FUTURE ACCELERATORS

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*** with contributions from M.Palmer and D.Denisov**

Fermilab, Batavia, IL , USA

APS DPF, Ann Arbor, MI

August 8, 2015

Future Accelerators

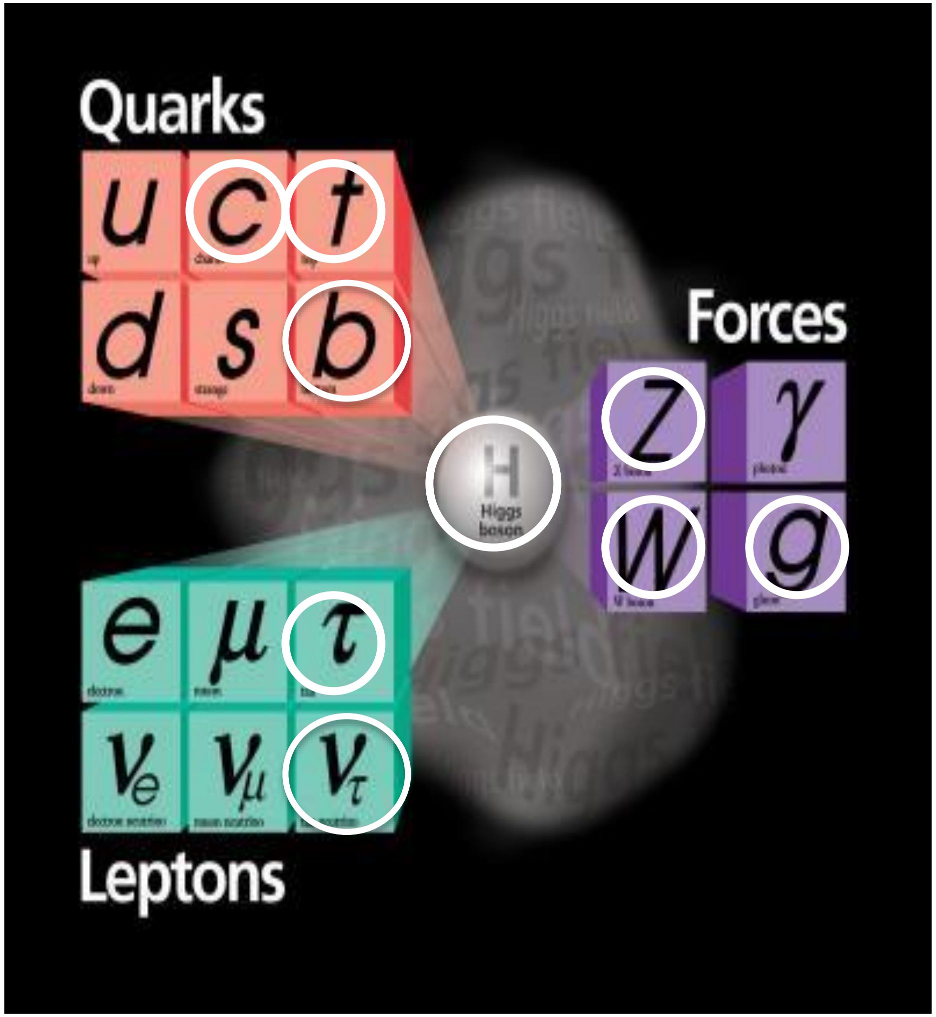
ENERGY FRONTIER COLLIDERS

LHC, HL-LHC, ILC, CepC, FCC-ee, SppC, FCC-pp, Muon-C, plasma

INTENSITY FRONTIER ACCELERATORS

FNAL MI, CNGS, JPARC, PIP-II, PIP-III, Neutrino Factory, …

Accelerators and the Standard Model

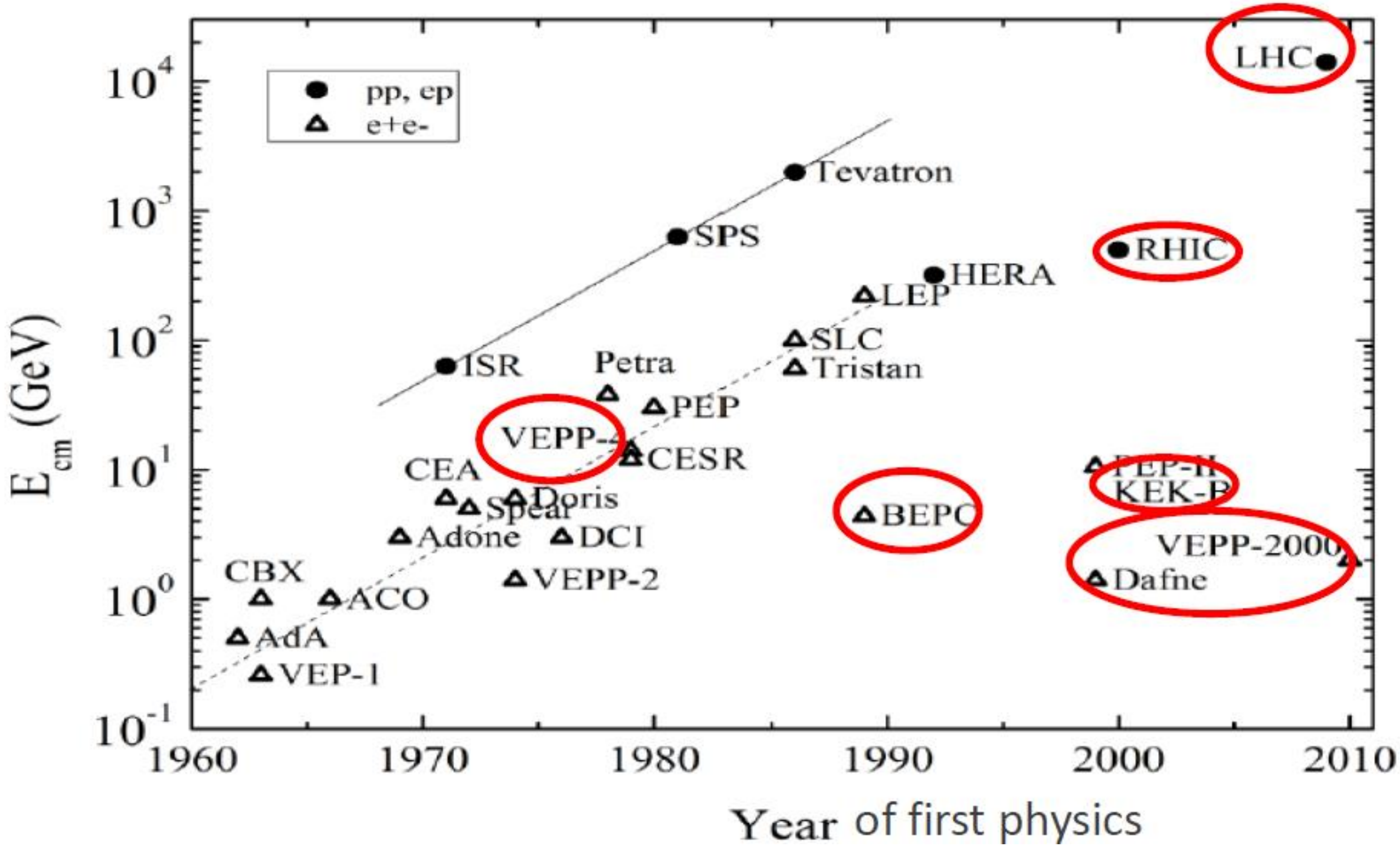


- Progress in particle physics over the past 40 years was closely related to discoveries at ever more powerful colliders
  - e^+e^- colliders
    - c quark, tau lepton, gluon

      (c quark also at AGS/BNL)
  - Use of antiprotons in the same ring as protons
    - W and Z bosons
  - Advent of Superconducting magnets
    - Top quark and the Higgs boson
- Discovered at fixed target experiments
  - b-quark and tau neutrino, at Fermilab
- All expected Standard Model (SM) particles have been discovered and the SM complete!
  - One of mankind's magnificent intellectual achievements!

At every step new accelerator ideas provided less expensive ways to get to higher beam energies and higher luminosities

Operating or Soon-to-be Operating Colliders



- 29 colliders built over 50 years
- At present: single high energy hadron collider – the LHC, now at 13 TeV
  - RHIC at BNL – nuclear physics studies
- DAFNE (Frascati), VEPP (Novosibirsk), BEPC (Beijing) – low energy e+e- colliders
- SuperKEK-B – b-factory at KEK to restart in 2016 with ~40 times higher luminosity
  - studies of particle containing b-quarks

Physics Goals and Challenges of Future Colliders

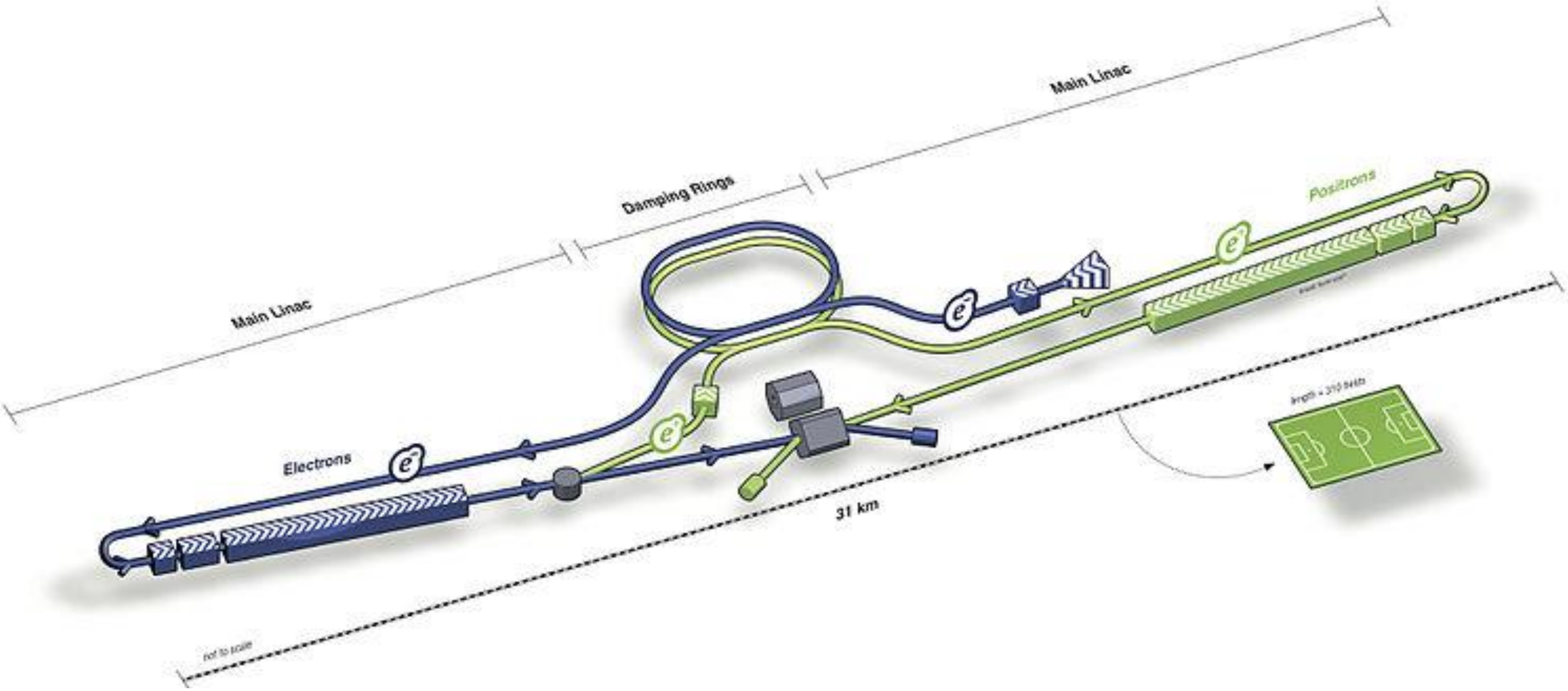
- Physics interests drive collider development
  - e.g., colliding antiprotons in the already existing ring of SpS at CERN leading to the discovery of W and Z bosons
- Today there are two areas where new colliders are especially important
  - "Higgs factory" – a collider (most probably e^+e^-) with a center of mass energy of 250 GeV and above and high luminosity to do precision studies of the Higgs boson
  - "~100 TeV" pp collider to get to the "next energy frontier" -- an order of magnitude above the LHC
    - Study distances down to $\sim 10^{-19}$ cm; discover and study particles masses up to ~50 TeV; complete elucidation of EWSB
- Both of the above options highlighted by the recent P5 panel report
- Challenges in building next generation of colliders
  - Progress in new acceleration methods has been relatively slow
  - Colliders are becoming rather expensive and require long time to build

Medium-Term Future Collider Projects

- **ILC - International Linear Collider**
  - 500 GeV linear e^+e^- collider (upgradable to 1 TeV)
  - Higgs factory (and top quark factory)
  - Location – Japan
  - Start of construction ~2019
  - Estimated cost ~$10B
- **CEPC – Circular Electron Positron Collider**
  - ~250 GeV circular e^+e^- collider (the tunnel could be later used for pp collider)
  - Higgs factory
  - Location – China
  - Start of construction ~2021
  - Estimated cost ~$3B
- **FCC – Future Circular Colliders**
  - 350 GeV e^+e^- and/or ~100 TeV pp
  - Higgs factory and/or next energy frontier
  - Location - CERN
  - Start of construction – ?
  - Estimated cost - ?

Fermilab

International Linear Collider

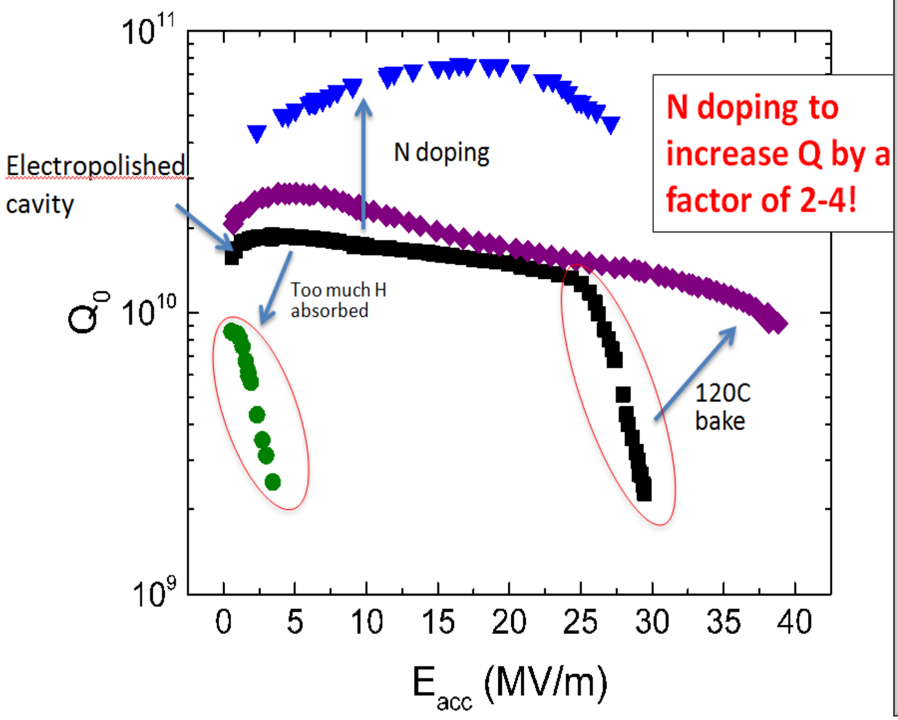


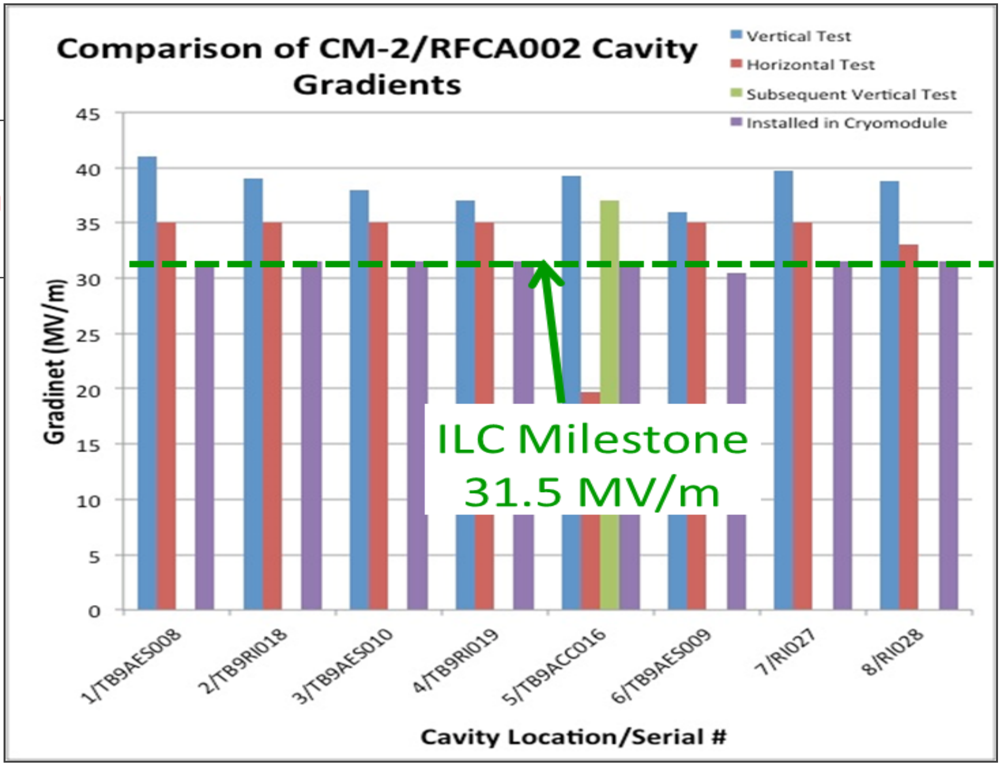
- ILC or International Linear Collider is an e^+e^- linear collider with the following main parameters
  - Center of mass energy ~500 GeV
  - Luminosity >10^{34} $cm^{-2}s^{-1}$
- No synchrotron radiation, but long tunnel to accelerate to ~250 GeV/beam
  - Excellent Higgs factory with many Higgs production and decay channels accessible
- Endorsed by P5

* see also J.Brau's talk Tuesday

ILC: Super-Conducting RF Progress at Fermilab

- **SCRF accelerating cavities**
  - Synergy with PIP-II and LCLS accelerating cryomodules
- R&D in accelerator systems, including controls





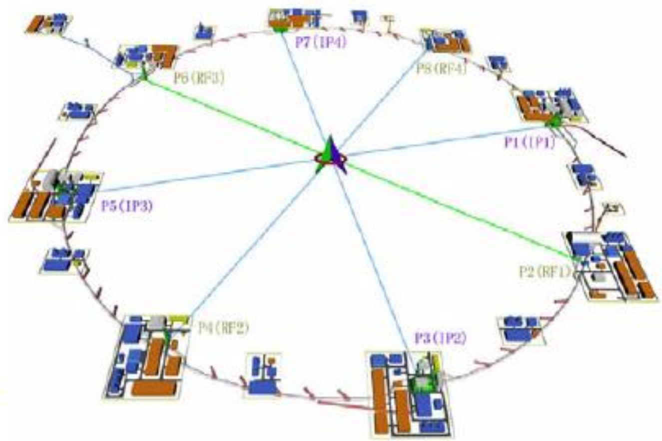
- Two excellent results for SCRF cavities obtained at Fermilab recently
  - Substantial **Q factor increase** of the cavities with nitrogen doping
  - Fermilab's cryomodule reached ILC specification of 31.5 MV/m

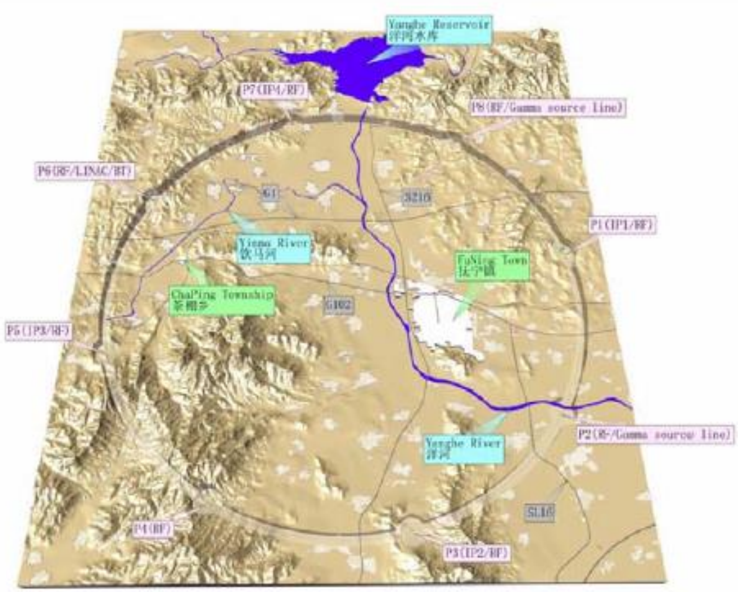
ILC Status and Plans

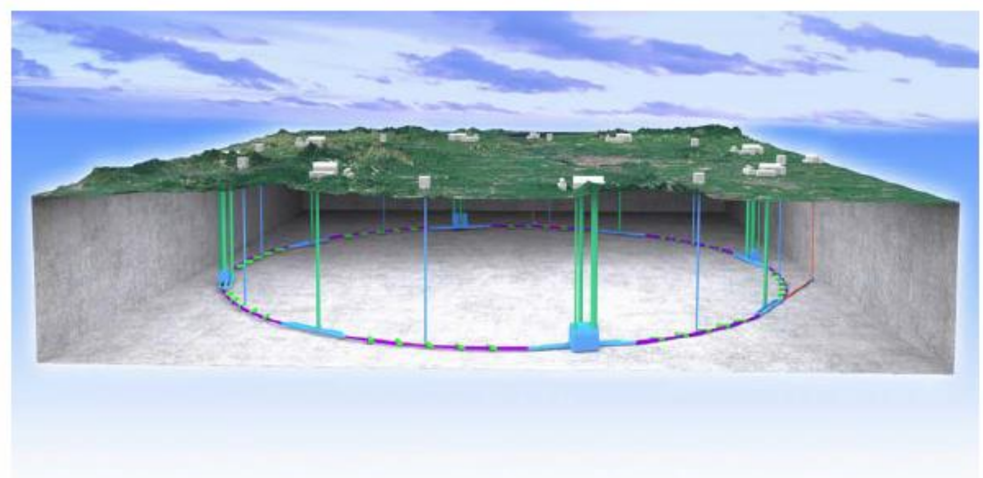
- After success of SLAC's linear e^+e^- collider in 1990's (SLC) various proposals developed to go to even higher colliding energy
  - Among them NLC(SLAC), TESLA(DESY), "ILC at Fermilab"
- Starting in 2008 Global Design Effort (GDE) progressed developing
  - Technical design of the ILC
  - Cost estimate and international cooperation plan
- GDE concluded in 2012
  - Delivered TDRs for the accelerator and detectors
  - Physics case strengthened with a Higgs discovery
- In 2012 Japan expressed strong interest to host the ILC
- Over the last two years
  - Substantial progress in technical developments
  - Development of cooperation between participants on "Governments level"
- All involved agree that ILC should be an international project with Japan as the host country
  - Challenges in establishing high level agreements between countries substantial
  - Funding for this international project, including in Japan, has to be "in addition to the existing particle physics funding"

Proposals for Colliders in China: CepC and SppC

- CEPC – Circular Electron Positron Collider
  - ~50 km long ring
  - 90-250 GeV in the center of mass
  - Z boson and Higgs factory
- SPPC – Super Proton Proton Collider
  - In the same ring as CEPC
  - ~50 TeV with 12 T magnets, ~70 TeV with 20 T

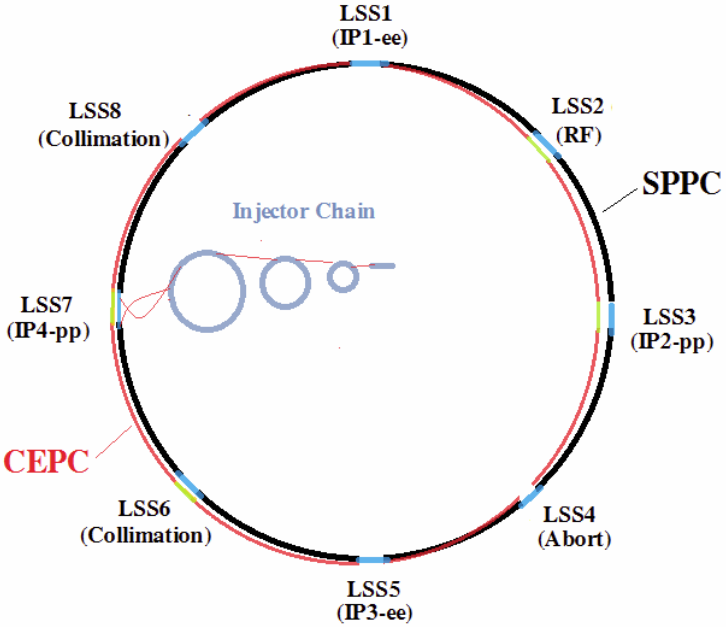






Future Colliders in China

- Very active progress with the CEPC and SPPC design over last two years
  - International reviews of the conceptual proposals in Spring of 2015 (positive)
- Plan is to get funding for detailed technical design report by later this year
  - ~$50 million per year effort
  - TDR to be completed by 2020
- Construction of CEPC to start in 2021
  - Complete in 2027
  - Data collection 2028-2035
- SPPC time line
  - Design 2020-2030
  - Construction 2035-2042
  - Physics at ~70 TeV starting in 2043
- The proposal is based on
  - Experience with BEPC e^+e^- collider
  - Relatively inexpensive tunneling in China
  - Strong Government interest in scientific leadership – both CEPC and SPPC are "national projects with international participation"
  - Setting realistic goals based on the expected availability of resources



FCC - Future Circular Colliders

- FCC activity follows the European particle physics strategy recommendation to develop future energy frontier colliders **at CERN**
  - "…to propose an ambitious post-LHC accelerator project….., CERN should undertake design studies for accelerator projects in a global context,…with emphasis on proton-proton and electron-positron high-energy frontier machines.…."
- There are three options in ~100 km long tunnel
  - pp collider with energy of ~100 TeV
  - e^+e^- collider with energy of ~350 GeV
  - ep collider
- Similar to "LEP then LHC" option of starting from 350 GeV e^+e^- collider and later going to 100 TeV pp collider is considered
  - But in no way decided

FCC pp 100 TeV Collider

Parameter	FCC-pp	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP_{main} [$cm^{-2}s^{-1}$]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25

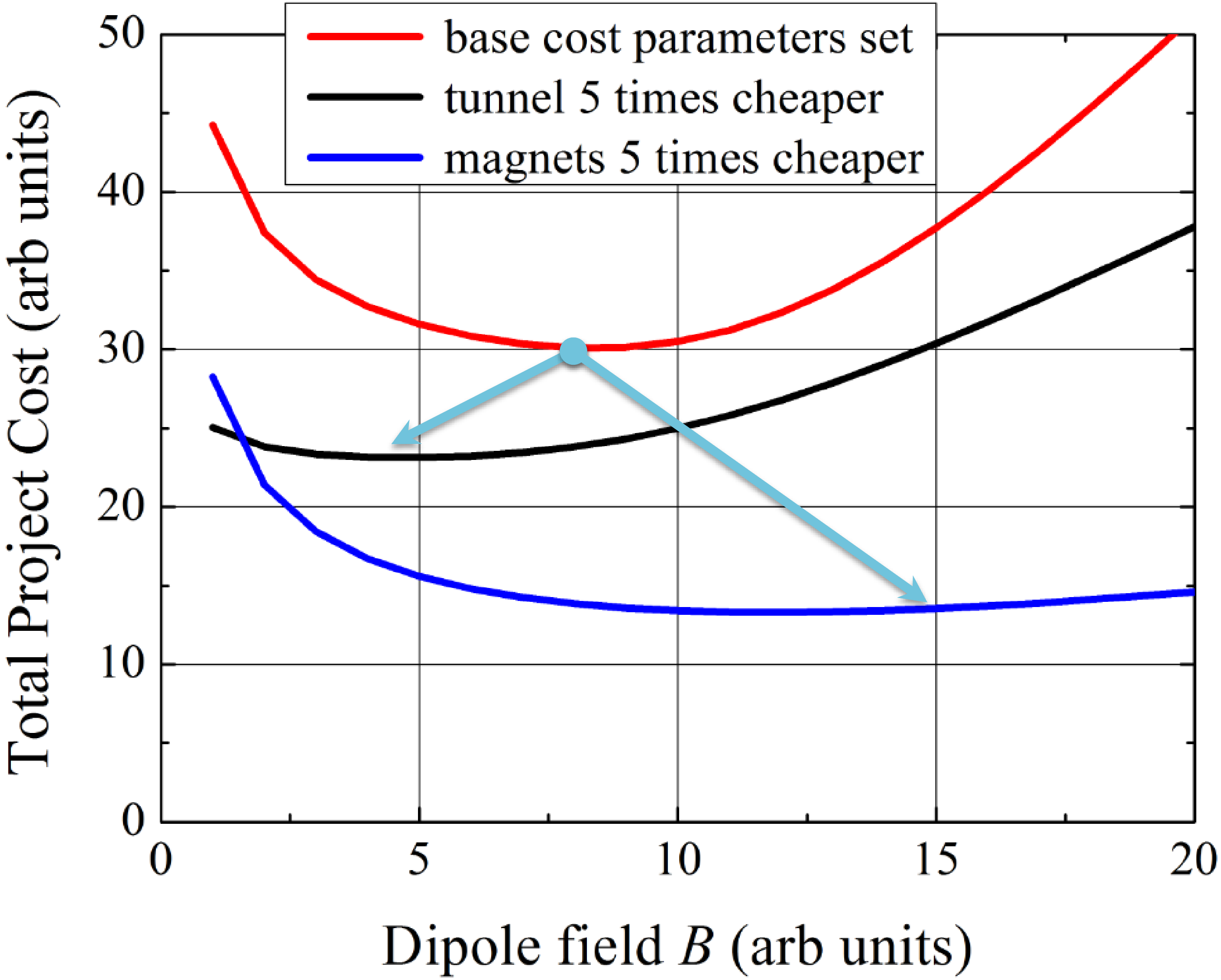
Main challenges

- Long tunnel — LHC x4
- High field magnets — LHC x2
- High synchrotron radiation load — LHC x100
- Cost — LHC x??

Tevatron and LHC experience demonstrate technical feasibility of such a collider

100 TeV *pp* Cost Feasibility Calls for Extensive R&D on High Field Superconducting Magnets

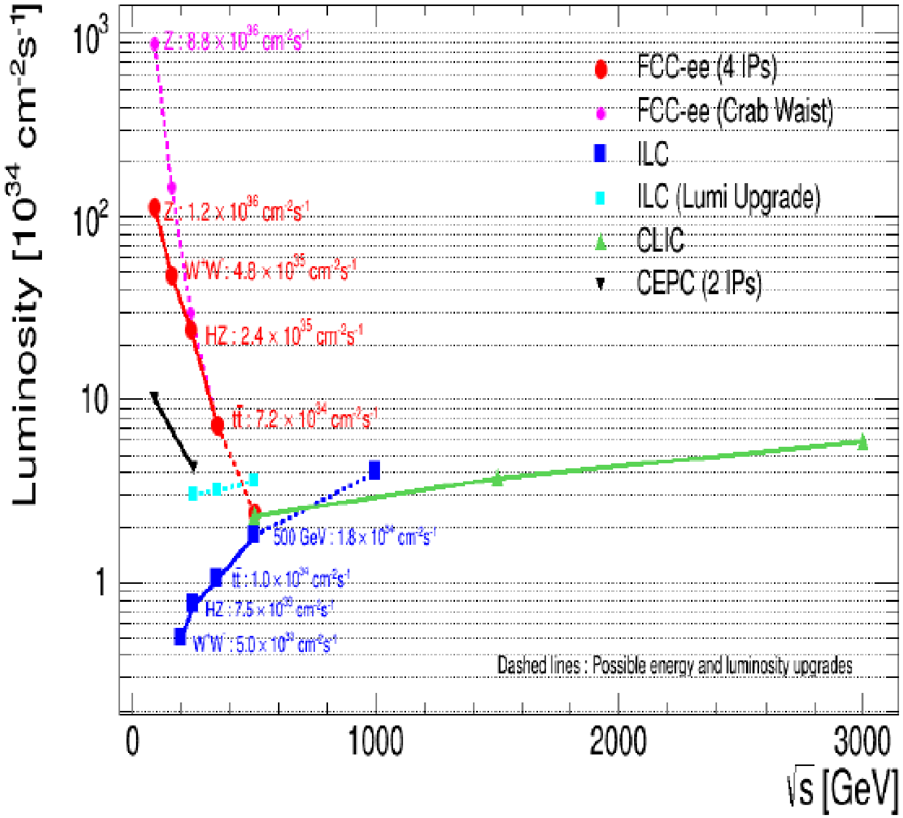
Qualitative Cost Dependencies



* see also V.Shiltsev talk Tuesday

* for illustration purposes only

FCC e+e- Collider



Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000-60000	500-1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} cm^{-2}s^{-1}	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.3-2.5	3.6-5.5	11	3.5

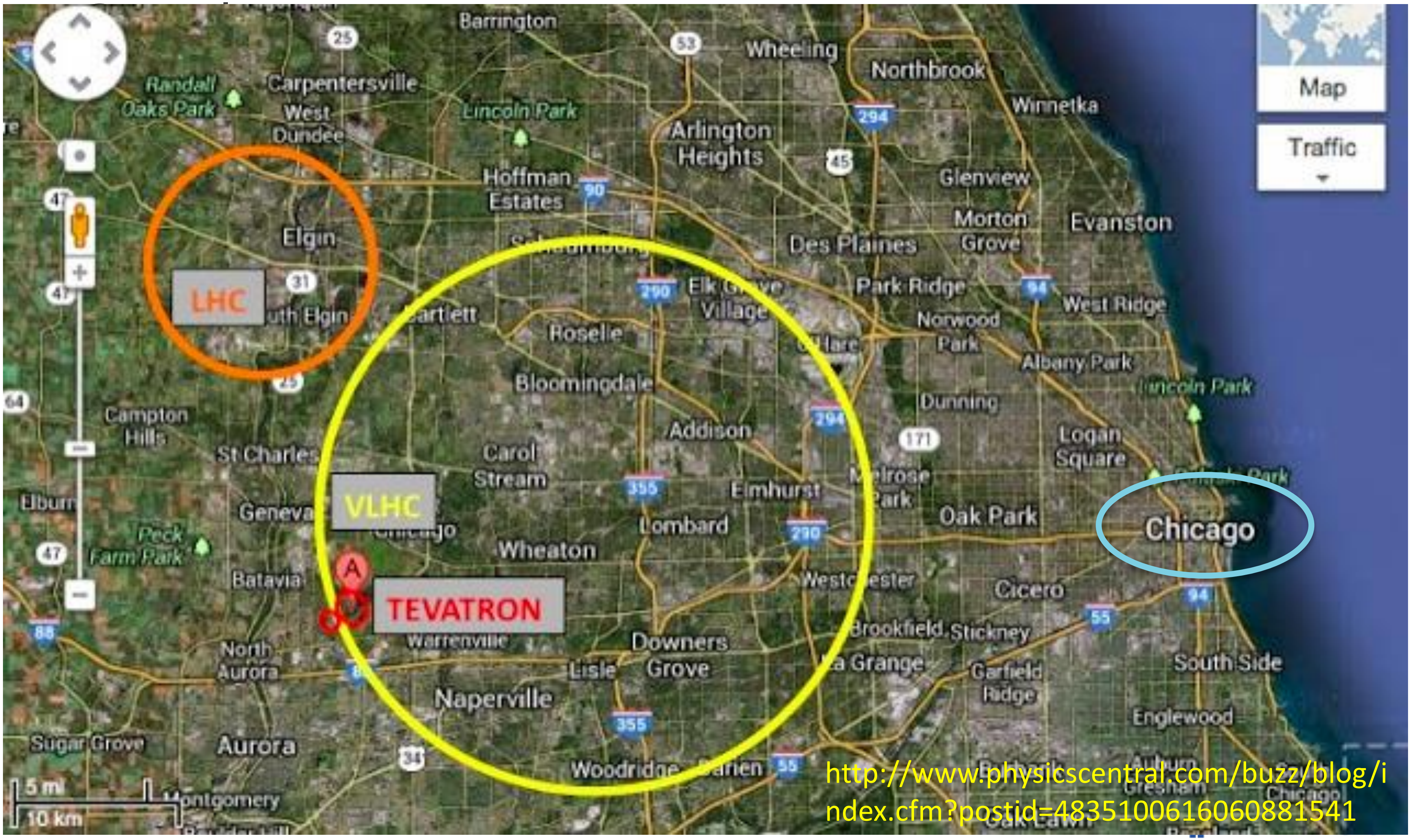
- Circular e_+e_- collider has substantially higher luminosity at lower energies compared to the linear collider
- Main challenges: long tunnel and high synchrotron losses requiring demanding superconducting RF system and high electricity consumption

FCC study is expected to provide by 2018 the CDR proposal and cost estimates for all three options: *pp*, *ee* and *ep*

100 km VLHC/VLEP

http://arxiv.org/pdf/1306.2369v1.pdf

PhysicsCentral Blog

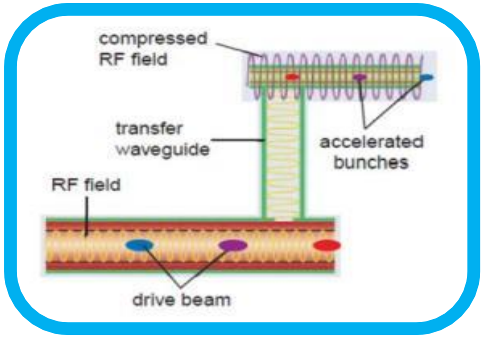


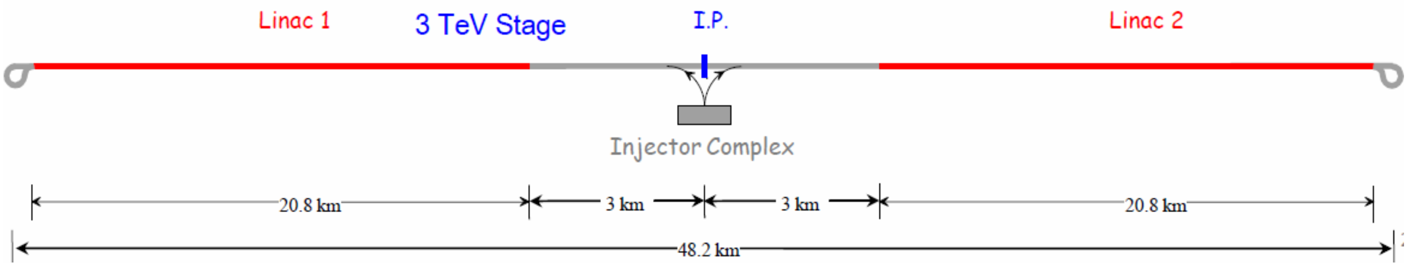
http://www.physicscentral.com/buzz/blog/index.cfm?postid=4835100616060881541

See Thursday talk by P.C. Bhat

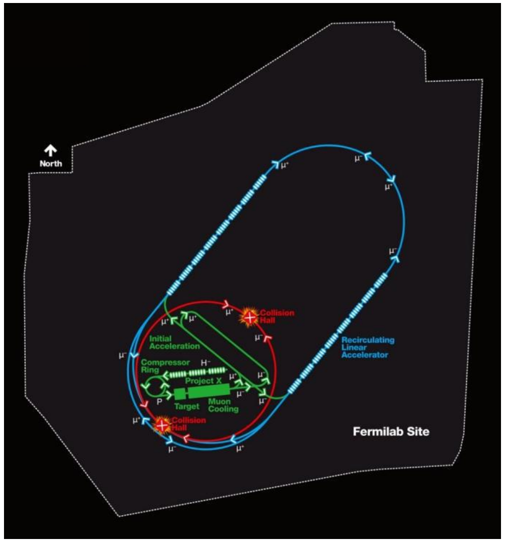
Multi-TeV Lepton Colliders (shelved for now)

- **CLIC – Compact Linear Collider** (CERN)
  - Based on two-beam acceleration in NC RF
  - 100 MV/m gradients demonstrated
  - about 50 km long for 3 TeV *e+e-*
  - ~600 MW power for 3 TeV *e+e-* prohibitive

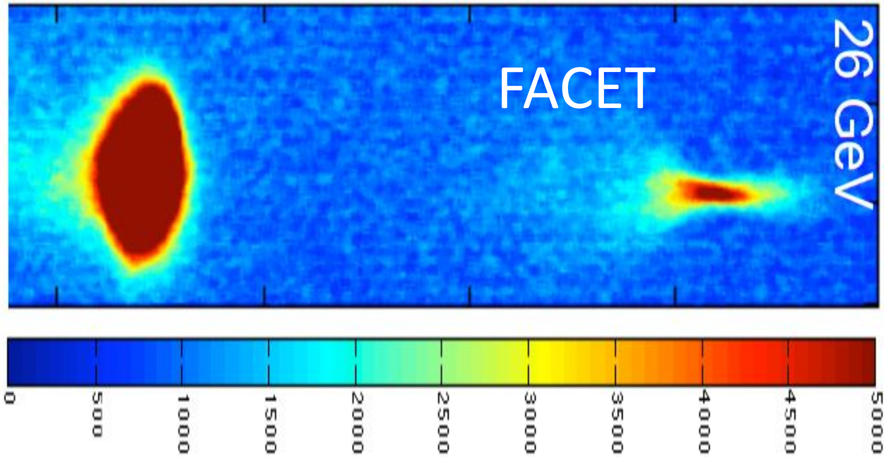


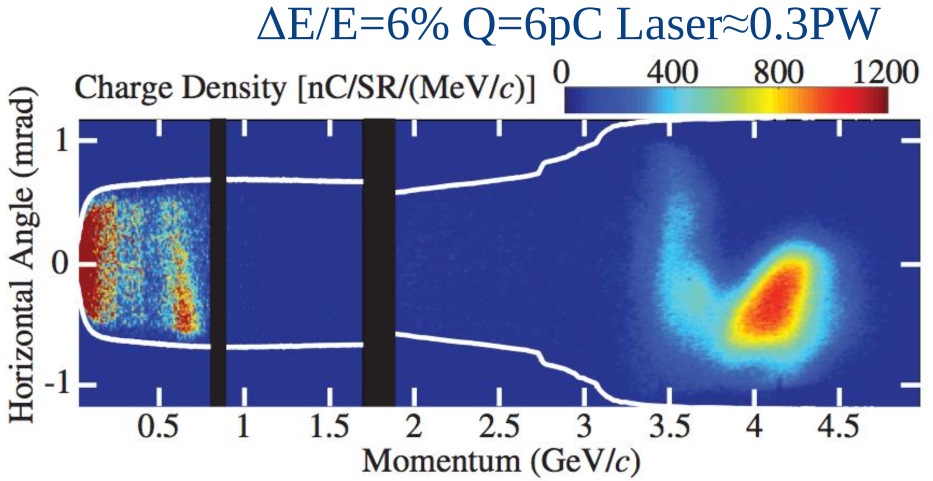


- **Muon Collider (US)**
  - Traditional technologies (SC Mag, SC RF)
  - Compact (circular) and power savvy
    - 3-6 TeV μμ fits on Fermilab site, 230 MW
  - Needs powerful proton complex p→π→μ
    - like CERN's or Fermilab's
  - P5 recommends not continue μ-Coll effort
    - Muon cooling be demonstrated at RAL in 2017



Promise of Plasma Wakefields





Option A (SLAC, UCLA):
Short intense e-/e+/p bunch
Few 10^{16}cm^{-3}, **6 GeV** over 1m

Option B (LBNL, UT Austin):
Short intense laser pulse
~10^{18}cm^{-3}, **4.2 GeV** over 9 cm

Attempts to conceptualize "Plasma-Collider" designs reveal serious challenges (R&D items):

See session on advanced acceleration Techniques Thursday afternoon

- Staging results in low average gradients of "only" 2-5 GeV/m
- *Beamstrahlung* formidable at >3 TeV
- Emittance control, luminosity, power efficiency, length, drivers…

…Still, some believe that ultimate 1000 TeV accelerator will be *linear plasma (crystal) muon* collider (see V. Shiltsev talk Tuesday)

Intensity Frontier Accelerators

- To explore the physics of rare particles and/or rare processes
  - E.g. neutrinos, muon/kaon decays, etc
- Different merit matrix from colliders – instead of fb^{-1} of $\int L dt$:

P5 goal 600 MW*kTon*years for Long-baseline Neutrino Exp't

PIP-II — Beyond PIP-II (mid-term)

	1st 10 years	2nd 10 years		
To Achieve :	100 kT-MW-year	500 kT-MW-year		
We combine :		Option 1	Option 2	Option 3
Mass	10 kT	50 kT	20 kT	10 kT
Power	1 MW	1 MW	2.5 MW	5 MW

- Thrust for MegaWatts of beam power → challenges:
  - High intensity sources
  - Efficient acceleration without losses
  - Halo control and collimation
  - Advanced injection and extraction
  - Novel high-power beam targets and focusing systems
  - Cost efficient accelerator ***MW/$$*** vs detector ***kTons/$$***

Present & Future IF Accelerators

300+ kW JPARC (Japan)

400+ kW CNGS (CERN) ⟵ Not active now

500+ kW Fermilab's Main Injector

EVOLUTION OF INTENSITY FRONTIER ACCELERATORS

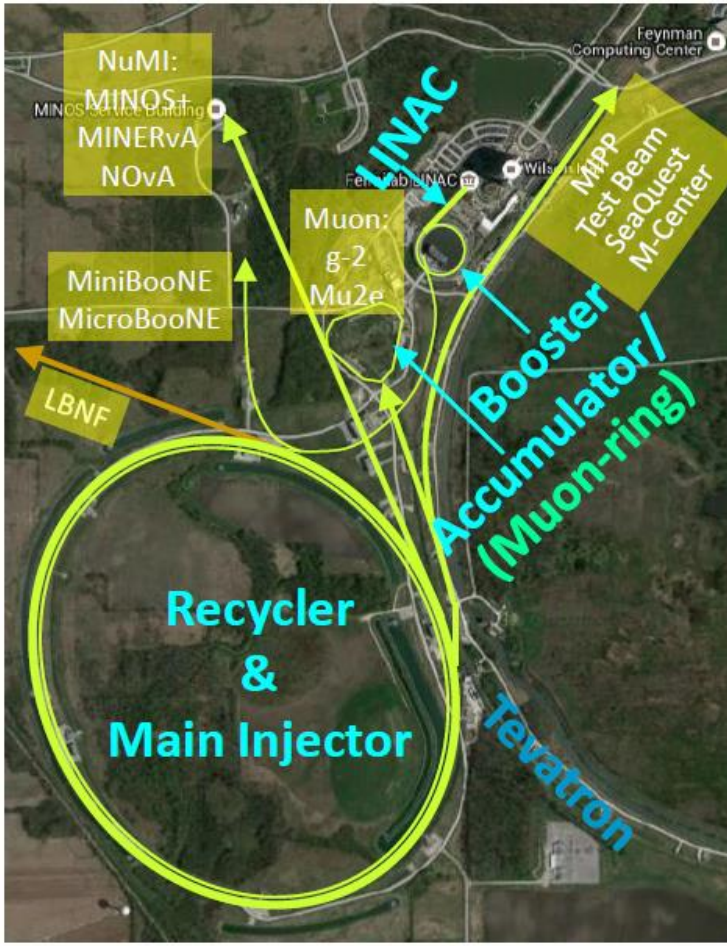
700+ kW Proton Improvement Plan (PIP, FNAL, 2017)

1.2+ MW Proton Improvement Plan-II (ca 2023)

2.5 MW → 5 MW?

Proton Improvement Plan-III (?, under study)

Fermilab, US Premier Particle Physics Lab

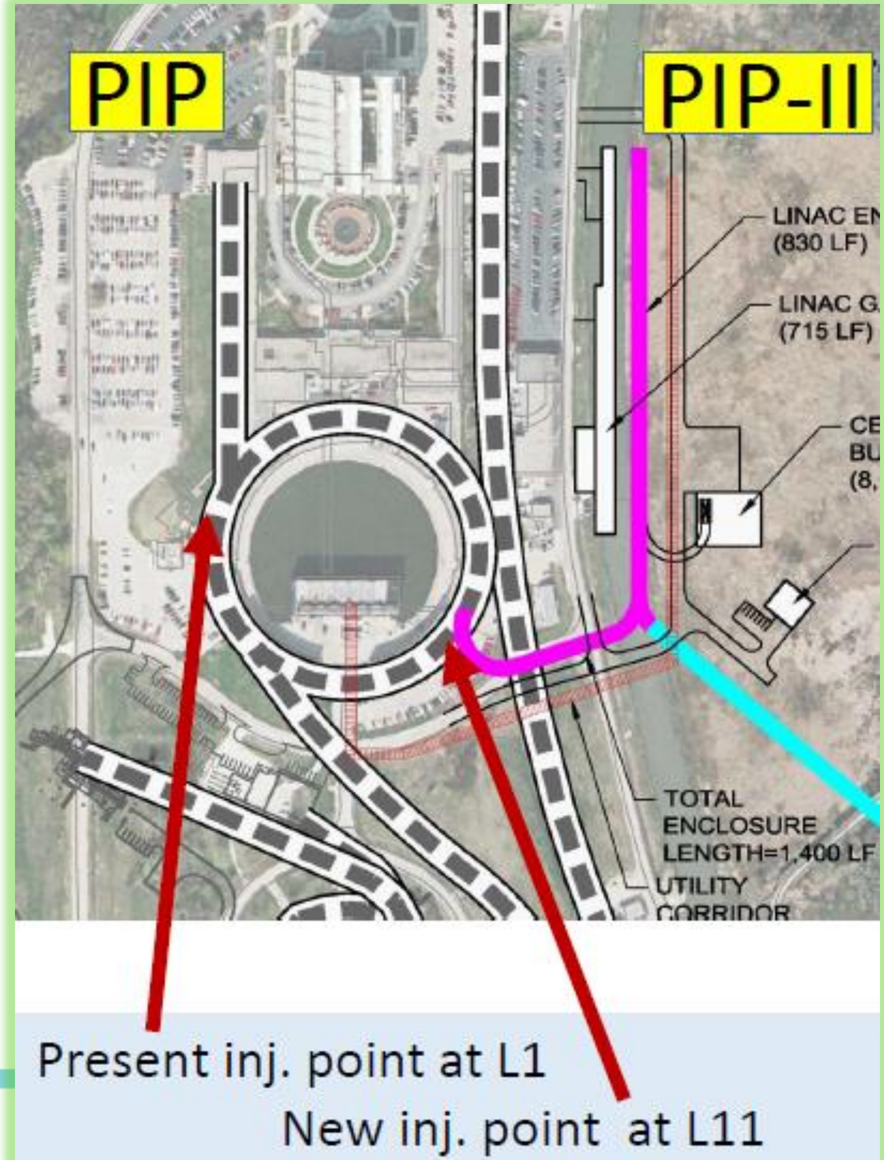


- Goal of the **Proton Improvement Plan** is to increase proton pulse rate from ~7 Hz to 15 Hz
  - **Requires significant investment into upgrade and maintenance of aging Linac and Booster**

PIP-II: New 800 MeV SC RF Proton Linac

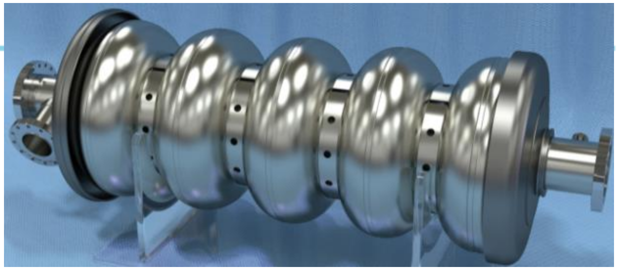
- Replace old 400 MeV NC RF linac (same Booster, RR and MI) to double 120 GeV beampower
  - **P5: PIP-II beam available on "Day One" of LBNF/DUNE**

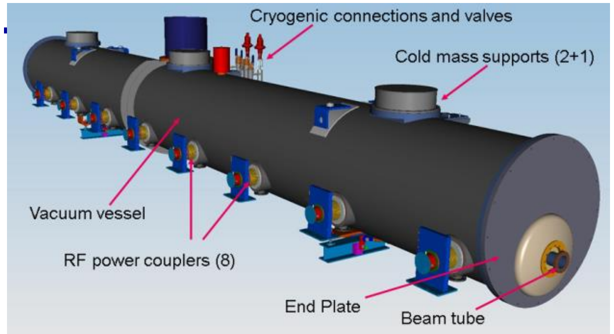
Parameter	PIP Completed	PIP-II
Injection Energy (KE) (GeV)	0.4	0.8
Extraction Energy KE (GeV)	8	8
Injection Intensity (p/pulse)	4.52E12	6.63E12
Extraction Intensity (p/pulse)	4.3E12	6.44E12
Bunch Removed	3	3
Efficiency (%)	95	97
Booster repetition rate (Hz)	15	20
Booster Beam Power at Exit (kW)	94	184
MI batches	12 per1.33 sec	12 per 1.2 sec
NOvA beam power (kW)	700	1200
Rate availability for other users (Hz)	5	8
Booster flux capability (protons/hr)	~ 2.3E17	~ 3.5E17
Laslett Tune shift at Injection	≈- 0.227	≈ -0.263
Longitudinal energy spread	< 6 MeV	< 6 MeV
Transverse emittances (p-mm-mrad)	< 14	18
Booster uptime	> 85%	> 85%

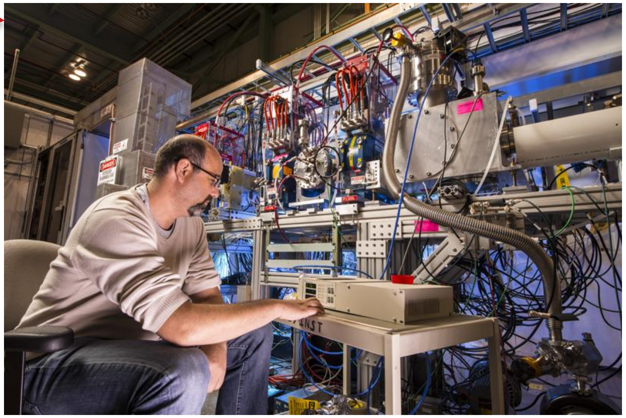


PIP-II Status

- **PIP-II Project is formed:**
  - an experienced management team is in place
  - successful CD-0 review in June 2015
  - Cost range ~0.6B$, almost ¼ from India collab.
- **R&D activities** are aligned with the technical and cost risks associated with the concept described in the RDR.
  - Injector Experiment (PXIE) is addressing risks associated with the front end
  - The SRF program is addressing risks associated with the superconducting accelerating modules
  - The R&D program is run jointly with our Indian collaborators
  - The R&D program to be completed in 2019



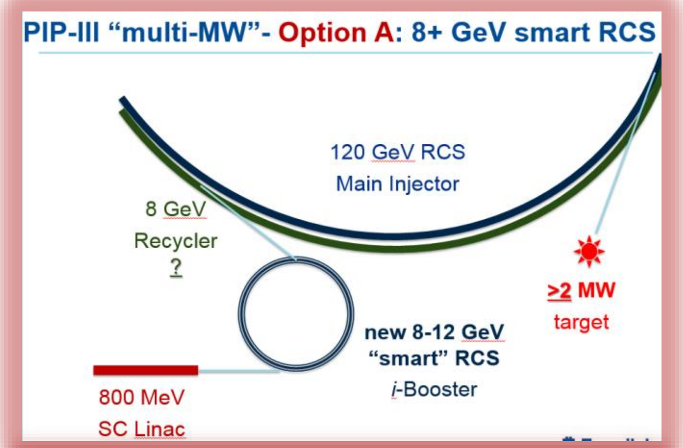


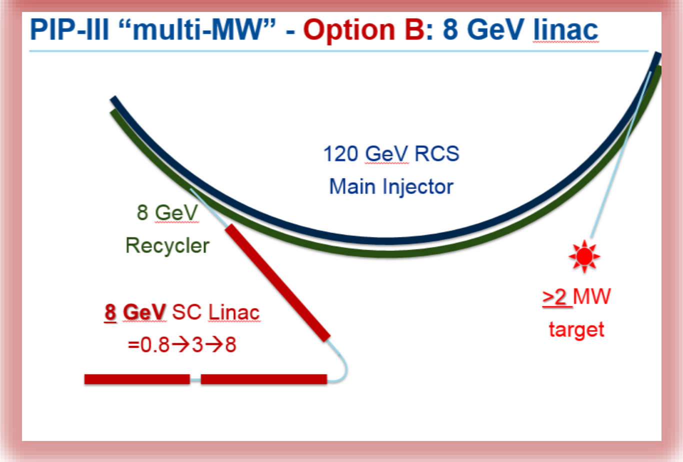


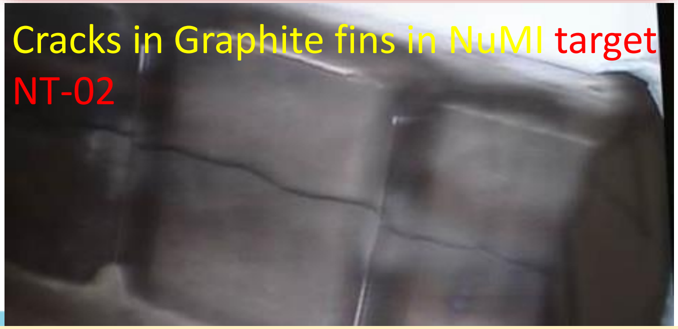
PIP-III: Next *x2* Step Beyond PIP-II (replace Booster)

So far , just at the beginning, formation of R&D Program to consider **two options**:

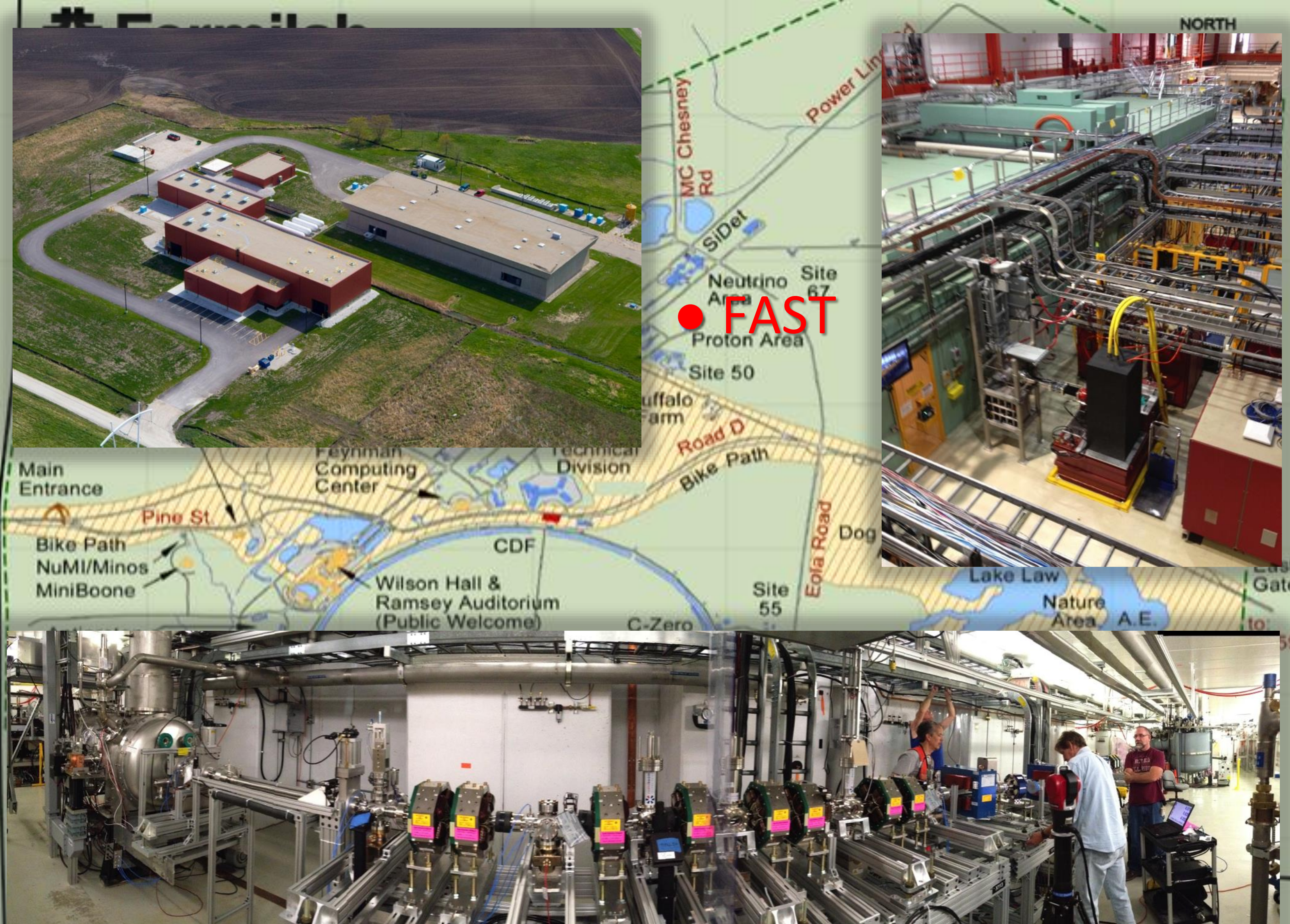
- Either increase performance of the synchrotrons by a **factor of 3-4**:
  - E.g. ***dQ_sc >1*** → need R&D
  - Instabilities/losses/RF/vacuum/collimation
  - IOTA/ASTA to be built to study new methods
- Or reduce cost of the **SRF / GeV** by a **factor of 3-4**:
  - Several opportunities → need R&D
- And – in any scenario – develop **multi-MW** targets:
  - do not exist now → extensive R&D needed







→ R&D beam test facility: ***FAST=Fermilab Accelerator Science and***


NORTH
MC Chesney Rd
SiDet
Neutrino Area
Site 67
FAST
Proton Area
Site 50
Road D
Bike Path
Main Entrance
Pine St
Bike Path
NuMI/Minos
MiniBoone
Computing Center
Division
CDF
Wilson Hall &
Ramsey Auditorium
(Public Welcome)
C-Zero
Site 55
Eola Road
Dog
Lake Law
Nature Area
A.E.

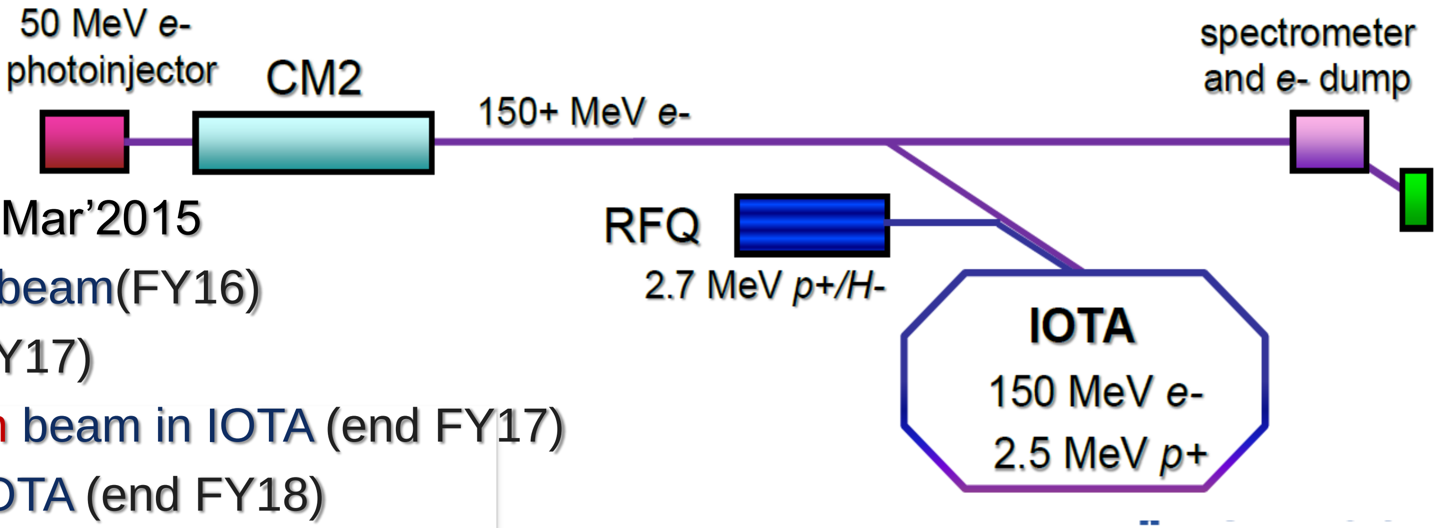
IOTA Storage Ring at FAST

- Integrable Optics Test Accelerator

- To learn how to increase beam current by a **factor of 3-4** **while keeping beam losses <1%**:
  - Very challenging (after 50 years of development)
- TWO innovative ideas:
  - *Integrable Optics*
  - *Space Charge Compensation*

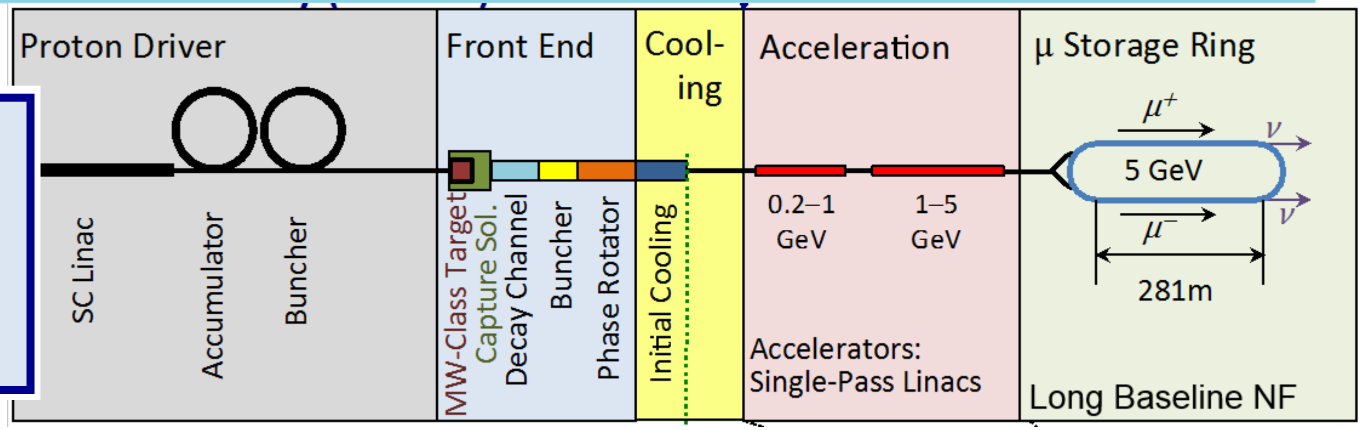
Timeline:

- 20 MeV e- beam Mar’2015
- 50 MeV electron beam(FY16)
- IOTA ring built (FY17)
- 150 MeV electron beam in IOTA (end FY17)
- proton beam in IOTA (end FY18)
- research at IOTA @ FAST (2019-2025)



Future Beyond Superbeams: Neutrino Factory

ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator acceptance

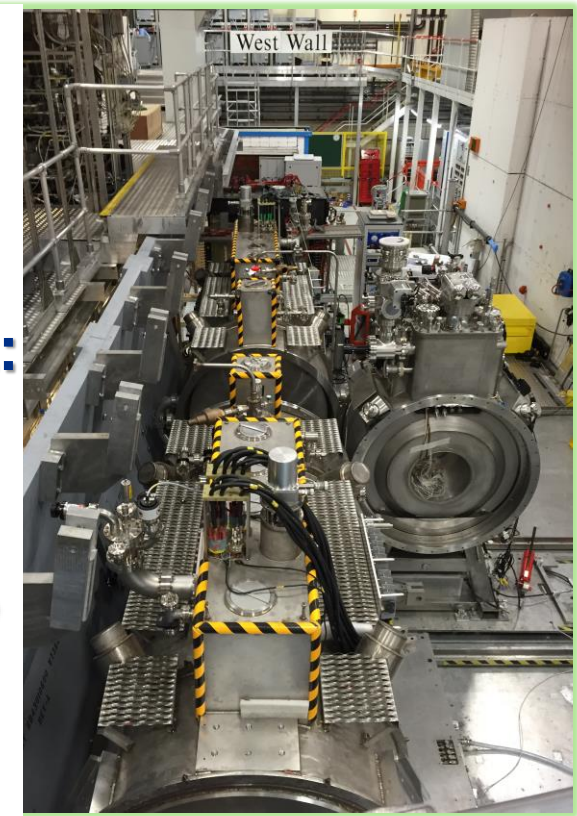


Neutrino Factory Design efforts:

- IDS-NF (Int'l Design Study), 10 GeV
- NuMAX (Fermilab site specific), 5 GeV

Muon Ionization Cooling Experiment@RAL:

- One cell of "real" NF cooling channel
- Accelerated plan (P5 recommended)
  - Muon cooling demo in 2017-18
- Impressive progress so far
  - Jun'15: first muon tracks seen in 2 T field



2015 HEPAP Accelerator R&D Subpanel

- 19 panelists, chaired by Don Hartill (Cornell)
  - P5 aligned National goals
  - Medium-term (10 yrs), long-term (20 yrs)
  - Balance, training, impediments
  - 40M$/yr budget and 28M$/yr facilities
- 15 recommendations
  - Scenarios A, B and C

R&D THRUSTS:

- Accelerator Physics and Technology
  - IOTA research for Intensity Frontier
  - Theory, modeling, studies
- Particle Sources and Targets
  - Multi-MW targets for Intensity Frontier
- RF acceleration
  - SC RF: high-Q, high-G, low-$$
- SC Magnets and Materials
  - 16 T, low-$$ for VHEPP
- Advanced Acceleration
  - Collider-capable plasma wakefields

* see also D.Hartill talk Tuesday

Future Accelerators - Summary

- Accelerators played major role in establishing the standard model
  - We have now discovered all of the expected standard model particles!
- Future proposed accelerators are of two types
  - Colliders: e^+e^- as “Higgs factory”, pp at the next energy frontier
  - Intensity frontier accelerators
- Several accelerators are under active discussion/planning
  - Colliders: ILC (Japan), CEPC and SPPC (China), FCC (CERN)
  - Intensity Frontier: PIP-II,PIP-III (Fermilab), Neutrino Factory (Int’l, US-specific)
  - ILC (Japan) and PIP-II (US) are shovel ready
- Many exciting opportunities are not discussed in the talk
  - VLHC, electron-ion colliders, DAEDALUS, etc.
- Key for all future accelerators is to reduce cost dramatically !!
  - That’s a repeating theme in the 2015 HEPAP Accelerator R&D Subpanel Report
- The US Accelerator community is actively realigning the future accelerator efforts to address P5 priorities:
  - accelerators physics, particle targets, SRF acceleration, SC high field magnets, advanced acceleration techniques

Fermilab

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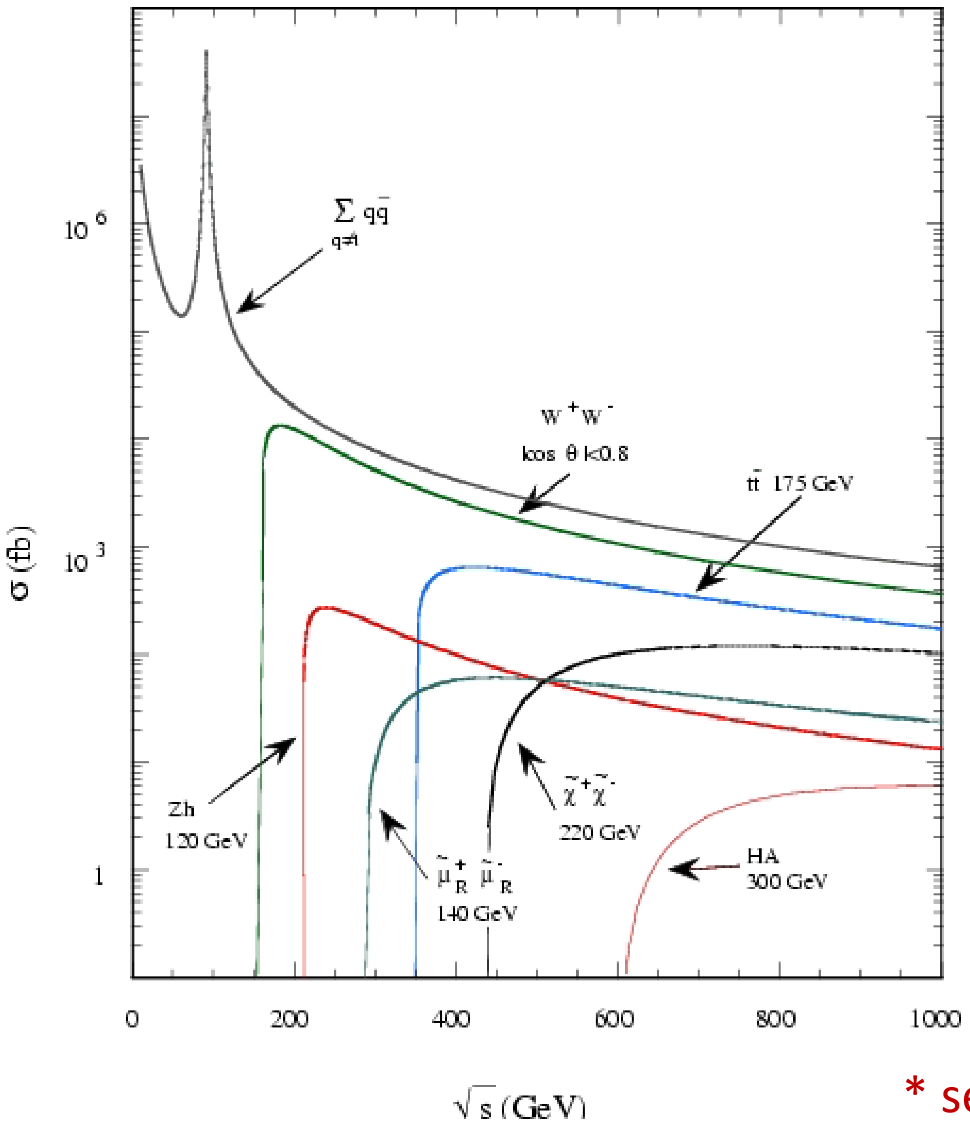
Back-up

ILC Physics and Experiments



- Low cross sections
  - High luminosity needed
- Low rate of interactions
  - Collect all events
  - High efficiency needed
- Large number of different production/decay channels
  - Have to detect all "standard objects" well
  - Jets/photons, leptons, charged tracks, missing energy

* see also J.Brau's talk Tuesday