Future Accelerators

Pier Oddone, Fermilab
DPF 2009
Detroit, July 31, 2009

Accelerator R&D active on many fronts

- Ignorance of the physics landscape leads us to push accelerator development along multiple directions:
  - At the energy frontier: huge uncertainties of what lies in the LHC range → affects the next energy scale
  - At the intensity frontier: lack of knowledge of $\sin^2 2\theta_{13}$ and possible neutrino surprises drives development of ever more powerful neutrino beams

Outline

- At the energy frontier:
  - VLHC
  - ILC
  - CLIC
  - Muon Collider
  - Plasma based accelerators
- At the intensity frontier
  - Super B-factories
  - Super proton beams
  - Neutrino factories, Beta beams

Energy frontier moves to the LHC

Beyond LHC, directions are uncertain

- In principle: 1) explore LHC range with a lepton collider – the community’s consensus, or 2) forward in energy with proton colliders
- Lepton colliders: choice of technology depends on the energy scale where physics becomes compelling; cost also an issue
- Proton colliders: the best understood and developed machines but cost is the main issue

Proton colliders after the LHC

- We know how to build superconducting accelerators: established practice with Tevatron, HERA, RHIC and LHC

- A "modest" step would be to double the energy of the LHC by going to Niobium-Tin superconductors; R&D in progress

- But, if cost (and complexity) of magnetic lattices is proportional to energy stored, then

$$\text{Cost} = A\ (\text{length}) \times (\text{field})^2 + B \times \text{length}$$

Proton colliders after the LHC

- Presently the stored energy term dominates by a large factor over the tunnel term ➔ minimize the cost by going to simpler magnets in a bigger tunnel

- A VLHC at 40 TeV with low B-field in long tunnels: combined function superferric magnets at 2T that are nothing but a transmission line in a 233km tunnel (Fermilab TM-2149).

Lepton colliders beyond LHC

LHC Results

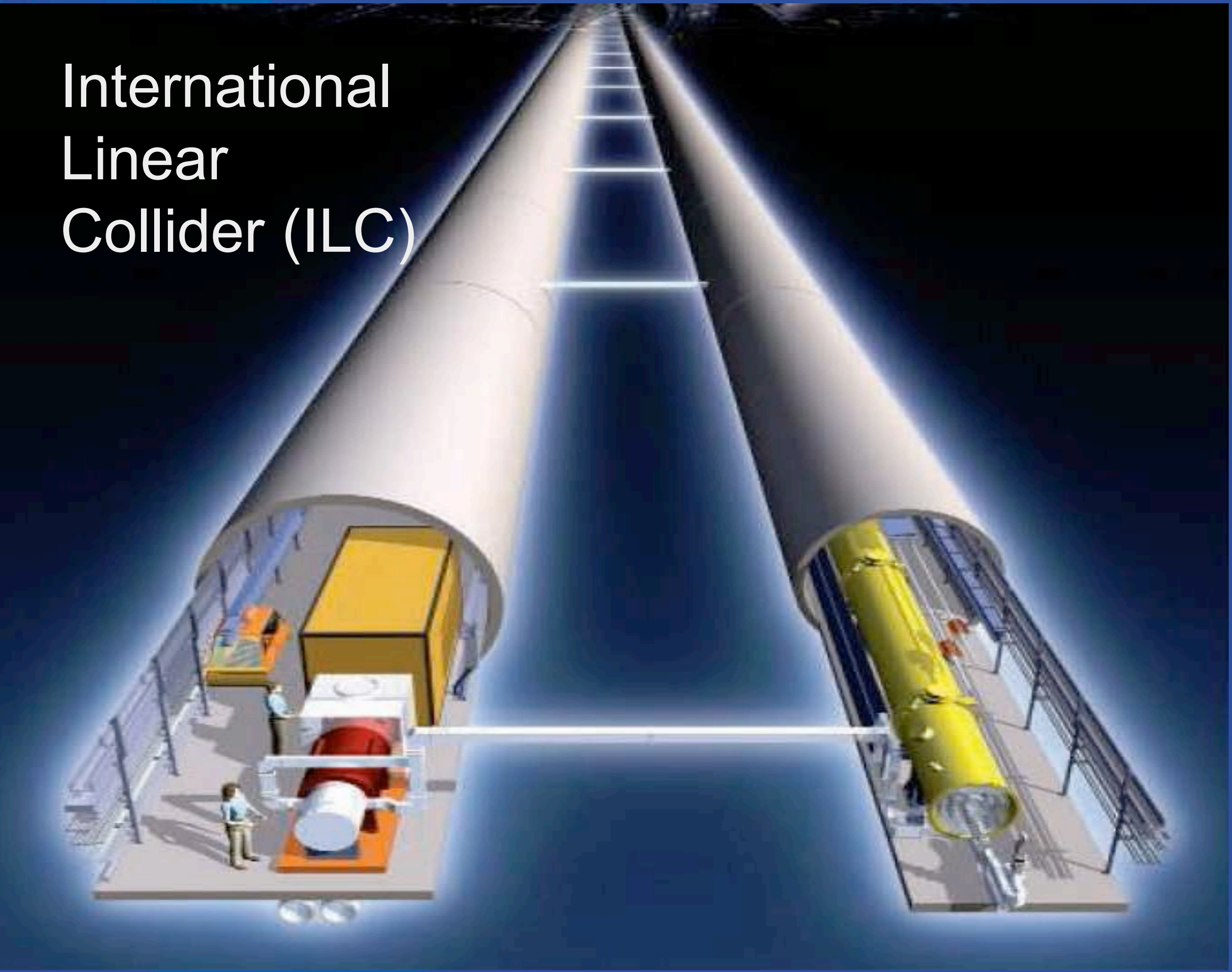
or

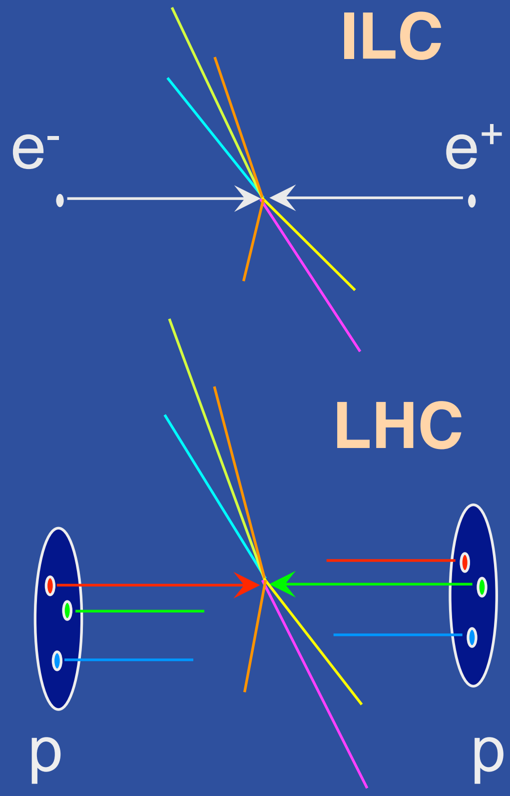
- ILC Enough ⟹ By far the easiest!
- ILC not enough

  or

  - CLIC
  - Muon collider

HEP world: need TeV lepton collider

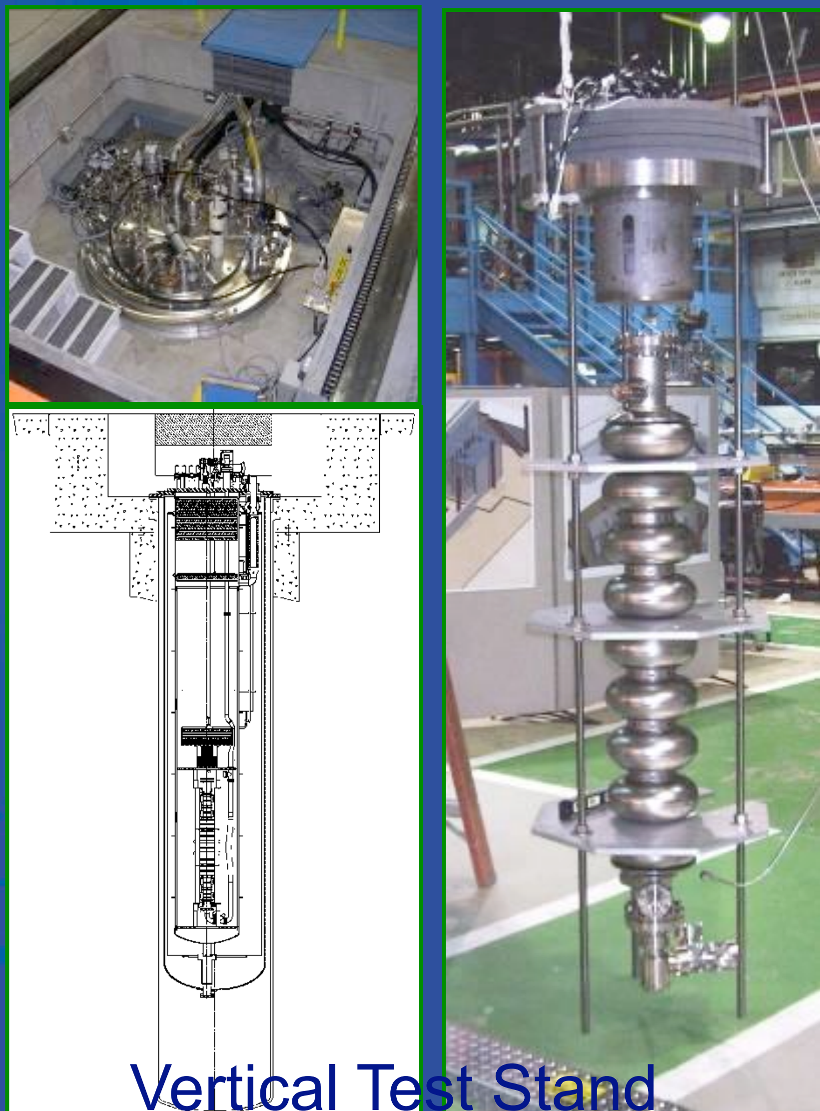




ILC design is well understood

- Technology is very forgiving: large apertures relax the precision requirements to maintain the required emittance
- Superconducting technology demonstration at 10% with XFEL; high efficiency wall plug to beam power
- World-wide distributed R&D program; TDR by 2012 under guidance from GDE

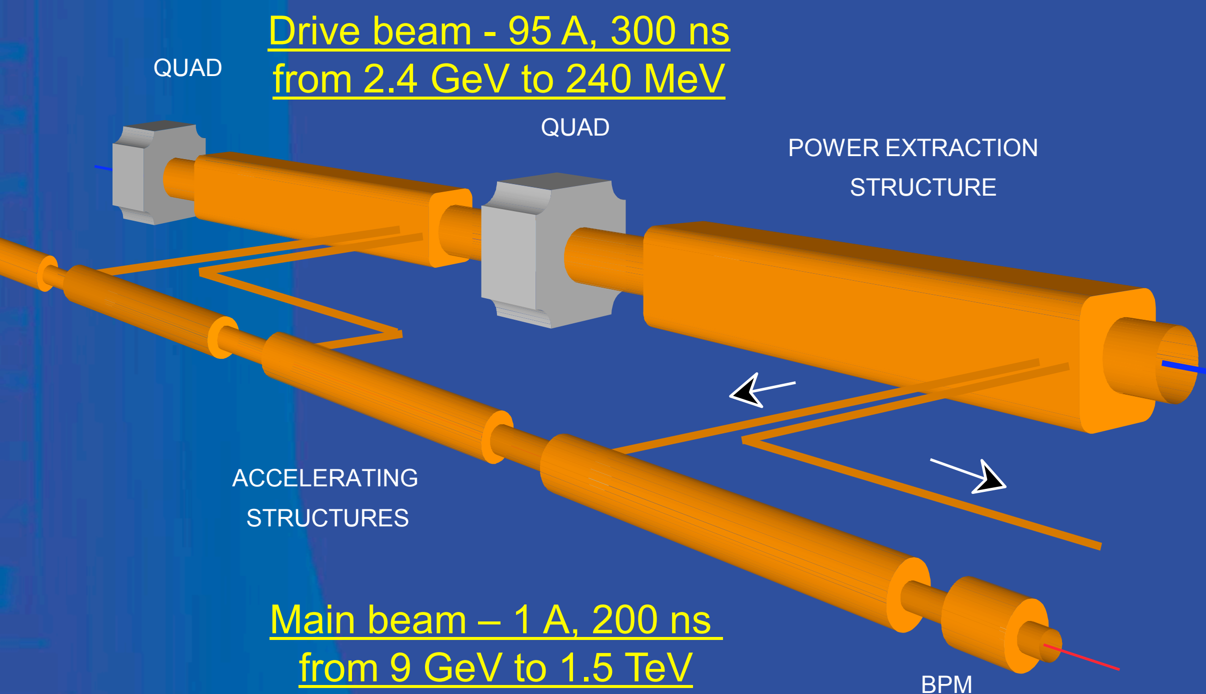
Example: Fermilab and ILC technology

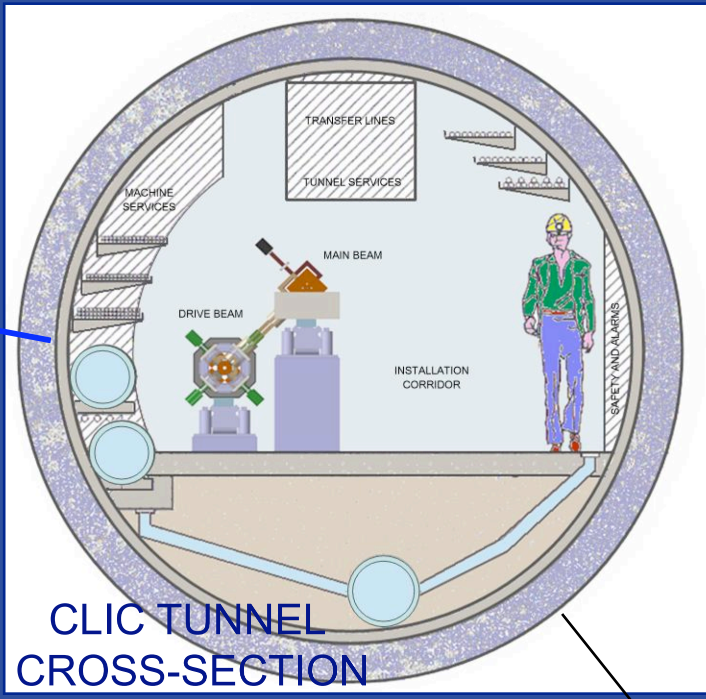


If 0.5+ TeV is not enough

- The CLIC design offers the possibility of a 3 TeV collider
- Muon collider offers the possibility of a 4 TeV machine or higher
- But much R&D is necessary before anyone can reliably achieve the required luminosity for either of these machines

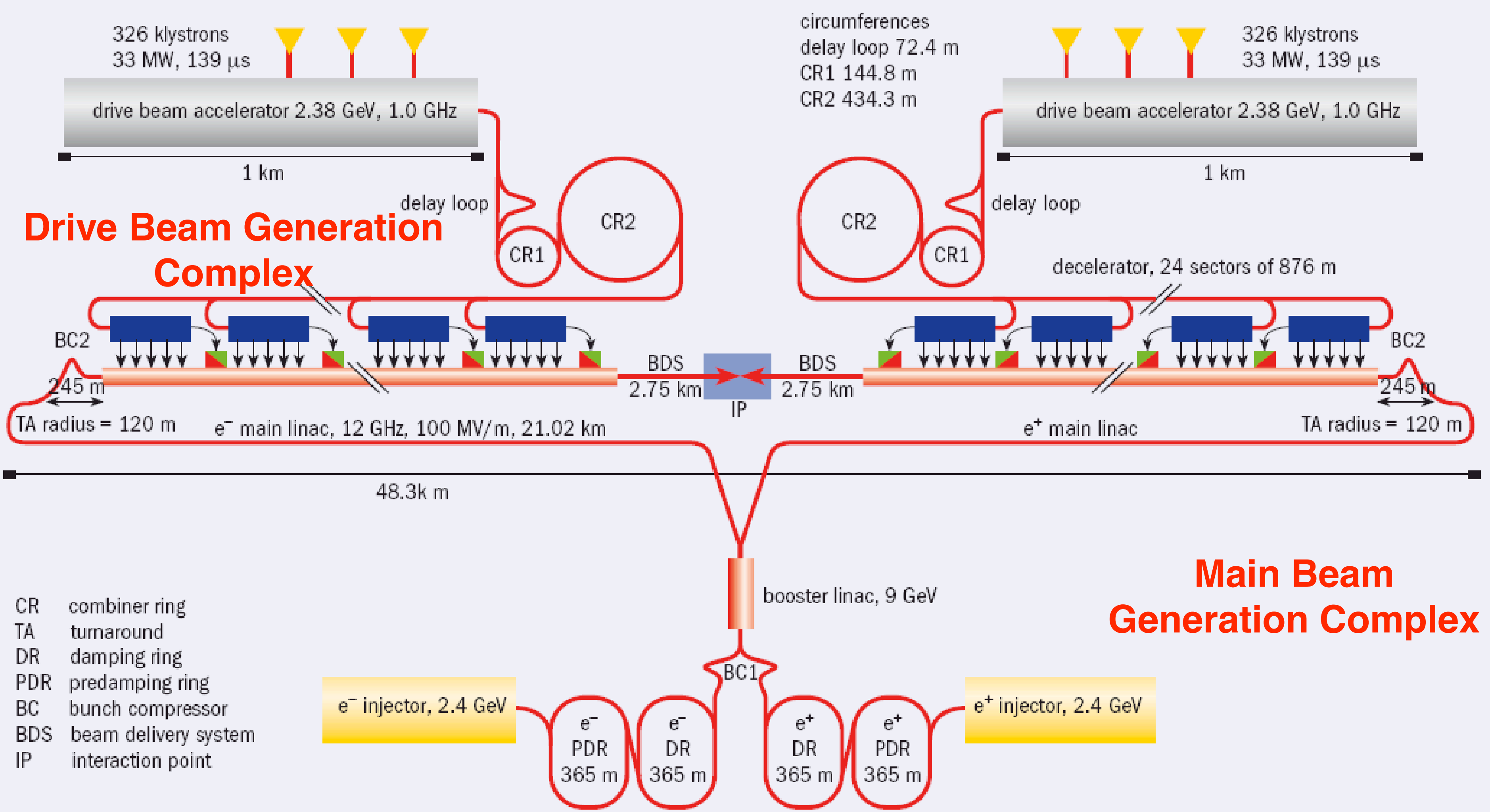
CLIC – basic features





High gradient, high efficiency two beam accelerator

CLIC Layout 3 TeV



World-wide CLIC&CTF3 Collaboration

http://clic-meeting.web.cern.ch/clic-meeting/CTF3_Coordination_Mtg/Table_MoU.htm

33 Institutes involving 22 funding agencies from 18 countries

Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
Gazi Universities (Turkey)

Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute (UK)

JINR (Russia)
Karlsruhre University (Germany)
KEK (Japan)
LAL / Orsay (France)
LAPP / ESIA (France)
NCP (Pakistan)
North-West. Univ. Illinois (USA)
Patras University (Greece)

Polytech. University of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Thrace University (Greece)
University of Oslo (Norway)
Uppsala University (Sweden)

CLIC challenges

- Demonstrate viability of two-beam acceleration
- Reliable high gradient cavities >100 MV/m
- Power handling
- Precision and stability: micron scale alignment for quads and nano meter scale stability
- Demonstration of emittance preservation through prototype section ??

Collaboration CLIC/ILC

- Important connections have developed between the ILC and CLIC efforts
- While the main linacs are incompatible, there are common elements such as the e+ sources, damping rings, final focus, civil construction where a joint approach is valuable

An alternate approach: muon collider

- Collider based on a secondary beam: we do this with antiprotons. For muons must do it in 20 msec.
- The biggest advantages are: narrow energy spread (no beamstrahlung) and small physical footprint (no synchrotron radiation)
- No new methods of acceleration, but new method of deceleration!: muon cooling

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.

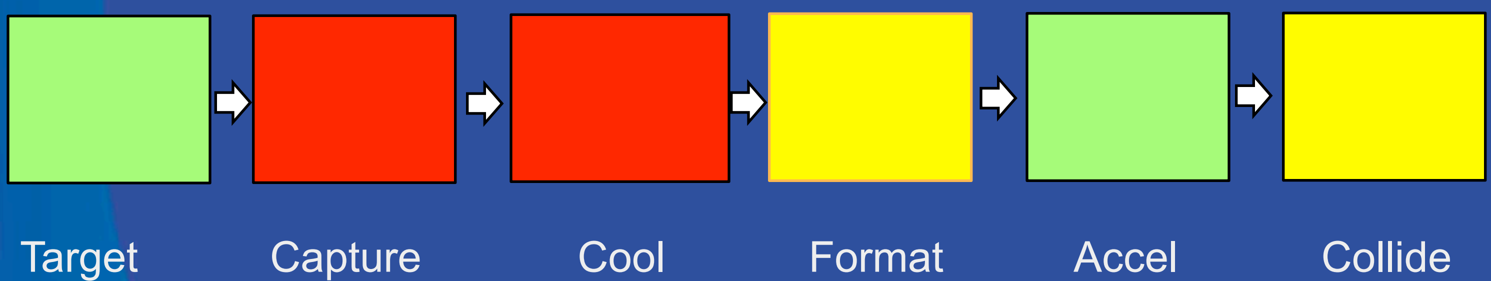
Muon Cooling
Reduce the transverse motion of the muons and create a tight beam.

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.

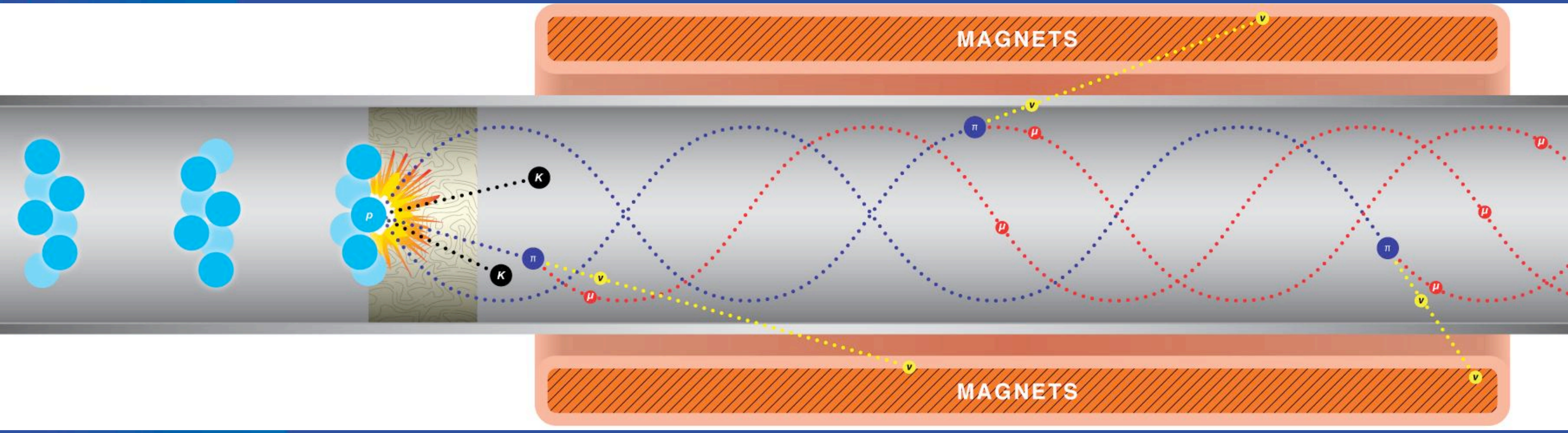
Collider Ring
Located 100 meters underground. Muons live long enough to make about 1000 turns.

Muon collider functional layout

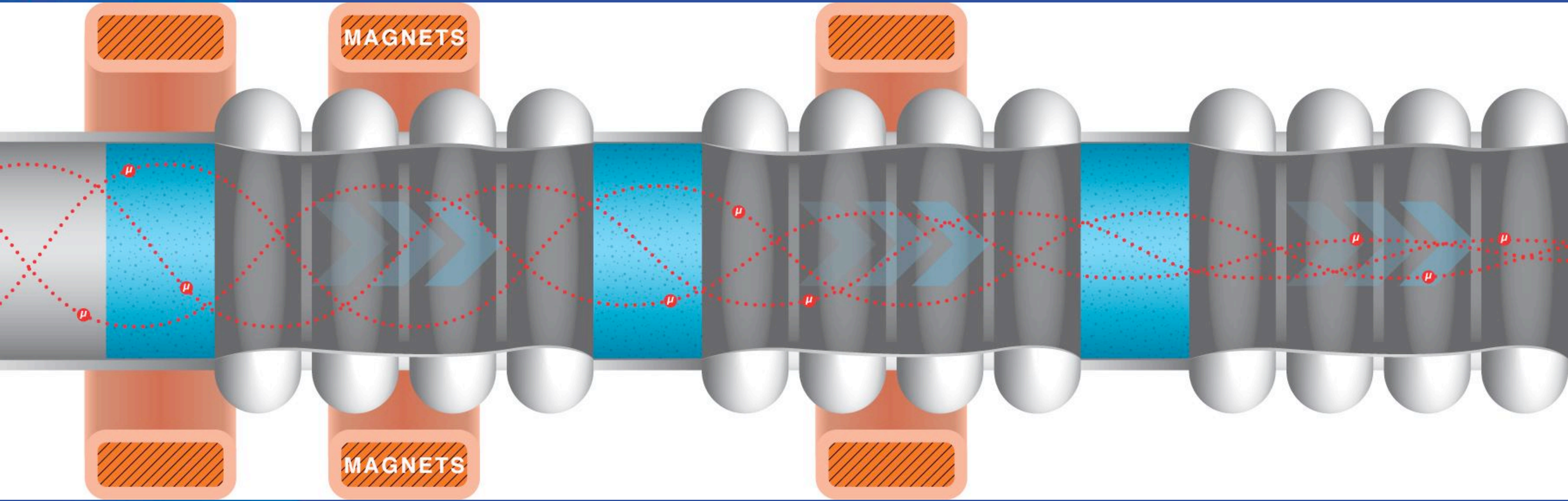


Color indicates degree of needed R&D (difficulty) and demonstration

Targeting and capturing



Capturing and cooling



Muon collider challenges

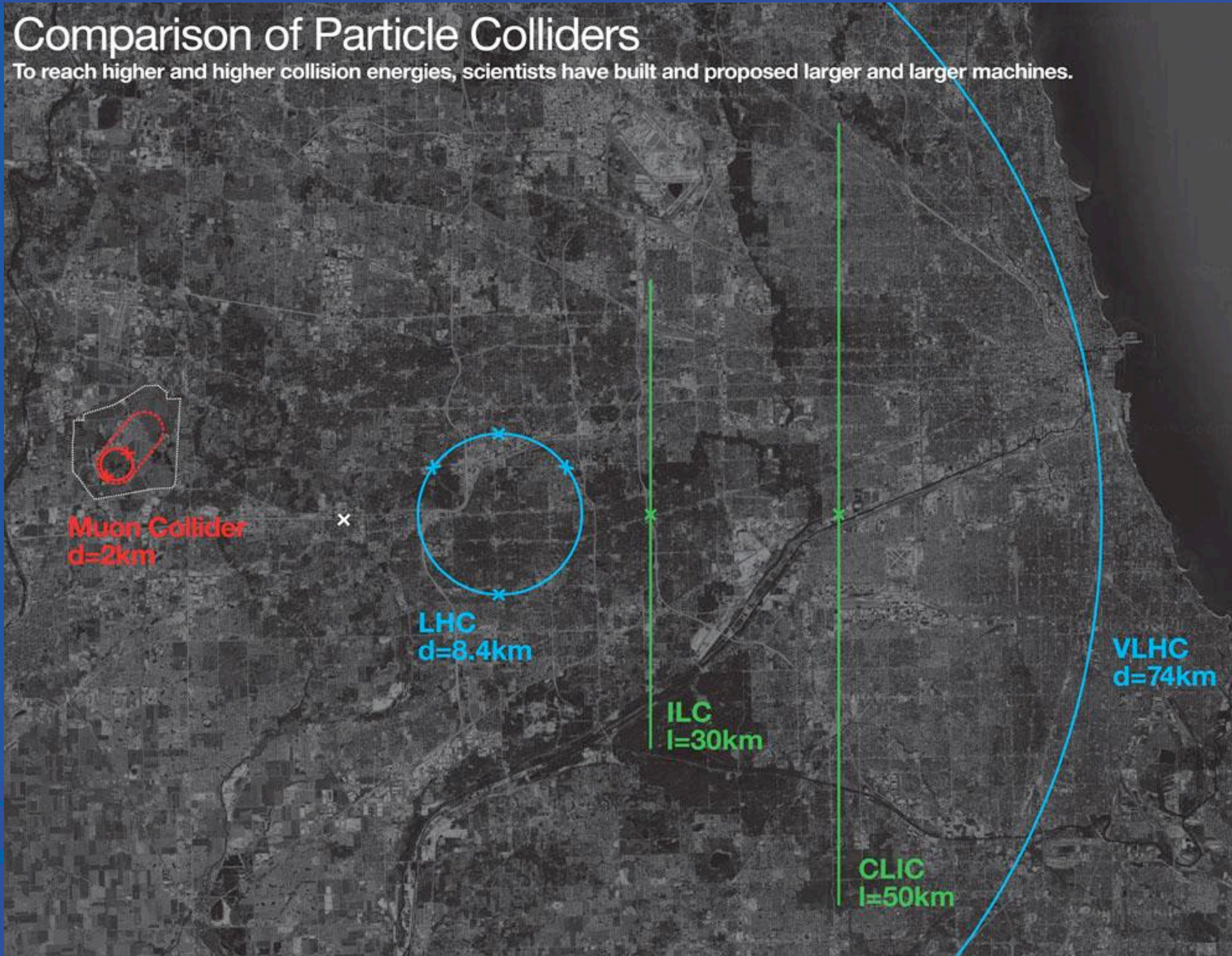
- Capture and cooling could be done effectively provided we learn how to operate RF cavities inside magnetic fields
- An important shortcut would be to demonstrate operation in magnetic fields with gas filled cavities. Done already with no beam. Next with beam.
- Need demonstration of 6D cooling

Muon collider challenges

- Need development of very high fields solenoids for last stages of cooling (luminosity proportional to field). Ideally upwards of 40T
- Need end-to-end system simulation to understand ultimate losses, emittances
- Understand full physics reach with backgrounds and masks regions (come to Fermilab Nov 10-12 workshop, with help from ILC and CLIC)

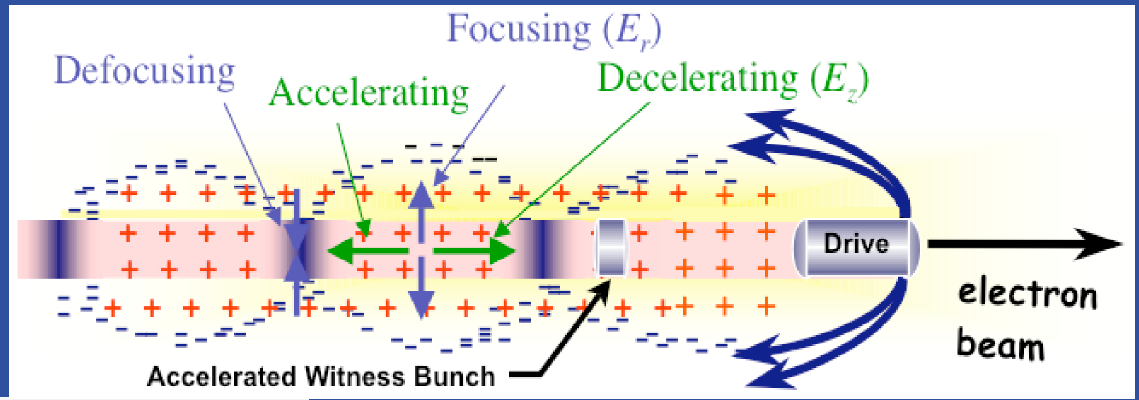
Muon collider/ILC

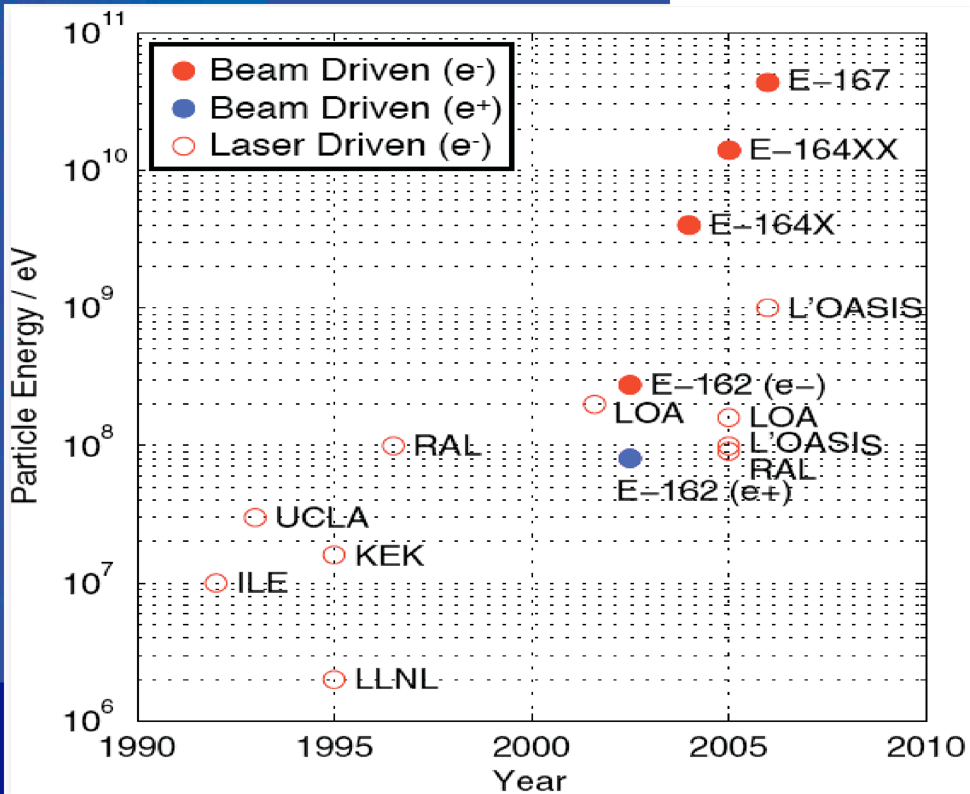
- ILC is developing very efficient accelerating structures that can be run economically
- Muon collider requires substantial acceleration (few km) that ideally would use ILC technology

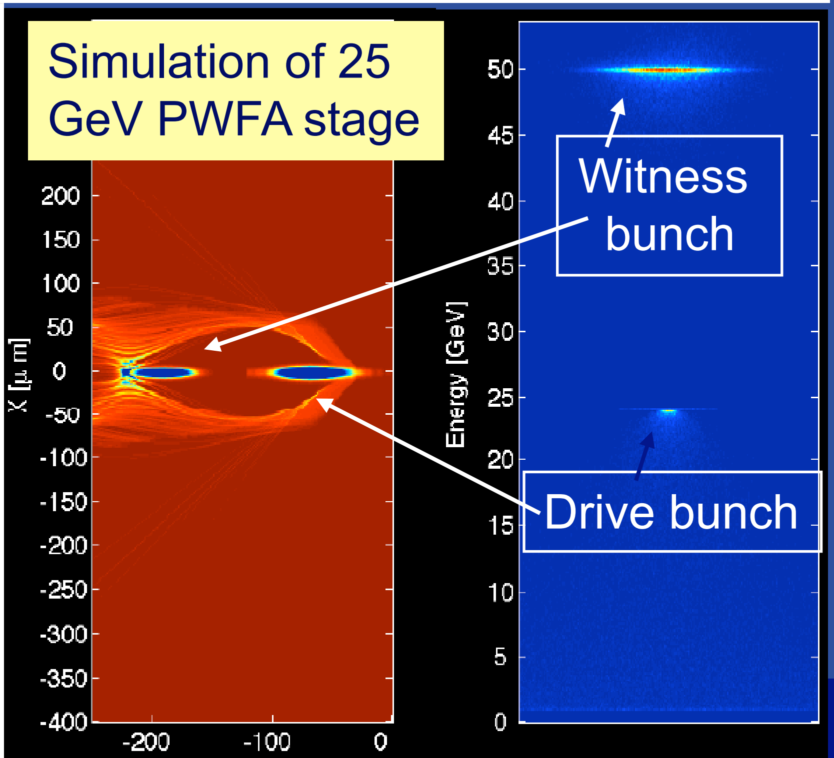

Comparison of Particle Colliders
To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.
Muon Collider
d=2km
LHC
d=8.4km
ILC
l=30km
CLIC
l=50km
VLHC
d=74km

Promise of Plasma Acceleration (Beam-driven or Laser-driven)

- 50 GV/m in FFTB
  - Potential linear colliders and radiation sources

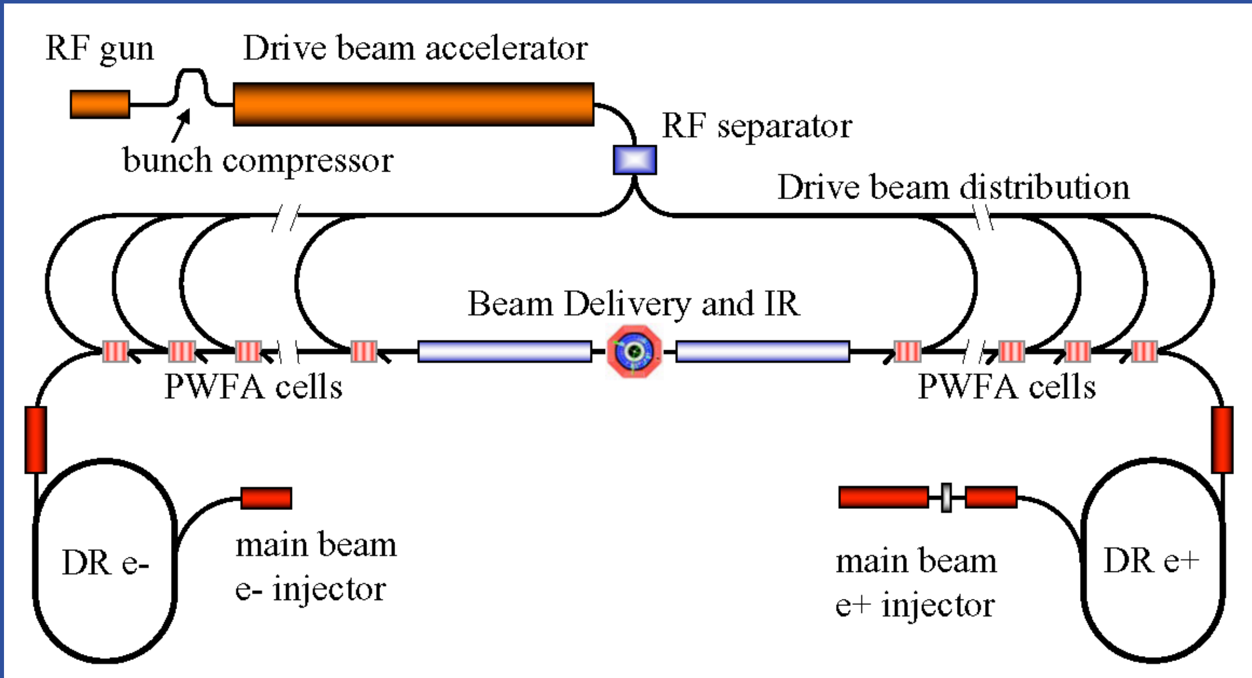






Example: PWFA-Linear Collider Concept

- Developed a concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes best use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - PWFA concept could be used to upgrade LCLS or simply other e- acc.



FACET FACILITY FOR ADVANCED ACCELERATOR EXPERIMENTAL TESTS

U.S. DEPARTMENT OF ENERGY

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SLAC NATIONAL ACCELERATOR LABORATORY

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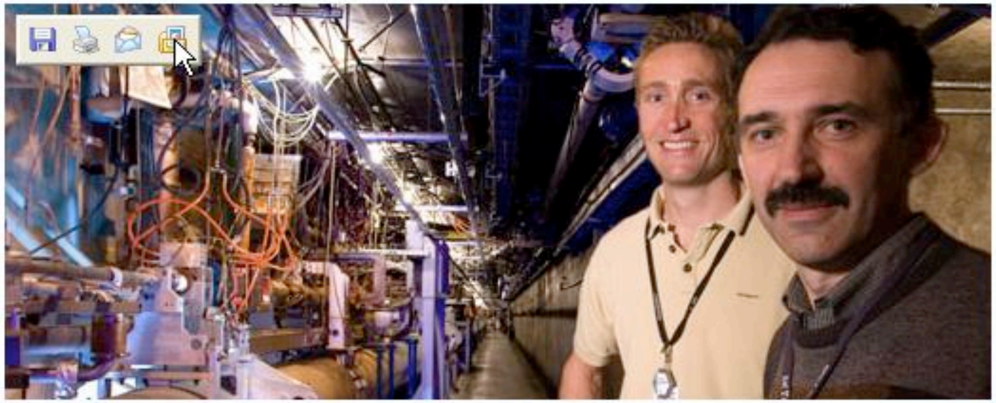


News and Events

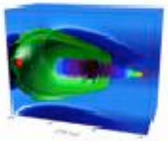
SLAC National Accelerator Laboratory to Receive $68.3 Million in Recovery Act Funding - March 23, 2009

New Accelerator Technique Doubles Particle Energy in Just One Meter - February 14, 2007

» more

What Is FACET?

Advanced accelerator research promises to improve the power and efficiency of today's particle accelerators, enhancing applications in medicine and high-energy physics, and providing potential benefits for research in materials, biological and energy science. Experiments on future acceleration techniques require high-quality, forefront facilities.



FACET—Facilities for Accelerator science and Experimental Test beams at SLAC—will study plasma acceleration, using short, intense pulses of electrons and positrons to create an acceleration source called a plasma wakefield accelerator. FACET will meet the Department of Energy Mission Need Statement for an Advanced Plasma Acceleration Facility.

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Research

With FACET, the SLAC linac will support a unique program concentrating on second-generation research on plasma wakefield acceleration.

- Plasma Wakefield Acceleration
- THz Radiation
- Plasma Focusing
- Dielectric Wakefield Acceleration

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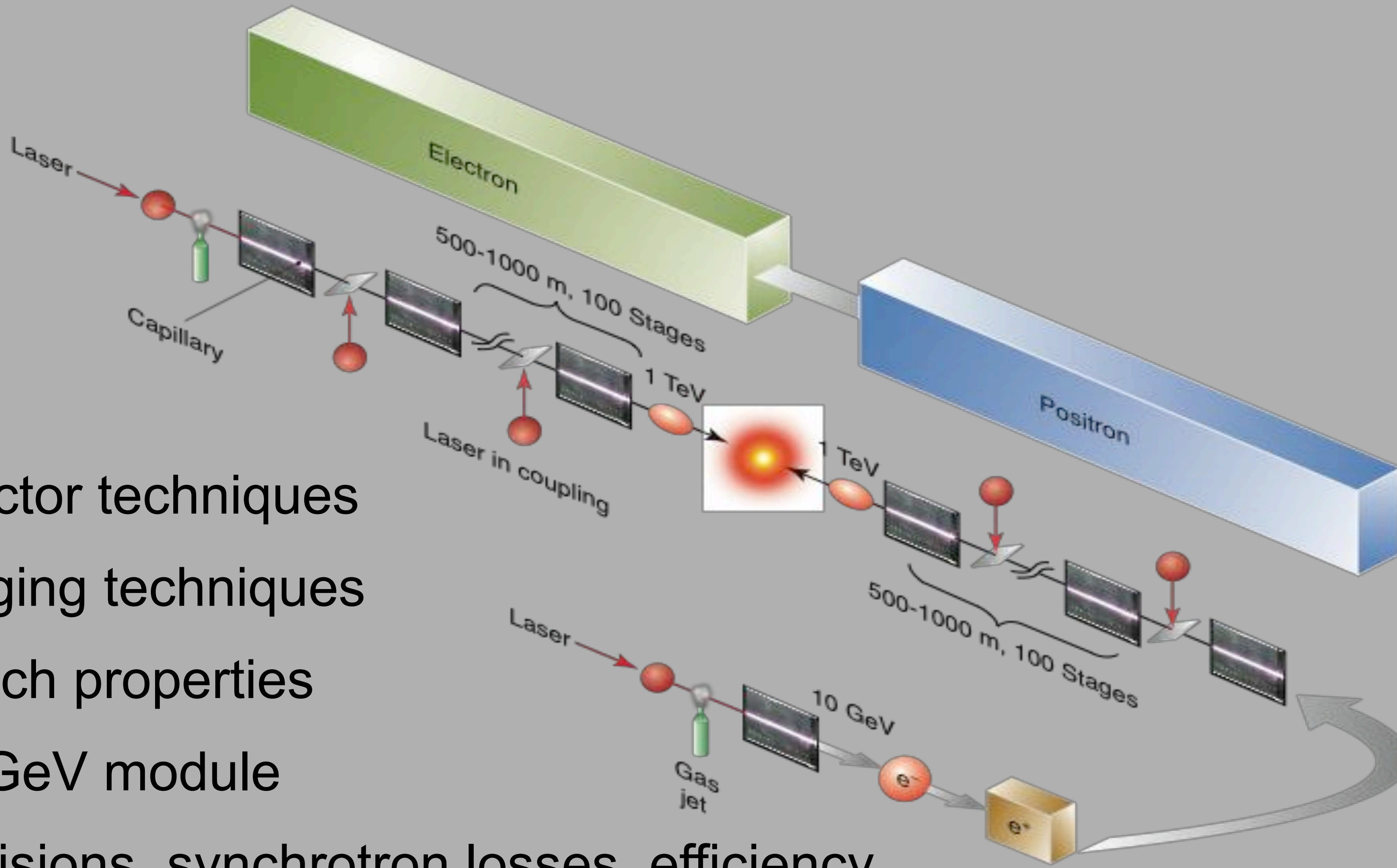
SLAC National Accelerator Laboratory, Menlo Park, CA
Operated by Stanford University for the U.S. Dept. of Energy
Office of Science

Beam based plasma challenges

- Need for efficiency - efficiencies multiply: wall plug to drive beam, drive beam to plasma, plasma to high energy beam. ILC achieves 20% beam to plug efficiency which is hard to beat

- Fields following the plasma create dispersion and energy spread: how does one get uniform enough fields to preserve emittance??

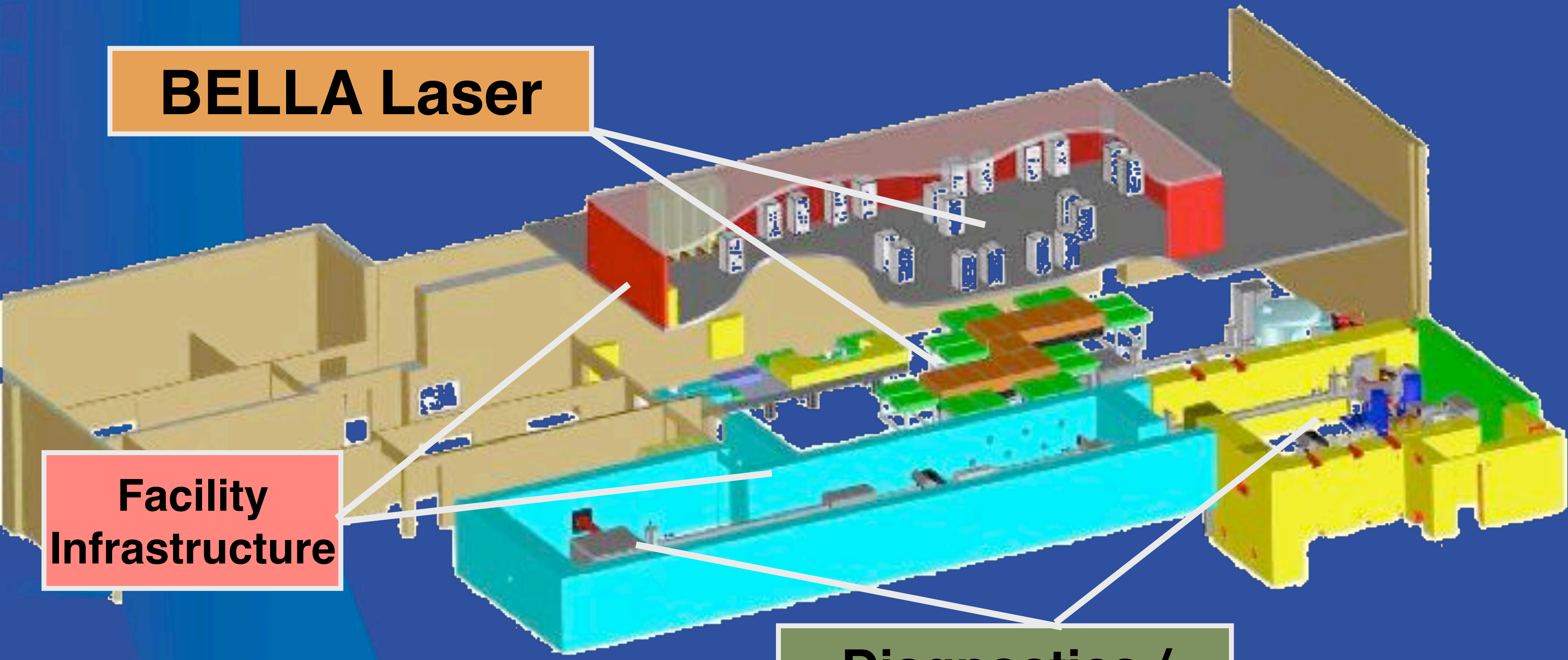
Laser driven plasma acceleration



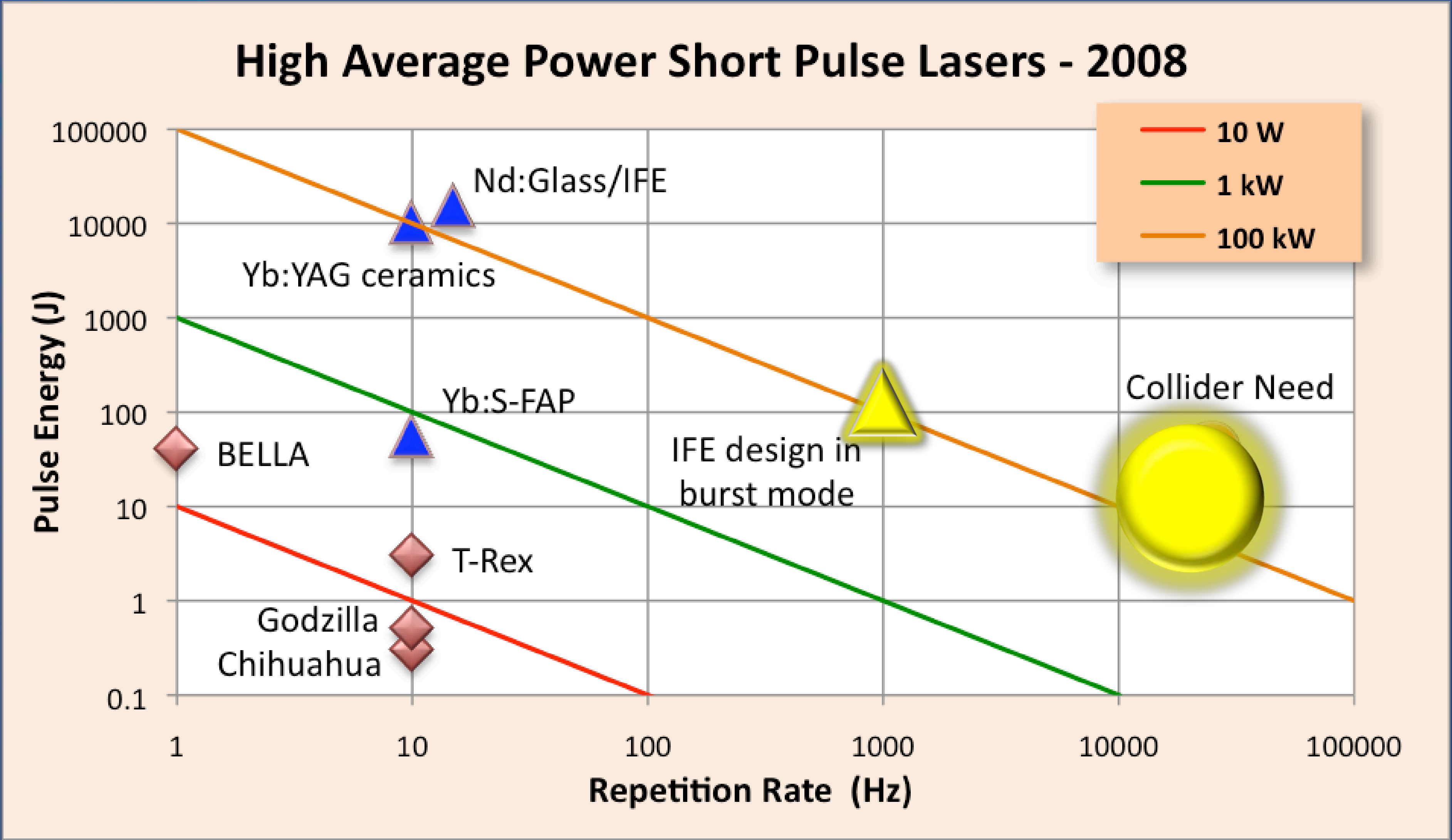
- Injector techniques
- Staging techniques
- Bunch properties
- 10 GeV module
- Collisions, synchrotron losses, efficiency

BELLA Facility

- High rep rate (1 Hz), Petawatt class laser (>40 J in < 40 fs)
- Laser bay and target area
- Laser diagnostics



Challenges


High Average Power Short Pulse Lasers - 2008
10 W
1 kW
100 kW
Nd:Glass/IFE
Yb:YAG ceramics
Yb:S-FAP
BELLA
IFE design in burst mode
Collider Need
T-Rex
Godzilla
Chihuahua
Pulse Energy (J)
100000
10000
1000
100
10
1
0.1
1
10
100
1000
10000
100000
Repetition Rate (Hz)

Challenges

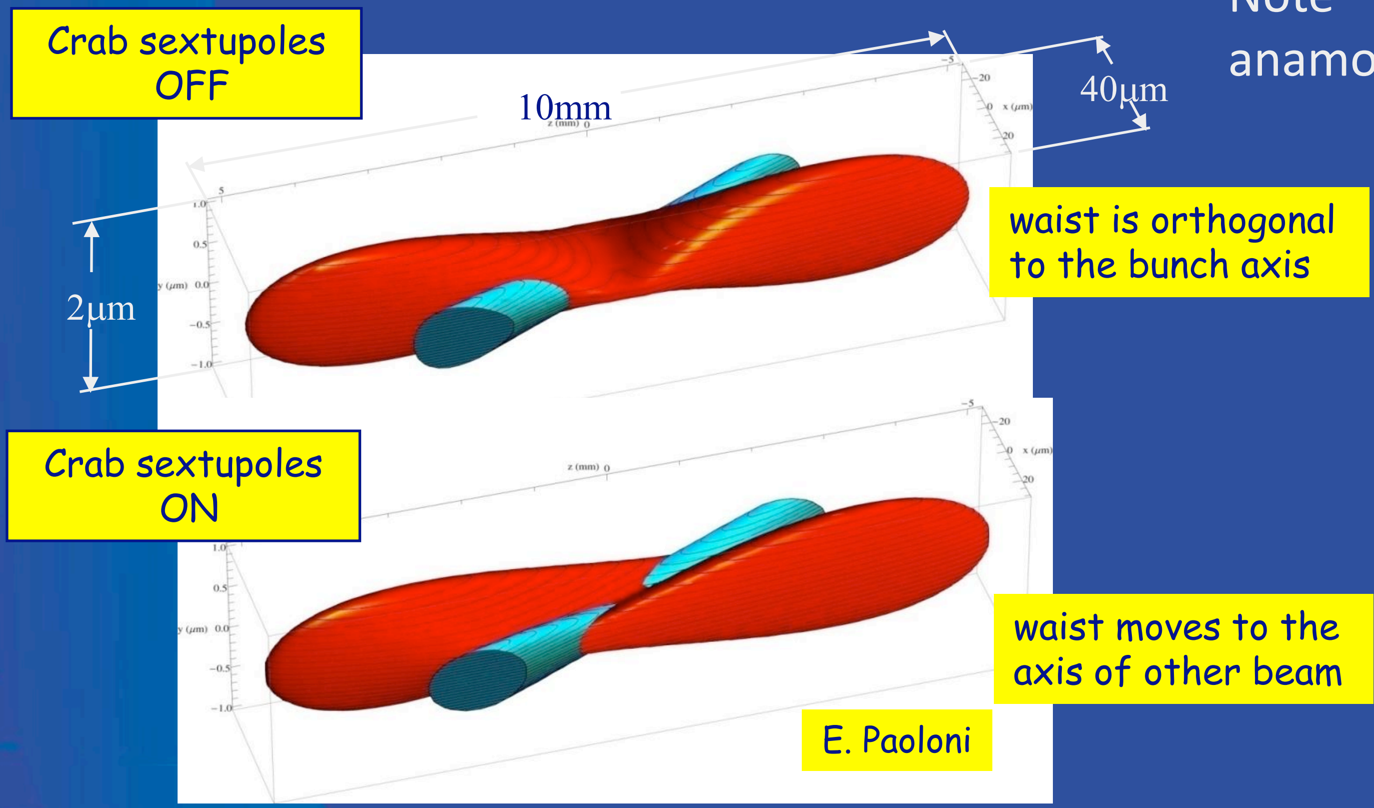
- High average power, high peak power, high rep rate, short pulse lasers
- Efficiency: wall plug to laser power to plasma to beam
- Uniformity of plasma acceleration
- Power into capillaries is huge for such small structures. Are they self protecting?

At the intensity frontier: Super B

- One hundred times the luminosity of existing B-factories.
- Complementary program to LHC: flavor physics will manifest discoveries at LHC as well as higher mass scales
- Unlikely to be produced with present designs due to huge power loads: go to low emittances and waist focus. The main challenge is to maintain the low emittance. Two designs one in Japan and one in Italy

Super B: 4 Gev x 7 GeV

Note
anamorphic scales



With crabbed waist, all particles from both beams collide in the minimum β_y region, producing a net gain in luminosity and a broad tune plane


26 Mag 2008
1:56pm
Frascati
Italian Super - B
Due Torri
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Google
41°50'39.90" N
12°38'45.38" E
98 m elev
1.07 km Alt

Proton Super Beams

- They drive experiments at the intensity frontier: neutrino oscillation experiments and rare decays
- Great variety in the design of experiments
- Project X at Fermilab and upgrades to the JPARC complex to reach 2 to 4 MW of beam power

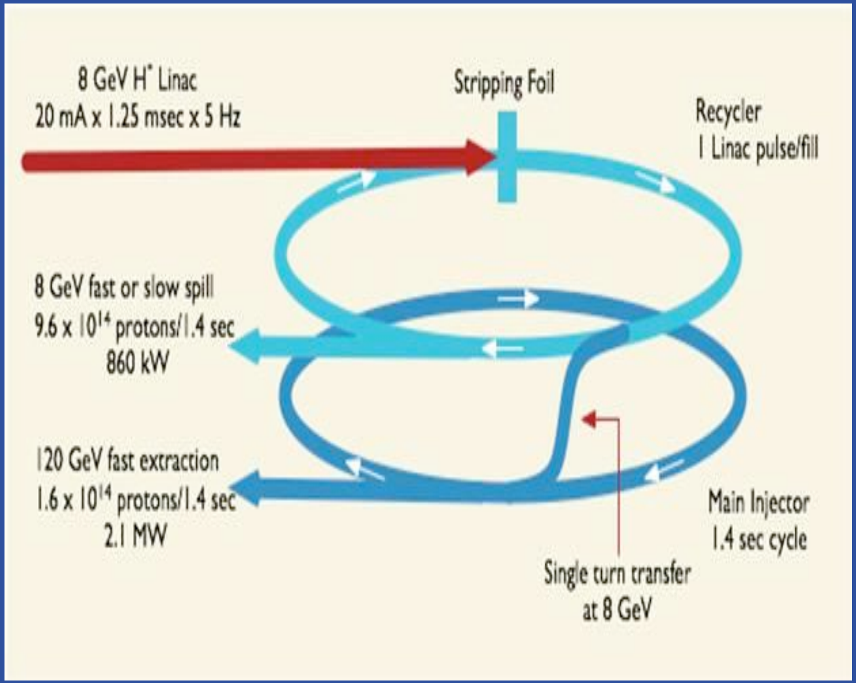
Project X

Powerful beams at 120 GeV and at lower energies for neutrinos and rare decays

Reuses much of existing infrastructure

Uses ILC technology

Serves as front end of possible neutrino factory or a muon collider



Challenges

- Design a machine that satisfies optimally the stated goals, especially flexibility for the future
  - As part of the CD-process we are studying alternative configurations including a front-end CW linac
- Technical challenges come from high intensities: e.g. electron cloud in the Main Injector?

Neutrino factories

- Same challenges in producing and storing muon beams as the muon collider, except the cooling requirements are more relaxed
- International Scoping Study will define conceptual designs
- Important that intense proton accelerators be compatible with future extensions into neutrino factories: they greatly extend the parameter reach in neutrino physics.

Conclusions

- It is the best of times and the worst of times: only the intensity frontier is relatively well defined, although likely to be affected by the value of $\sin^2 2\theta_{13}$. Beyond that, the energy frontier could take us in many directions.

- As a result: a vital and extensive R&D program, probably the biggest and most innovative in accelerator R&D we have ever seen