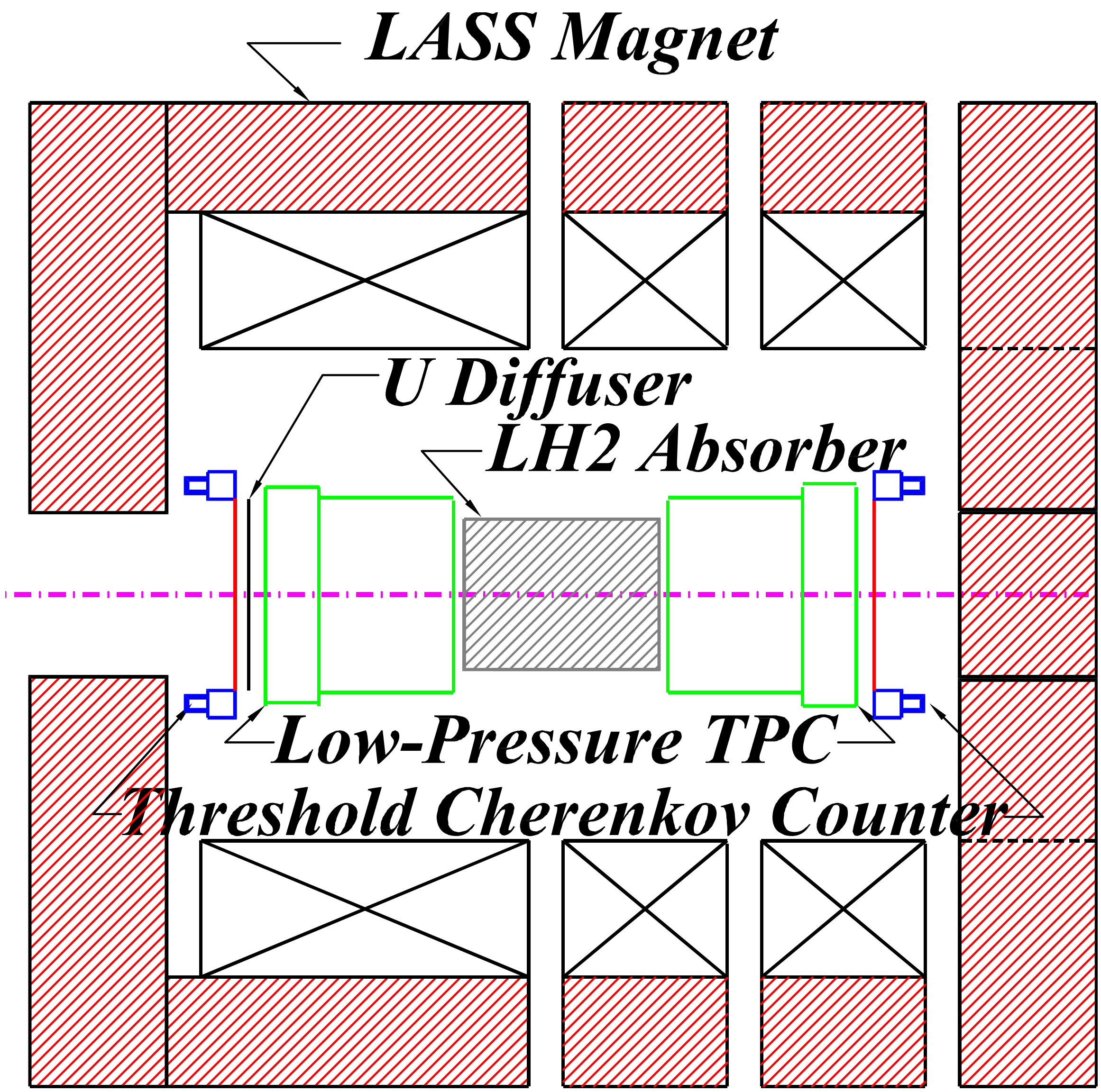
An Initial Ionization Cooling Demonstration



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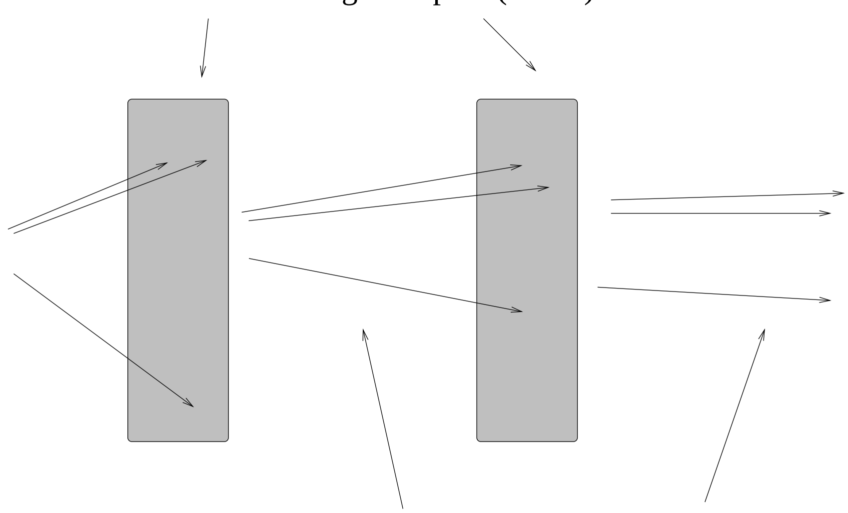
Ionization Cooling

An Idea So Simple It Might Just Work

- In 1955 G.K. O'Neill realized that the key to successful storage rings is beam cooling.
- O'Neill proposed ionization cooling be used with proton beams.



- But scattering of protons (and electrons) in matter is too strong for useful ionization cooling.
- Ionization cooling is only practical for muon beams.
- Ionization cooling has never been demonstrated.

Why Should We Demonstrate Ionization Cooling?

- Ionization Cooling is critical for a neutrino factory and for a muon collider.
- Ionization Cooling is delicate (bricks are bad for beams).
- Ionization Cooling depends on somewhat unfamiliar concepts.
- Ionization Cooling requires advanced technology.
- $\Rightarrow$ Lab work as well as theory.

What Should We Demonstrate?

- Ideally, we should demonstrate both transverse and longitudinal cooling in a channel long enough that the effect of perturbations can be shown to be negiligible.
- At present we have neither the conceptual nor the technological basis for such a demonstration.

  [X-rays from rf cavities saturate diagnostics.]
- Therefore, our efforts should be threefold:

  1. Improve our concepts of cooling via theory and simulation.
  2. Perform R&D on key technology issues.
  3. Demonstrate the basic features of ionization cooling in the lab now.

     Add sophistication when available via items 1 and 2.

  Basic philosophy: Do everything that can be done.

Cooling Demonstration Options

1. Long cooling channel, bunched muon beam, high intensity.
2. Skip bunched beam and high intensity [MUCOOL].
3. 2 − rf cavity [Present proposal].
4. 2 − magnet [P. Gruber].
5. 2 − rf − magnet [RAL/TRIUMF scattering experiment].
6. Simulations only.

Basic Features of Ionization Cooling

1. dE/dx loss does not cool geometric transverse emittance, but it can cool invariant transverse emittance.

   $$m^2c^2\epsilon_{x,N}^2 = \langle x^2 \rangle \langle \Pi_x^2 \rangle - \langle x\Pi_x \rangle^2 \,,$$

   where $\Pi = \mathbf{P} + e\mathbf{A}/c$ is the canonical momentum.

   Diagnostics should measure invariant emittance, not geometric emittance.

2. We want to cool large initial emittances.

   $\Rightarrow$ Large beams with large-angle particles.

   $\Rightarrow$ Transverse confinement via solenoids, not quads.

   $$\text{For a solenoid, } A_\phi(r,z) = \frac{1}{r}\int_0^r r' B_z(r',z)dr' \approx \frac{rB_z}{2}.$$

Basic Features, cont'd.

3. There is an equilibrium transverse emittance.

dE/dx cools, but multiple scattering heats:

$$\begin{aligned}\frac{d\epsilon_{\perp,N}}{dz} &\approx \frac{\epsilon_{\perp,N}}{\beta^2 E}\frac{dE}{dz} + \frac{\beta_\perp^\star (13.6\ \mathrm{MeV}/c)^2}{2\beta^3 E m_\mu L_R} \\ &\approx \frac{1}{\beta^2 E L_R}\left[-\frac{\pi m_e c^2 \epsilon_{\perp,N}}{\alpha(Z+1)\ln\frac{287}{\sqrt{Z}}}\left(\frac{1}{\beta^2}\ln\frac{2\gamma^2\beta^2 m_e c^2}{I} - 1\right)\right. \\ &\qquad \left. + \frac{\beta_\perp^\star (13.6\ \mathrm{MeV}/c)^2}{2\beta m_\mu}\right], \\ &\approx \frac{1}{\beta^2 E L_R}\left[-\frac{220\epsilon_{\perp,N}}{(Z+1)\ln\frac{287}{\sqrt{Z}}}\left(\frac{12}{\beta^2} - 1\right) + \frac{0.88\beta_\perp^\star}{\beta}\right].\end{aligned}$$

$$\Rightarrow \qquad \epsilon_{\perp,N,\mathrm{min}} = \frac{3.3\times 10^{-4}\beta\beta_\perp^\star (Z+1)\ln\frac{287}{\sqrt{Z}}}{1-\beta^2/12}.$$

$\Rightarrow$ Transverse cooling is faster and better at low β.

$\Rightarrow$ Use low Z absorber: LH_2, LiH, Li, ...

$\Rightarrow$ Put the absorber at a low $\beta_\perp^\star$ point.

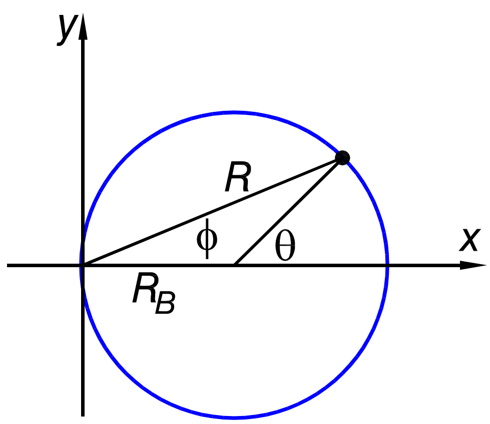
$\Rightarrow$ Nongaussian tails to multiple scattering can raise the equilibrium emittance.

Basic Features, cont'd.

4. Particle orbits in a uniform solenoid have constant radius about a guiding ray.

   Orbits of particles with zero canoncical angular momentum pass through the solenoid axis.

   Then angular velocity $\omega_L = \dot{\phi}$ of such a particle about the solenoid axis is 1/2 the angular velocity $\omega_B = \dot{\theta} = e\beta_z B_z / P_z$ about the guiding ray.



   In a frame that rotates with angular velocity $\omega_L = e\beta_z B_z / 2P_z$ the orbit is a sine wave about the solenoid axis.

   $\Rightarrow$ The langauge of betatron oscillations is meaningful for solenoids only in this rotating frame.

   In this frame, $\beta_\perp^\star = 2eP_z / eB_z$ for a solenoid.

Basic Features, cont'd.

5. Transverse emittance and (canonical) angular momentum are coupled in a solenoid [K.-J. Kim and C.-X. Wang].

$$\epsilon_{\perp,N}^{(4)} = \epsilon_{x,N}\epsilon_{y,N} - \frac{\langle L_z \rangle^2}{4}.$$

Defining $\epsilon \equiv \epsilon_{x,N} + \epsilon_{y,N}$ and $L \equiv \langle L_z \rangle$, then

$$\frac{d(\epsilon + L)}{dz} = \frac{0.88\beta_\perp^\star}{\beta^3 E L_R},$$

$$\frac{d(\epsilon - L)}{dz} = \frac{1}{\beta^2 E L_R}\left[-\frac{440(\epsilon - L)}{(Z+1)\ln\frac{287}{\sqrt{Z}}}\left(\frac{12}{\beta^2} - 1\right) + \frac{0.88\beta_\perp^\star}{\beta}\right].$$

An initial cooling demonstration should include this.

If create L_0 in a 1-X_0 uranium diffuser, then

$$\frac{L_0}{\epsilon_0} \approx \frac{\Delta E}{P_0} \approx 0.08.$$

$\Rightarrow$ Need $\sigma_\epsilon/\epsilon \lesssim 0.02$ to show coupling of ϵ and L, as well as to show 10% cooling.

Basic Features, cont'd.

6. Longitudinal emittance is heated by

   (a) Decreasing $\langle dE/dx \rangle$ loss with increasing E;

   (b) Fluctuations about $\langle dE/dx \rangle$ (= straggling).

   $\Rightarrow$ Operation at low β as favored for transverse cooling aggravates heating of the longitudinal emittance.

   $\Rightarrow$ Need another mechanism to cool longitudinal emittance.

   $\Rightarrow$ Delicate to have full 6-d cooling of phase volume.

In a simple system with magnetic confinement, it is difficult to have good measurements of both longitudinal and transverse phase space.

While we are not ready to demonstrate more sophisticated aspects of ionization cooling, a demonstration that encompasses the above basic features will show mastery of many nontrivial effects.

An Initial Cooling Demonstration

- Demonstrate basic cooling concepts rather than (still to be developed) cooling technology.
- Keep capital costs down:
  1. Use an existing muon beam – without bunching.
  2. Use an existing solenoid magnet.
  3. No rf acceleration (and no need for picosecond timing).
- Use the single-particle method: bunches via software cuts.
- Show up to 10% cooling of $\epsilon_{\perp,N} \approx 10,000\ \pi$ mm-mrad.
- Use low-Z absorbers: 50-cm-long LH_2, ...
- Diagnose invariant transverse momentum with low pressure gas tracking in a pair of TPC's.
- Maintain 1 mrad angular resolution to permit study of tails of multiple scattering.
- $\pi/\mu/e$ identification via threshold Čerenkov counters.

Parameters of the Proposed Cooling Demonstration

Parameter	Value
Before diffuser:	
P_0 (MeV/c)	184
E_0 (MeV)	212
$\sigma_x = \sigma_y$ (mm)	50
$\sigma_{x'} = \sigma_{y'}$ (mrad)	20
After diffuser:	
P_0 (MeV/c)	168
E_0 (MeV)	198
γ	1.89
β	0.85
$\gamma\beta$	1.60
$\epsilon_{x,N} = \epsilon_{y,N}$ (π mm-mrad)	10,000
$\epsilon_x = \epsilon_y$ (π mm-mrad)	6,250
$\beta^\star$ (cm) at 2.5 T	45
$\epsilon_{x,N\mathrm{min}} = \epsilon_{y,N,\mathrm{min}}$ (π mm-mrad)	1,500
$\sigma_x = \sigma_y$ (mm)	53
$\sigma_{x'} = \sigma_{y'}$ (mrad)	120
$\sigma_{\Pi_x} = \sigma_{\Pi_y}$ (MeV/c)	20
σ_P/P	0.10
$\sigma_E/E = \beta^2\sigma_P/P$	0.076
After 50 cm LH_2 absorber:	
P_0 (MeV/c)	150
E_0 (MeV)	183
$\gamma\beta$	1.43
$\epsilon_{x,N} = \epsilon_{y,N}$ (π mm-mrad)	9,100
$\epsilon_x = \epsilon_y$ (π mm-mrad)	6,370

Features of the Initial Cooling Demonstration

Use $P_\mu \approx 170$ MeV/c.

Use $\epsilon_{\perp,N,\mathrm{initial}} \approx 10,000\ \pi$ mm-mrad as for a neutrino factory.

A muon beam with quads of peak fields $\approx$ 2 T can transport only $\approx 1,500\ \pi$ mm-mrad – which is also roughly the equilibrium emittance for cooling in a 2-T solenoid.

So must blow up the beam emittance with a uranium diffuser before can demonstrate cooling.

The 2.5-T LASS magnet, now idle at LANL is a good candidate.

The D2 beamline at BNL is a good candidate.

The proposed detector systems are a subset of those considered for a major cooling demonstration.

The largest infrastructure item would be the cryogenic system for the 2.5-T magnet. A 100 W refrigerator is available at BNL.

Possible Layout of the Cooling Demonstration

BNL D2 beamline: