MUON COLLIDERS

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WHY MUONS

μ is a High mass Lepton

- **Lepton Energy advantage over p**
- **Suppressed Synchrotron Radiation**
  . $(\propto \ \gamma^4 \ \propto \ m^{-4})$
  - **Circular & Smaller than e^+e^-**
  - **Luminosity $\propto \ n_{turns} \ \approx$1000**
  - **Narrow Energy Spread $\rightarrow$ 0.003%**
- **Less Initial State Radiation**
- **Direct Higgs Production**
  - $\mu^+ \ \mu^- \ \rightarrow \ h, A, H \ (\sigma \ \propto \ m^2)$
- **μ p interactions at high energies**
  - **50 GeV μ + 1 TeV p: $\approx$ 1.3 HERA**
  - **200 GeV μ + 1 TeV p: $\approx$ 3 HERA**
  - **1.5 TeV μ + 1.5 TeV p: $\approx$ 10 HERA**

R & D STATUS
For First Muon Collider

			Need
Proton Source	**Intensity** **Short Bunch**	$\surd\surd$ $\surd\surd$	
Target	**Survival** π **Prod.**	$\surd$ $\surd$	**PtO_2 Exp.** **E910 Anal.**
Capture	**Solenoid**	$\surd\surd$	
Phase Rot.		$\surd$	**Details**
Polarization		$\surd$	**Details**
Cooling	**Init Trans.** **Final Trans.** **Long. Exchange**	$\surd$ $\surd$ **–**	**Details** **Space Charge** **Design**
Acceleration		$\surd$	**Details**
Collider	**Lattice** **Impedance** **Scraping** **Magnets**	$\surd$ $\surd$ $\surd\surd$ $\surd$	**Details** **2nd Harm.** **Details**
Background	**Occupation** **Radiation**	$\surd\surd$ $\surd\surd$	
Experimental	**B tagging** **E determination**	$\surd$ $\surd\surd$	**Details**

TARGET

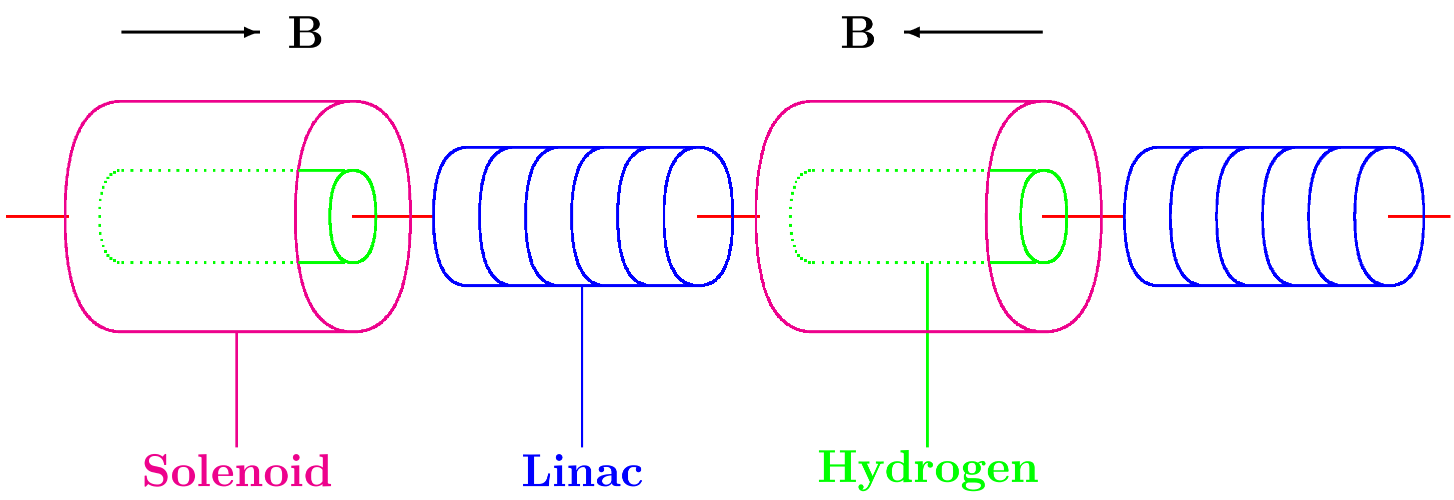
- **High Z material**
- **Small diameter**
- **Heating problem**
- **Liquid jet**
- **EM forces entering capture magnet**
- **Insulating material:** PtO_2/Re_2O_3 **?**

BASELINE PARAMETERS

c of m Energy	GeV	3000	400	100		
p Energy	GeV	16	16	16		
p's/bunch	10^{13}	2.5	2.5	5		
bunches/fill		4	4	2		
rep rate	Hz	15	15	15		
p power	MW	4	4	4		
μ/bunch	10^{12}	2	2	4		
μ power	MW	28	4	1		
wall power	MW	200	120	80		
collider circ	m	6000	1000	300		
$\approx$ depth	m	500	50	5		
rms dp/p	%	.16	.14	.12	.01	.003
6D emit. ϵ_6	$10^{-12}(\pi m)^3$	170	170	170	170	170
trans. ϵ_n	mm mrad	50	50	85	195	280
β^*	cm	0.3	2.3	4	9	13
σ_z	cm	0.3	2.3	4	9	13
σ_r spot	μm	3.2	24	82	187	270
tune shift		0.043	0.043	0.05	0.02	.015
luminosity	cm^{-2}sec^{-1}	5 10^{34}	10^{33}	1.2 10^{32}	2 10^{31}	10^{31}
c of m dE/E	10^{-5}	80	80	80	7	2
Higgs/year	10^3 $year^{-1}$			1.6	4	4

HOW TO GET LOW $\beta_\perp$

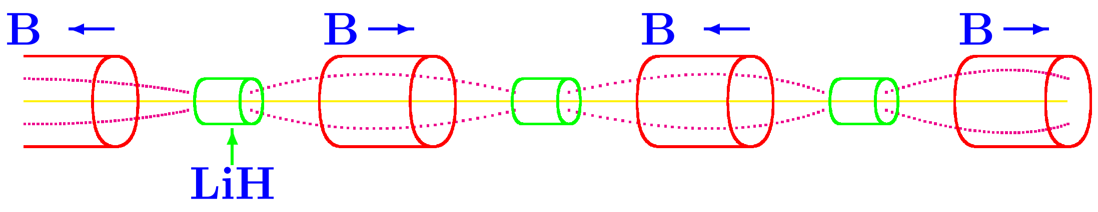
- **Alternating solenoids**



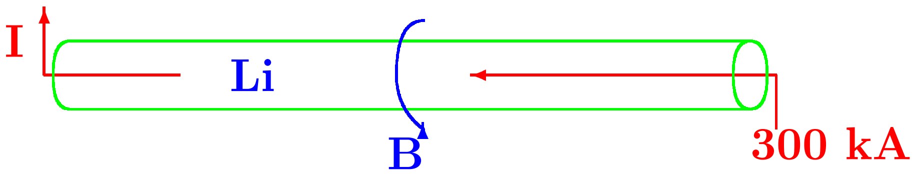
- **B must alternate to avoid Canonical Ang. Mom. buildup**

- **Problem is to match between reversals**

- **FOFO** **(No Longer Favored)**



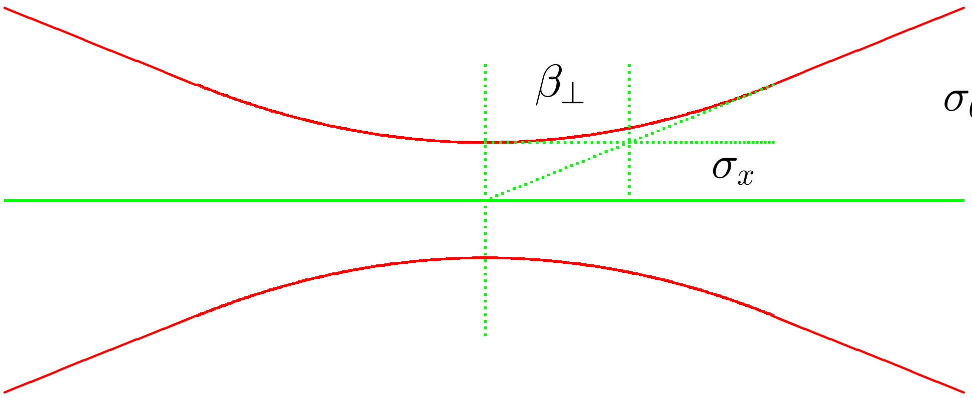
- **Lithium Lens** **(Possibly for Late Stages)**



WHAT IS BETA$_{Courant-Snyder}$?

Again upright ellipse, e.g. at Focus:

$$\beta_\perp = \frac{\sigma_x}{\sigma_\theta}$$



Then, using emittance definition:

$$\sigma_x = \sqrt{\epsilon_\perp \ \beta_\perp \ \frac{1}{\beta_v \gamma}}$$

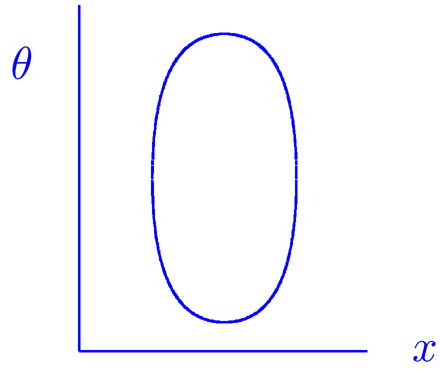
and:

$$\sigma_\theta = \sqrt{\frac{\epsilon_\perp}{\beta_\perp} \ \frac{1}{\beta_v \gamma}}$$

WHAT IS EMITTANCE

("normalized", rms, SLAC Convention)

e.g. upright ellipse



$$\epsilon_\perp = \sigma_\theta \sigma_x \quad (\gamma\beta_v) \qquad\qquad (m\ rad)$$

$$= \frac{dp_\perp dx}{m} = \frac{\Phi_\perp}{\pi m}$$

$$\epsilon_\| = dp/p\sigma_z \quad (\gamma\beta_v) \qquad\qquad (m\ rad)$$

$$= \frac{dp_\| dz}{m} = \frac{\Phi_\|}{\pi m}$$

$$\epsilon_6 = \epsilon_\perp^2 \quad \epsilon_\| \qquad\qquad (\pi\ m)^3$$

TRANSVERSE COOLING

- **Energy Loss lowers** $\epsilon_\perp$
- **Coulomb Scattering Increases** $\epsilon_\perp$
- **At Equilibrium:**

$$\epsilon_\perp(Eq) \;=\; \beta_\perp \frac{14\ MeV}{2\beta_v L_R\ dE/dx}$$

- **Need:**
  - **Low Z material ($\mathbf{H_2}$ > Li > Be)**
  - **Low** $\beta_\perp$
- **e.g. If**

Material = Hydrogen/Lithium/Beryllium
p = 180 MeV
Cooling = 3/4 Max. $\left(\epsilon_\perp = 4 \times \epsilon_{equ}\right)$
Acceptance = 4 × rms,

$$\theta_{acceptance} \;=\; \frac{A}{\sigma_\theta} \times \sqrt{\frac{\epsilon_\perp}{\epsilon_{equilib}} \;\; \frac{14\ MeV}{2\gamma\ \beta_v^2\ L_R\ dE/dx}}$$

$$\approx\ \mathbf{0.35}_H/\mathbf{0.5}_{Li}/\mathbf{0.6}_{Be}\ \textbf{radians}$$

HOW ARE WE DOING?

- **Muon Production**
  - Baseline: 0.3 Muons/proton
  - Simulation with 20 T: 0.38
  - Simulation with 28 T: 0.45
- **Minimum 6D emittance**
  - Baseline: 170 10^{-12} $(\pi\ m)^3$
  - Simulation 30 10^{-12} $(\pi\ m)^3$
- **Losses in Cooling**
  - Baseline: 50 %
  - Estimate: 30 %
- **Losses in Acceleration**
  - Baseline: 50 %
  - Simulation: 27 %
- **Collider Circumference**
  - Baseline: 300 m
  - Design: 330 m

COOLING SYSTEM

- **Initial 6D emittance $\approx$ 1.5 10^{-4} $(\pi m)^3$**
- **Final 6D emittance $\approx$ 1.7 10^{-10} $(\pi m)^3$**

Reduction $\approx 10^6$

- **6D emittance reduction/stage $\approx$ 2**
- **Typical length 20 m**
- **Trans Cool & Long Exch Alternate**

Number of stages $\approx$ 15
Total Length $\approx$ 400 m
Momentum $\approx$ 180 MeV/c
Decay Loss $\approx$ 30 %

- **Parameters awaiting Exch. Design**

CONCLUSION

MOTIVE

- Lower $/TeV
- Small size: 3 TeV fits on FNAL site

BUT FIND ALSO:

- Very low dE/E
- Precision E Determination
- S Coupling to Higgs

PROGRESS

- Theory well understood
- Baseline Simulations almost complete
- Need Experimental Program

NEUTRINO RADIATION

- Radiation $\propto$ Current$_\mu$ x E^3/length^2
  $\propto$ Current$_\mu$ E^3/depth
- Use: 1/10 Federal limit = 10 mR/year

THEN

- Negligible problem at 1.5 TeV
- E = 3 TeV ok at 500 m depth
- E > 3 TeV Requires:
  - Beam wobbles, and/or
  - Special Locations, and/or
  - Deeper, and/or
  - Lower Muon Current $\rightarrow$
  - Lower Luminosity
- But Luminosity not so Low
  - If Tune Shift corrected:
  - At 10 TeV: $\mathcal{L} \approx 10^{35}$

ENERGY SCALING

- **E $<$ .5 TeV**
  Angle and N$_\mu$ Limited

$$\mathcal{L} \propto (n_\mu f)\ \theta^{2/3}\ \gamma^2\ \frac{n_\mu^{1/3}\ \delta^{2/3}}{(\epsilon_6/n_\mu)^{2/3}}$$

- **E $>$ .5 TeV**
  Aperture and $\Delta\nu$ Limited

$$\mathcal{L} \propto (n_\mu f)\ \gamma^{3/2}\ \sqrt{\Delta\nu\ \frac{\delta\ A\ B}{(\epsilon_6/n_\mu)}}$$

- **E $>$ .5 TeV ($\Delta\nu$ Corrected)**
  Aperture and N$_\mu$ Limited

$$\mathcal{L} \propto (n_\mu f)\ n_\mu^{1/3}\ \gamma^{5/3}\ \frac{\delta^{2/3} A^{1/3}\ B^{1/3}}{(\epsilon_6/n_\mu)^{2/3}}$$

ORGANIZATION

- **Formal Collaboration:**
  - **3 US Labs: BNL,FNAL,LBNL**
  - **1 non US lab: BNIP**
  - **3 Univ: Miss., Princeton, UCLA**
  - $>$ **100 members**
  - $\approx$ **30 FTE's**
- **Funding Needs**
  - $\approx$ **6 M\$/year for theoretical**
  - $\approx$ **12M\$/year for exp's**
- **Funding**
  - **DOE Blessing of existing efforts**
    ($\approx$ 3 M\$/year)
  - **Formal request for expanded effort**
  - **No formal funding yet**

FUTURE MEETINGS

- **Collaboration Meeting**
  - **Gulf Shores, ALABAMA**
  - **March 18-22, 1998**
- **Workshops**
  - **Cooling, BNL Jan 20-24, 98**
  - **RF, LBNL Feb 16-17, 98**
  - **Collider, UCLA Feb 12-13, 98**
  - **Target, BNL Feb 27, 98**
  - **SC Magnets, LBNL April 1-2, 98**

TIME SCALE

- 5 years: 1997-2002: R and D
  - Theoretical Studies
  - Demonstrate cooling
  - Demonstrate Capture
  - 2002: Decision Point
- 4 years: 2002-2006: Prototype work
  - Front End Construction
  - Recycler Magnet Prototype
  - SC Collider Magnet Prototype
  - Proposal would be submitted 2004
  - Fix Energy on the basis of LHC results
- 4 years: 2006-2010:
  Build First Muon Collider
  - Higgs Factory
- 10 years: 2010-2020:
  Upgrade Energy
  - Energy $\sqrt{S} \rightarrow$ .5, 1, 2, 3 TeV

COLLIDER RING

- **Low beta**
  - **3mm at 3 TeV, 4 cm at 100 GeV**
  - **Needs Local Chromatic corr.**
  - **Large Quadrupoles only at 3 TeV**
- **Short Bunches**
  - **equal to above beta's**
  - **Needs nearly isochronous ring**
  - **Use Flexible Momentum Compaction**
- **Tungsten Beam Shield**
  - **6 cm at 3 TeV, 2-3cm at 100 GeV**
  - **large dipole coil diams**
    16 cm at 3 TeV, 8-9 cm at 100 GeV
- **Status**
  - **Feasibility Lattice ok at 4 TeV**
  - **Several ok Latices at 100 GeV**
  - **Beam Scraping ok at 4TeV & 100 GeV**

CAN LUMINOSITY BE INCREASED

- **Lower trans emittance (x 2)**
  - **Higher B solenoids/Li Lenses**
- **Lower beta (x 2)**
  - **stronger quads**
- **Reduce circumference (x 1.5)**
  - **Higher B dipoles**
- **Increase muons (x $1.4^2 = 2$)**
  - **Higher B capture**

Gain $\approx$ 10 times

Many other ideas and possibilities
Ultimate Luminosity (Skrinsky/King)

Gain $>$ 100 times