Energies beyond LHC: Technology challenges of high energy lepton colliders

ILC, CLIC
Gamma-gamma Collider
Wakefield Accelerator
Muon Collider

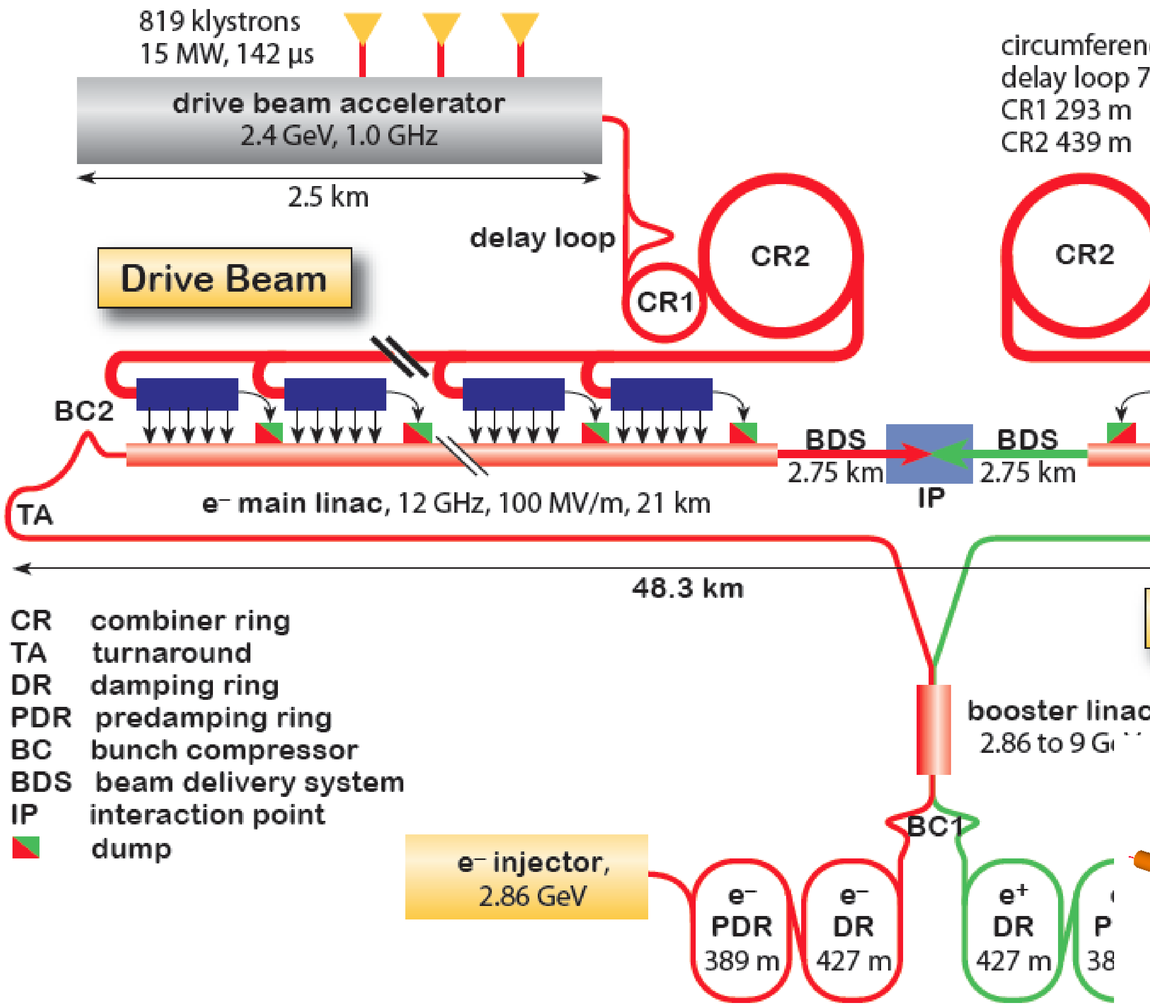
K.Yokoya (KEK)

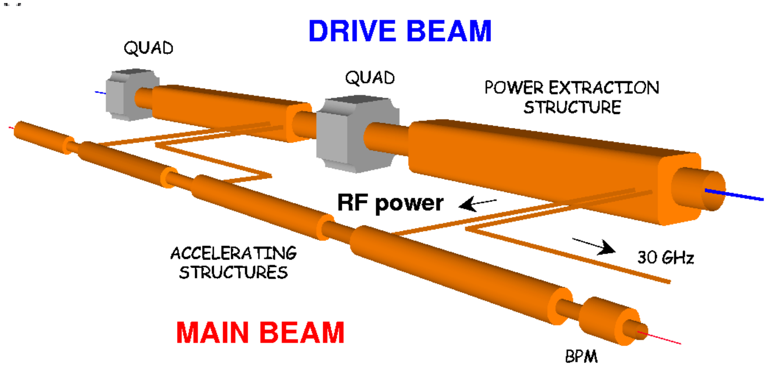
2013.8.2. Snowmass on the Mississippi

ILC 1.5TeV (if it is “Beyond LHC”)

- Technically, the only problem is the accelerating gradient when the available site length is given
- Development of higher gradient cavities
  - > 45MV/m for 1TeV
  - Cost reduction from 35MV/m is O(10%)
  - Even higher gradient desired for 1.5 TeV

CLIC (CERN Linear Collider)





CLIC Main Parameters

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N [10^9]	6.8	3.72
bunch length	σ_z [μm]	72	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	271	582

CLIC project time-line

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

2017-22 Preparation Phase

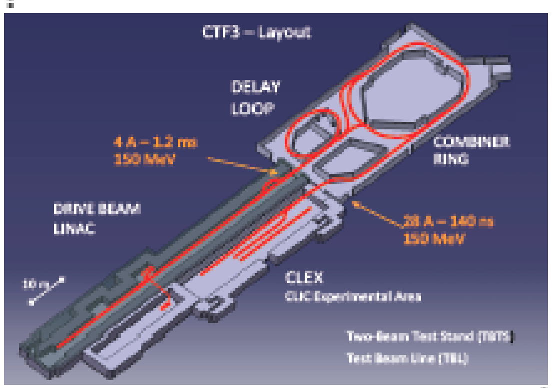
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

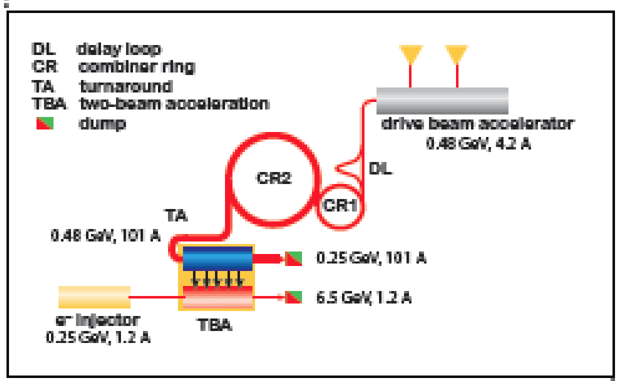
Prepare detailed Technical Proposals for the detector-systems.

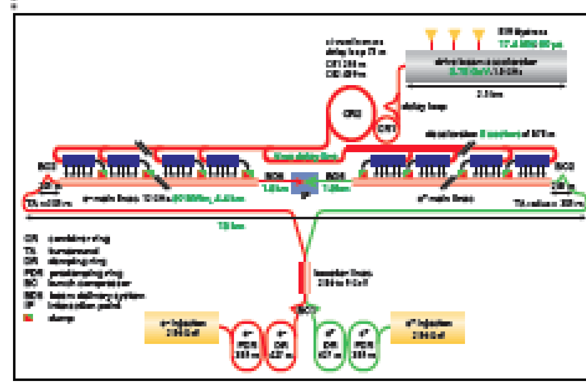
2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.







2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2022-23 Construction Start

Ready for full construction and main tunnel excavation.

LCWS12, Arlington,

2030 Commissioning

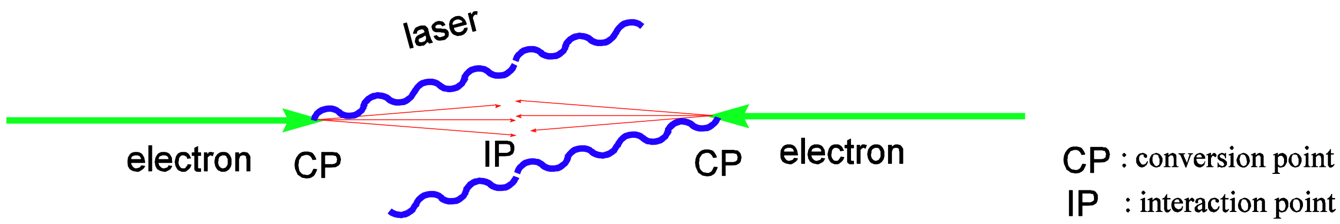
From 2030, becoming ready for data-taking as the LHC programme reaches completion.

CLIC Technology Maturity

- CDR published
- Cavity with accelerating gradient ~100MV/m almost confirmed
- Drive Beam generation demonstrated. Emittance and stability to be further improved
- Deceleration in PETS in progress
- Emittance preservation in linac with stabilization system developed
- Linac beam dynamics being tested at FACET
- Final Focus System to be tested at ATF2

Gamma-Gamma Collider

- electron-electron collider
- irradiate lasers just before ee collision
- create high energy photons, which made to collide
- no need of positrons



- Lots of recent proposals of $\gamma\,\gamma \rightarrow$ H (not “beyond LHC”)
- ILC and CLIC can be converted to γ-γ collider if physics demands
- In principle, advanced linear colliders (plasma, etc) can also be converted to γ-γ collider. In particular when positron acceleration is difficult.

Technology for Gamma-Gamma

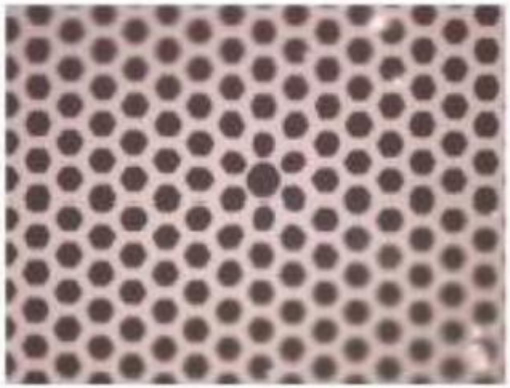
- Laser
  - Pulse structure must match with the electron beam (difference between NC and SC linacs)
  - Flash energy : a few to 10 Joules
  - Some lasers close to gamma-gamma application
    - LIFE (fusion), fiber
    - But still needs years of R&D including the adaptation of pulse structure
- Optical cavity
  - Can accumulate laser pulse from relatively weak lasers (mostly for SC linac case)
  - Many R&D studies in the world for other applications
- IR design
  - Path of laser beam
  - In particular complex with optical cavity is used
  - background studies

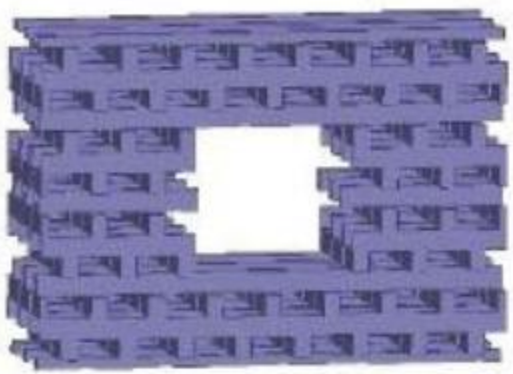
Advanced Acceleration Mechanisms

- Dielectric material
  - Laser-driven (DLA)
  - Beam driven
- Plasma wakefield acceleration
  - Laser-driven (LWFA)
  - Beam driven (PWFA)

Dielectric Laser Accelerator (DLA)

- Direct extension of present accelerator concept (microwave + resonant structure)
  - Klystron → laser
  - Resonant cavity → micron scale dielectric crystal (semiconductor technology)
  - less power loss than metal at optical frequencies
  - expected higher breakdown thresholds (> 1 order of magnitude than Cu structure)
- Very short wavelength (micron)
- Require very low bunch charge $O(10^4)$ plus very high repetition rate O(GHz)
  - In one hand this relaxes the beam-beam interaction





DLA

- Challenges
  - material to ensure the gradient
  - power coupler of high efficiency
  - electron beam with required bunch pattern (hundred bunchlets in picosecond repeated a few MHz)
  - for colliders
    - emittance growth by transverse wake (alignment)
    - positron beam
      almost impossible to create the beam structure?
    - Can go to γ-γ collider?
      But require extreme laser (~5TW x 1ps, average ~50MW)

An example of 10TeV collider

Bunch population	3.80E+04
bunches per train	159
rep rate	5 MHz
macro bunch length	150 μm
wavelength	1.89 μm
normalized emittance	1e−10 m
IP spot size	0.06nm
Luminosity	4.90E+36
Beam power	24.2MW
Wall-plug power	242MW
Gradient	400MV/m
Total linac length	25km
Laser pulse energy	1μJ
Average power	1kW
Pulsewidth	1ps
Wall-plug efficiency	30−40%

one of the examples in ICFA-ICUIL report

Plasma Wakefield Accelerator

Linac in the past has been driven by **microwave technology**

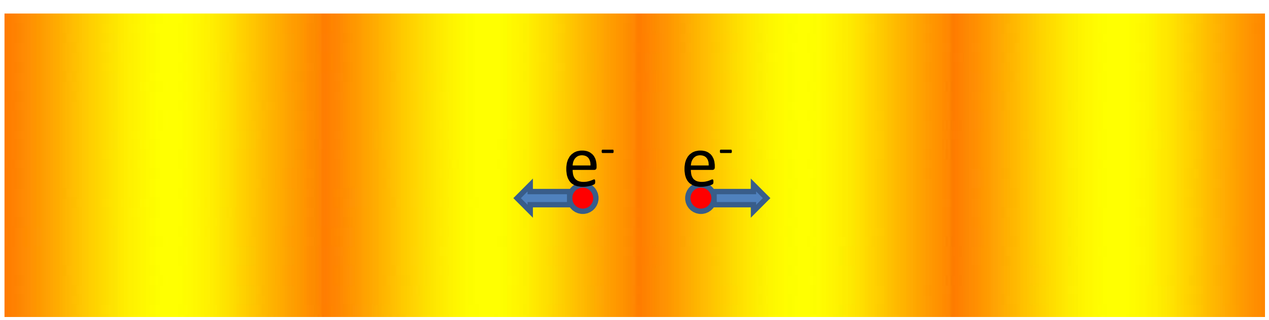
- Plane wave in vacuum cannot accelerate beams: needs material to make boundary condition
- Breakdown at high gradient

Excite **plasma wave** by some way (electron beam, laser beam)

- Charged particles on the density slope are accelerated, like surfing.
- Need not worry about breakdown with plasma
  - can reach > 10GeV/m
- Plasma oscillation frequency and wavelength are related to plasma density

$$\omega_p = \sqrt{\frac{e^2}{\epsilon_0 m_e} n_0}, \qquad \lambda_p = \frac{2\pi c}{\omega_p} = \frac{3.3 \times 10^4}{\sqrt{n_e[\mathrm{cm}^{-3}]}} \quad [\mathrm{m}]$$

$$n_e = \text{plasma density}$$



How to Generate Plasma Wave

- Beam-Driven (PWFA)
  - Use particle (normally electron) beam of short bunch
- Laser-Driven (LWFA)
  - Use ultra-short laser beam
- In both cases the driving beam
  - determines the phase velocity of plasma wave, which must be close to the velocity of light
  - must be shorter than the plasma wavelength required
  - can also ionize neutral gas to create plasma

LWFA

- kick out plasma electrons by pondermotive force of laser
- Laser intensity characterized by the parameter a_0
  - $a_0 < 1$: linear regime
  - $a_0 > 1$: blow-out regime (all electrons expelled out of the drive beam region)

$$a_0 \approx 8.5 \times 10^{-10} \lambda_L[\mu\mathrm{m}] I^{1/2}[\mathrm{W/cm^2}]$$

- Accelerating field

$$E = E_0 \frac{a_0^2/2}{\sqrt{1 + a_0^2/2}}$$

$$E_0 = c m_e \omega_p / e = 96 n_0^{1/2}[\mathrm{cm}^{-3}]$$

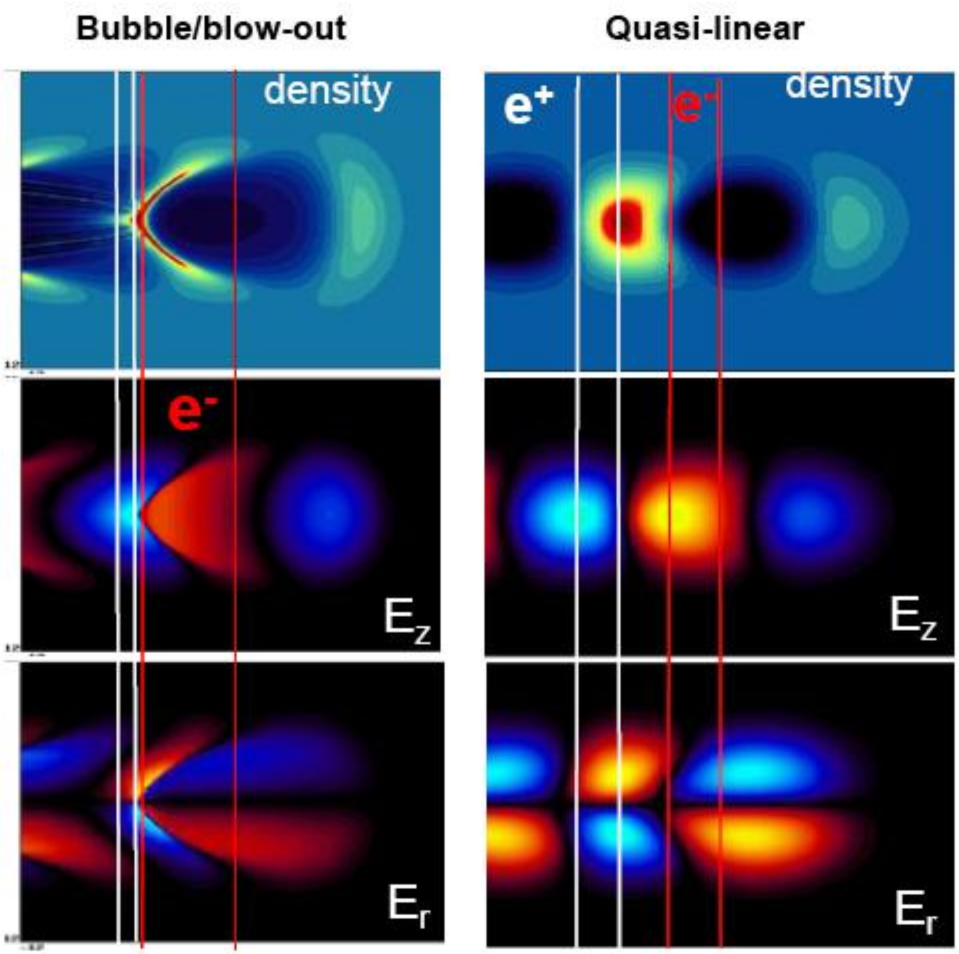
Blowout and Linear Regime

- The gradient can be higher in the blowout regime but
  - difficult to accelerate positron
  - narrow region of acceleration and focusing

acceleration field

plasma density

transve rse field



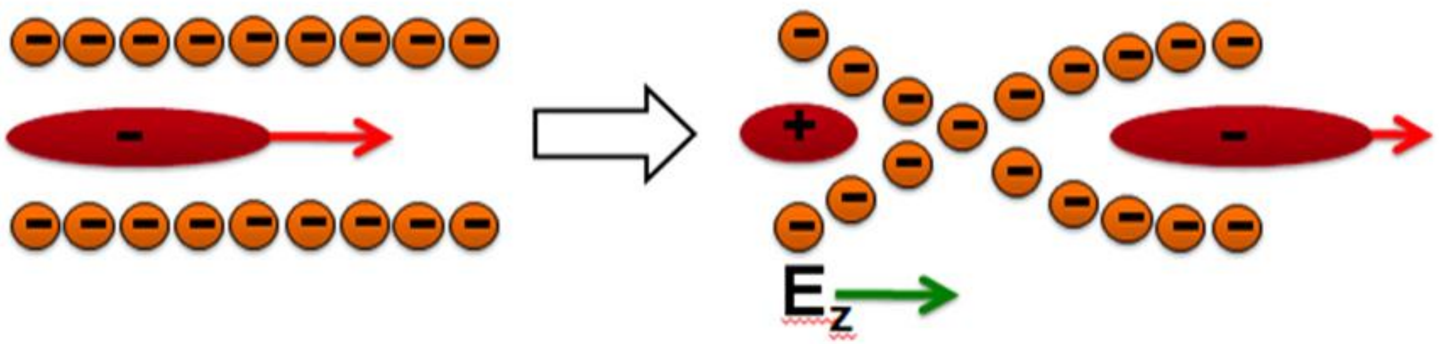
a=4

a=1

Figure from ICFA Beamdynamics News Letter 56

Positron Acceleration

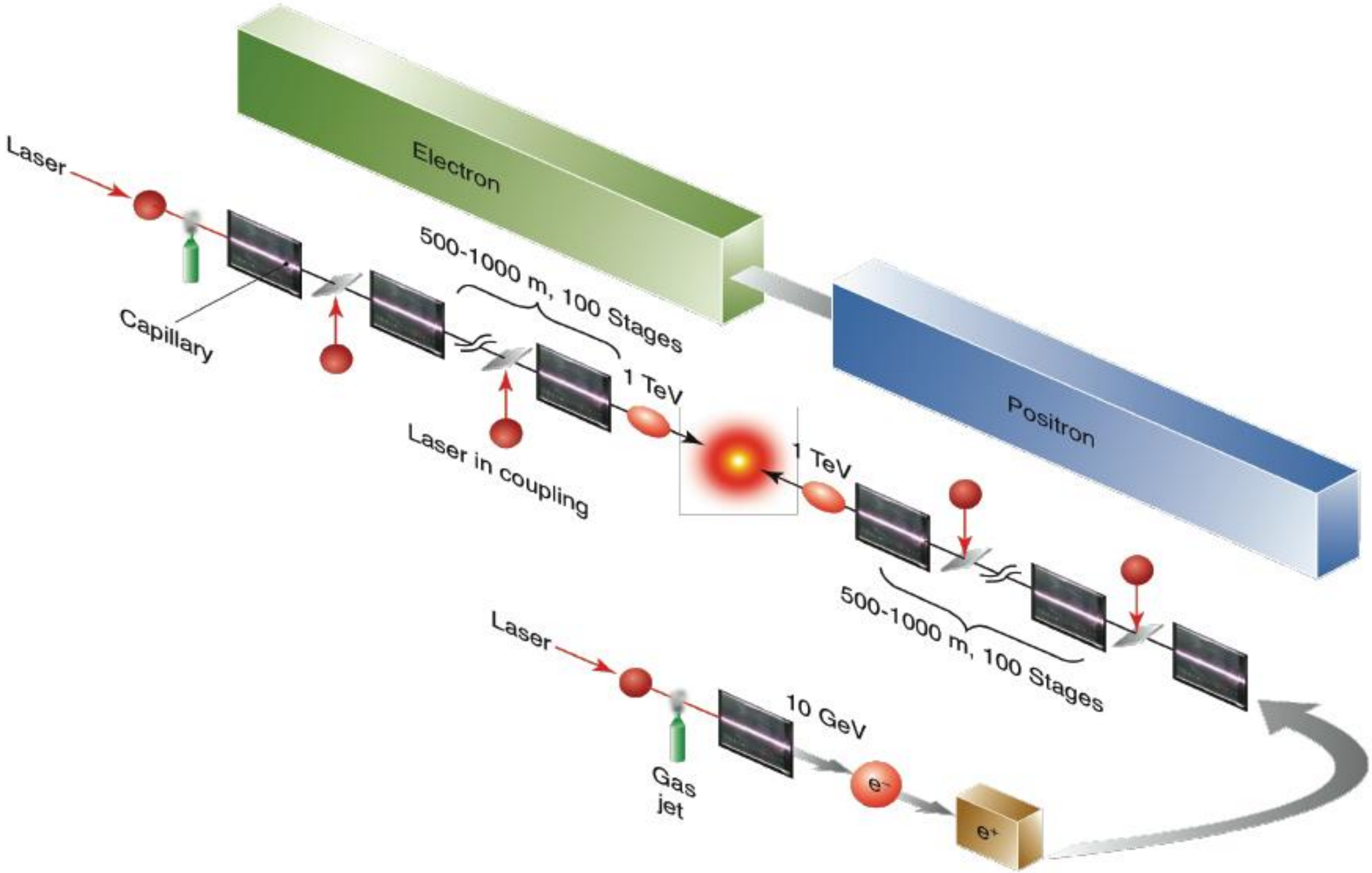
- Positron beam is defocused in the acceleration phase
- Use hollow plasma channel
- Acceleration+focusing phase created when plasma electrons go back to the axis



Limitation by Single Stage

- Laser must be kept focused (Rayleigh length)
  - solved by self-focusing and/or preformed plasma channel
- Dephasing: laser velocity in plasma
  - longitudinal plasma density control
- Eventually limited by depletion
  - depletion length proportional to $n_0^{-3/2}$
  - acceleration by one stage proportional to I/n_0
- Multiple stages needed for high energy, introducing issues of
  - phase control
  - electron orbit matching

Concept of LWFA Collider



Example Beam Parameters of 1-10TeV LWFA

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

From ICFA Beamdynamics News Letter 56 (ICFA-ICUIL White paper)

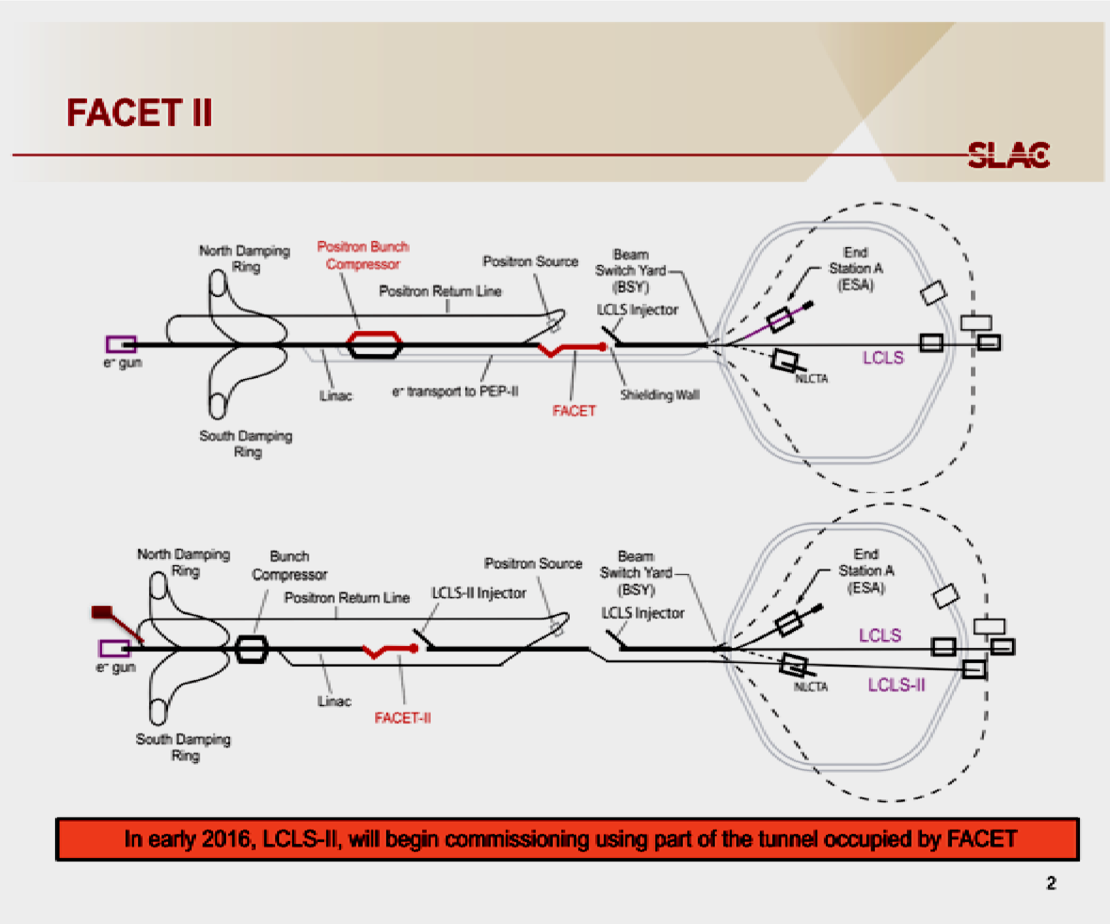
Example Laser Parameters of 1/10TeV LWFA

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Wavelength (μm)	1	1	1	1
Pulse energy/stage (kJ)	0.032	11	0.032	11
Pulse length (ps)	0.056	0.4	0.056	0.4
Repetition rate (kHz)	15	0.3	15	0.3
Peak power (PW)	0.24	12	0.24	12
Average laser power/stage (MW)	0.48	3.4	0.48	3.4
Energy gain/stage (GeV)	10	500	10	500
Stage length [LPA + in-coupling] (m)	2	500	2	500
Number of stages (one linac)	50	1	500	10
Total laser power (MW)	48	3.4	480	34
Total wall power (MW)	160	23	960	138
Laser to beam efficiency (%) [laser to wake 50% + wake to beam 40%]	20	20	20	20
Wall plug to laser efficiency (%)	30	30	50	50
Laser spot rms radius (μm)	69	490	69	490
Laser intensity (W/cm^2)	3×10^{18}	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a_0	1.5	1.5	1.5	1.5
Plasma density (cm^{-3}), with tapering	10^{17}	2 x 10^{15}	10^{17}	2 x 10^{15}
Plasma wavelength (mm)	0.1	0.75	0.1	0.75

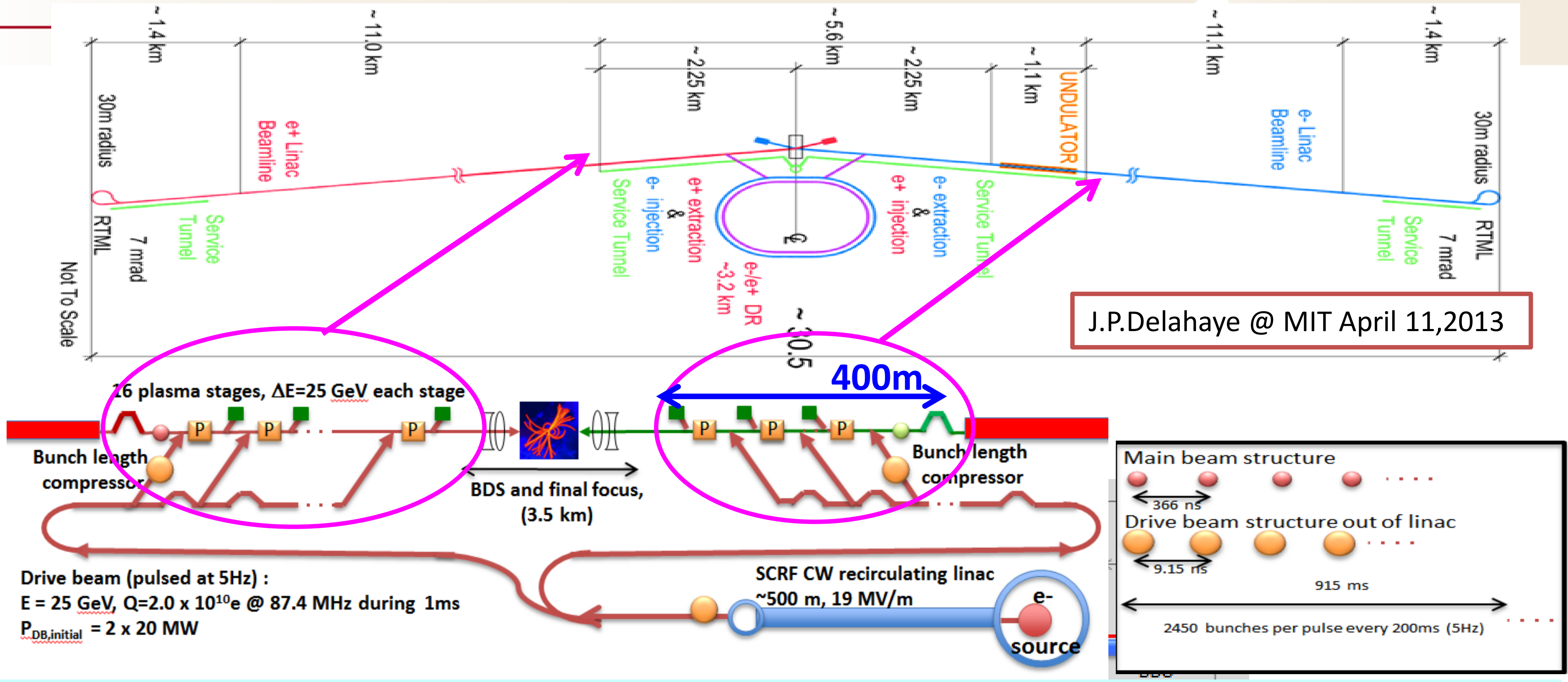
From ICFA Beamdynamics News Letter 56

Beam-Driven Plasma Accelerator

- Use electron beam to generate plasma wave
- Bunch pattern is more flexible than in LWFA (not constrained by the laser technology)
- R&D works led by SLAC (FACET/FACET2)



An alternative ILC upgrade by PWFA



One possible scenario could be:

1) **Build & operate the ILC as presently proposed up to 250 GeV (125 GeV/beam): total extension 21km**
2) **Develop the PFWA technology in the meantime (up to 2025?)**
3) **When ILC upgrade requested by Physics (say up to 1 TeV), decide for ILC or PWFA technology:**
4) **Do not extend the ILC tunnel but remove latest 400m of ILC linac (beam energy reduced by 8 GeV)**
5) **Reuse removed ILC structures for PWFA SC drive beam accelerating linac (25 GeV, 500m@19MV/m)**
6) **Install a bunch length compressor and 16 plasma cells in latest part of each linac in the same tunnel for a 375+8 GeV PWFA beam acceleration (382m)**
7) **Reuse the return loop of the ILC main beam as return loop of the PWFA drive beam**

ILC upgrade from 250 GeV to 1 TeV by PWFA

Parameter	Unit	ILC	ILC	ILC (to 250GeV) + PWFA
Energy (cm)	GeV	250	1000	PFWA = 250 to 1000
Luminosity (per IP)	$10^{34}cm^{-2}s^{-1}$	0.75	4.9	4.9
Peak (1%)Lum(/IP)	$10^{34}cm^{-2}s^{-1}$	0.65	2.2	2.2
# IP	-	1	1	1
Length	km	21	52	21
Power (wall plug)	MW	128	300	128+135*1.2=290?
Polarisation (e+/e-)	%	80/30	80/30	80/30
Lin. Acc. grad. (peak/eff)	MV/m	31.5/25	36/30	7600/1000
# particles/bunch	10^{10}	2	1.74	1.74
# bunches/pulse	-	1312	2450	2450
Bunch interval	ns	554	366	366
Average/peak current	nA/mA	21/6	22.9/7.6	22.9/7.6
Pulse repetition rate	Hz	5	4	5
Beam power/beam	MW	2.63	13.8	13.8
Norm Emitt (X/Y)	$10^{-6}/10^{-9}$rad-m	10/35	10/30	10/30
Sx, Sy, Sz at IP	nm,nm,µm	729/6.7/300	335/2.7/225	485/2.7/20
Crossing angle	mrad	14	14	14
Av # photons	-	1.17	2.0	1.0
δb beam-beam	%	0.95	10.5	16
Upsilon	-	0.02	0.09	0.8

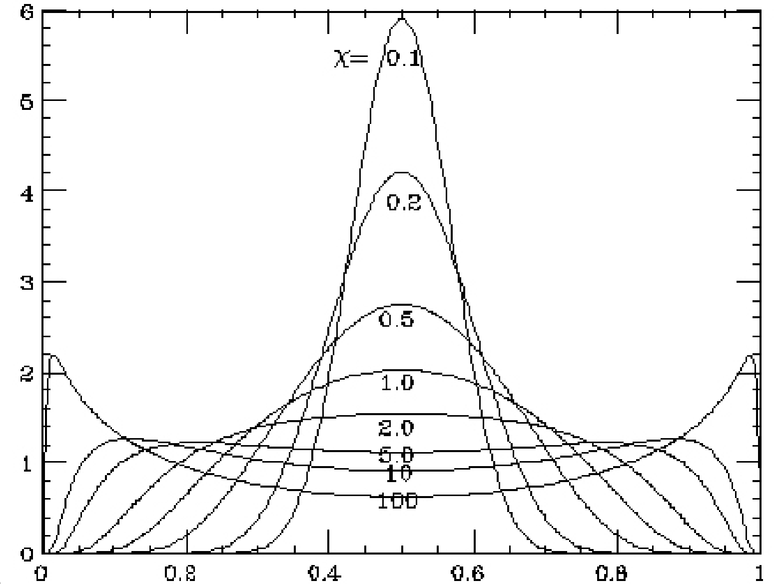
What's Needed for Plasma Collider

- High rep rate, high power laser (Laser-driven)
- Beam quality
  - Small energy spread << 1%
  - emittance preservation (alignment, instabilities, laser stability, Coulomb scattering)
- High power efficiency from wall-plug to beam
  - Wall-plug → laser (Laser-driven)
  - Laser (beam) → plasma wave
  - plasma wave → beam (high-beam loading required)
- Staging (BELLA at LBNL--- 2 stage acceleration to 10GeV)
  - laser phase (Laser-driven)
  - beam optics matching
- Positron acceleration
- Beam-beam interaction
- Very high component reliability
- Low cost per GeV
- **Colliders need all these, but other applications need only some of these**
  - Advantage of LWFA (PWFA requires big drive linac)
- Application of plasma accelerators would start long before these requirements are established

A Challenge for Detectors

- Wakefield accelerators adopt short wavelength
  - The bunch length inevitably short
  - High beamstrahlung parameter

$$\Upsilon \equiv \frac{\text{critical energy}}{E_0} \propto \frac{N\gamma}{\sigma_z(\sigma_x + \sigma_y)}$$

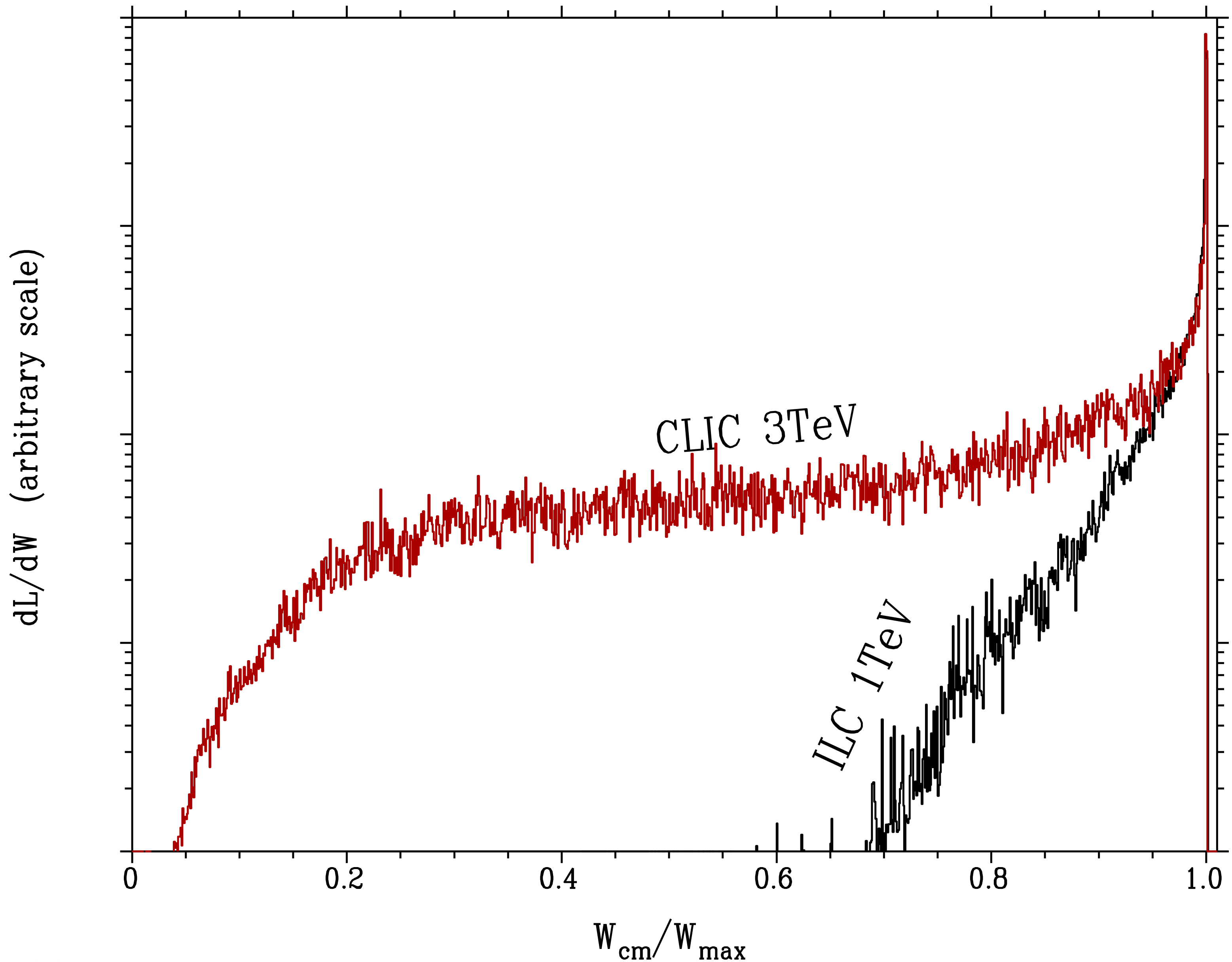


- High field effects
  - Beamstrahlung e → e + γ
  - Coherent pair creation γ → $e^+ e^-$
  - Minimum electron energy

$$E_{min} \sim E_0/\Upsilon, \qquad (\Upsilon \ll 1)$$

  - Come out with very large angles
  - Previous LWFA example gives Υ=18000, E_{min} ~ 300MeV, angle = O(1radian)
  - Much more abundant than the pairs from particle-particle collision

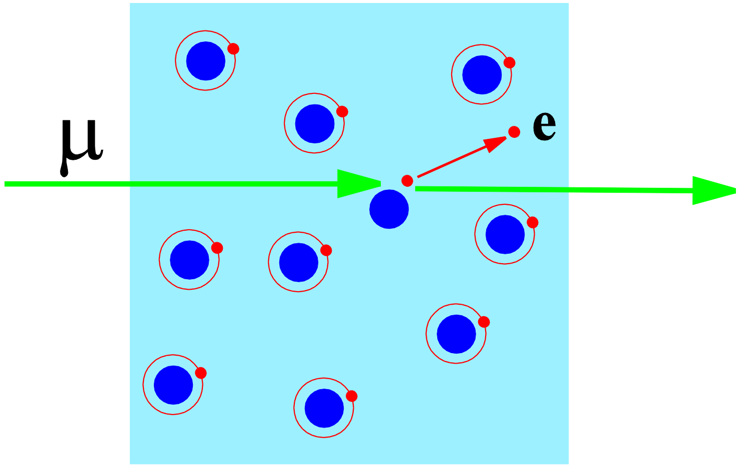
Luminosity Spectrum (e^-,e^+)



Muon Collider

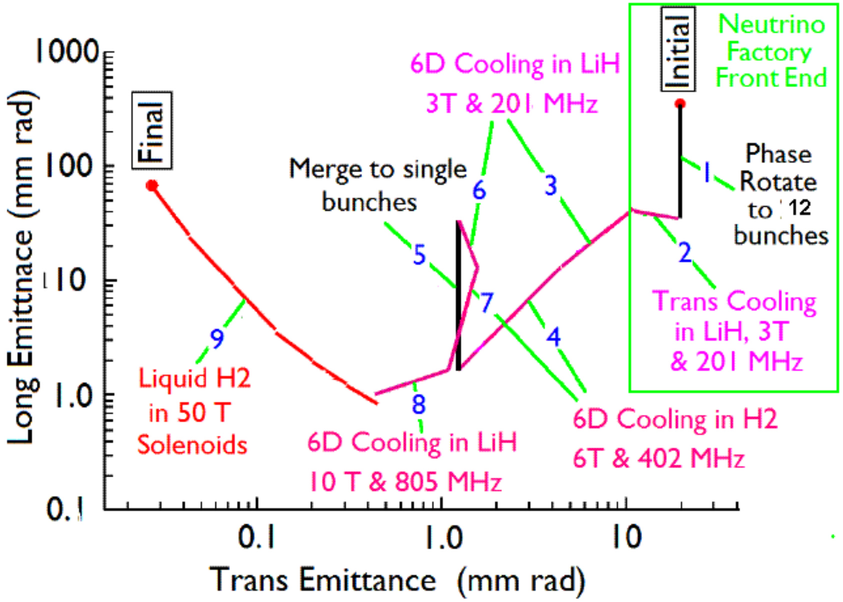
- Properties of muons are quite similar to electron/positron
  - What can be done in e+e- can also be done in $\mu^+\mu^-$
- but muon is 200x heavier → can be accelerated to high energies in circular accelerator
- $\mu^+\mu^-$ collider is much cleaner than e+e- (beamstrahlung negligible)
  - except the problem of background from muon decay
- But muons do not exist naturally
  - need cooling like antiproton
- "Ionization cooling" invented by Skrinsky-Parkhomchuk 1981, Neuffer 1983

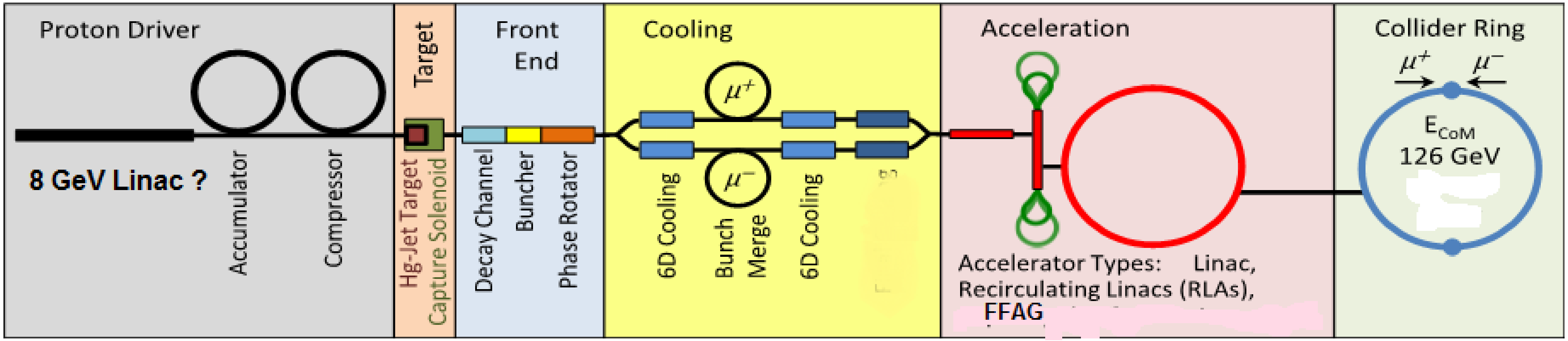
- Make use of energy loss dE/dx by ionization
- Coulomb scattering heats the beam



Create and Cool Muon Beam

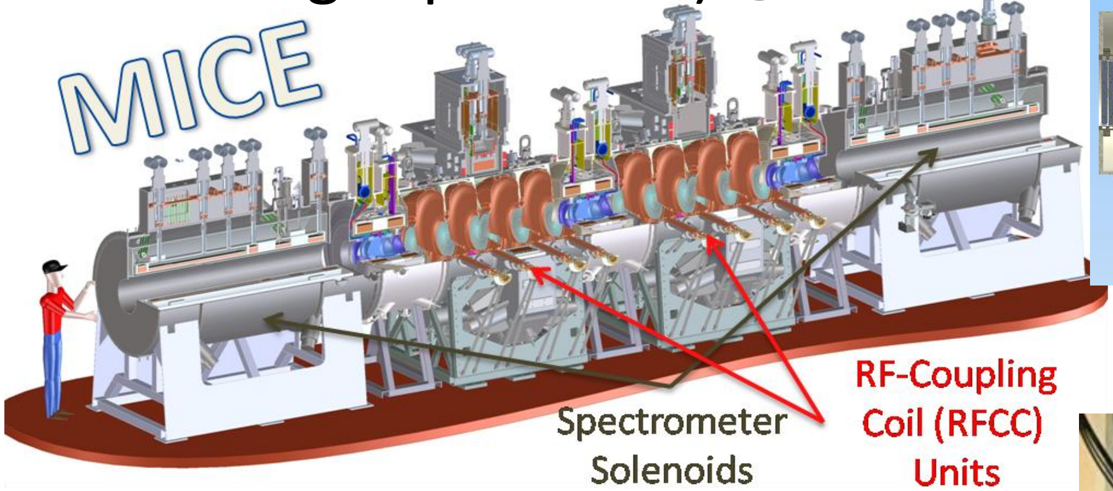
- Muons created by hadron collision
- Muons decay within 2μs in the rest frame
  - must be accelerated quickly
- Staging
  - Higgs factory at E_{cm}=126GeV (Z-pole used to be the first target)
  - Neutrino factory
  - TeV muon collider

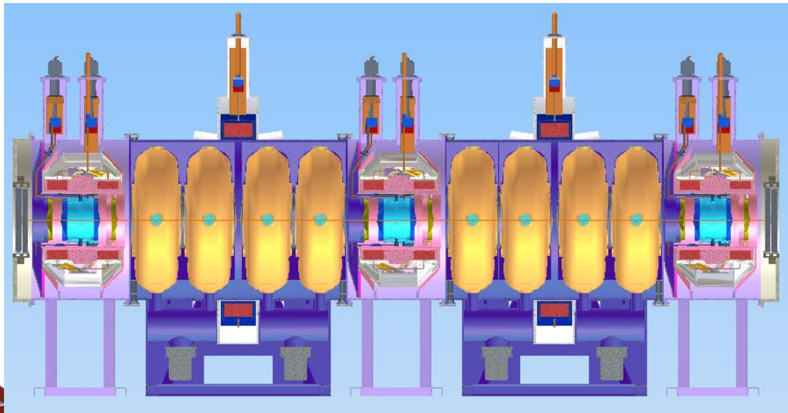




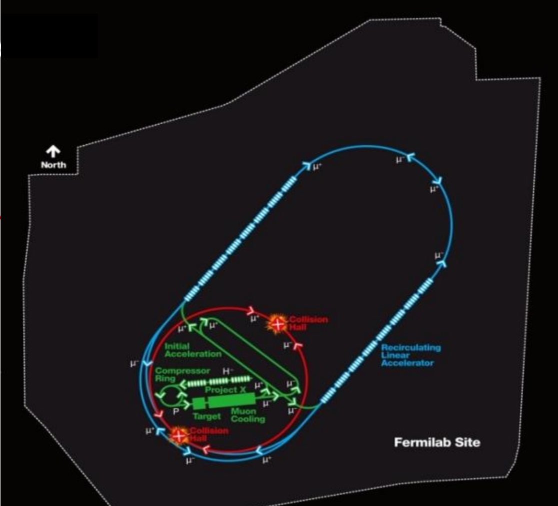
Cooling Test Facilities

- MICE (Muon Ionization Cooling Experiment) @RAL





- MTA (MuCool Test Area) @FNAL
  - cavity test



MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders

Range of Top Params:
$\delta E/E \sim 0.01 - 0.1\%$
$L_{avg} \sim 0.7 - 6 \cdot 10^{33}$

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Muon Collider Baseline Parameters

		Higgs Factory		**Multi-TeV Baselines**	
Parameter	***Units***	Startup Operation	Production Operation		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
eam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
b*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1	1.5	70	70
Bunch Length, s_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	mm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4#	4	4	4

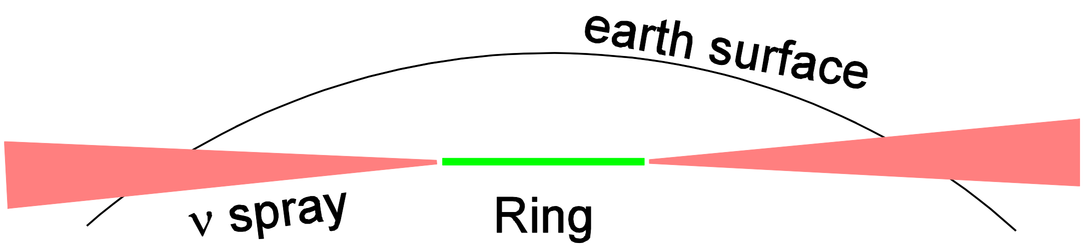
Could begin operation with Project X Stage 2 beam

Success of advanced cooling concepts ⇨ several × 10^{32}

M.Palmer, Jul.30

Technical Challenges on Muon Collider

- Proton driver of several MW
- Target at several MW
- Ionization cooling
  - ~10^7 in 6D emittance
  - High field HTS solenoid (>30T)
  - High gradient acceleration in magnetic field (Teslas)
- collider ring issues
  - High field dipole (10-20T)
  - muon decay (background, magnet shielding)
- Will require tens of years of R&D
- Energy limit comes from radiation (~10TeV?)

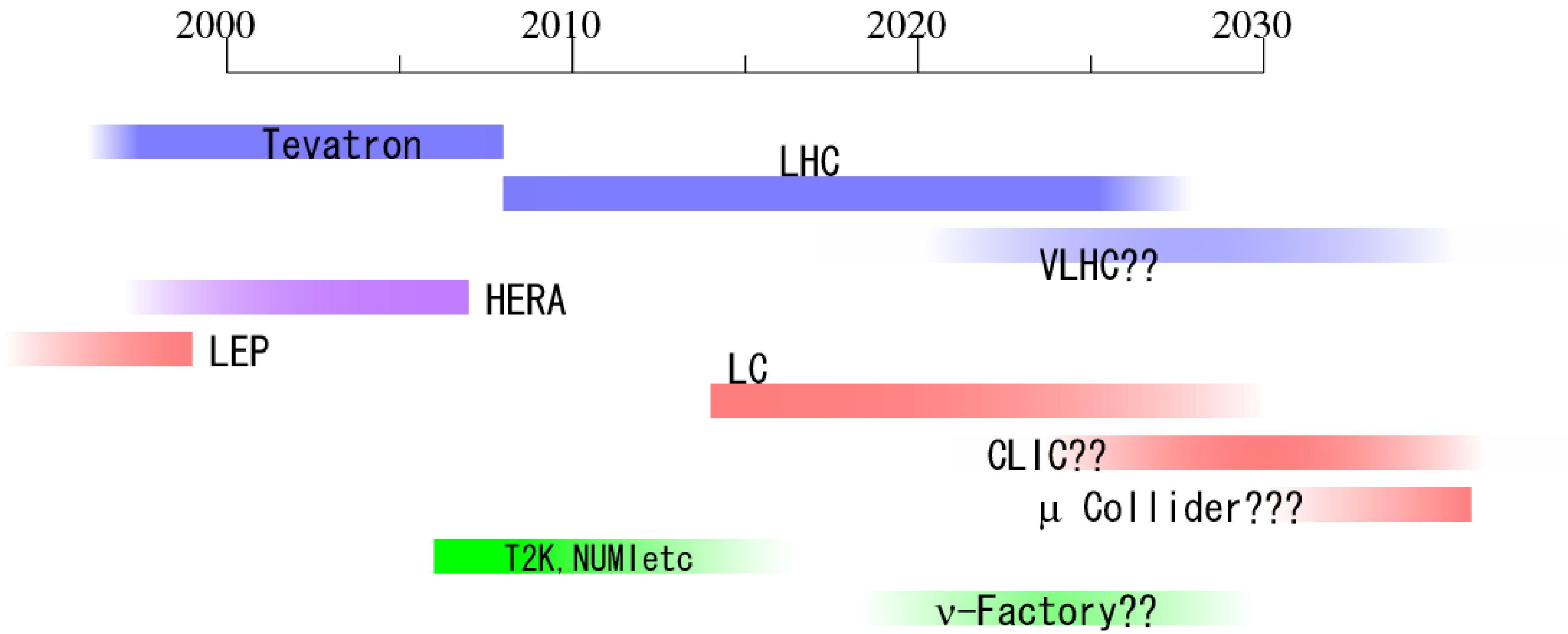


Summary

- Microwave acceleration up to 3TeV (ILC + CLIC)
  - Accelerator technology nearly ready
- Gamma-gamma collider
  - Laser technology not too far
  - Need detailed design including IR
- Muon collider
  - Staging possible (Higgs → nu factoryb → TeV collider)
  - several beyond-state-of-art components needed
  - but already in the region of accelerator physics
- Plasma collider
  - Still long, long way to colliders
    - Still in the level of plasma physics. Not yet at the stage of accelerator physics
  - PWFA seems to be better for colliders
  - LWFA can have lower-energy application, so step-by-step experience can be gained
- US is in leading position in most of the collider R&D

Time Line???

- An example of poor prediction : Don’t make prediction!



Does not include R&D and construction period

Aug.2004 ICHEP at Beijing