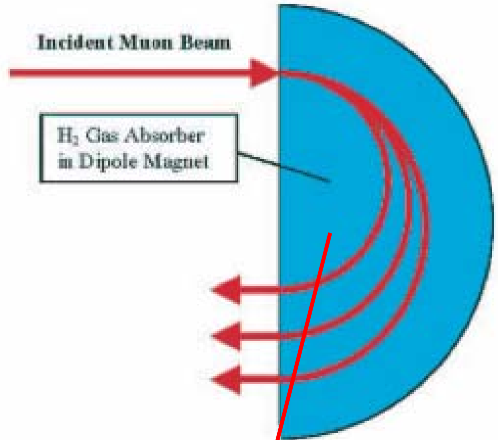
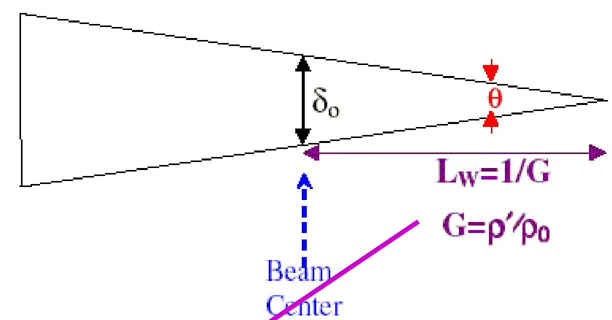


Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Geometry of wedge absorber



- **Cooling derivative is changed by use of dispersion + wedge**

  (Dependence of energy loss on energy can be increased)

$$\frac{\partial \frac{dE}{ds}}{\partial E} \Rightarrow \left.\frac{\partial \frac{dE}{ds}}{\partial E}\right|_0 + \frac{1}{\beta c p}\frac{dE}{ds}\frac{\eta\rho'}{\rho_0} = g_L \frac{dp/ds}{p}$$

(if due to path length)

$$\Delta g_L = \frac{1}{\gamma_T^2} = \frac{(ka)^2}{1+(ka)^2}\left(\frac{a}{p}\frac{dp}{da}\right)^{-1}$$

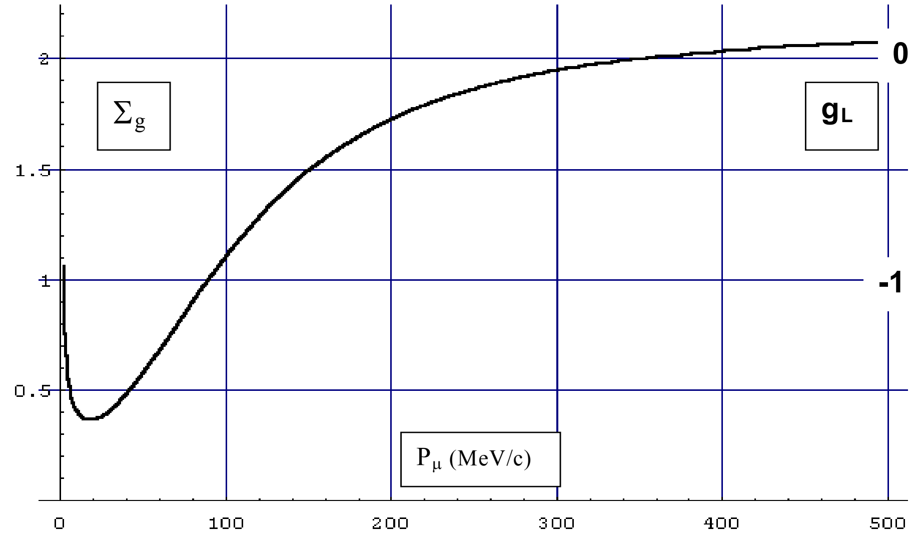
Partition Numbers, δE-δt cooling

With emittance exchange the longitudinal partition number g_L changes:

$$g_L \Rightarrow g_{L,0} + \frac{\eta\rho'}{\rho_0}$$

But the transverse cooling partition number decreases:

$$g_x \Rightarrow 1 - \frac{\eta\rho'}{\rho_0}$$



The sum of the cooling partition numbers (at P = P_μ) remains constant:

$$\Sigma_g(P_\mu) = g_x + g_y + g_L = 2 + g_{L,0}$$

$$\Sigma_g = 2\beta^2 + 2\frac{(1-\frac{\beta^2}{\gamma^2})}{\left(\ln\left[\frac{2m_e c^2\beta^2\gamma^2}{I(Z)}\right] - \beta^2\right)}$$

$\Sigma_g > 0$

Cooling + Energy straggling ...

Energy spread (σ_E) cooling equation:

$$\frac{d\sigma_E^2}{ds} = -2\frac{g_L \frac{dE}{ds}}{\beta^2 E}\sigma_E^2 + 4\pi\left(r_e m_e c^2\right)^2 n_e \gamma^2\left(1-\frac{\beta^2}{2}\right)$$

Equilibrium σ_p:

$$\frac{\sigma_p}{p} = \sqrt{\frac{m_e\gamma}{2 g_L m_\mu} \times \frac{1-\frac{\beta^2}{2}}{\log[]-\beta^2}}$$

Longitudinal Emittance Cooling equation:

$$\frac{d\varepsilon_L}{ds} = -\frac{g_L}{p_\mu}\frac{dp_\mu}{ds}\varepsilon_L + \frac{\beta_{c\tau}}{2}\frac{d\langle \Delta E_{rms}{}^2\rangle}{ds}$$

$$\beta_{c\tau} = \sqrt{\frac{1}{\beta^3\gamma\, eV'\cos\varphi_s}\frac{\lambda_{RF}}{2\pi}\frac{\alpha_p}{mc^2}}$$

Longitudinal Cooling requires:

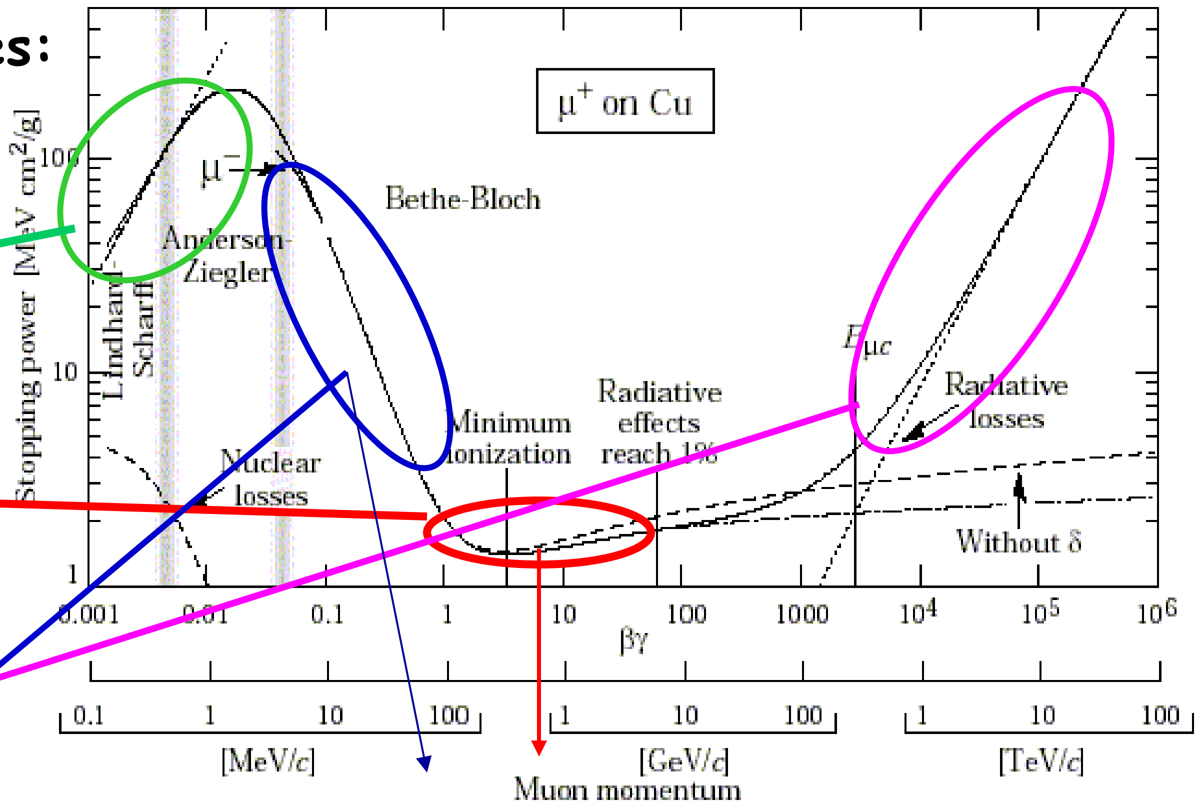
- Positive $\mathbf{g_L}$ (η, "wedge"), Strong bunching ($\boldsymbol{\beta_{c\tau}}$ small)
  - Large V_{rf}, small λ_{rf}

Energy loss/recovery
Before decay requires:

$$V'_{rf} \gg \frac{\Delta p_\mu}{L_\mu} >> \frac{(m_\mu\beta\gamma)}{L_0\beta\gamma} = \frac{105.66\ \mathrm{MeV}}{660\ \mathrm{m}} = 0.16\ \mathrm{MeV/m}$$

μ Cooling Regimes

- **Efficient cooling requires:**
  $$\frac{\partial \frac{dE}{dx}}{\partial E} > \sim 0$$
- **Frictional Cooling (<1MeV/c)** $\Sigma_g = \sim 3$
- **Ionization Cooling (~0.3GeV/c)** $\Sigma_g = \sim 2$
- **Radiative Cooling (>1TeV/c)** $\Sigma_g = \sim 4$
- **Low-ε_t cooling** $\Sigma_g = \sim 2\beta^2$ **(longitudinal heating)**

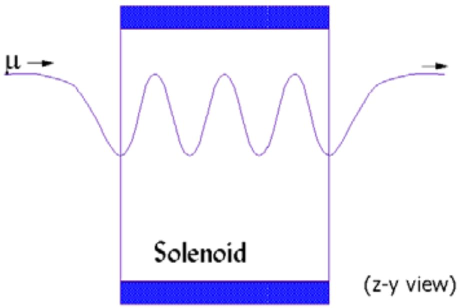


$$\frac{dE}{ds} = 4\pi N_A \rho r_e^2 m_e c^2 \frac{Z}{A}\left[\frac{1}{\beta^2}\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right) - 1 - \frac{\delta}{2\beta^2}\right]$$

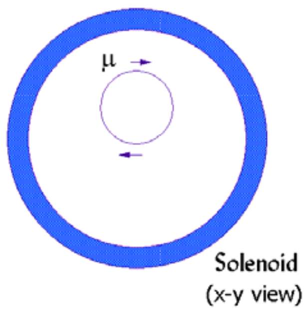
Focusing for Cooling

- **Strong focussing needed** – magnetic quads, solenoids, Li lens ?
- **Solenoids** have been used in most (recent) studies
  - Focus horizontally and vertically
  - Focus both μ^+ and μ^-

$$r'' = -\left(\frac{B}{2B\rho}\right)^2 r \qquad \beta_{\perp,\mathrm{equil.}} = \frac{2B\rho}{B}$$



- **Strong focussing possible:**
  - $\beta_\perp$ = 0.13m for B=10T, p_μ = 200 MeV/c
  - $\beta_\perp$ = 0.0027m for B=50T, p_μ = 20 MeV/c
- But:
  - Solenoid introduces angular motion
  - L damped by cooling + field flips
  - B within rf cavities ?



$$\theta' = B/(2B\rho)$$

Solenoidal focusing for cooling

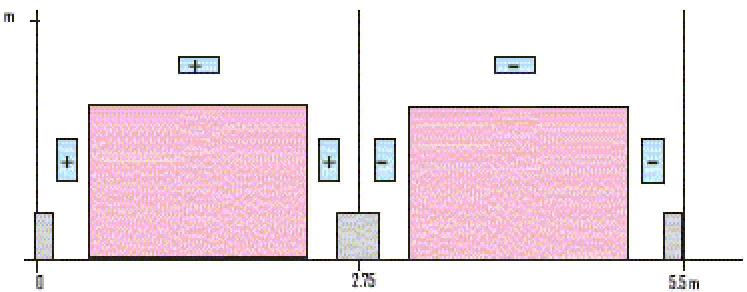
Fernow, Palmer PRSTAB 10, 064001 (2007)

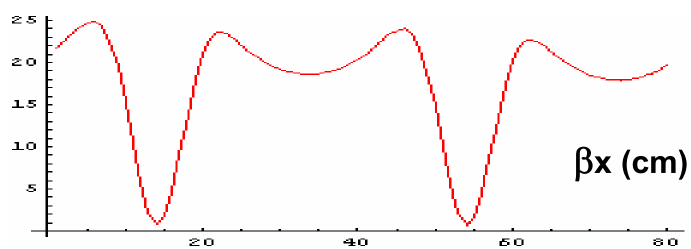
- Lattices are sequences of solenoids and drifts (rf interlaced) (+,-)
  - FOFO, ASOL, RFOFO, SFOFO, DODO, SOSO …
- Can have nearly constant focusing or focusing to small β^*
- Large $\delta p/p$ acceptance possible
  - Need >± 10% $\delta p/p$
- Low β^* can be much less than:

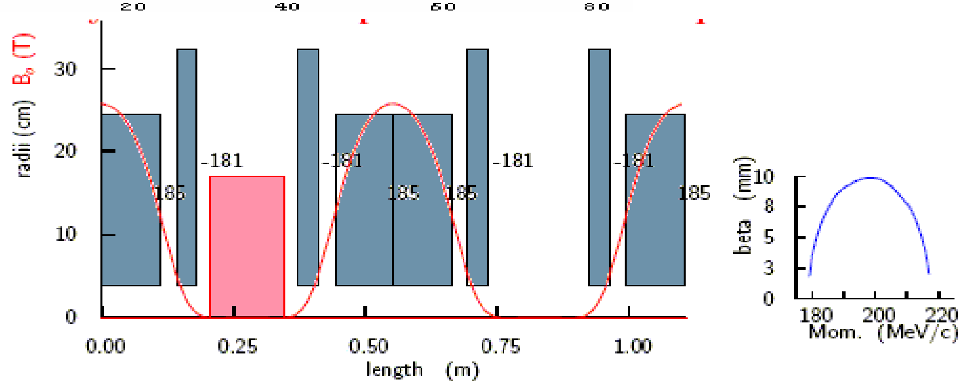
$$\beta_{\perp,\mathrm{equil.}} = \frac{2\,B\rho}{B}$$

  - >5× smaller

- Recent example: $\beta^* = 1\mathrm{cm}$ (!!)
  - At 200 MeV/c, B_{max}=25T
  - Field flip not required







• Current densities < 200 A/mm² ok for HTS

Cooling with ⊥– 🖮 exchange and solenoids

Wang and Kim, NIM A532, 260 (2004)

Example: rms Cooling equations with dispersion and wedges (at $\eta'=\alpha=0$) in x-plane:

$$\frac{d\varepsilon_x}{ds} = -g_x \frac{\frac{dP}{ds}}{P}\varepsilon_x + \beta_\perp \frac{d\theta^2_{rms}}{ds} + \frac{1}{2}\frac{\frac{dP}{ds}}{P}\beta_\perp \theta'_L L + \frac{1}{2} H_x \frac{d\delta^2_{rms}}{ds} \qquad H_x = \frac{\eta^2}{\beta_x}$$

$$\frac{d\varepsilon_y}{ds} = -\frac{\frac{dP}{ds}}{P}\varepsilon_x + \beta_\perp \frac{d\theta^2_{rms}}{ds} + \frac{1}{2}\frac{\frac{dP}{ds}}{P}\beta_\perp \theta'_L L$$

$$\theta'_L = B/(2\,B\rho)$$

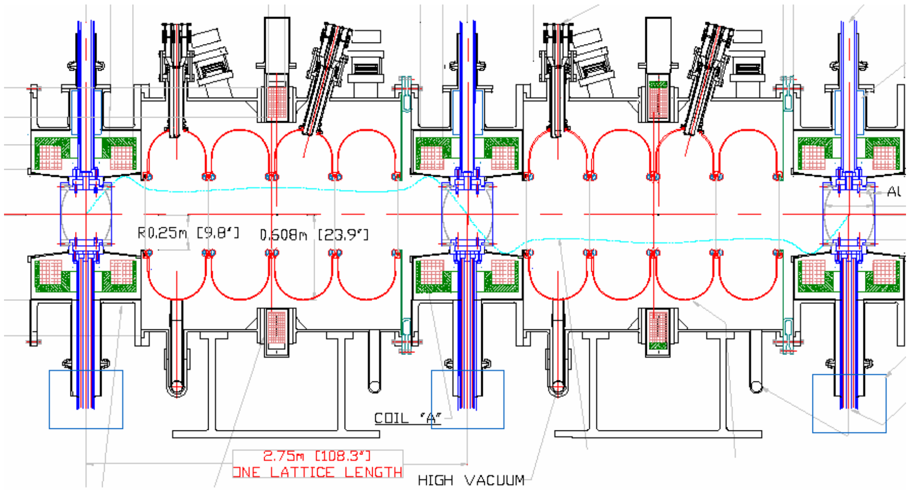
$$\frac{d\varepsilon_z}{ds} = -g_L \frac{\frac{dP}{ds}}{P}\varepsilon_z + \frac{1}{2}\beta_z \frac{d\delta^2_{rms}}{ds} + \frac{1}{2}\frac{\eta^2}{\beta_z}\frac{d\theta^2_{rms}}{ds}$$

$$L = x\,y' - y\,x'$$

$$\frac{dL}{ds} = -(1-\frac{\delta g}{2})\frac{\frac{dP}{ds}}{P} L + \frac{1}{2}\frac{\frac{dP}{ds}}{P}\beta_\perp \theta'_L(\varepsilon_x + \varepsilon_y) + \frac{\eta^2}{\beta_z}\frac{d\delta^2_{rms}}{ds}$$

The additional correlation and heating terms are "small" in "well-designed" systems.

Study 2 Cooling Channel (≈ MICE)



sFOFO 2.75m cells

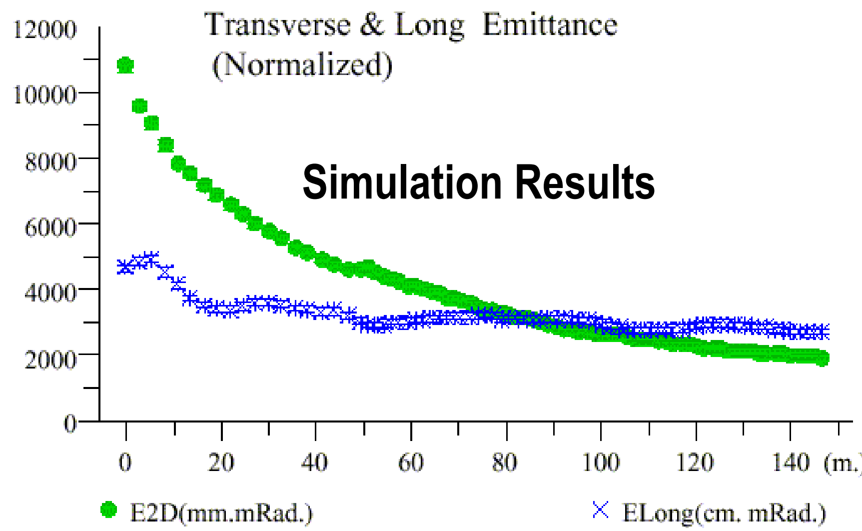
108 m cooling channel consists of:

16 2.75m cells + 40 1.65m cells

Focusing increases along channel:

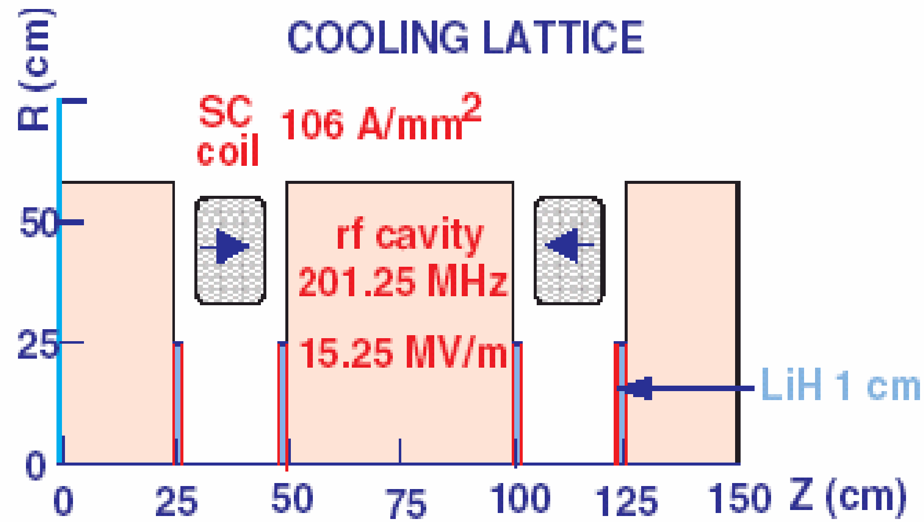
B_{max} increases from 3 T to 5.5 T

- Cell contains
  - Rf for acceleration/bunching
  - H_2 absorbers
  - Solenoidal magnets

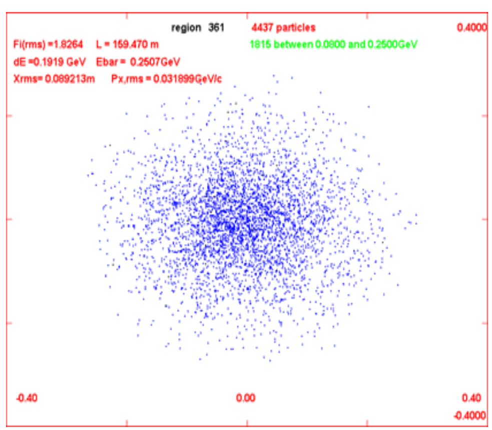


ν-Factory Study 2A cooling channel

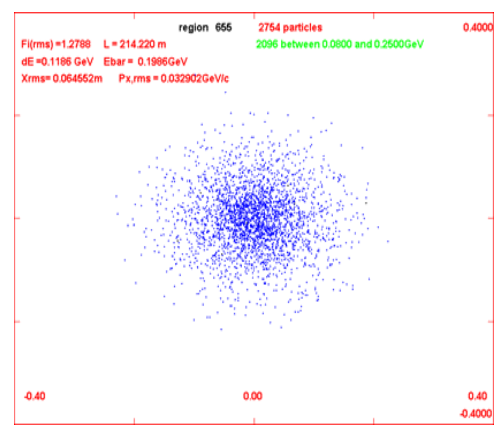
- Lattice is weak-focusing
  - B_{max} = 2.5T, solenoidal
  - $\beta_{\perp} \cong 0.8$m
- Cools transversely
  - $\varepsilon_{\perp}$ from ~0.018 to ~0.007m
  - in ~70m



Before



After cooling



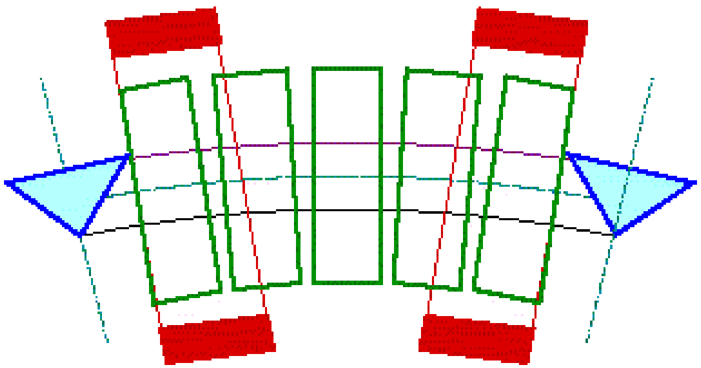
-0.4m +0.4m

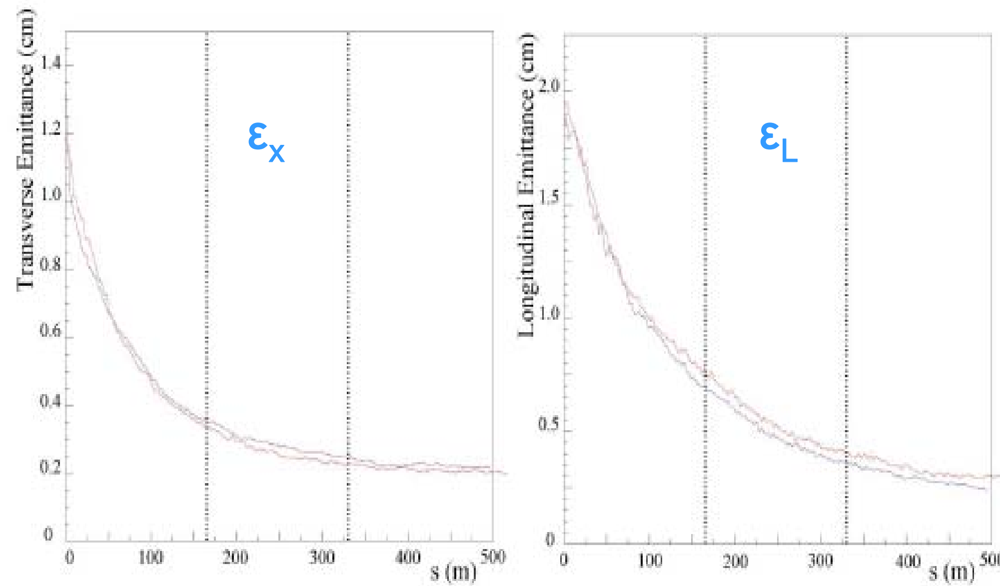
Problem: Check with rms cooling equations; How is answer changed if H_2 is used?

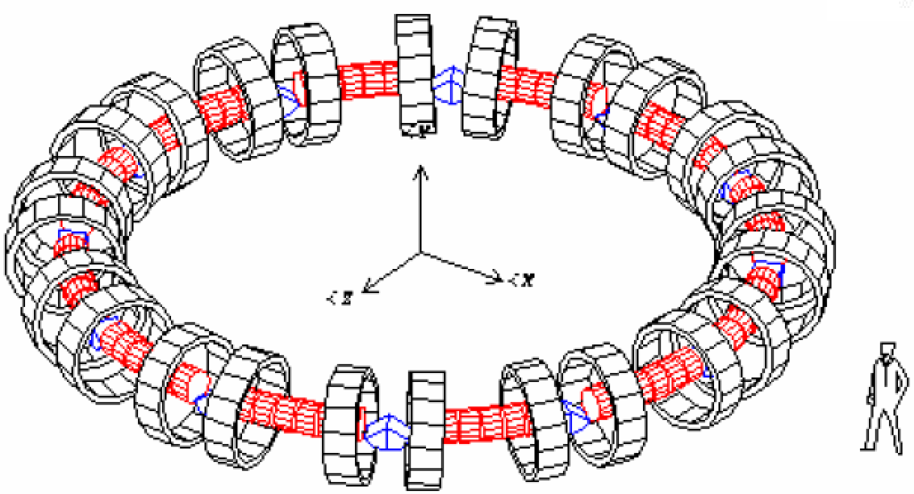
RFOFO Ring Cooler performance

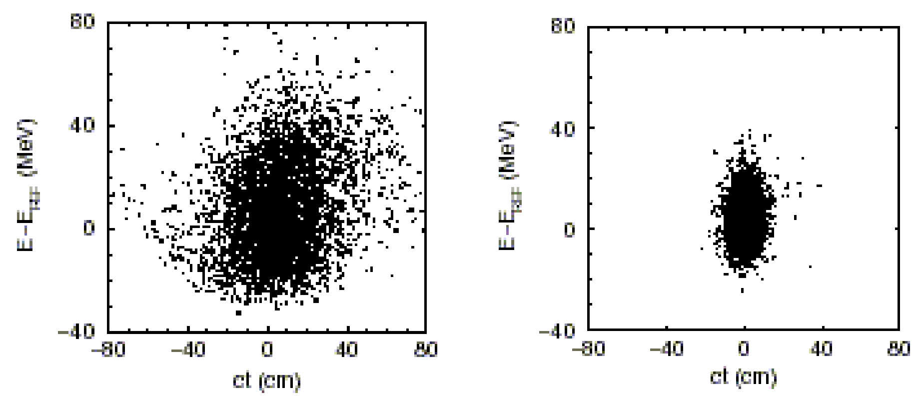
R. Palmer et al., PR STAB 8, 061003 (2005)

- **Cools longitudinally** and transversely







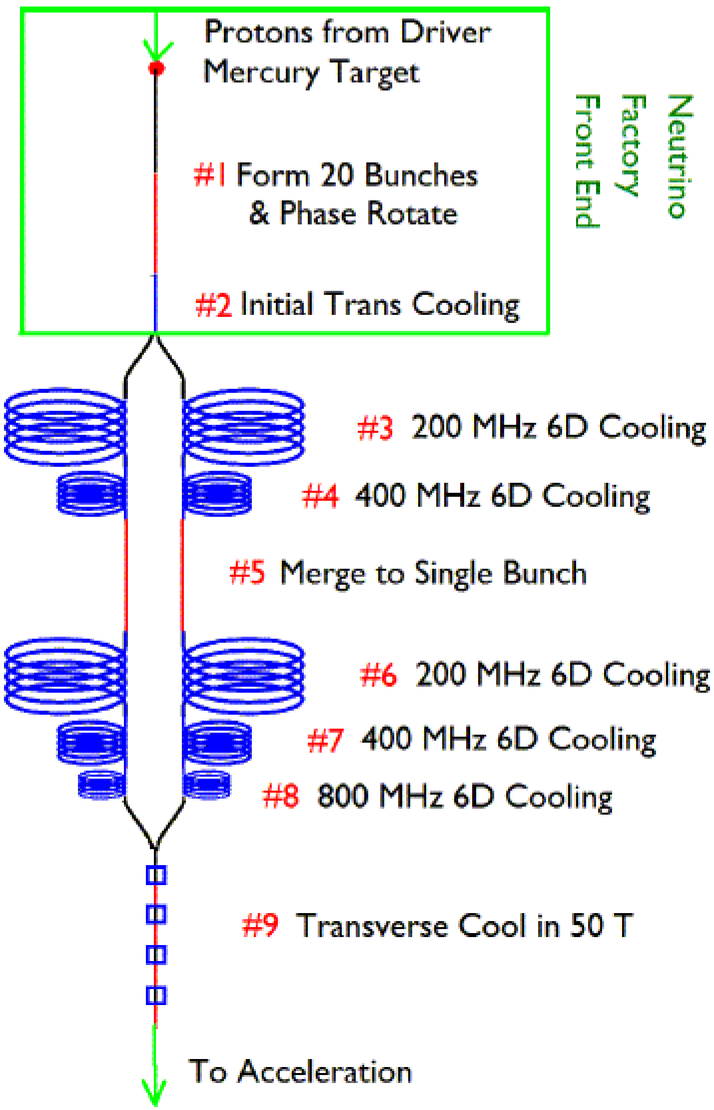


E-ct before and after

μ^+-μ^- Collider Cooling Scenarios

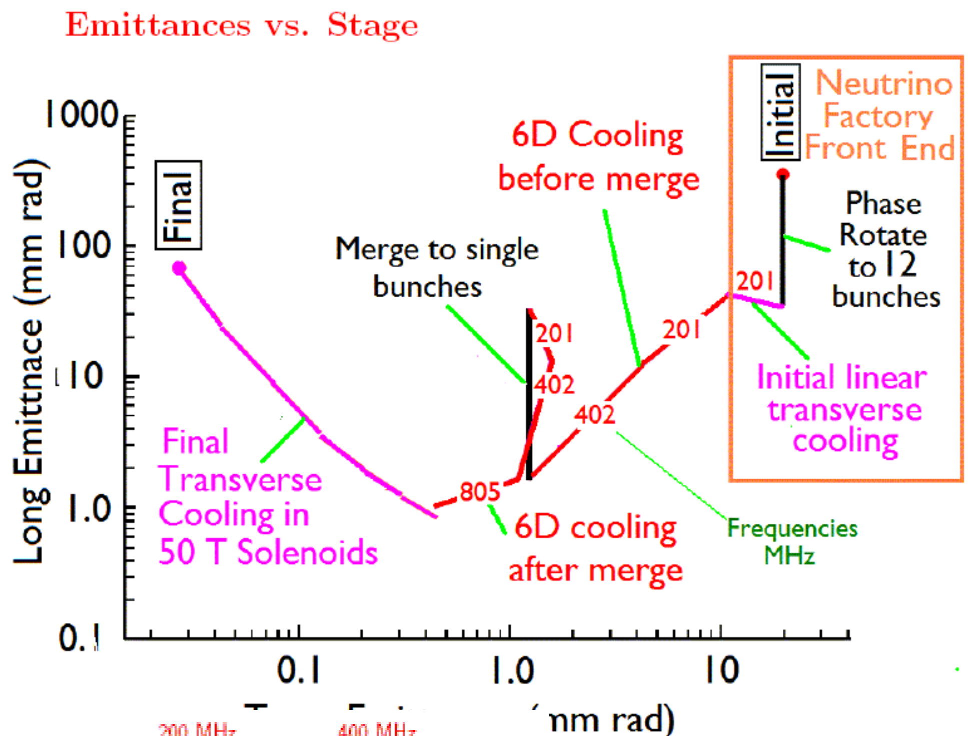
Palmer et al.

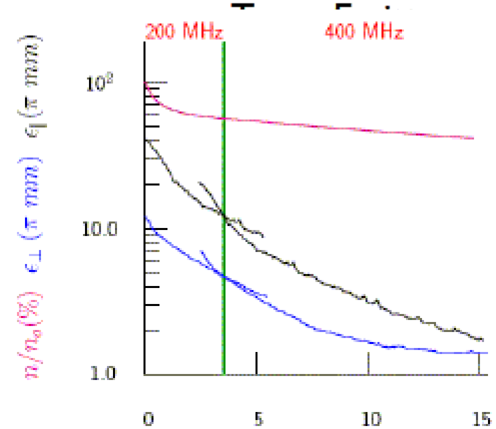
- requires energy cooling and emittance exchang (and anti-exchange) to obtain small ε_L, ε_x, ε_y
- Start with large beam from target, compress and cool, going to stronger focussing and bunching the beam gets smaller …
  - $\delta p/p$ ~10%, σ_θ ~0.1
- Bunching rf frequency increases
- In final cooling stages longitudinal emittance increases while transverse emittance decreases

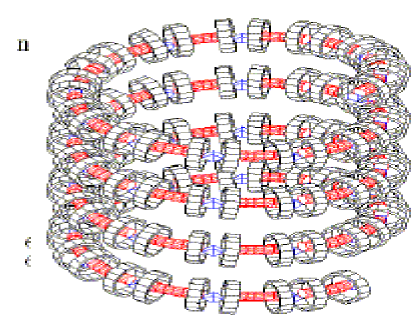


Cooling Scenario for Collider

- **Steps 1,2**: Bunching, phase rotation, cooling (=ν factory)
  - σ_μ: **10cm → 6cm**
- **3,4**: 6-D cooling with 200, 400 MHz "Ring Coolers"
  - σ_μ: **6cm → 2.4cm→ 1.0cm**
- **5**: compress to 1 bunch
- **6, 7**: 6-D 200, 400 MHz Coolers
  - σ_μ: **3cm→ 1.0cm**
- **8**: 800 MHz "Ring Cooler"
  - σ_μ: **1.0cm→ 0.3cm**
- **9**: up to 50T coolers (H_2, solenoids)
  - σ_μ: **0.4cm→ 0.08cm**
- **Total length of system ~0.8km**



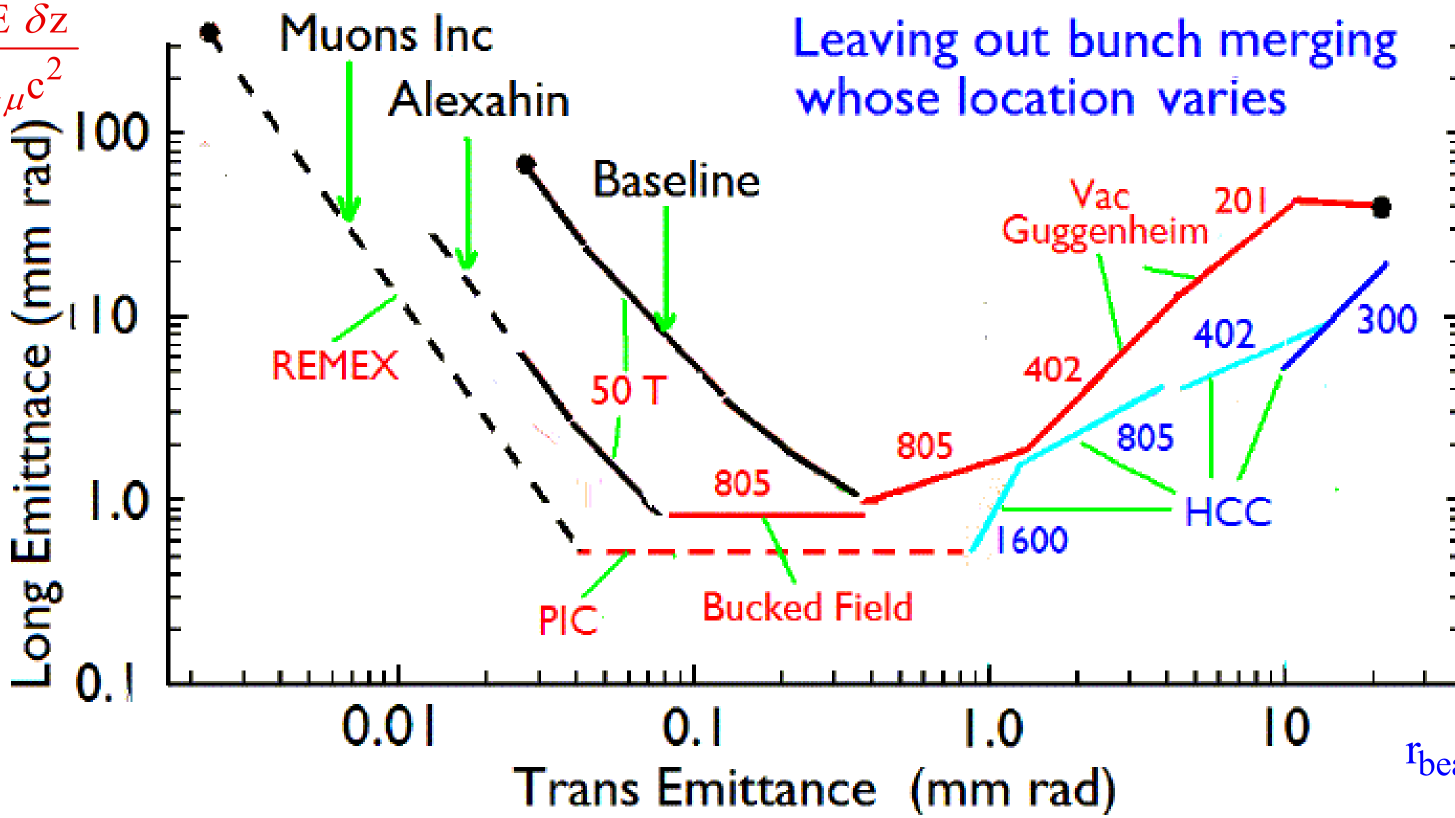




Other Cooling scenarios

- **HCC**- Helical Cooling Channel
- **PIC**-Parametric-resonance Ionization Cooling
  - Use resonance beam dynamics to intensify focusing
- REMEX, low-energy emittance exchange
- Very low energy cooling

$$\varepsilon_L = \frac{\Delta E\ \delta z}{m_\mu c^2}$$



$$r_{beam} = \sqrt{\frac{\varepsilon_N \beta_\perp}{\beta\gamma}}$$

Helical 6-D Cooler

Y. Derbenev and R. Johnson, Phys. Rev. STAB. 8, E041002 (2005)

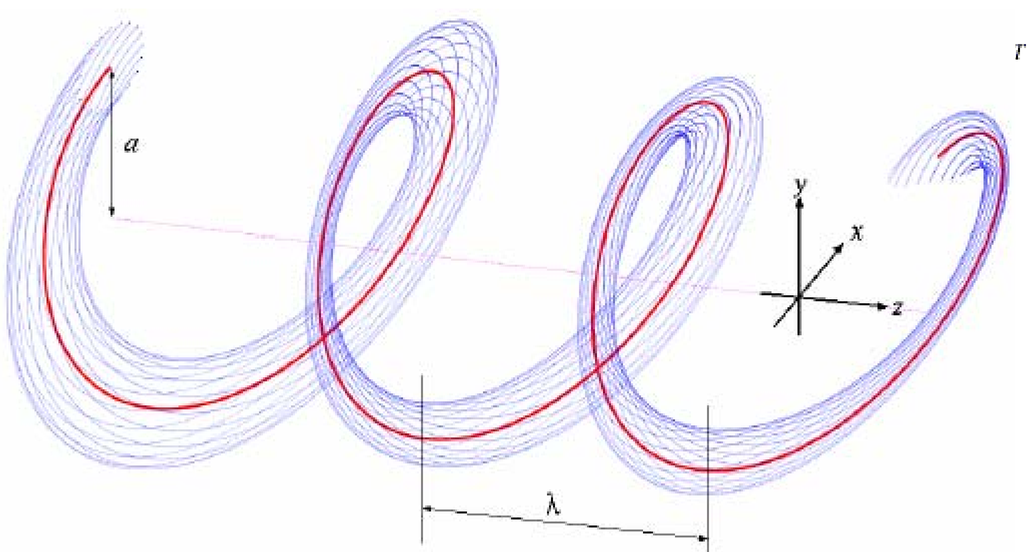
- Magnetic field is solenoid B_0+ dipole + quad + …
- System is filled with H_2 gas, includes rf cavities
- Cools 6-D (large E means longer path length)

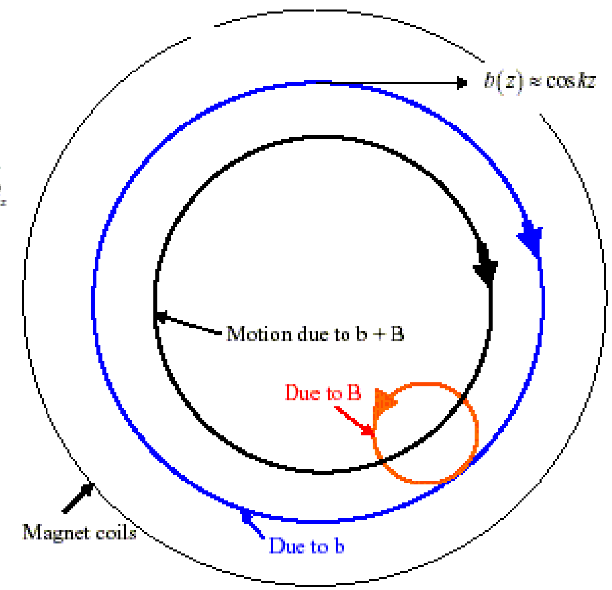
$$\Delta g_L = \frac{1}{\gamma_T^2} = \frac{(ka)^2}{1+(ka)^2}\left(\frac{a}{p}\frac{dp}{da}\right)^{-1}$$

Key parameters:
a, $k=2\pi/\lambda$, solenoid field B_0, transverse field b(a)

$$p(a) = \frac{\sqrt{1+(ka)^2}}{k}\left[B - \frac{1+(ka)^2}{ka}b(a)\right]$$

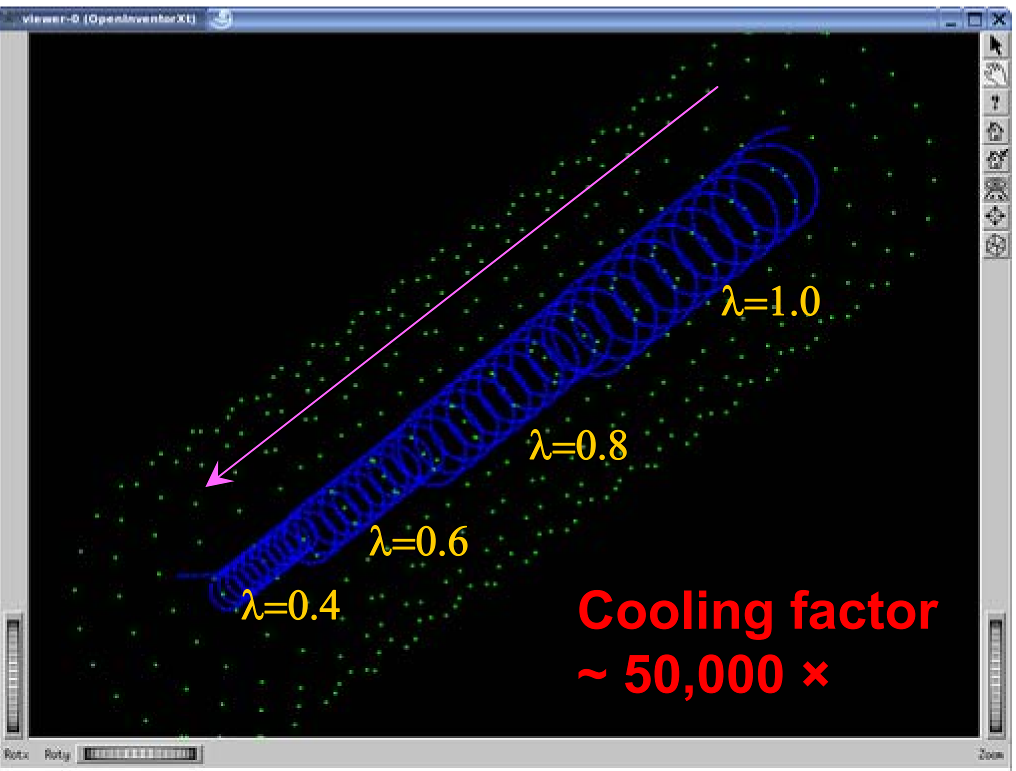
$$F_{h-dipole} = p_z \times B_\perp; \quad b = B_\perp$$
$$F_{solenoid} = -p_\perp \times B_z; \quad B = B_z$$

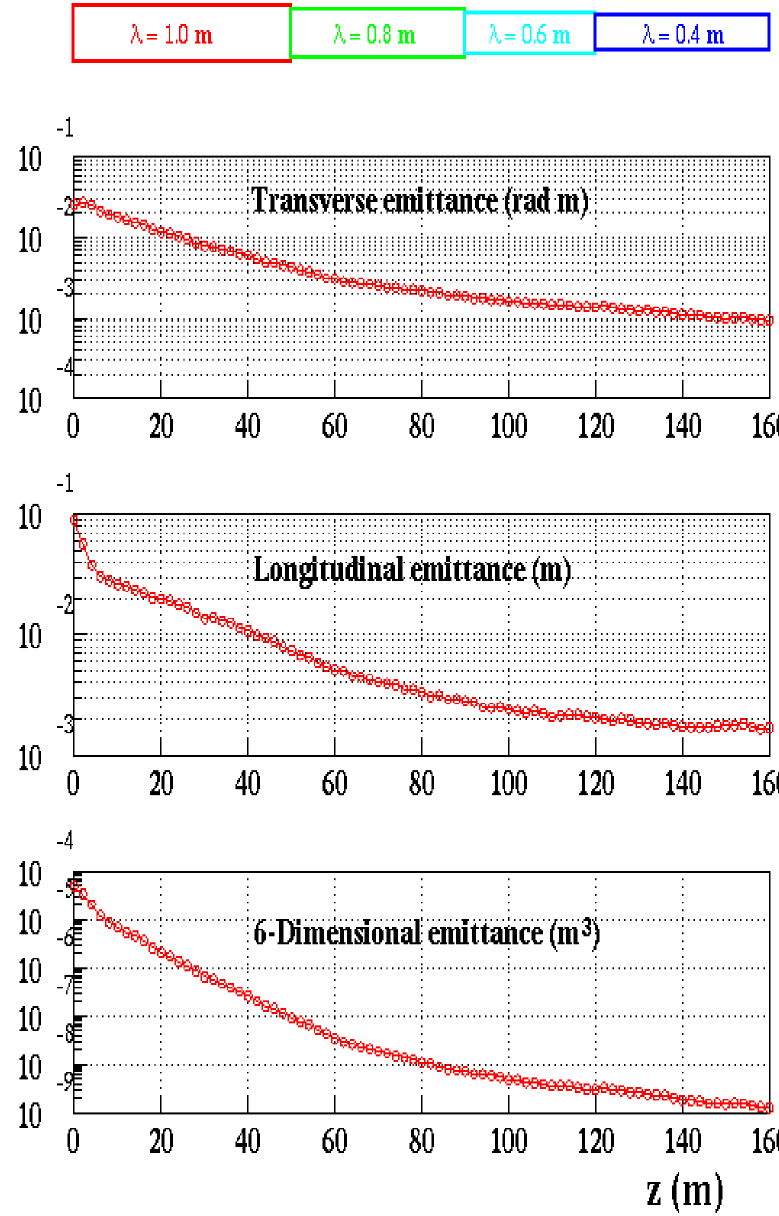




Helical Wiggler 3-D Cooling (P_μ=250MeV/c)

Series HCCs							
			Segment				
			1st	2nd	3rd	4th	
L	*Length*	m	50	40	30	40
λ	*Helix period*	m	1.0	0.80	0.60	0.40
a	*Reference orbit radius*	m	0.16	0.13	0.095	0.064
κ	*Helix pitch*		1.0	1.0	1.0	1.0
B	*Solenodial component*	T	-6.95	-8.68	-11.6	-17.4
b_d	*Helix dipole coefficient*	T	1.81	2.27	3.02	4.53
b_q	*Helix quadrupole coefficient*	T/m	-0.35	-0.44	-0.59	-0.88
b_1	*Helix sextupole coefficient*	T/m2	0.031	0.039	0.051	0.077

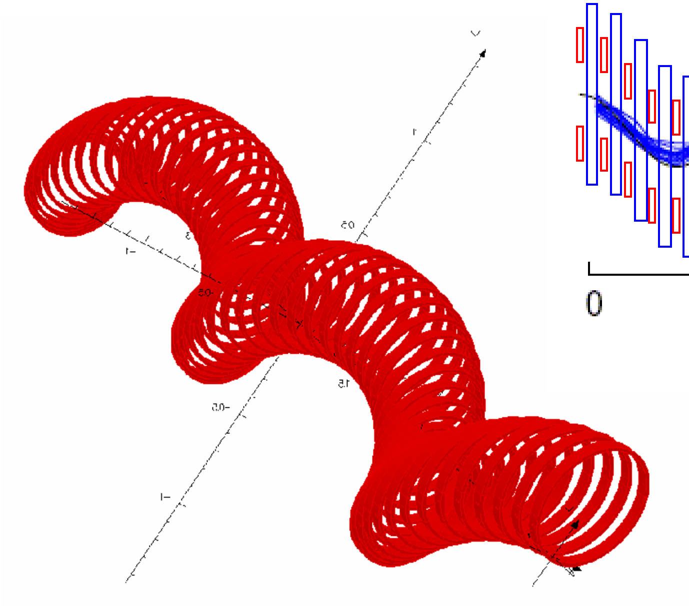


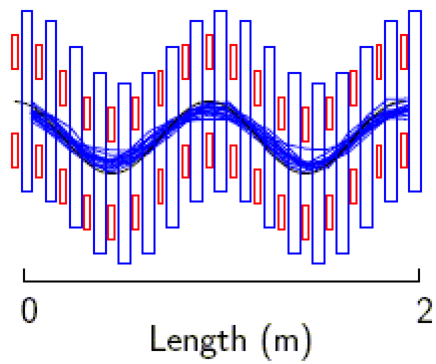


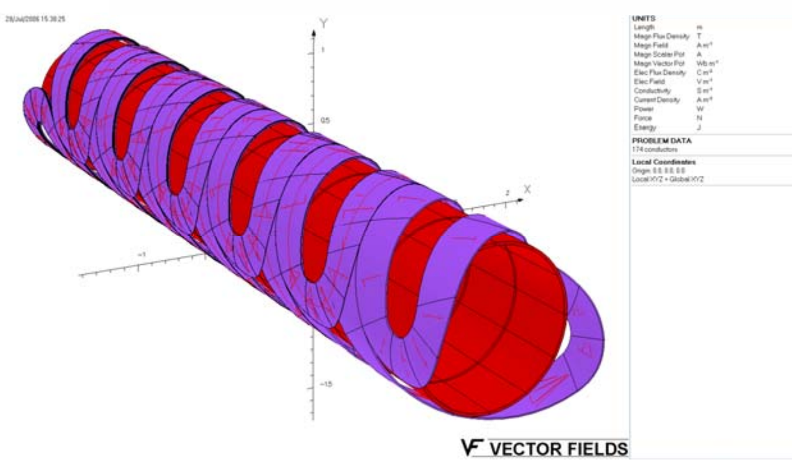
Yonehara, et al.

Comments on Helical Cooling channel

- Requires fitting magnets + rf into very tight geometry





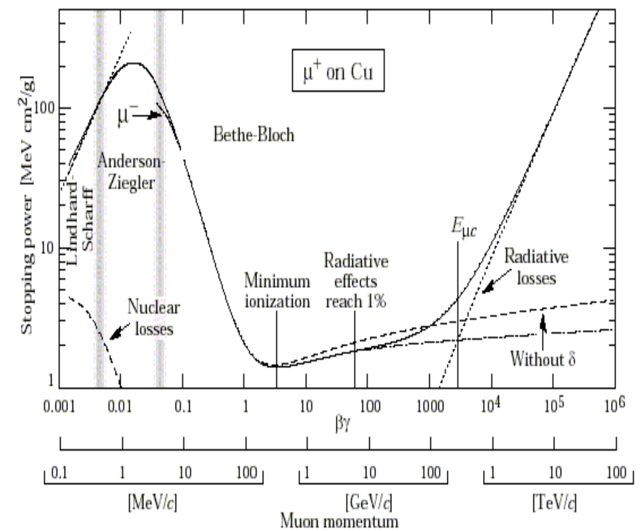


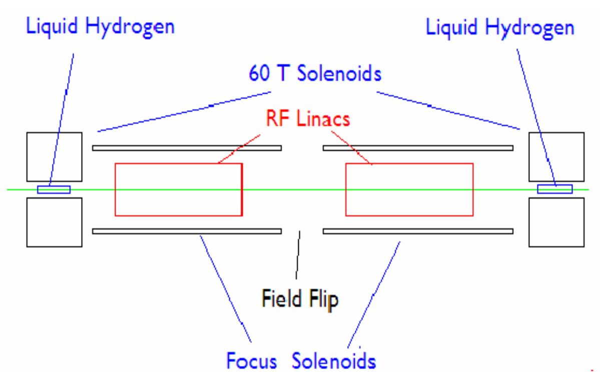
Reference Example

P_μ	200 MeV/c (0.67T-m)
λ	1.0m
a	0.16m
κ=ka= $P_\perp/P_z$	1
B	5.5T (Bρ/B=0.12m)
b(a)	1.28T (Bρ/b=0.52m)
b'(a)	-0.46T/m
D(a)- dispersion	0.29m
$\Delta_g = 1/\gamma_T^2$	0.9

Low-Energy "cooling"=emittance exchange

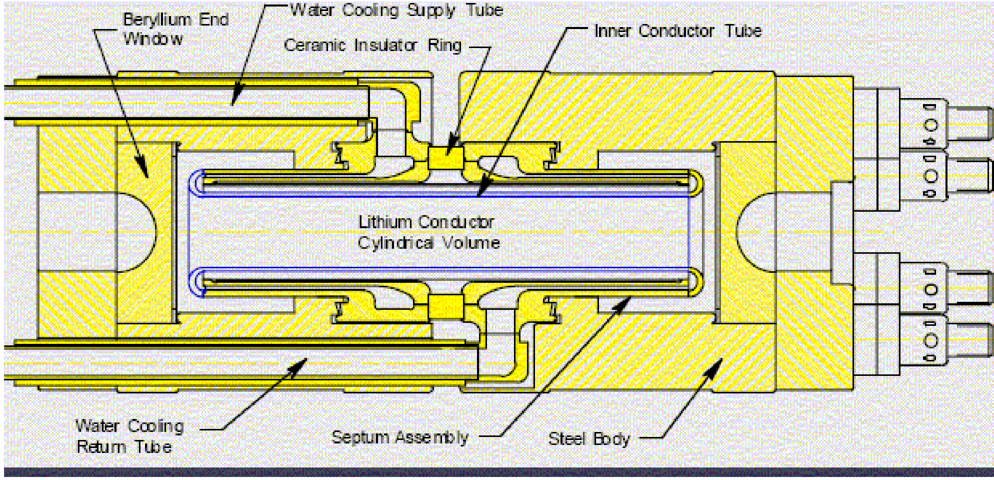
- dP_μ/ds varies as $\sim 1/\beta^3$
- "Cooling" distance becomes very short
- **Focusing can get quite strong:**
  - Solenoid: $\beta_\perp \approx \frac{2B\rho}{B} = \frac{2P_\mu}{0.3B}$
  - $\beta_\perp$=0.0013m at 50T, **10MeV/c**
- $\varepsilon_{N,eq}$= **1×10⁻⁶ m** at 10MeV/c
  - Small enough for "low-emittance" collider
- **But** Beam is heated longitudinally
  - ($\varepsilon_{6\text{-}D}$ is ~ constant)





Li-lens cooling

- **Lithium Lens** provides strong-focusing and low-Z absorber in same device
- **Liquid Li-lens** may be needed for highest-field, high rep. rate lens
- **BINP (Silvestrov)** started **prototype liquid Li lens** for FNAL, but not completed



$$\beta_\perp \approx \sqrt{\frac{B\rho}{B'}} = \sqrt{\frac{P_\mu}{0.3B'}}$$

μ-Cooling Li lens parameters

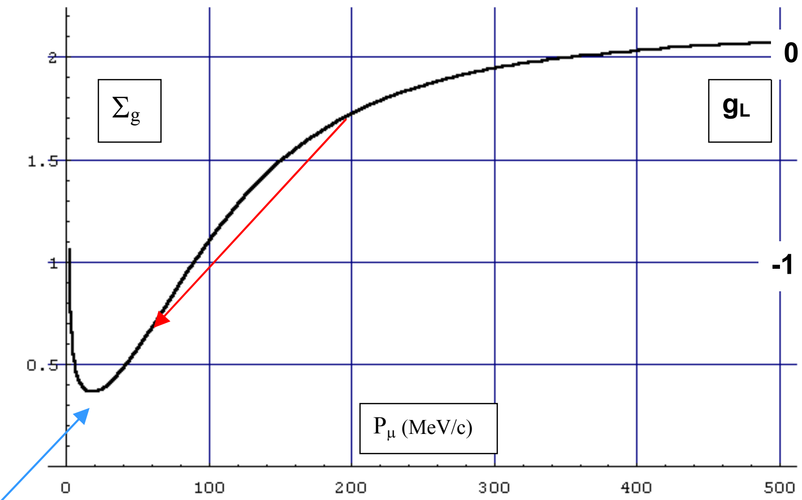
B(T)	B′ (T/m)	radius(cm)	Length(m)	I (MA)	τ(δ=0.7r)
10	1000	1	1	0.50	0.25ms
15	3000	0.5	1	0.375	64μs
20	8000	0.25	1	0.25	16μs

$\beta_\perp$ =0.026m (200 MeV/c, 1000 T/m)

$\beta_\perp$ =0.004m (40 MeV/c, 8000 T/m)

Other applications- not just muons!

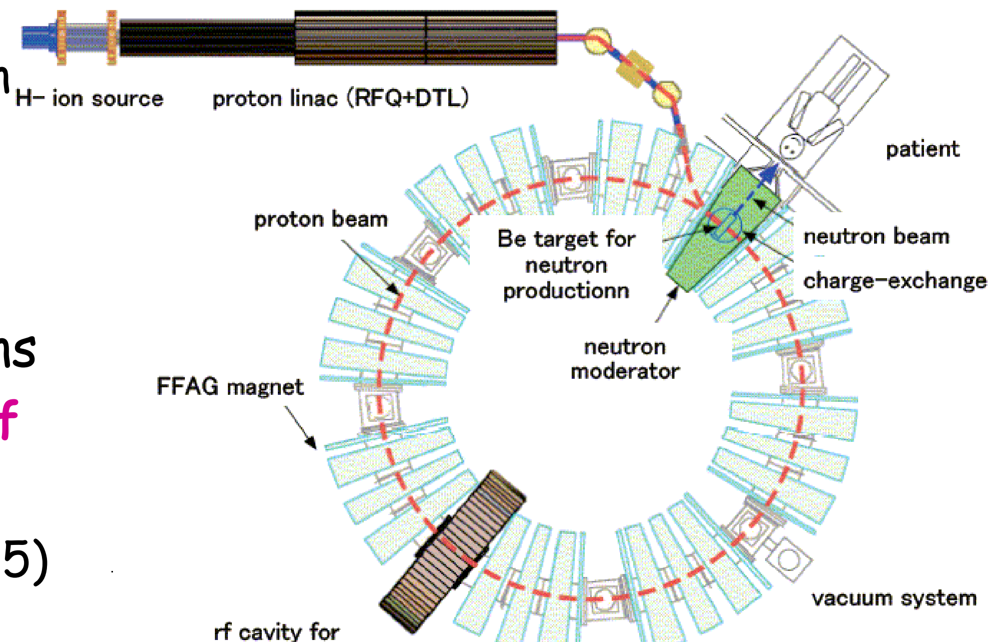
- . **Stopping μ beam**
  - (for μ2e conversion experiment)
  - C. Ankenbrandt et al., Muons, Inc.



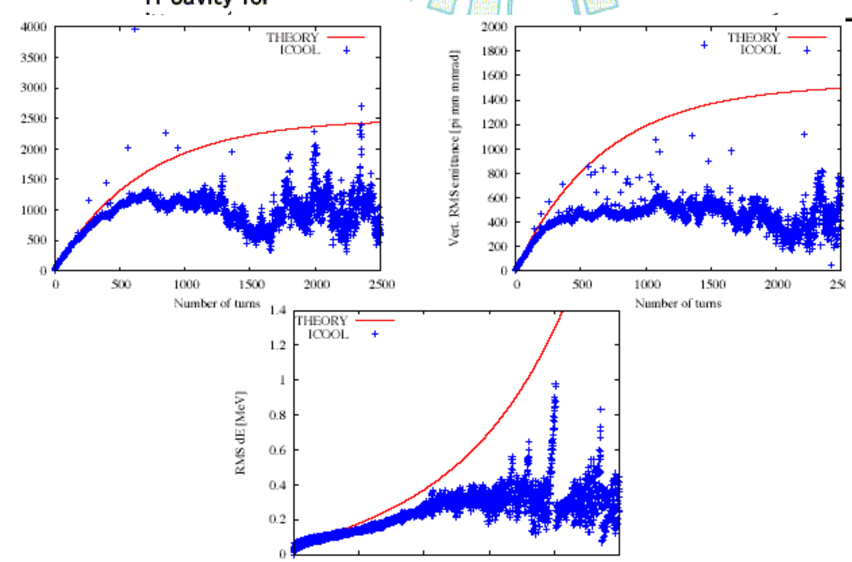
- For BCNT **neutron source**
  - Y. Mori - KURRI
- For **beta-beam** source
  - C. Rubbia et al
    - Nucl. Inst. and Meth. A 568, 475 (2006).
- …

FFAG-ERIT neutron source (Mori, KURRI)

- Ionization cooling of protons/ ions is unattractive because nuclear reaction rate ≅ energy-loss cooling rate

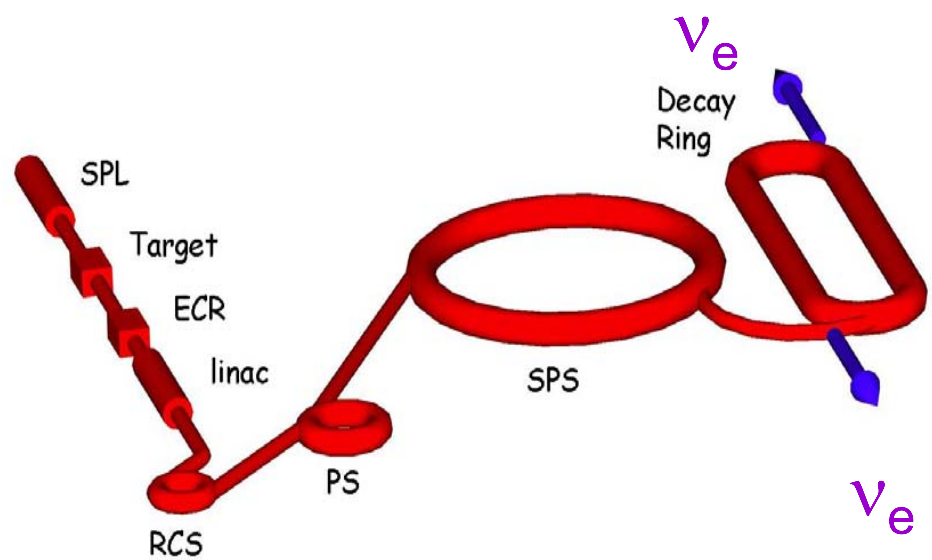


- **But** can work if the goal is beam storage to obtain nuclear reactions
  - ***Absorber is beam target, add rf***
- ERIT-P-storage ring to obtain neutron beam (Mori-Okabe, FFAG05)
- **10 MeV protons** (β = v/c =0.145)
  - ^{10}Be target for neutrons
  - 5μ Be absorber, wedge (possible)
  - δE_p=~36 keV/turn
- Increases beam lifetime to ~ 1000 turns (not actually cooling …)

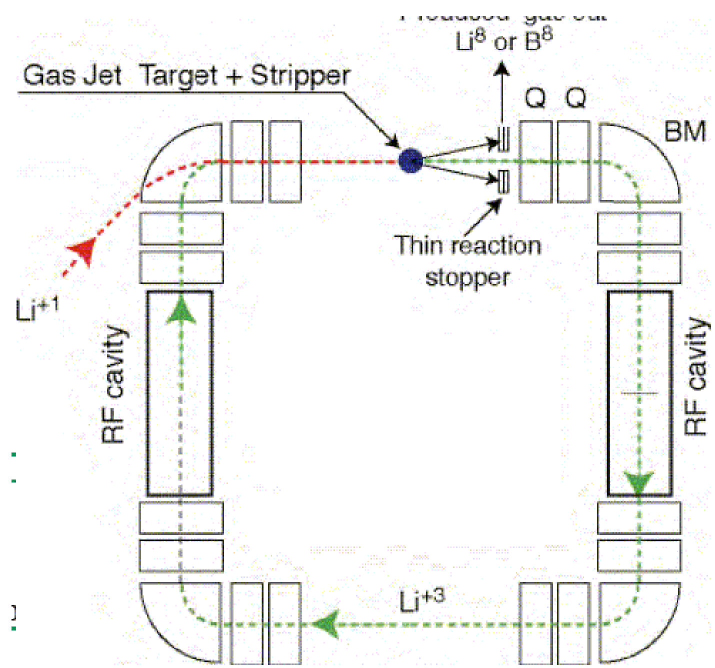


β-beam Scenario (Rubbia et al.)

- **β-beam** – another ν_e source
  - Produce accelerate, and store unstable nuclei for β-decay
  - Example: $^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ or $^{8}Li \rightarrow {}^{8}Be + e^{-} + \nu^{*}$



- Source production can use ionization cooling
  - Produce Li and inject at 25 MeV
  - nuclear interaction at gas jet target produces ^{8}Li or ^{8}B
    - $^{6}Li + {}^{3}He \rightarrow {}^{8}B + p$
  - Multiturn storage with **ionization “cooling”** maximizes ion production
  - ^{8}Li or ^{8}B is caught, is ion source for β-beam accelerator
  - Concept needs development



β-beams example: $^6Li + ^3He \rightarrow ^8B + n$

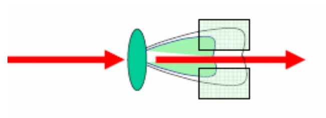
- Beam: **25MeV $^6Li^{+++}$**
  - P_{Li} =530 MeV/c Bρ = 0.6 T-m; v/c=0.094 **$J_{z,0}$=-1.6**
- Absorber: **^3He**
  - Z=2, A=3, I=31eV, z=3, a=6
    - dE/ds= 1180 MeV/gm/cm^2, L_R= 70.9 gm/cm^2
- If $g_{x,y,z}$ = 0.13 (**Σ_g = 0.4**), $\beta_\perp$ =0.3m at absorber
  - **Must mix both x and y with z**
  - $\varepsilon_{N,eq}$= ~ 0.000046 m-rad,
  - $\sigma_{x,rms}$= ~2 cm at $\beta_\perp$ =1m
- $\sigma_{E,eq}$ is ~ 0.4 MeV
- Promising but many problems …
- **Better with ^3He beam , ^6Li target**
  - D. Neuffer, NIM A 583, p.109 (2008).

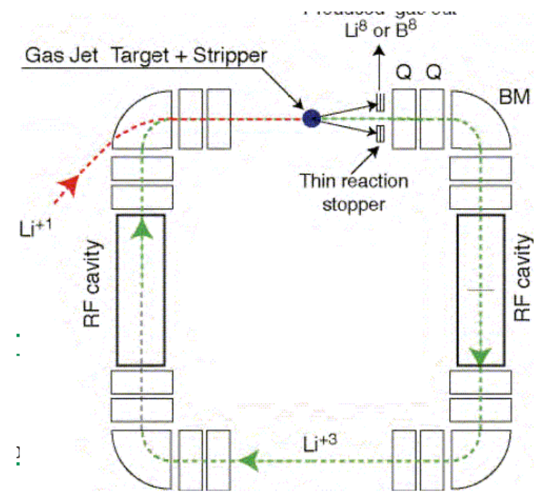
$$\varepsilon_{N,eq} \cong \frac{z^2 \beta_\perp E_s^2}{2 J_x \beta\, a m_p c^2 L_R \frac{dE_{z,a}}{ds}}$$

$$\sigma_{E,eq}^2 = \frac{(m_e c^2)(a m_p c^2)\beta^4 \gamma^3}{2 J_L \ln[]}\left(1 - \frac{\beta^2}{2}\right)$$

Beta beam source

- Key Difficulties
  - Gas jet target
  - Separation of created from circulating ions
  - MW cooling power

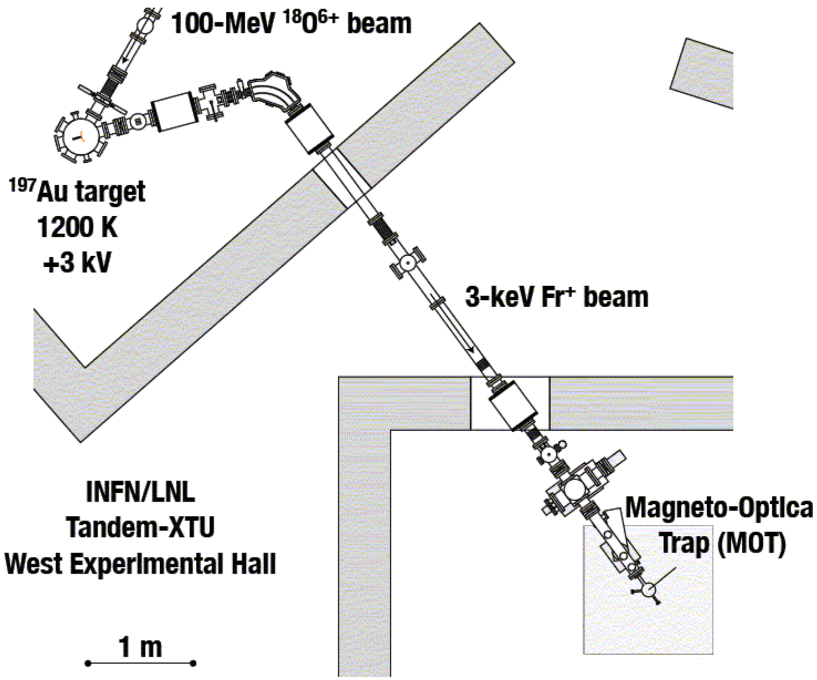


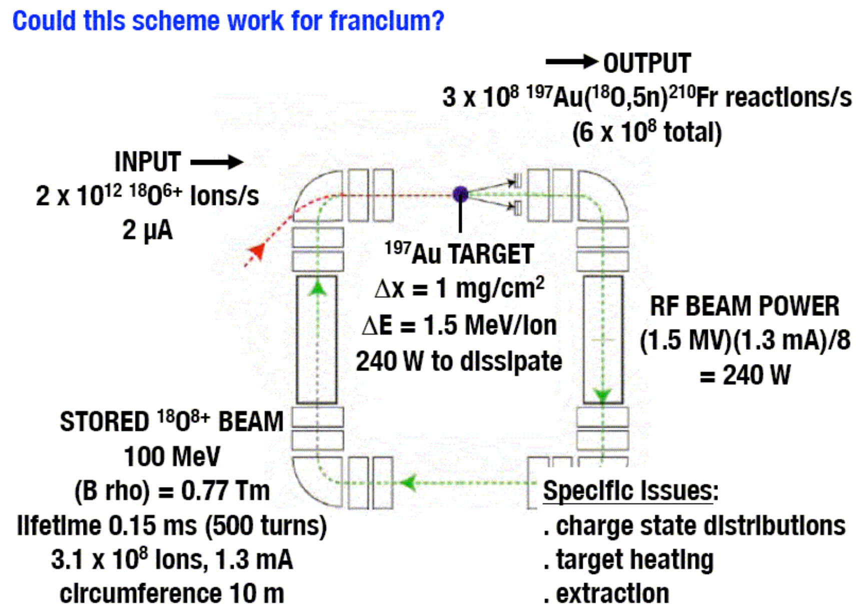


- Easier with He-3 beam, Li-6 target
  - Liquid Li "waterfall" target
  - B-8 more separated from He-3
  - 0.5 MW

Low energy Ion cooling for B-8 production			
Parameter	**Symbol**	**Reverse Dynamics**	**Direct Scenario**
Beam		$_6$Li	$_3$He
Absorber		$_3$He	$_6$Li
Momentum	P	530 MeV/c	265 MeV/c
Kinetic energy	T_a	25	12.5 MeV
Speed	$\beta = v/c$	0.094	0.094
Absorber density	ρ_{ref} (liquid or solid)	0.09375	0.46
Energy loss	dE/ds	110.6 MeV/cm	170.4 MeV/cm
Radiation Length		756cm	155cm
Betatron functions	$\beta_\perp, \eta$	0.3m, 0.3m	0.3m, 0.3m
Rms angle	$\delta\theta_{rms}$ ($\beta_t = 0.3$m)	2.25 K_s °	3.8 K_s °
Rms beam size	σ_t (at $\beta_t = 1$m)	2.15K_s cm	3.6K_s cm
Absorber thickness ()	L_{abs} (liquid)	0.018cm	0.00725cm
Characteristic Cooling Length	$(dP/ds/P)^{-1}$	0.45cm	0.147cm
Multiple scattering	d (θ^2) /ds	$8.84\times10^{-4}K_s^2$/cm	0.0078K_s^2/cm
Energy straggling	d(δE^2)/ds	0.0886 MeV^2/cm	0.143
Sum of partition numbers.	ΣJ_i	0.4	0.4
Eq. transverse emittance	$\varepsilon_{T,N,rms}$	$4.35\times10^{-5}K_s^2$ m	0.000123 K_s^2 m
Equilibrium $\delta P/P$ (J_z=0.13)	δ_{rms}	0.0078	
Maximum production angle	θ_{max}	14.5 °	30 °

Another possible application: Fr atoms

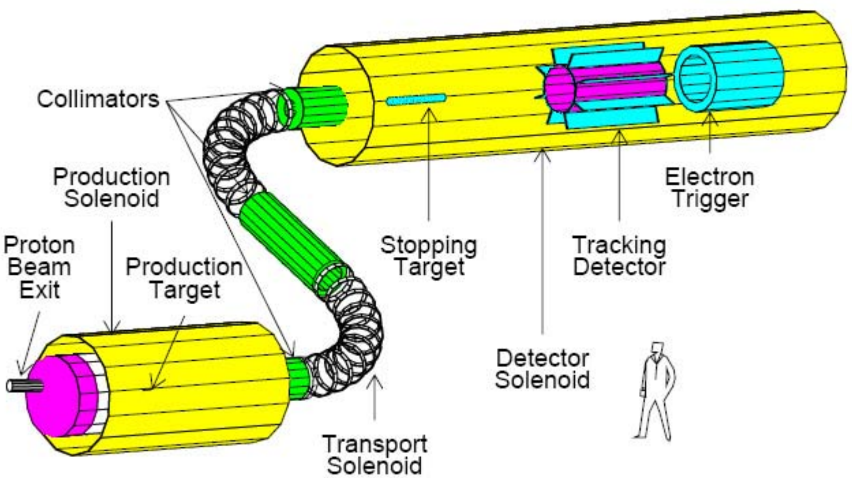


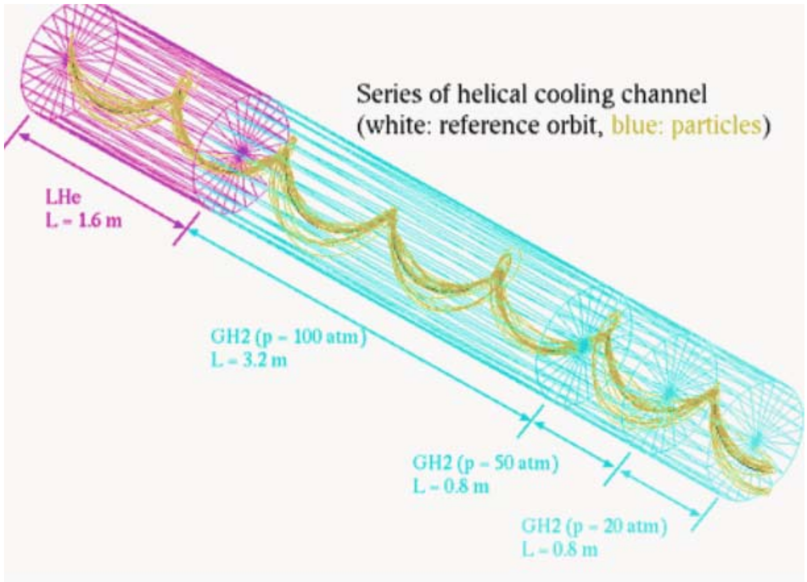


- Francium desirable for atomic parity violation measurements and Electric dipole moment.
- Scantari et al., INFN

μ2e experiment ~MECO

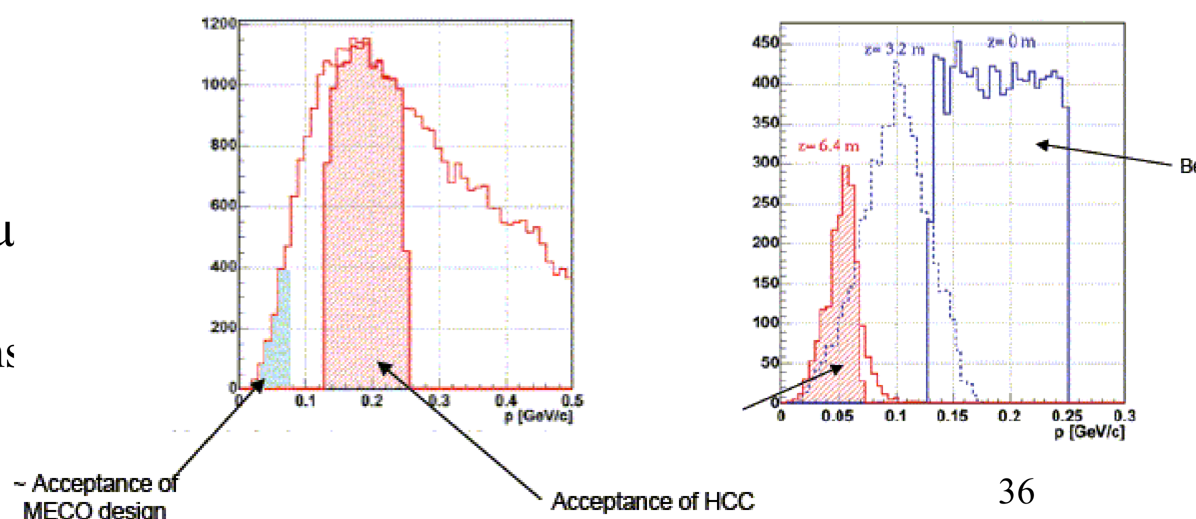
MECO





- Mu-E COnversion Experiment
  - $\mu^- + Z \rightarrow e^- + Z$
- Stopped μ^- beam
- Helical energy-loss cooling channel can greatly increase μ intensity
  - C. Ankenbrandt et al., Muons Inc./FNAL

Pi / Mu Production from Target



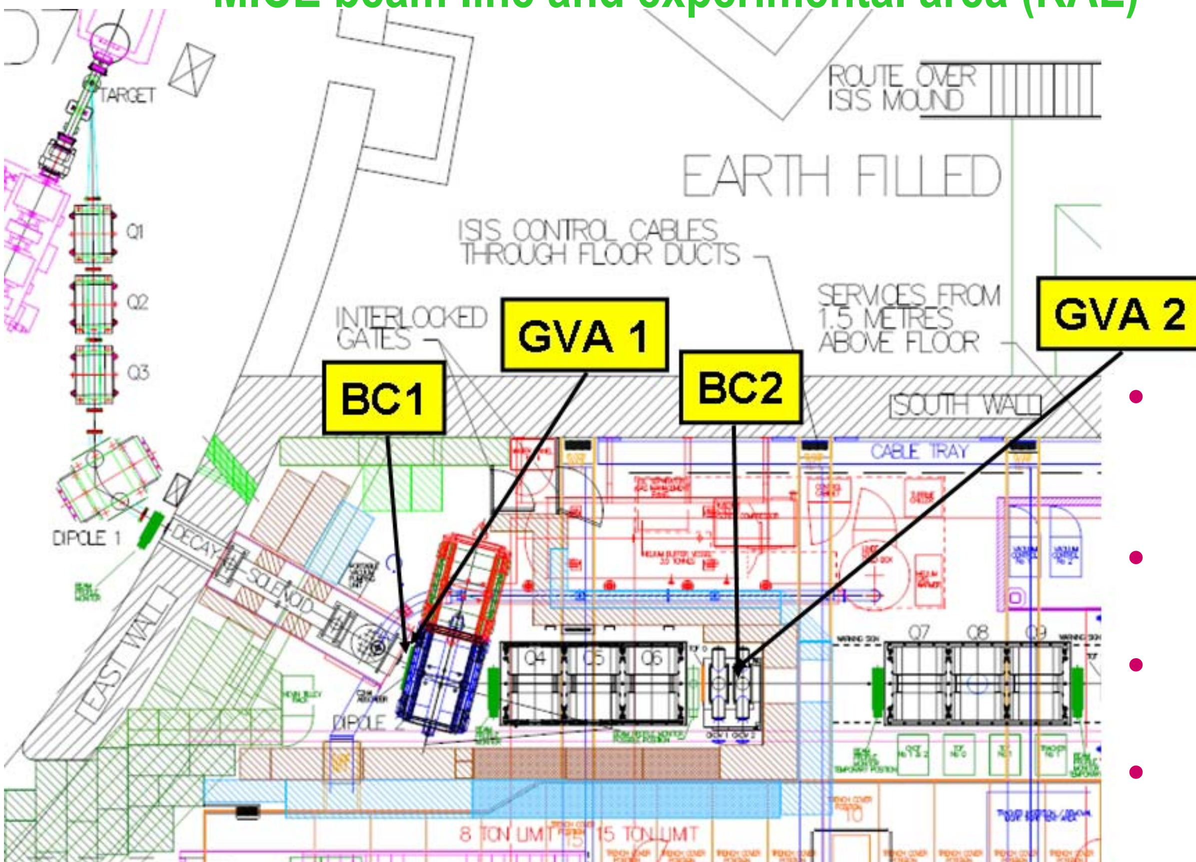
Ionization Cooling
Experimental R&D Program

- **MICE** –International Muon Ionization Cooling Experiment
  - μ-beam at RAL ISIS
  - Systems test of complete cooling system
- **MuCOOL** Program
  - Rf, absorber, magnet R&D-supports MICE
  - MuCOOL test area (Fermilab)
  - Muon Collider Task Force
- **MUONS, Inc.** (R. Johnson, et al.)
  - High-pressure rf cavities
  - Helical cooler, Parametric resonance cooler

MICE beam line (ISIS, RAL)

- MICE (International Muon Ionization Cooling Experiment)
- To verify ionization cooling (for a neutrino factory)
  with a test of a complete cooling module in a muon beam

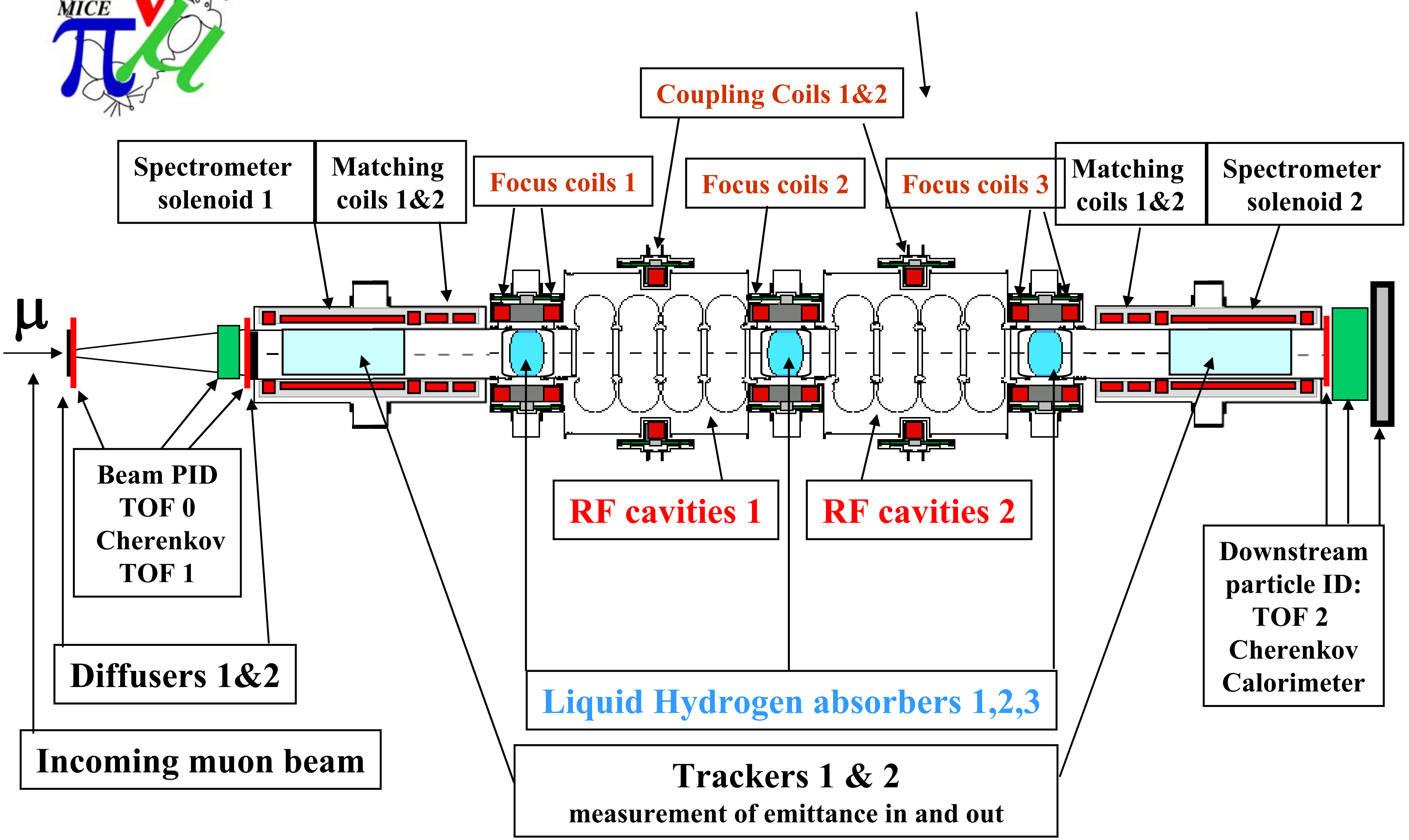
MICE beam line and experimental area (RAL)



- **Target** – Titanium paddle inserted into ISIS beam
- **GVA 1,2** – Scintillating paddles
- **BC1, 2** – Scinitllating fiber arrays
- **CKOV 1,2** – Cherenkov threshold detectors to identify pions

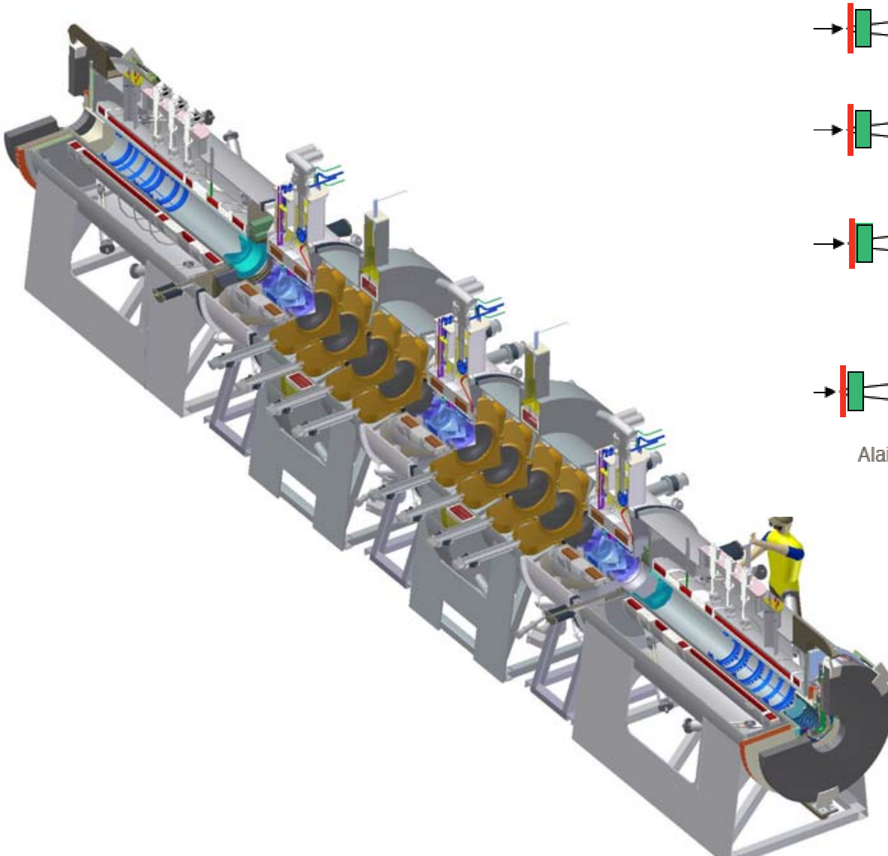
10% cooling of 200 MeV muons requires ~ 20 MV of RF

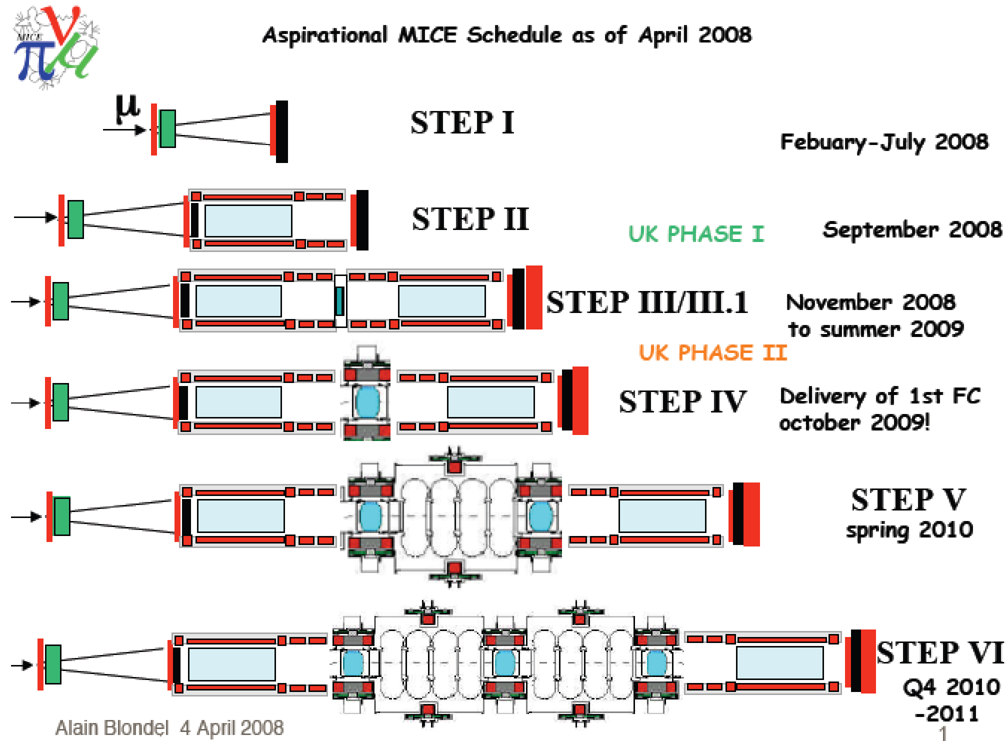
<u>single particle measurements</u> => $\Delta(\varepsilon_{out}/\varepsilon_{in}) = 10^{-3}$

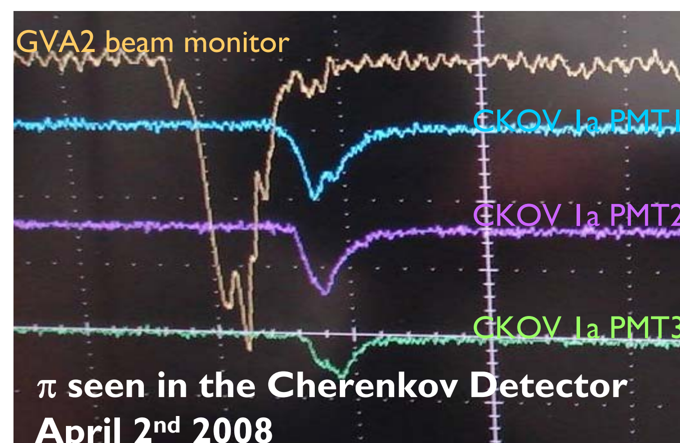


Muon Ionization Cooling Experiment (MICE)

MICE
Measurement of Muon Cooling
Emittance Measurement @ 10^{-3}
First Beam February 2008



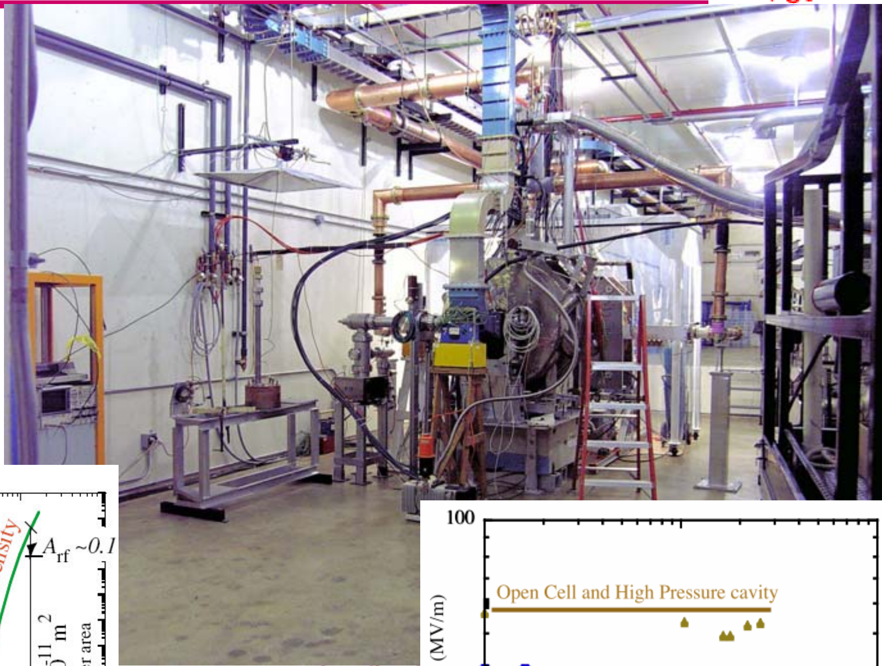


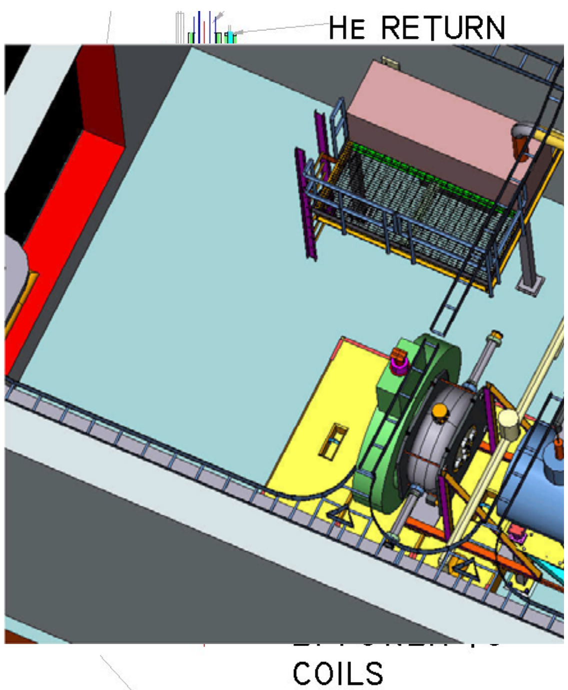


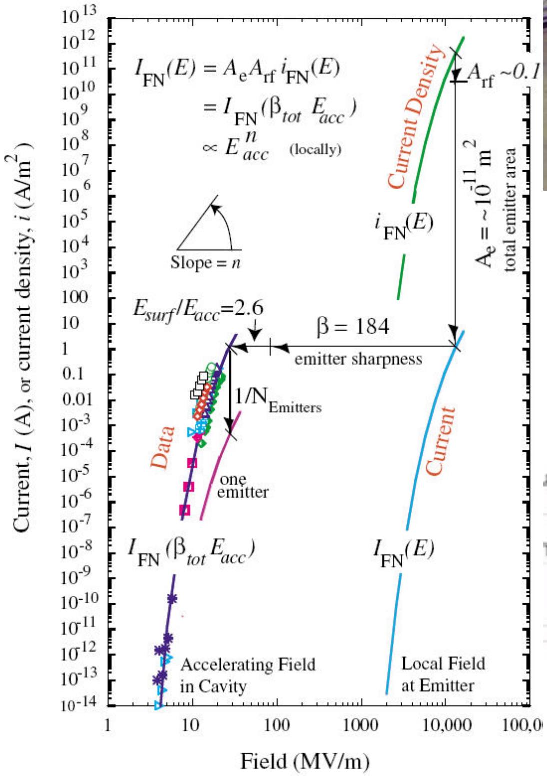
MICE components

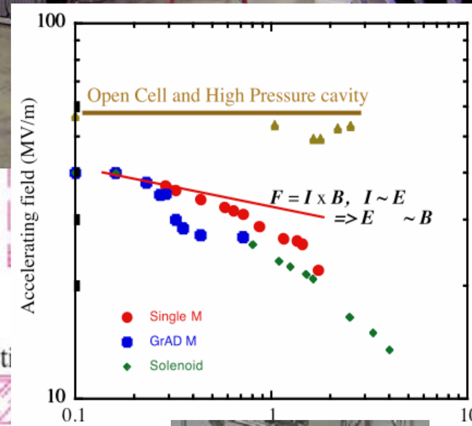
MuCOOL-MTA experimental program

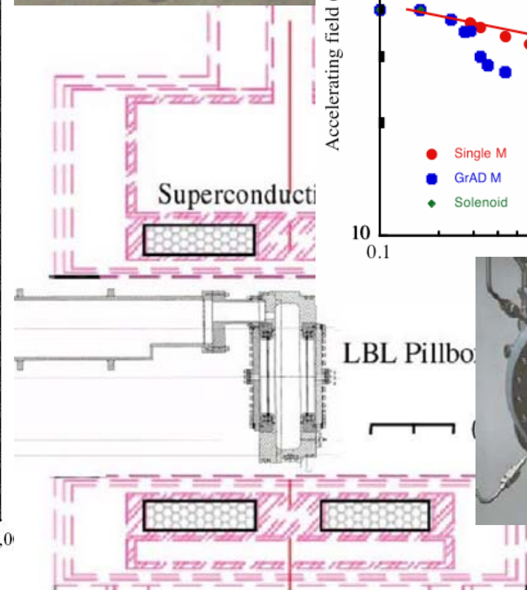
- Rf: 805, 201 MHz, gas-filled
  - **201MHz reached 16 MV/m**
  - 805 MHz 3T, gas-cavity test
- H_2 absorbers
- Solenoids





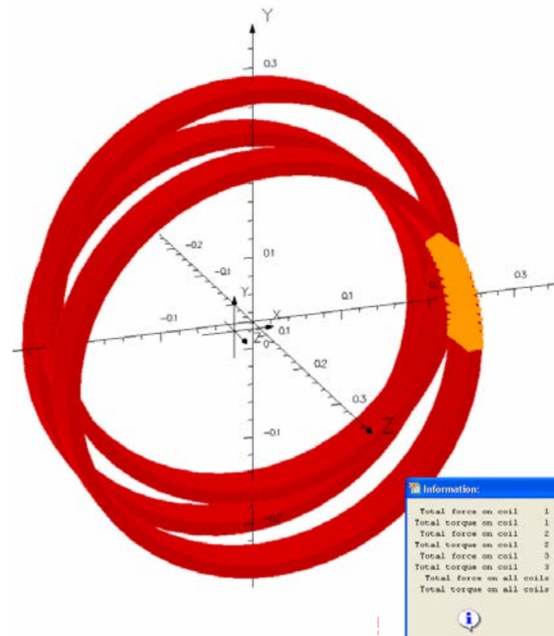


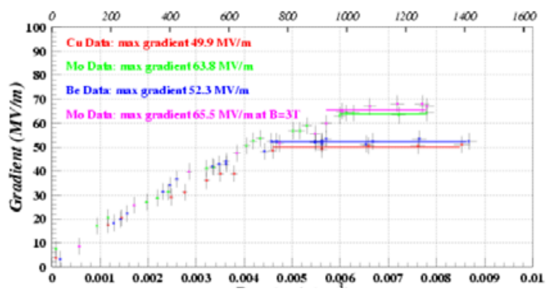




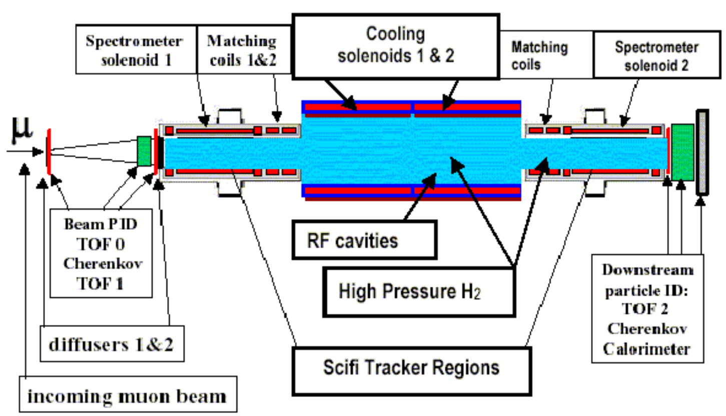
Muons, Inc. Experimental Program

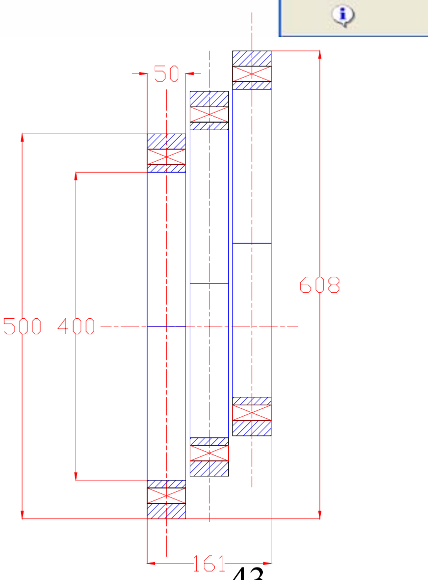
- **High Pressure Gas Cavities**
  - Absorber and energy recovery in
  - Gas limits breakdown, may permit **higher gradients**
  - Can operate in magnetic fields?
- Helical Wiggler 6-D cooling
  - 3-coil magnet prototype





MANX



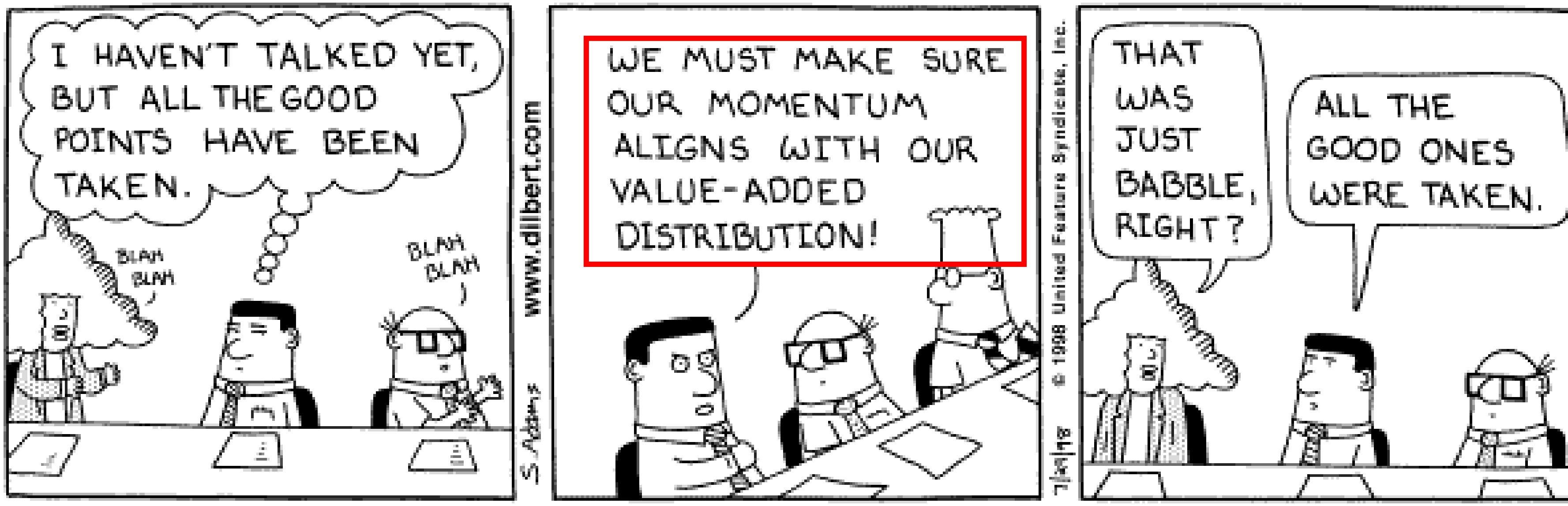


Summary

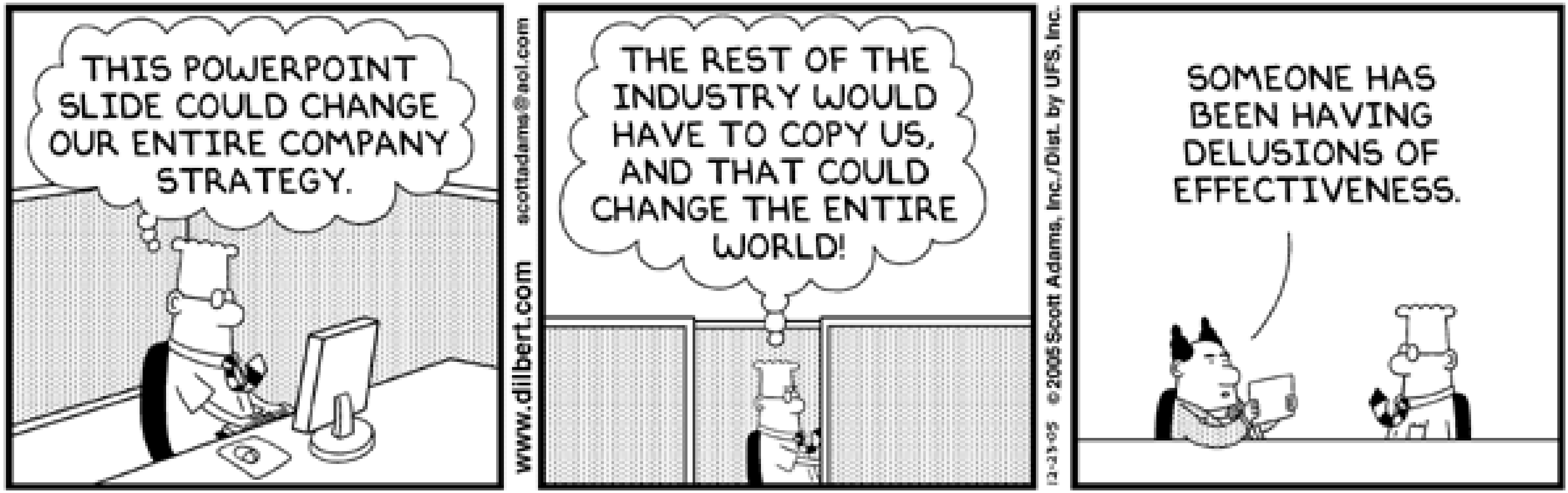
- Cooling for **Neutrino Factory** is practical
  - Components are being built & tested
- **Collider** cooling scenario has made great progress but needs development
  - **Longitudinal cooling** by large factors …
  - **Transverse cooling** by very large factors
  - **Final beam compression** with emittance exchange

Other Ionization Cooling applications are appearing

Cooling Summary:



Summary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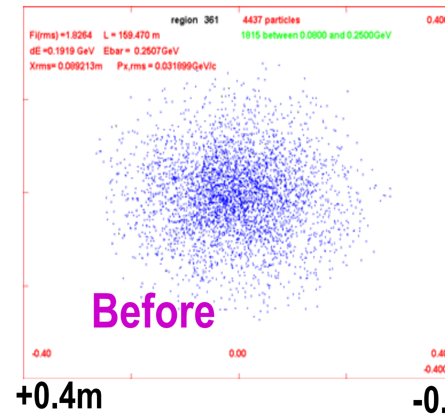
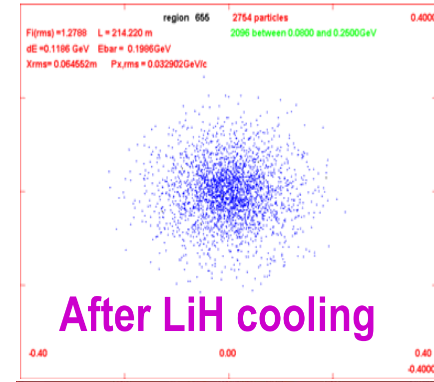
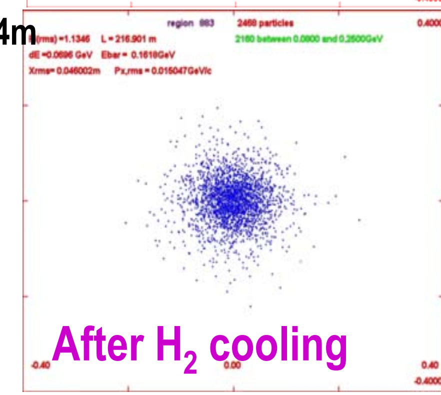
SOMEONE HAS BEEN HAVING DELUSIONS OF EFFECTIVENESS.

Variation: ν-Factory Cooling Channel

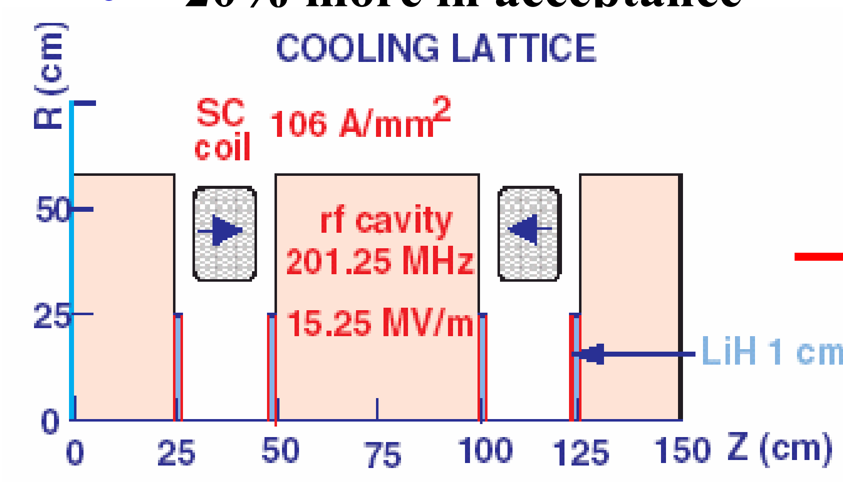
- Cooling is limited:
  - **LiH** absorber, $\beta_\perp \cong 0.8\text{m}$
  - $\varepsilon_\perp$ **from ~0.018 to ~0.0076m in ~80m**
  - $\varepsilon_{eq} \cong 0.0056\text{m}$
- Could be improved
  - **H_2 Absorber (120A) or smaller** $\beta_\perp$
  - $\varepsilon_\perp \rightarrow$ **~0.0055**
  - $\varepsilon_{eq} \cong 0.003\text{m}$
  - **~20% more in acceptance**

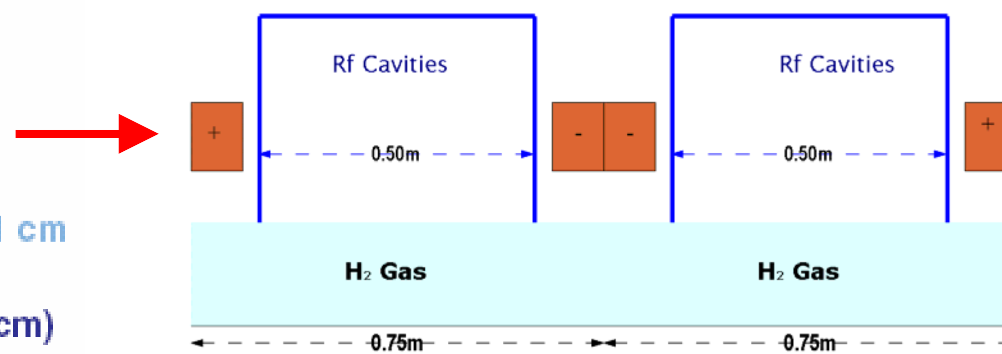






$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta c p_\mu}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{E_s^2}{\beta^2 c^2 p_\mu^2 L_R}$$

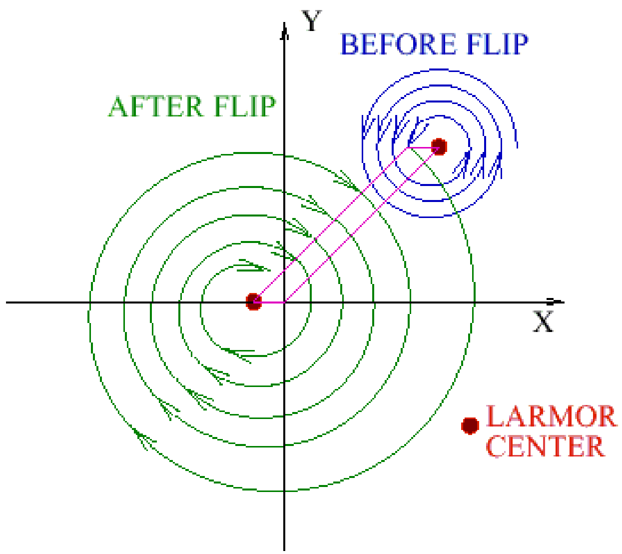




Solenoidal Focusing and Angular Momentum

- **Angular motion with focusing complicates cooling**
- **Energy loss in absorbers reduces $P_\perp$, including P_θ**

Orbits cool to Larmor centers, not r = 0



Solution:

Flip magnetic fields; new Larmor center is near r=0

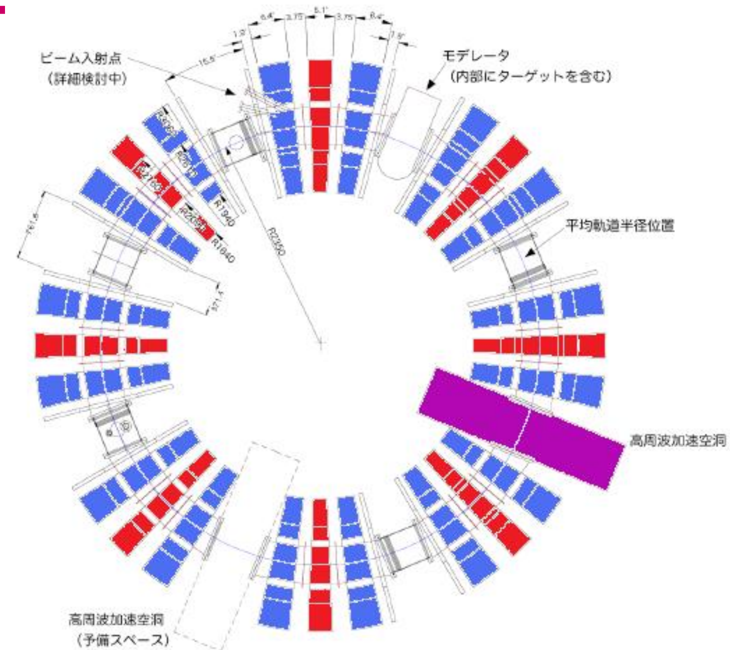
FFAG-ERIT – under construction

With baseline parameters, cannot cool both x and δE

$\Sigma J_i \cong 0.36;\ J_z = -1.6$

- Optimal x-E exchange could increases storage time from ~1000 to 3000 turns
- With x-y-E coupling, can cool 3-D with $g_i = 0.12$
  - Cooling time would be ~5000 turns
  - With $\beta_\perp$=0.2m, δE_{rms} = 0.4MeV $\varepsilon_{\perp,N}$ = 0.0004m (x_{rms}=2.3cm)
  - x_{rms}= 7.3cm at $\beta_\perp$=2m

- **Construction complete:**
  - **November 2007**
- First “cooling” demonstration

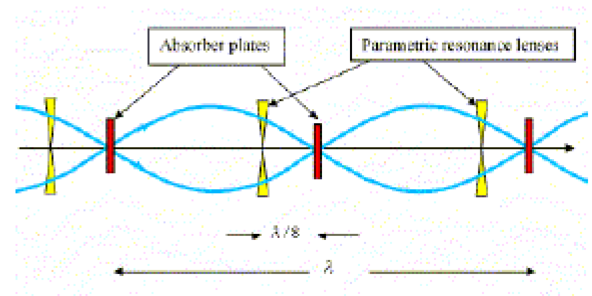


beam energy		11 MeV
ave. radius		2.35 m
most ext. radius of magnet		3.06 m
Fmagnet		
	field strength	0.825 T
	AT	58500 AT
	orbit length (@ave. radius)	26.25 cm
	mass	4.1 ton
Dmagnet		
	filed strength	0.727 T
	AT	54500 AT
	orbit length (@ave. radius)	20.92 cm
	mass	3.4 ton

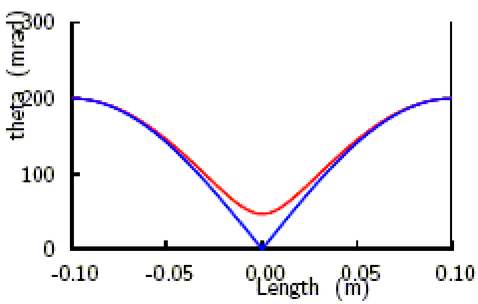
PIC-Parametric-resonance Ionization Cooling

(Y. Derbenev) (also Balbekov, 1997)

Excite ½ integer parametric resonance (in Linac or ring)



- Similar to vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx'=const to reduce x, increase x'
- Use Ionization Cooling to reduce x'



$$\begin{pmatrix} e^{-\Lambda} & 0 \\ 0 & e^{+\Lambda} \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ 0 & e^{-\lambda} \end{pmatrix} \rightarrow \begin{pmatrix} e^{-\Lambda} & 0 \\ 0 & 1 \end{pmatrix}$$

Then:

First: