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- Introduction – circular vs linear
- Status of ILC
- Status of CLIC
- Circular machines
- The (far) future for e^+e^- - PWFA
- Political status & outlook
- Summary

Introduction

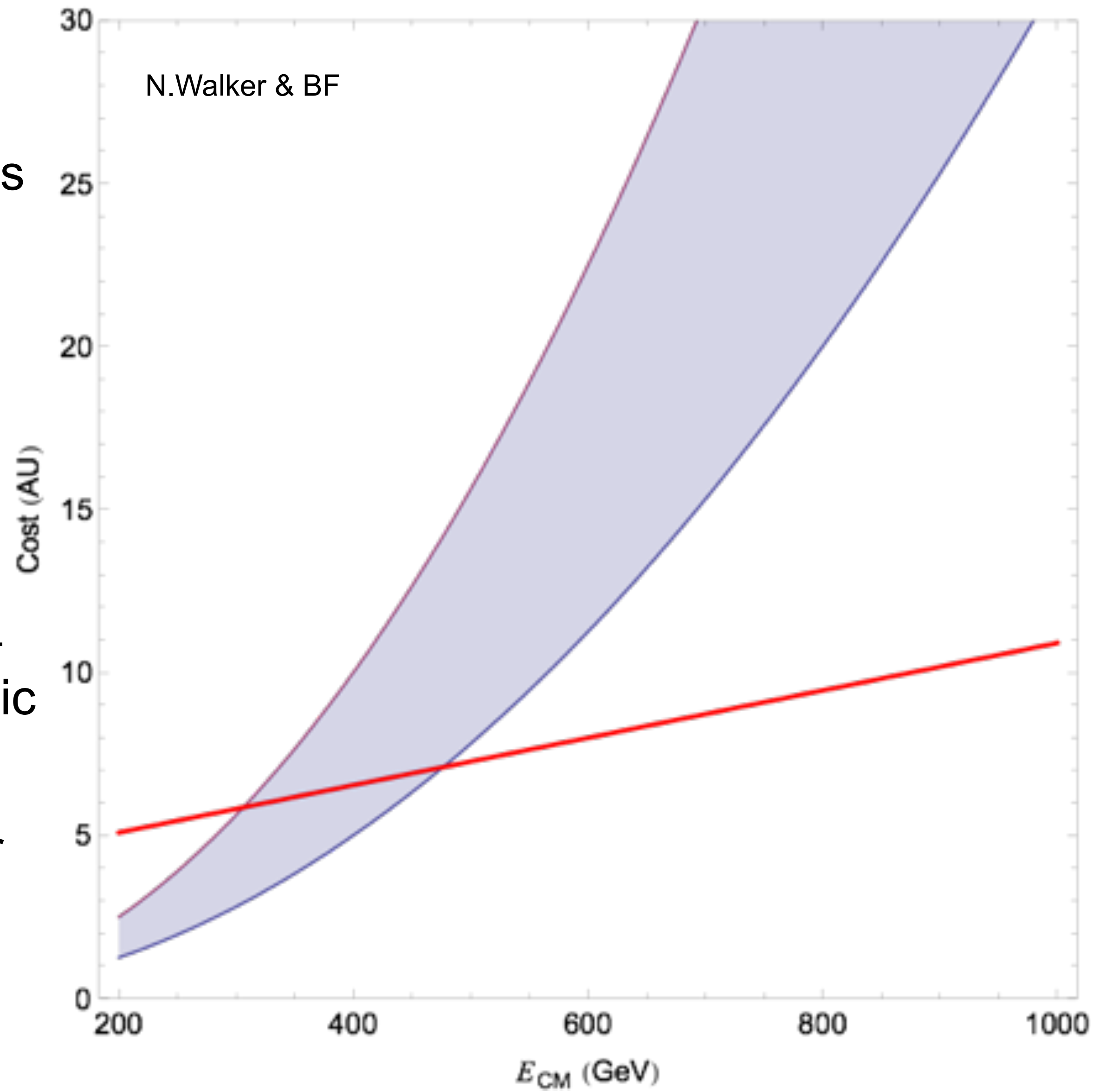
- We have been building circular accelerators for generations – all Nobel prizes in experimental pp in recent past have come from such machine.
- Only one linear collider has ever been built – at SLAC in the 1980s – and it was widely agreed to have been a disappointment.
- Why then do the the particle physics strategies from all three regions unanimously agree that the next major energy-frontier machine for particle physics should be a LC?

Circular e^+e^- machines

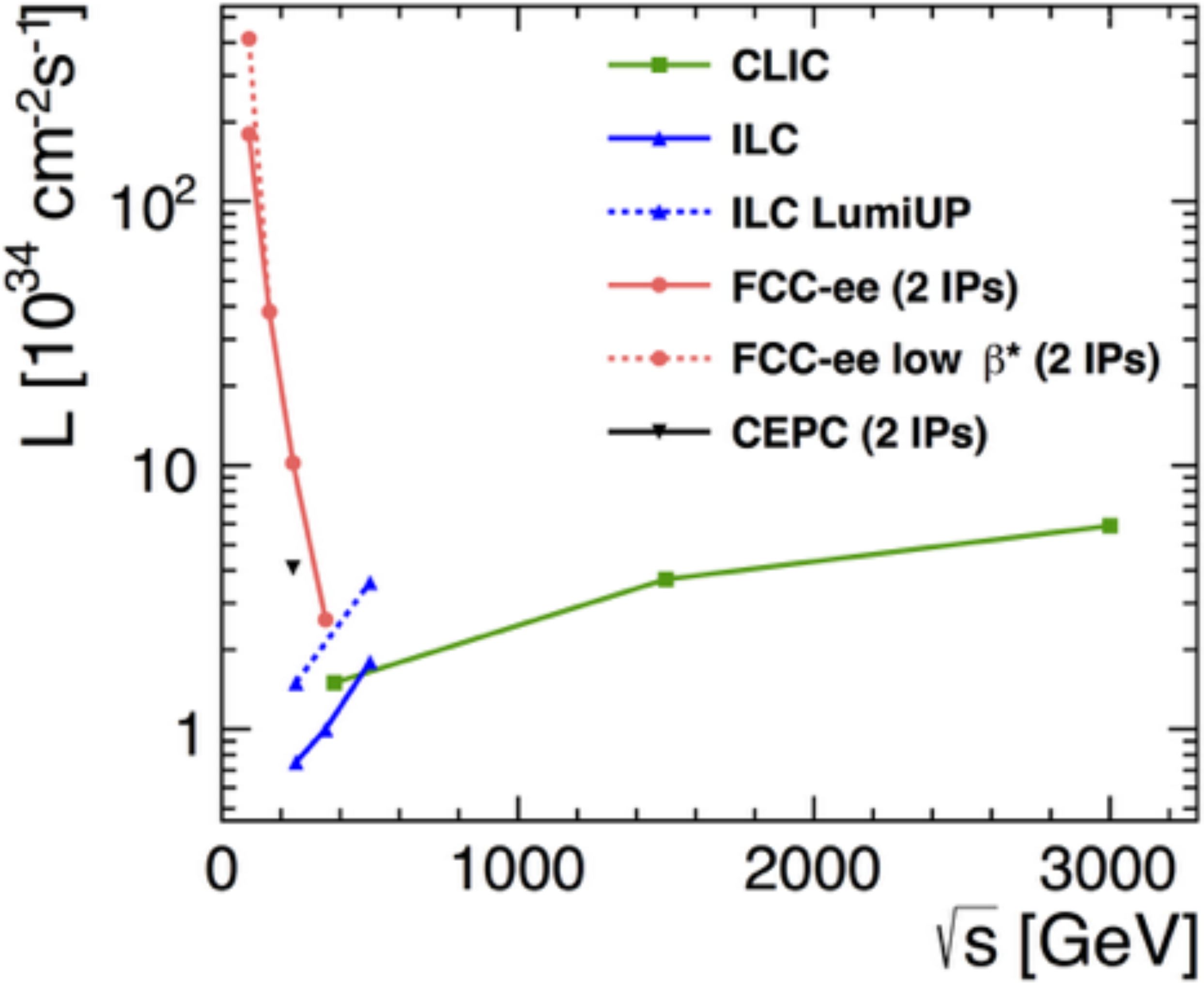
Response to basic laws of physics: charged particle in circular orbit radiates photons with a power ~ E^4/R^2

Very approximate cost optimum of LC vs circular based on minimum of cost model:
Cost = $aE^4/R + bR$
where a,b "fixed" from LEP – two curves are most optimistic and pessimistic LEP cost.

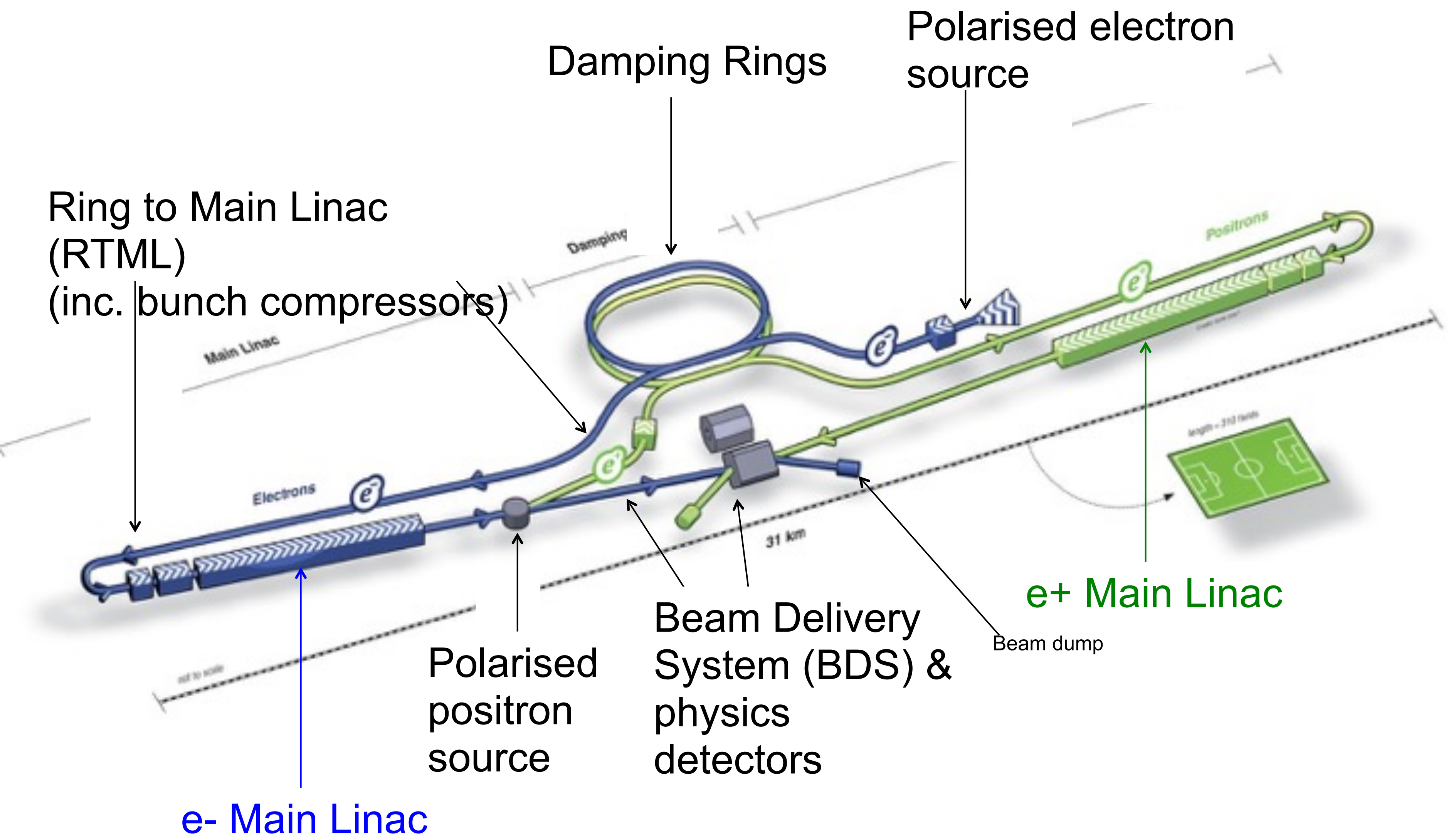
BUT – luminosity of circular machine in this picture dropping steeply with E.



Luminosity vs E for e^+e^- machines



LC Overview



not to scale

ILC Scheme | © www.form-one.de

SCRF Linac Technology

- solid niobium
- standing wave
- 9 cells
- operated at 2K (Lqd. He)
- 35 MV/m
- $Q_0 \geq 10^{10}$

1.3 GHz Nb 9-cell Cavities	16,024
Cryomodules	1,855
SC quadrupole package	673
10 MW MB Klystrons & modulators	436 / 471*

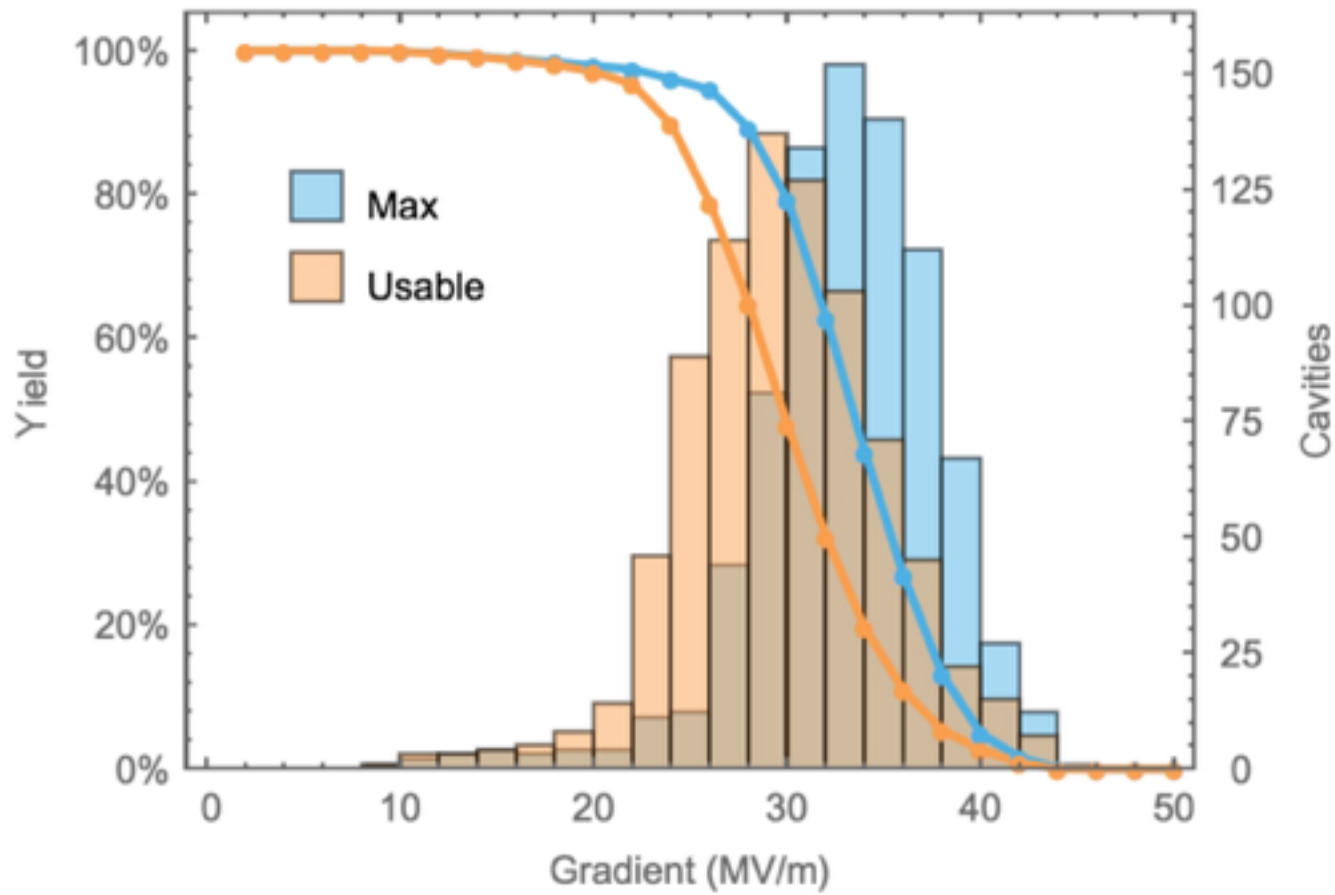
* site dependent

Approximately 20 years of R&D Worldwide → Mature technology

Industrial production - XFEL

European XFEL ENLIGHTENING SCIENCE

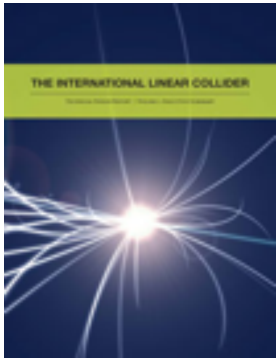
- All 832 9-cell XFEL cavities included, after retreatment of some cavities.

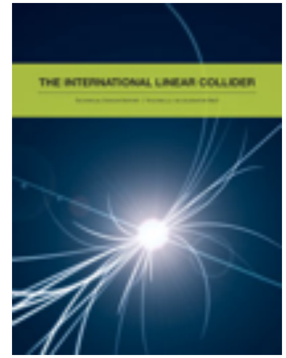


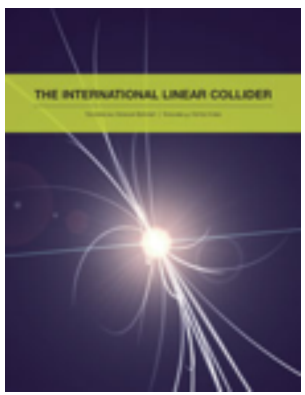
(Reschke et al., PRAB 20, 042004 (2017))

ILC Status

- On June 12th, 2013 ILC TDR was published.

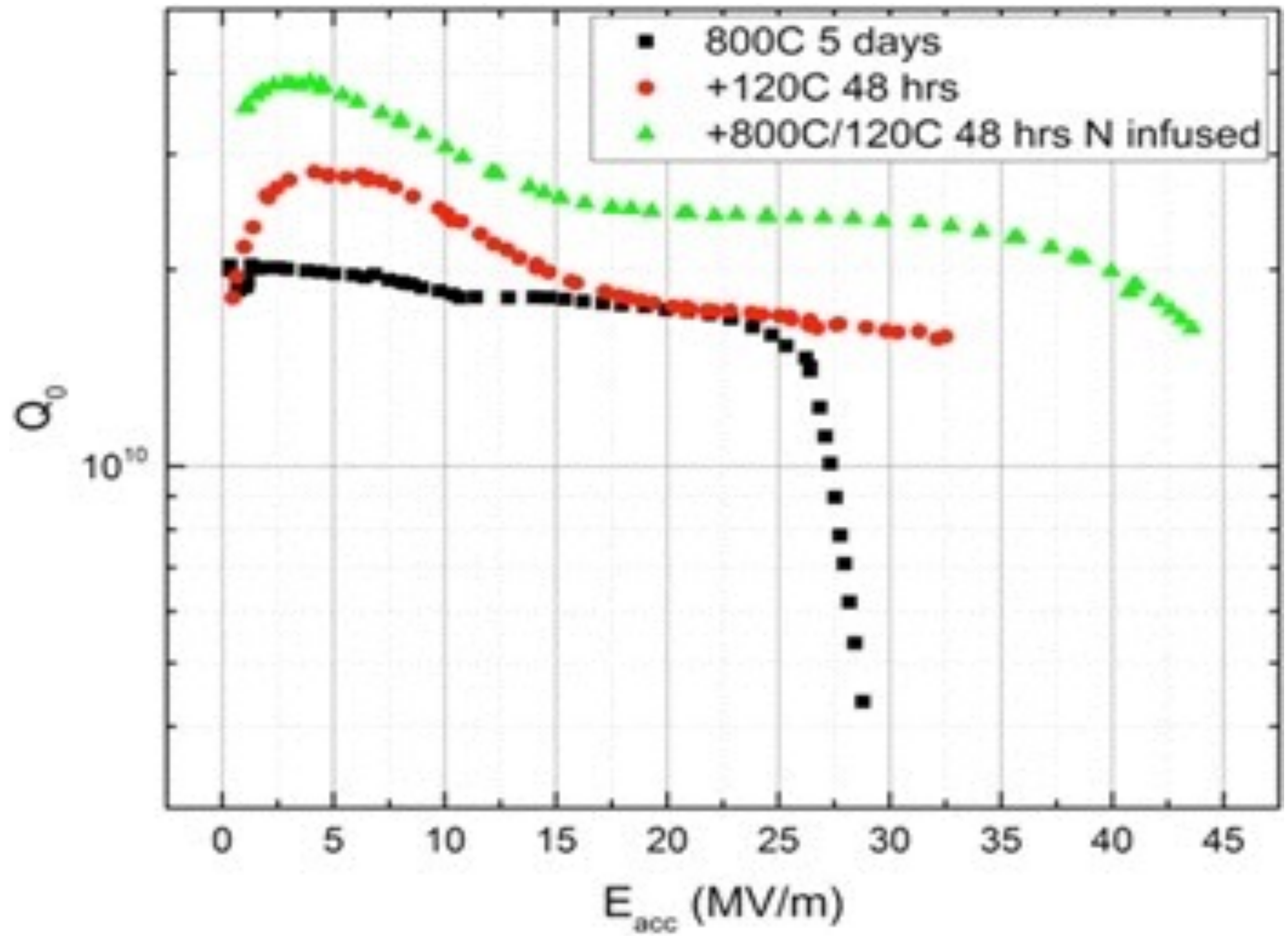






- The design is ~ complete. Current efforts to reduce cost include descoping to 250 GeV, use of N_2 infusion, etc.

Nitrogen Infusion in Niobium cavities



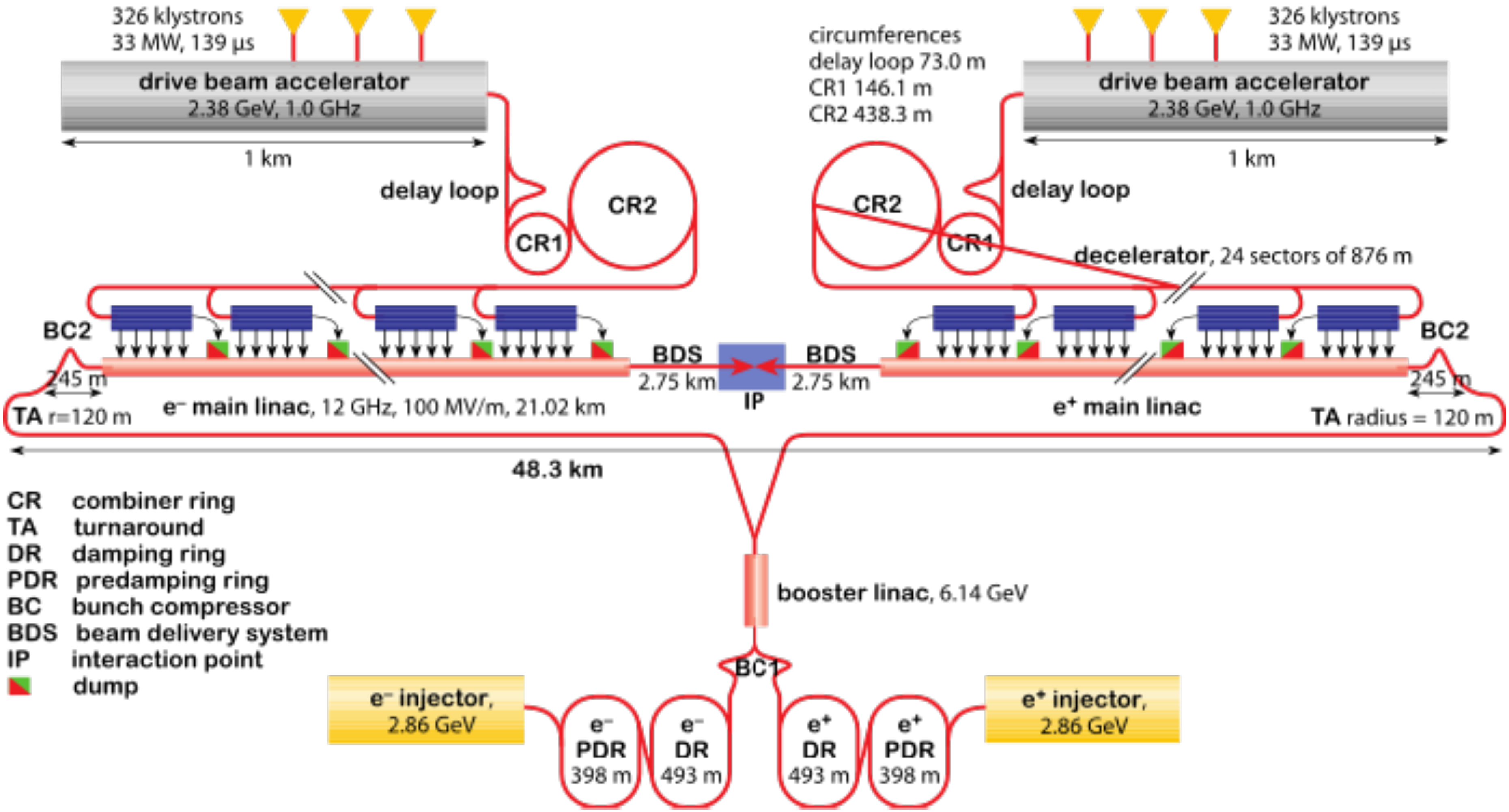
A Grassellino et al 2017 Supercond. Sci. Technol. 30 094004 doi:10.1088/1361-6668/aa7afe

Japanese Site

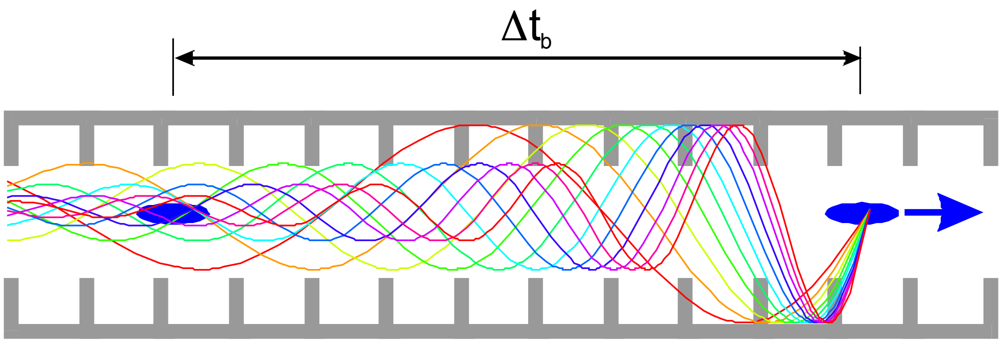
Japanese Site

Virtual reality tools

CLIC


326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m
326 klystrons
33 MW, 139 μs
drive beam accelerator
2.38 GeV, 1.0 GHz
1 km
delay loop
CR2
CR1
decelerator, 24 sectors of 876 m
BC2
BDS
2.75 km
BDS
2.75 km
BC2
245 m
TA r=120 m
e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km
IP
e⁺ main linac
245 m
TA radius = 120 m
48.3 km
CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump
booster linac, 6.14 GeV
BC1
e⁻ injector,
2.86 GeV
e⁻
PDR
398 m
e⁻
DR
493 m
e⁺
DR
493 m
e⁺
PDR
398 m
e⁺ injector,
2.86 GeV

CLIC Accelerating Structures



- CLIC acceleration travelling wave – too high Ohmic losses from standing wave
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities

- Effect depends on *a/λ* (*a* iris aperture) and structure design details
- Transverse wakefields roughly scale as $W_\perp \propto f^3$
- Long-range minimised by structure design

Current status

Luminosity

- Damping ring like an ambitious light source, no show stopper
- Alignment system principle demonstrated
- Stabilisation system developed, benchmarked, better system in pipeline
- Simulations on or close to the target

Conceptual design complete

Operation & Machine Protection	– Start-up sequence ergy operation defined
Implementation	– Consistent staged implementation scenario defined – Schedules, cost and power developed and presented – Site and CE studies documented

Design optimisation for 350 GeV machine input for next European Strategy

FCC Overview

FCC-hh hadron collider with 100TeV proton cms energy

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

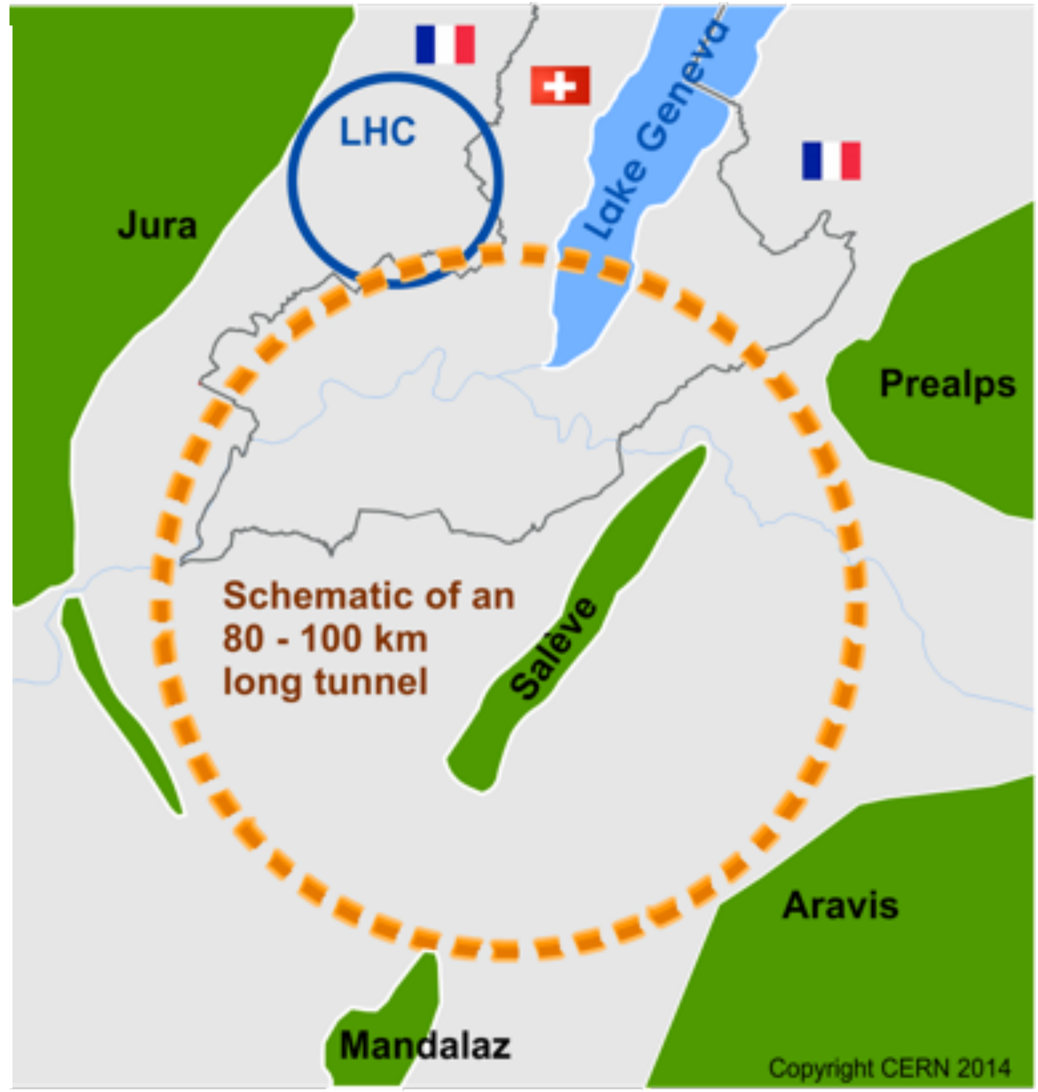
FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2019

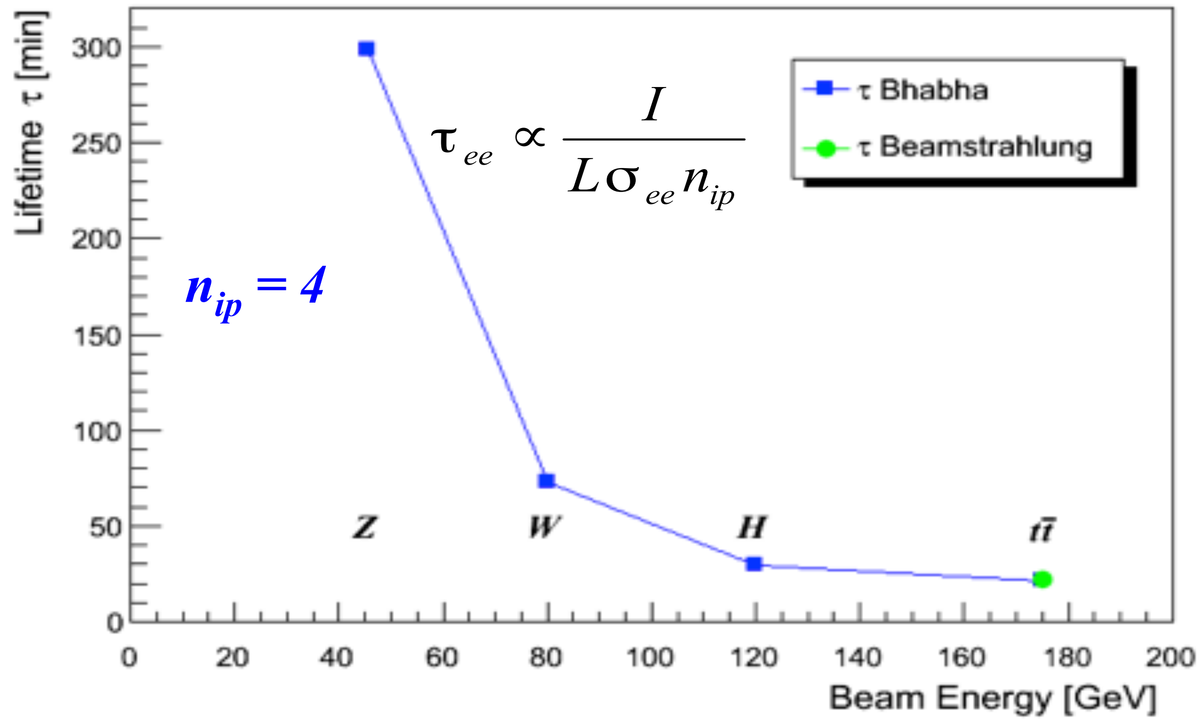


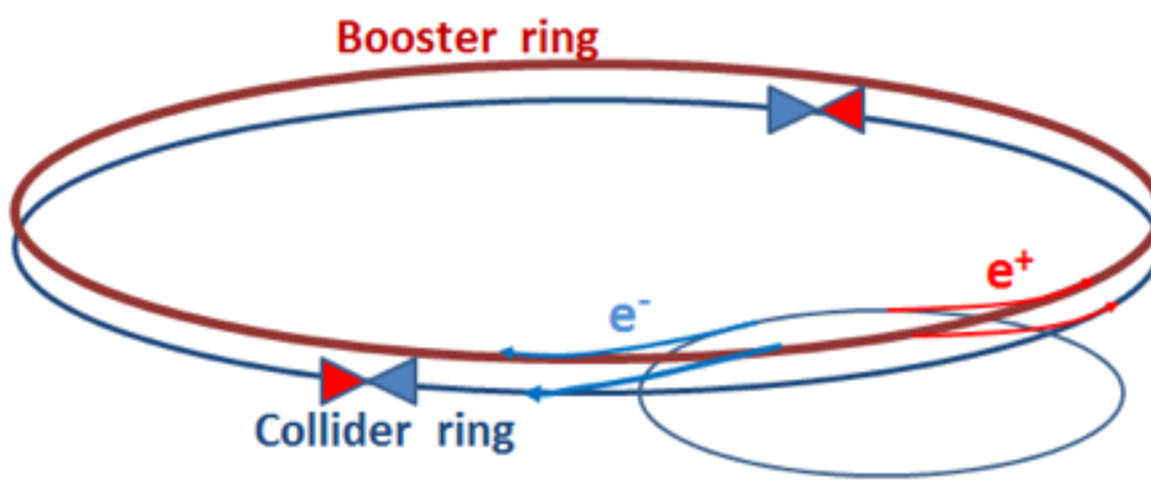
(FCC slides thanks to D.Schulte.)

FCC-ee Luminosity Lifetime

Large particle energy loss in IPs and limited energy acceptance (2%) cause limited lifetime

- Radiative Bhabha scattering is proportional to luminosity
- Beamstrahlung as in linear colliders
- Beam dynamics is very difficult because of large dynamic aperture requirement.





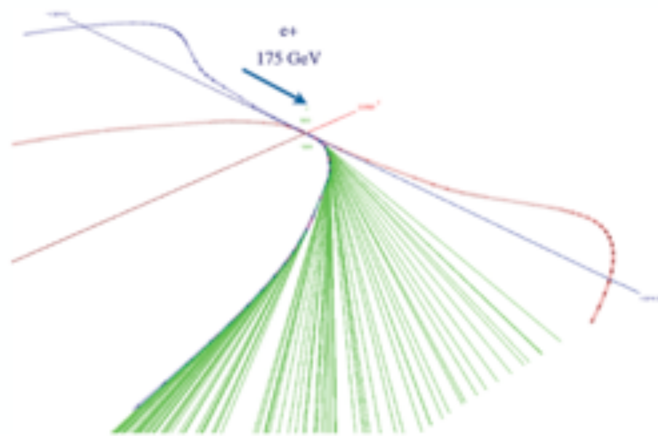
Need continuous injection (top-up)

FCC-ee Synchrotron Radiation

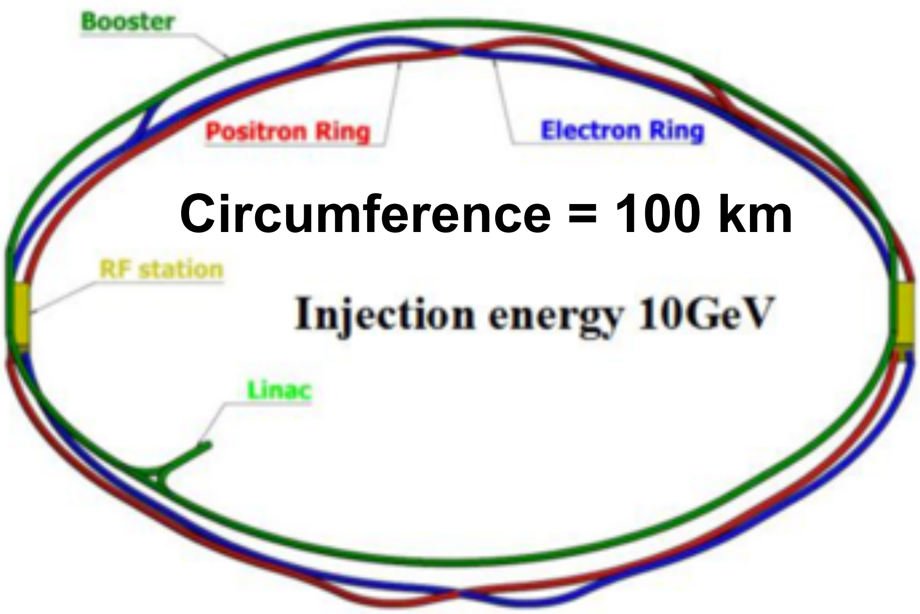
Property	Unit	FCC-ee (100 km)				CEPC (54 km)
Energy/beam	GeV	45.6	80	120	175	120
Energy loss / turn	GeV	0.03	0.33	1.67	7.55	3.11

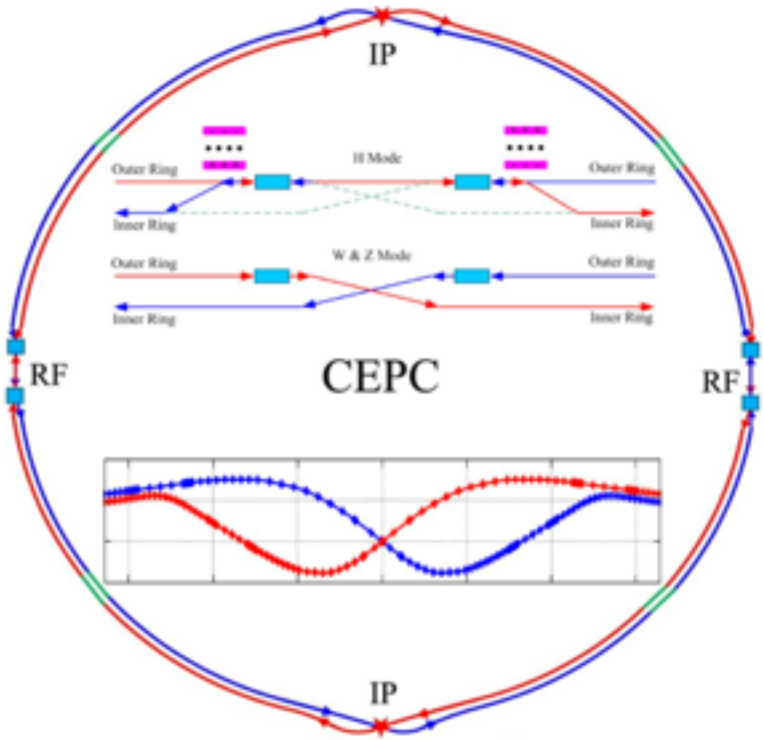
- Synchrotron radiation from bending high-energy electron beam on circular trajectory
  - Limit synchrotron radiation in interaction region by bending the beams as little as possible upstream to the IP → **"Asymmetric layout"**

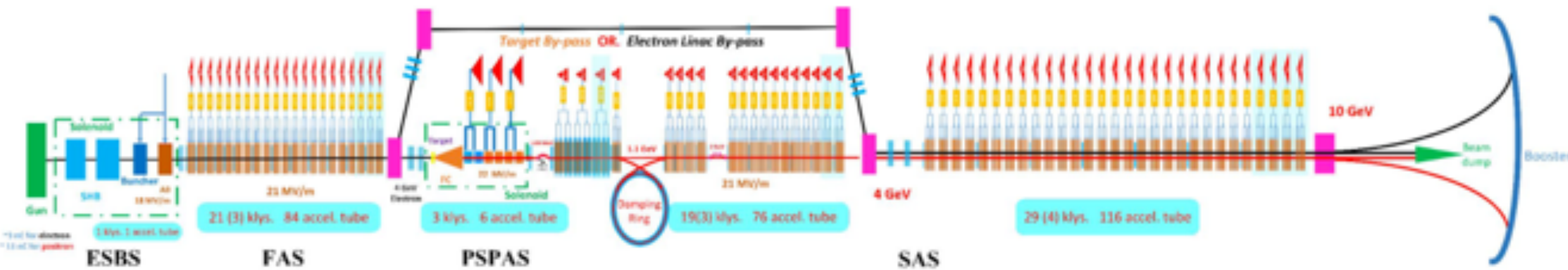
FCC-ee simualtions



CEPC & SppC Layout

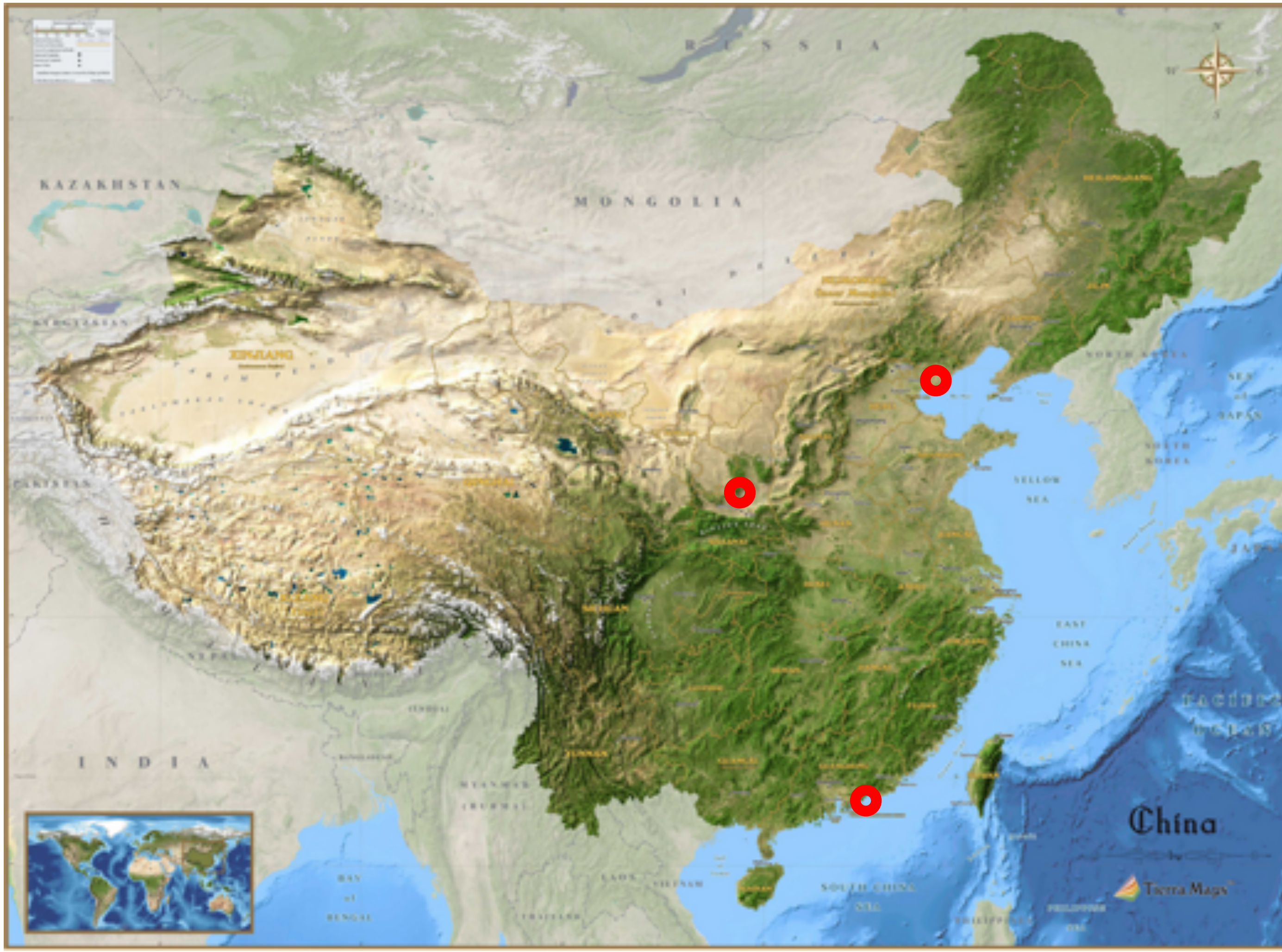






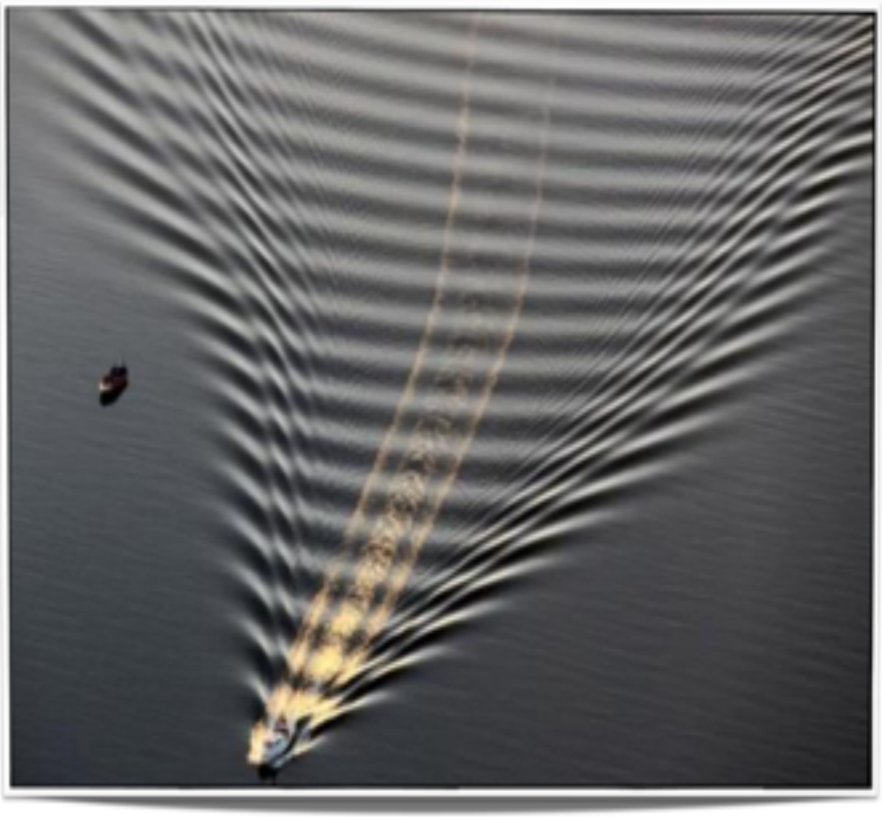
CEPC & SppC Site Selection

Funing,
Shen-Shan
and Huangling



Current Status – funding awarded in next 5-year plan for R&D – not as much as requested, but still significant. Further funding will be sought and work going ahead. CDR evaluated next month.

Plasma Wave Acceleration



Wake excitation

Particle injection

What is a plasma?

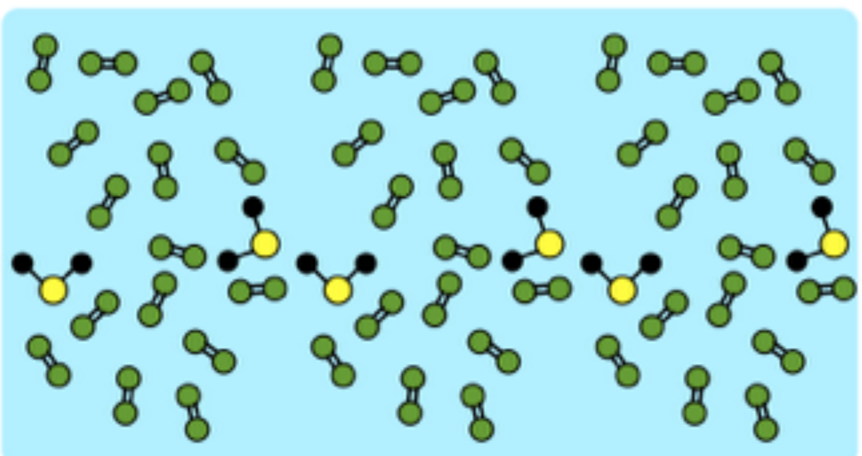
Gas:

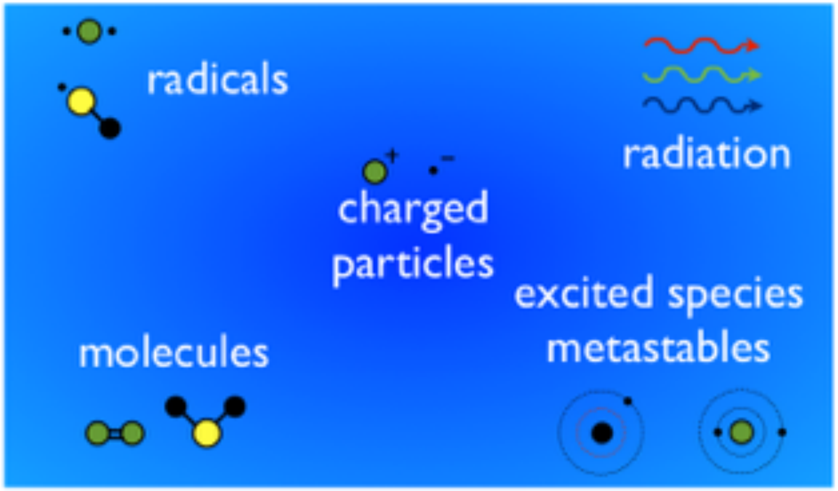
- Atoms, molecules
- No order
- no strong intermolecular forces

Energy →

Plasma:

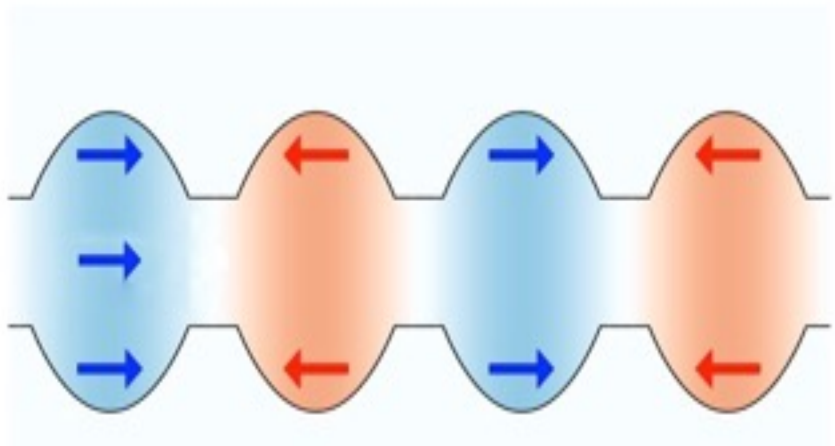
- Charged particles (electrons, ions)
- macroscopically quasi neutral
- Coulomb interaction
- particles show collective behaviour
- conductive



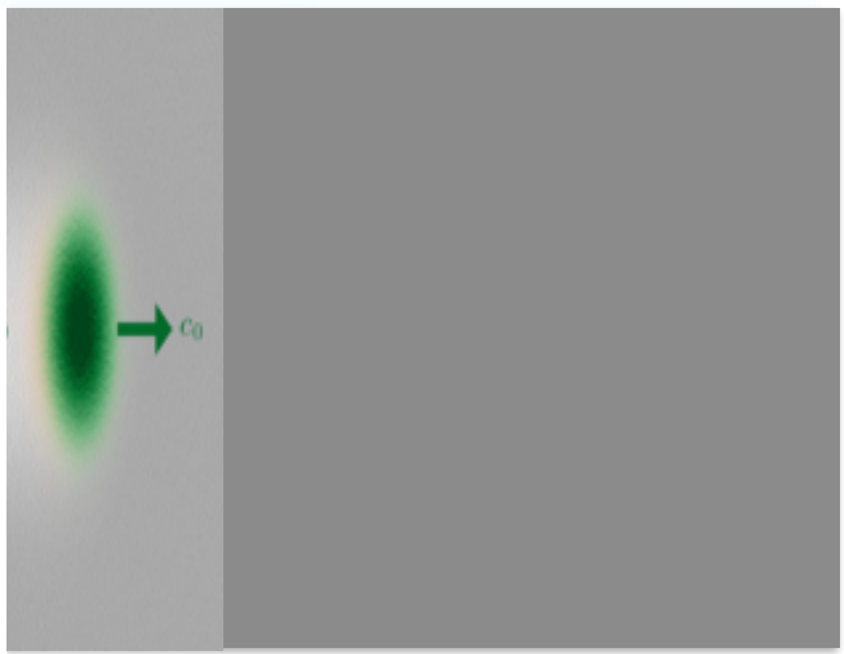


Cavities accelerate particles via EM standing waves

RF Cavity

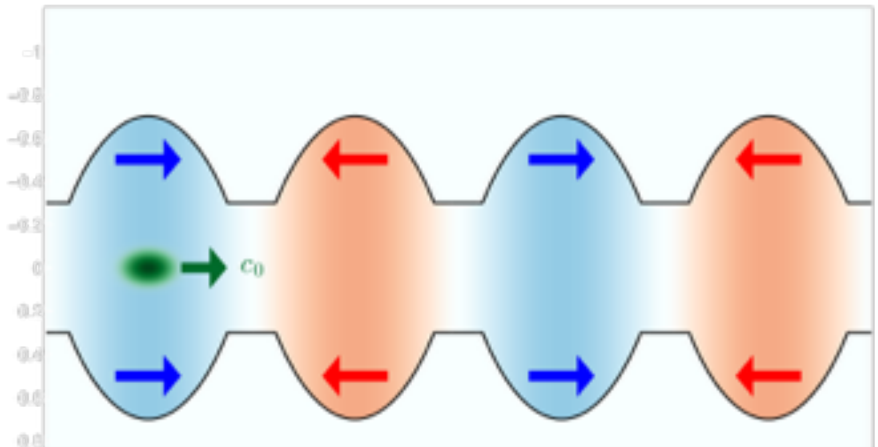


Plasma wakefield

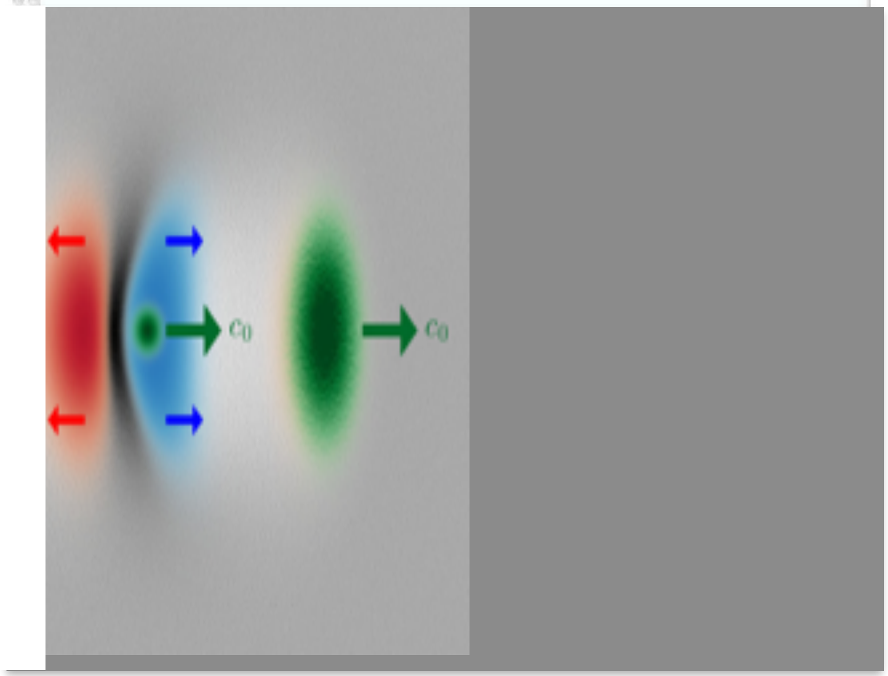


Cavities accelerate particles via EM standing waves

RF Cavity

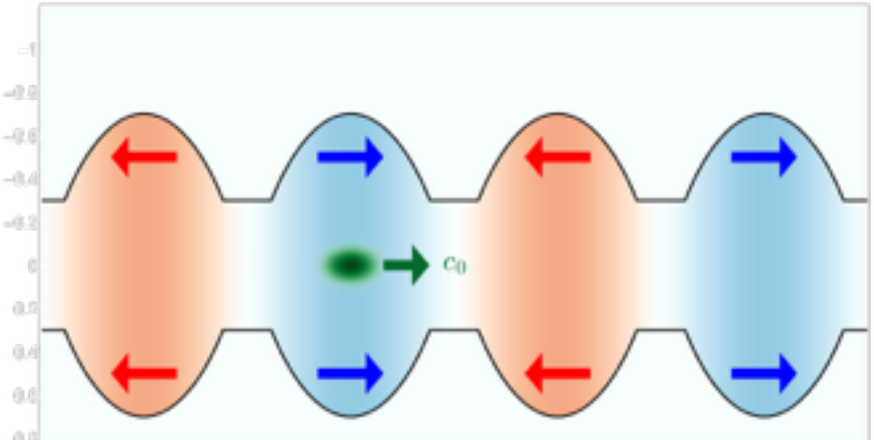


Plasma wakefield

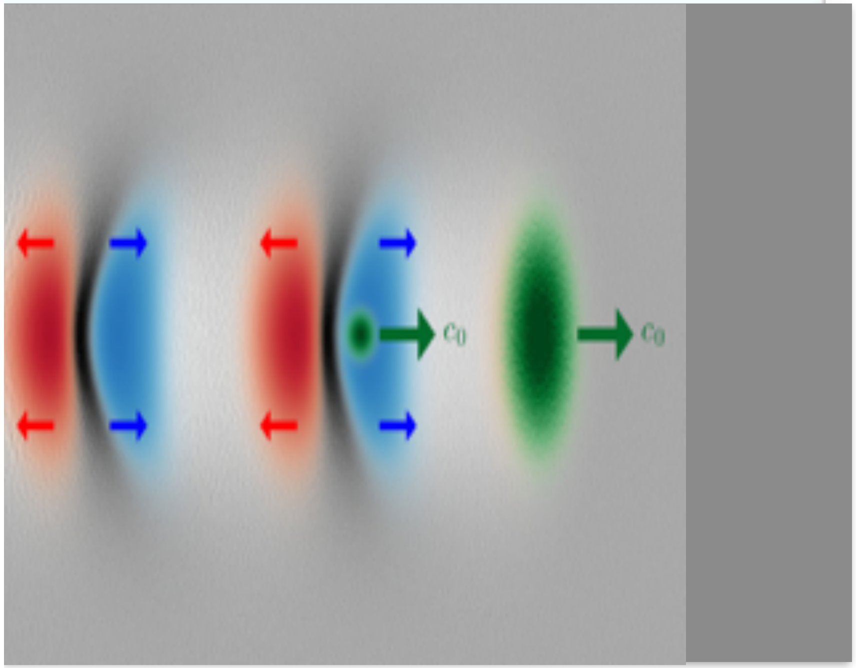


Cavities accelerate particles via EM standing waves

RF Cavity

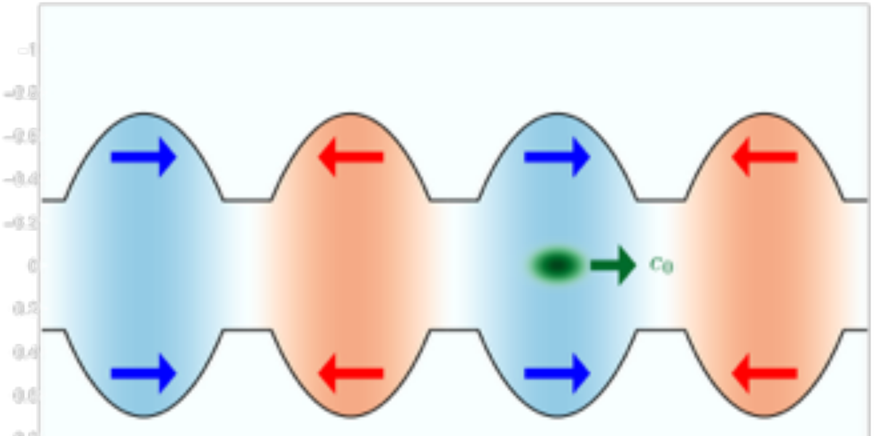


Plasma wakefield



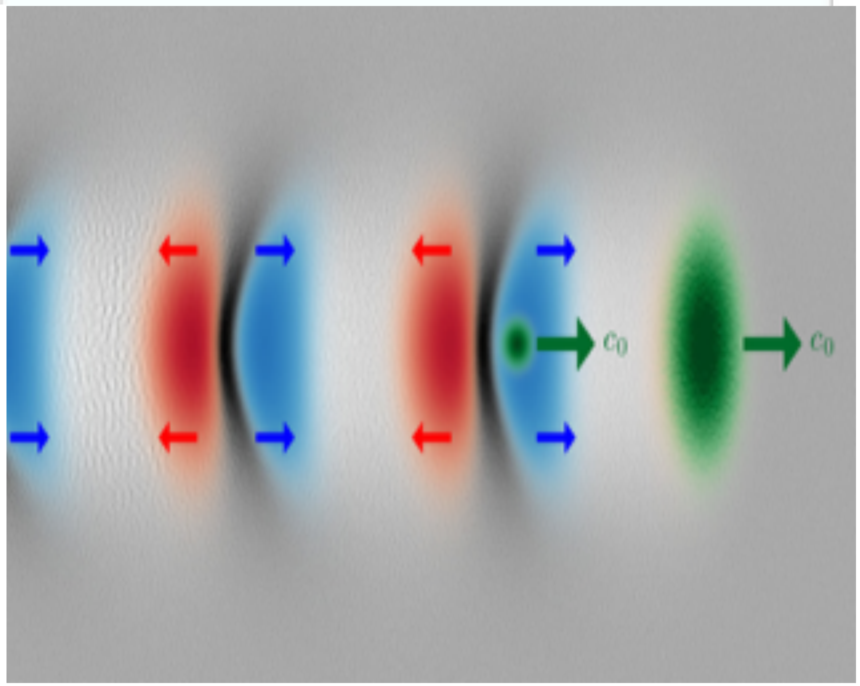
Cavities accelerate particles via EM standing waves

RF Cavity



20 – 40 MV/m

Plasma wakefield



10 – 1000 GV/m

Setting the scale

Plasma frequency depends only on density

$$\omega_p^2 = \frac{4\pi n_p e^2}{m}$$

$$k_p = \frac{\omega_p}{c}$$

$$\lambda_p = \frac{2\pi}{k_p} = 1mm\sqrt{\frac{1 \cdot 10^{15}\ \mathrm{cm}^{-3}}{n_p}}$$

LWFA & PWFA

- Two main methods of exciting a wake-field in a plasma
  a) Using a high-powered laser (LWFA)
  b) Using electric field from intense particle beam (PWFA)

- Each has advantages & disadvantages – for PWFA:

Advantages

> **Particle beams may be produced at high average power** (up to MWs) for high-luminosity applications
  - < 100 W average power of state-of-the-art TW to PW laser technology

> **Particle-beam production is efficient** (~10 % from the wall plug)
  - ≪ 1 % wall-plug efficiency for high-intensity lasers

> **Driver-beam stability** (≪ 1 %)
  - best high-power lasers fluctuate ~1% in intensity

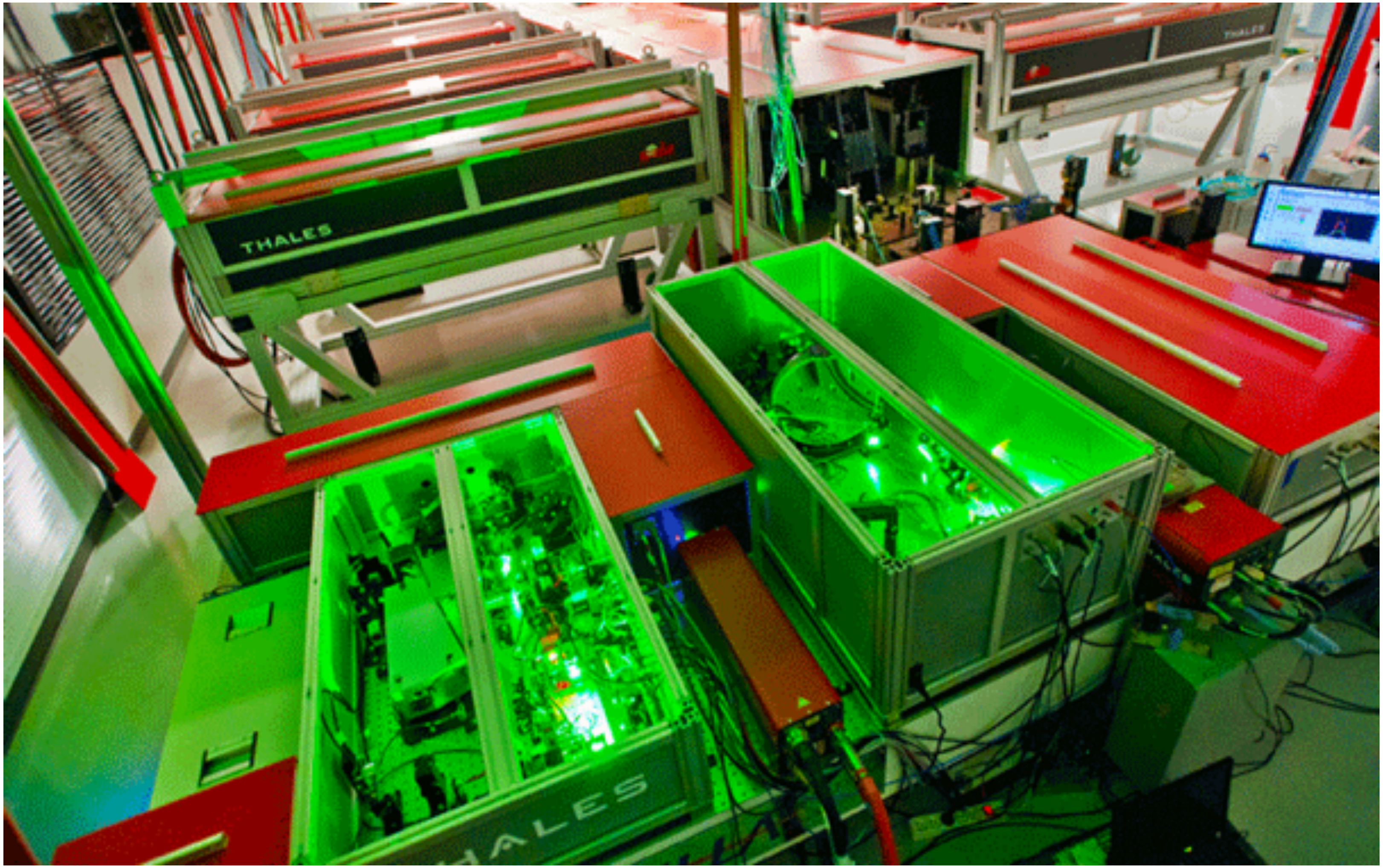
> **No dephasing** of plasma wakefield and electron beam
  - laser pulse velocity less than *c*, electrons outrun wake

> **Diffraction lengths longer than energy depletion scales** for beams of μm normalized emittance
  - diffraction length of laser pulse shorter than depletion distances → limits witness beam energy

Disadvantage

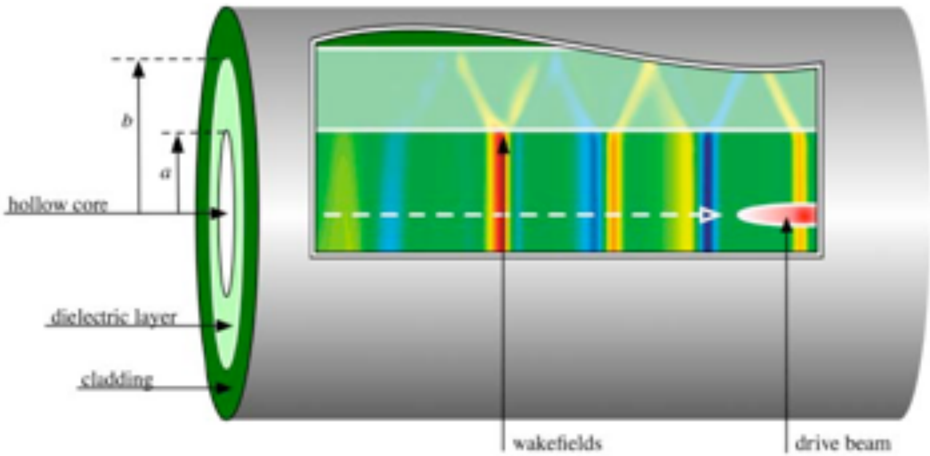
> Requires a large conventional accelerator

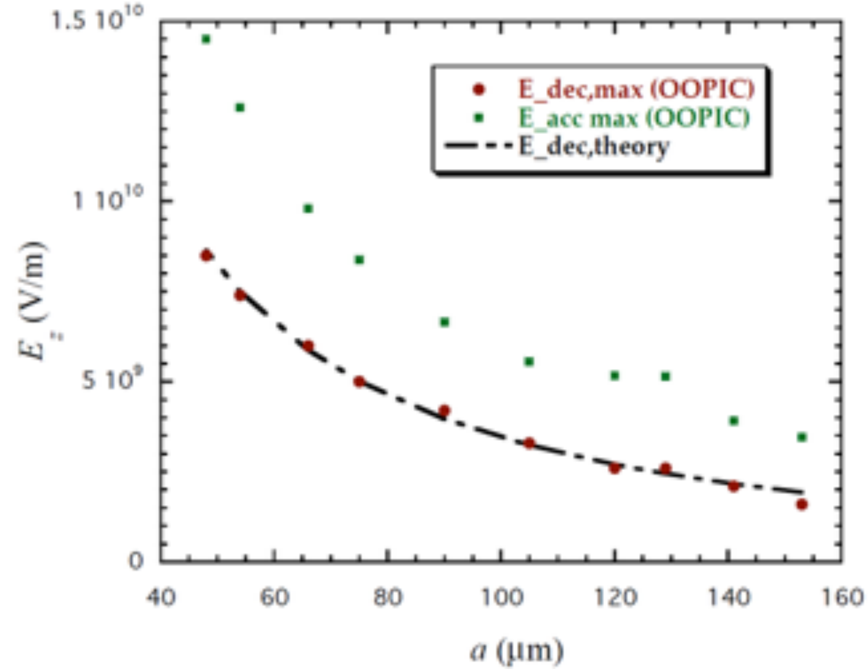
BELLA @ LBNL



Dielectric Wake Accelerators

Hollow ceramic tubes with metal outer jacket.

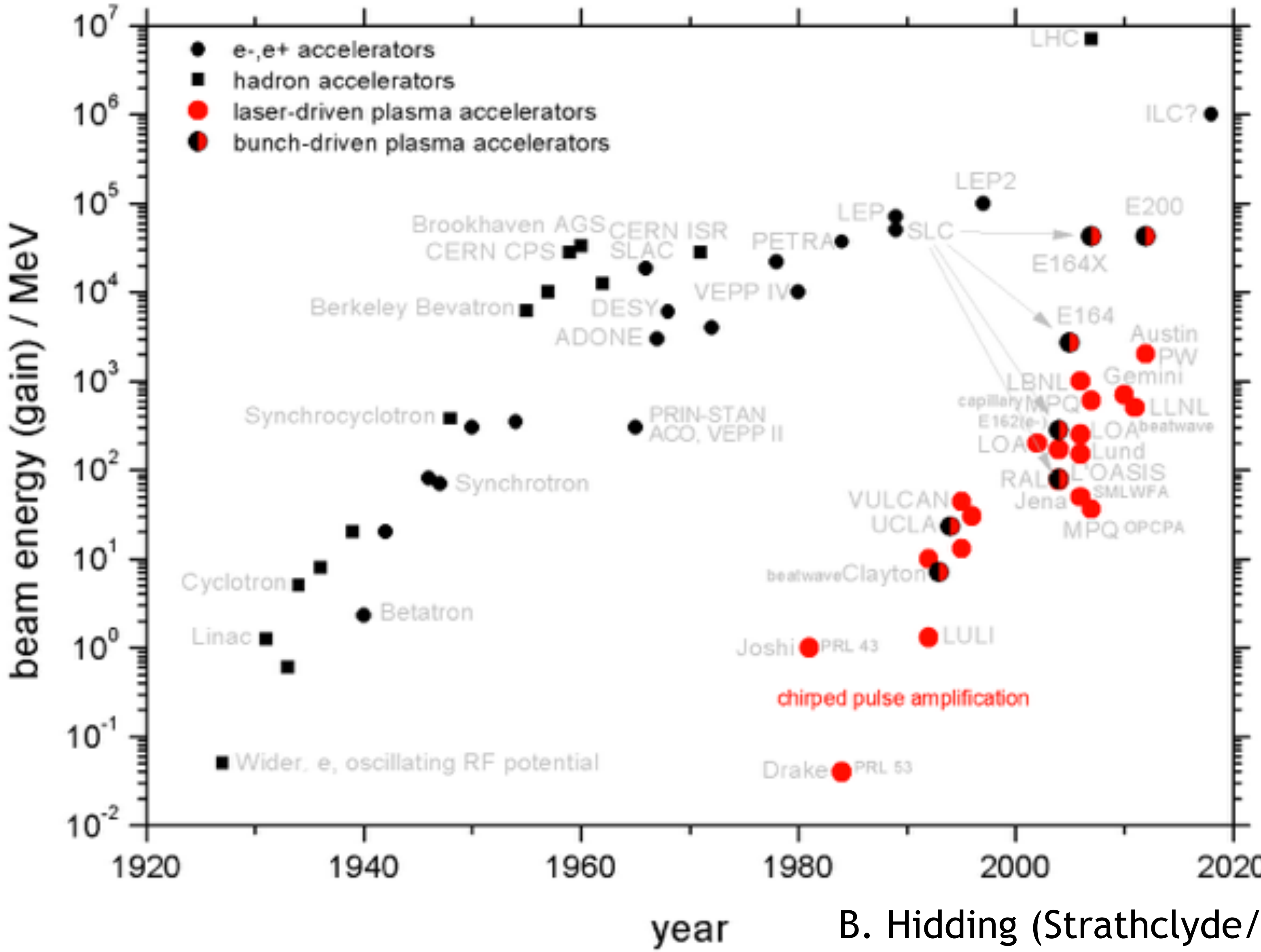




If a= 150 microns and b = 200 microns = 2.8 GeV/m
If a= 225 microns and b = 320= microns = 1.0 GeV/m

- I will concentrate on beam-driven facilities

The New Livingston Plot

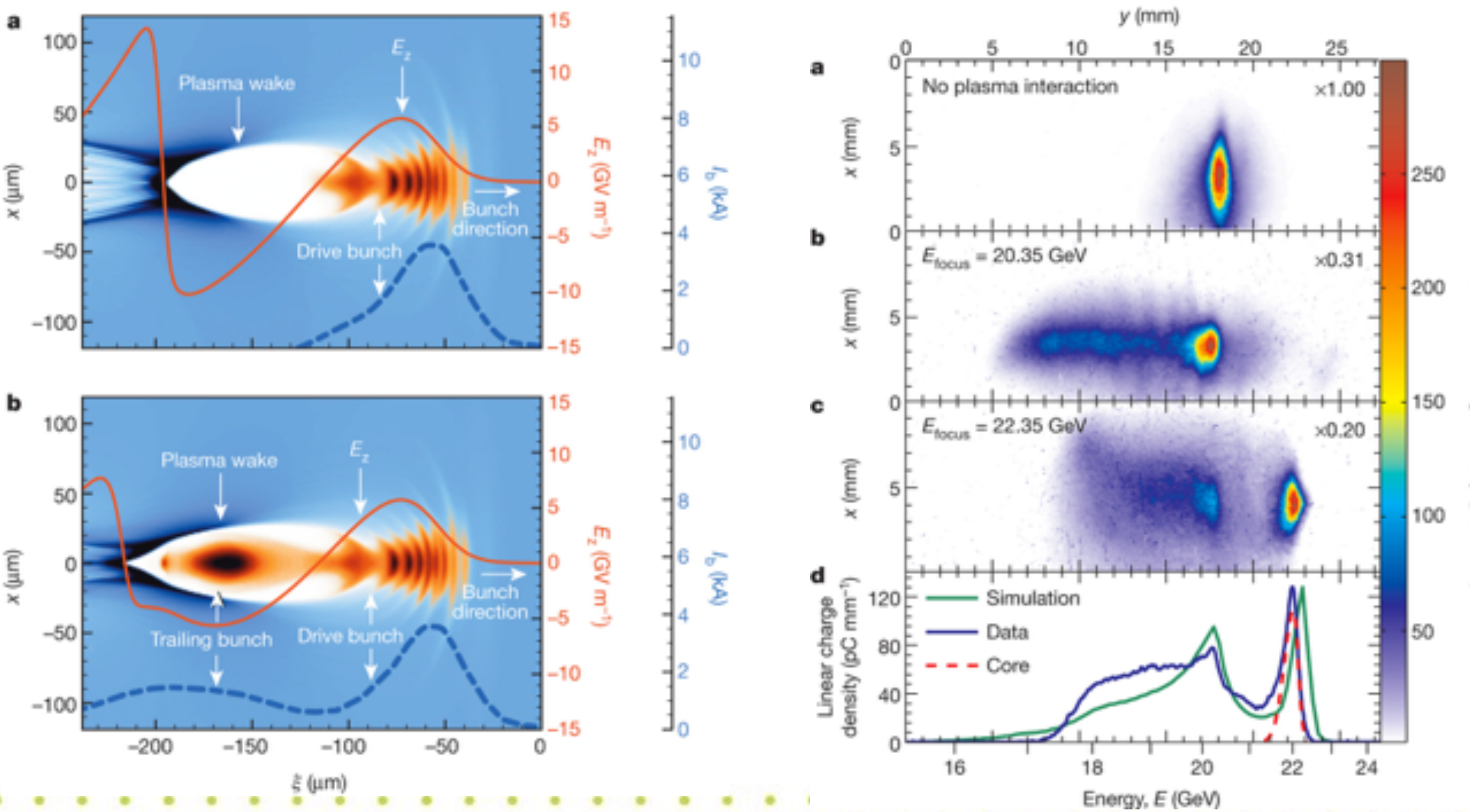


B. Hidding (Strathclyde/Hamburg)

Inject beam

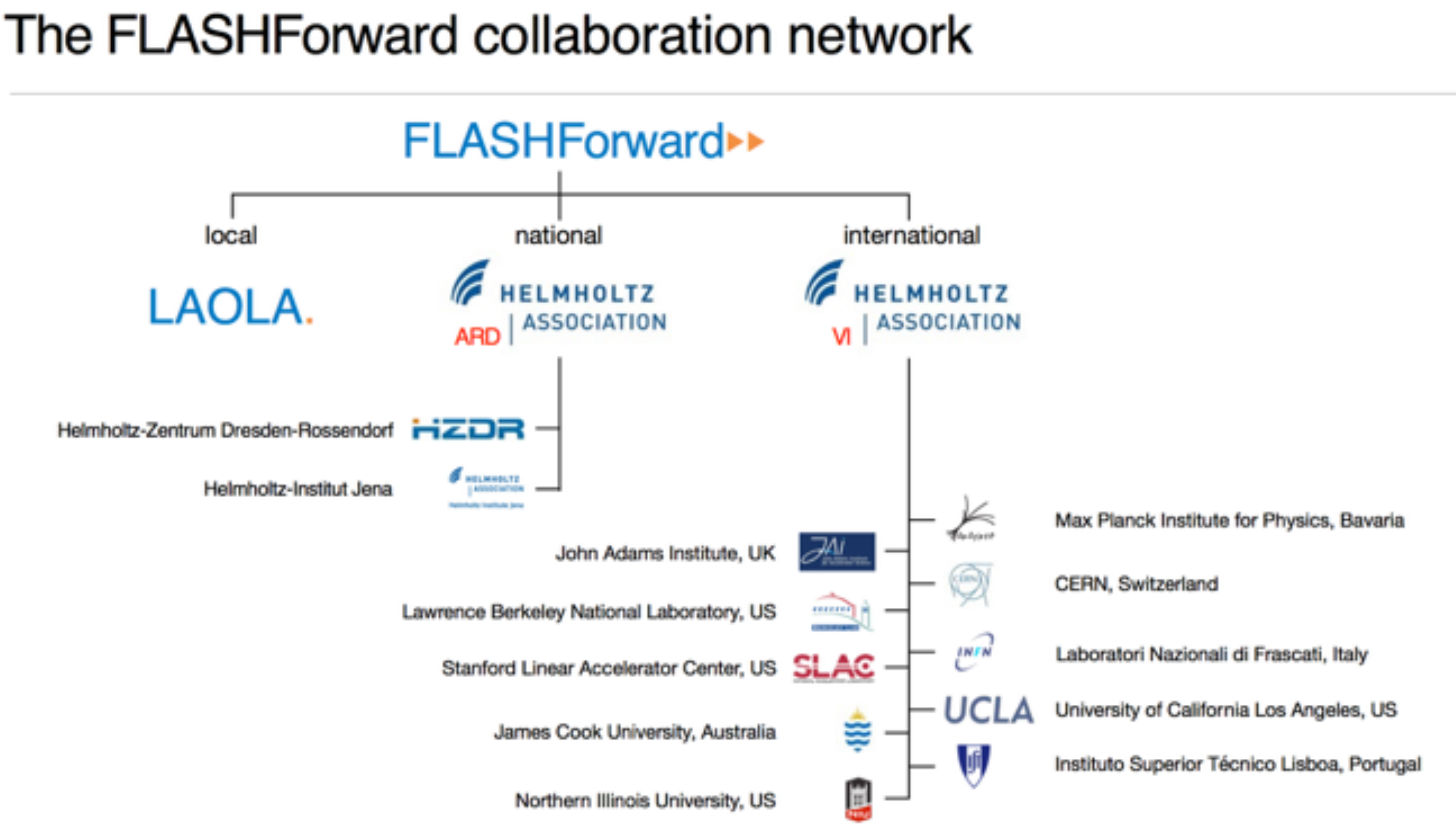
- **To understand acceleration in plasma, inject high-quality beam into plasma – requires excellent time and spatial precision.**

Litos et al., Nature 515, 92-95 (06.11.2014)



An example project - FLASHForward @ DESY

NB: All facilities I discuss are "pure research". Devices are still some way off – needs much activity at test facilities to find best way forward.

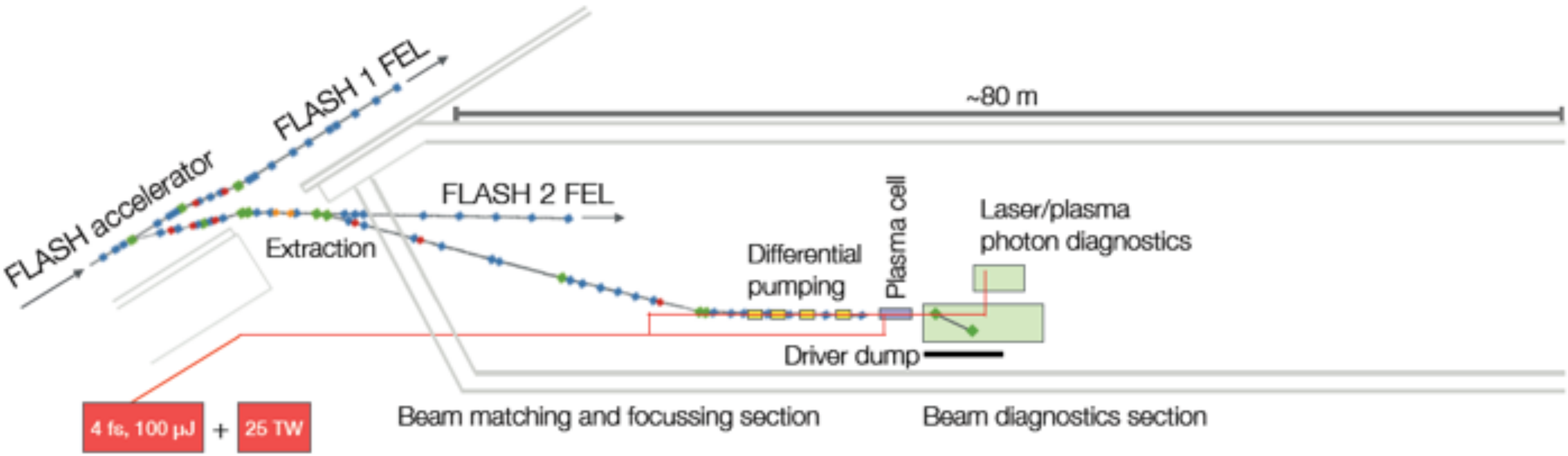


FLASHForward @ DESY

FLASHForward▸▸ beamline overview

Capabilities of the plasma-wake driver beam

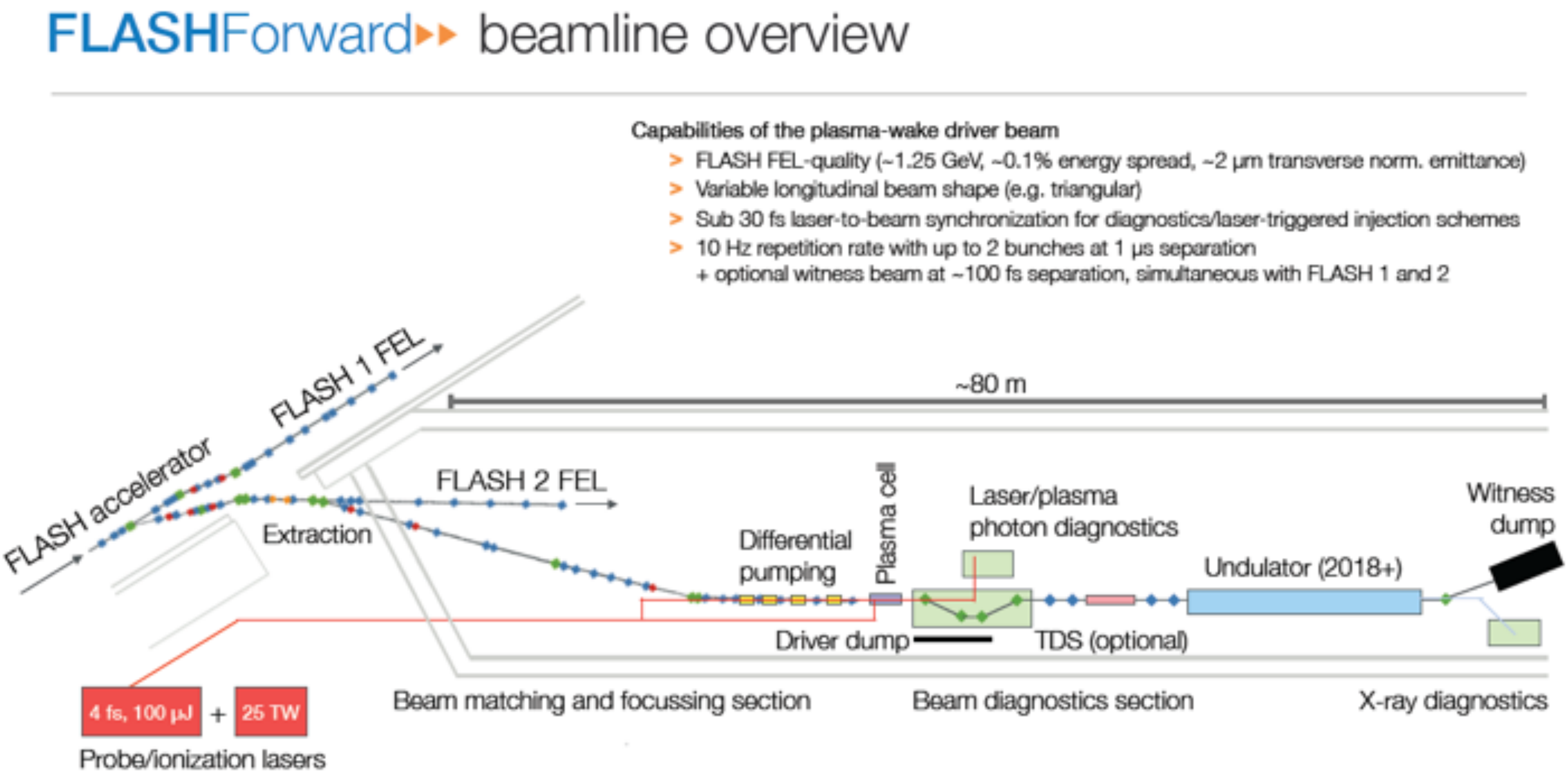
- FLASH FEL-quality (~1.25 GeV, ~0.1% energy spread, ~2 µm transverse norm. emittance)
- Variable longitudinal beam shape (e.g. triangular)
- Sub 30 fs laser-to-beam synchronization for diagnostics/laser-triggered injection schemes
- 10 Hz repetition rate with up to 2 bunches at 1 µs separation
  + optional witness beam at ~100 fs separation, simultaneous with FLASH 1 and 2



Phase I (2018-2020)

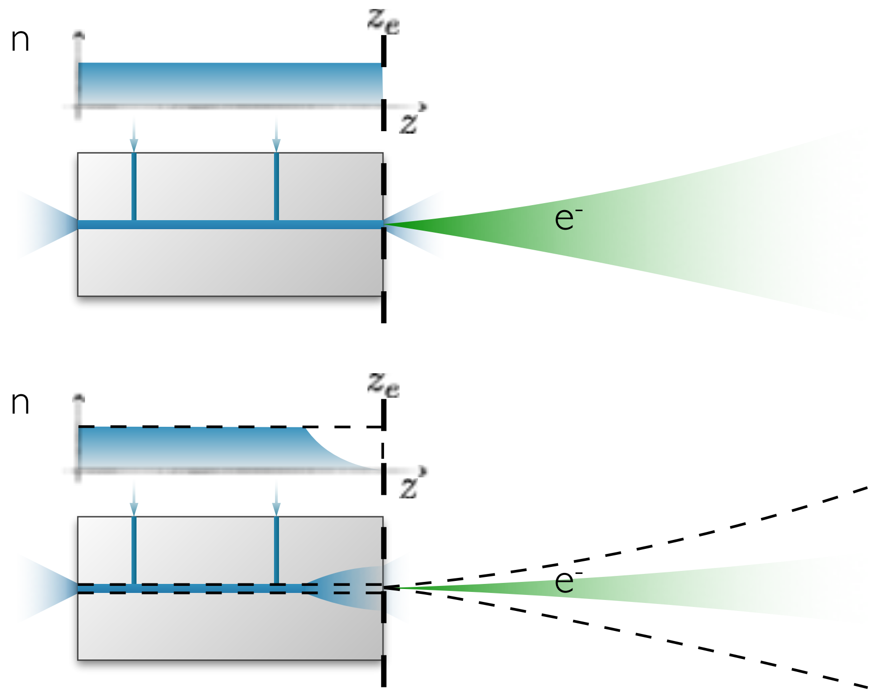
(see A. Aschikhin et al., NIM A806, 175-183 (2016))

FLASHForward @ DESY

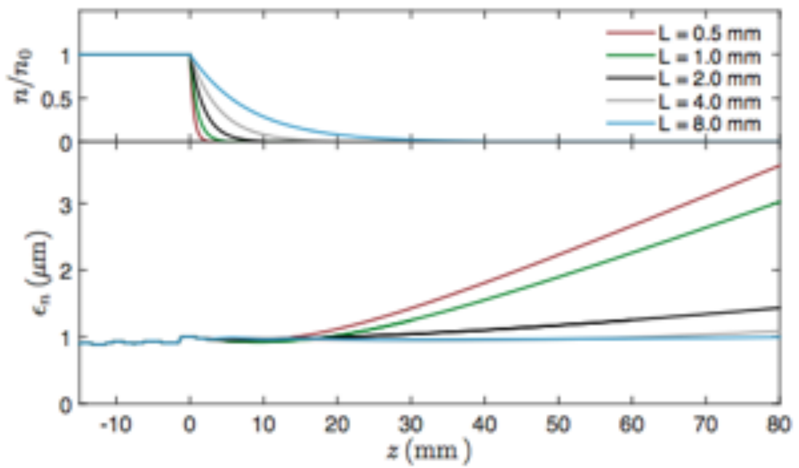


(see A. Aschikhin et al., NIM A806, 175-183 (2016))

Some concepts that can be tested:
Emittance preservation between accelerating stages using density gradients.



Emittance growth depending on transition length

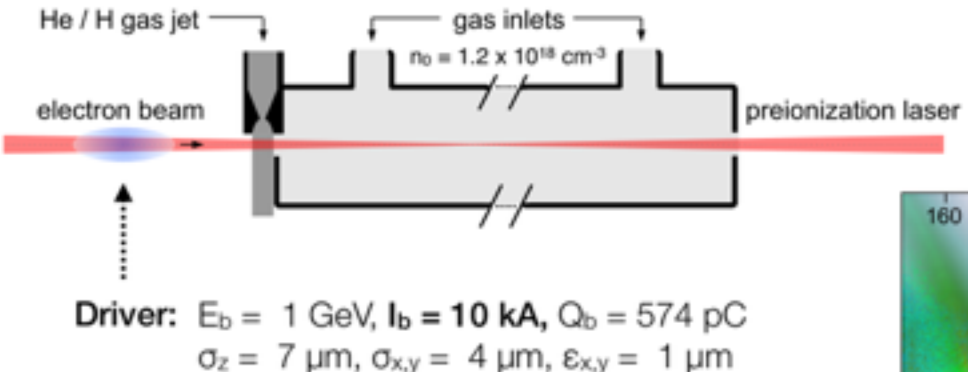


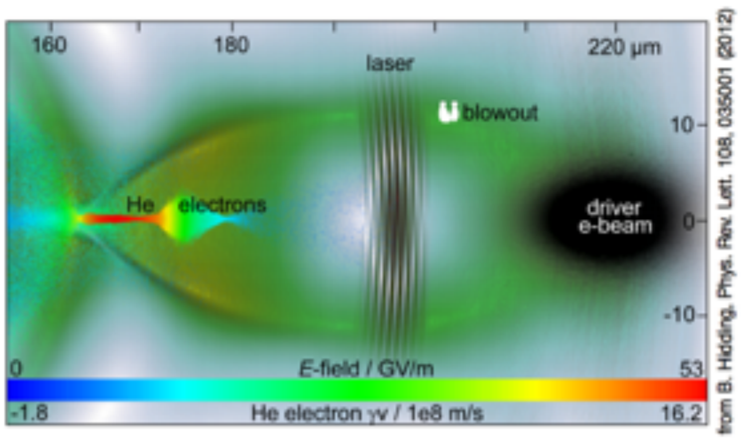
- Plasma-to-vacuum transition » beta for emittance preservation

- Concept, theory: T. Mehrling (DESY), to be published

FLASHForward @ DESY

Use laser to ionise dopant gas with higher ionisation potential than bulk plasma. Can give well controlled bunch of electrons to be accelerated by the wake-field.





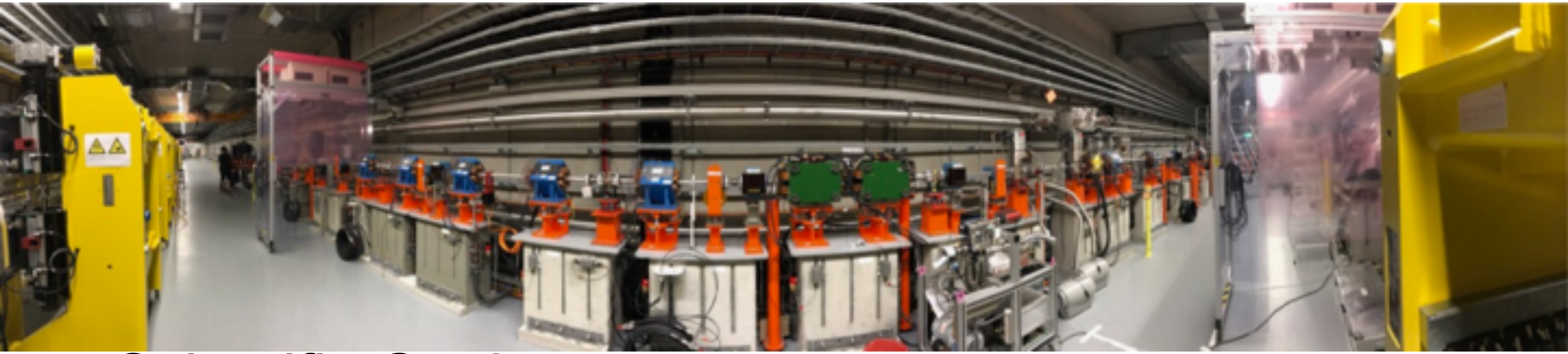
Laser triggers ionisation from He
Laser-to-beam synchronisation crucial
First tests recently at FACET@SLAC successful

FLASHForward @ DESY

- First magnets installed in beam line, June 2016.

FLASHForward @ DESY

- Beamline ~ complete, end 2017



- Scientific Goals

Phase I
> Characterization of **externally injected** electron beams and their release with energies **> 1.6 GeV**

> Exploration of novel **in-plasma whitnes-bunch generation** to energies **> 1.6 GeV**
> Also: < 100 nm transverse normalized emittance,
> ~1 fs duration and
> > 1 kA current electron bunches

> **Transformer ratios** of 2 and beyond yielding energies **> 4.0 GeV**

Phase II
> first demonstration of **FEL gain** with above beams at few nanometer wavelength-scale

Proton Drivers

- The problem with both LWFA and PWFA is energy conservation & the point-like nature of pp processes.
- Point-like pp processes have $\sigma \sim 1/s$. Large beam currents and therefore energy required for interesting pp applications..
- BUT PW laser like BELLA has typically 40J/pulse and wall-plug efficiency << 1%.
Electron PWFA facilities like FACET have 30J/bunch
- Accelerating 10^{10} (ILC bunch size) particles to 1 TeV needs a few kJ.
- SPS bunch has 20kJ/bunch; LHC has 300 kJ/bunch

(Thanks to A. Caldwell for following slides)

Proton Drivers

- So either multi-accelerating stages for LWFA/PWFA or use proton bunches.
- Staging difficult and not yet demonstrated. Also inefficiency of power transfer, particularly for LWFA makes such machines very power hungry.
- Problem with proton machines is that they typically have long bunch length – 10s of cm.
- Induced electric field goes like

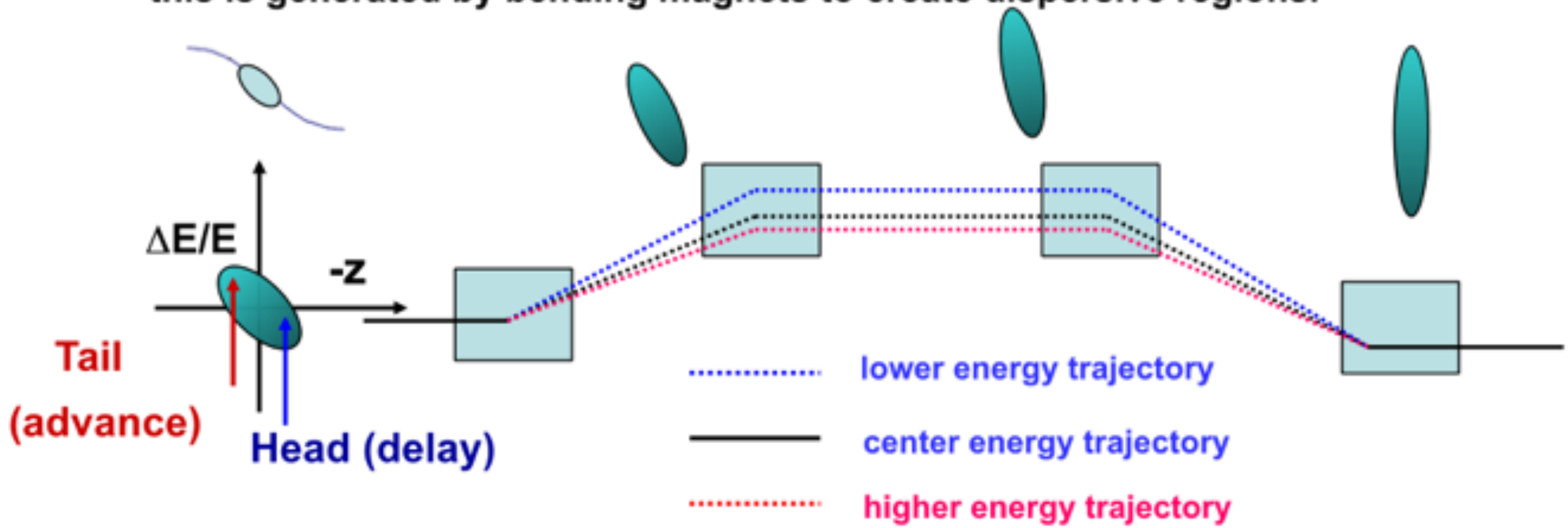
$$E_{z,\max} \approx 2\,\mathrm{GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right)^{1} \cdot \left(\frac{100\,\mu\mathrm{m}}{\sigma_z}\right)^{2}$$

Proton Drivers

- Bunch compression can be achieved:

(1) by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage

(2) and passing beam through a region where path length is energy dependent: this is generated by bending magnets to create dispersive regions.



❑ To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.

- But for 1 TeV beam takes 4.1 km!

Proton Drivers

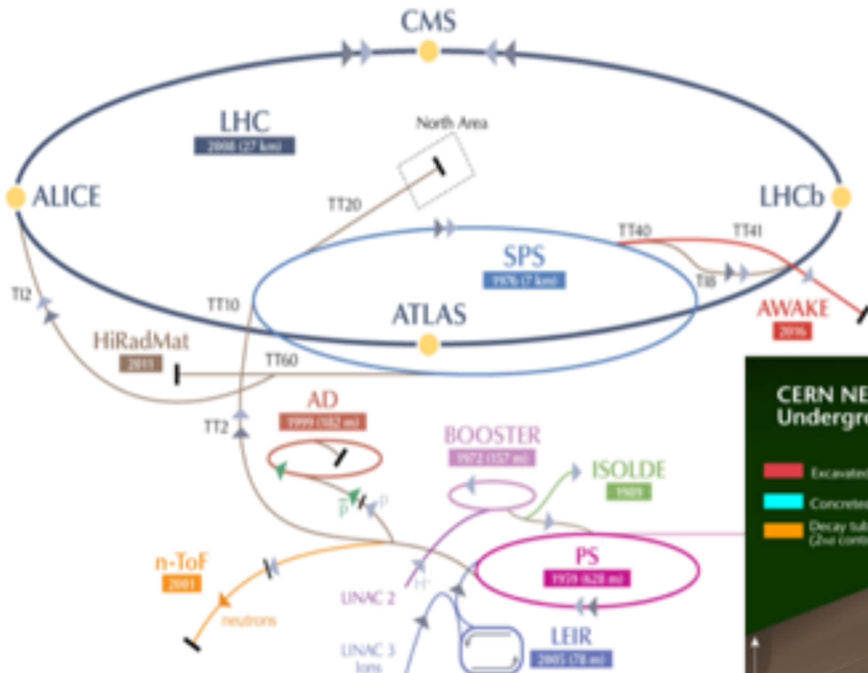
- Fortunately, for once, Nature is on our side: Passing a proton bunch through a plasma generates instabilities which causes the bunch to naturally form microbunches which have separation = plasma wavelength.

N. Kumar, A. Pukhov, and K. V. Lotov, Phys. Rev. Lett. **104**, 255003 (2010)

- This not only produces bunches of the right size but also produces a resonance effect in accelerating electrons. There are lots of subtleties that make life difficult, but it might just work….

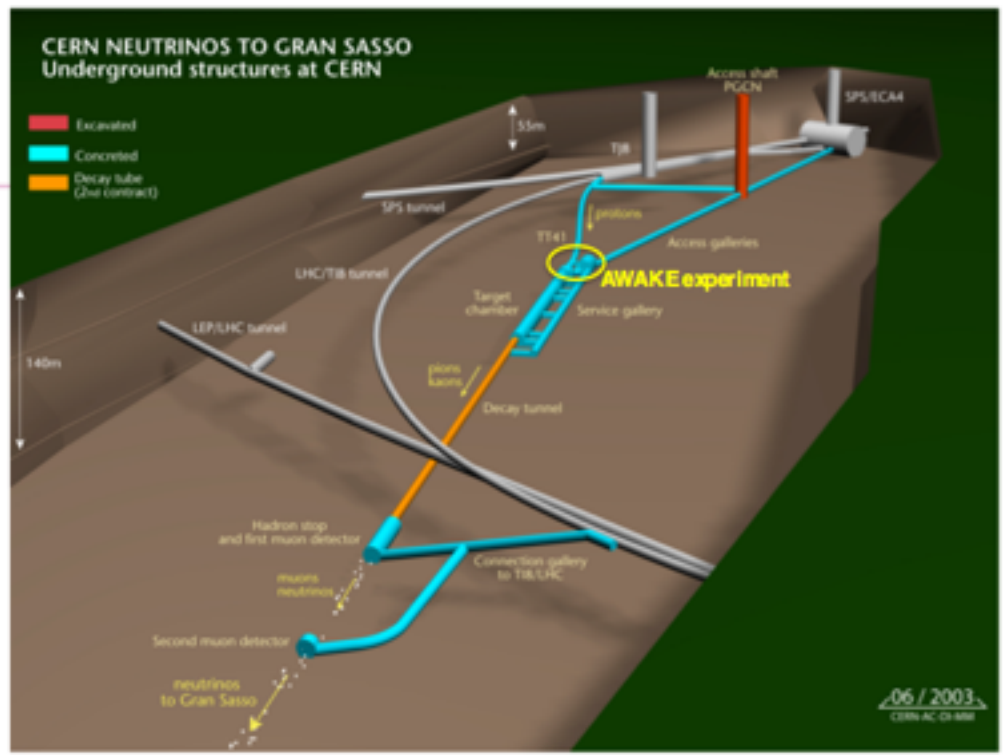
A. Caldwell, K. V. Lotov, Phys. Plasmas **18**, 13101 (2011)

AWAKE



AWAKE is installed in CNGS Facility (CERN Neutrinos to Gran Sasso)

✂ CNGS physics program finished in 2012



Proton-driven plasma wakefield acceleration: a path to the future of high-energy particle physics

R Assmann et al.,
Plasma Physics and Controlled Fusion
[Vol 56, Number 8]

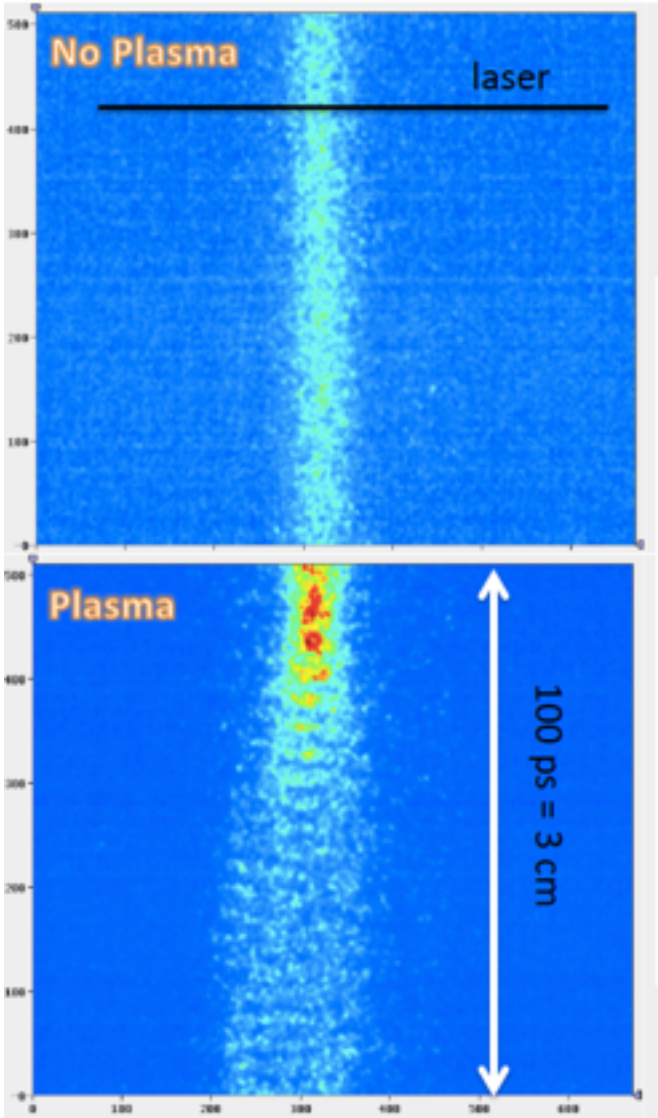
AWAKE

Plasma source 10m long, 4cm diameter
Density $10^{14} – 10^{15} cm^{-3}$

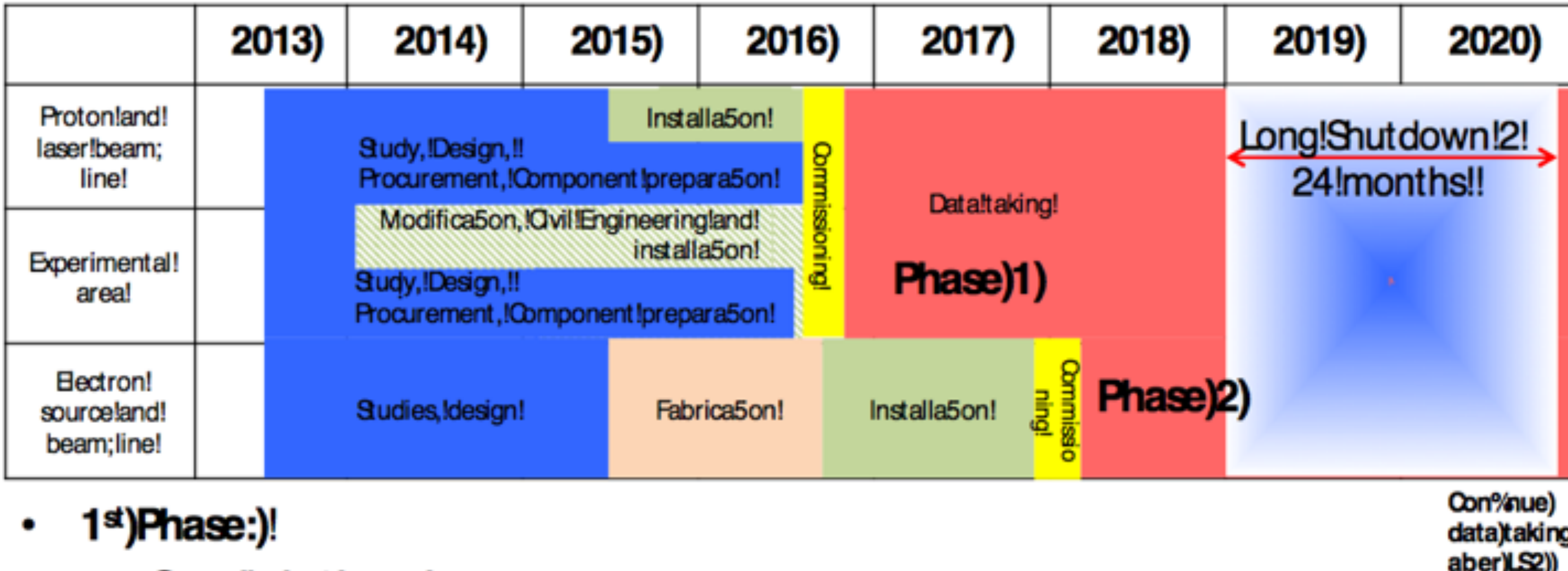
Results from Dec. 2016 run

Optical Transition Radiation from beam viewed with streak camera.

Clear observation of microbunching.



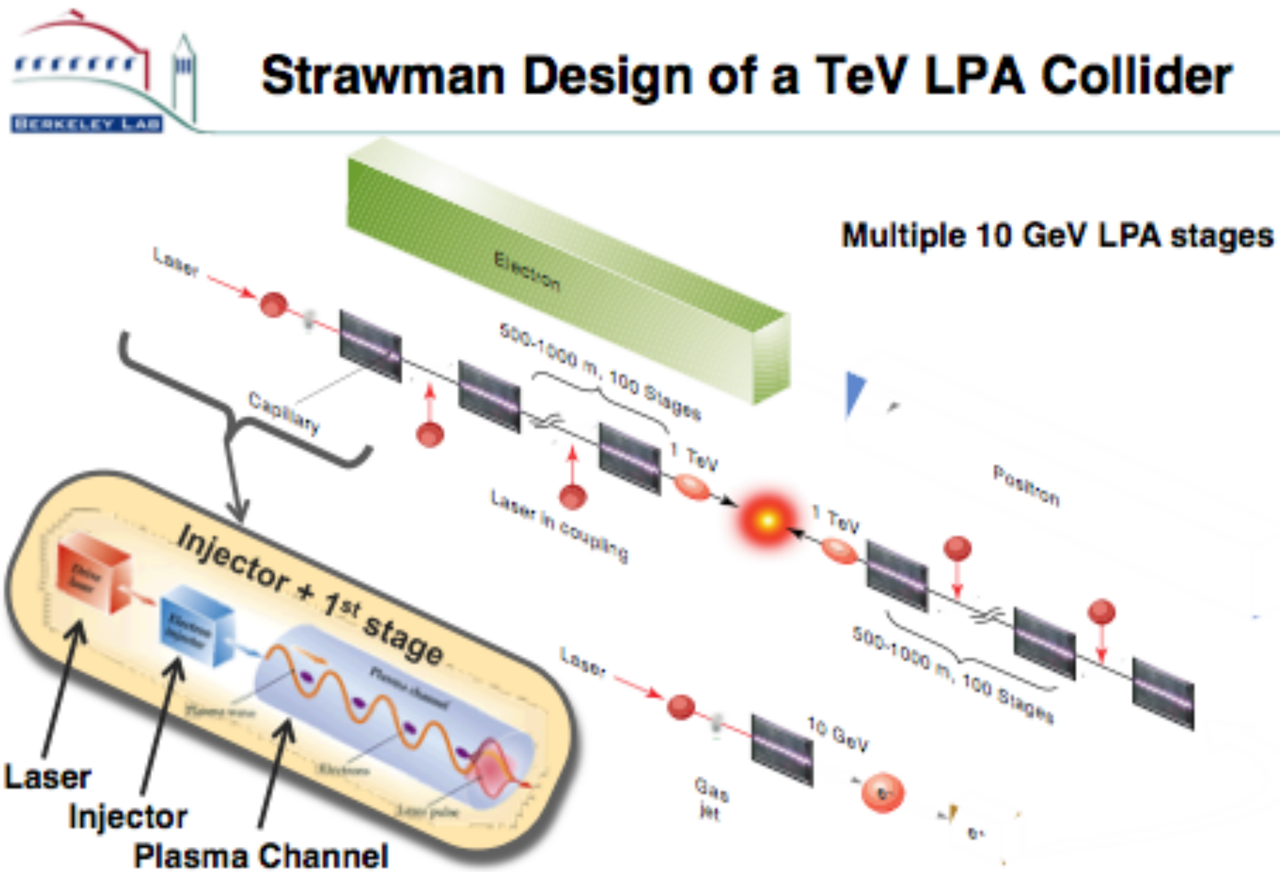
AWAKE Timeline



- 1st)Phase:)!
  - Start!in!~1!year!
  - Demonstrate!proton!bunch!modula5on!
- 2nd)Phase:)!
  - Start!in!~2!years!
  - Demonstrate!electron!accelera5on!with!GeV/m!scale!gradients!!

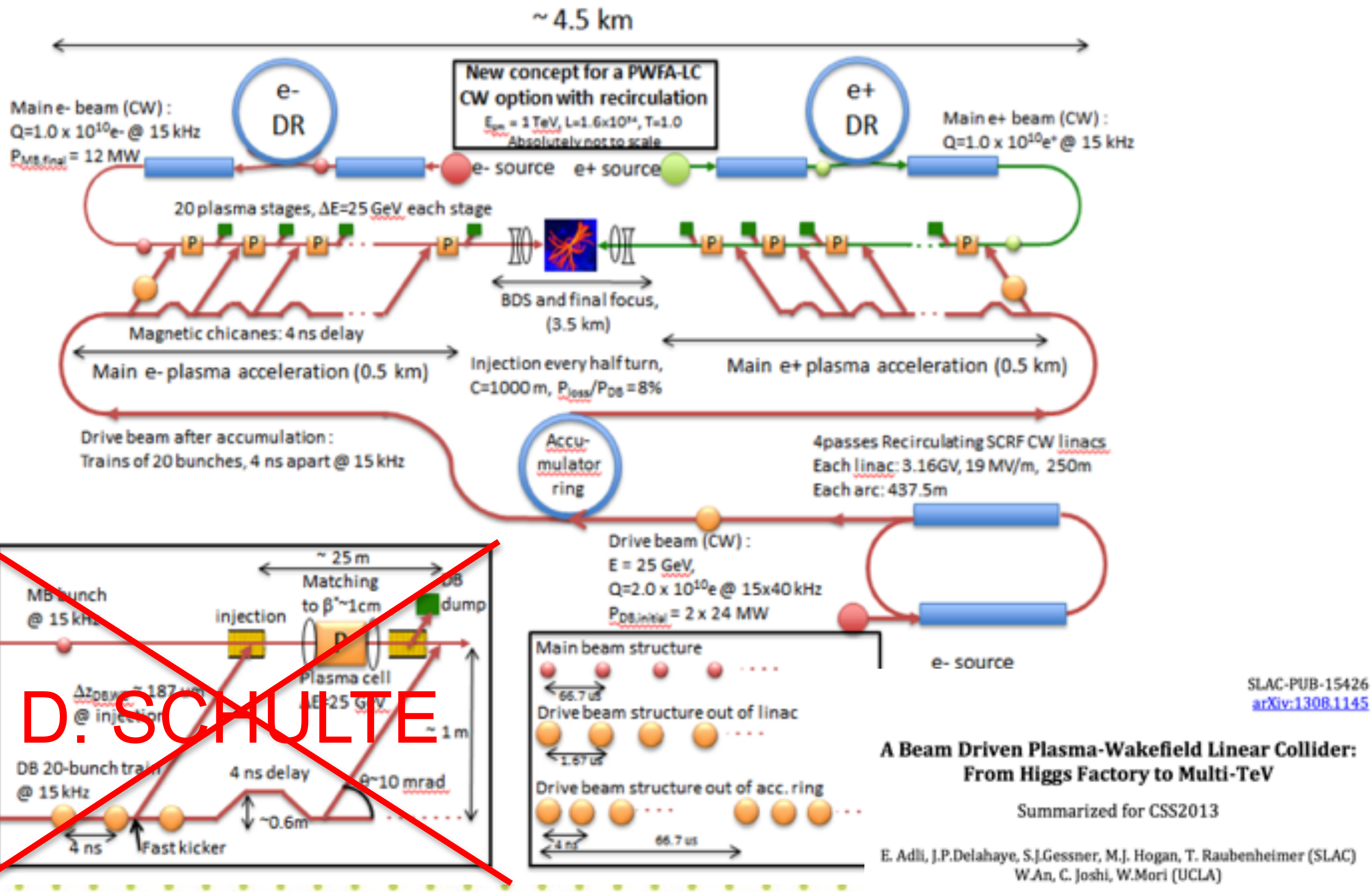
Realising the dreams?

- **A laser-plasma-driven linear collider?**



Leemans & Esarey, Physics Today, March 2009

Beam-driven PWFA LC?



Future Applications in Particle Physics

Advanced LinEar collider study GROup Workshop 2018

Inaugurated by ANA, Advanced and Novel Accelerator Panel, an ICFA subpanel, chaired by Brigitte Cros.

Second Alegro workshop held in Oxford, 26-29/3/18

Future Applications in Particle Physics

ALEGRO 2018

Working Groups

• Physics Case (PC); WG1 coordinators: Michael Peskin (SLAC), Junping Tian (U. Tokyo), TBD ()
• Collider machine design/definitions (CMD) ; WG2 coordinators: Daniel Schulte (CERN),
Andrei Seryi (JAI), Hitoshi Yamamoto (Tohoku Uni)
• Theory, Modelling, Simulations (TMS); WG3 coordinators: Jean-Luc Vay (LBNL), Jorge Vieira (IST), Henri Vincenti (CEA)
• LWFA; WG4 coordinators: Carl Schroeder (LBNL), Simon Hooker (JAI/Oxford), Brigitte Cros (CNRS/Univ Paris Sud)
• PWFA; WG5 coordinators: Jens Osterhoff (DESY), Edda Gschwendtner (CERN), Patric Muggli (MPP) • SWFA; WG6 coordinators: Philippe Piot (NIU), John Power (ANL)
• DLA; WG7 coordinators: Joel England (SLAC), Ben Cowan (Tech-X)
• Joint sub-WG on positron acceleration (PAC); WG8 coordinators: Sebastien Corde (LOA),

ALEGRO 2018

M. Peskin – Physics Case

When we think about advanced linear accelerators, we could be thinking about even more ambitious discovery goals:

Imagine a 5 GeV/m effective gradient after staging.

This is SLAC in 10 m
- but a collider still requires a multi-km beam delivery region and final focus, 100 m detectors

So, better to imagine 10 km of accelerating structure.

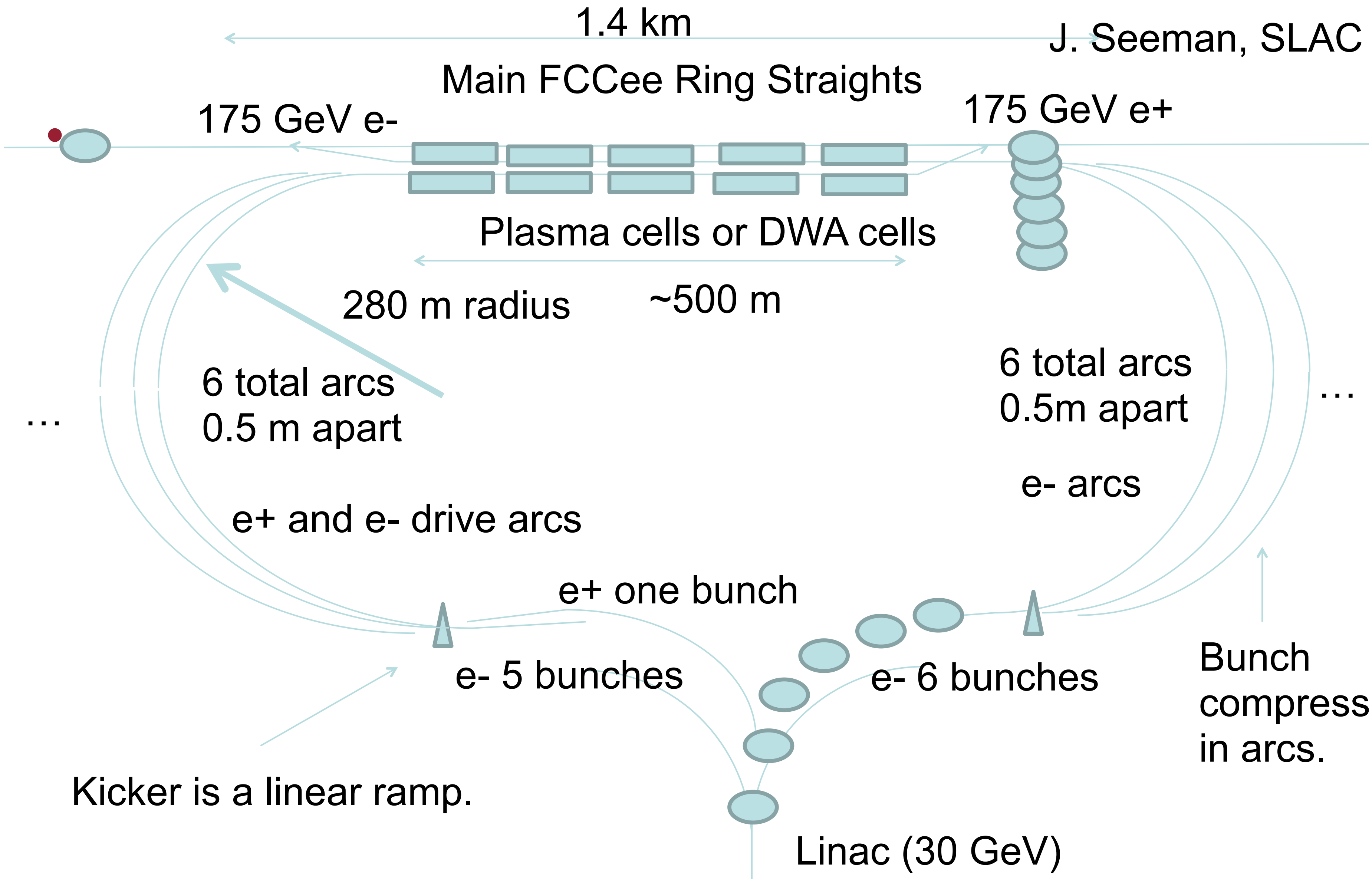
This is a 50 TeV e+e- or γγ collider .

illustrative case of a vectorlike heavy lepton ($I^3 = Y = \frac{1}{2}$)

$$= 10^5 \text{ events/yr}/10^{35}/(E_{\rm CM}\ (\text{TeV}))^2$$

=> We need 50 TeV collider with L = 10^{36}

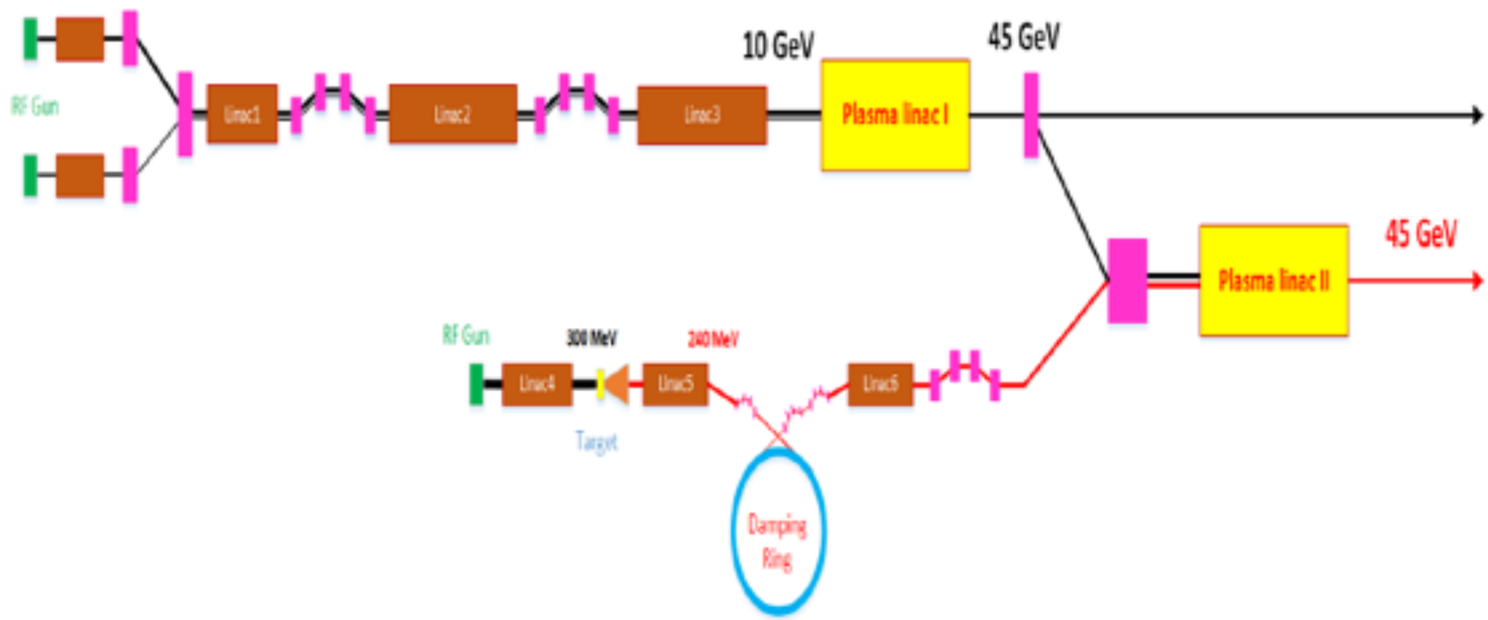
PWFA Applications for CEPC



PWFA Applications for CEPC

Wei Lu
Tsinghua University

Can also boost energy in linac or replace (part of) the linac



By Cai Meng et al.

Political Situation

ILC:

- Apparent realisation by Japanese government that e.g. CERN strategy process requires a "decision" from them before end 2018;
- MEXT seem to be engaged and are sending reps. on Diet Delegations to Europe, USA. Visits to France, Germany already and seen as positive – visits to UK, Italy, Spain under discussion on timescale of summer;
- Strong local support from Iwate and neighbouring provinces;
- "Final" report from Science Council of Japan in ~ summer

BUT – Abe government seems to be in substantial local difficulties at moment;

AND – even a positive response – and what does one look like? – is only the start of a LONG process.

Political Situation

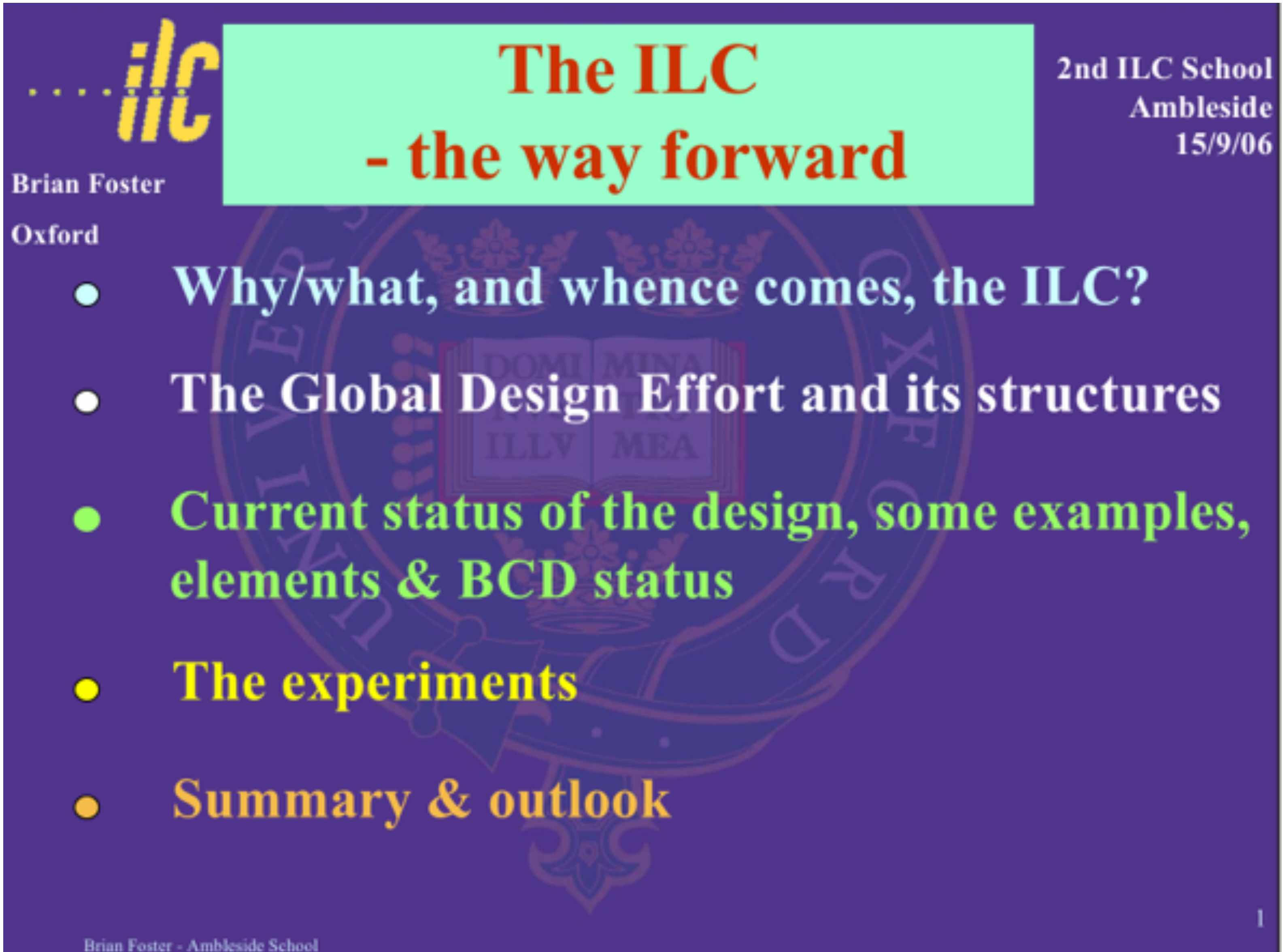
FCC/CLIC/HELHC:

- Everything to play for in Strategy process
- For FCC, the cost will be the crucial factor
- CLIC cost is ~ known, and could ~ fit inside CERN budget, but one detects little enthusiasm for CLIC at CERN;
- HELHC (and of course FCC) depends on development of very challenging and expensive SC magnets

CEPC/SppC:

- CEPC costs ~ $10B – my guess – much smaller than some of the projects, even in science, they are undertaking.
- How does one get approval?
- If approved, substantial experts from rest of world would be required – as well as financial contributions. If forthcoming, it could be done “quickly”.

A Blast from the Past



Site-specific work plan