Neutrino factories & muon colliders at the energy frontier

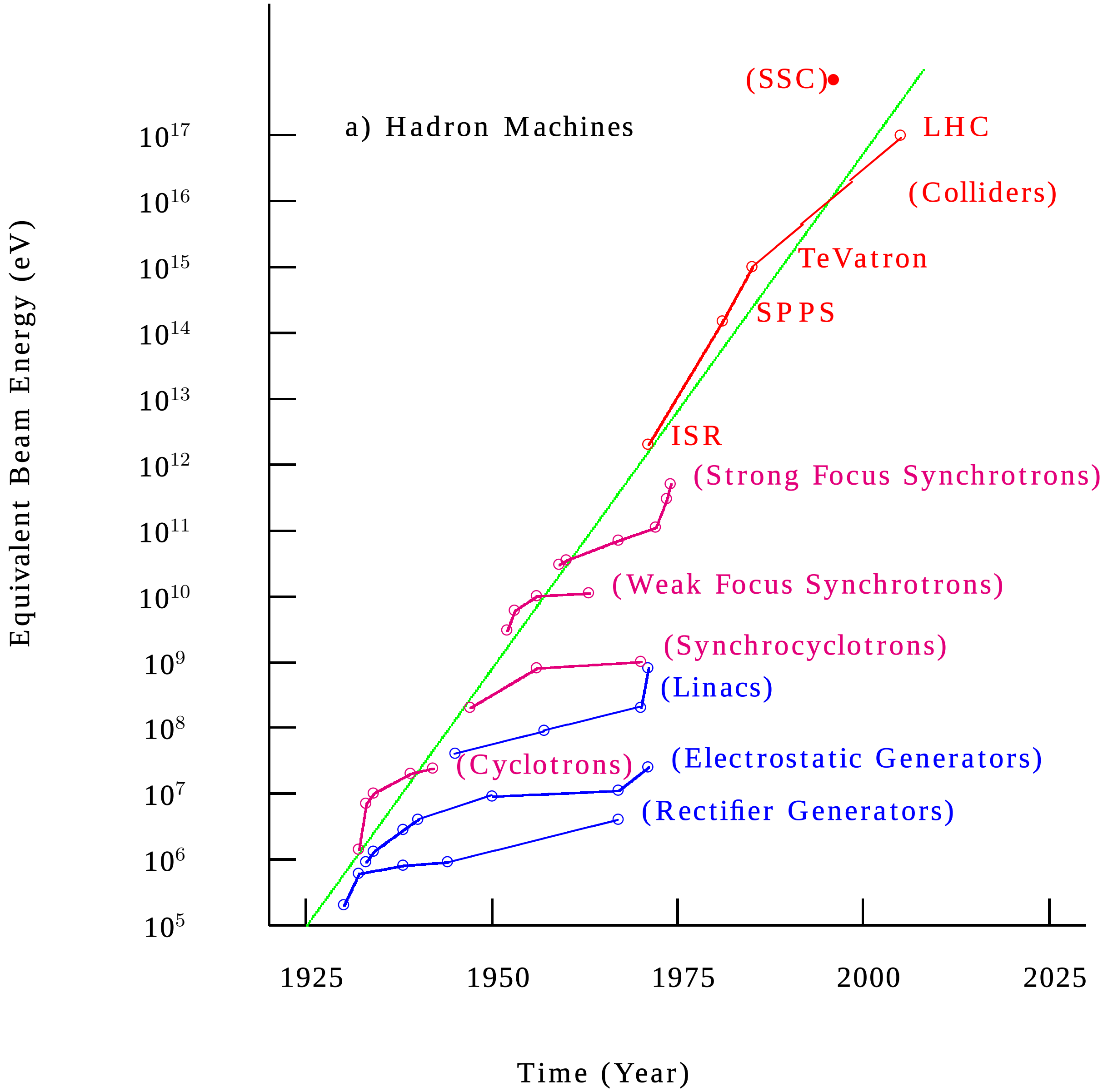
R. B. Palmer

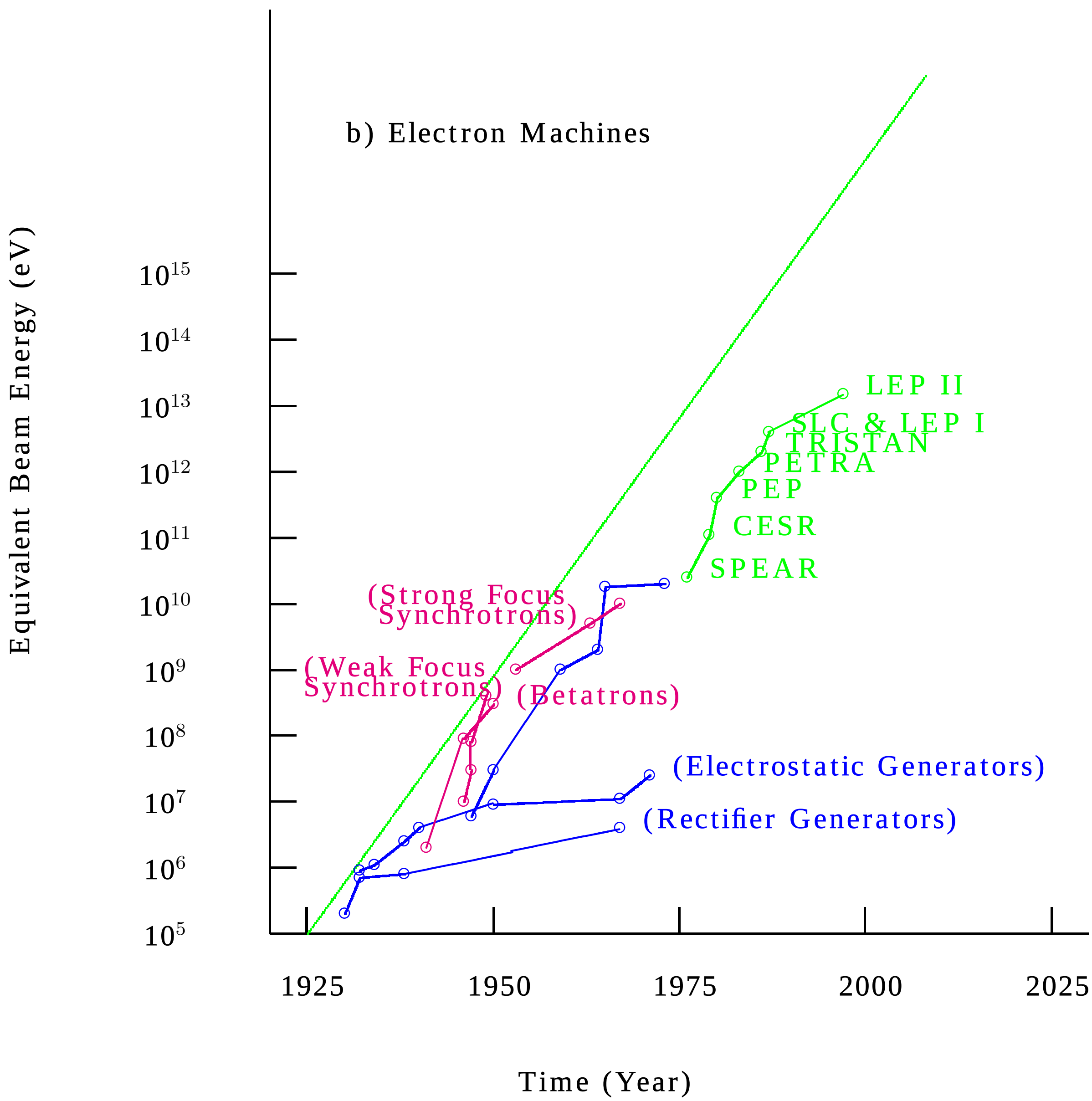
Brookhaven Nat. Lab

Oxford
November 2001

- Electron Colliders
- Hadron Colliders
- Muon Colliders
- Neutrino Factories

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
LEP II
SLC & LEP I
TRISTAN
PETRA
PEP
CESR
SPEAR
(Strong Focus
Synchrotrons)
(Weak Focus
Synchrotrons)
(Betatrons)
(Electrostatic Generators)
(Rectifier Generators)
1925
1950
1975
2000
2025
Time (Year)

e^+ e^- COLLIDERS

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

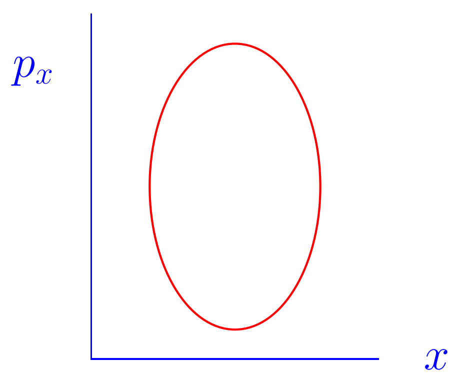
WHAT IS LUMINOSITY

$$L \quad = \quad \frac{\text{event rate}}{\text{interaction cross section}}$$

WHAT IS EMITTANCE

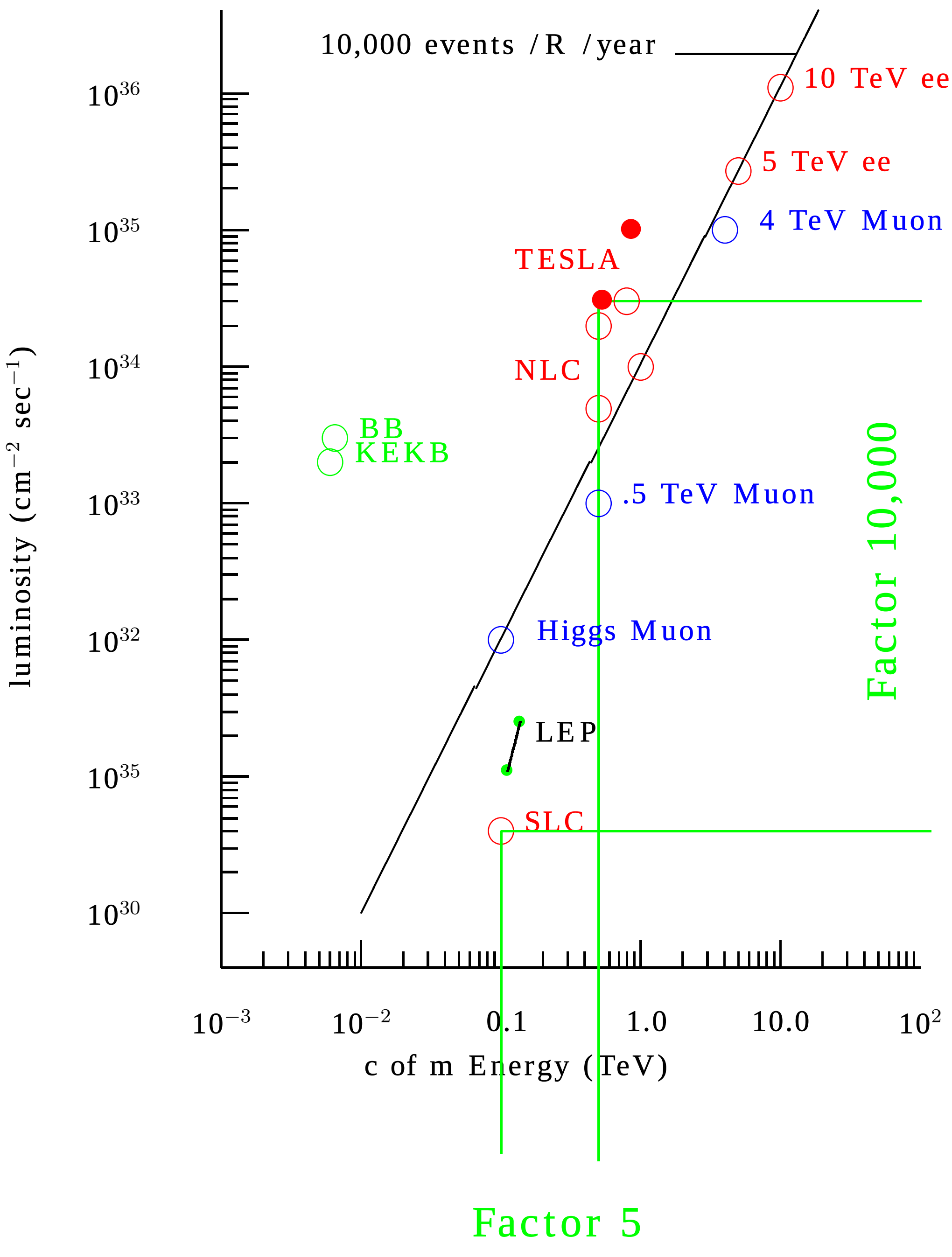
$$\text{normalized emittance} = \frac{\text{Phase Space Area}}{\text{m c}}$$

If x and p_x both Gaussian and uncorrellated, then area is an upright ellipse



$$\epsilon_\perp = \frac{dp_\perp dx}{mc} = \sigma_\theta \sigma_x \ \ (\gamma \beta_v) \qquad\qquad (\pi\ m\ rad)$$

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
10^{36}
10^{35}
10^{34}
10^{33}
10^{32}
10^{35}
10^{30}
luminosity (cm^{-2} sec^{-1})
10^{-3}
10^{-2}
0.1
1.0
10.0
10^{2}
c of m Energy (TeV)

WHY IS LUMINOSITY HARD ?

$$L \;\propto\; \frac{P_{ave}}{\gamma} \left(\frac{N}{\sigma_x}\right) \left(\frac{1}{\epsilon_n{}^{(5/7)}}\right) \;\propto\; \gamma^2$$

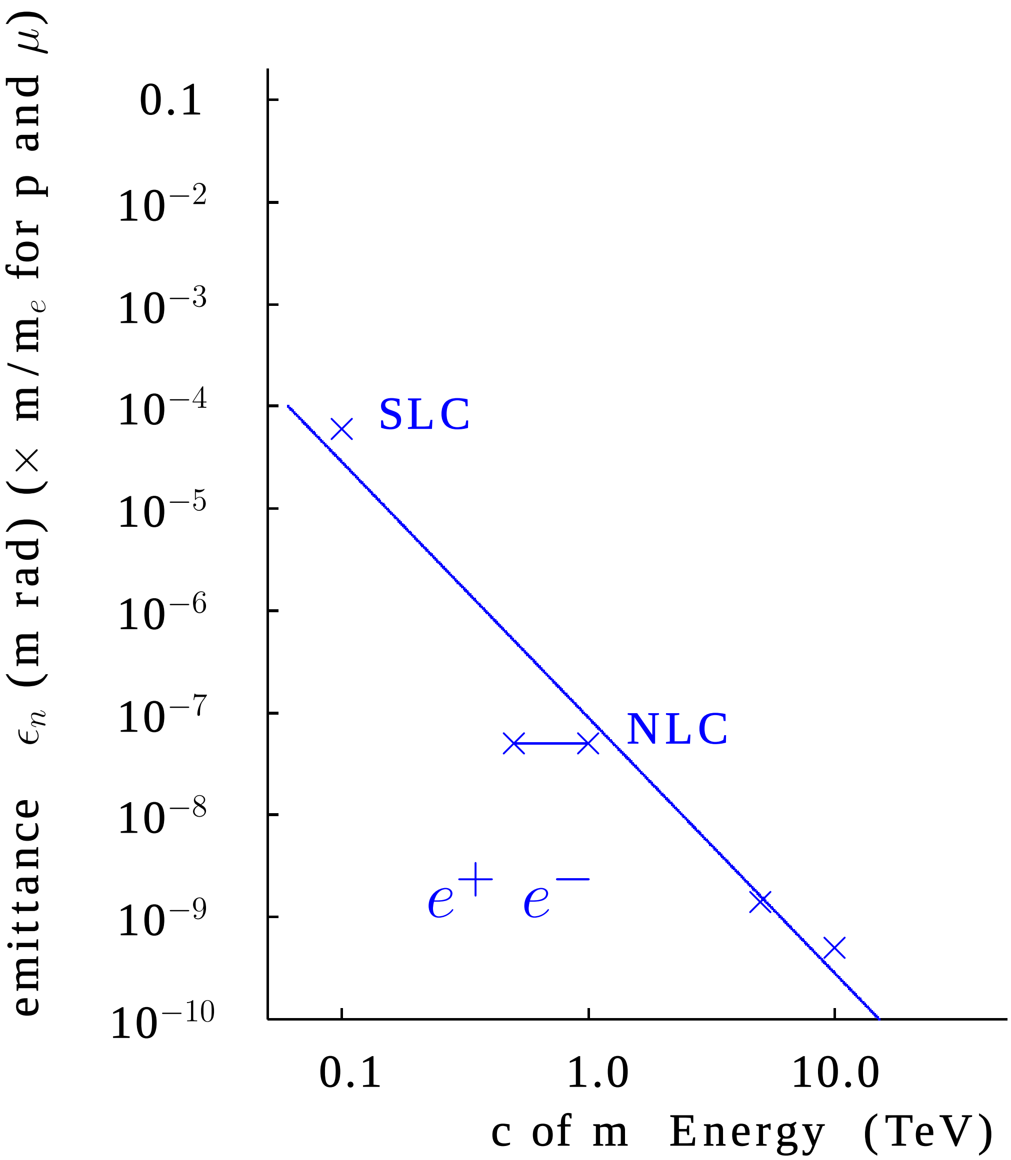
N/σ_x is limited by radiation considerations, so

$$\frac{P_{ave}}{\epsilon_n{}^{(5/7)}} \;\propto\; \gamma^3$$

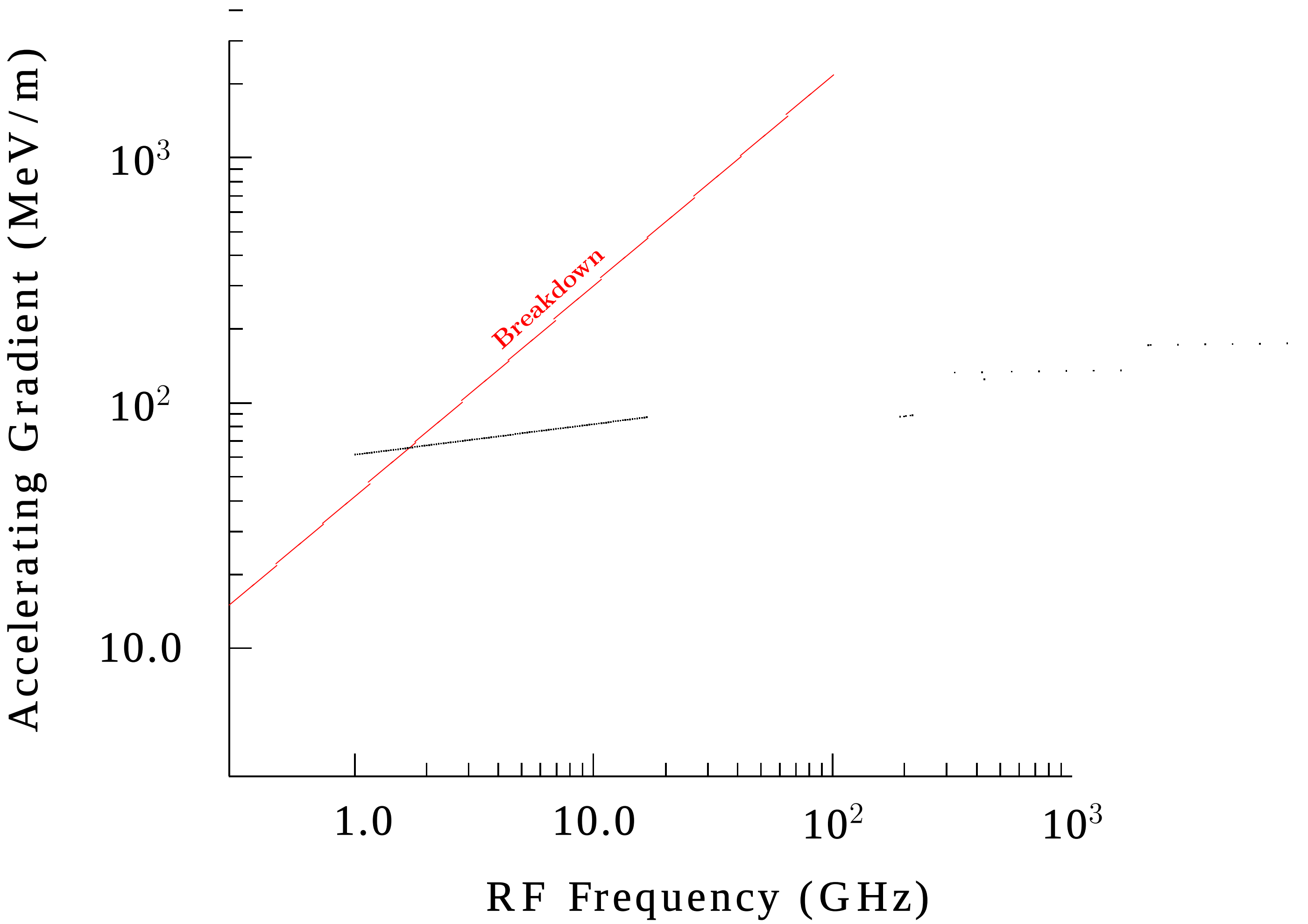
So we Need:

- High Beam Power
- Low normalized emittance

Required Emittances

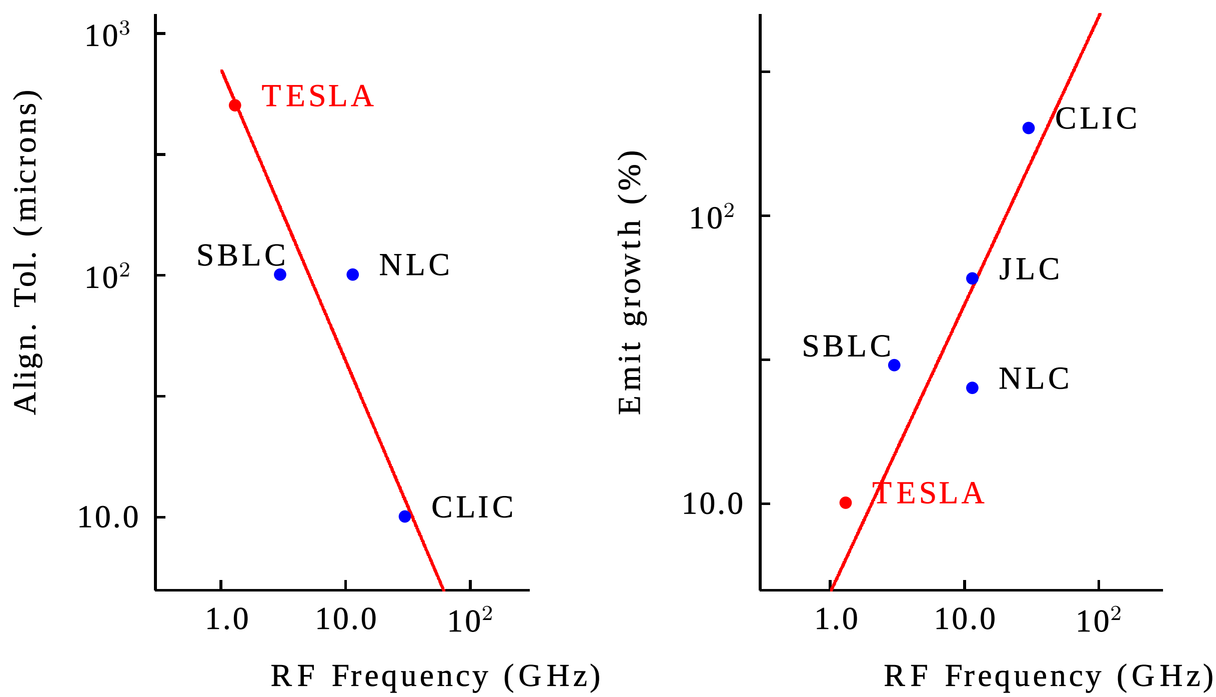


SIZE AND COST



But

Alignment and emittance growth:



High Freq not favored for Lum.

Laser and Plasma Accelleration will have huge problems with luminosity

Note: with SC cavities (TESLA)

- Easier tolerances
- Low emittance growth
- 2 $\times$ wall to beam e ciency
- 1/2 Wall Power
- Better Luminosity at
- Gradient only $\approx$ 40% lower

HADRON COLLIDERS

Can Costs/TeV be reduced

"Pipeatron" or transmission line magnet (Foster)

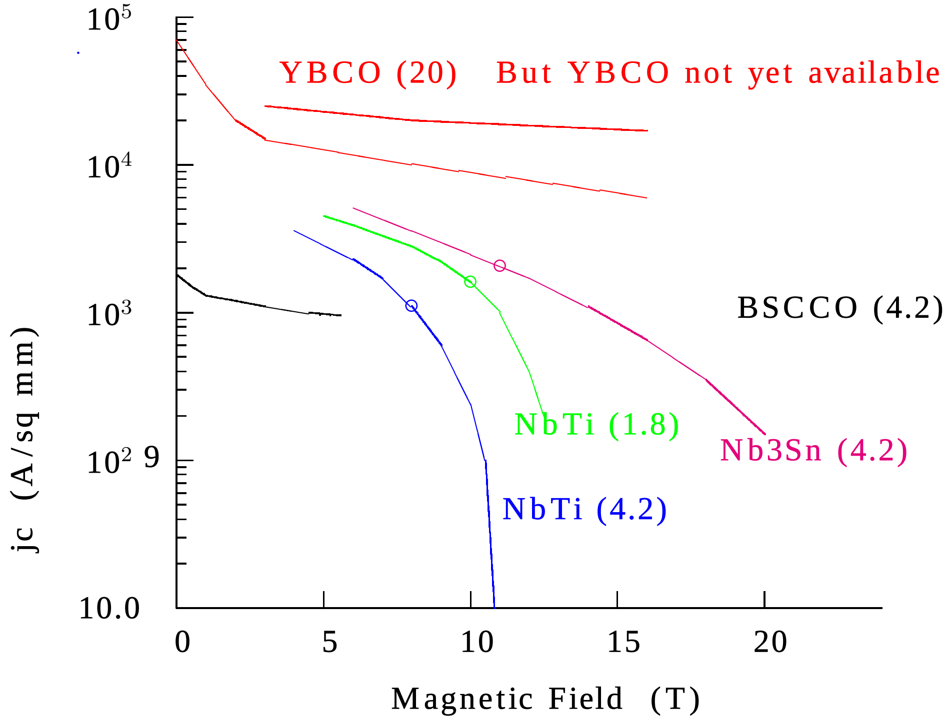
- Linear costs can be reduced
  - improved tunneling methods?
  - low stored magnetic energy
  - low forces
  - very long combined function magnets
- Impedance contrains ($\propto r^3/B$) $\approx$ $1/30$
  - More sophisticated Feedbacks
  - Smooth tube

Snowmass study:

Cost/TeV of 2T Pipeatron $\approx$ SSC

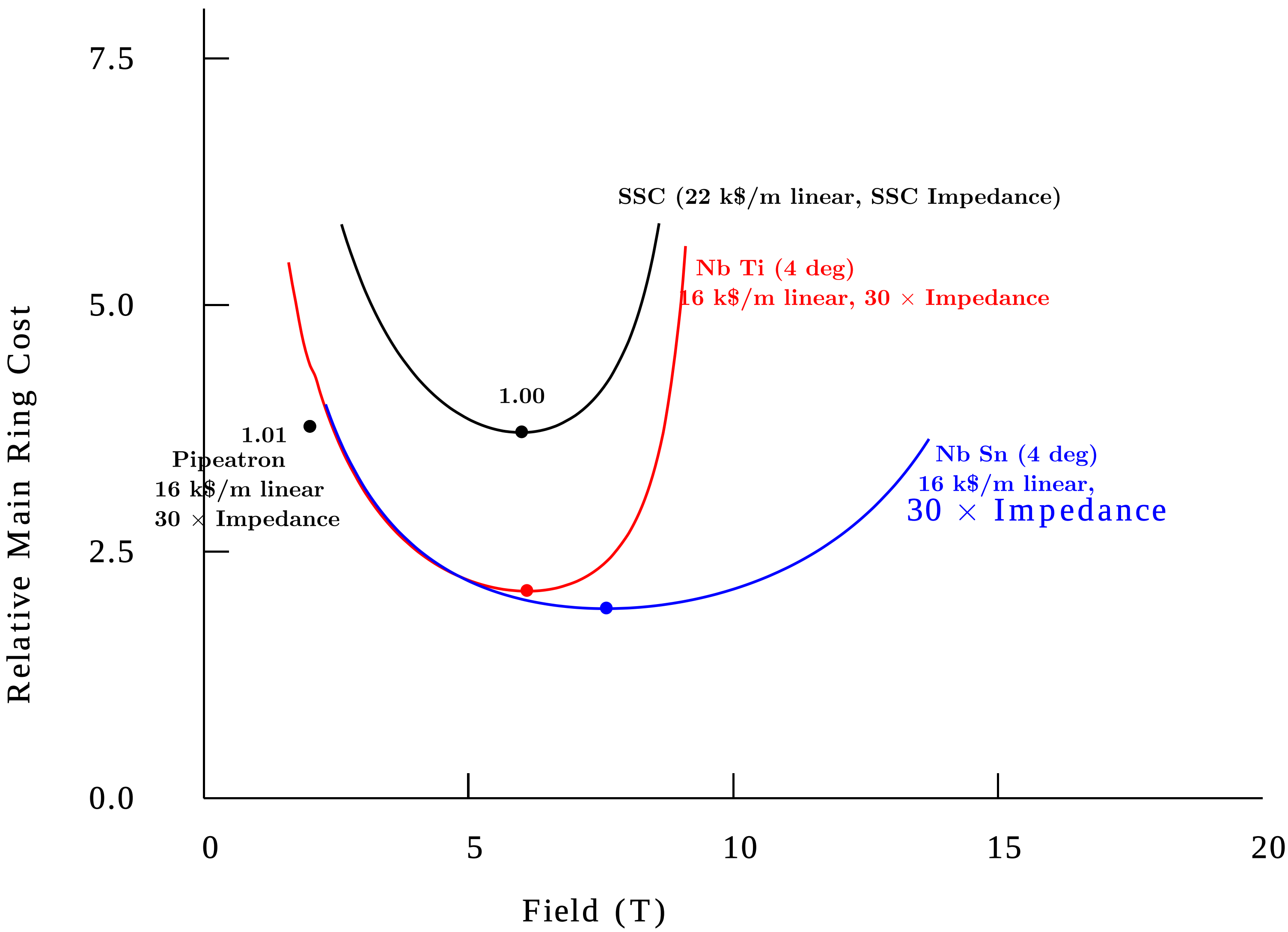
Disappointing

Will High Field reduce costs ?



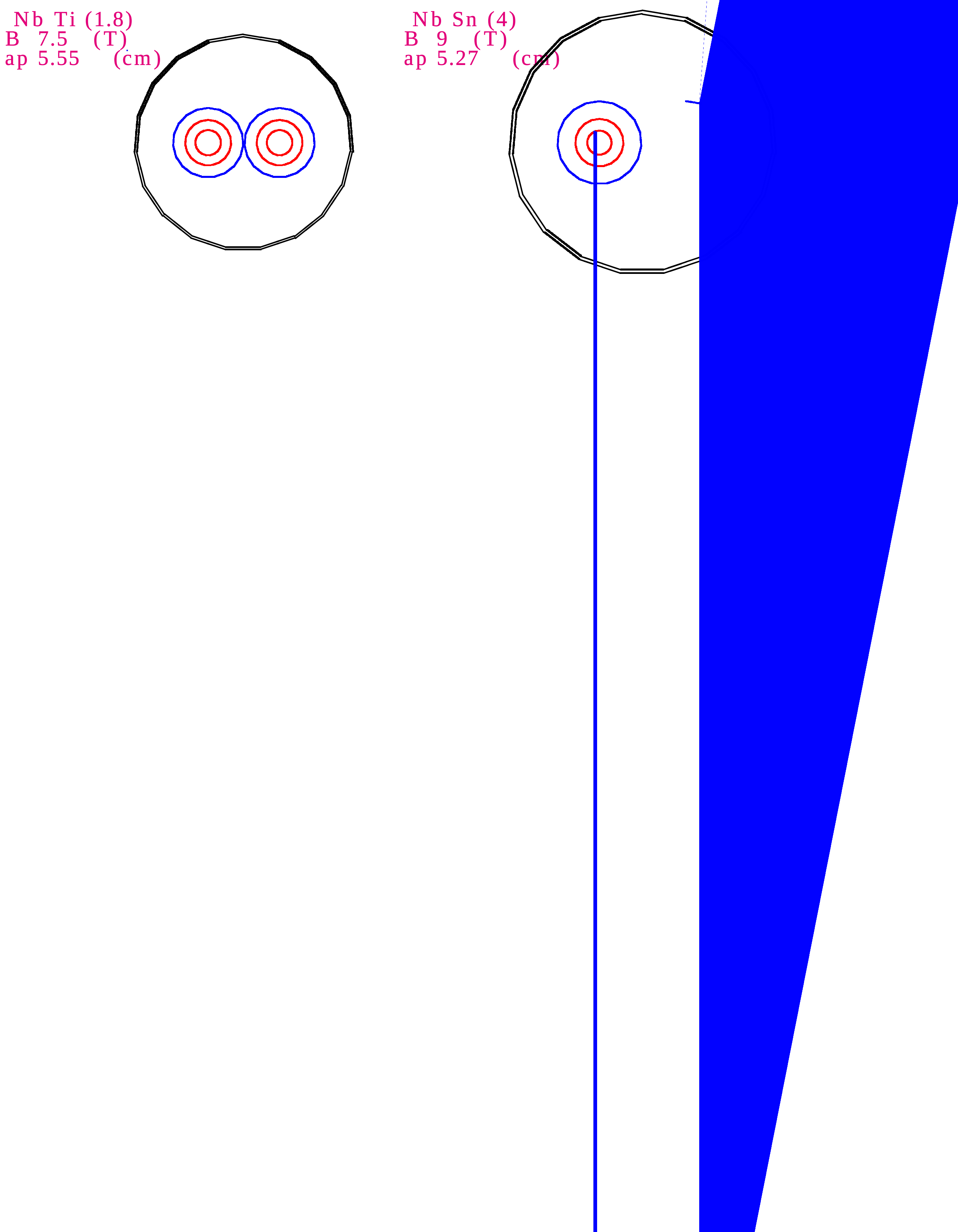
Relative Costs vs. Fields

WARNING: Qualitative Only



At Cost Minimums

With SSC costs & LHC Impedance



MUON COLLIDERS

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

- CERN (Switzerland)
- RAL (UK)

- KEK (Japan)

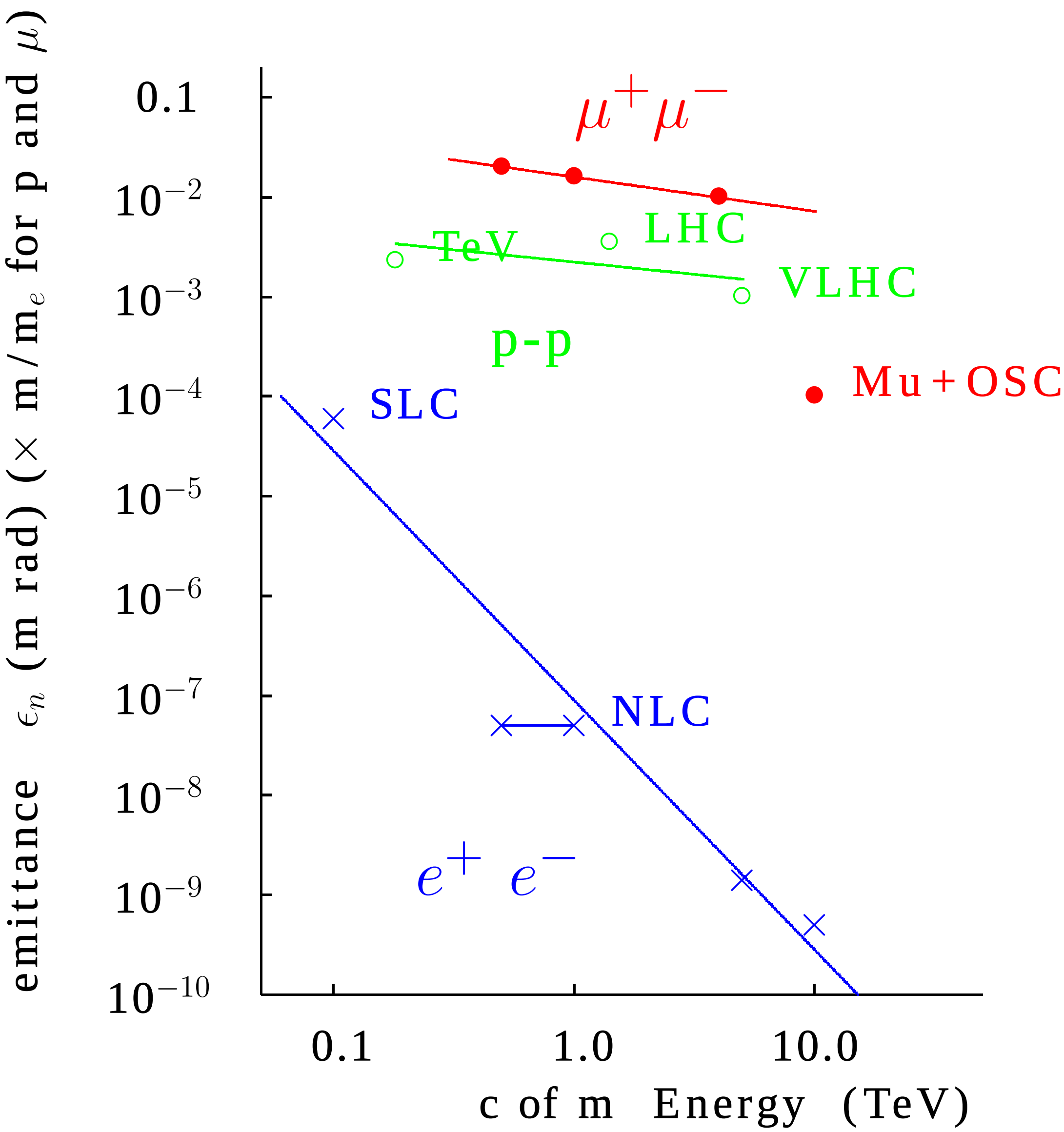
- BINP (Russia)

- + many others

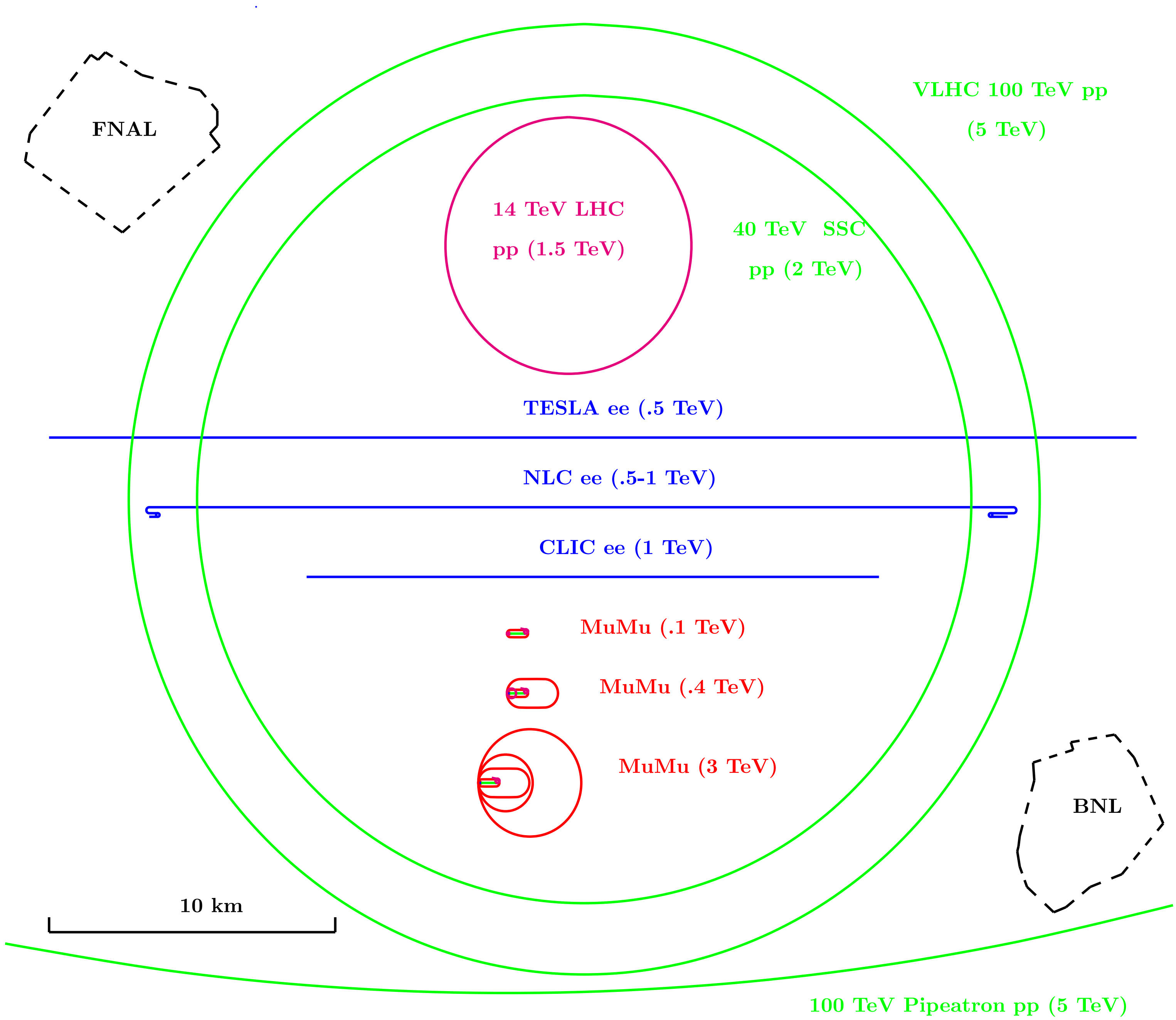
WHY

- 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

Easier Tollerances



Muon Colliders are smaller

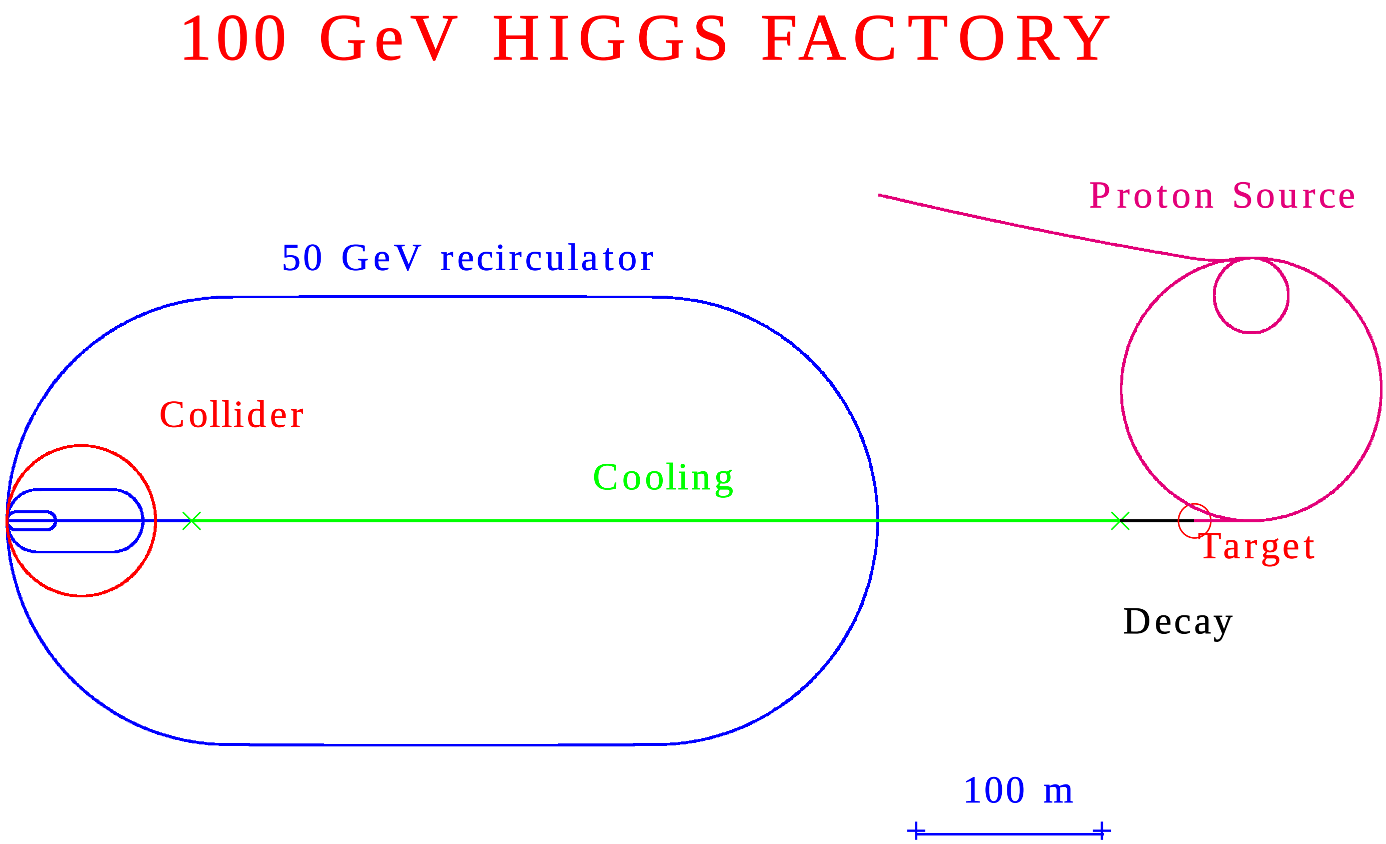


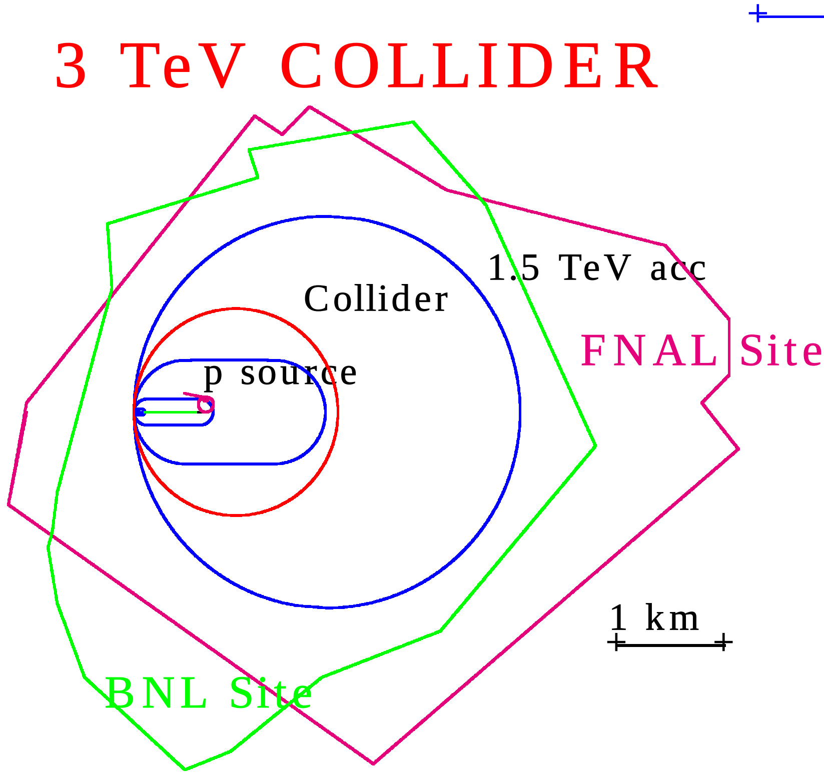
But: μ's in di uce phase space and μ's Decay

- **E cient μ Production**
  - 20 T Solenoid to capture π's
  - 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 $\approx$ 3 TeV

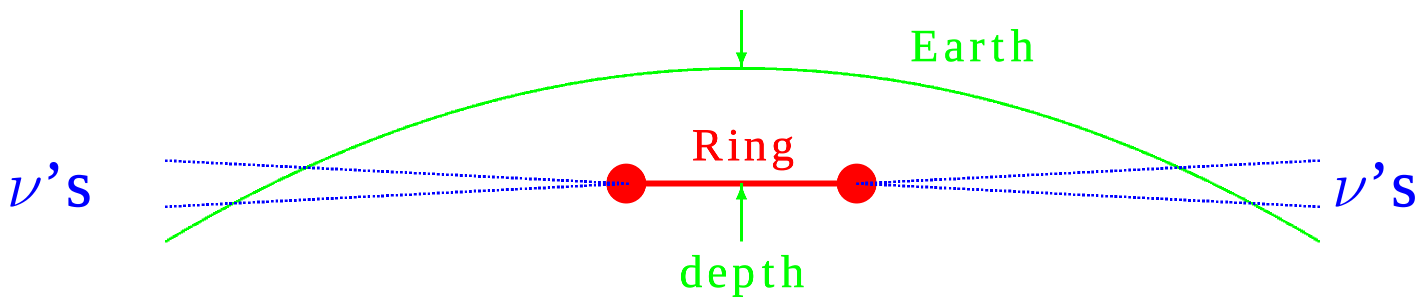
PARAMETERS

CoM energy	TeV	3	0.4	0.1	
p energy	GeV	16-24	16-24	16-24	
p's/bunch		2.5×10^{13}	2.5×10^{13}	5×10^{13}	
Bunches/fill		4	4	2	
Rep. rate	Hz	15	15	15	
p power	MW	4	4	4	
μ/bunch		2×10^{12}	2×10^{12}	4×10^{12}	
μ power	MW	28	4	1	
Wall power	MW	204	120	81	
Collider circ.	m	6000	1000	350	
Ave bend B	T	5.2	4.7	3	
Depth	m	500	100	10	
Rms $\frac{\Delta p}{p}$	%	0.16	0.12	0.01	0.003
6D ϵ_6	$(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
Rms ϵ_n	$\pi\ 10^{-6} m$	50	50	85	290
β^*	cm	0.3	2.6	4.1	14.1
σ_z	cm	0.3	2.6	4.1	14.1
σ_r spot	μm	3.2	26	86	294
σ_θ IP	mrad	1.1	1.0	2.1	2.1
Tune shift		0.044	0.044	0.051	0.015
n_{turns} (e ective)		785	700	450	450
Luminosity	$cm^{-2}s^{-1}$	7×10^{34}	10^{33}	1.2×10^{32}	10^{31}
Higgs/year				1.9×10^3	3.9×10^3


100 GeV HIGGS FACTORY
Proton Source
50 GeV recirculator
Collider
Cooling
Target
Decay
100 m


3 TeV COLLIDER
1.5 TeV acc
Collider
FNAL Site
p source
1 km
BNL Site

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?)

.)

STATUS

- Good theoretical progress

But

- no cooling yet to req. emittance
- Technical challenging

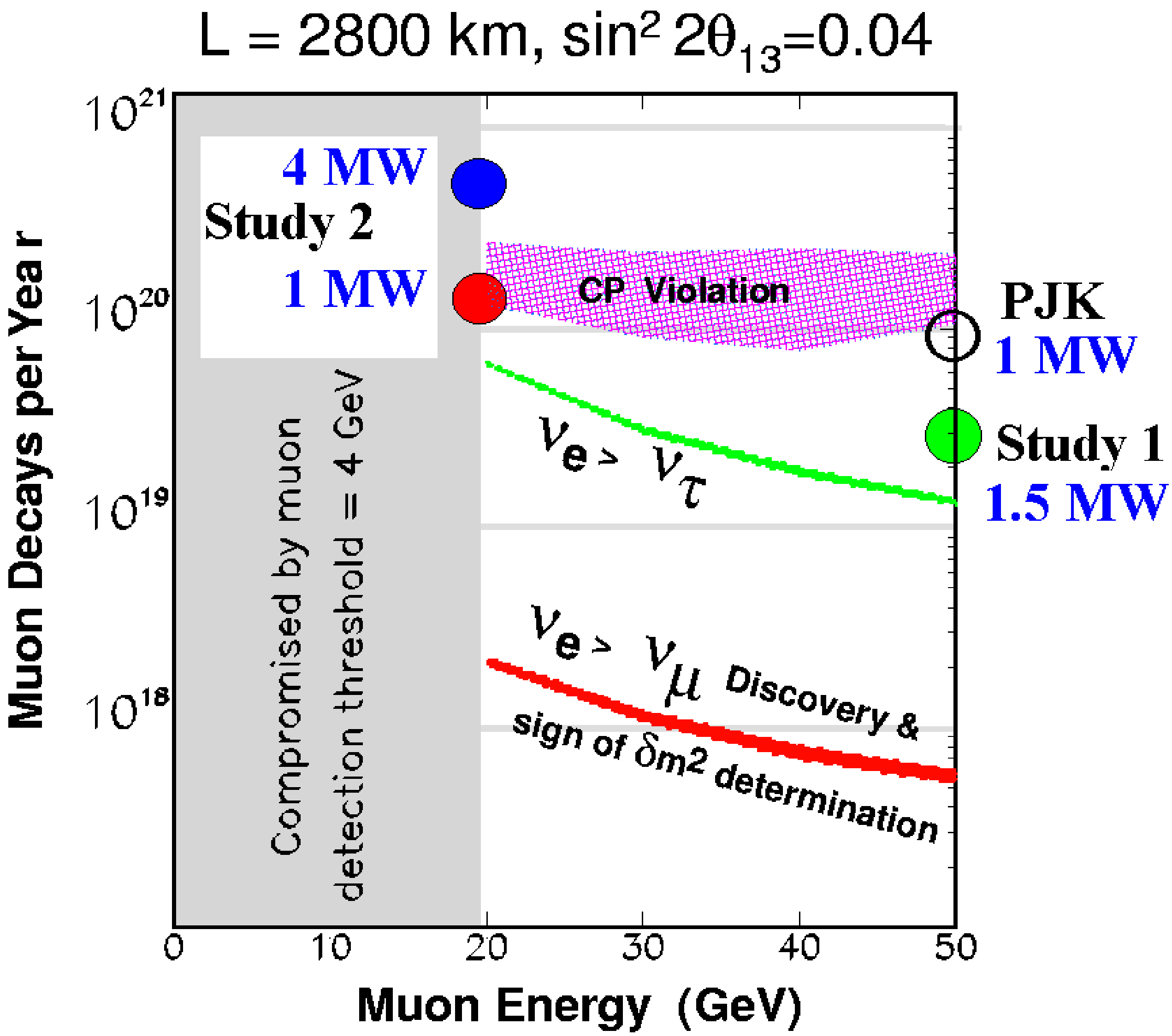
CURRENT PLANS

- Continue theoretical studies of Muon Collider
- AGS Experiment on Hg (and other) Targets (BNL)
- Testing of RF and absorber systems (FNAL)
- Prposed International Muon Cooling Experiment (MICE)
- Feasibility Studies of "ν Factories"

μ STORAGE RING
ν FACTORY

- Study I
  - sponsored by Fermi
  - finished March 00
  - Uses new 16 GeV driver
  - ”Entry Level” ($\approx 3\ 10^{19}\ \mu/10^{7}\mathrm{sec}$)
- Study II
  - sponsored by BNL
  - finished April 01
  - Uses upgraded AGS driver
  - ”Higher Flux” ($\approx 1.5\ 10^{20}\ \mu/10^{7}\mathrm{sec}$)
- CERN Work
  - Uses 2.2 GeV proton linac driver
- KEK Work
  - Uses 50 GeV JHF driver

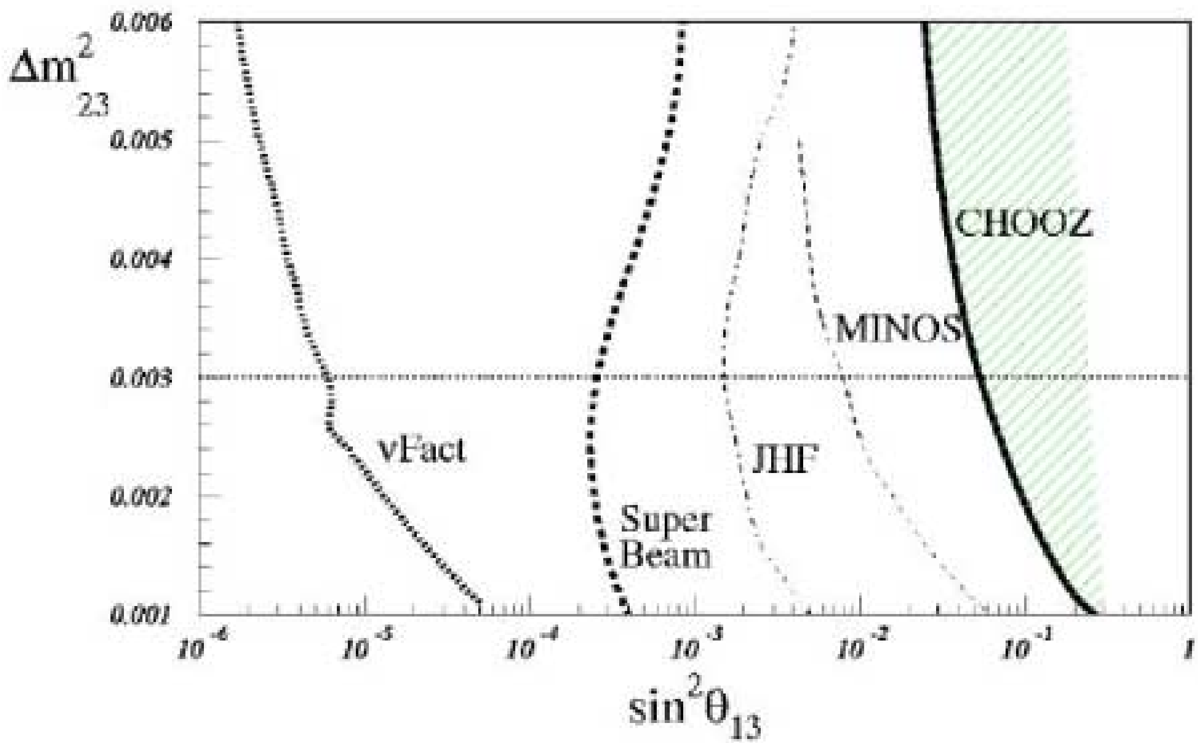
Physics Reach



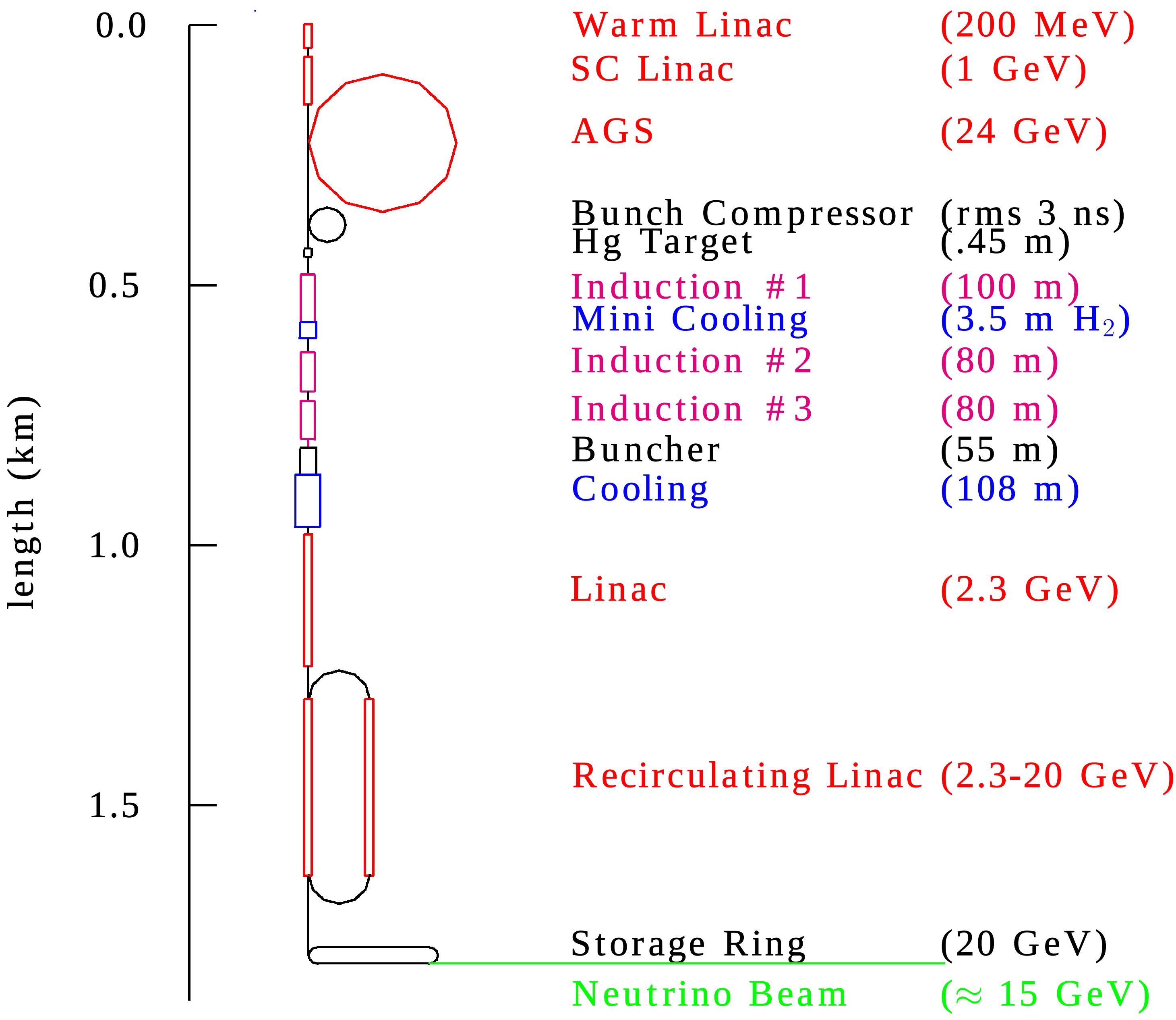
- muon decays in straight section / 1 10^7 sec
- For Detector mass 50 kT
- Best distance: 2000 - 3000 km

WIPP = 2900 km   Homestake = 2500 km

Comparisons

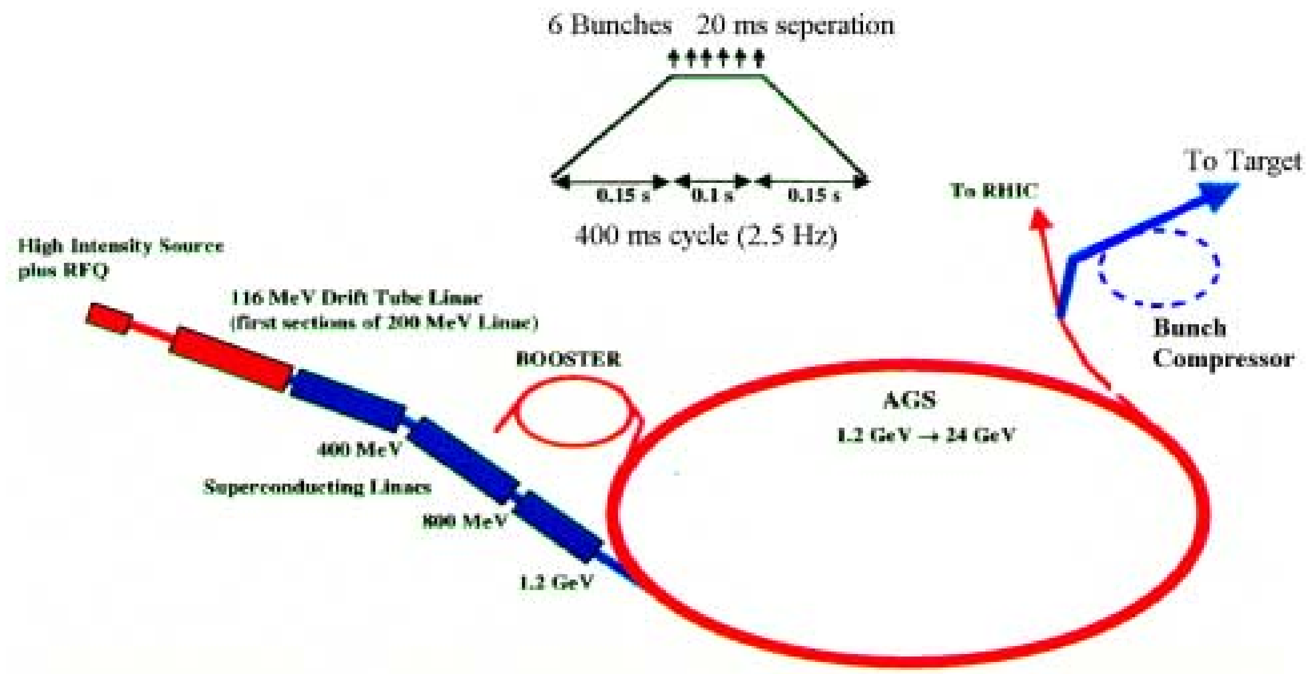


Schematic


0.0
0.5
1.0
1.5
length (km)
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 H2)
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)
Neutrino Beam (≈ 15 GeV)

PROTON DRIVER

- 1 MW BNL AGS Upgrade

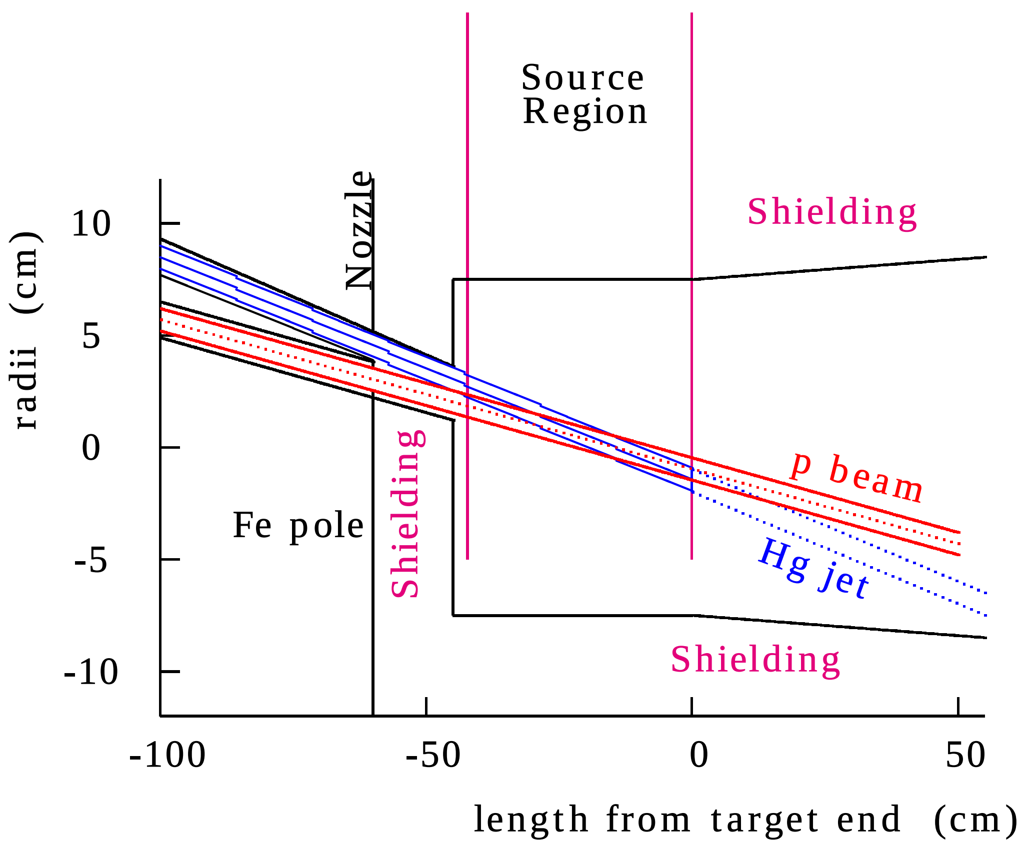


- 4 MW further upgrade
- Similar performance with new 16 GeV Booster at FNAL

TARGET

Mercury jet Target

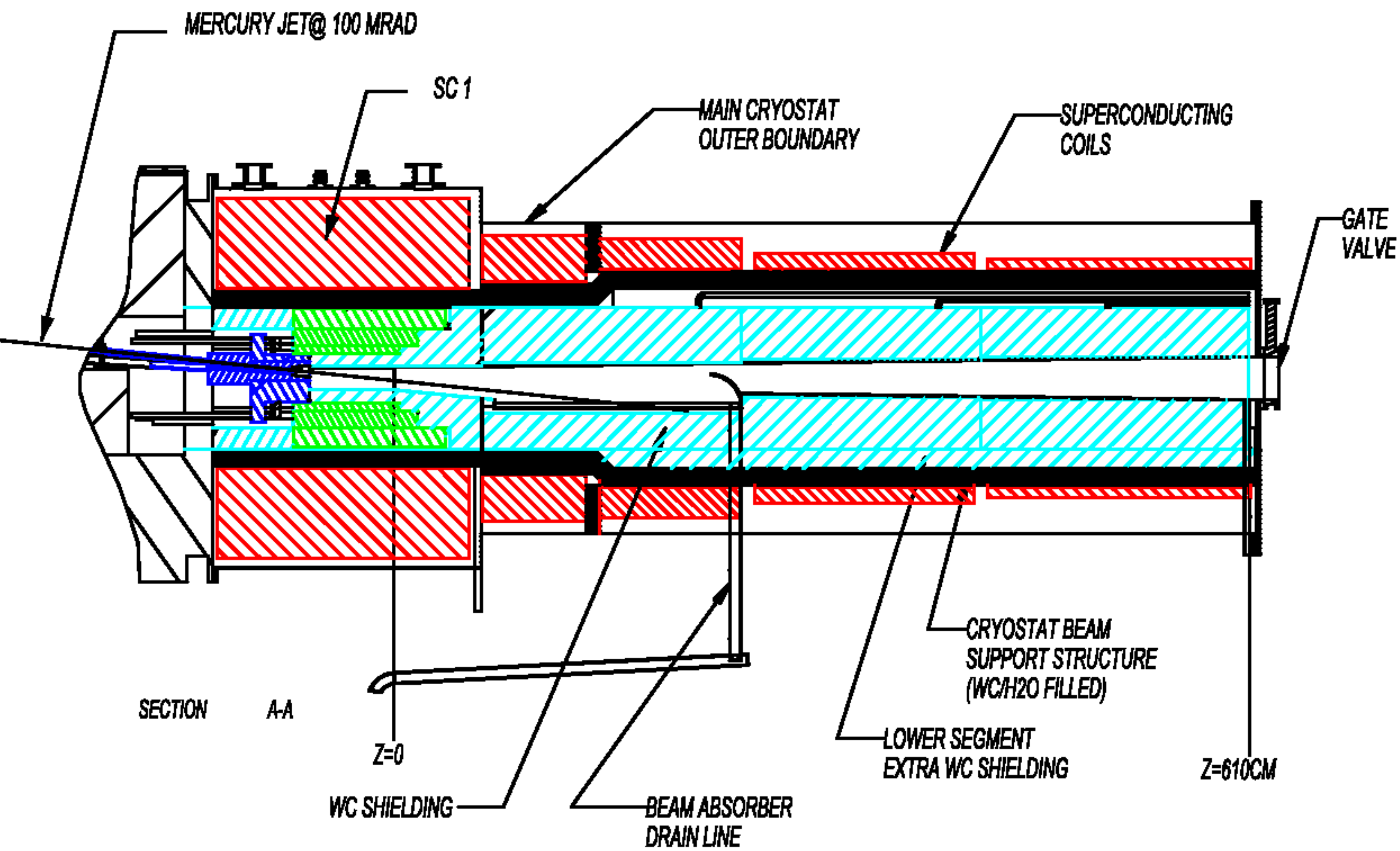
- $\approx 2 \times$ Carbon (of study 1)
- 20 m/s replaces disturbed
- Nozzle inside field
- OK to 4 MW ?



Capture Solenoid & Dump

- 20 T hybrid magnet
  - Hollow Conductor Insert
  - Superconducting Outsert

- Taper field to 1.25 T in 18 m
- Mercury pool Beam Dump



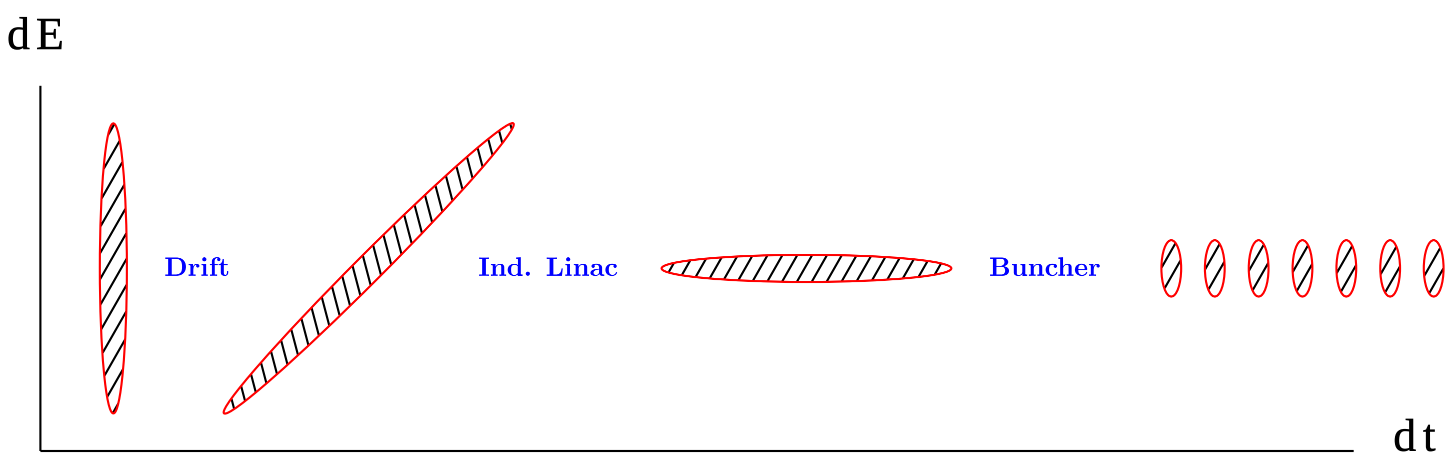
PROBLEM

- Initial pions have rms dp/p ≈ 100%
- rms Acceptance of cooling ≈ 8%

SOLUTION:

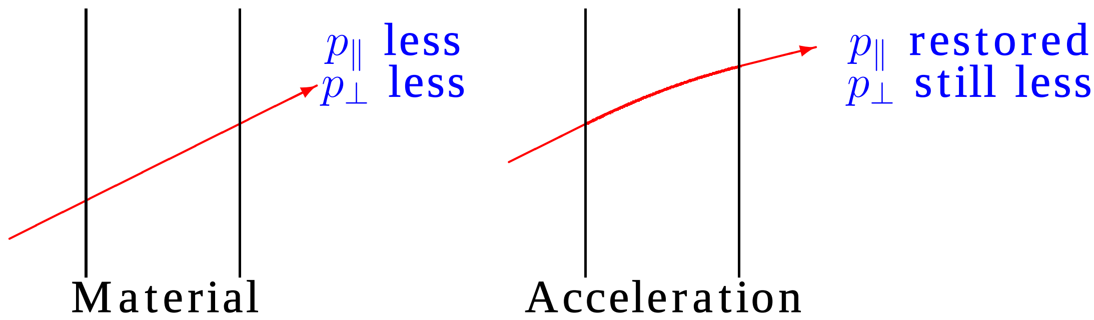
Phase Rotate & Re-Bunch

- Increase dt
- Decrease dE

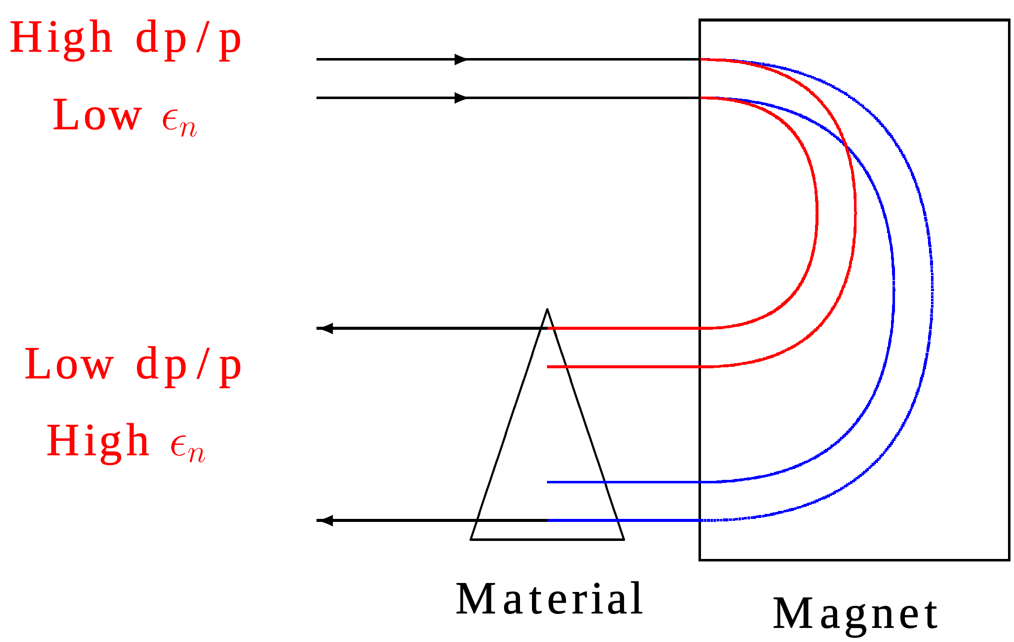


IONIZATION COOLING

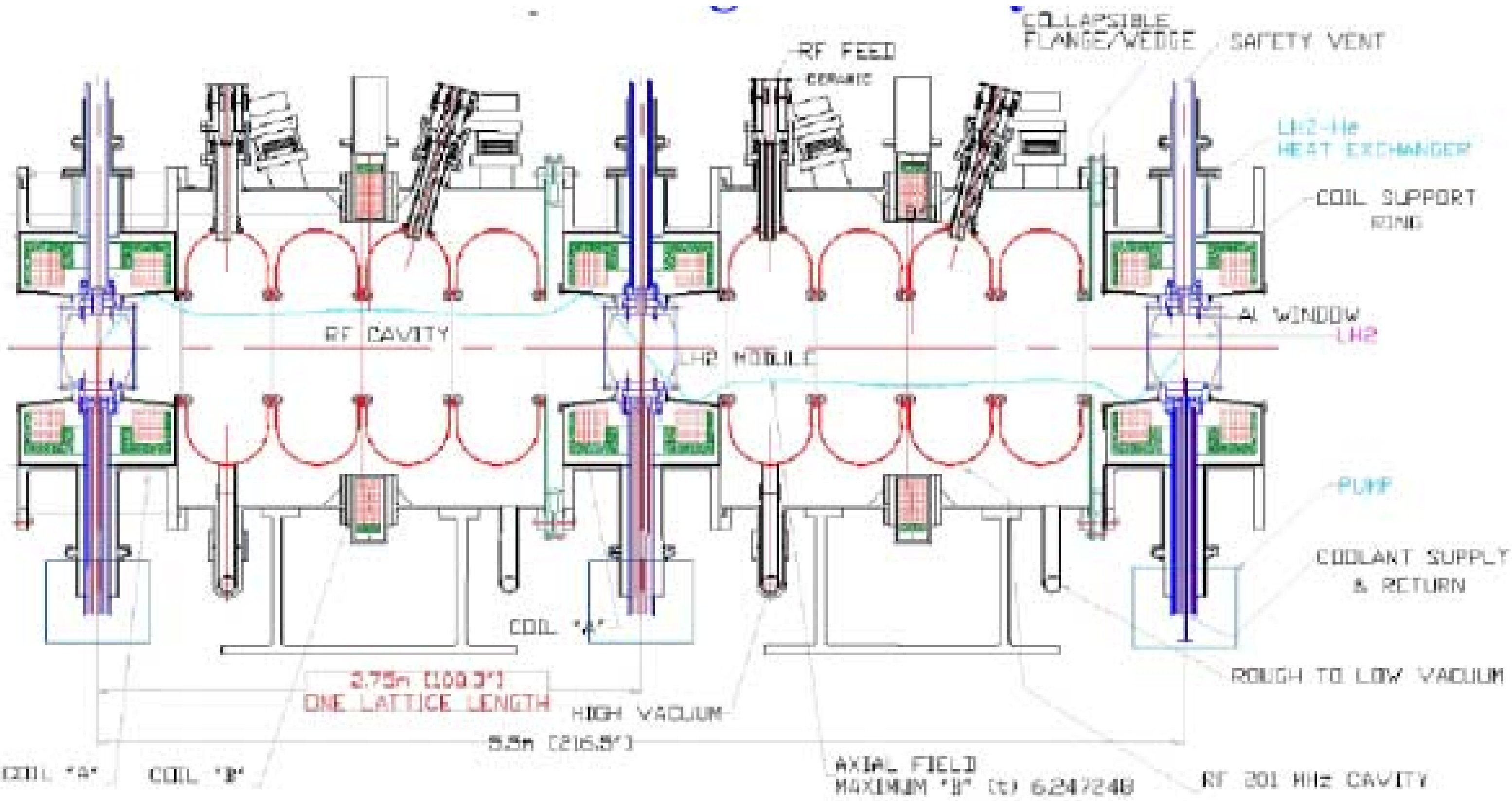
- TRANSVERSE



- dE/E Red by EMIT EXCHANGE



Cooling Lattice

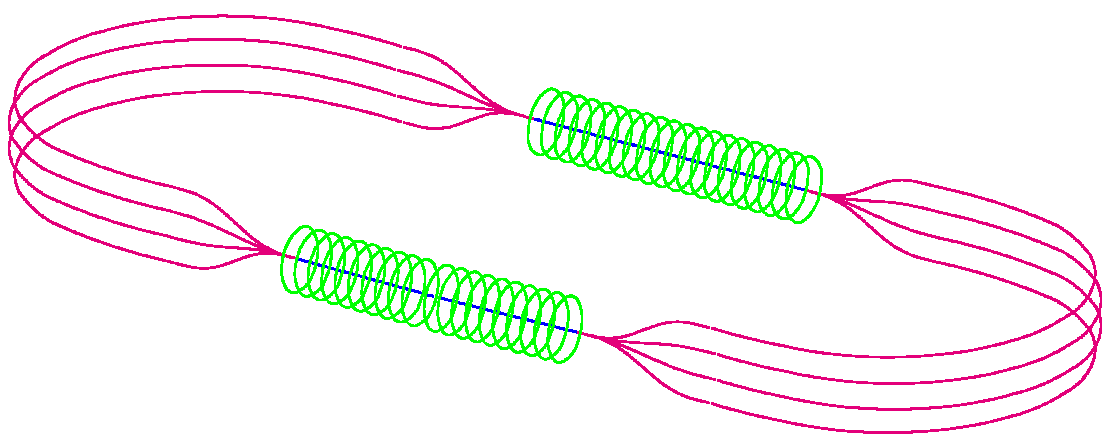


ACCELERATION

SC Linac followed by
Recirculating SC Linear Accelerator (RLA)

as at JLAB

in

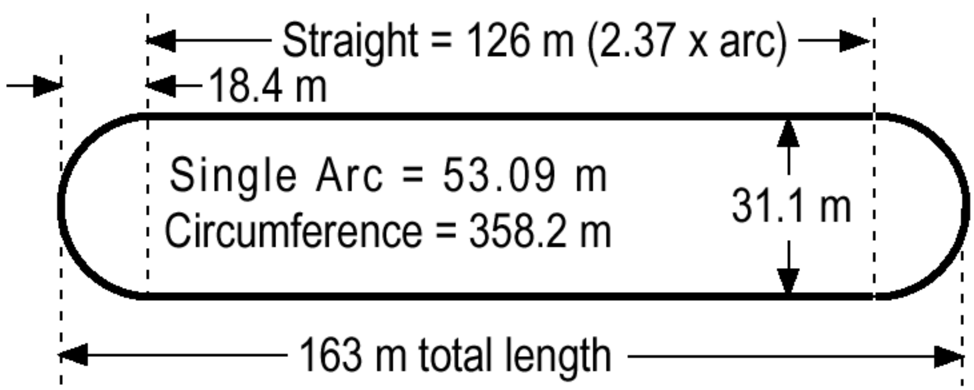


switchyards are passive, using di erent bending
for each momentum

Storage Ring

Arc Magnet Parameters:

$B_1 = 6.93$ T,	$G_1 = 0$ T/m,	$L_1 = 1.89$ m
$B_2 = 0.$ T,	$G_2 = 35.0$ T/m,	$L_2 = 0.76$ m
Average B = 4.94 T,		$L_{cell} = 5.3$ m



10 Cell Solution
60° Arc Cell Phase
$\beta_{arc} = 8.69$ m

Empty cell has warm quadrupoles with G = 27.2 T/m.

$$\text{Geometric Decay Ratio} = \frac{126\text{ m}}{358\text{ m}} = 0.35 \text{ per straight section}$$

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
- $\mu^+ \mu^-$
  - Needs much R&D
- μ storage ring ν Factory
  - ”feasible” but expensive
  - Needs R&D to reduce cost