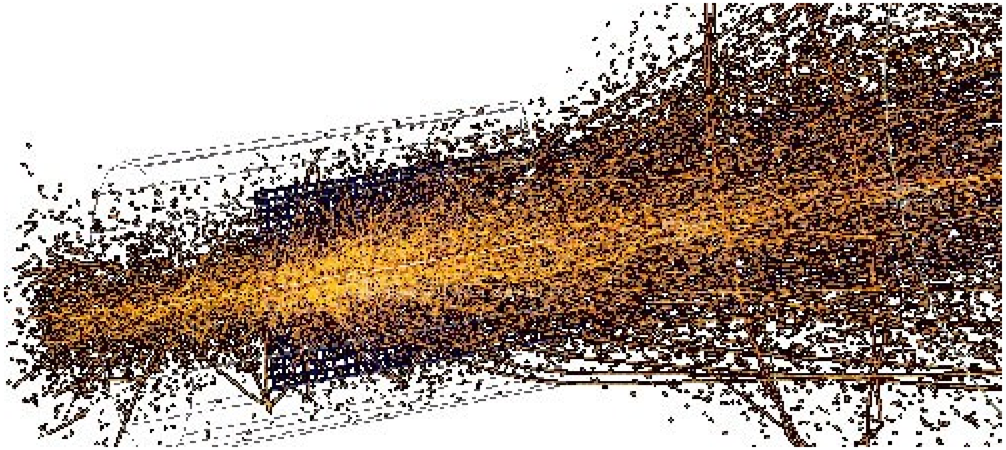
Accelerators for the Energy and Intensity Frontier



Chris Rogers,
ASTeC,
Rutherford Appleton Laboratory

The Energy and Intensity Frontier

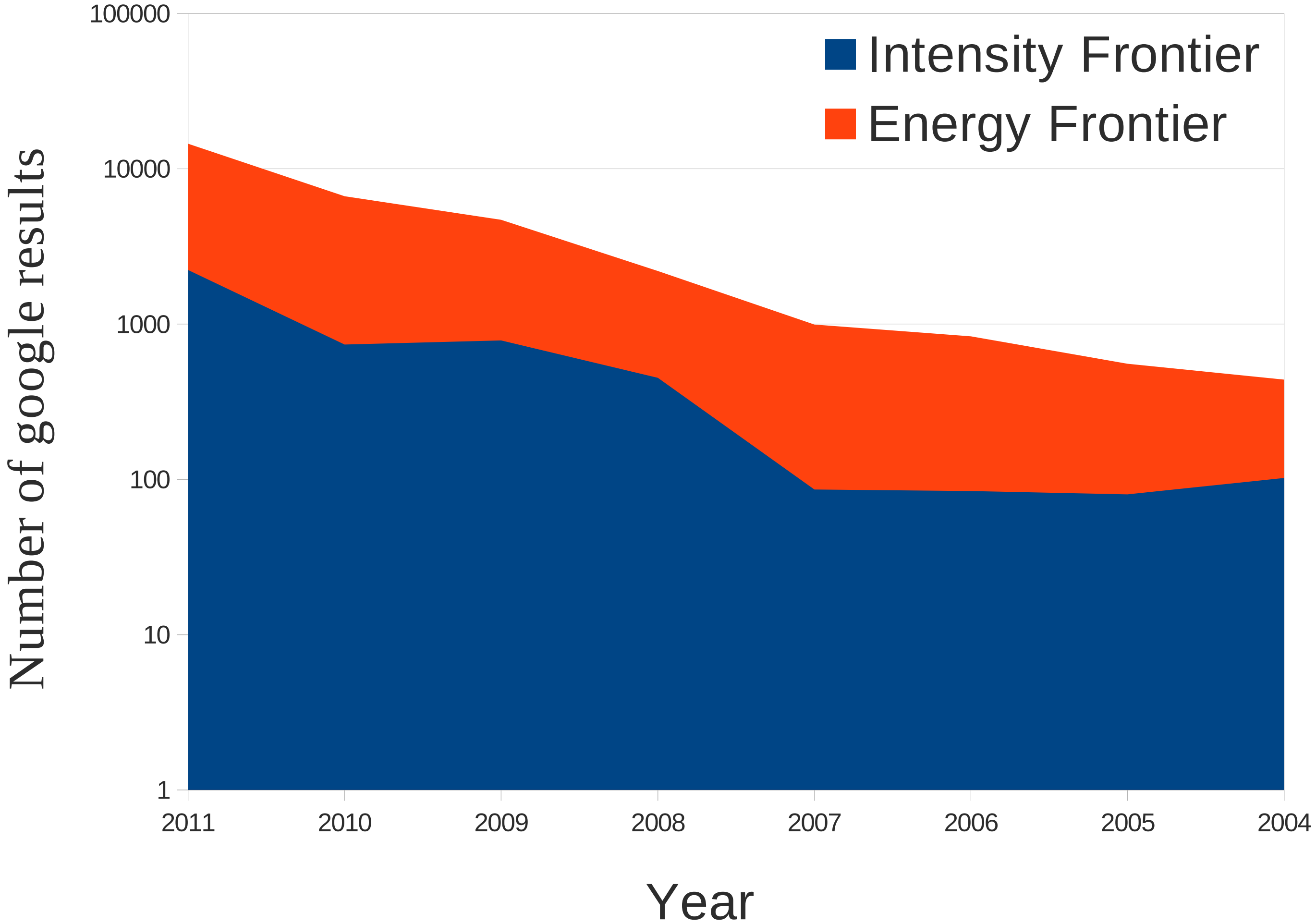
- Symmetry magazine, October 2009

At the Energy Frontier, for instance, we use high-energy colliders, such as the Tevatron and the Large Hadron Collider, to search for new particles and forces that provide information on the makeup of matter and space. At the Cosmic Frontier, we scan the heavens with particle detectors and telescopes to learn more about cosmic rays, dark matter, and dark energy, and to understand the role they have played in the evolution of the universe.

The strategy of research at the Intensity Frontier is to generate the huge numbers of particles needed to study rare subatomic processes, such as the transformation of one type of neutrino into another or the not-yet-observed conversion of a muon into an electron. This requires extreme machines, multi-megawatt proton accelerators that produce high-intensity beams of particles.

- **B Factories?**

Numerology



Intensity Frontier
Energy Frontier
Number of google results
100000
10000
1000
100
10
1
2011
2010
2009
2008
2007
2006
2005
2004
Year

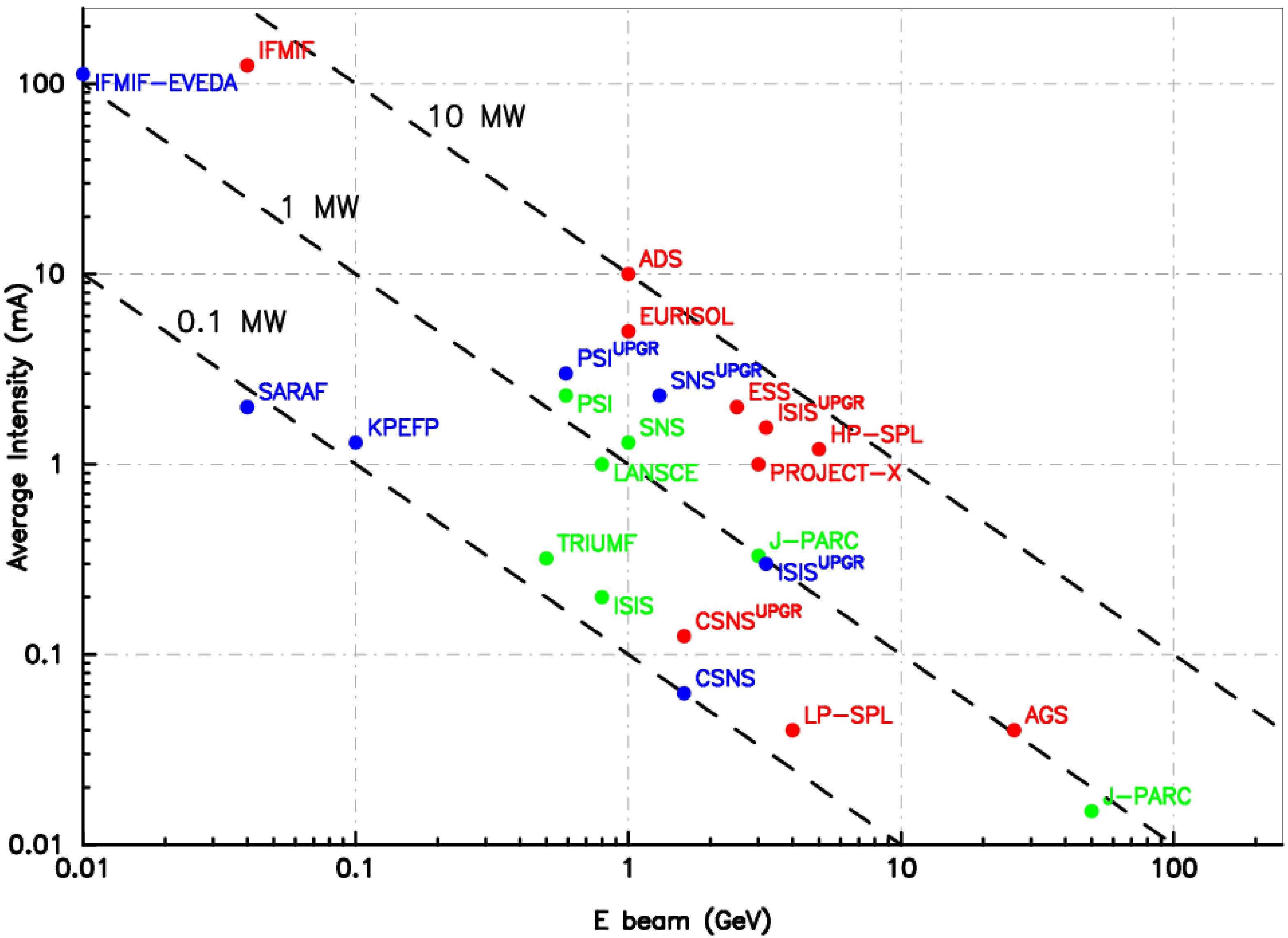
State of the Art

- CERN
  - Collisions at 7 TeV Centre of Mass
  - CNGS beam for neutrinos
- Fermilab
  - Tevatron ring switched off September 2011
  - Fermilab Booster (8 GeV) and Main injector (150 GeV) used for neutrino experiments
- KEK
  - Neutrino beamline operated at 30 GeV before the earthquake
  - Multiphysics facility for spallation neutrons and ADS
  - KEKB – B-factory undergoing upgrade
- SNS, PSI, ISIS, TRIUMF, LANSCE
- SLAC, LEP, HERA

Where Next?

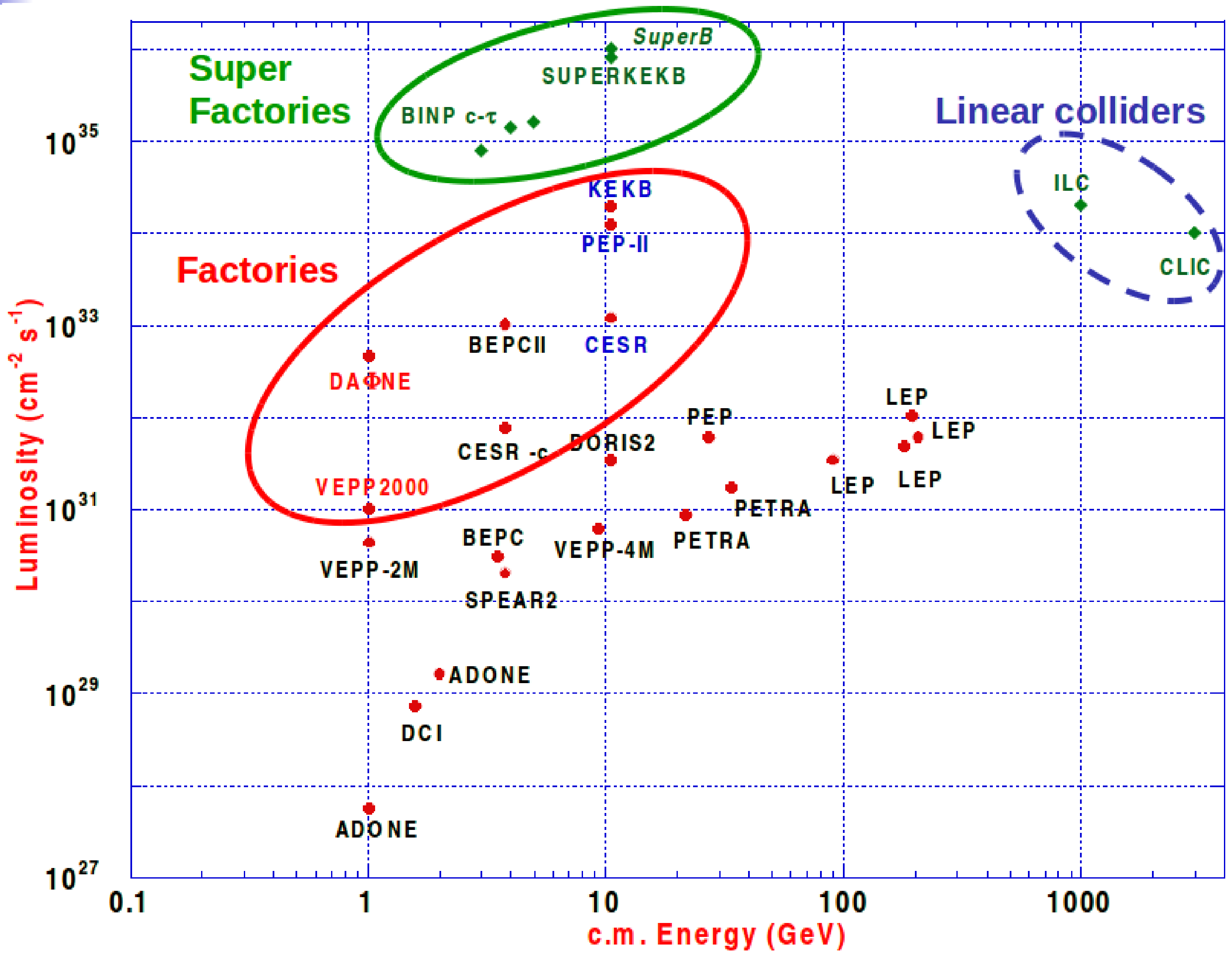
- The proton road
  - LHC upgrades
- The electron road
  - B "Super Factories"
  - Linear Colliders
- The neutrino/muon/rare decays road
  - Project X and JPARC upgrades
  - ISIS, ESS
  - Neutrino Factory
  - Muon Collider

Proton Machines



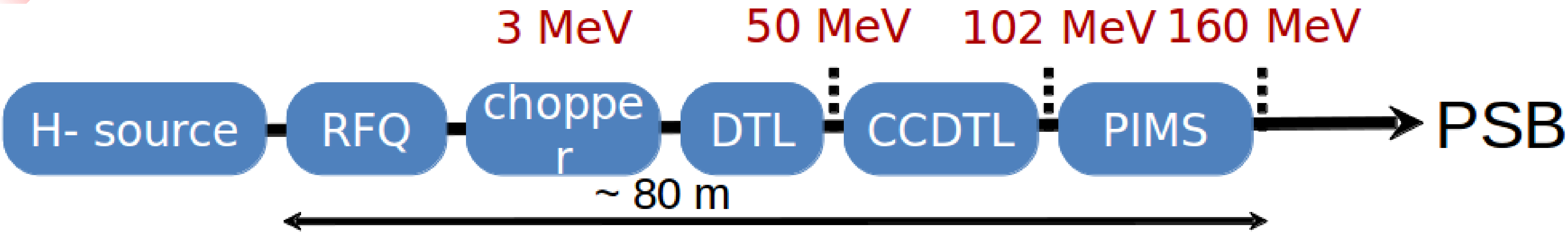
LHC

e+e- Machines



Super Factories
SuperB
SUPERKEKB
BINP c-τ
Linear colliders
ILC
CLIC
Factories
KEKB
PEP-II
BEPCII
CESR
DAΦNE
CESR -c
DORIS2
PEP
VEPP2000
LEP
LEP
LEP
LEP
PETRA
PETRA
BEPC
VEPP-4M
VEPP-2M
SPEAR2
ADONE
DCI
ADONE
10^{35}
10^{33}
10^{31}
10^{29}
10^{27}
Luminosity (cm^{-2} s^{-1})
0.1
1
10
100
1000
c.m. Energy (GeV)

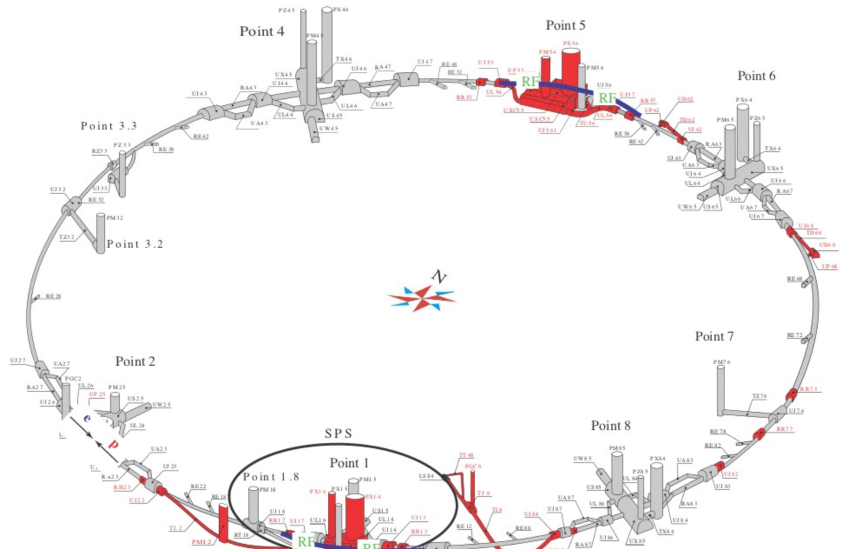
Super Large Hadron Collider (SLHC)

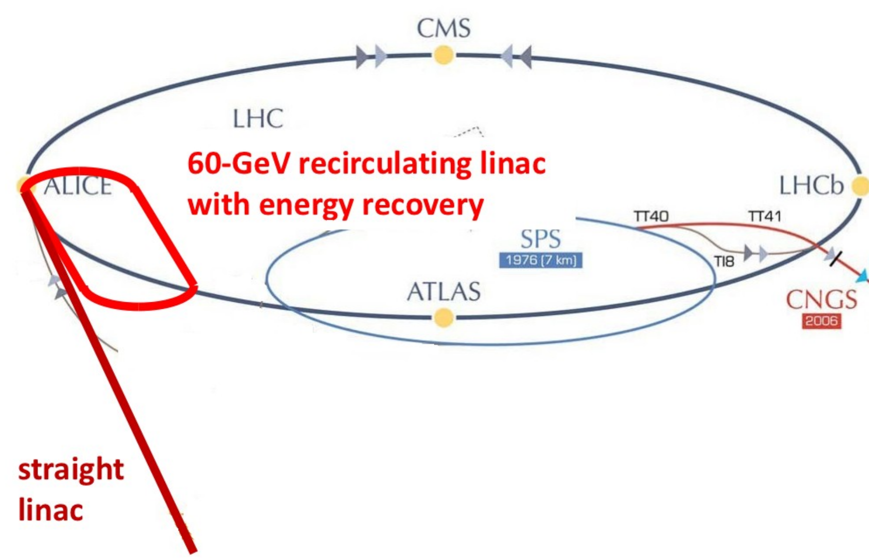


- New injector
  - Increased current
  - Improved injector systems
- Tighter final focus
- Factor 4-10 improvement in luminosity
- Improved statistics for physics

Large electron Hadron Collider

- Probe proton structure function using electron collisions
- 60 GeV electron ring (baseline)
  - In the LHC tunnel
  - Bypass existing experiments
- Linac, then Energy Recovery Recirculating Linac
  - Linac option has high power requirements
  - Recover it by reverse wakefield
  - Prototype at J-Lab, Daresbury, KEK



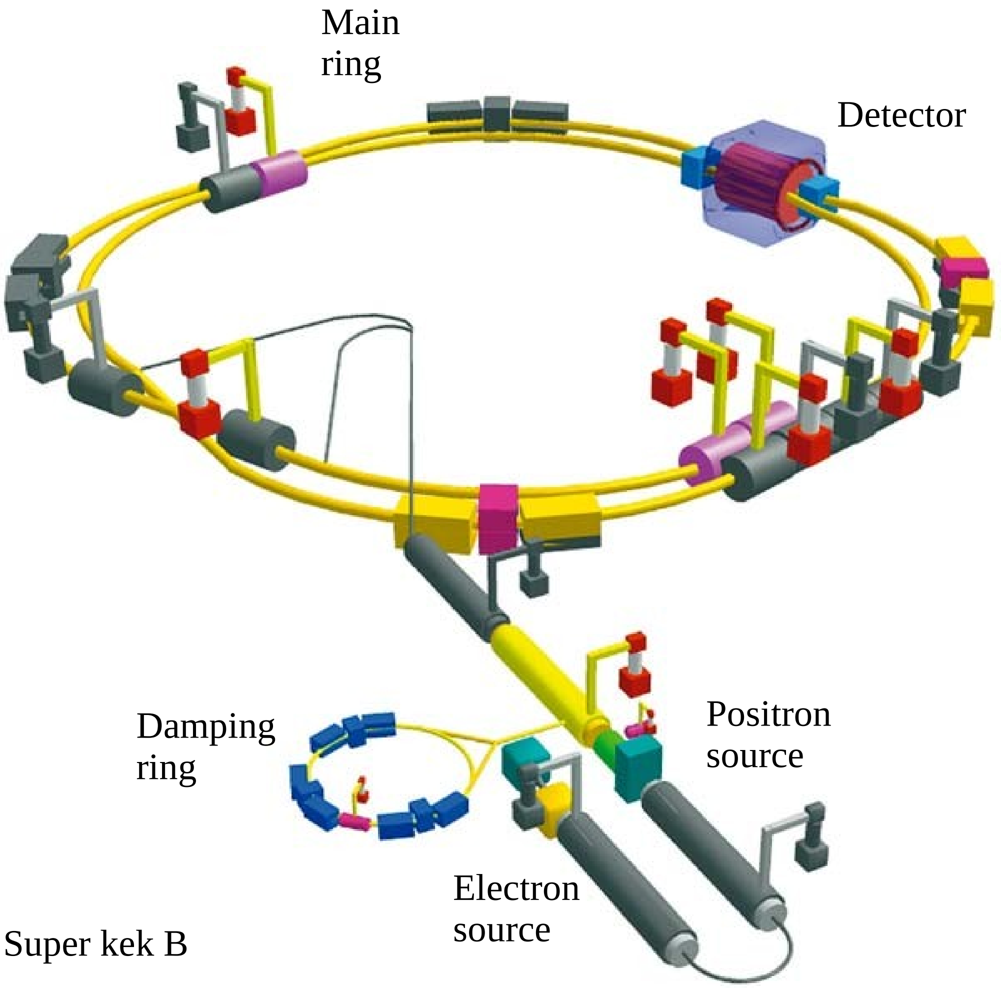


The Proton road

- Proton collider energy is limited by ring circumference
  - Cost ~ tunnel length
  - Energy ~ tunnel length
  - Critical technology is superconducting magnet field strength
  - LHC is at current financial limit?
- Rate limited by injection chain
  - Can detectors handle more rate?

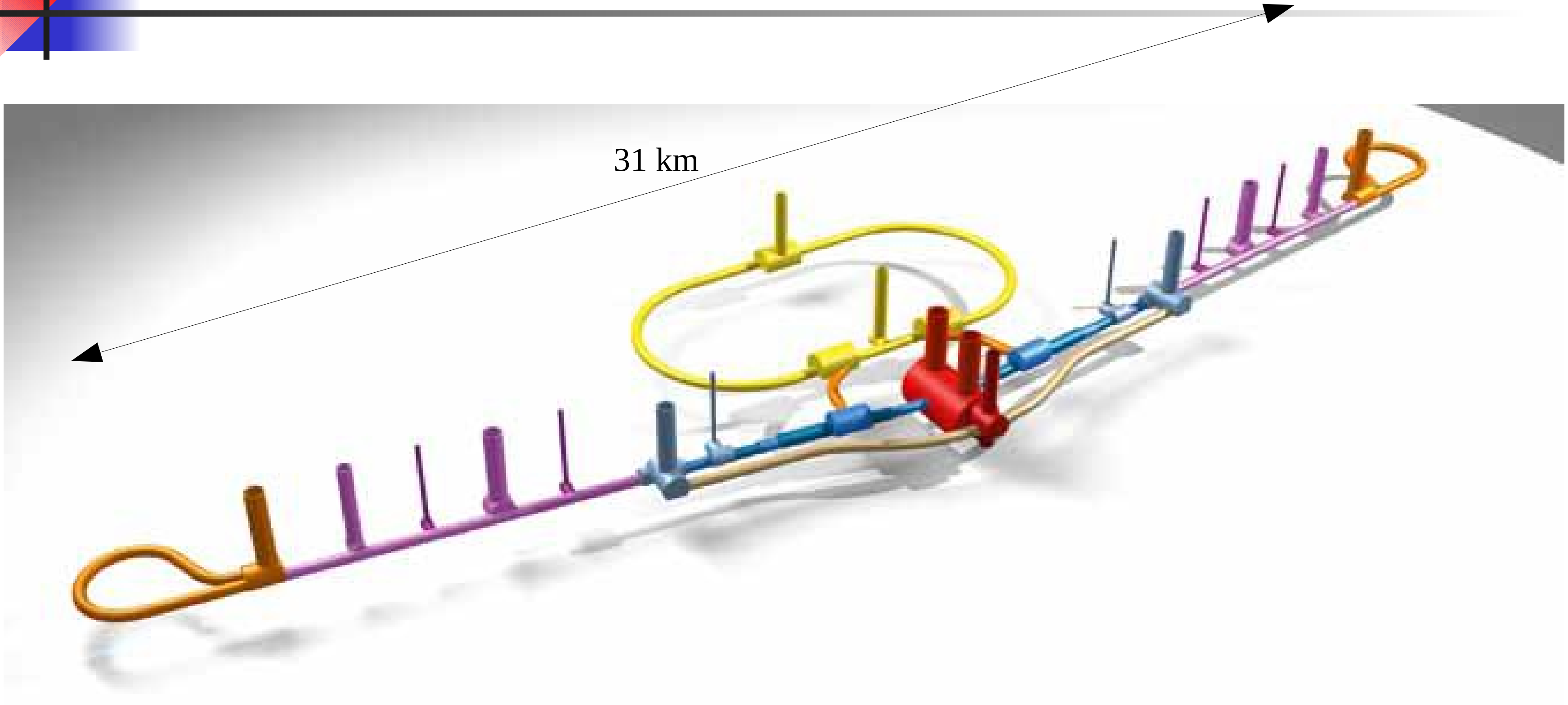
Super B Factories

- Like to look for CP violation and rare processes in B mesons
- Higher luminosity e+ e- colliders
  - More RF to fight longitudinal space charge
  - Tighter focussing at IR
- Super KEK B
- SuperB (Rome)
  - Multiphysics Facility



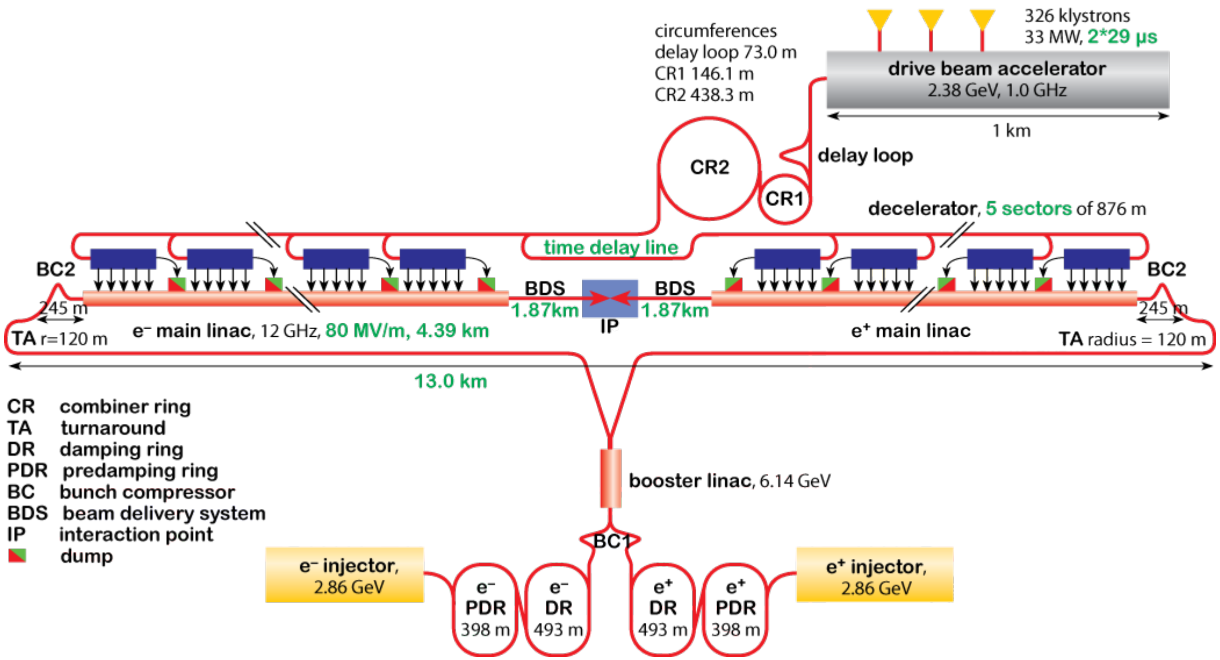
Super kek B

Lepton Colliders



- Lepton colliders for particle physics
  - Monochromatic collisions for Higgs/SUSY factory
  - Two technoligies
    - Superconducting “ILC”
    - Normal Conducting “CLIC”

CLIC



- Superconducting option uses lower frequency RF
  - 1.3 GHz standing wave
- Normal Conducting has higher power requirements
  - Low duty factor => short compact bunches
    - Generate power with drive bunch and travelling wave
  - High frequency 12 GHz => smaller losses per energy gain

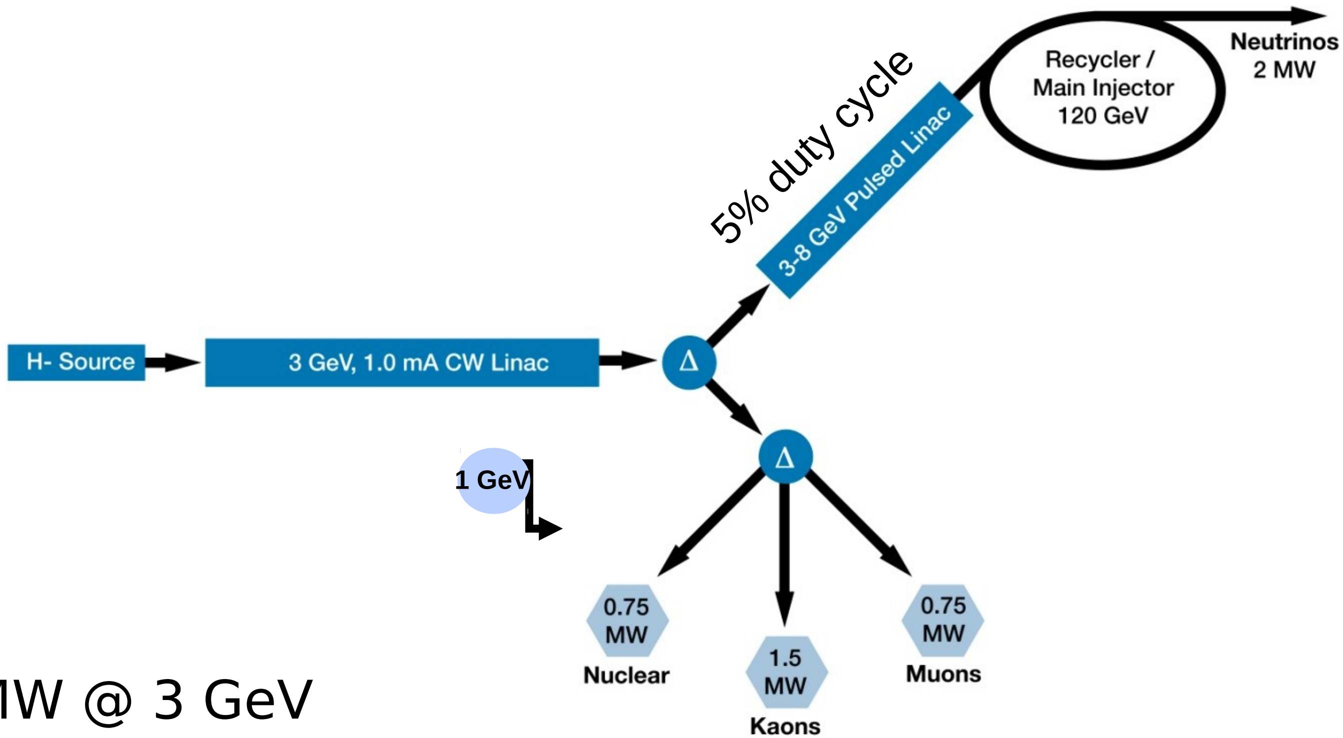
Warm vs cold

- Normal Conducting
  - Small stored energy => strong wakefields
  - Generation of high peak RF power
  - Gradient ~ 150 MV/m
- Superconducting
  - long pulse => low peak power
  - larger stored energy => low wakefield
  - very long pulse train => feedback within train
  - SC structures => high efficiency
  - Gradient limited < 40 MV/m => longer linac

The Electron Road

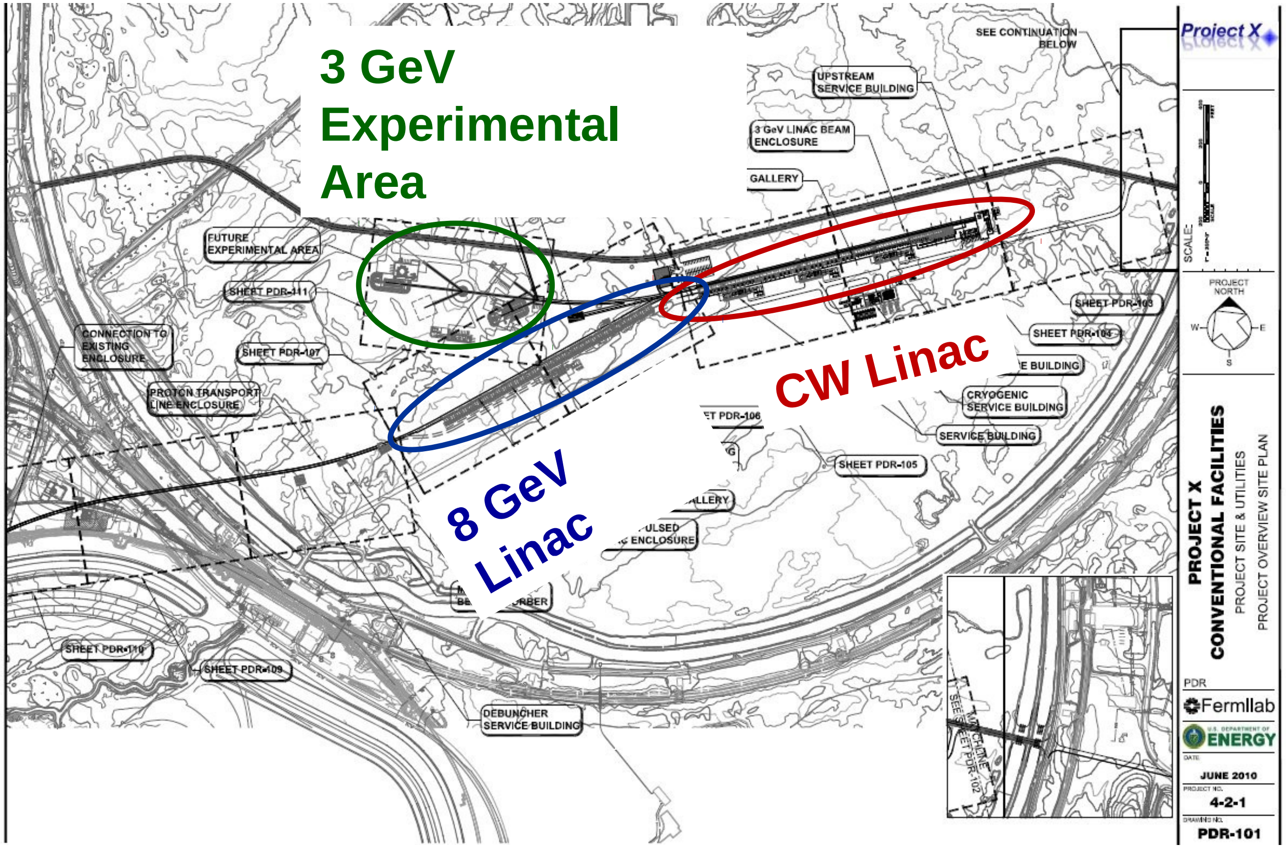
- Electron collider energy is limited by linac length
  - Cost ~ tunnel length
  - Critical technology is available RF gradient
- Electron collider luminosity can be improved by RF field and final focus strength
  - Final focus improved with stronger magnets
  - Current is limited by RF technology

Project X



- 3 MW @ 3 GeV
- 200 kW @ 8 GeV
- 2 MW @ 120 GeV
- Prototype ILC SC RF technology
- Accumulator/compressor upgrade possible for muon accelerator

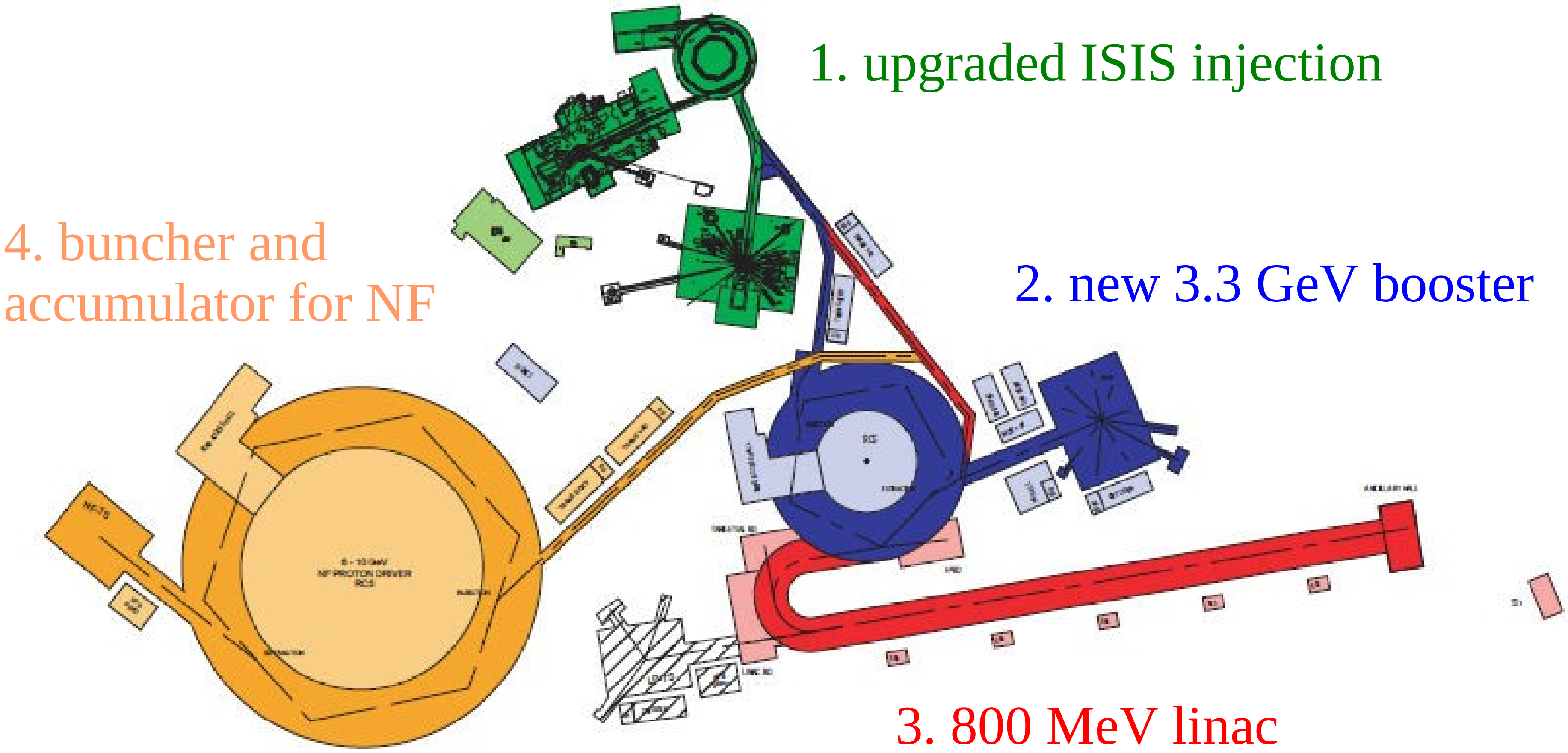
Project X – Site Map



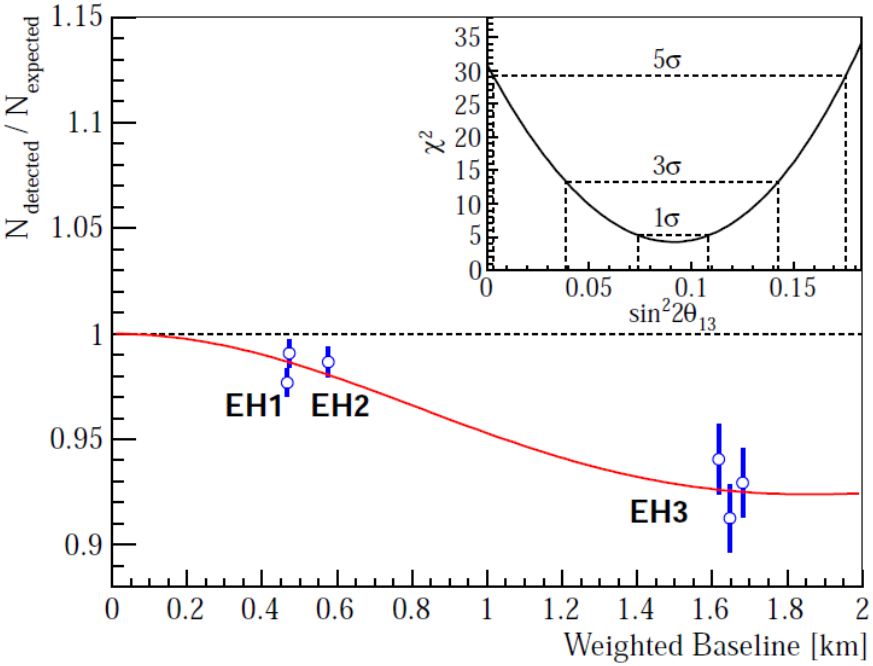
Project X - Hardware R&D Program

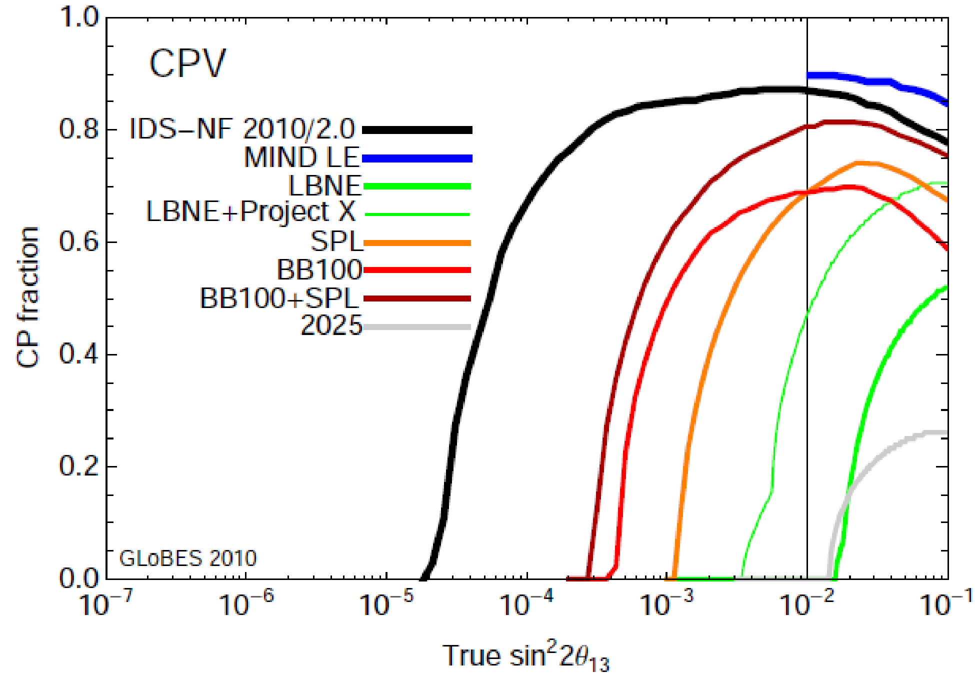
- Goal is to mitigate risk: technical, cost, and schedule
- Primary elements of the R&D program:
  - Development of front end including wide-band chopper
  - Development of an H- injection system
  - Superconducting rf development
    - Cavities, cryomodules, rf sources – CW to long-pulse
    - Development of partners and vendors
  - High Power targetry, including ISOL targets
  - Integrated facility design
    - Physics performance requirements
    - reliability analysis
  - Upgrade paths
  - Test Facilities
- Goal is to complete R&D phase by 2016

ISIS Upgrade Path



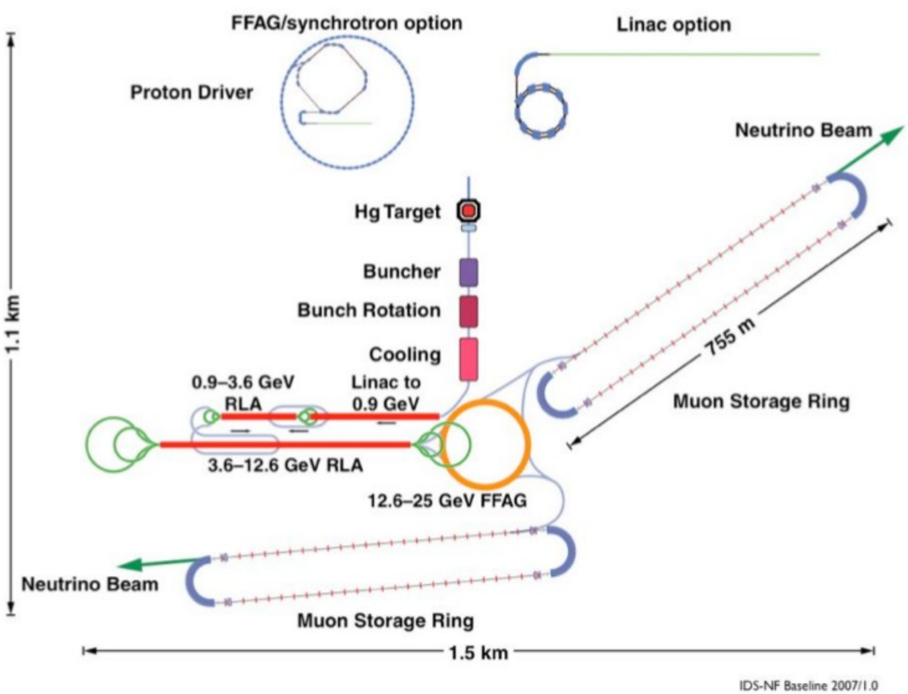
Neutrino Factory - Physics





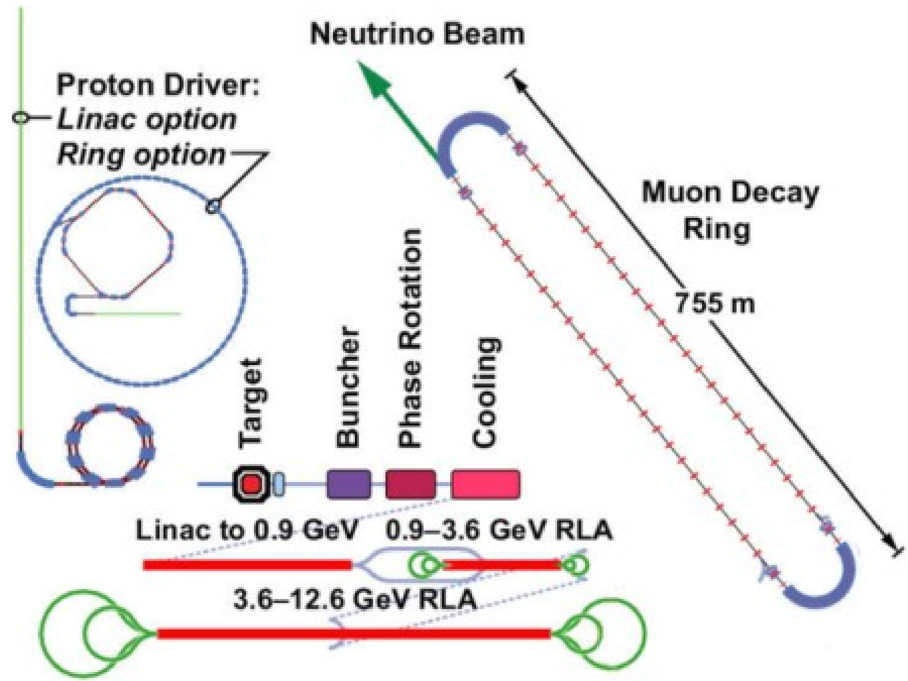
- March 2012 - Discovery of θ_{13}
  - Helps us design an optimal Neutrino Factory
  - Mass hierarchy determination
  - CP violation

Facility – February 2012



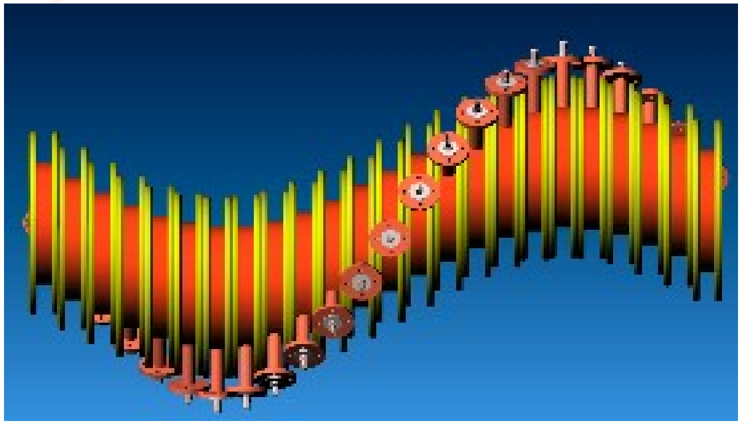
- Baseline swap?

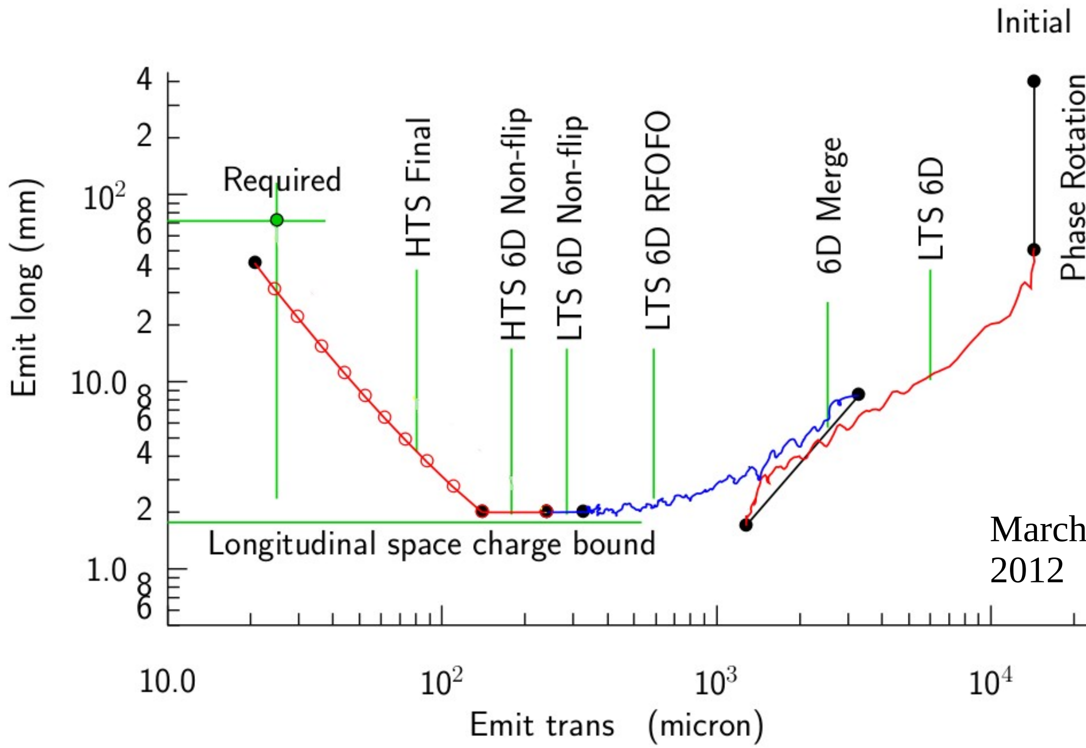
Facility – April 2012?



- 10^{21} neutrinos per year @ 10 GeV
- Challenge to capture muons
  - RF capture and ionisation cooling
- Challenge to accelerate quickly
  - Recirculating linac or FFAG

Muon Collider

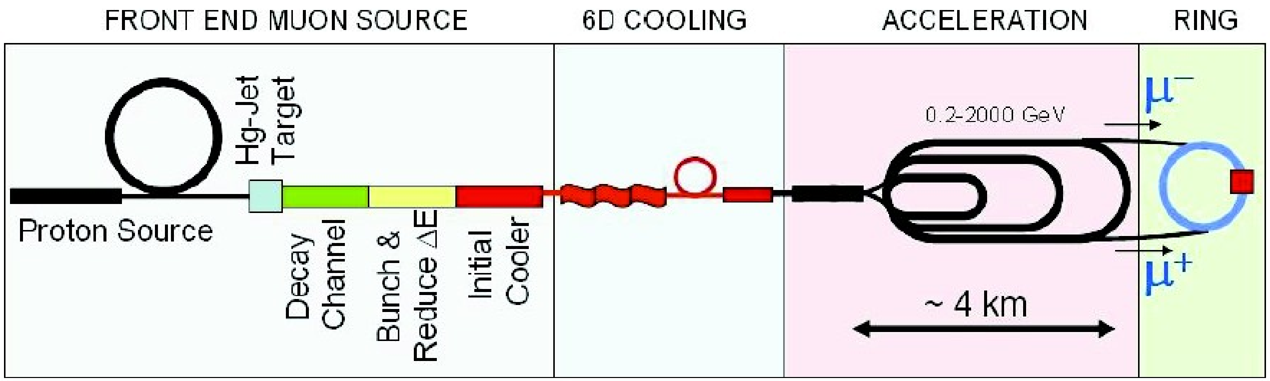




- Muons are born as tertiary particles
- Muon lifetime ~ 2.2 μs
- 1 km mean path at 250 MeV
- Demanding cooling scheme required
  - Magnet and RF challenges

The Muon Road

- A flexible scenario with physics at each stage:



Proton Source:
Upgraded PROJECT X
(4MW, 2±1 ns long bunches)

- μ -> e conversion
- Kaon physics
- EMD electron
- cold muons

10^{21} muons per year which fit within acceptance:

$\varepsilon_\perp \approx 6000\,\mu$m

$\varepsilon_{||} \approx 25$ mm

- neutrino beams to DUSEL

Muon final acceleration

- Neutrino factory
- MC Higgs Factory

Multi-TeV MC

- $\sqrt{s}$ = 3 TeV
- L = 3.5 x 10^{34} cm^{-2} sec^{-1}
- μ/bunch = 2x10^{12}
- circumference = 4.5 km
- σ(p)/p = -0.1%

Muon collider Comparison to CLIC

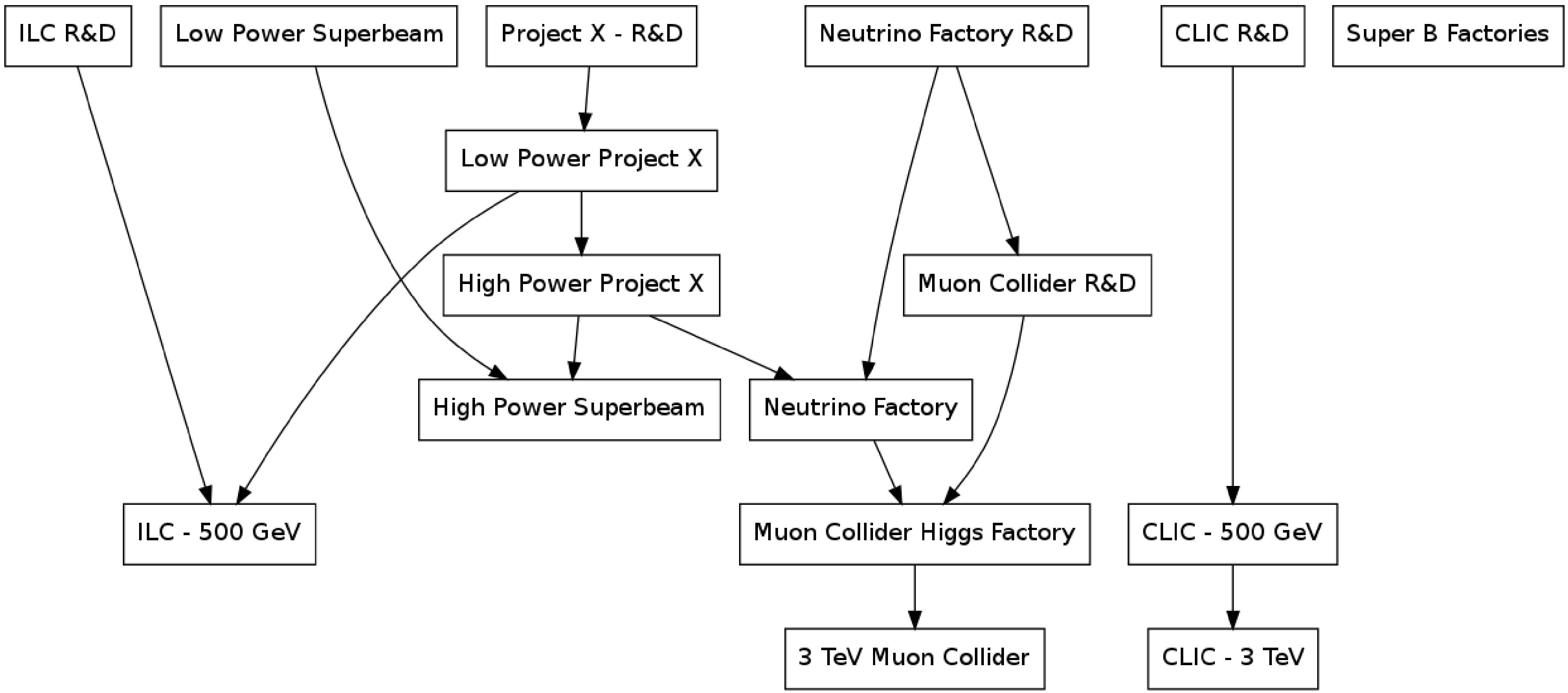
		$\mu^+\mu^-$	e^+e^-
Luminosity	10^{34} cm^{2}sec^{-1}	4	2
Detectors		2	1
β^* at IP $= \sigma_z$	mm	5	0.09
Lepton Trans Emittance	μm	25	0.02
rms bunch height	μm	4	0.001
Total lepton Power	MW	11.5	28
Proton/electron Driver power	MW	4	188
Wall power	MW	140	465

- Muon collider looks appealing compared to e.g. 3 TeV CLIC
  - More luminosity
  - More detectors
  - Less wall power
- But less well developed conceptually

The Muon Road

- Muon collider energy is limited by ring circumference
  - Cost ~ tunnel length
  - Energy ~ tunnel length
  - Critical technology is superconducting magnet field strength
- Luminosity limited by ionisation cooling
  - Critical technology is RF peak field
  - Improved magnetic fields may help with e.g. final focus

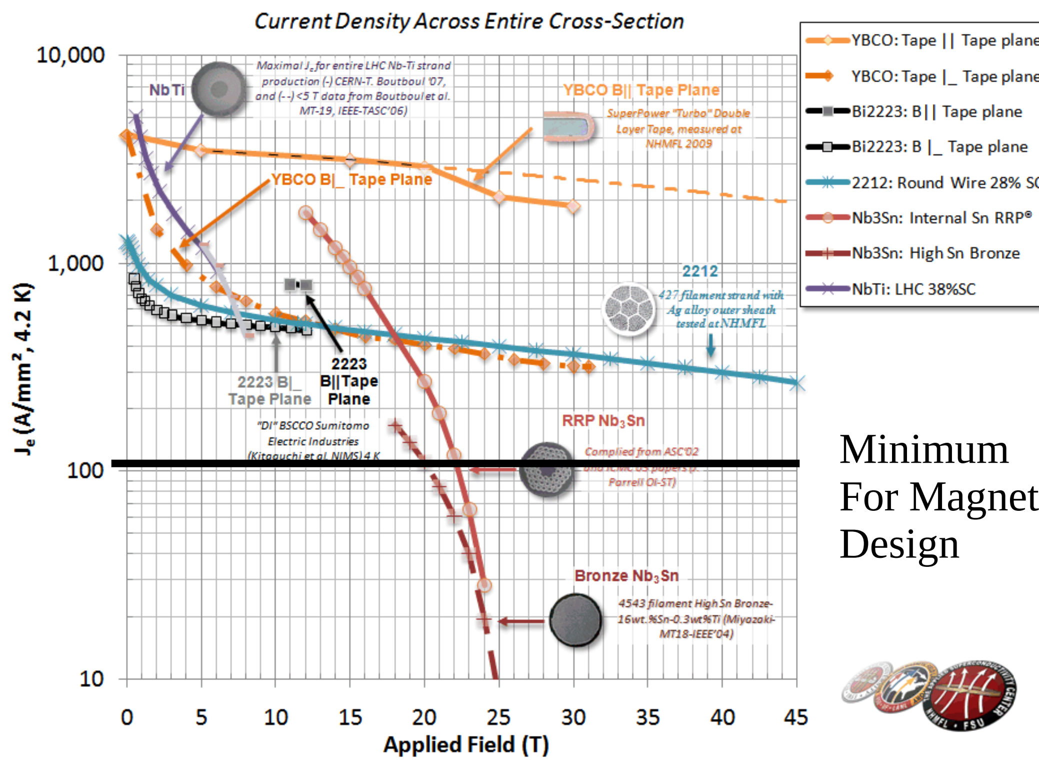
Possible Routes



- Energy frontier looks expensive compared to LHC
  - Muon collider is less expensive but higher risk
    - Mitigate by staging
  - Electron linear collider is more expensive but lower risk

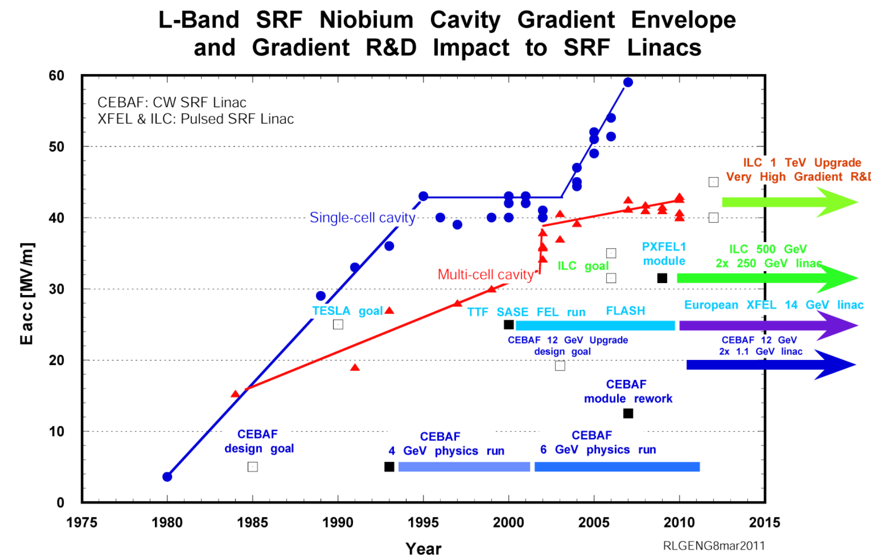
Cost Drivers – Magnets

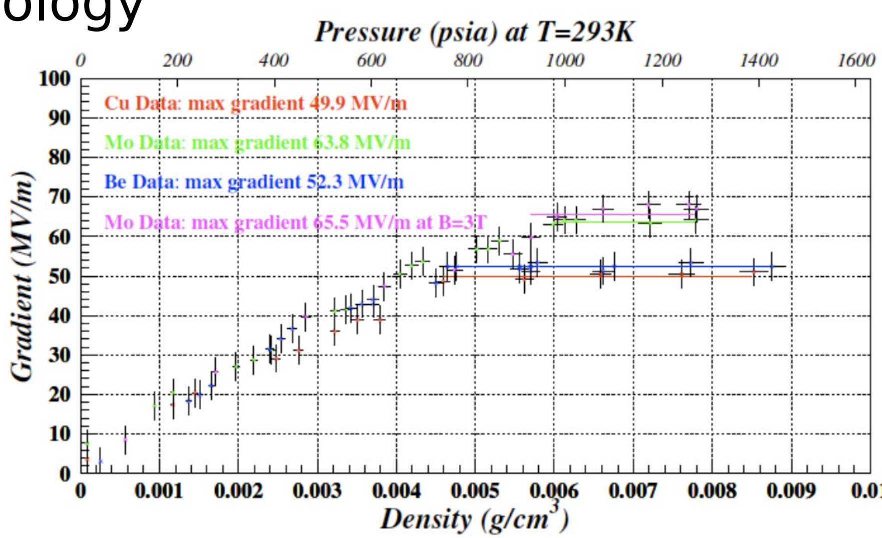
- Improved superconducting (SC) magnets can
  - Improve final focus (higher luminosity)
  - Reduce ring diameters
  - (Muon accelerator) improve ionisation cooling
- “High Temperature” SC development
  - Coils operated in 35 T field
  - Potential for much more
  - Funding limited programme
  - Long lead times

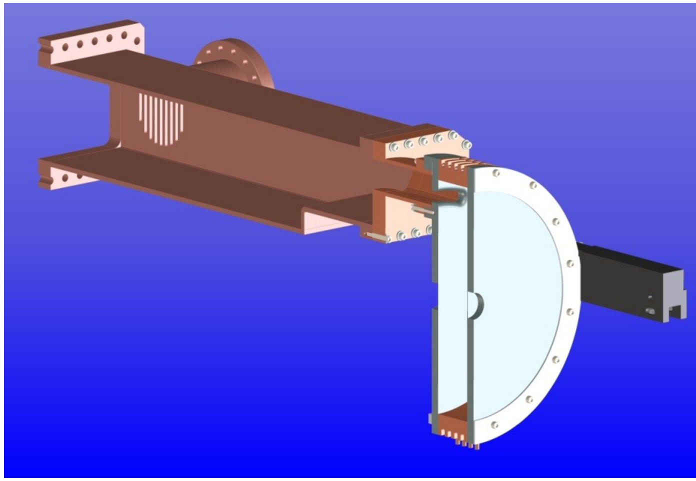


Cost Drivers - RF

- Improved RF can
  - Make linacs shorter
  - (Muon accelerator) improve ionisation cooling
- ILC focus on SC industrialisation @ 1.3 GHz
- MC focus on NC breakdown mechanism and novel technology







The Energy and Intensity Frontier?

- Pushing the energy frontier beyond the LHC is not a given
  - Even reaching the same energy with leptons looks hard
  - Limited by underlying technology and cost
    - Needs development
    - Long lead times
- Intensity frontier is probably more fun
  - Lots of small, interesting experiments
  - Upgradable to the energy frontier… if you really want
  - Collaboration with non-HEP