U.S. Accelerator R&D for High Energy Physics

A biased perspective

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Why Accelerator R&D
The view from HEPAP - P5

- *"The U.S. could move boldly toward development of transformational accelerator R&D. There are profound questions to answer in particle physics, and recent discoveries reconfirm the value of continued investments.*
- *Going much further, however, requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program.*
- *A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost.*
- *Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators."*

Strategic Goals

- Accelerators for HEP have become too expensive for a single country.
  - Clearly recognized by CERN, DESY, FNAL, ILC with different details but featuring significant international contributions.
- The U.S. HEP Accelerator R&D program should support future machines *that will be built in an international context.*
- The U.S. should aspire to hosting forefront machines as well as cooperating abroad.
- The U.S. should support R&D that can significantly lower the cost of a facility.

Who does Accelerator R&D in the U.S.

- HEP accelerator R&D in the U.S. is done by the national labs and by several universities.
- University research programs have produced a rich harvest of ideas that have evolved into major research facilities such as LCLS, FACET and BELLA.
  - Experimental capabilities on campus are essential to continued progress
  - University research programs are critical for the education of accelerator physicists and engineers.
- Most facilities are at the labs, and the user facilities work with researchers from the universities.
  - The collaboration is vital and necessary for progress.

Support for accelerator R&D in the U.S.

- Most of the U.S. Accelerator R&D aimed at particle physics is funded within the Office of HEP of the DOE, of roughly $60M/yr
- HEP also operates a Stewardship program
  - Supports more broadly applicable accelerator R&D, e.g. radiation oncology, with a budget of order $10M
- NSF supports an accelerator R&D program at universities ~$10M per year.
  - Emphasizes potentially transformational accelerator physics

Context:
European Efforts in Advanced Accelerators

- Europe has had a rich program in plasma-based accelerators based at a dozen leading research universities
  - Funding of these efforts is not restricted by application, i.e., high energy physics versus photon science

- AWAKE, a test facility for proton driven PWFA, is being built at CERN to be operational from 2017

- A very large E.U. initiative in laser-based technology, the Extreme Light Infrastructure, is building a major advanced acceleration facility in Romania that will rival BELLA capabilities in the U.S.
  - Already U.S. researchers have depended on European industry for laser and optics technology

Future Proton Colliders

Thirty years ago: (1984-1988)
INFN finances ELOISATRON (ELN) Project

- Full Scale ELOISATRON PROJECT:
  - 1st step - Conceptual Design Report (Kjell Johnson)
  - 2nd - R&D in fundamental technologies
  - 3rd - Construction of long (15 m) superconducting magnets
- 1989 Start model magnet construction for 10% ELN

  By 1992 feasibility of LHC magnets was demonstrated
- 1991, 1992 ELN conceptual design workshop 1

  Feedback systems from ALS can scale to 100 TeV protons
- 1991, 1992 ELN conceptual design workshop 1 & 2

  No fundamental obstacle to 200 TeV collider at 10^{35} cm^{-2}s^{-1}
- 1995, 1999 ELN workshops on magnets beyond the LHC

  Inspired the 2001 US multi-lab study of VLHC

Early technological insights in ELN project

- We know how to build a proton synchrotron for 100 TeV at a luminosity of 10^{33} $cm^{-2}s^{-1}$
- Invest in R&D to learn how to build an adequate detector
  - Hermeticity is important
- Build a large tunnel (300 km)
  - Minimize the magnet & vacuum challenges
  - Minimize costs
  - Maximize the potential of the facility
- Devote equal effort to experimental set-ups & to machine construction

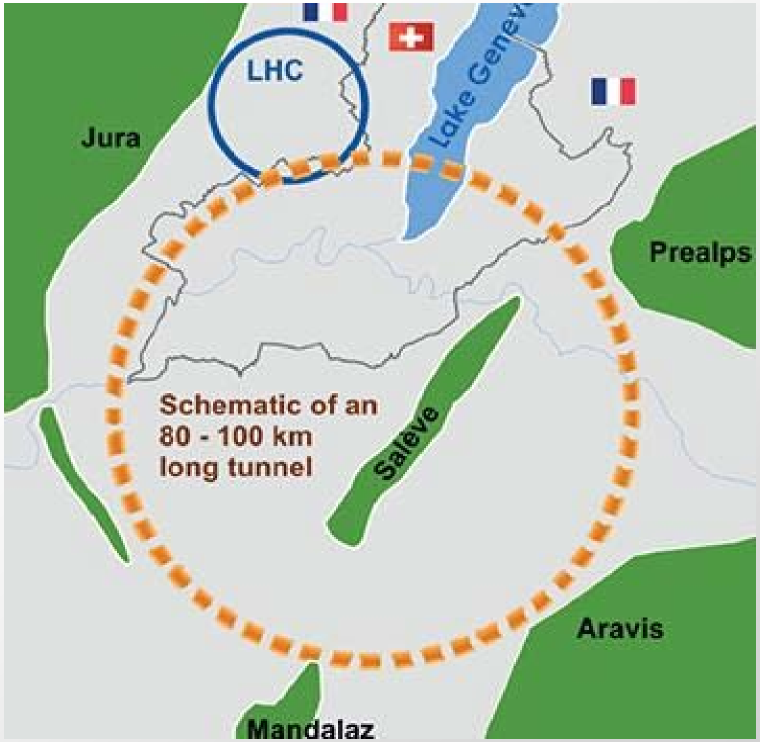
ELN - 300 km (1985)

Focused engineering development is no substitute for innovative R&D

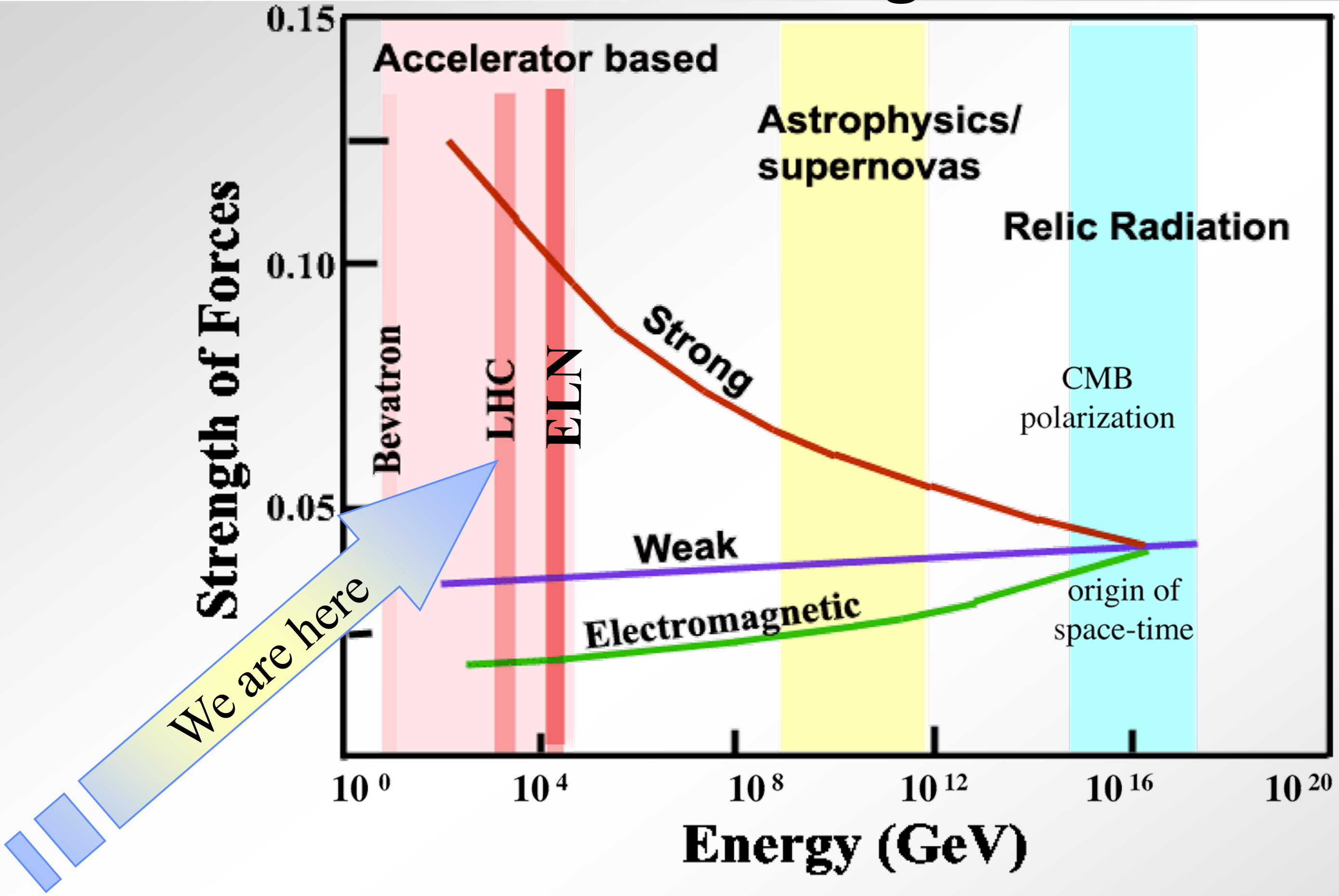
Present perspective: p-p Colliders

- P5 stated that the U.S. should consider hosting a large scale p-p machine, and should participate in studies of this machine.
  - CERN-led Future Circular Collider (FCC) study for both e^+e^- and p-p
  - China's study for the Super pp Collider (SppC) as well as the Circular e^+e^- Collider (CEPC) Higgs Factory.

CERN-led FCC studies consider a 80 to 100 km circumference machine that fits in the difficult geology near CERN, allowing a 100 TeV p-p collider.



“If there is a desert, it is a desert of our imagination” - Zichichi



Accelerator-based physics: Origin of Mass, Beyond Standard Model (BSM), Superworld

Astrophysics: BSM physics , The Dark Universe

Relic radiation: Neutrino astronomy, quantum gravity

As long as Standard Model continues to work, "Higher energy is always better"

- What is the cost *vs* benefit for
  - Higher energy
  - Higher luminosity
  - What is the Energy *vs* Luminosity tradeoff?
- Physics case studies must generate answers to these questions
- Naturalness arguments push towards higher masses => higher energy
  - Collider energy wins rapidly at higher masses
- Dark Matter, electroweak baryogenesis *may* relate to physics at lower masses & smaller coupling ==> high luminosity is more important
  - At 100 TeV, 10x increase in luminosity ==> 7 TeV increase in mass reach
- For a 100 TeV scale collider, discovery luminosity ~2×10^{35}
  - Studies of high mass particle will need ~10x more luminosity

Different physics call for different optimizations

I. Hinchcliffe et.al.; arXiv:1504.06108

Luminosity:
The fundamental challenge of the energy frontier

Assume that bunch length, $\sigma_z < \beta^*$ (depth of focus)
Neglect corrections for crossing angle

Set $N_1 = N_2 = N$

Collision frequency = $(\Delta t_{coll})^{-1} = c/S_{Bunch}$

$$\mathcal{L} = \frac{N^2 c\gamma}{4\pi\varepsilon_n \beta^* S_B} = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n} \left[\frac{EI}{\beta^*} \right] = \frac{1}{e r_i m_i c^2} \frac{N r_i}{4\pi\varepsilon_n} \left[\frac{P_{beam}}{\beta^*} \right] \qquad i = e, p$$

Linear or Circular

Tune shift

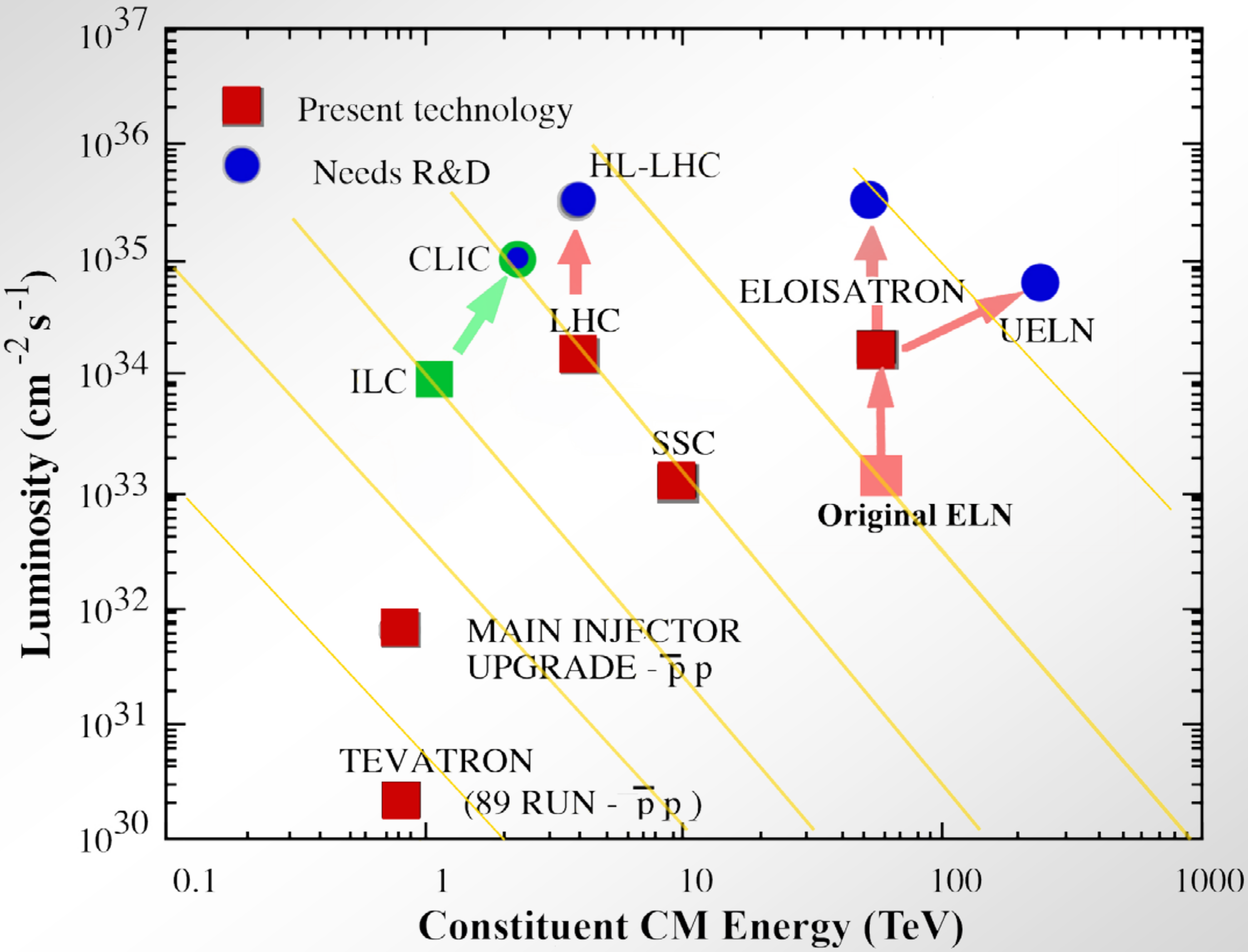
Other parameters remaining equal

$\mathcal{L}_{\mathbf{nat}} \propto$ **Energy** but $\mathcal{L}_{\mathbf{required}} \propto$ **(Energy)^2**

"Pain" associated with going to higher energy grows non-linearly

Most "pain" is associated with increasing beam currents.

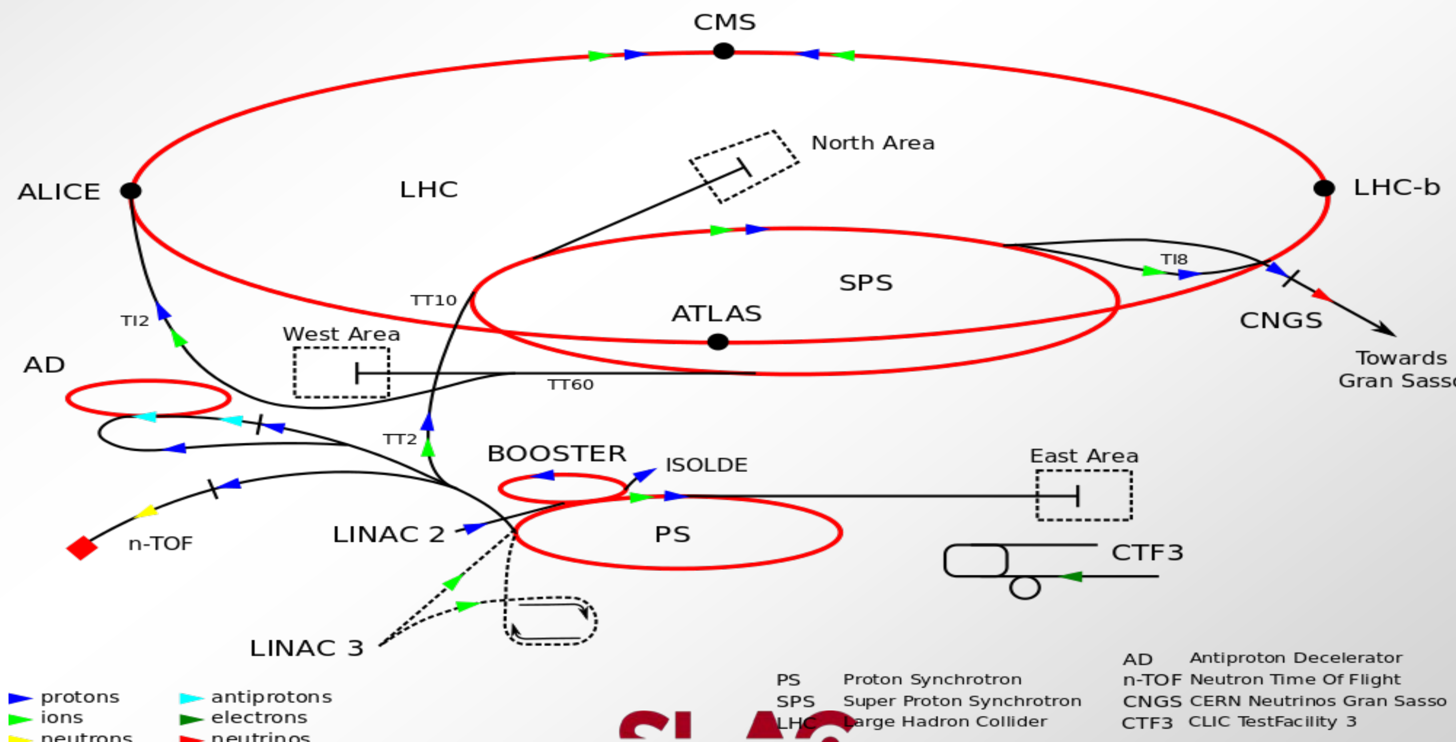
Design the machine for the highest energy & luminosity



WAB edit

p-p Colliders

- Unlike e^+e^-, there are no new concepts for p-p machines.
  - They are proton synchrotrons, with the major variables being circumference and luminosity.
- The world stage will be dominated by the LHC and its high luminosity upgrade (HL-LHC) for the next few decades.



p-p Colliders - Luminosity

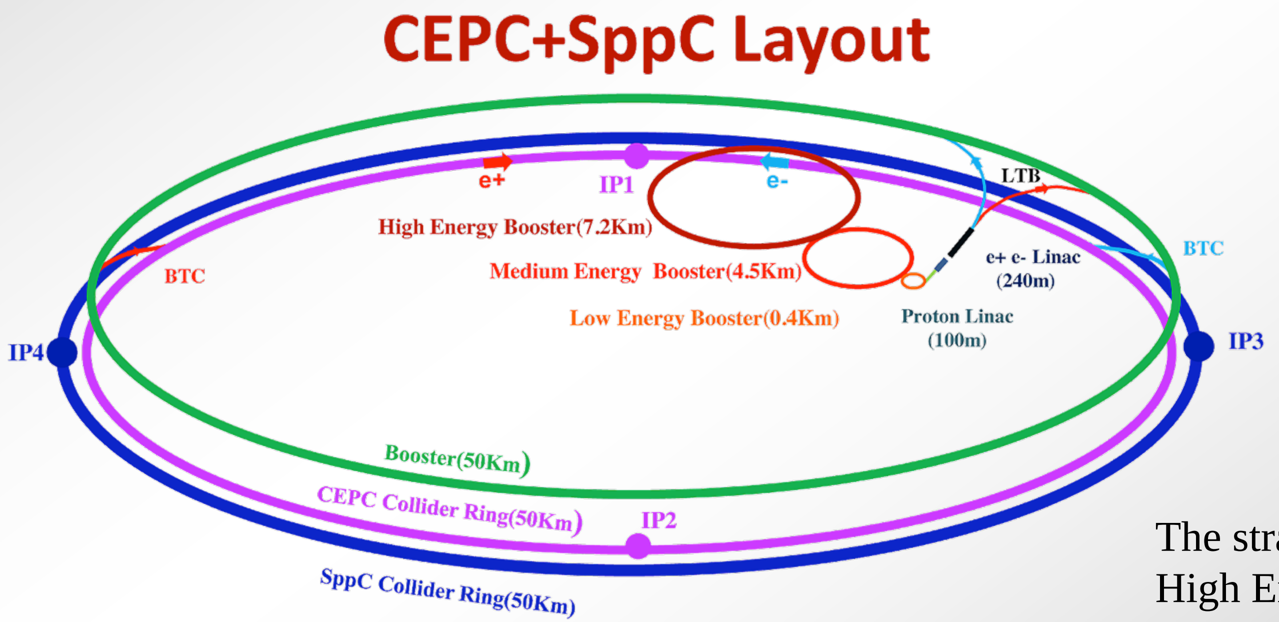
- The "required" luminosity for a 100 TeV-class discovery machine is a complex issue.
  - Lower mass particles (e.g. Higgs) have increasing cross sections with energy, and luminosities could be lower than the LHC for these studies.
  - Maintaining the same reach for new high mass particle discovery requires luminosity scaling faster than *s* because of PDF's.
  - For a 100 TeV scale machine, the discovery luminosity is ~2×10^{35} [Ian Hinchcliffe et.al.; arXiv:1504.06108]
  - Being able to *study* a high mass, newly discovered particle may require a luminosity ~10x that required for a 5σ discovery, i.e. ~10^3
  - Nominal proposed luminosities:
    - SppC: 1.2×10^{35}
    - FCC: $5\ [\rightarrow 20] \times 10^{34}$

Detectors need also R&D:
Luminosity also drives detector challenges

- Measure all detectable particles over as much of the angular phase space as possible
- Minimize reducible backgrounds from misidentified particles
  - **Hermeticity is important**
- Enable data-taking in high instantaneous luminosity environment
  - Very large track multiplicity, hundreds of uninteresting events per crossing
  - Total exposure of sensors to radiation flux scales with integrated luminosity & falls off with distance from collision point
    - Radiation damage degrades sensor efficiency & increases noise
- Undetectable particles like neutrinos & Dark Matter can only have their transverse momentum sum inferred
  - Catch all visible momentum; impose transverse momentum conservation
  - **Hermeticity is important**

p-p Colliders - China

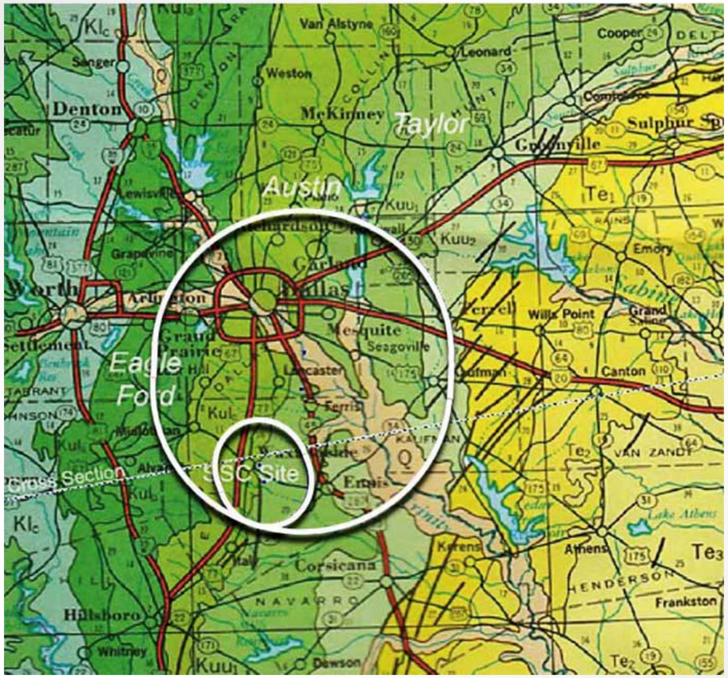
- The CEPC and SppC studies show 54 km circumference rings in the same tunnel.
- The SppC has a cm energy of 71.2 TeV with 20T dipoles.
- It would seem that this choice is intended to keep the cost low to get the 5 year design study going.



The strategy of Accelerator based High Energy Physics of China; J. Gao

p-p Colliders – the U.S.

- There is a study* from P. McIntyre et al for a 270 km circumference 100 TeV machine in Texas chalk.



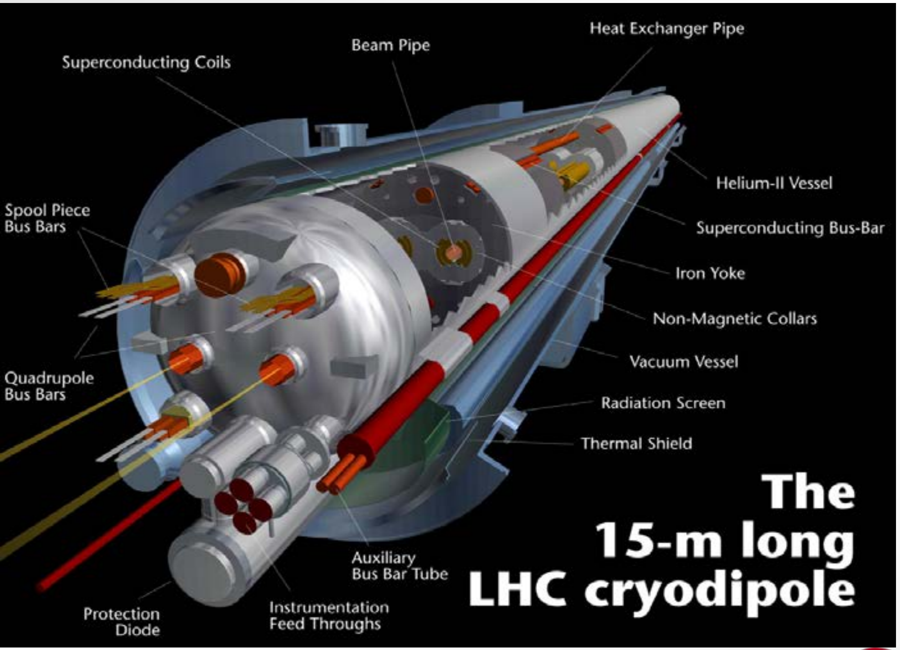
- The 2003 BNL-FNAL-LBNL VLHC study considered a 230 km machine.

*S. Assadi et.al. arXiv:1402.5973

Proton colliders: Magnets

- For a 100 TeV machine:
  - 270 km requires 4.5 T
  - 100 km requires 16 T
- LHC dipoles operate at 8T *

* Level at which all dipoles operate reliably, less than the highest test field.

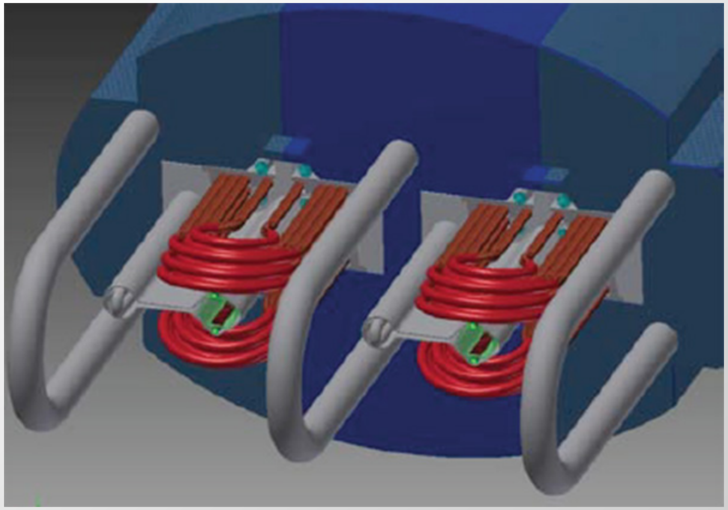


- The LHC dipoles are wound with Nb-Ti.
  - They are industrialized, but expensive
  - ~1/2 total cost of collider ring
- 16 T magnets will require Nb_3Sn or HTS (or both)
- The U.S. leads the world in innovative magnet R&D, but support has declined significantly

Protons radiate!

- Proton synchrotron radiation is real at the LHC (7 TeV Beam, 27 km circumference, 0.5 A) ; 7.5 kW total; 0.22 W/m.
- At 100 km (50 TeV Beam, 0.5 A) SR power is 4 MW; 26 W/m.
  - SR at a 100 TeV scale machine determines the beam dynamics.
  - It is also an important consideration because it is likely that the machine needs a cold bore to pump desorbed hydrogen.
- For significant synchrotron radiation power, the magnets may have to take on aspects of an electron synchrotron, including antechambers & open mid-plane designs.

Engineering issues become daunting as fields increase beyond several Tesla.

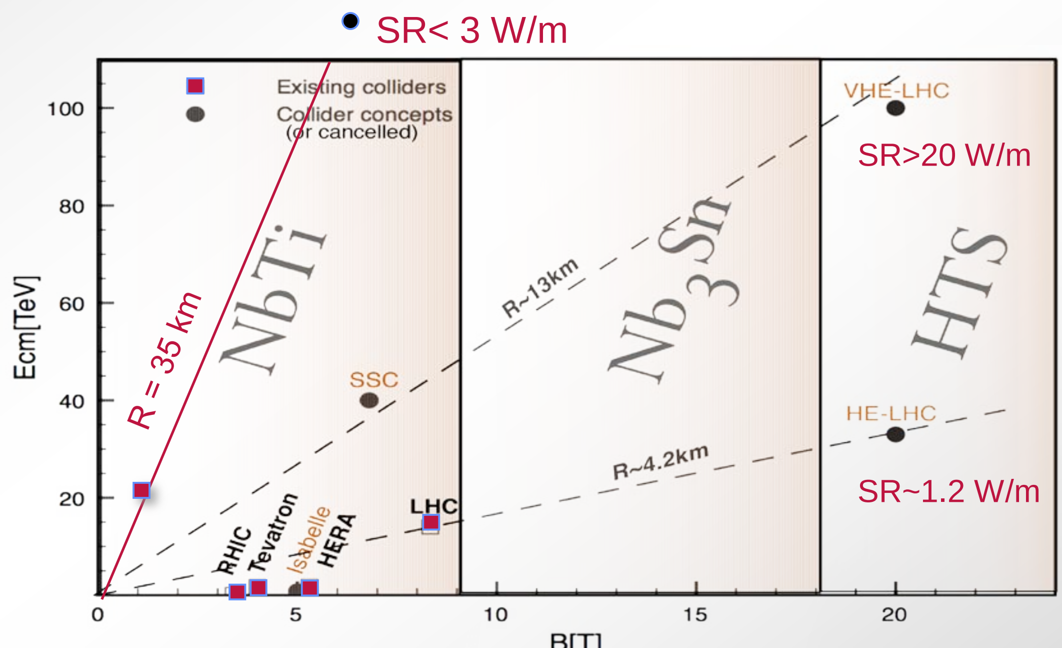


Proton colliders beyond 14 TeV:
Managing SR is coupled with magnet challenges

- Reach of an LHC energy upgrade is very limited (~26 TeV)
  - No engineering materials beyond Nb_3Sn (Practical limit <16 T)
  - Synchrotron radiation management is challenging

$$P_{proton}(kW) = 6.03 \frac{E(TeV)^4 \, I(A)}{\rho(m)}$$

- Proton colliders at 50 - 100 TeV
  - US multi-lab study of VLHC (circa 2001) is still valid - 233 km ring



Breakpoints in technology are also breakpoints in cost [1::8::20(?) per kA-m]$_{cern}$

WAB edit

Machine protection will be challenging

- Proton colliders have enormous stored energy in their magnets & beams

For luminosity = 10^{35} $cm^{-2}s^{-1}$

	E_{cm} (TeV)	Circumference (km)	Energy in beams (GJ)	Energy in dipoles (GJ)
LHC-14	14	27	~2 x 0.4	11
FCC-100 km*	100	100	~2 x 11	~180
Texas-270 km*	100	270	~2 x 30	~60

* *Needs many more machine sectors to keep dipole energy per sector similar to LHC*

* *Needs many more beam abort lines to keep energy per abort line similar to LHC*

- Tunneling costs vary significantly with geography:
  - Scaled costs/m for 4m diameter tunnel:
    - CERN (LEP) molasse/limestone 35 K€
    - FNAL dolomite 14 K€
    - Dallas chalk/marl 5 K€

Conclusions: p-p Colliders

- Luminosity lifetime will be a significant issue as $L > 10^{35}$
  - For FCC 100, luminosity lifetime is 5 hours at 2×10^{35}
    - Practical limiting value without full energy accumulator/injector

- Very little optimization has been done, but it appears that:
  - Magnets will remain a dominant cost component
  - Drastically cheaper ($/T-m) will not make these machines “affordable” (defined as 2-3 x cost of LHC.)

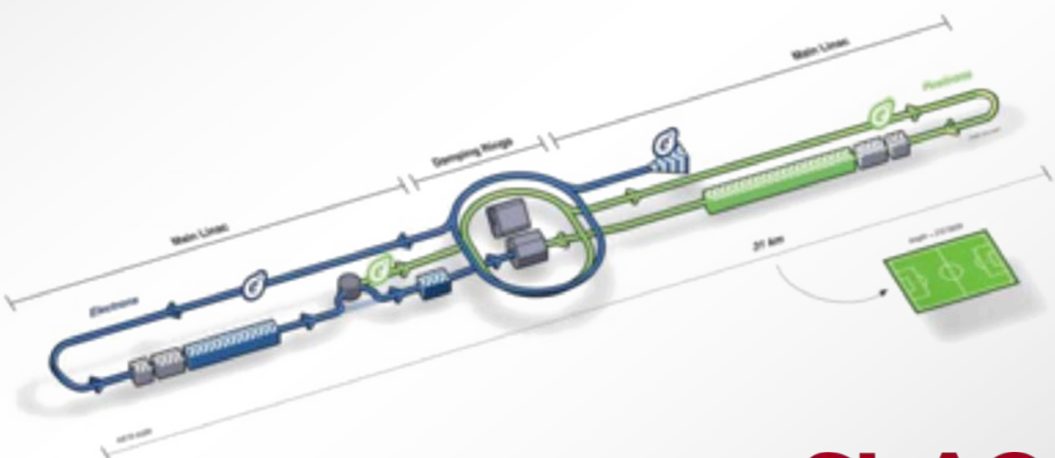
- General HEP community feeling is that a p-p collider should be the next big machine after the ILC.
  - But it is not obvious that the cost can be managed.
  - Interest in an LHC energy upgrade depends on results from Run-II, and on developing practical magnet technology.

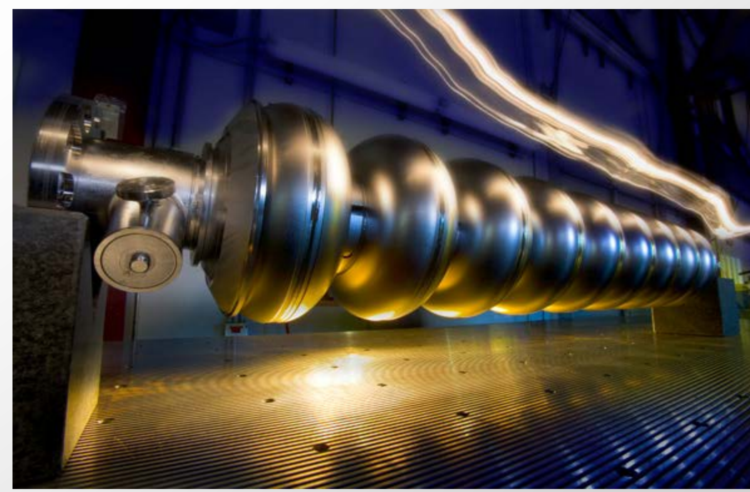
- There is insufficient support for the study of large circumference, low field machines.

Electron-positron colliders

The ILC

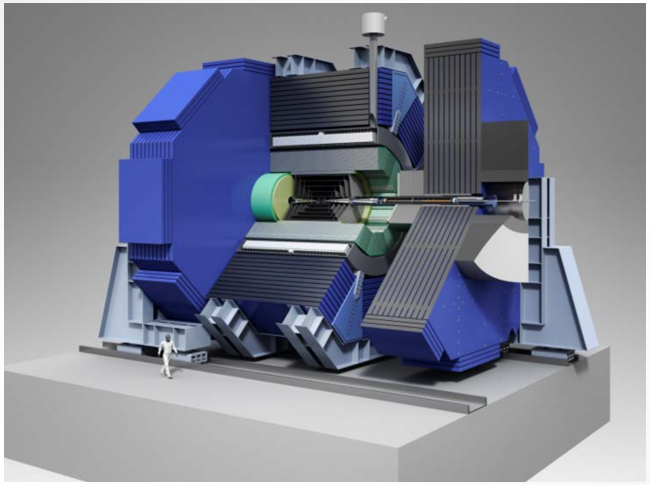
- The ILC is a 500 GeV c.m. SRF machine.
  - Japan is seriously considering a bid to host.
- Cavity gradient is expected to be ~31.5 MeV/m. Cryomodules are complex and expensive.
  - Their technology will be validated by extensive use in the DESY XFEL and the SLAC LCLS-II.
- No other big project is anywhere near this level of technical maturity.

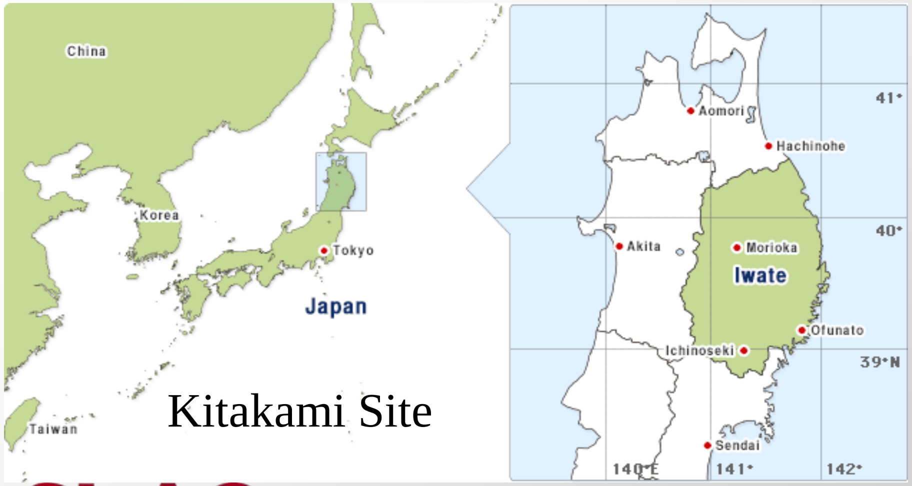




The ILC

- The ILC has broad support in the Japanese Diet, but is going through a long and painful decision process at MEXT
  - MEXT also has to run the summer Olympics in 2020.
- Europe is supportive of ILC work, but funds are tight.
- The U.S. community is barely surviving on life support.
  - Will collapse without a decision soon.



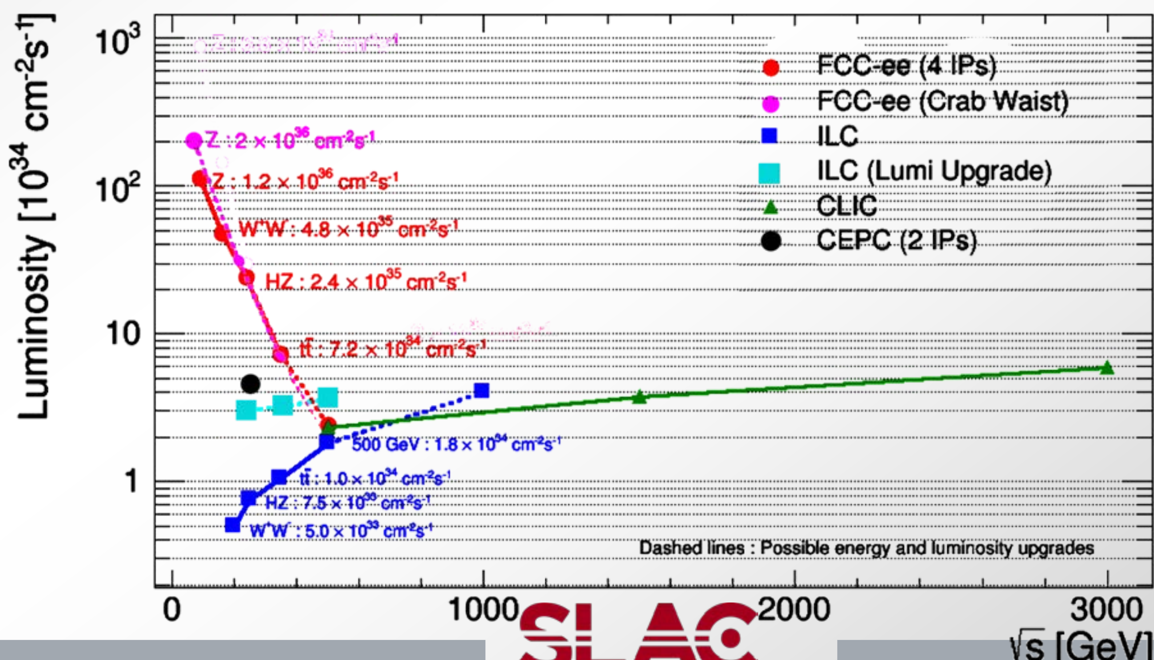


The ILC and SRF

- Preservation of the ILC SRF and its unique train/bunch format appears to require SRF for upgrading from 0.5 to 1.0 TeV
  - Bunch train structure is a challenge for a plasma based machine
  - ILC inter-bunch spacing may be too small for sufficient plasma relaxation between successive bunches – needs study.
- If the ILC proceeds, the agencies should increase R&D on higher gradient SRF to decrease the cost of the upgrade
- R&D towards 80 MeV/m is planned.
  - 80 MeV/m is ~2.5 X present gradient
  - Basic path is development of new SRF materials over 10 years

Circular e^+e^- Colliders

- Both the CERN FCC-ee & China's CEPC studies consider p-p and e^+e^- occupying the same tunnel
- Synchrotron radiation strongly constrains the energy reach of the lepton collider at luminosities $\geq 10^{34}$ $cm^{-2}s^{-1}$
  - ~250 GeV for the CEPC and ~450 GeV for FCC-ee
  - Luminosity drops rapidly with operating energy of the collider
  - Limiting issue is beamstrahlung induced energy spread in the ring.



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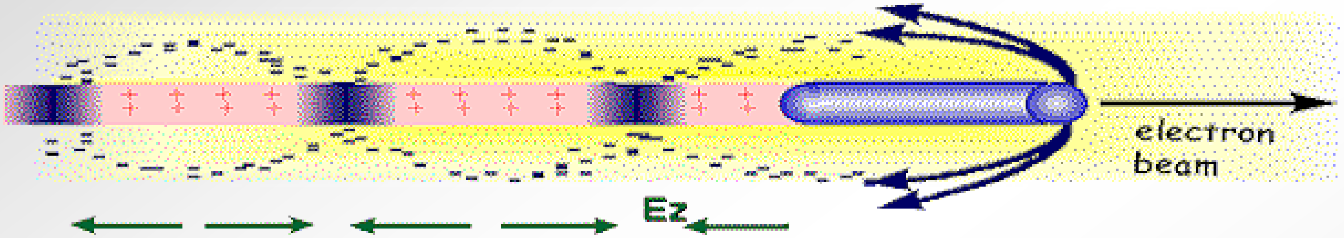
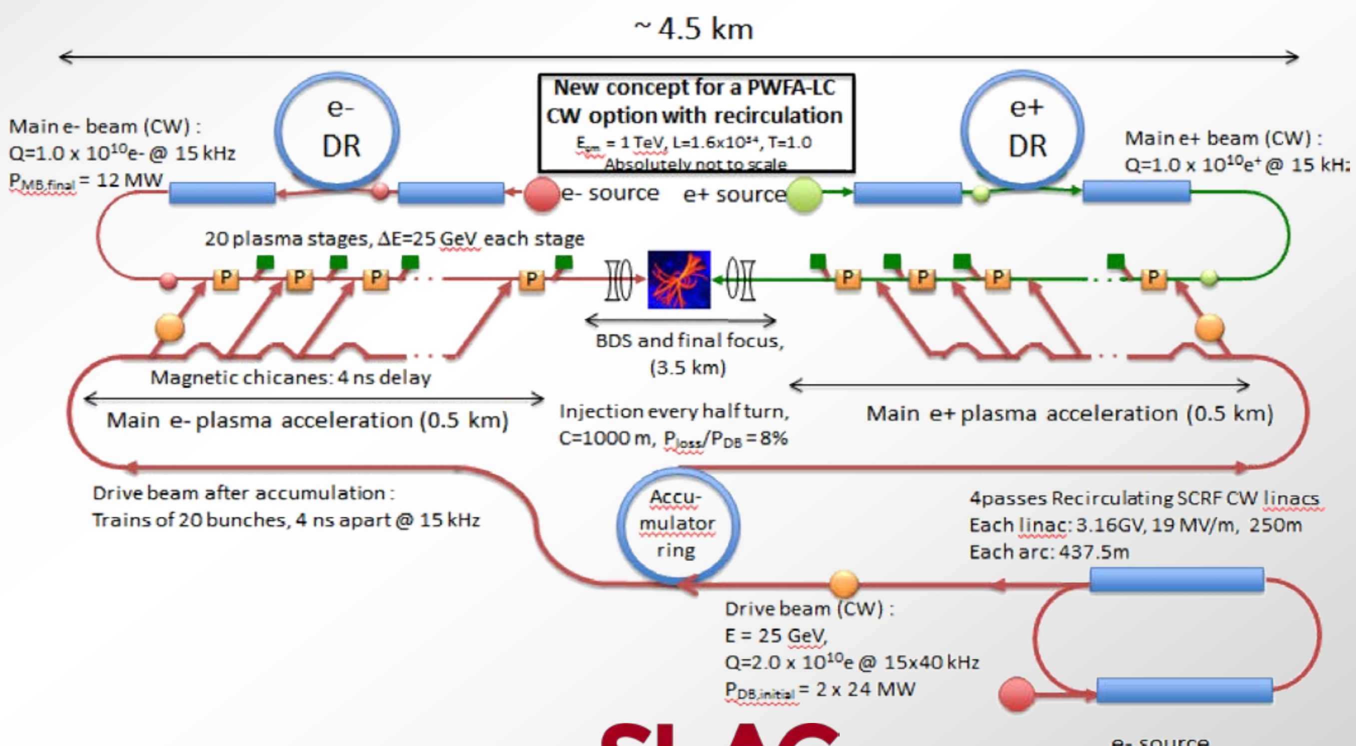
Beyond the ILC

- Many ideas are being developed for TeV scale e^+e^- acceleration that would have gradients >> 100 MeV/m, and lower capital cost ($/TeV), and lower operating costs.
  - Wakefield Acceleration
    - Plasma wakefields driven by beams or lasers.
    - Dielectric wakefields that accelerate a beam in vacuum.
  - Direct Laser Acceleration
  - Next Generation Normal Conducting RF
  - Next Generation Superconducting RF
- The panel recommended that the advanced acceleration community develop a set of common goals and requirements:
  - *"Budget constraints demand that down-selection of advanced acceleration techniques be performed before extensive further investments are made."*

Beam-Driven Plasma Wakefield Accelerators (PWFA)

- An e^- bunch of high charge, small σ_z, and low emittance creates a wakefield of O(10 GV/m) in a (possibly pre-ionized) plasma.





E. Adli et al, arXiv:1308.1145

PWFA R&D Facilities

- Premier PWFA R&D facility in the world is FACET at SLAC:
  - Proposal-driven user facility using the first 2/3 of the SLAC linac.
  - FACET can deliver appropriate drive and witness beams of e^- or e^+, but cannot have e^- drive with e^+ witness.
  - FACET will end in mi d 2016when LCLS-II takes the first 1/3 of the SLAC linac.
- Demonstrated gradients with low to moderate energy spread:
  - e^- 4.4 GeV/m over 0.36 m with 1.4% energy spread.
  - e^+ 3.8 GeV/m over 1.3 m with 1.8% energy spread.
- A new facility, FACET-II, will utilize the 2nd 1/3 of the linac.
  - FACET-II Phase 2 will be able to study all combinations of drive and witness beams.
- AWAKE, a test facility for proton driven PWFA, is being built at CERN to be operational from 2017.

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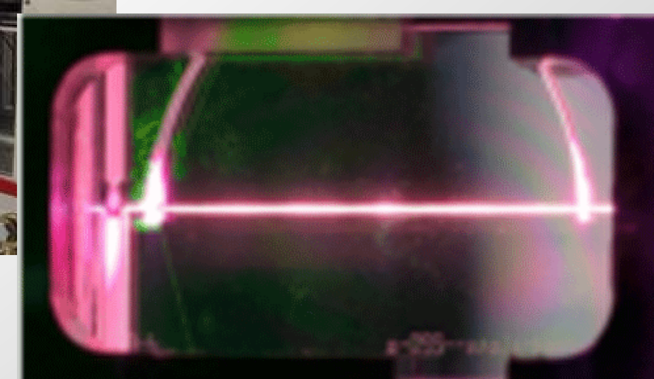
Laser-driven Plasma Wakefield Accelerators (LWFA)

- BELLA is a LWFA experiment at LBNL, utilizing a petawatt laser facility (40 J pulses, 40 fs duration, rep rate 1 Hz).
  - Has accelerated e^- beam > 4 GeV with ~1% energy spread.
  - First demonstration of staging from gas jet to plasma channel
  - Currently world leading, but threatened by European ELI project.
- Expected next step is a 1 kHz laser, perhaps a fiber laser system.
- Can sapphire channels survive high average power operation?



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PWFA and LWFA Challenges

- PWFA & LWFA are thought to offer effective gradients of O(1 GeV/m)
  - Energy gain per stage is of order 10 to 25 GeV.
- Thus O(100) stages will be needed for a multi-TeV machine. Staging has not been demonstrated.
  - PWFA e^- drive beams could be magnetically steered into a plasma channel, but LWFA appears to need mirrors (which can be damaged by the beam, but may be expendable).
  - Matching, phasing, and steering from one stage to the next will likely be challenging.
- Emittance preservation through *all* the stages of the linac is essential.
  - Linear colliders rely on very low emittance & low energy spread beams that can be focused to nm scale to get reasonable luminosity with their low rep rate relative to round machines
- LWFA has not accelerated e^+; PWFA has not accelerated e^+ with an e^- drive.
  - The plasma physics for e^+ and e^- main beams are different.
  - Laser efficiency is critical for LWFA.

Dielectric Wakefield Acceleration (DWA)

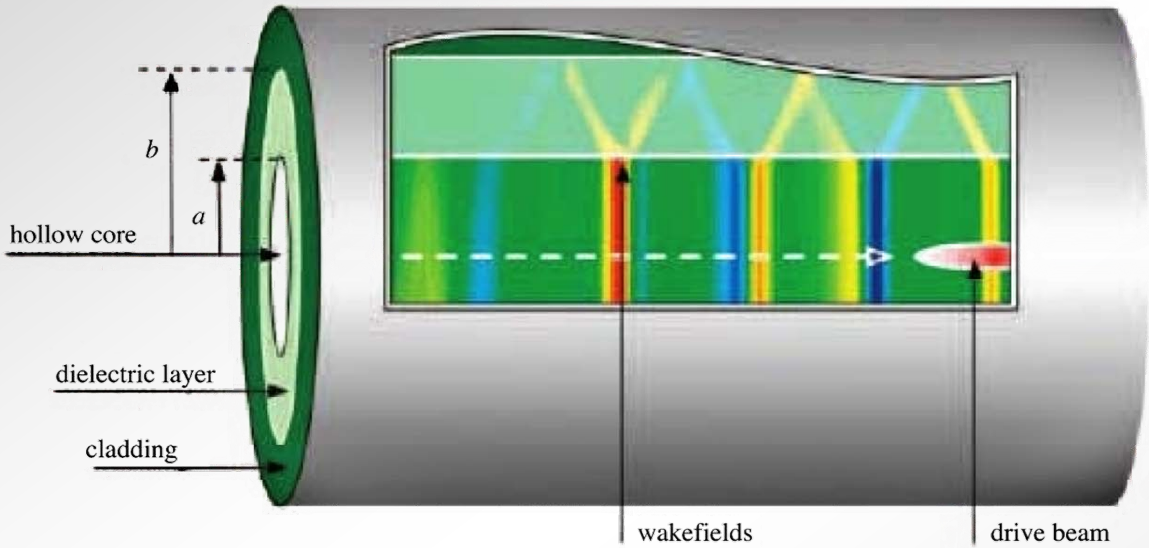


FIGURE 1. Conceptual schematic of a generic dielectric lined cylindrical waveguide. The inner diameter is given by a, the thickness of the dielectric is given by (b−a). A drive beam excites wakefields in the dielectric layer which can be sampled by a subsequent witness beam.

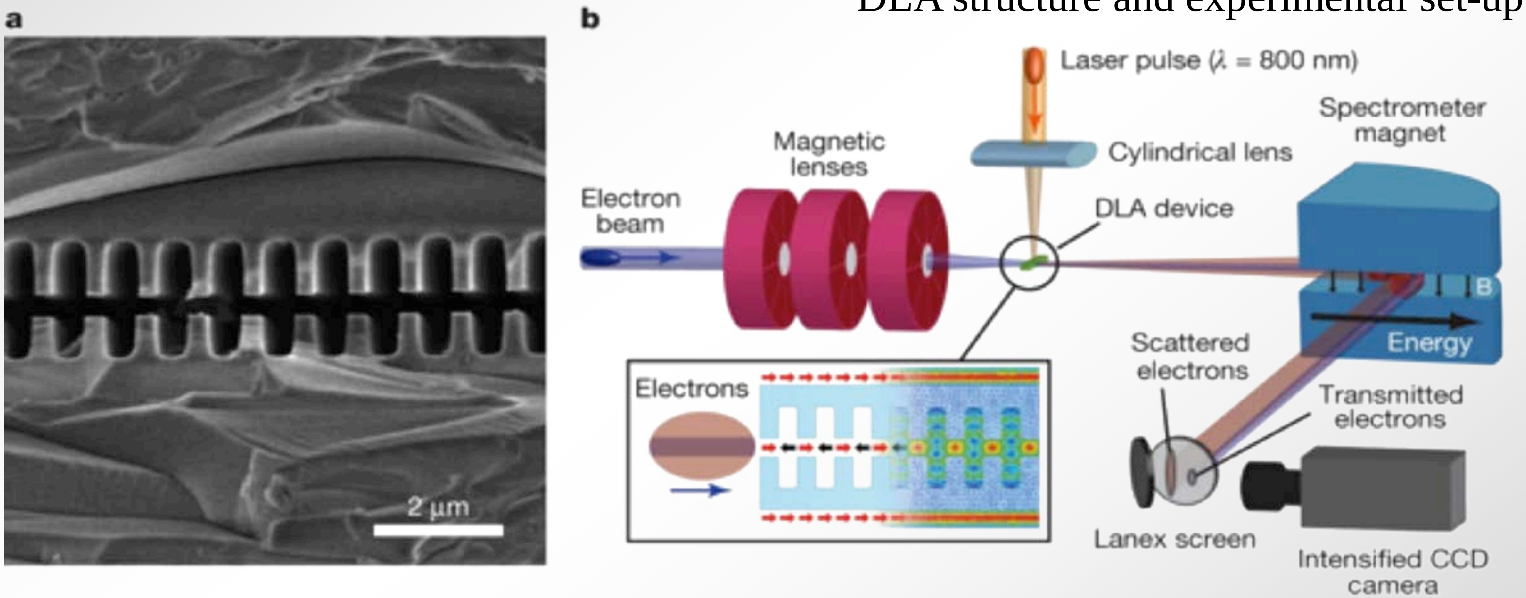
G. Andonian, AIP Conference Proceedings **1507**, 94 (2012);

- DWA experiments have been done at Argonne Wake Field Accelerator, SLAC’s FACET, and BNL’s Accelerator Test Facility.
- The DWA collider topology based on Two-Beam technology is nearly identical to CLIC.

Direct Laser Acceleration (DLA)

- A nano-machined structure of order 0.5 μm clear aperture is used to generate a longitudinal electric accelerating field from a laser.

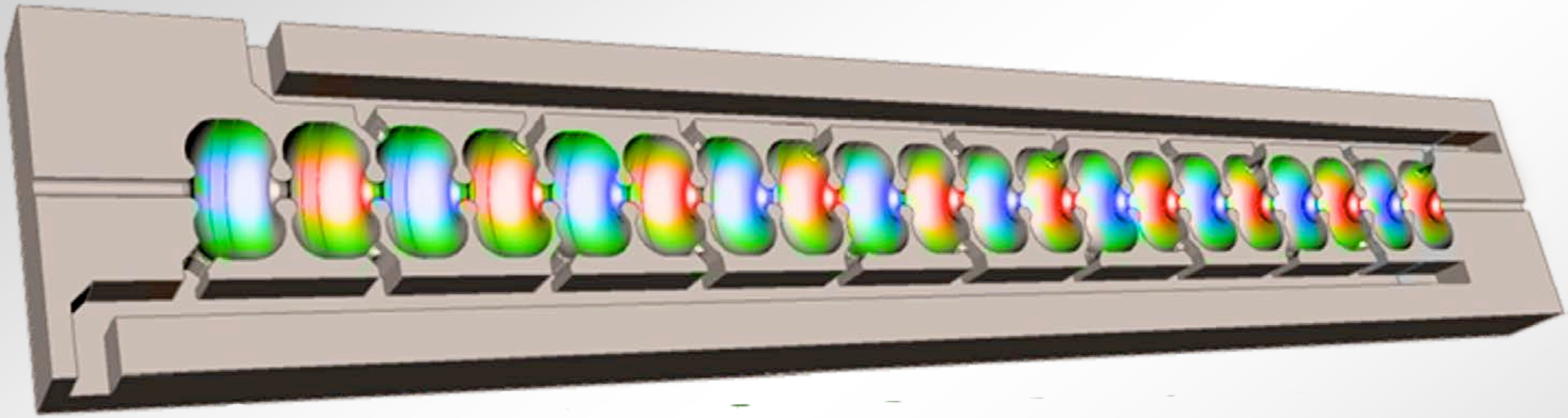
DLA structure and experimental set-up.



- “The subpanel found that direct laser acceleration (DLA) is less likely than other techniques to be the technology of choice for e^+e^- colliders, and recommends reducing DLA funding.”

EA Peralta *et al. Nature* **503**, 91-94 (2013)
doi:10.1038/nature12664

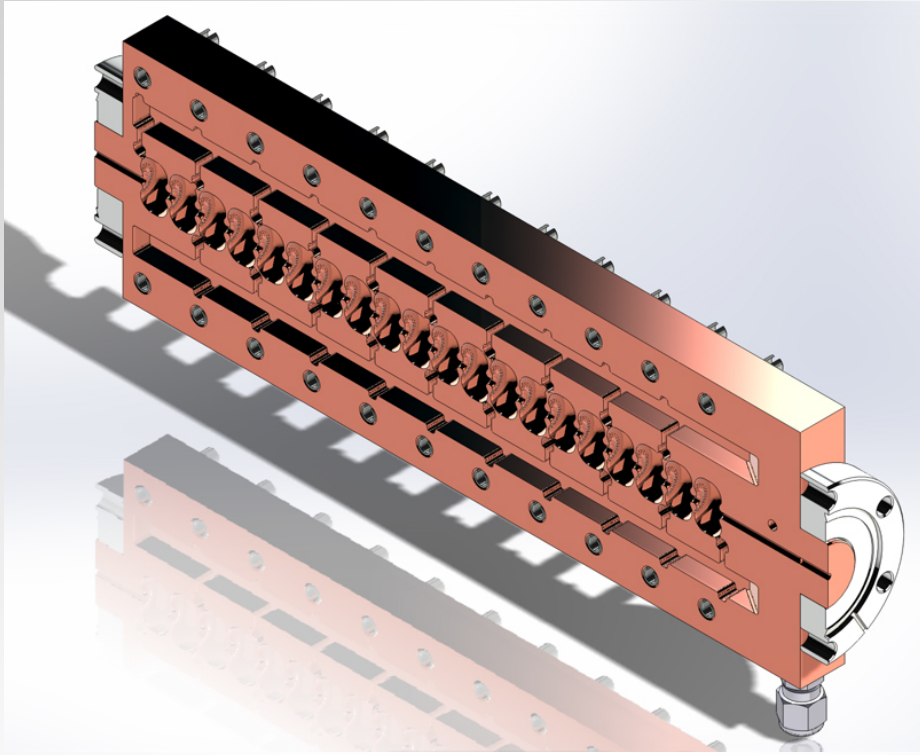
Advanced Normal Conducting RF (NCRF)



RF-distribution manifold individually feeds tailored, standing wave cells in π-mode

- Distributed coupling to each cell allows higher RF to beam efficiency and Ultra-High-Gradients.
- Optimize individual cell shape for maximum gradient and shunt impedance without cell-to-cell coupling constraint
- Requires only 66 MW/m for 100 MV/m gradient compared to 200 MW/m for a typical X-band structure

Advanced NCRF



Test structure, fabricated in industry, being processed at SLAC.

Now at 120 MeV/m and breakdown frequency of 10^{-6} m^{-1} $pulse^{-1}$

- The structures do not have higher order mode (HOM) damping,
  - That might interfere with the high shunt impedance.
- The HOM do not matter if there is only one bunch per train,
  - But then energy recovery from the cavities is required for reasonable efficiency.

Accelerator Efficiency

- L P_{beam}/β^*_y. β^*_y is typically < 1 mm (σ^*_y a few nm) and L O(10^{34} cm^{-2} s^{-1}) so high energy colliders will have beam powers of 10’s of MW.
- In turn this puts a heavy premium on accelerator wall plug to beam power efficiency to keep the total wall plug power under control (< 1 nuclear power plant!)
- CLIC technology is limited to a colliding beam energy of < 3 TeV due to high power consumption (600 MW).

Number of power conversions

- CLIC: Wall →RF →Beam →RF →Beam
- DWA: Wall →RF →Beam →RF →Beam
- PWFA: Wall →RF →Beam →Plasma →Beam
- LWFA: Wall →Laser →Plasma →Beam
- NCRF: Wall →RF →Beam
- SRF: Wall →(RF,Cryo) →Beam

- The wakefield approaches have ultra-high gradients & would use less real estate (good!).
- CLIC has a high efficiency approach to RF pulse compression (good).
- CLIC, DWA, and PWFA have same basic topology of energy conversions…different technologies have different efficiencies.
- LWFA suffer from the (presently) low laser efficiency.

Crudely Comparable Efficiencies

- Very crude comparison, different maturities, *attempt at linac only*.
  - Only CLIC and ILC are ~ mature numbers.
  - Efficiencies are values claimed by proponents

CLIC:	Wall →RF →Beam →RF →Beam		8%
AWA:	Wall →RF →Beam →RF →Beam	*why better than CLIC?*	21%
PWFA:	Wall →RF →Beam →Plasma →Beam		13%
BELLA:	Wall →Laser →Plasma →Beam		
		with energy recovery from plasma	11%
NLC	Wall →RF →Beam		8%
ILC:	Wall →(RF,Cryo) →Beam	*with cryogenics*	10%
Adv NCRF:	Wall →RF →Beam		
		with energy recovery…maybe	45%

Our Opinions!
Advanced accelerator technology

- Both PWFA and LWFA are long shots, but they deserve another decade of support.
  - Both are intellectually rich and attract outstanding students.
  - Both techniques need to demonstrate full staging and emittance preservation, as well as e+ acceleration to be plausible for HEP.
  - BELLA is already working on application to FEL.
  - LWFAs seem promising for FELs (or hyperspectral sources) if more cost-effective lasers are developed.
- Dielectric Wall Acceleration
  - Can be explored at existing facilities.
  - Beam travels in vacuum with simpler dynamics than PWFA.
- DLA – no convincing plausibility for a HEP collider anytime soon.

Our Opinions!
$e^+ e^-$ colliders

- NCRF – Probably best chance for a real, "affordable" machine. Beam travels in vacuum with reasonable aperture.
  - There should be no staging or emittance growth issues beyond those due to HOM in the structure.
  - Energy recovery (or HOM damping) must be demonstrated.
  - Gradients > 200 MeV/m possible
- NCRF should be pushed vigorously
  - Significant potential applications across the Office of Science
- SRF as an option for linear colliders will certainly be "stress-tested" for "affordability" with the ILC
- If the ILC does not proceed in Japan, a new effort is likely to wait on much higher gradient technology.

Resources for General Accelerator R&D

- Our panel heard of the possibility of targeted funding pulses to enable particular projects or programs.
- These pulses would enable work impossible to fit into the present funding scenarios:
  - Ramp up R&D for superconducting magnets targeted for a very high energy pp collider.
    - Included would be significant prototypes, manufacturing development, industrial scale up of conductors, and HTS R&D on accelerator quality magnets.
  - "Develop, construct, and operate a next-generation facility" for PWFA R&D, targeting a multi-TeV e+e- collider."
    - This is FACET-II.

More Opinions:
Proton colliders

- Both CERN and China are pursuing 100 km or smaller circumference rings for first e^+e^- and then 100 TeV scale pp colliders.
  - It seems very unlikely that both will happen.
  - The e^+e^- machines have enormous synchrotron radiation loads, usually fixed as a design parameter at 50 MW/beam.
- Such p-p machines will require high field magnets that are beyond the state of the art, dramatically so for 20 T dipoles.
- Serious optimization studies, including consideration of much larger rings, are eagerly awaited.
  - The VLHC study is a solid basis
  - We hope U.S. participation in the ongoing studies will help with the optimization work.

More Opinions
Future colliders

- Next generation p-p machines may not be "affordable"
  - Energy frontier discovery machines might move to e^+e^- with their ~x10 advantage in constituent energy.
    - BUT, much lower cost e^+e^- acceleration would be required.
      - Same order of $/GeV as proton synchrotrons
    - See Burton Richter arXiv:1409.1196
    - Collision energy > 2 – 3 TeV will need adiabatic final focus (e.g., plasma lens) to overcome quantum excitation of emittance

- We'd have to rethink muon colliders

The Accelerator R&D Subpanel could not meet P5 hopes.

- There are no new concepts for proton acceleration out there.
  - A serious optimization study including careful analysis of $/T-m for magnets is still in the future.
- ILC is (to put it mildly) uncertain.
- DOE funding is too small to push hard on the new techniques.
  - The wakefield acceleration approaches for e^+e^- are interesting, but their wall plug efficiency seems unlikely to surpass CLIC, and there are many technical problems, particularly for the plasmas.
  - SRF is relatively low gradient and expensive.
  - NCRF is promising but so far has relatively modest support.
- Support for new initiatives in fundamental & computational accelerator physics is minimal.

A distilled bottom line

- To make substantial advances in accelerator capabilities consistent with P5's aspirations the U.S. accelerator R&D program needs a budget which grows with inflation as planned for the remainder of OHEP.
- Special "funding pulses" (25 – 50M$) are required to keep the US at the forefront of magnet technology and wakefield acceleration research.

Acknowledgements

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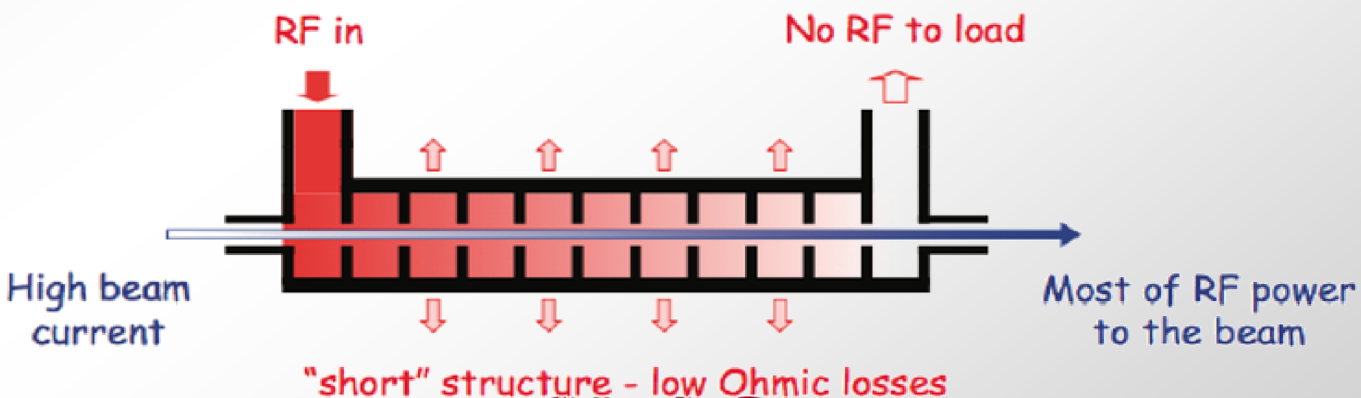
Backup

Drive Beams

- "Conventional RF" – Modulator, Klystron, RF distribution but no pulse compression can have wall plug to RF efficiency ~50%.
- "Drive Beam Accelerators" required for CLIC, PWFA, and DWA must use highly beamloaded linacs, with efficiencies ~90%.
  - However, such linacs have very low gradients, energy transients, and couple beam current fluctuations to energy fluctuations.
  - (CW SRF is an attractive alternative for beam driven PWFA)



Efficiency: CLIC and DWA

- Drive Beam to RF efficiency: ~80%
- CLIC: Main Linac RF to beam efficiency is ~28%
- Overall efficiency for CLIC is ~10%, but there are significant loads from beam transport magnets, giving 7-8%
  - "Low field" SC (~2T) magnets or low torque, adjustable PM quadrupoles might improve overall efficiency)
- Argonne Wakefield Accelerator (AWA): Main Linac RF to beam efficiency claimed to be 26% at 26 GHz, compared to CLIC 28% at 12 GHZ
  - At a gradient of 300 MeV/m which is 3 x CLIC, seems quite good.

Efficiency: LWFA

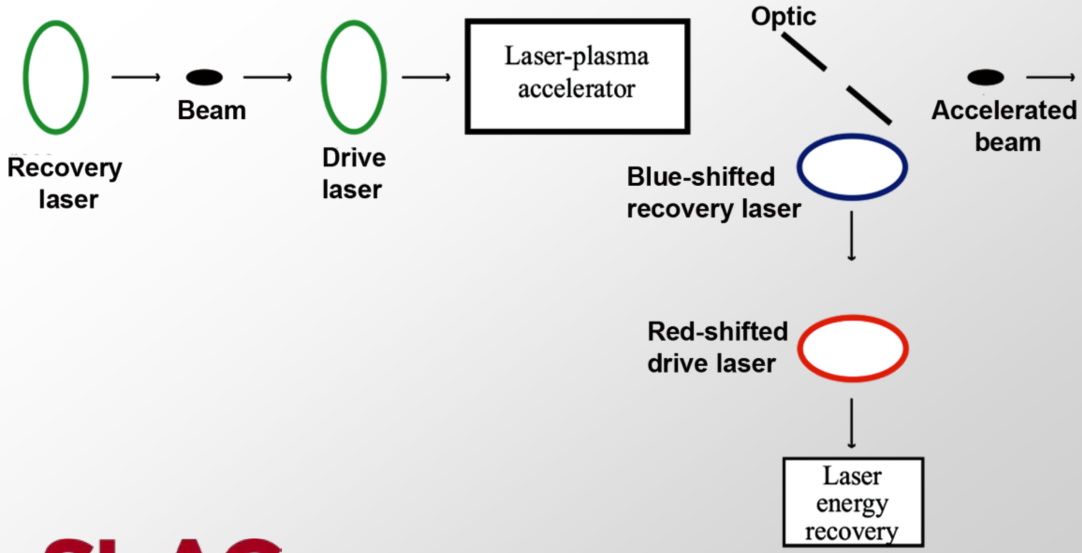
- LWFA for HEP would need lasers with efficiency > RF sources.
  - 35% efficient fiber lasers exist, but not with the high peak power needed for LWFA.
  - Lasers are rapidly improving. BELLA group assumes fiber lasers with high peak and average power will reach 40%. *

US Navy Laser Weapon System uses 6 fiber lasers incoherently combined for a single 33 kW output.
50 kW commercial lasers exist.

* C.B. Schroeder et al, July 24, 2015

LWFA Energy Recovery

- BELLA argues that:
  - 70% of laser energy exits the accelerating column; i.e., 30% drives the wake.
  - Wake to main beam efficiency is 75%
  - Recovery of the red shifted drive laser beam with a photodiode is possible, with an efficiency of 90%.
  - A second laser pulse trailing the electron beam could extract energy from the plasma (blue shift) and be recovered with the photodiode.
  - Overall efficiency ~11%.



The photodiode efficiency involving different wavelengths and high power density seems optimistic….

PWFA Efficiency*

- 25 GeV drive beam is produced by a recirculating SC CW linac. Efficiency, including cryogenics, ~40%.
- Drive beam to wakefield simulations indicate 80-90% efficiency (non-linear blowout regime, shaped electron bunches) possible…
- Wake to main beam efficiency requires attention to energy spread. For electrons, 65% is claimed (QuickPIC)
- Overall wall plug to main beam efficiency 13% at 1 TeV

* A Beam Driven Plasma-Wakefield Linear Collider: From Higgs Factory to Multi-TeV arXiv:1308.1145

Superconducting RF (SRF)

- “Standard” efficiency of wall plug to RF is ~50%
- RF to beam efficiency highly dependent on application, with primary differences from beam loading and duty cycle.
  - ILC main linac efficiency of ~10 % at 500 GeV, with cryogenics and all ancillary systems. 30% of wall plug power is cryogenics[1]
- PWFA Drive Beam efficiency overall ~44%.
- Appears to be very attractive for CW machines, perhaps less so for HEP colliders because of capital costs.

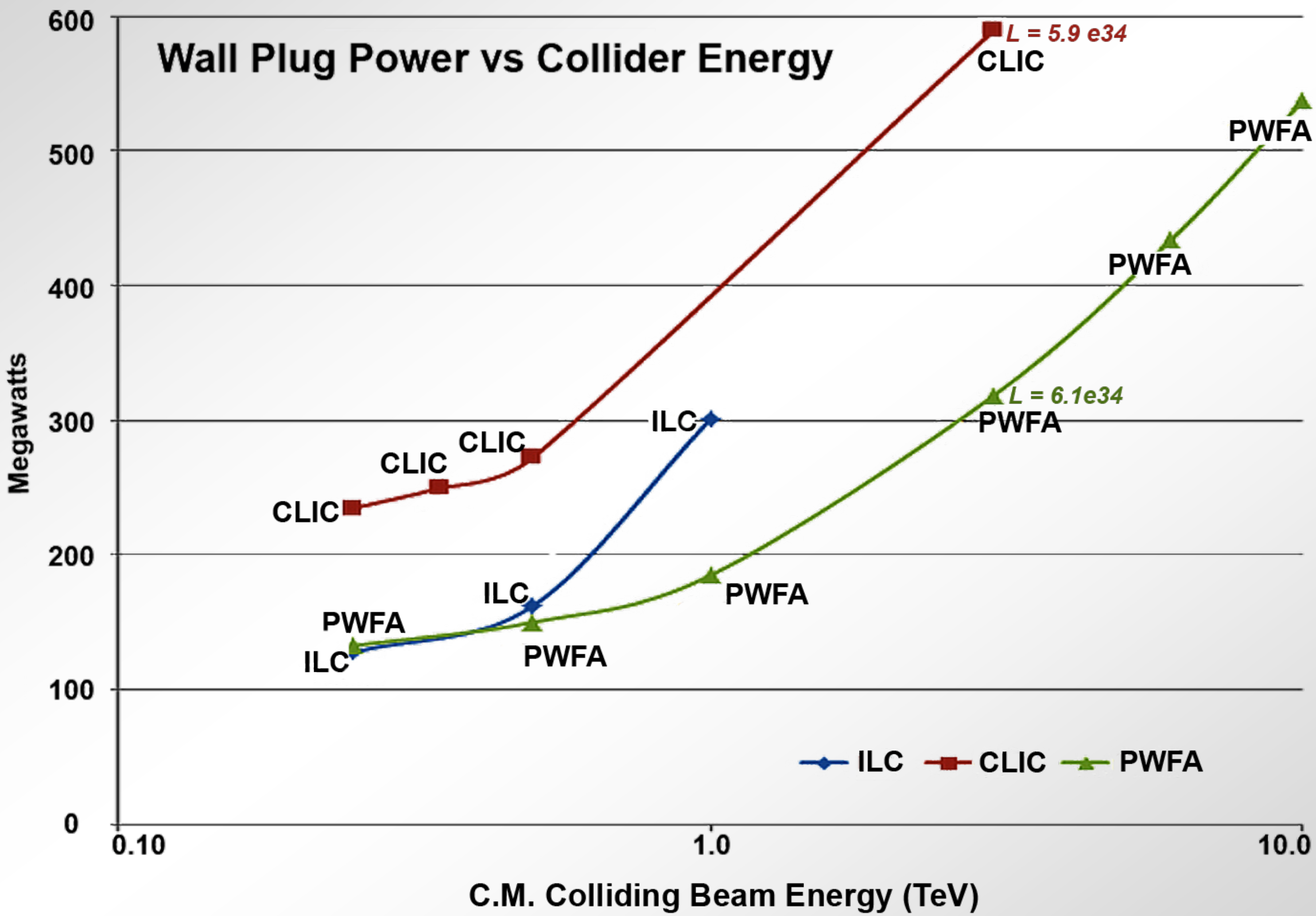
[1] The ILC TDR, Vol. 3, p 26

Efficiency: Advanced NCRF

- NCRF must deal with HOM
  - Option1: Large bunch spacing (or single bunch trains)
  - Option 2: HOM damping scheme that does not spoil shunt impedance
- NCRF must produce efficient high peak power sources as an integral part of the design challenge, particularly if single bunch trains are the solution to HOM issues.
  - Energy recovery from the cavities is likely necessary.
    - Modulator (90%) and “normal” RF (60%) familiar 45%
    - Energy Recovery and low voltage (60kV) klystrons ~85%
    - Structures with wakefield solutions ~60%
    - Overall efficiency *might* get to ~45%.
- NLC “Conventional NCRF” had overall efficiency of 8%[1]

[1] NLC ZDR NLC-1b Table 1-3

Electric Power Consumption Comparison*



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