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Future Accelerator Facilities

for Particle Physics

Brian Foster (Uni Hamburg/DESY/Oxford)

Natal School October 2014

Outline

- ~~Lecture 1: Introduction to accelerators~~
  - ~~Historical development & status including LHC & upgrades~~
- Lecture 2: Overview of ideas for future facilities
  - **Hadron-hadron machines – LHC (& beyond)**
  - **Lepton-lepton Machines**
    - e^+e^- - linear, circular; $\mu^+\mu^-$
  - **Lepton-hadron machines**
  - **Plasma-wave acceleration**
- Lecture 3: The future in depth – the ILC Project – status & prospects

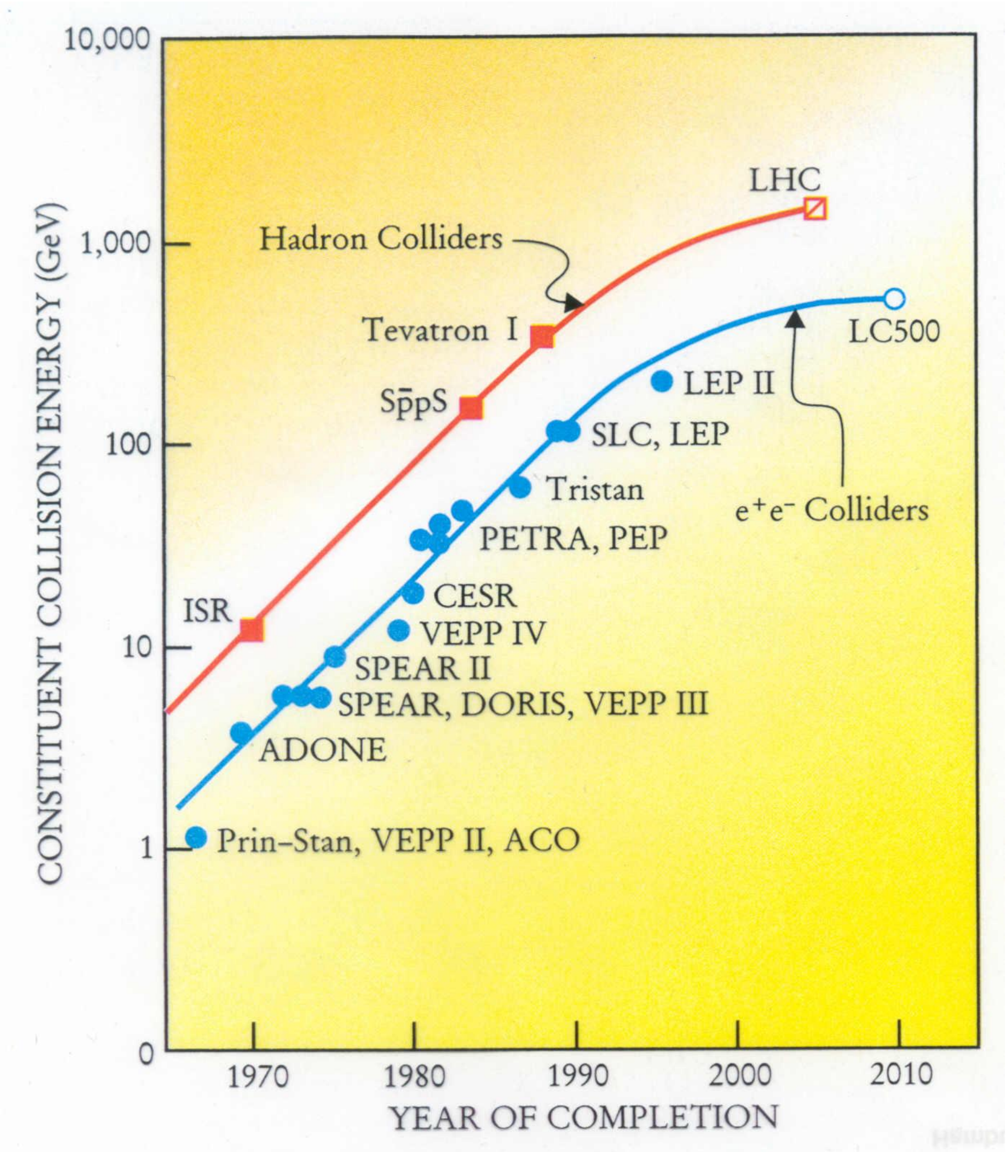
Introduction

Discovery of Higgs brings us to cusp in pp – is it the

SM Higgs, ~ SM Higgs, or is it quite different but in disguise as the Higgs?

- What is (are) the best machine(s) to allow us to investigate this fundamentally new type of particle in enough detail that we can really understand its implications for how the Universe works?
- The obvious answer is the LHC. It will be our only source of information for many years to come. Beyond that, what sort of machine can be built in the next few years that will complement LHC and go beyond it in crucial areas.
- The answer to this question needs not only a view on the maturity and capability of new machines, but also a prediction on what LHC can achieve in the meantime.

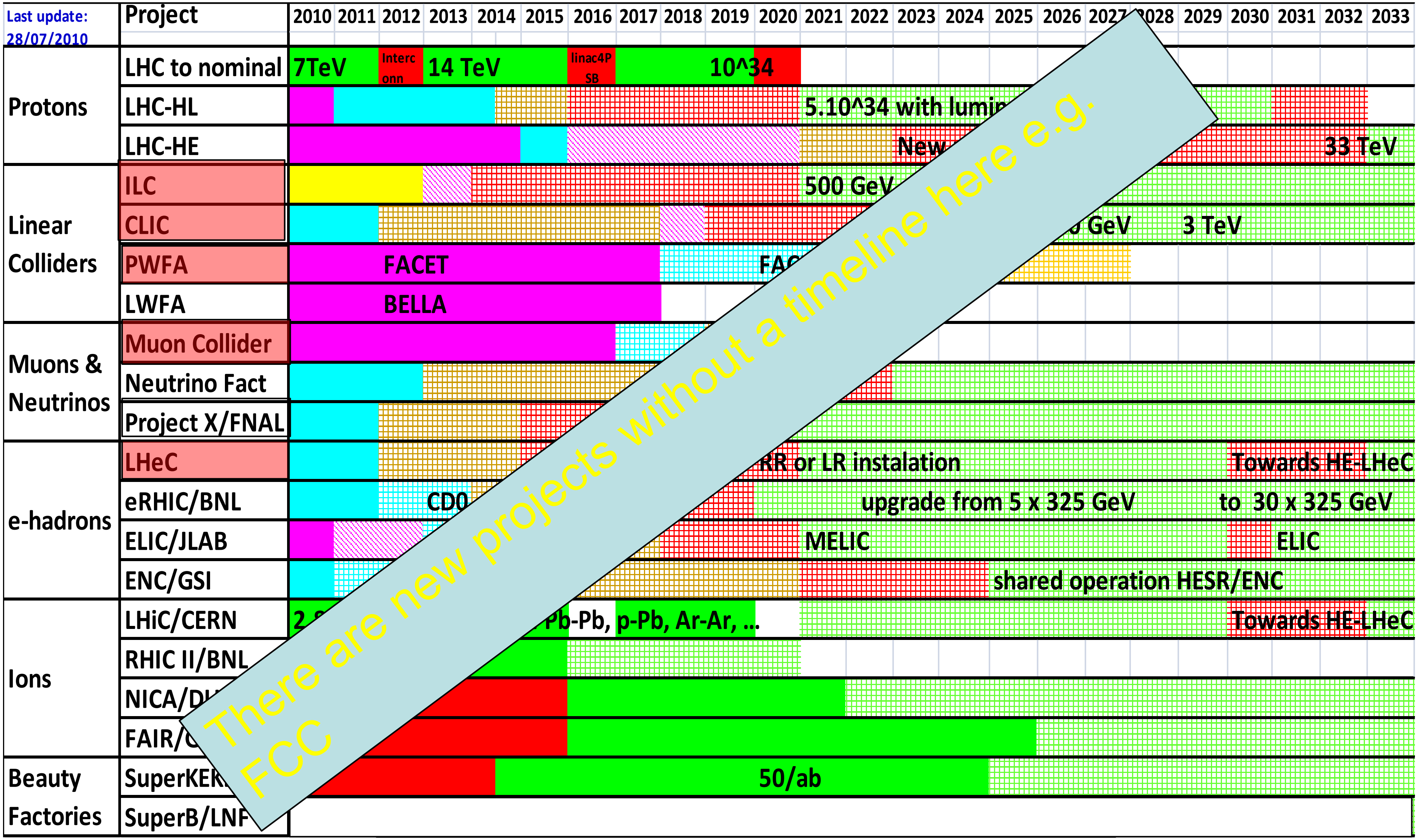
Lessons of history



Tentative schedule new projects

(J-P Delahaye)

Color code	approved	envisaged/proposed
R&D		
R&D to CDR		
Technical design to TDR		
Construction		
Operation		



FCC Overview

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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

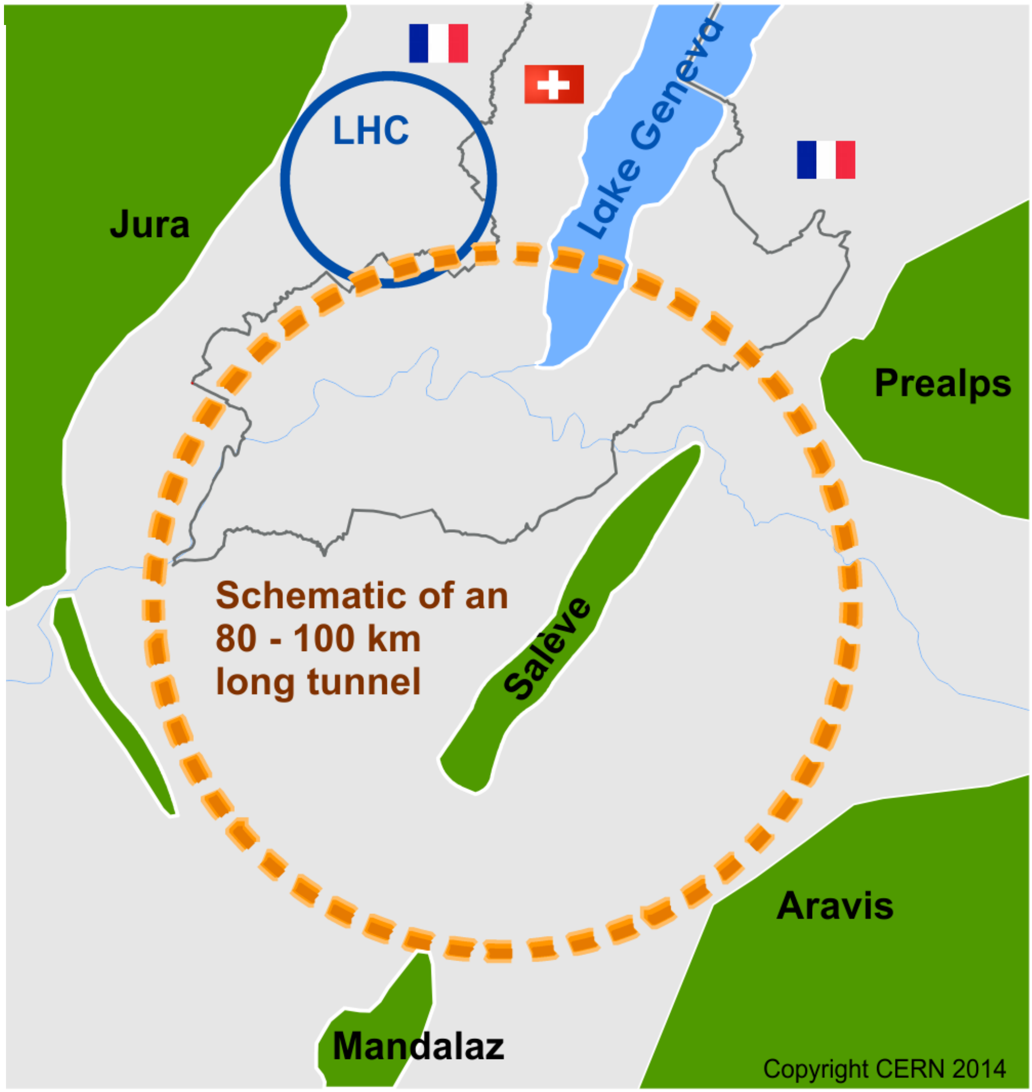
FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2018



(FCC slides thanks to D.Schulte.)

FCC Preliminary Layout

First layout developed (different sizes under investigation)

⇒ Collider ring design (lattice/hardware design)

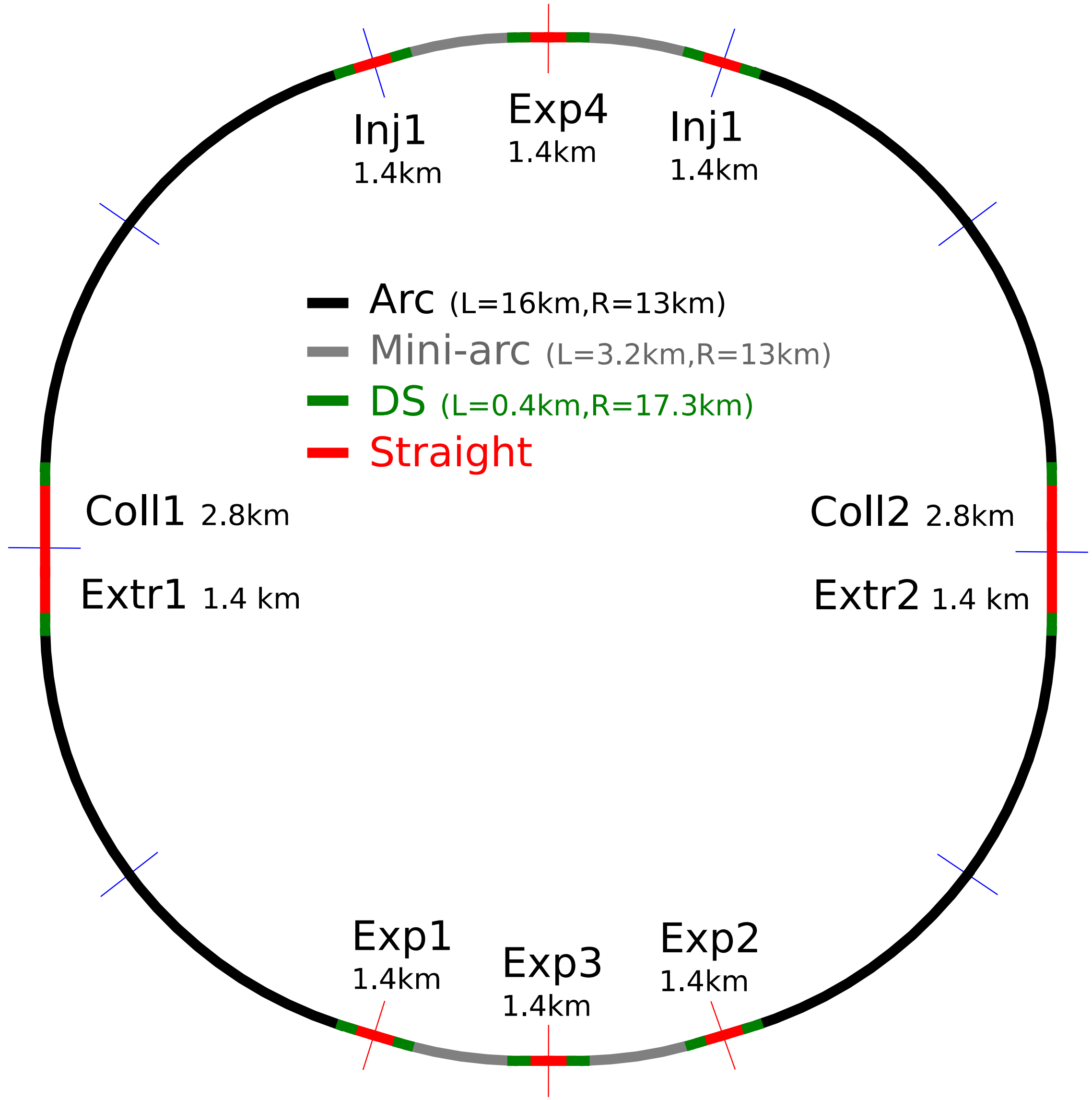
⇒ Site studies

⇒ Injector studies

⇒ Machine detector interface

⇒ Input for lepton option

Will need iterations

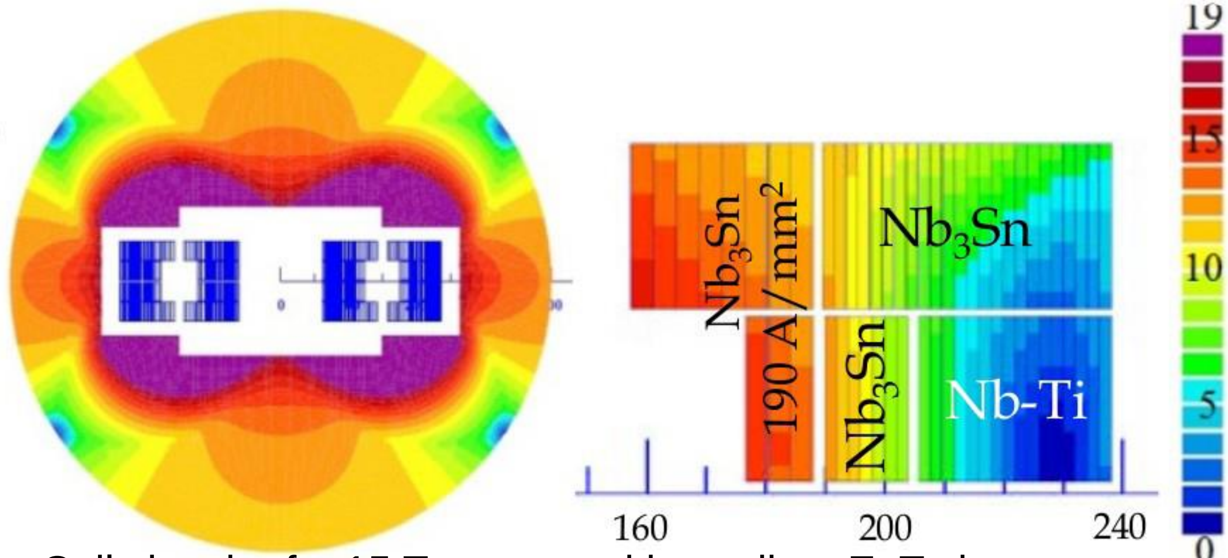


FCC Magnets

Arc dipoles are the main cost and parameter driver

Baseline is Nb_3Sn at 16T

HTS at 20T also to be studied as alternative



Coil sketch of a 15 T magnet with grading, E. Todesco

Field level is a challenge but many additional questions:

- Aperture
- Field quality

Different design choices (e.g. slanted solenoids) should be explored

Goal is to develop prototypes in all regions, US has world-leading expertise

FCC Synchrotron Rad.

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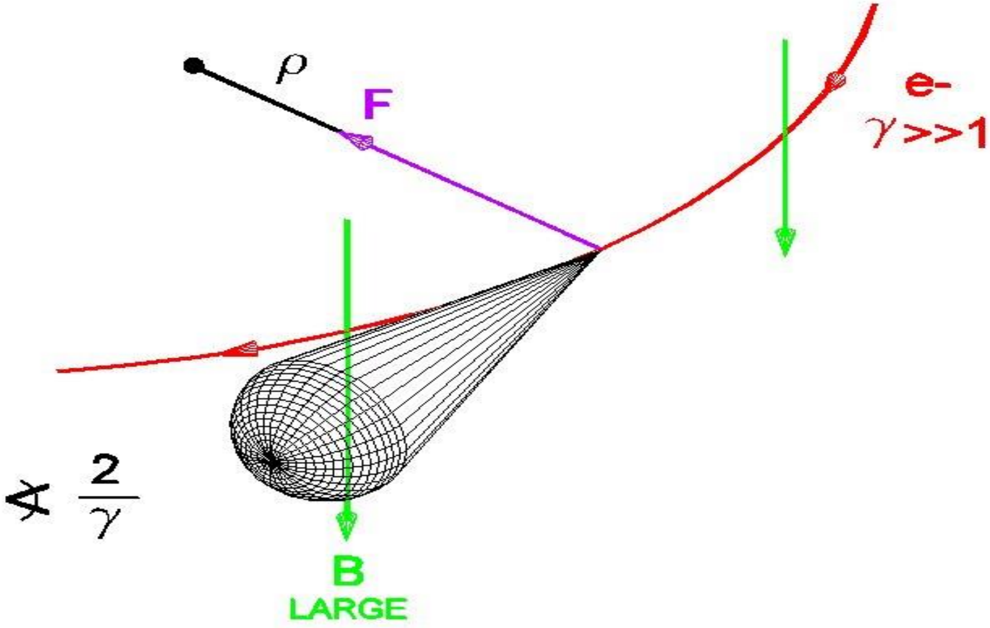
At 100 TeV even protons radiate significantly

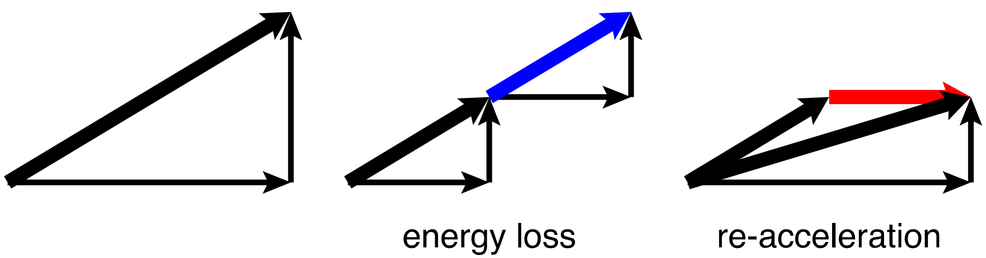
Total power of 5 MW (LHC 7kW)
$\Rightarrow$ Needs to be cooled away

Equivalent to 30W/m /beam in the arcs

- LHC <0.2W/m, total heat load 1W/m

Critical energy 4.3keV, close to B-factory





Protons loose energy
$\Rightarrow$ They are damped
$\Rightarrow$ Emittance improves with time

- Typical transverse damping time 1 hour

FCC Machine Protection

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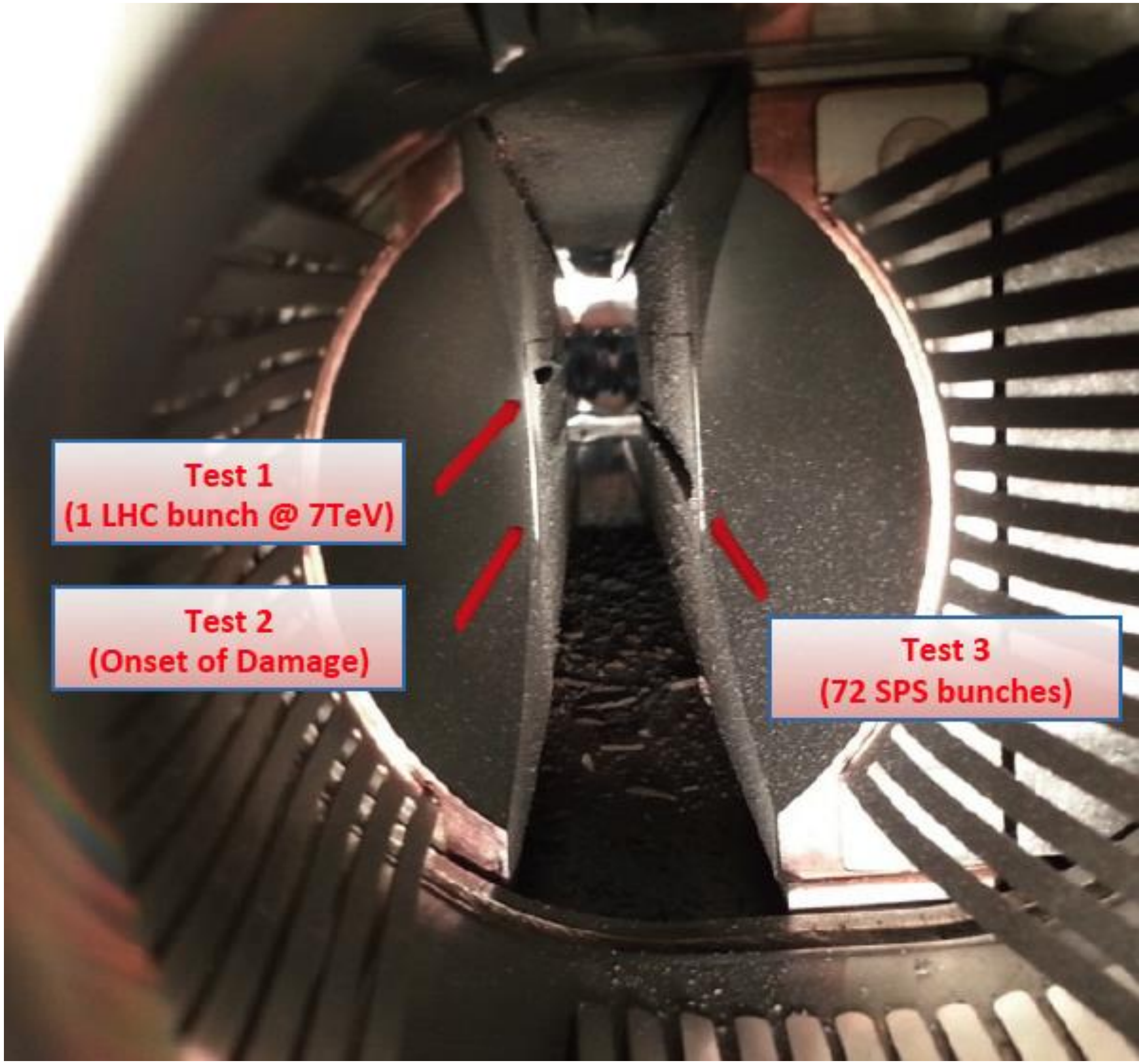
- >8GJ kinetic energy per beam
  - Airbus A380 at 720km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ **Machine protection**
- Also small loss is important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background for the experiments
  - Activation of the machine
  - ⇒ **Collimation system**



Backgrounds from IP

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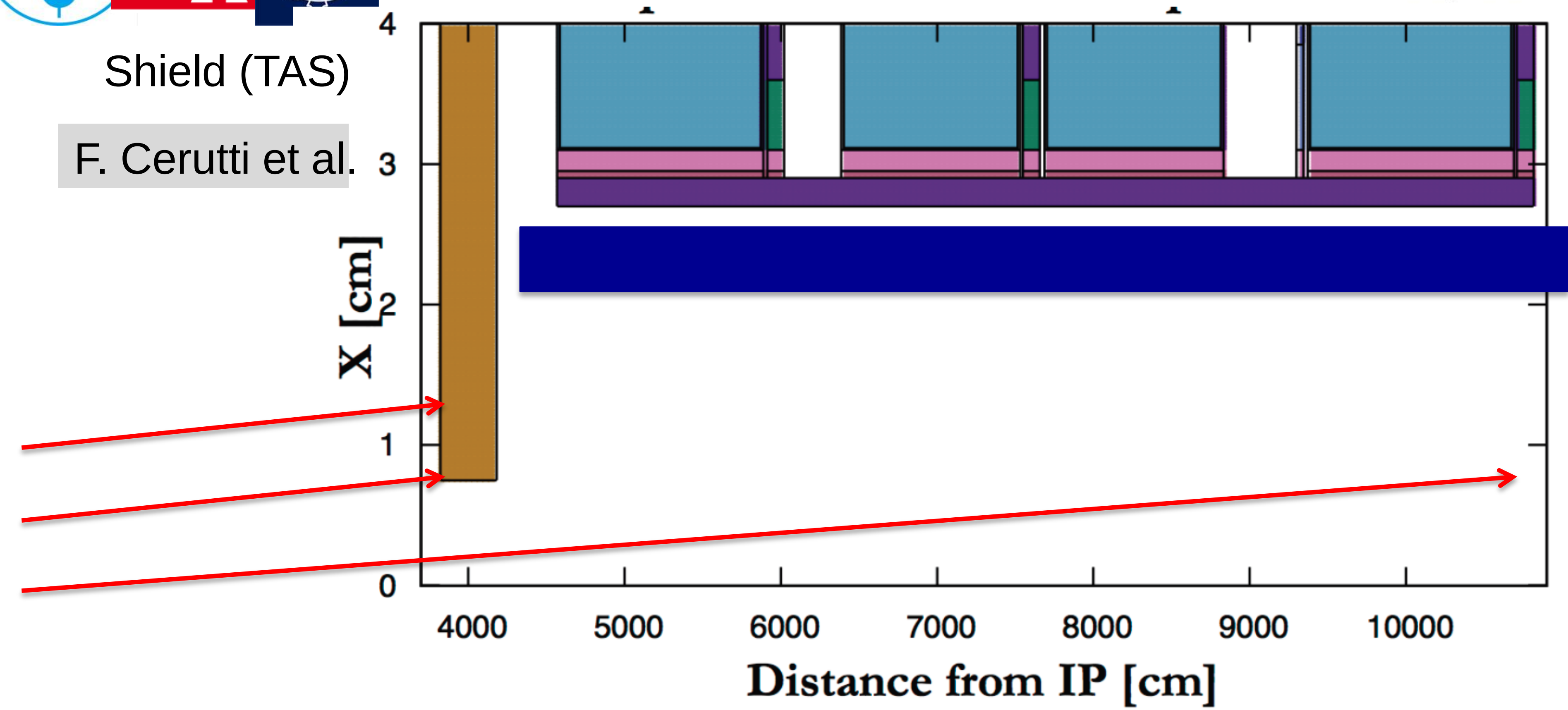
Shield (TAS)

F. Cerutti et al.

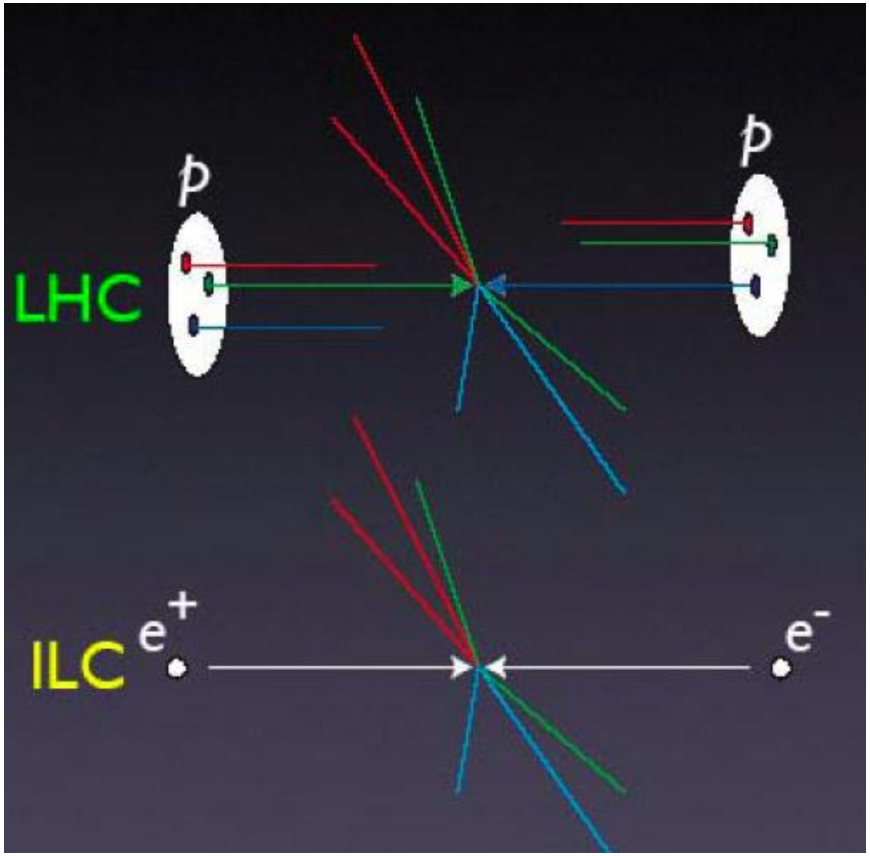


- Total power of background events 100kW per experiment (a car engine)
- Already a problem in LHC and HL-LHC (heating, lifetime)

⇒ Improved shielding required. Lots of work to do before CDR.

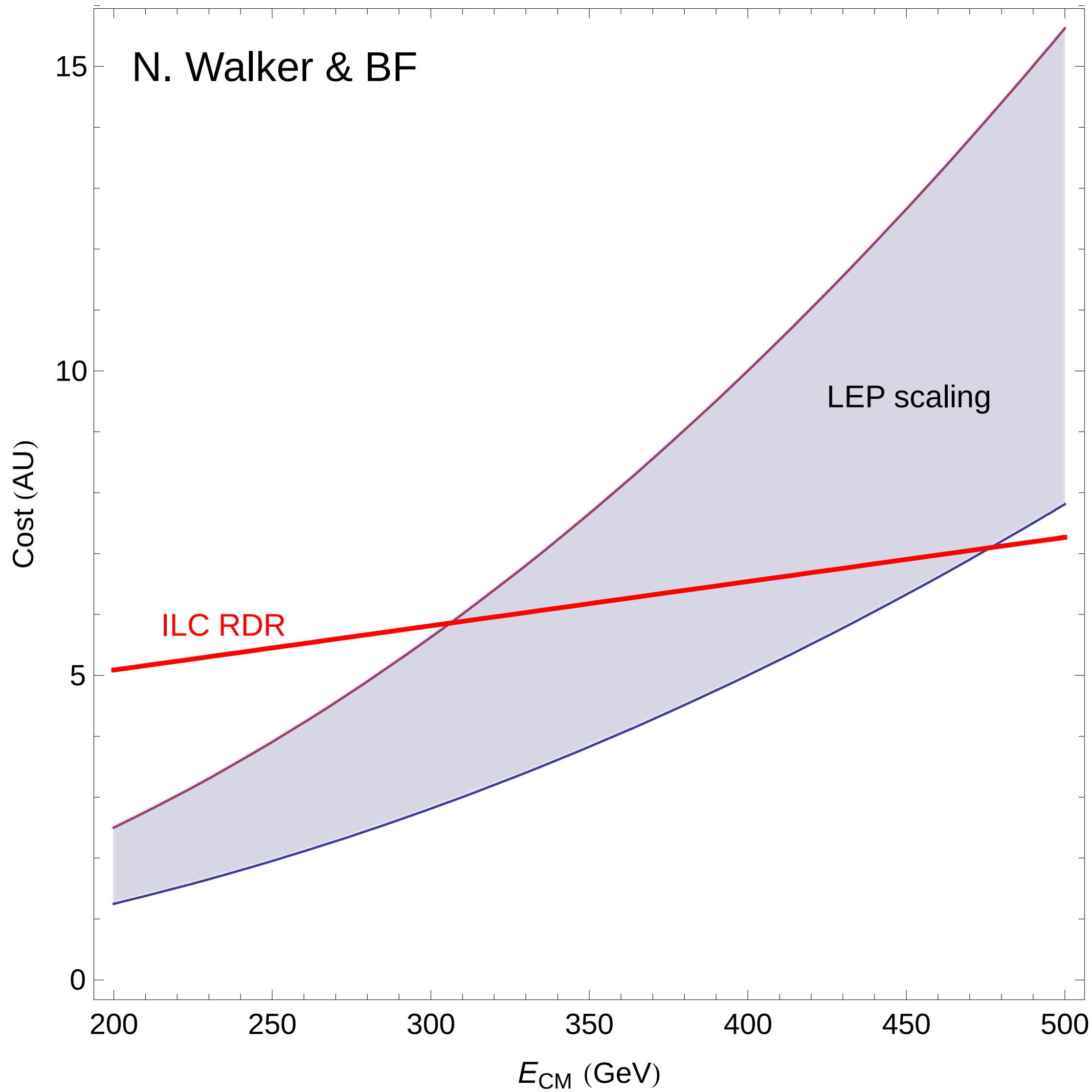
e^+e^- vs pp

- Simple particles
- Well defined:
  energy, angular mom.
- E can be scanned
  precisely
- Particles produced
  ~ democratically
- Final states generally
  fully reconstructable



Circular e^+e^- machines

Very approximate cost 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.

Circular e^+e^- machines

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At Beamstrahlung & tune-shift limit, assuming 100 MW power consumption:

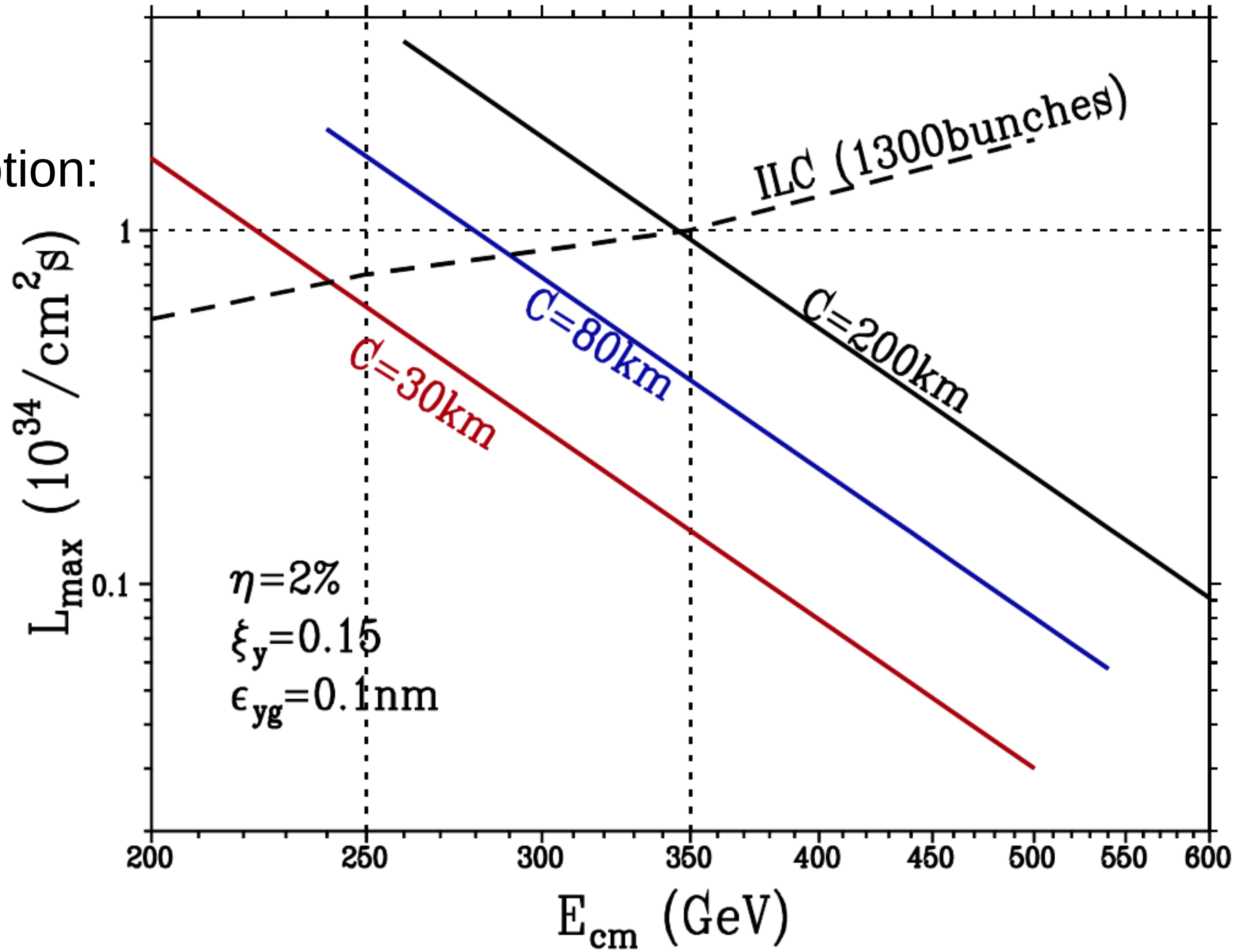
$$\mathcal{L} \propto \frac{\rho P_{SR}}{E^{13/3}} \left(\frac{\xi_y \eta^2}{\varepsilon_{g,y}} \right)^{1/3}$$

P_{SR} : syn.rad.power

ρ : bending radius

ξ_y : tune-shift

$\varepsilon_{g,y}$: geometric emit.



(Telnov via Yokoya)

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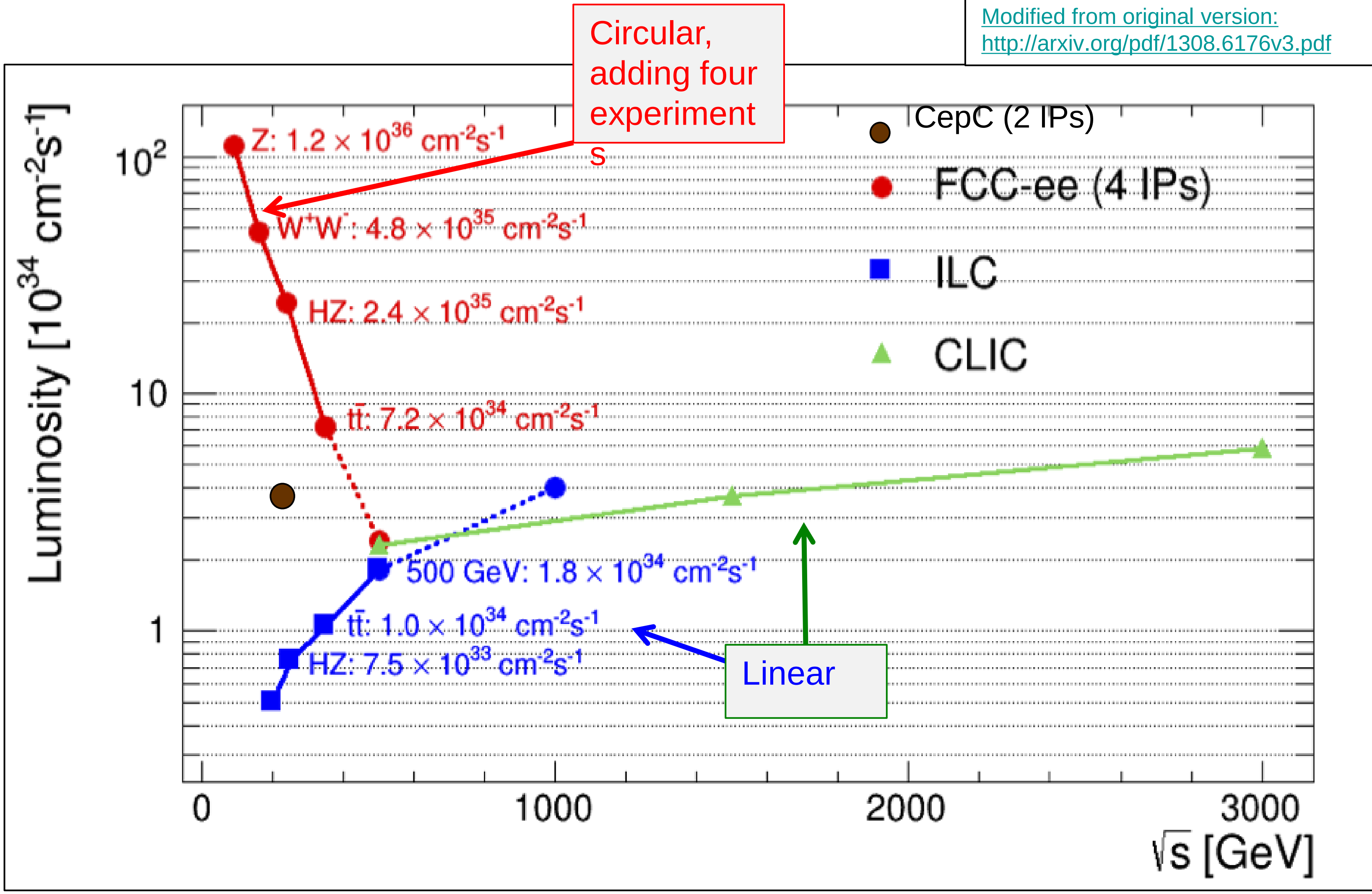
Circular e^+e^- machines

Modified from original version:
http://arxiv.org/pdf/1308.6176v3.pdf



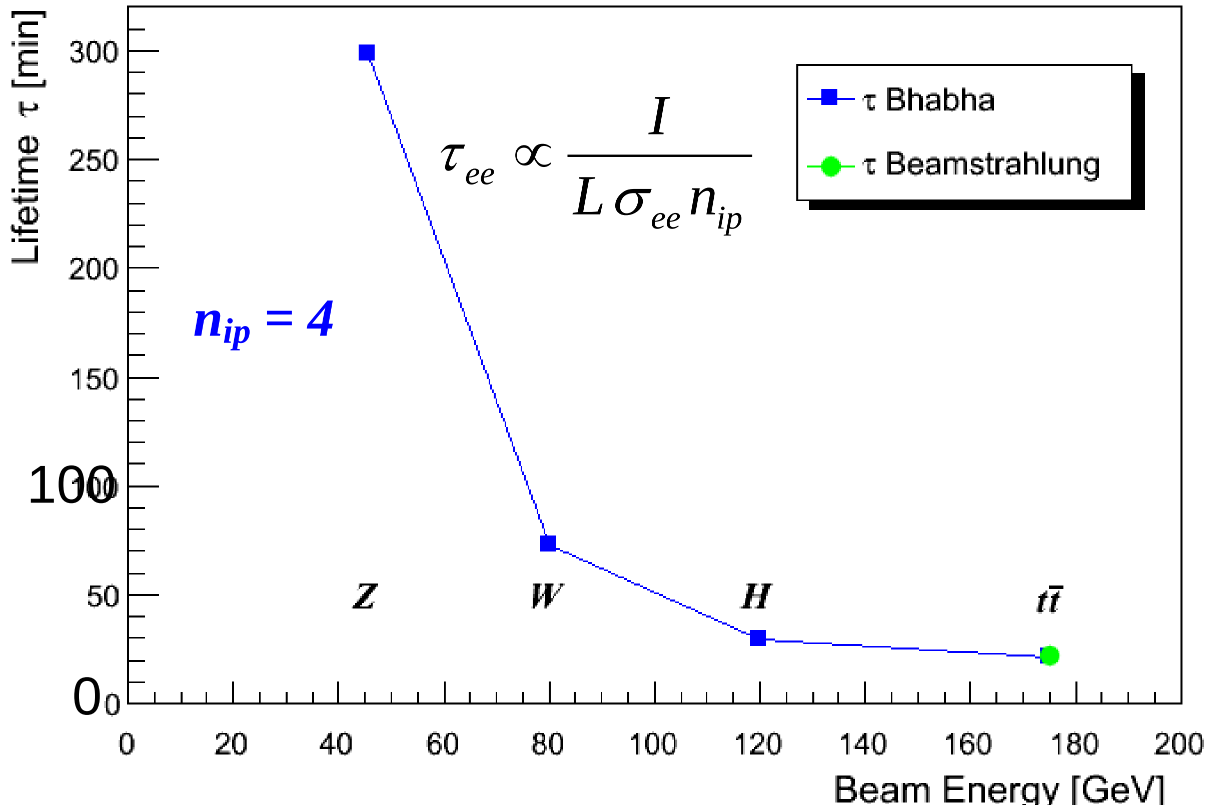
(D. Schulte)

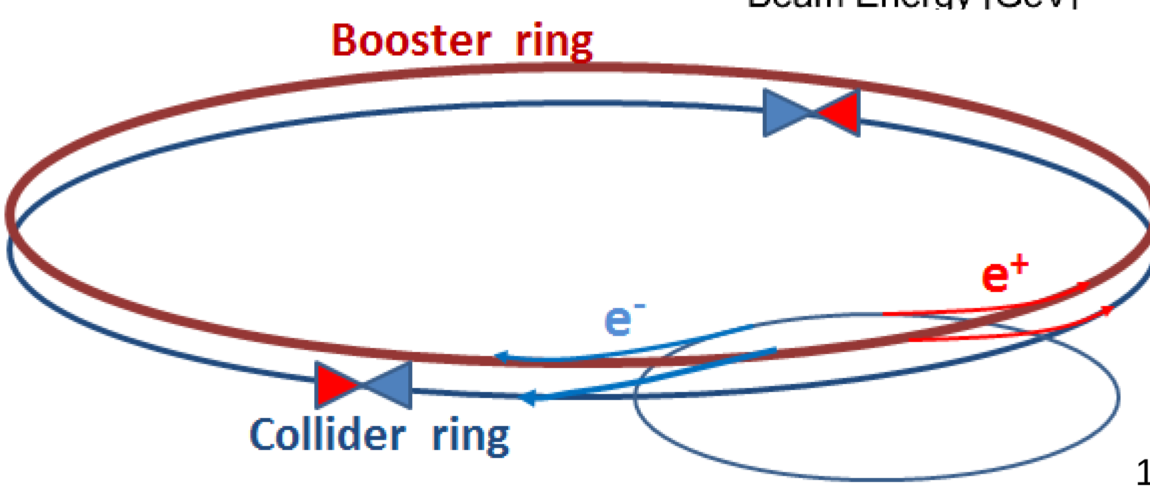
FCC-ee Luminosity Lifetime

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

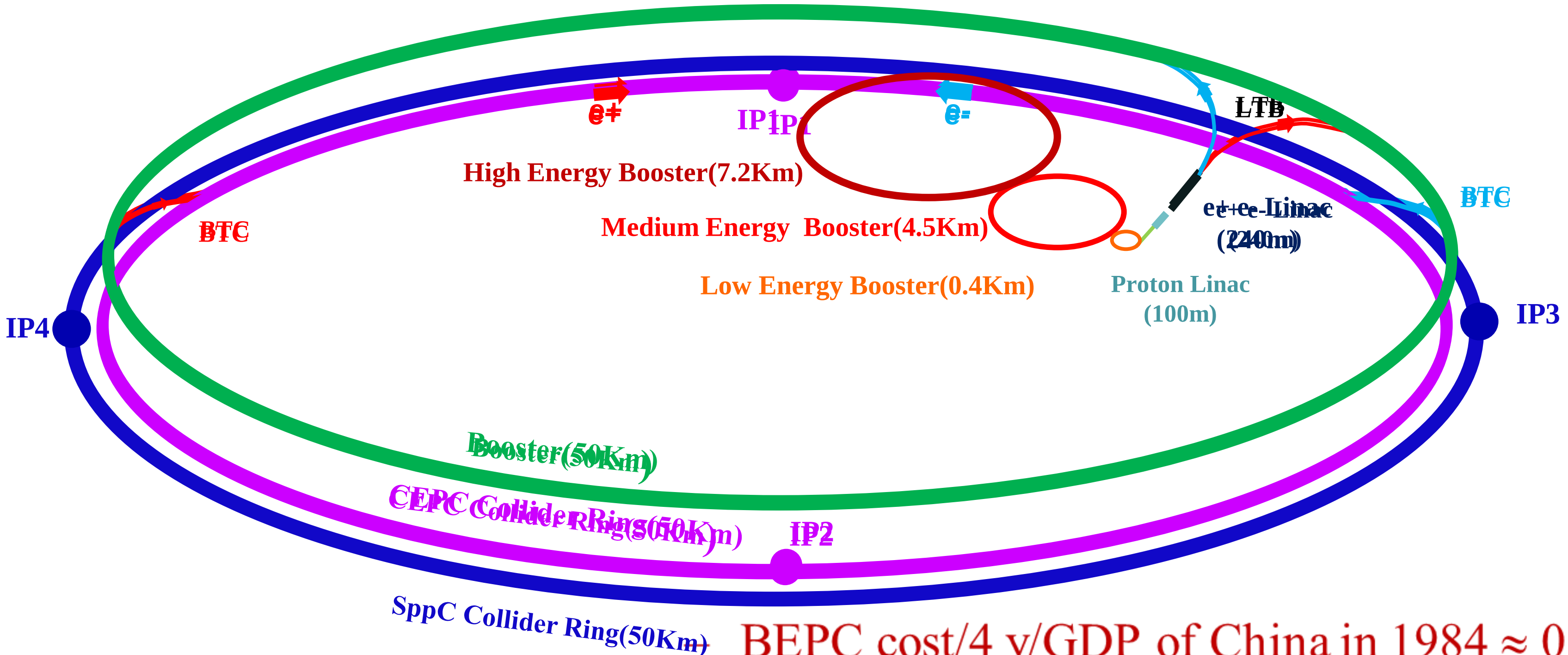
- Radiative Bhabha scattering is proportional to luminosity
- Beamstrahlung as in linear colliders
- As yet no acceptable beam dynamics solution.

Need continuous injection (top-up)





Chinese plans – CEPC & SppC Layout



LTB : Linac to Booster

BTC : Booster to Collider Ring

BEPC cost/4 y/GDP of China in 1984 ≈ 0.0001

- SSC cost/10y/GDP of US in 1992 ≈ 0.0001
- LEP cost/8y/GDP of EU in1984 ≈ 0.0002
- LHC cost/10y/GDP of EU in 2004 ≈ 0.0003
- ILC cost/8y/GDP of Japan in 2018 ≈ 0.0002
- CEPC cost/6y/GDP of China in 2020 ≈ 0.00007
- SPPC cost/6y/GDP of China in 2036 ≈ 0.0001

(J. Gao)

CEPC Parameters

Parameter	Unit	Value	Parameter	Unit	Value
Beam Energy	GeV	120	Circumference	km	50
Number of IP		2	L_0/IP (10^{34})	$cm^{-2}s^{-1}$	2.62
No. of Higgs/year/IP		1E+05	Power(wall)	MW	200
e+ polarization		0	e- polarization		0
Bending radius	km	6.2	N_e/bunch	1E10	35.2
N_b/beam		50	Beam current	mA	16.9
SR loss	(GeV/turn)	2.96	SR power/beam	MW	50
Critical energy of SR	MeV	0.6	ε_x,n	mm-mrad	1.57E+06
ε_y,n	mm-mrad	7.75E+03	β_{IP} (x/y)	mm	200/1
Trans. size (x/y)	µm	36.6/0.18	Bunch length	mm	3
Energy spread SR	%	0.13	Full crossing angle	mrad	0
Lifetime due to Bhabha	sec	930	Damping part. No. (x/y/z)		1/1/2
b-b tune shift x/y		0.1/0.1	Syn. Osci. tune		0.13
RF voltage V_{rf}	GV	4.2	Mom. compaction	1E-4	0.4
Long. Damping time	turns	40.5	Ave. No. of photons		0.59
dB beam-beam	%	0.014			

SppC Parameters

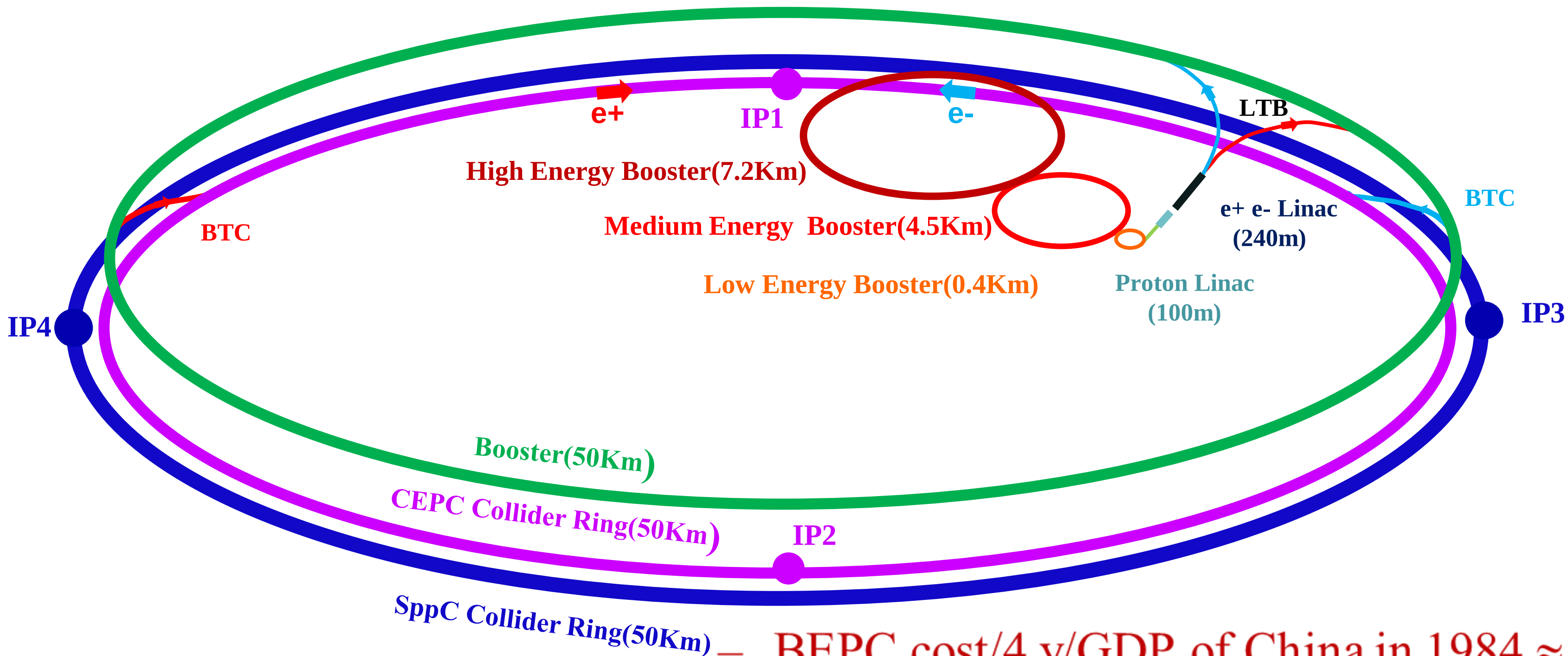
Parameter	Value	Unit
Circumference	52	km
Beam energy	35	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56	W/m

CEPC Site

- **Preliminary selected Qinhuangdao (秦皇岛）(one of the candidate sites)**
- **Strong support by the local government**

- **Base rock: granite**
- **Base rock depth: 0.5 - 2 m**
- **Earth quake: < 7, 0.1g**
- **Earth vibration(RMS, nm): < 1.9 (1 – 100 Hz)**

CEPC & SppC Layout



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- CEPC cost/6y/GDP of China in 2020 ≈ 0.00007
- SPPC cost/6y/GDP of China in 2036 ≈ 0.0001

SC predicts 2020 China GDP = $24.6 Trillion

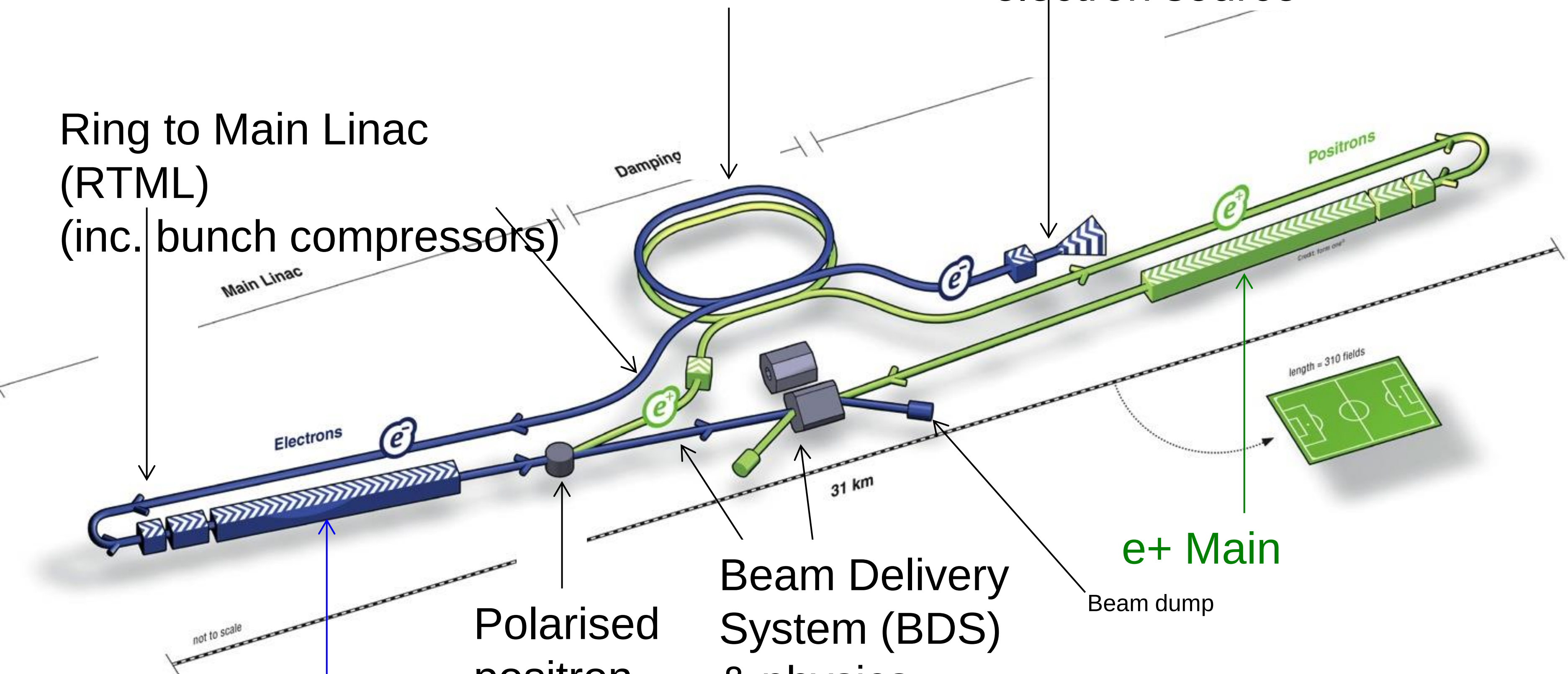
=> Cost of CEPC ~ 0.07*24.6*6 B ~ 10B

ILC Overview

Polarised electron source

Damping Rings

Ring to Main Linac (RTML)
(inc. bunch compressors)



e+ Main

Beam dump

Beam Delivery System (BDS) & physics detectors

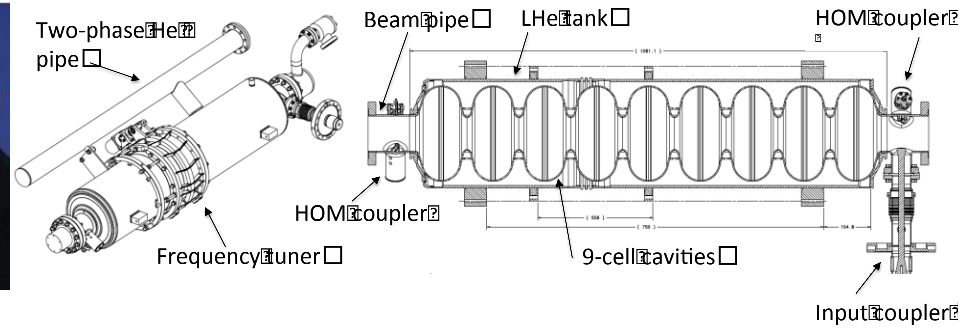
Polarised positron source

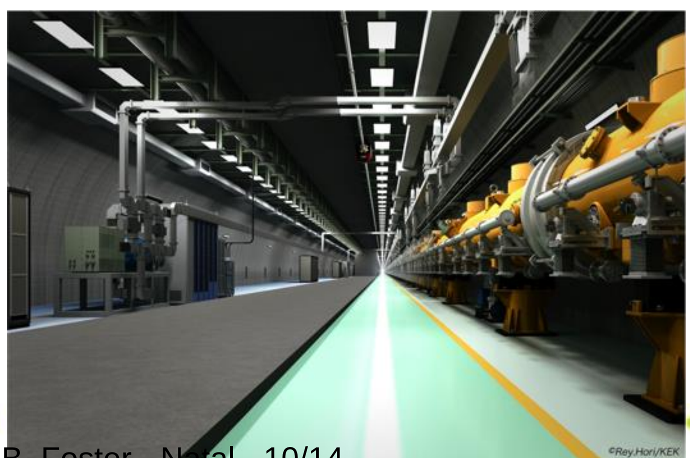
e- Main Linac

not to scale

ILC Scheme | © www.form-one.de

SCRF Linac Technology





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

* site dependent

Approximately 20 years of R&D worldwide
→ Mature technology

CLIC

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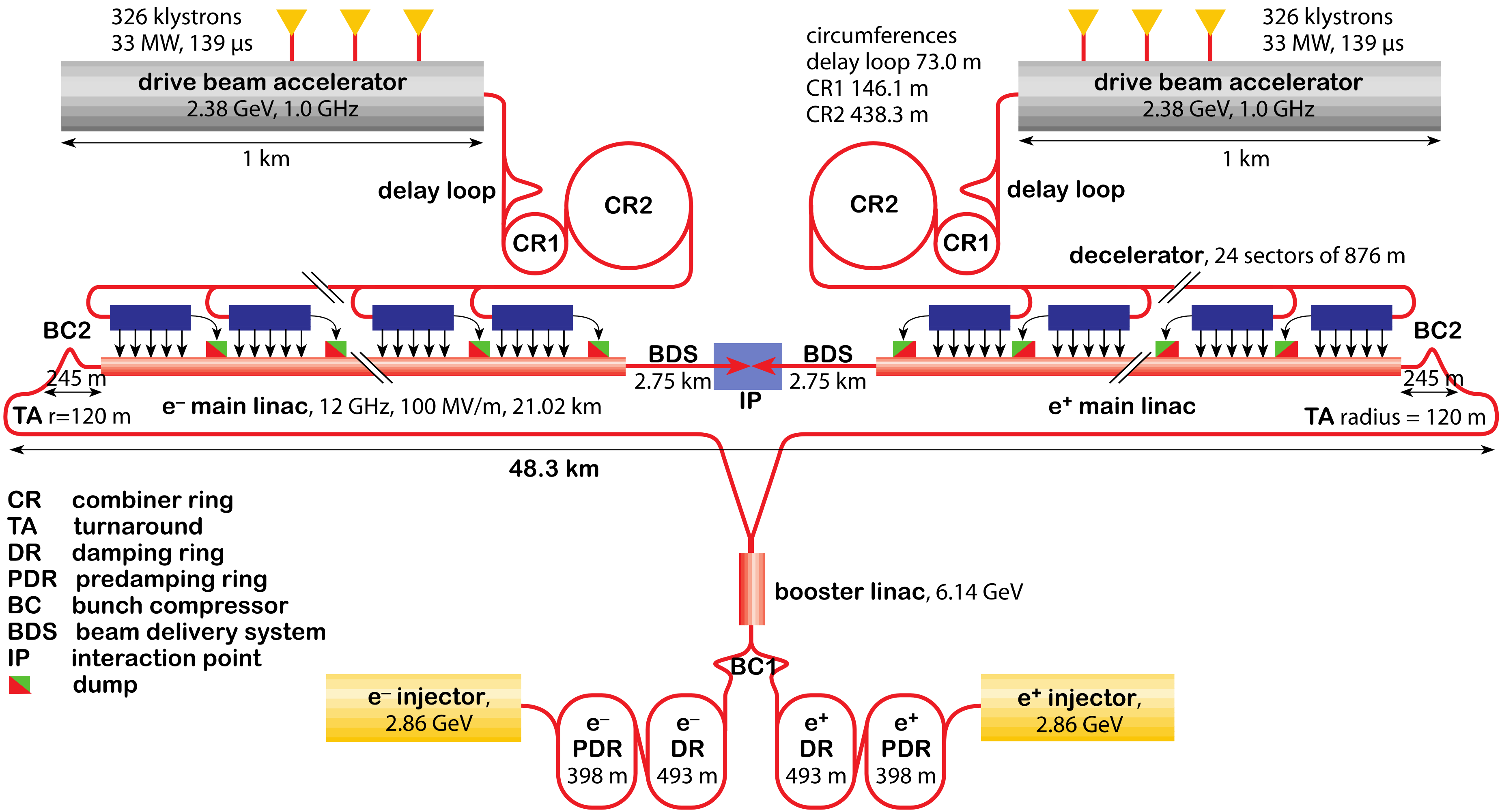

CLIC Power Source Concept

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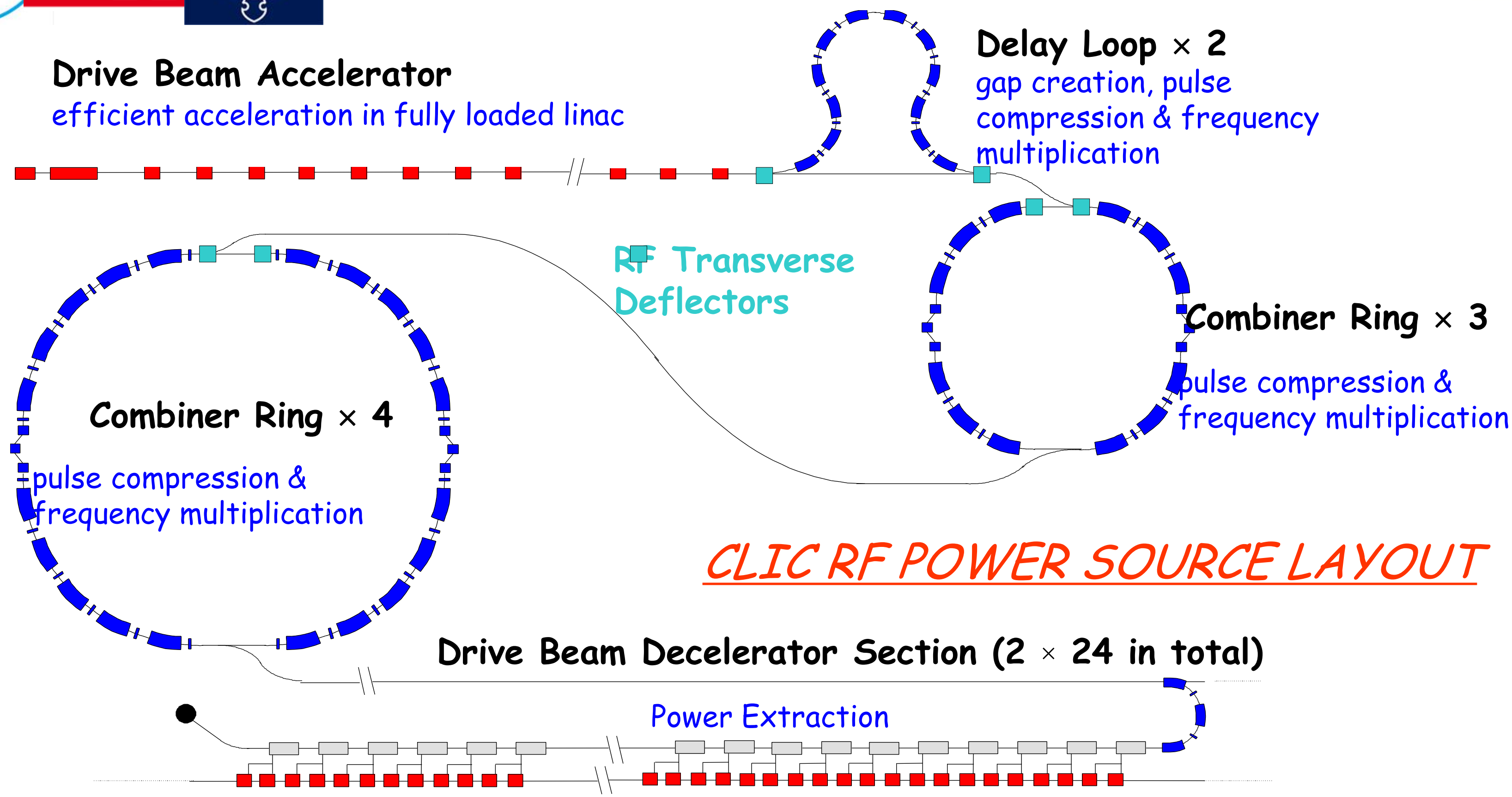

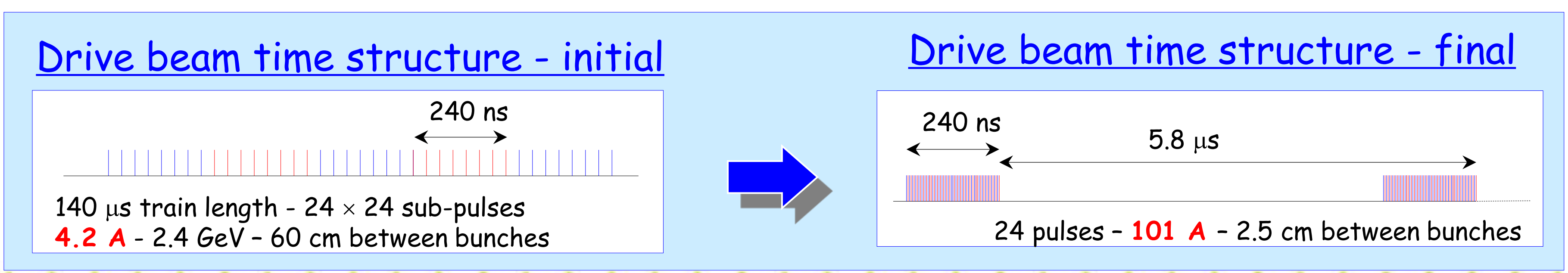

CLIC Accelerating Structures

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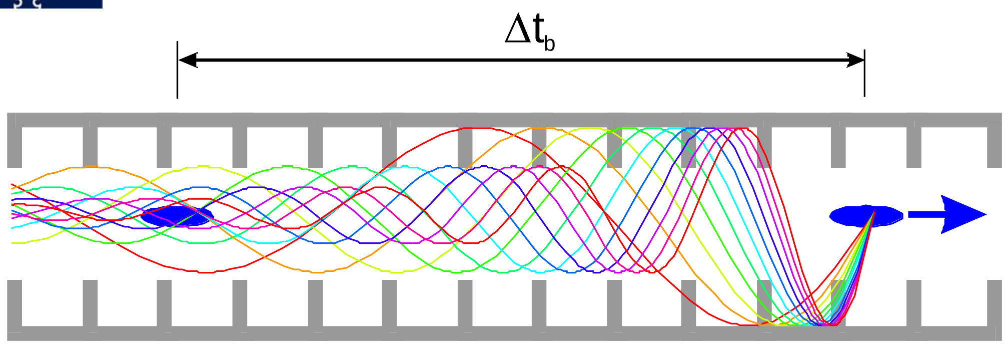
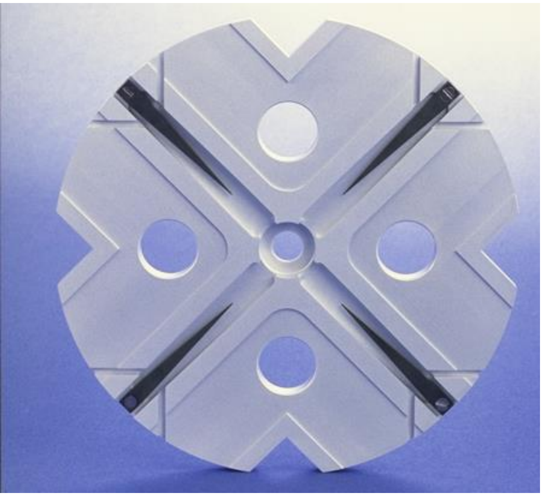
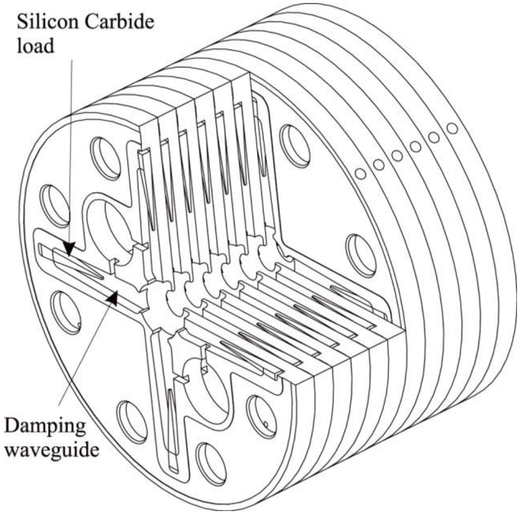


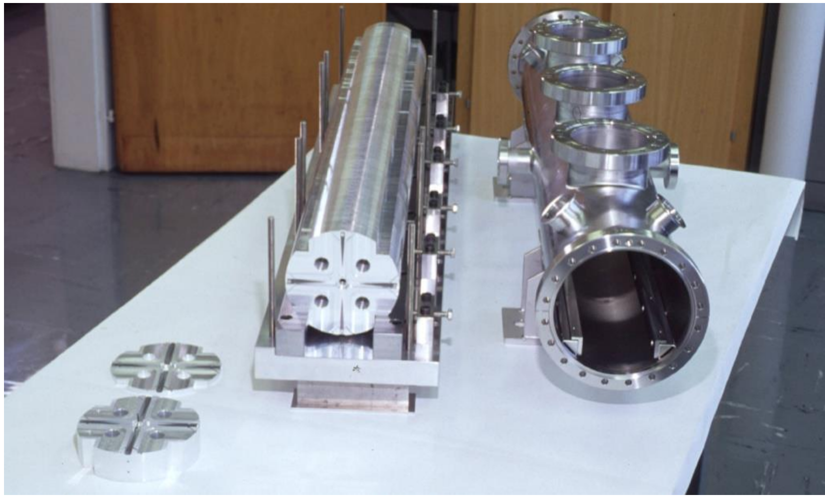
- CLIC acceleration travelling wave – too high Ohmic losses from standing wave
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities

- 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

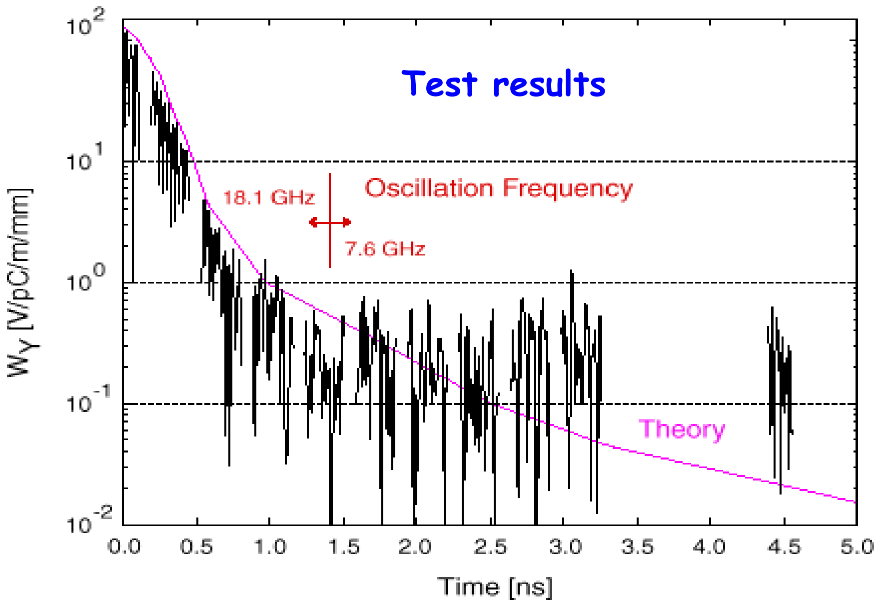
CLIC Accelerating Structures





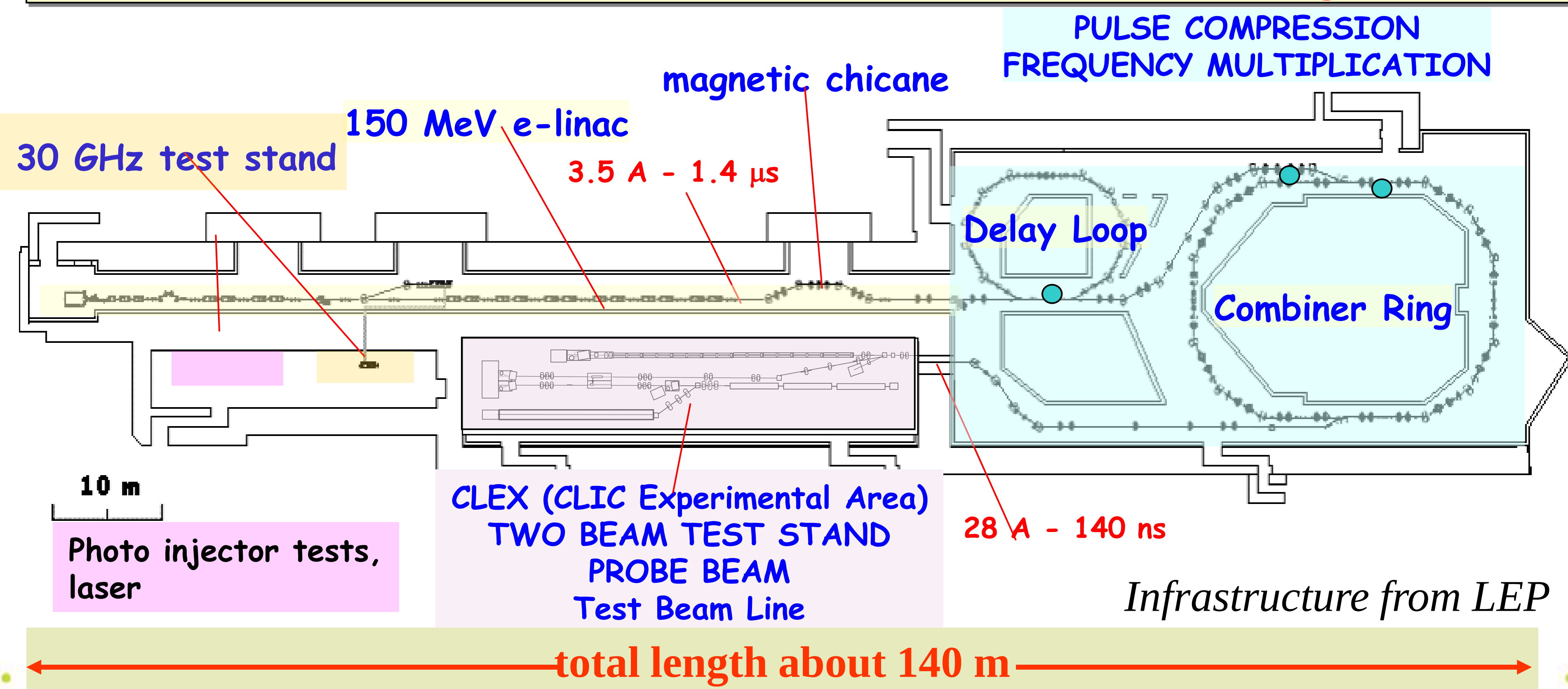


- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped



CTF3 @ CERN

- Demonstrate Drive Beam generation
  (fully loaded acceleration, beam intensity and bunch frequency multiplication x8)
- Demonstrate RF Power Production and test Power Structures
- Demonstrate Two Beam Acceleration and test Accelerating Structures



Current status of accelerating structures

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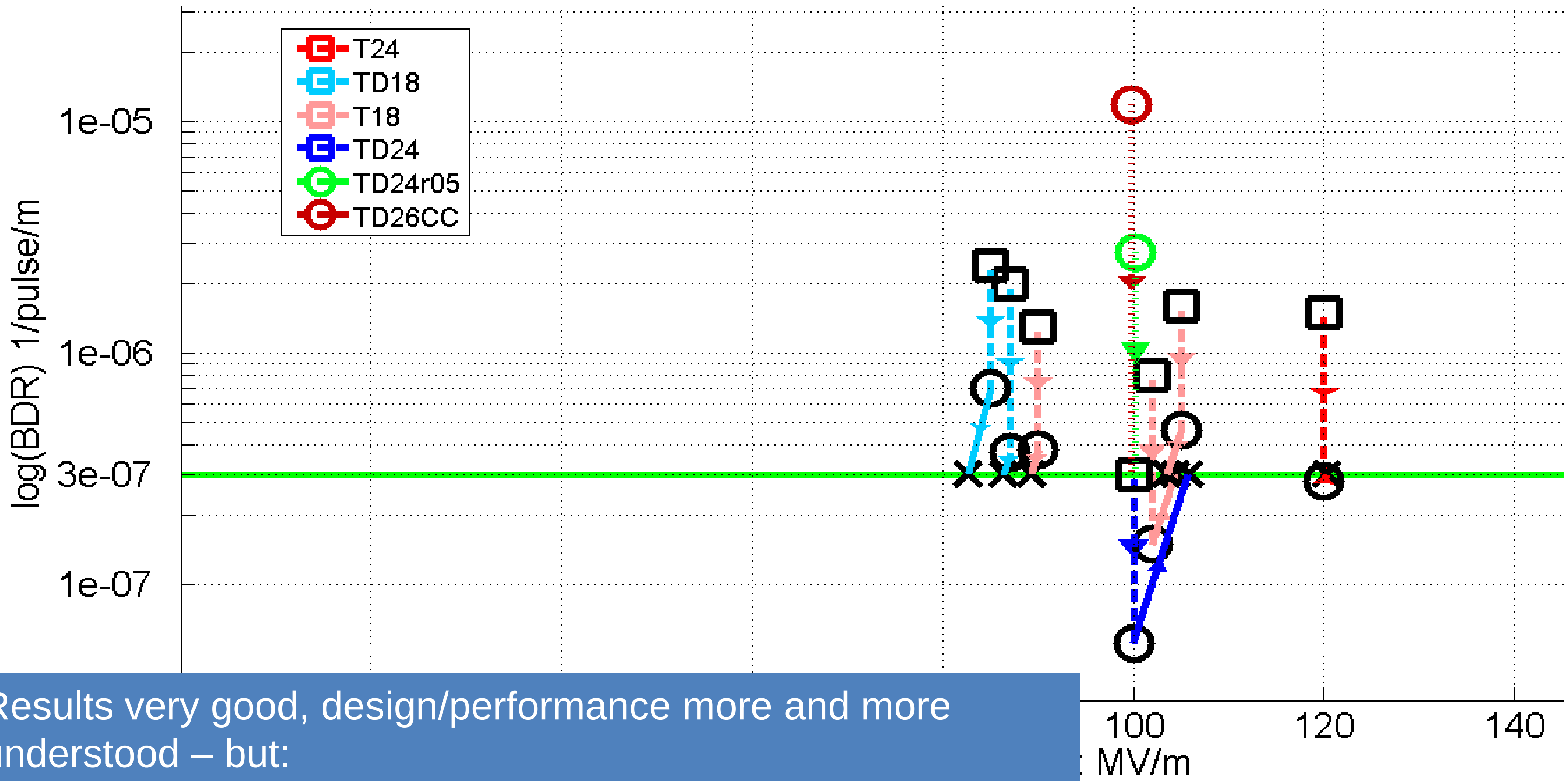

Results very good, design/performance more and more understood – but:

- numbers limited, industrial productions also limited
- basic understanding of BD mechanics improving
- condition time/acceptance tests need more work
- use for other applications (e.g. FELs) needs verification

In all cases test-capacity is crucial

Current status

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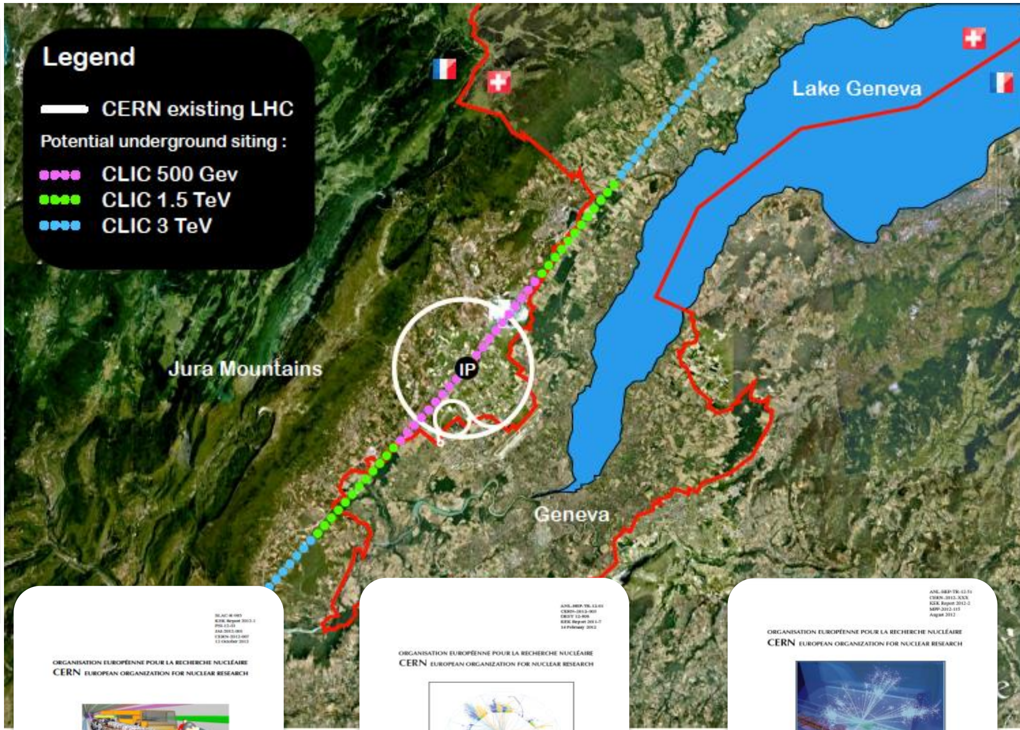
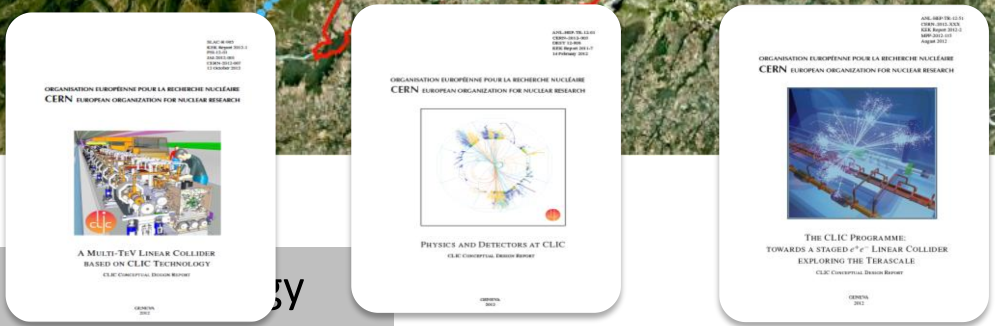
Luminosity
- Damping ring like an ambitious light source, no show stopper
- Alignment system principle demonstrated
- Stabilisation system developed, benchmarked, better system in pipeline
- Simulations on or close to the target

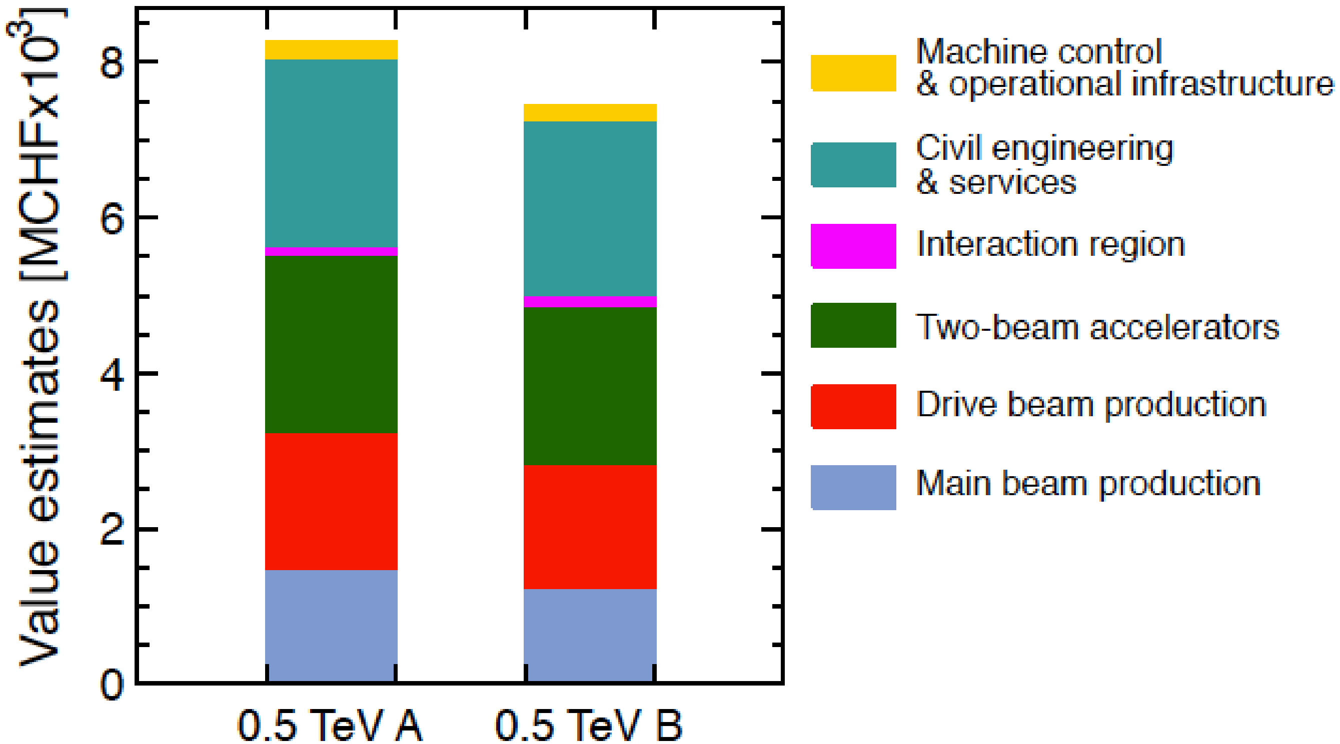


Conceptual design complete



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

CLIC



First to second stage: 4 MCHF/GeV (i.e. initial costs are very significant)

Caveats:

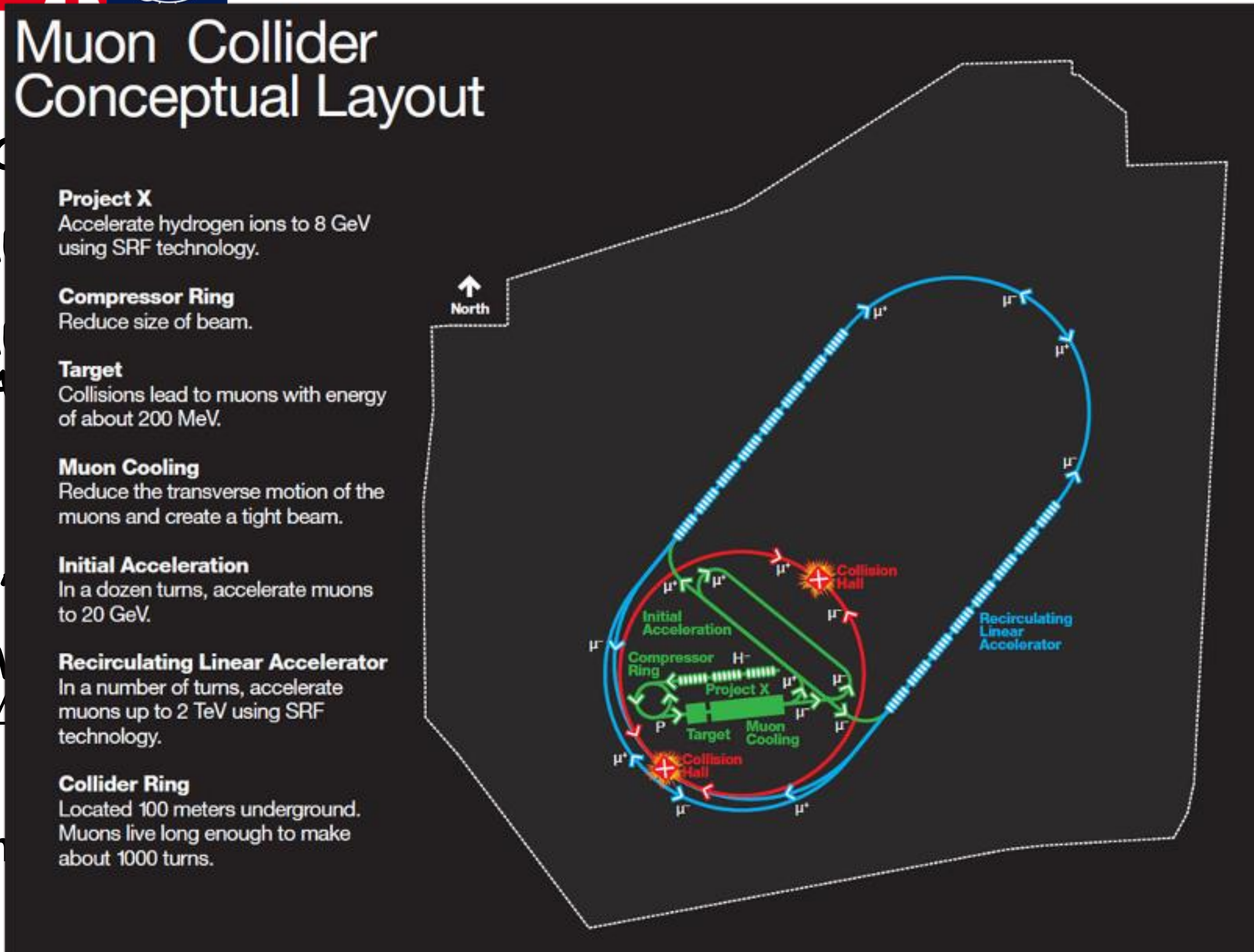
Uncertainties 20-25%
Possible savings around 10%
However – first stage not optimised (work for next phase), parameters largely defined for 3 TeV final stage

CLIC project summary

The goals and plans for 2019 are well defined for CLIC, focusing on the high energy frontier capabilities – well aligned with current strategies – also preparing to align with LHC physics as it progresses in the coming years:

- Aim provide optimized stages approach up to 3 TeV with costs and power not too excessive compared to LHC
- Very positive progress on Xband technology, due to availability of power sources and increased understanding of structure design parameters
  - Applications in smaller systems; FEL linacs key example – with considerable interesting in the CLIC collaboration
- Also recent good progress on performance verifications, drivebeam, main beam emittance conservation and final-focus studies
  - CTF3 running and plan until end 2016, strategy for system tests beyond
- Technical developments of key parts well underway – with increasing involvement of industry – largely limited by funding
- Detector and physics programme well defined, moving ahead well – linking gradually with FCC hadron community

Muon Collider



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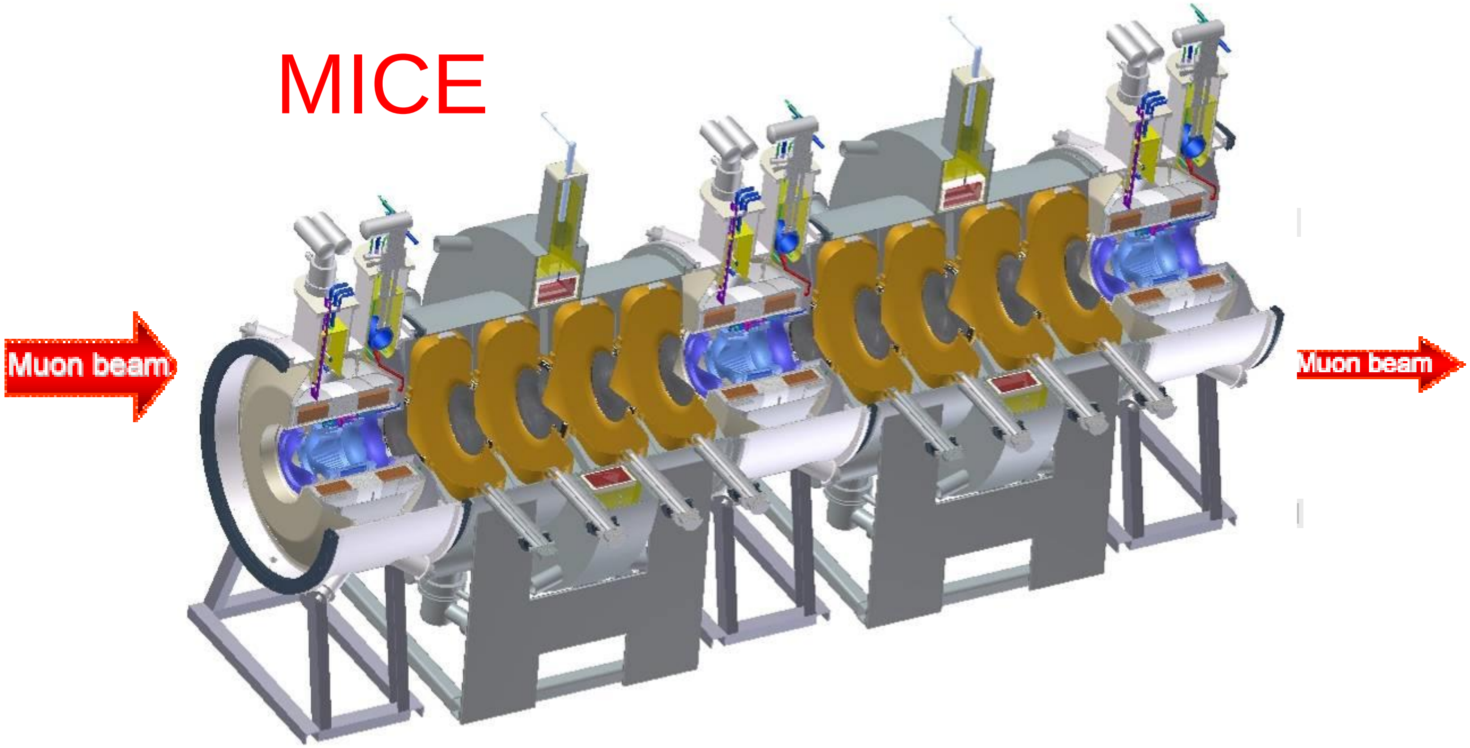
Muon Collider Cooling

- Ionization cooling analogous to familiar SR damping process in electron storage rings
  - **energy loss (SR or *dE/ds*) reduces p_x, p_y, p_z**
  - **energy gain (RF cavities) restores only p_z**
  - **repeating this reduces $p_{x,y}/p_z$ (⇒ 4D cooling)**

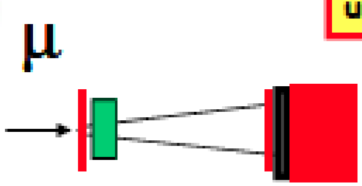
MICE



MICE Schedule

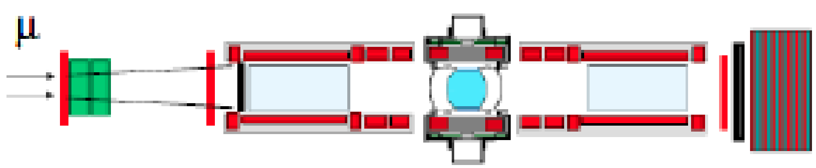
Provisional MICE SCHEDULE
update: October 2012

Run date:



STEP I

EMR run Q1-Q2 2013

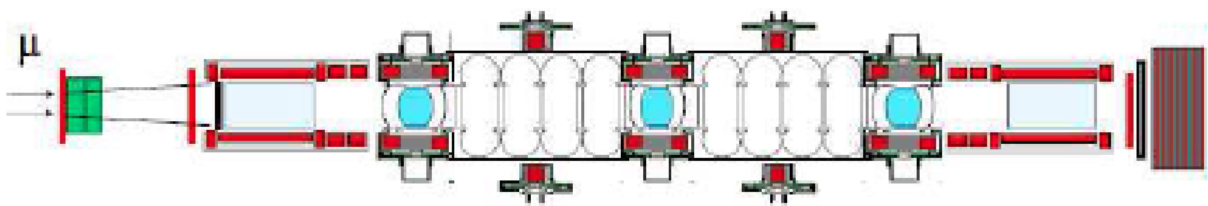


STEP IV

Q2 2014
till
Q4 2015

Under construction:

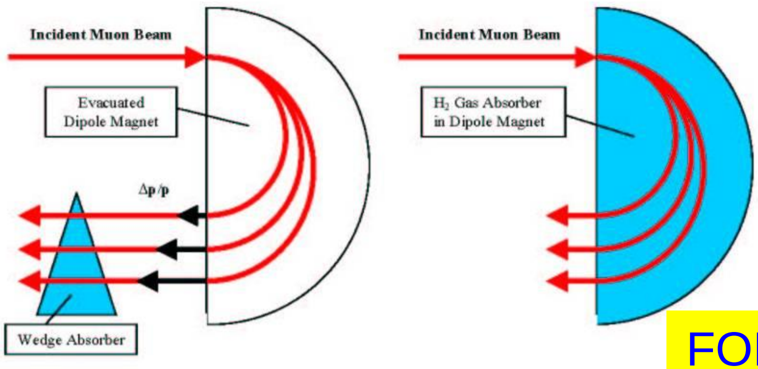
STEP VI



target date Q3 2018
Step V run possible Q3 2017

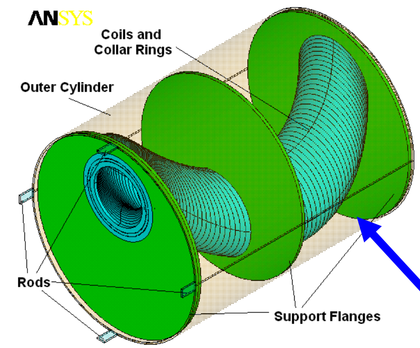
Muon Collider Cooling

- Need 6D cooling (emittance exchange)
  - increase energy loss for high-energy compared with low-energy muons
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber

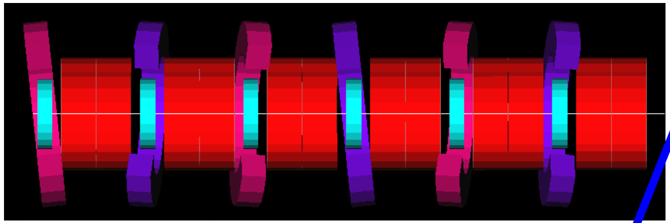


Muons, Inc.

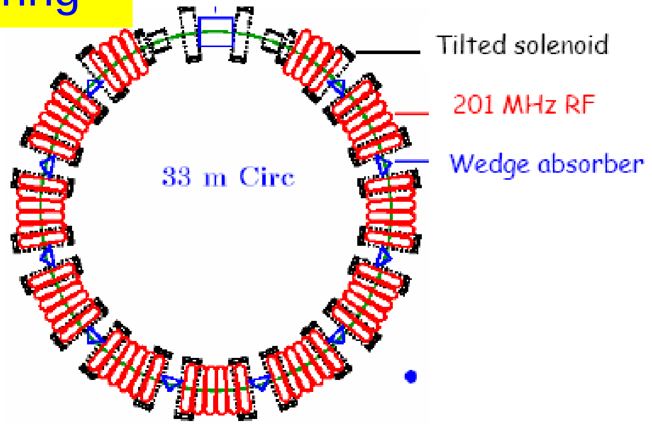
HCC

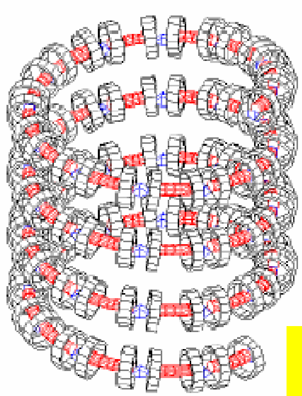


FOFO Snake



Cooling ring





Single pass; avoids injection/extraction issues

“Guggenheim” channel

Muon Collider Cooling

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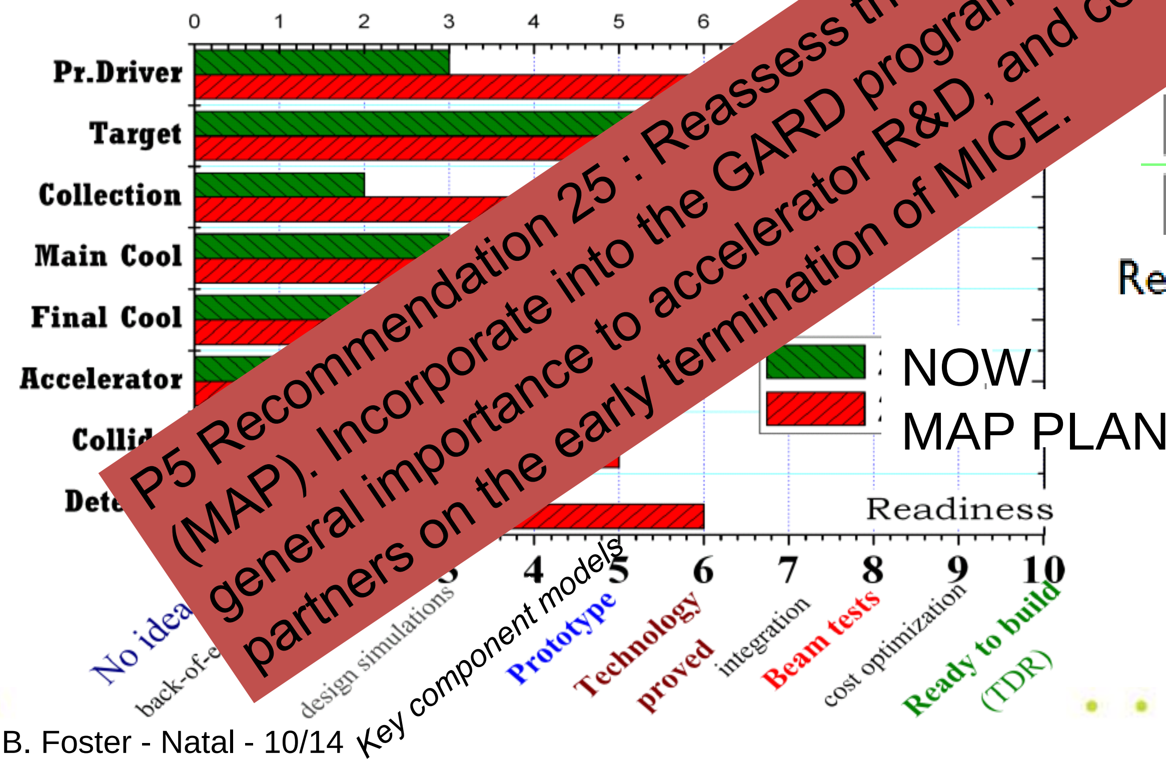
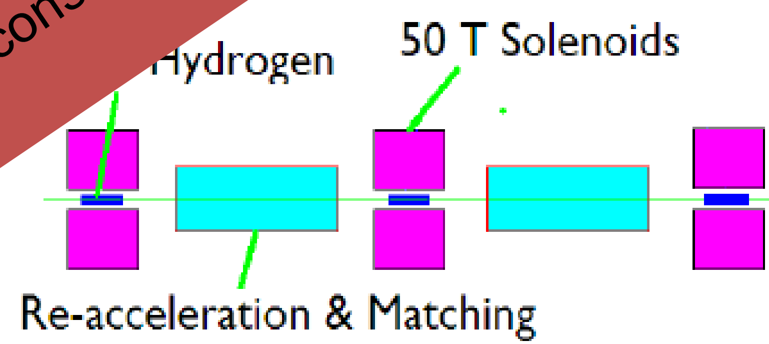
- **Final cooling to 25 μm emittance requires str[…]enoids**
  - **— not exactly a catalog item ⇒ R&D effort**
  - **— latest design uses 30 T**
- **45 T hybrid device exists**
  - **— very high power device, so not a go[…]**
  - **— exploring use of HTS for this ta[…]**

P5 Recommendation 25 : Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.

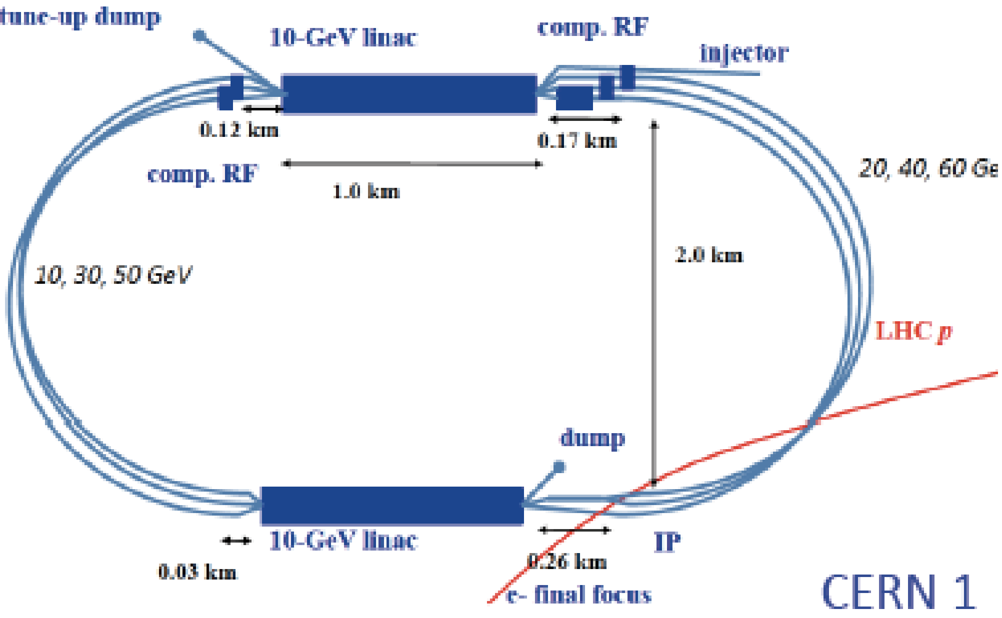
Palmer, Fernow



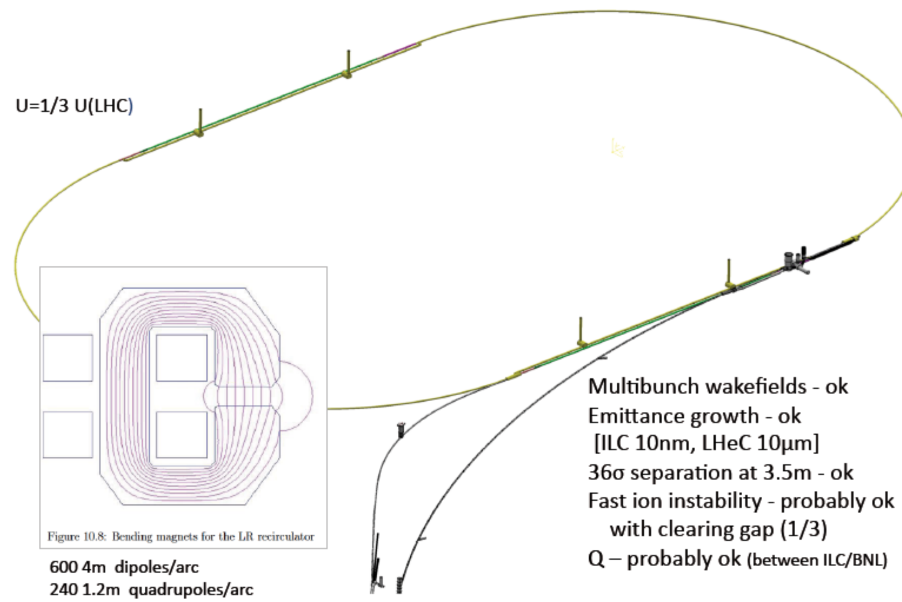


LHeC (FCC-eh) Linac Option

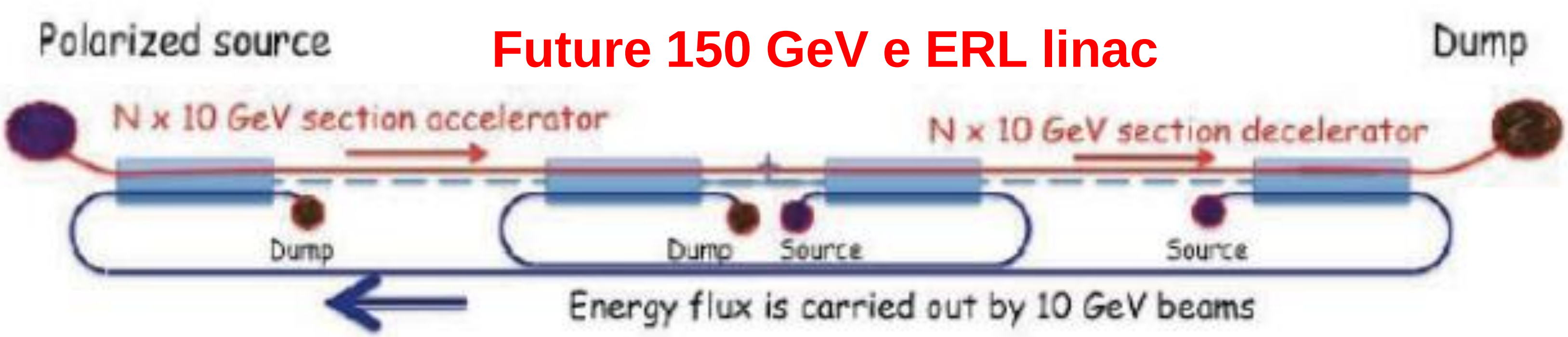
THREE-PASS ERL



Single-PASS 60 GeV ERL



Future 150 GeV e ERL linac

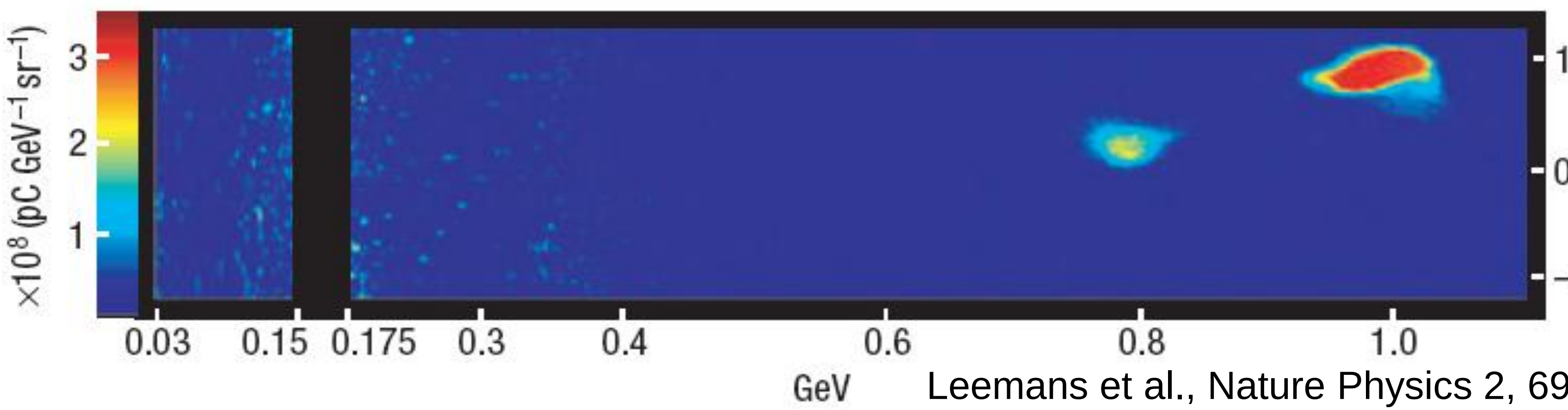


Surfing the wave

- We know that electric fields inside an atom are enormous. Can we find a way to use them to accelerate? In a plasma, yes.

Plasma Wake-Field Acceleration

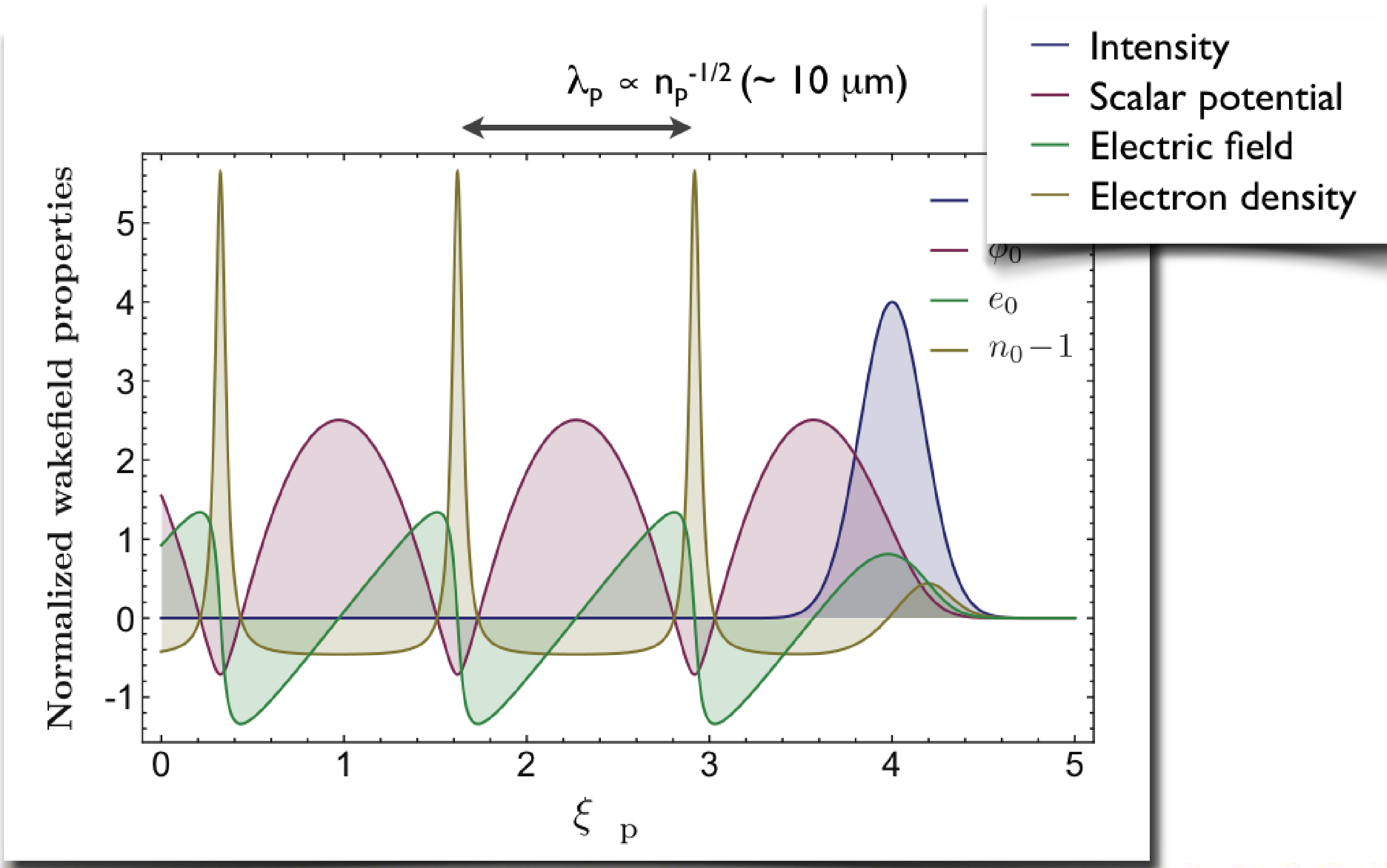
- Development of much higher gradient accelerator not only pushes back frontier for particle physics – also permits current accelerators to be built much smaller/cheaper.
- 1 GeV electron beams on “table top”.



Leemans et al., Nature Physics 2, 696 (2006)

Inject beam

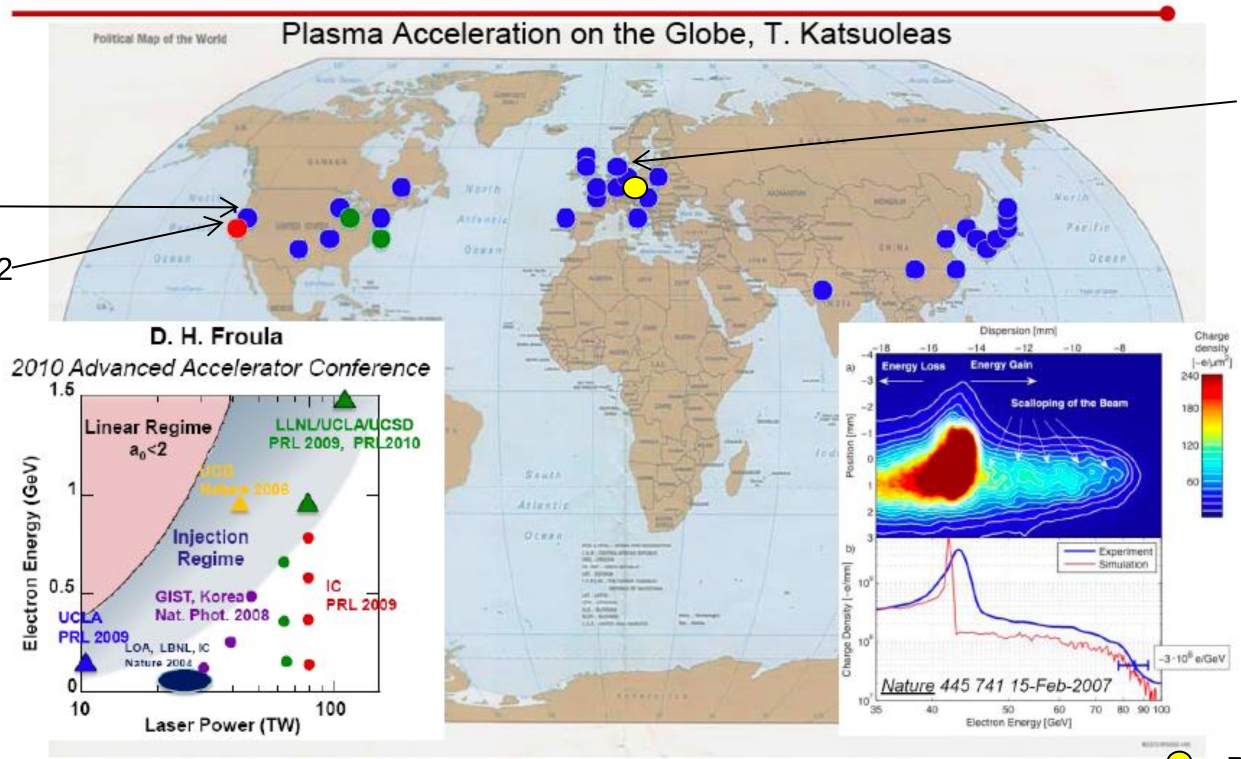
- **To understand acceleration in plasma, inject high-quality beam into plasma – requires excellent time and spatial precision**



World-wide acceleration

- **Enormous growth in activity world-wide – interesting experiments can be done at Universities but most activity at accelerator labs.**

World-Wide Interest in Plasma Acc.



LAOLA: Helmholtz VI, ELI, FLASH, PITZ, REGAE

BELLA

FACET, FACET2

Laser Wake Expts · Electron Wake Expts · e-/e+ Wake Expts · Proton driven

The New Livingston Plot

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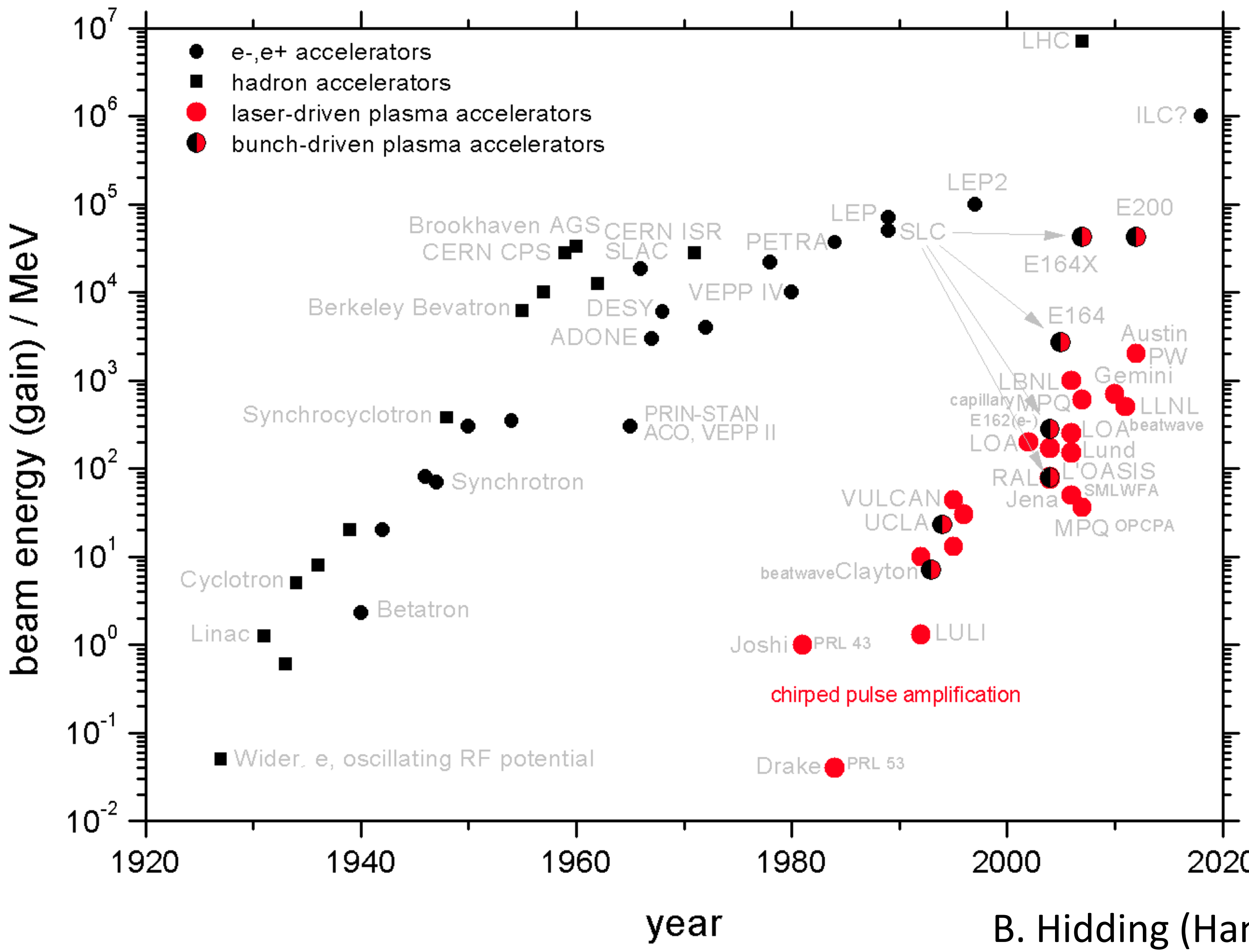

B. Hidding (Hamburg)

Realising the dreams?

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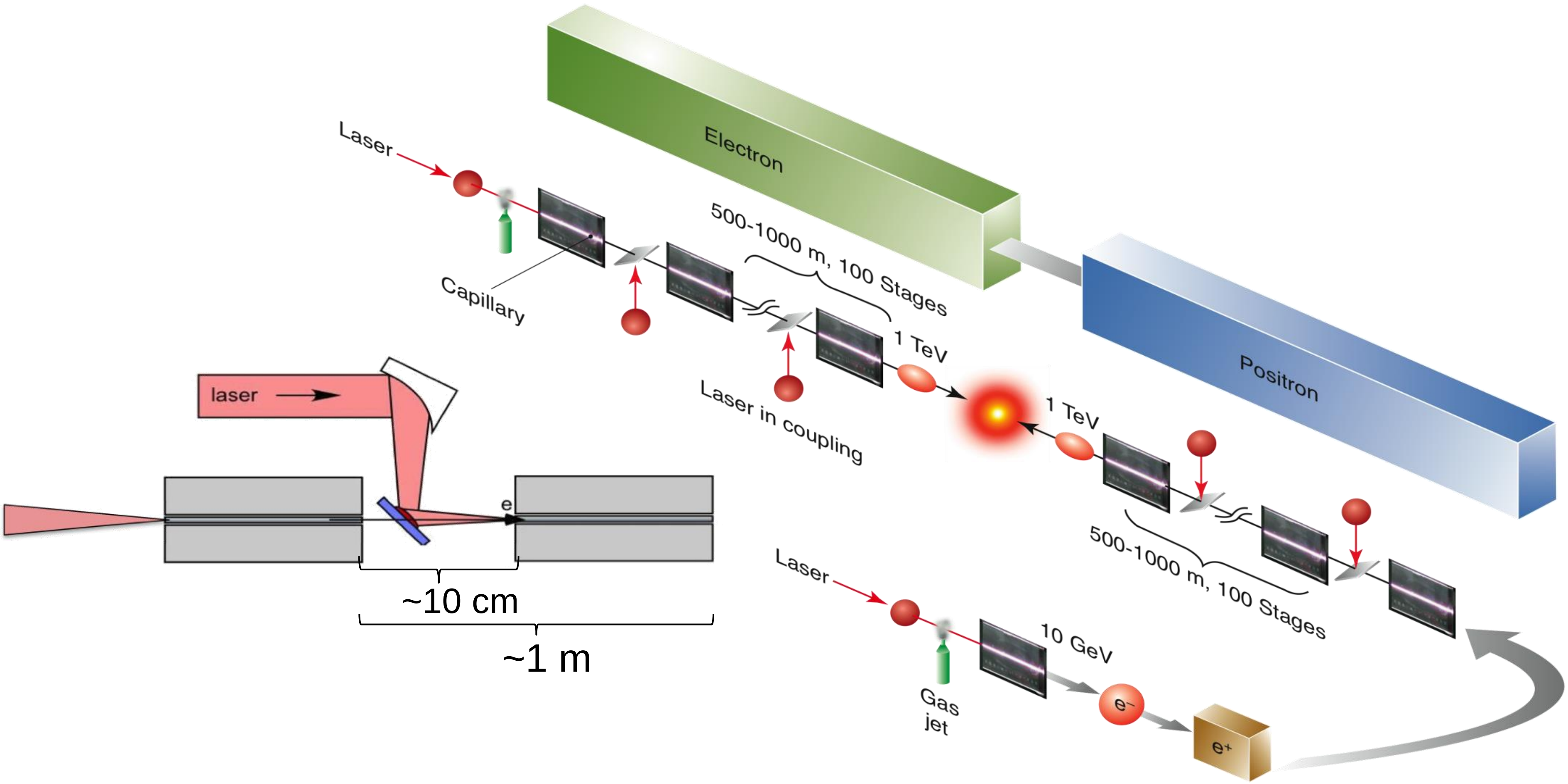
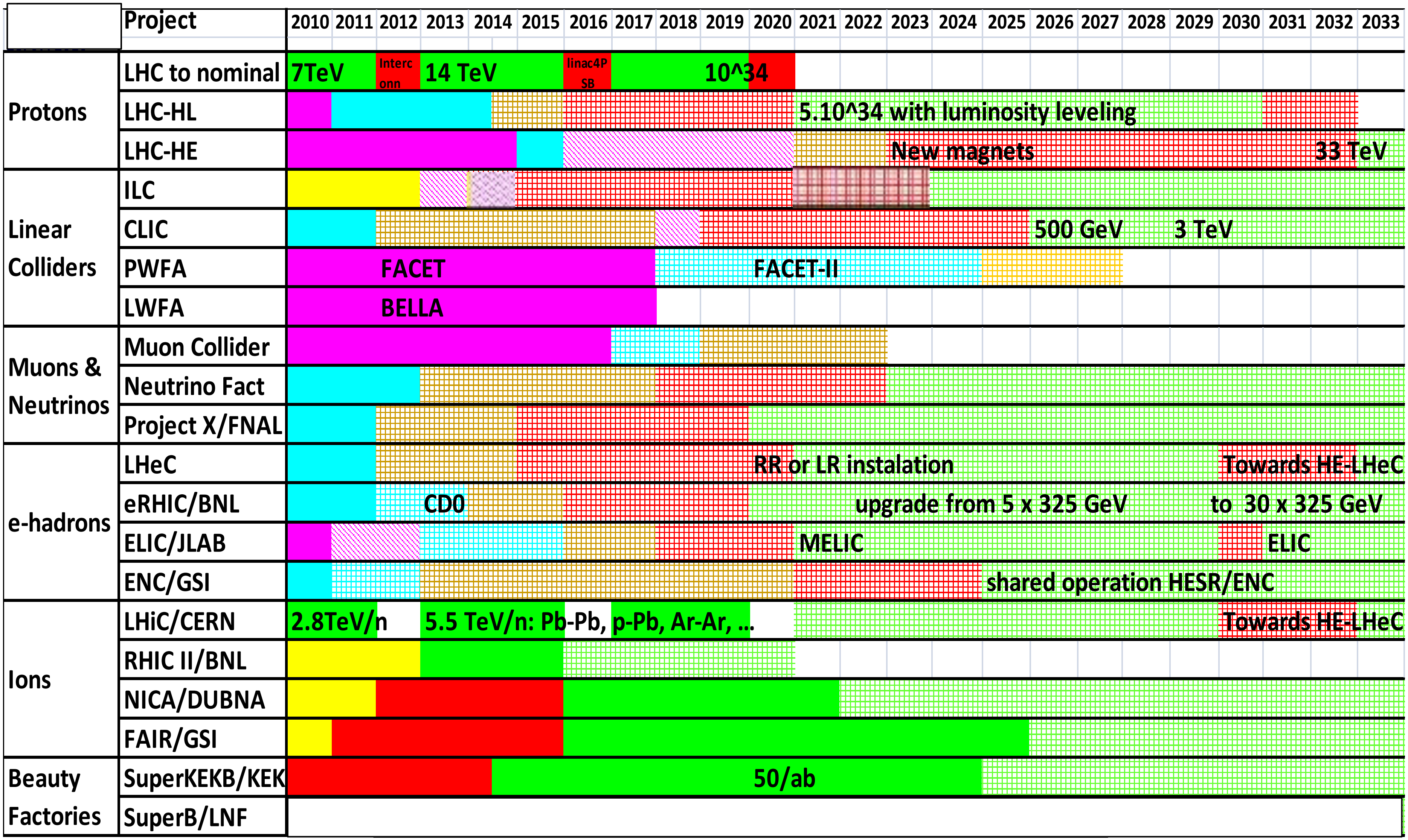
- **A laser-plasma-driven linear collider?**

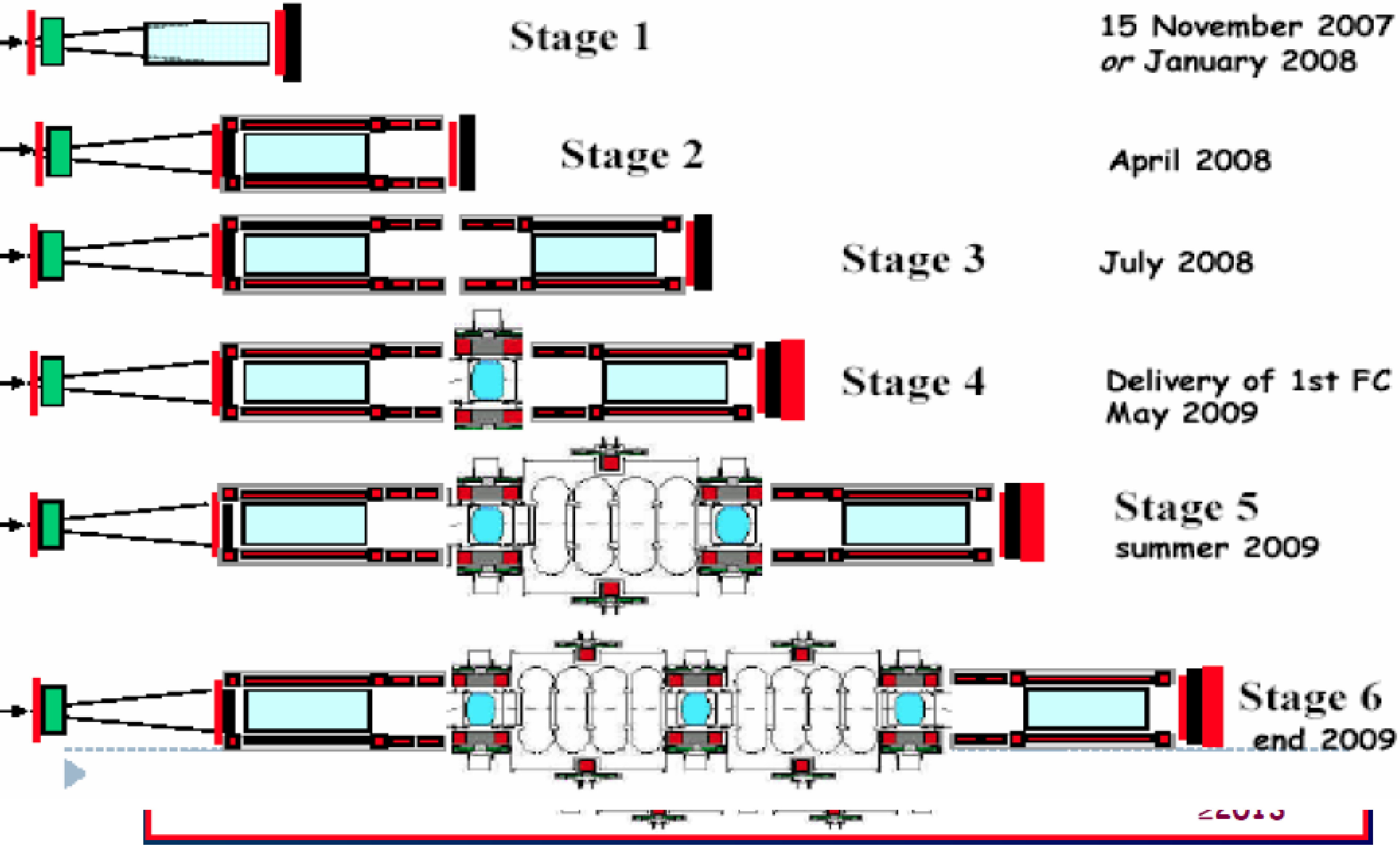


Tentative schedule new projects

Color code	approved	envisaged/proposed
R&D		
R&D to CDR		
Technical design to TDR		
Construction		
Operation		



MICE Schedule



Summary and Outlook

- Particle & accelerator physics very lively – many ideas out there.
- In last ~ year, great upsurge of interest in new large rings, aimed at ~ 100 TeV pp but with possibility of initial e^+e^-
- ILC – technically mature – but expensive
- CLIC – significant development required – < 1 TeV, cost ~ ILC
- Circular e^+e^- – Higgs factory cheaper than LC – but not trivial accl. physics & no energy-upgrade path…
- μC – It's a great idea but don't hold your breath….
- LHeC/FCC-eh – technically "OK" once protons there. Cost/physics?
- PWA – very exciting, but long way from a LC for particle physics
- A Japanese offer to host ILC is being discussed. In the next lecture we will look at its design in detail and the status of realising the project.