Low-Energy Ionization “Cooling”

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Outline

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

- Efficient cooling requires:
  \[
  \frac{\partial dE}{\partial E} > \sim 0
  \]

- 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-\( \varepsilon_\perp \) cooling \( \Sigma_g = \sim 2\beta^2 \) (longitudinal heating)

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

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

\[
\frac{d\left\langle \frac{\theta^2}{\text{rms}} \right\rangle}{ds} = \frac{z^2 E_i^2}{3\beta^2 c^2 p_\mu^2 L_R}
\]
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 $\beta = v/c$
  - Add heating through nuclear interactions
  - Ionization/recombination should be included
- For small $\beta$, longitudinal $dE/dx$ heating is large
  - At $\beta = 0.1$, $g_L = -1.64$, $\Sigma_g = 0.36$
  - Coupling only with $x$ cannot obtain damping in both $x$ and $z$

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

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

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

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

\[
\frac{d\varepsilon_N}{ds} = -\frac{1}{P \frac{dP}{ds}} \varepsilon_N + \frac{\beta_\perp}{2} \frac{z^2 E_s^2}{\beta^2 m c P L_R}
\]

\[
\varepsilon_{N,eq} = \frac{z^2 \beta_\perp E_s^2}{2g_x \beta a m c^2 L_R} \frac{dE_{\gamma,eq}}{ds}
\]

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

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

For small \(\beta\):

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

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

Better for larger mass?
Example

- ERIT-P-storage ring to obtain directed neutron beam (Mori-Okabe, FFAG05)
- 10 MeV protons
  - $^9$Be target for neutrons
  - $\sigma \approx 0.5$ barns
  - $\beta = v/c = 0.145$
  - Large $\delta E$ heating
- Baseline Absorber
  - 5$\mu$Be absorber
  - $\delta E_p = \sim 36$ keV/turn
- Design Intensity
  - 1000Hz, $6.5 \times 10^{10}$p/cycle
  - 100W primary beam
  - $< 1.5$ kW on foil
  - 0.4 kW at $n_{\text{turns}} = 1000$

Table 1: Reference parameters of the ERIT Ring

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Ref. Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Kinetic Energy</td>
<td>$E_p$</td>
<td>10</td>
<td>MeV</td>
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<tr>
<td>Beam Momentum</td>
<td>$P_p$</td>
<td>137.4</td>
<td>MeV/c</td>
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<tr>
<td>Beam velocity</td>
<td>$\beta = v/c$</td>
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<tr>
<td>Beam current</td>
<td>$I_0$</td>
<td>40</td>
<td>mA</td>
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<tr>
<td>Ring Circumference</td>
<td>$C$</td>
<td>11.3</td>
<td>m</td>
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<td>Ring tunes</td>
<td>$\nu_1, \nu_2$</td>
<td>1.89, 1.34</td>
<td>m</td>
</tr>
<tr>
<td>Mean Betatron function</td>
<td>$\beta_0$</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>Maximum betatron functions</td>
<td>$\beta_{\text{max}}, \beta_{\text{tan}}$</td>
<td>1.48, 2.03</td>
<td>m</td>
</tr>
<tr>
<td>Dispersion (at wedge)</td>
<td>$\gamma_1$</td>
<td>0.6</td>
<td>m</td>
</tr>
<tr>
<td>Transition gamma</td>
<td>$\gamma_1$</td>
<td>1.7</td>
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</tr>
<tr>
<td>Energy loss (Be) at ref. energy</td>
<td>$\delta E/\delta s$</td>
<td>72</td>
<td>MeV/cm</td>
</tr>
<tr>
<td>Sum of partition numbers (at $E_p$)</td>
<td>$\Sigma_{\delta}$</td>
<td>0.37</td>
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</tr>
<tr>
<td>Absorber central thickness</td>
<td>$\delta z$</td>
<td>5</td>
<td>$\mu$</td>
</tr>
<tr>
<td>Mean energy loss / turn</td>
<td>$\delta E_{\text{AVL}}$</td>
<td>36</td>
<td>keV</td>
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<tr>
<td>RF voltage</td>
<td>$V_{\text{RF}}$</td>
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<td>kV/turn</td>
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<td>RF harmonic</td>
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<td>RF frequency</td>
<td>$f_{\text{RF}}$</td>
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<td>MHz</td>
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<tr>
<td>Longitudinal focusing function</td>
<td>$B_{\text{long}}$</td>
<td>2.1</td>
<td>Radians/MeV</td>
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</table>
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 $\beta_\perp=0.2m$, $\delta E_{\text{rms}}=0.4\text{MeV}$, $\varepsilon_{\perp,N}=0.0004\text{m}$ ($x_{\text{rms}}=2.3\text{cm}$)
  - $x_{\text{rms}}=7.3\text{cm}$ at $\beta_\perp=2\text{m}$ (would need $r=20\text{cm}$ 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 $g_{L,0} = -1.63$, $\eta = 0.5\text{m}$,
  - need $G = 3.5\text{m}^{-1}$ to get $g_L = 0.12$
    - $(L_W = 0.3\text{m})$

- 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: $BL = \pi B \rho$
    - For 10 MeV $p$: $BL = 1.44\text{T-m}$
  - 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.)
  \[ \delta(x) = \delta_R \sqrt{1 + y'(x)^2} = \delta_0 (1 + \frac{x-x_0}{L_W}) = \delta_R (1 + \frac{x}{a}) \]

- Choose \(x_0=0.15\)m, \(L_W=0.3\), \(\delta_o=5\mu\)
  - then \(a=0.15\), \(\delta_R=2.5\)
  - for \(g_{L,0} = -1.63\), \(\eta = 0.5\)m
- Barely Compatible with \(\beta^* = 0.2\)m
- Beam energy loss not too large?
  - \(<1\)kW Power on foil

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

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

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

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

At ERIT parameters: \( \beta_x = 1.0 \text{m} \), \( \beta_z = 16 \text{m} \), \( \eta = 0.6 \text{m} \), Be absorber, \( \frac{d\delta^2}{ds} = 0.00032 \), \( \frac{d\theta^2}{ds} = 0.0133 \) only 5%, 1.5% changes …

At \( \beta_x = 0.2 \text{m} \), ~25% change …

\[
\frac{d\langle \theta_{\text{rms}}^2 \rangle}{ds} = \frac{Z^2 E_s^2}{\beta^2 c^2 P_a^2 L_R}
\]

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

\[
\beta_L = \sqrt{\frac{\beta^2 P c C \lambda_{RF}}{2\pi e V_{RF} \cos \phi_S}}
\]
**β-beam Scenario**

### Ion production
- **Ion Driver**
  - 25MeV Li ?
- **Ion production**:
  - Target - Ion (8B or 8Li ?)
  - Conversion Ring
- **Beam preparation**
  - ECR pulsed
- **Ion acceleration**
  - Linac
- **Acceleration to medium energy**
  - RCS

### Acceleration
- **Acceleration to final energy**
  - Fermilab Main Injector

### Neutrino source
- **Neutrino Source**
- **Decay Ring**
  - Bρ = 400 Tm
  - B = 5 T
  - C = 3300 m
  - Lss = 1100 m
- 8B: γ = 80
- 8Li: γ = 50

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**Experiment**
- ν, \( \bar{\nu} \)
Conventional Beta beam ion source

- Want:
  - lifetime ~1s
  - large $\nu$-energy
  - $\nu$ and $\nu^*$
  - easily extracted atoms

- Number of possible ions is limited ($\nu$ sources easier)

- Noble gases easier to extract
  - $^6$He$_2$ “easiest” $E_{\nu^*}$ =1.94MeV
  - $^{18}$Ne$_{10}$ for $\nu$ $E_{\nu}$ =1.52MeV

- ($^8$B, $^8$Li) have $E_{\nu^*}$, $\nu^* = \sim$7MeV

- Want $10^{20}$ $\nu$ and $\nu^*$ / year…
**β-beam Scenario** (Rubbia et al.)

- Produce Li and inject at 25 MeV
  - Charge exchange injection
- Nuclear interaction at gas jet target produces $^8\text{Li}$ or $^8\text{B}$
- **Multiturn with cooling maximizes ion production**
- $^8\text{Li}$ or $^8\text{B}$ is caught on stopper (W)
  - Heated to reemit as gas
- $^8\text{Li}$ or $^8\text{B}$ gas is ion source for β-beam accelerate
- Accelerate to $B\rho = 400 \text{ T-m}$
  - Fermilab main injector
- Stack in storage ring for:
  - $^8\text{B} \rightarrow ^7\text{Be} + e^+ + \nu$ or $^8\text{Li} \rightarrow ^7\text{Be} + e^- + \nu^*$
  - Neutrino source
Cooling for $\beta$-beams  (Rubbia et al.-NuFACT06)

- $\beta$-beam requires ions with appropriate nuclear decay
  - $^8\text{B} \rightarrow ^8\text{Be} + \text{e}^+ + \nu$
  - $^8\text{Li} \rightarrow ^8\text{Be} + \text{e}^- + \nu^*$

- Ions are produced by nuclear interactions
  - $^6\text{Li} + ^3\text{He} \rightarrow ^8\text{B} + \text{n}$
  - $^7\text{Li} + ^2\text{H} \rightarrow ^8\text{Li} + ^1\text{H}$
  - 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 $^2\text{H}$ 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: $^6\text{Li} + ^3\text{He} \to ^8\text{B} + n$

- **Beam:** $25\text{MeV} \ ^6\text{Li}^{++}$
  - $P_{\text{Li}} = 529.9 \ \text{MeV}/c \ \beta \rho = 0.59 \ \text{T-m}; \ \nu/c=0.09415$

- **Absorber:** $^3\text{He}$
  - $Z=2, \ A=3, \ l=31\text{eV}, \ z=3, \ a=6$

- $dE/ds = 1180 \ \text{MeV}/\text{gm/cm}^2, \ L_R = 70.9 \ \text{gm/cm}^2$

\[ (\rho_{\text{He-3}} = 0.09375 \ \text{gm/cm}^3)_{\text{Liquid}}, \quad (\rho_{\text{He-3}} = 0.134 \cdot 10^{-3})_{\text{P gm/cm3/atm in gas}} \]

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

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

\[
\varepsilon_{N,eq} \equiv \frac{z^2 \beta_{\perp} E_s^2}{2g_x \beta am_p c^2 L_R} \frac{dE_{z,a}}{ds}
\]

\[
\sigma_{E,eq}^2 = \frac{(m_e c^2)(am_p c^2)\beta^4 \gamma^3}{2 \ g_L \ ln[]} \left(1 - \beta^2 \right)
\]
Cooling time/power: $^6\text{Li} + ^3\text{He} \rightarrow ^8\text{B} + n$

- Nuclear cross section for beam loss is 1 barn ($10^{-24}$ cm$^2$) or more
  - $\sigma = 10^{-24}$ cm$^2$ corresponds to $\sim$5 gm/cm$^2$ of $^3\text{He}$
    - $\sim$10 3-D cooling e-foldings …
  - Cross-section for $^8\text{B}$ production is $\sim$10 mbarn
    - At best, $10^{-2}$ of $^6\text{Li}$ is converted
  - Goal is $10^{13}$/s of $^8\text{B}$ production
    - then at least $10^{15}$ Li$^6$/s needed
- Space charge limit is $\sim 10^{12}$ Li$^6$/ring
  - Cycle time is $<10^{-3}$ s
    - If C=10m, $\tau=355$ 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- \( ^7\text{Li} + ^2\text{H} \rightarrow ^8\text{Li} + ^1\text{H} \)

- Nuclear cross section for beam loss is 1 barn \((10^{-24} \text{ cm}^2)\) or more
- \(\sigma = 10^{-24} \text{ cm}^2\) corresponds to \(\sim 3.3 \text{ gm/cm}^2\) of \(^2\text{H}\)
  - \(\sim 9\) 3-D cooling e-foldings …
- Cross-section for \(^8\text{Li}\) production is \(\sim 100\) mbarn
  - \(10^{-1}\) of \(^7\text{Li}\) is converted ?? \(10 \times\) better than \(^8\text{B}\) neutrinos
- Goal is \(10^{13}/\text{s}\) of \(^8\text{Li}\) production
  - then at least \(10^{14}\) \(^7\text{Li}/\text{s}\) needed
- Space charge limit is \(\sim 10^{12}\) \(^7\text{Li}/\text{ring}\)
  - Cycle time can be up to \(10^{-2}\) s, but use \(10^{-3}\)s
  - If \(C=10\text{m}\), \(\tau = 355\) ns, 2820 turns
  - \(3.3/2820 = 1.2 \times 10^{-3}\) 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)

- Is “direct” source better than “inverse” source?
  - $^6\text{Li}_3$ beam + $^3\text{He}_2$ target
    - or
  - $^3\text{He}_2$ beam + $^6\text{Li}_3$ target

- Beam energy, power on target less (1/2 to 1/3)
- Li foil or gas-jet target?
  - Gas-jet nozzle for wedge effect
- $> 0.1$ MW power on target
Rubbia et al. not completely wrong

• ...But contains mistakes
• Longitudinal emittance growth 2x 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% ...
Low-Energy “cooling” - emittance exchange

- $dP_\mu / ds$ varies as $\sim 1/\beta^3$

- “Cooling” distance becomes very short: for liquid H at $P_\mu = 10\text{MeV}/c$

- Focusing can get quite strong:
  - Solenoid: $\beta_\perp \approx \frac{2BP_\mu}{B} \approx \frac{2P_\mu}{0.3B}$
  - $\beta_\perp = 0.002\text{m}$ at $30\text{T}$, $10\text{MeV}/c$

- $\varepsilon_{N,eq} = 1.5 \times 10^{-4} \text{ cm}$ at $10\text{MeV}/c$

- Small enough for “low-emittance” collider

\[ L_{cool} = \left( \frac{1}{P_\mu} \frac{dP}{ds} \right)^{-1} \]

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

\[ \varepsilon_{N,eq} \propto \beta^2 \]
ICOOL Simulation results

- Low-Energy muons in H$_2$ absorber
  - 50 MeV/c (4 cm H$_2$)
  - 30 MeV/c (0.7 cm H$_2$)
  - 15 MeV/c (0.8 mm 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
  - $\varepsilon_x$, $\varepsilon_y$ 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 H₂, M4 scattering ~10% > rms eq.
  - M6 scattering (θ²) 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 (θ²) is ~60% less than rms eq.
- Which is more accurate? rms eq., model 4 or 6 or ??

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

\[
\frac{d\langle \theta_{rms}^2 \rangle}{ds} = \frac{z^2 E_s^2}{\beta^2 c^2 p_\mu L_R} \left(1 + 0.0381 \ln \left(\frac{ds}{L_R}\right)\right)^2
\]

\[
\varepsilon_{N,eq} = \frac{\beta_\perp E_s^2}{2g_1\beta m_\mu c^2 L_R} \frac{dE}{ds}
\]
Comments

- Can fit into end-stage cooling (with similar effects?)
- Can use gas jet absorbers to avoid having windows
  - $P_{\text{jet}} > 1$ 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 $\sim 1$m bunches

Approximate effect
Of low-E emittance exchange
Summary

- Low energy ionization cooling has possible important applications
  - Protons for neutron generation (Mori et al.)
  - $\beta$-beam source production (Rubbia et al.)
  - Cooling of $\mu$’s to minimum transverse emittance
    - REMEX that might work …
- “Cooling” is predominantly emittance exchange
  - X-y-z exchange needed for “real” cooling
OUR NEW PRODUCT IS EITHER WILDLY SUCCESSFUL OR UNDERWATER...

DEPENDING ON HOW YOU WANT TO ALLOCATE MANAGEMENT OVERHEAD EXPENSES.

APPARENTLY YOU DON’T WANT TO THINK ABOUT IT AND GET BACK TO ME.
X-sections, kinematics