MUON COLLIDERS

R. B. Palmer

Brookhaven Nat. Lab
SUNY, Stonybrook
LBNL

COLLABORATION

- > 100 Collaborators (30-40 FTE's)
- Lead Spokesperson :Bob Palmer (BNL)
- Associate Spokesmen:
  A. Sessler (LBNL), A. Tollestrup (FNAL)
- Lead Institutions
  BNL, FNAL, BINP, LBNL,
  Mississippi, Princeton, UCLA
- Members also from :
  ANL, CERN, Ecole Poly., Fairfield, Indiana,
  KEK, Oak Ridge, Saclay
- Experiments
  - Cooling Exp: S. Geer
  - Target & Capture Exp K. McDonald
  - BNL E910 (Pion Prod) H. Kirk
  - BNL E932 (Proton compression) J. Norem

BRIEF HISTORY

Muon Collider mentioned
- Tinlot(1960)
- Budker(1969)
- Skrinsky(1971)
- Neuffer(1979)

Ionization Cooling
- Skrinsky&Parkhomchuk(1981)

High Luminosity
- Neuffer&Palmer(1994)
- ⋮
- Meetings&Workshops

- $\mu^+\mu^-$ Collider: A Feasibility Study
  Snowmass (1996)
  BNL−52503 // Fermi Lab−Conf.−96/092 //
  LBNL−38946
  18 Institutions, 83 Collaborators.

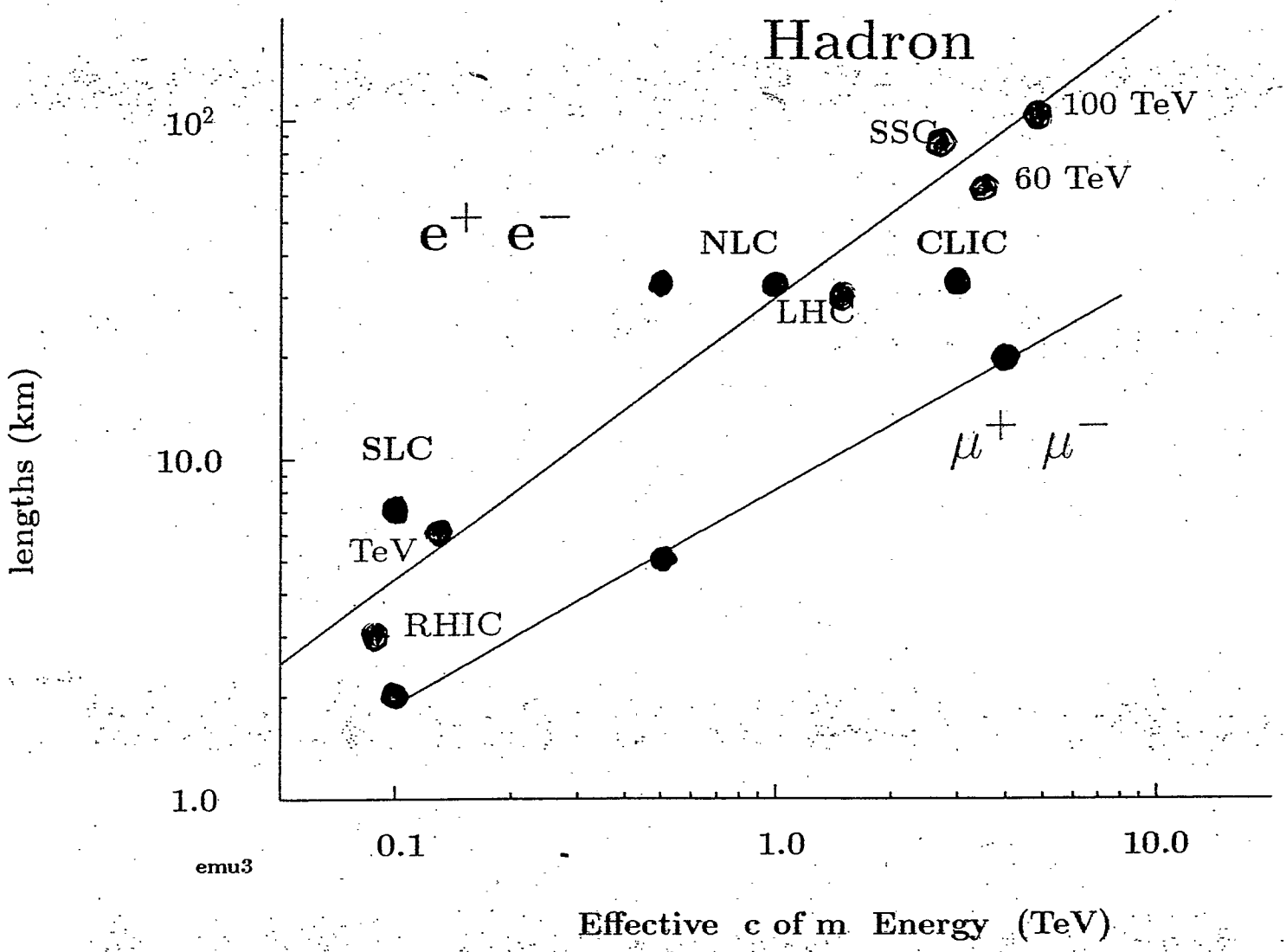
- WEB Home page
  URL `http://www.cap.bnl.gov/mumu/mu_home_page.html`

MUON COLLIDER

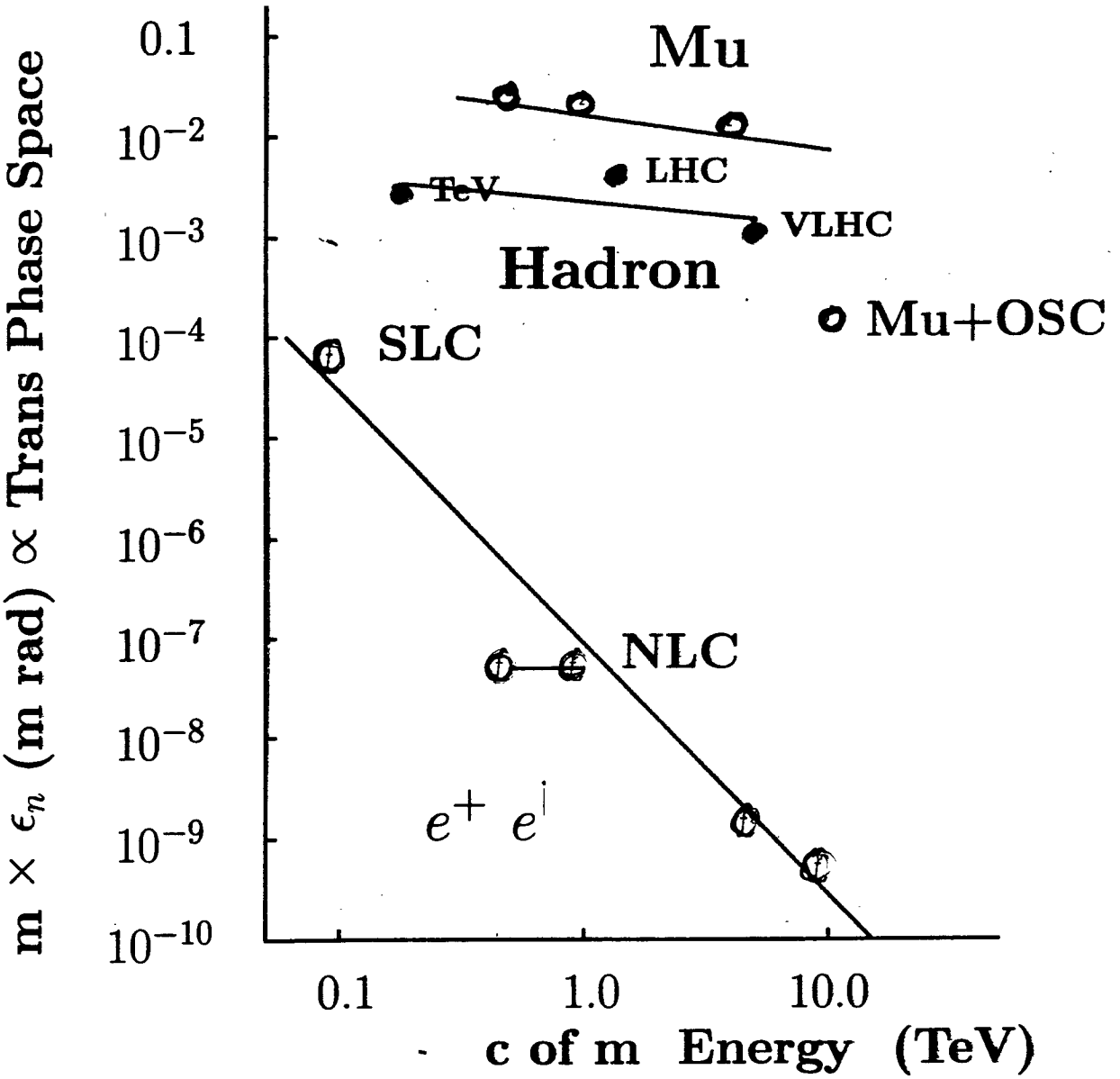
μ is a High mass Lepton

- **Energy Advantage vs. Protons**
- **Suppressed Synchrotron Rad. vs. electrons** $(\propto \gamma^4 \propto m^{-4})$
  - **Circular and Smaller**
  - **Easier Tolerances**
  - **Narrow Energy Spread → 0.003%**
- **Direct Higgs Production**
  - $\mu^+ \mu^- \rightarrow \mathbf{h}$ $(\sigma \propto m^2)$
- **Intense Neutrino Beams**

LENGTHS


Hadron
100 TeV
SSC
60 TeV
$e^+ e^-$
NLC
CLIC
LHC
SLC
TeV
RHIC
$\mu^+ \mu^-$
10^2
10.0
1.0
0.1
1.0
10.0
lengths (km)
emu3
Effective c of m Energy (TeV)

TOLERANCES


Mu
LHC
TeV
VLHC
Hadron
Mu+OSC
SLC
NLC
$e^+ e^-$
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
m × ϵ_n (m rad) ∝ Trans Phase Space
0.1
1.0
10.0
c of m Energy (TeV)

BUT:

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

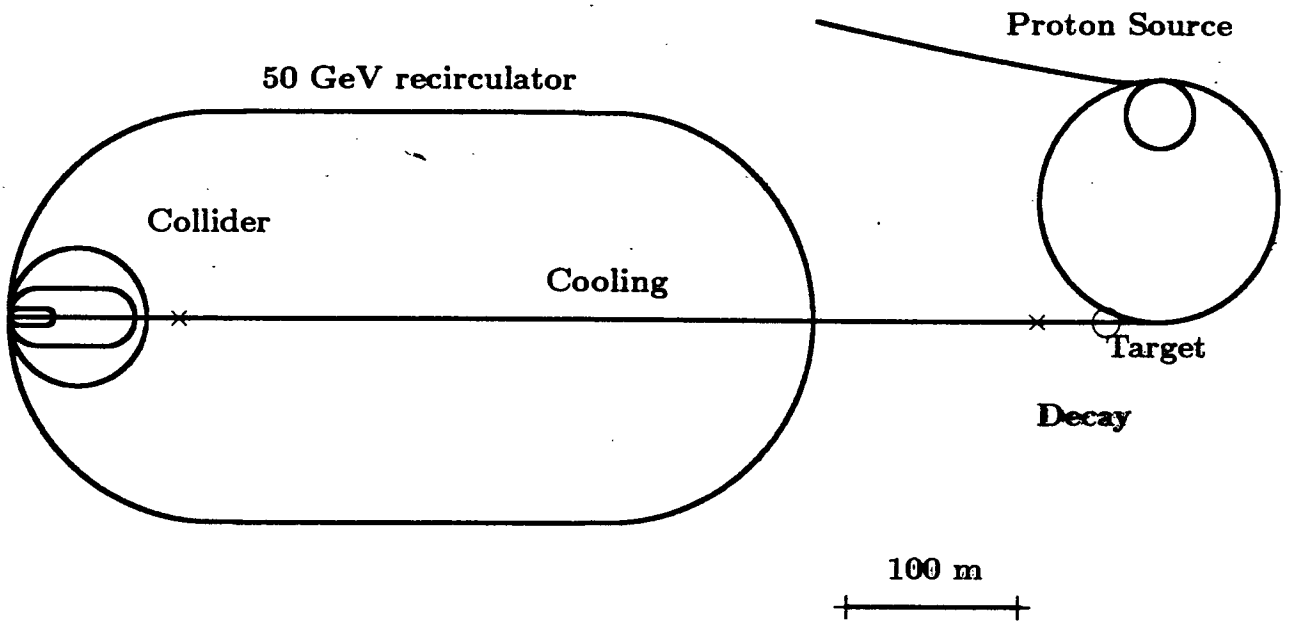
Need

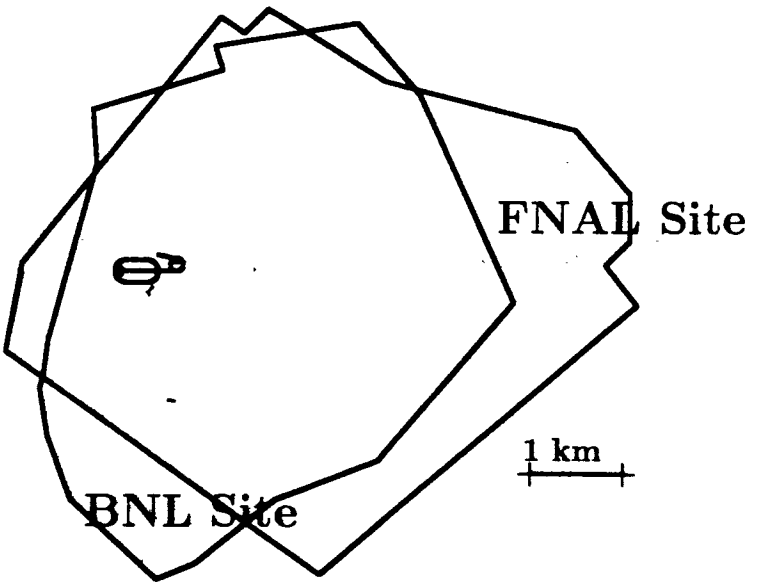
- Efficient μ Production
- Rapid Cooling
- Rapid Acceleration

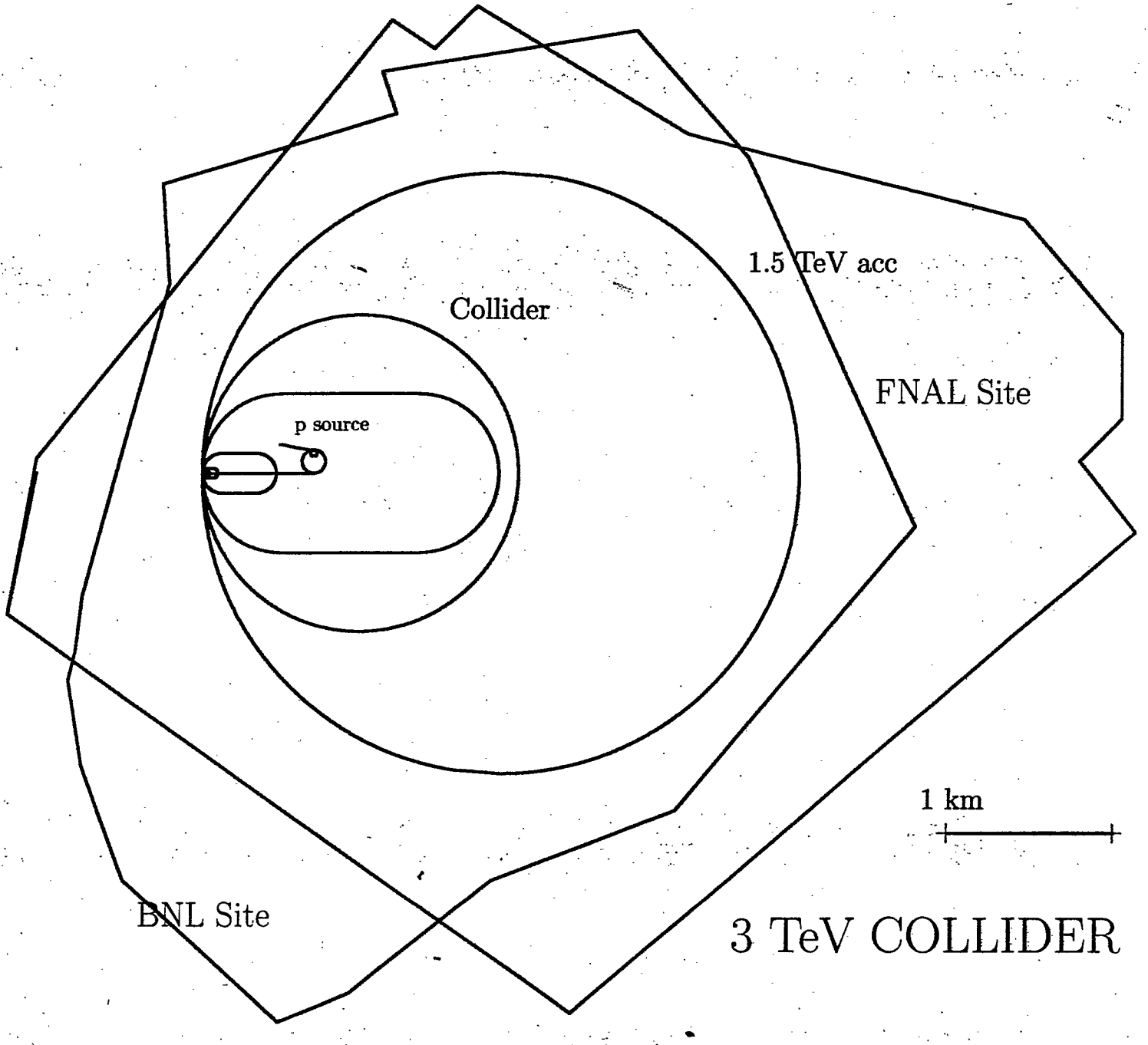
Deal With

- Beam Pipe Heating
- Detector Background
- Neutrino Radiation

100GeV HIGGS COLLIDER





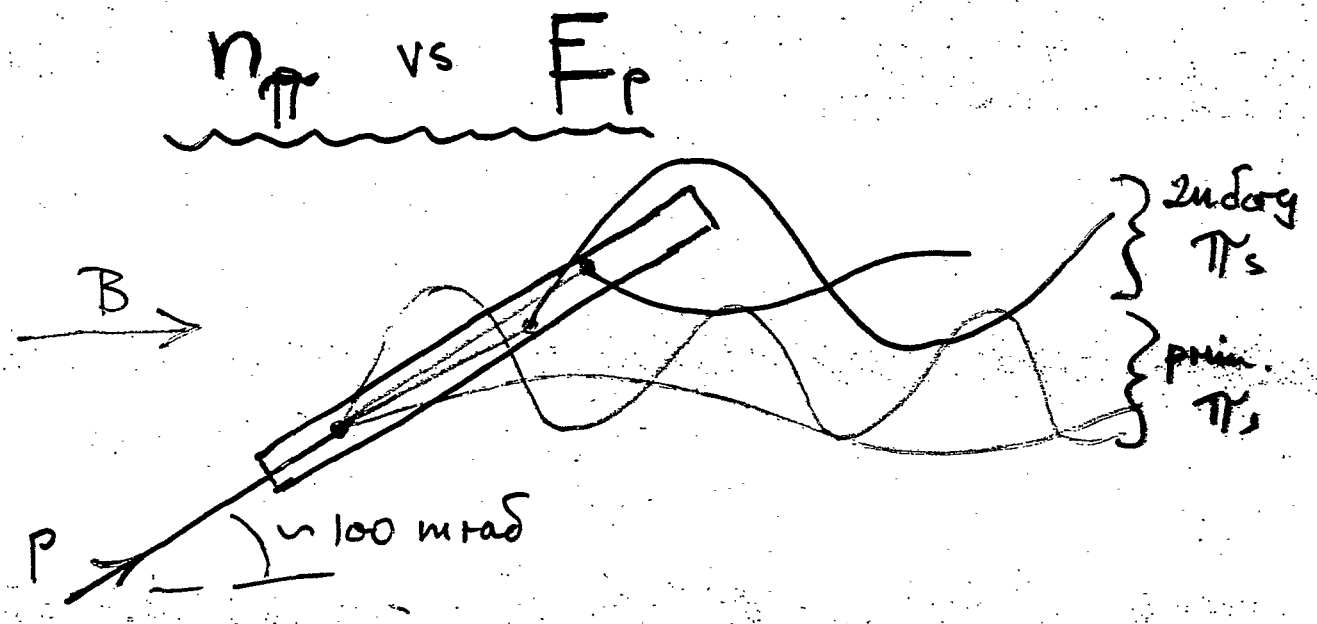

1.5 TeV acc
Collider
FNAL Site
p source
1 km
BNL Site
3 TeV COLLIDER

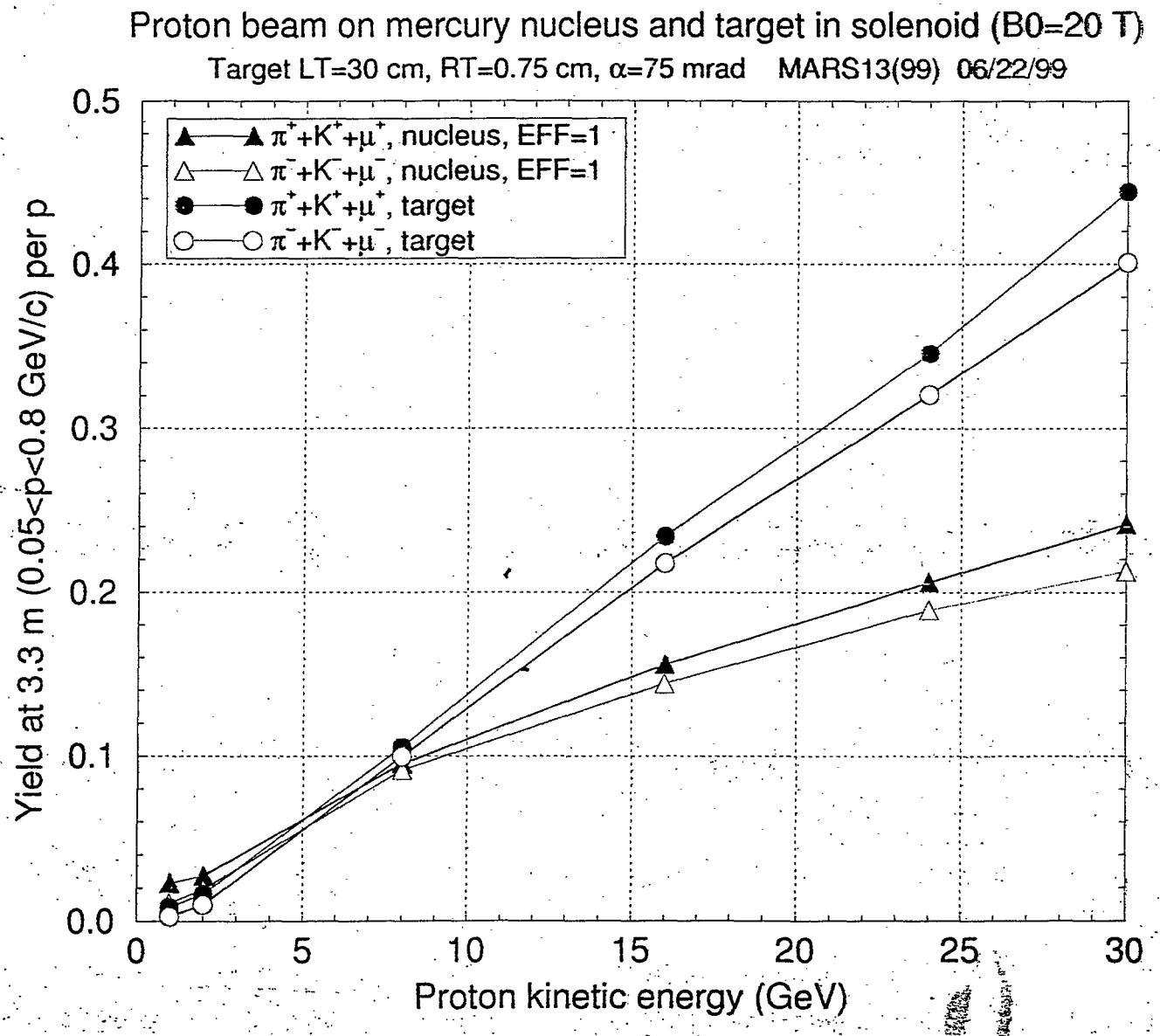
FIRST μ COLLIDER ?

PARAMETERS

CoM energy	TeV	3	0.4	0.1	
p energy	GeV	16	16	16 *	
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}	
Wall power	MW	204	120	81	
Collider circ.	m	6000	1000	350	
Ave bend B	T	5.2	4.7	2	
Rms $\frac{\Delta p}{p}$	%	0.16	0.14	0.12	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
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

$$* \quad \mathcal{L} \propto N_p^2 \cdot f \propto I_p \cdot \frac{N_p}{\xi}$$


n_π vs E_p
B
p
~100 mrad
secondary π's
prim. π's


Proton beam on mercury nucleus and target in solenoid (B0=20 T)
Target LT=30 cm, RT=0.75 cm, α=75 mrad MARS13(99) 06/22/99
π⁺+K⁺+μ⁺, nucleus, EFF=1
π⁻+K⁻+μ⁻, nucleus, EFF=1
π⁺+K⁺+μ⁺, target
π⁻+K⁻+μ⁻, target
Yield at 3.3 m (0.05<p<0.8 GeV/c) per p
Proton kinetic energy (GeV)
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
25
30

P DRIVER REQUIREMENTS

Need:

- High n_π/sec per p power
  Independent of p Energy (see plot)

- Large absolute $n_\pi \approx 10^{12}$/bunch
  Proportional to proton energy
  Thus: $n_p \propto 1/E_p$ $\sim 5\ 10^{13}$ at 24 GeV

- Small 6D π Phase Space
  Only σ_t carried to π's
  $\sigma_t \approx$ 1 nsec

- Tune Shift before extraction

$$\Delta\nu \propto \frac{N_p}{\sigma_z} \frac{R}{\gamma^2 \epsilon_n}$$

$$\propto \frac{N_\mu}{\sigma_z \gamma} \cdot \frac{\gamma}{\gamma^2 \langle B \rangle \epsilon_n}$$

$$\propto 1/\gamma^2$$

eg for AGS $\langle B \rangle$ & ϵ_n

E_p	$\Delta\nu$	
8	3	✗
16	.8	✓
24	.4	✓✓

- proton Phase Space Consid's

In practice:

$$\phi_{\parallel} \propto p's / \text{bunch}$$

Assume: $\phi_{\parallel} = 1\,\text{eVsec} \times \frac{n_p}{10^{13}}$ (see plot)

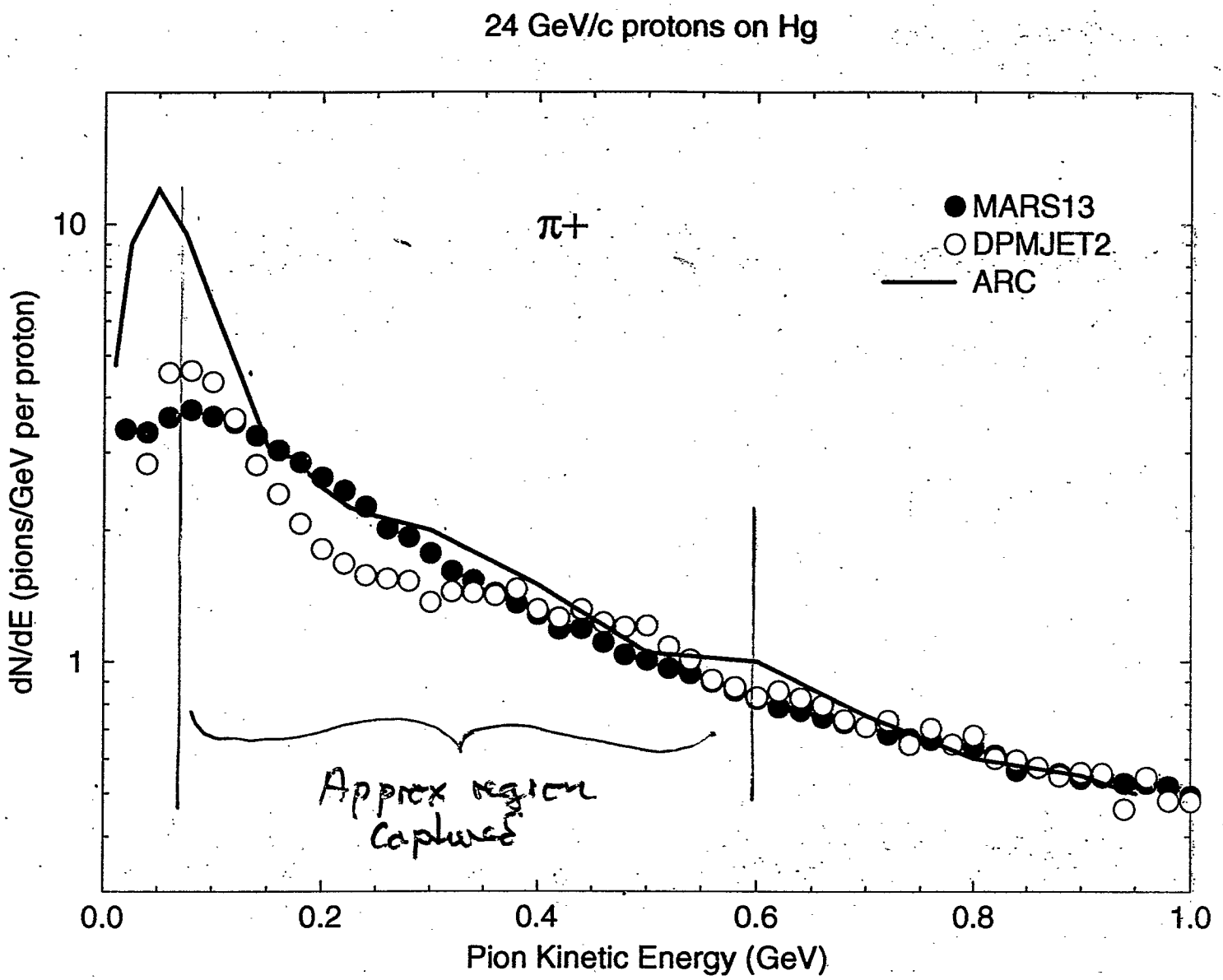
Then: $\phi_{\parallel} \propto \frac{1}{E_p}$ ← (because lower π/p at low E)

$$\frac{dp}{p} \propto \frac{\phi_{\parallel}}{\sigma_t \, E_p} \propto \frac{1}{E_p^2}$$

eg 1 nsec σ_t

E_p	$\frac{\partial p}{p}$ (rms)	$\frac{\partial p}{p}$ (95%)	
8	9%	±22%	X
16	2.3%	±6%	✓?
24	1%	±2.5%	✓✓

Where are the Pions ?



almost no Data

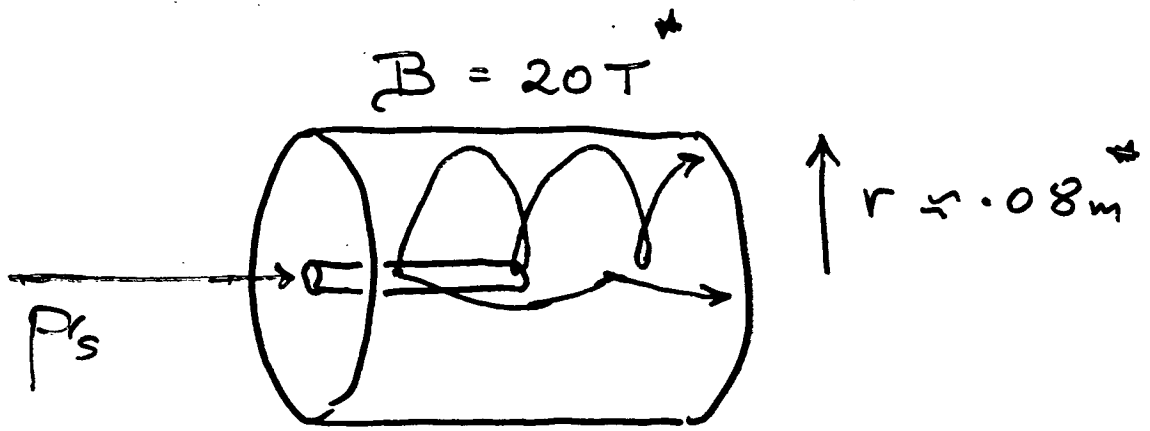
good Data

Pion Capture

E: ·05 → ·5 GeV ?

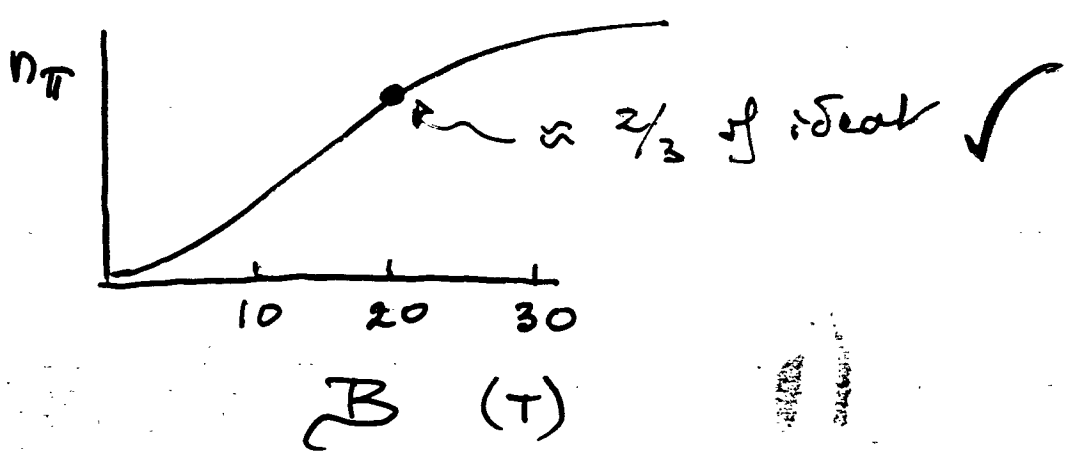
$p_\perp$: 0 → 300 MeV/c ?

Solenoid

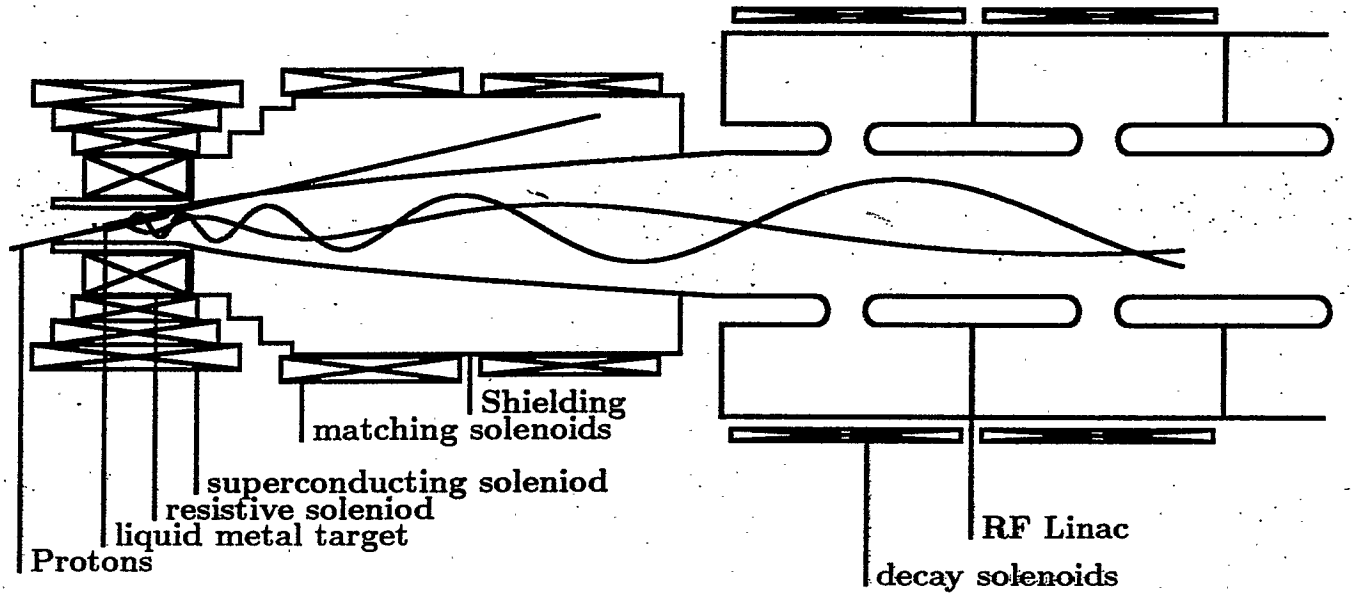


* Existing Magnet

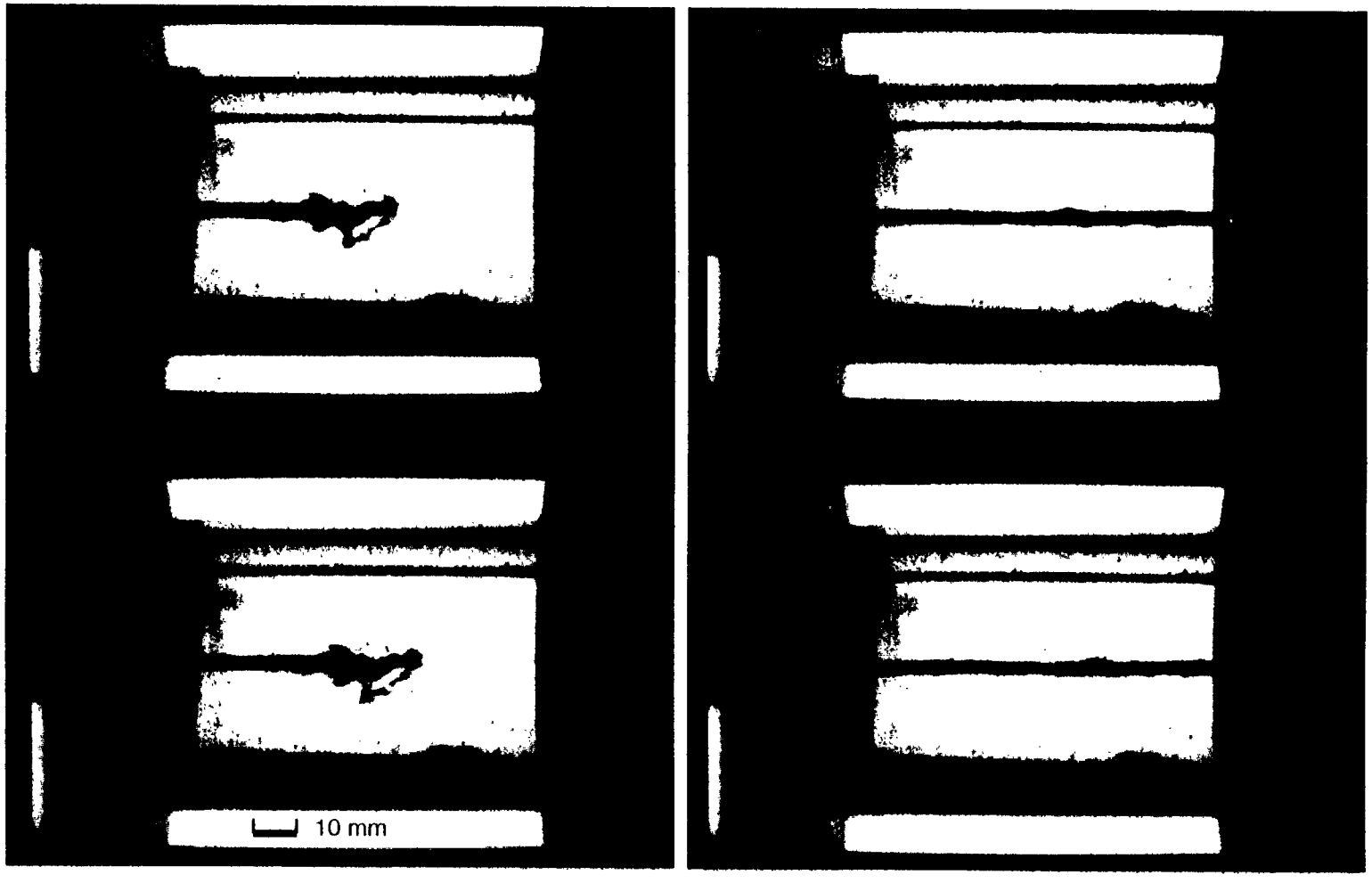
- All $p_\parallel$ ✓
- $p_\perp$ (GeV/c) ≤ ·15 r(m) B(T) = ·24 GeV/c



TARGET, CAPTURE & DECAY



- TARGET: Liquid Metal Jet
- CAPTURE: 20 T Solenoid
- DUMP
- MATCING
- DECAY & PHASE ROT.: 1.25 T



High-speed photographs of mercury jet target for CERN-PS-AA. (laboratory test)
4,000 frames per second, Jet speed: 20 ms^{-1}, diameter: 3 mm, Reynold's Number: >100,000

A.Poncet

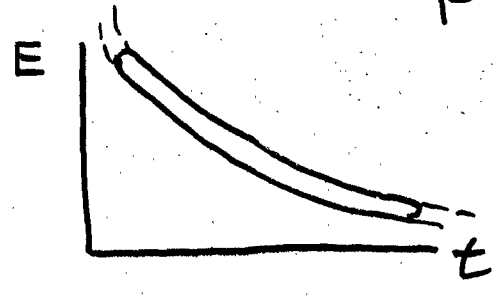
(CERN) C. Johnson

Kirk, Palmer

• Phase Rotation

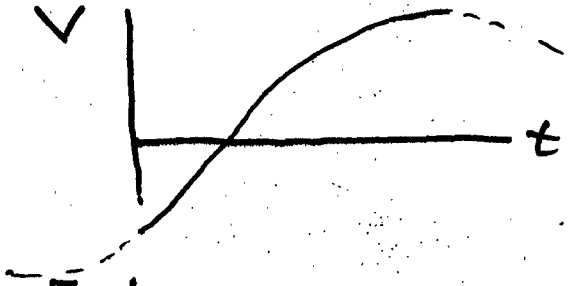
Use Linac to Reduce $\frac{\Delta p}{p}$ of μ's :

• If No Linac



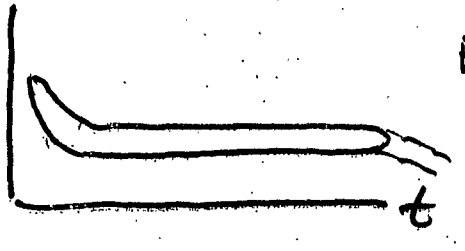
E • 1 - 1 GeV

• RF Linacs



+ harmonics

• Final



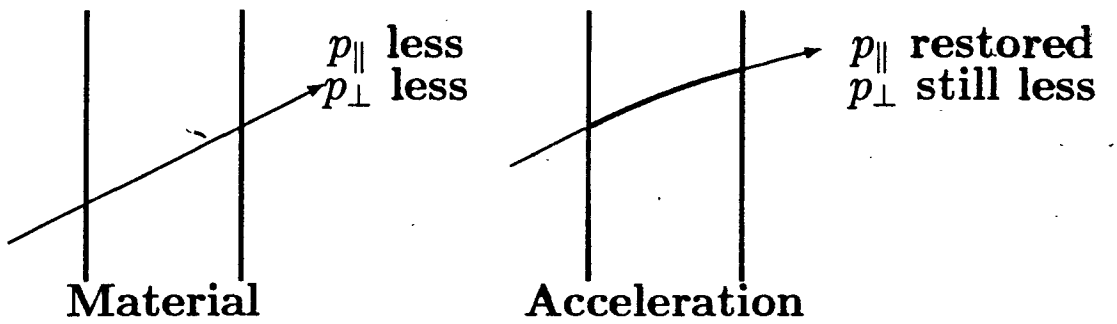
E = • 4 ± 7-15 %

σ_{t_p} 1 nsec 3 nsec

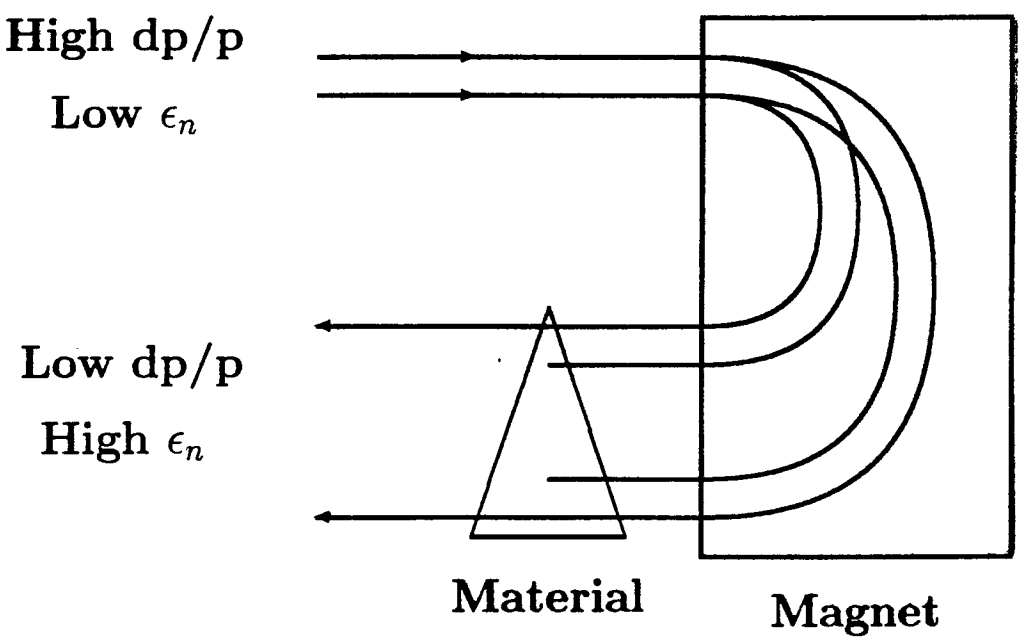
Budker 69
Skrinsky 81

IONIZATION COOLING

- TRANSVERSE

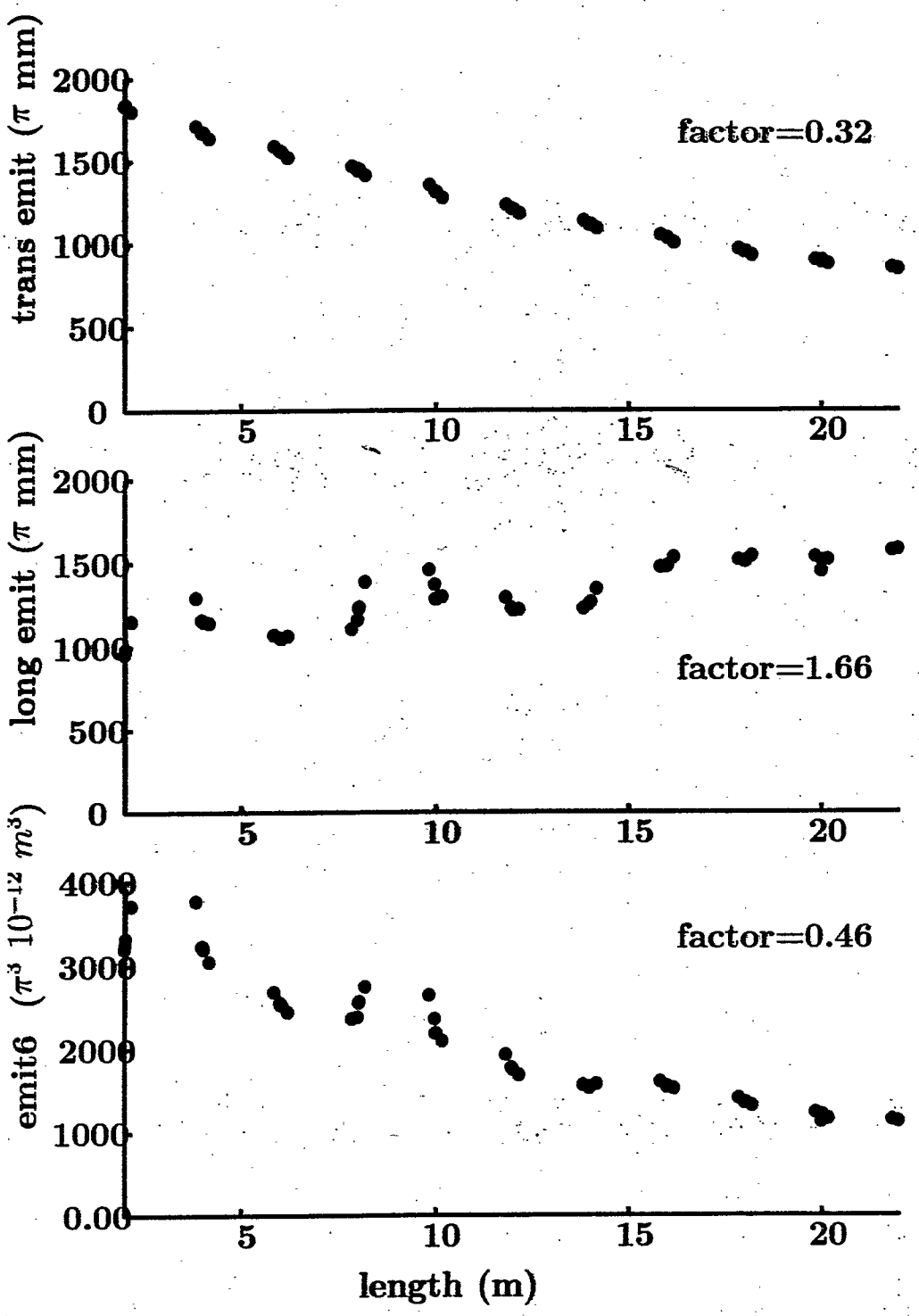


- LONGITUDINAL EMIT EXCH



SIMULATION at 15 T

R Fenow
BNL

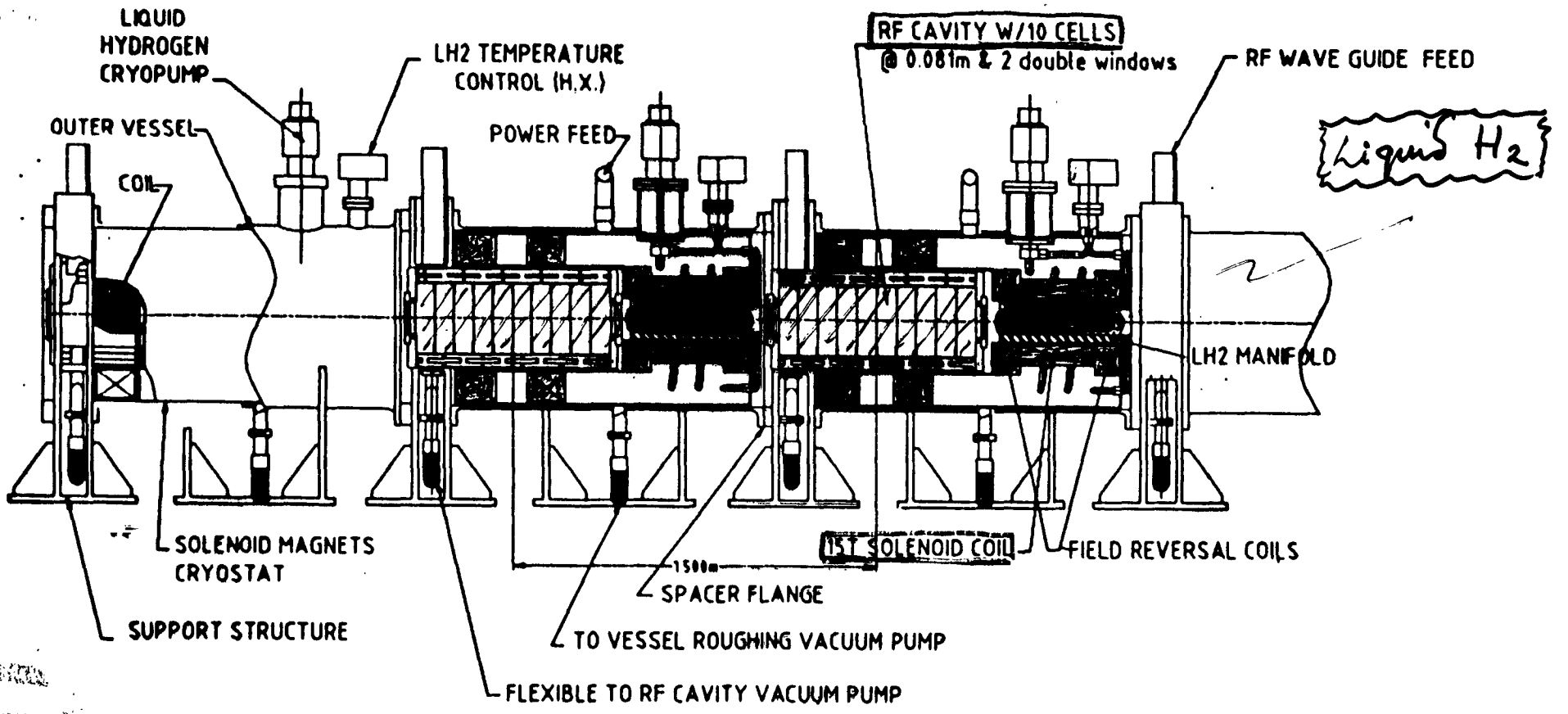


Higgs Collider Params Achieved at 30 T, but
Lithium Lenses may be more economical.

Conceptual Design of Transverse Cooling

PRELIMINARY CONCEPTUAL DESIGN

ALL MAGNETIC COILS IN A SEGMENT ARE ENCAPSULATED IN A COMMON CRYOSTAT.



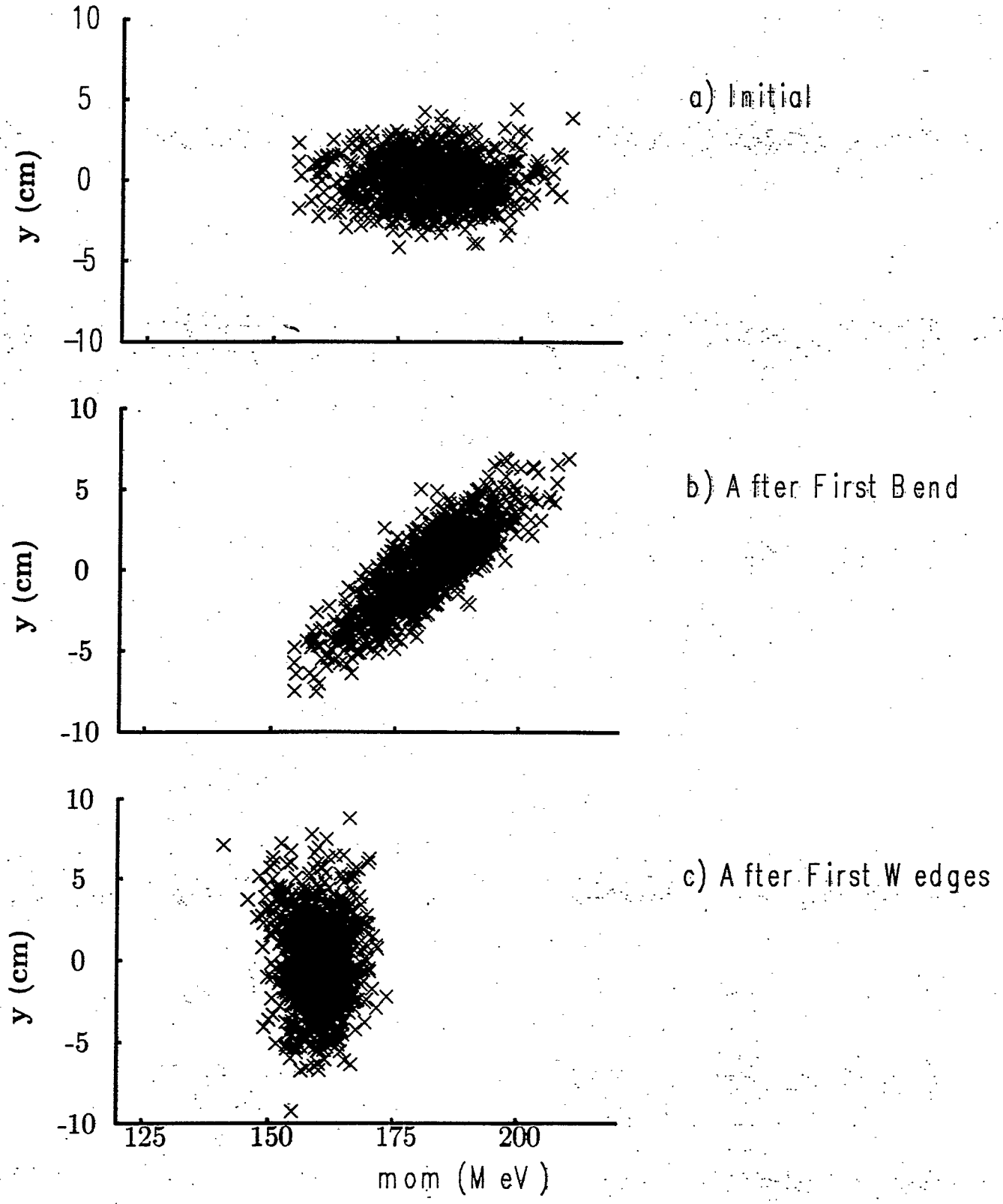
COOLING APPARATUS
15T SHORT LATTICE SEGMENTS

Edgar Black
IIT
11/16/98
e-mail: black@fnal.gov

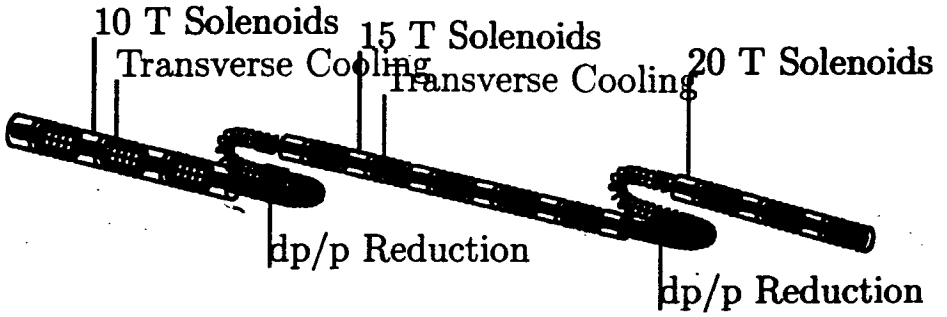
15TSH116.DWG

* FNAL Experiment

EMIT EXCH SIMULATION



9.7 Complete Cooling System



- 6D emit reduction/stage ≈ 2
- Typical length 20 m/stage
- Trans Cool & Long Exch Alternate

Required 6D reduction $\approx 10^6$

Number of stages ≈ 20

Total Length ≈ 500 m

Momentum ≈ 180 MeV/c

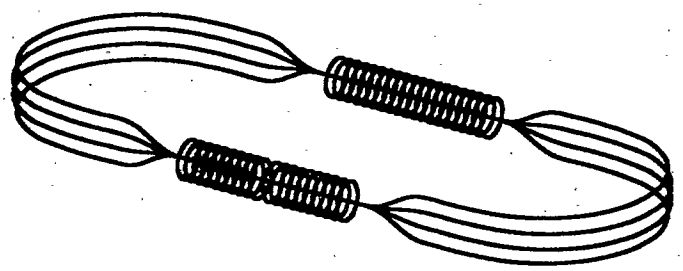
Decay Loss ≈ 36 %

ACCELERATION

Acceleration must be rapid

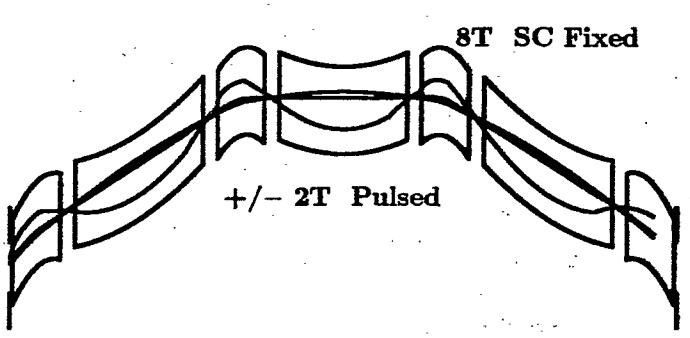
- **At very low Energies:**
  Linacs (one pass)
- **Intermediate Energies:**
  Recirculating-Linac (or FFAG)
  ($\approx$ 10 turns)

C. Johnstone
FNAL



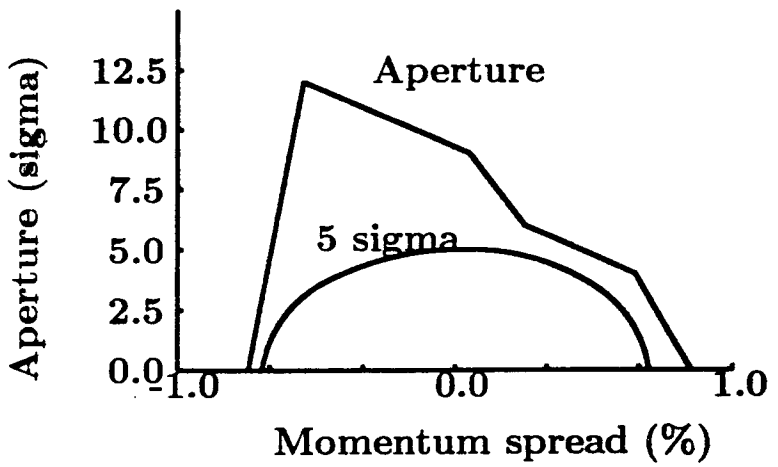
- **High Energies:**
  Hybrid Pulsed & SC Synchrotron
  ($\approx$ 40 turns)

D. Summers
Mississippi

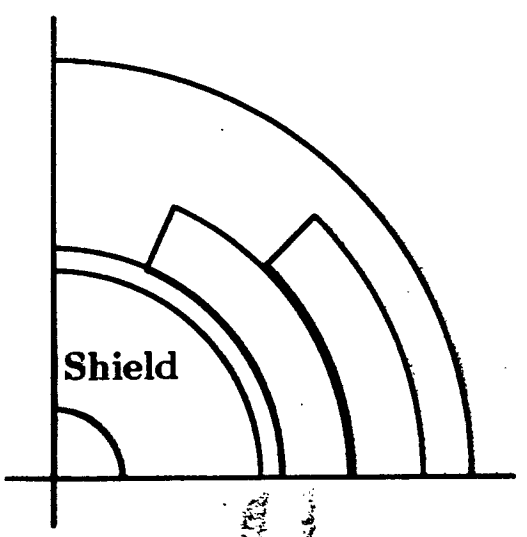


COLLIDER RING

- Low beta
  Local chromatic corr.
- Short Bunches
  Isochronous ring
  Flexible Momentum Compaction
- Status
  - feasibility demonstrated at 4 TeV C. Johnstone
  - 100 GeV Lattices: Good Aperture D. Trbojevic

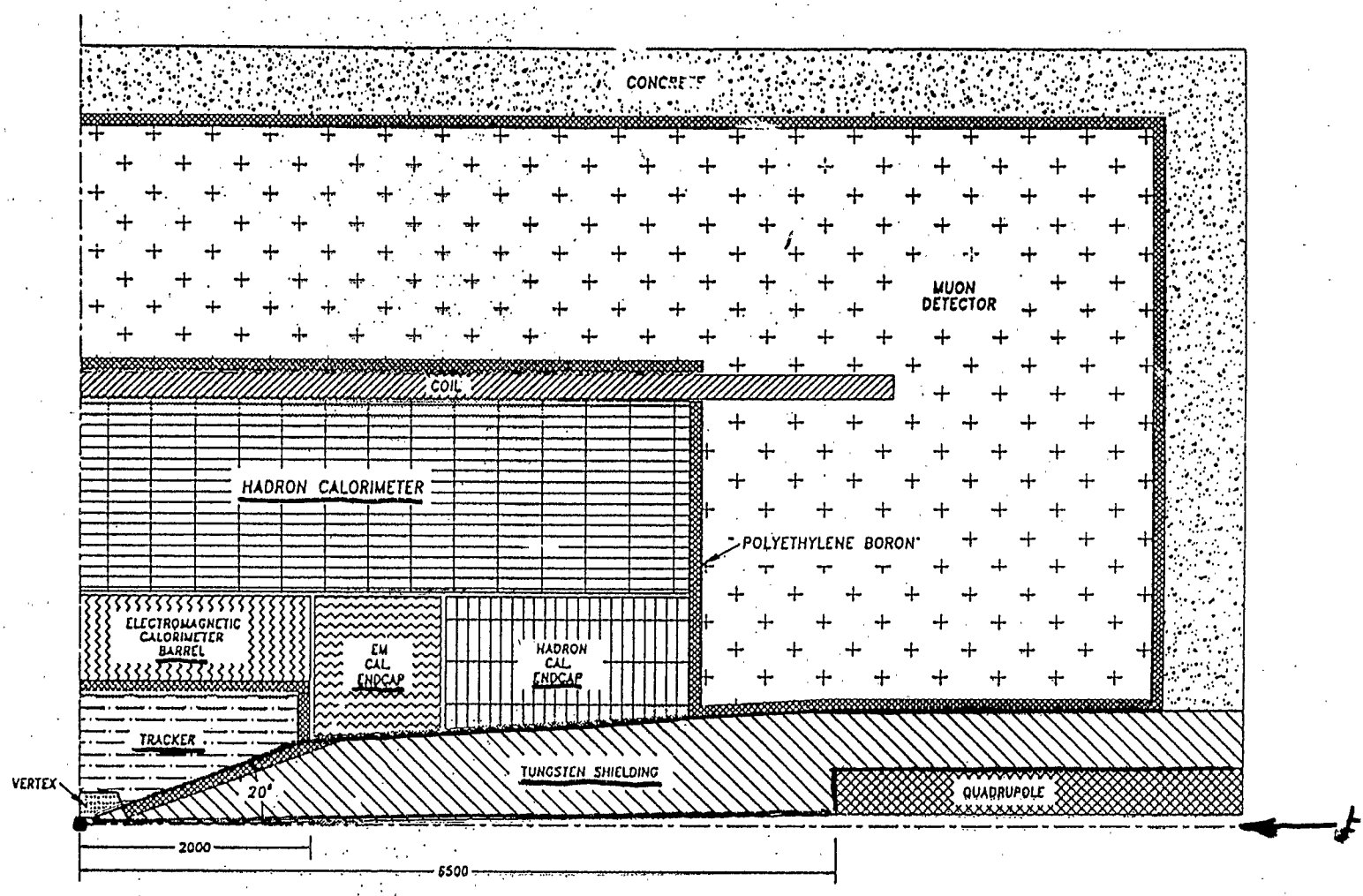


- Tungsten Beam Shield
  6 cm at 3 TeV,
  3 cm at 100 GeV



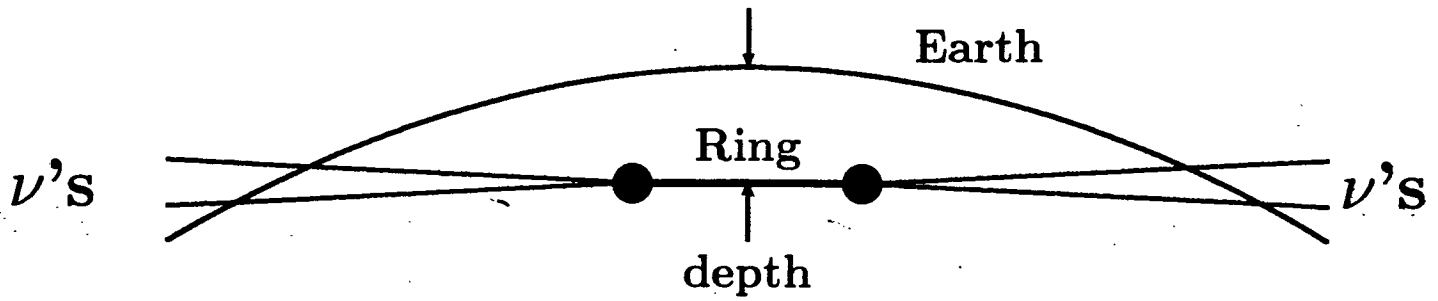
• Background Sielding of Detector

Lissaur



B King
BNL

NEUTRINO RADIATION



- Radiation $\propto$ $E^3/length^2$ $\propto$ $E^3/depth$
- Use: 1/10 Federal limit = 10 mR/year ≈ 3% of Natural Rad

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?)

M. Zolotorev

Muon Collider Collaboration

Phase I: Is it Possible ?

- Proof of Principle Near
- Done:
  - Proton Drivers
  - Liquid Target
  - Capture and Phase Rotation
  - Complete Cooling (with ideal focus)
  - First Cooling Stage
  - Last Cooling Stage (no Space Charge)
  - Emittance exchange (no rf yet)
  - Acceleration inc. wakes
  - Collider Lattice
  - Impedance effects
  - Beam-Beam effects (but not with lattice)
- Needed:
  - Space Charge in Cooling
  - rf in emittance exchange
  - ~~Beam-beam with Lattice~~

Phase II : Is it Practical

Experimental Studies

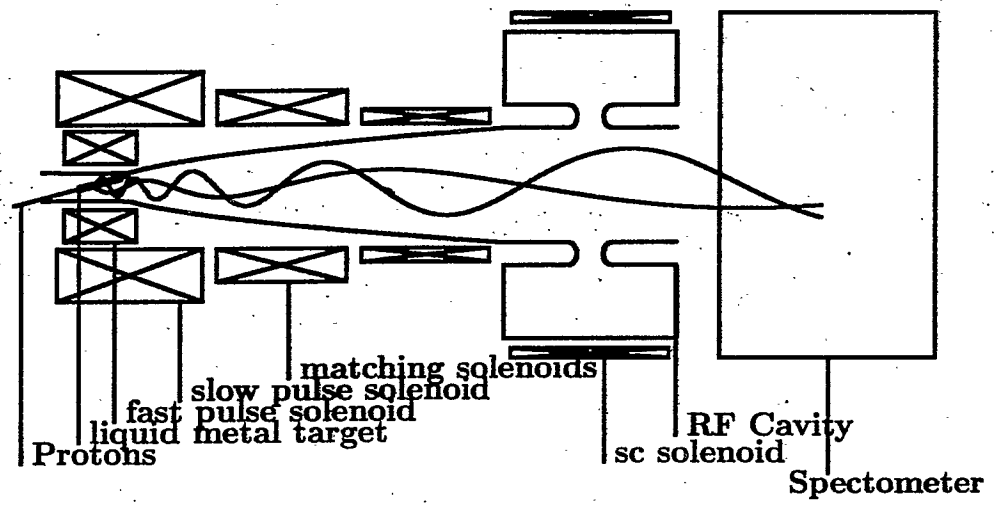
- Ongoing
  - Pion Production
  - Proton Driver Studies
- Starting
  - Target and Capture (BNL)
  - Cooling Demonstration (FNAL)
  - Scattering (Rutherford) ???

More Detailed Studies

- Complete Cooling Sequence
- Latices for all Acceleration Stages
- Complete Simulation
- Cost Optimization

TARGET EXP

(Proposed to BNL)



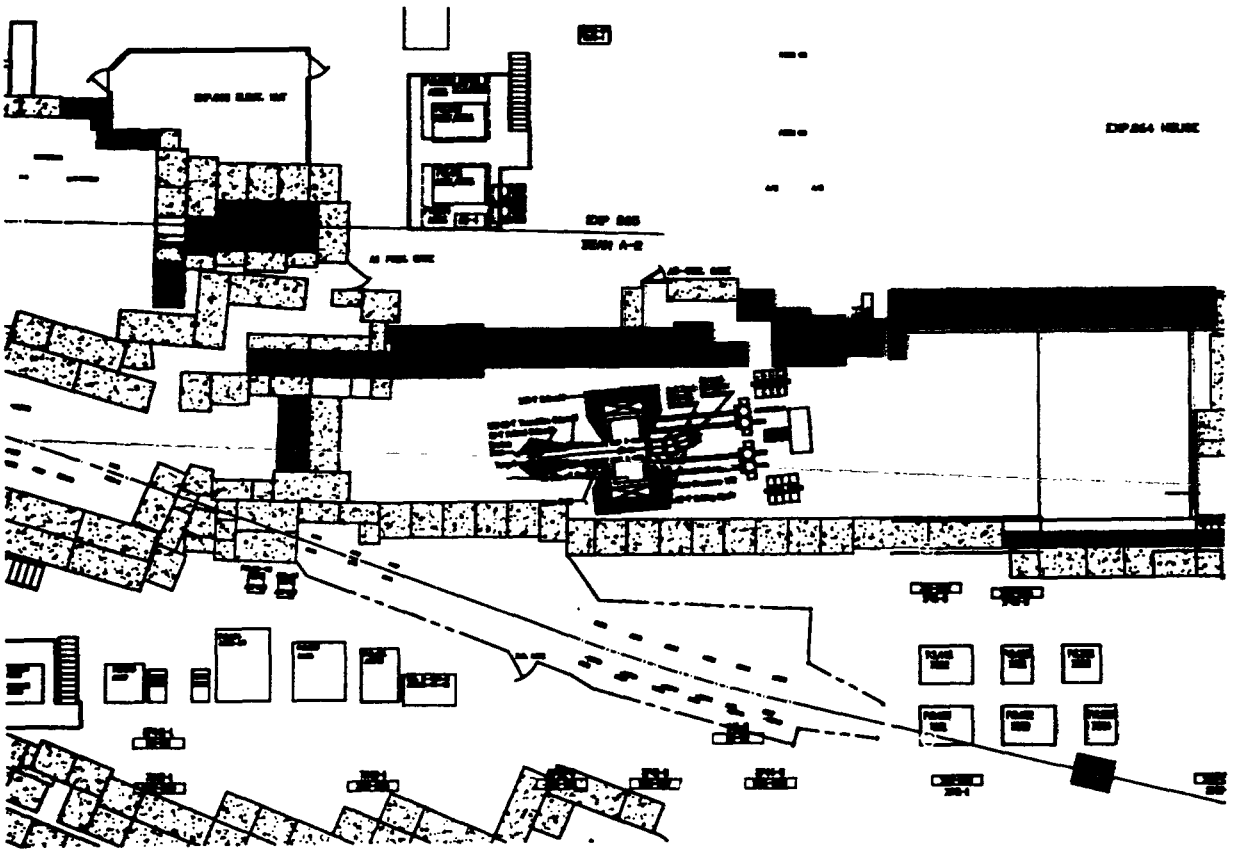
In 2 Years

1. Beam on static liquid (AGS)
2. Jet in Magnetic Field (FSU)
3. Beam in jet (AGS)

In $\approx$ 3 Years

4. Low Frequency rf offline
5. Beam in jet in Pulse Field (AGS)
6. LF rf in Beam
7. Add Field over RF
8. (Measure particle Flux ?)

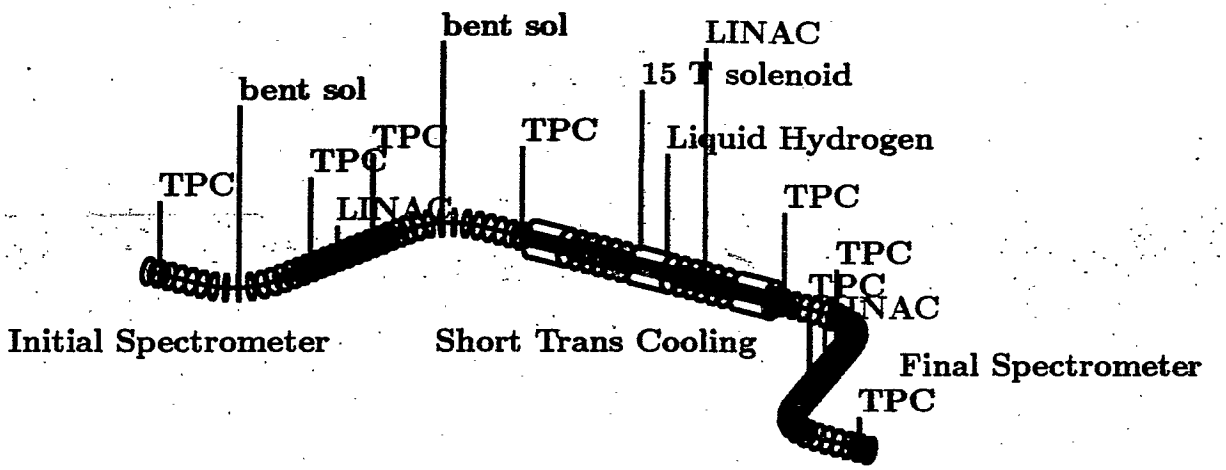
Layout of the
$\mu\mu$ Targetry Experiment



S. Geer

COOLING EXP

(Proposed to FNAL)



In 2 Years

1. Low Power RF Cavity Test (LBL)
2. High Power RF Cavity Test (FNAL)
3. Add Solenoidal Field

In $\approx$ 3 Years

4. Build 10 m of channel
5. Measure 6D Cooling
6. Build Bent Sol ϵ exch.
7. Measure dp/p reduction
8. Develop liquid Li Lenses
9. Measure Cooling in Li Lenses

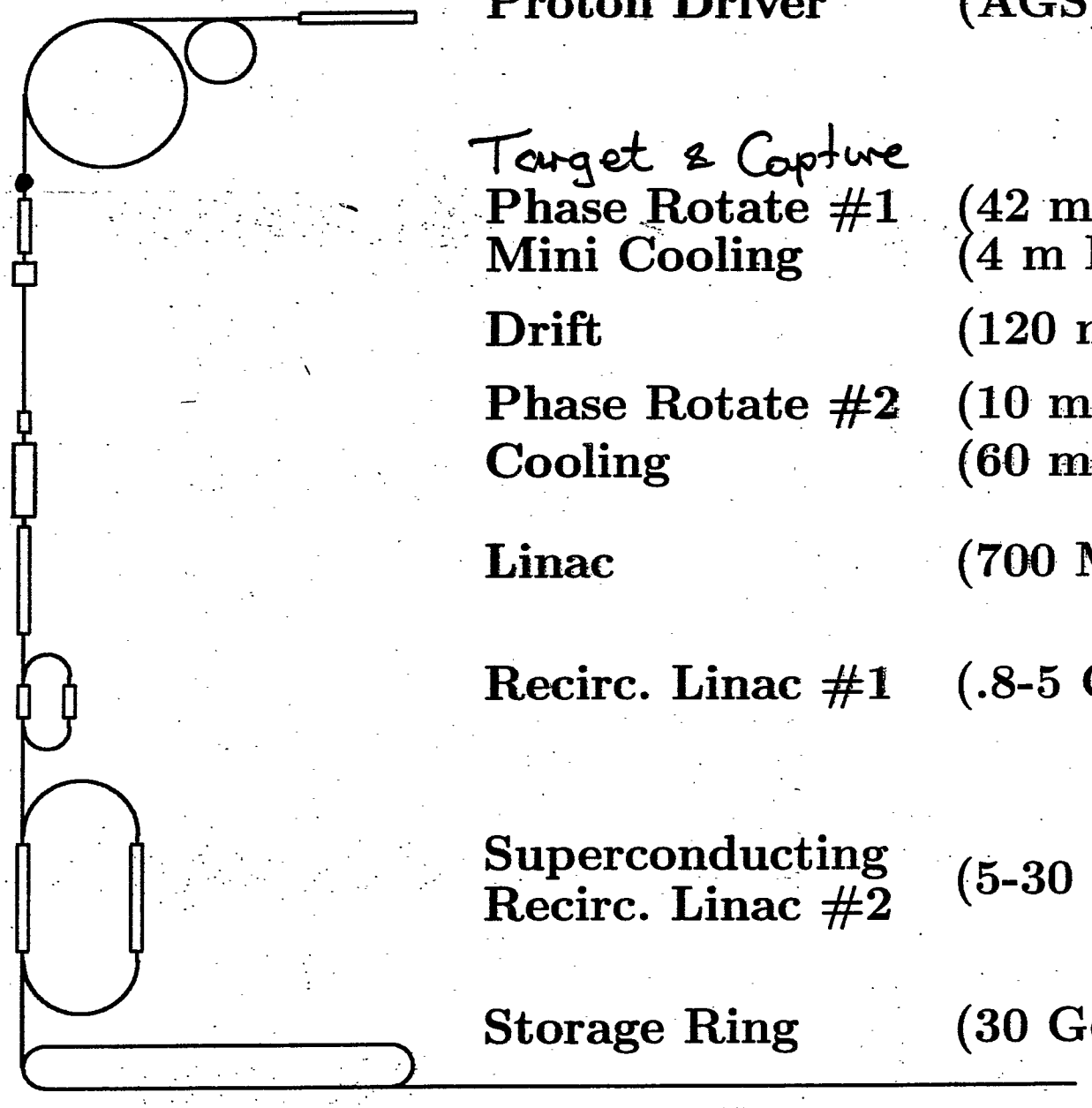
MUON STORAGE RING NEUTRINO BEAM

- First Phase of Collider
- Muon production as in Collider
- Minimal Cooling
- 30 GeV Muon Ring
- 30 × SPS Intensity
- up to 7000 km for oscillations
- ν_μ and μ_e
- Exactly known
- Beam to Gran Sasso or Soudan

for $P_p \approx 1$ mA
eg 10^{14} PPP
2.5 Hz

Phase III ?

NEUTRINO FACTORY



	e.g.*
Proton Driver	(AGS)
Target & Capture	
Phase Rotate #1	(42 m rf)
Mini Cooling	(4 m H_2)
Drift	(120 m)
Phase Rotate #2	(10 m rf)
Cooling	(60 m)
Linac	(700 MeV)
Recirc. Linac #1	(.8-5 GeV)
Superconducting Recirc. Linac #2	(5-30 GeV)
Storage Ring	(30 GeV)
Neutrino Beam	

* Very Preliminary Design in Collaboration with Keil & Johnsen (CERN)

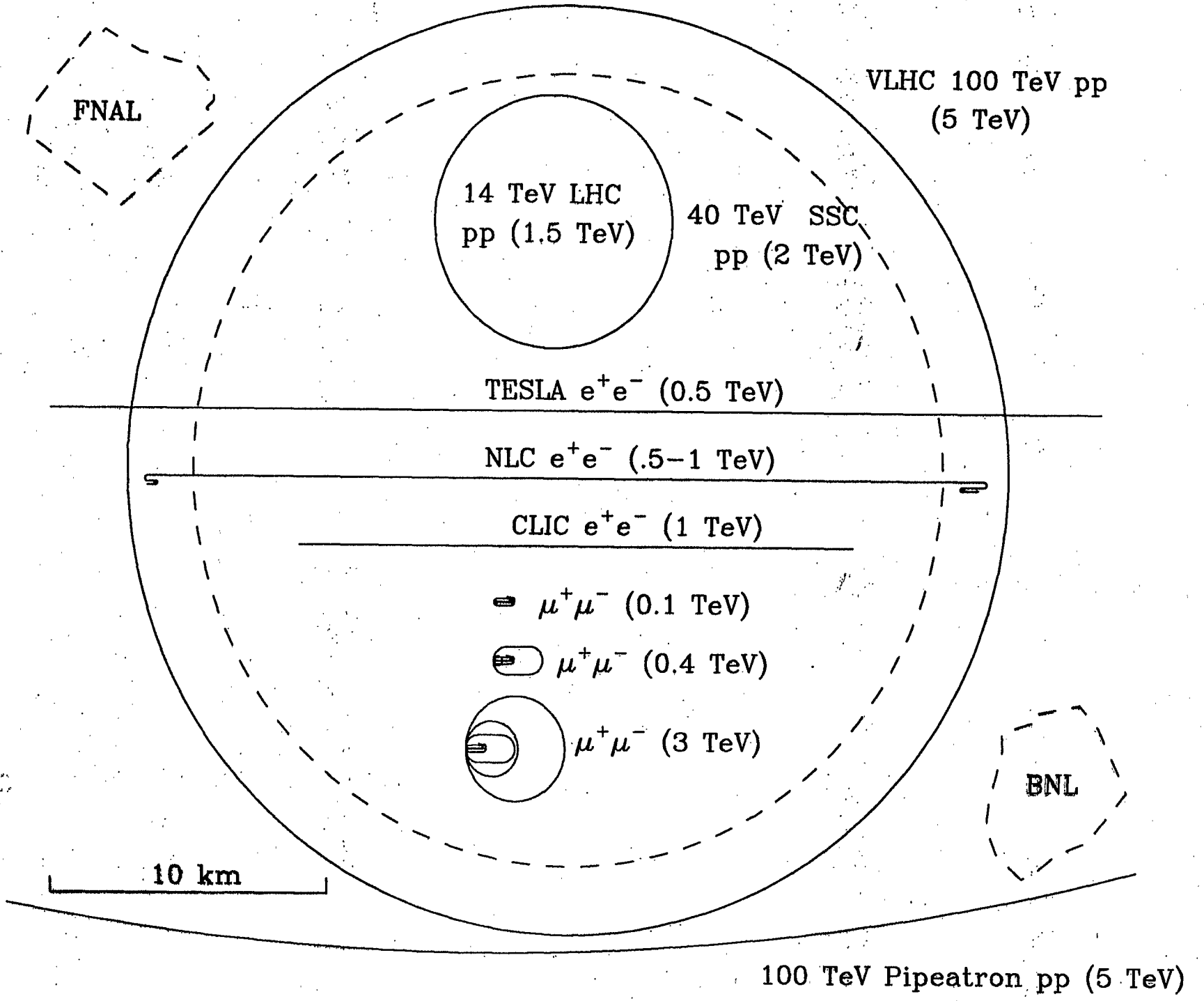
CONCLUSION

MOTIVE

- Small size (e.g. 3 TeV fits at BNL/FNAL)
- Easier Tollerances ?
- Lower \$/TeV ?
- Very low dE/E (e.g. 3 $\times 10^{-5}$)
- Precision E Det ($\approx 10^{-6}$)
- S Coupling to Higgs ($\propto m^2$)
- ν Beams

PROGRESS

- Theory well understood
- Simulations progressing well
- No "Fatal Flaw" found
- Experimental Program Starting


FNAL
VLHC 100 TeV pp
(5 TeV)
14 TeV LHC
pp (1.5 TeV)
40 TeV SSC
pp (2 TeV)
TESLA e^+e^- (0.5 TeV)
NLC e^+e^- (.5–1 TeV)
CLIC e^+e^- (1 TeV)
$\mu^+\mu^-$ (0.1 TeV)
$\mu^+\mu^-$ (0.4 TeV)
$\mu^+\mu^-$ (3 TeV)
BNL
10 km
100 TeV Pipeatron pp (5 TeV)