Muon Collaboration

Muon Colliders:

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Why consider a Muon Collider?

The mass of the muon ($m_{\mu}/m_e = 207$) gives a μ collider some very desirable features:

- Less synchrotron ($\sim m^{-4}$), brem and initial state radiation ➔ muons don't radiate as readily as electrons:

- Larger couplings to Higgs-like particles - if $m_h < 2m_W$, possible to study Higgs boson production in the s-channel

This gives four compelling arguments for the muon collider versus other machines:

1. Possible low energy Higgs Factory
2. Narrower energy spread
3. Easier acceleration
4. Smaller machine footprint

From a Neutrino Factory to Muon Collider

Much of what has been learned from the neutrino factory feasibility studies can be applied to a muon collider:

Targetry
Capture and Decay
Transverse Cooling
Accelerating a Large Beam

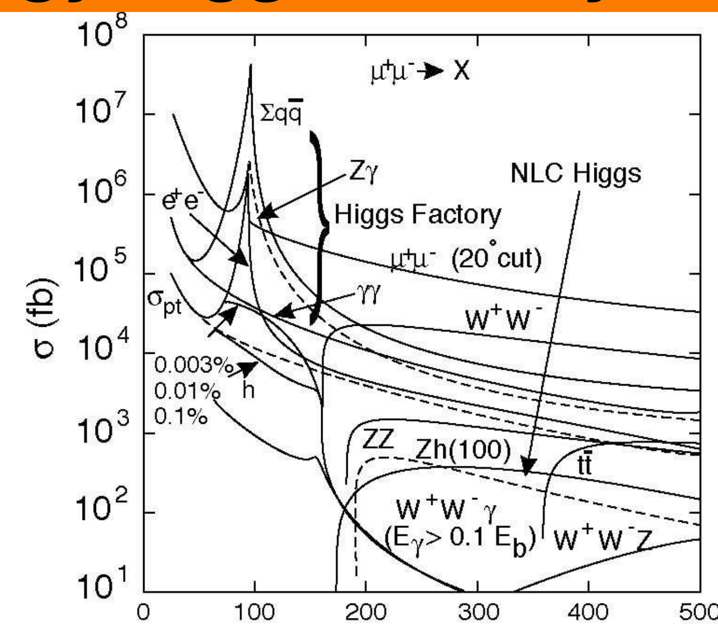
A muon collider requires the muon beams to be cooled by several orders of magnitude compared with a neutrino factory.

All the muons must be in one bunch ➔ **6 dimensional cooling!**

Low Energy Higgs Factory

Muons are massive...

- Only scenario where s-channel resonance can be observed
- The Higgs width can be measured directly
- h → $\mu\mu$ coupling is a direct test of the fermion mass generation mechanism. It can be measured to +/-4% with L = 0.2 fb-1 if the beam energy resolution R=0.003%



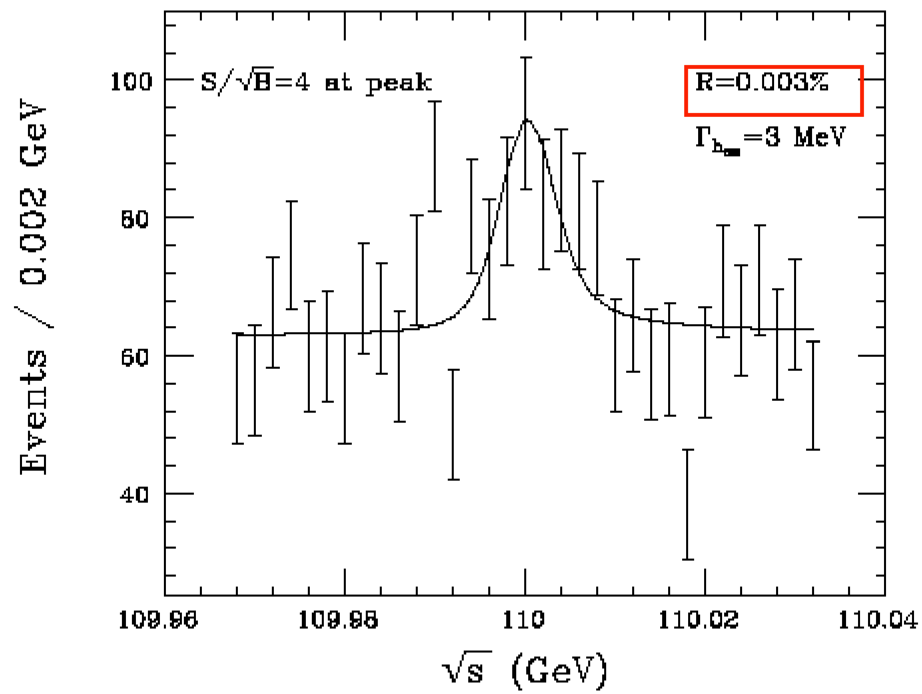
...also, you can get a narrow beam energy spread

$$(m_e/m_\mu)^4 = 6\times10^{-10}$$

Muon collider can provide the most precise measurement of the mass of a light Higgs using a beam energy scan of the resonance

	LHC	LC	$\mu^+\mu^-$
$\mathcal{L}$		500 fb^{-1}	0.2 fb^{-1}
m_h	9×10^{-4}	3×10^{-4}	$1-3\times10^{-6}$
Γ_h^{tot}	>0.3	0.17	0.2

Exceeds precision of theoretical predictions?



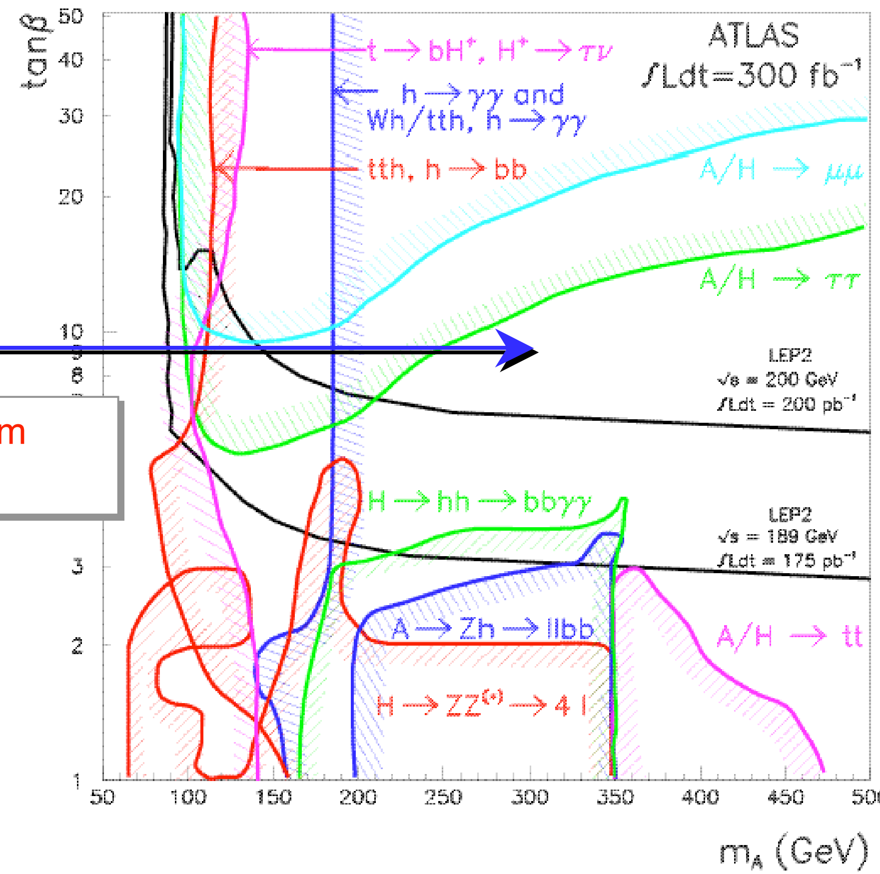
SUSY Higgs Factory

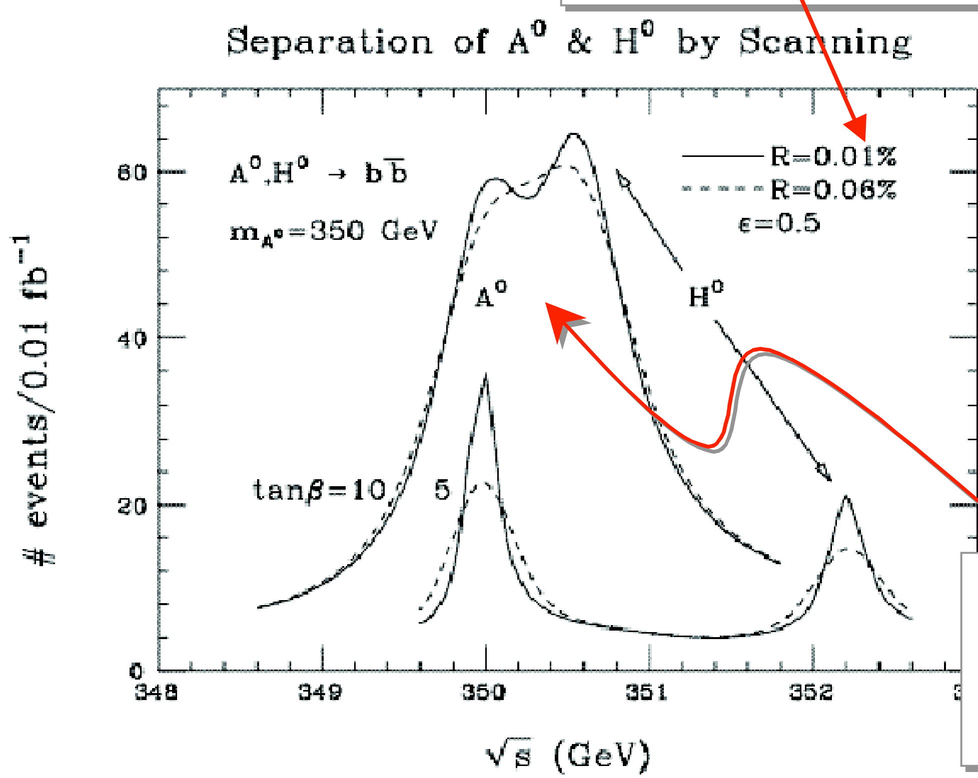
Regions of parameter space other machines just can't probe

...but must first raise $\sqrt{s}$!

A possible LHC and LC "blind spot"

Note dependence on beam energy resolution!





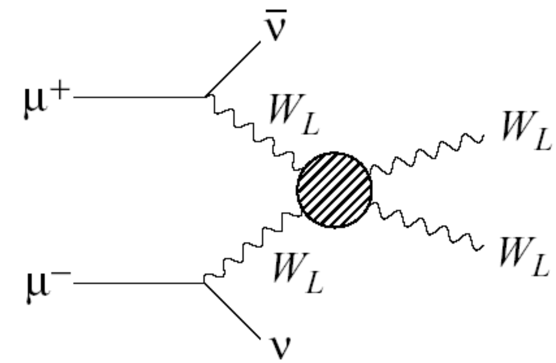
$$m_{A^0} \gtrsim max \left\{ \frac{\sqrt{s}}{2} \text{ (LC)}, 250 \text{ GeV (LHC)} \right\}$$

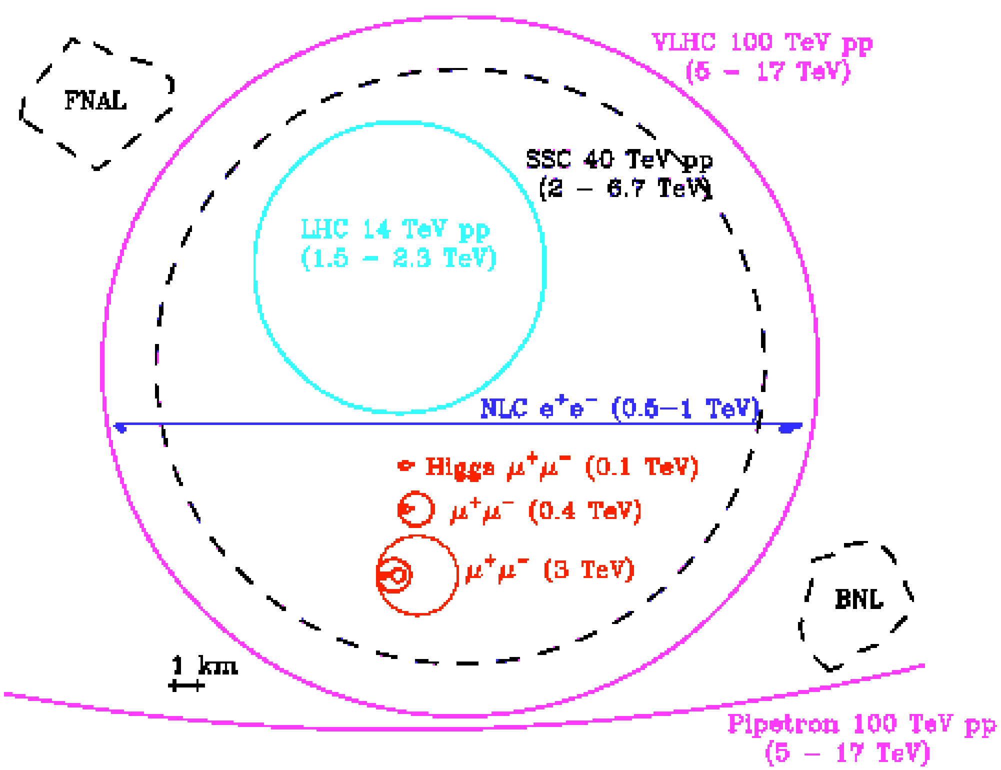
m_H-m_A: If masses are degenerate, they can only be resolved by exploiting the narrow beam energy spread at a muon collider using a scan.

Energy Frontier Machines

And, we don't know what lies beyond the electroweak scale.

The current story suggests that there "has" to be something at or approaching the TeV energy scale, but sooner or later we will want a multi-TeV lepton machine for precision measurements of SEWS (strongly interacting electroweak sector)





Muon colliders are smaller than other machines for a given energy
less real estate

The energy not radiated away is that much less for RF to accelerate

High energy muon colliders retain the possibility of narrow beam energy spread

High energy machine chosen will be the one that optimizes the cost/luminosity/energy equation

Other muon collider issues

- ***R***: Gaussian spread in beam energy can be made very small, but at cost of luminosity:
  - Some "conservative" calculations:
  - L ~ (0.5,1,6) * $10^{31}cm^{-2}\,s^{-1}$ for R = (0.003, 0.01, 0.1)% and $\sqrt{s}$ ~ 100 GeV
  - L ~ (1,3,7) * $10^{32}cm^{-2}\,s^{-1}$ for $\sqrt{s}$ = (200, 350, 400) GeV and R ~ 0.1%
  - So, μC best for: h → $\mu^+\mu^-$ $\sqrt{s}$ μE_{beam}/E_{beam} = 0.01R
    - H0 and A0 peak separation, Higgs scan
    - CP of Higgs bosons
  - Good measurement of h → μ+μμ possible
- At FNAL unique opportunity for μp collisions:
  - 200 GeV μ beams in collision with 1 TeV p beam:
  - L ~ 1.3 *10^{23} $cm^{-2}\,s^{-1}$, $\sqrt{s}$ = 894 GeV
- Neutrino Factory a natural intermediate step!
- Luminosity can be improved by further R & D in emittance exchange, cooling, targetry.
  - May be the best for extreme energies
  - Can guarantee access to heavy SUSY particles, Z' and strong WW scattering if no Higgs Bosons and no SUSY
- If μ's and *e*'s are fundamentally different, a μC is necessary!

The machine parameters…

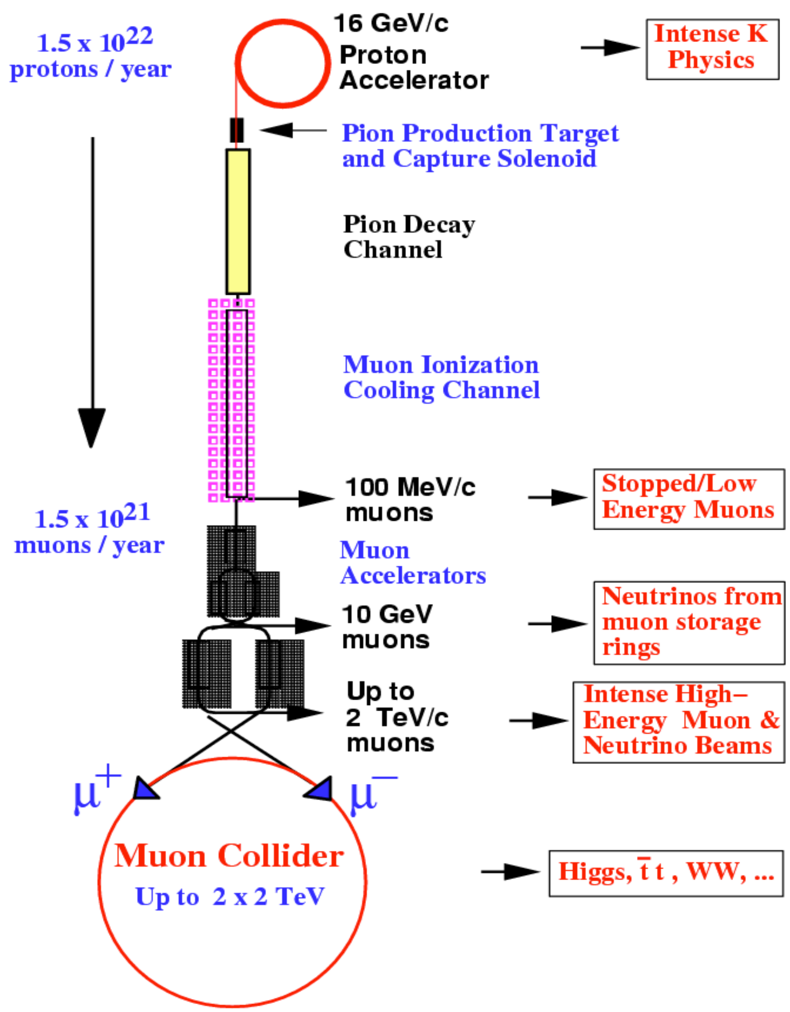
			Higgs Factory		
CoM energy (TeV)	3	0.4	0.1		
p's/bunch	2.5×10^{13}	2.5×10^{13}	5×10^{13}		
μ/bunch	2×10^{12}	2×10^{12}	4×10^{12}		
Rms $\Delta p/p$ %	0.16	0.14	0.12	0.01	0.003
6-D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n (π mm-mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
$\sigma_r$spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Luminosity $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
□ = 5□10^4 fb					
Higgs/year			1.9×10^3	4×10^3	3.9×10^3

orders of magnitude more cooling than for a ν factory!

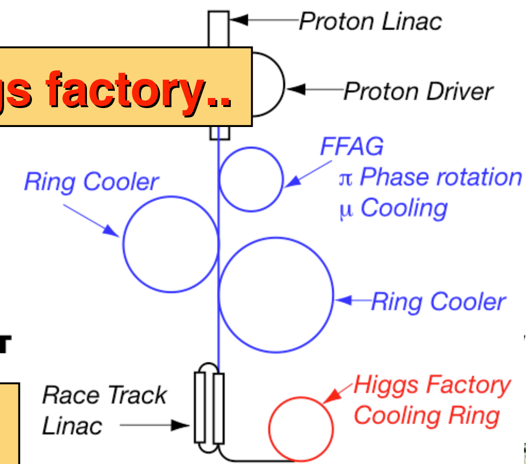
Also, high luminosity means fewer bunches!

Technical Staging and Physics

Muon Collider Schematic



Possible Higgs factory..



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CANDIDAT

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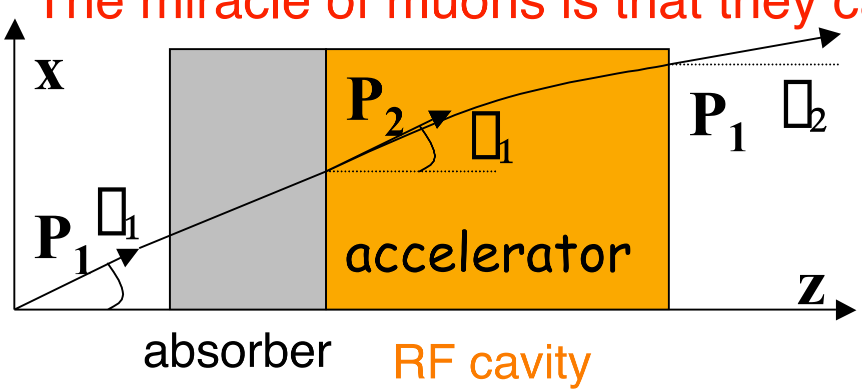
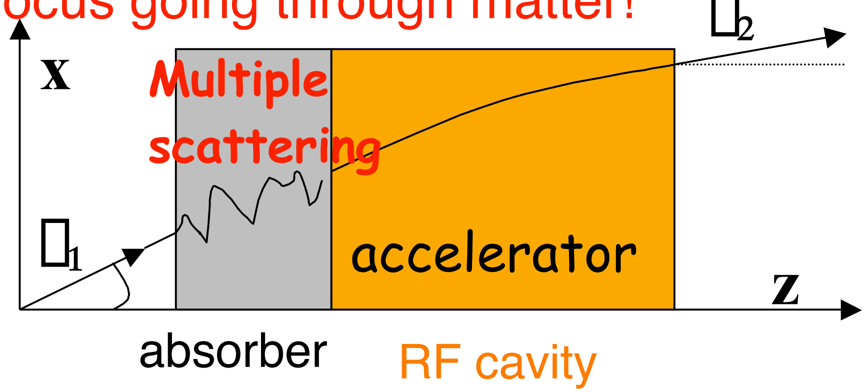
FNAL 500 GeV candidate..

PHOTO DATE: OCTOBER 1997

Ionization Cooling

The miracle of muons is that they can focus going through matter!





Liouville's Theorem states that phase space is invariant.. need to remove energy to increase particle density…

Phase space equation:

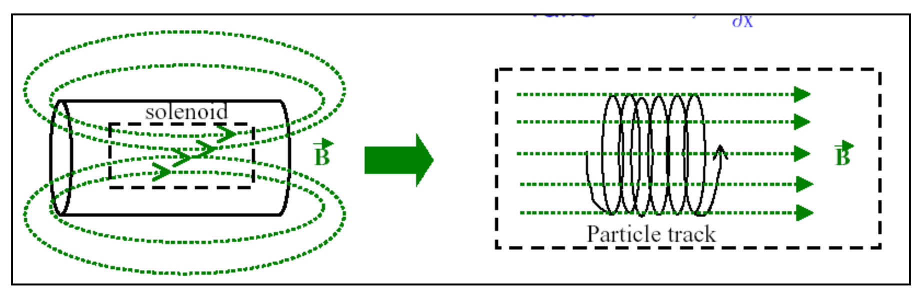
Cooling term

Heating term (mult.scatt.)

$$\frac{d\varepsilon_x}{dz} = -\frac{\varepsilon_x}{L_{trans}} + f\left(\frac{\beta_\perp}{\beta^3 E m_\mu L_R}\right)$$

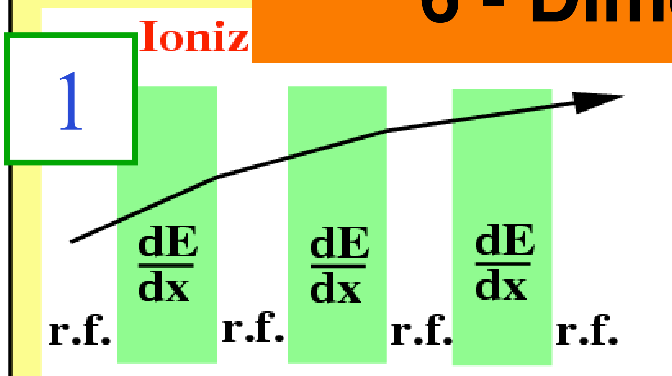
With transverse focussing (solenoid)

$\beta_\perp$ ~ beam envelope:



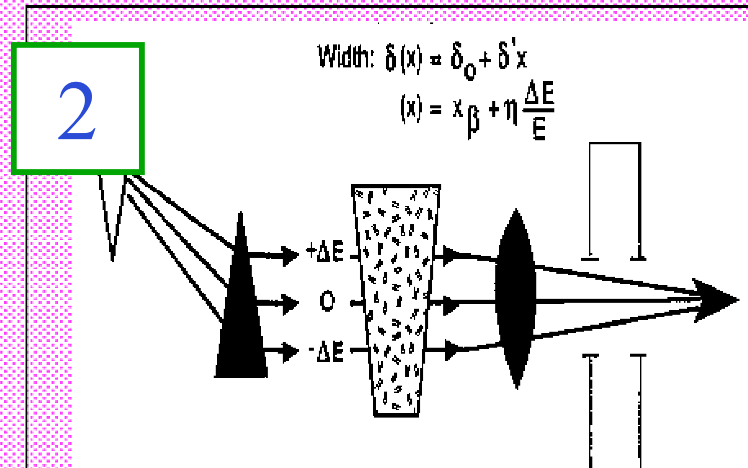
6 - Dimensional Cooling

Ioniz



Muons lose energy by dE/dx and long–itudinal momentum replaced by r.f.

- **To Minimize heating from Coulomb Scattering:**
  - **Small $\beta_\perp$ (strong focusing) :** **High–field solenoids** or **Lithium Lenses**
  - **Large L_R (low–Z absorber) : Liquid H_2**



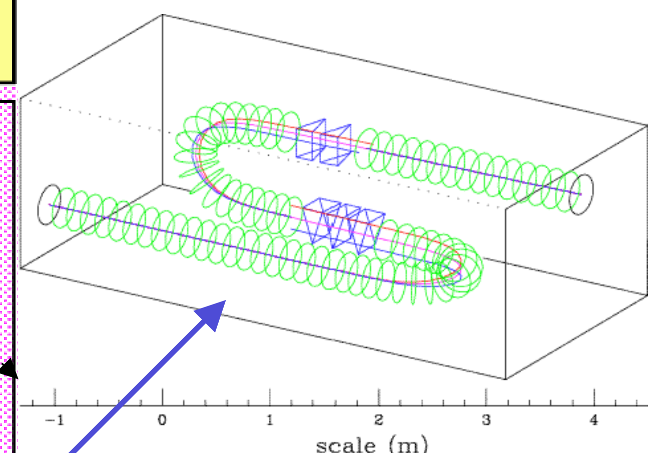
Energy "Cooling"

Ionization cooling using a wedge plus dispersion.

Exchanges emitt–ance between transverse & long–itudinal directions

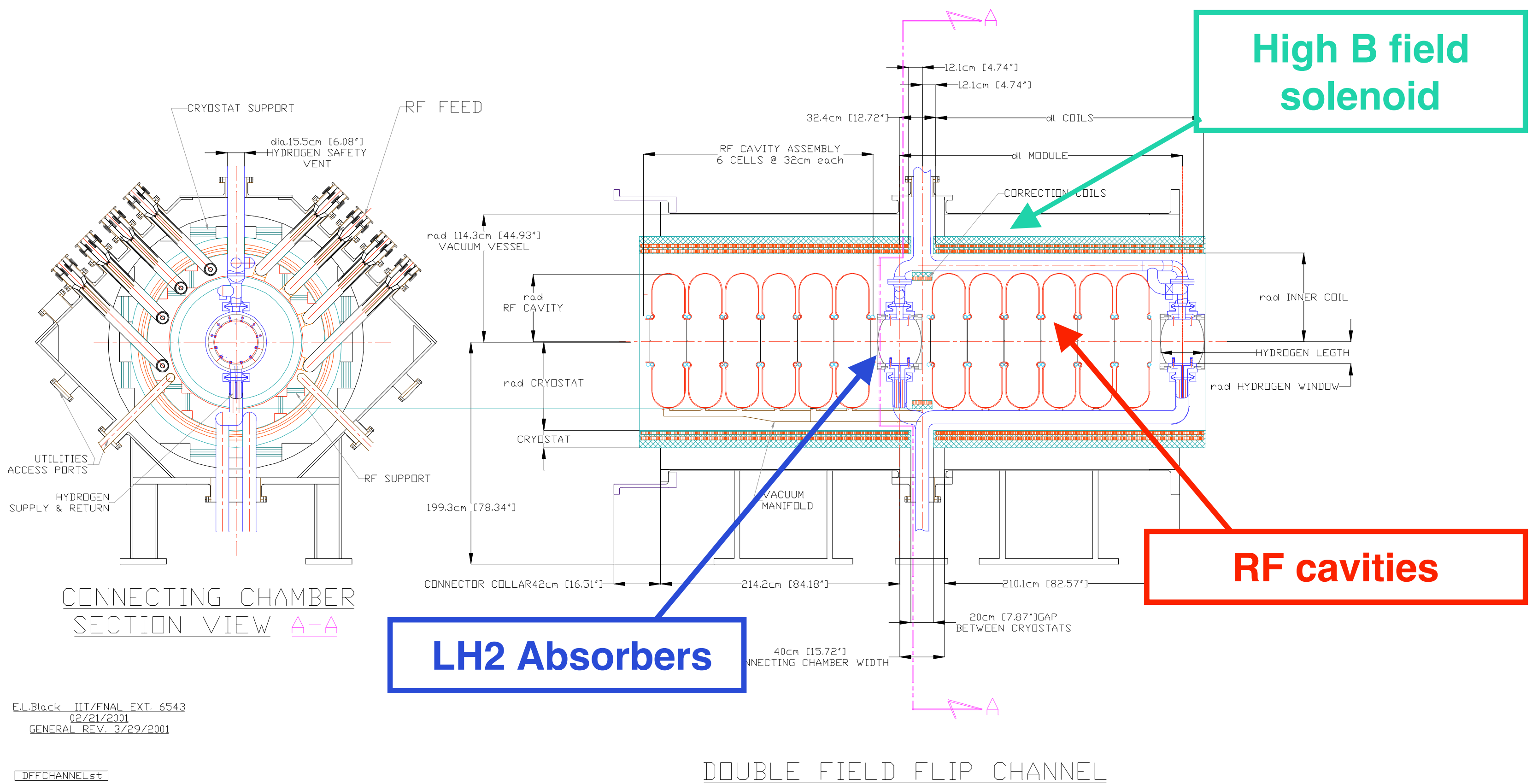
Cooling merit factor:
□6(init)/□6(final)

1. Neutrino source: 4-dimensional cooling
2. Muon collider: 6-dimensional cooling



Bent Solenoid: drift proportional to particle's momentum, introduces dispersion, □

Transverse Cooling Channel Design

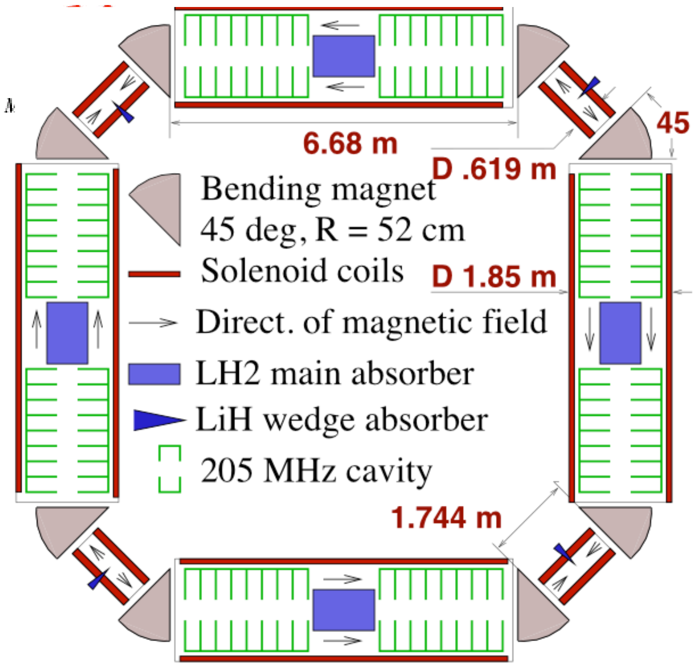


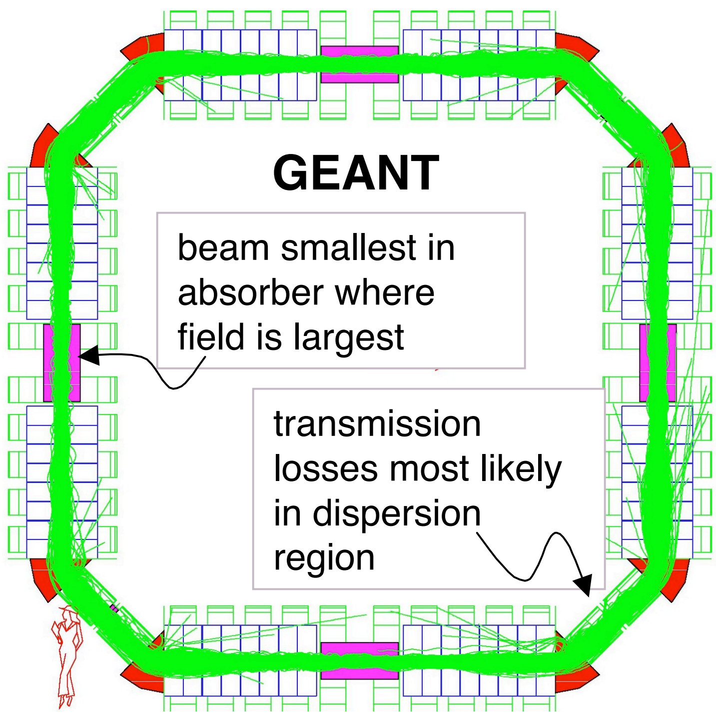
- Shown here, a cooling cell with LH_2 Absorbers, RF cavities and Solenoid Magnet:
- Issues:

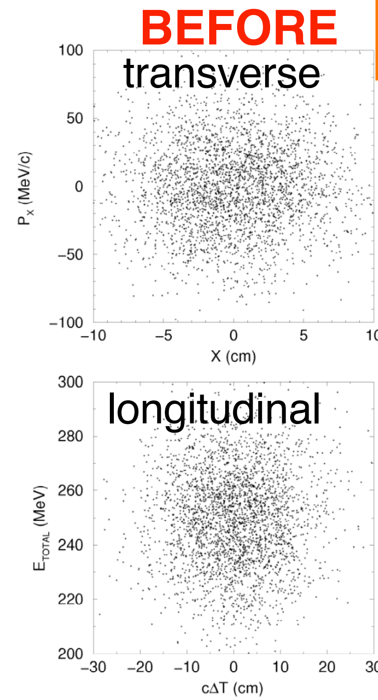
  LH2 safety, windows strong but thin, RF cavities "benign", structural intregrity in very large E and B fields

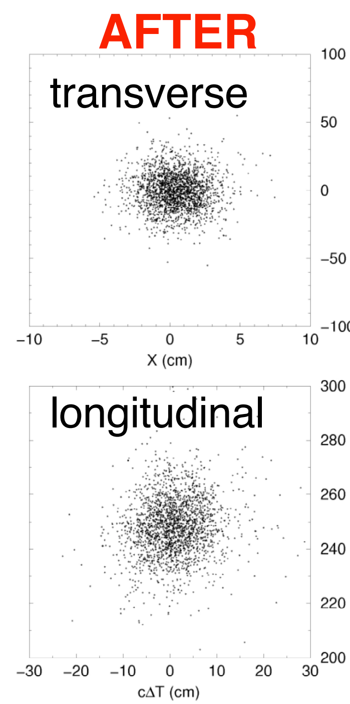
Ring Coolers

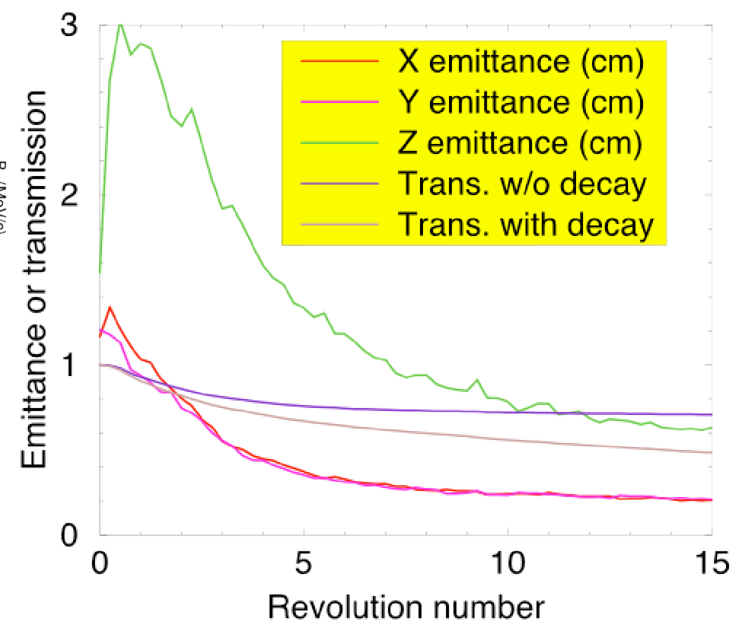
- Provides same transverse cooling as sFOFO linear channel considered in neutrino factory Study II.
- Heat dissipation in absorber could be challenging
- Injection and extraction is difficult-no space









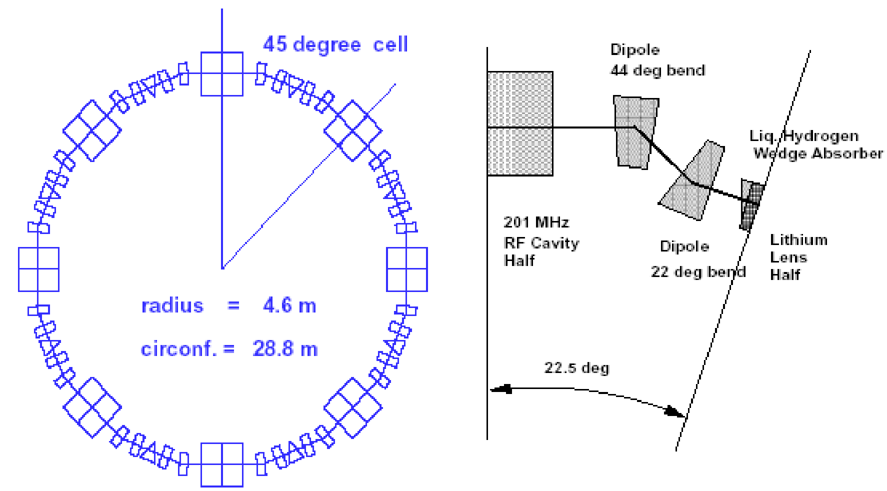


Merit Factor=38 after 15 turns

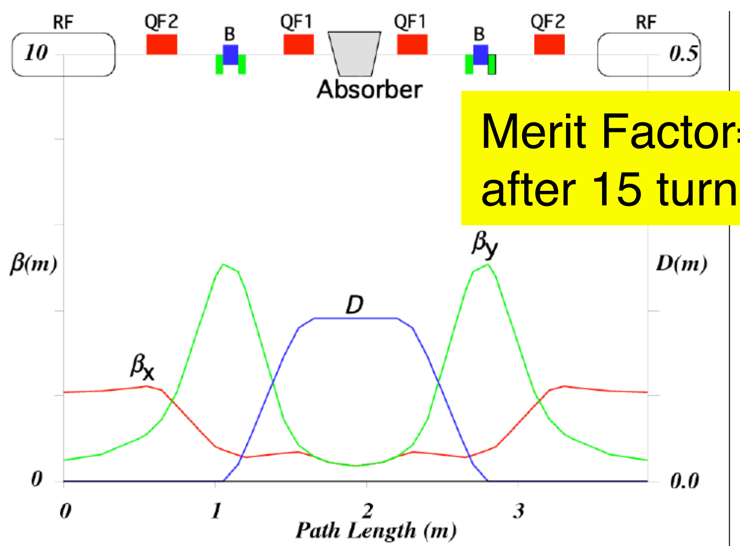
Lattice cooling rings

Use only convention quadrupole and/or dipole magnets to contain beam.

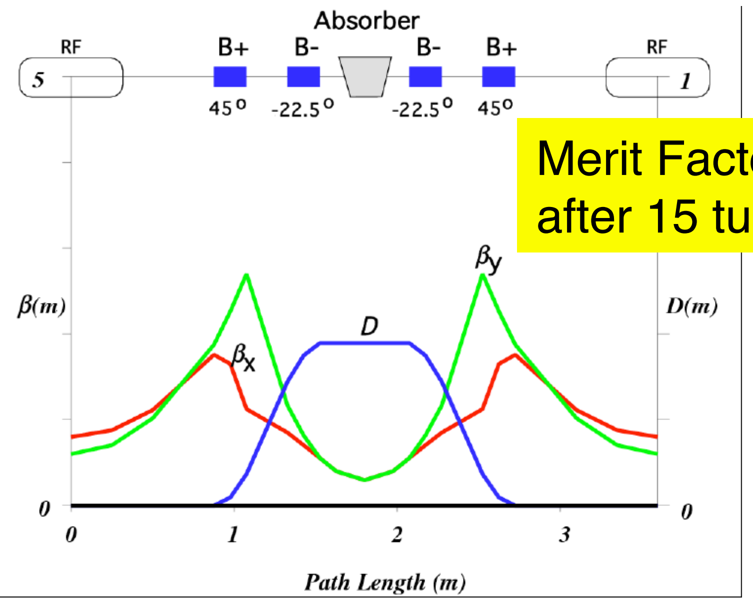
dipole only



Quadrupole/dipole ring



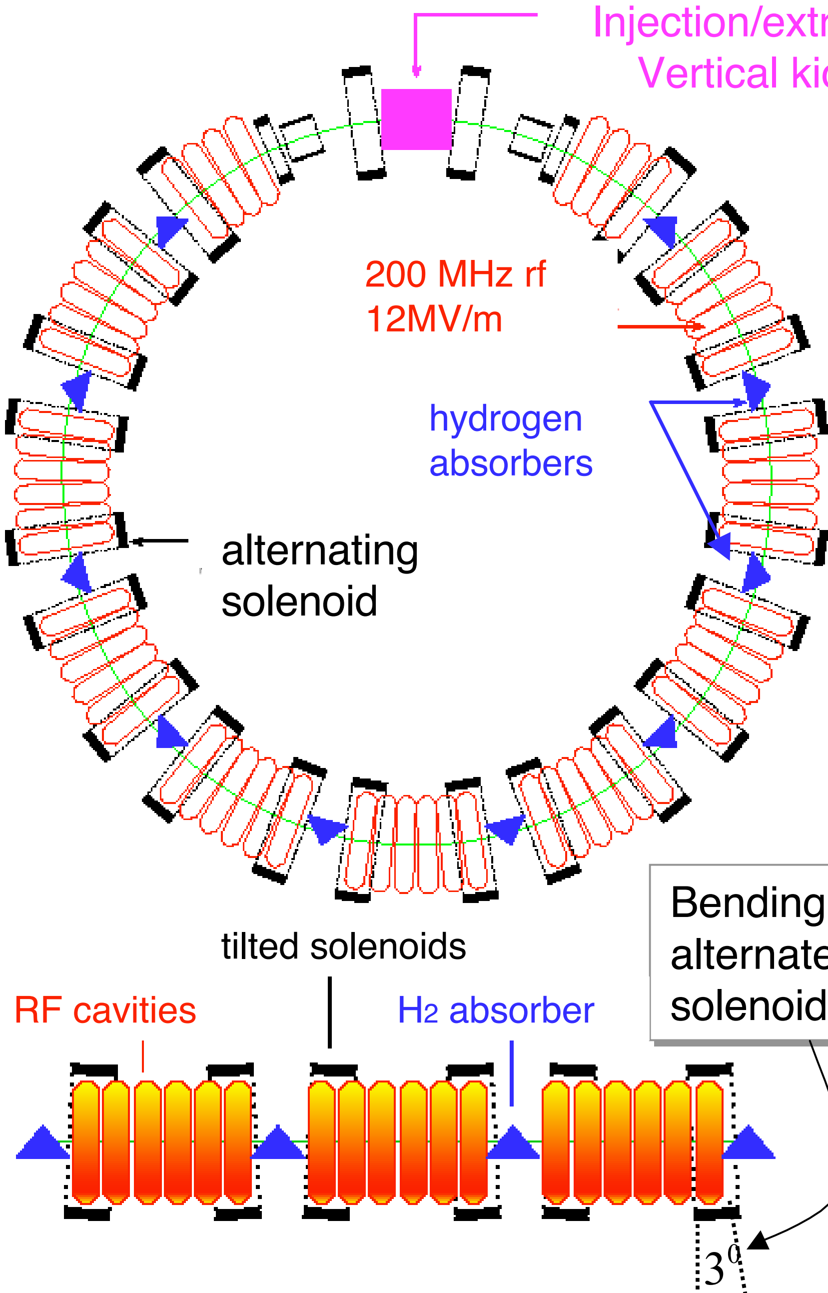
Merit Factor=15 after 15 turns



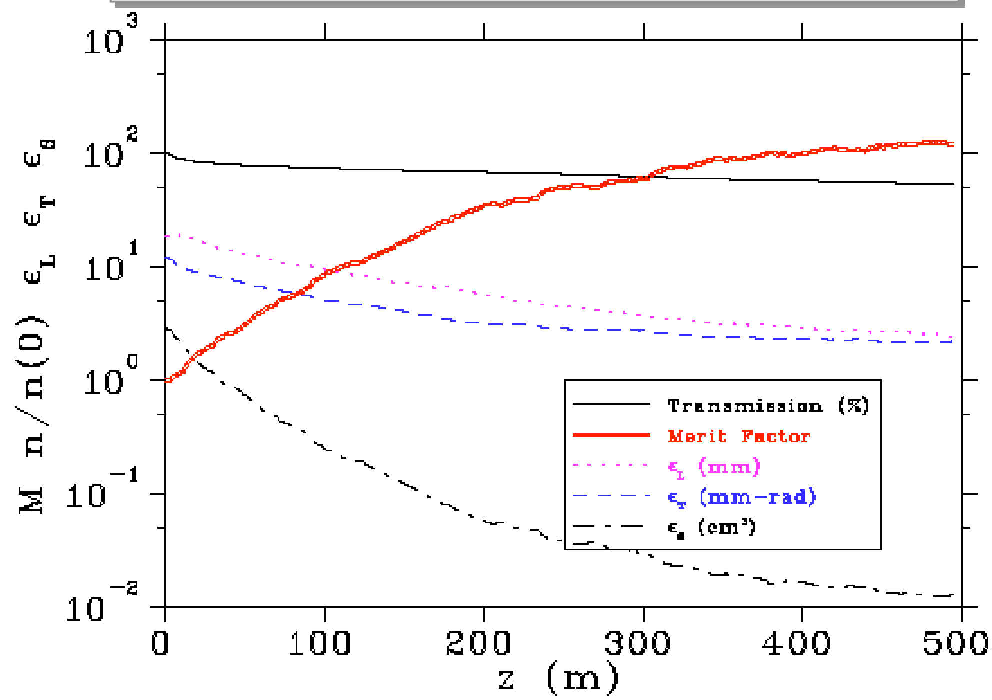
Merit Factor=80 after 15 turns

Performance improves for more compact lattices-could be a problem for injection/extraction

Alternating Solenoid Ring



Solenoids flip polarity at the center of a cell. All cells are identical.



Bending generated by alternately tilting the solenoids.

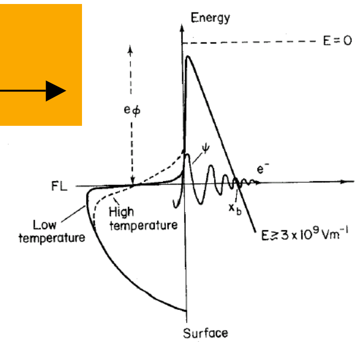
Merit factor decreases by ~30% after accounting for injection/extraction.

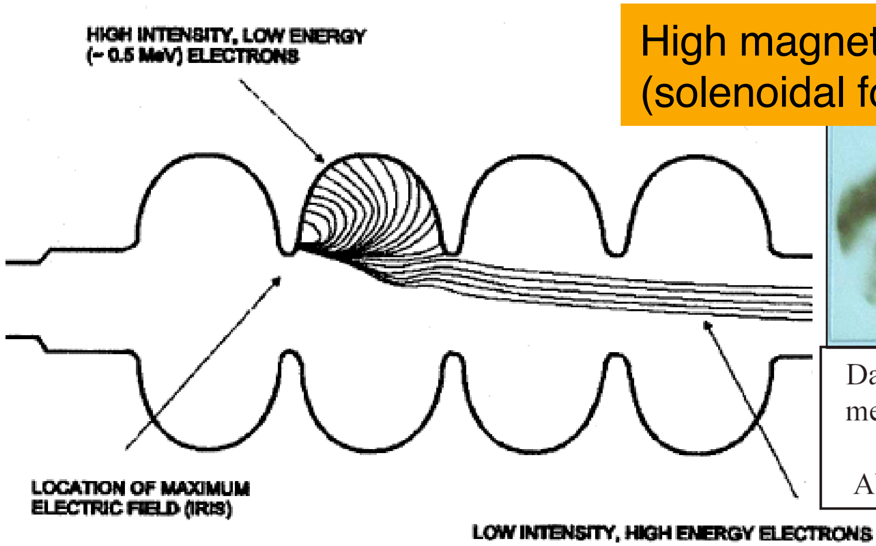
Dark currents

Dark matter dominates the universe
Dark Energy controls its destiny …
Dark currents keep us from unveiling its secrets…

Fowler-Nordheim field emission
(quantum tunnelling effect):

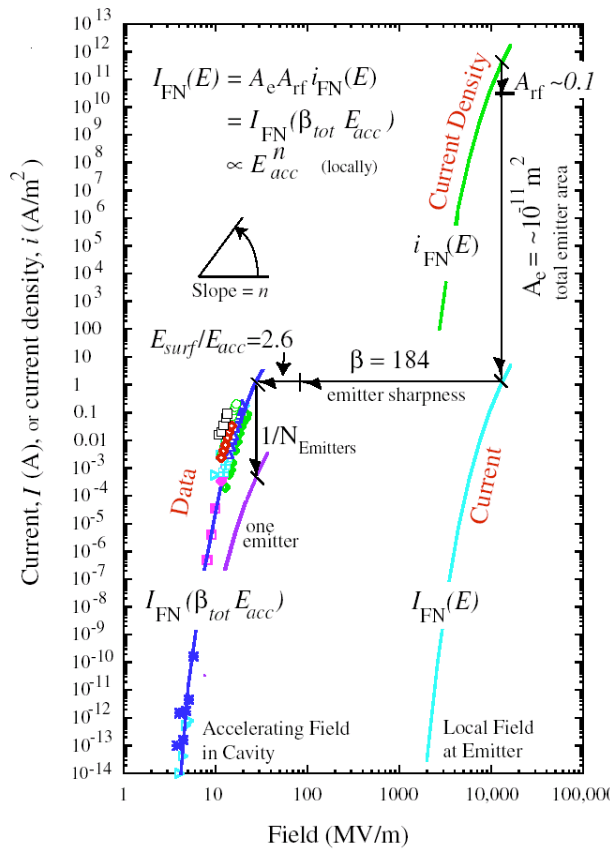
$$I(E) = \frac{A_{FN} A_e (\beta_{FN} E)^2}{\phi} \exp\left[-\frac{B_{FN}\phi^{3/2}}{\beta_{FN} E}\right]$$

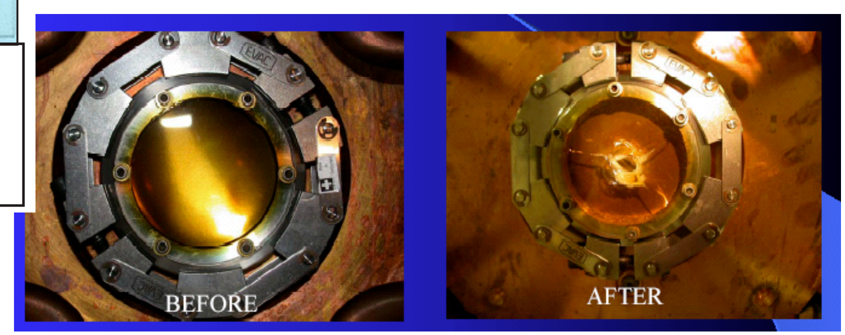




High magnet field
(solenoidal focussing!)

Dark current ring measurements on glass plate – ANL/FNAL/IIT





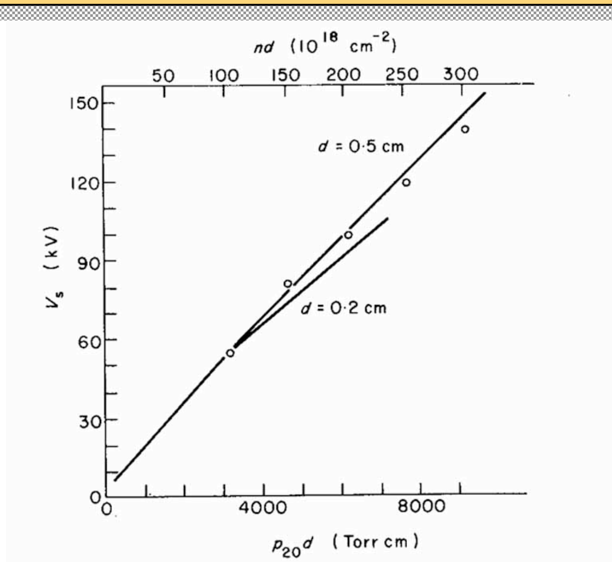
High Gradient Cavities: a gas filled approach

Paschen's Law (1889): breakdown voltage for discharge between electrodes in gases is a function of the product of pressure and distance.

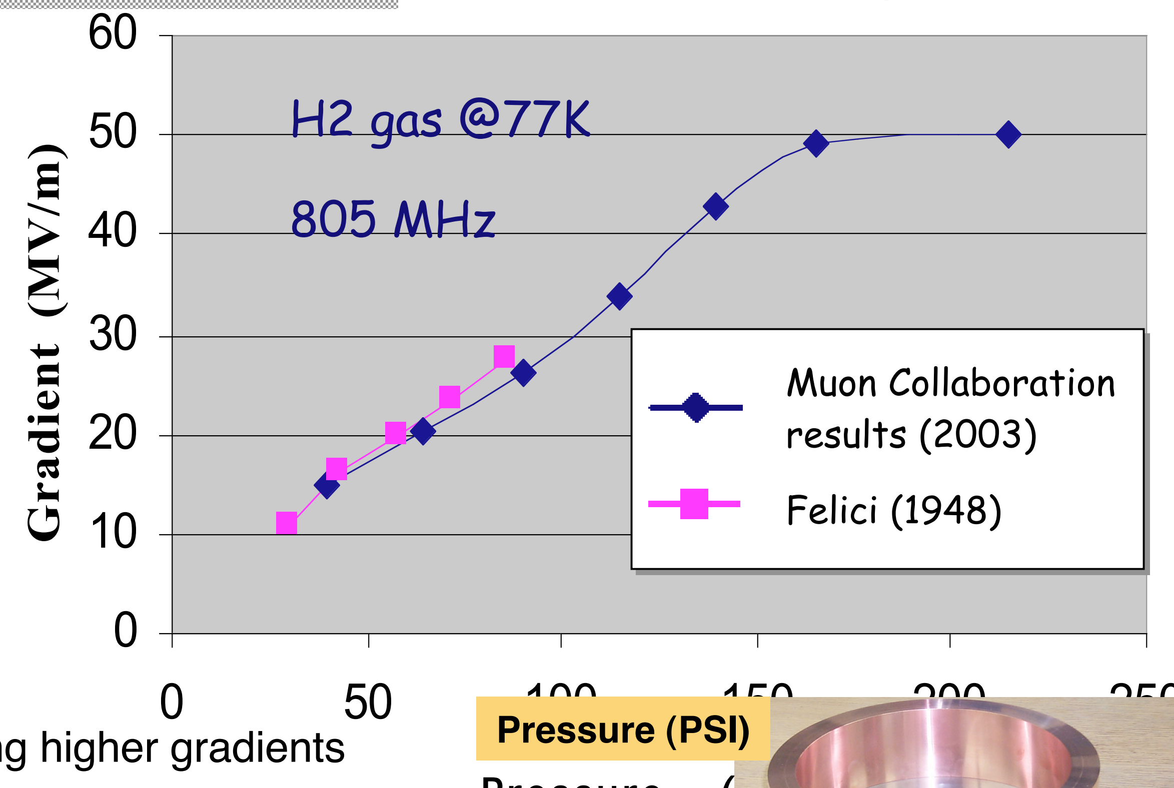
Gaseous hydrogen:

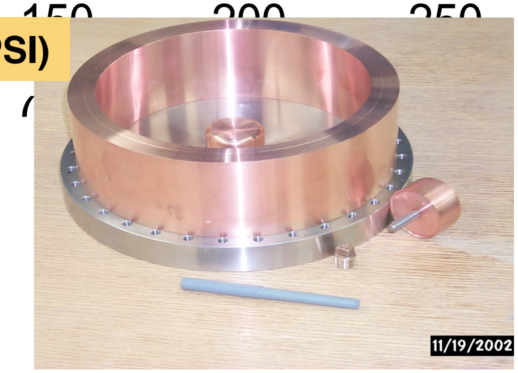
$$V_{breakdown} = 0.448nd + 0.6\sqrt{nd}$$

density n; pressure required decreases with temperature



Breakdown voltages in hydrogen (Müller, 1966. Repr... permission of Springer–Verlag)
—— Müller (1966)
○ Félici and Marchal (1948)





- Suppresses breakdown, allowing higher gradients
- Absorbs dark current radiation
- Gas with high heat capacity cools RF windows and increases electrical efficiency
- Gas can even act as a homogeneous absorber to provide ionization cooling!

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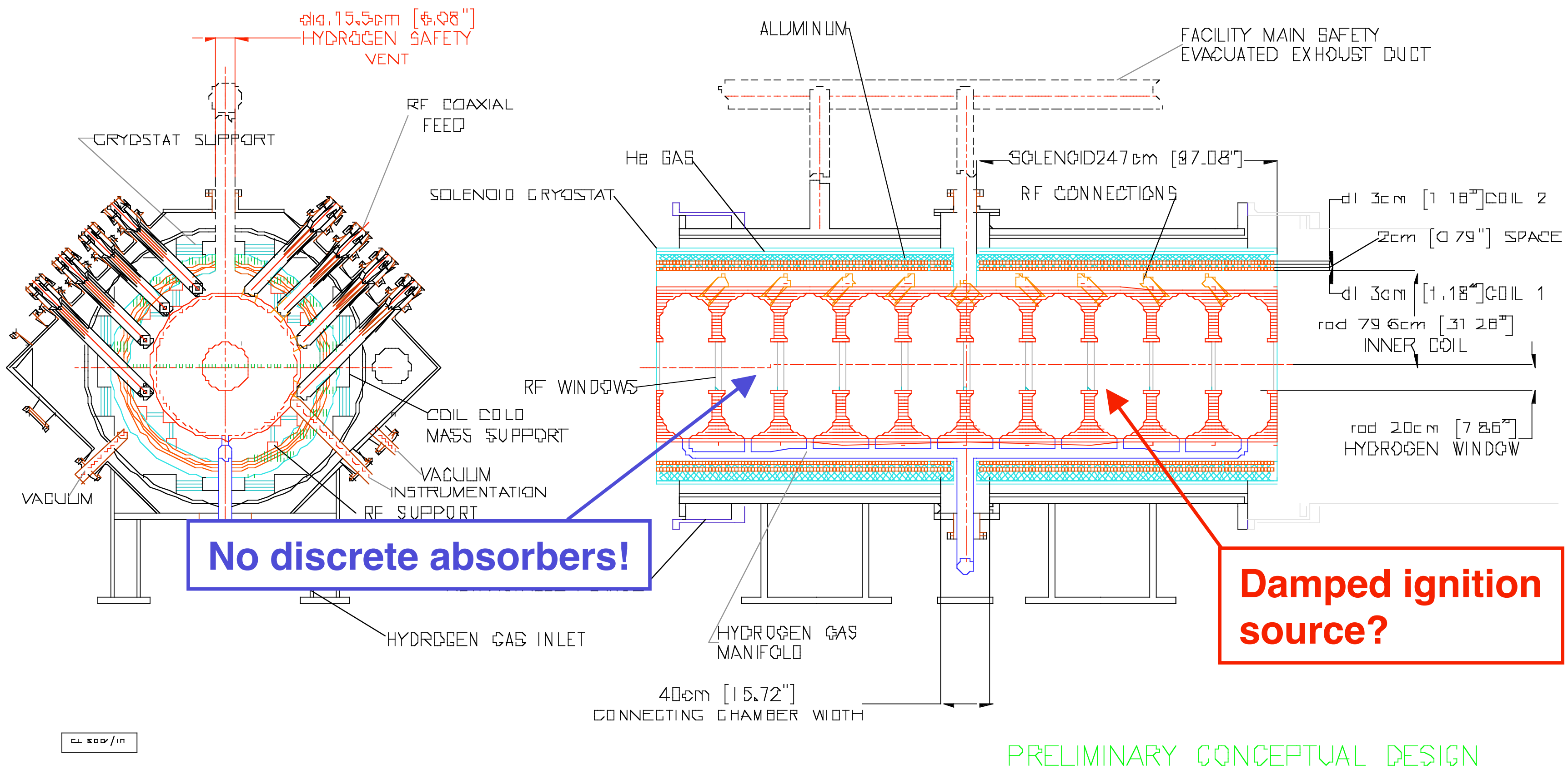
Gaseous Hydrogen Cooling Channel



- Dense GH_2 suppresses high-voltage breakdown
  inhibits avalanches (**Paschen's Law**)
- No absorber windows necessary!
- Best for uniform solenoidal fields

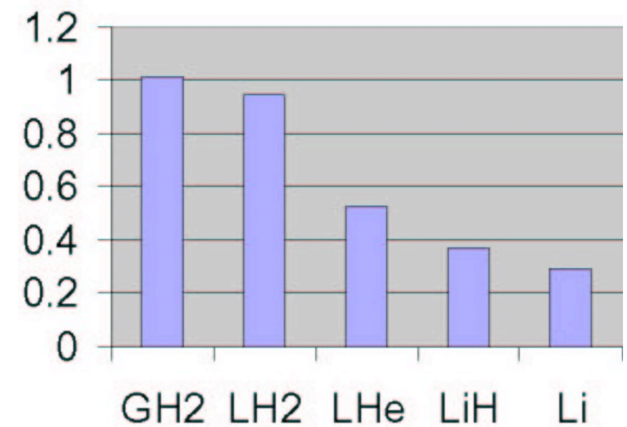
Major challenge to the prevailing safety culture!

6D Cooling in a gas filled RF cavity

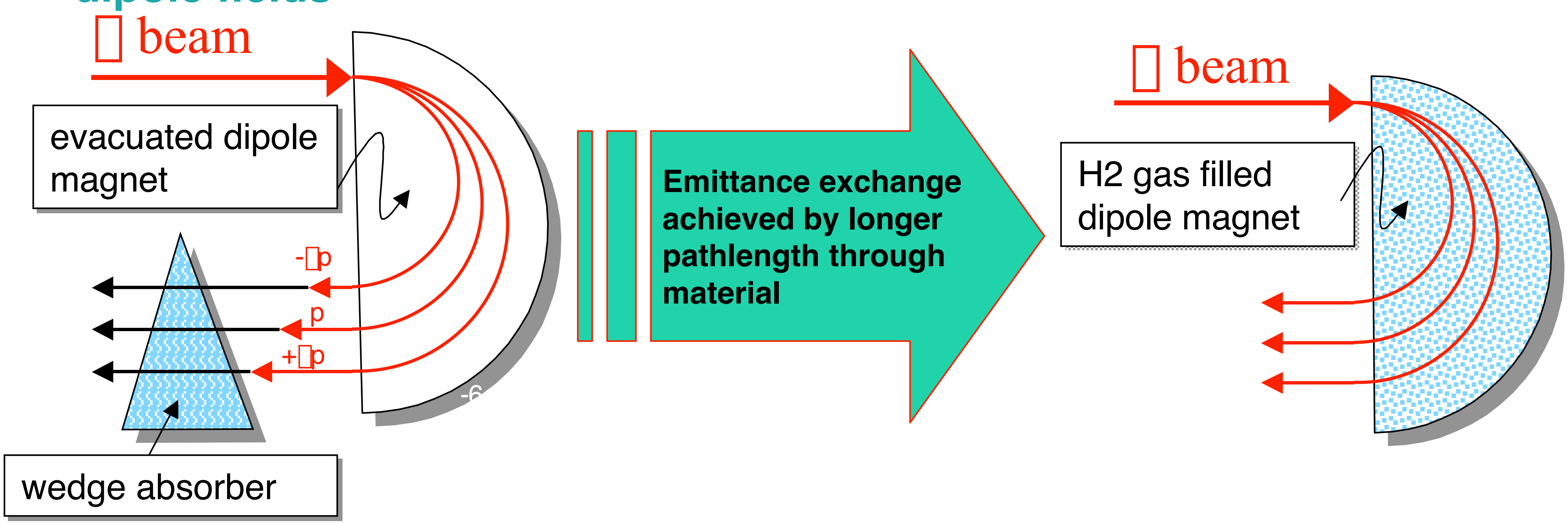
To achieve the same cooling power : $\left(X_0 \bullet {dE}/{dx}\right)^2$

for transverse cooling as in current LH2 cooling channels requires a GH2 pressure above that needed to suppress breakdown

Transverse Cooling Effectiveness



6D Cooling Channel: a gas–filled cavity in a solenoid plus transverse helical dipole fields



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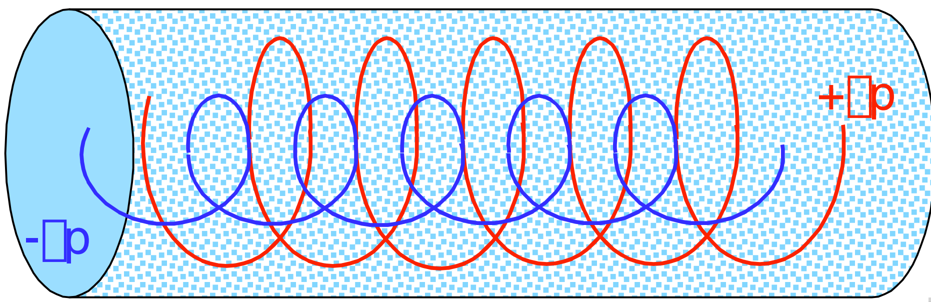
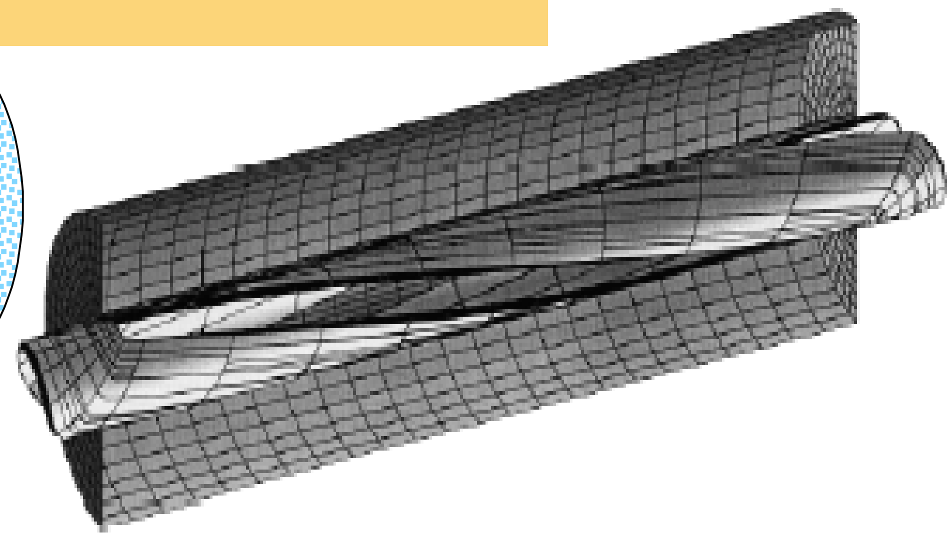
6D Cooling with GH2

- Derbenev channel: Solenoid plus transverse helical dipole fields
- Analytically see equal cooling decrements and 10^6 phase space reduction in ~150 m channel with energy loss of 1/3
- Not a ring channel – avoids ring problems
  1. Injection and Extraction simpler
  2. No Multi-pass Beam loading or Absorber heating
  3. Can adjust channel parameters as beam cools





Direct Wind Type

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Paper contributed to COOL03 Meeting Hotel Fuji, Japan

http://members.aol.com/muonsinc/COOL03_6-d_rev1.pdf

Concluding remarks

- Hadron colliders have traditionally been the “discovery” machines, and the Tevatron and LHC at this time, may be no exception.
- We don’t have enough information to make a decision to commit to any ~ $10G machine, and couldn’t build any if we did at this time.
- Accelerator and detector R & D is needed for all major proposed machines, and breakthroughs in any of them help all of them.
- Muon colliders are the farthest reaching machines, but recent developments suggest that it NOT necessarily the furthest away from being built at this time: both statements support a strong R & D program.
- Furthermore, an early stage of the □C, the □ factory, is a machine that may be technically and financially feasible ~ next 10 years.
- Aggressive accelerator and detector R & D is the only way we move from a “story” driven field to become a data driven field – and the muon collaboration is doing just that: a strong group of accelerator and particle physicists, reversing a > 40 year trend.