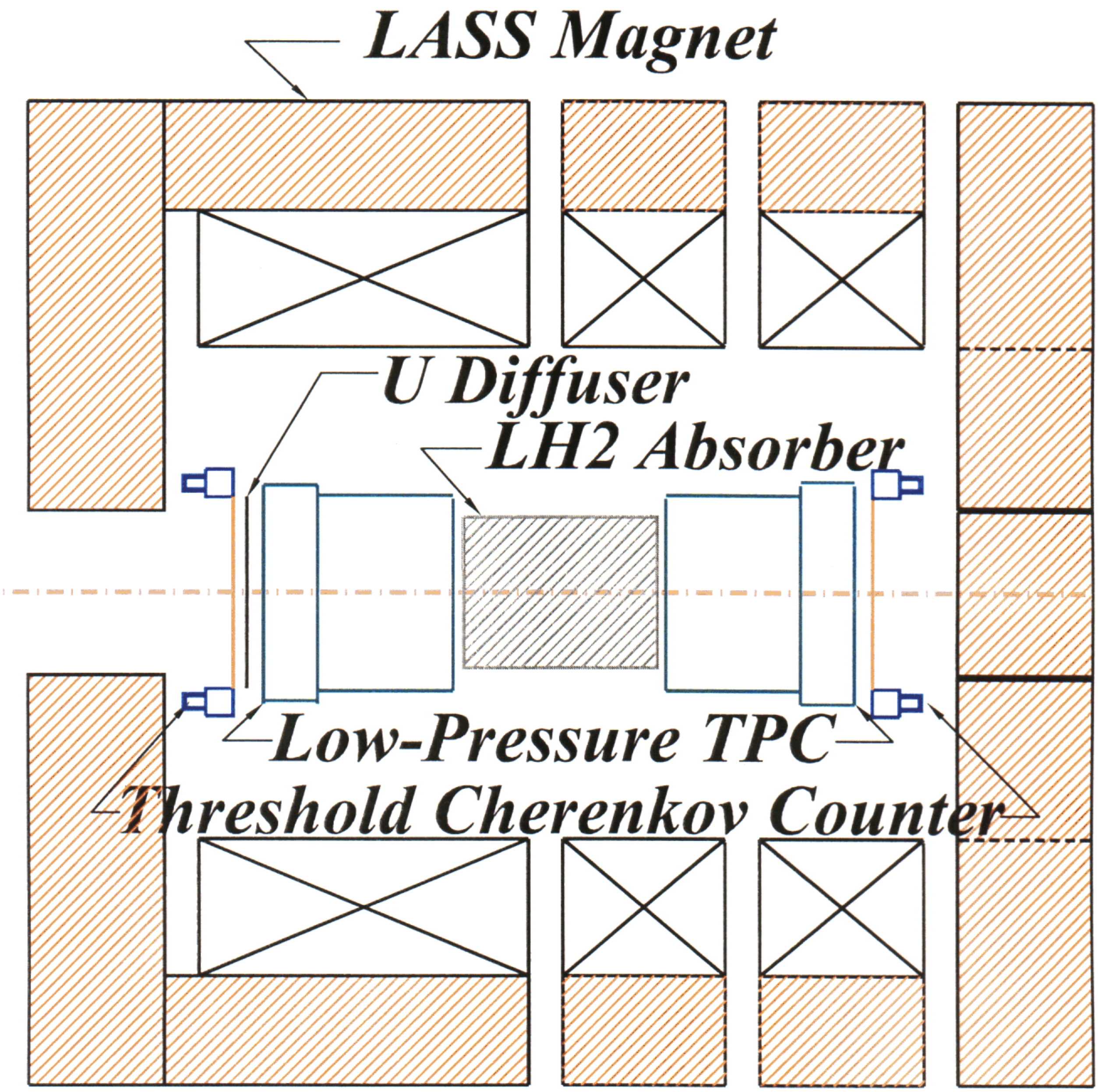
An Initial Ionization Cooling Demonstration



K.T. McDonald

Princeton University

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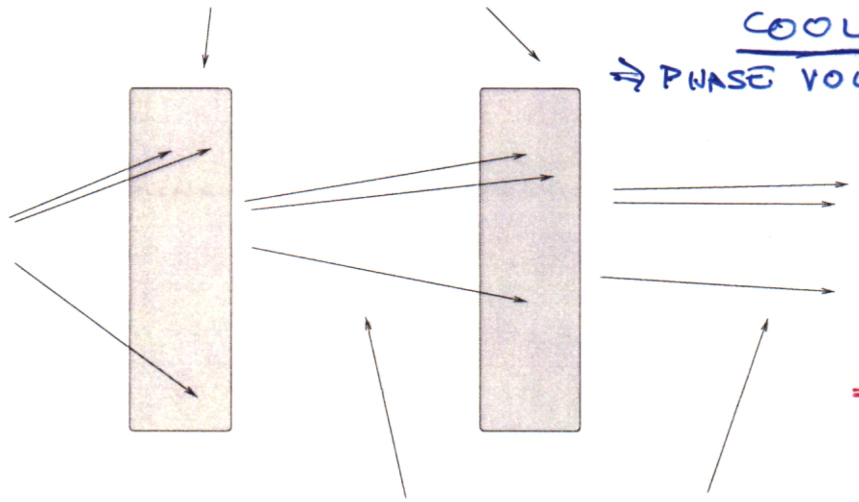
`http://puhep1.princeton.edu/mumu/cool1.ps`

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.



Particles are slowed along their path (dE/dx) ⇒ INVARIANT EMITTANCE COOLS

⇒ PHASE VOLUME REDUCED

⇒ PHASE VOLUME CONSERVED

Particles are accelerated longitudinally ⇒ GEOMETRIC EMITTANCE REDUCED

- But scattering of protons (and electrons) in matter is too strong for useful ionization cooling.
- Ionization cooling is only practical for muon beams.
  (OR HEAVY IONS WITH $E <$ COULOMB BARRIER: IGASOL)
- Ionization cooling has never been demonstrated.
- [Electron cooling and frictional cooling are variants of ionization cooling, and have 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.
- ⇒ 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 THE 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.

COMPROMISES:

① SKIP BUNCHED BEAM & HIGH INTENSITY [MUCOOL]

② = ① – RF CAVITY [THIS PROPOSAL]

③ = ① – MAGNET [P. GRUBER]

⑤ DON'T DEMONSTRATE COOLING.

④ = ① – MAGNET – RF = RAL/TRIUMF SCATTERING EXPT.

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.

   ⇒ Large beams with large-angle particles.

   ⇒ Transverse confinement via solenoids, not quads.

   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:

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

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

⇒ Transverse cooling is faster and better at low β.

⇒ Use low Z absorber: LH_2, LiH, Li, ...

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

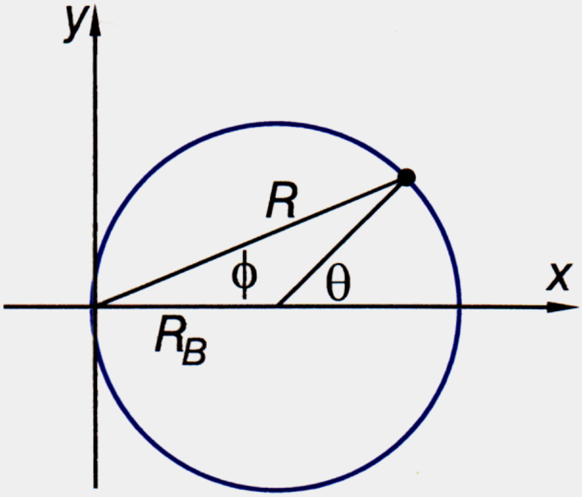
⇒ Nongaussian tails to multiple scattering can raise the equilibrium emittance.

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.

⇒ 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.

ANGULAR MOMENTUM

TRANSVERSE EMITTANCE IS COUPLED TO (CANONICAL) ANGULAR MOMENTUM IN A SOLENOID (K.-J. KIM & C.-X. WANG)

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

WITH $\epsilon \equiv \epsilon_{x,N} + \epsilon_{y,N}$ & $L \equiv \langle L_z \rangle$, THEN

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

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

CAN WE DEMONSTRATE THIS?

CREATE L_0 IN THE URANIUM DIFFUSER:

$$\frac{L_0}{\epsilon_0} \sim \frac{\Delta E}{P_0} \sim \frac{14}{168} \sim 0.08$$

$\Rightarrow$ NEED $\frac{\sigma_\epsilon}{\epsilon} \lesssim 0.02$.

BASELINE RESOLUTION IS $\frac{\sigma_\epsilon}{\epsilon} \sim 0.002$ ✓

Basic Features, cont'd.

5. 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, DIFFICULT TO HAVE GOOD MEASUREMENT OF BOTH TRANSVERSE & LONGITUDINAL PHASE SPACE.

$\frac{\sigma_{P_z}}{P_z} = \gamma^2 \frac{\sigma_\beta}{\beta} = \gamma^2 \frac{\sigma_t}{t}$. $\gamma \sim 2$, $t \sim 6\,\mathrm{NS}$, $\frac{\sigma_{P_z}}{P_z} \sim 0.01 \Rightarrow \sigma_t \sim 15\,\mathrm{PSEC}$

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 an initial invariant emittance of $\approx 10,000\ \pi$ 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.
- ČERENKOV TIMING TO 15 PSEC ⇒ GOOD MEASUREMENT OF LONGITUDINAL EMITTANCE GROWT

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 ≈ 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.

2.5 T BETTER THAN 1.25 T : LOWER MIN $\epsilon_{\perp,N}$; SMALLER BEAM RADIUS.

⇒ MUST LAY CLAIM TO LASS MAGNET IN NEXT FEW MONTHS ⇐

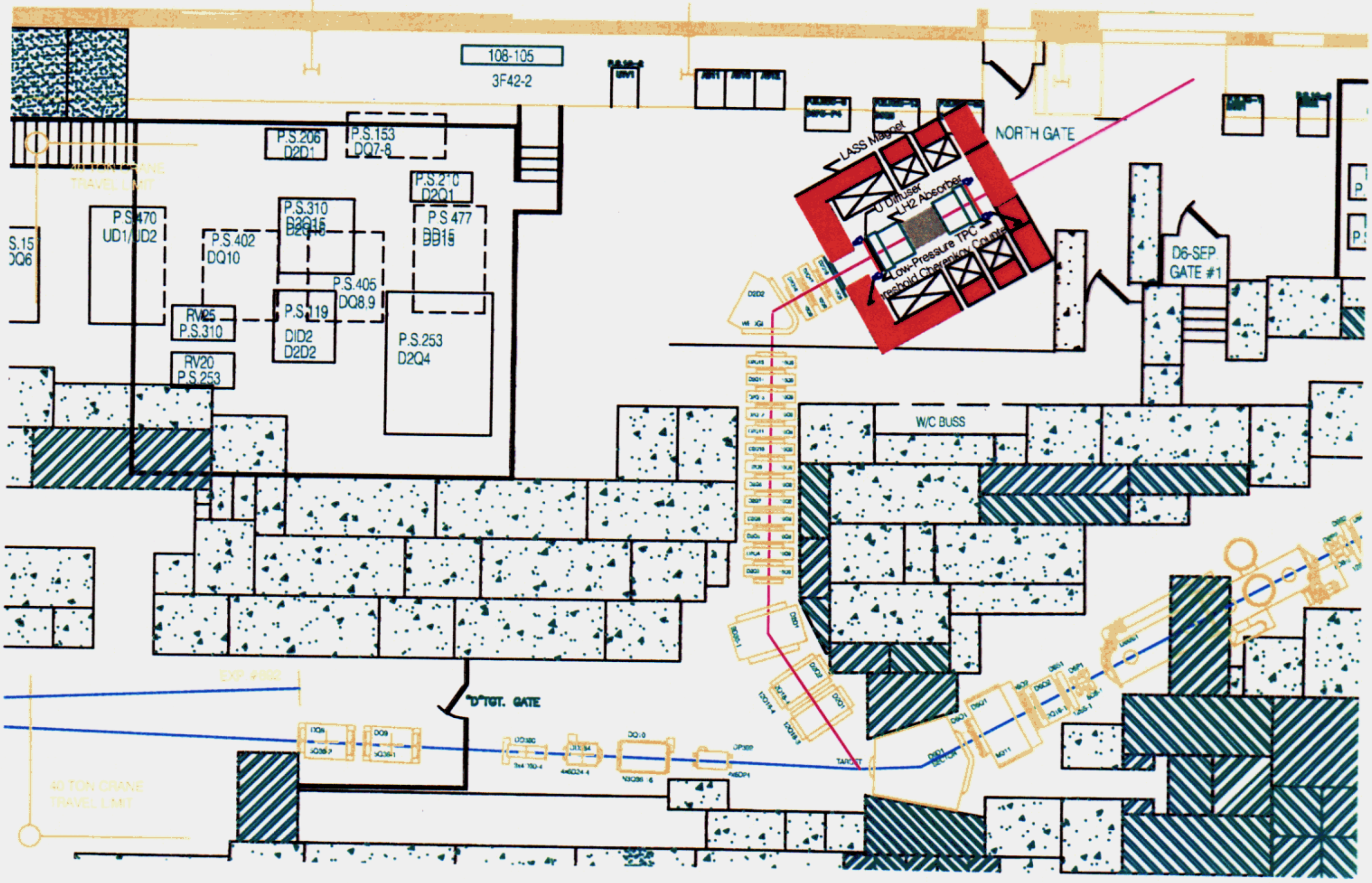
The D2 beamline at BNL is a good candidate. (TRIUMF ?)

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. @ BNL

Possible Layout of the Cooling Demonstration

(BNL D2 BEAMLINE)



A3 BEAMLINE

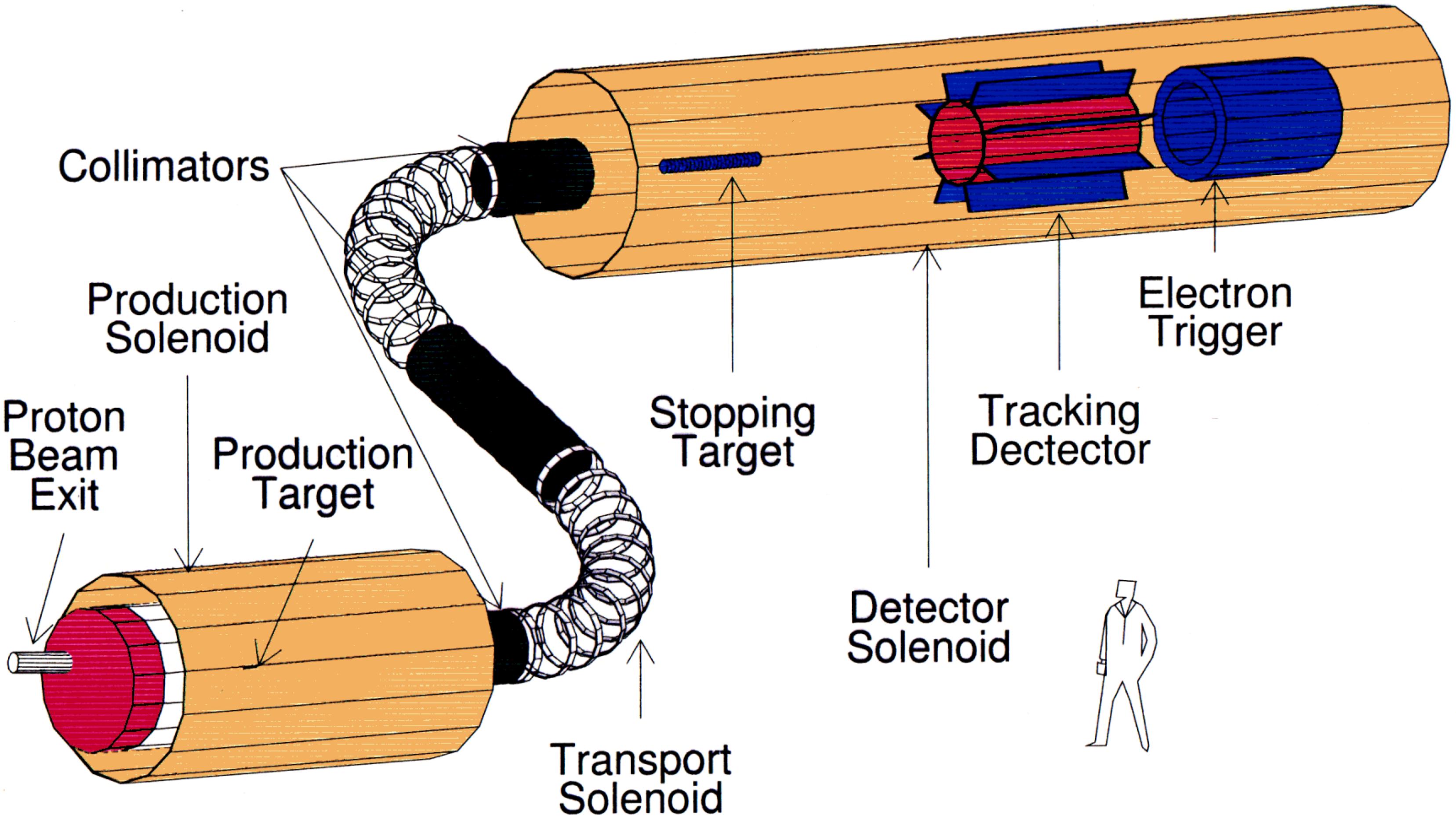
Summary

- Ionization cooling is critical for a neutrino factory based on a muon storage ring.
- Although simple in principle, ionization cooling is subtle in practice.
- Ionization cooling has never been demonstrated in the lab.
- We are not ready to mount a large-scale cooling demonstration facility.
- We can and should make a demonstration of the basic features of ionization cooling, using an absorber in an existing solenoid magnet in an existing muon beam.

FUTURE STEPS:

① DEMONSTRATE A SINGLE FLIP (WITHOUT ABSORBERS OR RF); USE THE WANG MAGNET + 2 SOLENOIDS (PERHAPS THOSE FOR STEP 7 OF E951).

② STUDIES IN THE MECO MUON CHANNEL (UP TO $10^{12}\,\mu/s$; COULD BE BUNCHED) WITH ABSORBERS RF, FLIPS ....



mecoapparatus

wmolzon