H.E.P. Accelerator R&D in the U.S. – A biased perspective

M. Breidenbach
W. Barletta

Snowmass 2020 Workshop
August 2020

Our purpose today…

- We were both members of the 2015 HEPAP Subpanel on Accelerator R&D, and that experience initiated this talk.
- This is *NOT* our view of that Subpanel report
  - *NOR* is it our view of what the Report should have been. We participated fully in the Subpanel process and approve the report!
- This presentation is updated to address the Snowmass process
- Broadly, we will look at:
  - Motivations for Accelerator R&D
  - pp colliders,
  - e^+e^- colliders,
  - High intensity proton accelerators for neutrino sources –

all interlaced with our biases and (and perhaps non-PC) opinions.

Why Accelerator R&D

- *From 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 requires changing the capability-cost curve of accelerators, which can only happen with an aggressive, sustained, and imaginative R&D program****.*
  - *That has not happened to the degree recomm*ended
- A primary goal, therefore, remains 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.*”*

U.S. Accelerator R&D Support

- Most of the U.S. Accelerator R&D aimed at particle physics is funded by the General Accelerator R&D (GARD) program within the Office of HEP of the DOE, of roughly $81M/yr. HEP also operates a Stewardship program to support more broadly applicable accelerator R&D, e.g. radiation oncology, with a budget ~$13M.
- A new Office of Accelerator R&D and Production will emphasize manufacturing and generic accelerator R&D.
  - Under Office of Engineering & Technology
- NSF supported an accelerator R&D program at universities ~$10M/yr.
  - Emphasizes potentially transformational accelerator physics
  - Now on hold (No call for proposals for several years)

Strategic Goals

- Accelerators for HEP are *politically* beyond the investment strategy of single countries.
- 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.

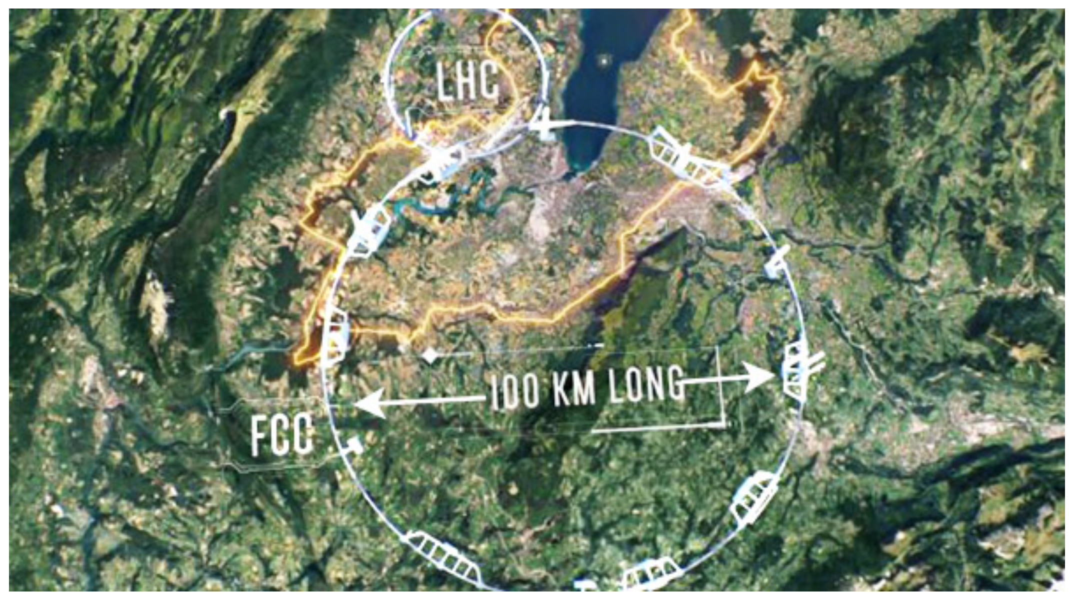
Context: European Efforts in Plasma Accelerators

- Europe & the UK have a rich program in plasma-based accelerators at a dozen research labs and 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 now operates at CERN
- A very large E.U. initiative in laser-based technology, the Extreme Light Infrastructure, is building a major research facilities in Frascati
- DESY will have a laser facility with the capabilities of the LBNL-proposed k-BELLA
- Already U.S. researchers depend on European industry for laser and optics technology

p-p Colliders

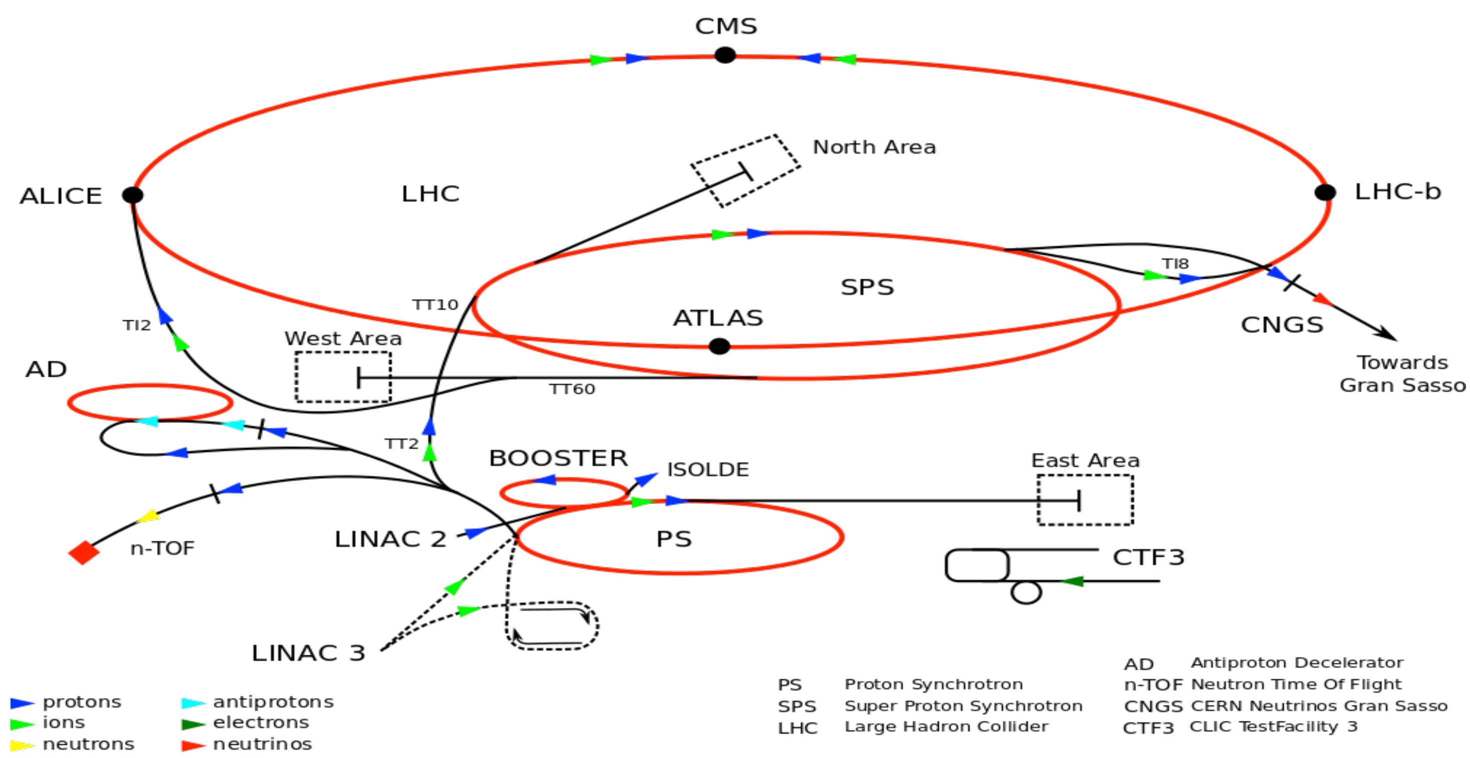
- After Snowmass ’13, P5 recommended that the U.S. should consider hosting a ~100 TeV class collider & participate in international studies of such a machine. *Nothing was done on this front.*
  - » CERN-led Future Circular Collider (FCC) design for both e^+e^- and p-p
    - » https://fcc-cdr.web.cern.ch/
    - » China’s study for Super pp Collider (SppC) and the Circular e^+e^- Collider (CEPC). http://cepc.ihep.ac.cn/preCDR/volume.html
- » FCC is now part of the updated EU strategy

FCC studies analyze a 100 km circumference machine that fits in the difficult geology near CERN, allowing a ~100 TeV p-p collider.



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.

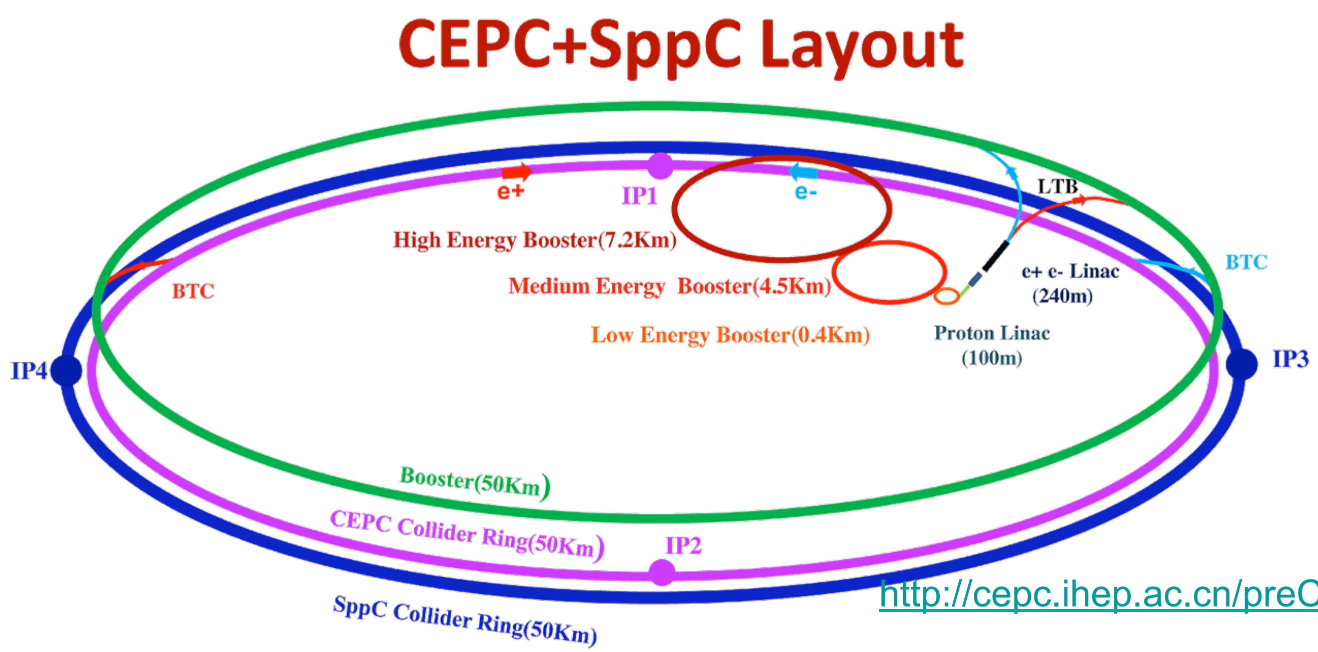


p-p Colliders - Luminosity

- 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^{36}
  - Nominal proposed luminosities:
    - SppC 1.2×10^{35}
    - FCC 5 [→30] x 10^{34}

p-p Colliders - China

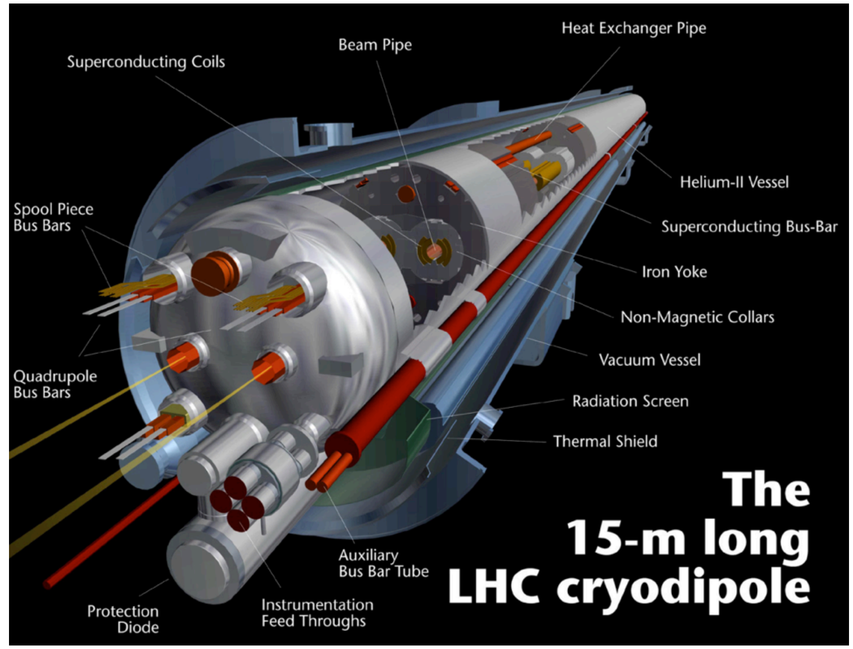
- The CEPC and SppC studies show ~100 km circumference rings in the same tunnel.
- The SppC has a cm energy of ~70 to 100 TeV
- The present political and strategic environment make large international intellectual cooperation with China unlikely
- *Timescale is uncertain*



http://cepc.ihep.ac.cn/preCDR/volume.html

p-p Colliders – Magnets

- For a 100 TeV machine:
  - » 270 km requires 4.5 T
  - » 100 km requires 16 T
- LHC dipoles operate at 8T *
- The HEPAP-recommended Magnet Development Program in the U.S. is led by LBNL to explore the limits of Nb_3SN and HTS accelerator magnets
- Significant, but slow, progress in the US towards a 14 T accelerator dipole
  - » In 1997 D20 achieved 13.5 T (50 mm bore)

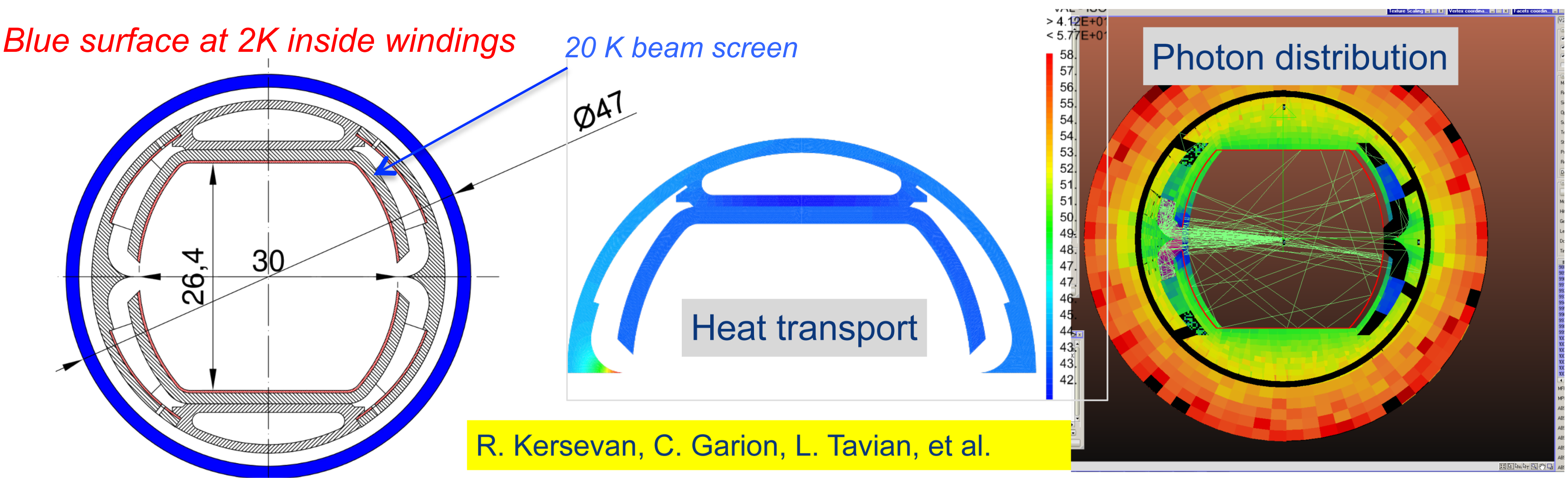


** Level at which all dipoles operate reliably, less than the highest test field.*

*** https://usmdp.lbl.gov/*

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, a 50 TeV, 0.5 A beam radiates 4 MW; 26 W/m.
  - » At ~100 TeV, SR determines the beam dynamics.
- For P_{SR}> ~2 W/m, magnets require aspects of an electron synchrotron.
  - » Significant experimental progress by CERN vacuum group
  - » Engineering issues are daunting as fields exceed several T.



R. Kersevan, C. Garion, L. Tavian, et al.

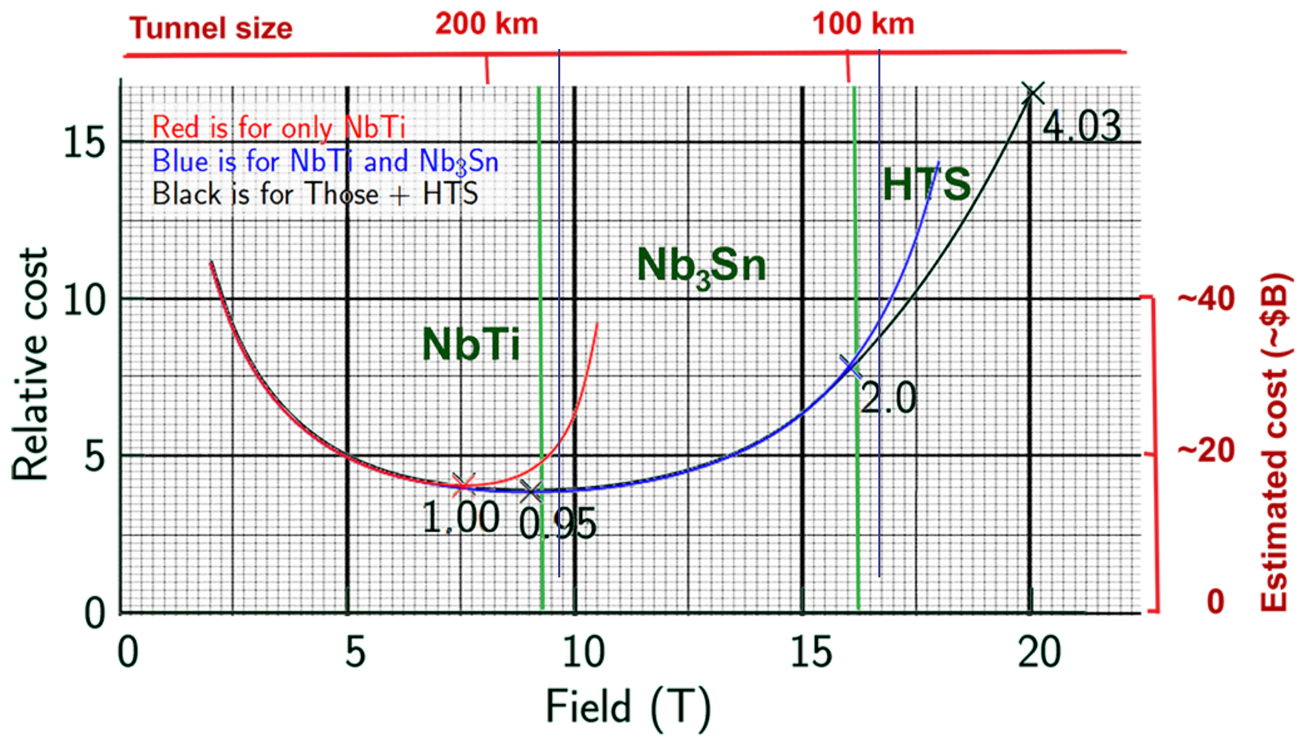
p-p Colliders – Magnets - 2

- The LHC dipoles are wound with Nb-Ti.
  - They are industrialized, but expensive
  - ~1/2 total cost of machine
- 16 T magnets will require Nb_3Sn or HTS (or both).
- The U.S. leads the world in innovative magnet R&D, but support from HEP has declined significantly
  - BNL & LBNL have been starved of GARD support in recent years
  - AUP (Accelerator Upgrade Project) has replaced LARP
  - FNAL has a facility for building LHC and HL-LHC magnets built under the LARP program.
  - The new U.S. Magnet Development Program is led by LBNL
  - There is little support for studying the accelerator physics of large circumference, low field machines.

Scaling of collider cost with machine size
Is this practical in any scenario?

- Given a conductor technology, dipole cost scales as stored energy

$$*C_{dipole}(\$) = const.*B\rho* \, [(r+0.5)/2]^{0.43}[0.25+0.55(8/L_d)]^{0.6} \, [0.3+0.7(B/4.3)]$$ *RHIC scaling*



Estimated cost assumes 2x reduction in cost of magnets per T-m

- Results are for Temp=1.8 K Costs are always higher for 4.2 K
- The minimum cost is at relatively low fields (≈ LHC's 8.3 T).

Source: R. Palmer et al.Accelerator and optimization issues for 100 TeV... (2014)

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

Machine protection will be challenging

- Proton colliders have enormous stored energy in their magnets and 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

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

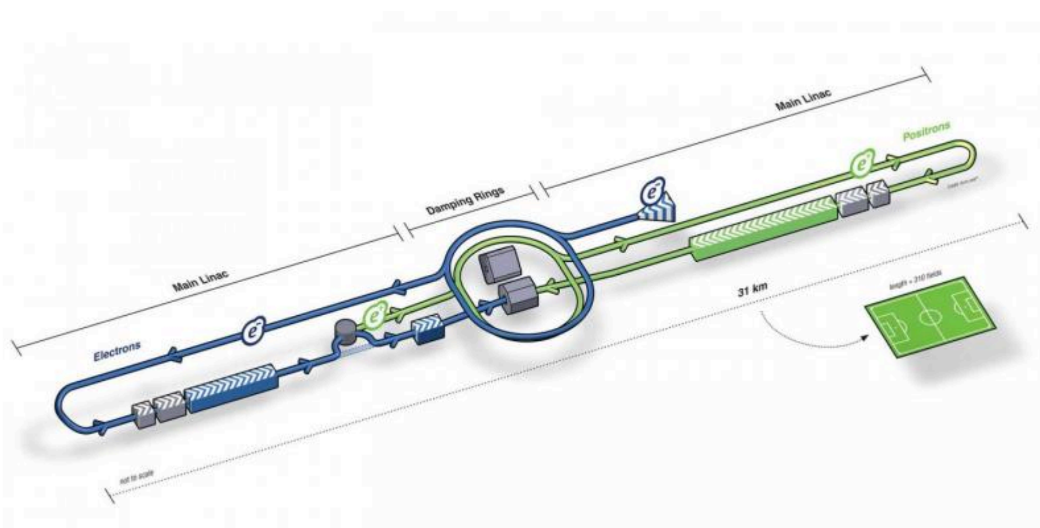
- At 100 TeV per beam & $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1}, P_{debris} = 180 kW/side
  - » With no shielding *Dose (Q1)* ≈ 4 x 10^8 Gy/year

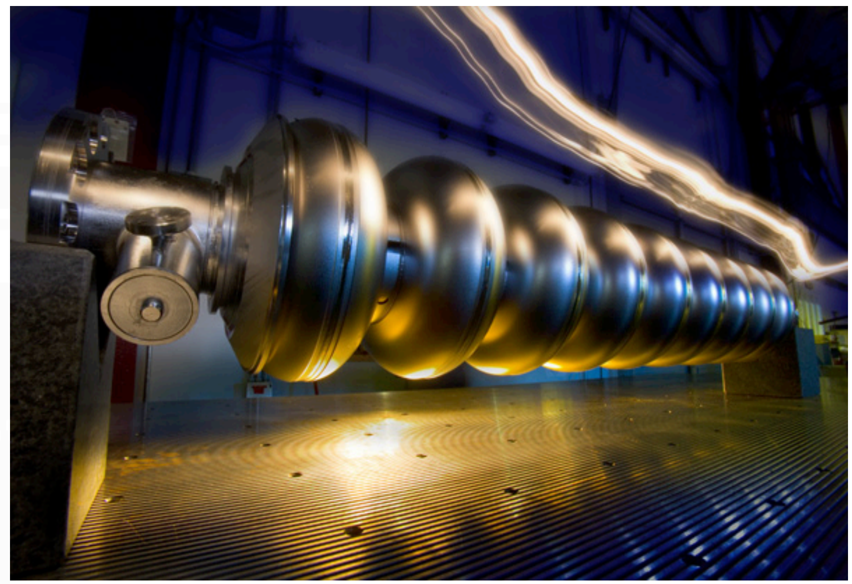
p-p Colliders

- Luminosity lifetime will be a significant issue as L > 10^{35}
  - For FCC 100, luminosity lifetime is 5 hours at 2 x 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 the LHC.)
- General HEP community feeling is that a p-p collider should be the next big machine after the ILC.
  - Industrial projects of this scale have been managed successfully
    - BUT can costs can be managed?
- Interest in an LHC energy upgrade is all but dead
  - *Would require compelling results from Run-II and on developing practical magnet technology at >16T*
    - Not mentioned in EU strategy update

The ILC

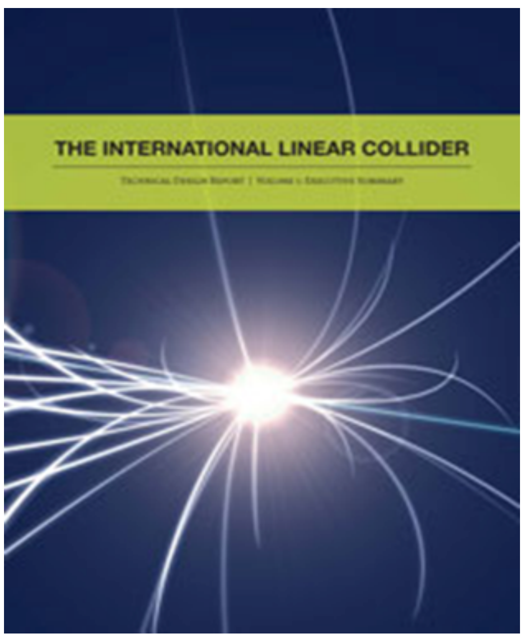
- The ILC was originally a 500 GeV_{cm} SRF accelerator.
  - Japan has been considering a bid to host.
- ILC would start at 250 GeV_{cm} upgradable to 500 GeV_{cm}
  - Gradient of Nb cavities is expected to be ~31.5 MeV/m.
    - Cryomodules are complex and expensive
      - Their maturity is being validated by extensive use in the EuroXFEL and the SLAC LCLS-II.
  - Nano-beam technology is essential for luminosity





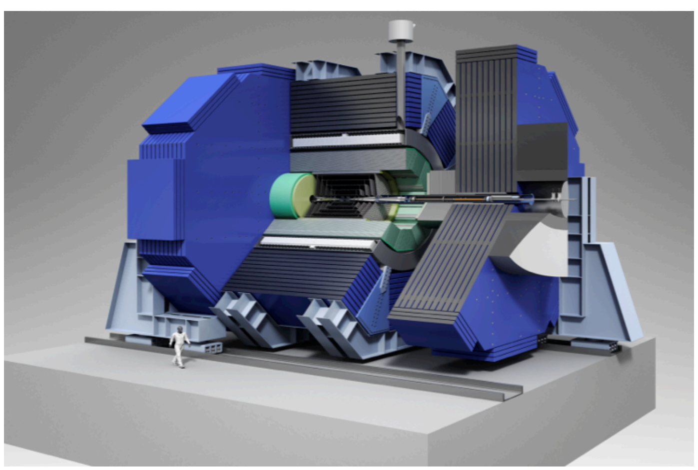
The ILC

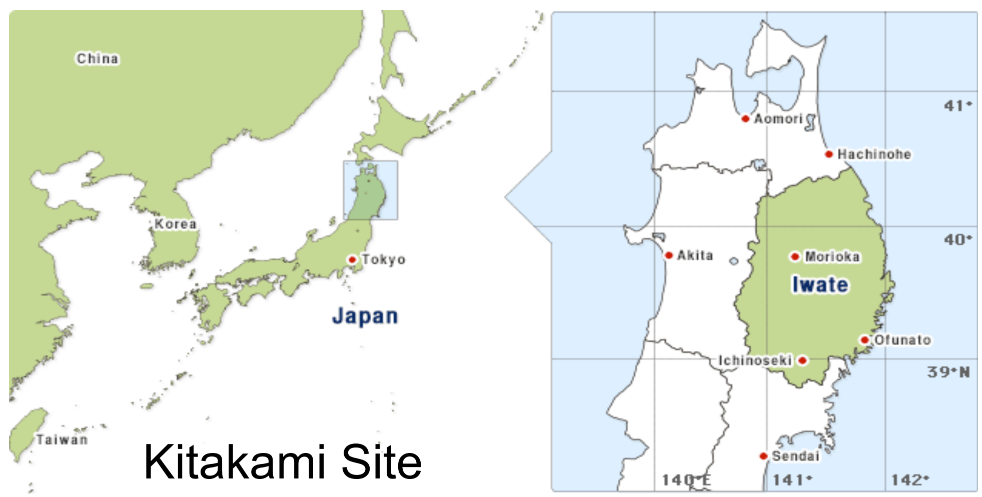
- The ILC has a mature Technical Design Report & technology
  - Performance of Superconducting RF (SRF) cryomodules has reached expectations.
  - No other big project is anywhere near this level of technical maturity.



The ILC

- International collaborations have led ILC R&D since 2005.
  - In summer 2020 ICFA launched the IDT(International Development Team to define the pre-Laboratory phase prior to construction
- The ILC has broad support in the Japanese Diet, but has been going through a long and painful decision process at MEXT
- European Strategy Update is supportive of ILC,
  - But funds are tight.
  - The U.S. community is barely surviving on life support.





Kitakami Site

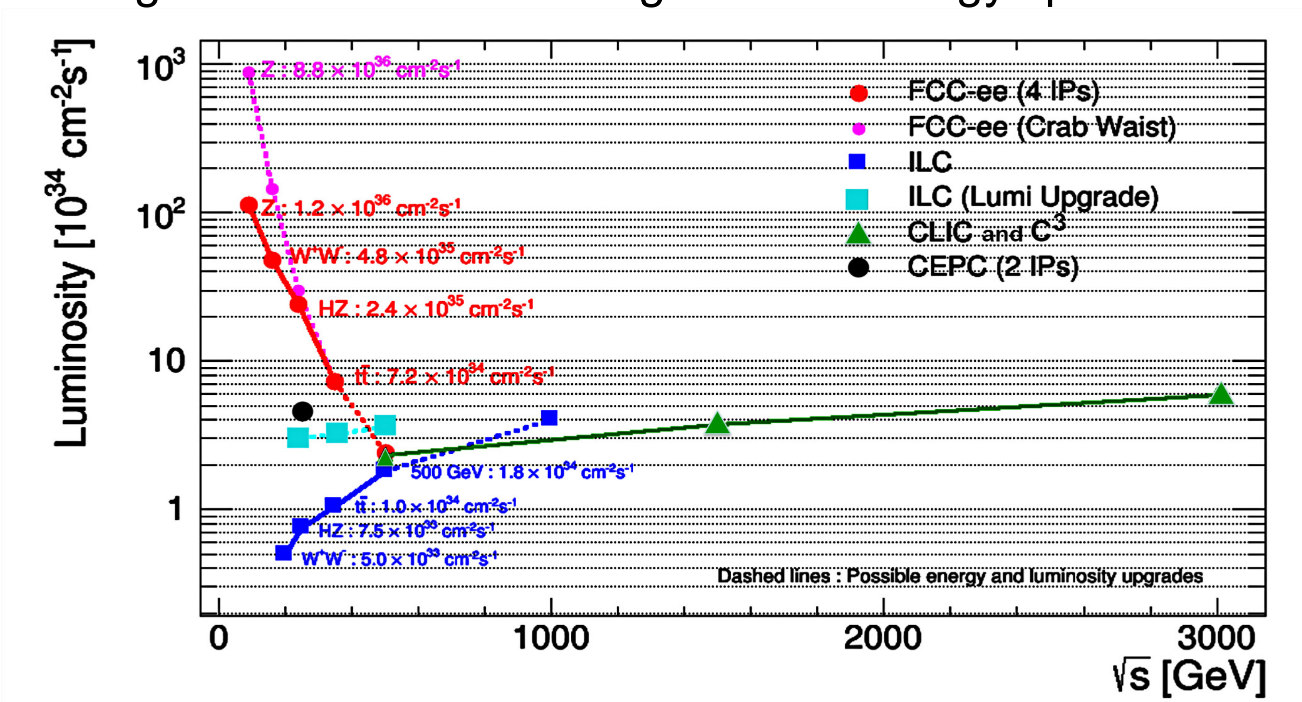
The ILC and SRF

- Preservation of the ILC SRF and its unique train/bunch format appears to require SRF for upgrading from 0.25 to 1.0 TeV
- If the ILC proceeds, the agencies should increase R&D on higher gradient SRF to decrease the cost of the upgrades
- R&D towards 80 MeV/m is planned.
  - Goal of 80 MeV/m is ~2.5 X present gradient
  - Basic path is developing new SRF cavities over next 10 years
    - US efforts at Cornell, FNAL & JLab are focused on Nb_3SN coated Nb cavities that operate at 4.2K
    - Support from NSF (Cornell), HEP (FNAL), and NP (JLab)**
- Replacement of SRF with C^3 technology is an interesting option but with different train/bunch format

** Porter et al. doi:10.18429/JACoW-IPAC2018-WEPMF050, Posen et al. https://arxiv.org/abs/2008.00599, Eremeev et al. Review of Scientific Instruments **91**, 073911 (2020)

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 ≥ 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.



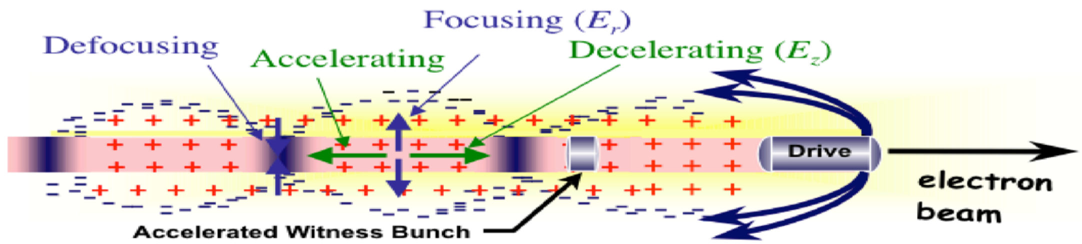
Beyond the ILC

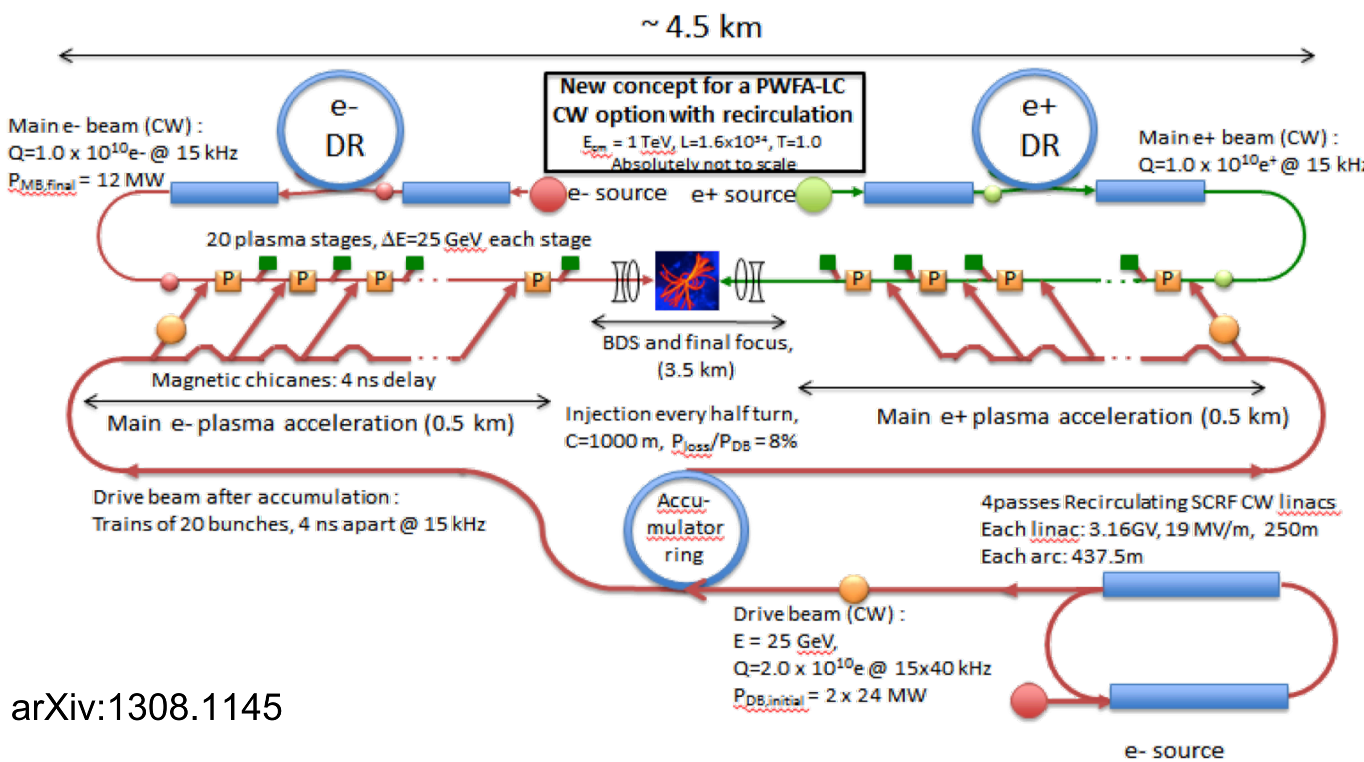
- Many ideas are being developed for TeV scale e^+e^- acceleration that would have gradients > 100 MeV/m, and lower capital cost ($/TeV), and lower operating costs.
  - » Wakefield Acceleration
    - Plasma wakefields driven by beams or lasers.
    - Dielectric wakefields that accelerate a beam in vacuum.
  - » Next generation Normal Conducting RF (C^3 technology)
  - » Next generation Superconducting RF
  - » Other collider components also require cost control, e.g., rf power sources and e^+ sources.
- DOE roadmap* sets of common goals and requirements for advanced acceleration techniques:
  - » *"Budget constraints demand that down-selection of advanced acceleration techniques be performed before extensive further investments are made."*

* Advanced Accelerator Concepts Research Roadmap Workshop Report, *Feb. 2016*

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 SLAC's FACET-II
  - Proposal-driven user facility using utilize the 2nd 1/3 of SLAC linac.
  - Produces witness beams of e^- or e^+, but cannot have e^- drive with e^+ witness beams.
  - Phase 2 will be able to study all combinations of drive and witness beams.

- 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.
    - Nature *Sci Rep* **7,** 14180 (2017). https://doi.org/10.1038/s41598-017-14524-4
- AWAKE, a test facility for proton driven PWFA, has been operating at CERN since 2017.

Laser-Driven Plasma Wakefield Accelerator (LWFA)

- BELLA is a LWFA experiment at LBNL using a petawatt laser (40 J pulses, 40 fs duration, rep rate 1 Hz).
  - Has accelerated e^- beam > 6 GeV with ~1% energy spread.
  - First demonstration of staging from gas jet to plasma channel
    - S. Steinke et al., Nature **530**, 190 (2016)
  - Capabilities will be exceed by DESY facility and other ELI work
- Proposed next step is a 1 kHz laser (k-Bella)
- Can sapphire channels survive high average power operation?
  - Good progress by controlling laser mode
  - Alternately, formation of long hollow plasma channels under study

PWFA and LWFA Challenges

- PWFA & LWFA are thought to offer effective gradients of O(1 GeV/m)
  - Energy gain per stage is ~10 to 25 GeV.
- => O(100) stages are needed for a multi-TeV machine. Robust staging has not been demonstrated.
  - PWFA e^- drive beams can be magnetically steered into a plasma channel; LWFAs 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 6-D emittance beams to focus to nm scale for reasonable luminosity at their low rep rate relative to circular machines
- LWFA has not accelerated e^+, and PWFA has not accelerated e^+ with an e^- drive.
  - The plasma physics for e^+ and e^- main beams are different.
  - Full simulation requires exoscale computation
  - Laser efficiency is critical for LWFA.

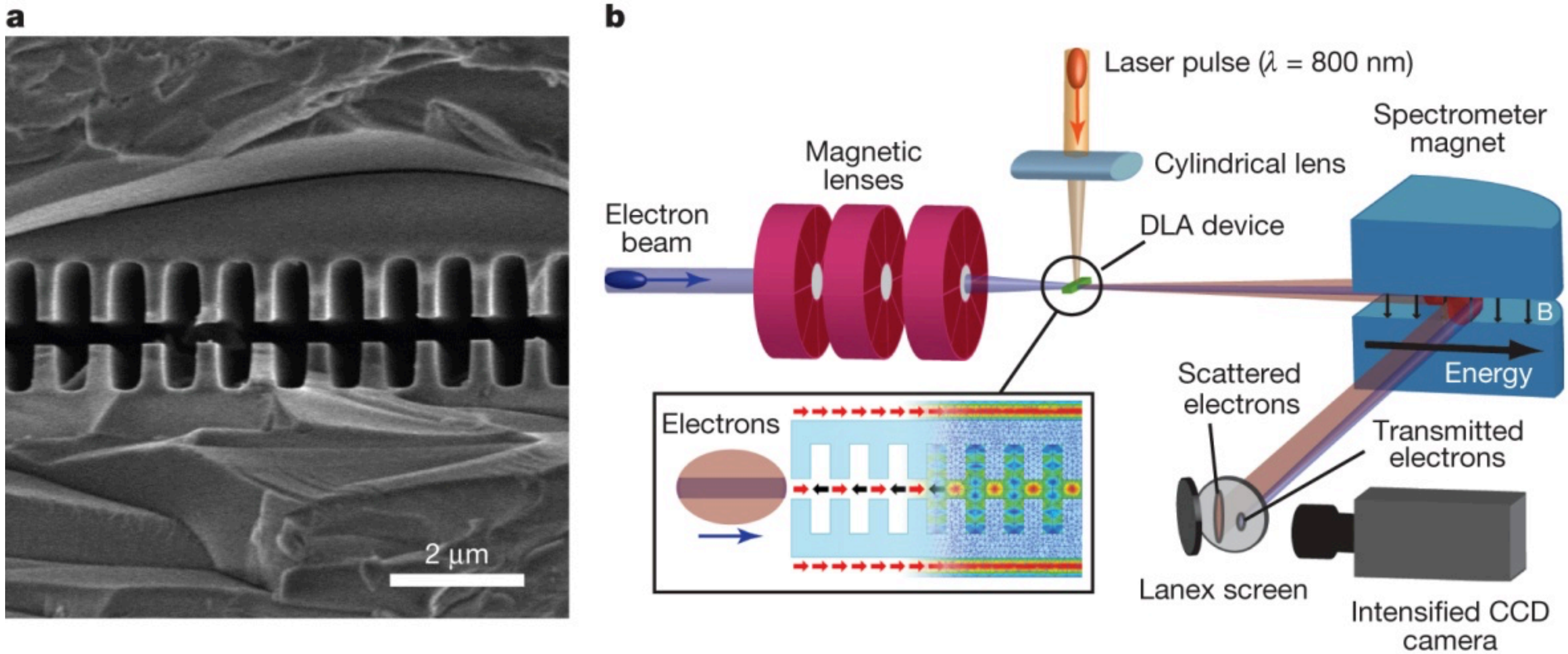
A PWFA Issue

- Stability requirements for a PWFA drive beam are heroic due to the large energy (and correspondingly small beam emittance) mismatch with a multi-TeV "physics beam"
- Under idealized PWFA operating conditions, a 3 TeV collider would require relative drive beam stability of < 1 part in 10,000 for example
- Typical operating conditions for existing linear accelerators: beam jitter is >10%
- Probably similar issue for LWFAs

" Transverse Jitter Tolerance Issues for Beam-Driven Plasma Accelerators", T. Raubenheimer & G. White, IPAC2019, doi:10.18429/JACoW-IPAC2019-THPGW087

Direct Laser Acceleration (DLA)

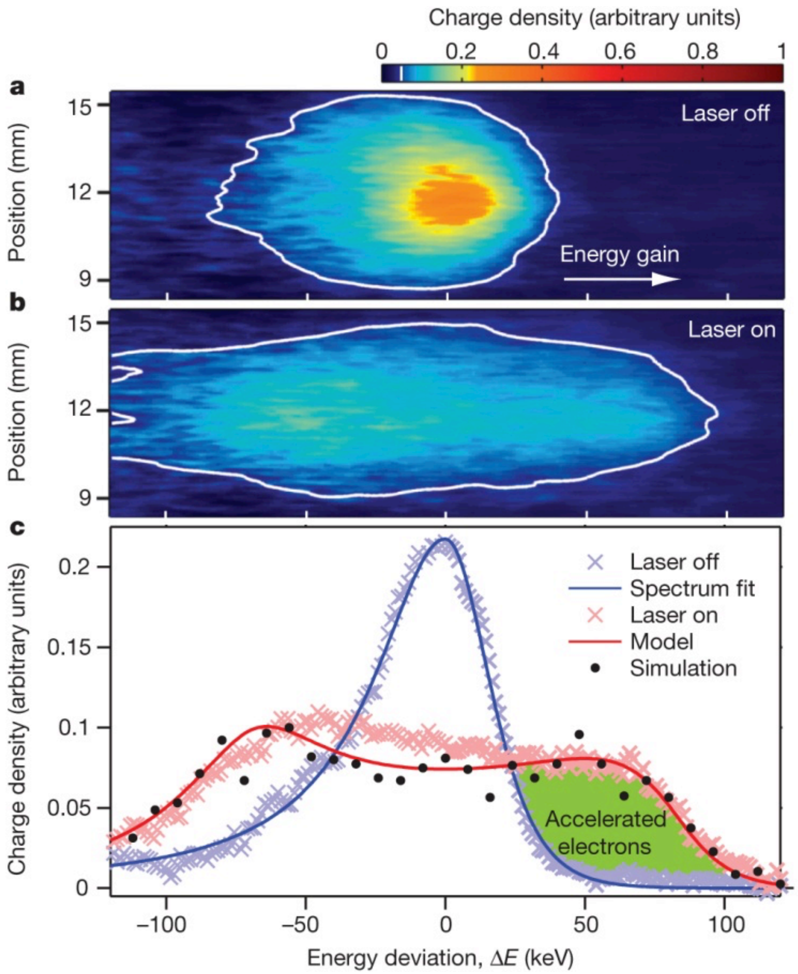
- A nano-machined structure of order 0.5 μm clear aperture is used to generate a longitudinal electric accelerating field from a laser.



DLA structure and experimental set-up.

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

DLA Energy Modulation



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

DOE/HEP no longer supports DLA research. Effort at SLAC now supported by the Moore foundation.

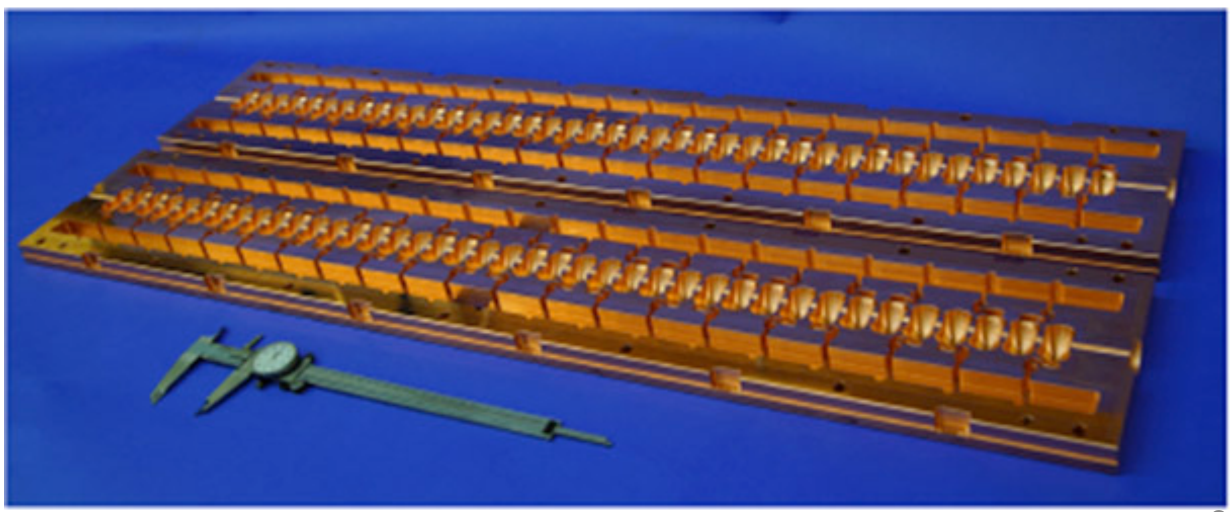
Passing MW's of beam through sub-μm guides is not yet credible.

As transverse wakefields scale as the inverse cube of aperture, beam breakup requires in-depth analysis.

Possible options for other applications such as medicine. 700 MeV/m gradient demonstrated.

C^3 – The Cool Copper Collider

- C^3 is a concept for a staged 2 TeV_{cm} e^+e^- collider based on high gradient, copper structures & distributed RF developed at SLAC.
- The linac, operating under liquid Nitrogen, will have a gradient of 120 MeV/m, based on the GARD cost goal for RF sources.
- The optimal RF frequency is C-Band (~6 GHz)
  - » A structure is being readied for high power testing at LANL.
- The ILC IP, BDS, and e+ sources are accepted as good designs for C^3 , but the Damping Rings are not optimal.

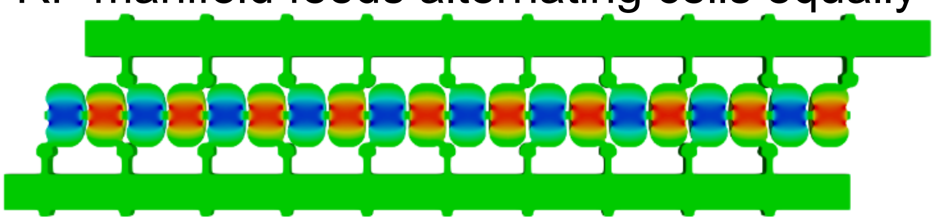


Two halves of a 1-m long C-band structure

Invention of Distributed Feeding Realizes Potential of Highly Optimized Standing-Wave Structures

- Distributed coupling, split-block fabrication, high-shunt impedance and suppression of breakdown to form new architecture for future facilities
- High system efficiency with high gradient and heavy beam loading from 3x less power into structure.

RF manifold feeds alternating cells equally



Tantawi et al. "Distributed coupling and multi-frequency microwave accelerators," Jul. 5 2016, US Patent 9,386,682.

Frequency	**a/λ**	**Phase Adv.**	**Rs (MΩ/m) 300K**	**Rs (MΩ/m) – 77K**
C-band (5.712 GHz)	0.05	2π/3	133	300
SLAC structure		2π/3	57	----

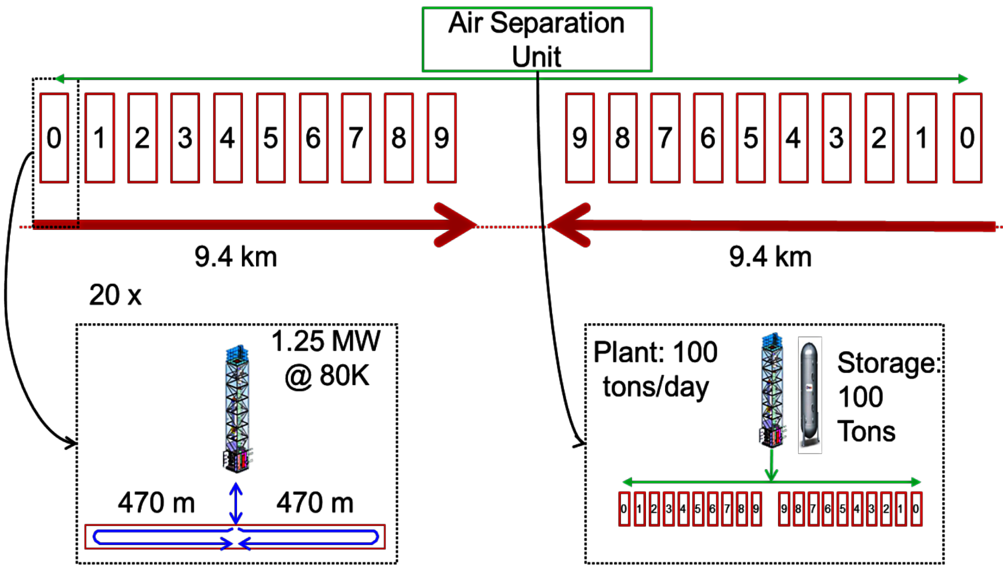
Large isolation between the manifolds and the cavities

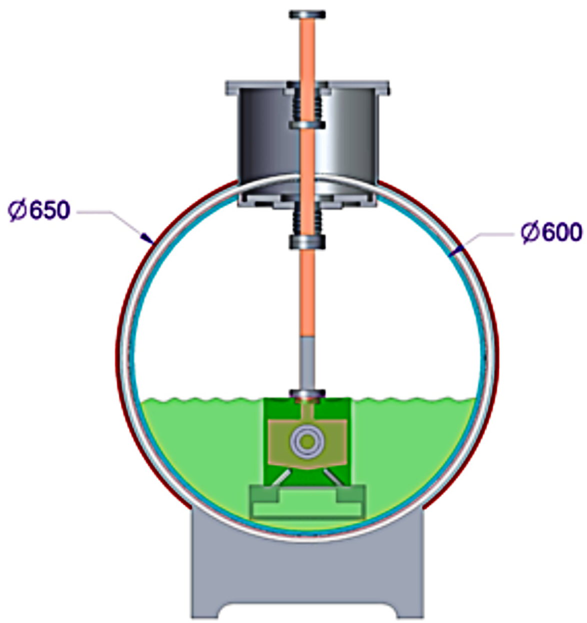
New Scaling Laws Determine the Best Performance for Accelerating Structures

Scalable technology with enhanced shunt impedance capable of reaching high duty factors

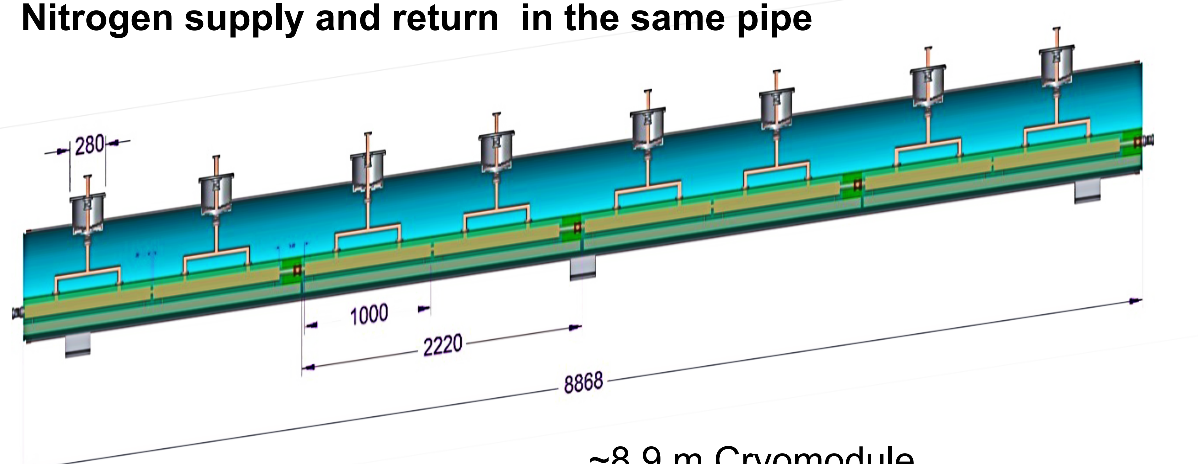
Cryomodule design concept for high average power implementation for 90% fill factor

- Increased conductivity and hardness enable higher gradients at 77 K
- 2.5x less power establishing gradient allows for heavy beam loading even at high gradient – Improves system efficiency





Nitrogen supply and return in the same pipe



~8.9 m Cryomodule

Parameters for 2 TeV Conceptual Design Based on C-Band 5.712 GHz, a/λ=0.05, 2π/3 Structure

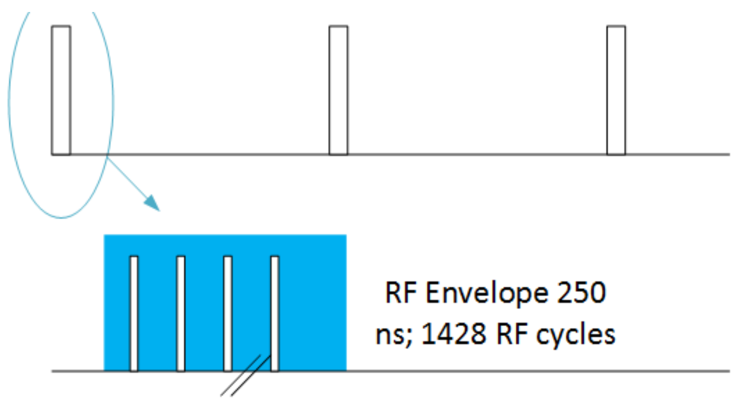
RF Source Cost ($/Peak kW)*	2
Temperature (K)	77
Main Linac Cost (G$ for 2 TeV COM)	6.4
Beam Loading (%) (Beam/RF power)	42.5
Gradient (MeV/m)	117
Pulse Length (μs)	0.25
Cryogenic Load @ 77K (MW)	25
Electrical Load (MW)	135

Parameter*	Value
Source Efficiency (%)	50
Repetition Rate (Hz)	120
Electrical Pwr (cents/ kW-hr)	7
Instr. Add on Length (%)	10
Tunnel Cost ($k/m)	50
Structure Cost (k$/m)	100
Single Beam Power (MW) (for 2 TeV COM)	9

Trains repeat at 120 Hz

Pulse Format

75 1 nC bunches spaced by 19 RF periods (3.3 ns)

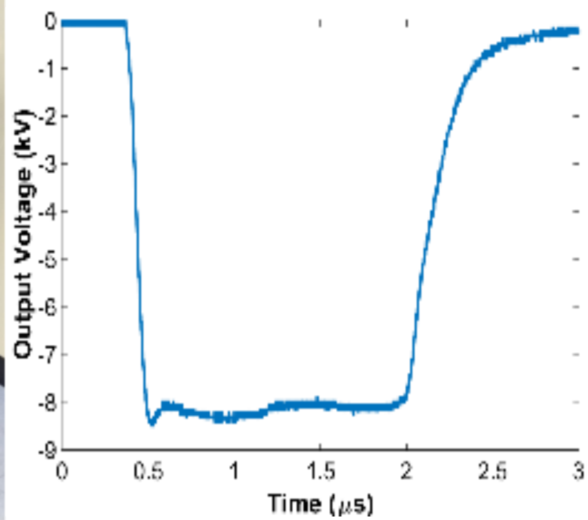


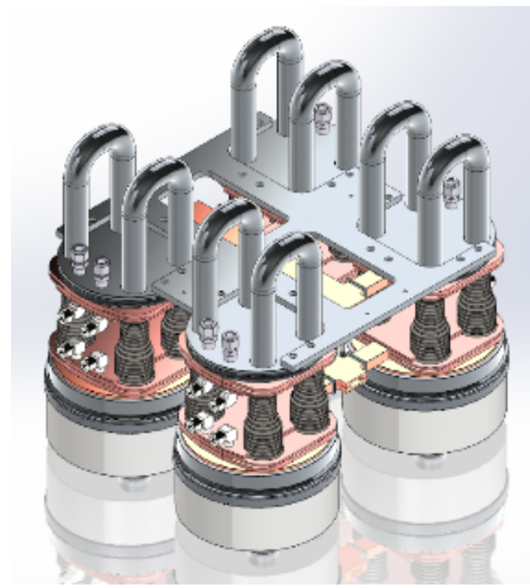
**Assumptions from GARD RF Roadmap Decadal Goals; Includes 21M$ for each 1.2 MW LN reliquification plant*

Significant Progress towards GARD RF Goals

- GARD Decadal survey goal is $2/peak kW. Modulator + RF Source
- Modulator from “COTS” parts already at $1 /peak KW,
- Modular “Klystrino” Array is making progress, but funding limited.

Low-cost “Digikey Catalog” Marx Modulator





Modular Klystron Array operating at extremely low voltages

Accelerator Efficiency

$$L \sim P_{beam} / \beta^*_y$$

- β^*_y is typically < 1 mm (σ^*_y a few nm) and L ~ O(10^{34} cm^{-2} s^{-1}) => high energy colliders will have beam powers of 10's of MW.
- Puts a heavy premium on AC-to-beam power efficiency to control total power consumption < 1 nuclear power plant!
- High power consumption (600 MW) limits CLIC technology to a colliding beam energy of < 3 TeV

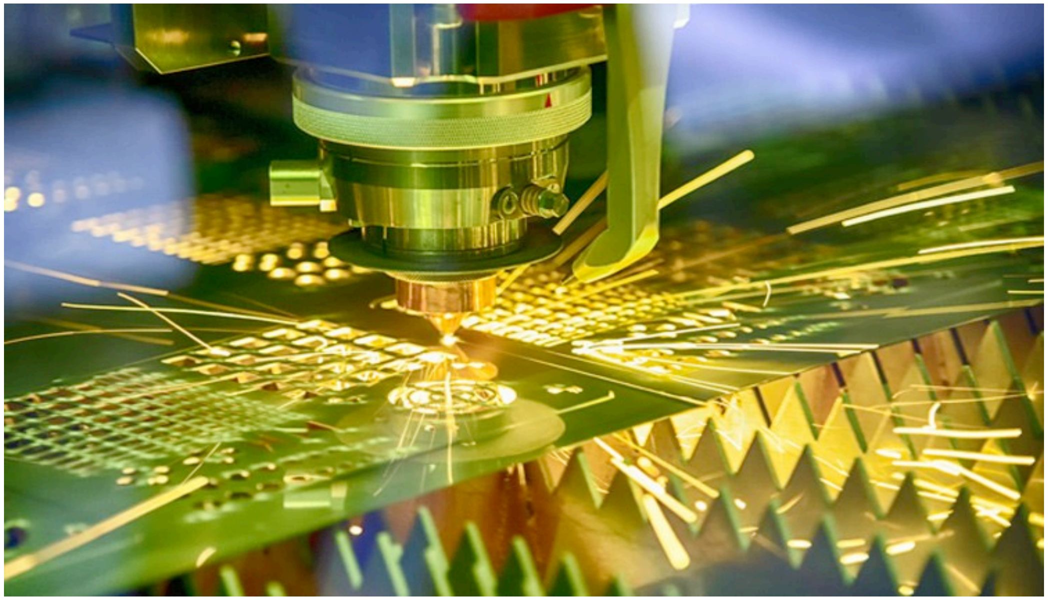
Minimal DOE/HEP support of research in more efficient RF sources

- CLIC: Wall →RF →Beam →RF →Beam
- PWFA: Wall →RF →Beam →Plasma →Beam
- LWFA: Wall →Laser →Plasma →Beam
- C^3: Wall →RF →Beam
- SRF: Wall →(RF,Cryo) →Beam

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

Efficiency: LWFA

- LWFA for HEP needs lasers with efficiency > RF sources.
  - » ~35% efficient diode-pumped ytterbium-fiber lasers exist, but not with high peak power needed for LWFA.
    - » ~100 kW multi-mode fiber laser exist
  - » Lasers are rapidly improving. BELLA group* assumes fiber lasers with high peak and average power will reach 40%
    - » Can independent lasers efficiently drive coherent plasma waves?



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]
  - » New SRF cavities with Nb_3SN coating would make a large difference here.
  - » PWFA Drive Beam efficiency overall could be ~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
  - Requires HOM damping scheme that does not spoil shunt impedance
    - On-going work is promising
- NCRF must produce low cost, efficient high peak power sources as an integral part of the design challenge.
  - Modulator (90%) and “normal” RF (60%) ➔ familiar 45%
  - Energy Recovery and low voltage (60kV) klystrons ~85%
  - Structures with wakefield solutions ~60%
  - Overall efficiency under study.
- NLC “Conventional NCRF” had overall efficiency of 8%[1]
- C^3 first study emphasized capital cost minimization and was too conservative, recent estimate are >13% at 120 MeV/m.
  - Much higher shunt impedance, ~3x for C-Band.

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

Crudely Comparable Efficiencies

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

CLIC:	Wall →RF →Beam →RF →Beam	8%
PWFA:	Wall →RF →Beam →Plasma →Beam	13%
LWFA:	Wall →Laser →Plasma →Beam	
	assuming energy recovery from plasma	11%
NLC	Wall →RF →Beam	8%
ILC:	Wall →(RF,Cryo) →Beam (with cryogenics)	10%
Adv NCRF (C^3):	Wall →RF →Beam	>13%

-

Our Opinions!

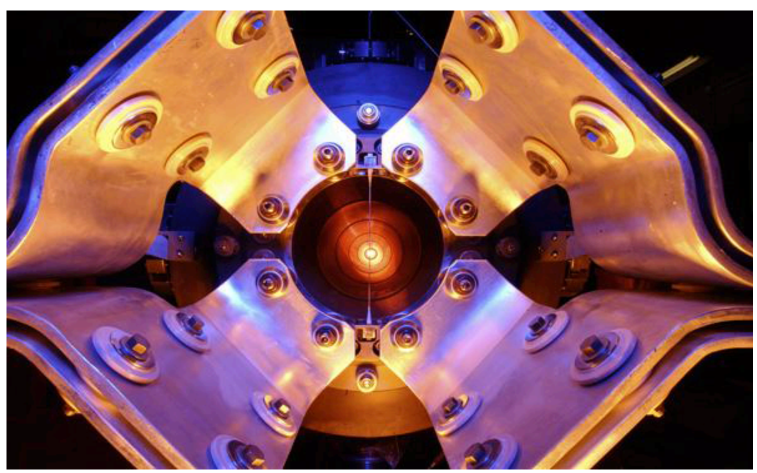
- C^3 – Probably best chance for a real, "affordable" machine .
  - Beam travels in vacuum with reasonable aperture.
  - No staging or emittance growth issues beyond those due to HOM in the structure.
    - HOM damping must be demonstrated.
  - Practical gradients > 100 MeV/m have already been demonstrated
- Advanced NCRF should be pushed vigorously
  - Significant potential applications across DOE
    - Hopefully new SC Office of Accelerator R&D & Production will help
- SRF as an option for linear colliders is being "stress-tested" for "affordability" with PIP-II and LCLS-II.
- If the ILC does not proceed in Japan, a new effort will need much higher gradient technology.

Our Continuing Opinions!

- 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, UK, and European efforts are already working on applications to FEL.
  - LWFAs could be promising for FELs (or hyperspectral sources) if more cost-effective lasers are developed
    - A credible science case requires development
- Direct Laser Acceleration – no convincing plausibility for a TeV-class collider anytime soon.

High Intensity Protons

- Long Baseline Neutrino oscillations are the major scientific thrust in the U.S. – an international effort led by FNAL.
- FNAL will provide neutrino beams to kiloton-scale liquid Ar detectors at Homestake.
- FNAL will put 800 kW on target at the beginning, and move towards 2 MW.
- These powers require improved targets and horns, with better reliability and more neutrinos towards Homestake.
  - R&D in these areas is supported by GARD and LBNF.



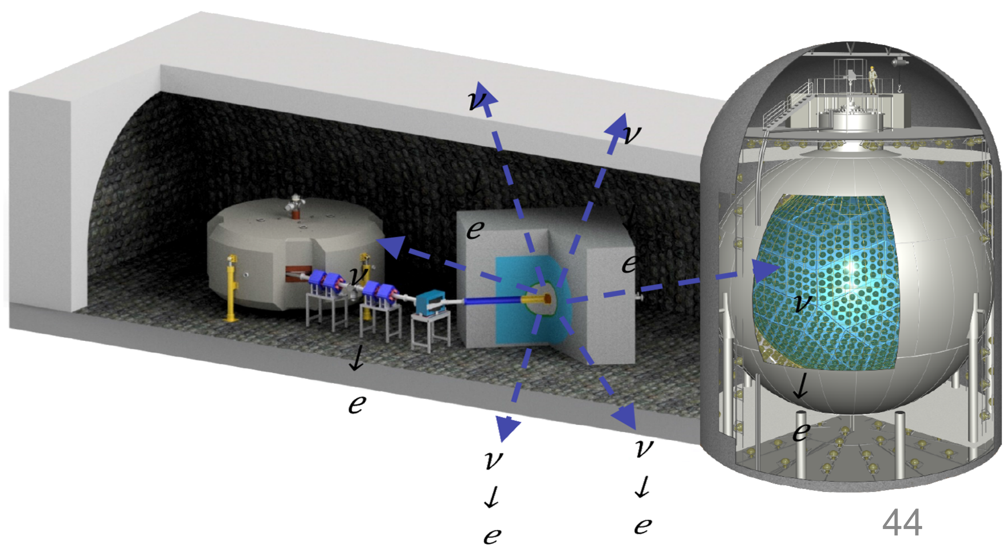
Looking down a neutrino horn

Yun He (FNAL)

High intensity protons from cyclotrons IsoDAR

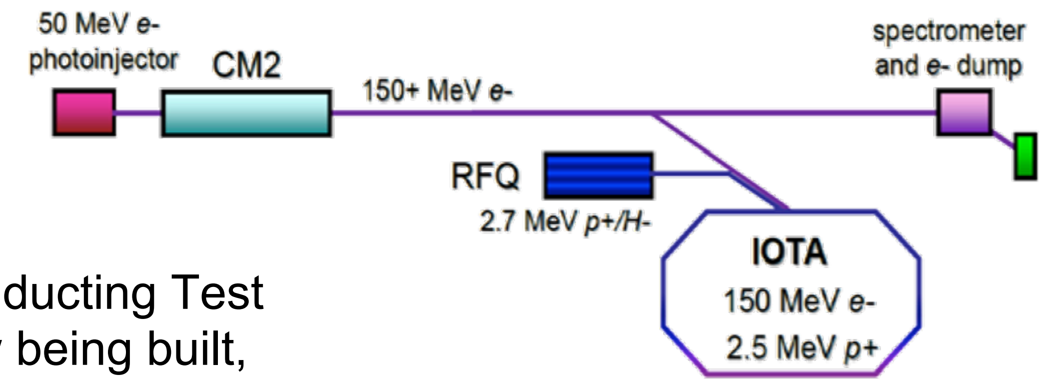
- The collaboration is developing a high current, 600 kW_{cw} low energy cyclotron H_2^+ for a definitive sterile neutrino search
- Under NSF funding the group has tested a suitable ion source, is building a RFQ injector, and has tested a suitable spiral inflector
- The cyclotron design has been a collaboration with INFN/Catania, PSI, and three commercial cyclotron manufacturers
- Ongoing end-to-end simulations show no show-stoppers to deliver 5 mA of H_2^+ beam on target.

A well-shielded target converts the beam protons into copious electron-anti-neutrinos for injection into the KamLAND detector



High Current Dynamics

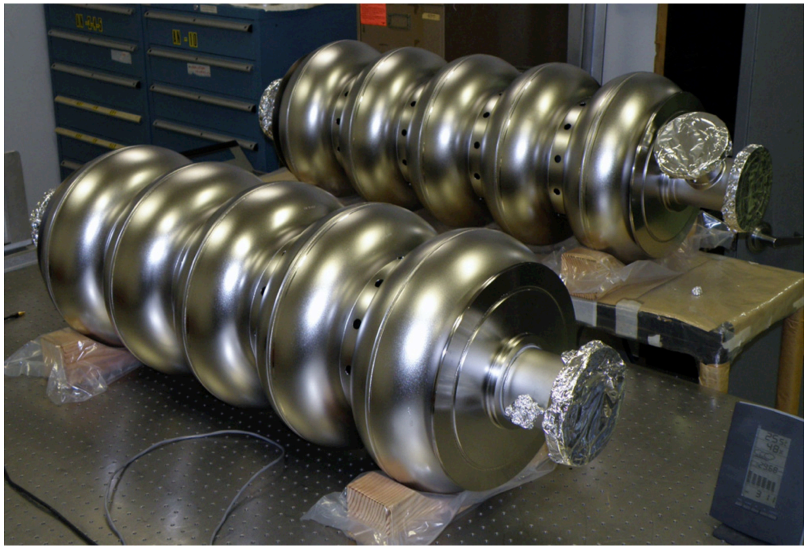
- The high power beams require high currents where space charge is a problem at low energy.
- Advances in integrable nonlinear focusing lattices, hold significant promise to control resonances and space charge tune shift and will be studied at the FNAL IOTA ring.
- For cyclotrons, experiments at PSI have discovered a “vortex motion” that mitigates space charge defocusing of a well-matched beam.



The Advanced Superconducting Test Accelerator (ASTA), now being built, will provide a high peak current e^- beam to IOTA.

FNAL Protons

- Proton Improvement Plan II (PIP-II) is now being built as a new SRF linac taking protons to 800 MeV.
  - It will feed the existing Booster (8 GeV); and then to the existing Main Injector complex to 120 GeV.
- The next step: replace the aging booster, perhaps by another superconducting linac or a rapid cycling synchrotron.
  - GARD supported R&D will inform this choice.



More Opinions

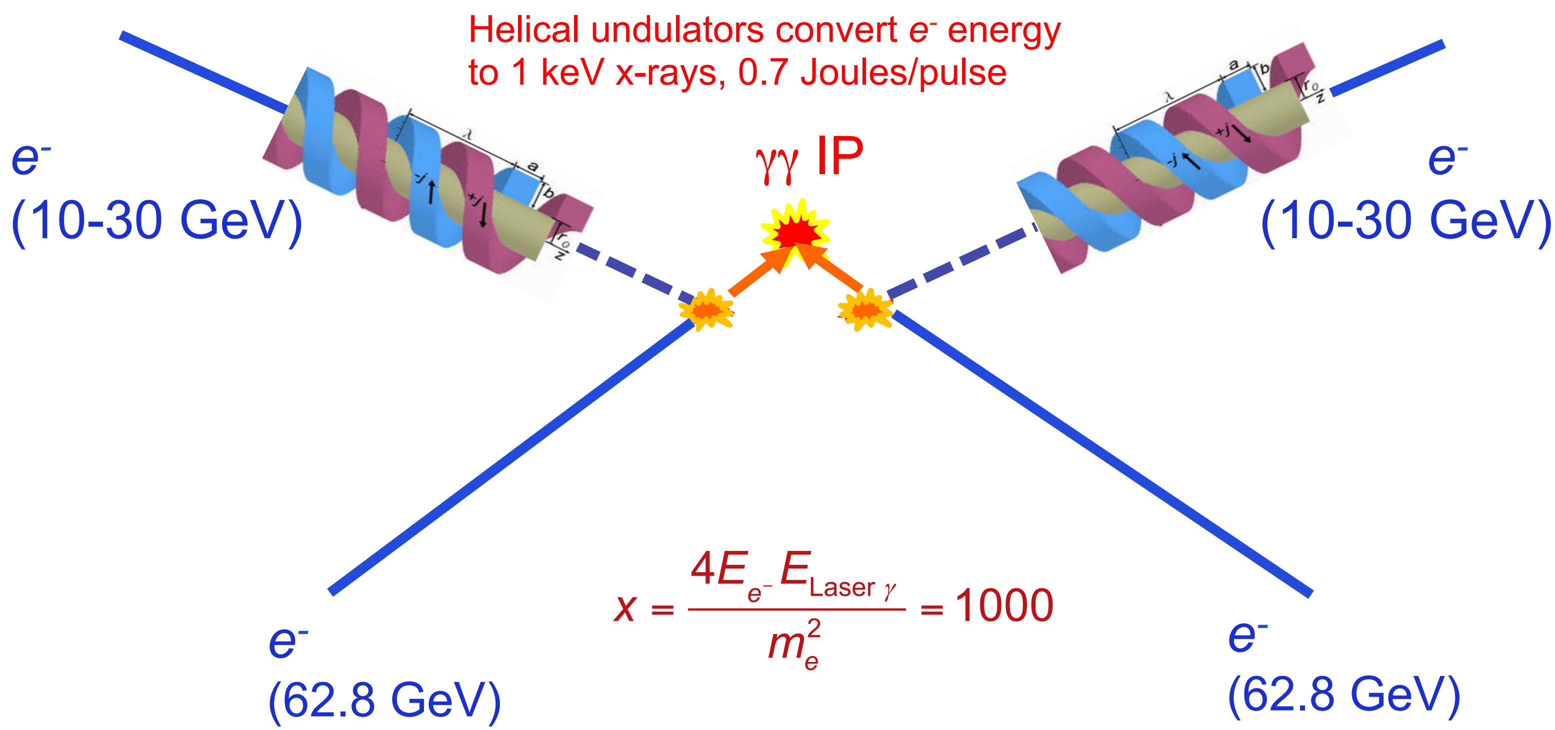
- Both CERN and China are pursuing 100 km circumference rings for first e^+e^- and then 100 TeV scale pp colliders.
  - It seems *very unlikely* that both will happen.
  - The e^+e^- machines have enormous synchrotron radiation loads, usually fixed as a design parameter at 50 MW/beam.
- The p-p machines 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 FCC report is a thorough, modern basis for programmatic decision given strong enough physics justification
    - U.S. participation in the FCC effort was embarrassingly weak
    - We should participate in optimization studies

More Opinions

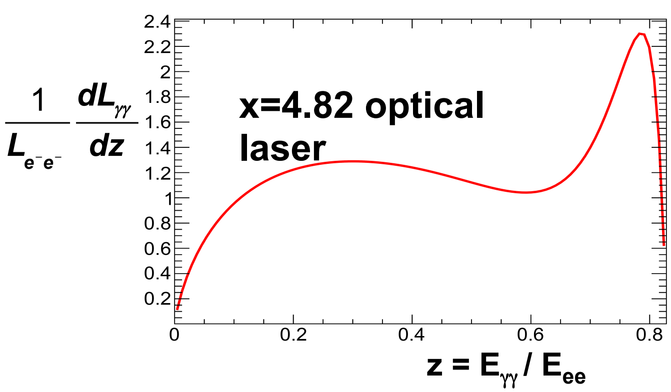
- Next generation p-p machines may not be "affordable"
  - Energy frontier discovery machines might move to e^+e^- with their ~x10 advantage in constituent energy.
    - BUT much lower cost e^+e^- acceleration would be required.
      - Same order of $/GeV as proton synchrotrons
      - See Burton Richter, "High Energy Colliding Beams; What Is Their Future?," arXiv:1409.1196
    - Collision energy > 2 – 3 TeV needs adiabatic final focus (e.g., plasma lens) or 4 beams to overcome quantum excitation of emittance

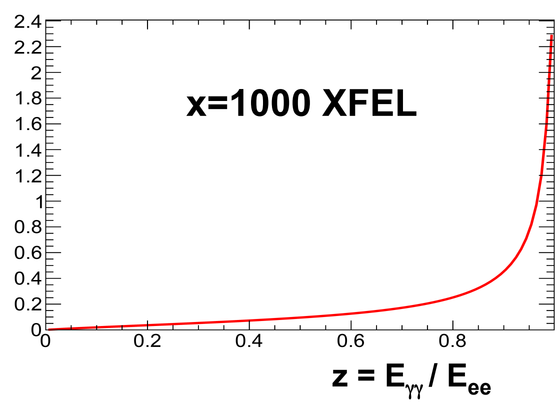
- There is new interest in muon colliders
  - Muon colliders were not considered following the P5 recommendation
  - Significant challenges with muon decays, as background and radiation hazards
  - A muon based neutrino source would be a future possibility if warranted by the science

XFEL $\gamma\gamma$ Collider Higgs Factory, $\sqrt{s_{\gamma\gamma}} = 125$ GeV



$$x = \frac{4E_{e^-}E_{\text{Laser}\,\gamma}}{m_e^2} = 1000$$





$\sigma_{ex} / \sigma_{ey}$	5.4 / 5.4 nm
σ_{ez}	30 μm
$L^{e^-e^-}_{geom}$	$9.7\ 10^{34}$ cm^{-2} s^{-1}
Higgs/yr	40,000

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

- There are no new concepts for proton acceleration.
  - A serious optimization study that includes careful analysis of $/T-m for magnets is still in the future.
- ILC is (to put it mildly) uncertain.
- GARD funding is too small to push hard on the new techniques.
  - Advanced NCRF (e.g., C^3) is promising, but so far has received insufficient support.
  - Wakefield acceleration approaches for e^+e^- are interesting, but their wall plug efficiency seems unlikely to surpass that of CLIC
    - Many technical problems remain, particularly for the plasmas
  - SRF is relatively low gradient and expensive
- Support for fundamental theoretical & computational accelerator physics is *grossly insufficient* to ensure a healthy, broad program of accelerator research.

A distilled bottom line

- To make substantial advances in accelerator capabilities consistent with P5's aspirations the GARD program needs an *investment budget that*
  - *Grows with inflation*
  - *Is not a slave to institutional priorities*

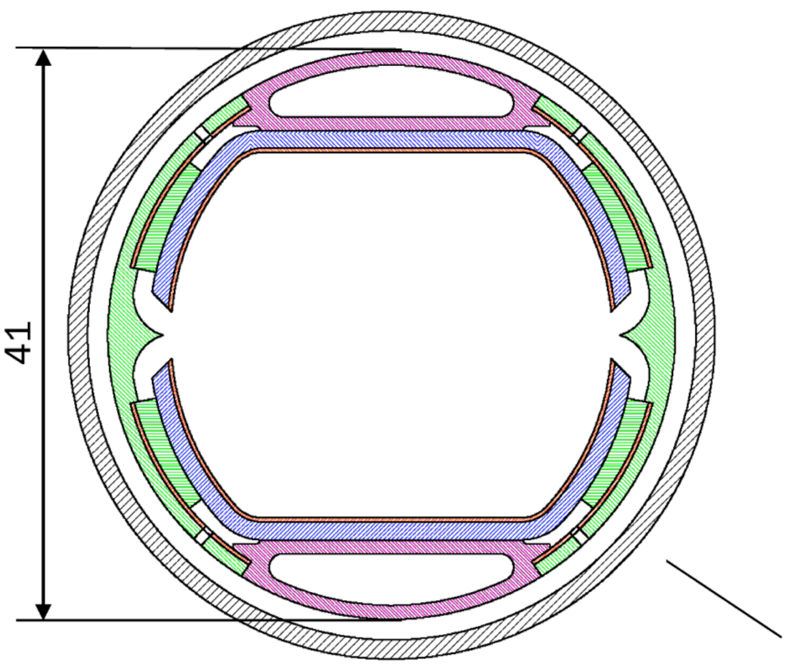
Acknowledgements

- We would like to acknowledge many helpful discussions with

  Barry Barish, Tim Barklow,
  Jean-Pierre Delahaye, Cameron Geddes,
  Steve Gourlay, Bob Hettel, Mark Hogan,
  John Jaros, Wim Leemans, Nan Phinney,
  Tor Raubenheimer, Burton Richter,
  Lia Merminga, Emilio Nanni, Sami Tantawi,
  Glen White, and Vitaly Yakimenko

Backup

New Beam Screen Design
tested by the VCS-Group at CERN

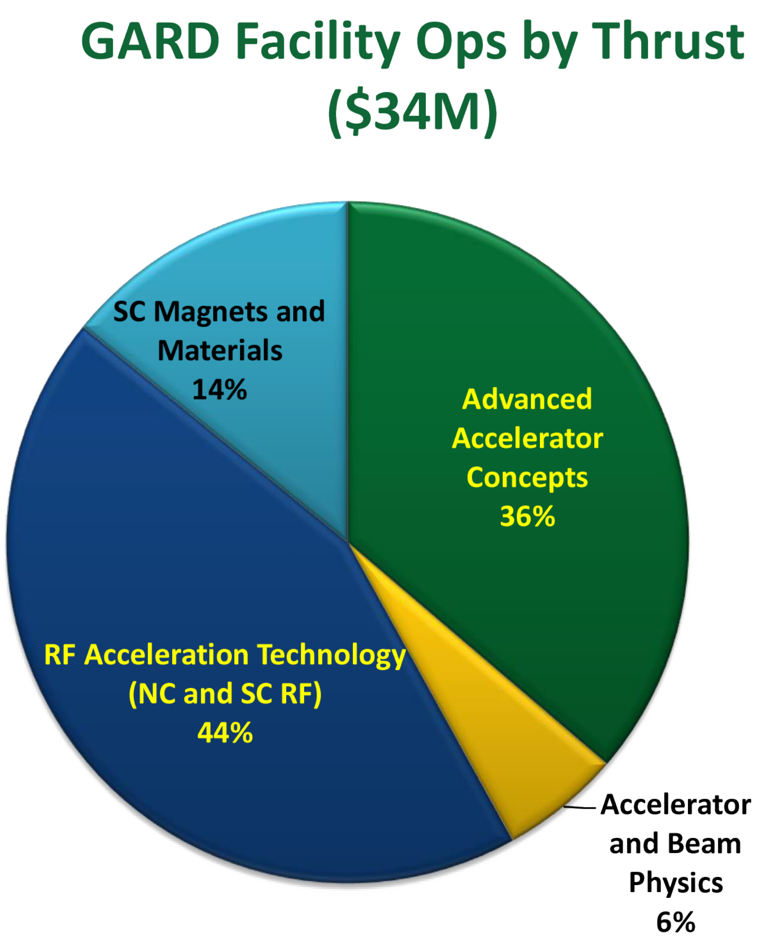


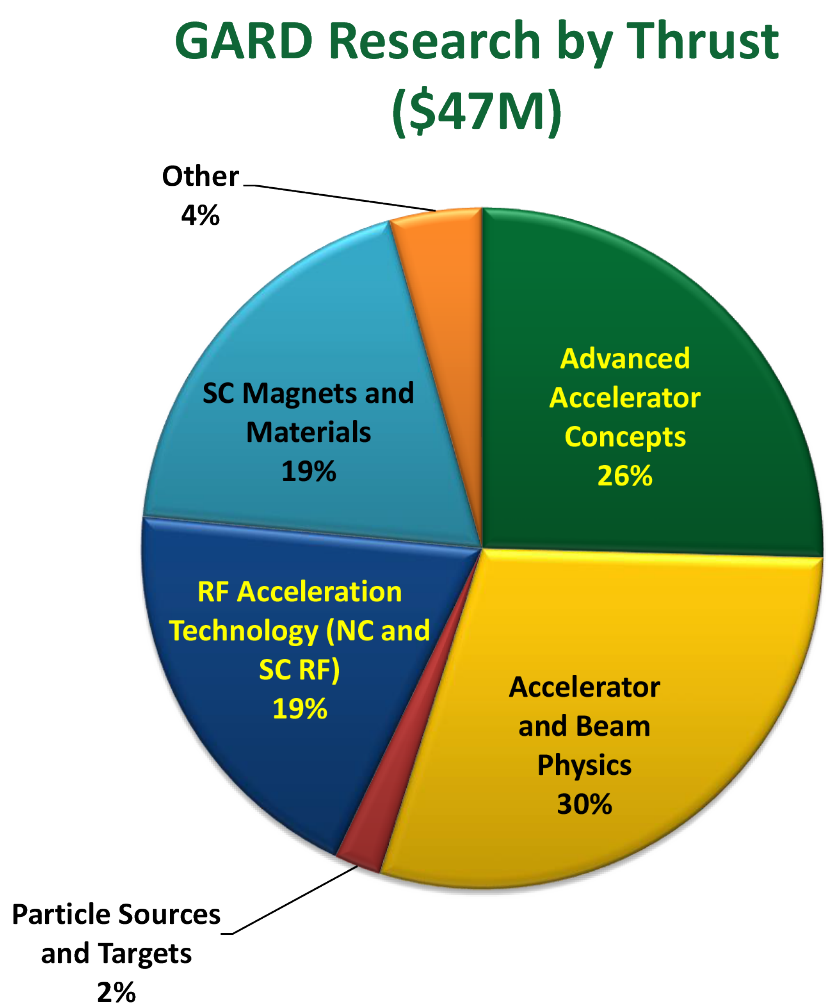
- Beam Tube
- Copper layer(s)
- Shield (Antechamber)
- Capillaries

In caption list temperatures

Key issue is managing pressure drops in capillaries

The OHEP GARD Program



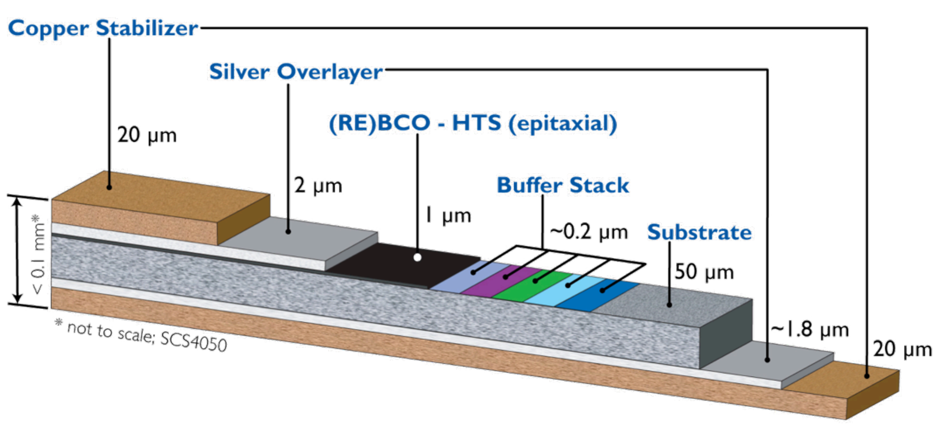


FY2018 data

REBCO – a "silver bullet?

Does not include manufacturing costs

	Units	NbTi	Nb_3Sn	REBCO
Peak field at conductor	Tesla	~ 9.5	<19	>30
Operating field of dipole	Tesla	8	16	20 (?)
Operatng temperature	K	1.9	4.2	20 – 40
Current density in SC	A/mm^2	900	400	>3000
Fraction SC in wire	%	60	50 – 60	1
Relative cost wrt NbTi	$ / kA-m	1	8	100
Relative cost / m of SC for dipole	$ / kA-m	1	8	33*
Relative length of dipoles		1	0.5	0.4
Relative cost of structure		1	4	6.25
Stored energy	MJ / m	0.35	1	6.9



* assumes HTS insert

Who does U.S. Accelerator R&D

- HEP accelerator R&D in the U.S. is done by the labs (Argonne, BNL, Cornell, FNAL, JLab, LANL, LBNL, MSU, SLAC) and by several universities:
  - » Duke, Indiana U, MIT, Northern Illinois, Old Dominion, Purdue, Stanford, Texas A&M, UCLA, U Maryland, U Michigan, USC, UT-Austin, U New Mexico, Yale
- University research programs have produced a rich harvest of ideas that have evolved into major research facilities such as LCLS, FACET-II 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.

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 and PWFA must use highly beam-loaded 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)