



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Energy Frontier On Fermilab Site

Options

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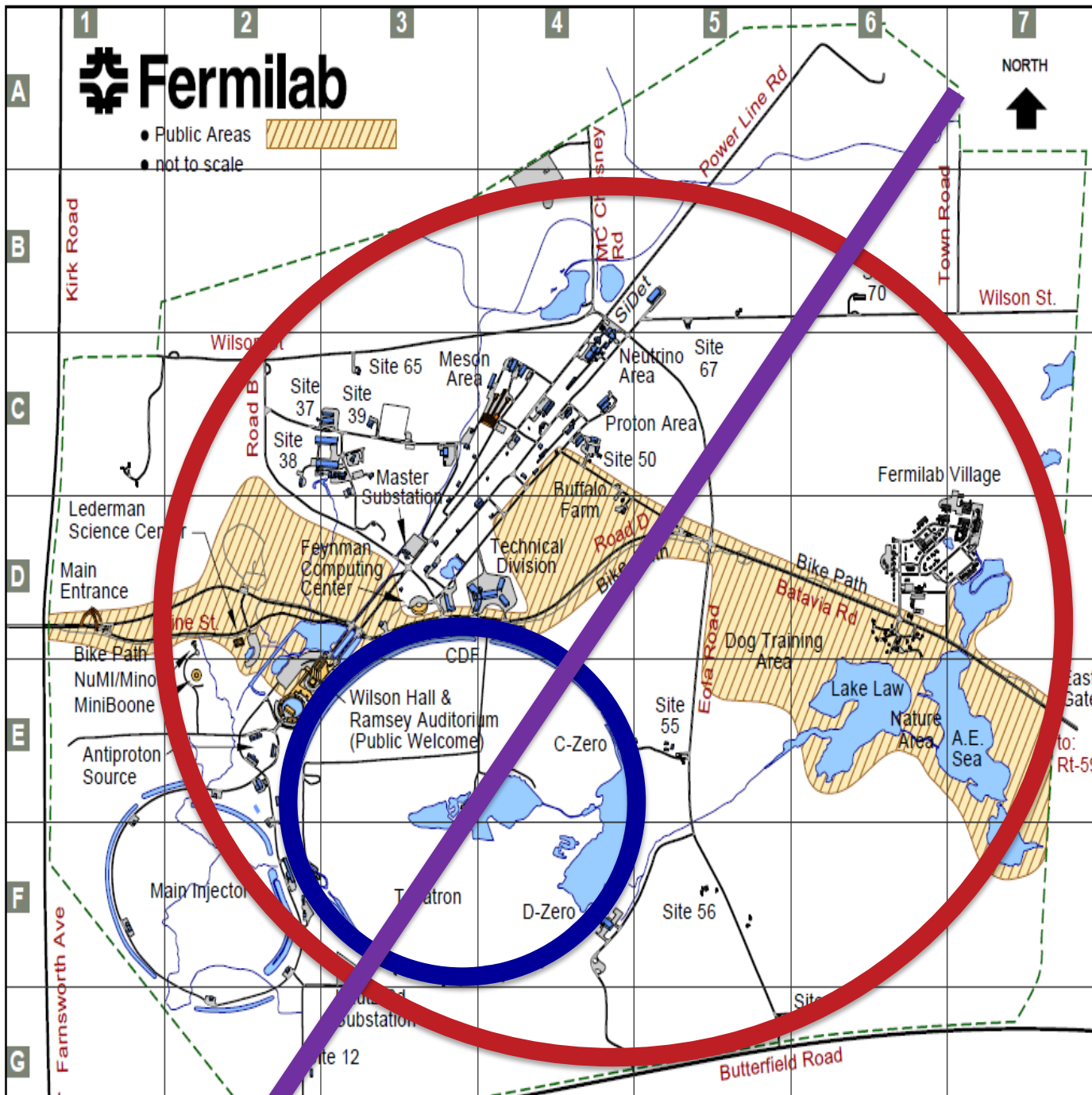
Accelerator Physics Center

All-Sci Retreat, April 24, 2021

3x5
mi

Max C
16 km

Max L
7.3km



Fermilab

“On site” Energy Frontier Options

- **Hadron pp colliders:**
 - $16/6.3=2.5 \times$ Tevatron, future SC magnets 24 T (vs 4.5) \rightarrow 27 TeV cme
- **$e+e-$, $\gamma\gamma$ colliders:**
 - Circular Higgs factory – high lumi
 - Linear Higgs Factory CLIC-NLC type
 - $\gamma\gamma$ collider (SAPHIRE type)
 - linear plasma beam/laser driven (far future?)
- **Energy frontier $\mu+\mu-$ colliders:**
 - “traditional” with 20T SC magnets (Fermilab site filler) 6 TeV cme
 - Far-far-future Crystal/CNT acceleration 100-1000 TeV cme, low- L
- **Below are just high level comments along the line of (potential) FEASIBILITY**
that is a product of (Y/N) three “feasibilities”:

ENERGY x PERFORMANCE x COST

! WARNING !

$\alpha\beta\gamma$ - Cost Estimate Model:

$$\text{Cost(TPC)} = \alpha L^{1/2} + \beta E^{1/2} + \gamma P^{1/2}$$

- a) $\pm 33\%$ estimate, for a “green field” accelerators
- b) “US-Accounting” = TPC ! ($\sim 2 \times$ *European Accounting*)
- c) Coefficients (units: 10 km for L , 1 TeV for E , 100 MW for P)
 - $\alpha \approx 2\text{B}\$/\text{sqrt}(L/10 \text{ km})$
 - $\beta \approx 10\text{B}\$/\text{sqrt}(E/\text{TeV})$ for SC/NC RF
 - $\beta \approx 2\text{B}\$ /\text{sqrt}(E/\text{TeV})$ for SC magnets
 - $\beta \approx 1\text{B}\$ /\text{sqrt}(E/\text{TeV})$ for NC magnets
 - $\gamma \approx 2\text{B}\$/\text{sqrt}(P/100 \text{ MW})$

USE AT YOUR OWN RISK!

Option 1: 27 TeV cme pp Collider



Piotr Komorowski, R&D engineer at Bruker and Professor Carmine Senator (UNIGE) pointing to the record field of 25T

- Feasibility of Energy : (possibly, **YES**), some 15-20 years
- Feasibility of Performance : (possibly, **YES**), $L \sim 1e34 +$
- Feasibility of Cost : (possibly, **NO**) $\sim 15B\$$

Option 2: Circular Higgs Factory

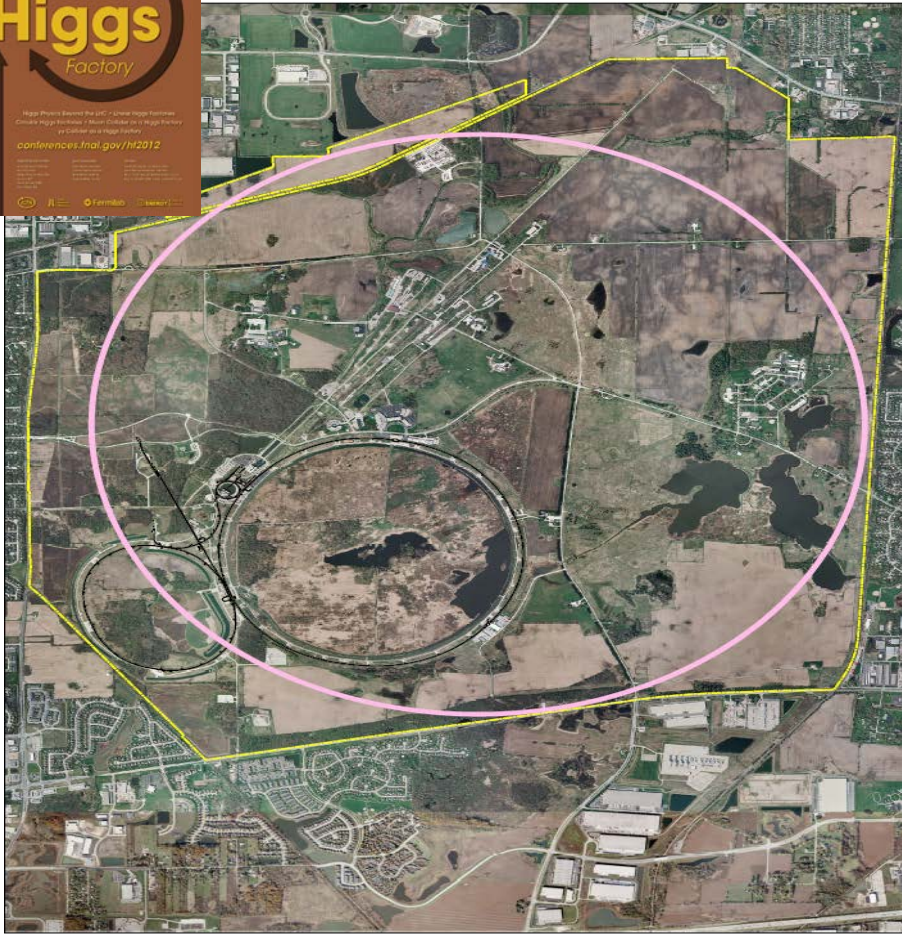
Higgs factory

T.Sen (2012)

- Beam Energy = 120 GeV
- SR power, both beams=100MW
- Initial luminosity= $5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- $\beta_x^*, \beta_y^* = (20, 0.2) \text{ cm}$
- Beam-beam tune shifts = (0.067, 0.095)
- Beam current = 5 mA

Z Factory

- Beam Energy = 46 GeV
- SR power, both beams= 60 MW
- Initial luminosity= $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Beam-beam tune shifts= (0.032, 0,045)
- Beam current = 134 mA



- Feasibility of Energy : **YES**
- Feasibility of Performance : (possibly, **YES**), $L \sim 1 \text{e}34$ + if some 100 MW SRF
- Feasibility of Cost : (possibly, **NO**) $\sim 7\text{B}\$$

Option 3: Linear Higgs Factory



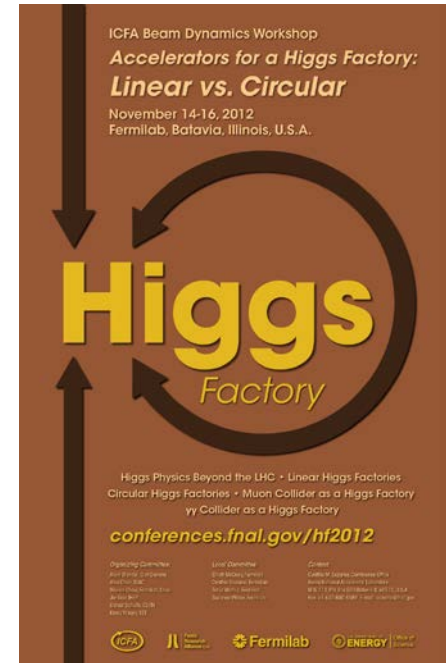
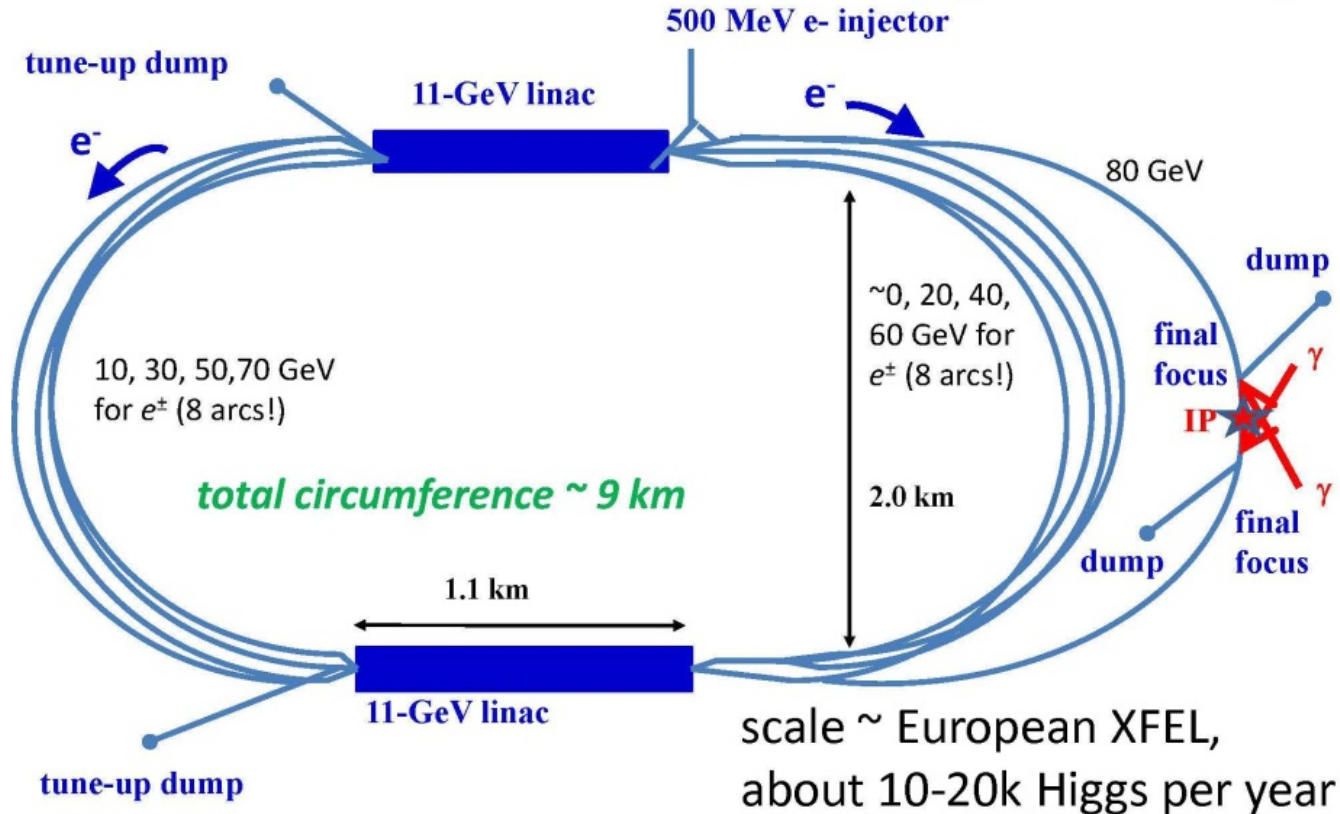
4 km for Final Focus
 3 km to reach 250 GeV in two beams → 100 MV/m → NC



- Feasibility of Energy : (possibly, **YES**), CLIC-scheme or Klystrons
- Feasibility of Performance : (possibly, **YES**), $L \sim 1e34 +$
- Feasibility of Cost : (possibly, **NO**) ... ~80% of CLIC-380 ~5B\$ European account

Option 4: Higgs Gamma-Gamma

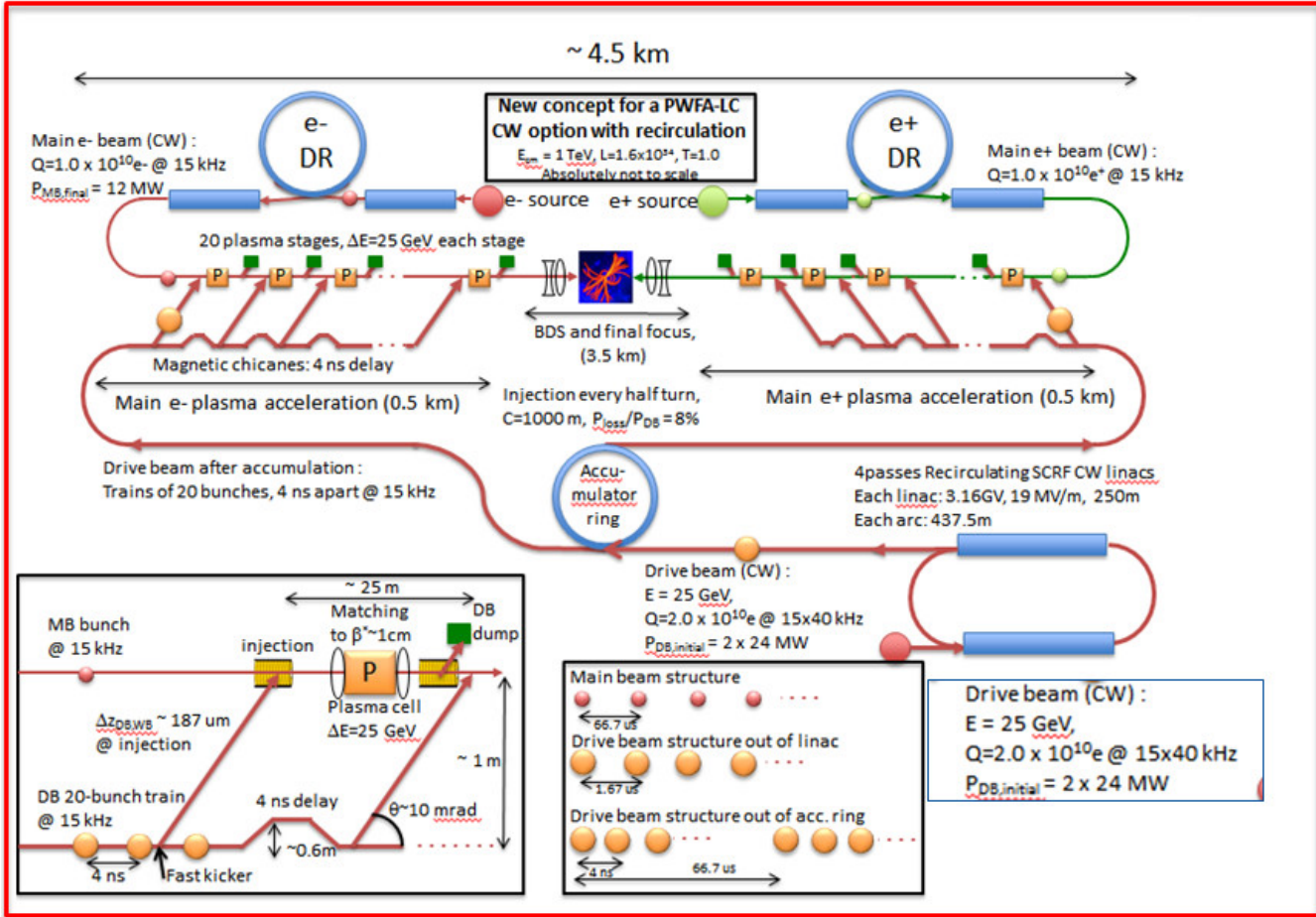
SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory



SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

- Feasibility of Energy : **YES**
- Feasibility of Performance : (possibly, **YES**), $L \sim 1e34$ +
- Feasibility of Cost : (possibly, **NO**) ~10B\$

Option 5: Linear Plasma Collider



Driven by 25 GeV e-beam... 25 GeV per stage, max energy in **7 km ~ 3 TeV**

Or driven by lasers.. about the same

- **Feasibility of Energy** : (staging not proven, **N...ES**), for either scheme
- **Feasibility of Performance** : (possibly, **NO**), $L \sim 1e34 +$ is impossible e+ ?
- **Feasibility of Cost** : (possibly, **NO**), > 20 B\$ even for 1 TeV

Option 6: Muon Collider

Muon Collider Conceptual Layout

Project X

Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring

Reduce size of beam.

Target

Collisions lead to muons with energy of about 200 MeV.

Muon Capture and Cooling

Capture, bunch and cool muons to create a tight beam.

Initial Acceleration

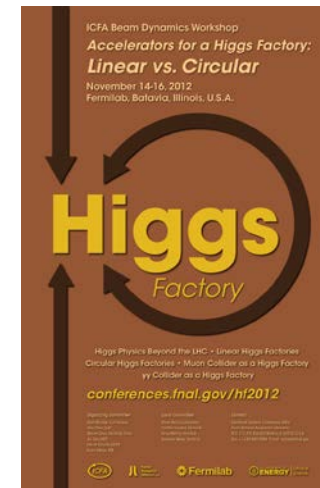
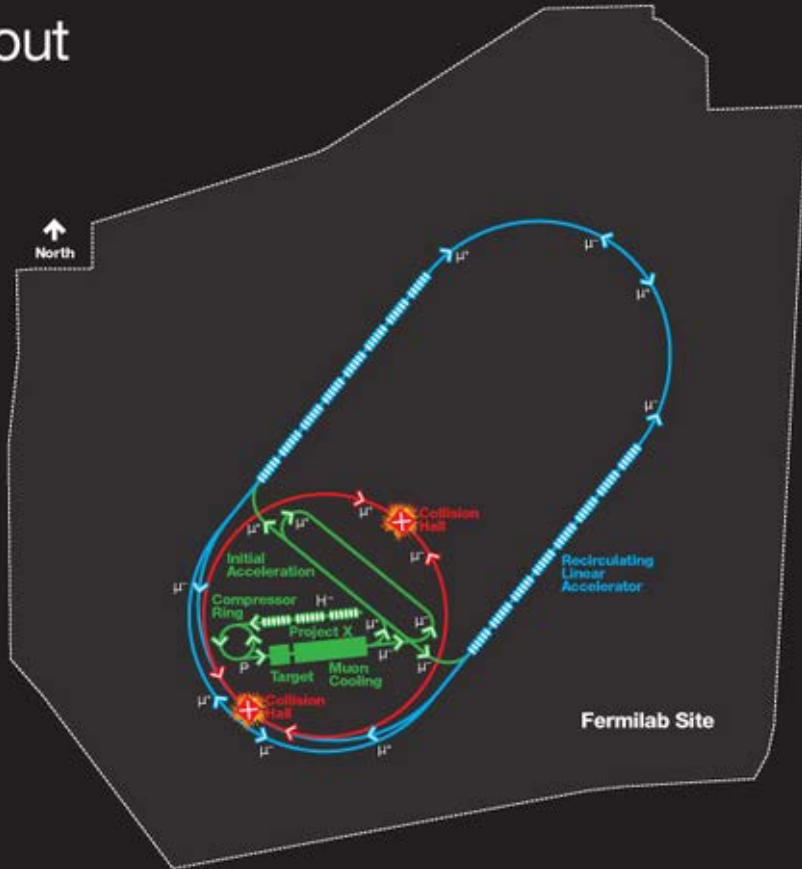
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator

In a number of turns, accelerate muons up to 2 TeV using SRF technology.

Collider Ring

Bring positive and negative muons into collision at two locations 100 meters underground.



Several options :

Higgs factory (fits the site)

1.5 TeV cme (fits the site)

3 TeV cme (fits the site)

6 TeV cme (site filler)

- **Feasibility of Energy** : **YES**, 8-10 T for 3, 20 T for 6 TeV option
- **Feasibility of Performance** : (**NOT** now ...R&D → **YES**), $L \sim 1e31$ w/o cooling
- **Feasibility of Cost** : (possibly, **NO**) ...~8-10 B\$ TPC

Option 7: Muon-Crystal-Plasma

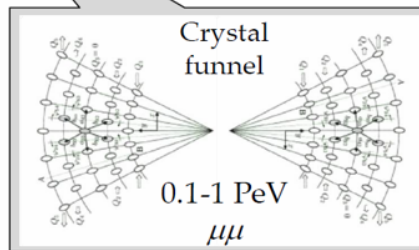
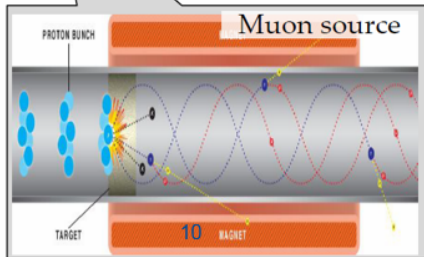
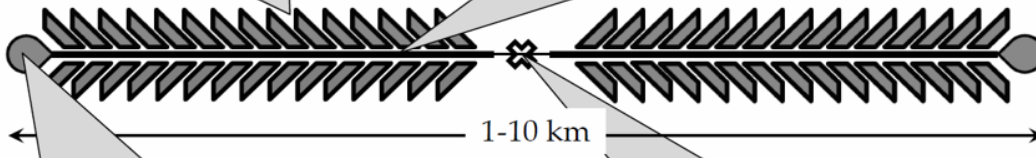
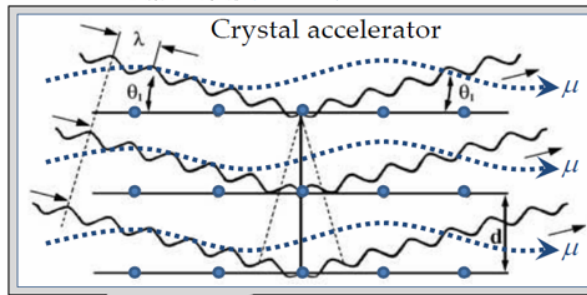
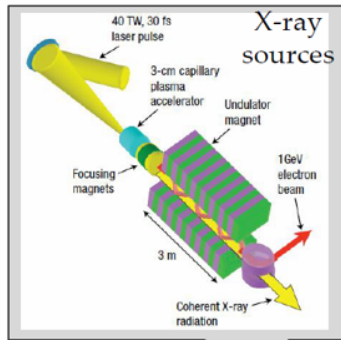
Futuristic: Crystals & Muons

$n \sim 10^{22} \text{ cm}^{-3}$, **10 TeV/m** \rightarrow

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[\frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{ cm}^{-3}]} \text{ PeV} = 1000 \text{ TeV}$$

$n_\mu \sim 1000$
 $n_B \sim 100$
 $f_{rep} \sim 10^6$
 $L \sim 10^{30-32}$

V.Shiltsev, Phys. Uspekhy 55 965 (2012)



ilab

Has no substance now except ~5 papers and ~5 enthusiasts

... “just an idea”

Dream of 1-10 TeV/m (0.1-1 TeV in CNTs)

... makes possible **1000 TeV collider on FNAL site - ?**

- Feasibility of Energy : (just a dream, **NO**), ~2-3 decades of R&D with many “ifs”
- Feasibility of Performance : (surely, **NO**), $L \sim 1e28-1e30$
- Feasibility of Cost : (by definition, **YES**) too early to talk about that t