NEUTRINO FACTORY STUDIES

B&B HEAP
Subpanel 4/19/01

R. B. Palmer

3 Studies:

- **PKJ Example (1998)**
  BNL/CERN Palmer, Johnson, Keil
- **Feasibility Study 1 (2000)**
  FNAL/Collaboration
  Edd. Holtkamp
- **Feasibility Study 2 (2001)**
  BNL/Collaboration
  Edd. Ozaki, Palmer, Zisman

Will not discuss studies at:
CERN RAL or KEK

Basic Parts

in all cases

- A proton Driver
  16-24 GeV, 1-4 MW
- Target in a capture Solenoid
  C or Hg, 20 T field
- Phase Rotation
  $\delta E_{\ \delta t} \rightarrow {}_{\delta E}\ \delta t$
- Cooling
  Hydrogen Absorber
  + RF Acceleration
- Acceleration
  Linac + RLA(s)
- Storage Ring
  Racetrack pointing to Detector
- Detector
  2000-3000 km, 50-200 kT

PJK Example

- BNL/CERN + Collaboration
- Palmer, Johnson, Keil
- Paper at Lyon (1998)

- Good performance
- including polarization

BUT

- 1 ns rms proton bunch ?
- pulsed Hg jet target ?
- 10^{14} ppp on target ?
- RF only 3 m from target ?
- 10^{13} μ's per spill ?

Probably Not Feasible

Feasibility Study 1

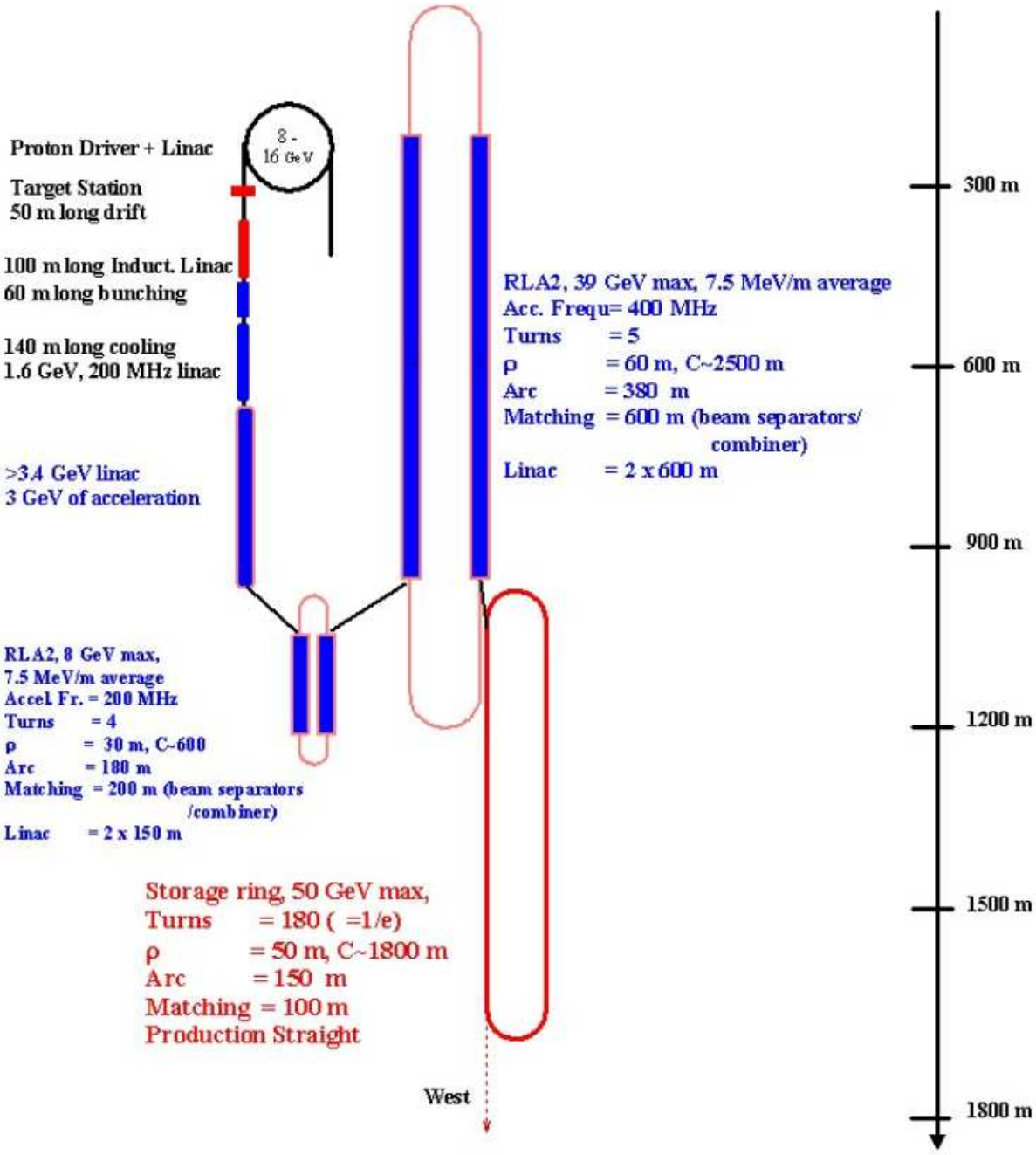
- Commissioned by FNAL Director
- FNAL Site specific (where relevant)
- FNAL + Collaboration
- Edd. Holtkamp (April 2000)

- Emphasize Feasibility
- "Entry Level" Performance

- 3 ns (1) rms proton bunch √
- Solid C Target √
- 1.6 (10) 10^{13} ppp on target √
- RF now 50 (3) m from target √
- 1 (10) 10^{12} μ's per spill √

Feasible, but less performance

Schematic


Proton Driver + Linac
8 - 16 GeV
Target Station
50 m long drift
100 m long Induct. Linac
60 m long bunching
140 m long cooling
1.6 GeV, 200 MHz linac
>3.4 GeV linac
3 GeV of acceleration
RLA2, 8 GeV max,
7.5 MeV/m average
Accel. Fr. = 200 MHz
Turns = 4
ρ = 30 m, C~600
Arc = 180 m
Matching = 200 m (beam separators /combiner)
Linac = 2 x 150 m
RLA2, 39 GeV max, 7.5 MeV/m average
Acc. Frequ= 400 MHz
Turns = 5
ρ = 60 m, C~2500 m
Arc = 380 m
Matching = 600 m (beam separators/ combiner)
Linac = 2 x 600 m
Storage ring, 50 GeV max,
Turns = 180 (=1/e)
ρ = 50 m, C~1800 m
Arc = 150 m
Matching = 100 m
Production Straight
West
300 m
600 m
900 m
1200 m
1500 m
1800 m

Feasibility Study 2

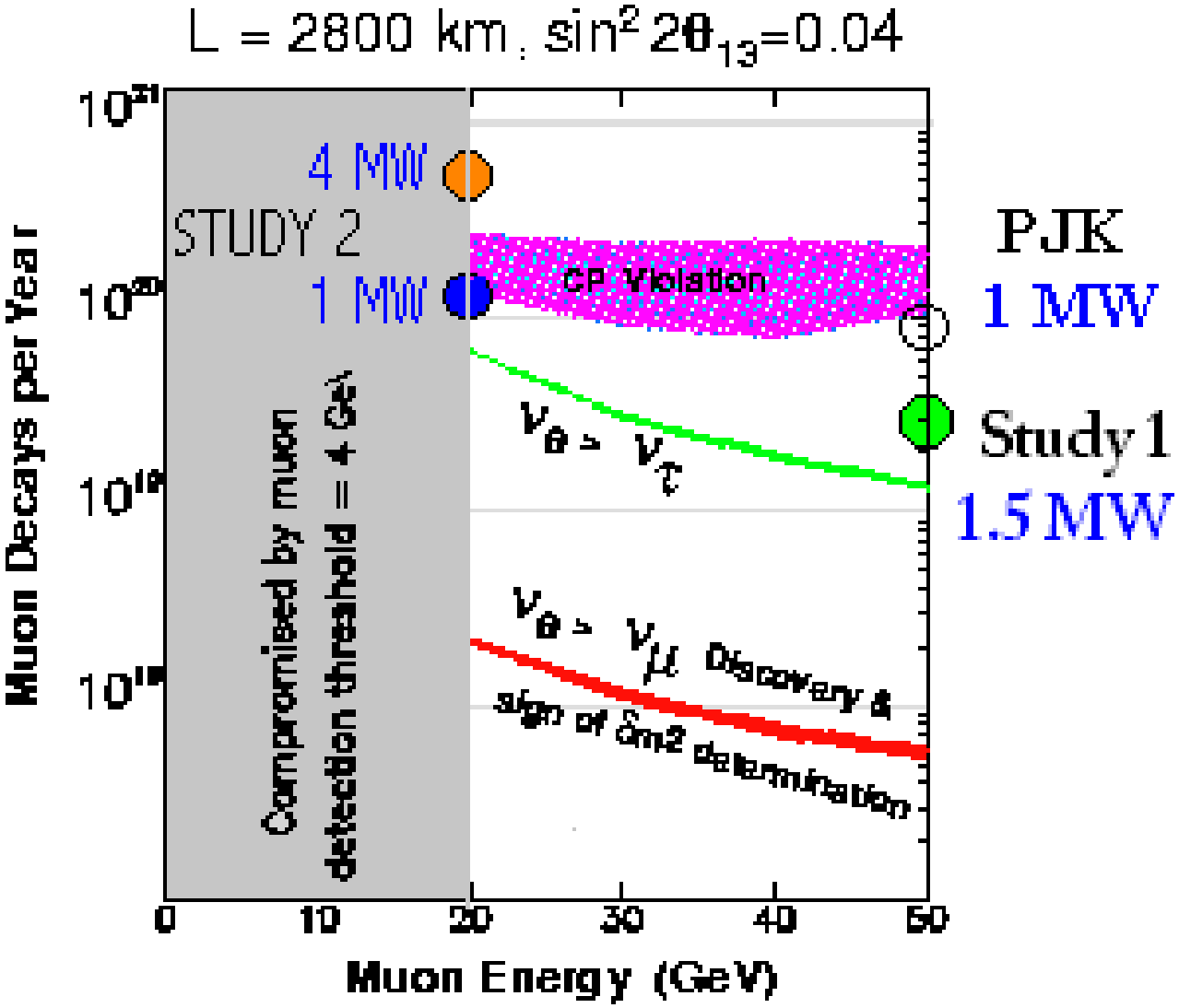
- Commissioned by BNL Director
- BNL Site specific (where relevant)
- BNL + Collaboration
- Edd. Ozaki, Palmer, Zisman
- Closeout May 4 2001

- **Build on Study 1**
- **Maintain Feasibility**
- **Raise Performance**

- **3 ns (3) rms proton bunch** √
- **Continuous Hg Jet** √
- **1.6 (1.6)** 10^{13} **ppp on target** √
- **RF 38 (50) m from target** √
- **3 (1)** 10^{12} μ**'s per spill** √

Feasible, and 6 $\times$ μ**/p**

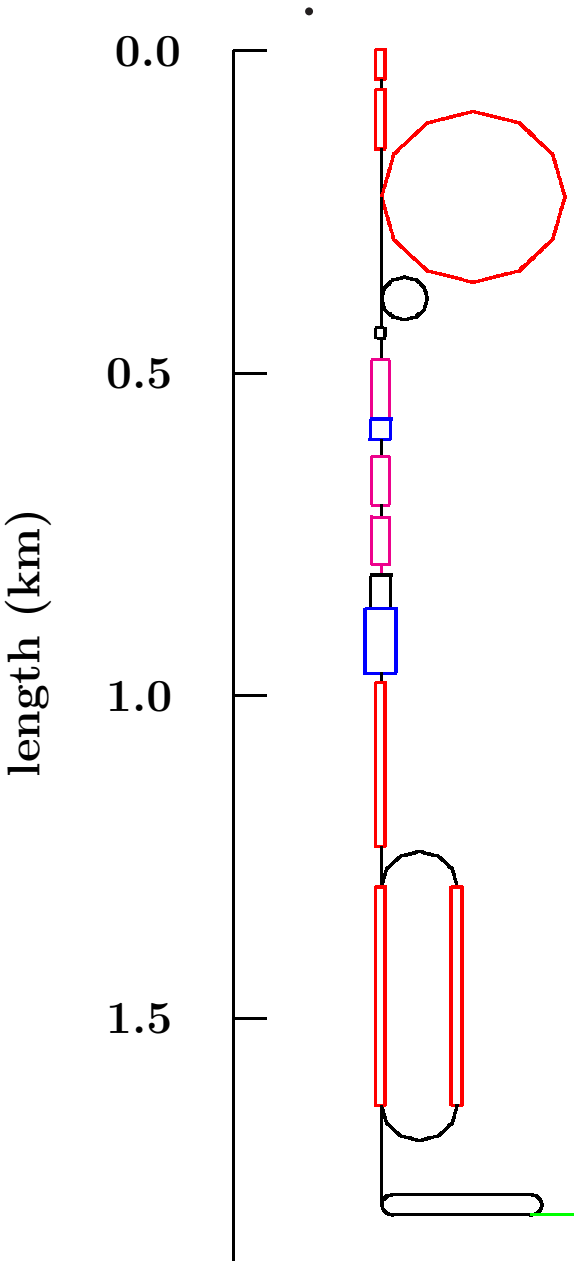
Physics Reach



- 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

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)
Neutrino Beam	($\approx$ 15 GeV)

Study 1 Proton driver

- Upgraded Linac
- New 16 GeV Booster

	PRESENT	(ν-FACTORY) PHASE I	UPGRADE PHASE II
Linac (operating at 15 Hz)			
Kinetic energy (MeV)	400	400	1000
Peak current (mA)	40	60	80
Pulse length (μs)	25	80	200
H^- per pulse	6.3×10^{12}	3×10^{13}	1×10^{14}
Average beam current (μA)	15	72	240
Beam power (kW)	6	29	240
Pre-booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)			3
Protons per bunch			2.5×10^{13}
Number of bunches			4
Total number of protons			1×10^{14}
Norm. transverse emittance (mm-mrad)			200π
Longitudinal emittance (eV-s)			2
RF frequency (MHz)			7.5
Average beam current (μA)			240
Beam power (kW)			720
Booster (operating at 15 Hz)			
Extraction kinetic energy (GeV)	8	16	16
Protons per bunch	6×10^{10}	7.5×10^{12}	2.5×10^{13}
Number of bunches	84	4	4
Total number of protons	5×10^{12}	3×10^{13}	1×10^{14}
Norm. transverse emittance (mm-mrad)	15π	60π	200π
Longitudinal emittance (eV-s)	0.1	2	2
RF frequency (MHz)	53	1.7	7.5
Extracted bunch length σ_b (ns)	0.2	3	1
Average beam current (μA)	12	72	240
Target beam power (kW)	100	1200	4000

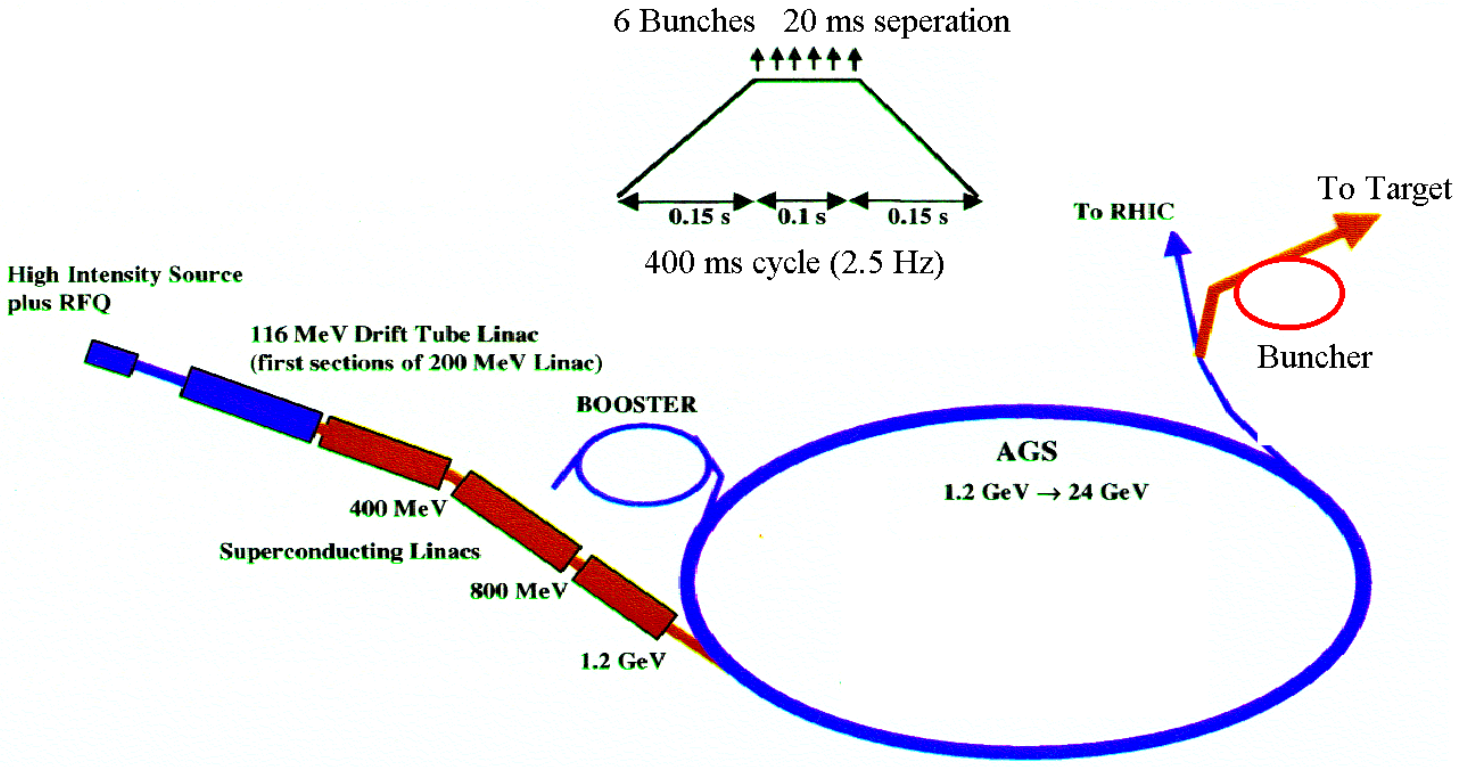
Table 1: Proton Driver Parameters of Present, Phase I and Phase II.

New Pre-Booster only for 4 MW

Study 2 Proton driver

- Present First Linac
- New (SNS like) SC Linac
- Upgraded AGS (.5 → 2.5 Hz)
- New Bunch Compressor

- 1 MW → 4 MW
- 6 single bunch extractions



Study 1 Target & Capture

Carbon Target

- Radiation Cooled
- Replace every 3 months (1.5 MW)
- Replacement time 6 days

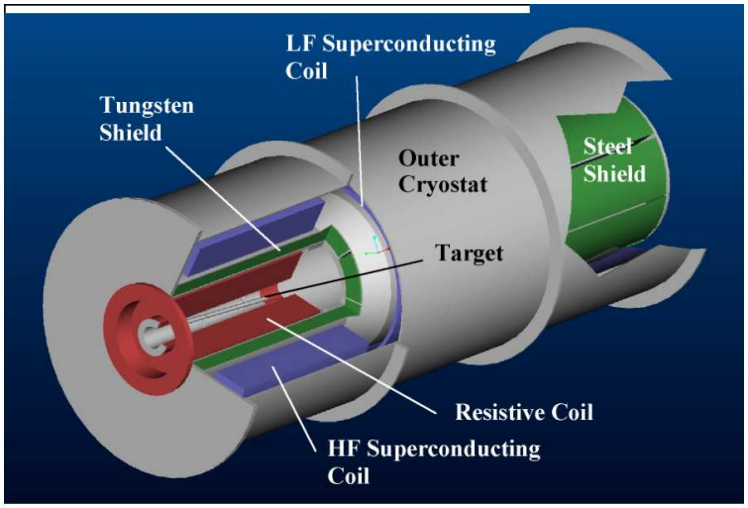


Figure 6. Cutaway view of the high-field solenoid, target, and shielding in the cryostat module.

20 T Capture Solenoid

- Bitter Magnet Insert
  - Replace every 6 months
  - replacement time 7 days
- Superconducting outsert

Enclosure: Study 1 or 2

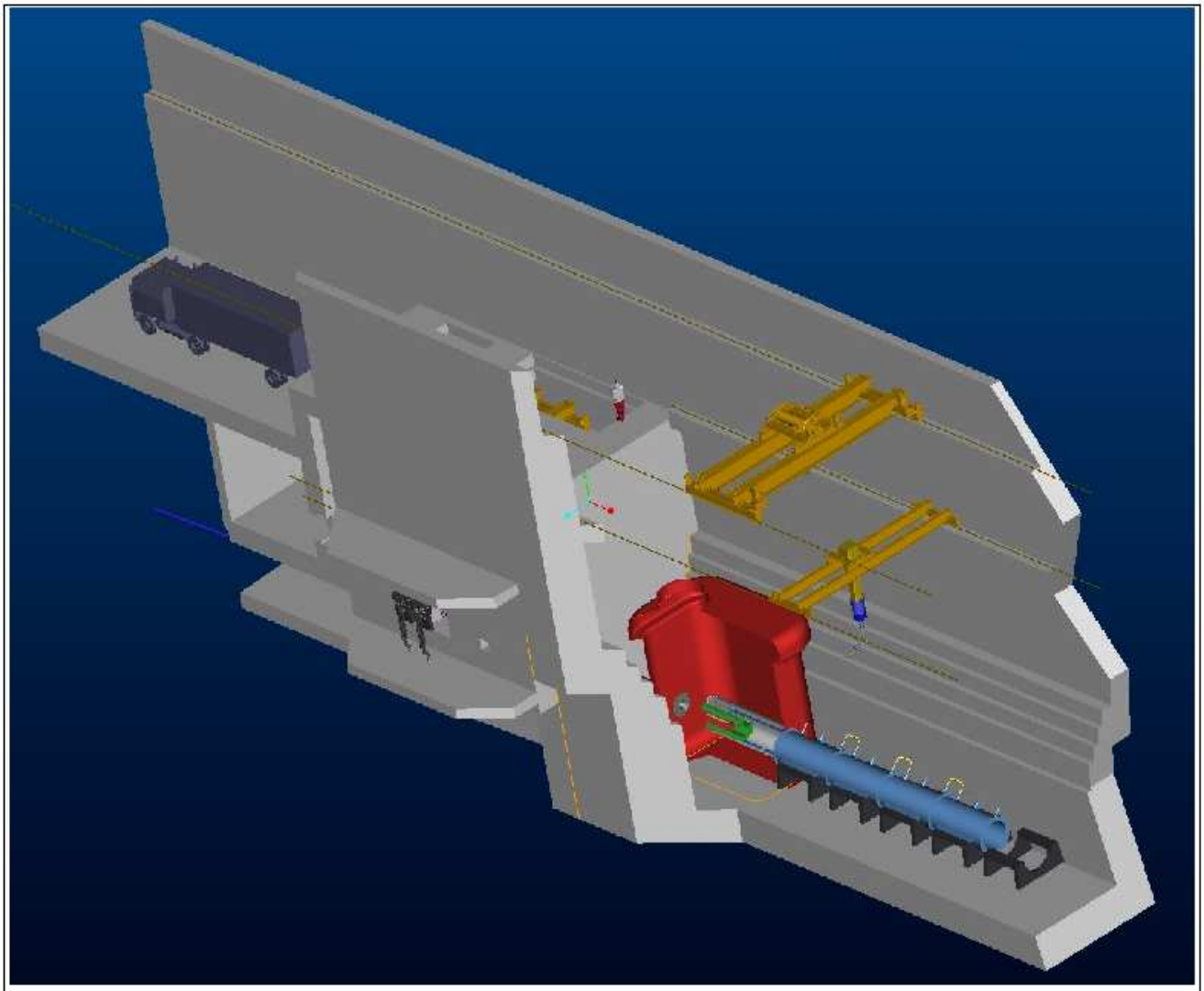
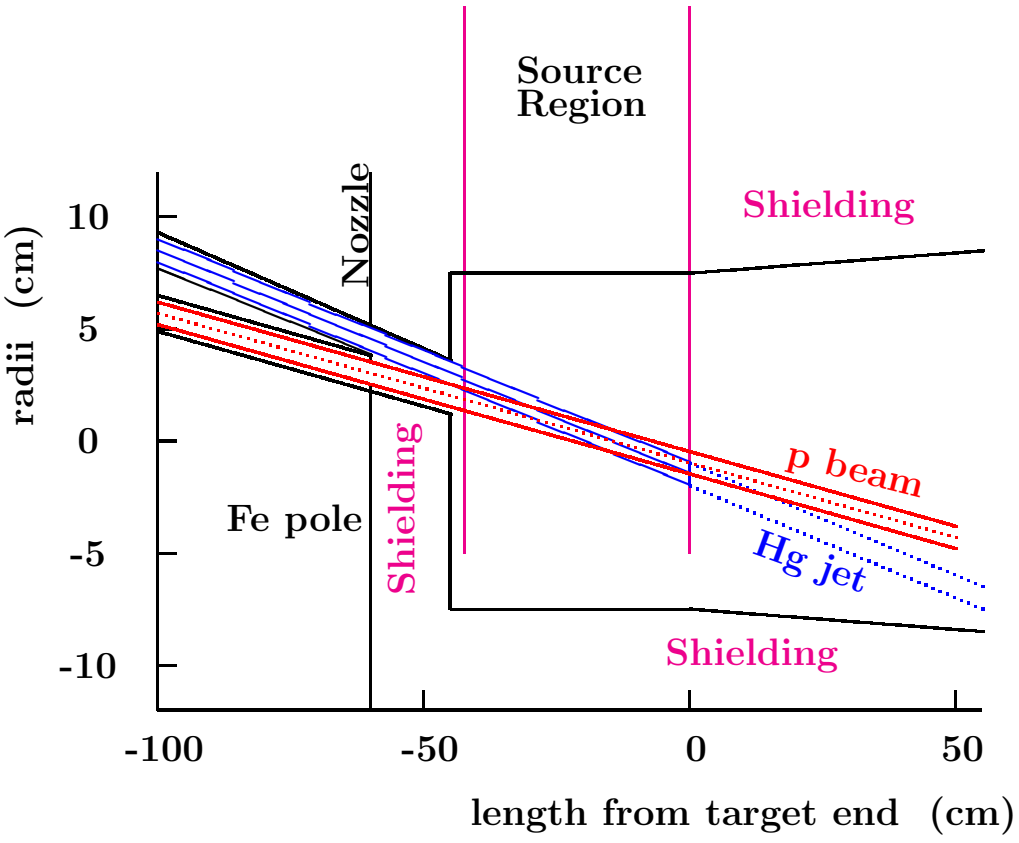


Figure 5. Overview of the Target Support Facility.

Study 2 Target & Capture

Mercury jet Target

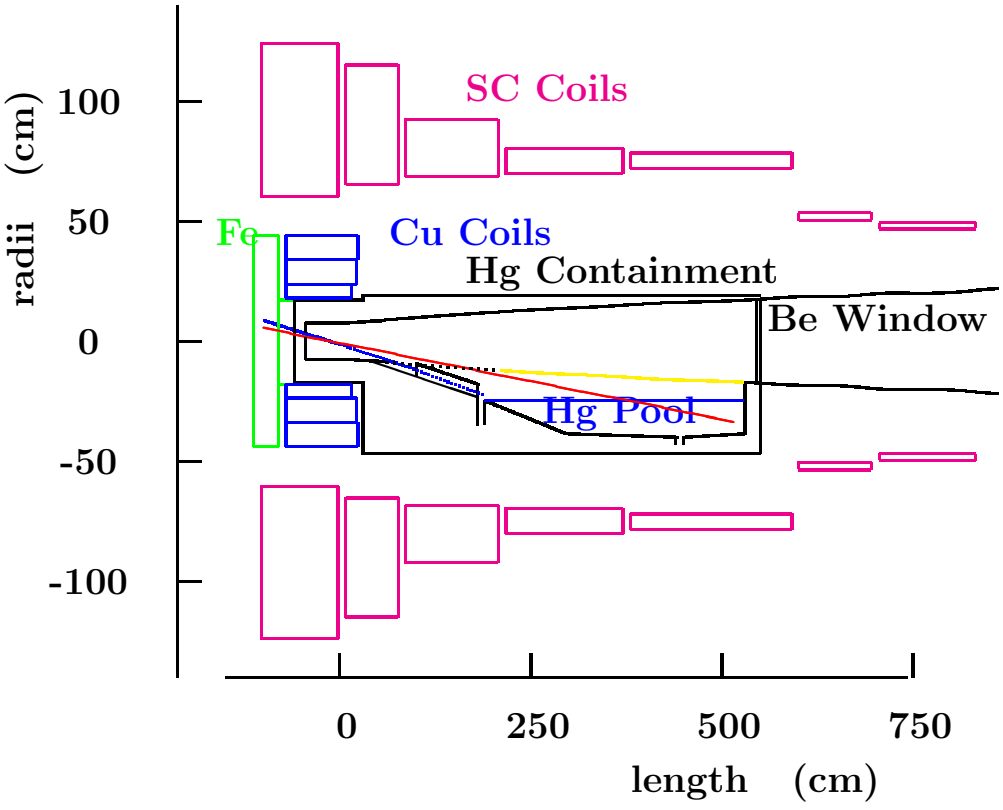
- $\approx 2 \times$ Carbon
- Continuous jet
- Nozzle inside field
- OK to 4 MW ?



Capture Solenoid & Dump

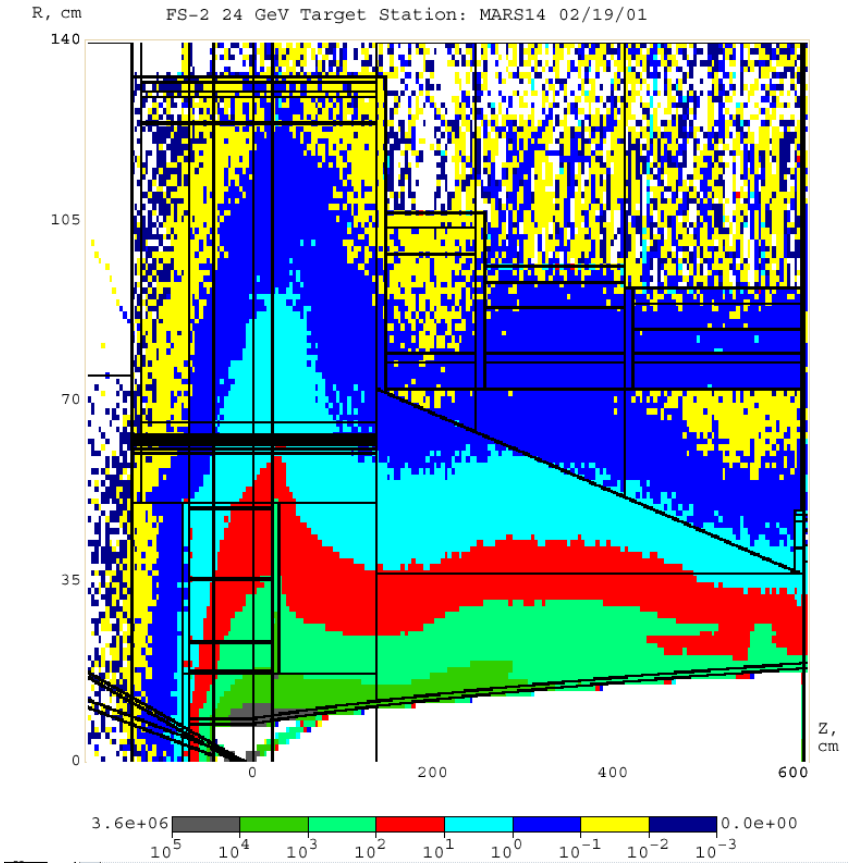
- 20 T hybrid magnet
  - Hollow Conductor Insert
    - More expensive, but long life
  - Superconducting Outsert

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



Study 2 Radiation Levels

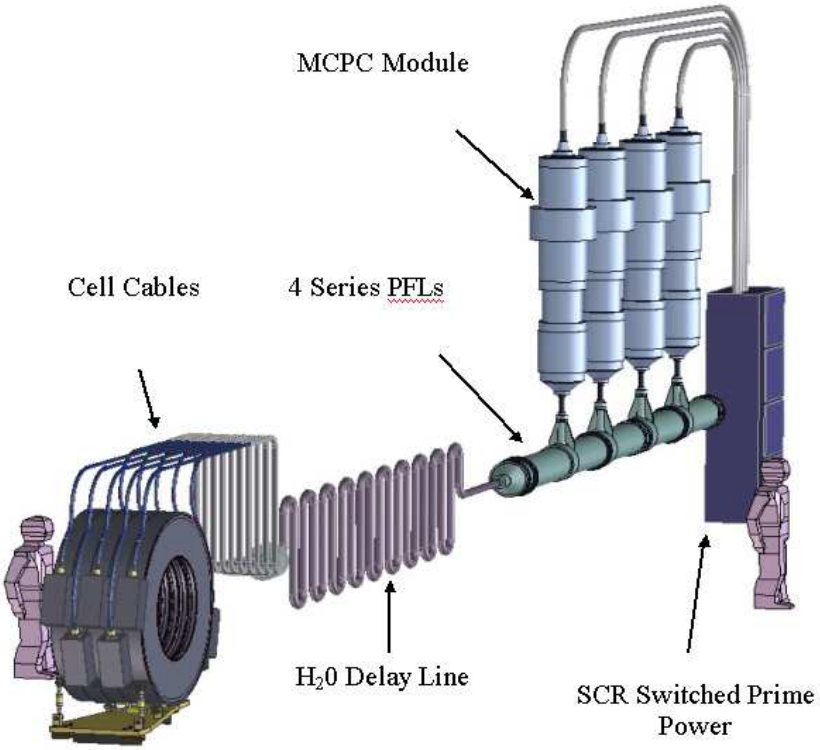
from Mokhov



Component	1MW Life years	4 MW life years
Inner Shielding (SS)	40	10
Containment (SS)	500	125
Hollow Conductor (SS)	200	50
Superconducting Coil	100	25

Study 1 Phase Rotation

- 50 m drift
- Single 100 m Induction Linac
- 4 bi-polar pulses in train



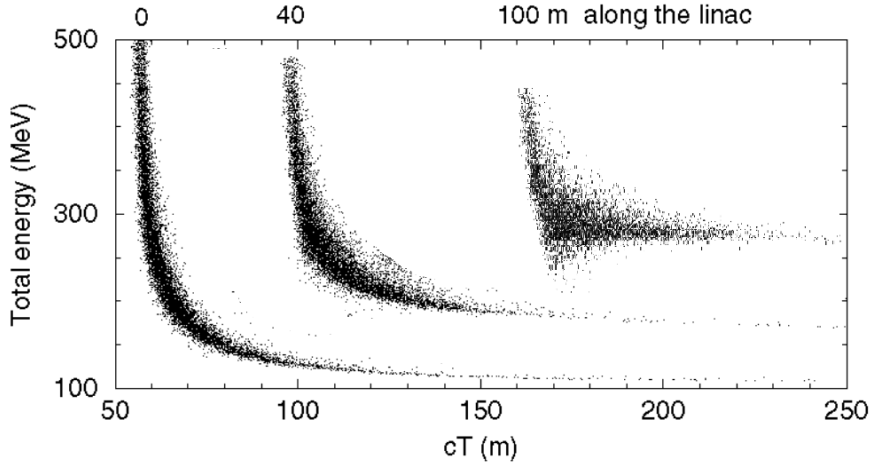
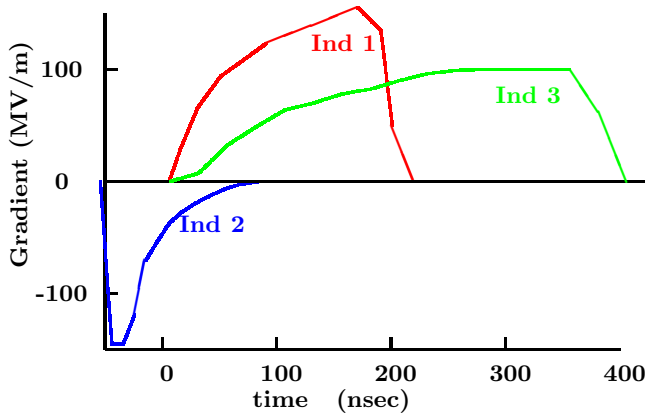


Figure 6: Beam distributions in E-cT phase space along the induction linac. Distributions from L = 0, 20, 60, and 100 m are shown.

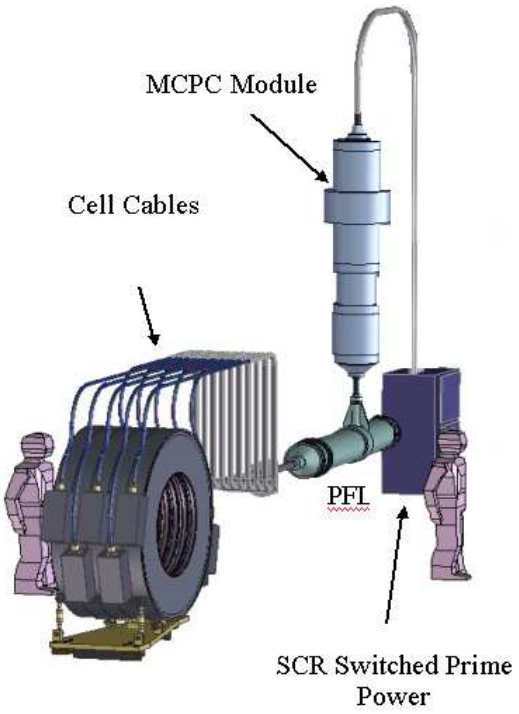
Study 2 Phase Rotation

- Non-distorting
- 3 Unipolar Units
- total length 260 m (c.f. 100)
- Single pulses (c.f. 4)

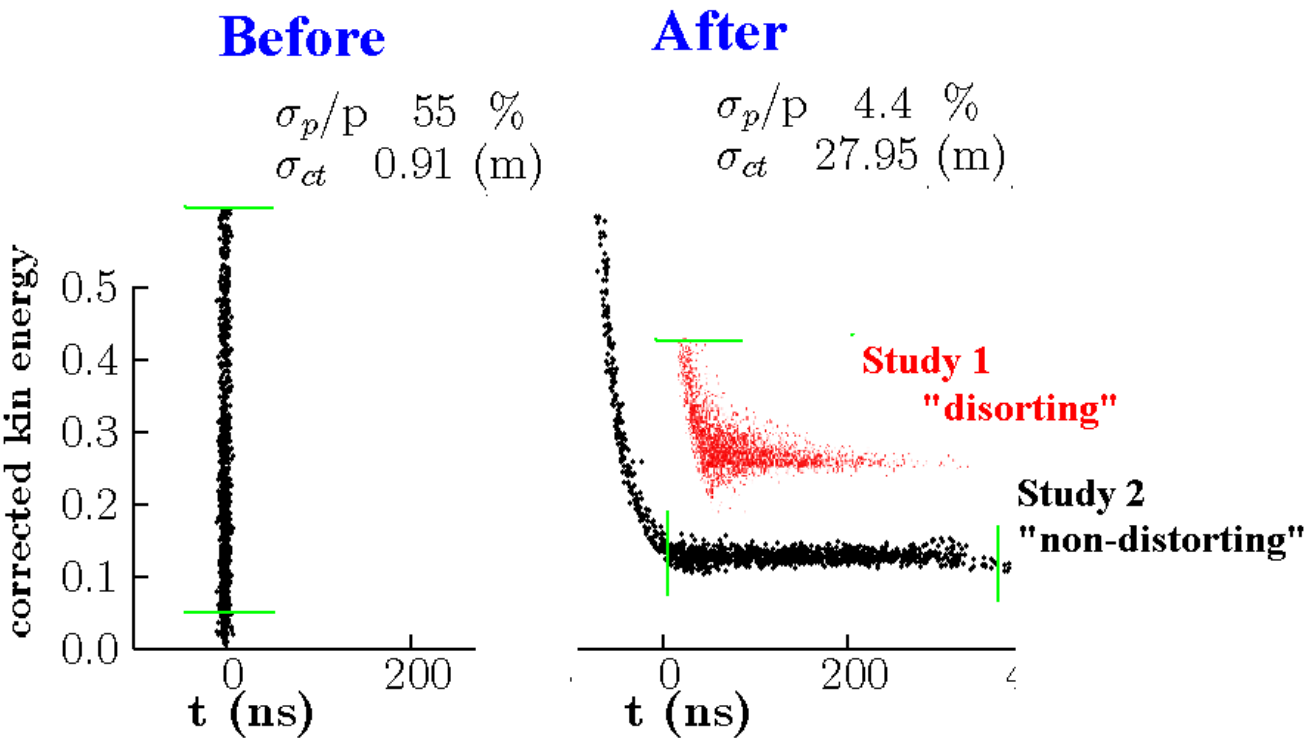


2m Section

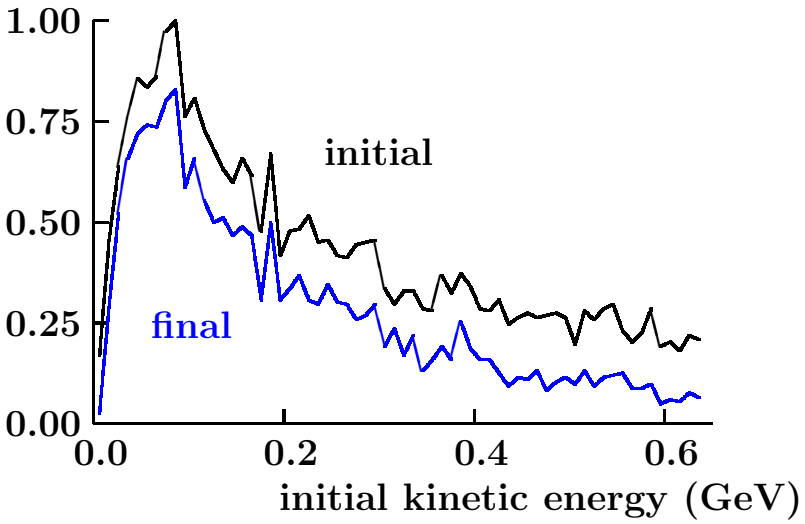
95 cm radius
similar to
ATA or DARHT
but
Superconducting
inside coil



Performance



From target to phase rotation:



Study 2 Buncher

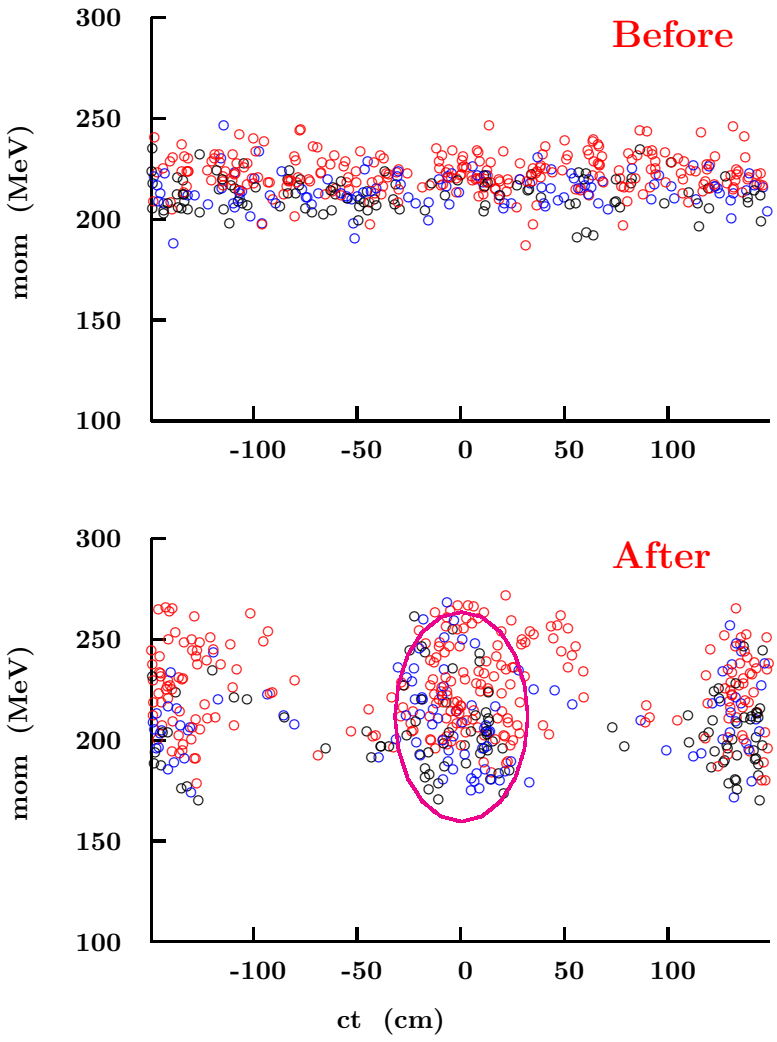
Three stages:

1: Low field 200 MHz rf + 400 MHz harmonic

2. Med. field 200 MHz rf + 400 MHz harmonic

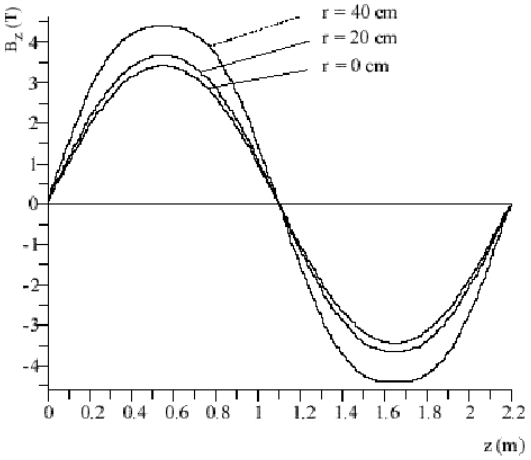
3. Higher field 200 MHz rf

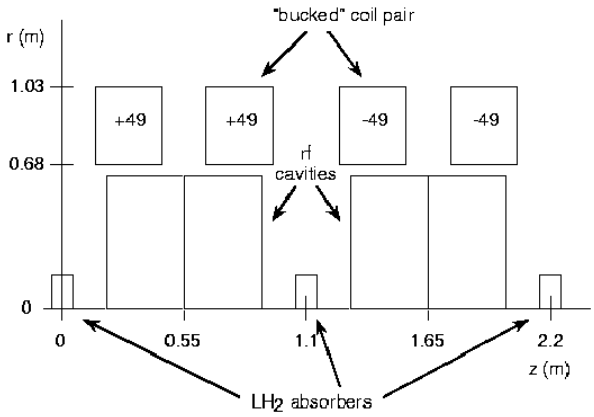
Similar to Study 1

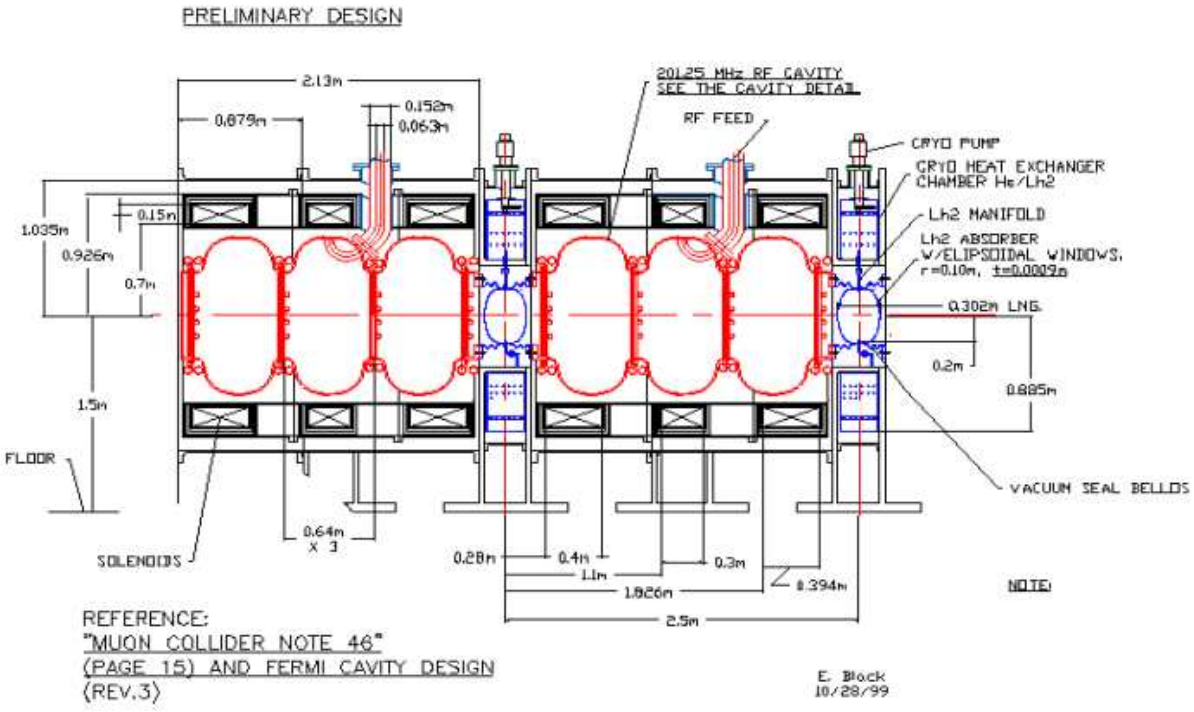


Study 1 Cooling

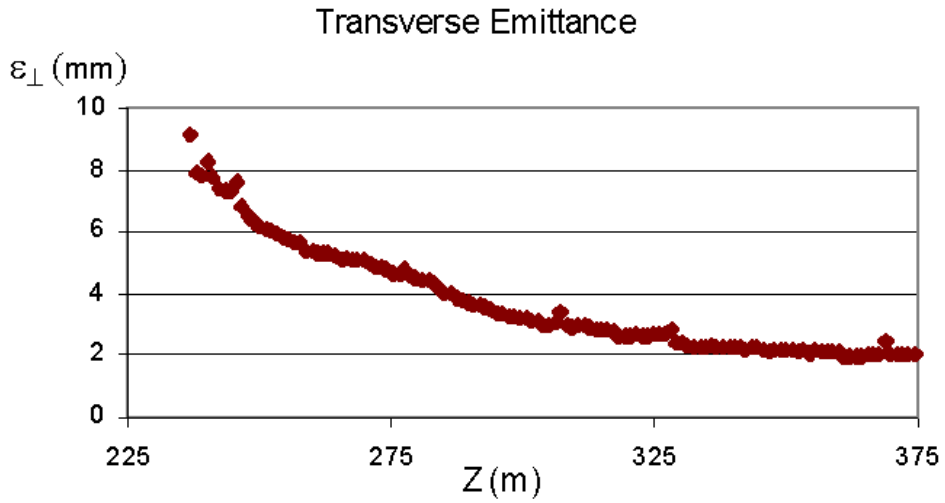
- 120 m long
- focus-focus (FOFO) Lattice
- 15 Mv/m 201 MHz RF
- Hydrogen absorbers

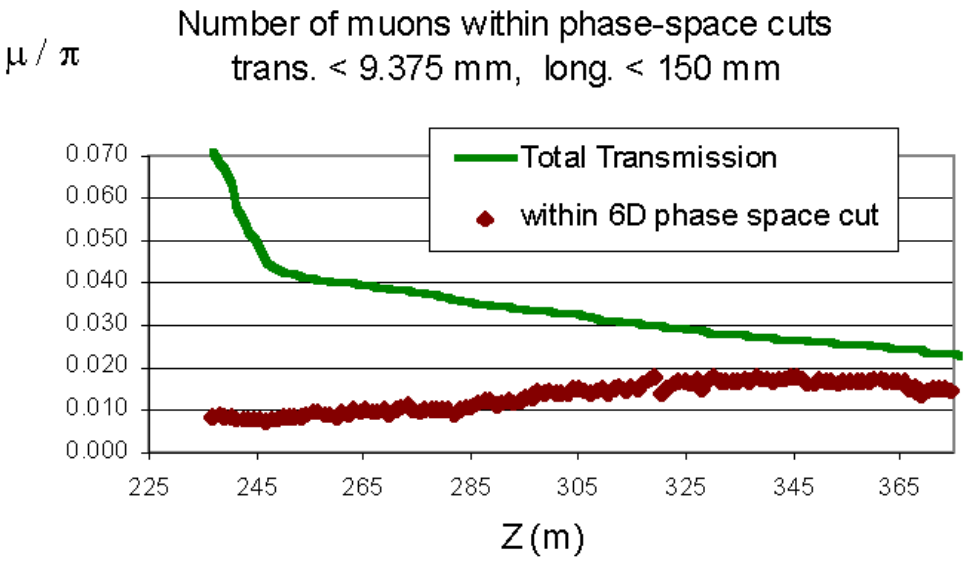






Performance

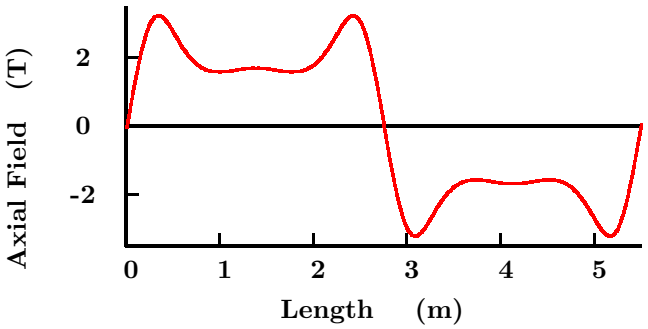


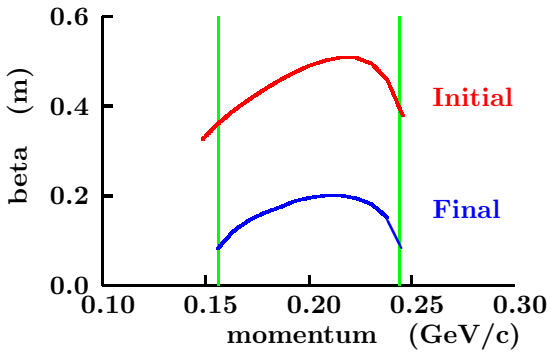


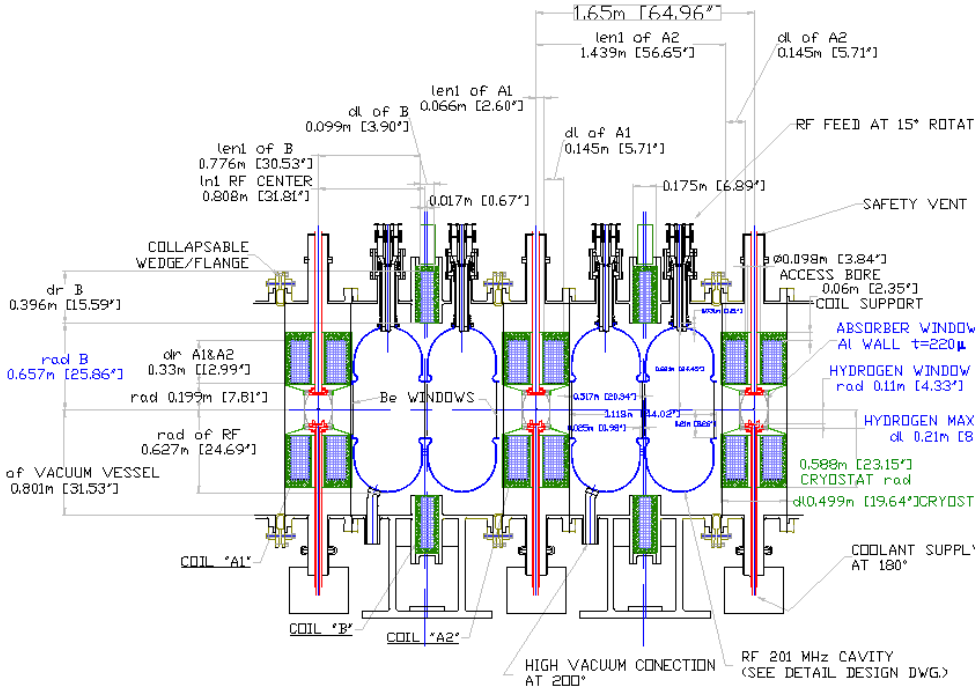
- Gain Factor = 2.0
- Loss from growth of long emit.
- Need Longitudinal Cooling

Study 2 Cooling

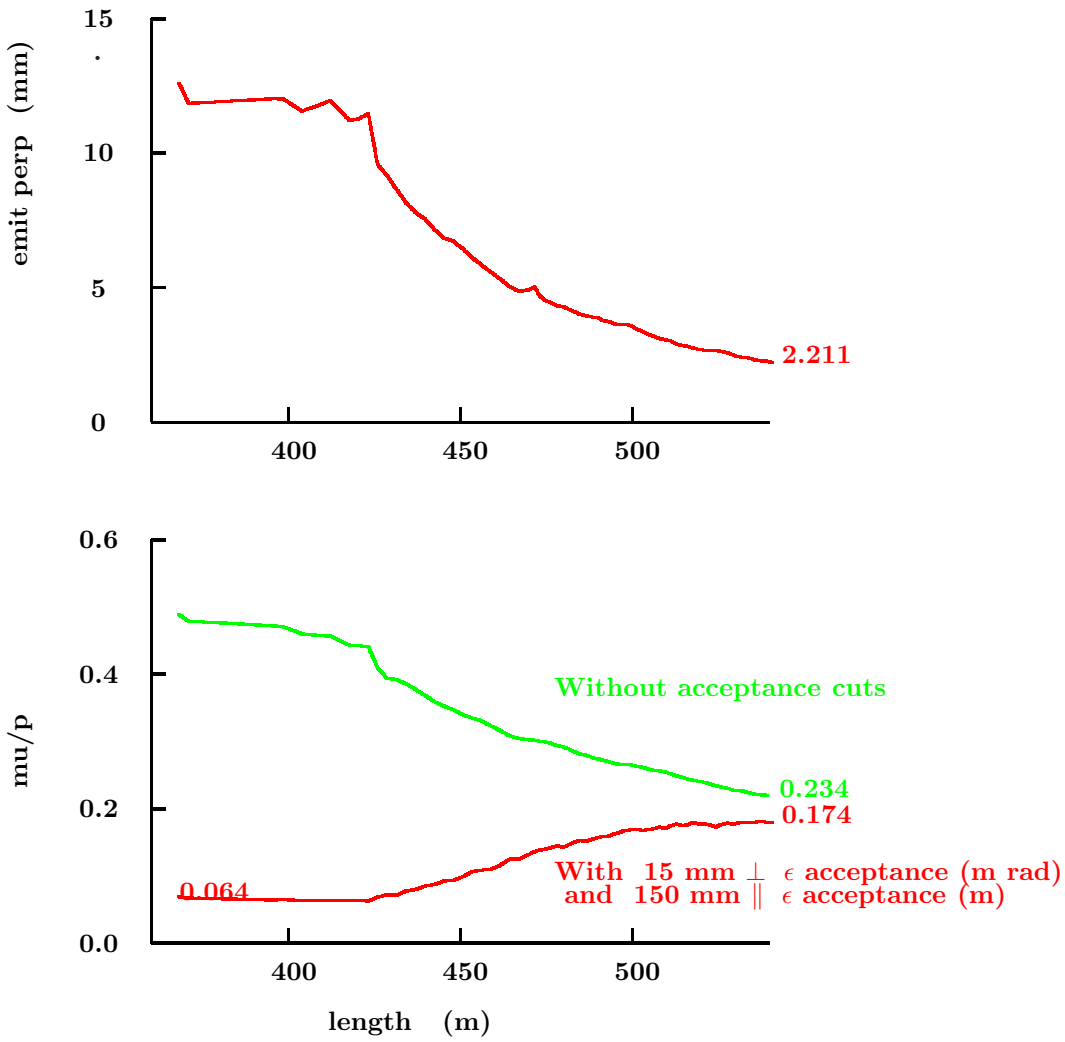
- 110 m long
- 16 MV/m RF
- Super FOFO Lattice
  - Stronger focus
  - Lower fields
  - smaller Stored E ($\approx 1/5$)







Cooling Performance



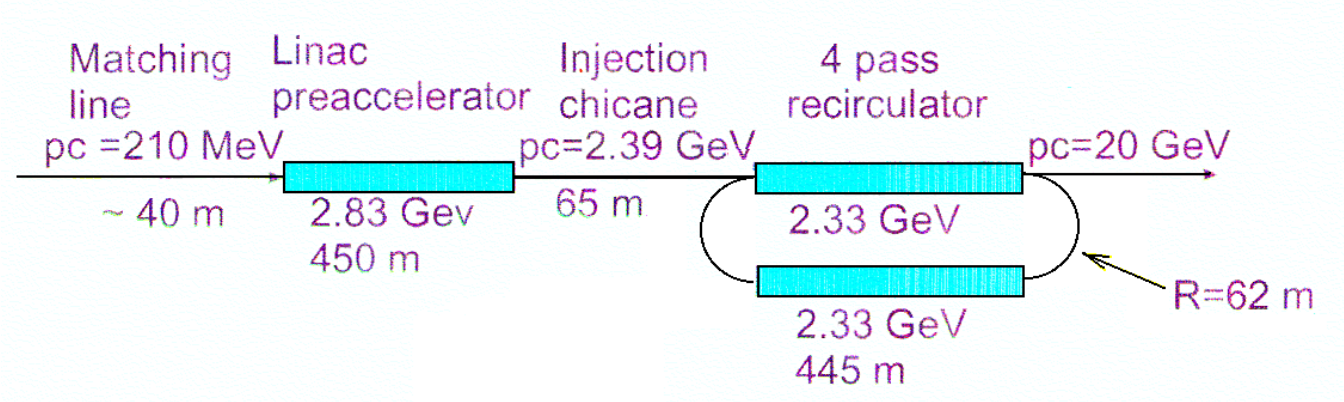
- Gain Factor = 3
- Loss from growth of long emit.
- Need Longitudinal Cooling

Acceleration

Lebedev

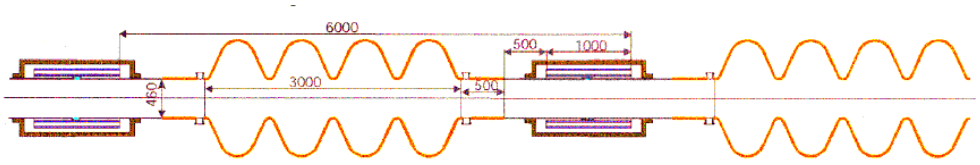
Study 1: 50 GeV (Linac + 2 RLA's)

Study 2: 20 GeV (Linac + 1 RLA)

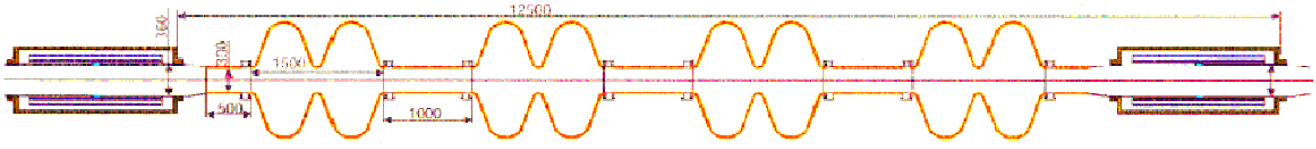


Superconducting Cavities (200 MHz)

Cornell



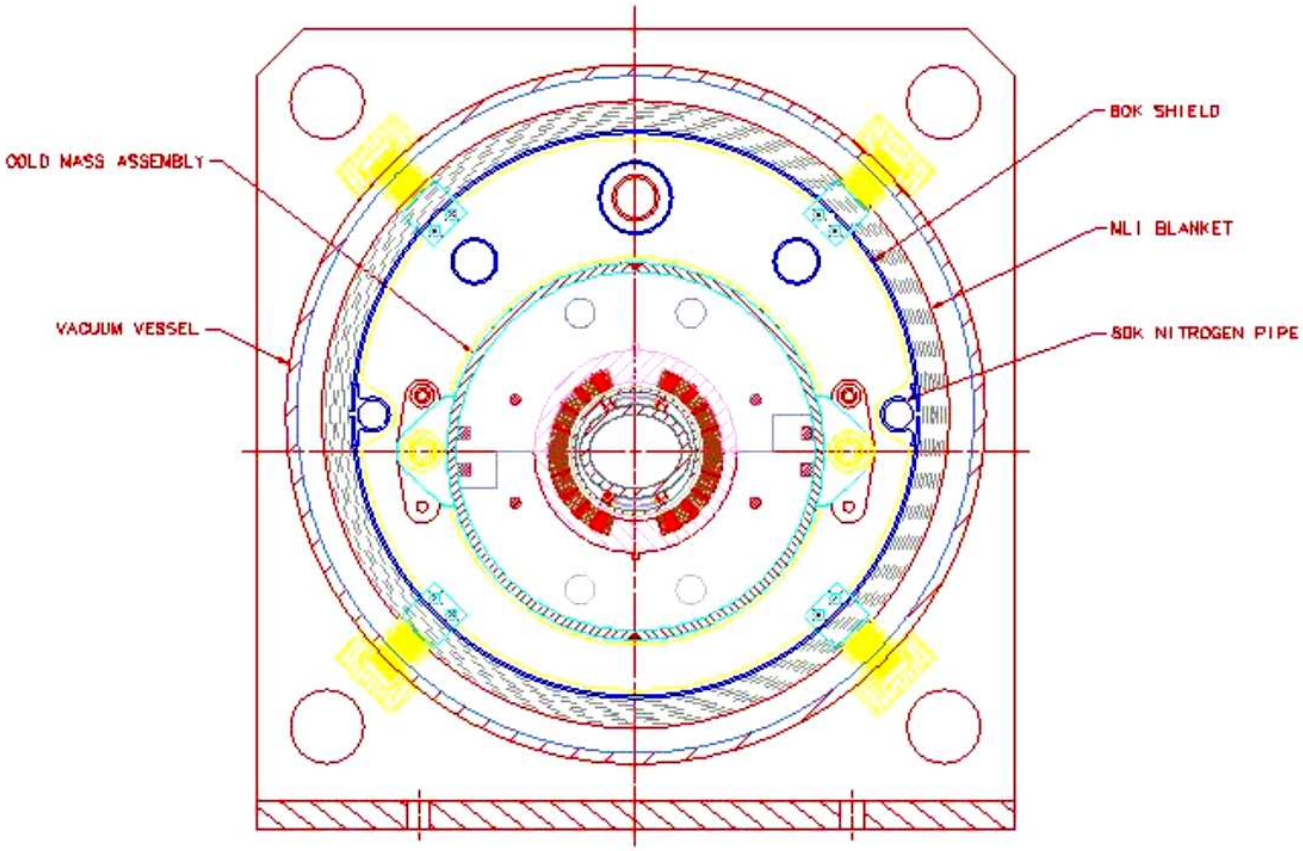
Short cryomodule layout



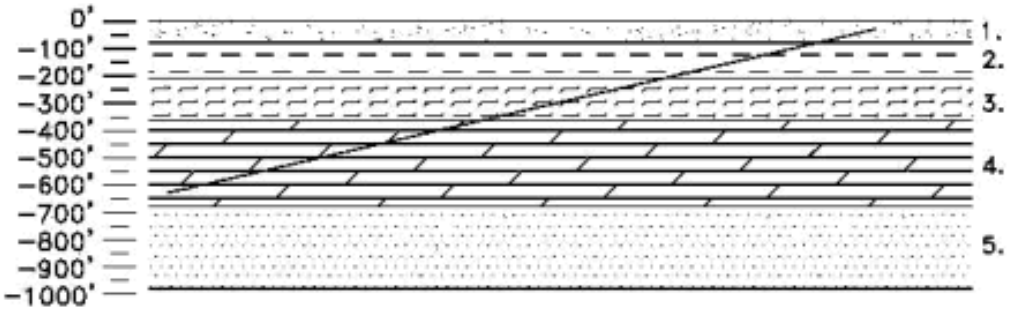
Long cryomodule layout.

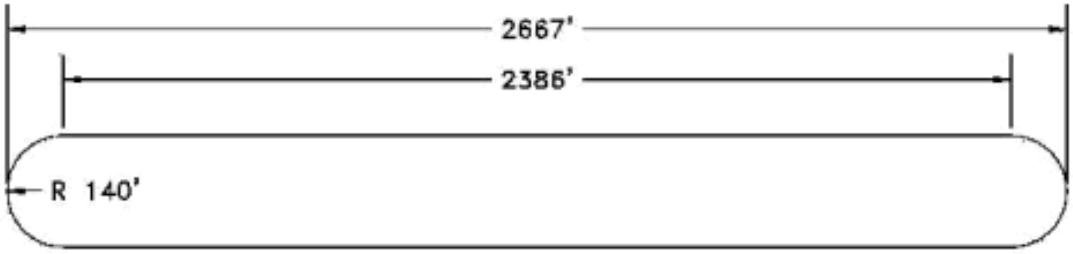
Study 1 Storage Ring

- Conventional FODO Lattice
- Cosine Theta Magnets
- 20 kW (14 W/m) decay electrons
- Warm shield inside



Ring Layout

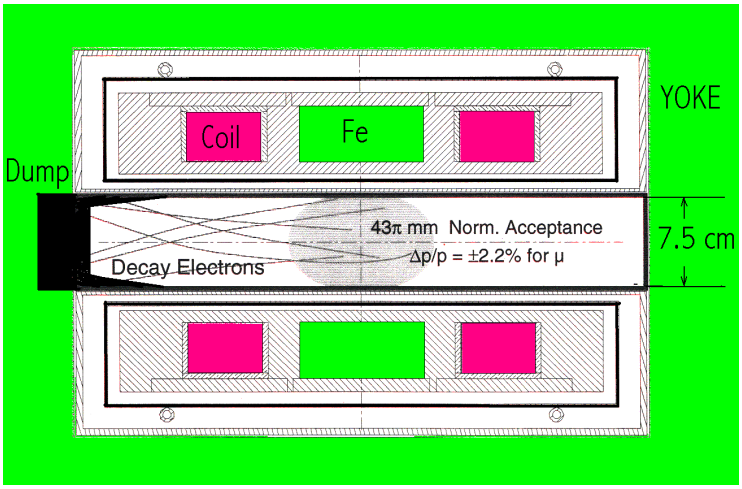


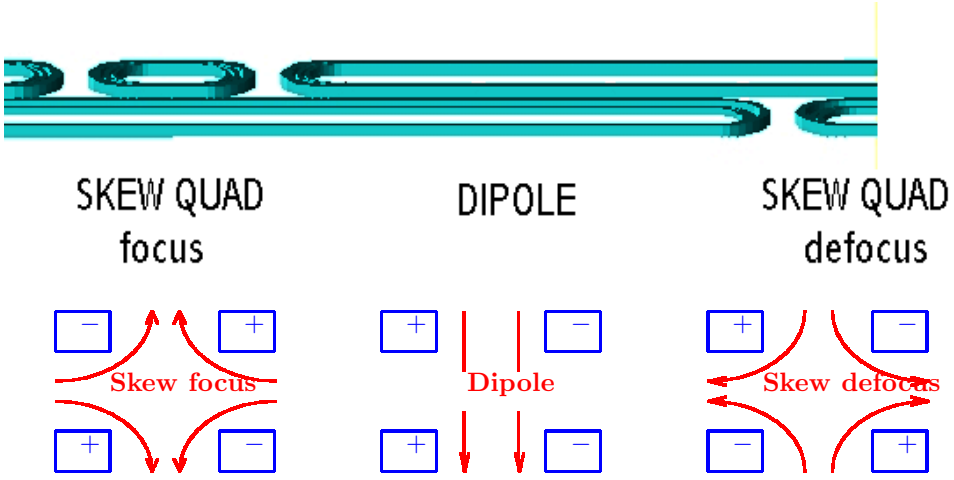


CE 2.1 LATTICE PLAN

Study 2 Storage Ring

- High Field (to maximize useful straight/circumference)
- 30 kW (100 W/m) Decay electrons
- Strong focus (large emittance & dp/p)
- Good longitudinal packing factor



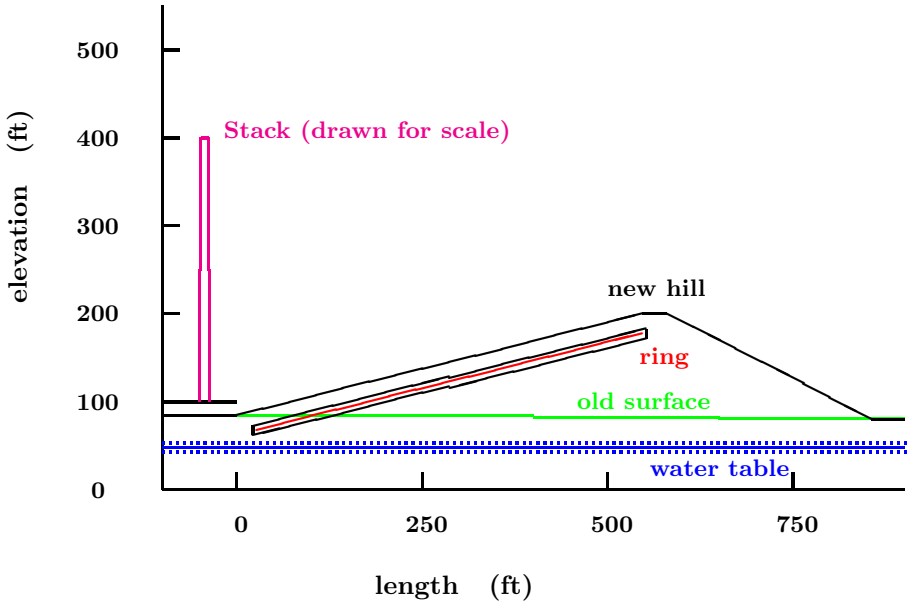


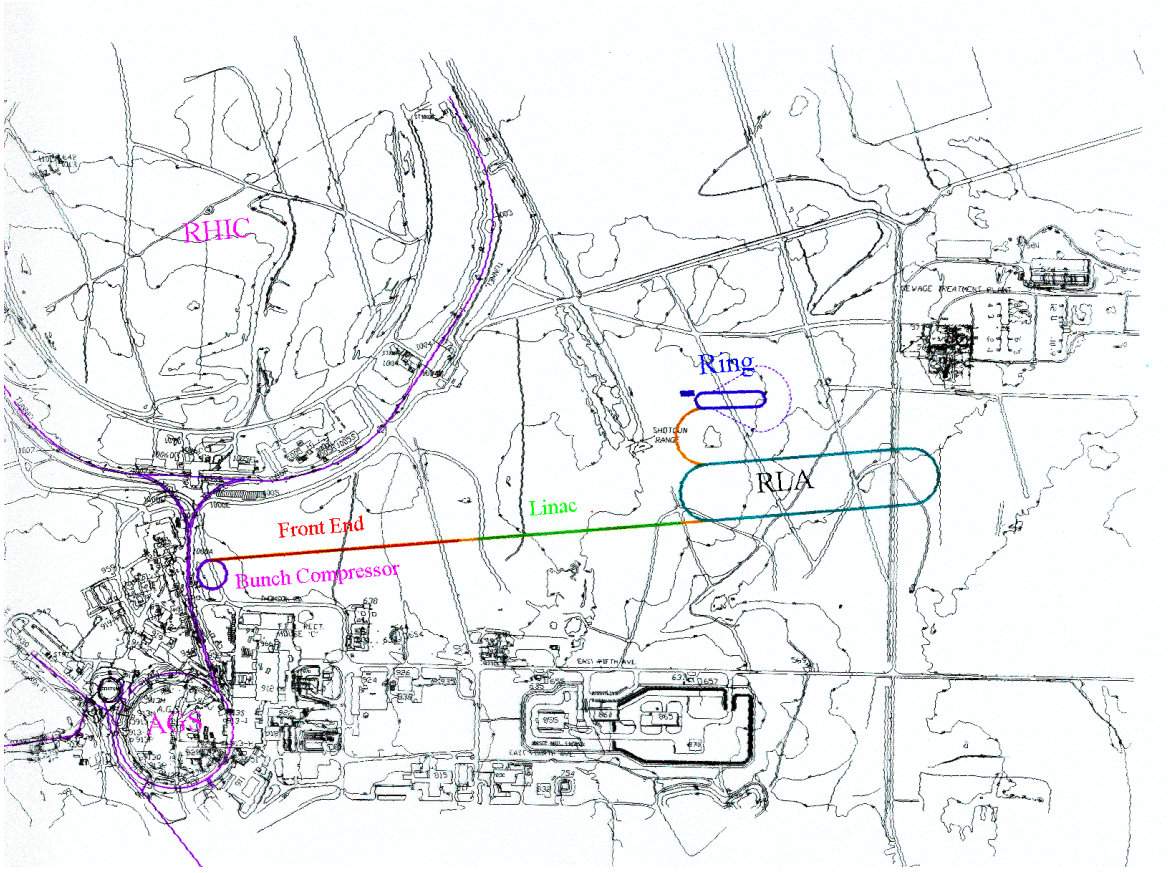
Also:

Alternative Conventional Lattice

Ring Layout

To Carlsbad	2903	km
Dip angle	13.1	deg
straight	116	m
circ	332	m
decay/circ	35	%
hill	35	m
vol	300	m^3
To Homestake	2528	km
Dip angle	11.4	deg
straight	138	m
circ	376	m
decay/circ	37	%
hill	35	m
vol	350	m^3





Front-End Performance

	p energy GeV	μ/p	μ/p/GeV %/GeV
Study 1	16	0.018	.11
Study 2	24	0.17	.71

Total efficiency gain = 6.6 $\times$

- No change per MW from 24 vs 16 GeV
- From use of the mercury: 1.9 $\times$
- From phase rotation $\approx$ 2 $\times$
- From cooling design: $\approx$ 1.4 $\times$
- From larger acceptance: 1.2 $\times$

Possible μ/p Improvements

- Bunch Beam Phase Rotation (both signs)
- Longitudinal Cooling ($\approx$ 2 $\times$)
  (Emittance exchange)

Conclusions

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- Two Feasible Neutrino Factories have been studied
- Either could be built at either Fermilab or BNL
- Study 2 has
  6 $\times$ efficiency of study 1
- further improvements possible

- Need more Study
- Need component development:
  - Target
  - Cooling
  - Acceleration
- Next 3 talks