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Future Accelerator Facilities

for Particle Physics & beyond

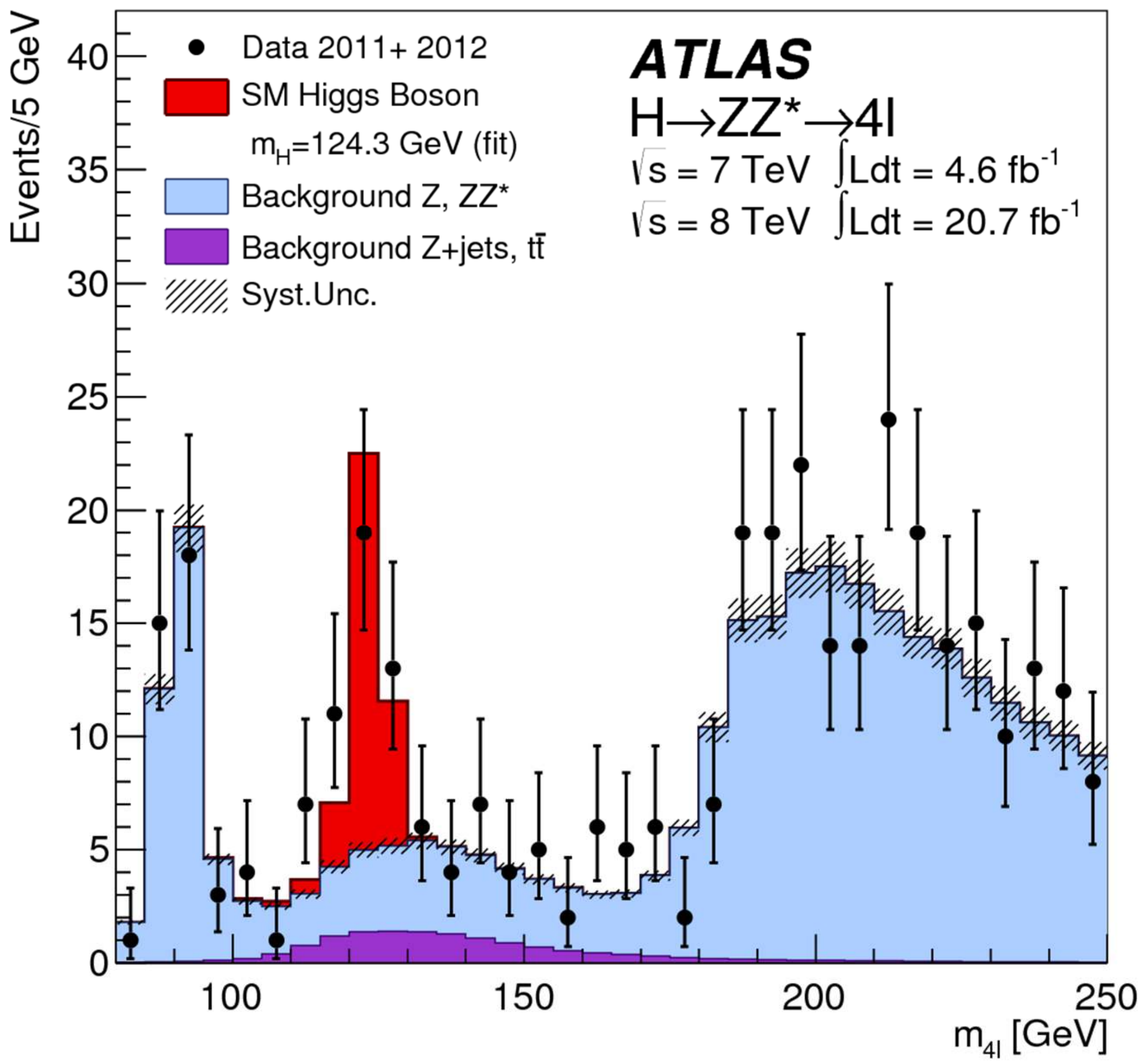
Brian Foster (Uni Hamburg/DESY)

PIER Colloquium
November 2014

Outline

- Overview of ideas for future facilities
  - **Hadron-hadron machines – LHC (& beyond)**
  - **Lepton-lepton Machines**
    - e$^+$e$^-$ - linear, circular; μ$^+$μ$^-$
  - **(Lepton-hadron machines)**
  - **Plasma-wave acceleration**
- Status & prospects

The Higgs – particle physics at a cusp?



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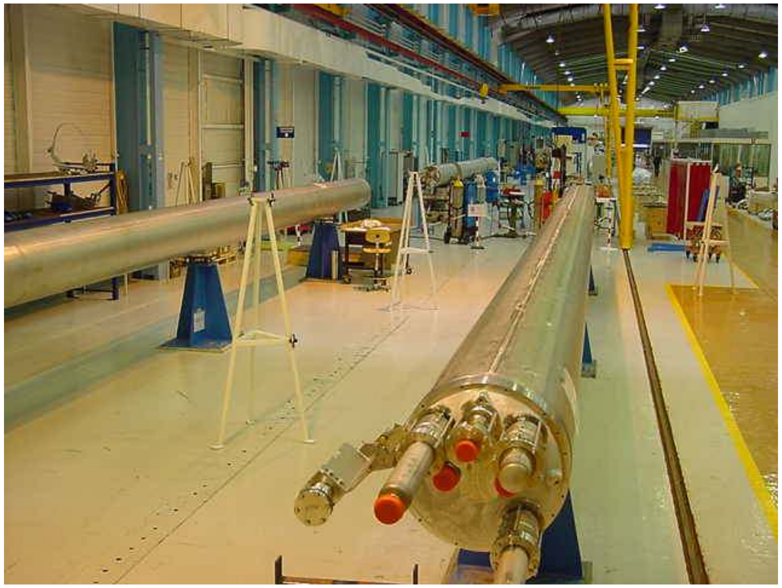
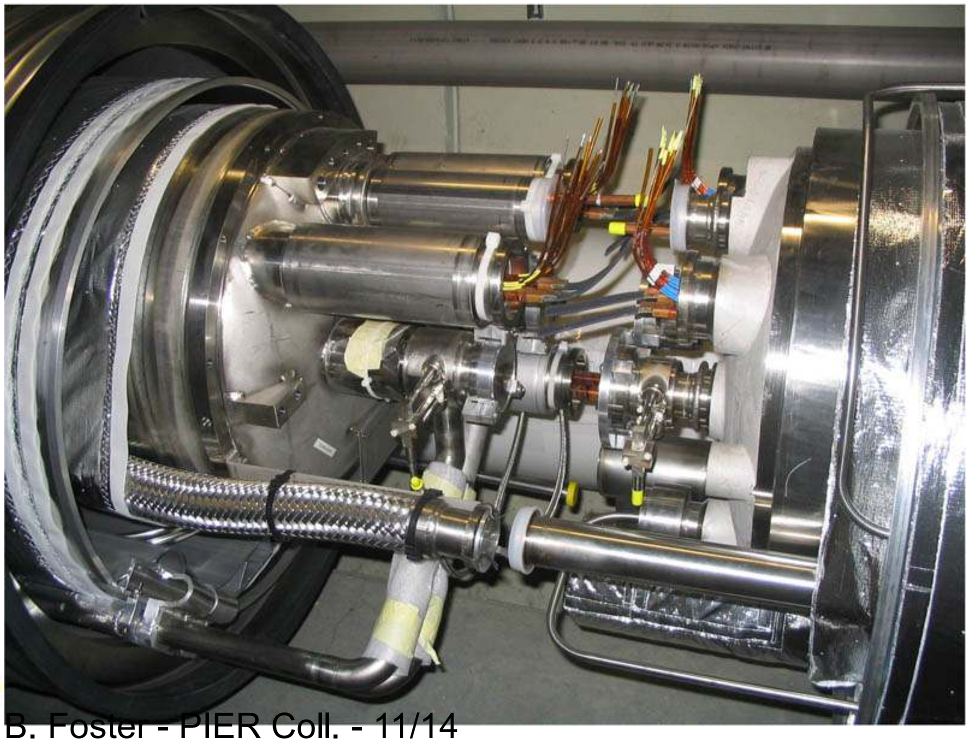
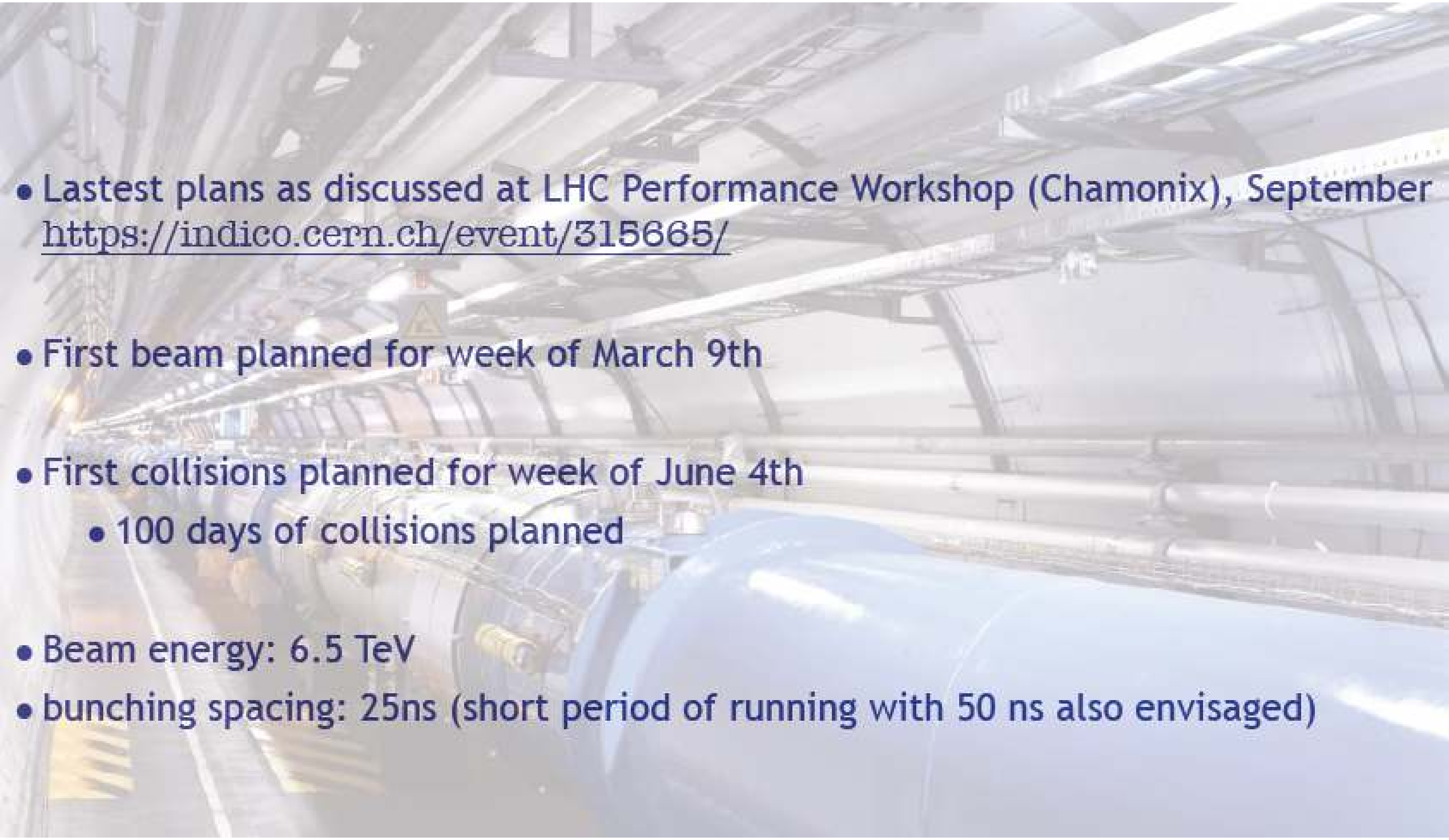
The LHC Accelerator

The LHC is an amazing feat of engineering - 27 km of the most high-tech equipment in the world’s biggest instrument.





Run 2 Startup



- Lastest plans as discussed at LHC Performance Workshop (Chamonix), September
  https://indico.cern.ch/event/315665/

- First beam planned for week of March 9th

- First collisions planned for week of June 4th
  - 100 days of collisions planned

- Beam energy: 6.5 TeV
- bunching spacing: 25ns (short period of running with 50 ns also envisaged)

LHC Strategy

LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

🟩	Physics
🟥	Shutdown
🟨	Beam commissioning
🟦	Technical stop

30 fb^{-1}

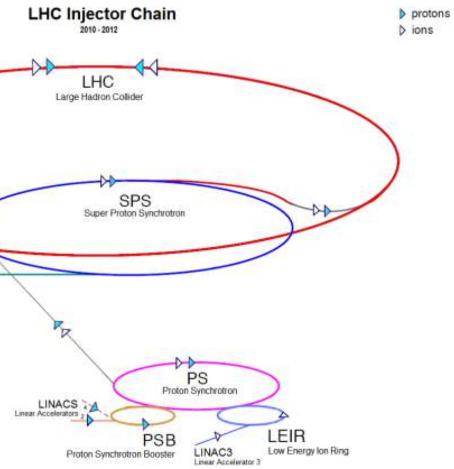
300 fb^{-1}

(Extended) Year End Technical Stop: (E)YETS

3’000 fb^{-1}

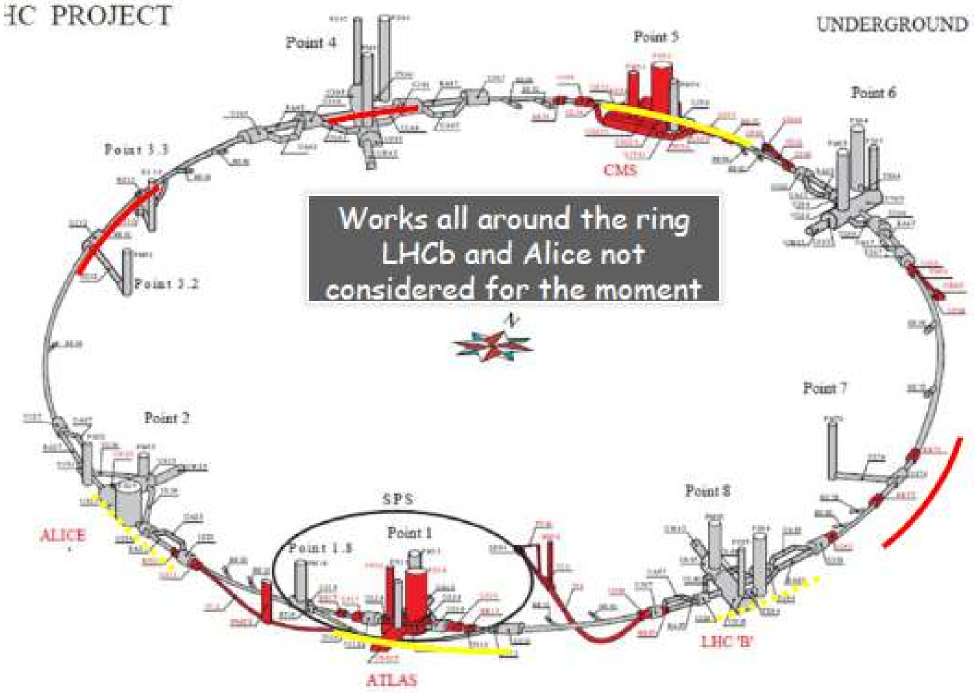
HL-LHC

Goal is to obtain about 3 - 4 fb^{-1}/day (250 to 300 fb^{-1}/year)



Many improvements on the injector chain

- Linac 4 - PS booster
- PS
- SPS



Works all around the ring
LHCb and Alice not
considered for the moment

Many improvements on the LHC ring

- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

LHC Technology

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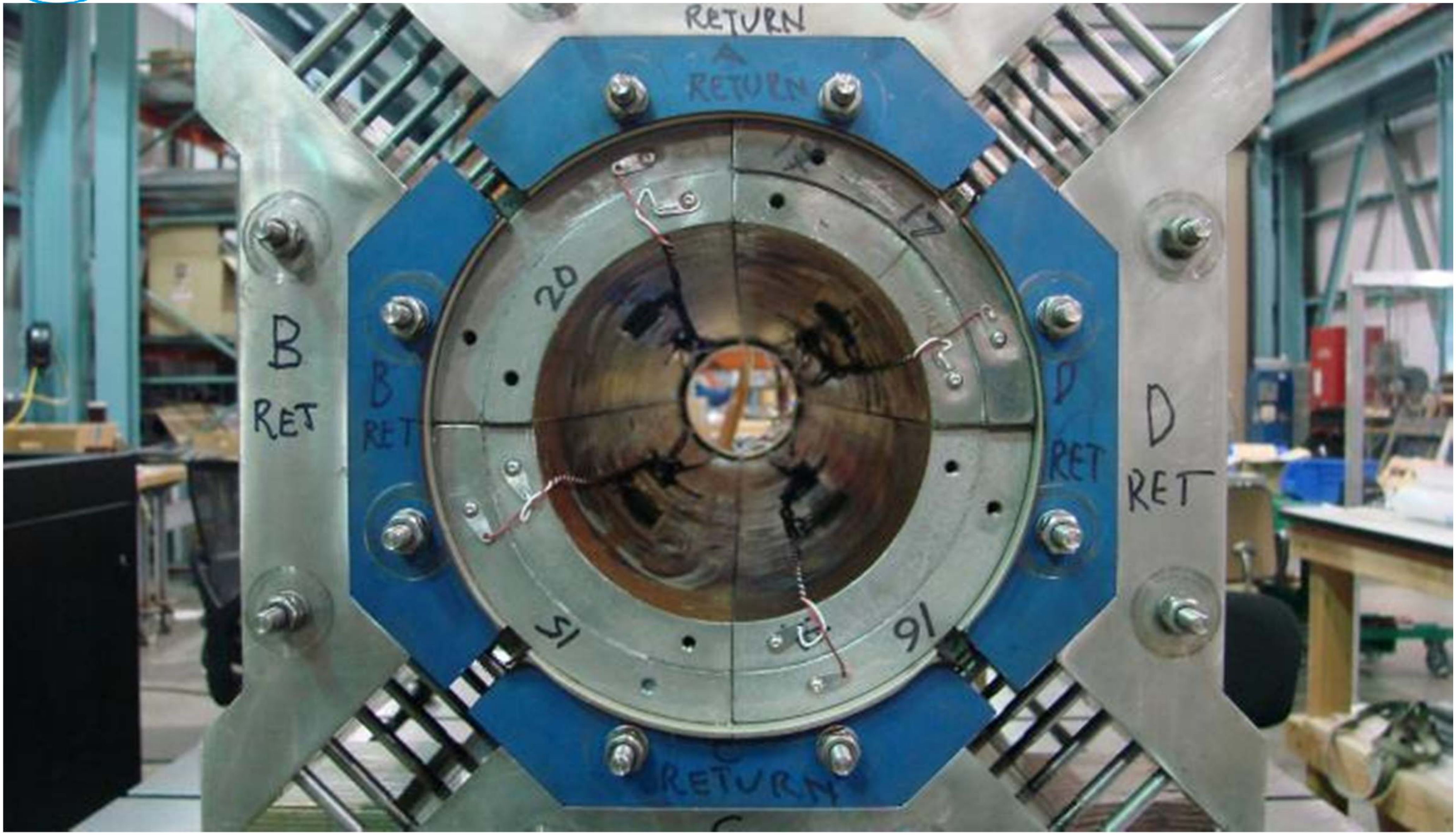

Successful US test in 2013 of new Nb_3Sn quads for IR

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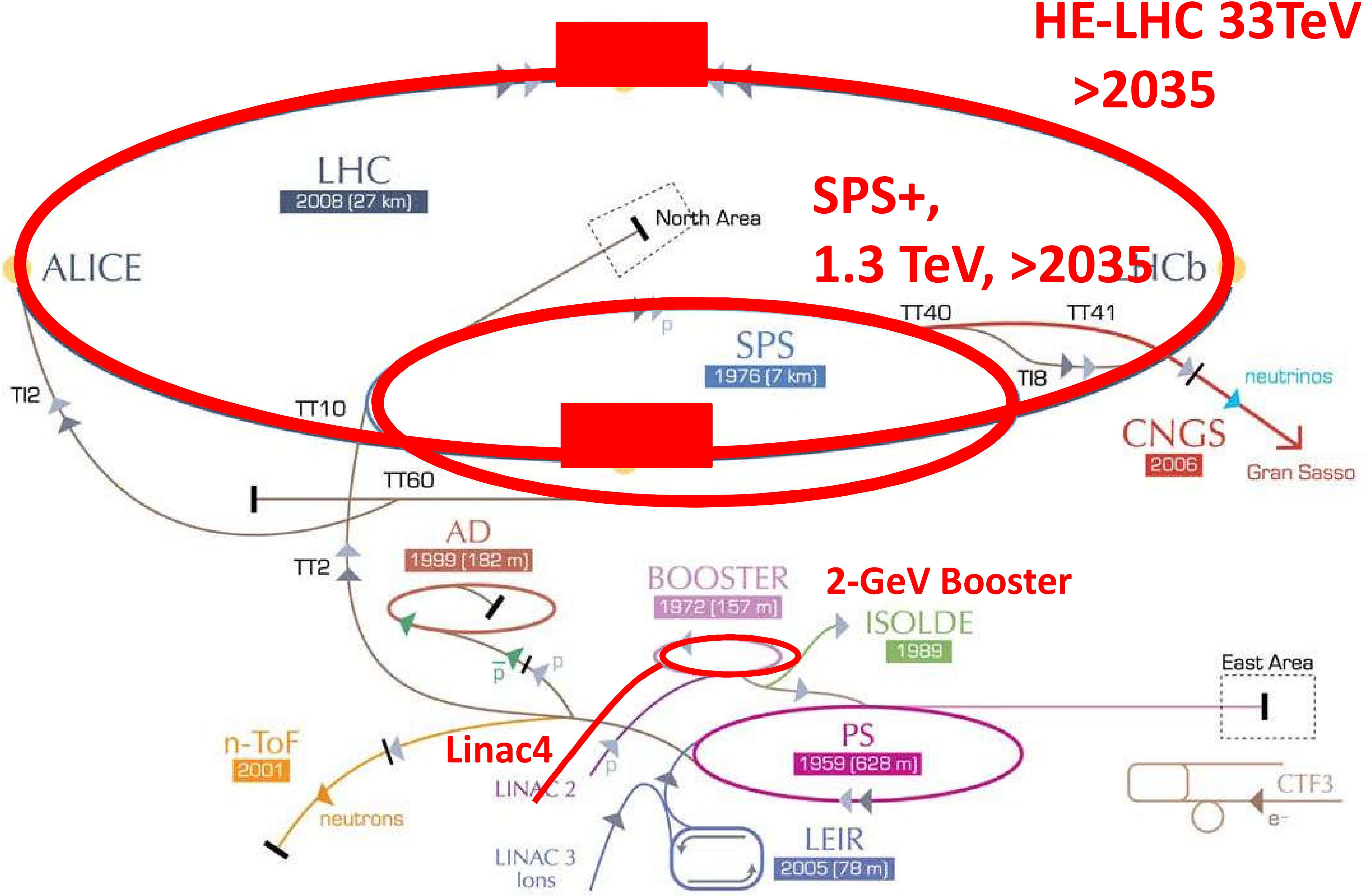
High Energy LHC



HE-LHC 33TeV
>2035

SPS+,
1.3 TeV, >2035

2-GeV Booster

Linac4

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

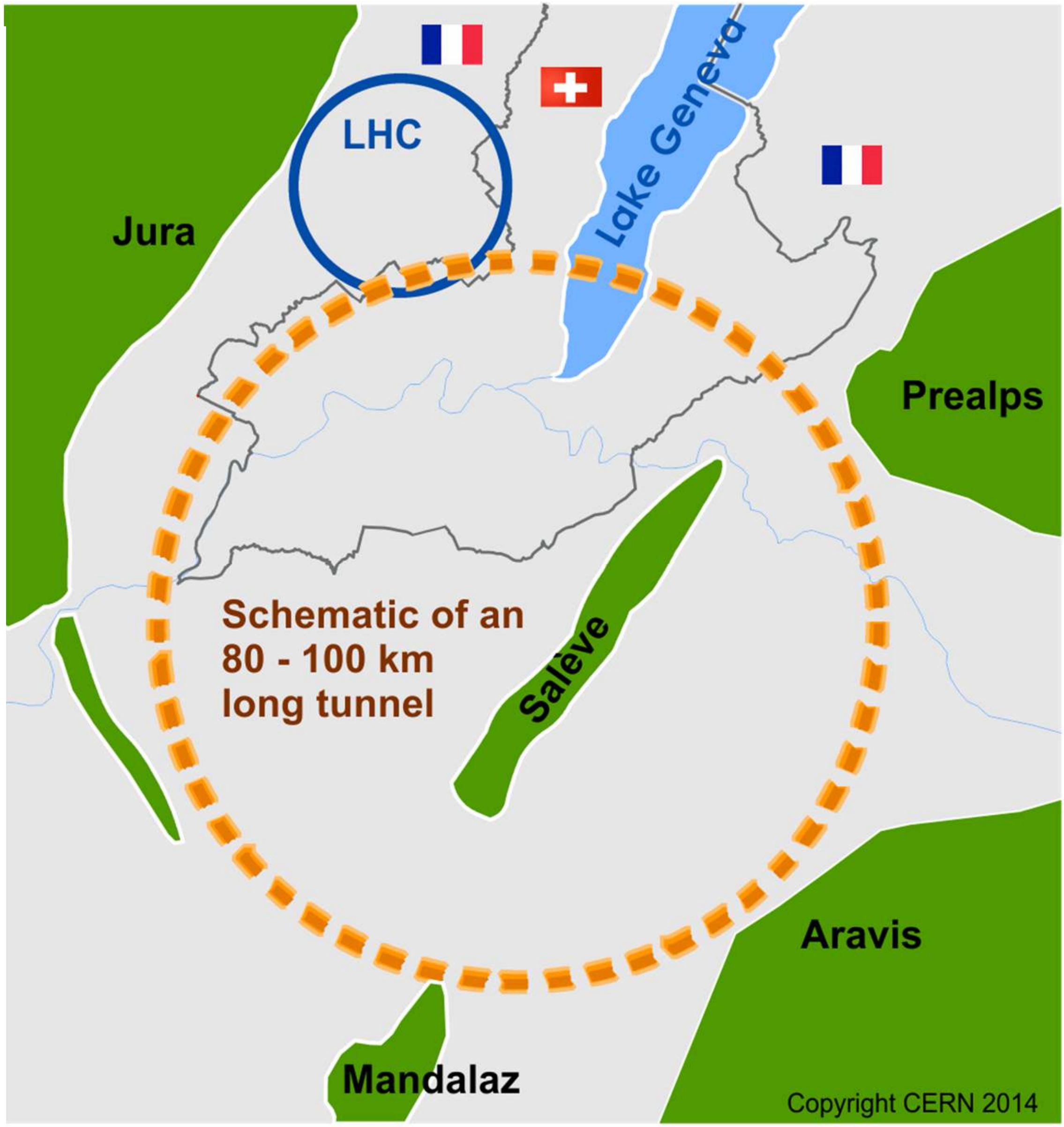
FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2018



(FCC slides thanks to D.Schulte.)

FCC Preliminary Layout

First layout developed (different sizes under investigation)

⇒ Collider ring design (lattice/hardware design)

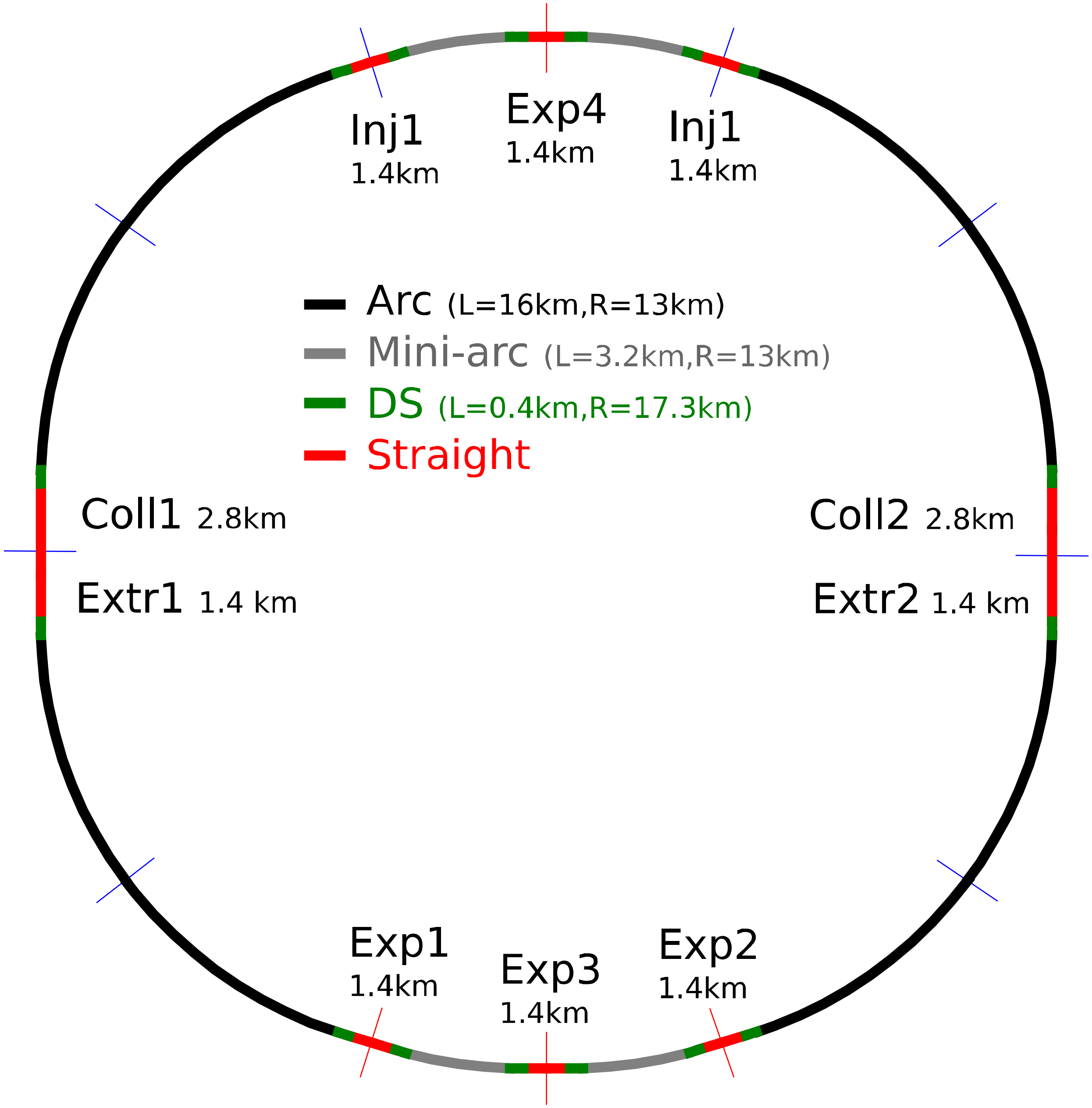
⇒ Site studies

⇒ Injector studies

⇒ Machine detector interface

⇒ Input for lepton option

Will need iterations

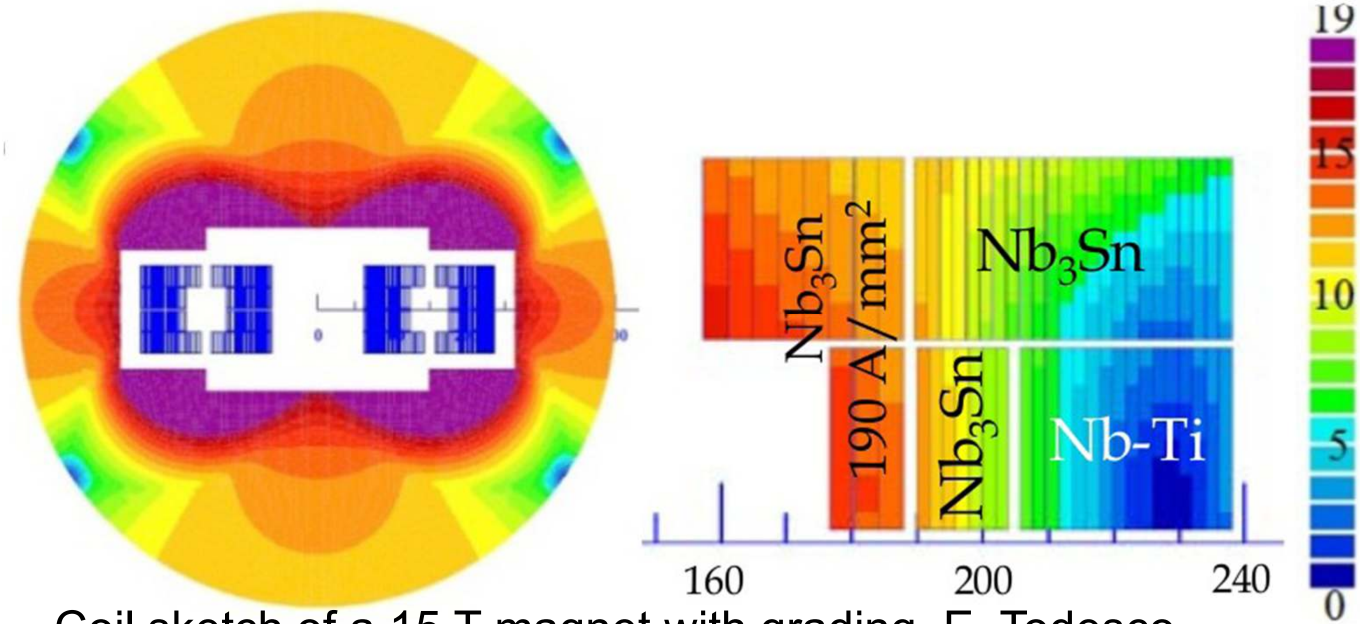


FCC Magnets

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

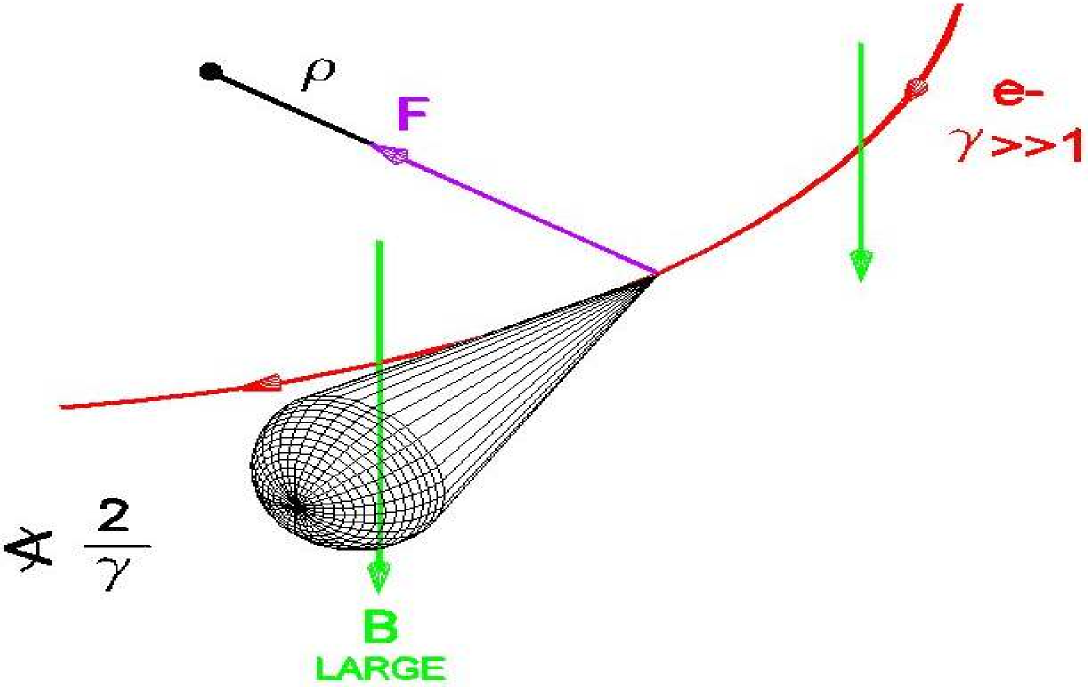
FCC Synchrotron Rad.

At 100 TeV even protons radiate significantly

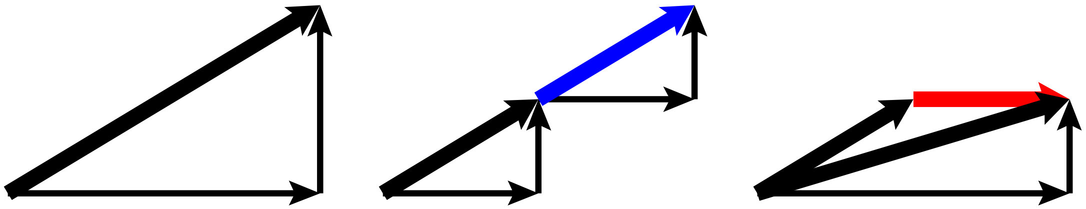
Total power of 5 MW (LHC 7kW)
⇒ Needs to be cooled away

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

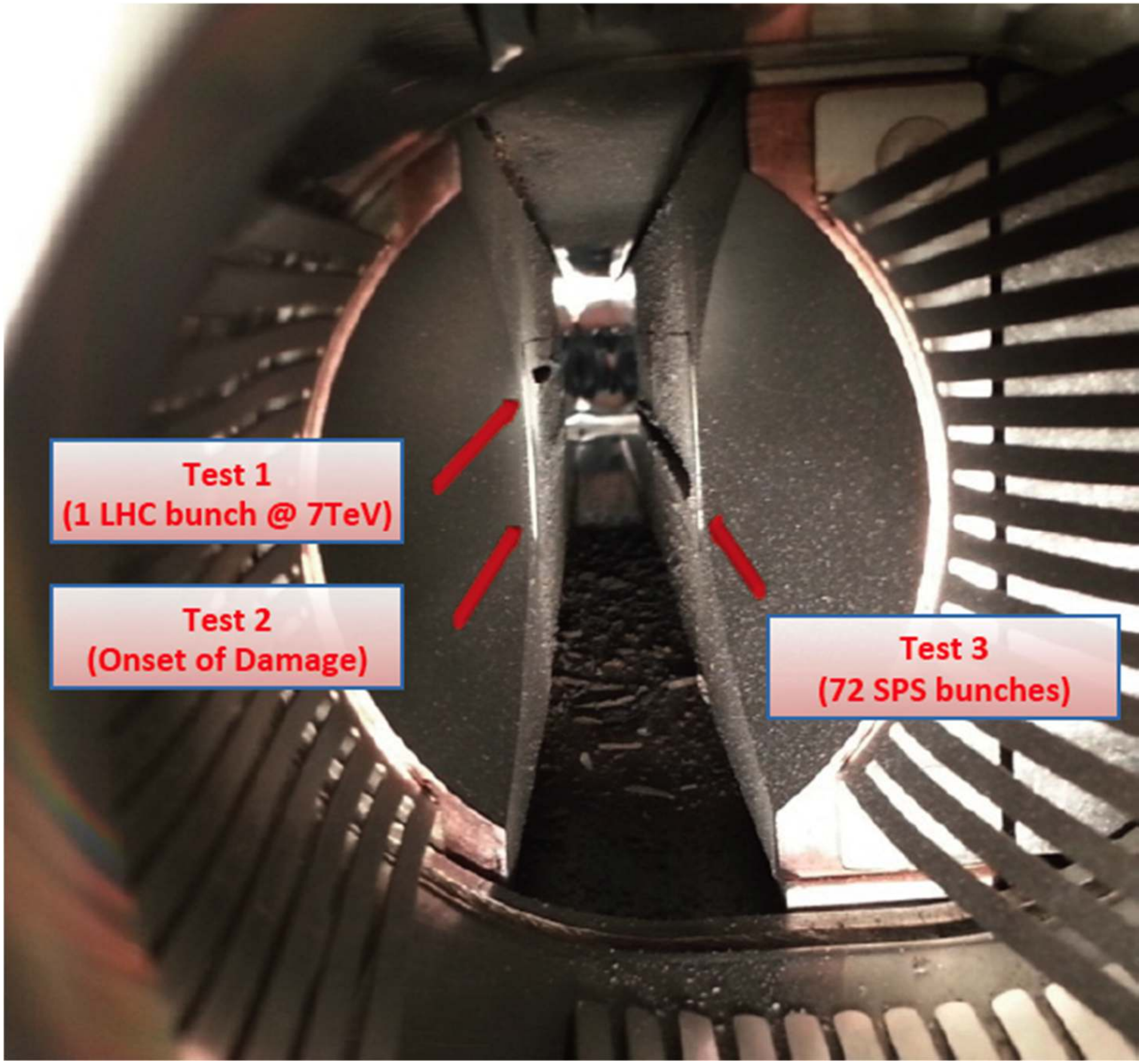


Protons loose energy
⇒ They are damped
⇒ Emittance improves with time

- Typical transverse damping time 1 hour

FCC Machine Protection

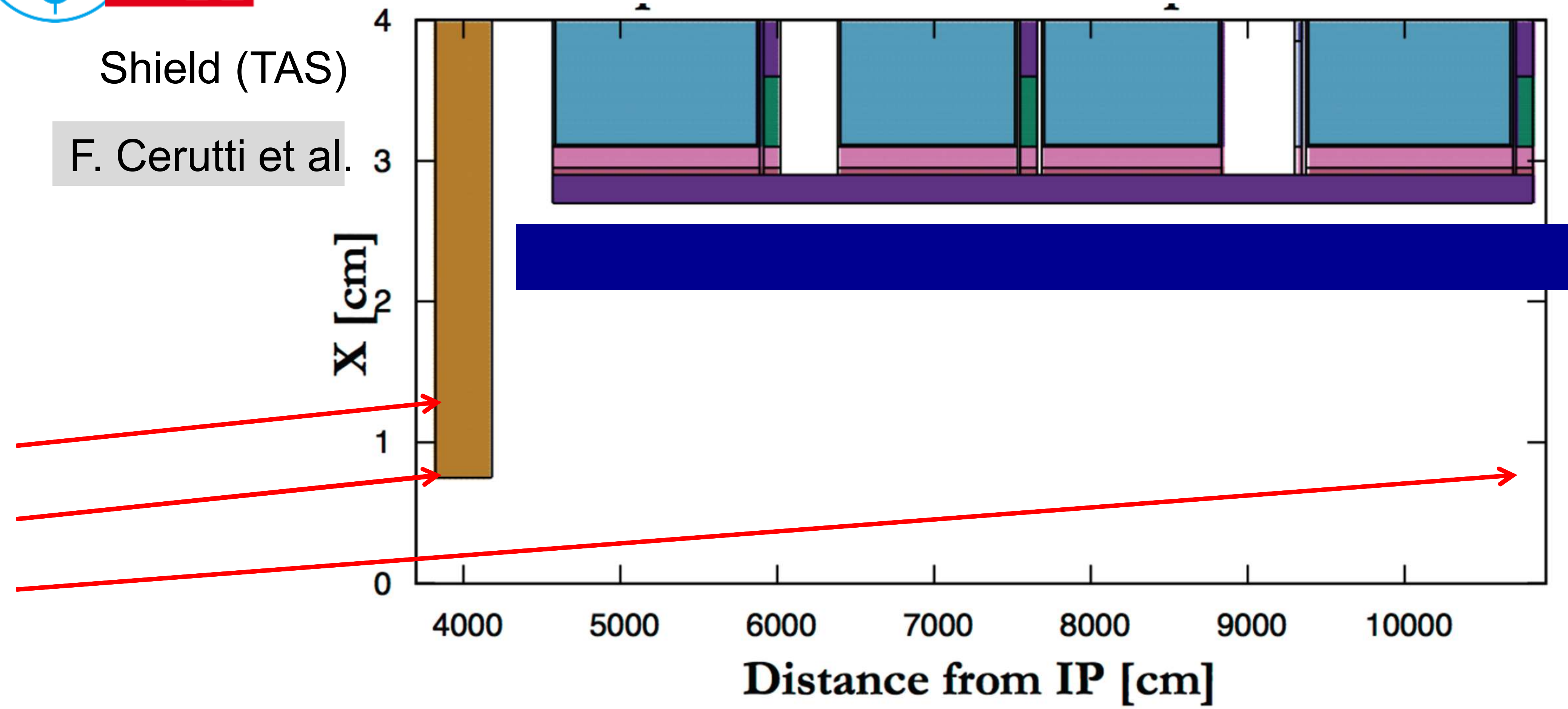
- >8GJ kinetic energy per beam
  - Airbus A380 at 720km/h
  - 24 times larger than in LHC at 14TeV
  - Can melt 12t of copper
  - Or drill a 300m long hole
  - ⇒ **Machine protection**
- Also small loss is important
  - E.g. beam-gas scattering, non-linear dynamics
  - Can quench arc magnets
  - Background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



Backgrounds from IP

Shield (TAS)

F. Cerutti et al.

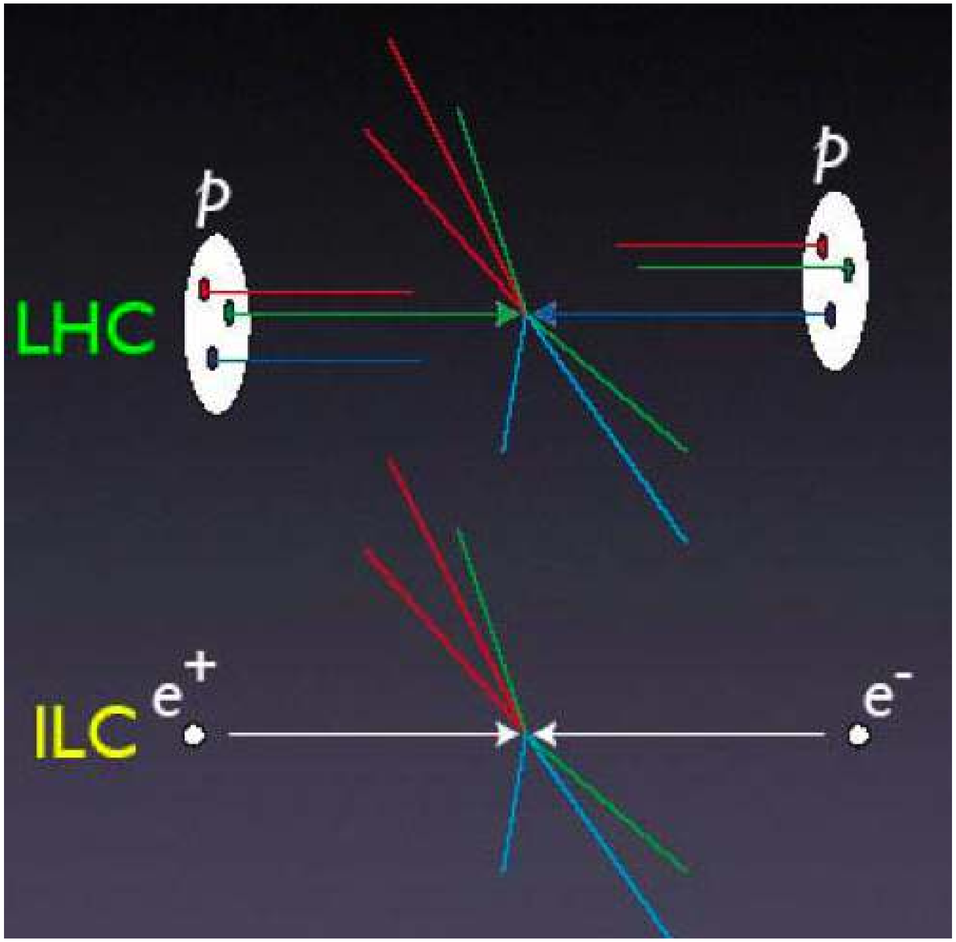


- Total power of background events 100kW per experiment (a car engine)
- Already a problem in LHC and HL-LHC (heating, lifetime)

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

e^+e^- vs pp

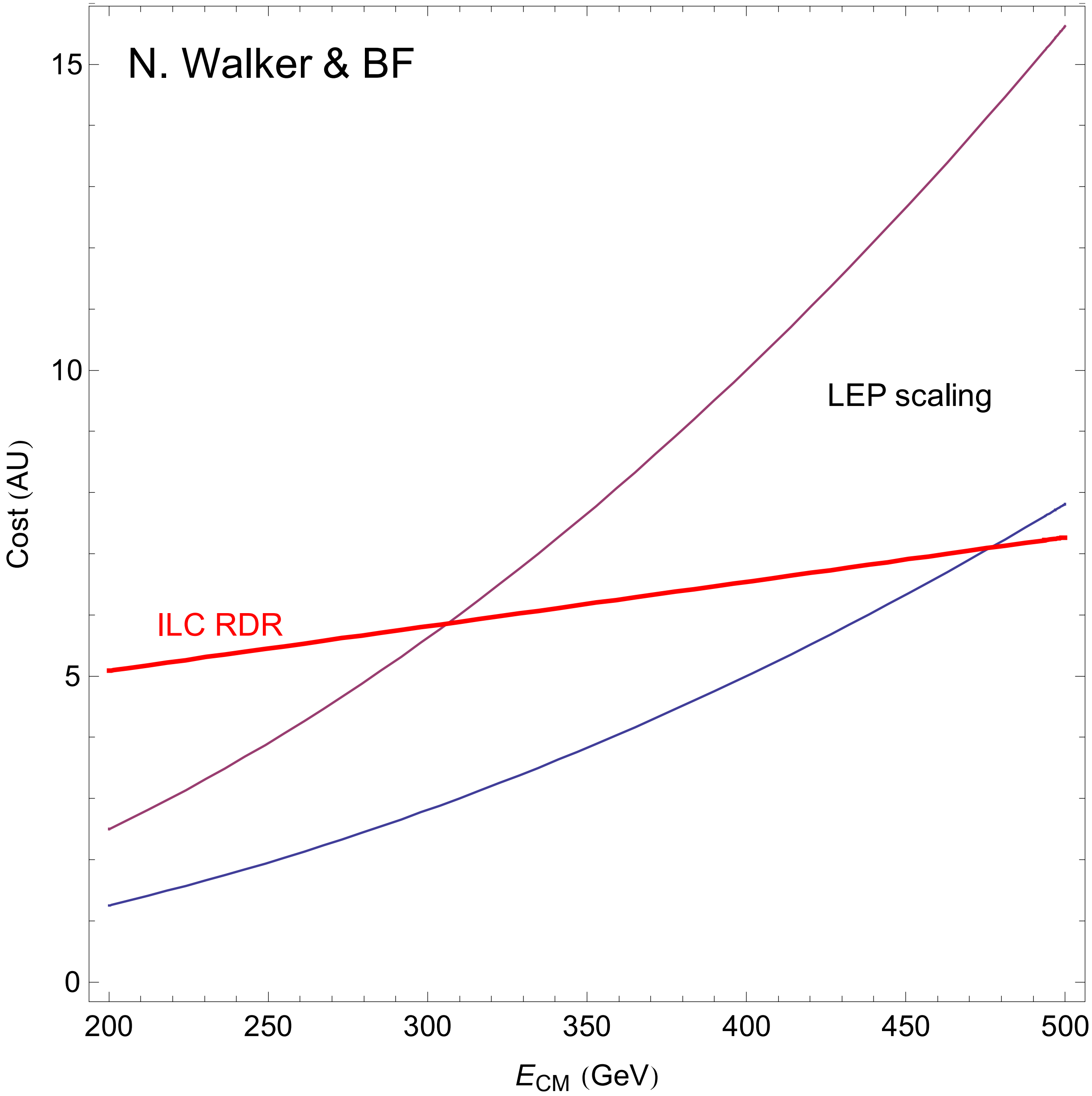
- Simple particles
- Well defined:
  energy, angular mom.
- E can be scanned precisely
- Particles produced ~ democratically
- Final states generally fully reconstructable



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.

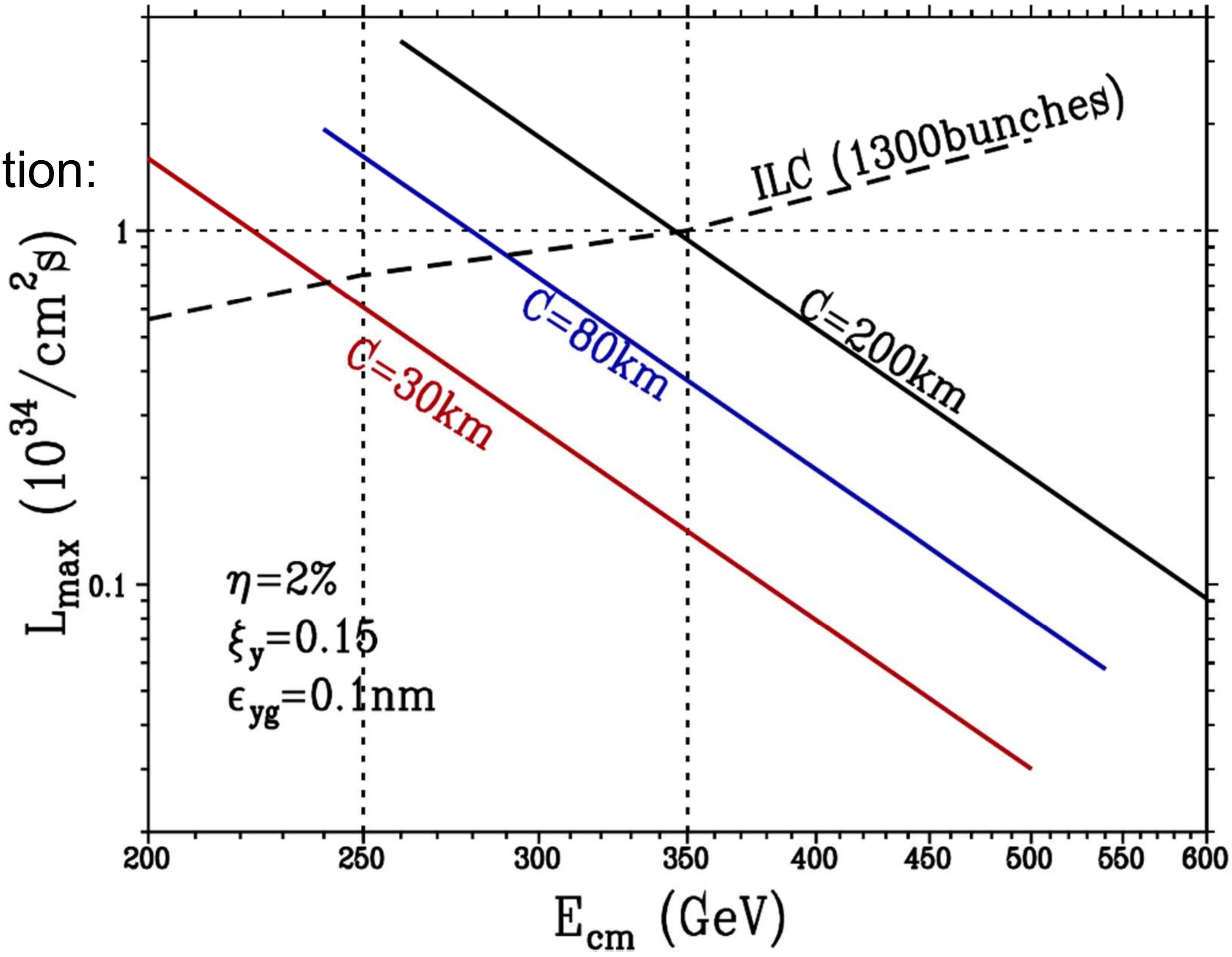


Circular e^+e^- machines

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

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

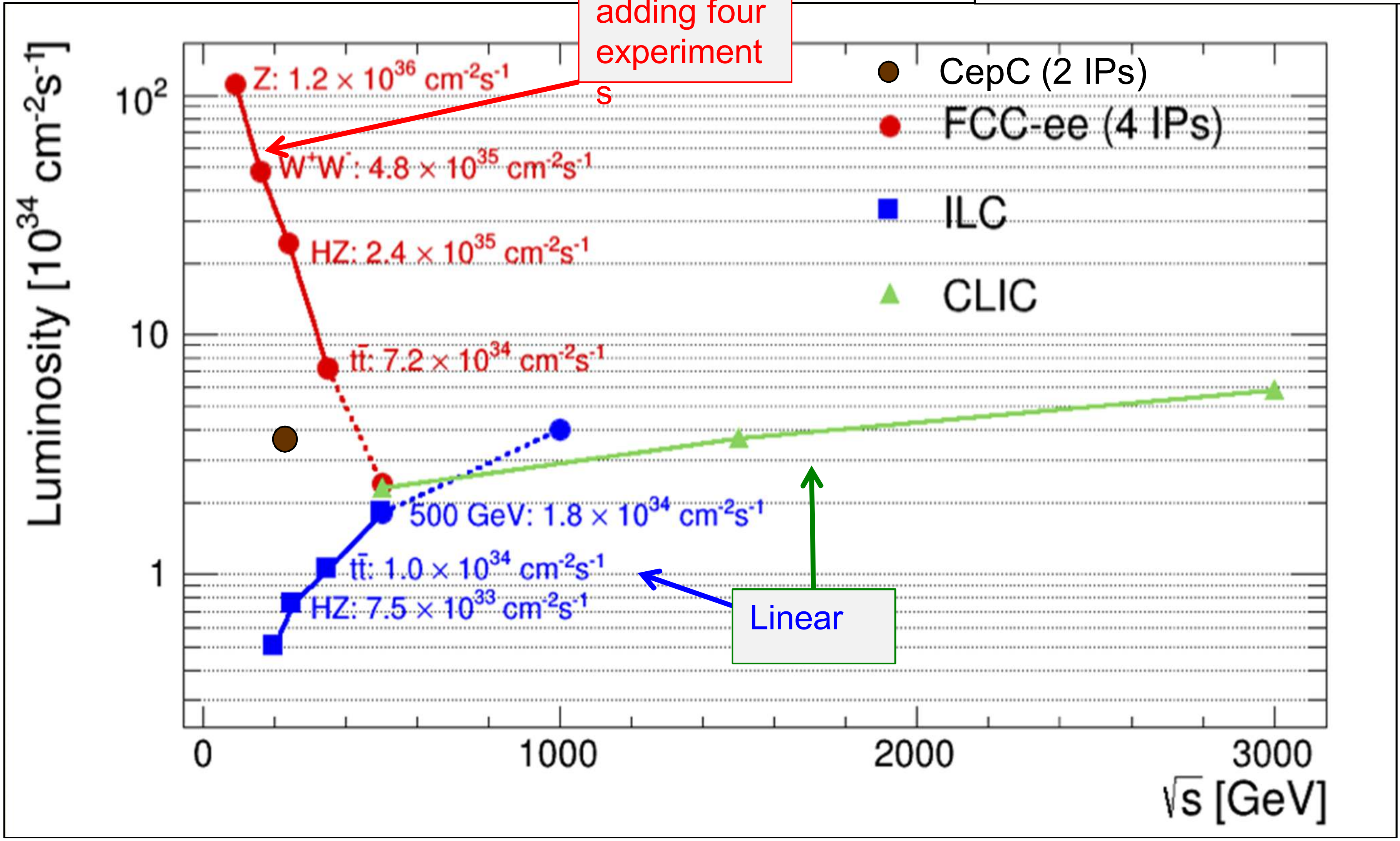
P_{SR} : syn.rad.power
ρ : bending radius
ξ_y : tune-shift
$\varepsilon_{g,y}$: geometric emit.



(Telnov via Yokoya)

Circular e^+e^- machines

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



Circular, adding four experiments

Linear

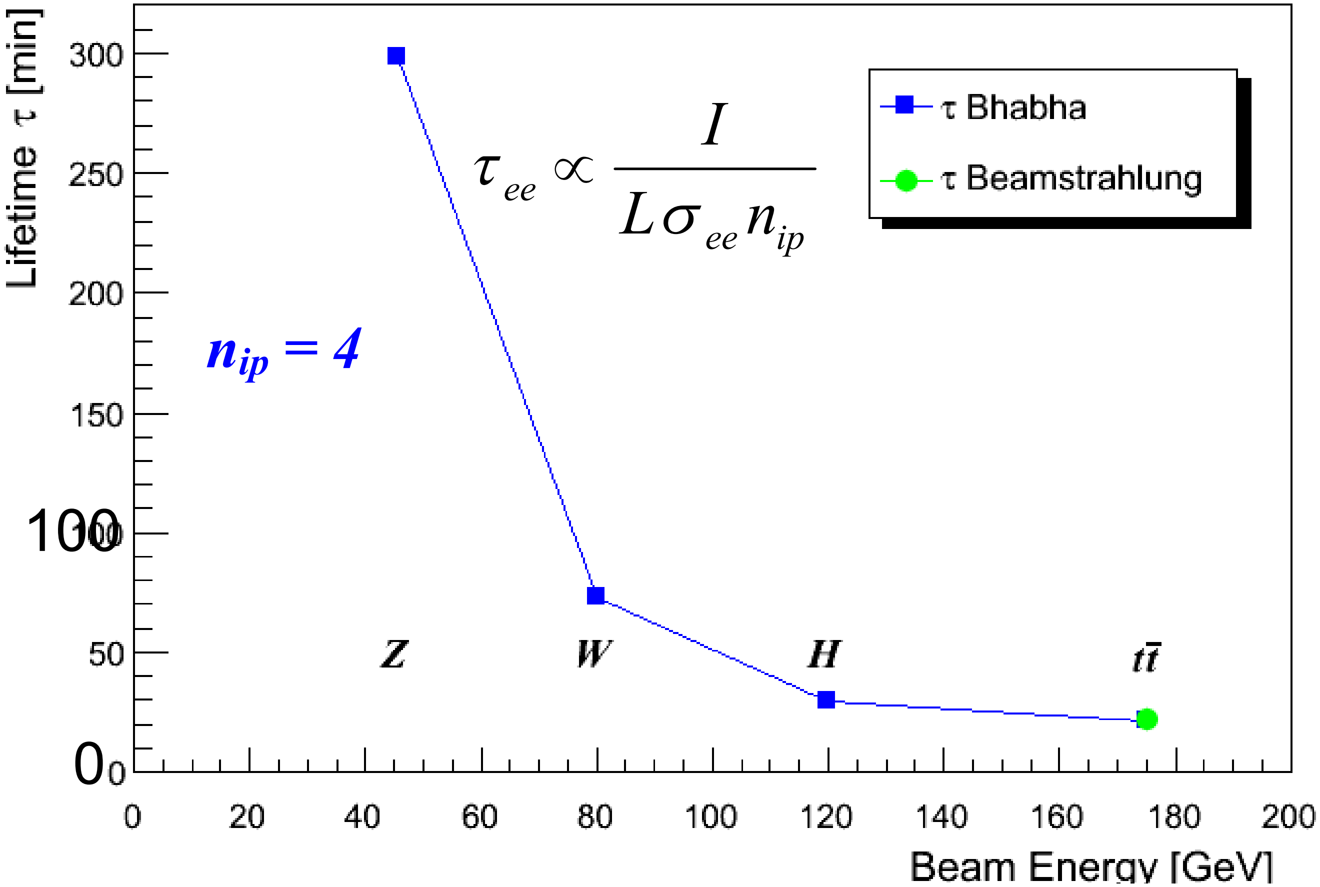
(D. Schulte)

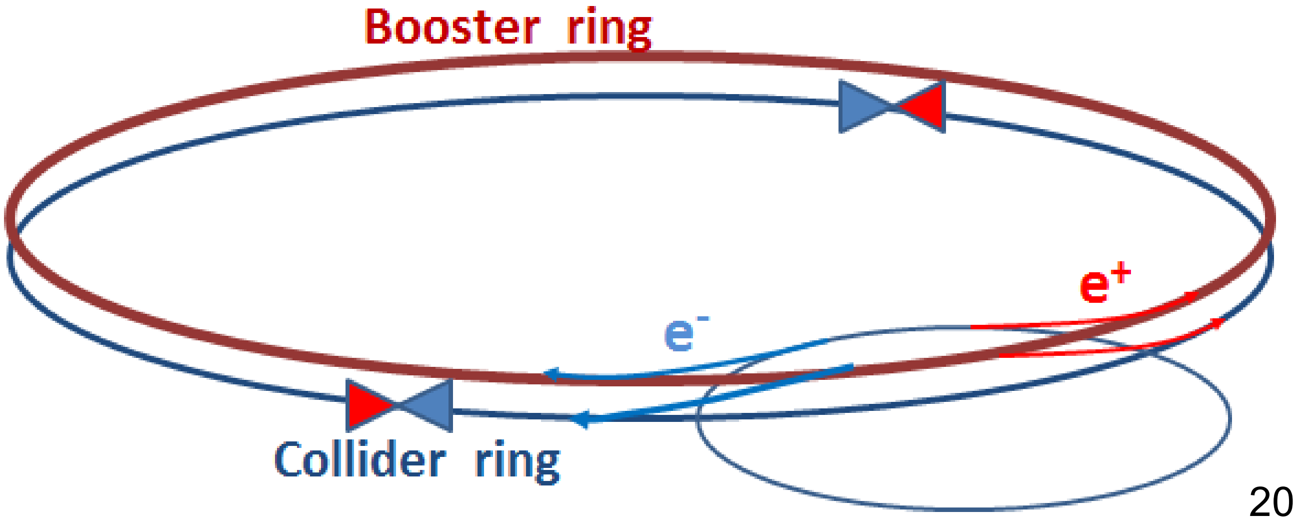
FCC-ee Luminosity Lifetime

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

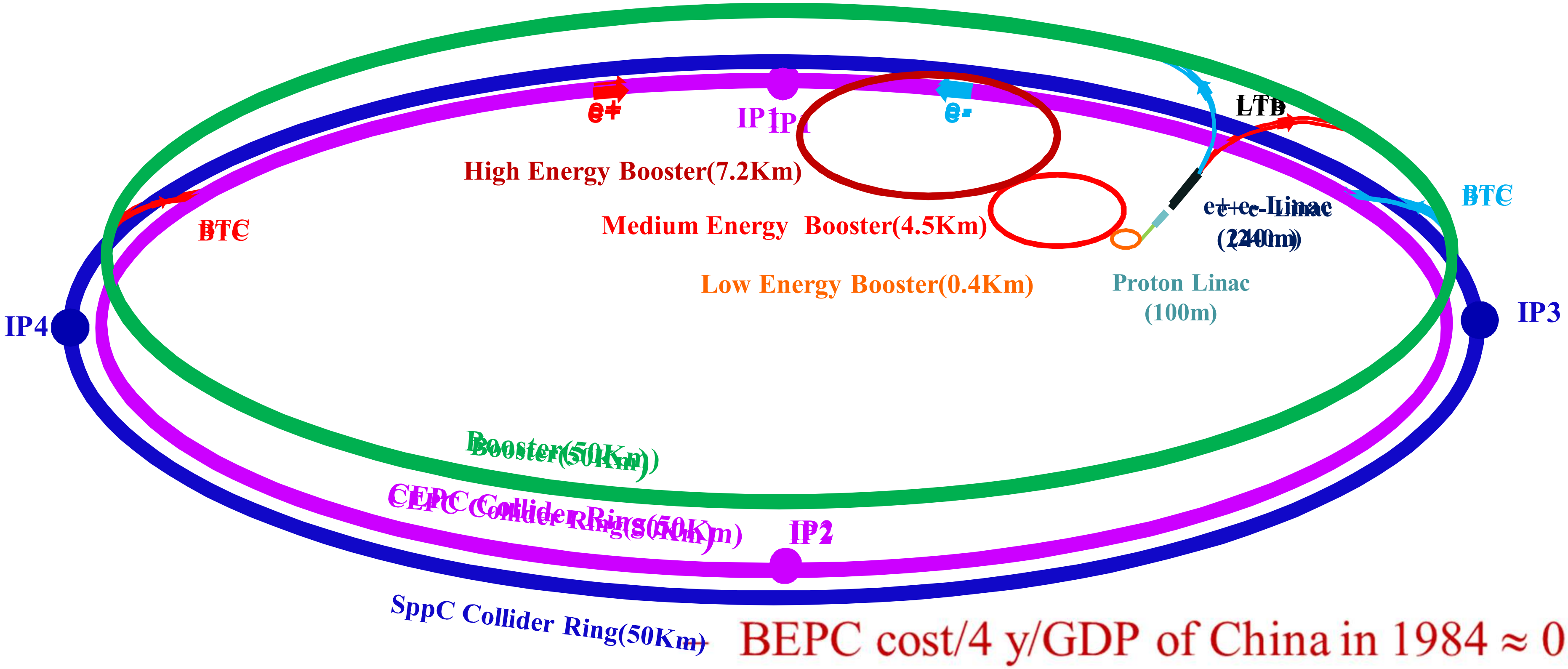
- Radiative Bhabha scattering is proportional to luminosity
- Beamstrahlung as in linear colliders
- As yet no acceptable beam dynamics solution.

Need continuous injection (top-up)





Chinese plans – CEPC & SppC Layout



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

LTB : Linac to Booster

BTC : Booster to Collider Ring

(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

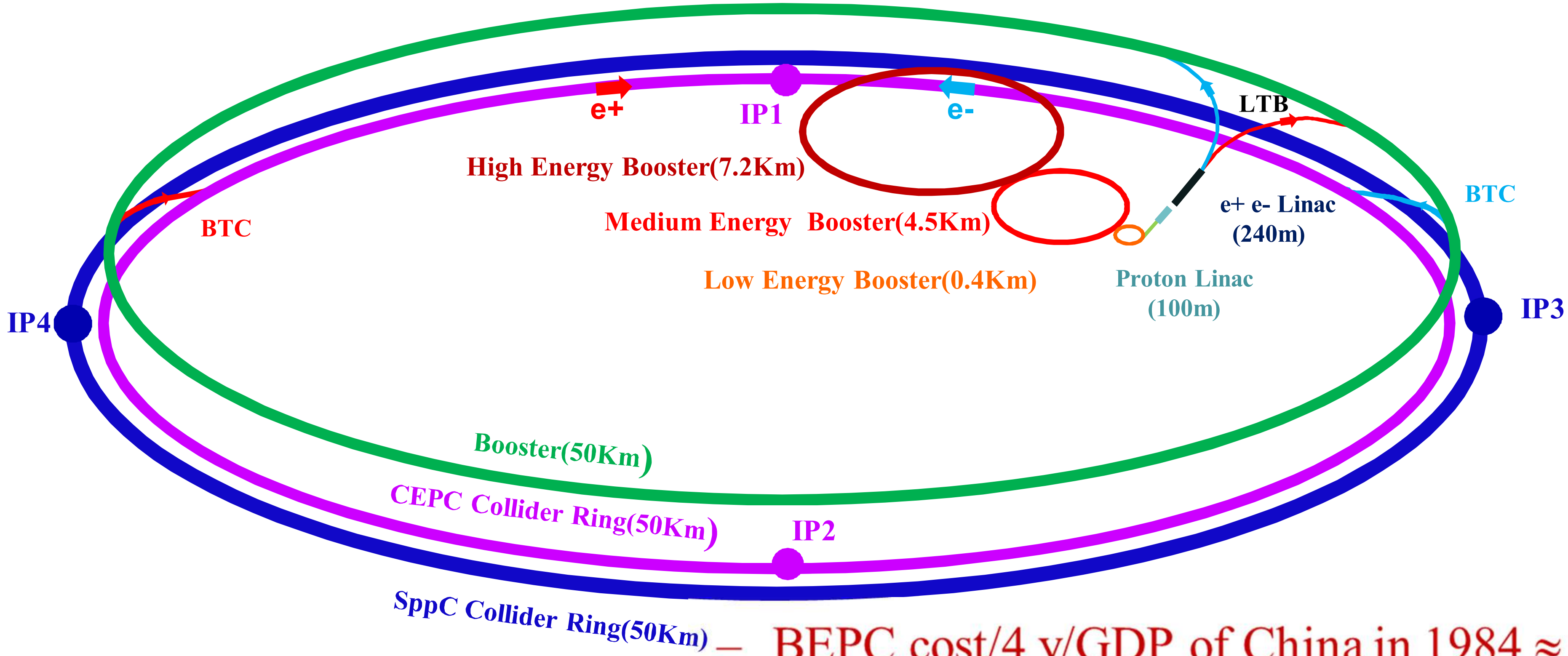
Parameter	Value	Unit
Circumference	52	km
Beam energy	35	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch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

CEPC Site

- **Preliminary selected Qinhuangdao (□□□□(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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- 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

SC predicts 2020 China GDP = $24.6 Trillion
=> Cost of CEPC ~ 0.07*24.6*6 B ~ $10B

ILC Overview

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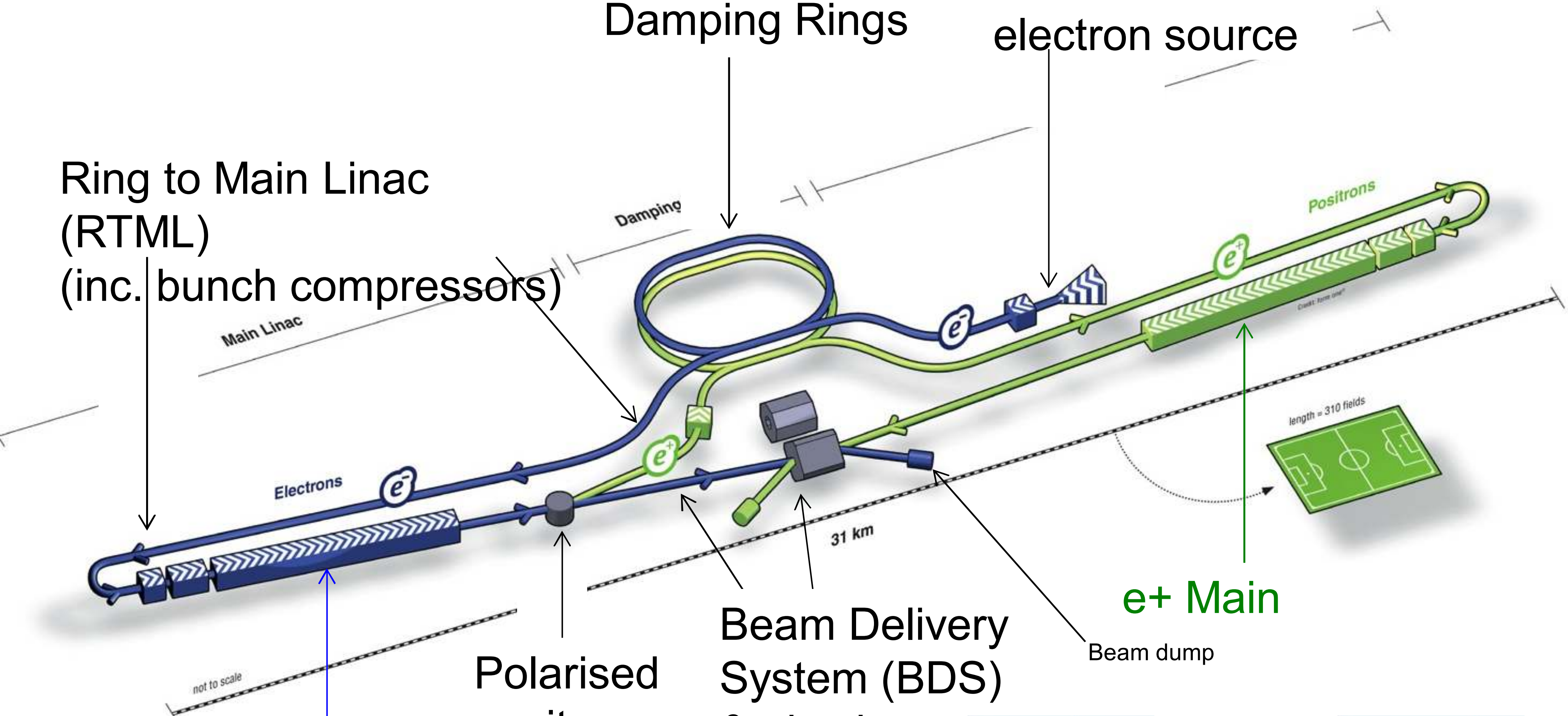


Damping Rings

Polarised
electron source

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

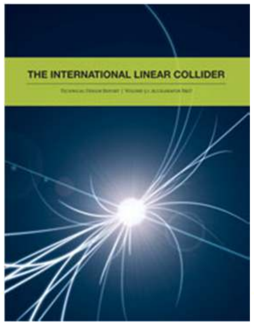
e+ Main

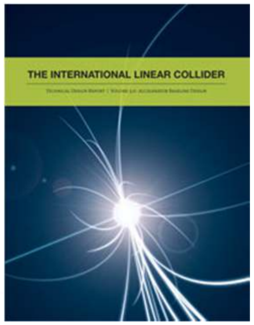
Beam dump

Polarised
positron
source

Beam Delivery
System (BDS)
& physics
detectors

e- Main
Linac





not to scale
ILC Scheme | © www.form-one.de

SCRF Linac Technology

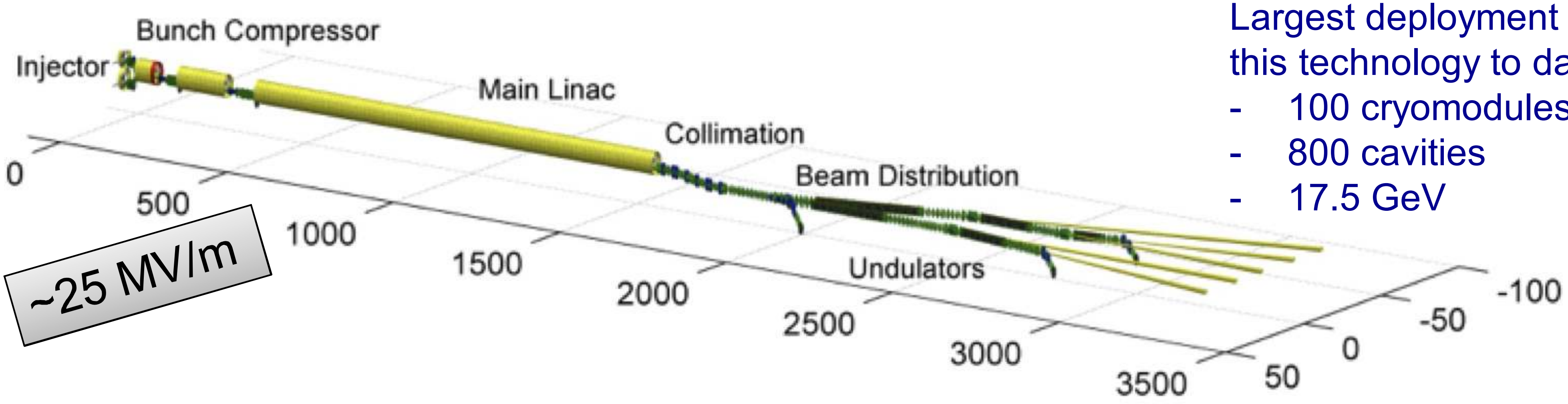
- solid niobium
- standing wave
- 9 cells
- operated at 2K (Lqd. He)
- 35 MV/m
- $Q_0 \geq 10^{10}$

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

European XFEL @ DESY



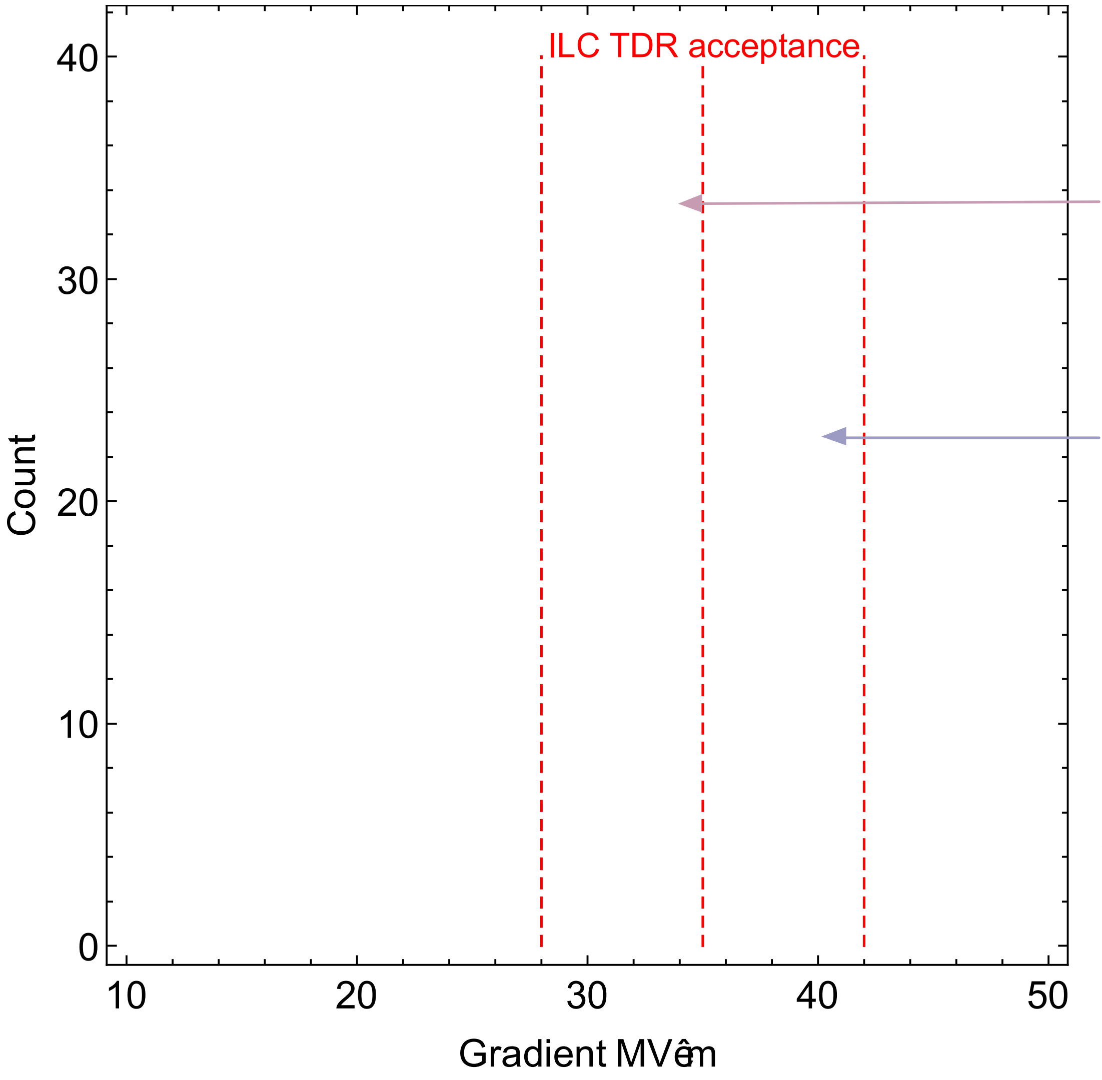
~25 MV/m

Largest deployment of this technology to date

- 100 cryomodules
- 800 cavities
- 17.5 GeV

The ultimate ‘integrated systems test’ for ILC. Commissioning with beam begins 2016

Industrial production - XFEL



XFEL usable gradient (FE limited)

Maximum field

XFEL industrial production following ILC baseline process

(Thanks to Nick Walker)

Technology optimisation

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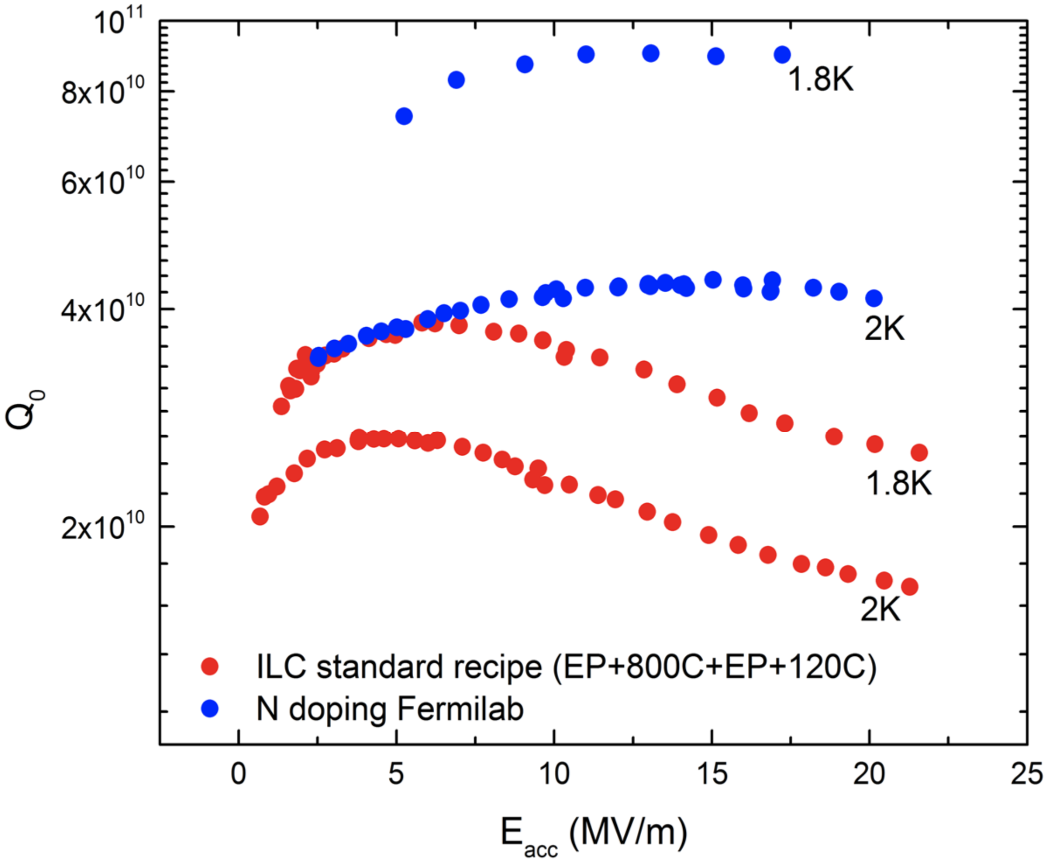
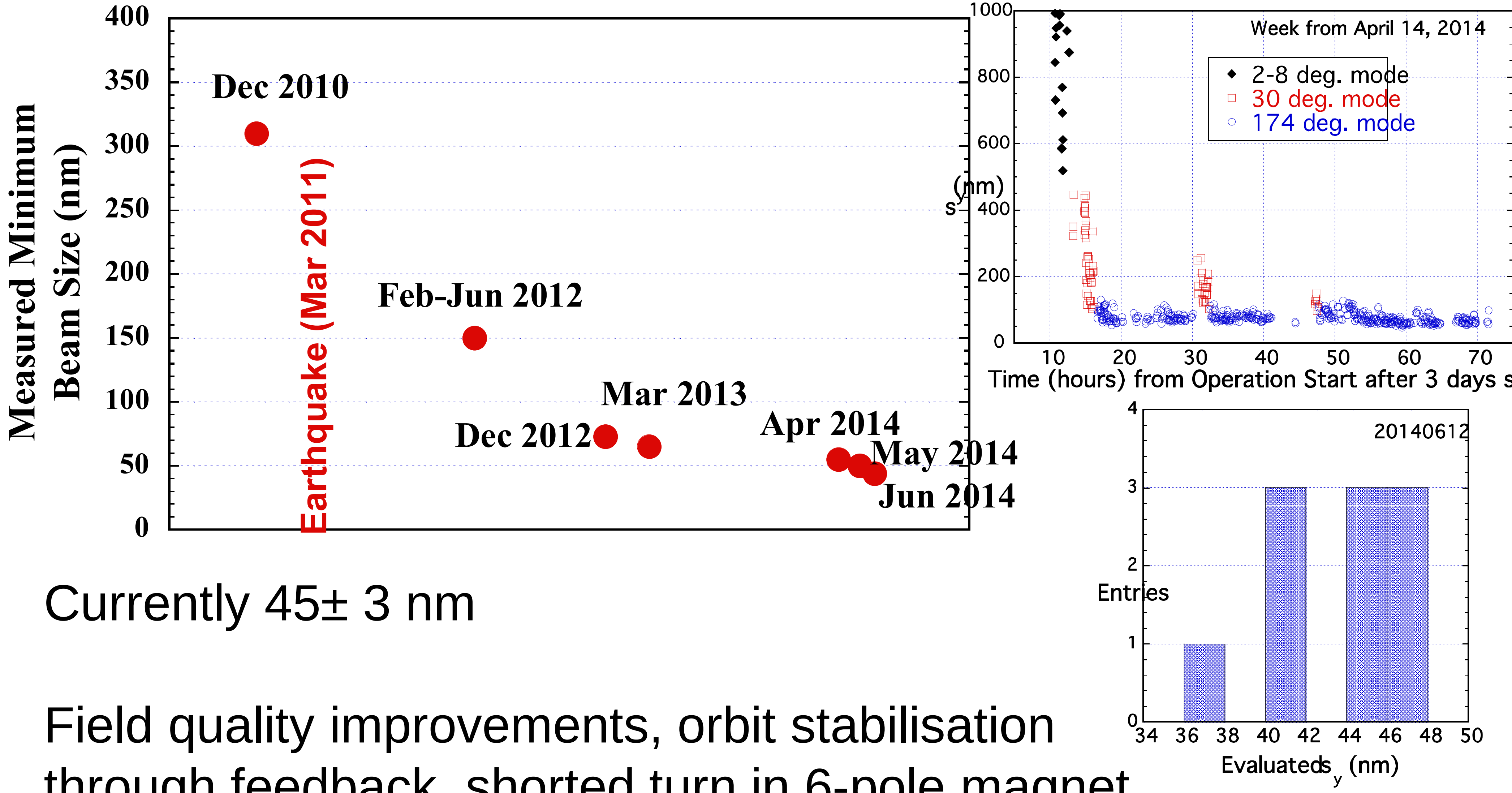


- Higher Q via nitrogen doping surface processing
- High Q via efficient flux expulsion cooling
- No high gradient yet

Barrel Polishing in HiGrade lab @ DESY – No EP ?

ATF2 beam-size success



Currently 45± 3 nm

Field quality improvements, orbit stabilisation through feedback, shorted turn in 6-pole magnet, beam size monitor improvements

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Japanese Site

Site-specific work plan

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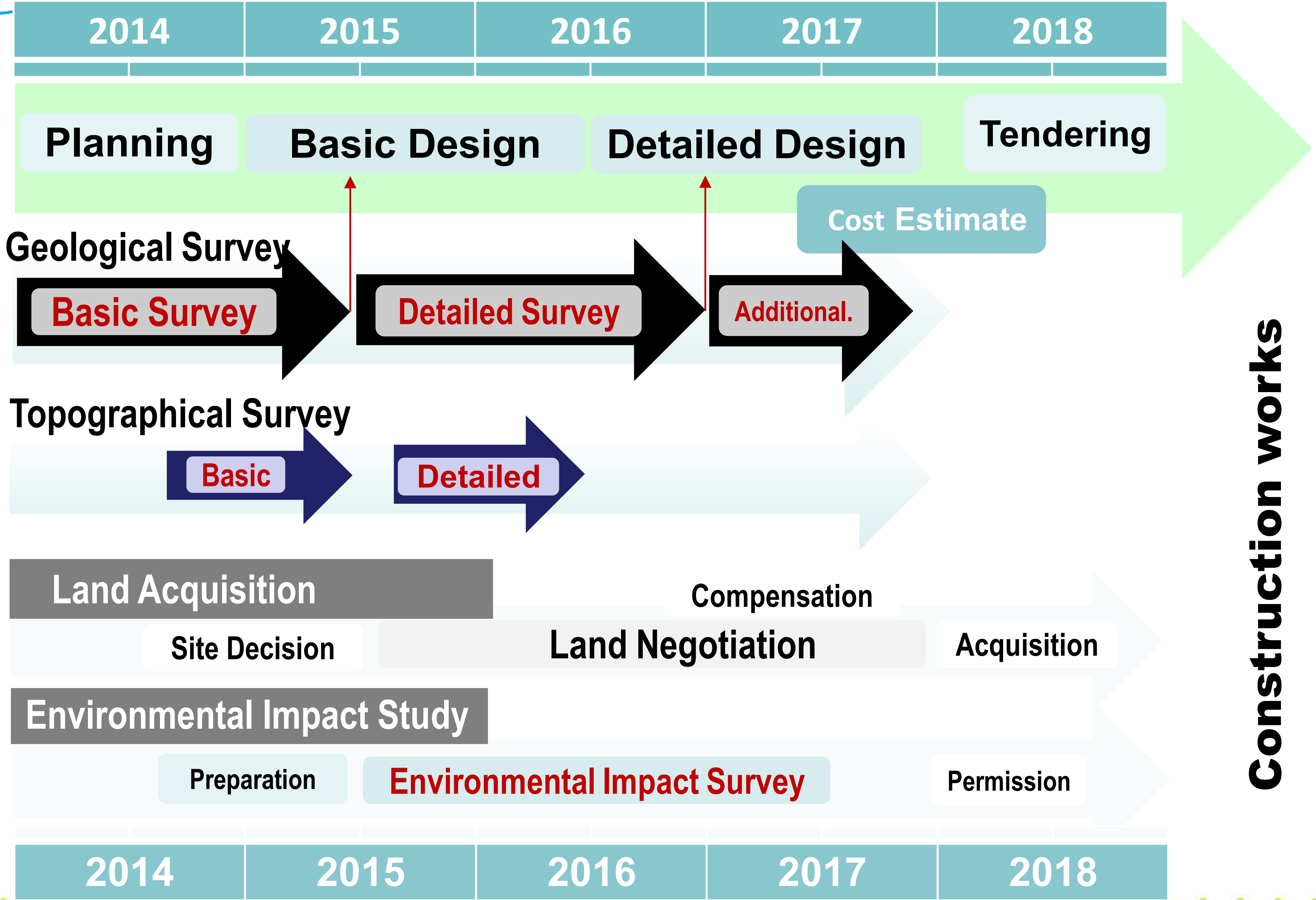

2014 2015 2016 2017 2018

Planning

Basic Design

Detailed Design

Tendering

Cost Estimate

Geological Survey

Basic Survey

Detailed Survey

Additional.

Topographical Survey

Basic

Detailed

Land Acquisition

Compensation

Site Decision

Land Negotiation

Acquisition

Environmental Impact Study

Preparation

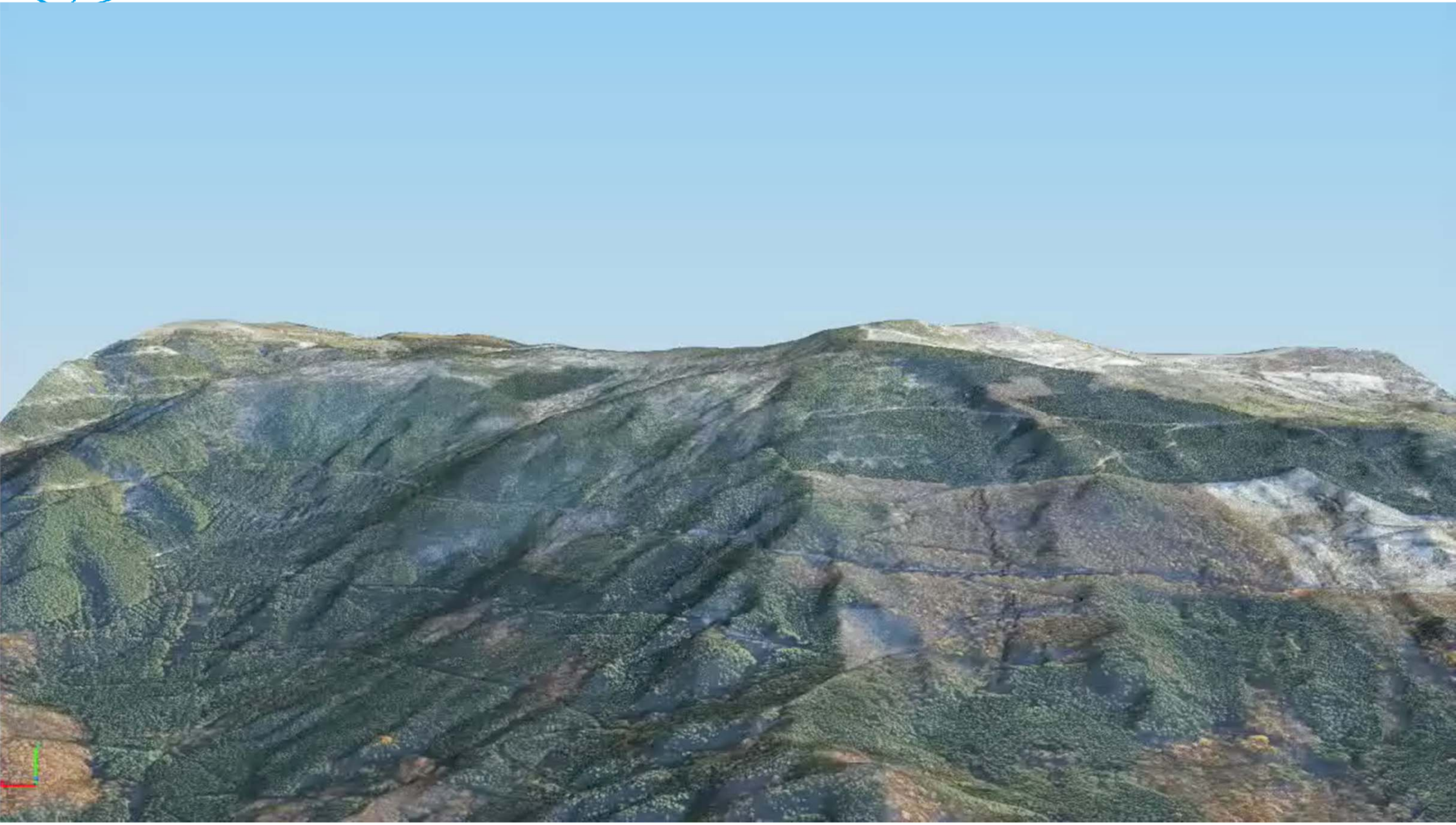
Environmental Impact Survey

Permission

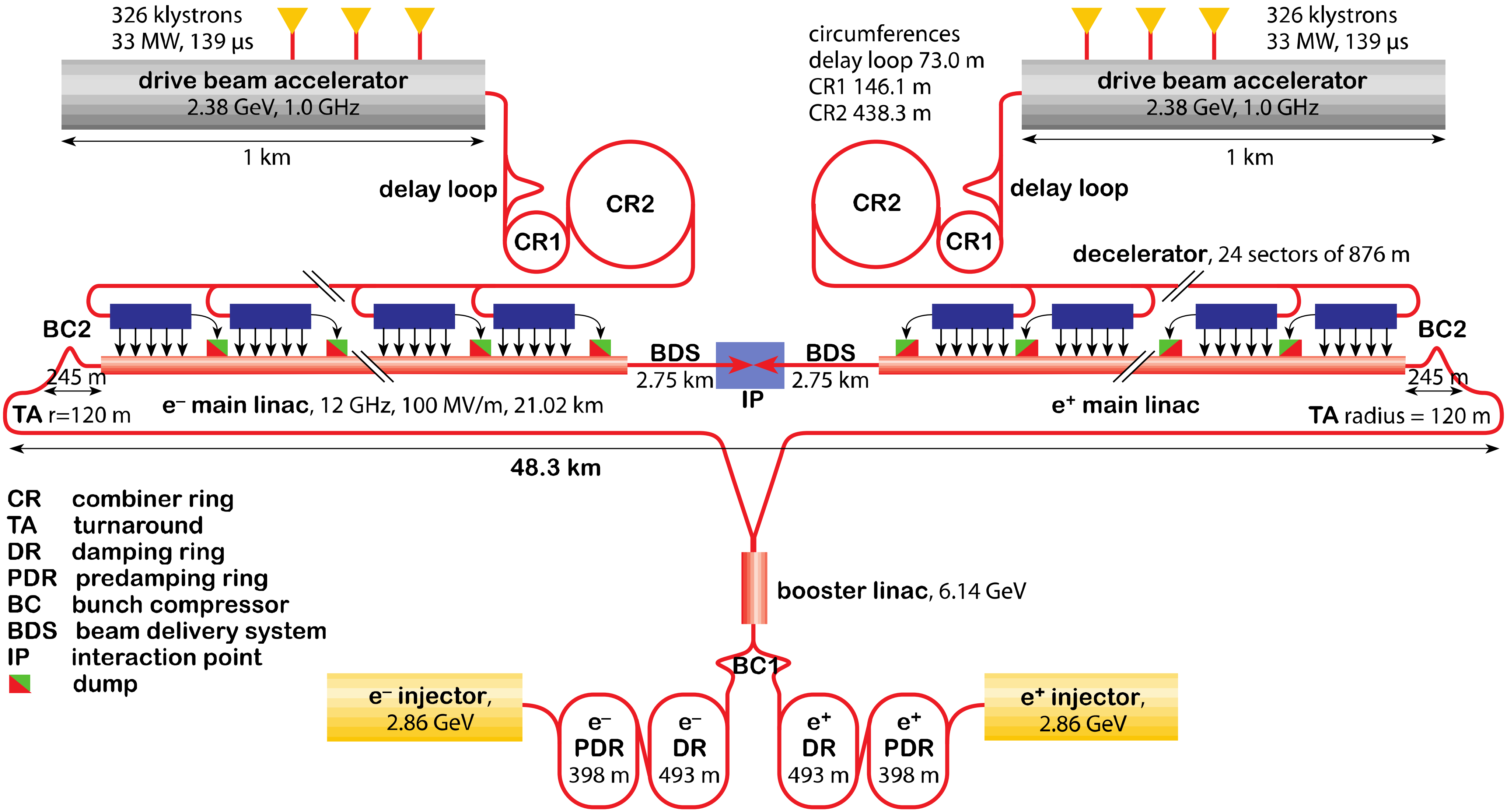
Construction works

2014 2015 2016 2017 2018

Virtual reality tools



CLIC



CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**

CLIC Power Source Concept

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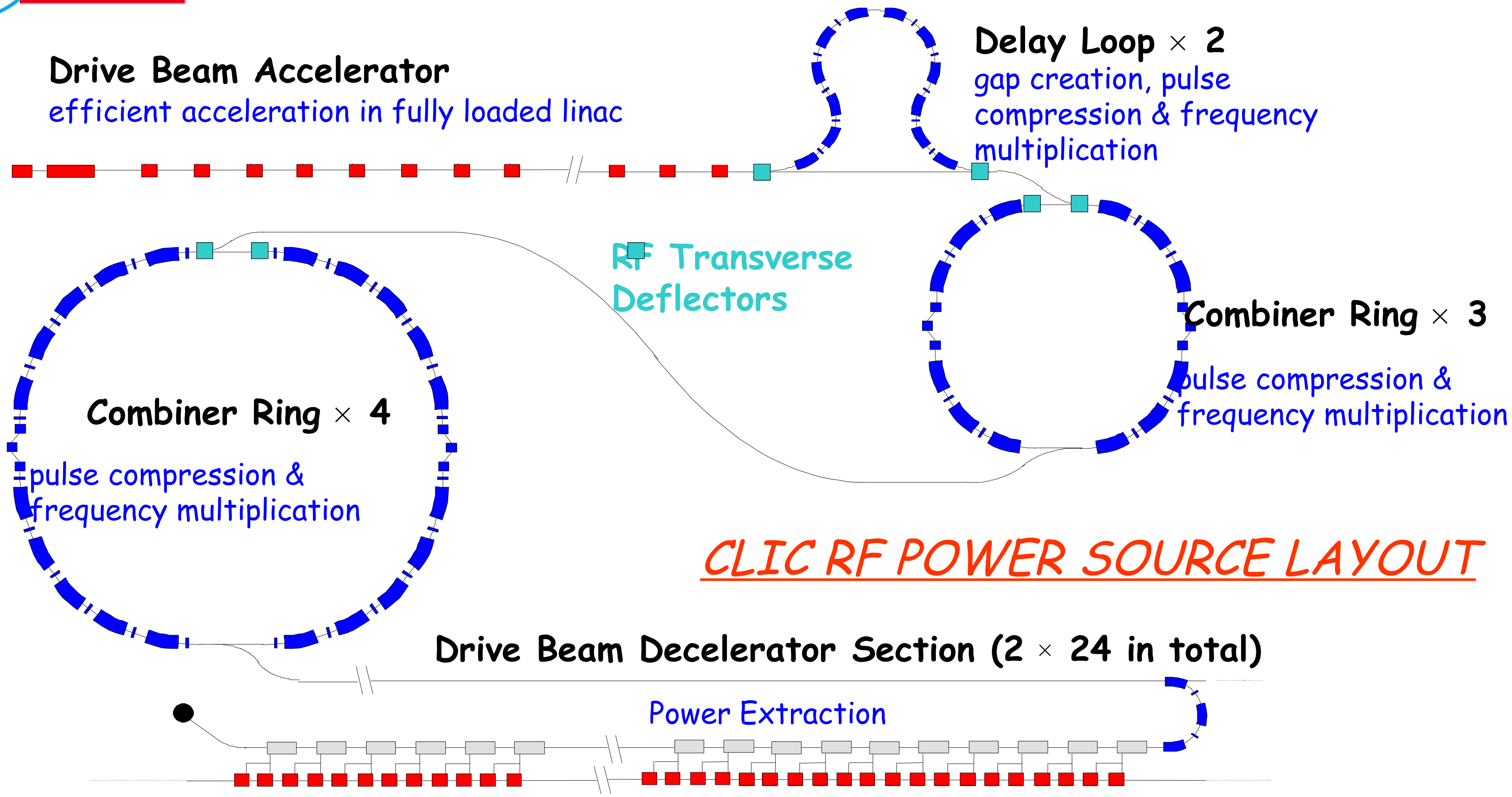


Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop × 2
gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3
pulse compression & frequency multiplication

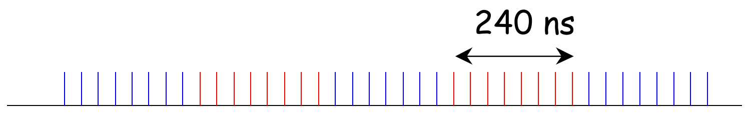
Combiner Ring × 4
pulse compression & frequency multiplication

CLIC RF POWER SOURCE LAYOUT

Drive Beam Decelerator Section (2 × 24 in total)

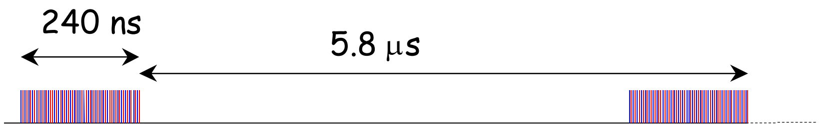
Power Extraction

Drive beam time structure - initial



140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches

CTF3 @ CERN

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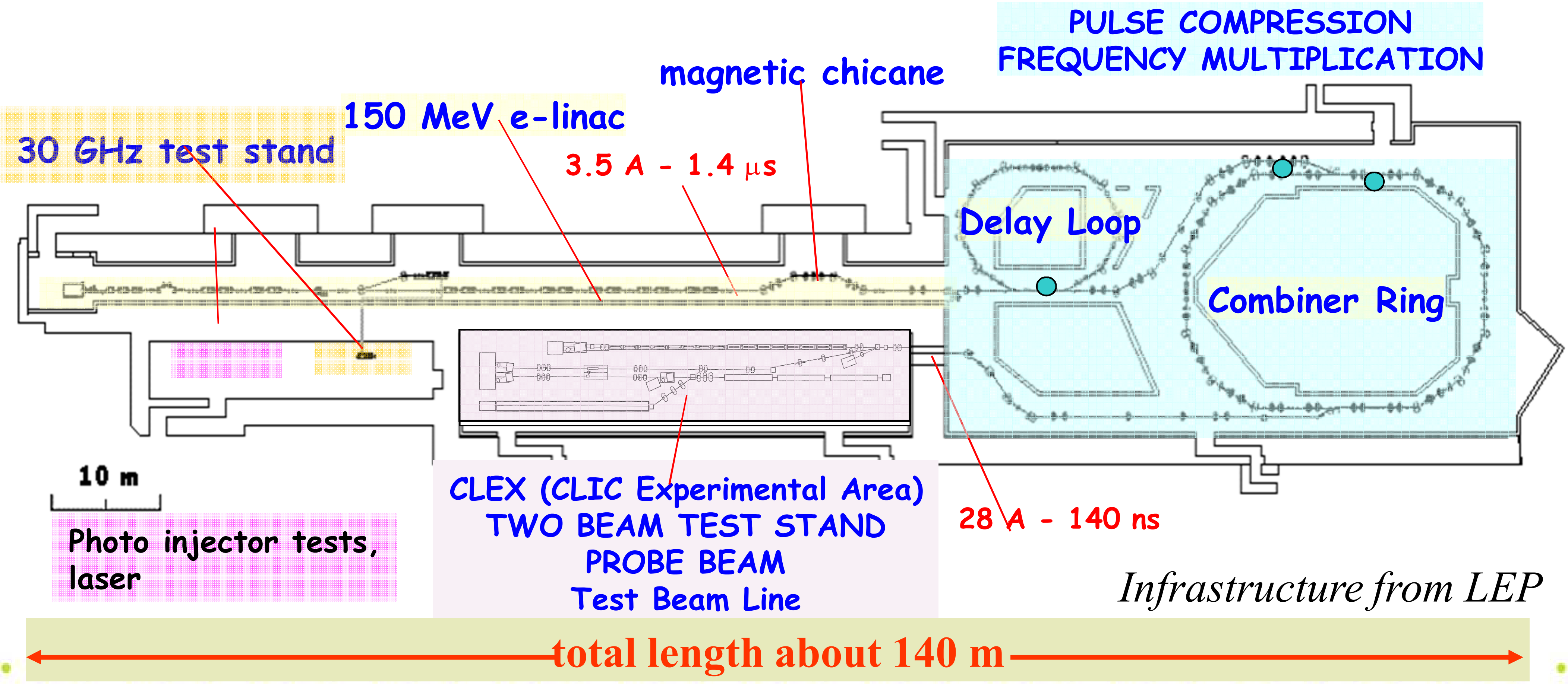
- Demonstrate Drive Beam generation
  (fully loaded acceleration, beam intensity and bunch frequency multiplication x8)
- Demonstrate RF Power Production and test Power Structures
- Demonstrate Two Beam Acceleration and test Accelerating Structures



Infrastructure from LEP

total length about 140 m

CLIC Accelerating Structures

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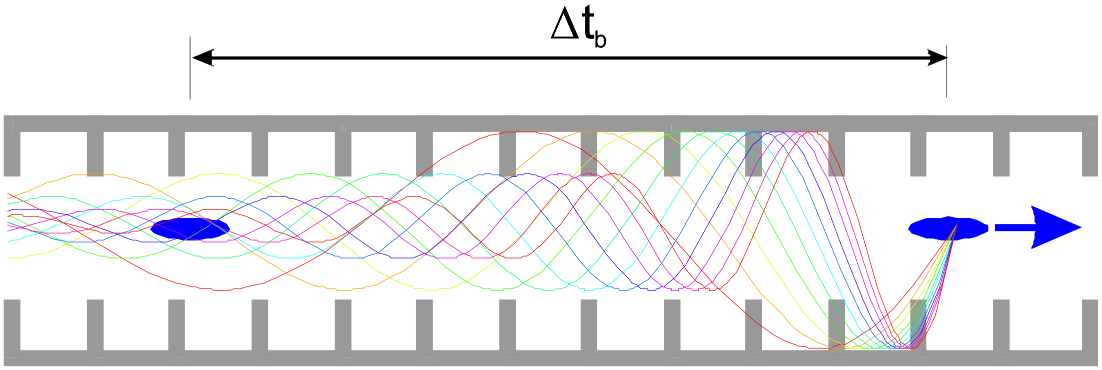

- CLIC acceleration travelling wave – too high Ohmic losses from standing wave
- Bunches induce wakefields in the accelerating cavities
- Later bunches are perturbed by these fields
- Can lead to emittance growth and instabilities

- 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

Current status of accelerating structures

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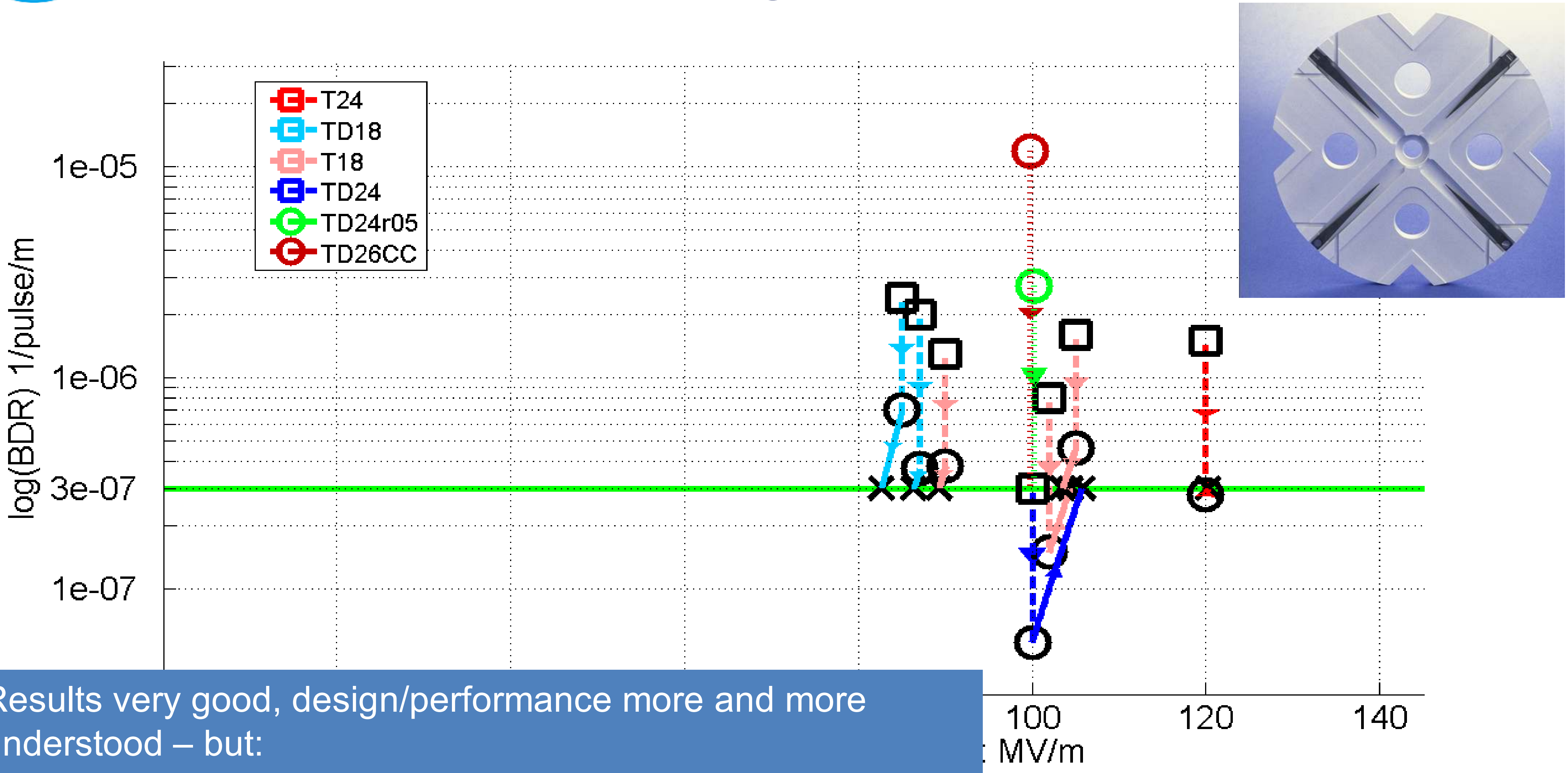


Results very good, design/performance more and more understood – but:

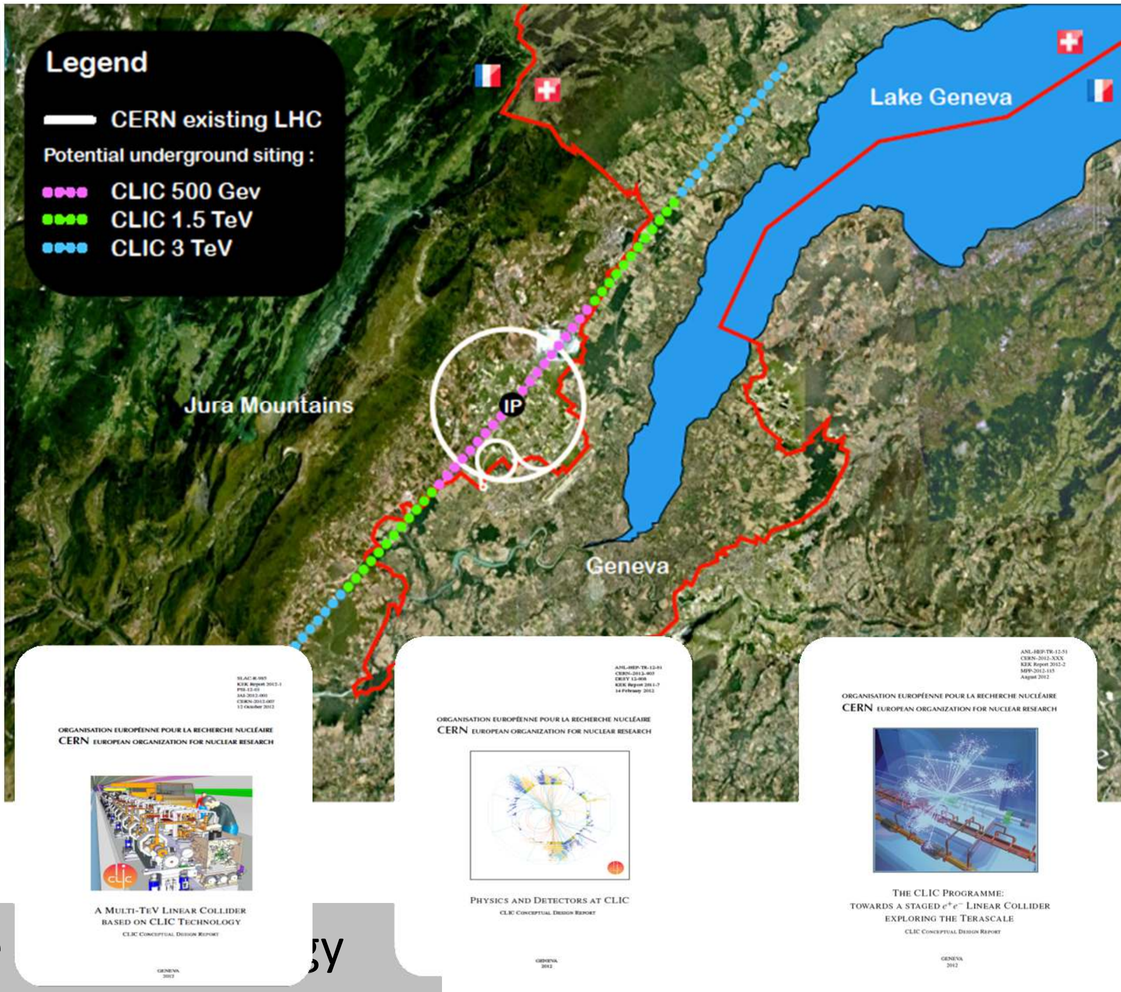
- numbers limited, industrial productions also limited
- basic understanding of BD mechanics improving
- condition time/acceptance tests need more work
- use for other applications (e.g. FELs) needs verification

In all cases test-capacity is crucial

Current status

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

Muon Collider

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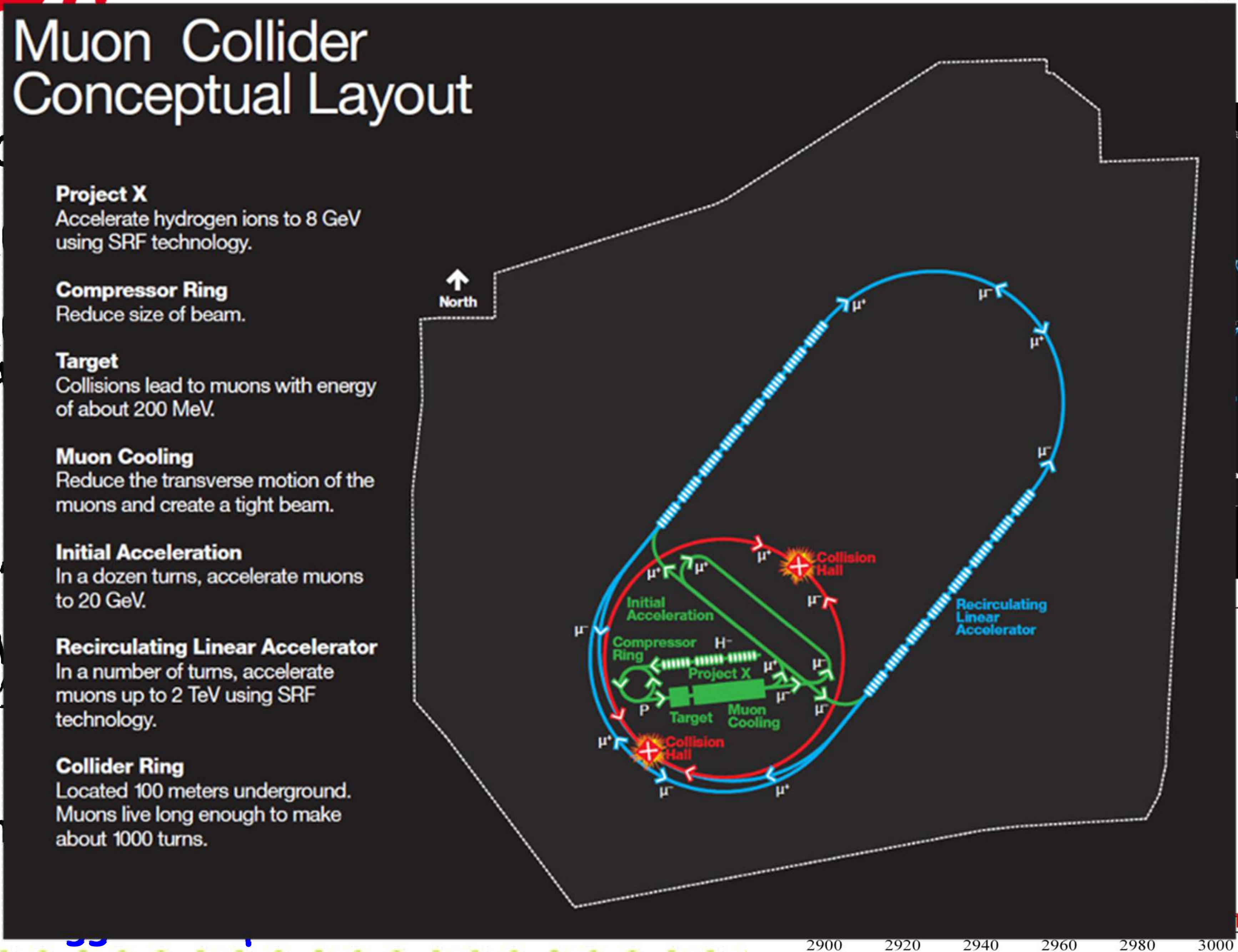


Muon Collider Conceptual Layout

Project X
Accelerate hydrogen ions to 8 GeV using SRF technology.

Compressor Ring
Reduce size of beam.

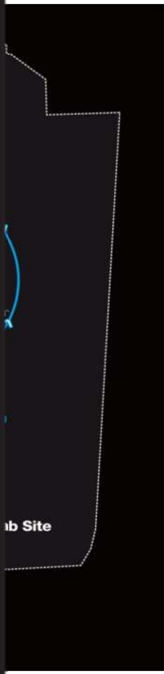
Target
Collisions lead to muons with energy of about 200 MeV.

Muon Cooling
Reduce the transverse motion of the muons and create a tight beam.

Initial Acceleration
In a dozen turns, accelerate muons to 20 GeV.

Recirculating Linear Accelerator
In a number of turns, accelerate muons up to 2 TeV using SRF technology.

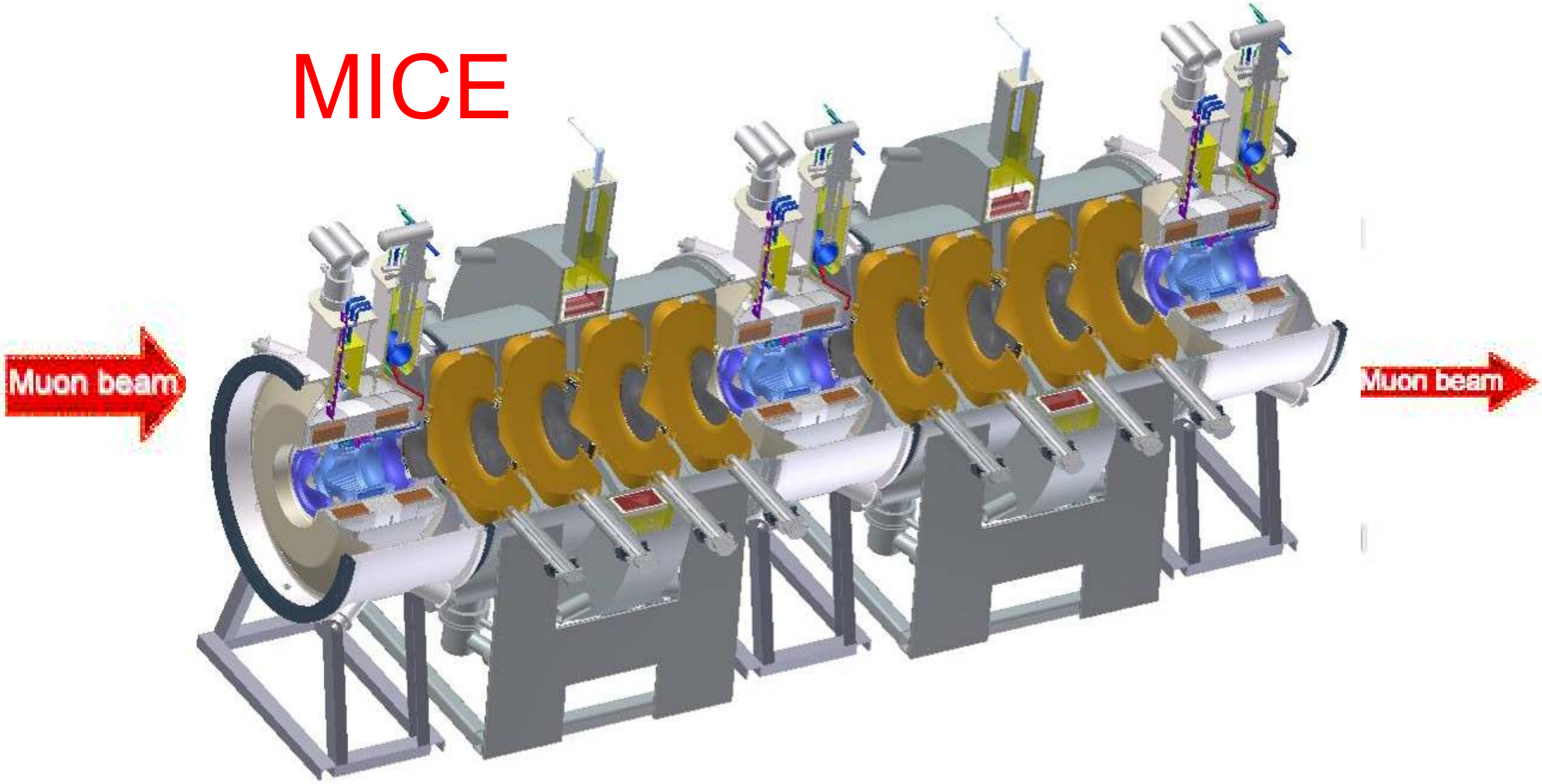
Collider Ring
Located 100 meters underground. Muons live long enough to make about 1000 turns.



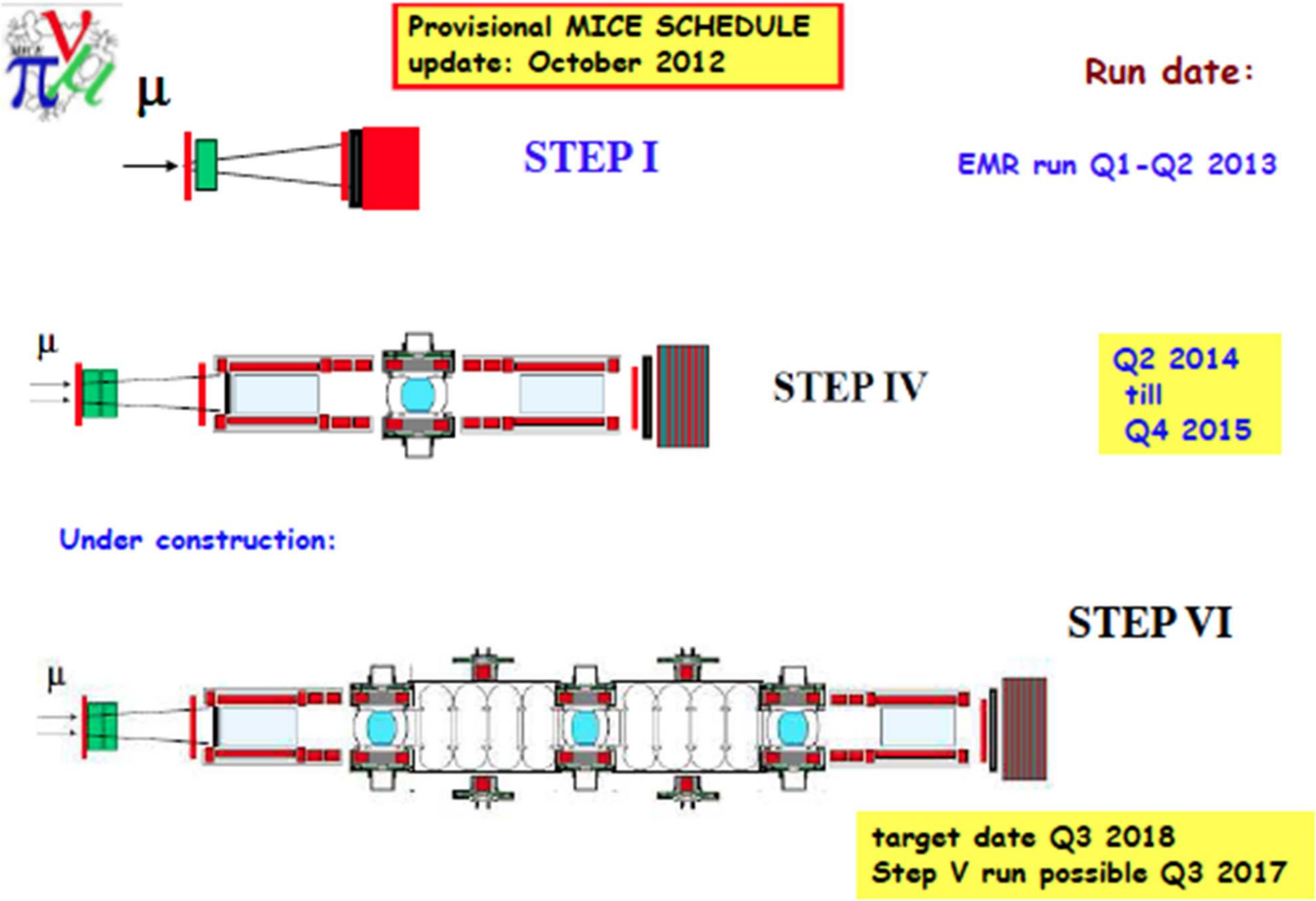
Muon Collider Cooling

- 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

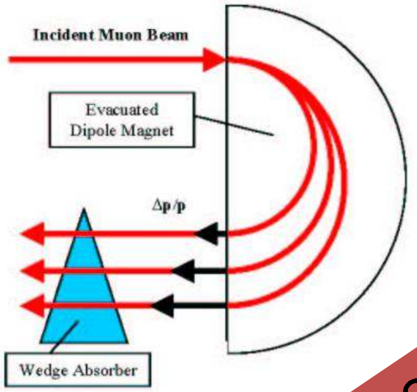
Under construction:

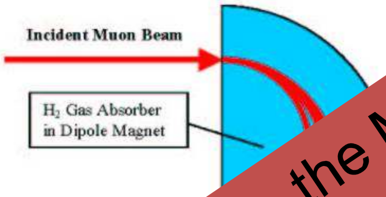
STEP VI

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**
    - put wedge-shaped absorber in dispersive region
    - use extra path length in continuous absorber

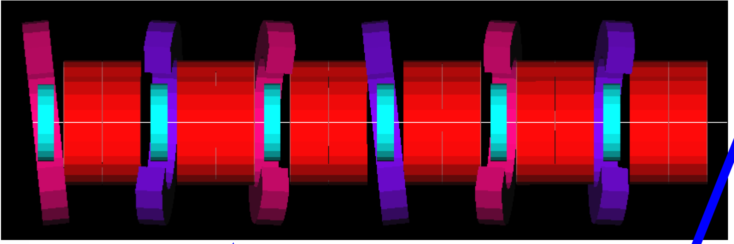


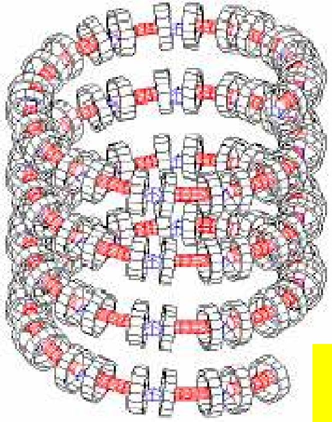


P5 Recommendation 25 : Reassess the Muon Accelerator Program (MAP). Incorporate into the GARD program the MAP activities that are of general importance to accelerator R&D, and consult with international partners on the early termination of MICE.

Cooling ring

Snake



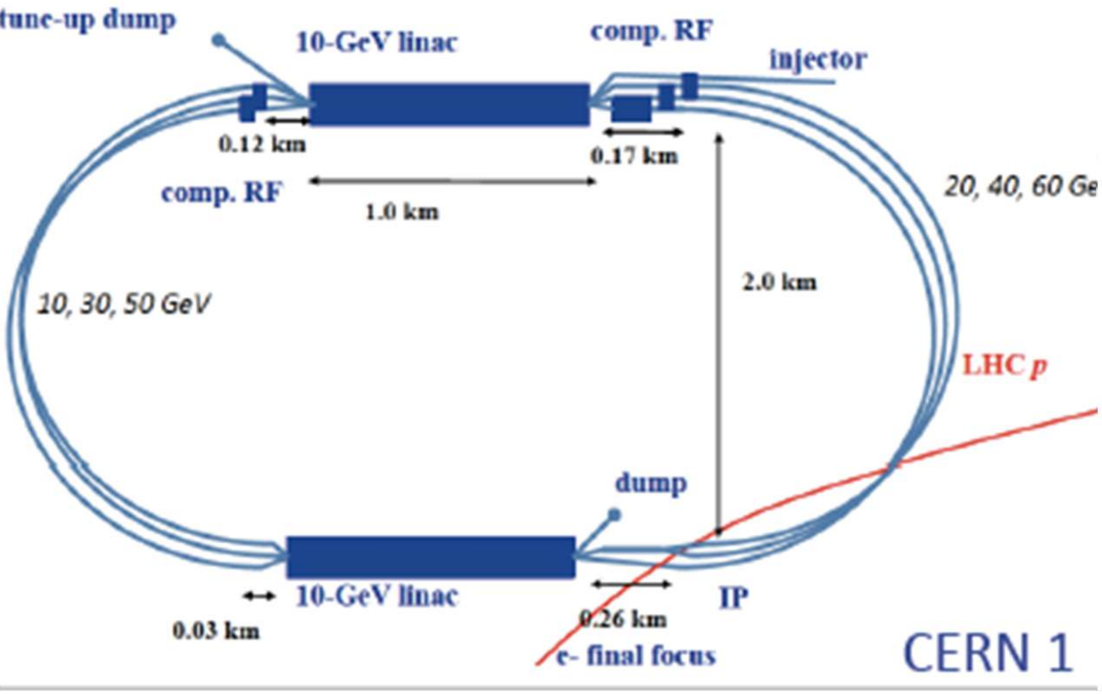


Single pass; avoids injection/extraction issues

“Guggenheim” channel

LHeC (FCC-eh) Linac Option

THREE-PASS ERL



Single-PASS 60 GeV ERL

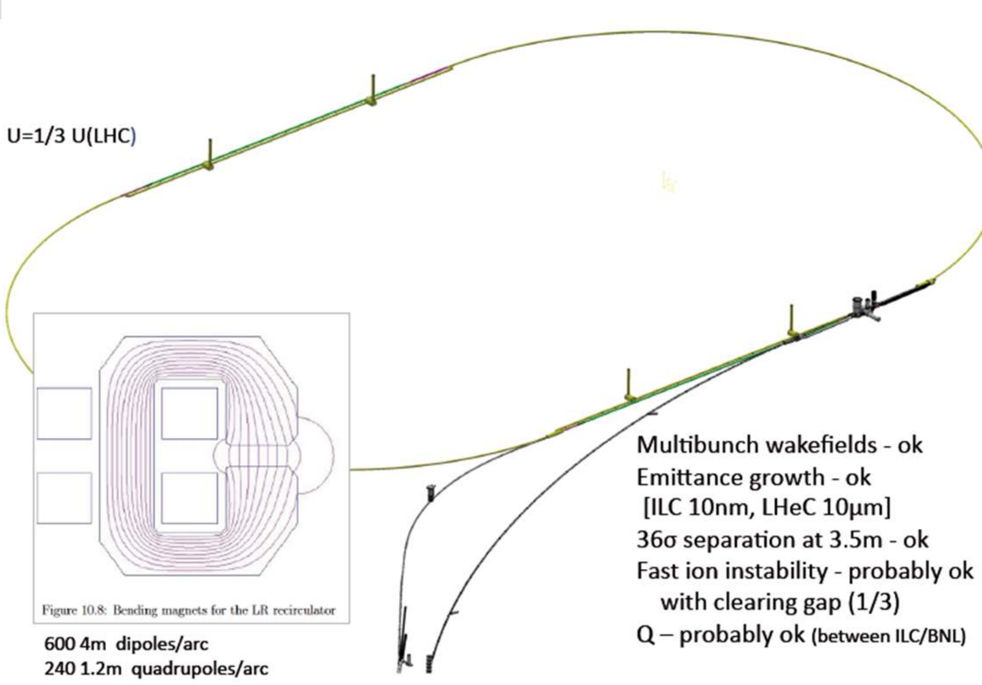
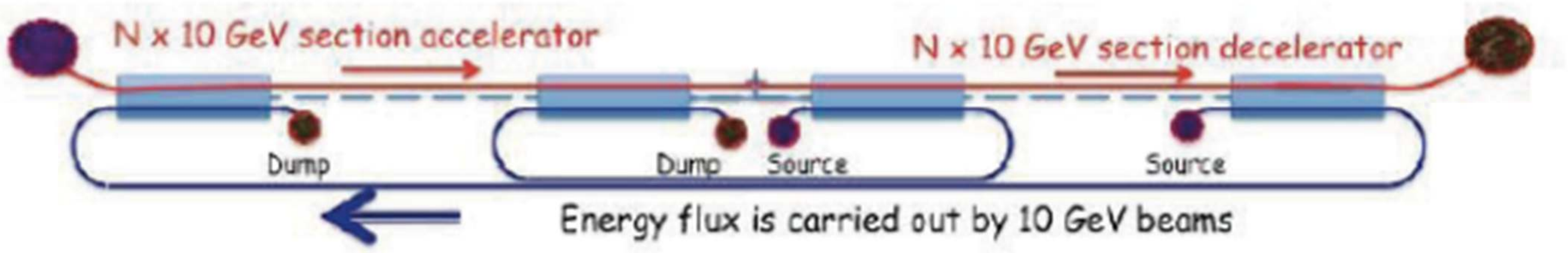


Figure 10.8: Bending magnets for the LR recirculator

600 4m dipoles/arc
240 1.2m quadrupoles/arc

Multibunch wakefields - ok
Emittance growth - ok
[ILC 10nm, LHeC 10μm]
36σ separation at 3.5m - ok
Fast ion instability - probably ok
with clearing gap (1/3)
Q – probably ok (between ILC/BNL)

Future 150 GeV e ERL linac



Surfing the wave

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- 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

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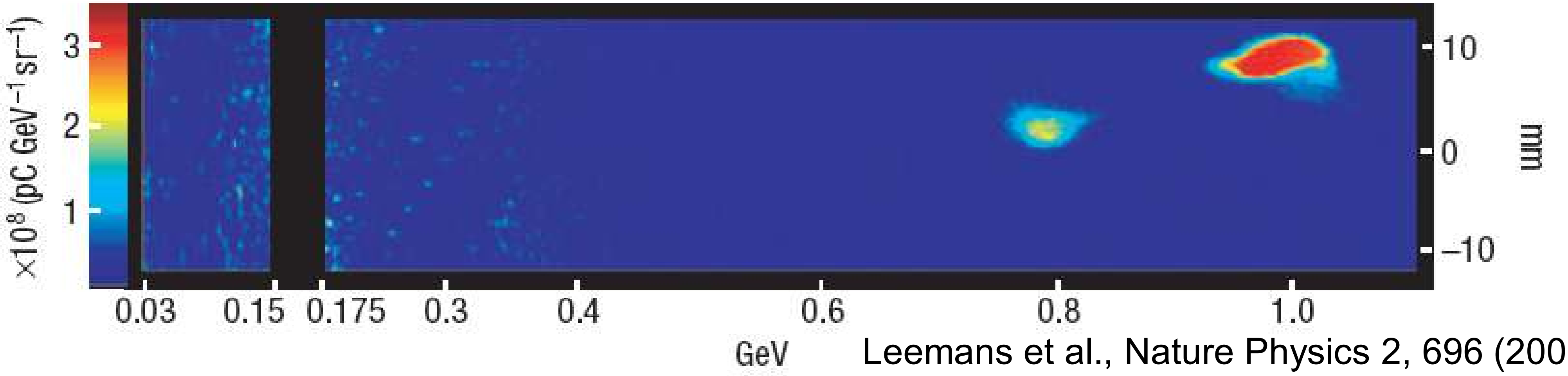
- Development of much higher gradient accelerator not only pushes back frontier for particle physics – also permits current accelerators to be built much smaller/cheaper.
- 1 GeV electron beams on "table top".

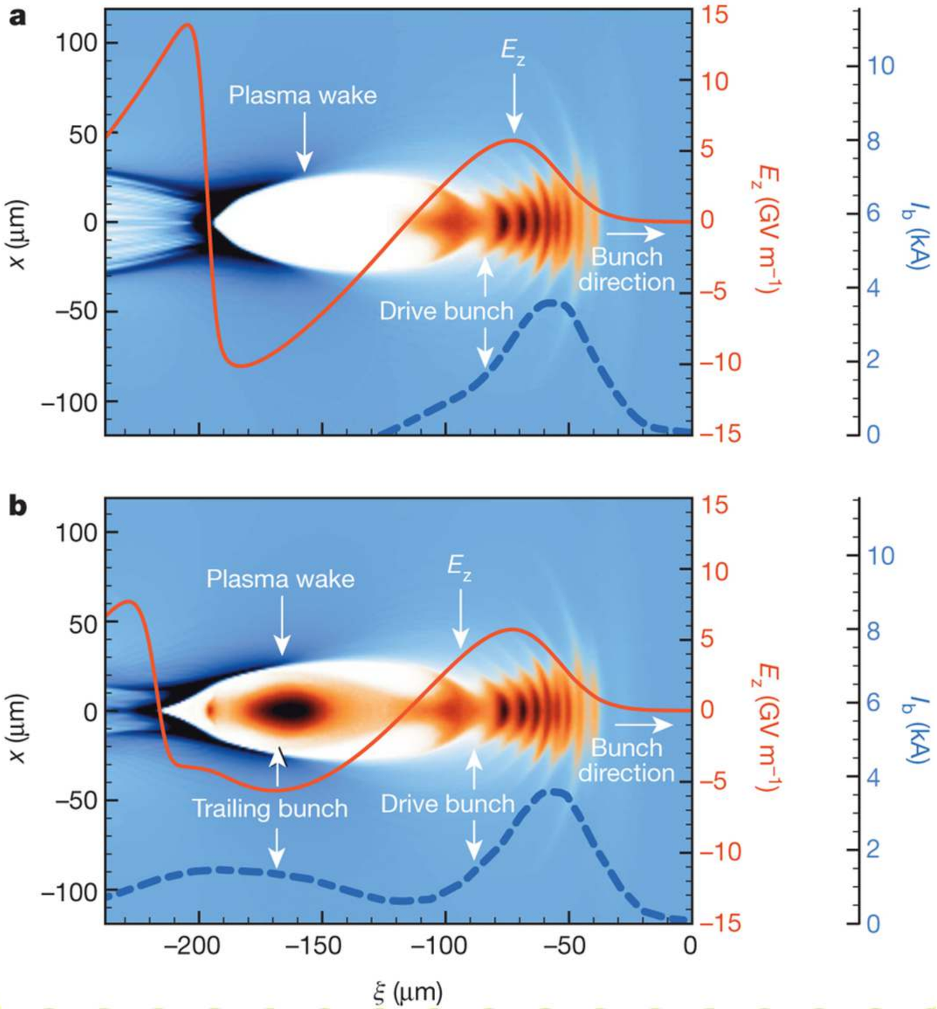


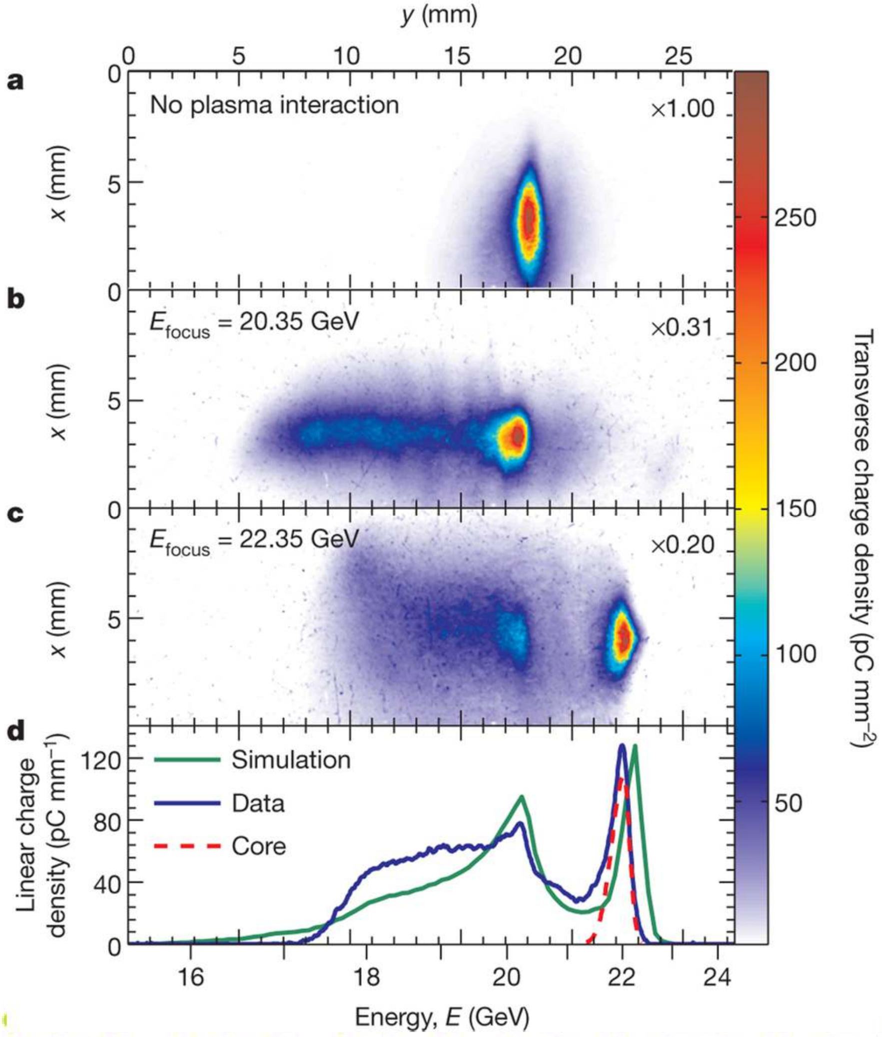
Leemans et al., Nature Physics 2, 696 (2006)

Inject beam

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

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





Inject beam

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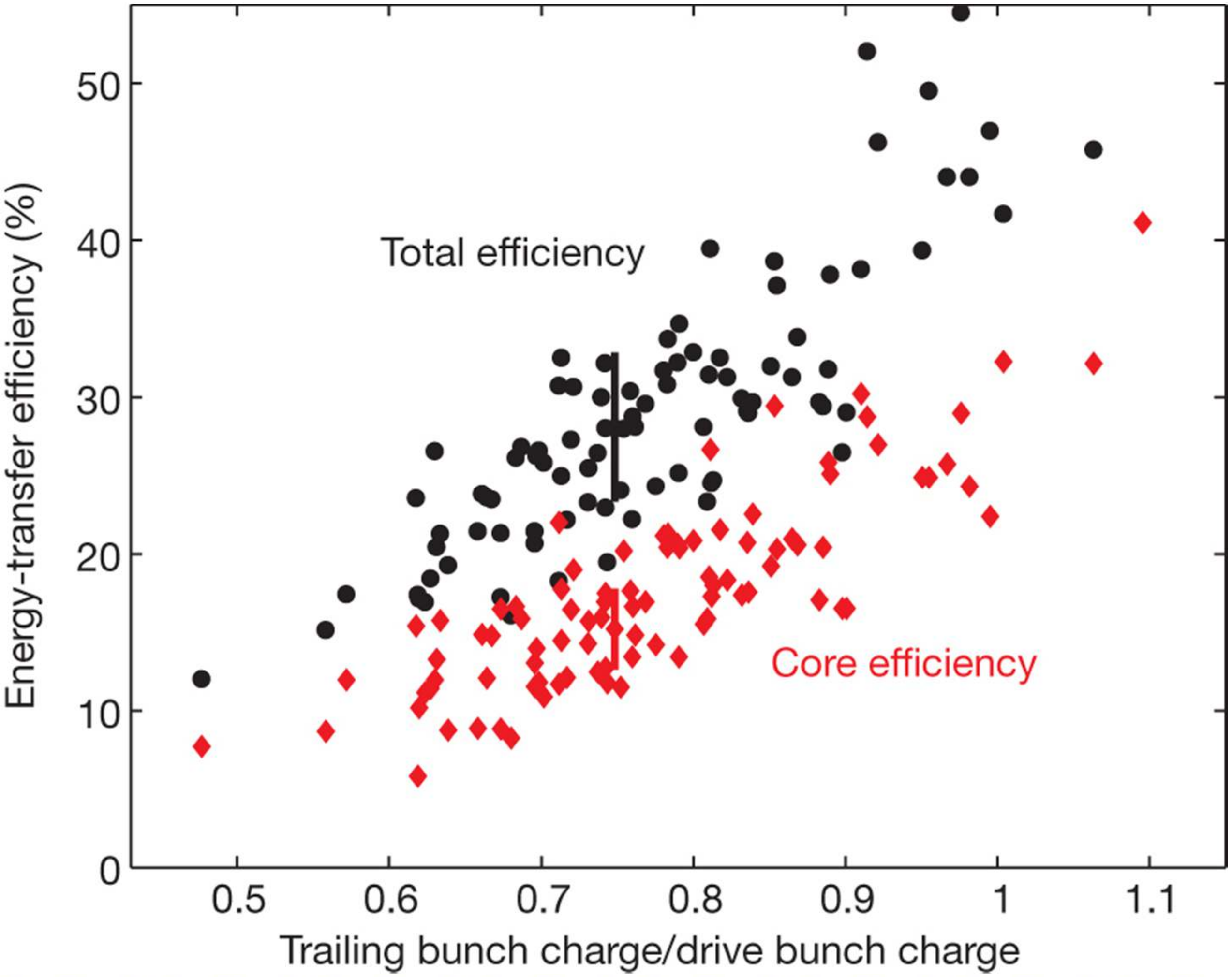
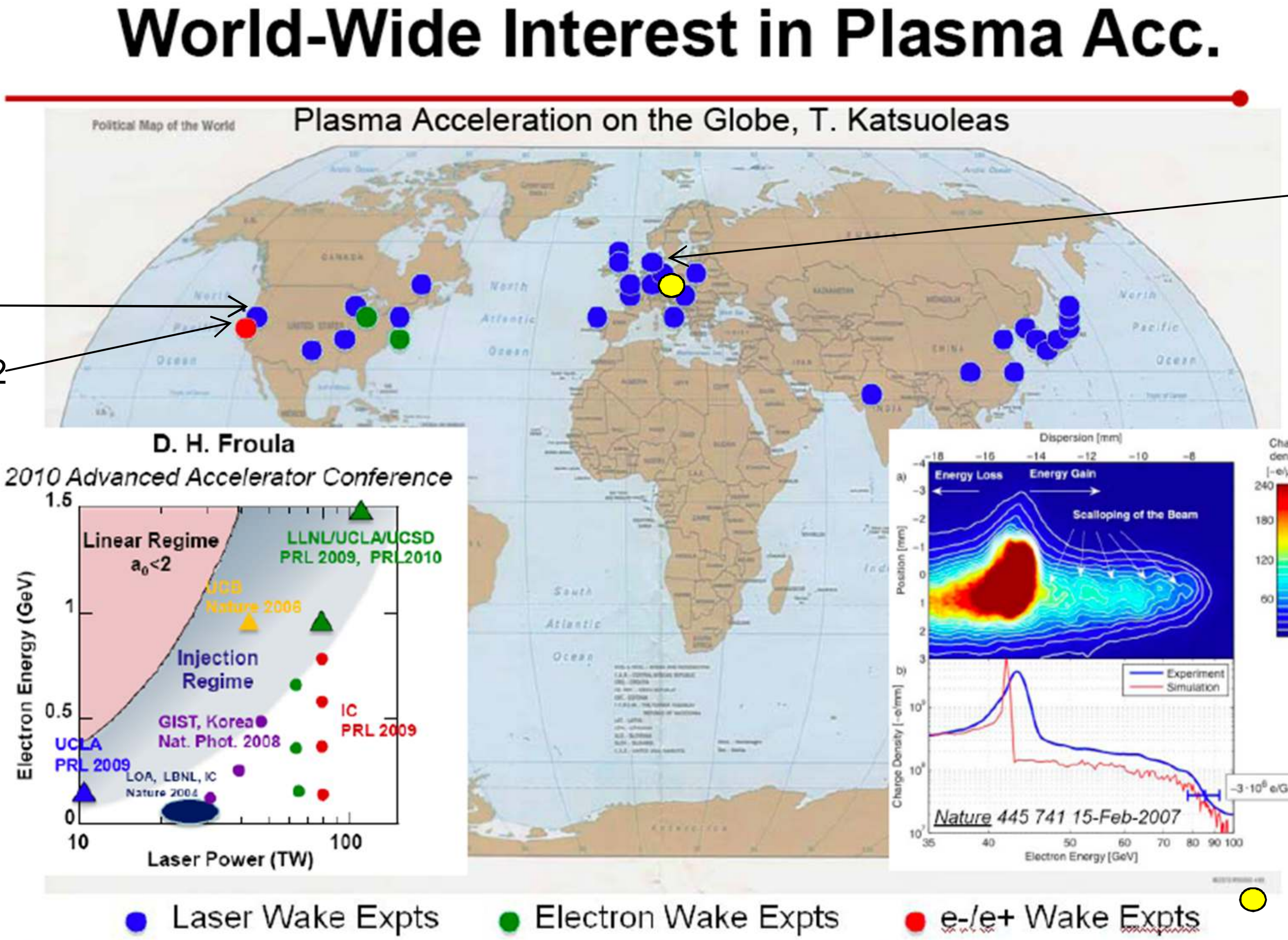


World-wide acceleration

- 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.

Plasma Acceleration on the Globe, T. Katsuoleas

BELLA

FACET, FACET2

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

○ Proton driven

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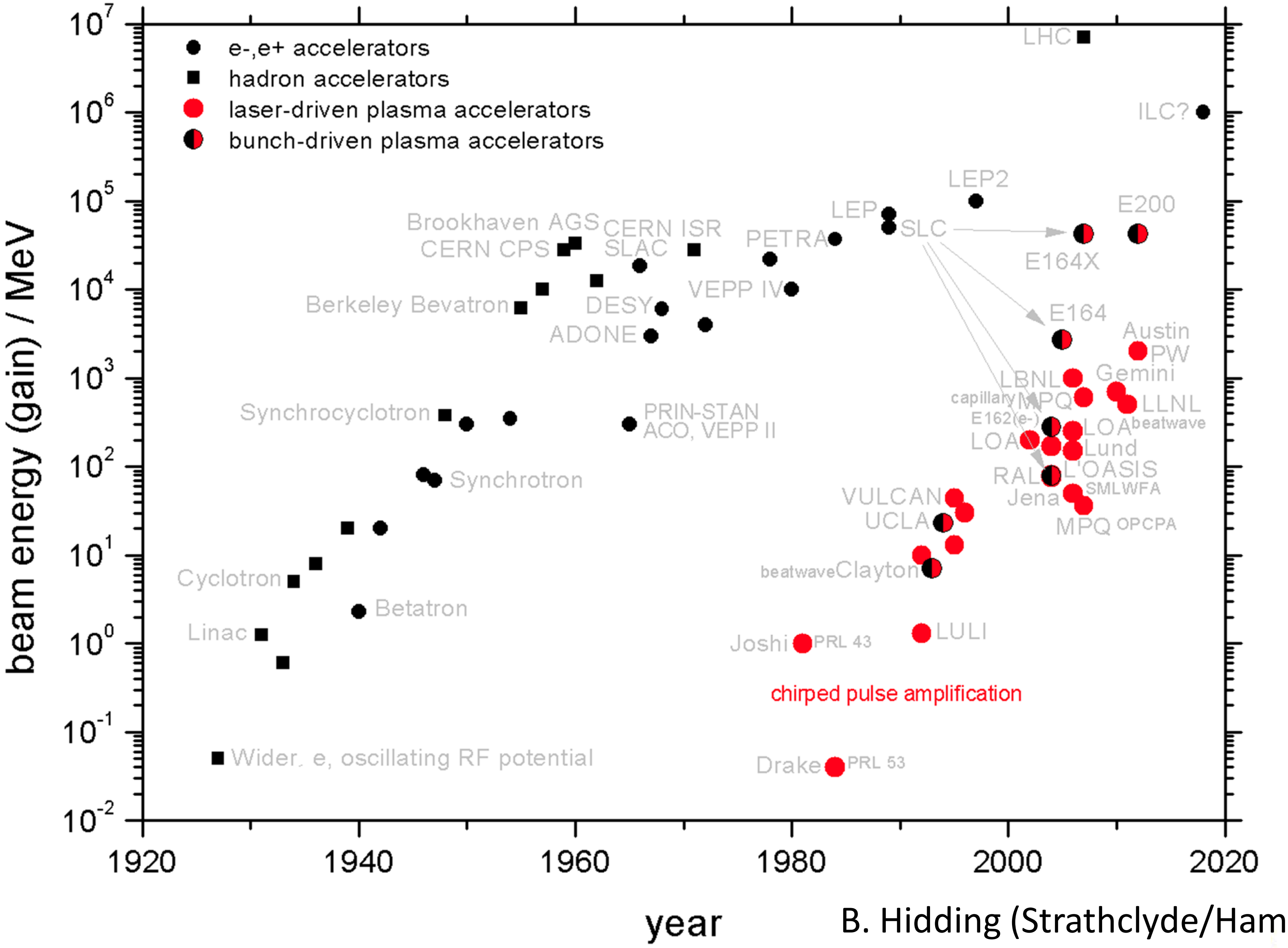
The New Livingston Plot



B. Hidding (Strathclyde/Hamburg)

LAOLA @ DESY

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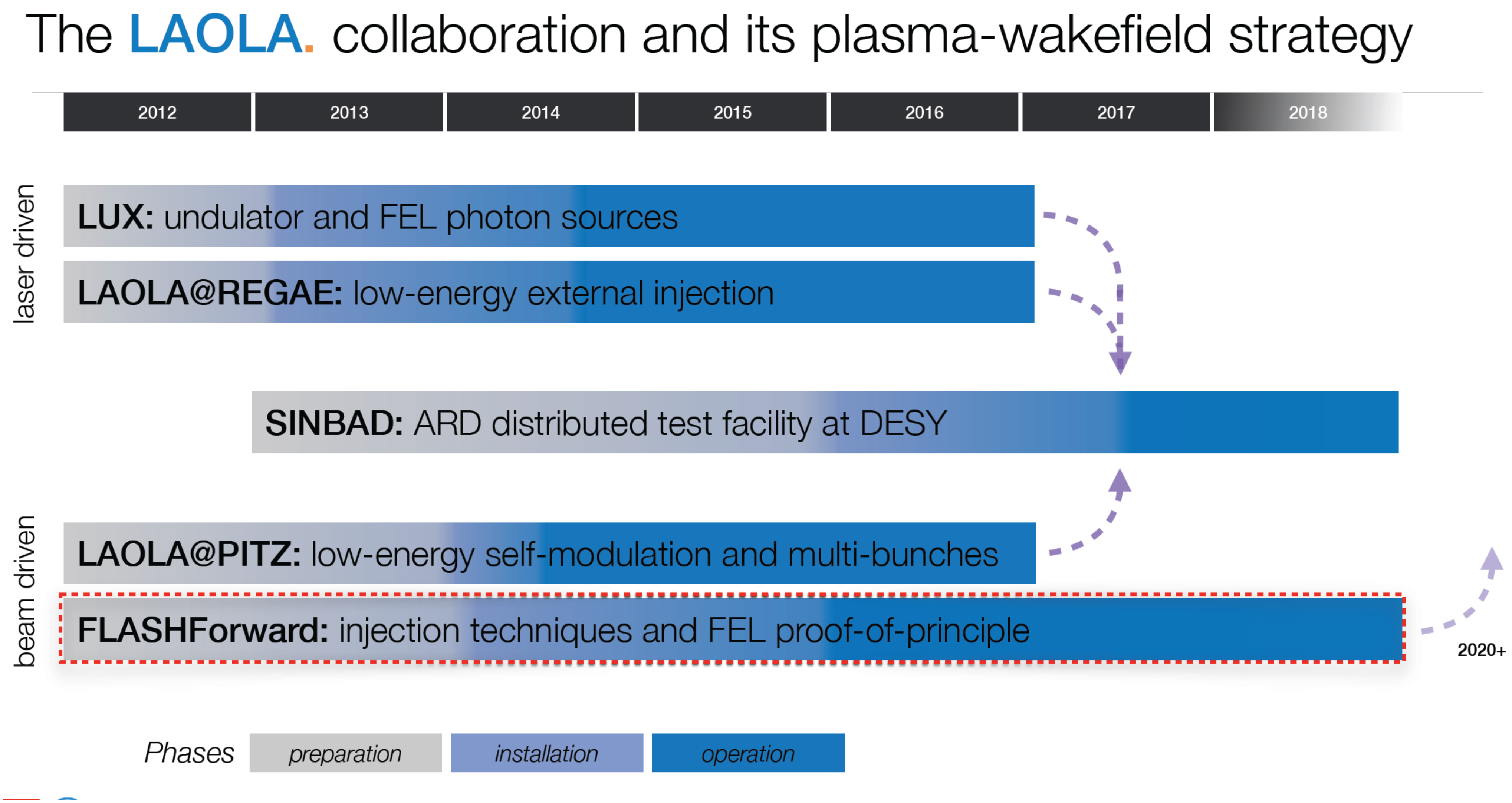

The LAOLA. collaboration and its plasma-wakefield strategy

2012 2013 2014 2015 2016 2017 2018

laser driven

LUX: undulator and FEL photon sources

LAOLA@REGAE: low-energy external injection

SINBAD: ARD distributed test facility at DESY

beam driven

LAOLA@PITZ: low-energy self-modulation and multi-bunches

FLASHForward: injection techniques and FEL proof-of-principle

2020+

Phases *preparation* *installation* *operation*

FLASHforward @ DESY

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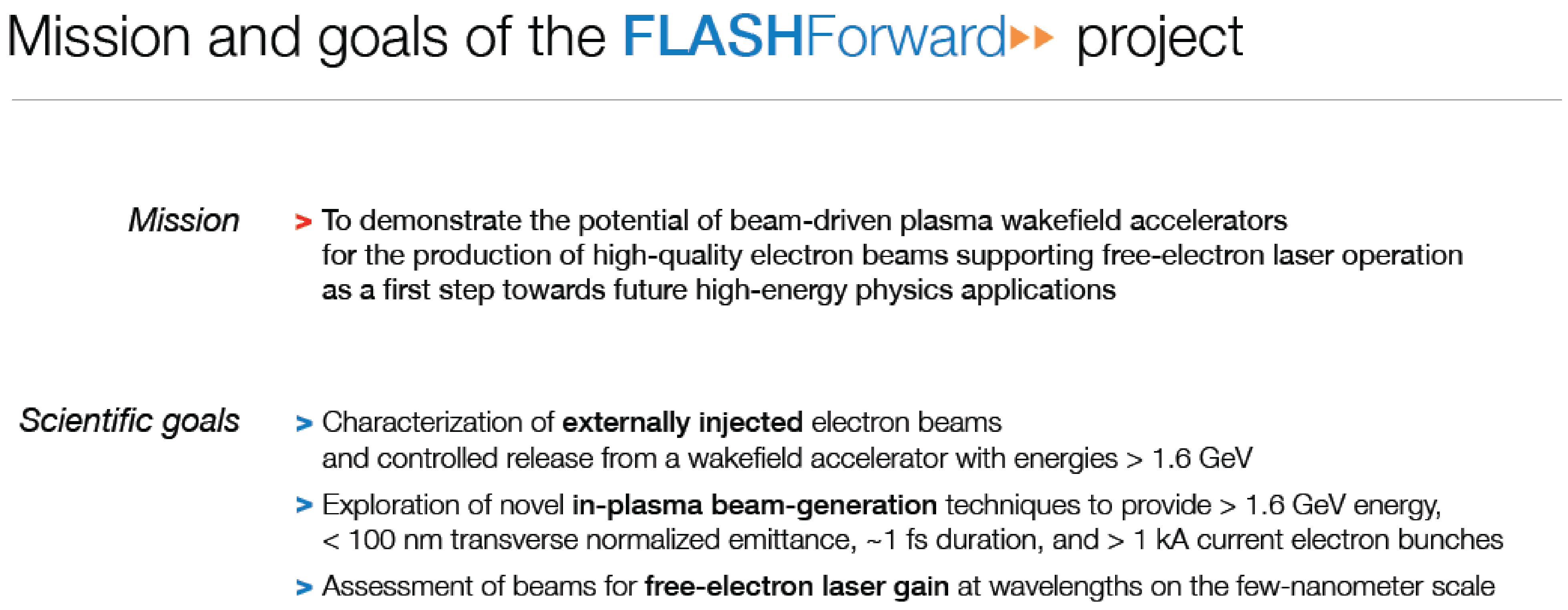


Mission and goals of the FLASHForward▸▸ project

Mission

- To demonstrate the potential of beam-driven plasma wakefield accelerators for the production of high-quality electron beams supporting free-electron laser operation as a first step towards future high-energy physics applications

Scientific goals

- Characterization of **externally injected** electron beams and controlled release from a wakefield accelerator with energies > 1.6 GeV
- Exploration of novel **in-plasma beam-generation** techniques to provide > 1.6 GeV energy, < 100 nm transverse normalized emittance, ~1 fs duration, and > 1 kA current electron bunches
- Assessment of beams for **free-electron laser gain** at wavelengths on the few-nanometer scale

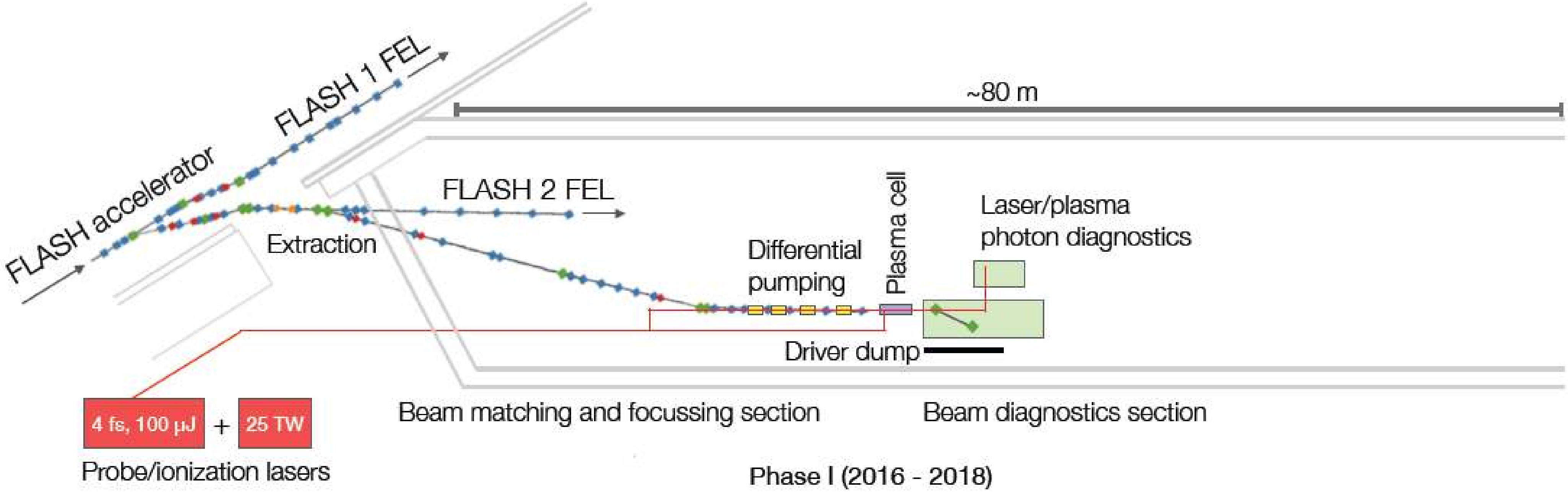
FLASHforward @ DESY

FLASHForward▸▸ beamline overview

Conceptual design finished
Technical design in progress
Operation to start in ~2016, run for 4 years+

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 (2016 - 2018)

FLASHforward @ DESY

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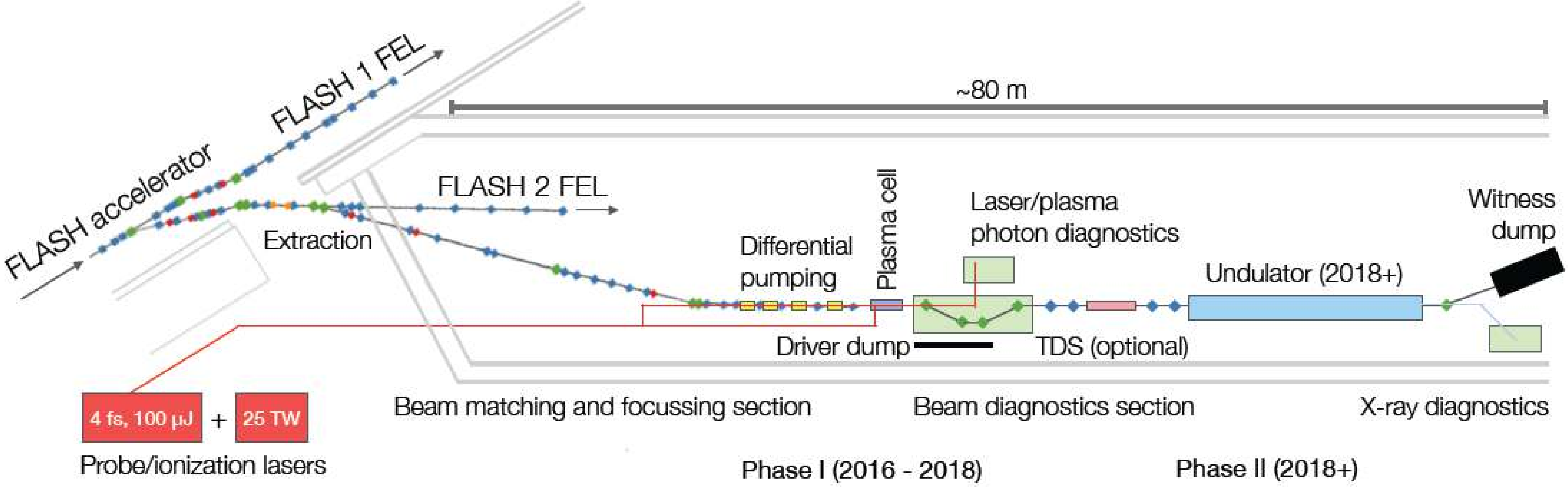

FLASHforward @ DESY

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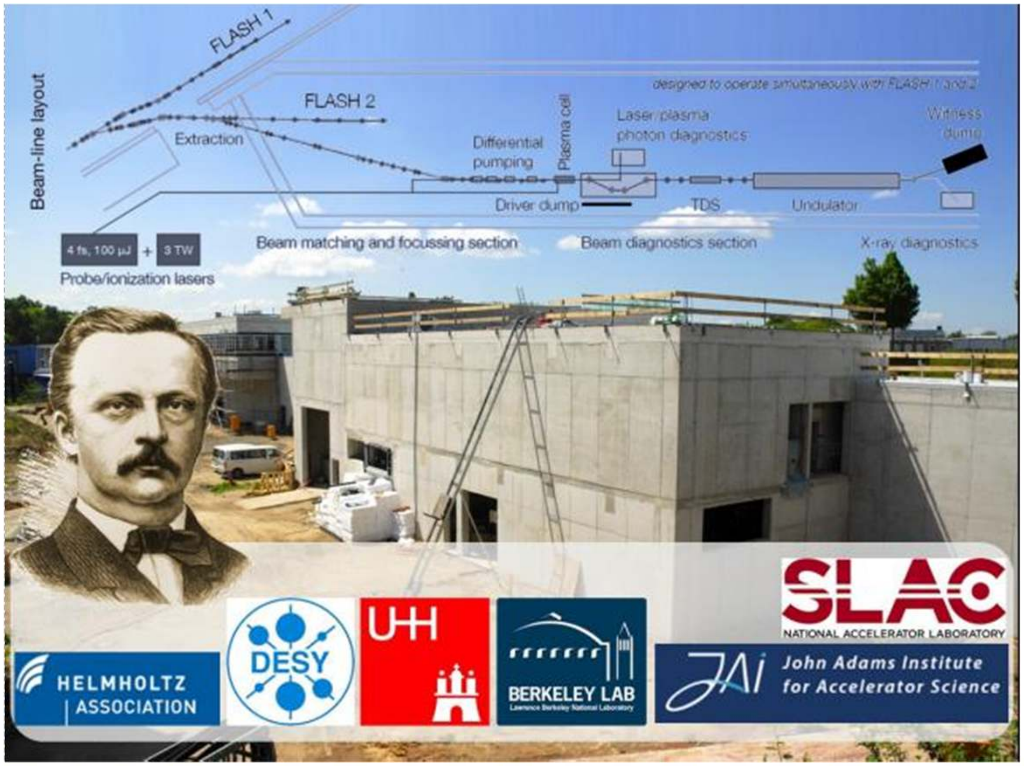
Beamline installation
to start in May 2015

Preliminary FLASHForward installation plan in place

- Preparation of FLASH extraction area in May 2015, 3 weeks duration
- Installation of vacuum components not before 2016 owing to
  - unavailability of some technical groups in 2015 due to XFEL work
  - user run at FLASH 1
- Further installations require
  - 1 month of work in FLASH extraction area in 2016
  - Total of 2x 1 month of work in FLASH II tunnel in 2015/16, can be partially in parallel with extraction area work
- Exact installation time slots in 2016 still to be defined

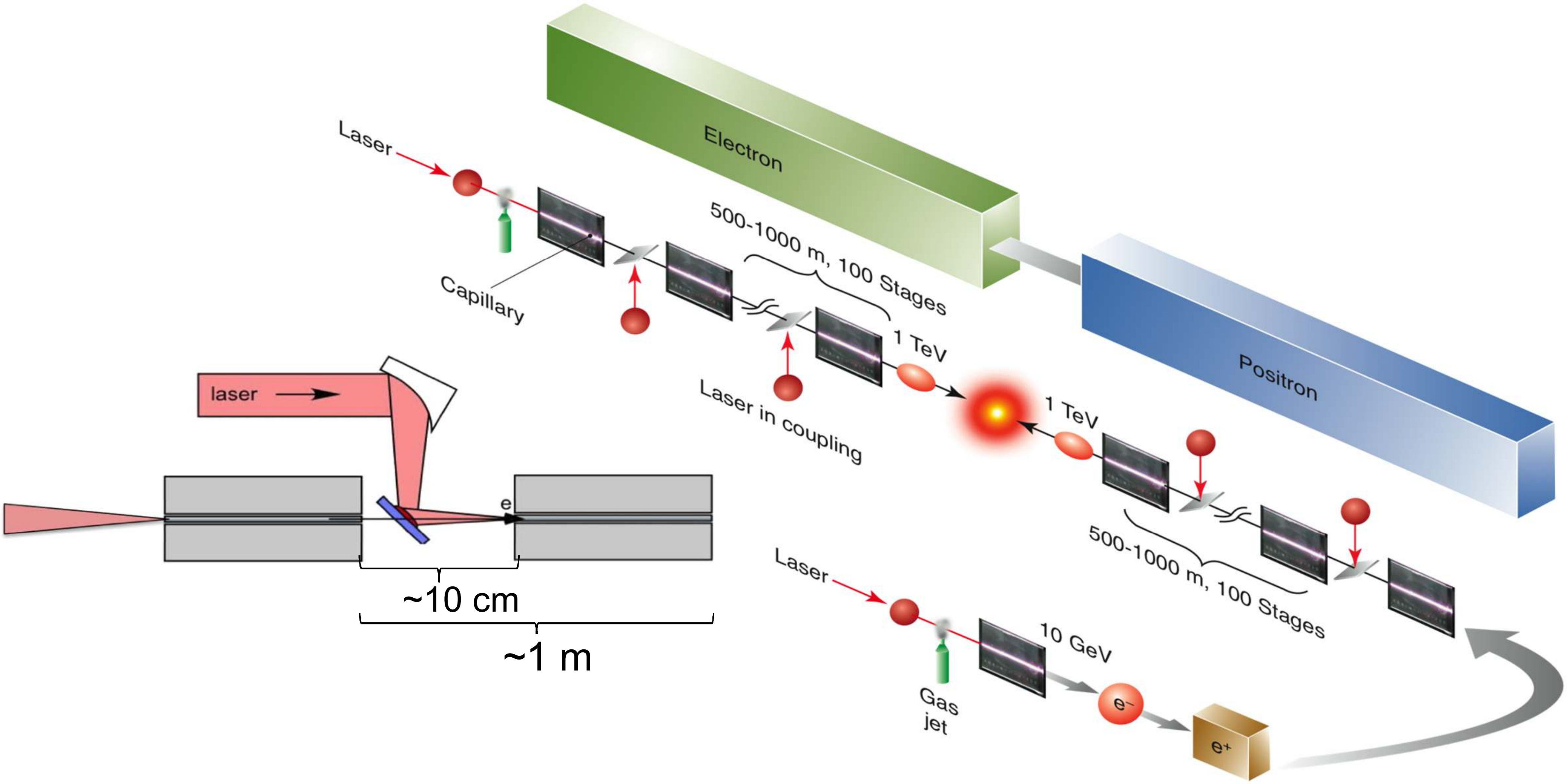
FLASH coordinators extremely supportive in implementation of plan, regular coordination meetings have been established.

Helmholtz Virtual Institute for Plasma Wakefield Acceleration of highly Relativistic electrons with FLASH

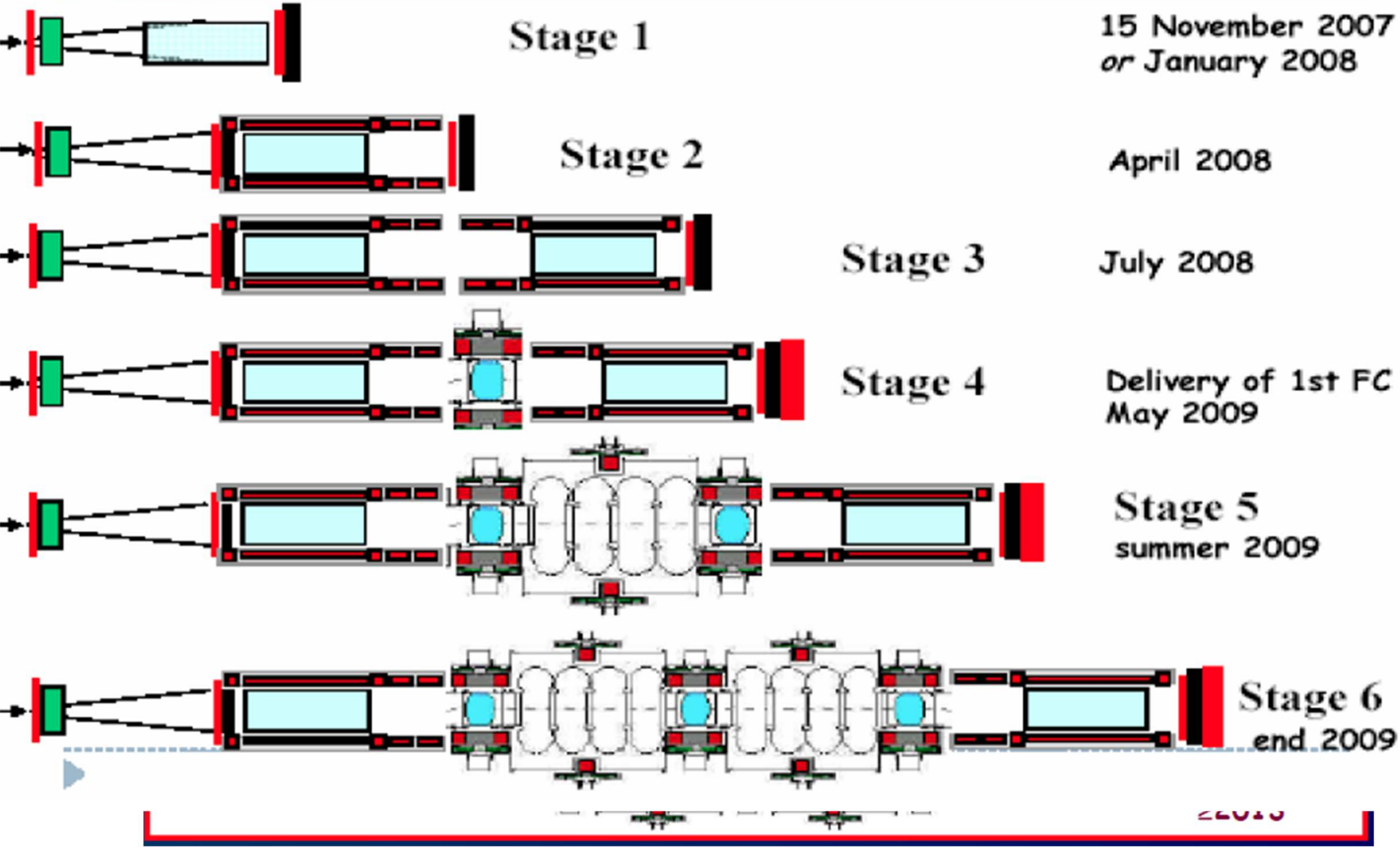


Realising the dreams?

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



MICE Schedule



Stage 1 — 15 November 2007 or January 2008

Stage 2 — April 2008

Stage 3 — July 2008

Stage 4 — Delivery of 1st FC May 2009

Stage 5 — summer 2009

Stage 6 — end 2009

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
- In the immediate future, Japanese interest in hosting ILC is being discussed. A strong physics case exists, irrespective of LHC results. The next 2-3 years will be criticial.

Backup slides

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