Summary of Future accelerators?

A Discussion Not a Survey

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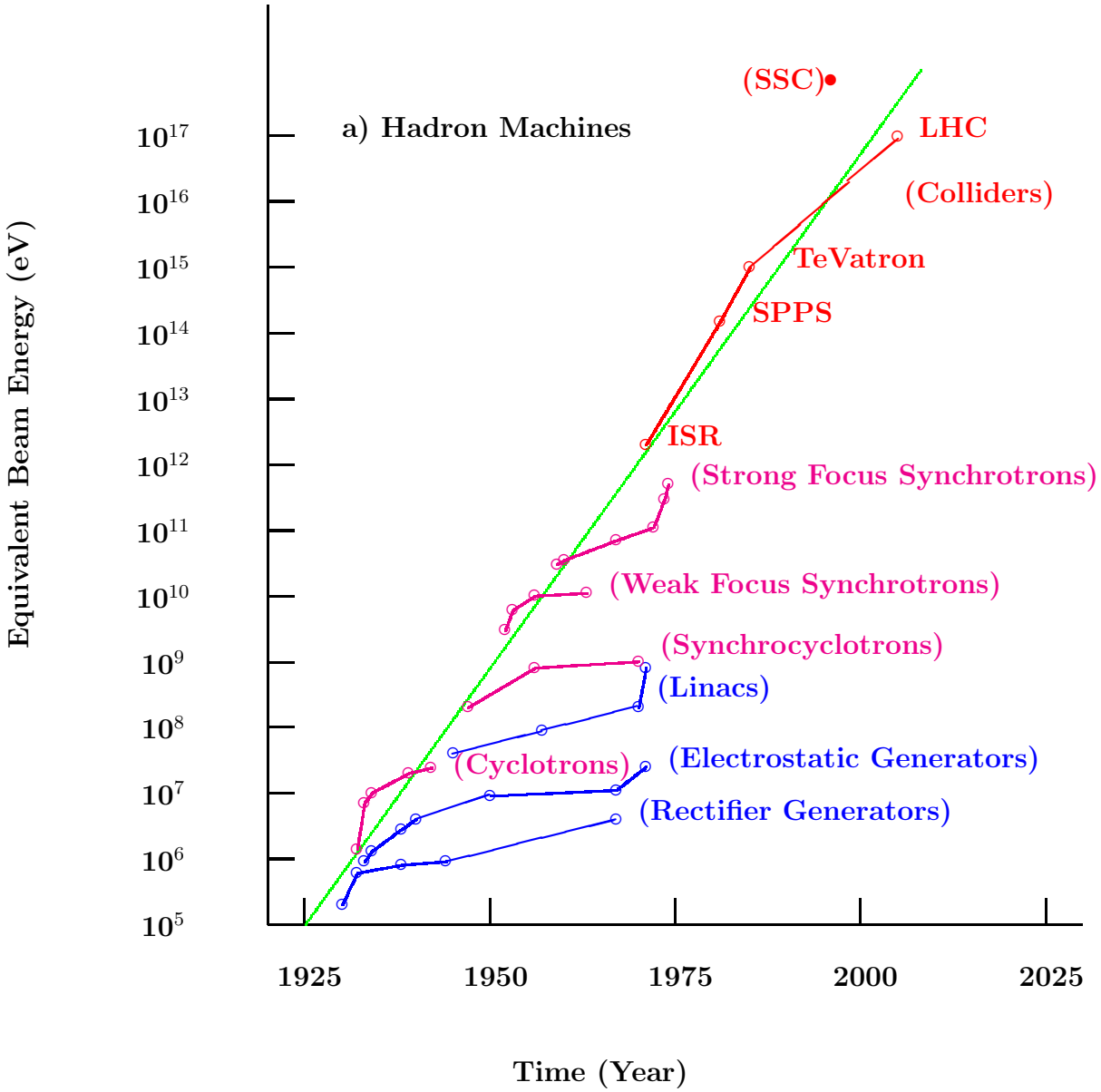
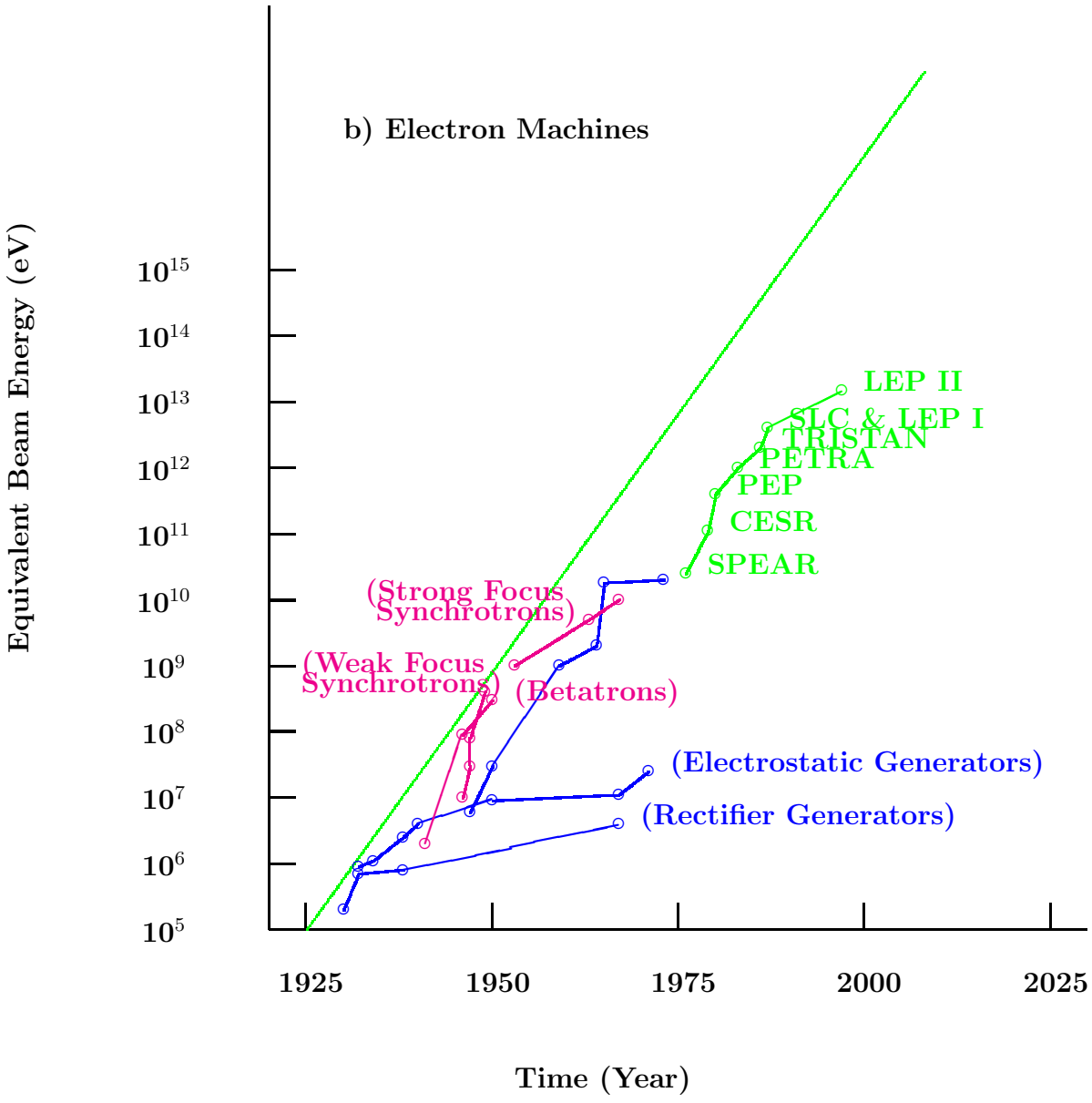
Aspen
January 2001

http://pubweb.bnl.gov/people/palmer/talk/Aspen.ps

LIVINGSTON PLOTS



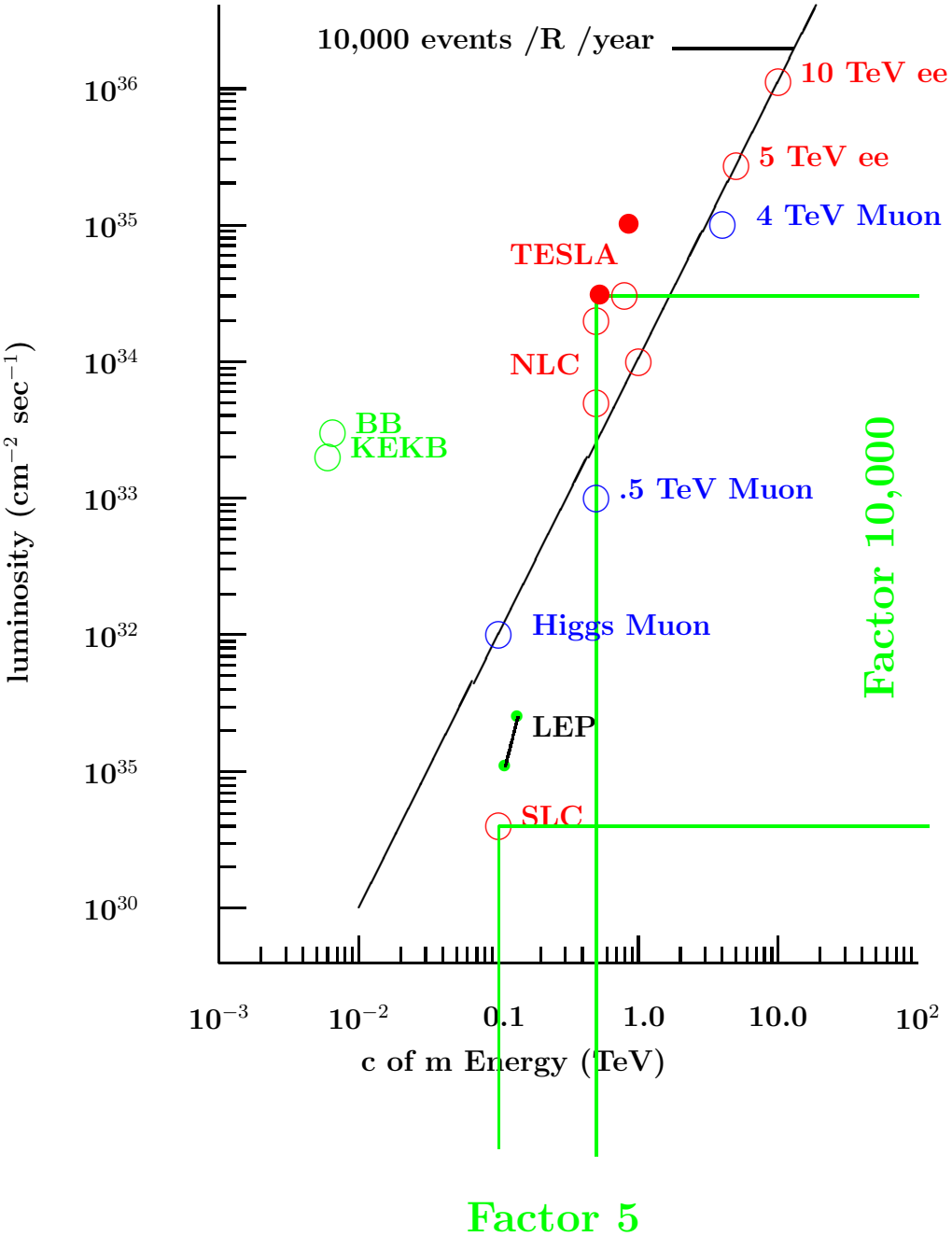

b) Electron Machines
Equivalent Beam Energy (eV)
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
1925
1950
1975
2000
2025
Time (Year)
LEP II
SLC & LEP I
TRISTAN
PETRA
PEP
CESR
SPEAR
(Strong Focus Synchrotrons)
(Weak Focus Synchrotrons)
(Betatrons)
(Electrostatic Generators)
(Rectifier Generators)

$e^+ e^-$ COLLIDERS

- **E advantage over protons (5-10)**
- **Known initial state**
- **Low backgrounds & radiation**
- **Complements protons**
- **Must be linear for E > .2 TeV**

- **1.3 GHz Superconducting**
  - **TESLA (DESI, Germany)**
- **11 GHz Copper**
  - **NLC (SLAC, USA)**
  - **JLC (KEK, Japan)**
- **30 GHz Copper**
  - **CLIC (CERN, Swizerland)**
- **90 MHz**
  - **Matrix (SLAC, USA)**
- **Laser, Wake, Plasma**
  - **Many**

LUMINOSITY


10,000 events /R /year
10 TeV ee
5 TeV ee
4 TeV Muon
TESLA
NLC
BB
KEKB
.5 TeV Muon
Higgs Muon
LEP
SLC
Factor 10,000
Factor 5
luminosity (cm^{-2} sec^{-1})
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{35}
10^{30}
10^{-3}
10^{-2}
0.1
1.0
10.0
10^{2}
c of m Energy (TeV)

WHY IS LUMINOSITY HARD ?

$$L = \frac{N_e^2 \; f \; n_c}{4 \; \pi \; \sigma_x \; \sigma_y}$$

$$L \propto \frac{P_{ave}}{\gamma} \; n_c \quad \frac{N_e}{\sigma_x \; \sigma_y}$$

At energies $\geq$ about 0.2 TeV: accelertion linear: $n_c = 1$

At energies $\geq$ about 2 TeV: Radiation problems in Final Focus and Intersection.

1. Radiation in focus

limit (Oide) on σ_y:

$$\sigma_y \quad \geq \quad const \quad \epsilon_n^{5/7}$$

(**This minimum requires** $\beta_{focus} \quad = const \quad \epsilon_n^{3/7}$)

independent of energy.

$\rightarrow$ **Need small** ϵ_n

Use Adiabatic focussing to remove Oide Limit

But we do not have a practical way of doing this.

2. Radiation at intersection

function of Field B from oncoming bunch:

$$B \quad \propto \quad \frac{N}{\sigma_z \ \sigma_x}$$

Radiation generates energy spread and backgrounds.

$\rightarrow$ **Need small N/σ_x**

Use 4 beams colliding to
Cancel Field from oncoming bunch

But instabilities and jitter

Luminosity :

$$L \quad \propto \quad \frac{P_{ave}}{\gamma} \quad \left(\frac{N}{\sigma_x}\right) \quad \left(\frac{1}{\epsilon_n^{5/7}}\right)$$

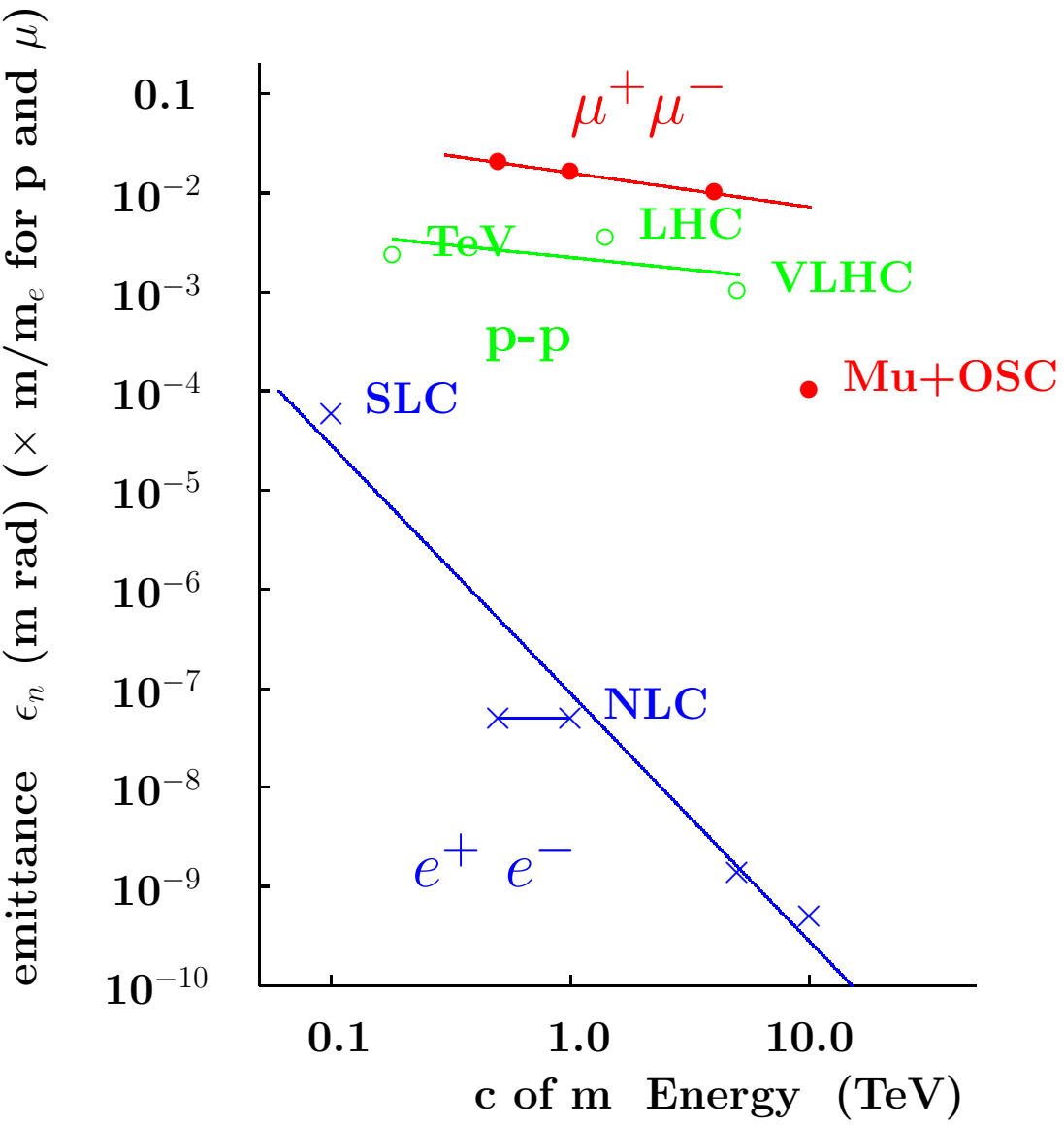
N/σ_x is limited by radiation considerations, and we need

$$L \quad \propto \gamma^2$$

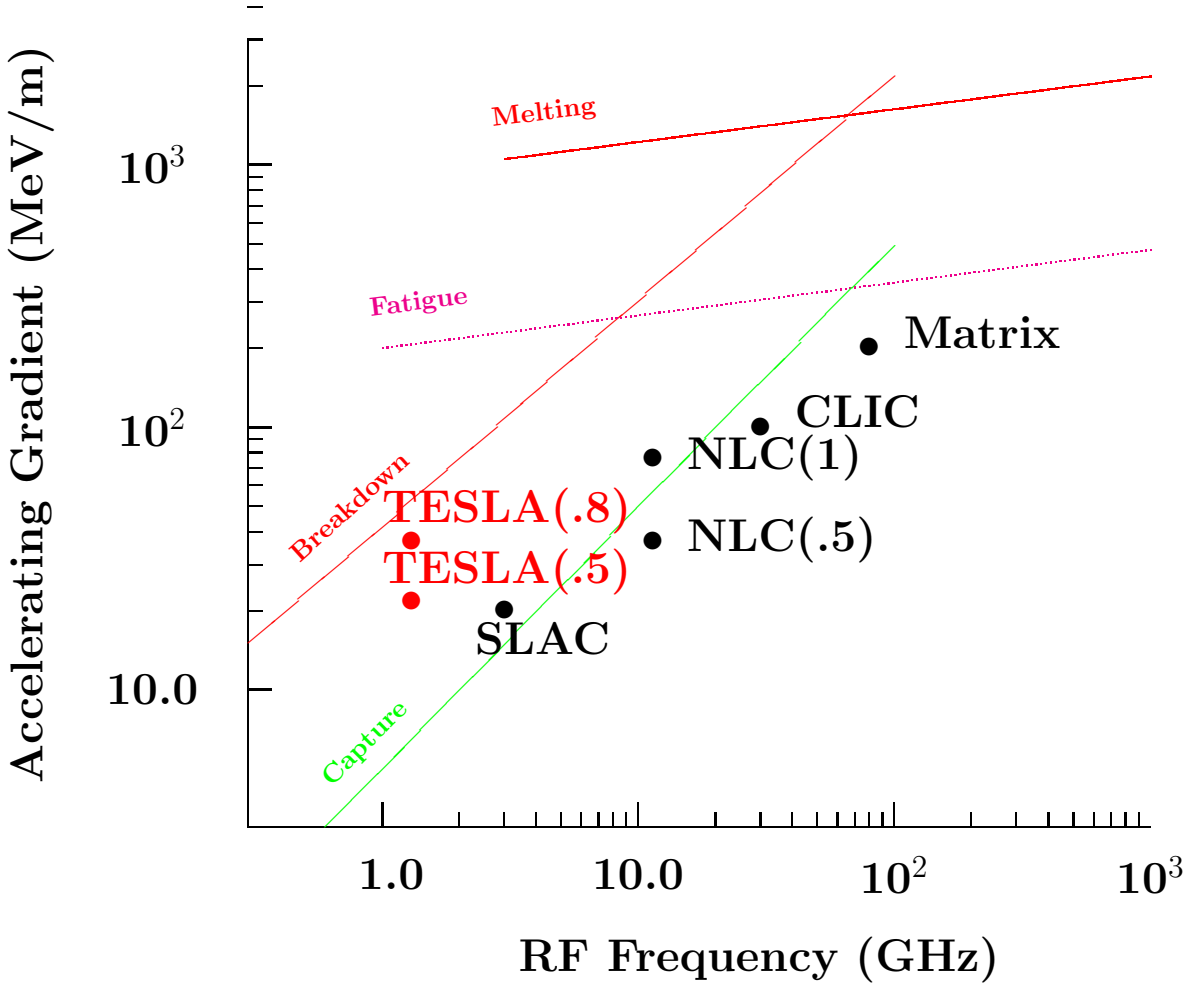
So we Need:

- **High Beam Power**
- **Low normalized emittance**

EXAMPLE:


emittance ϵ_n (m rad) ($\times$ m/m$_e$ for p and μ)
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
$\mu^+\mu^-$
TeV
LHC
VLHC
p-p
Mu+OSC
SLC
NLC
e^+ e^-
0.1
1.0
10.0
c of m Energy (TeV)

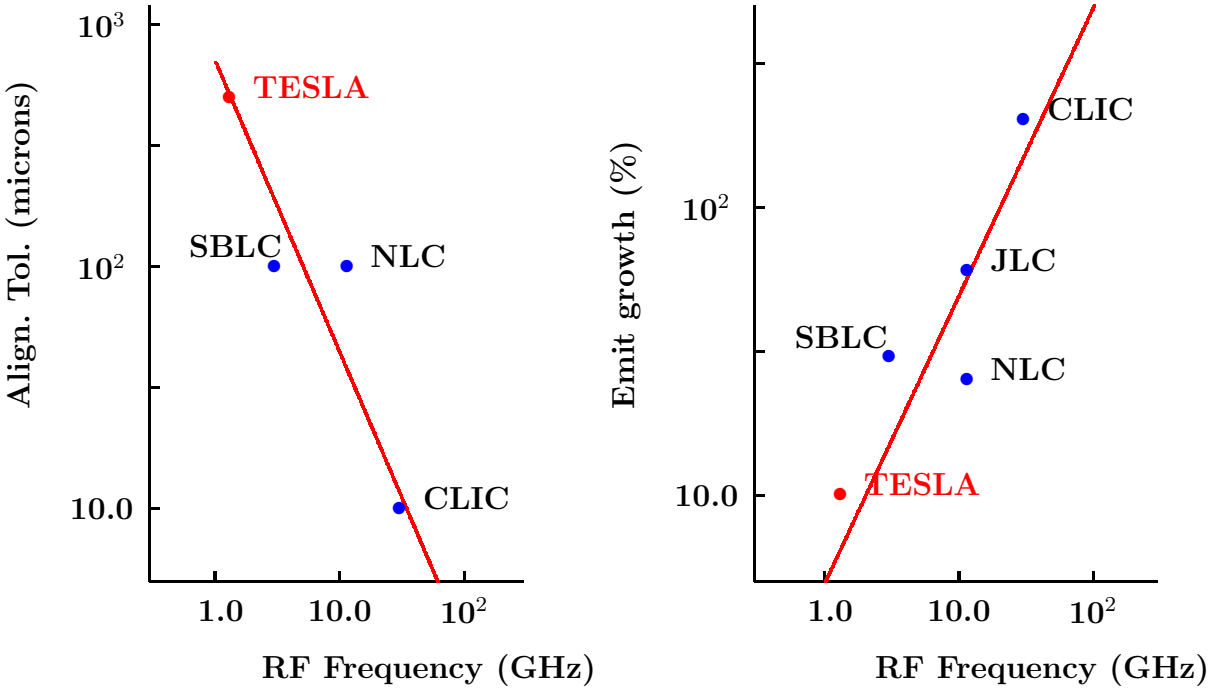
SIZE AND COST



Higher Frequencies favoured
SC (TESLA), also helps

But

Alignment and emittance growth:



High Freq not favored for Lum.

Note: with SC cavities (TESLA)

- Easier tolerances
- Low emittance growth
- 2 × wall to beam efficiency
- 1/2 Wall Power
- 1.5(2) × better Luminosity at .5(.8) TeV)
  (or 6 × using NLC "base")
- Gradient only 40(30)% lower

For NLC High Luminosity Parameters:

	E TeV	Lum 10^{34}	grad MV/m
TESLA	.5	3	22
TESLA	.8	5.9	35
NLC	.5	2	37-50
NLC	.88	3.4	50

Note:
Both: grad for .5 TeV in full struct.
Both: grad for 0.8 TeV in short struct.
Neither: grad for .8 TeV in full struct.

Laser and plasma Acc's even higher gradients

.

.

Record Holders:

		I W/cm^2	λ μm	ΔE MeV	E_z GV/m
Laser Wake	LULI(France)	4×10^{17}	1.05	1.6	1.5
Plasma Beat Wave	UCLA (USA)	10^{14}	10	28	2.8
Self Modulated LW	RAL (UK)	10^{19}	1.05	44	100

c.f. conventional

	E_z GV/m
SLC	0.02
NLC	0.37
Matrix	0.2

However, Laser and plasma Acceleration have even worse problems for luminosity

But they are being studied, as they must be. In particular, the SLC plasma "afterburner" study is very important: what luminosity will they get?

Example of Problems with Exotic Acceleration:

BURT'S PROBLEM

Transverse jitter due to Klystron power fluctuations

Require

$$\Delta_{p_t} \quad < \quad \sigma_{p_t} \quad = \quad \frac{m_e \quad \epsilon_n}{\sigma_{x,y}}$$

Compare with total acceleration:

$$\Delta_{p_z} \quad \approx \quad \frac{E_{c \ of \ m}}{2}$$

For: $\sigma_{x,y} = 1 \ \mu\mathbf{m}$, $\epsilon_n = 1 \ 10^{-9} \quad \mathbf{m}$, **E=**$2 \ 10^{12} \quad \mathbf{eV}$, $\mathbf{m}_e = .5 \ 10^6$ **eV:**

$$\frac{\Delta_{p_t}}{\Delta_{p_z}} \quad \approx \quad 5 \ 10^{-10}$$

In a circular vacuum structure, transverse kicks come only from "bookshelf" errors

(for non circular structures & plasma, there are intrinsic transverse kicks)

If

- **Bookshelf angle** $< \;\; 10^{-5} \;\; (.1\ \mu\text{m/cm})$
- **Klystron fluctuations** $< \;\; 10^{-3}$
- **Number of klystons** $= 4000$

$$\frac{\Delta_{p_t}}{\Delta_{p_z}} \;\approx\; \frac{10^{-5} \;\; 10^{-3}}{\sqrt{4000}} \;\approx\; 2\,10^{-10}$$

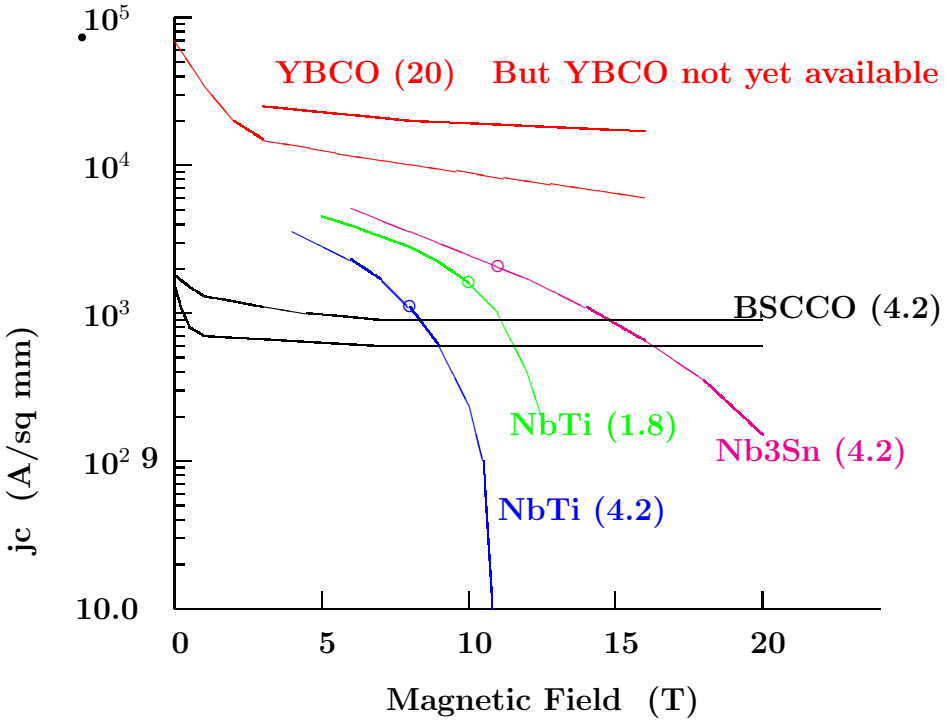
Which is just ok $\;\; (\text{c.f.req.} \;\; < \;\; 5\,10^{-10})$

But for smaller, non circular, 2 beam, plasma or other exotic acceleration, it is less clear that the requirement can be met.

HADRON COLLIDERS

- **High Field (B > 10 T)**
  - **LBNL (USA)**
  - **BNL (USA)**
- **Low Field (B ≈ 2 T)**
  - **Fermi (USA)**
- **Moderate Field (2<B<10 T)**
  - **?????**

Will High Field, HiTc, reduce costs?



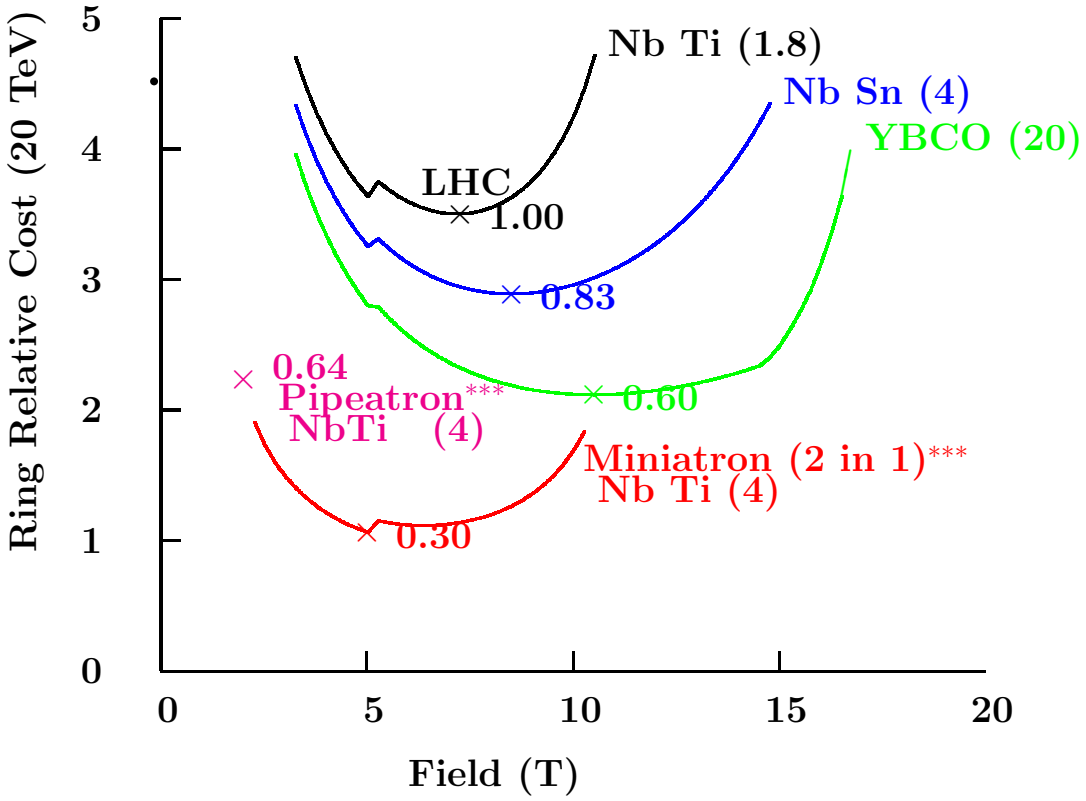
Parametric Study of Costs

http://pubweb.bnl.gov/people/palmer/magnet/pjmagopt.ps

- Calculate aperture for fixed impedance
- Design "2-in-1" and "pipeatron" magnets using approximate formulae
- Calc weights of materials etc.
- Scale unit costs from SSC

Relative Costs vs. Fields

WARNING: Qualitative Only



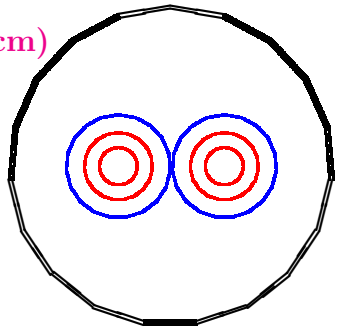
*** "Pipeatron" and "Miniatron"

- **Linear costs can be reduced**
  - improved tunneling methods?
  - low stored magnetic energy
  - low forces
  - very long combined function magnets
- **Impedance contrains** ($\propto r^3/B$) $\approx 1/30$
  - More sophisticated Feedbacks
  - Smooth tube

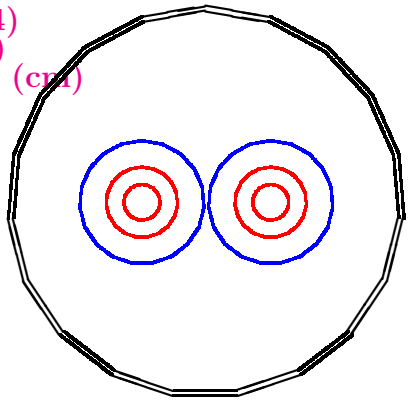
At Cost Minimums

With SSC costs & LHC Impedance

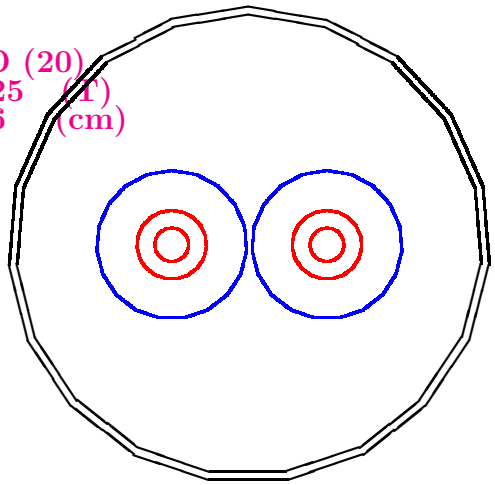
Nb Ti (1.8)
B 7.5 (T)
ap 5.55 (cm)

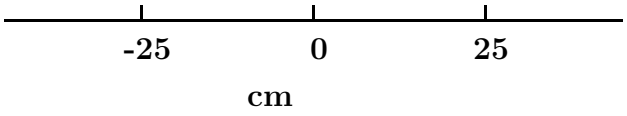


Nb Sn (4)
B 9 (T)
ap 5.27 (cm)



YBCO (20)
B 11.25 (T)
ap 4.96 (cm)

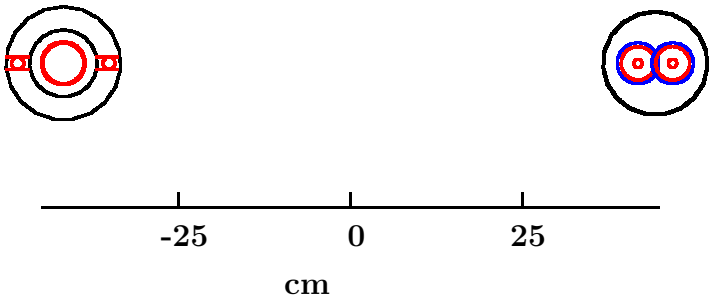




Linear $'s/3 & Impedance constraint/30

Pipeatron
B 2 (T)
ap 1.79 (cm)

Miniatron
B 5.25 (T)
ap 1.26 (cm)



Miniatron with same assumptions,
has less SC and Fe, and
uses a smaller circ. tunnel
than Pipeatron

100 km tunnel gives 20+20=40 TeV
($\approx$3 $\times$ LHC) at $\approx$ LHC Cost

Problems could be field tolerances

Needs further study and R&D

MUON COLLIDERS

- **BNL (USA)**
- **Cornell (USA)**
- **Fermi (USA)**
- **LBNL (USA)**

- **CERN (Switzerland)**
- **RAL (UK)**

- **KEK (Japan)**

- **BINP (Russia)**

- **+ many others**

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- **+ many others**

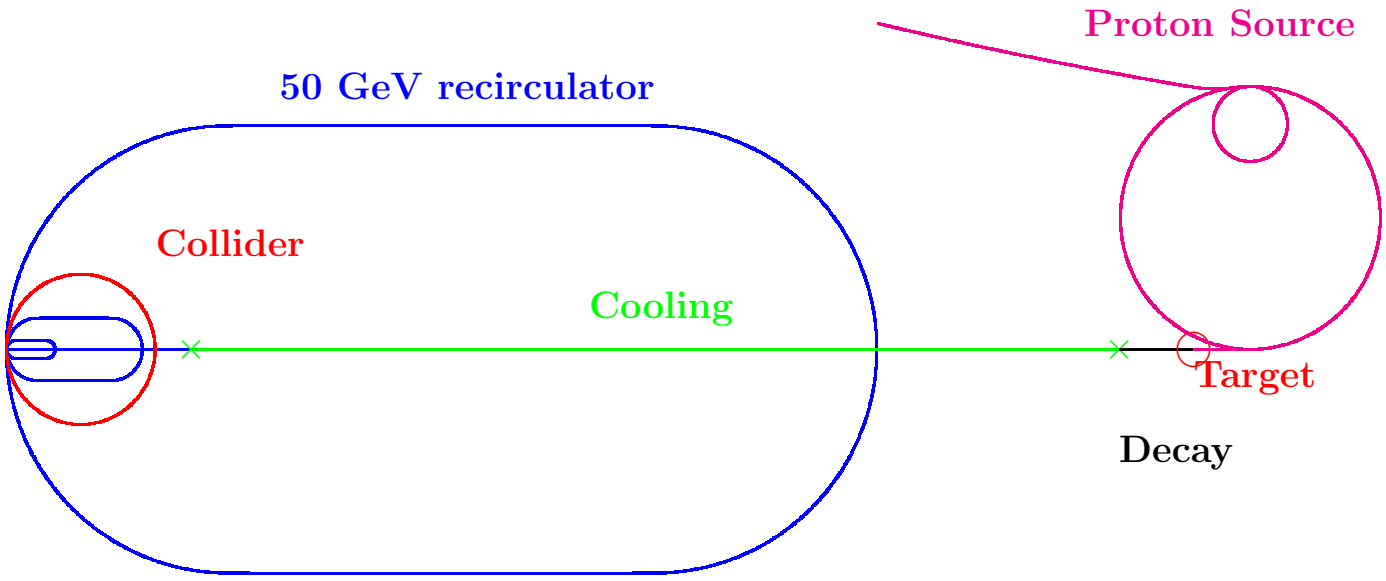
WHY

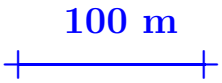
- **Energy advantage over p's (as for e's)**
- **Suppressed Synchrotron Radiation ($\propto \gamma^4 \propto m^{-4}$)**
  - **Circular**
    - **smaller**
    - **$\approx$ 1000 turns**
  - **no "beamstrahlung"**
    - **dE/E $\rightarrow$ 0.003 %**
    - **allows larger N**
  - **larger spot size & emittance**
    - **easier tollerances**
- **Direct Higgs Production**
  - $\mu^+ \mu^- \rightarrow h, A, H$ ($\sigma \propto m^2$)
- **ν_e & ν_μ Neutrino Beams**
  - **as bi-product, and/or**
  - **as phase 1**

But: μ's in diffuce phase space and μ's Decay

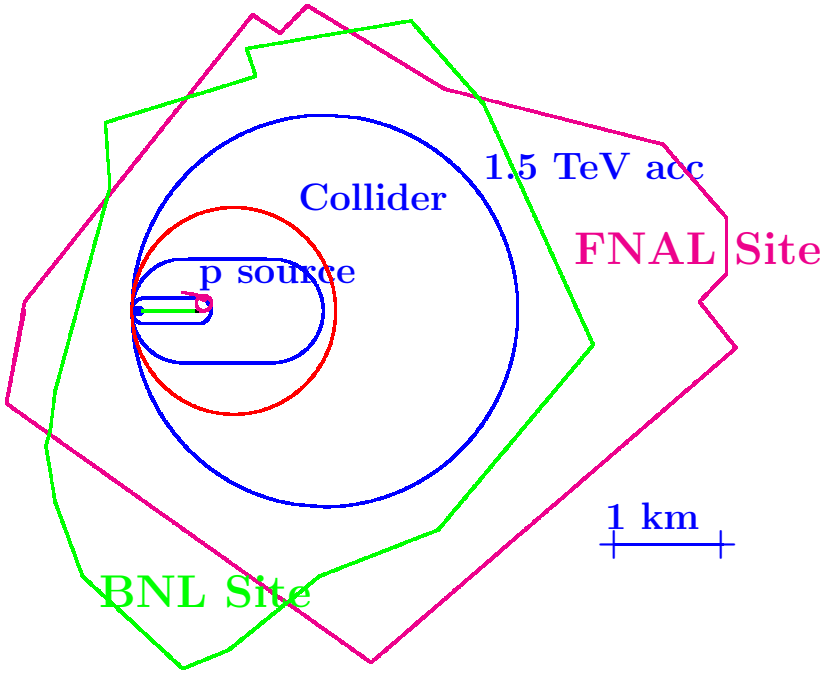
- **Efficient μ Production**
  - **20 T Solenoid to capture π's**
  - **RF Phase Rotation to reduce dE/E**
- **Rapid Cooling**
  - **ionization cooling certain**
  - **study optical and other exotics**
- **Rapid Acceleration Required**
  - **Recirculating Acceleration**
- **Beam Pipe Heating**
  - **3-6 cm Tungsten Shields**
- **Detector Background**
  - **Loss of Forward Cone**
- **Neutrino Radiation**
  - **Limits Energy to 3-10 TeV**

100 GeV HIGGS FACTORY



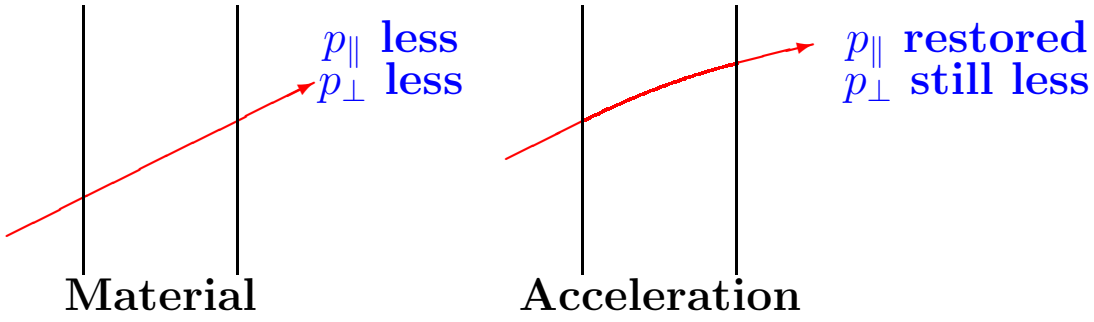


3 TeV COLLIDER

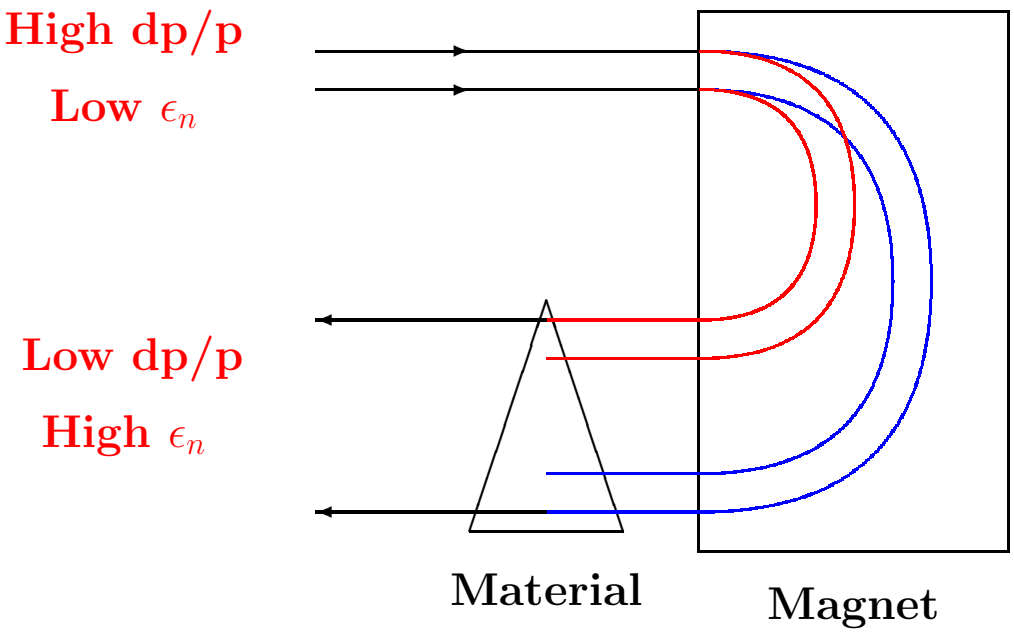


IONIZATION COOLING

- **TRANSVERSE**



- **dE/E Red by EMIT EXCHANGE**



TRANSVERSE COOLING

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

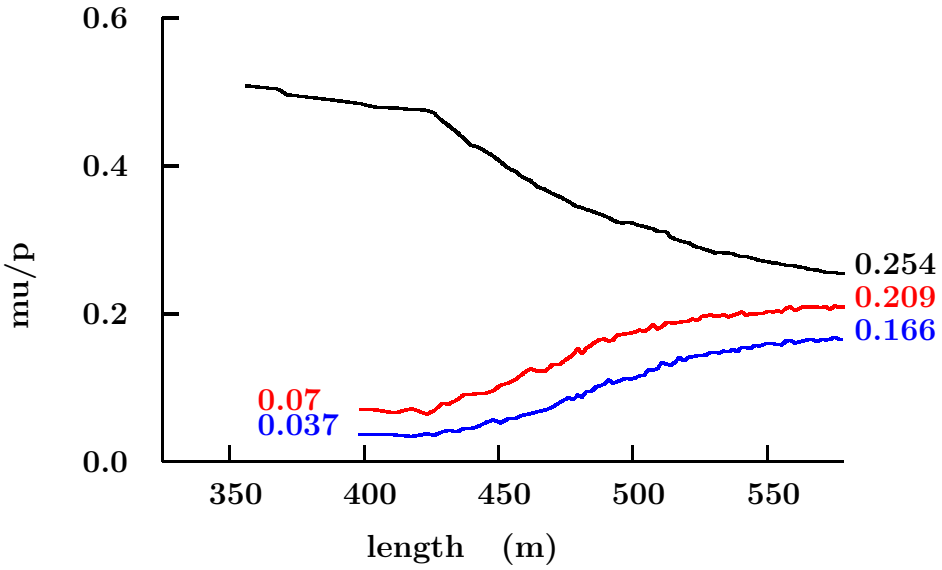
$$\epsilon_\perp \propto \beta_\perp \frac{1}{\beta_v L_R \, dE/dx} \propto \beta_\perp$$

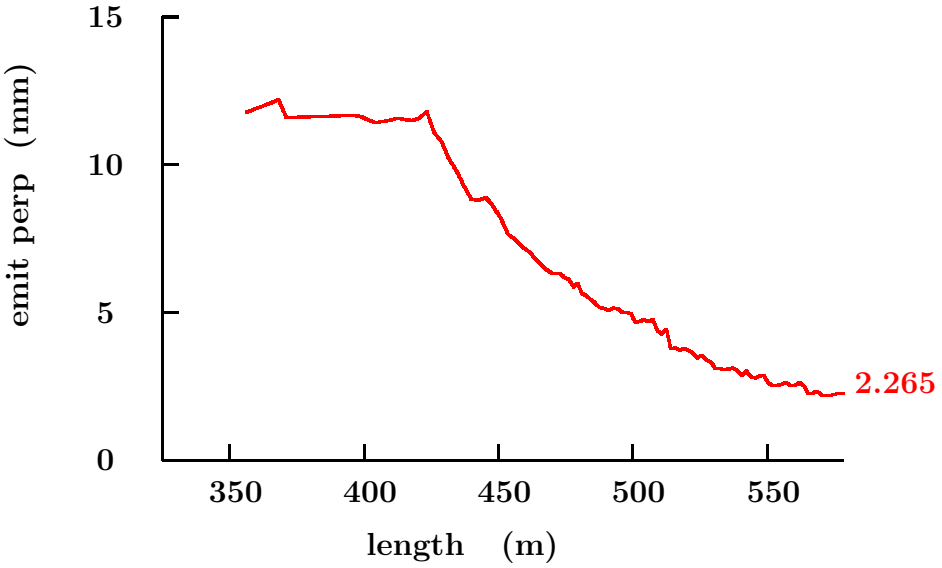
- **Need Low $\beta_\perp$**
- **Need Low Z Material**
  - **Hydrogen**
  - **Lithium Hydride**
  - **Lithium**

ICOOL Simulation of Study II Cooling

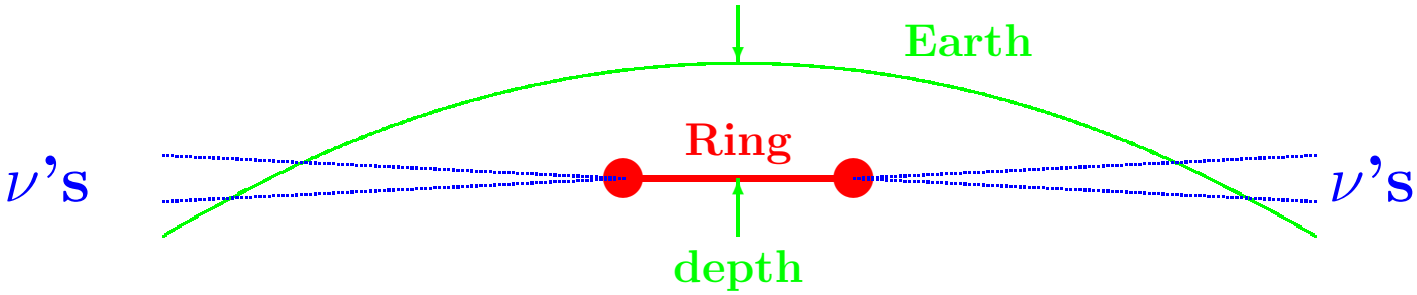
Preliminary

.3 Pzmax GeV/c
0.15 Pzmin in GeV/c
0.0095 first transverse acceptance cutoff (m rad)
0.015 second transverse acceptance cutoff (m rad)
0.150 longitudinal acceptance cutoff (m)





NEUTRINO RADIATION



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

THEN

- **Negligible problem at 1.5 TeV**
  - $\approx$ **1 mR/year**
- **E = 3 TeV ok at 300 m depth**
  - $\approx$ **10 mR/year**
- **E > 3 TeV Requires:**
  - **Beam wobbles, and/or**
  - **Special Locations, and/or**
  - **Better Cooling (Optical Stochastic?)**

BACKGROUND

- **at 5 cm rad**
- **Si Pixels**
- **60 $\times$ 150 μm**
- **acceptable n dose= 5 $\times$ 10^{14}**
- **1 year = 10^7 sec**

Energy	TeV	100	500	4000
Occupancy all	%	0.6	0.1	0.3
Occupancy Charged	%	0.14	0.1	0.1
neutron $>$ 100 KeV	n/cm^2	100	50	30
neutron dose	Hits/year	3 10^{13}	3 10^{13}	1.8 10^{13}
Lifetime	years	15	15	25

Significant Bethe Heitler Muons at Higher E's
Calorimeter Timing and Subdivion?

STATUS

- Good theoretical progress

But

- no emittance exchange lattice yet
- no cooling to emittance for Collider
- Many technical challenges

CURRENT PLANS

- Continue theoretical studies of Muon Collider
- Approved AGS Experiment on Hg (and other) Targets (BNL)
- Ongoing testing of model RF and absorber systems (FNAL)
- Feasibility Studies of "ν Factories"

μ STORAGE RING
ν FACTORY

- **Study I**
  - **sponsored by Fermi**
  - **finished March 00**
  - **50 GeV**
  - **"Entry Level"** ($\approx 3\ 10^{19}\ \mu/10^{7}$sec)
- **Study II**
  - **sponsored by BNL**
  - **finished April 01**
  - **20 GeV**
  - **"Higher Flux"** ($\approx 1.5\ 10^{20}\ \mu/10^{7}$sec)

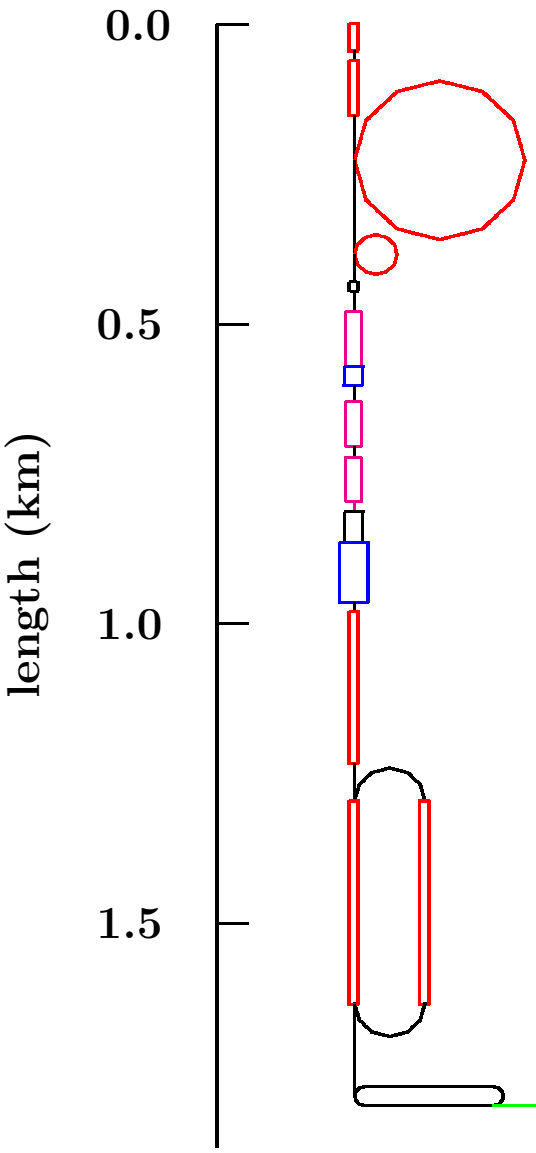
How to get the Higher efficiency

Study II vs. Study I

- **High Z Target**
  - **Hg or Ni vs. C**
  - **1.5 - 2**
- **Longer Drift**
  - **200 m vs. 50 m**
  - **1.5 - 2**
- **Non-distorting Phase Rotation**
  - **another induction linac**
  - **1.5 - 2**

Improvement 6-10

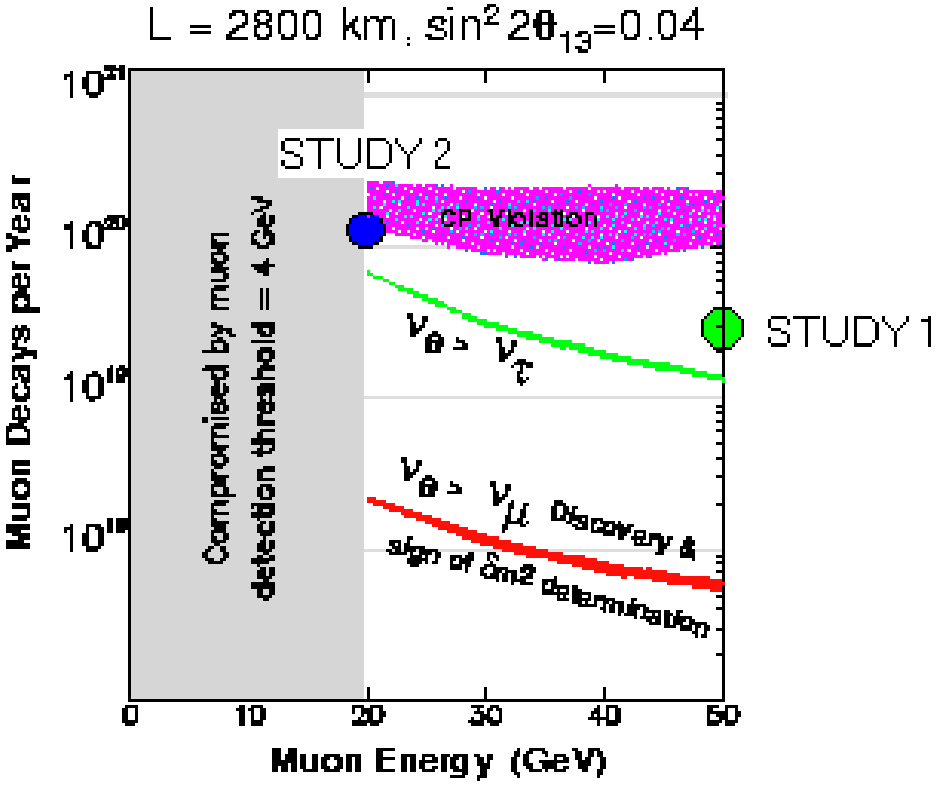
Study 2 Schematic



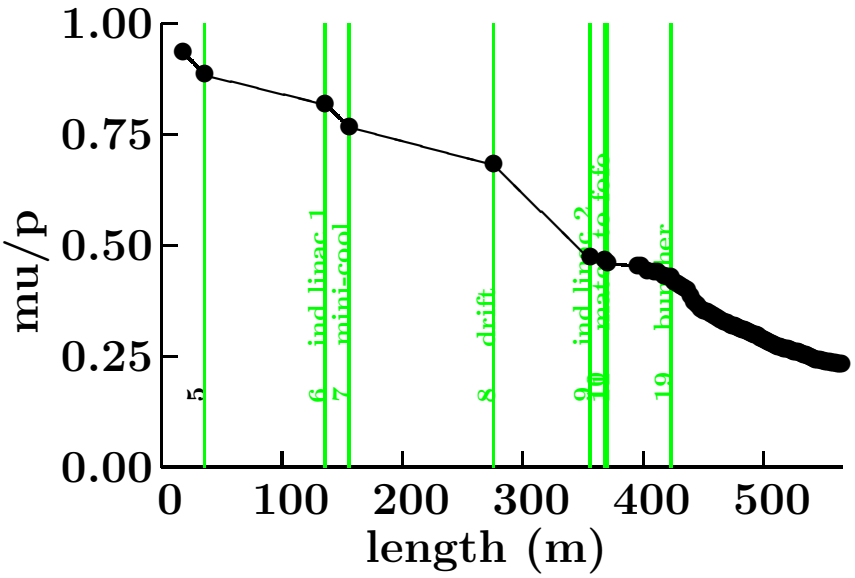
Warm Linac	200 MeV
SC Linac	1 GeV
AGS	24 GeV
Bunch compressor	rms 3 ns
Hg Target	(.45 m)
Induction #1	(100 m)
Mini Cooling	(3.5 m H_2)
Induction #2	(80 m)
Induction #3	(80 m)
Buncher	(55 m)
Cooling	(108 m)
Linac	(2.3 GeV)
Recirculating Linac	(2.3-20 GeV)
Storage Ring	(20 GeV)

c: aaprog scheme nupict.td

Physics Reach



Efficiency



Study 2 Conclusions

- $\geq 5\times$ improvement over Study 1
- But only 20 % mu/pi
- And only one sign
- i.e. efficiency only 10 %

But

- Bunch Beam Phase Rotation
  Simulated by Neuffer
  Gives both signs
- Emittance exchange promising
  Several schemes under study
  Could double efficiency
- Driver can be upgraded 1 $\rightarrow$ 4 MW

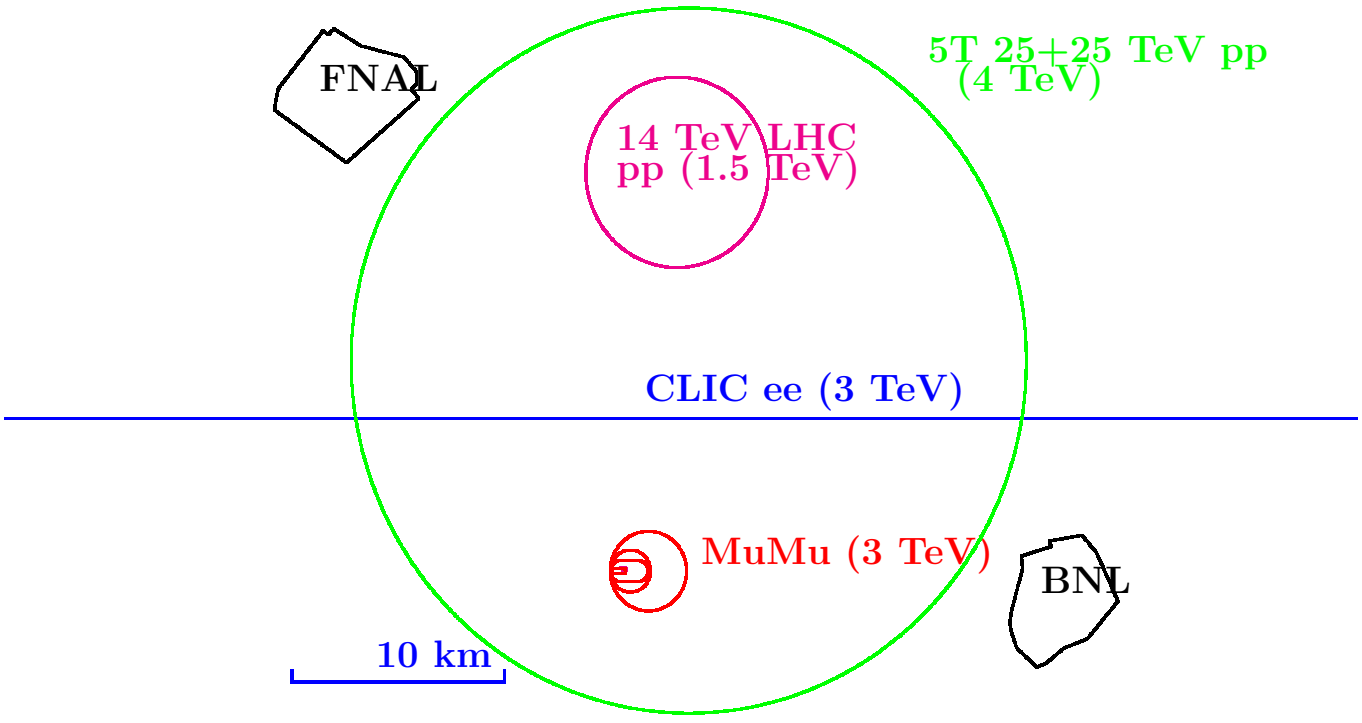
So

- **Study 2 will not be the last**

CONCLUSION

- e^+ e^- .
  - **High Grad + High Lum. is hard**
  - **for ≤ 800 GeV SC (TESLA) may be prefered**
  - **for ≥ 800 GeV more R&D required**
- p p
  - **No cost reduction with high fields**
  - **Significant cost reduction with small aperture.**
  - **R&D Required**
- μ^+ μ^-
  - **Needs much R&D**
- **μ storage ring ν Factory**
  - **Entry Level "feasible"**
  - **Needs R&D for higher flux**

SNOWMASS QUESTION:

How do we get beyond LHC?

- Neither NLC, nor TESLA, nor a ν Factory, do this
- CLIC, a muon Collider and a VLHC are the only possibilities
- Only the VLHC is currently plausible
- If we are not greedy and can use small apertures, the cost would be reasonable