Low-Energy Ionization “Cooling”

David Neuffer
Fermilab

Outline

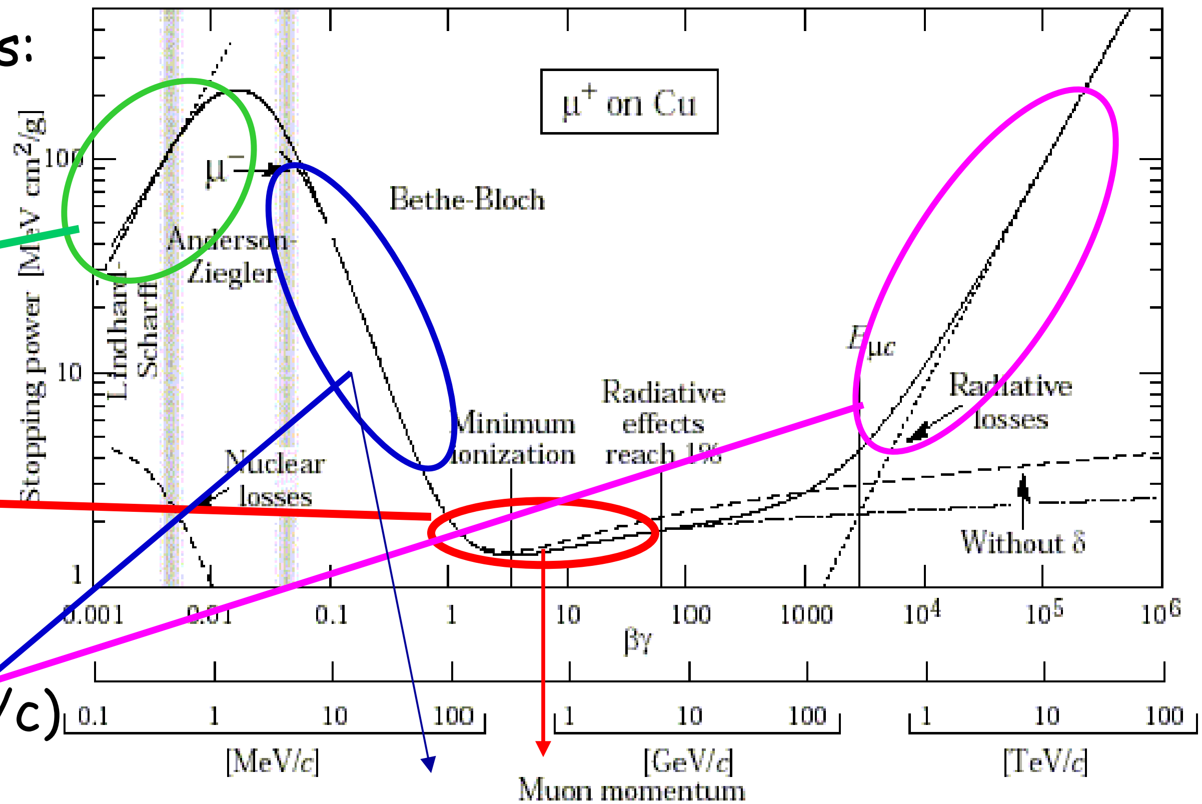
- Low-energy cooling-protons
- ions and “beta-beams”
- Low-energy cooling – muons
    - emittance exchange

μ Cooling Regimes

- Efficient cooling requires:

$$\frac{\partial \frac{dE}{dx}}{\partial E} > \sim 0$$

- Frictional Cooling (<1MeV/c) Σ_g=~3
- Ionization Cooling (~0.3GeV/c) Σ_g=~2
- Radiative Cooling (>1TeV/c) Σ_g=~4
- Low-ε_t cooling Σ_g=~2β^2 (longitudinal heating)



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

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

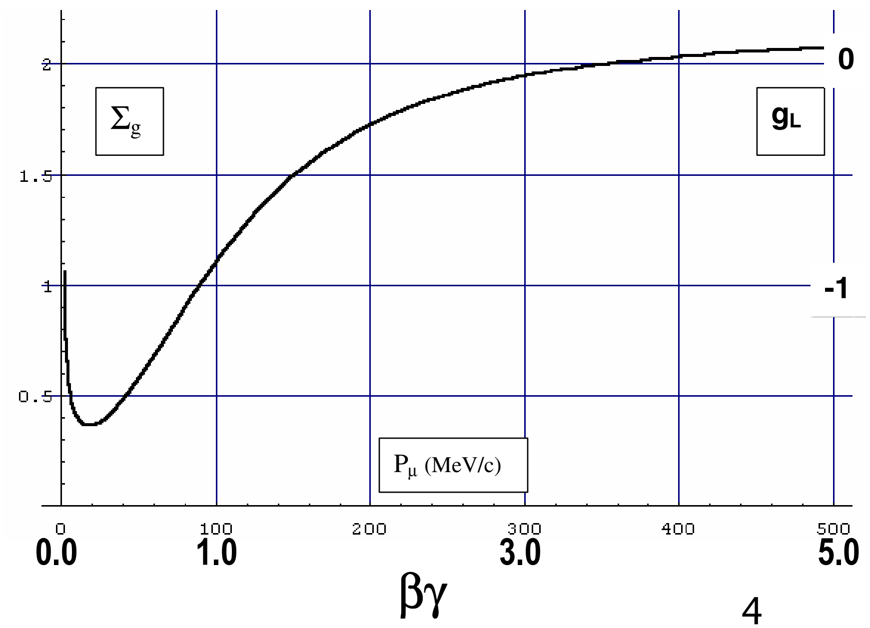
$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2 E_s^2}{3\beta^2 c^2 p_\mu^2 L_R}$$

Cooling/Heating equations

- Cooling equations are same as used for muons
  - mass = a m_p, charge = z e
  - Some formulae may be inaccurate for small β=v/c
  - Add heating through nuclear interactions
  - Ionization/recombination should be included
- For small β, longitudinal dE/dx heating is large
  - At β =0.1, g_L = -1.64, Σ_g = 0.36
  - Coupling only with x cannot obtain damping in both x and z

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

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



Low-energy "cooling" of ions

- **Ionization cooling of protons/ ions has been unattractive because nuclear reaction rate is competitive with energy-loss cooling rate**
  - **And other cooling methods are available**

- **But can have some value if the goal is beam storage to obtain nuclear reactions**
  - **Absorber is also nuclear interaction medium**
  - **Y. Mori – neutron beam source**
    - **NIM paper**
  - **C. Rubbia, Ferrari, Kadi, Vlachoudis – source of ions for β-beams**

Miscellaneous Cooling equations

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

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

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

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

$$\frac{d\varepsilon_N}{ds} = -\frac{1}{P}\frac{dP}{ds}\varepsilon_N + \frac{\beta_\perp}{2}\frac{z^2 E_s^2}{\beta^2 mc P L_R}$$

$$\ln[\,] \equiv \left[\ln\left(\frac{2m_e c^2\gamma^2\beta^2}{I(Z)}\right) - \beta^2\right]$$

Better for larger mass?

For small β:

$$\frac{\sigma_{p,eq}^2}{P_{z,a}^2} \cong \frac{m_e\gamma}{2 a m_p g_L \ln[\,]}$$

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

Example

- ERIT-P-storage ring to obtain directed neutron beam (Mori-Okabe, FFAG05)
- 10 MeV protons
  - ^{9}Be target for neutrons
  - σ ≈ 0.5 barns
  - β = v/c =0.145
  - Large δE heating
- Baseline Absorber
  - 5μ Be absorber
  - δE_p=~36 keV/turn
- Design Intensity
  - 1000Hz, 6.5×10^{10}p/cycle
  - 100W primary beam
  - < 1.5 kW on foil
    - 0.4 kW at n_{turns} =1000

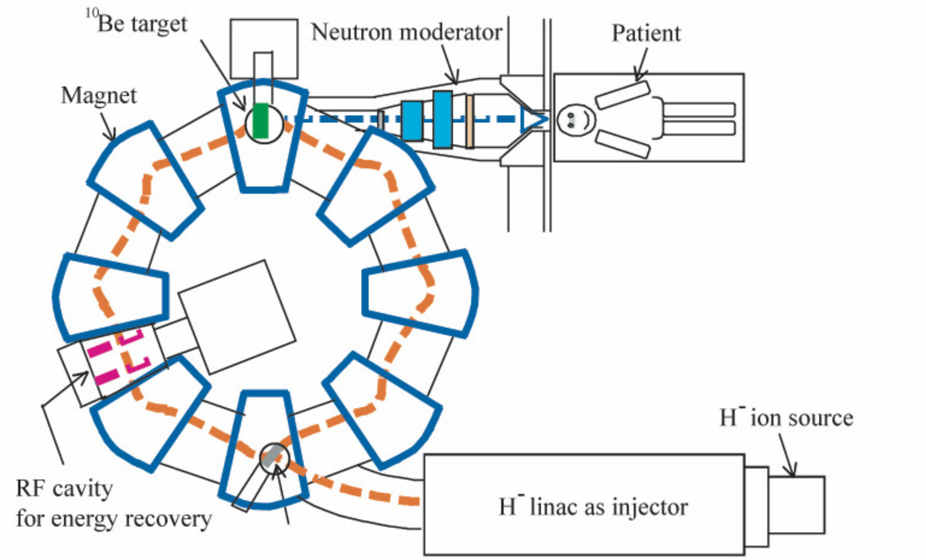
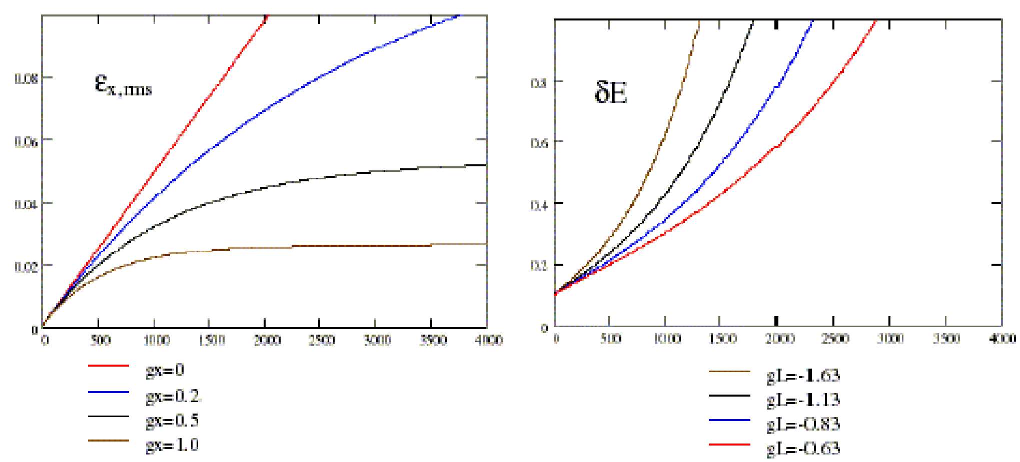


Table 1: Reference parameters of the ERIT Ring

Parameter	Symbol	Ref. Value	Units
Beam Kinetic Energy	E_p	10	MeV
Beam Momentum	P_p	137.4	MeV/c
Beam velocity	β=v/c	0.145	
Beam current	I_p	40	mA
Ring Circumference	C	11.3	m
Ring tunes	ν_x, ν_y	1.89,1.34	
Mean Betatron function	$\langle\beta_\perp\rangle$	0.95,	m
Maximum betatron functions	$\beta_{x,max}, \beta_{y,max}$	1.48,2.03	m
Dispersion (at wedge)	η_0	0.6	m
Transition gamma	γ_t	1.7	
Energy loss (Be) at ref. energy	dE/ds	72	MeV/cm
Sum of partition numbers (at E_p)	Σ_g	0.37	
Absorber central thickness	δz	5	μ
Mean energy loss / turn	δE_{AVE}	36	keV
Rf voltage	V_{rf}	200	kV/turn
Rf harmonic	h	5	
Rf frequency	f_{rf}	19.25	MHz
Longitudinal focusing function	β_ϕ	2.1	Radians/MeV

ERIT results

- **With only production reaction, lifetime is 30000 turns**
- **With baseline parameters, cannot cool both x and E**
  - **Optimal x-E exchange increases storage time from 1000 to 3000 turns (3850 turns = 1ms)**

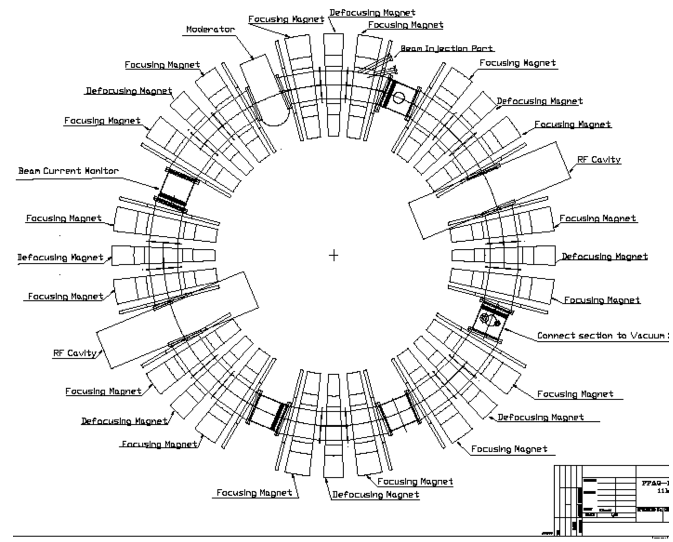


- **With x-y-E coupling, could cool 3-D with g_i= 0.12**
  - **Cooling time would be ~5000 turns**
  - **With $\beta_\perp$=0.2m, δE_{rms} = 0.4MeV, $\varepsilon_{\perp,N}$ = 0.0004m (x_{rms}=2.3cm)**
  - **x_{rms}= 7.3cm at $\beta_\perp$=2m (would need r =20cm arc apertures)**

    (but 1ms refill time would make this unnecessary)

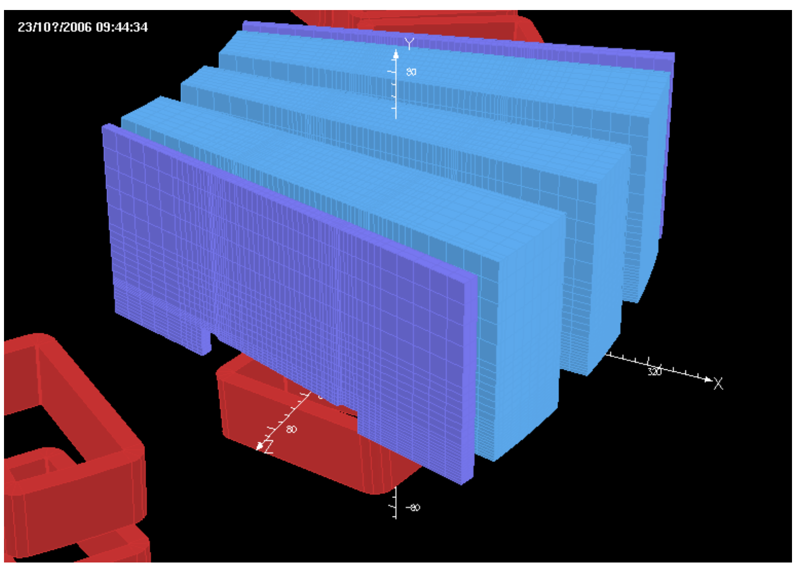
ERIT-recent results

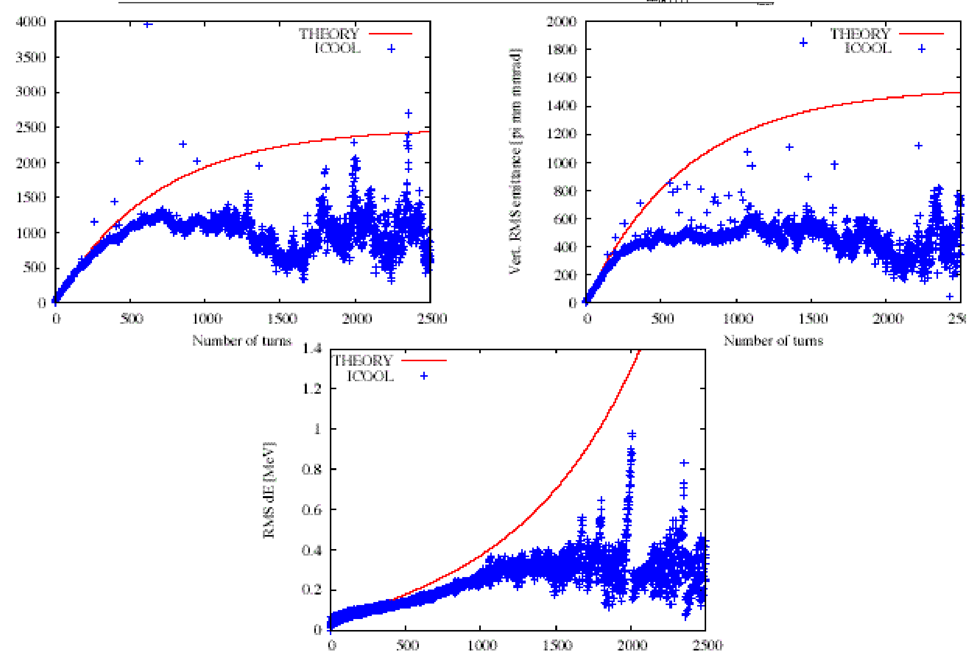
- **Lattice changed from spiral to radial sector**
  - **spiral sector had too small vertical aperture**



- **With cooling effects, beam has ~1000 turn lifetime in ICOOL simulation**

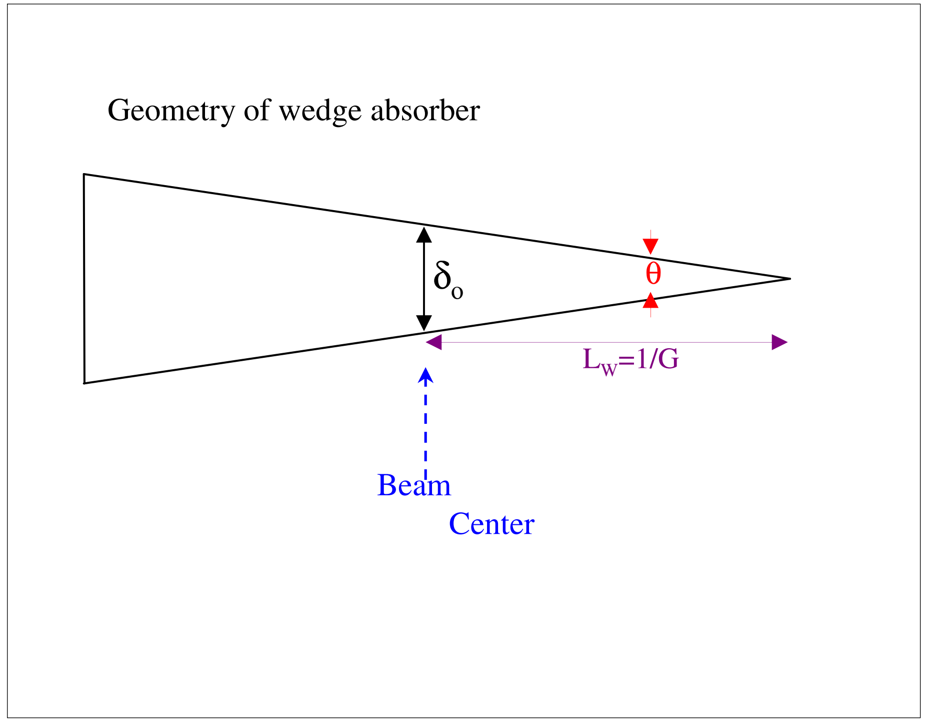
(Mori and Okabe FFAG06)





Emittance exchange parameters

- with $g_{L,0}$ = -1.63, η = 0.5m,
  - need G = 3.5m^{-1} to get g_L=0.12
    - (L_W =0.3m)
- For 3-D cooling, need to mix with both x and y
  - Solenoid cooling rings
- Also "Moebius" lattice (R. Talman)
  - Single turn includes x-y exchange transport
    - solenoid(s) or skew quads
    - in zero dispersion region for simplicity
    - Solenoid: BL = π Bρ
    - For 10 MeV p : BL = 1.44T-m
  - Complete period is 2 turns



$$g_L \rightarrow g_{L,0} + \frac{\eta\rho'}{\rho_0} = g_{L,0} + G\eta$$

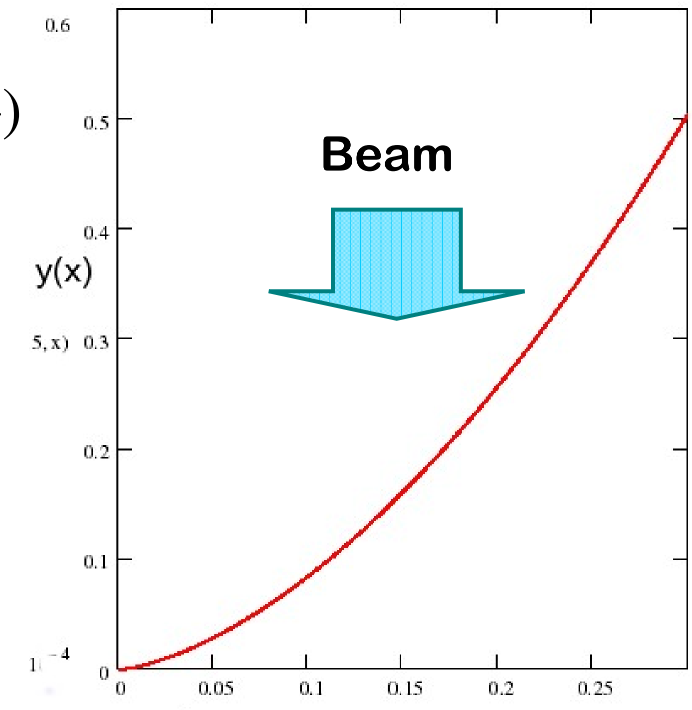
"Wedge" for thin foil

- **Obtain variable thickness by bent foil (Mori et al.)**

$$\delta(x) = \delta_R\sqrt{1 + y'(x)^2} = \delta_0\left(1 + \frac{(x - x_o)}{L_W}\right) = \delta_R\left(1 + \frac{x}{a}\right)$$

- **Choose x_0=0.15m, L_W=0.3, δ_o=5µ**
  - **then a=0.15, δ_R=2.5**
  - **for $g_{L,0}$ = -1.63, η = 0.5m**
- **Barely Compatible with β^* = 0.2m**

- **Beam energy loss not too large?**
  - **<1kW Power on foil**



a=0.15

$$y = \int\sqrt{\left(\frac{x}{a}\right)^2 + 2\left(\frac{x}{a}\right)}\cdot dx$$
$$= \frac{(a+x)\sqrt{x^2 + 2ax}}{2a} - a\ln\left[\sqrt{x} + \sqrt{a+x}\right]$$

Other heating terms:

- **Mixing of transverse heating with longitudinal could be larger effect: (Wang & Kim)**

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

$$\frac{d\varepsilon_x}{ds} = -g_x \frac{\frac{dP}{ds}}{P}\varepsilon_x + \frac{1}{2}\beta_x \frac{d\theta_{rms}^2}{ds} + \frac{1}{2}\frac{\eta^2}{\beta_x}\frac{d\delta_{rms}^2}{ds}$$

At ERIT parameters: β_x= 1.0m, β_z= 16m, η=0.6m, Be absorber, $d\delta^2/ds$= 0.00032, **$d\theta^2/ds$= 0.0133** **only 5%, 1.5% changes …**

At β_x= 0.2m, ~25% change …

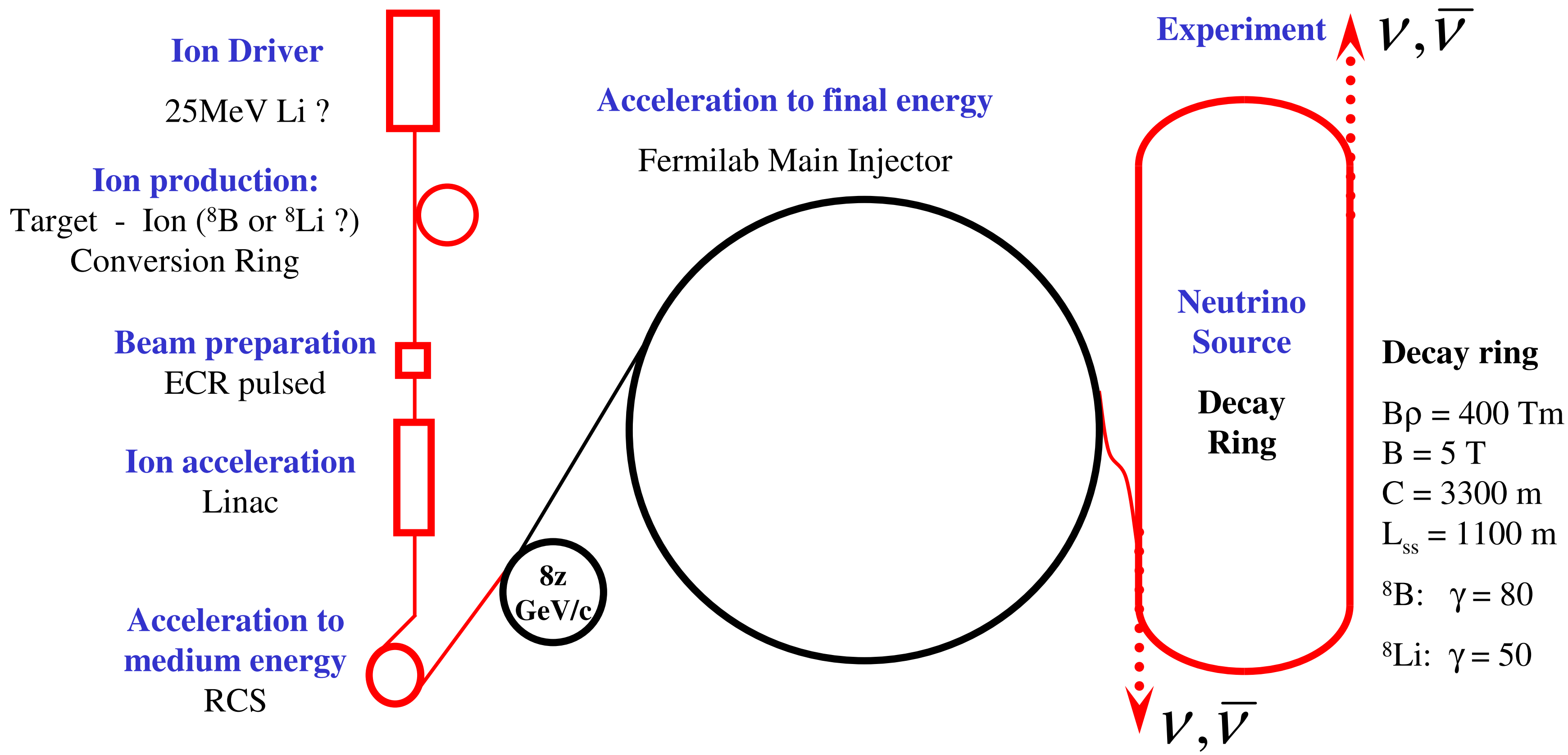
$$\frac{d\langle\theta_{rms}^2\rangle}{ds} = \frac{z^2E_s^2}{\beta^2c^2P_a^2L_R}$$

$$\frac{d(\delta_{rms}{}^2)}{ds} = 4\pi(r_e m_e c^2)^2 N_A \frac{Z}{A}\rho\frac{\gamma^2 z^2}{\beta^2 P_a^2}\left(1-\frac{\beta^2}{2}\right)$$

$$\beta_L = \sqrt{\frac{\beta^2 PcC\lambda_{RF}\left(\frac{1}{\gamma^2}-\frac{1}{\gamma_T^2}\right)}{2\pi eV_{RF}\cos\varphi_S}}$$

β-beam Scenario

Ion production | **Acceleration** | **Neutrino source**



Conventional Beta beam ion source

- **Want:**
  - **lifetime ~1s**
  - **large ν-energy**
  - **ν and ν***
  - **easily extracted atoms**
- **Number of possible ions is limited (ν sources easier)**

ν*-sources

Isotope	A/Z	T ½ (s)	Q_β g.s to g.s (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate (s^{-1})	rate / $E_{\nu\ av}$ (s^{-1})
^{6}He	3.0	0.80	3.5	3.5	1.57	1.94	$5 \cdot 10^{12}$	$4 \cdot 10^{10}$	$2 \cdot 10^{10}$
^{8}He	4.0	0.11	10.7	9.1	4.35	4.80	$5 \cdot 10^{12}$	$3 \cdot 10^{11}$	$6 \cdot 10^{10}$
^{8}Li	2.7	0.83	16.0	13.0	6.24	6.72	$3 \cdot 10^{12}$	$3 \cdot 10^{11}$	$4 \cdot 10^{9}$
^{9}Li	3.0	0.17	13.6	11.9	5.73	6.20	$3 \cdot 10^{12}$	$1 \cdot 10^{11}$	$2 \cdot 10^{10}$
^{11}Be	2.8	13.8	11.5	9.8	4.65	5.11	$3 \cdot 10^{12}$	$1 \cdot 10^{9}$	$2 \cdot 10^{8}$
^{15}C	2.5	2.44	9.8	6.4	2.87	3.55	$2 \cdot 10^{12}$	$5 \cdot 10^{9}$	$1 \cdot 10^{9}$
^{16}C	2.7	0.74	8.0	4.5	2.05	2.46	$2 \cdot 10^{12}$	$2 \cdot 10^{10}$	$6 \cdot 10^{9}$
^{16}N	2.3	7.13	10.4	5.9	4.59	1.33	$1 \cdot 10^{12}$	$1 \cdot 10^{9}$	$1 \cdot 10^{9}$
^{17}N	2.4	4.17	8.7	3.8	1.71	2.10	$1 \cdot 10^{12}$	$2 \cdot 10^{9}$	$1 \cdot 10^{9}$
^{18}N	2.6	0.64	13.9	8.0	5.33	2.67	$1 \cdot 10^{12}$	$2 \cdot 10^{10}$	$6 \cdot 10^{9}$

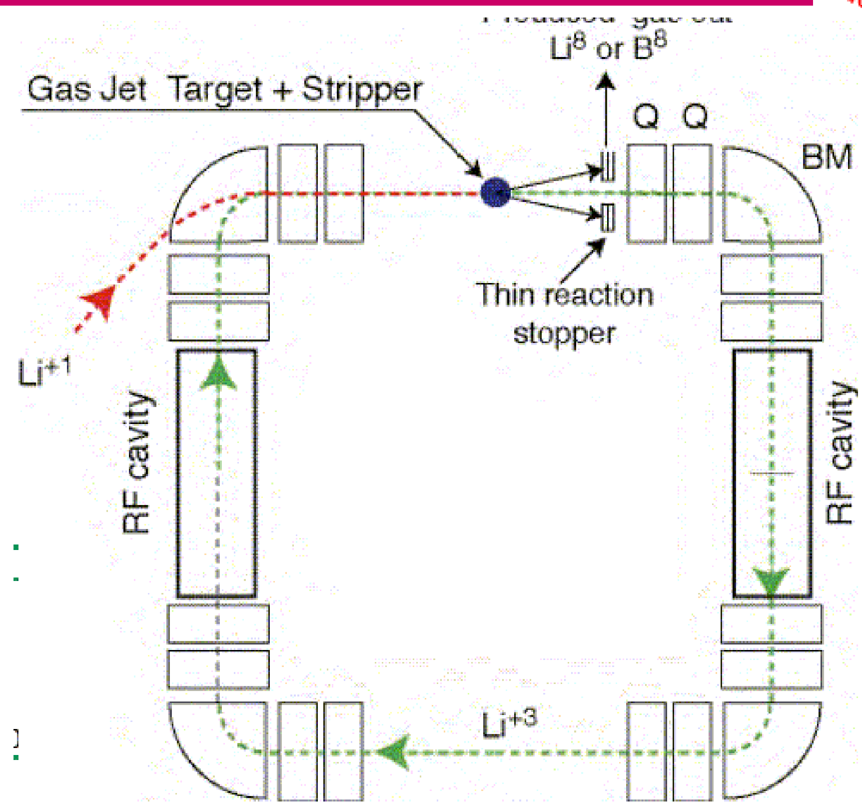
ν-sources

Isotope	A/Z	T ½ (s)	Q_β g.s. to g.s. (MeV)	Q_β eff (MeV)	E_β av (MeV)	E_ν av (MeV)	Ions/bunch	Decay rate (s^{-1})	rate / $E_{\nu\ av}$ (s^{-1})
^{8}B	1.6	0.77	17.0	13.9	6.55	7.37	$2 \cdot 10^{12}$	$2 \cdot 10^{10}$	$2 \cdot 10^{9}$
^{10}C	1.7	19.3	2.6	1.9	0.81	1.08	$2 \cdot 10^{12}$	$6 \cdot 10^{8}$	$6 \cdot 10^{8}$
^{14}O	1.8	70.6	4.1	1.8	0.78	1.05	$1 \cdot 10^{12}$	$1 \cdot 10^{8}$	$1 \cdot 10^{8}$
^{15}O	1.9	122.	1.7	1.7	0.74	1.00	$1 \cdot 10^{12}$	$7 \cdot 10^{7}$	$7 \cdot 10^{7}$
^{18}Ne	1.8	1.67	3.3	3.0	1.50	1.52	$1 \cdot 10^{12}$	$4 \cdot 10^{9}$	$3 \cdot 10^{9}$
^{19}Ne	1.9	17.3	2.2	2.2	0.96	1.25	$1 \cdot 10^{12}$	$4 \cdot 10^{8}$	$3 \cdot 10^{8}$
^{21}Na	1.9	22.4	2.5	2.5	1.10	1.41	$9 \cdot 10^{11}$	$3 \cdot 10^{8}$	$2 \cdot 10^{8}$

- **Noble gases easier to extract**
  - **$^{6}He_{2}$ "easiest" E_{ν^*} =1.94MeV**
  - **$^{18}Ne_{10}$ for ν E_{ν} =1.52MeV**
- **(^{8}B, ^{8}Li) have E_{ν,ν^*} =~7MeV**
- **Want 10^{20} ν and ν* / year…**

β-beam Scenario (Rubbia et al.)

- Produce Li and inject at 25 MeV
  - Charge exchange injection
- nuclear interaction at gas jet target produces ^{8}Li or ^{8}B
- Multiturn with cooling maximizes ion production
- ^{8}Li or ^{8}B is caught on stopper(W)
  - heated to reemit as gas
- ^{8}Li or ^{8}B gas is ion source for β-beam accelerate
- Accelerate to Bρ = 400 T-m
  - Fermilab main injector
- Stack in storage ring for:
- $^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ or $^{8}Li \rightarrow {}^{8}Be + e^{-} + \nu^{*}$ neutrino source



Cooling for β-beams (Rubbia et al.-NuFACT06)

- β-beam requires ions with appropriate nuclear decay
  - $^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$
  - $^{8}Li \rightarrow {}^{8}Be + e^{-} + \nu^{*}$
- Ions are produced by nuclear interactions
  - $^{6}Li + {}^{3}He \rightarrow {}^{8}B + n$
  - $^{7}Li + {}^{2}H \rightarrow {}^{8}Li + {}^{1}H$
  - Secondary ions must be collected and reaccelerated
- Either heavy or light ion could be beam or target
  - Ref. 1 prefers heavy ion beam – ions are produced more forward ("reverse kinematics")
  - He or ^{2}H beam on Li has other advantages ….
- Parameters can be chosen such that target "cools" beam
  - (losses and heating from nuclear interactions, however…)

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

- Beam: 25MeV $^6Li^{+++}$
  - P_{Li} =529.9 MeV/c Bρ = 0.59 T-m; v/c=0.09415
- Absorber: ^3He
  - Z=2, A=3, I=31eV, z=3, a=6
  - dE/ds= 1180 MeV/gm/cm², L_R= 70.9 gm/cm²

($\rho_{He\text{-}3}$= 0.09375 gm/cm³)Liquid, ($\rho_{He\text{-}3}$= 0.134·10^{-3}P gm/cm3/atm in gas)

- If g_x = 0.123 (Σ_g = 0.37), $\beta_\perp$ =0.3m at absorber
  - $\varepsilon_{N,eq}$= ~ 0.000046 m-rad
  - $\sigma_{x,rms}$= 1.2 cm at $\beta_\perp$ =0.3m,
  - $\sigma_{x,rms}$= 3.14 cm at $\beta_\perp$ =2.0m

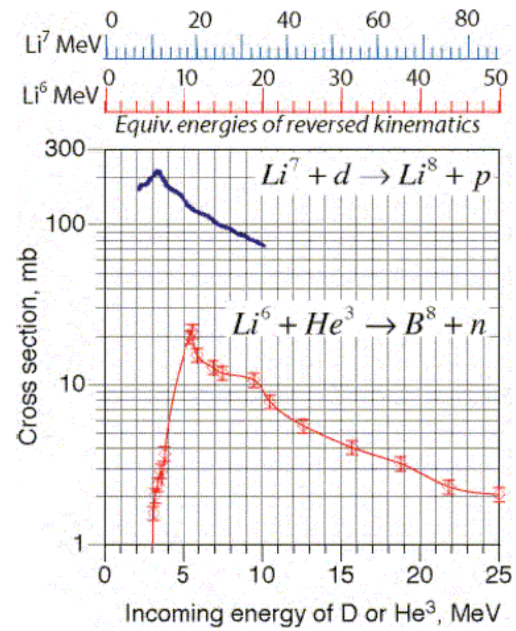
$$\varepsilon_{N,eq} \cong \frac{z^2 \beta_\perp E_s^2}{2 g_x \beta\, a m_p c^2 L_R \frac{dE_{z,a}}{ds}}$$

- $\sigma_{E,eq}$ is ~ 0.4 MeV
  - ln[ ]=5.68

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

Cooling time/power: $^6Li + {}^3He \rightarrow {}^8B + n$

- Nuclear cross section for **beam loss is 1 barn (10^{-24} cm^2)** or more
- $\sigma = 10^{-24}$cm^2 corresponds to ~5gm/cm^2 of ^{3}He
  - ~10 3-D cooling e-foldings …
- Cross-section for ^{8}B production is ~10 mbarn
  - At best, 10^{-2} of ^{6}Li is converted
- Goal is **10^{13}/s of ^{8}B** production
  - then at least 10^{15} Li^6/s needed
- Space charge **limit is ~10^{12} ^{6}Li/ring**
  - Cycle time is <10^{-3} s
  - If C=10m, τ =355 ns, 2820 turns/ms
  - 5/2820=1.773*10^{-3} gm/cm^2 (0.019 cm @ liquid density …)
  - 2.1 MeV/turn energy loss and regain required …(0.7MV rf)
  - **0.944 MW** cooling rf power…



Complementary case- $^{7}Li + ^{2}H \rightarrow ^{8}Li + ^{1}H$

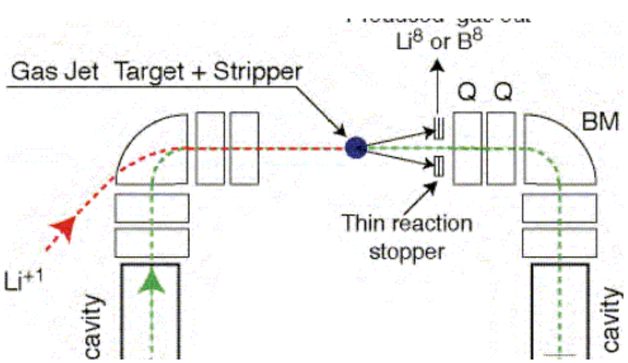
- Nuclear cross section for **beam loss is 1 barn (10^{-24} cm^2)** or more
- $\sigma = 10^{-24}$cm^2, corresponds to ~3.3gm/cm^2 of ^{2}H
  - ~9 3-D cooling e-foldings …
- Cross-section for ^{8}Li production is ~100 mbarn
  - 10^{-1} of ^{7}Li is converted ?? **10 × better than ^{8}B neutrinos**
- Goal is **10^{13}/s of ^{8}Li** production
  - then at least 10^{14} Li^{7}/s needed
- Space charge **limit is ~10^{12} ^{7}Li/ring**
  - Cycle time can be up to 10^{-2} s, but use 10^{-3}s
  - If C=10m, τ =355 ns, 2820 turns
  - 3.3/2820=1.2*10^{-3} gm/cm^2 (0.007 cm @ liquid D density …)
  - 1.3 MeV/turn energy loss and regain required …(0.43MV rf)
  - **0.06 MW** cooling rf power…

Space charge – Direct/inverse ?

- At $N = 10^{12}$, $B_F = 0.2$, $\beta = 0.094$, $z=3$, $a=6$, $\varepsilon_{N,rms} = 0.000046$:

  $\delta\nu \approx 0.2$

  - tolerable ??
- Space charge sets limit on number of particles in beam and on transverse emittance
- Effect is reduced for "direct kinematics"
  - (D/He beam, Li target)



$$\delta\nu \cong \frac{z^2 r_p N_{tot}}{4\pi\beta\gamma^2 a B_F \varepsilon_{N,rms}}$$

- Is "direct" source better than "inverse" source?
  - $^6Li_3$ beam + $^3He_2$ target
    - or
- $^3He_2$ beam + $^6Li_3$ target
- Beam energy, power on target less (1/2to 1/3)
- Li foil or gas-jet target?
  Gas-jet nozzle for wedge effect
- > 0.1MW power on target

Rubbia et al. not completely wrong

- …But contains mistakes
- Longitudinal emittance growth 2× larger
  - (than NuFACT06 presentation)
  - synchrotron oscillations reduce energy spread growth rate but not emittance growth rate
- Emittance exchange needs x-y coupling and balancing of cooling rates to get 3-D cooling
  - More complicated lattice
- 3-D cooling needed to get enough ions

- Increases equilibrium emittance, beam size
  - increase needed for space charge, however
- Ion production to storage ring efficiency is not 100% …

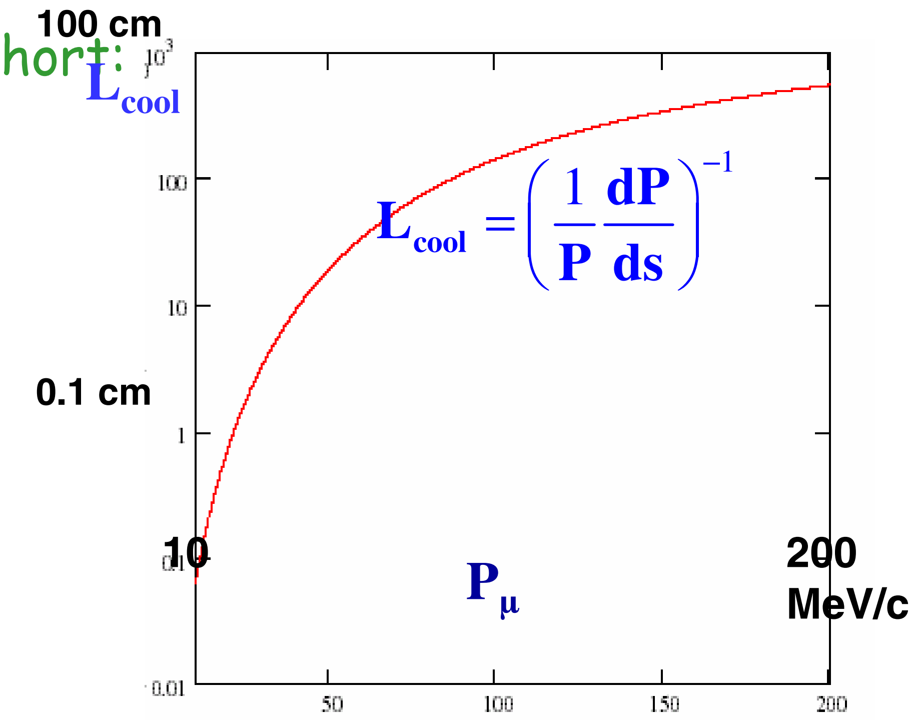
μ Low-Energy "cooling"- emittance exchange

- dP_μ/ds varies as $\sim 1/\beta^3$
- "Cooling" distance becomes very short:

$$\frac{dP_\mu}{P_\mu ds} = 16 cm^{-1}$$

for liquid H at P_μ=10MeV/c

- Focusing can get quite strong:
  - **Solenoid:** $$\beta_\perp \approx \frac{2B\rho}{B} = \frac{2P_\mu}{0.3B}$$
  - $\beta_\perp$=0.002m at 30T, 10MeV/c
- $\varepsilon_{N,eq}$= 1.5×10^{-4} cm **at 10MeV/c**
- **Small enough for "low-emittance" collider**

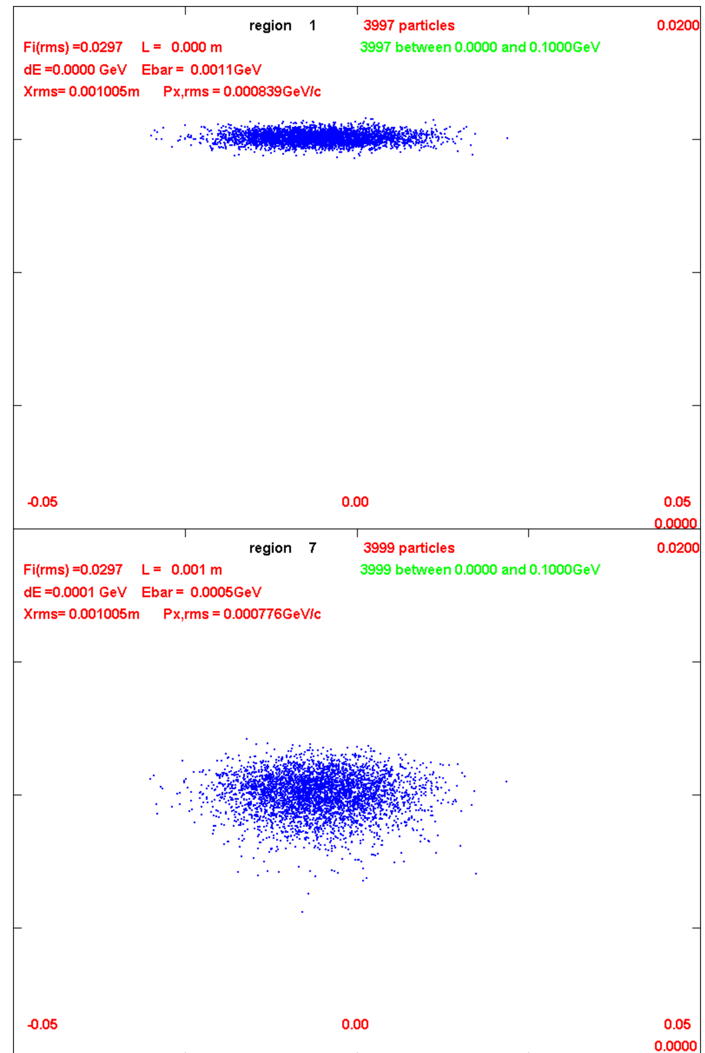


$$\varepsilon_{N,eq} = \frac{\beta_\perp E_s^2}{2 g_t \beta m_p c^2 L_R \frac{dE}{ds}}$$

$$\varepsilon_{N,eq} \propto \beta^2 \quad !!$$

ICOOL Simulation results

- Low-Energy muons in H_2 absorber
  - 50 MeV/c (4 cm H_2)
  - 30 MeV/c (0.7cm H_2)
  - 15 MeV/c (0.8mm H_2 or 80μ Be or…)
  - Could use gas absorbers/jets ?
- Results follow rms eqns
  - less multiple scattering …
- Typical section:
  - reduces P by 1/3P
  - δp increases by factor of 2
  - ε_x, ε_y reduced by $1/\sqrt{2}$



ICOOL Multiple Scattering effects

- **New Model 6 (Fano model) much less rms scattering than Model 4(Moliere/Bethe)**
  - **At 200 MeV/c μ on H_2, M4 scattering ~10% > rms eq.**
  - **M6 scattering (θ^2) is ~30% less than rms eq.**
- **Low energy scattering less at low momentum**
  - **At 15 MeV/c, M4 scattering ~40% < than rms eq.**
  - **M6 scattering (θ^2) is ~60% less than rms eq.**
- **Which is more accurate? rms eq., model 4 or 6 or ??**

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

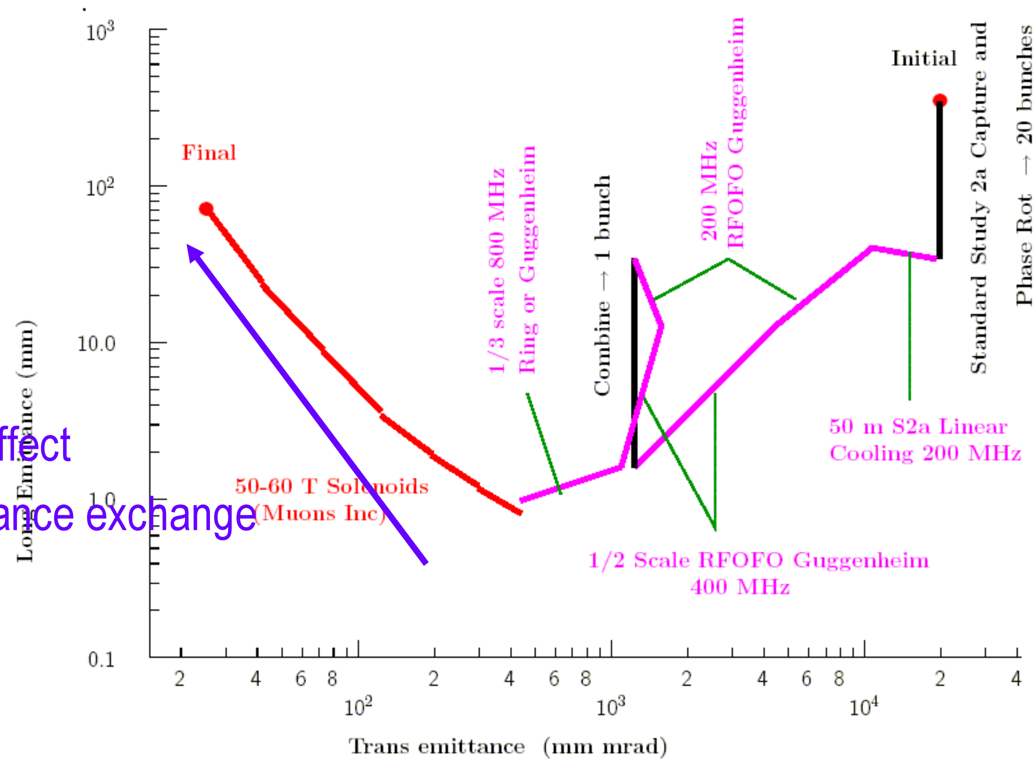
$$\frac{d\left\langle \theta_{rms}^2 \right\rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu^2 L_R}\left(1+0.038\ln\left(\frac{ds}{L_R}\right)\right)^2$$

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

Comments

- **Can fit into end-stage cooling (with similar effects?)**
- **Can use gas jet absorbers to avoid having windows**
  - **P_{jet} > 1 atm possible**
- **Need "rf" to reduce dp/p (longer bunches for multistep)**
  - **1mm bunch can grow to 1m bunch length**
- **Voltage is relatively small**
- **$L_{\mu} = 660\beta\gamma$**
- **Reacceleration of ~1m bunches**

Approximate effect
Of low-E emittance exchange



Summary

- **Low energy ionization cooling has possible important applications**
  - **Protons for neutron generation (Mori et al.)**
  - **β-beam source production (Rubbia et al.)**
  - **Cooling of μ's to minimum transverse emittance**
    - **REMEX that might work …**
- **"Cooling" is predominantly emittance exchange**
  - **X-y-z exchange needed for "real" cooling**

ILC Status

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X-sections, kinematics