Advanced Accelerators: Near and Far Future Options

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Outline

- Historical overview of accelerators in particle physics
- Limitations of present accelerators
- Connections to other scientific fields
- Near-term future accelerators
  - Effects of linear collider technology decision
- Farther-term future accelerators
- Exotic acceleration techniques
- Organization of future activities

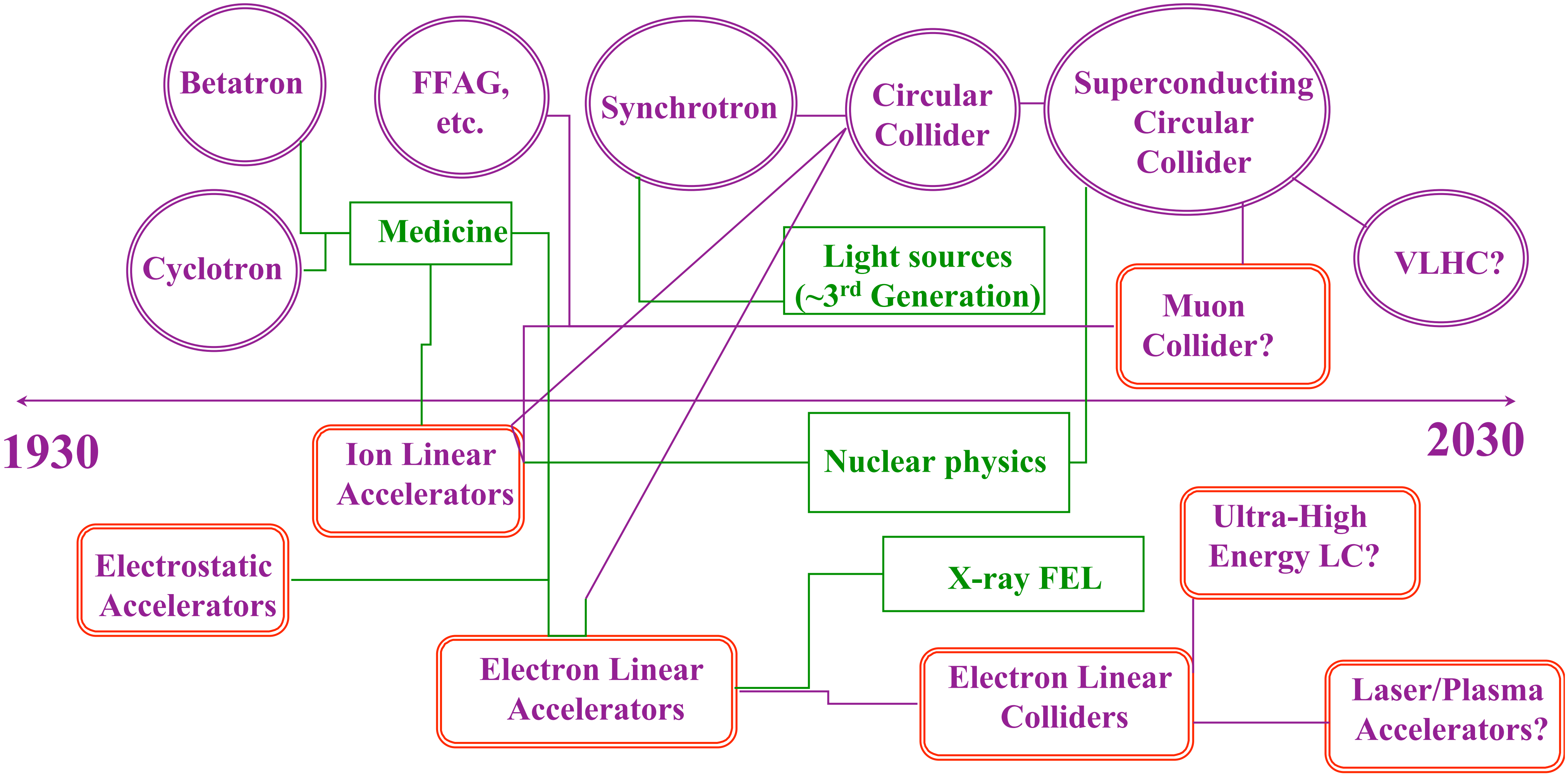
The Crystal Ball Clears 8/19/2004:
ITRP Selection of Linear Collider Technology

HEP accelerators meet a fork in the road…

HEP and accelerators have a shared history and destiny

- Groundbreaking discoveries have always been associated with innovations in accelerator and beam capabilities, e.g.
  - Lawrence (cyclotron, radioactive elements)
  - Rubbia and van der Meer (antiproton cooling, W/Z)
- Measurements at the energy frontier in accelerators complement astroparticle experiments
- Consensus in the field behind LHC and LC emphasize the centrality of accelerator-based HEP

Schematic view of accelerators for particle physics; related fields



A few ideas have driven HEP accelerators forward…

UCLA

- Induction acceleration
- Resonant electromagnetic acceleration
- Normal and superconducting RF cavities
- Alternating gradient magnetic focusing
- Fixed targetry, exotic particle sources
- Particle polarization
- Cooling of particle phase space
- Colliding beams in synchrotrons
- Colliding beams in linear accelerators

Are these enough for the future?
Do we need to re-invent the accelerator?

The Luminosity Challenge

$$\mathcal{L} = \frac{N_{e+}N_{e-}f_c}{4\pi\sigma_x\sigma_y} = \frac{\gamma N_{e+}N_{e-}f_c}{4\pi\sqrt{\beta_x^*\beta_y^*}\cdot\sqrt{\varepsilon_{x,n}\varepsilon_{y,n}}}$$

- Circular colliders provide high repetition rate
  - Beam-beam tune shift limitations
  - Coherent instabilities
  - Beam cooling (e.g. p-bar, muons) can be elaborate
- Linear colliders have much lower repetion rate
  - Use many particles? Power, instabilities,
  - Emphasize low emittance? Tolerances difficult
  - Strong beam-beam effects include beamstrahlung, particle production
- Inherent scaling for higher energy not enough ($\sim E^2$)!

Present limitations of HEP colliders

- Synchrotron radiation power loss
  - Forces future e^+-e^- colliders to be *linear*

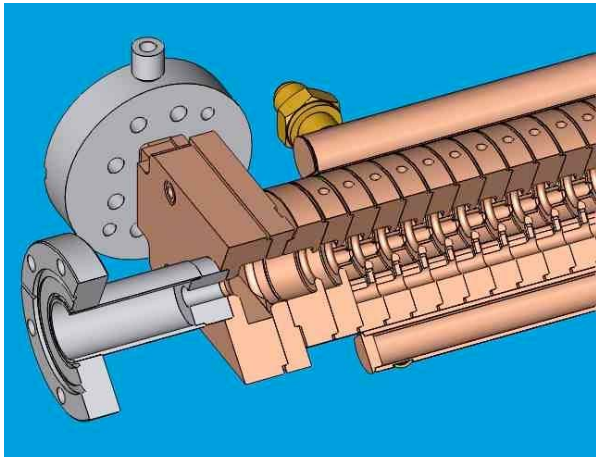
$$P_s \propto \frac{\gamma^4}{R^2}$$

- Technology
  - Magnet strength (hadron colliders)
  - Accelerating electric fields (linear colliders)
- Collective beam physics effects
  - Limitations on beam flux, quality

Approaches to new collider paradigms

- Advancement and perfection of existing techniques
  - Higher gradient RF cavities (X-band LC)
  - Superconducting RF cavities (TESLA LC)
  - Higher field (SC) magnets (VLHC)
  - Use of more exotic colliding particles (muons)
  - More elaborate sourcery and “cooling” techniques
- Use revolutionary new approaches
  - New sources: *i.e.*, lasers
  - New media: *i.e.*, plasmas
  - Realm of high *energy density physics*

The LC technology selection



X-band, high gradient, normal conducting traveling wave linac

Superconducting, L-band standing wave cavity

- ITRP committee determined that both technoligies were viable
- Decision forced by need to concentrate global LC R&D resources
- What drove the decision to endorse the “cold” option?
- What are the implications of this choice on accelerator R&D, in and outside of the LC?

The short answer…

- Warm technology allows greater energy reach
  - Now double accelerating gradient; perhaps more soon
  - A future consideration?
- SC technology allows favorable bunch format, wakefield mitigation
- SC cavity has lower risk
  - industrialization well advanced
- Reduced power consumption
- Synergistic development of technology for 4th generation light sources: X-ray FELs
  - X-band spin-off to medical linacs, not as compelling…

For more information, see ITRP report

LC parameter set overview

Parameter	TESLA		NLC-I	NLC-II
General Parameters				
Energy c.m.s. TeV	0.5	0.8	0.5	1.0
Luminosity $*10^{34}$ $cm^{-2}*s^{-1}$	3.4	5.8	2.0	3.4
Two Linac Length, km	33	33	12.6	30
Site / beam power, MW	105 / 2x11.3	150/	140 / 2x6.9	(?)
RF Frequency GHz	1.3		11.424	
Accelerating Gradient, MV/m	23.4	35	48.5	55
N/bunch, $* 10^{10}$	2	1.4	0.75	
# Bunches per train/ Rep. Rate	2820 /5	4886 /4	192 / 120	
Bunch spacing, ns	337	176	1.4	
Bunch train, μs	950		0.27	
Interaction Point				
Beamshtahlung δ (%)	3.2	4.3	5.4	10.4
Norm emittance $\varepsilon_{nx}/\varepsilon_{ny}$, mm*mrad	1000/3	800 / 1.5	360/3.5	
Transverse Beam size, ? σ_x/σ_y nm	553/5	391 / 2.8	245 / 2.7	190 / 2.1
Beta function β_x/β_y, mm	15 / 0.4		8 / 0.11	13/0.11
Longituinal beam size σ_z mm	0.3		0.11	
# Photons per electron	1.5		1.2	
Disruption parameter, Dy	25		14	---
Pinch factor H_D	2.0		1.43	1.5

The path not taken: the "warm" linear collider

- X-band chosen to mitigate power demands
- X-band traveling wave cavities developed, give >65 MV/m unloaded gradient
  - Serious breakdown issues recently resolved
  - Important work on the road to higher gradient
- Klystron power an issue, addressed with RF pulse compression (SLED, etc.)
  - A complication…

X-band klystron

X-band linac section

NLC testing has been aggressive, diverse

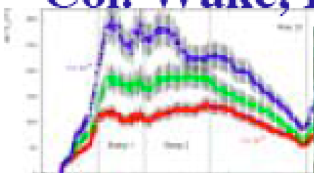
N. Phinney (Victoria, 2004)

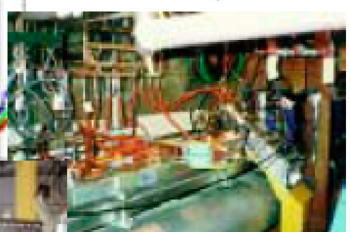
SLC and FEL's

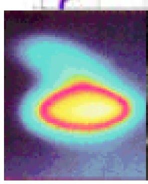
Bunch Comp.

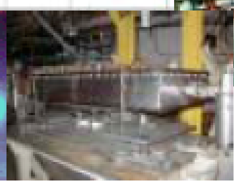
SLC, FFTB, ASSET, Col. Wake, E-158

ε preservation



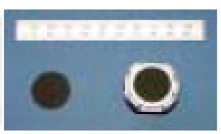






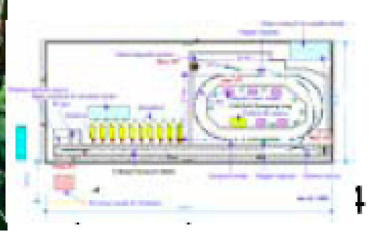
SLC, E158, Nagoya Univ.

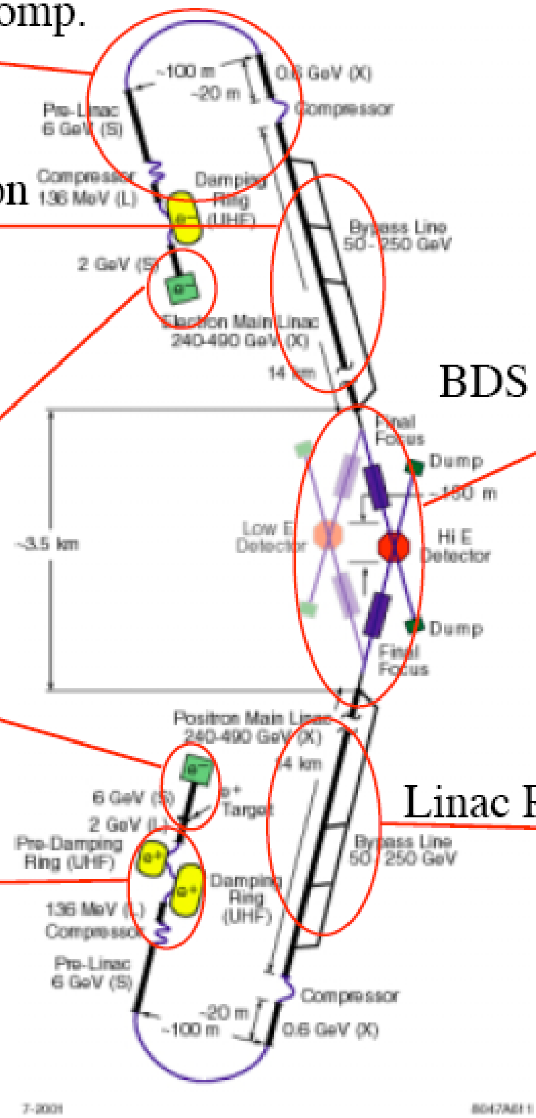
e+ / e- sources



ATF, 3rd gen. SRS, SLC

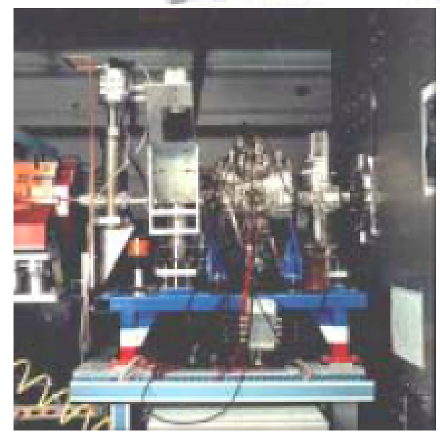
DR's





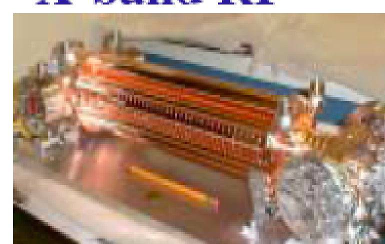
SLC and FFTB

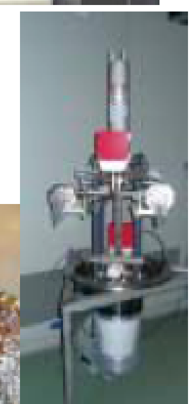
BDS & IR

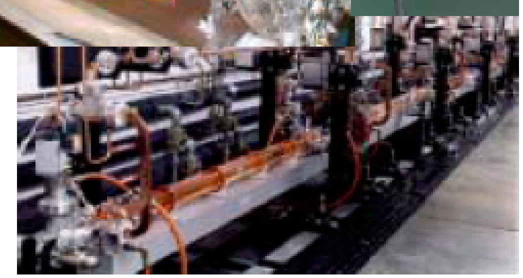


KEK and SLAC X-band RF

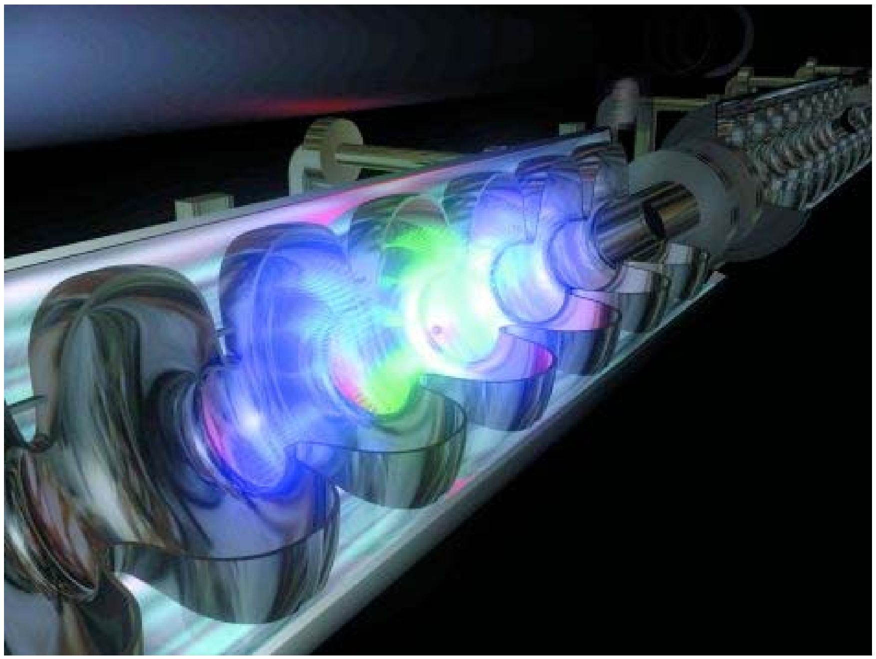
Linac RF







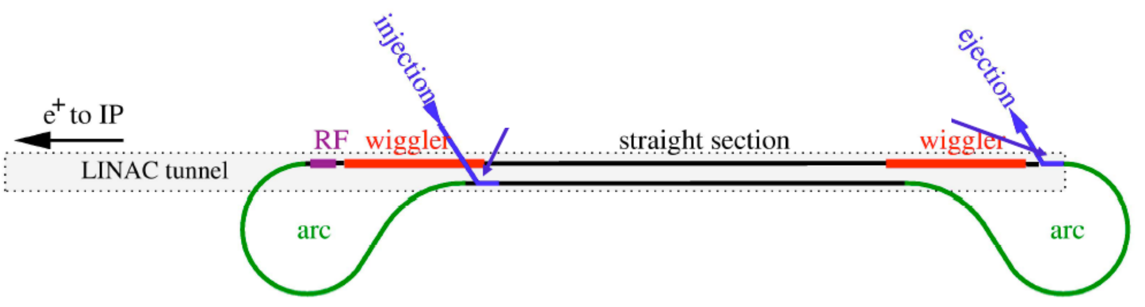
The linear collider technology: Superconducting RF cavities



- Very high intrinsic *Q* ($>10^9$), 6 orders of magnitude higher than NC
- Extremely beam-loaded operation possible
  - Many pulses, μs apart, in ms fill
  - Power goes into beam, not wall
- Even with "tax" from Carnot efficiency, SC more than twice as efficient
- Very large apertures, wakes and BBU *much* less an issue for L-band design

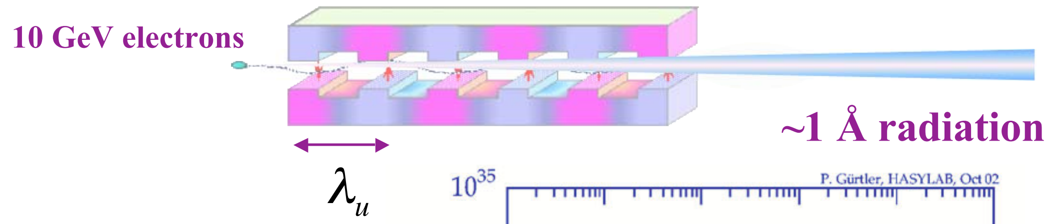
Some "TESLA" challenges

- Particle sources are demanding
  - Damping rings very large
  - Positron sources (polarized) also difficult
- Maximize gradient
  - Large effort at TTF (working FEL facility)
  - Intrinsic limit on surface field
- Intra-bunch-trains feedback
- Message from ITRP: adopt lessons from other designs
  - Already well underway

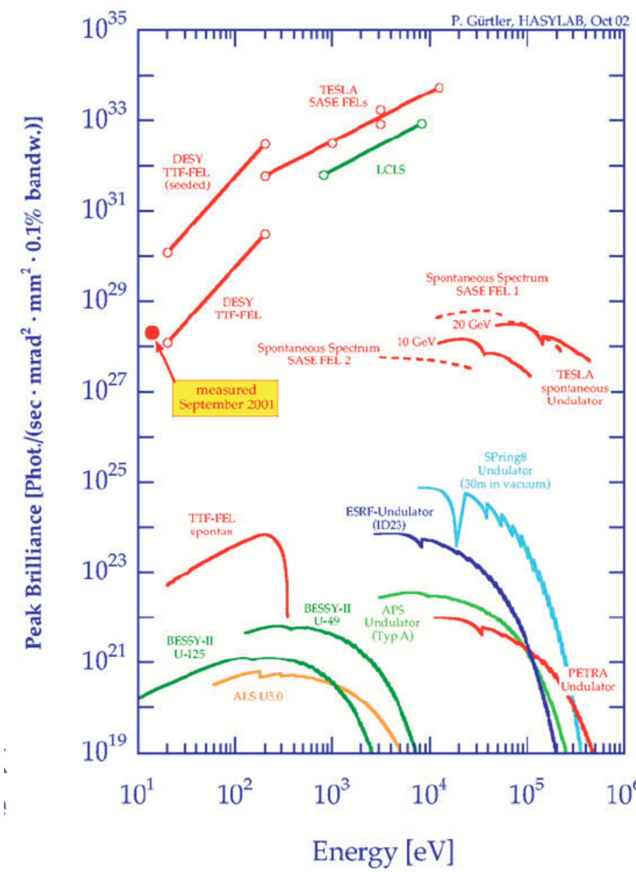


17 km "dogbone" damping ring!

X-ray SASE FEL based on SC RF linear accelerator



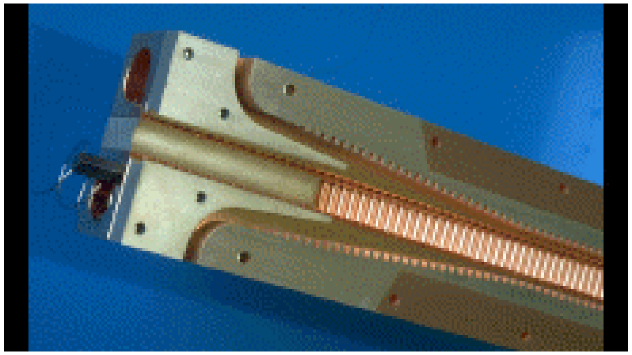
- Synchrotron radiation is (again) converted from vice to virtue
  - SASE FEL instability
- Coherent X-rays from high energy electron beam $\lambda_r \cong \frac{\lambda_u}{2\gamma^2}\left[1+\frac{1}{2}K^2\right]$
- Spin-off of TESLA program; split from TESLA project in late 2001
- Approval from German gov't, pending EU participations
- Better average beam power than warm technologies (e.g. LCLS at Stanford)
- Many SASE FEL projects worldwide



How does one arive at a 3 TeV LC?

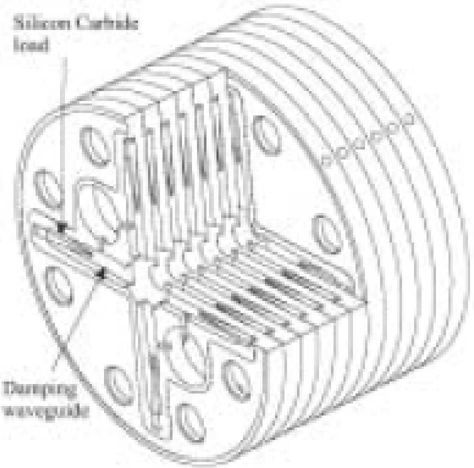
- Superconducting option does not scale well
  - Intrinsic low gradient (24 MV/m TESLA 500 GeV, 35 MV/m TESLA 800 GeV, ~42 MV/m theor. limit.)
- Even X-band is difficult
  - Power sources, efficiencies
- High gradient means high frequency
  - Where is power source?
- Look to *wakefields*
  - Source of energy is bunched, very relativistic e^- beam
  - Extendable to more exotic schemes…

Higher gradients demand high frequency, new power source

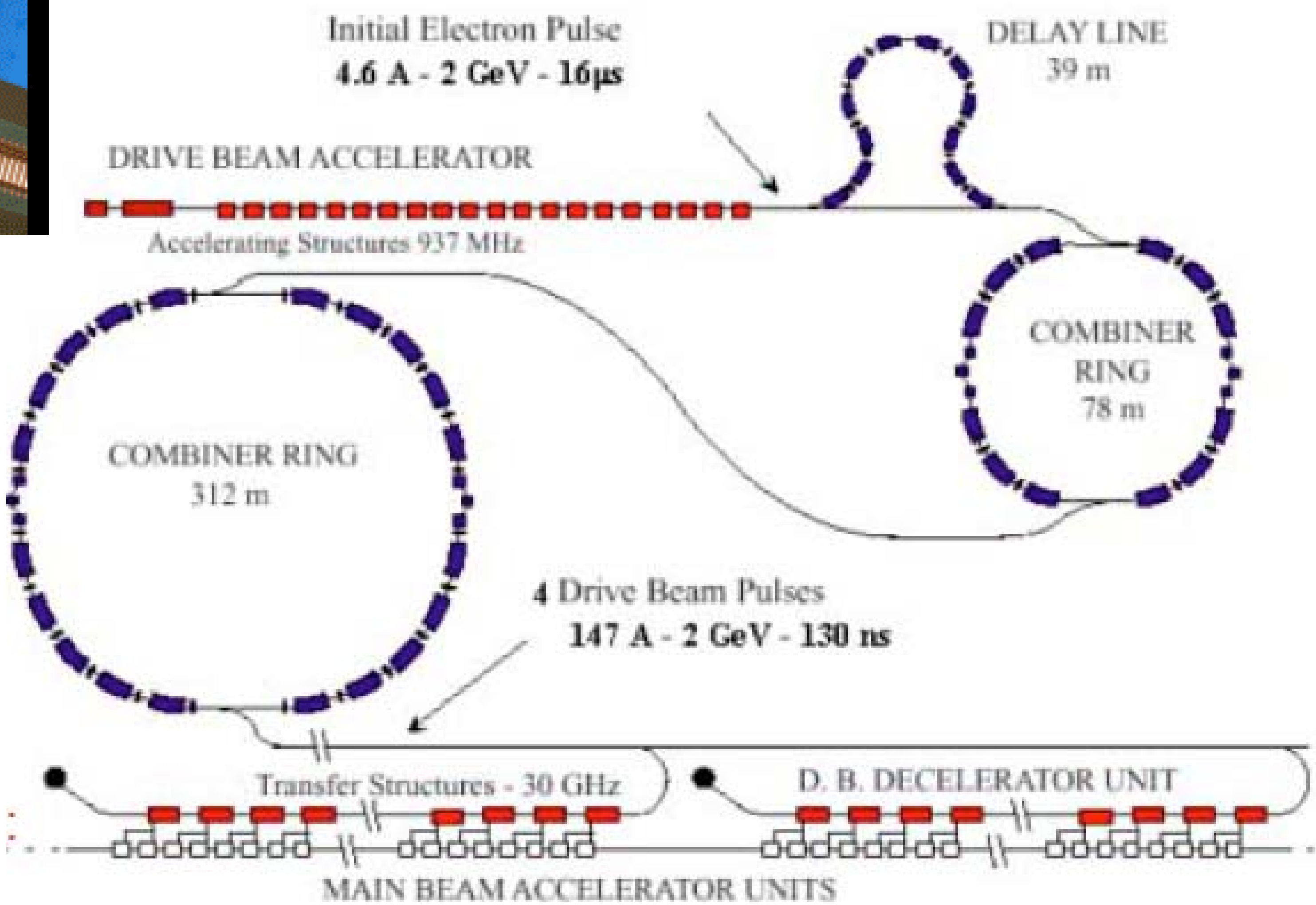


CLIC drive beam extraction structure

CLIC 30 GHz, 150 MV/m structures



CLIC wakefield-powered scheme



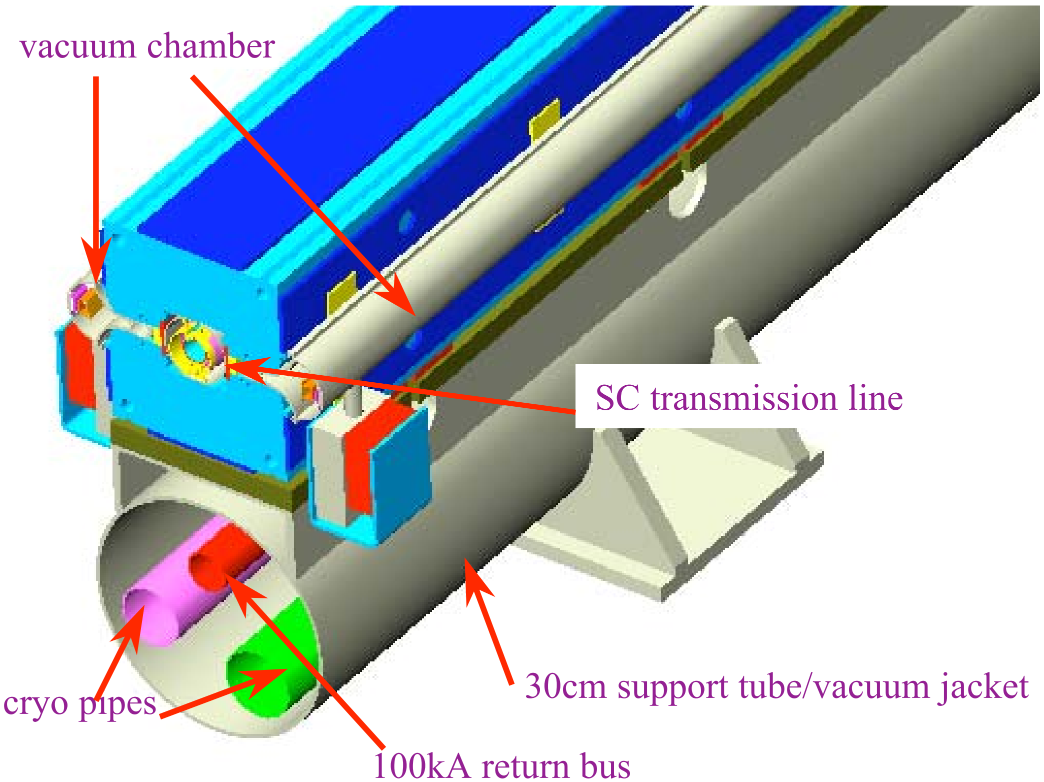
Near future in LCs

- Development of an international collaboration from existing links between labs
  - SLAC, KEK, DESY, FNAL, LBNL, LLNL, etc.
- Revisit SCRF LC design post-ITRP
  - More tight involvement with particle physicists
  - More university involvement
- Re-evaluation of sites
- The next few years will be a very exciting time… but a mechanism *must* be found to preserve high gradient techniques as options

Future circular colliders

- LHC! Linchpin of near-term physics
- Very Large Hadron Collider (VLHC)
- Muon Collider/Neutrino Factory

VLHC Possibilities

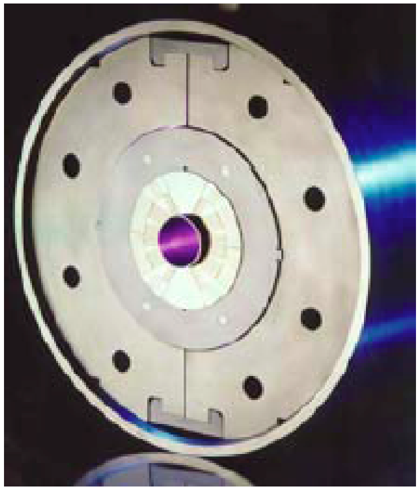


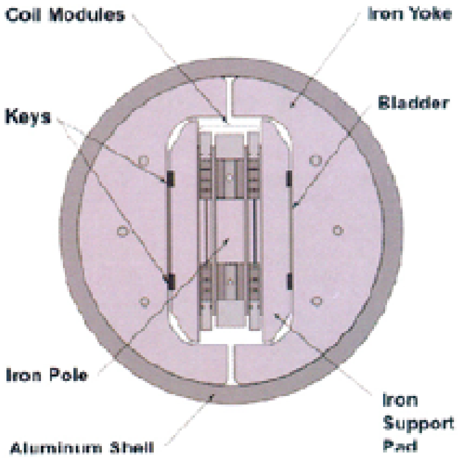
Superferric magnet (2 T) assembly for staged VLHC
(P. Limon)

- Recent *incremental* proposal: build 233 km long tunnel
- Start *staging* with 40 TeV collider based on 2 T superferric magnets
- Stage 2: upgrade to 11.2 T magnets for 200 TeV collider
- Estimated cost of Stage 1: $4B (European acct.)

Ultra-high field SC magnets

- LHC magnet program showed limit of NbTi magnet technology: ~10 T
- Recent work on Nb_3Sn has demonstrated ~16 T magnets
- Also SC quads for LHC IR upgrade (scheduled due to rad-damage)
- Incremental VLHC: possible energy (doubling) upgrade to 17 T magnets at LHC



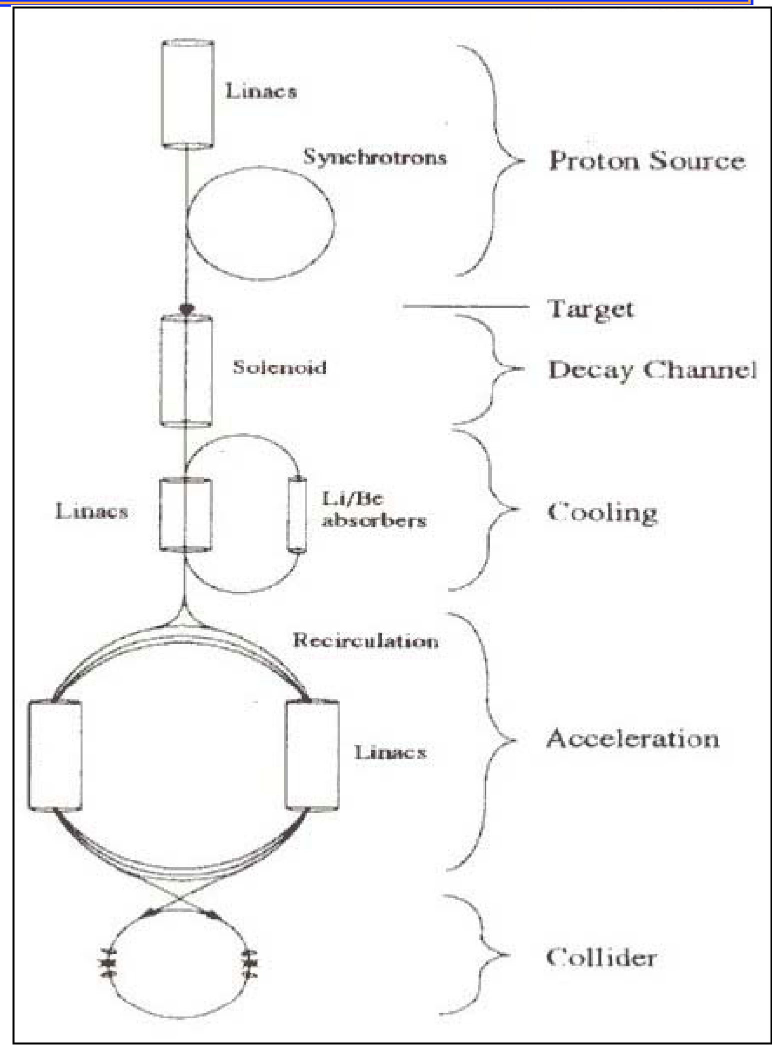


High field Nb_3Sn designs

Cryostat with 16 T Nb_3Sn magnet at LBNL

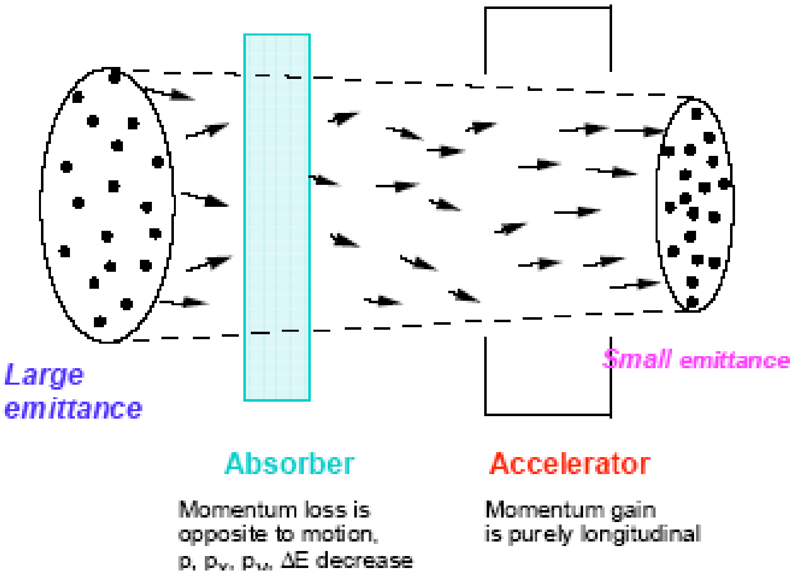
Muon collider

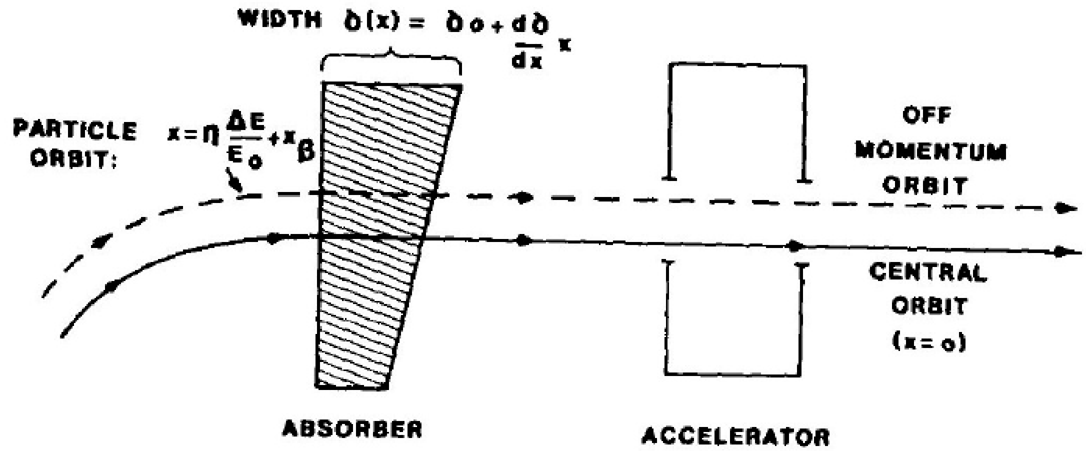
- The prospect of using muons for a collider is very attractive
- Beams
  - Diminish radiative effects
- Physics
  - Enhanced Higgs production?
- Serious challenges
  - Muon production and cooling
  - Rapid acceleration
- Large collaboration formed to study options



Muon collider schematic c. 1996 (Geer)

Ionization cooling



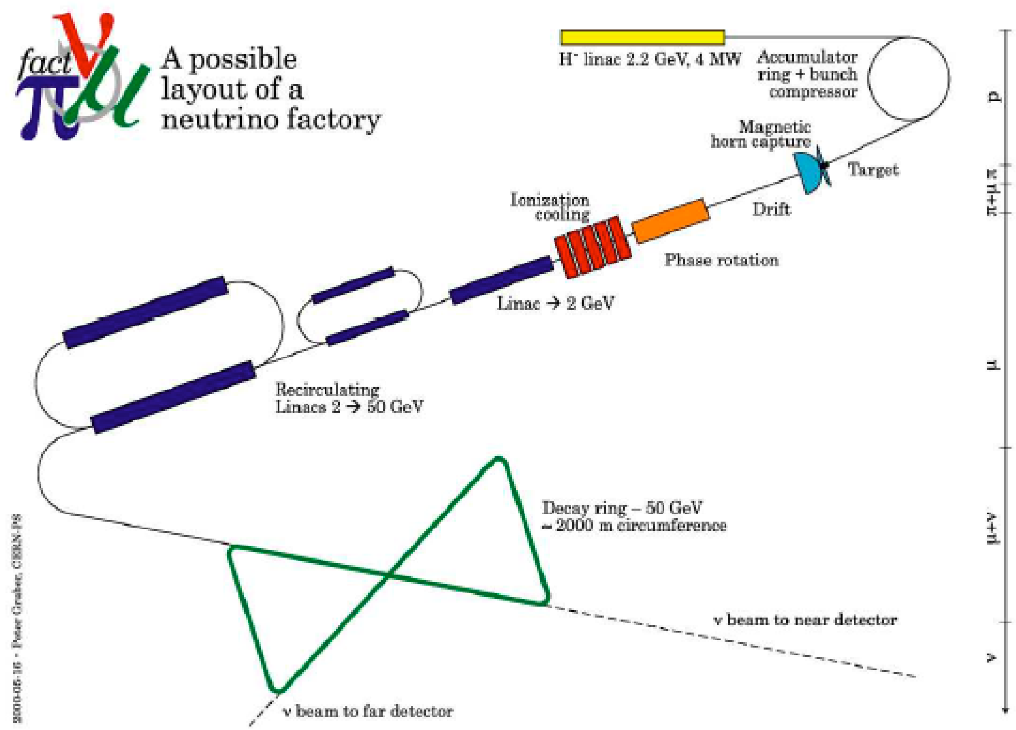


Wedge cooling (Neuffer, 1983)

- Ionization cooling works in a similar way to synchrotron radiation cooling - remove momentum and restore only longitudinal with acceleration
- Can also cool longitudinal phase space with wedge material in dispersive section
- MUCOOL and MICE experiments; very active R&D
- High gradient, low frequency RF, absorbers, lattices, etc.

Neutrino factory

- Muon collider R&D is indeed daunting
- Stepping stone: neutrino factory
- Less demanding than collider
  - Collider R&D
  - Compelling physics
  - Not so costly…



CERN neutrino factory schematic

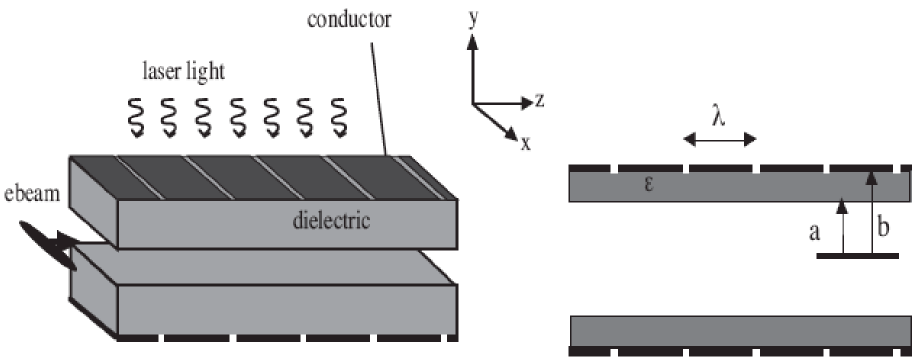
Prospects for “unconventional” circular colliders

- Snowmass 2001 provided decision point, LC designated highest priority
- Will other options stay alive?
- VLHC R&D may continue in the context of LHC upgrades
- Muon colliders are also synergistic with other devices than need MW class proton driver:
  - SC linear collider linacs
  - Spallation neutron sources
  - Accelerator driven fusion/fission

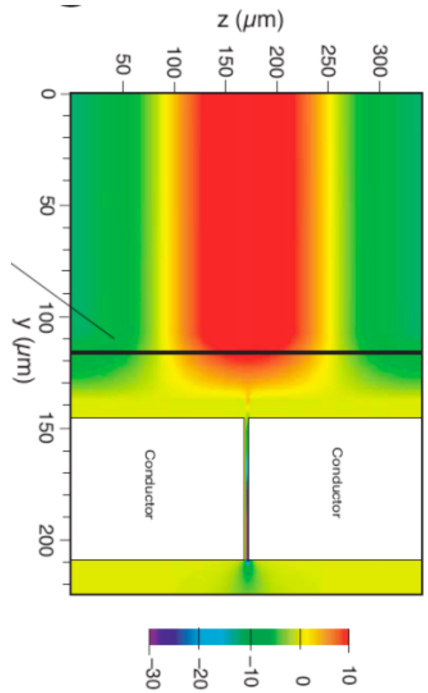
Historical glance at linac technology

- NC linac development was driven by post-WWII availability of high power microwave sources
- Basic acceleration scheme has not changed much, nor have microwave sources
- New EM sources have arisen with very high peak power and fields
  - Wakefield sources (CLIC and beyond)
  - Optical source: ultra-high power (>TW) lasers
- Can we use these new sources for linear accelerators?

The optical accelerator



Resonant dielectric structure schematic

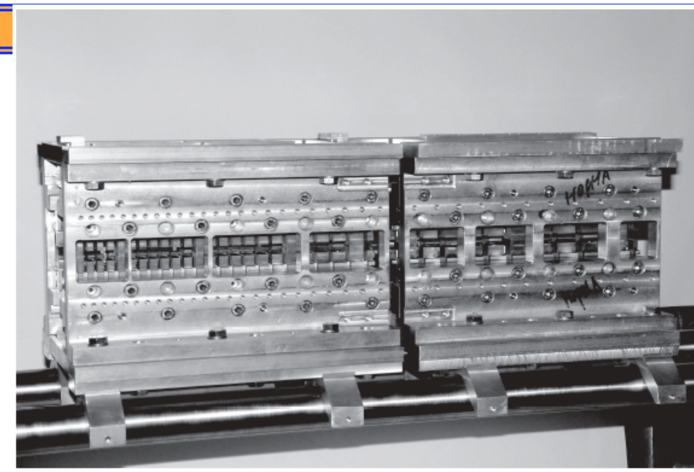


Simulated field profile (OOPIC)

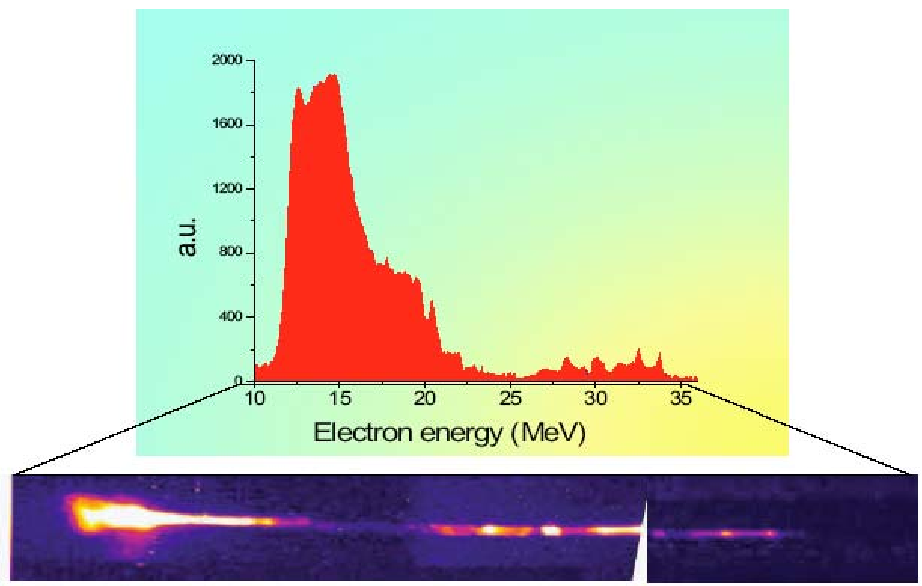
- Scale the linac from 1-10 cm to 1-10 μm laser!
- Resonant structure
- Slab symmetry
  - Take advantage of copious power
  - Allow high beam charge
  - Suppress wakefield
- Limit on gradient ~ 1 GV/m from avalanche ionization
- Experiments
  - ongoing at SLAC (1 μm),
  - planned at UCLA (340 μm)

Evading material breakdown: The inverse FEL accelerator

- Run FEL resonance backwards with high power laser
- No nearby material; laser can be very intense
  - Magnetic field = synchrotron rad.
- Accleration dynamics similar to ion linac
- Recent experiment at UCLA Neptune Lab accelerated 15 MeV beam to over 35 MeV
- Capture at 5%; improve to near 100% with configuration improvements

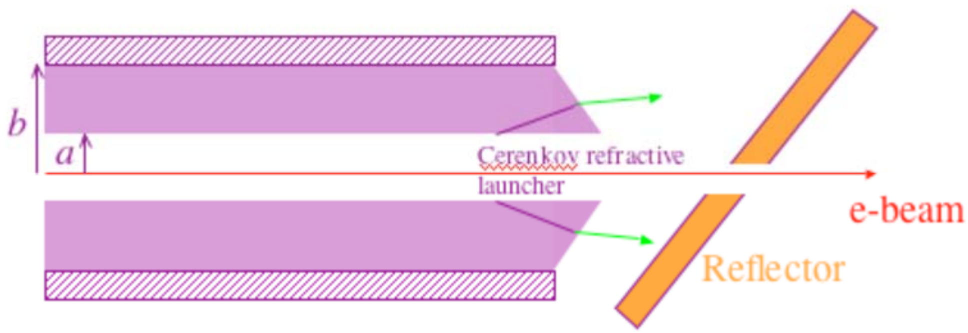


IFEL undulator (50 cm length)



Neptune IFEL single shot energy spectrum

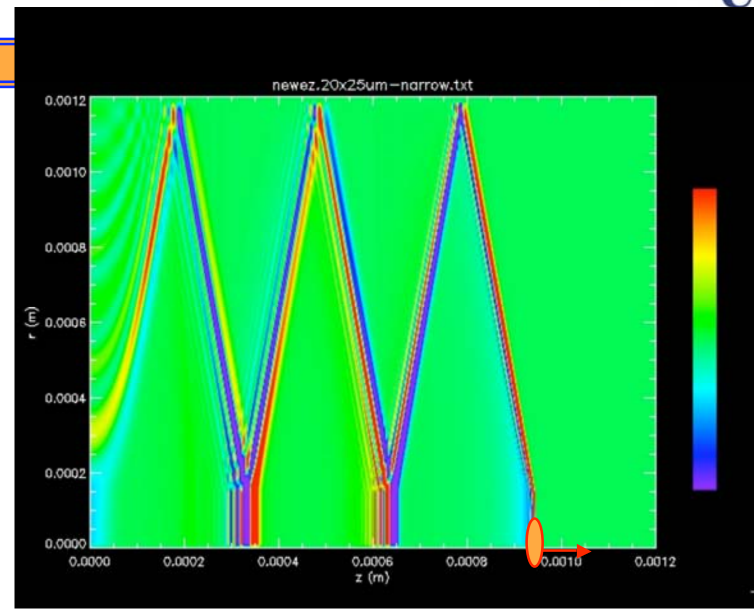
Inverse Cerenkov Acceleration

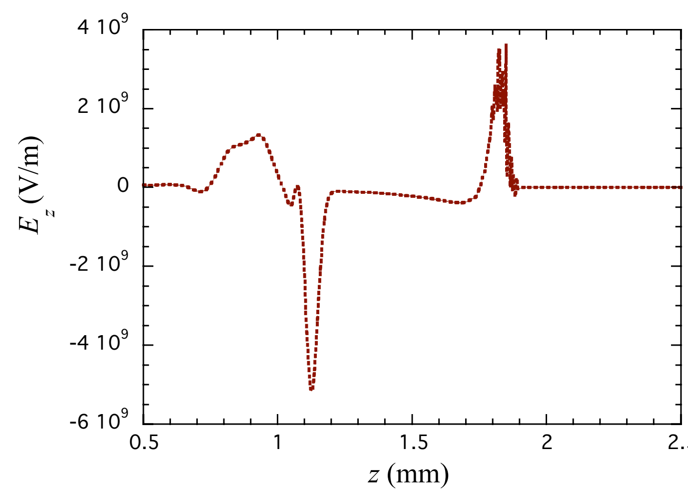


- Coherent Cerenkov wakes can be extremely strong

$$eE_{z\mathrm{dec}} \cong -\frac{2N_b r_e m_e c^2}{\sqrt{2\pi}\sigma_z a}\frac{\sqrt{\varepsilon-1}}{\varepsilon}$$

- At SLAC FFTB, σ_z= 20 μm, wakes exceed a few GV/m for *a*=125 μm
- Experiment is planned
  - Detect coherent Cerenkov radiation
  - Examine breakdown for ultra-short irradiation times



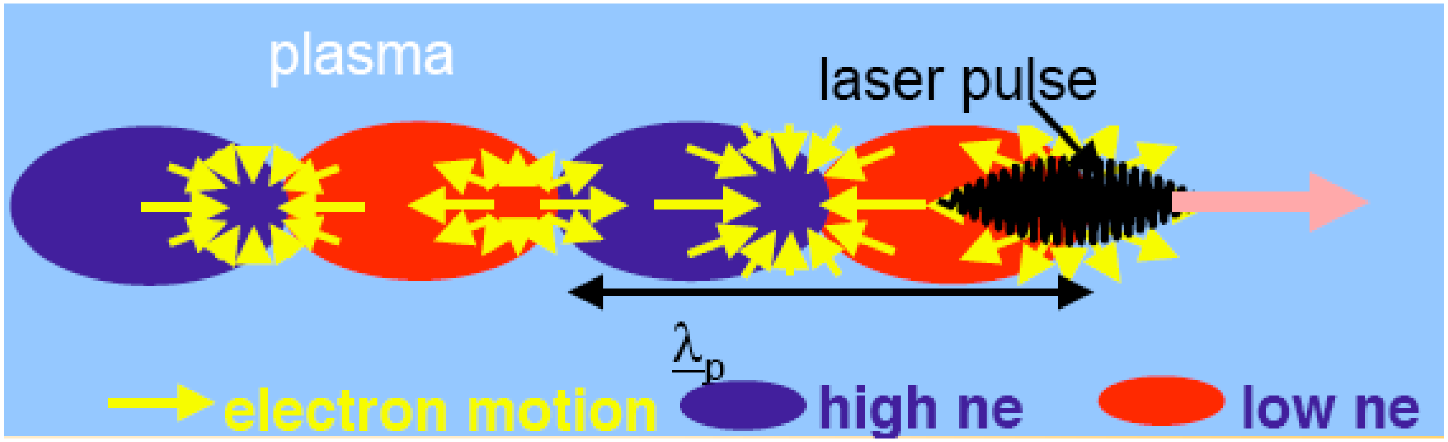


Simulated GeV/m Cerenkov wakes for FFTB parameters

Past the breakdown limit: Plasma Accelerators

- Very high energy density laser or electron beam excites plasma waves as it propagates

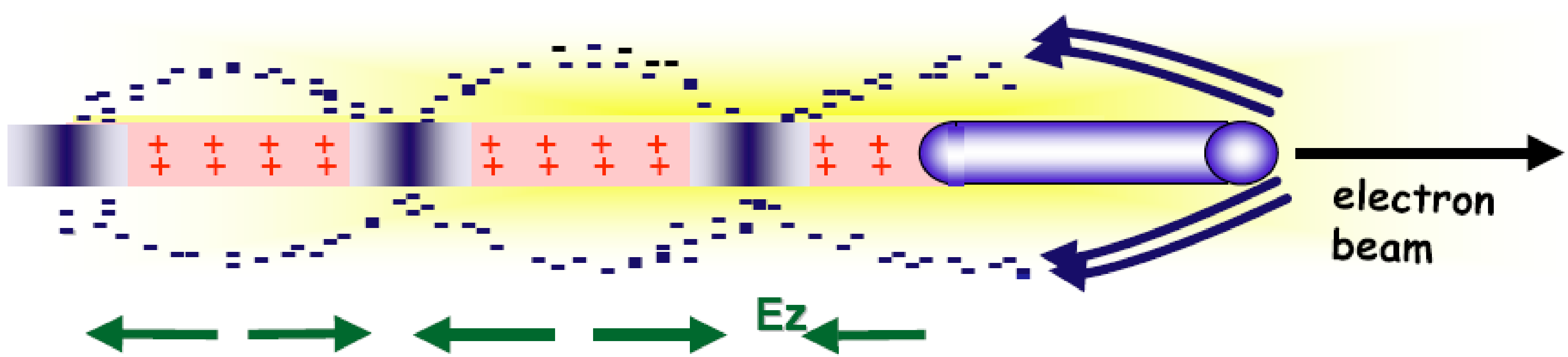
Schematic of laser wakefield Accelerator (LWFA)



- Coherent emission of "plasmons"
- Extremely high fields possible: $E(\text{V/cm}) \propto \sqrt{n_e(\text{cm}^{-3})}$

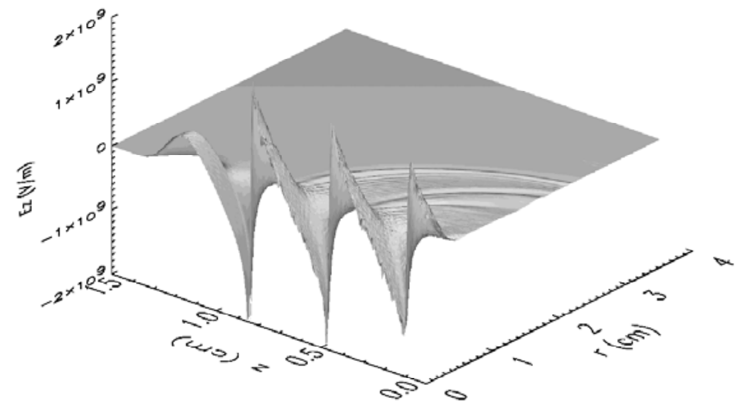
Plasma Wakefield Acceleration

- Electron beam shock-excites plasma
- Same scaling as Cerenkov wakes, maximum field scales in strength as $E \propto N_b k_p^2 \propto N_b \sigma_z^{-2}$
- Most favored running: the "blowout" regime

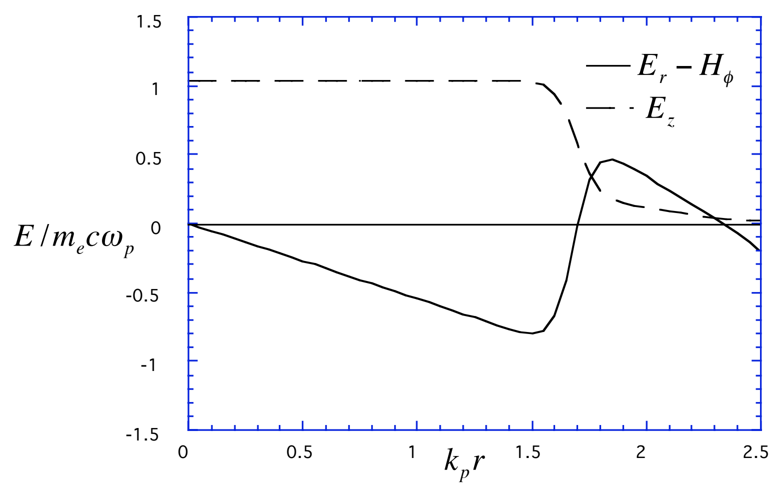


The PWFA Blowout Regime

- Beam much denser than plasma $n_b >> n_0$
- Very nonlinear plasma waves
  - Plasma electrons completely leave beam channel
- Very *linear* wakefield response
  - Longitudinal field constant in *r* (EM wave)
  - Transverse focusing linear in *r* (ES ion field)
  - Like linac + quadrupoles!
  - Good fields because of no free-charges/currents in beam channel

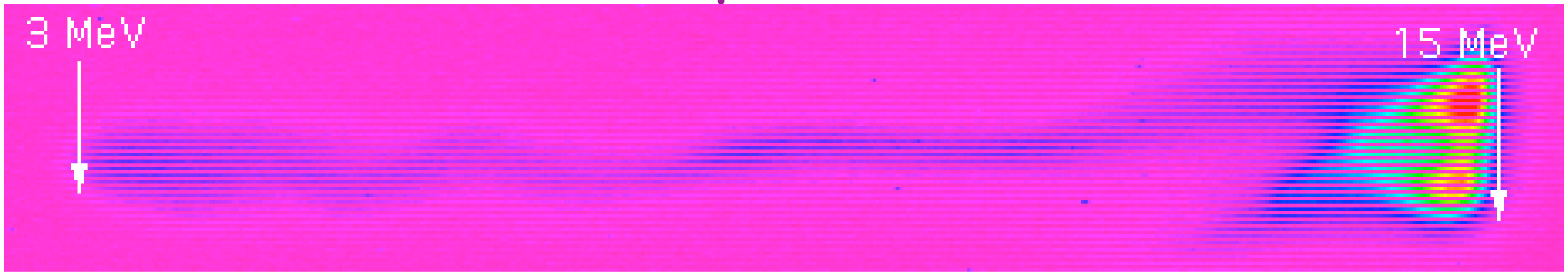


Plasma wake (E_z) response, blowout regime, OOPIC.
Below: radial dependence of fields in beam region

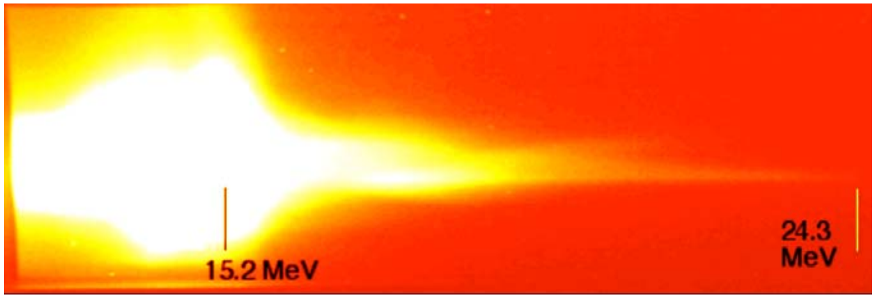


PWFA Experiments: Large fractional energy gain and loss

- 15 MeV Beam nearly stopped in 7 cm of plasma in UCLA/FNAL A0 experiment



- Accelerating wake is also stable; good efficiency

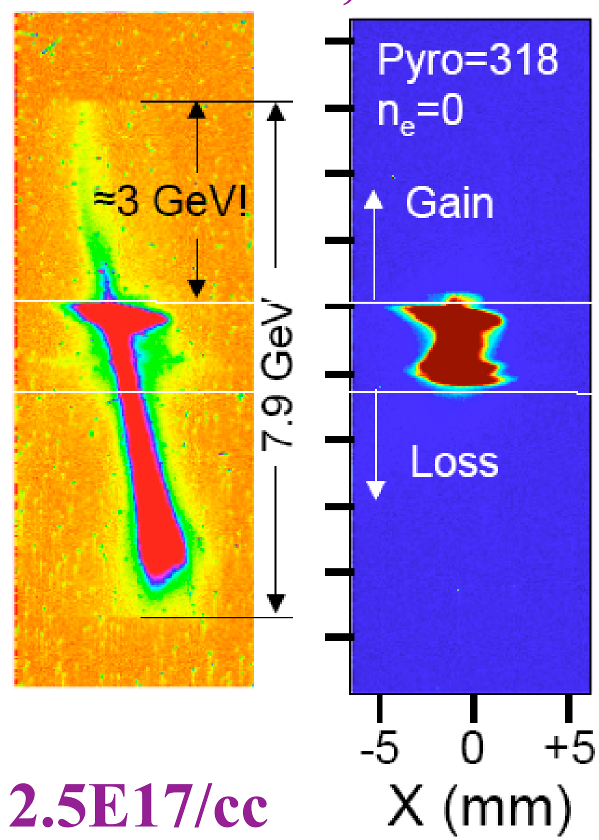


Acceleration to > 24.3 MeV (~130 MeV/m), 60% gain.

Ultra-high gradient PWFA: E164 experiment at SLAC FFTB

- Use extremely short beam
- Beam causes field ionization to create dense plasma
- Over 4 GeV(!) energy gain over 10 cm: 40 GV/m fields
- Self-trapping of plasma electrons due to enormous fields

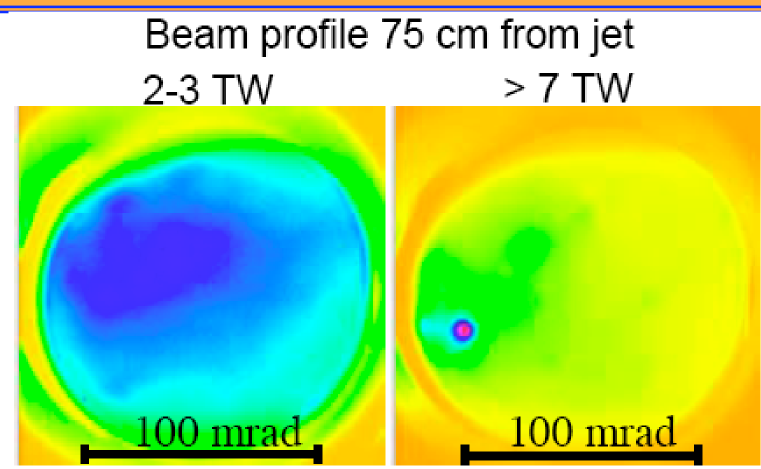
C. Joshi, et al.



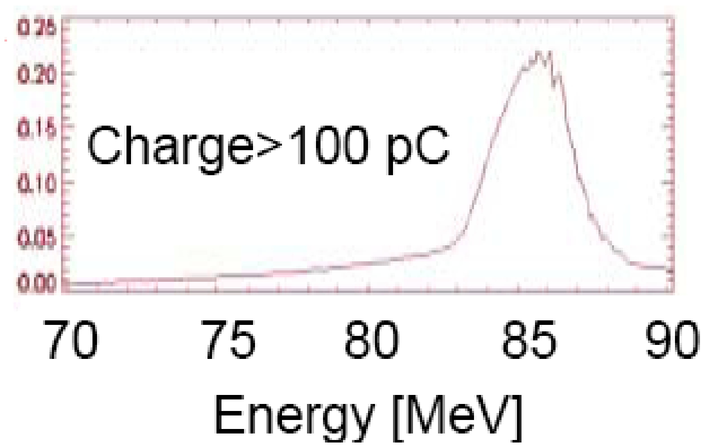
2.5E17/cc plasma

No plasma

Plasma wave excitation with laser: creation of very high quality beam

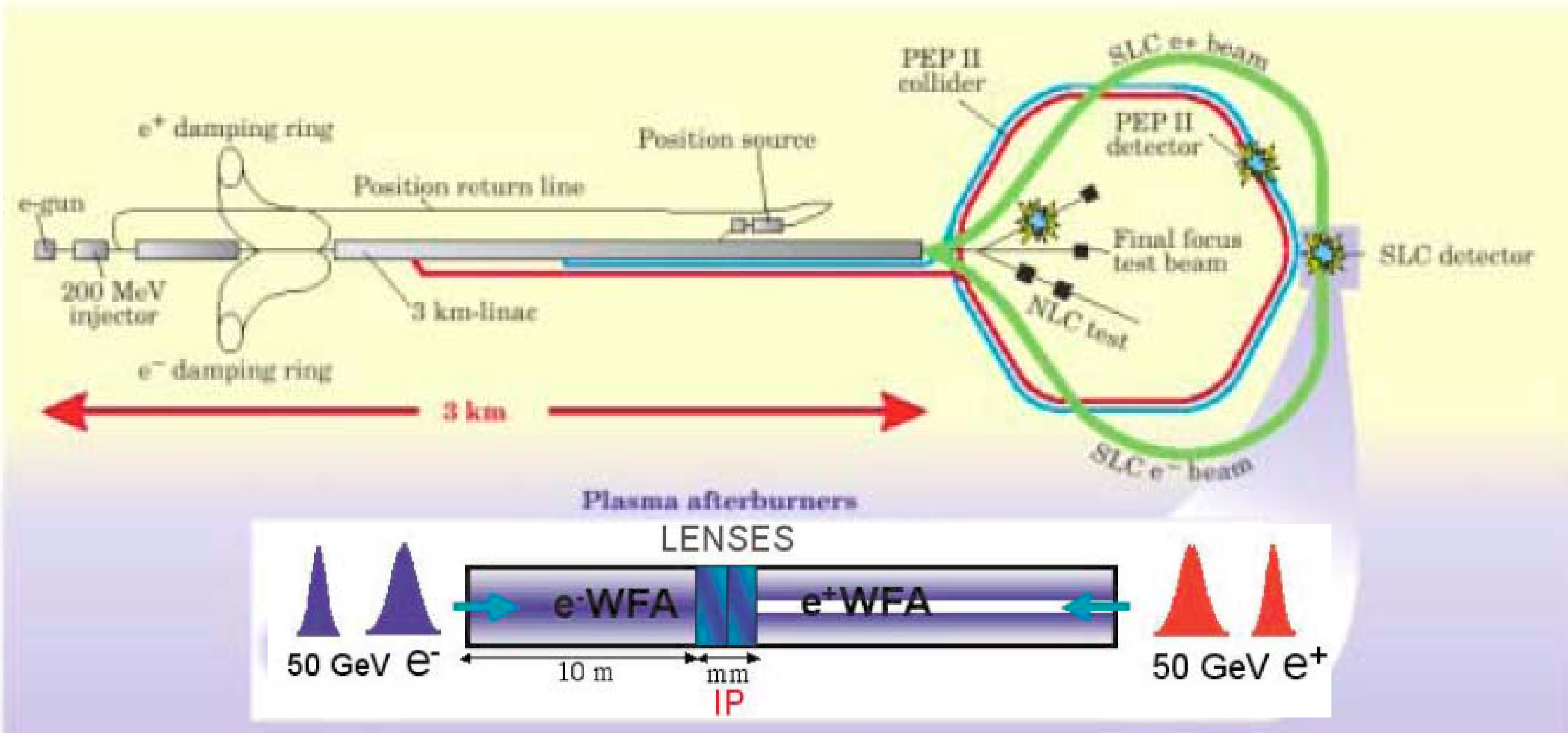


Leemans et al., Phys. Plasmas 11 (2004)



- Trapped plasma electrons in LWFA give ~1 mm-mrad emittances at ~ few nC charge
- Narrow energy spreads can be produced by accelerating in plasma channels
  - Not every shot (yet)
  - Self-wake effect?
- Looks like a beam!

Energy doubling of LC beams: the Afterburner Concept



Prospects for advanced accelerator application to HEP colliders

- Optical and plasma accelerators a challenge in experiment
  - Very large fields
  - Very small dimensions and time scales
- We have orders of magnitude in learning curve
- Lots of collective effects to worry about
  - Optical nonlinear response
  - PWFA hosing instability
  - PWFA ion collapse
- All effects give challenges for LC-type numbers…

Status

- People have worried and worked on future accelerator concepts with some urgency for 20 years.
- Despite lack of resources, we have many accomplishments to show for this effort; options that look promising…
- How do we take advantage?

Observations on how to proceed

- With the LC technology decision, massive efforts will be thrown into LC design and development
- It is critical to prioritize and organize research and development on longer range accelerator techniques
  - How can we continue to support the options in front of us?
  - More support likely needed from funding agencies
- High energy physics community must:
  - Continue to take lead in advanced accelerator research directions
  - Participate in research when possible!
- The ITRP committee represents a good paradigm for organizing the future — consensus and decision making built on hard work