# The Muon Storage Ring Design

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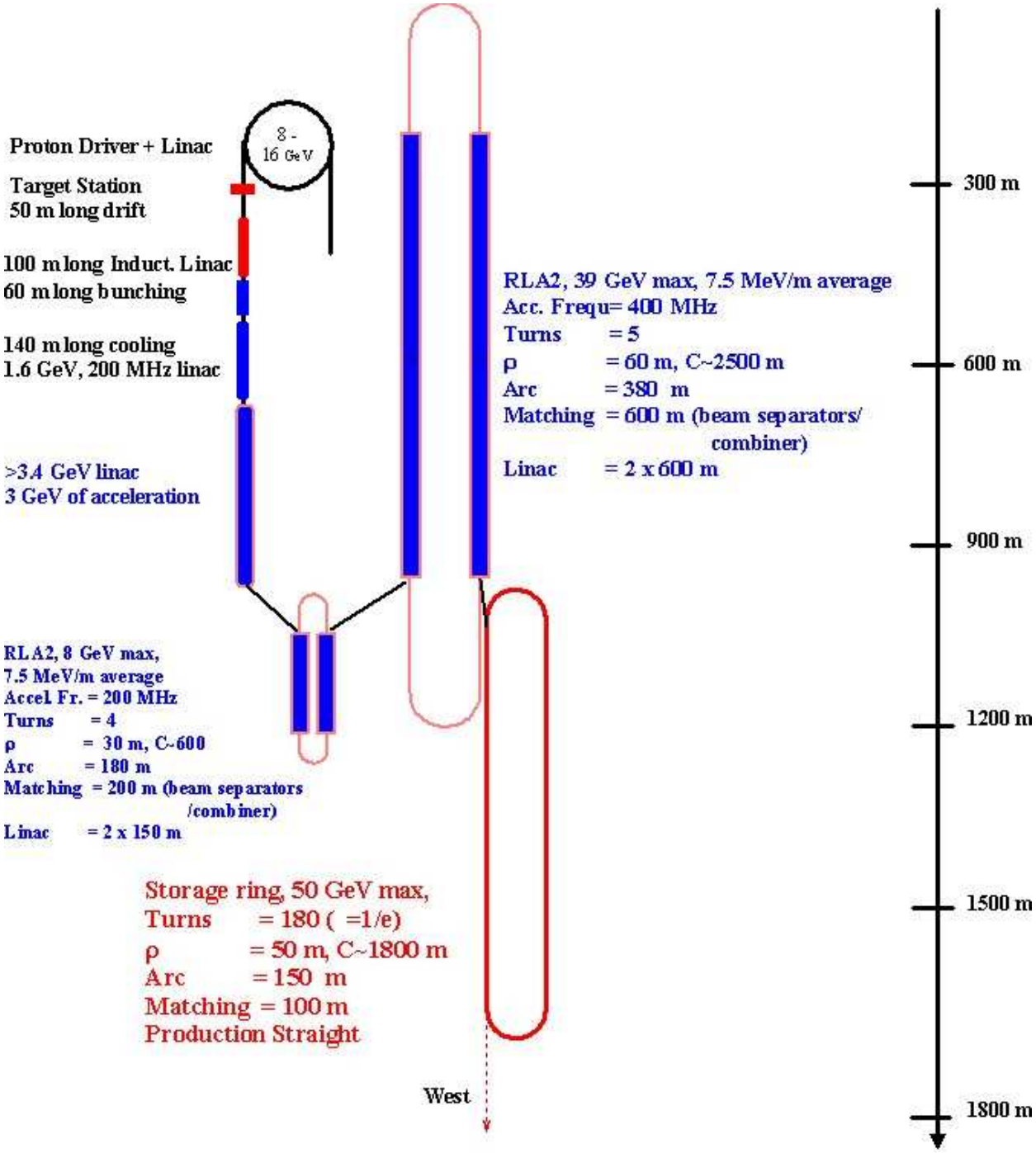
- Introduction
- Basic Parameters
- Tracking and Beam Stability
- Polarization
- Technical Feasibility
- Cost
- Further Work

# Footprint for a 50 GeV Neutrino Source

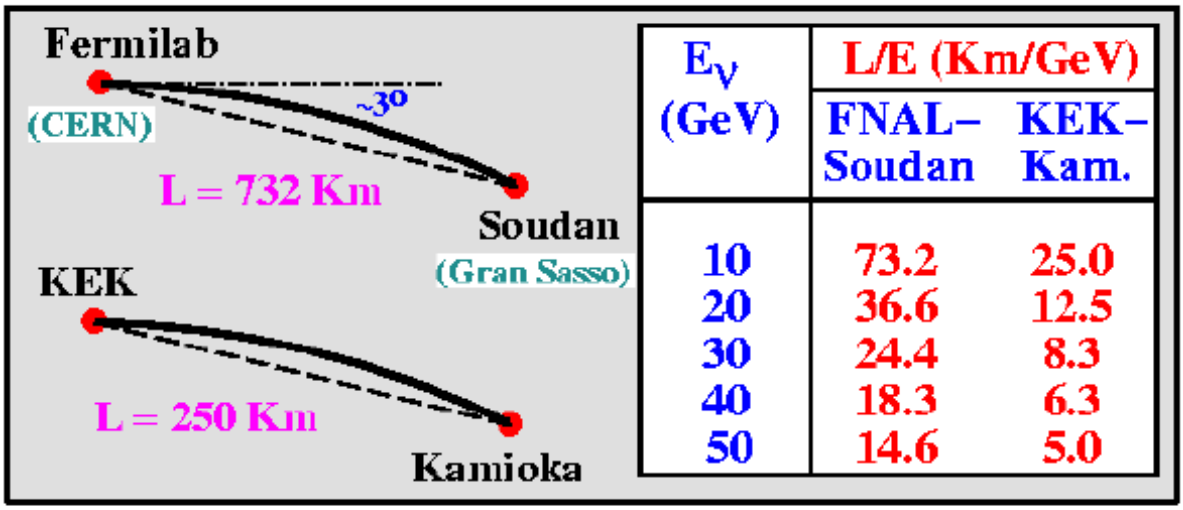
- $\Rightarrow$ Direction of P beam on target defines layout
- Ring is not largest facility and comparatively conventional
- Racetrack "requires" injection into downward straight



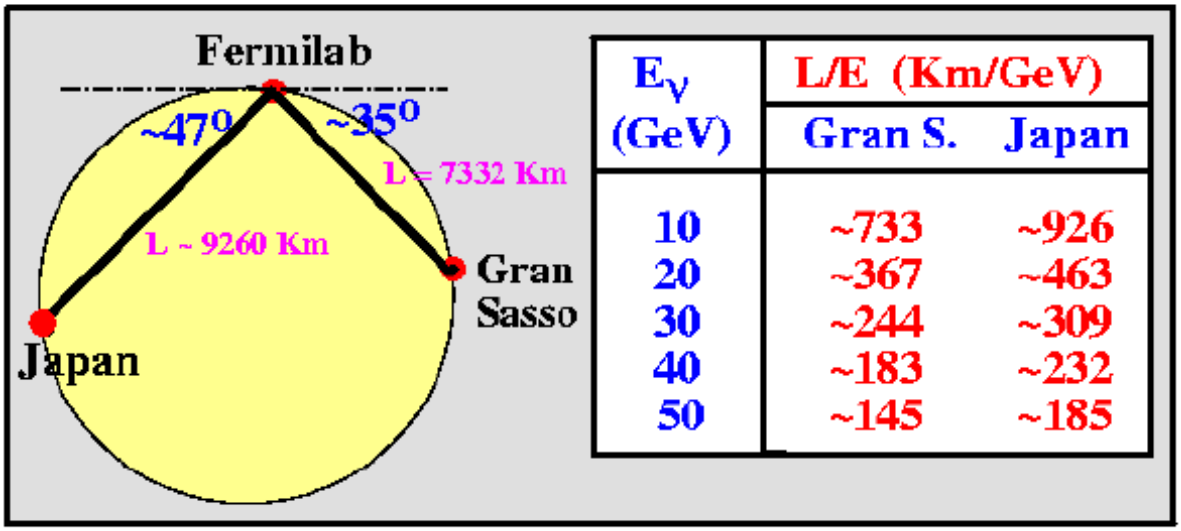
# The Energy Choice, the Experiment and the Options

- Choice of baseline beam line angle are connected

| | L (km) | Dip (Deg.) | Heading (Deg.) |
|---|---|---|---|
| FNAL –> Soudan | 732 | 3 | 336 |
| FNAL –> Gran Sasso | 7332 | 35 | 50 |
| FNAL –> Kamioka | 9263 | 47 | 325 |

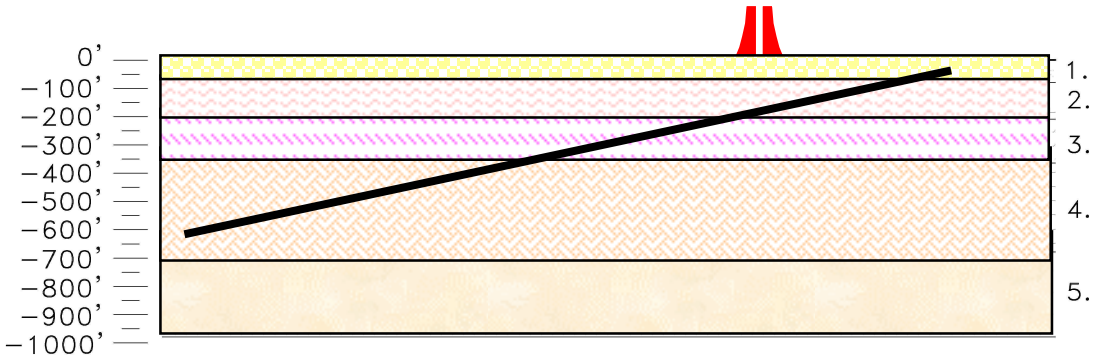



| $E_\nu$ (GeV) | L/E (Km/GeV) FNAL–Soudan | L/E (Km/GeV) KEK–Kam. |
|---|---|---|
| 10 | 73.2 | 25.0 |
| 20 | 36.6 | 12.5 |
| 30 | 24.4 | 8.3 |
| 40 | 18.3 | 6.3 |
| 50 | 14.6 | 5.0 |



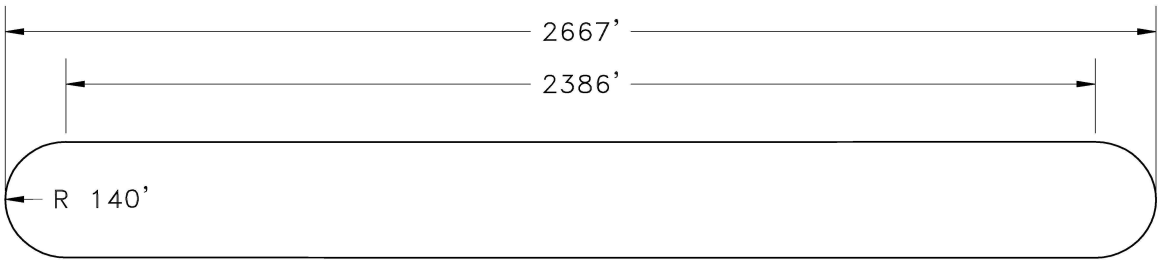

| $E_\nu$ (GeV) | L/E (Km/GeV) Gran S. | L/E (Km/GeV) Japan |
|---|---|---|
| 10 | ~733 | ~926 |
| 20 | ~367 | ~463 |
| 30 | ~244 | ~309 |
| 40 | ~183 | ~232 |
| 50 | ~145 | ~185 |

# What is Site Specific ?




**GEOLOGY DETAIL**
1"=100'-0"

1. GLACIAL TILL – AQUIFER
2. SILURIAN GROUP – AQUIFER (PRIMARILY DOLOMITE)
3. MAQUOKETA GROUP – AQUIFER (PRIMARILY SHALE)
4. GALENA / PLATTEVILLE GROUP – AQUATARD (PRIMARILY DOLOMITE)
5. ANCEL GROUP – AQUIFER (PRIMARILY SANDSTONE)




**CE 2.1 LATTICE PLAN**
N.T.S.

**ORIENTATION:**

| NAME | AZIMUTH (DEG–MIN–SEC) | VERT. ANGLE (DEG–MIN–SEC) |
|---|---|---|
| PALO ALTO CA. | 271–20'–42.27" | –13–09'–26.99" |

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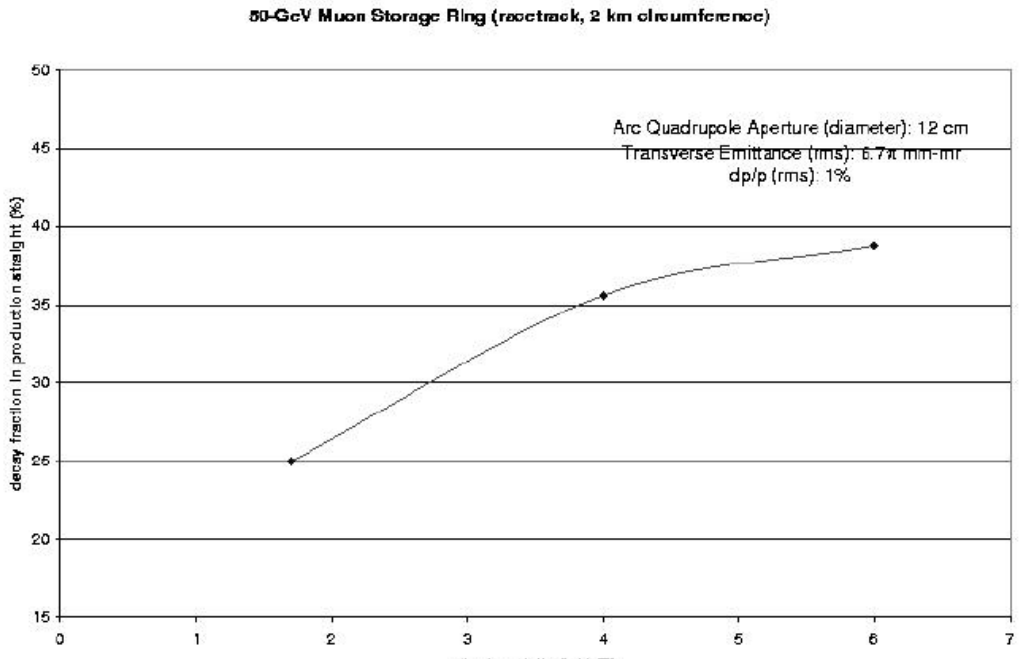
# Optimization of the Storage Ring

- The cheapest way to produce neutrinos is to make the straight section as long as possible !

$$\eta = \frac{\text{Nr of } \mu \text{ decaying in straight section}}{\text{Nr of } \mu \text{ injected}}$$

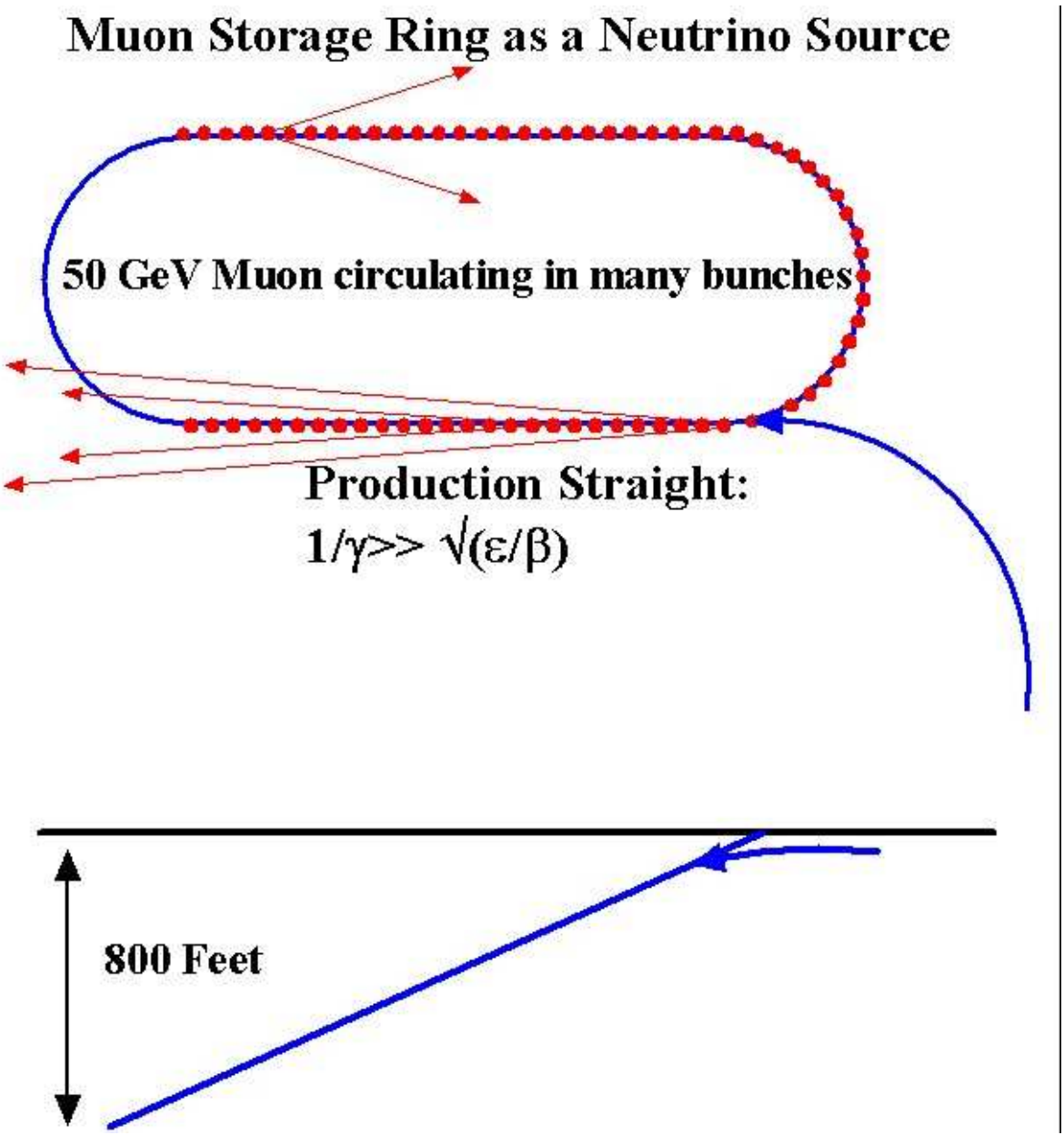
L=length of straight $\qquad \eta = \frac{1}{2\,(1+\pi\,\rho\,/L)} = \frac{1}{2\,(1+0.2)}$




B / Tesla

# Conceptual Layout of the Muon Storage Ring

- Circumference larger than bunch train:
  - Easy injection (long rise, short fall time of kicker)
- Injection into downward straight:
  - Injection line is natural ⇒ very close to the surface

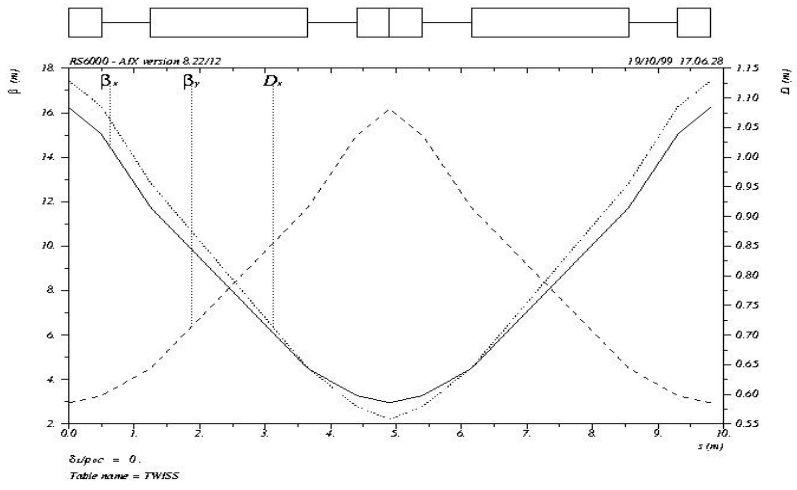


# Storage Ring Parameters

| Parameters for the Muon Storage Ring | | |
|---|---|---|
| Energy | GeV | 50 |
| decay ratio | % | 38 |
| Designed for inv. Emittance | m*rad | **0.0032** |
| Cooling designed for inv. Emitt. | m*rad | **0.0016** |
| Momentum Acceptance | % (rms) | 1 |
| β in straight | m | ~400 |
| $N_\mu$/pulse | $10^{12}$ | ~2 |
| typical decay angle of μ = 1/γ | mrad | 2.0 |
| Beam angle ($\sqrt{\varepsilon}/\beta_o$) = ($\sqrt{\varepsilon}\,\gamma_\beta$ ) | mrad | 0.2 |
| Lifetime c*γ*τ | m | $3x10^5$ |

$\gamma_\beta = (1-\alpha^2)/\beta$

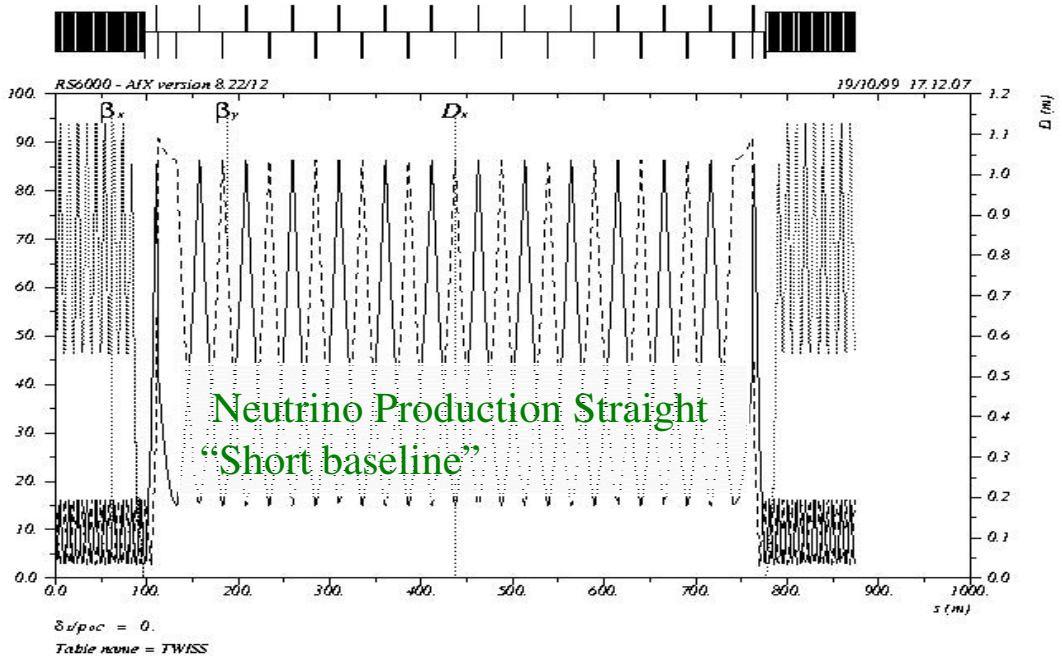
| | | |
|---|---|---|
| **General** | | |
| Tungsten shield thickness | cm | 1.0 |
| Beam-stay-clear | cm | 1.0 |
| Inter magnet spacing | m | 0.75 |
| **Dipoles** | | |
| Dipole length | m | 2.4 |
| Dipole bend | rad | 0.0859 |
| Dipole field | T | 6.0 |
| Beam size (6σ) WxH | cm | 8.0x5.3 |
| Dipole full aperture, WxH | cm | 12x9.3 |
| Sagitta | cm | 2.67 |
| **Quadrupoles** | | |
| Quadrupole length | m | 1.0 |
| Quadrupole strength | m-2 | 0.31 |
| Quadrupole poletip field | T | 3.6 |
| Beam size (6σ) WxH: | | |
| F quad | cm | 9.2x2.6 |
| D quad | cm | 4.2x6.2 |
| Quadrupole bore | cm | 14 |
| **Sextupoles** (overlay on quad field) | | |
| Horiz. Sextupole strength | m-3 | 0.64 |
| Vert. Sextupole strength | m-3 | 1.26 |
| Horiz. Sextupole field | T | 0.52 |
| Vert. Sextupole field | T | 1.03 |
| **Arc FODO cell parameters** | | |
| Cell length | m | 9.8 |
| Cell phase advance | deg | 90 |
| β(max) | m | 16.2 |
| Dx(max) | m | 1.3 |
| Total number of arc cells | | 31 |



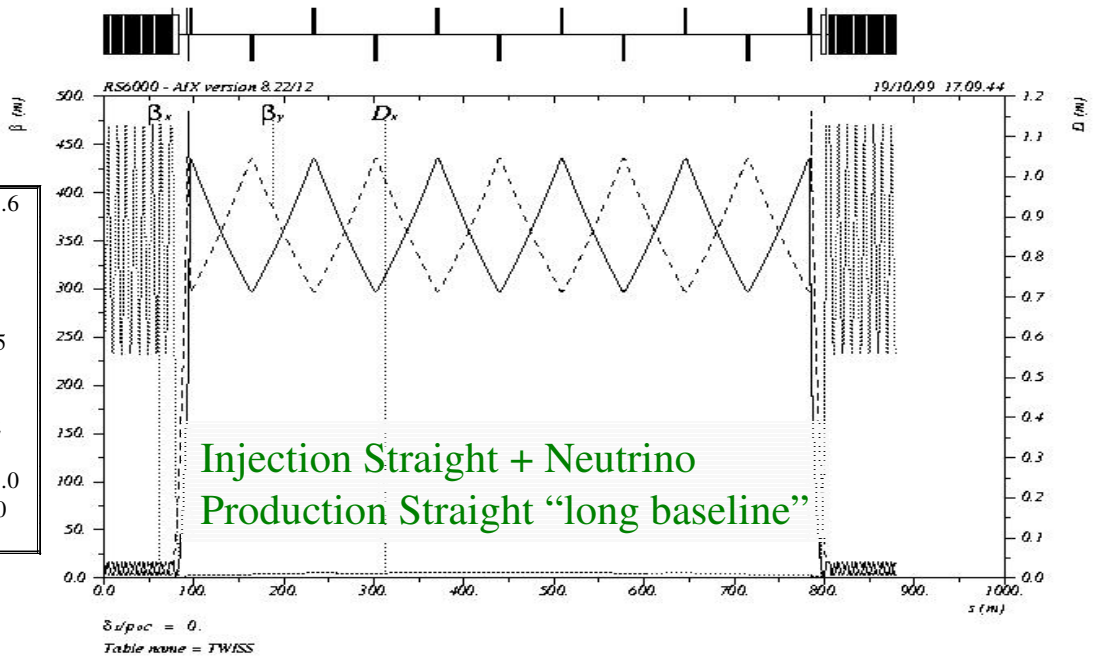

β function for one arc cell

# A Storage Ring for 2 Experiments

| | | |
|---|---|---|
| Cell length | m | 50.78 |
| Quadrupole length | m | 1 |
| Quadrupole strength | m-2 | 0.056 |
| Quadrupole poletip field | T | 0.84 |
| Quadrupole bore | cm | 18 |
| Cell phase advance | deg | 90 |
| β(max) | m | 86.3 |
| Rms divergence | mr | 0.73 |
| Number of cells | | 12 |

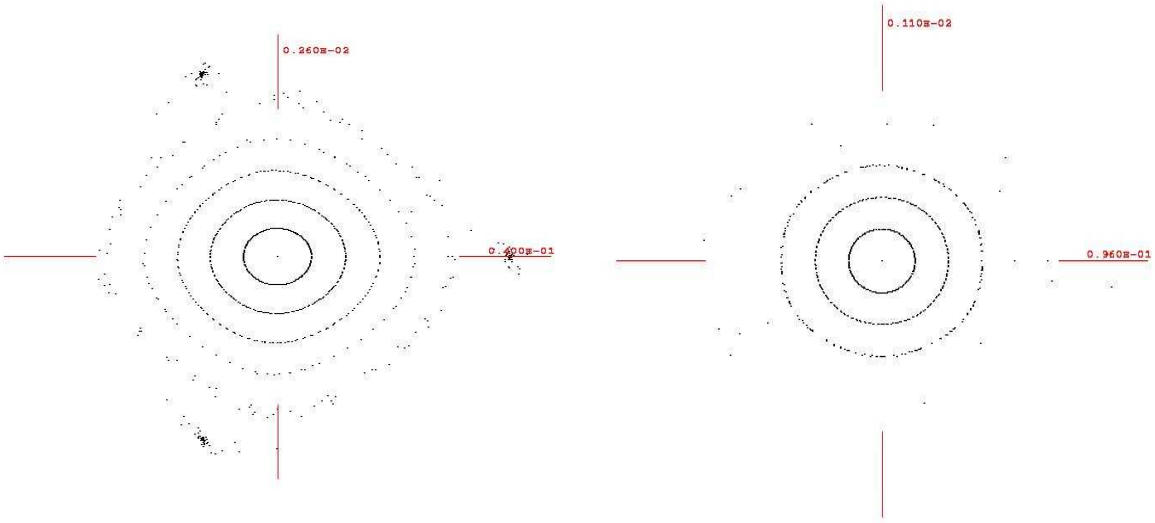


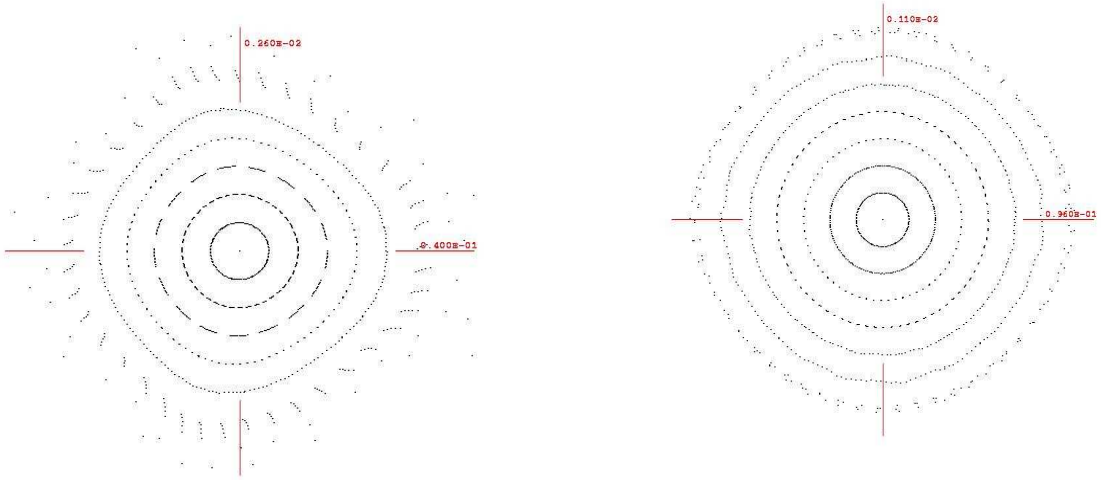

| | | |
|---|---|---|
| Cell length | m | 137.6 |
| Quadrupole length | m | 3 |
| Quadrupole strength | m-2 | 0.0019 |
| Quadrupole poletip field | T | 0.05 |
| Quadrupole bore | cm | 33 |
| Cell phase advance | deg | ≈22 |
| β(max) | m | 436.0 |
| rms divergence | mr | 0.20 |
| Number of cells | | 5 |



# Tracking

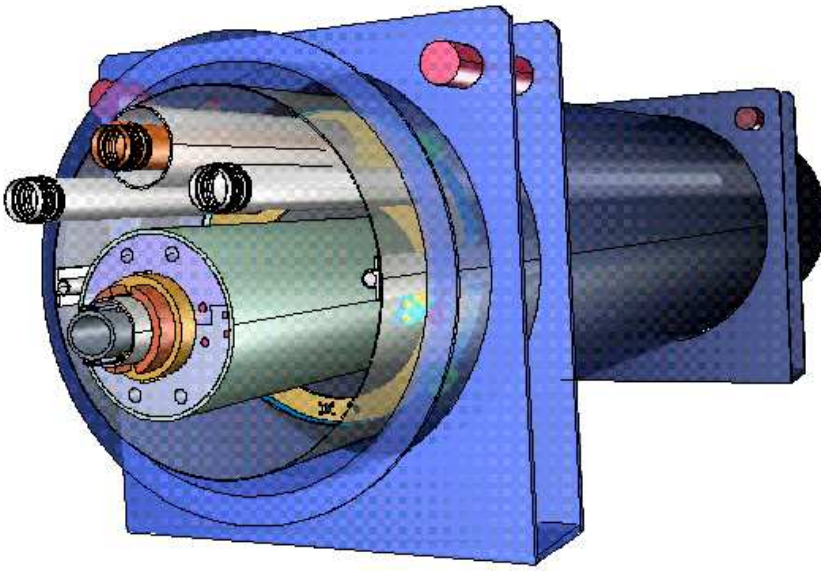
Top: Horizontal (left) and vertical (right) accepted phase space plots obtained by 9th order tracking including chromatic correction sextupoles and quadrupole fringe fields. Tracking is plotted in steps of 0.5 σ for an normalized emittance (rms) of 3200 π mm-mr. Bottom: Same as top plots but with quadrupole fringe fields in the matching sections to the production straight turned off.

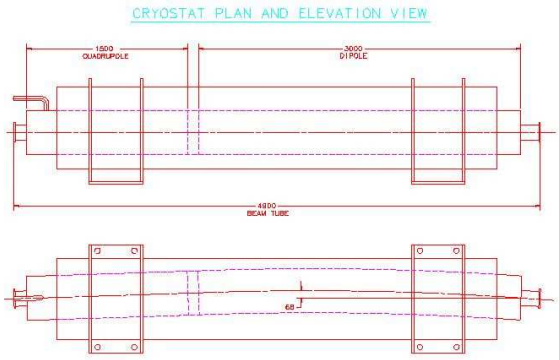


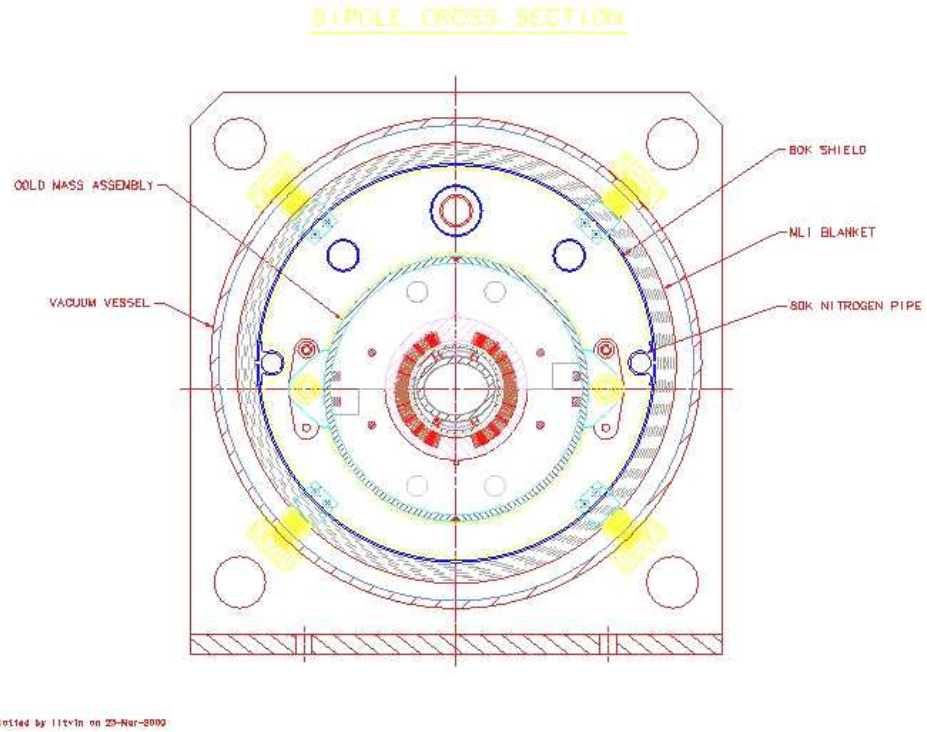



# SC Large Bore Magnets

- Low field quality helps reduce price although large aperture
- 7 Watts/m into LHe due to electrons from Muon decay
- 1 cm tungsten (liner instead of 3 cm)

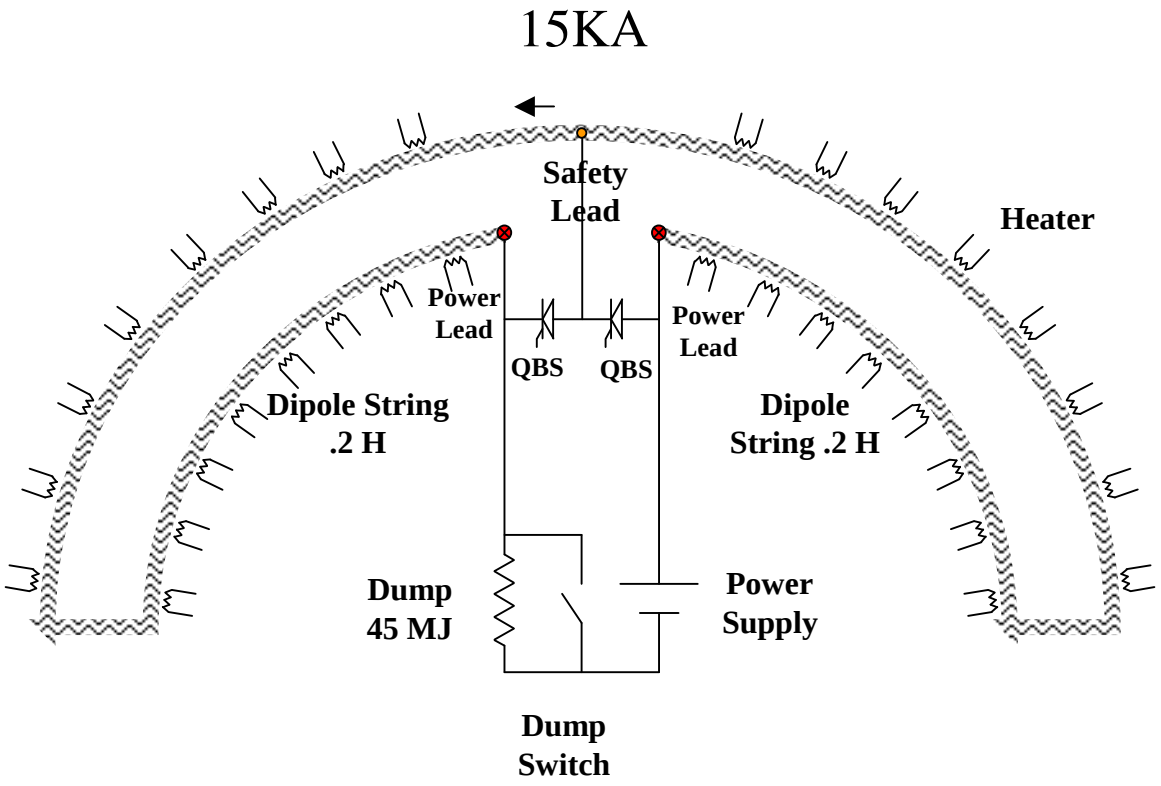




# Cryo

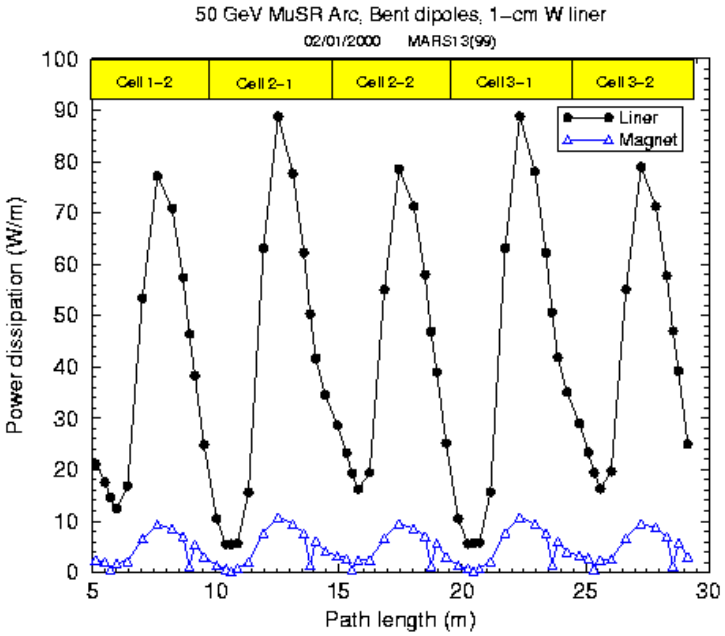
- Part of Lab wide facility with approximately 80 kW @ 4.5 K
- Loads for ring (@$2x10^7$ sec and $2x10^{20}$)
  - Static load ~ 3 W per cryostat
  - Dynamic load ~ 15 W cryostat

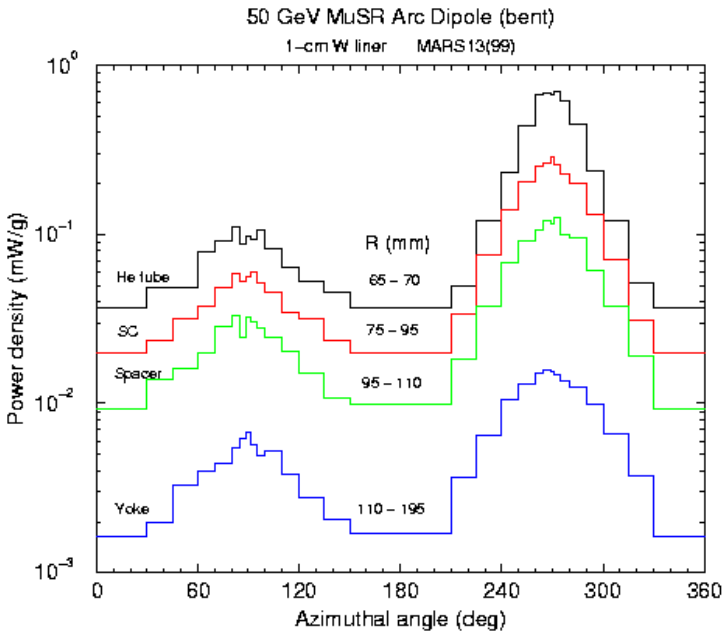



- Simple quench protection system
- Somewhat complicated LHe flux due to 10 m height difference in arc
- Plant upstairs but liquifier is 800 ft below, same with PS + support
  - Drop of 800 ft is too much for pumping LHe
  - Shielding is comparatively easy

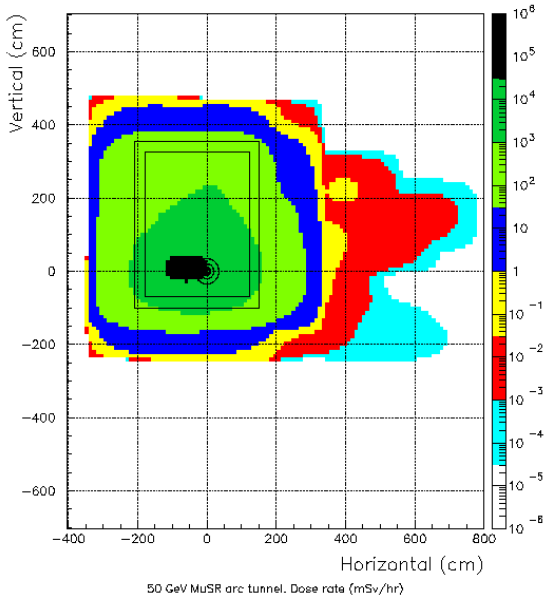
# Decay Electrons

- Beam power
  - 240 kW muon beam → 80 kW deposition due to electrons
  - long racetrack → helps: 22 % decays in arcs
  - ~ 50 Watt/m in arcs + 1 cm tungsten shielding ~ 7 W/m into LHe



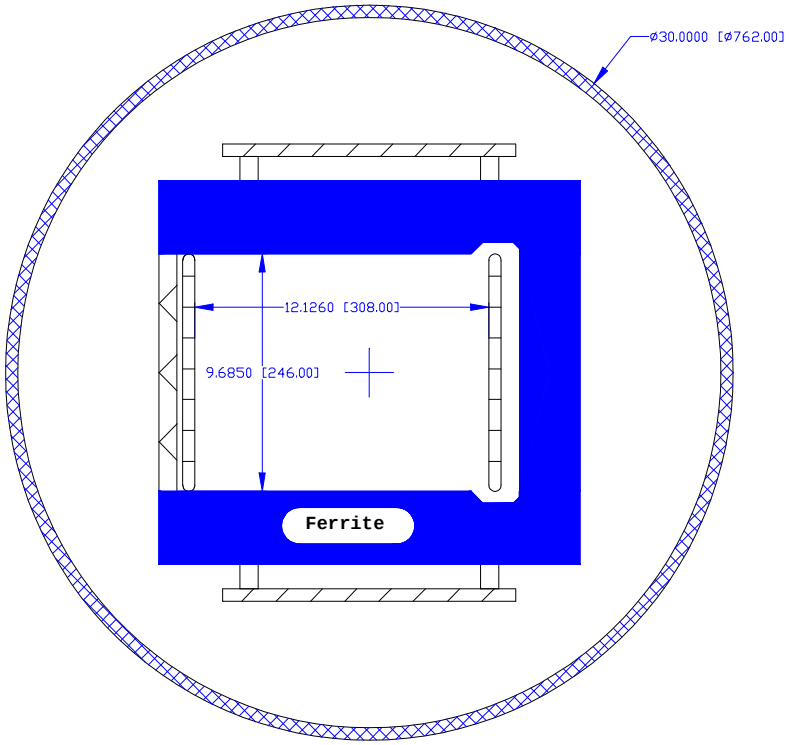




- Radiation in Tunnel
  - Mainly outward (7 m)
  - Inward ~ 3m is enough for unlimited occupancy



# Injection

- Inject into downward straight
  - Large β-function
  - Fast fall time of kicker for on axis injection



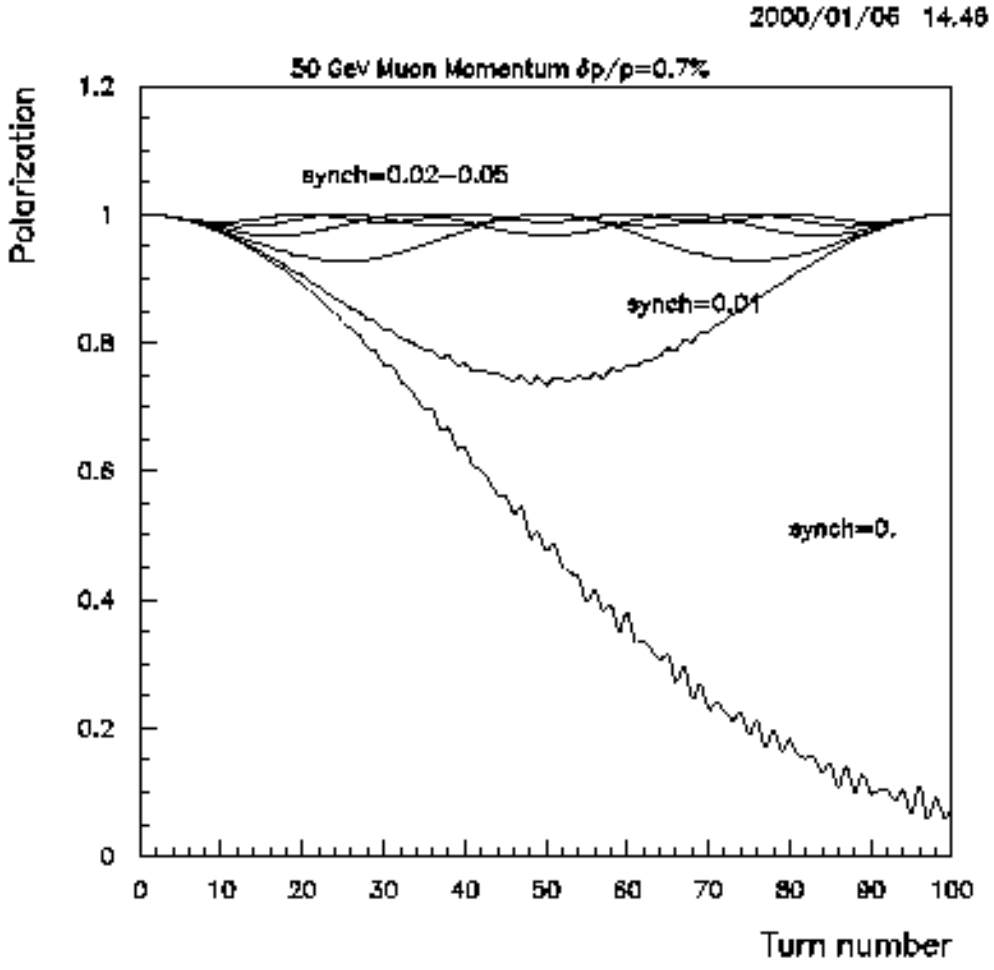

| Type | | Horizontal |
|---|---|---|
| Clear Gap WxH | mm | 308x246 |
| Integral BL | Tesla-meter | 0.6 |
| Field Flattop | μsec | 2.0 |
| Field Fall | μsec | 4.0 |
| Field Variation | % | 10 |
| Rep Rate | Hz | 15 |
| Length | m | 25 |
| Nr of Magnets | | 25 |

# Polarization

- Needs RF installed
  - How much: depends on incoming dp/p
  - acceptable polarization swing

$$\varepsilon V = \left(\frac{Q_s}{0.015}\right)\left(\frac{\delta p/p}{0.007}\right) 25 MV$$

$$rf\ frequency \approx \left(\frac{Q_s}{0.015}\right)\left(\frac{0.007}{\delta p/p}\right) 92 MHz$$



# Is 22 % steep ?

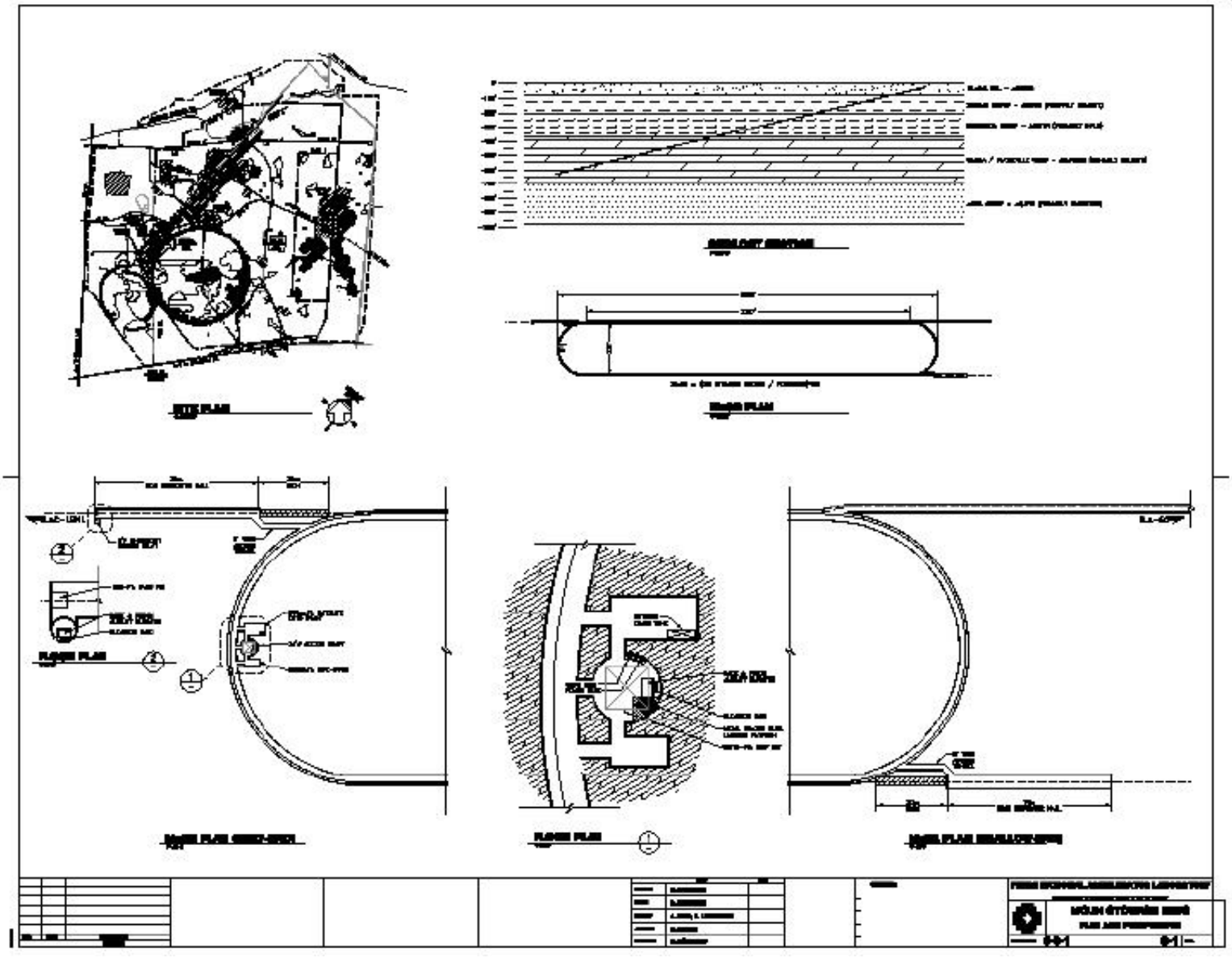
- 17 % into a quarry
- there is water !
- incremental cost small compared making more ν
- extend the ring up to the surface

Further down the ramp

Use vehicles

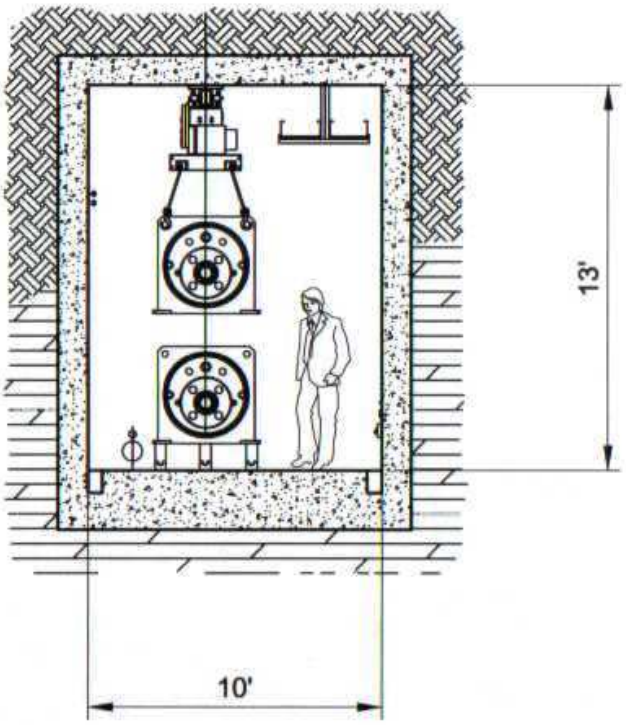
# FESS

- Alcove at bottom end
- Near detector at bottom end
- Hall on surface
- Unlimited Access to bottom facility during operation

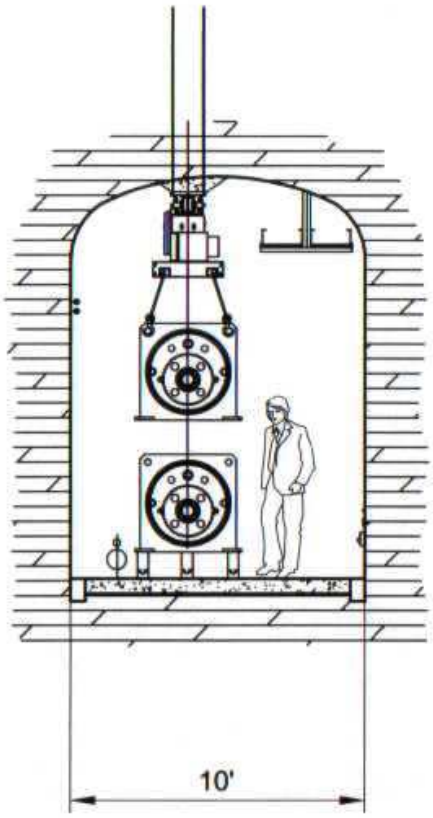


# Civil Engineering for the Storage Ring

- Tunnel for very different environments

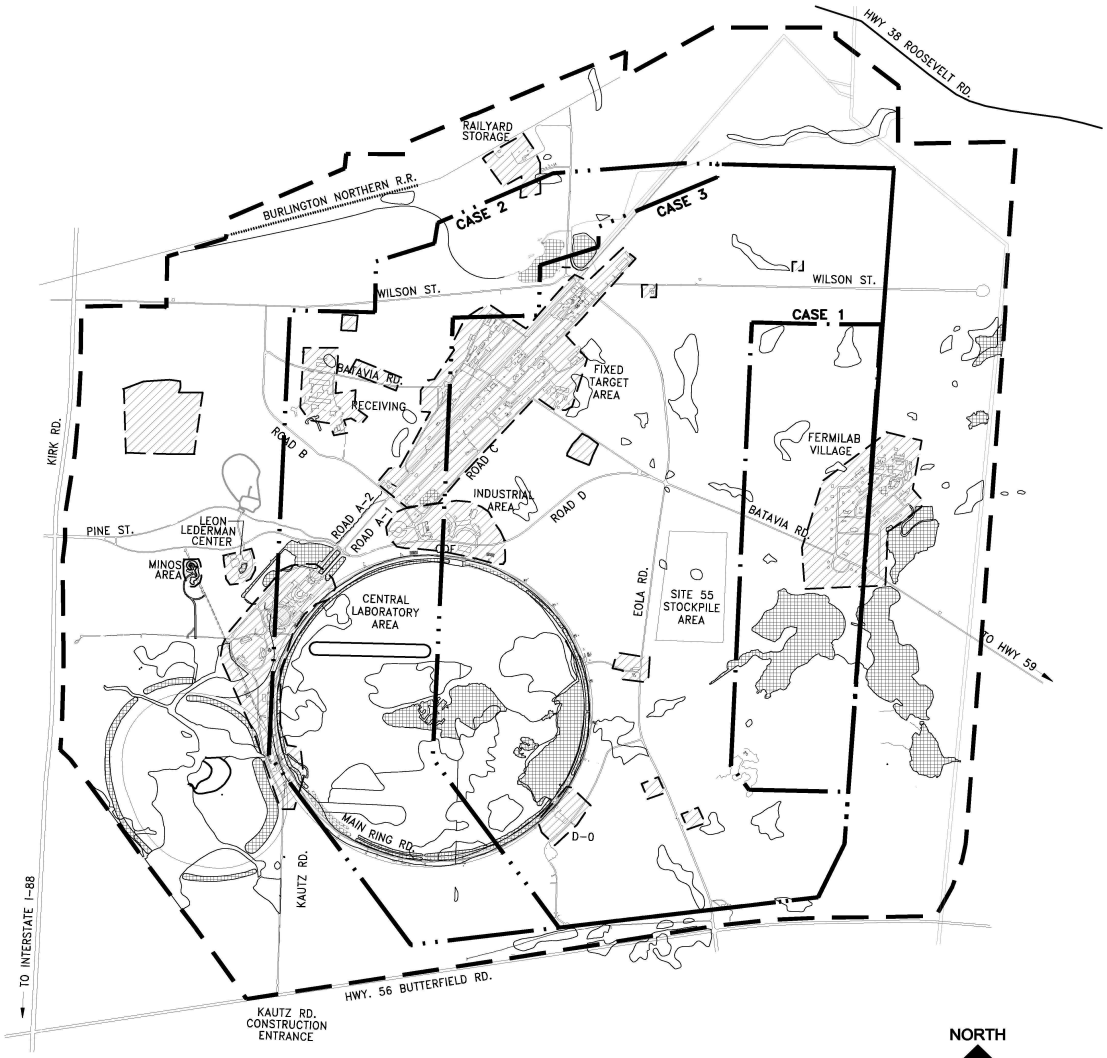



**SECTION G**
MuSR (SHALLOW)




**SECTION H**
MuSR (DEEP)

# Radiation from the Neutrino Source @ FNAL




**LEGEND:**

LIMITS CASE 1.
LIMITS CASE 2.
LIMITS CASE 3.
SITE BOUNDARY
LOCATION LIMITS
WETLAND LIMITS

LOCATION HATCH
WETLAND HATCH

NORTH
W E
S

| LIMITS: | mrem/year | CONTROL CYL. | |
|---|---|---|---|
| CASE 1. 50GeV | 10 | 4.5KM | RADIUS=4.0M |
| CASE 2. 50GeV | 100 | 1.4KM | RADIUS=1.2M |
| CASE 3. 30GeV | 10 | 2.5KM | RADIUS=5.0M |

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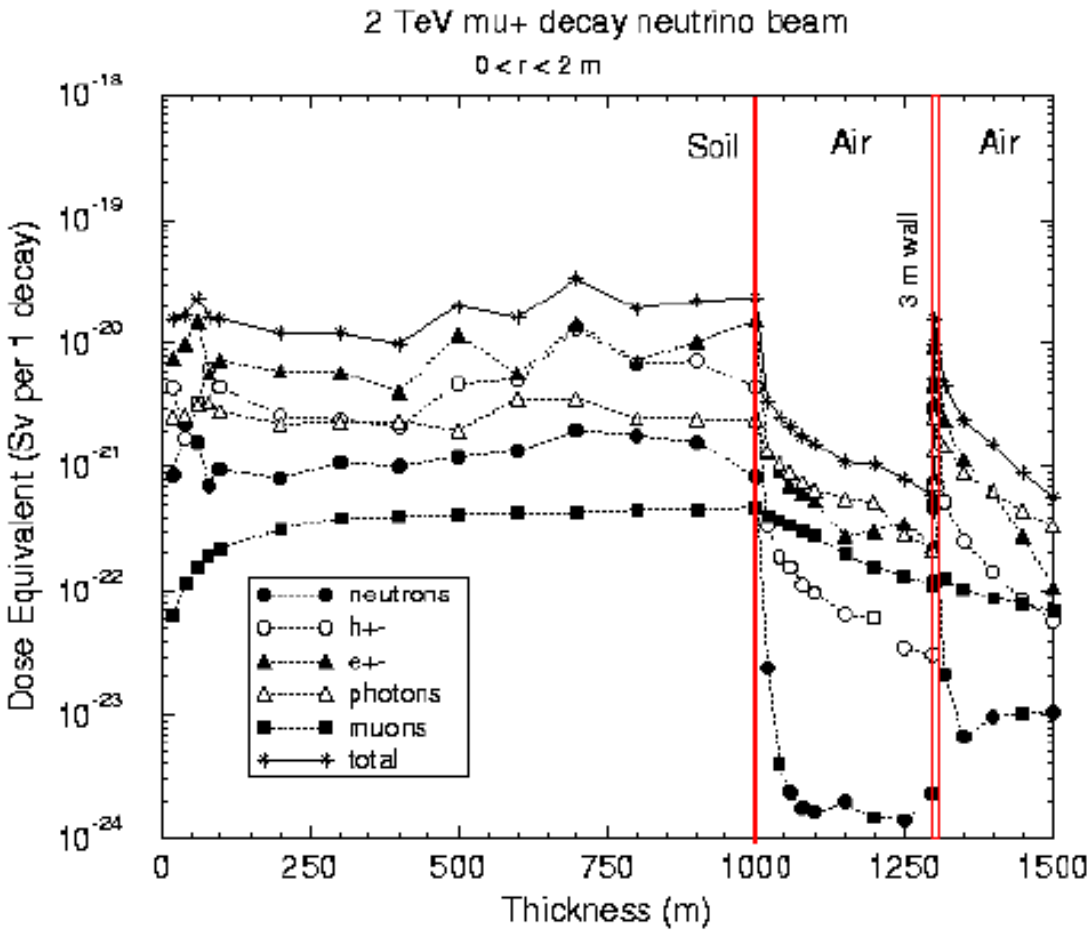
# Neutrino Radiation from the μ Storage Ring: Max $E_\mu$ ?

- Neutrinos come up to surface: ϕ~13 deg (22%) μ-beam from the straight section pointing up

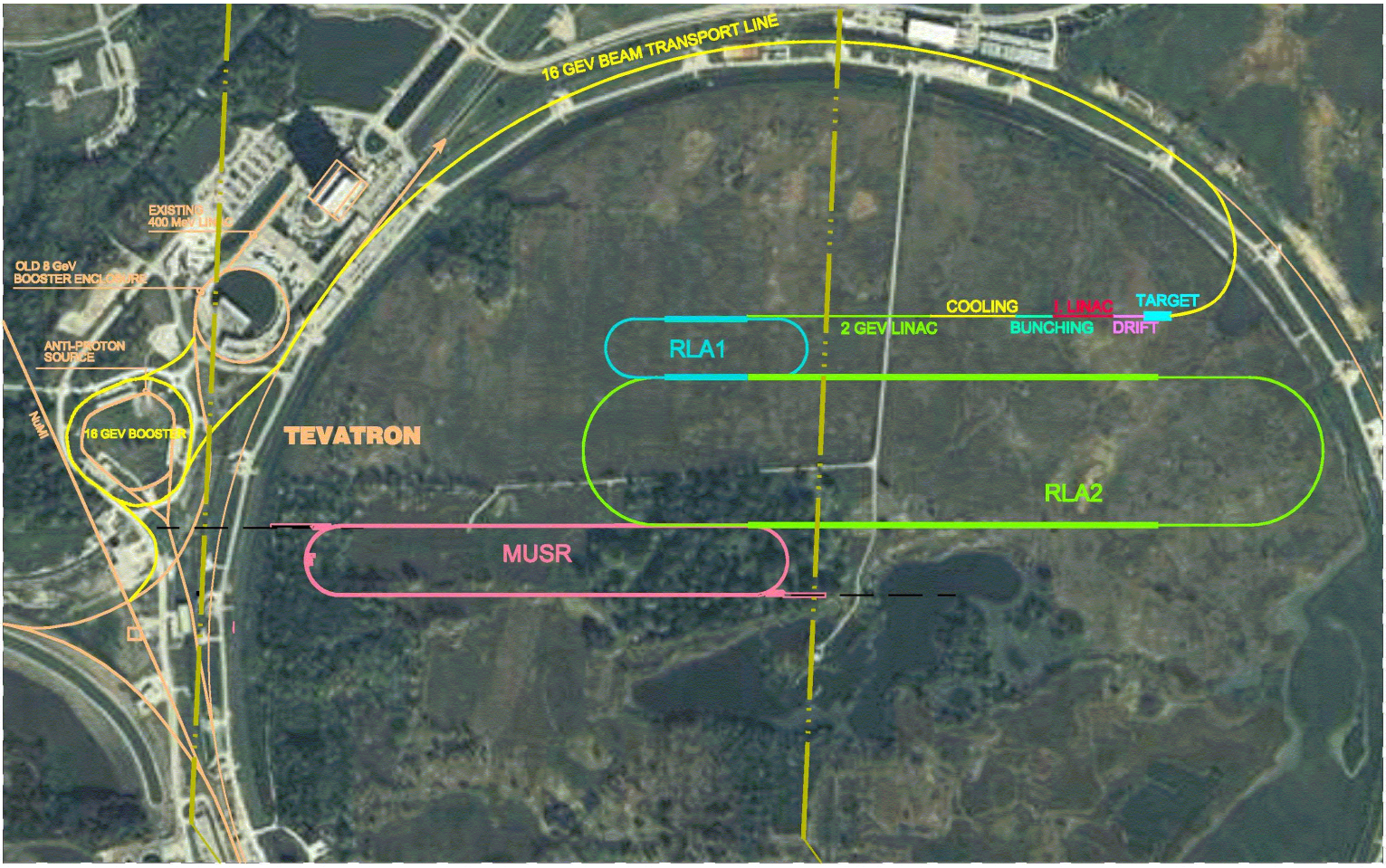


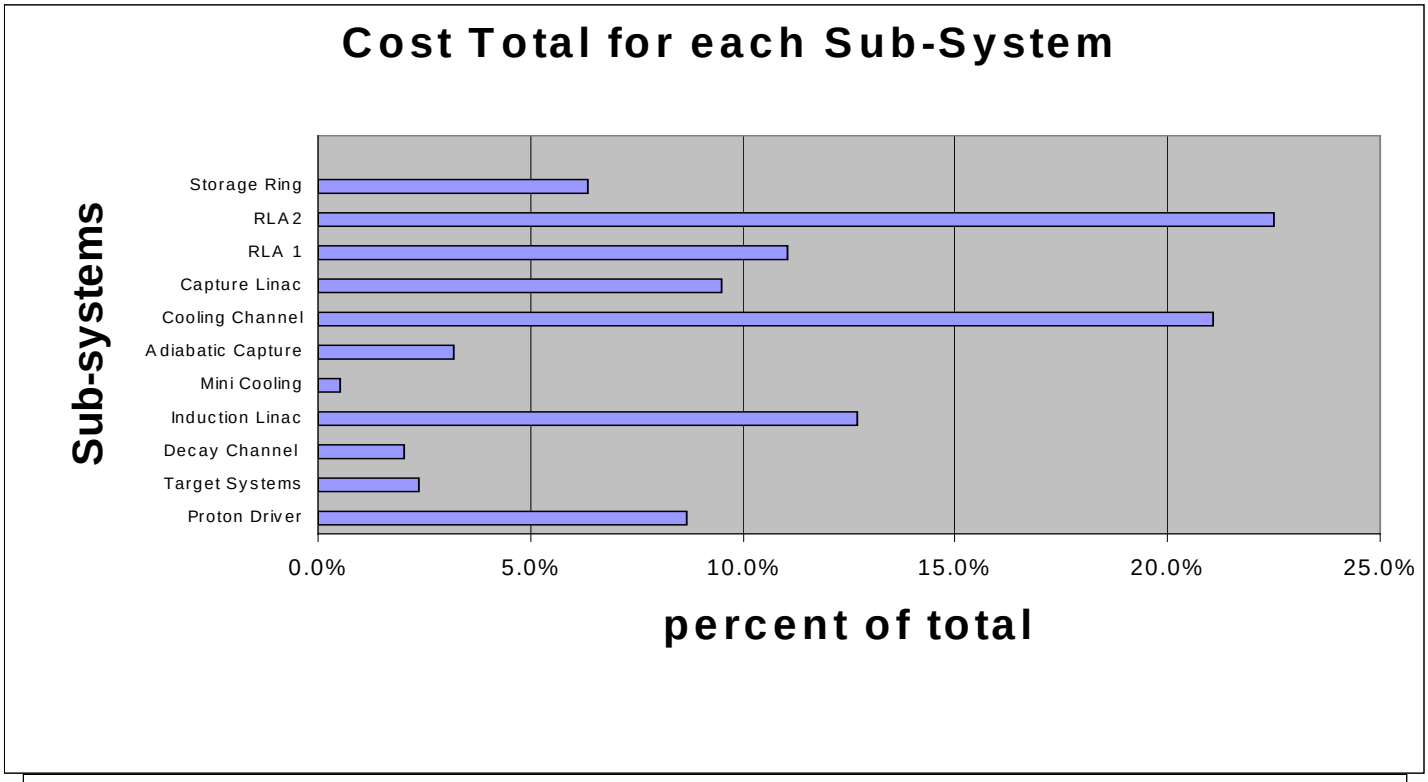
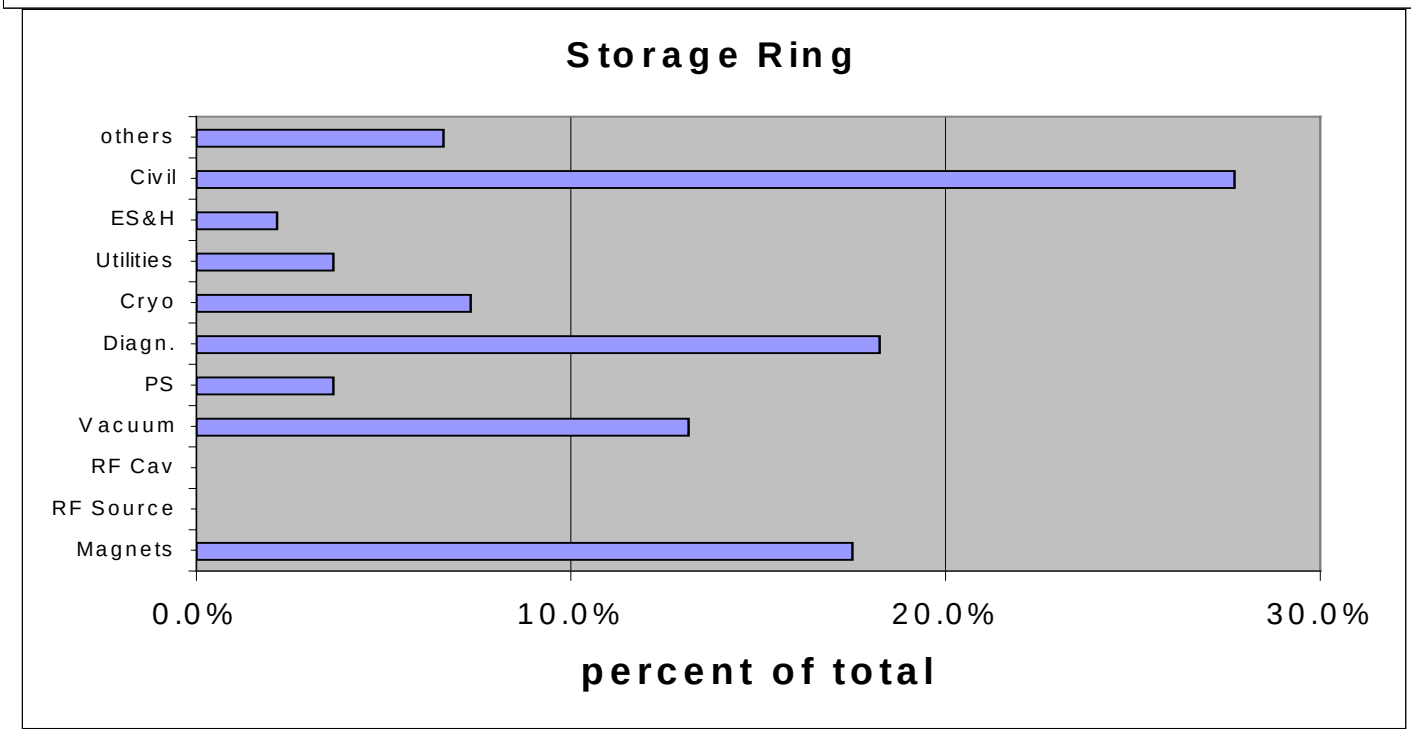

Fermi limit
0.1 mSv/year

Federal Limit
1.0 mSv/year

# Layout on this Site

- Why ?
  - Worldwide Unique facility
  - Detector cost and Accelerator cost can be balanced
  - Long Term program ⇒can be staged
  - Fits under a site
  - Has a large NSF/University/Illinois State/Inter Lab. collab



# Overall Cost

- Total