Future Machine Challenges

D. Schulte, CERN

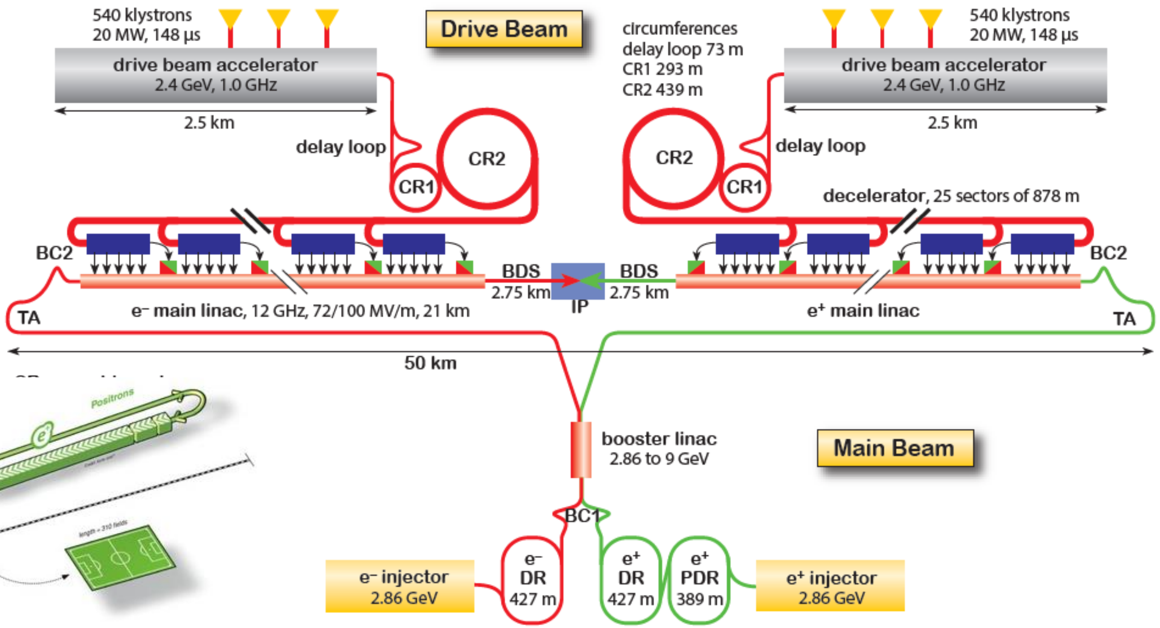
Linear Colliders

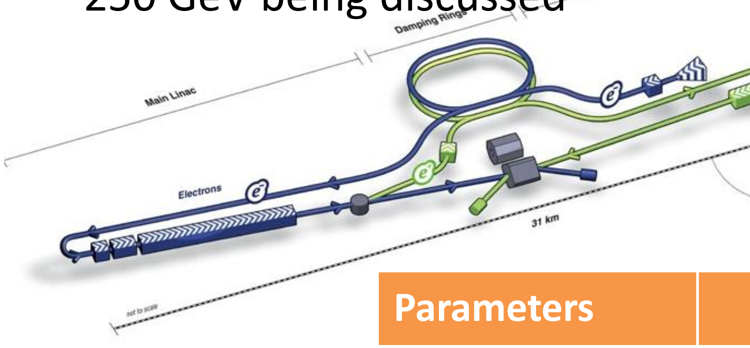
Compact LInear Collider (CLIC)

- Stages at 380, 1500 and 3000 GeV

International Linear Collider ILC

- 500 GeV
- 250 GeV being discussed





Parameters	ILC	CLIC 380 GeV	CLIC 3 TeV
C.M. Energy	500 GeV	380 GeV	3000 GeV
Peak luminosity	1.8 x10^{34} cm^{-2}s^{-1}	1.5 x10^{34} cm^{-2}s^{-1}	6 x10^{34} cm^{-2}s^{-1}
IP beam size	474 nm / 6 nm	150 nm / 3 nm	40 nm / 1 nm
Beam power	10.5 MW	5.6 MW	28 MW
E gradient	31.5 MV/m	72 MV/m	72/100 MV/m
Length	31 km	11 km	50 km

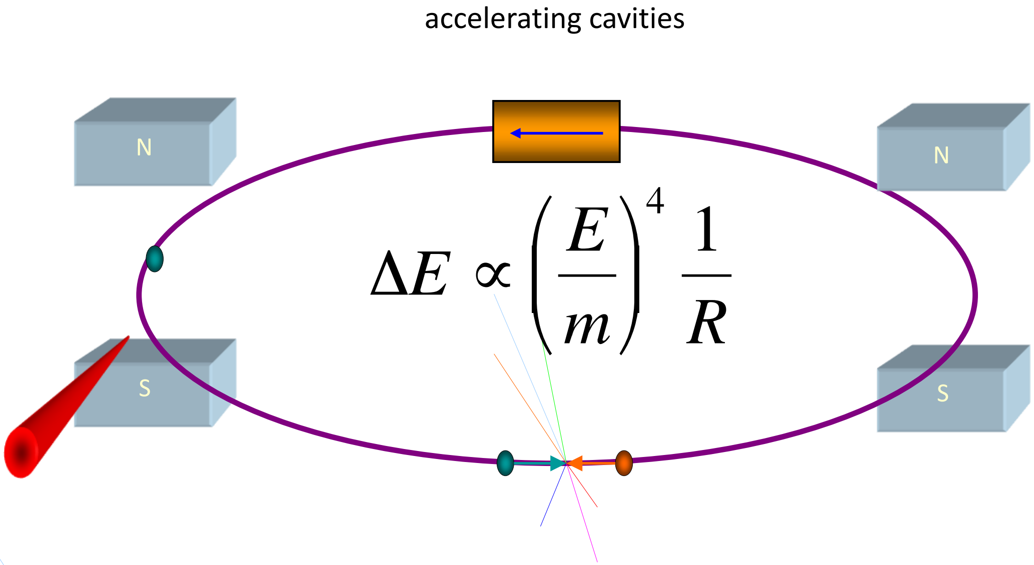
Lepton Colliders: Ring vs. Linear Collider

Can accelerate beam in many turns

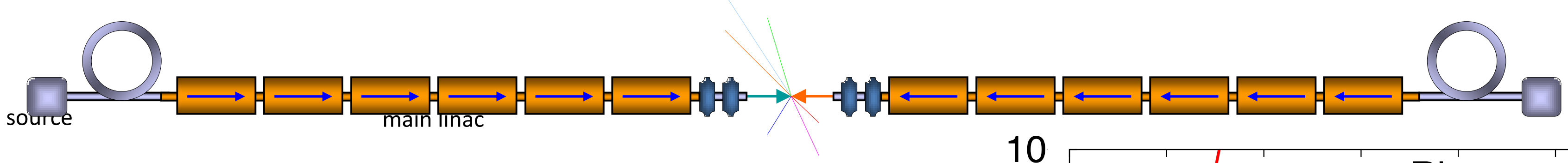
Can use beam many times

For light particles synchrotron radiation can be large

- At LEP2 lost 2.75GeV/turn for E=105GeV



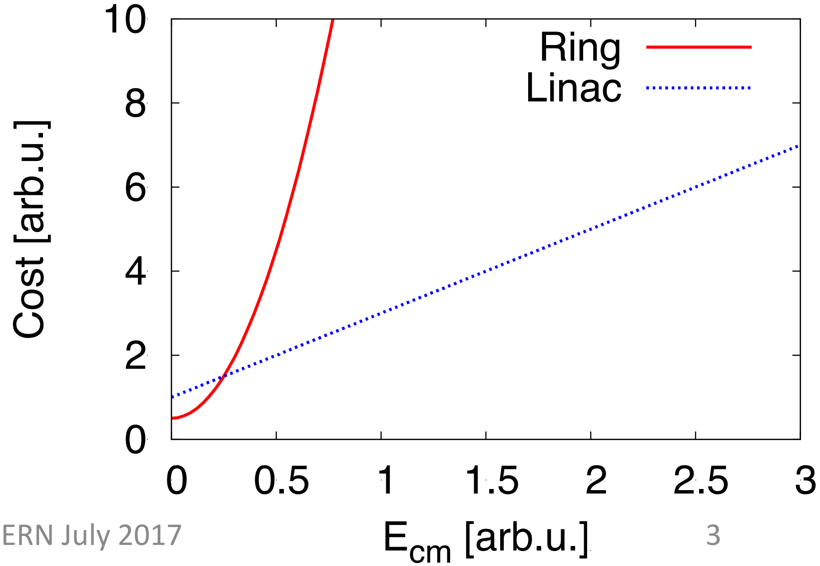
$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$



Almost no radiation in a linac, but

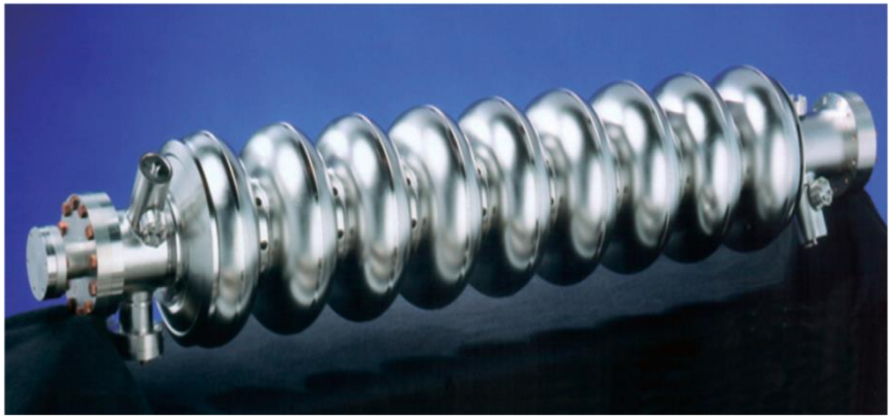
Have to achieve energy in single pass

Have to achieve luminosity with single pass



Acceleration

ILC

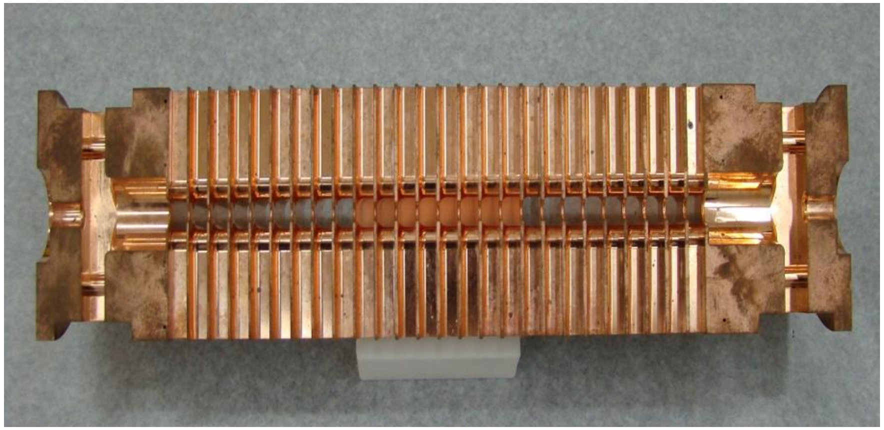


1.3 GHz, 1m-long, superconducting
$Q_0=O(10^{10})$

Effective gradient 31.5 MV/m
⇒ Limited by degradation of Q_0
⇒ 31 km for 0.5 TeV

5 RF pulses per second
(O(1.6ms), O(200kW), 1312 bunches)

CLIC



12 GHz, 23cm long, normal conducting

Loaded gradient 100 MV/m
(72 MV/m at 380 GeV)
⇒ Limited by sparking
⇒ 11 to 50 km long for 0.38 to 3 TeV

50 RF bursts per second
240ns, 60MW, 312 bunches

Achieved Gradients

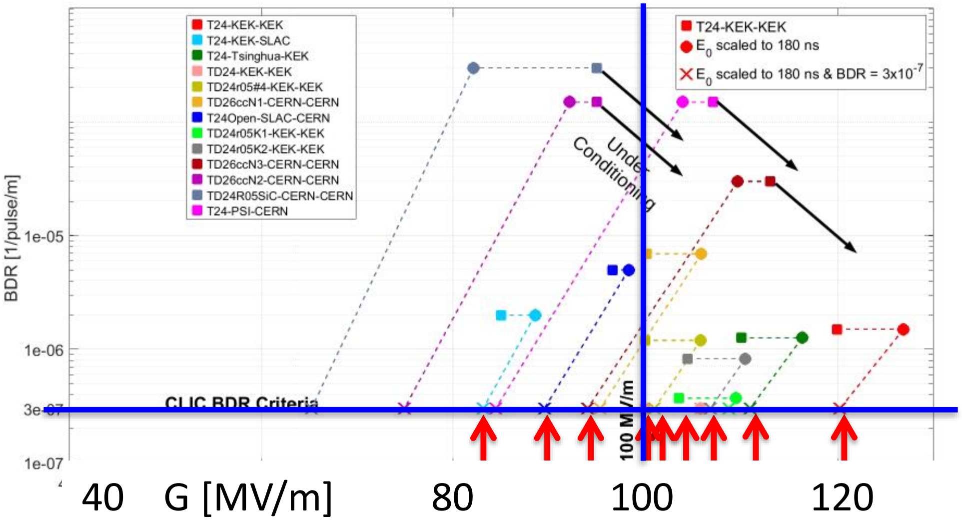
ILC and CLIC demonstrated that design gradients can be reached

Work is on reproducibility, improvements and cost reduction

Industrial fabrication

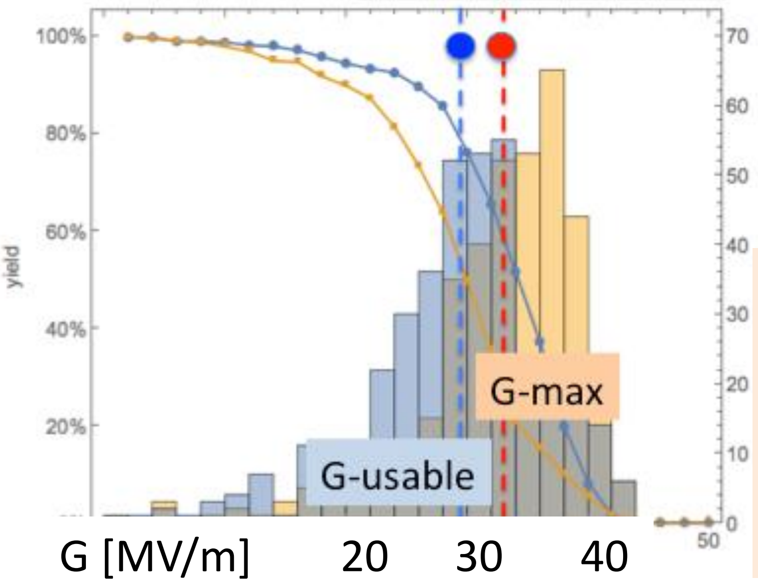
- 800 ILC-type cavities for X-FEL
- Several CLIC structures

CLIC structures



CLIC structures fabrication/conditioning is being improved
Preparing for industrialisation
Interest of other projects (FELs, DESY, INFN, PSI, Cockcroft,…)

N. Walker, D. Reschke, SRF'15



ILC goal 31.5 MV/m installed

X-FEL goal 24 MV/m
reached 29 MV/m

Recent N infusion might increase gradient by up to 20%

Luminosity

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$

Beam power

Luminosity spectrum

Beam Quality
(+bunch length)

Limited by quality of physics
(Luminosity spectrum,
beamstrahlung)

Part of structure design
optimisation

Need very small beams
Small phase space (emittance)
Squeeze it down

Challenge to produce the beams
and to collide them

Other Systems

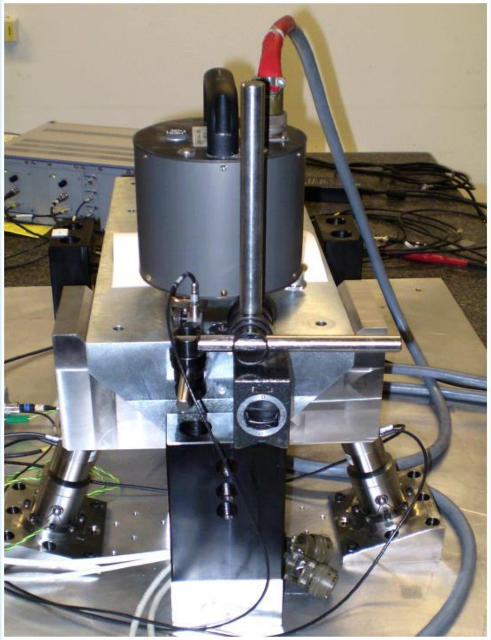
Preservation of beam quality is challenging
Collision beam sizes down to 1 nm for CLIC at 3 TeV
Many systems have been developed and tested
Now focus on preparing industrialisation/cost reduction

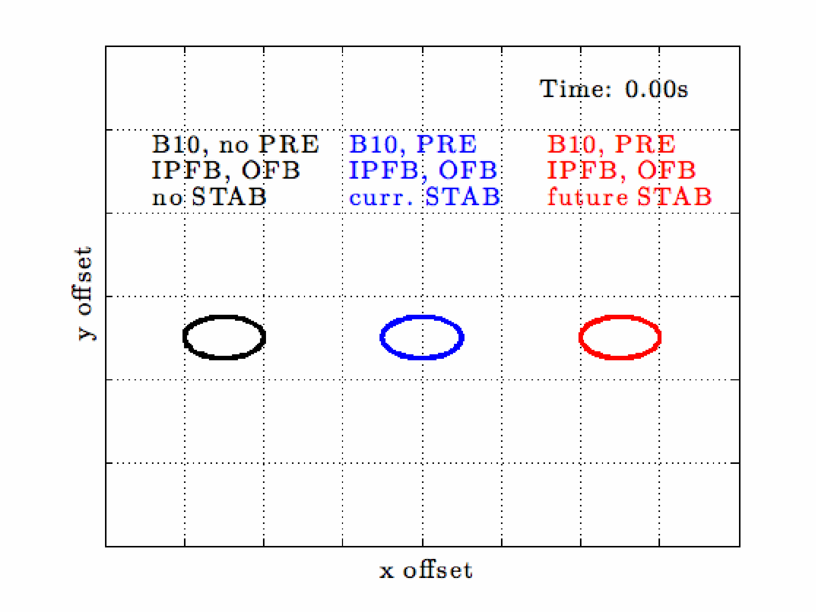
Novel high accuracy alignment

Novel beam-based alignment algorithms

Novel high precision instrumentation

Stabilisation of magnets against natural ground motion





Novel beam optics to squeeze beams

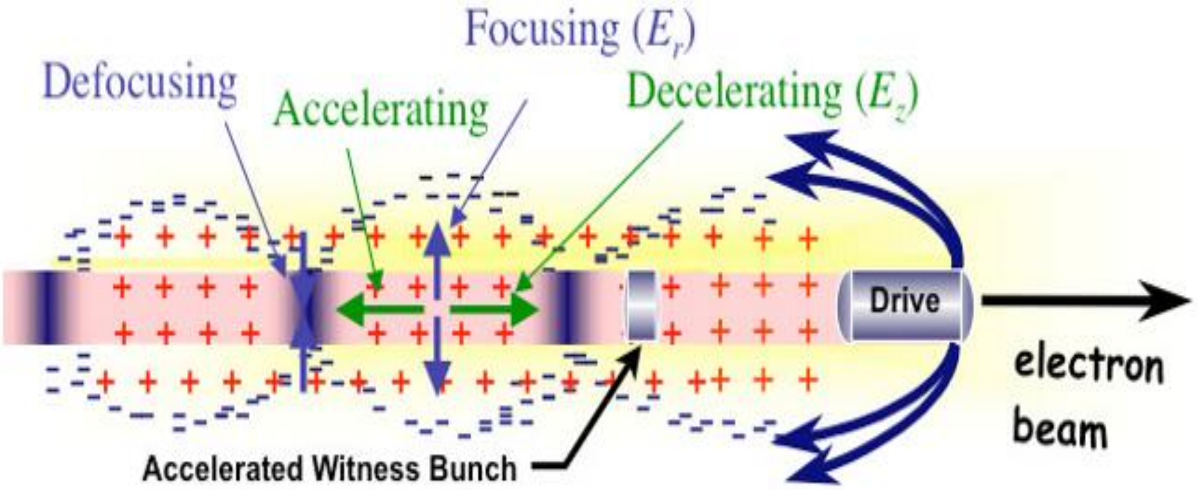
And many more …

Plasma Acceleration as Upgrade Option?

Very high gradients of 50 GV/m demonstrated

Can use laser or particle beam to generate field

R&D programmes are ongoing



Require excellent beam quality and high efficiency

- Preservation of beam quality during acceleration has to be studied in theory and experimentally
- This is particularly tough for high efficiency

Application of novel technologies to colliders

- Started a working group for CLIC to understand potential
- Plasma community started a working group on colliders

FCC and CEPC/SppC

Proposal for project at CERN
- CDR for EU strategy end 2018

FCC-hh
- pp collider with 100 TeV cms
- Ion option
- Defines infrastructure

FCC-ee
- Potential e^+e^- first stage

FCC-eh
- additional option

HE-LHC
- LHC with high field magnets

Proposal for project in China
- CDRs exist but changes since

CEPC
- e^+e^- collider 90-240 GeV
- focus on higgs

SppC
- Hadron collider to later be installed in the same tunne
- 75 to O(150) TeV

Focus on proton colliders:

Main challenge for proton colliders

Magnetic field strength and circumference

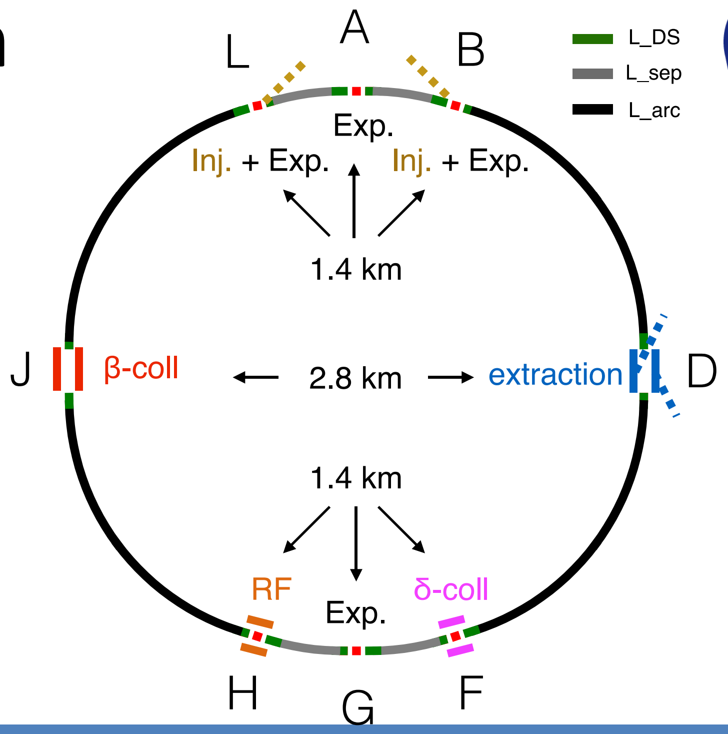
FCC-hh

FCC-hh layout
Two main experiments
Two additional experiments

Optimised for Geneva site
Circumference 97.75 km
Can use LHC or SPS as injector

Integrated luminosity
Goal 17.5 ab^{-1} per main experiment

CEPC/SppC uses 100 km tunnel



	LHC (HL-LHC)	HE-LHC (tentative)	FCC-hh		SppC	SppC ultimate
			Baseline	Ultimate		
Cms energy [TeV]	14	27	100	100	75	150
Luminosity [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	1 (5)	25	5	< 30	10	?
Machine circumference	27	27	97.75	97.75	100	100
Arc dipole field [T]	8	16	16	16	12	24
Bunch distance [ns]	25	25 (5)	25	25 (5)	25 (10/5)	?
Background events/bx	27 (135)	800 (160)	170	< 1020 (< 202)	490 (196/98)	?
Bunch length [cm]	7.5	7.5	8	8	7.55	?

FCC-hh Magnet Development

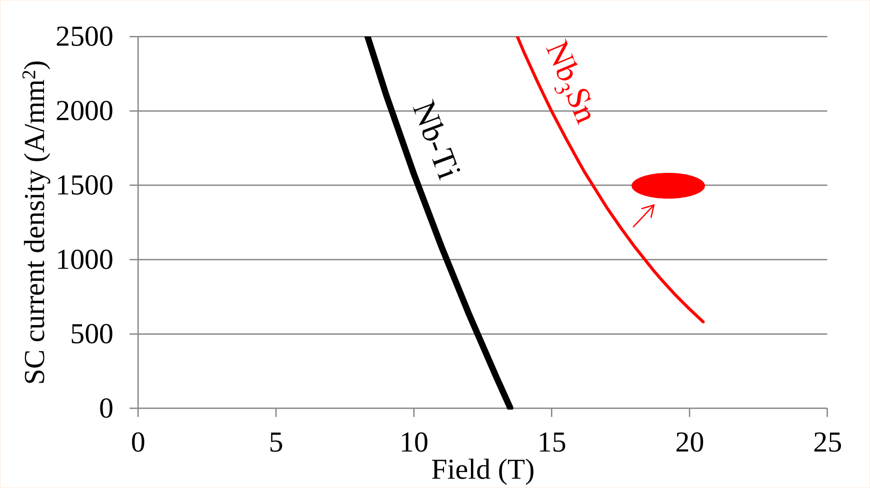
FCC goal is 16 T operating field
- Requires to use Nb_3Sn technology
- At 11 T used for HL-LHC

⇒ Strong synergy with HL-LHC

Key cost driver
16 T demonstrated in coil
But need full magnet

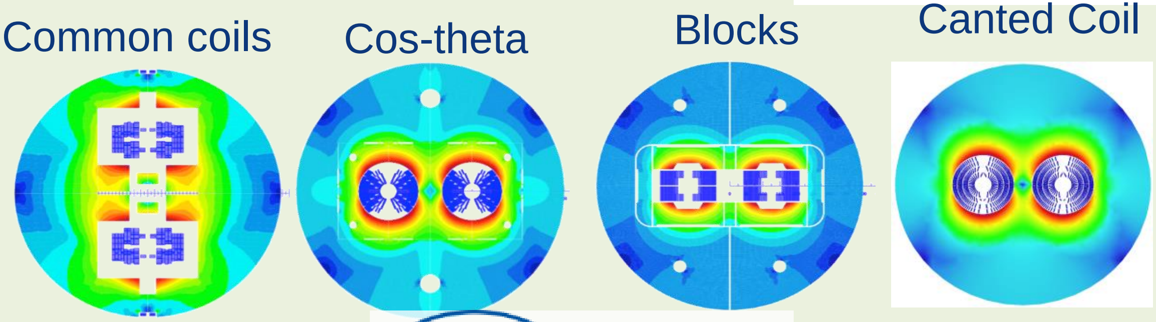
R&D on cables in test stand at CERN

Target: $J_C > 2300$ A/mm^2 at 1.9 K and



Magnet design to **minimise material** use and limit margins to essential level

D. Tommasini at al.



Swiss contribution via PSI

CIEMAT, CEA, INFN

High-temperature superconductors (HTS) are also explored

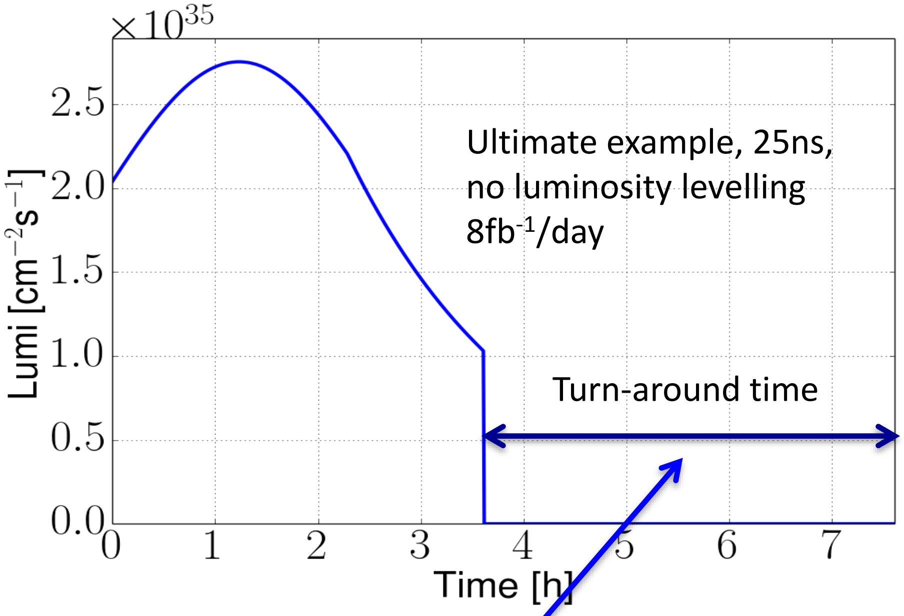
Luminosity

$$\mathcal{L} = \xi \frac{1}{\beta} \frac{N}{\Delta t} \eta_{fill}$$

Beam-beam tuneshift mostly limited by beam physics

Beta-function limited by lattice design (and magnet technology)

Stored beam important for luminosity



Ultimate example, 25ns, no luminosity levelling 8fb^{-1}/day

Turn-around time

High beam current is most important factor for luminosity

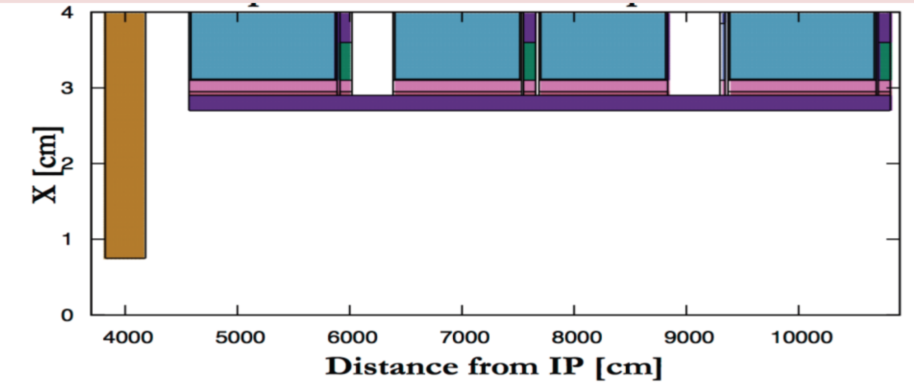
Other R&D

8 GJ kinetic energy per beam

- Airbus A380 at 720 km/h
- 2000 kg TNT
- 400 kg of chocolate
  - Run 25,000 km to spent calories
- O(20) times LHC

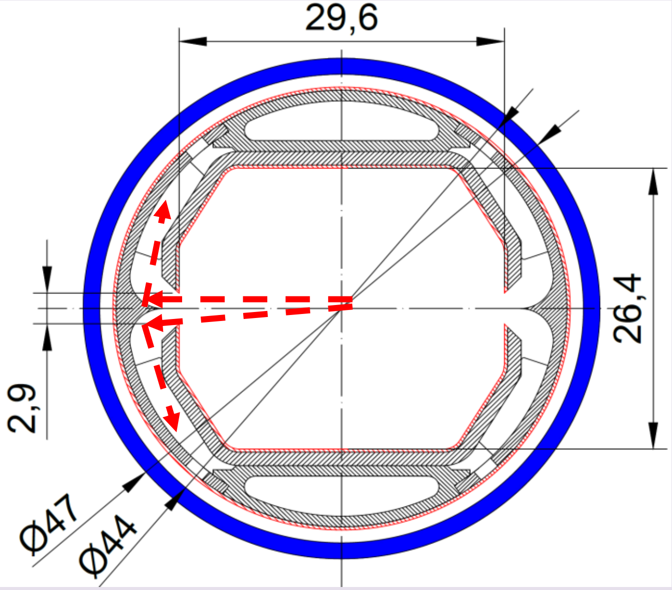
Up to 500 kW collision debris per experiment

Mainly lost in triplets, challenge for lifetime and quench



Many other components

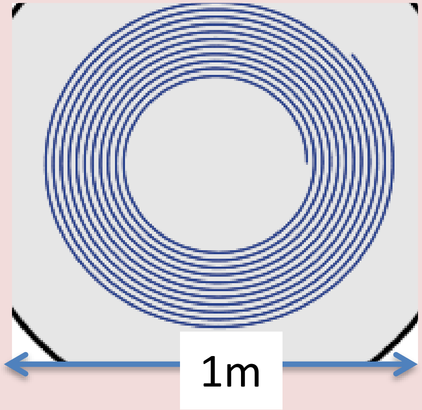
e.g. beamscreen



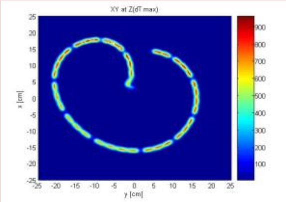
Collimation, injection and extraction are challenging

e.g. beam dump

FCC-hh dilution pattern



LHC dilution pattern

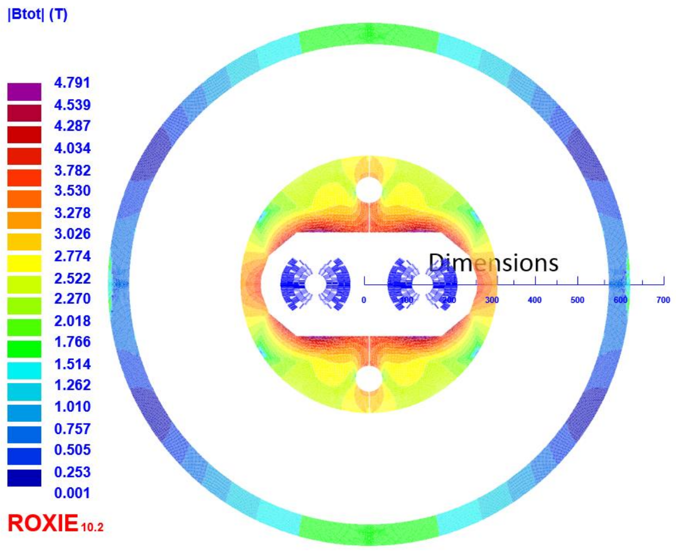


HE-LHC

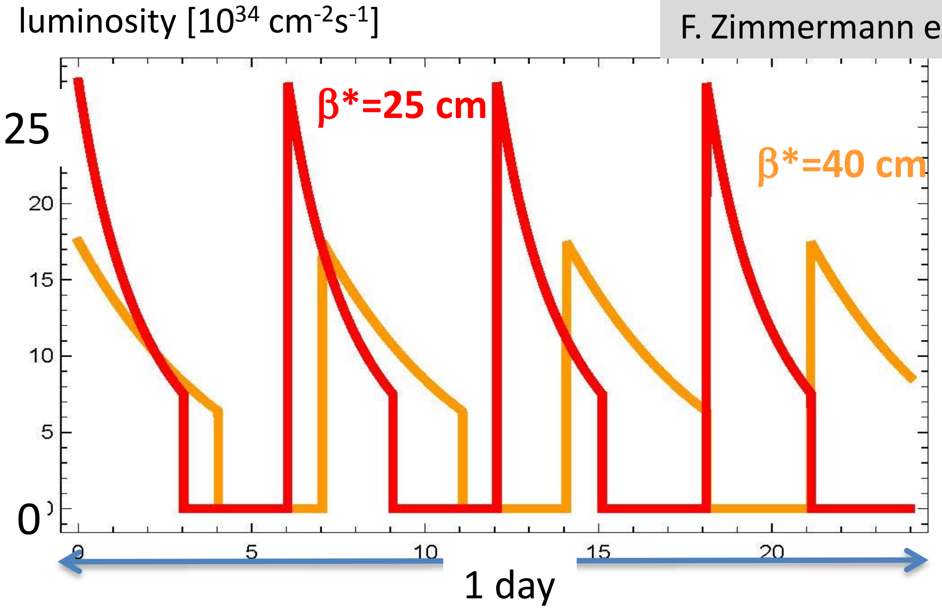
Goal is 4 x HL-LHC luminosity
HL-LHC injectors
FCC-hh magnets and vacuum system

Make FCC-hh magnets more compact to fit in LHC tunnel

- Challenge is field leakage into tunnel
- Use kryostat as partial return yoke
- Active compensation



Only magnetic elements shown

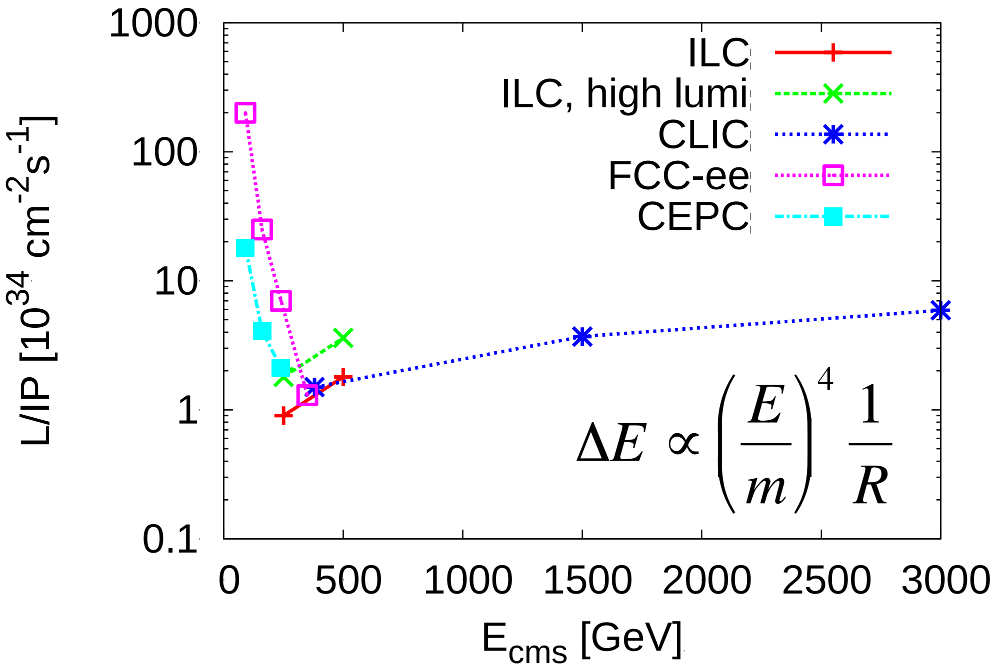


F. Zimmermann et al.

Cannot increase lengths of insertions

- Currently beta-function around 0.4 m
  - 0.7ab^{-1} per year
  - Hope to improve
- Beam extraction is a challenge
- Collimation to be looked at

FCC-ee / CEPC Parameters



Challenges:
Short beam lifetime at high energy requires top-up scheme

High background photon flux from machine

High current low energy beam but also high voltage at high energies

Make it cheap

Parameters are still moving targets FCC-ee and CEPC

L. Wang et al. IHEP-AC-2017-01
F. Zimmermann et al. priv. comm.

Parameter	Z	W	H	t	LEP2
Cms E [GeV]	91.2	160	240	350	208
I [mA]	1390 / 370-1450	147 / 51	29 / 11-30	6.4 / --	4
L [10^{34} cm^{-2}s^{-1}]	200 / 18-71	25 / 4.1	7 / 2.1-5.4	1.3 / --	0.012
Years op.	4	2	3	5	
Int L / IP [ab^{-1}]	75	5	2.5	1.5	

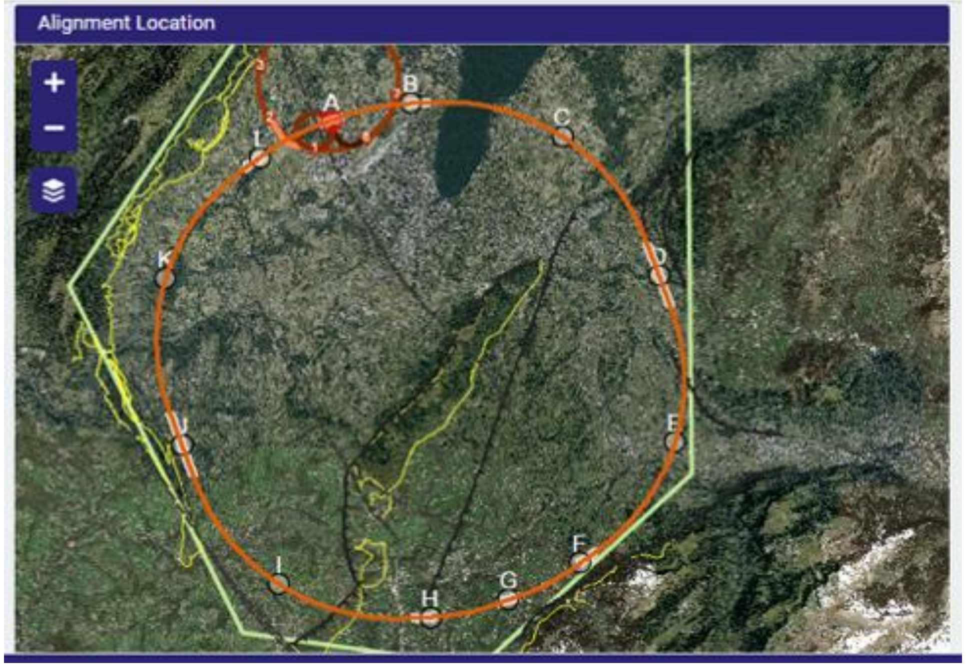
Civil Engineering

Typically 1/3 of the total cost

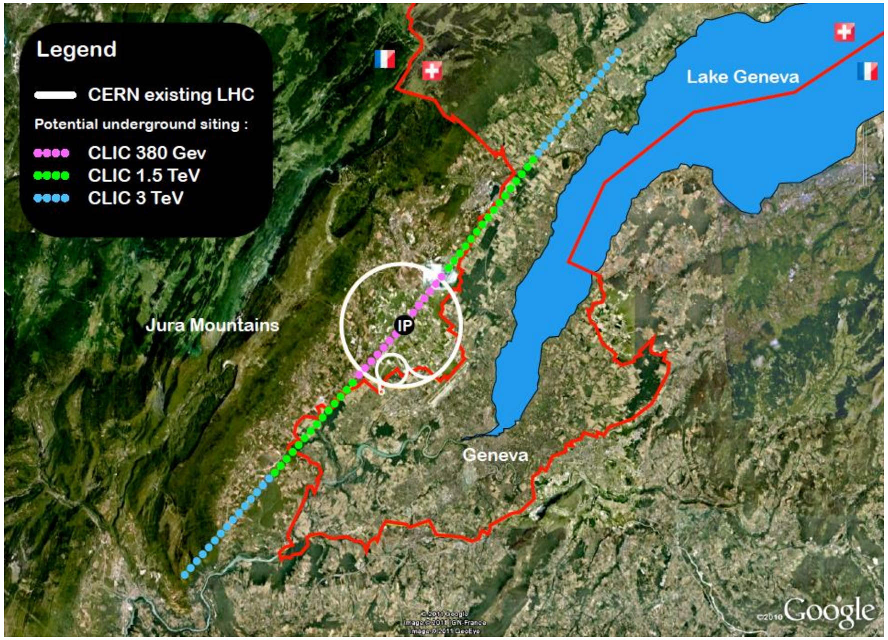
Can have severe constraints from site

E.g. had to change FCC layout to avoid bad rock under the Jura

FCC at Geneva



CLIC stages at Geneva



Site for ILC in Japan exists

- Detailed exploration for

CEPC/SppS site in China foreseen

CLIC Roadmap

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

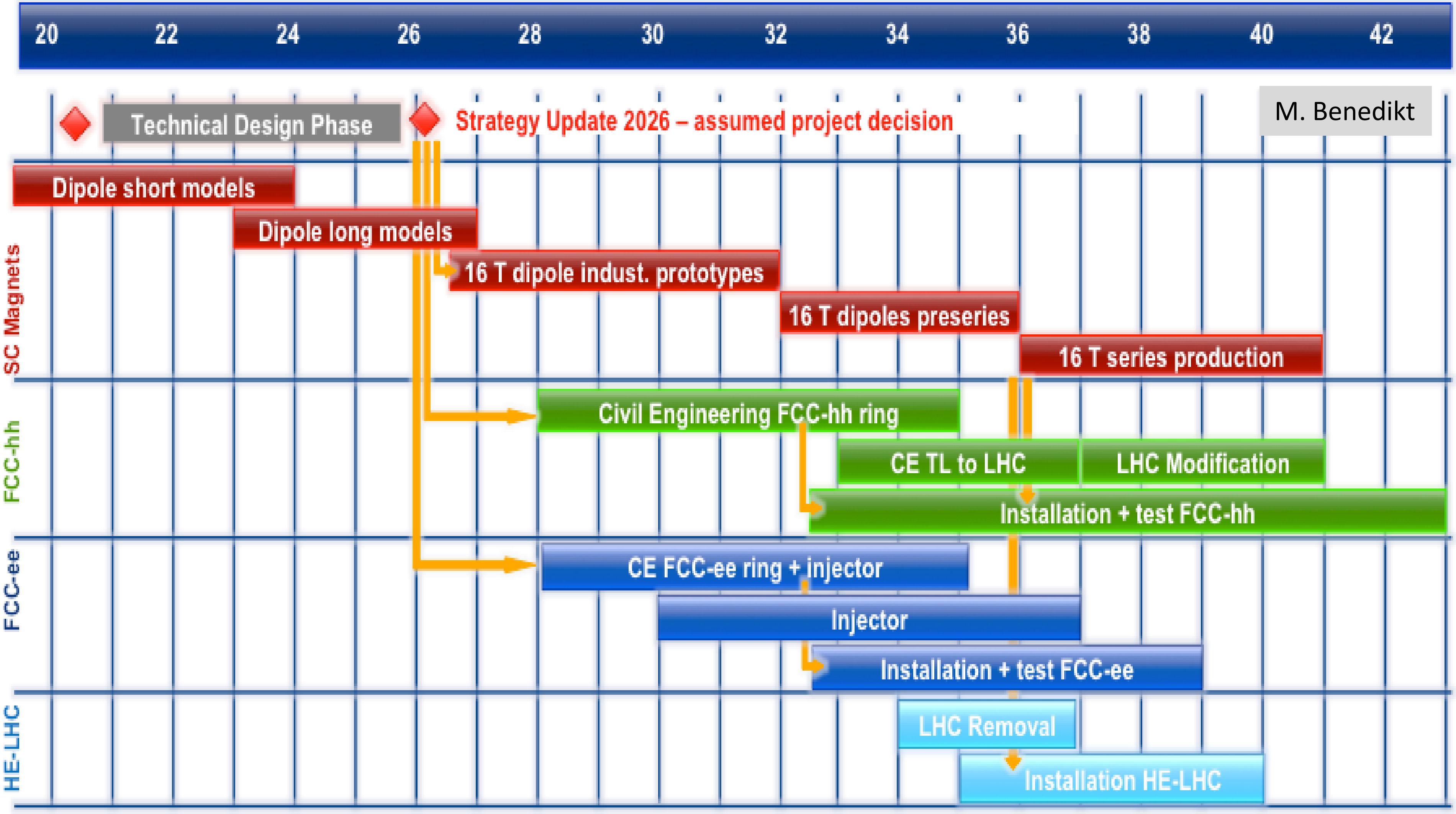
Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

Preliminary FCC Draft Schedules

Technically limited schedule



Conclusion

Important progress toward the EU strategy

- ILC
  - Focus on cost reduction and political process
- CLIC
  - Further optimising 380 GeV first energy stage
  - Work on further stages, including novel technologies
  - Project Implementation Plan for 2018
- SppC and CEPC
  - CDRs available
- FCC
  - CDR end of 2018 for hh (with he) , ee and HE-LHC options
  - Including R&D plan

Many thanks to L. Evans, S. Stapnes, W. Wuensch, Ph. Burrows, I. Syratchev, M. Benedikt, K. Oide, F. Zimmermann, M. Klein, …, the ILC, CLIC, FCC and SppC/CEPC teams

More in the Summer Student Lectures “Future Collider Technologies”, July 27+28
https://indico.cern.ch/event/634063

Reserve

Linear Collider

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

$$\mathcal{L} \propto H_D \underset{\substack{\uparrow \\ \text{Luminosity} \\ \text{spectrum}}}{\frac{N}{\sigma_x}} \quad \underset{\substack{\uparrow \\ \text{Beam power}}}{N n_b f_r} \quad \underset{\substack{\uparrow \\ \text{Beam Quality} \\ \text{(+bunch length)}}}{\frac{1}{\sigma_y}}$$

Need to ensure that we can achieve each parameter

Beam-beam Effect

$$\mathcal{L} \propto H_D \enclose{circle}{\frac{N}{\sigma_x}} N n_b f_r \frac{1}{\sigma_y}$$

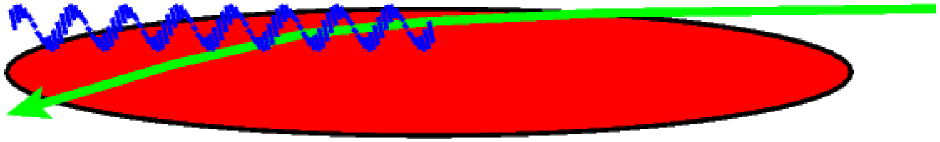
Intense beams for luminosity

Strong electromagnetic fields

Particles travel on curved trajectories

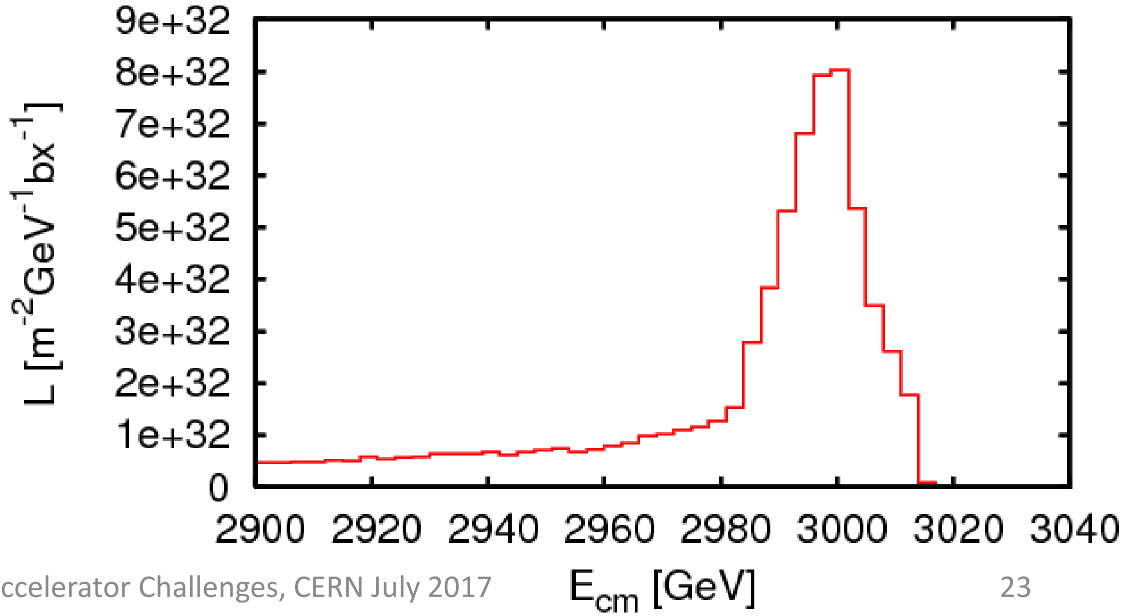
They emit O(1) photons (beamstrahlung)

They can collide with less than nominal energy



$$n_\gamma \propto E_\gamma \propto \frac{N}{\sigma_x + \sigma_y} \qquad \sigma_x \gg \sigma_y$$

$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \qquad \sigma_x + \sigma_y \approx \sigma_x$$

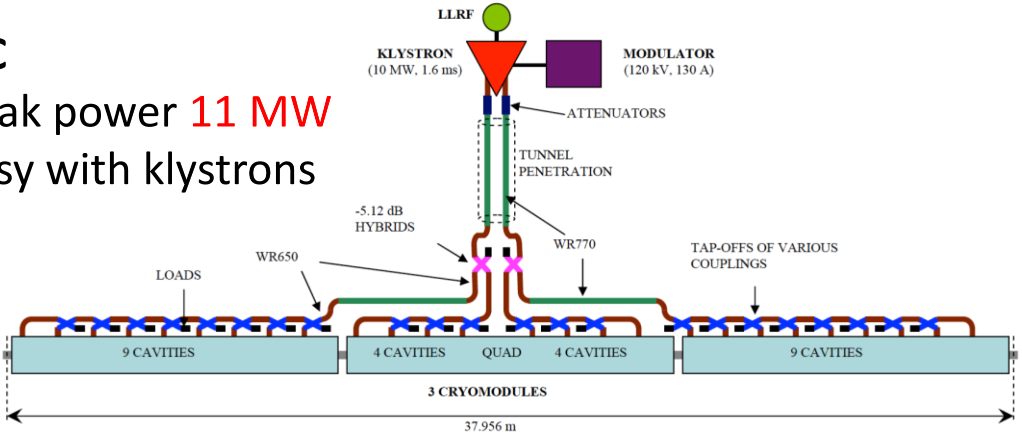


Klystrons vs. Drive Beam

ILC

Peak power 11 MW

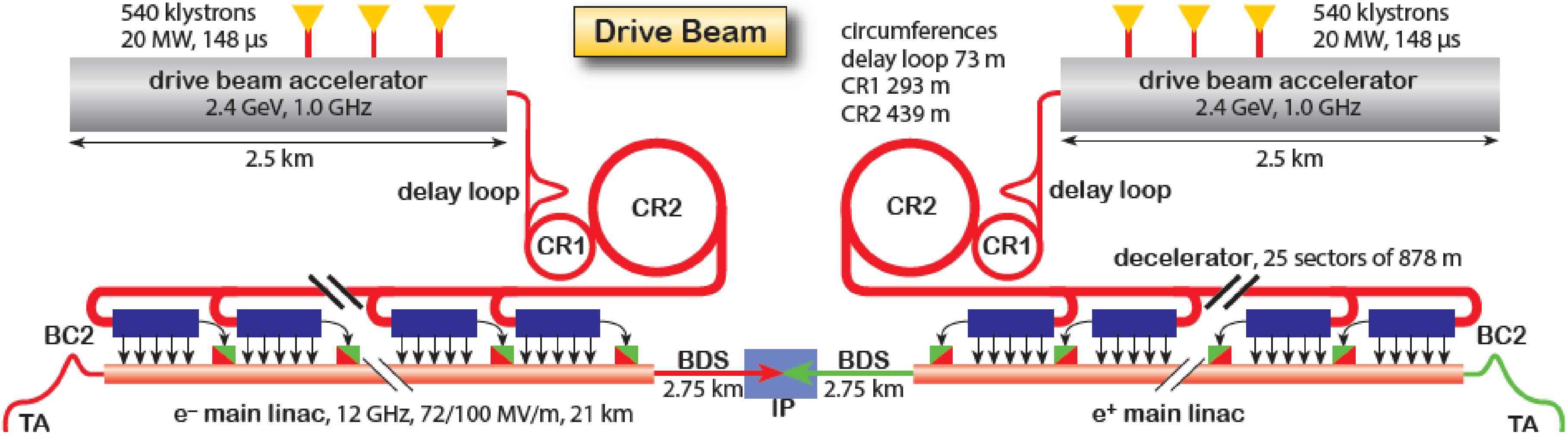
Easy with klystrons



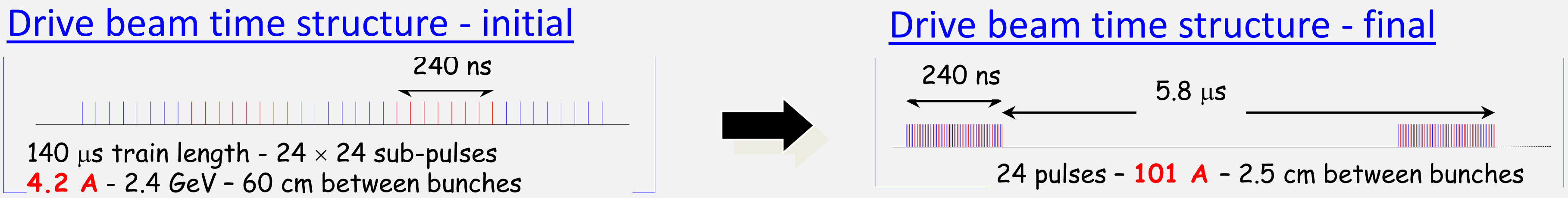
CLIC

Peak power 8.5 TW

Novel scheme required



Klystrons vs. Drive Beam



Drive beam time structure - initial

240 ns

140 μs train length - 24 × 24 sub-pulses

4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

240 ns

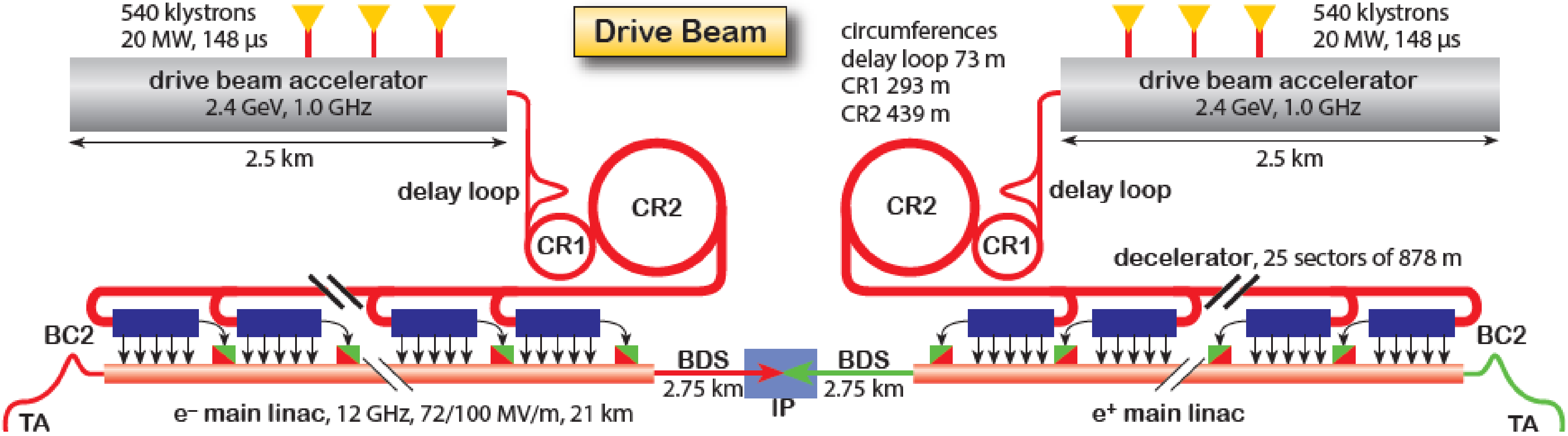
5.8 μs

24 pulses – 101 A – 2.5 cm between bunches

148 μs x 4.2 A x 2.4 GV

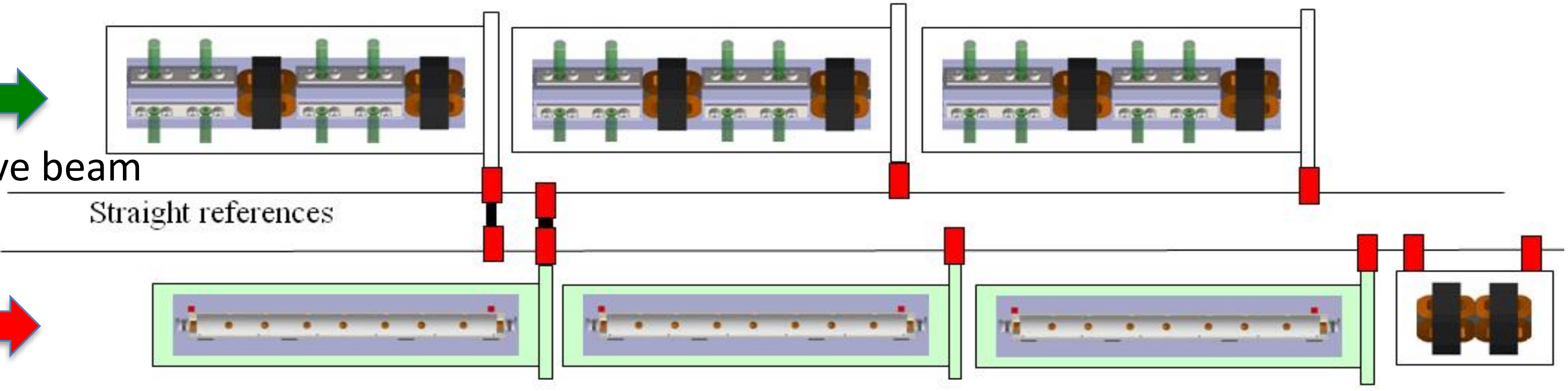
24 x 101 A x 2.4 GV

2 x 10 GW x 148 μs => 2 x 5.8 TW x 240 ns = 11.6 TW x 240 ns



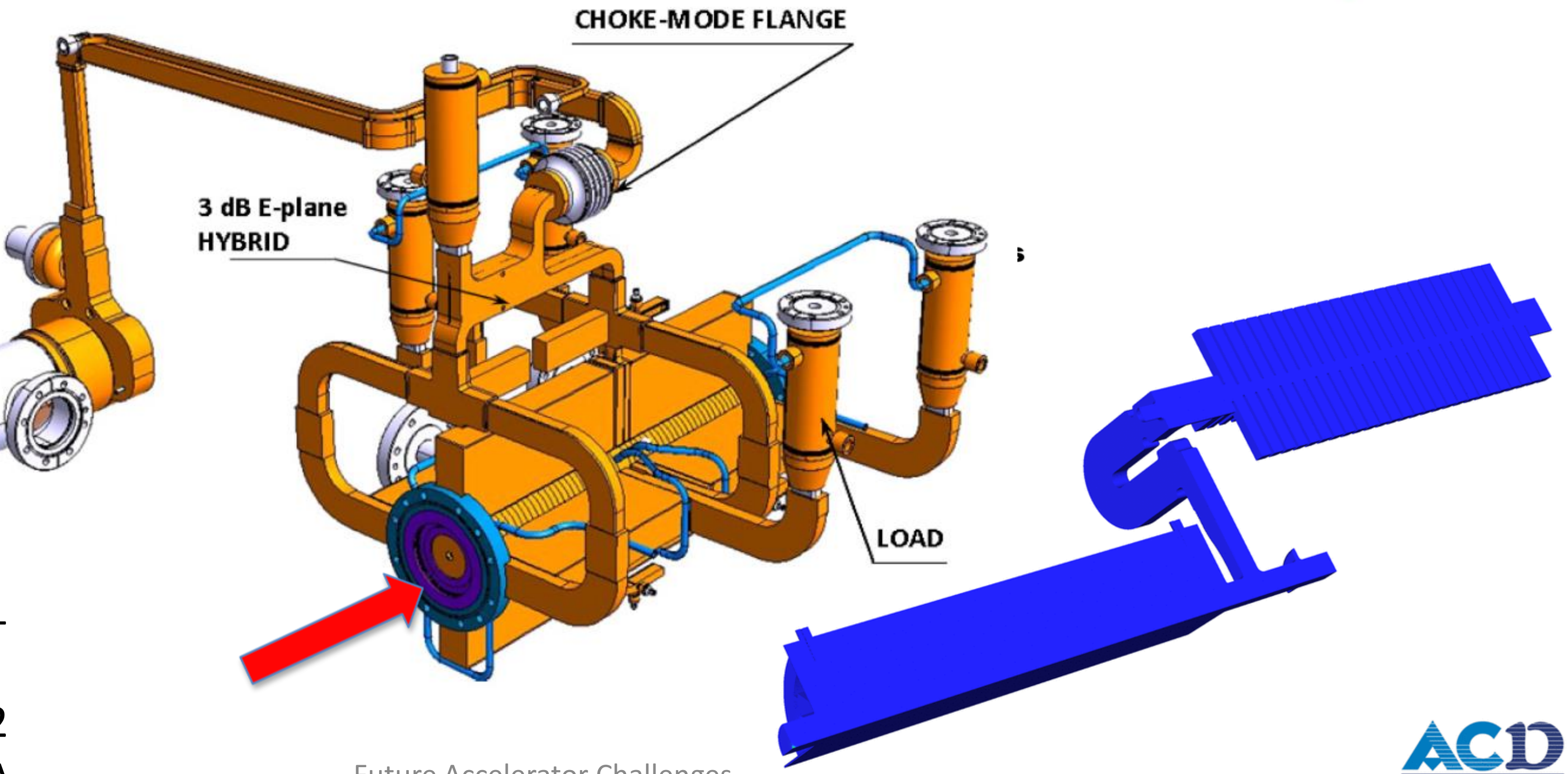
Novel Power Generation Scheme

100A drive beam



1.2A main beam

100A drive beam

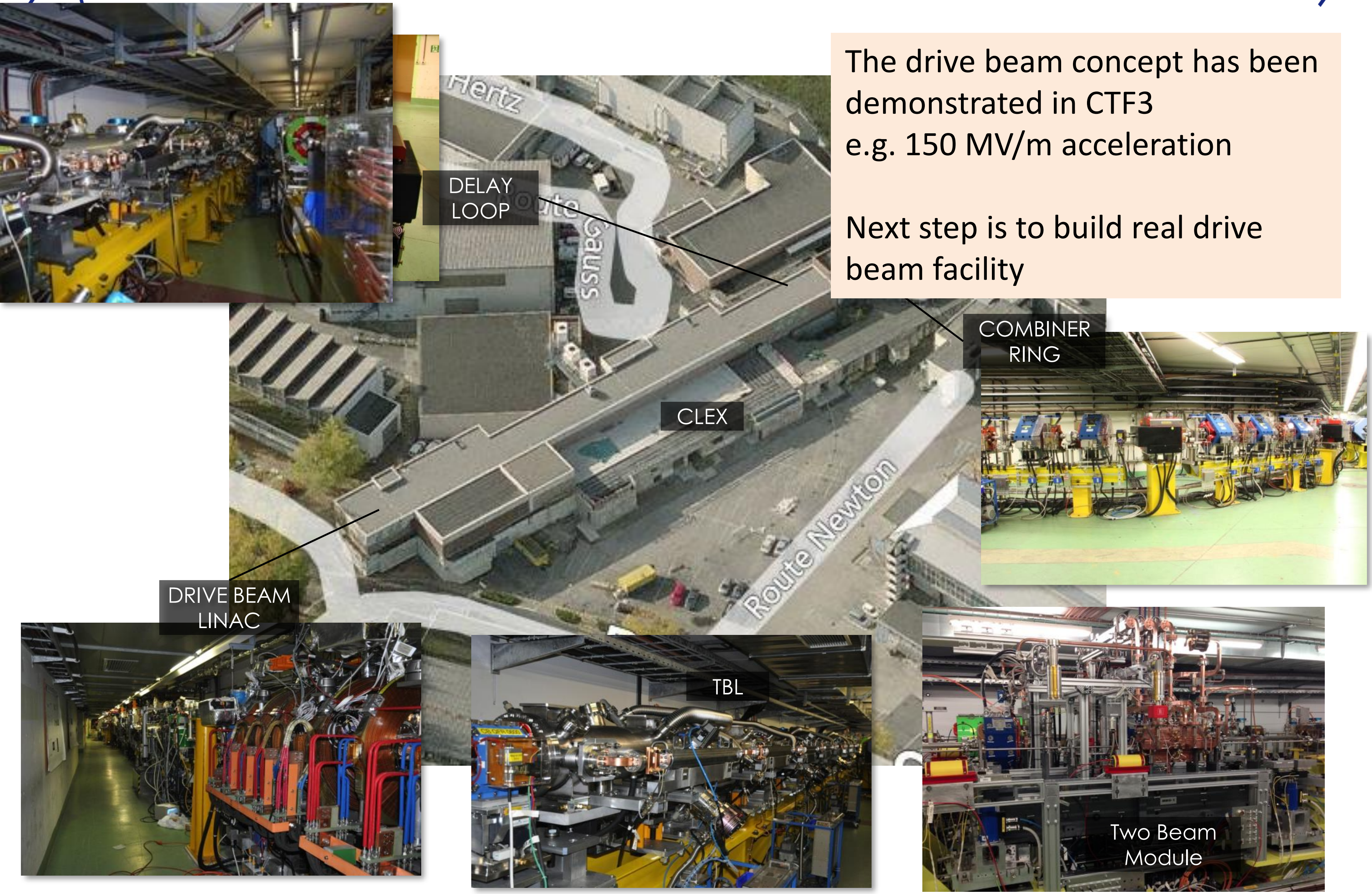


1.2A

Demonstration in CTF3

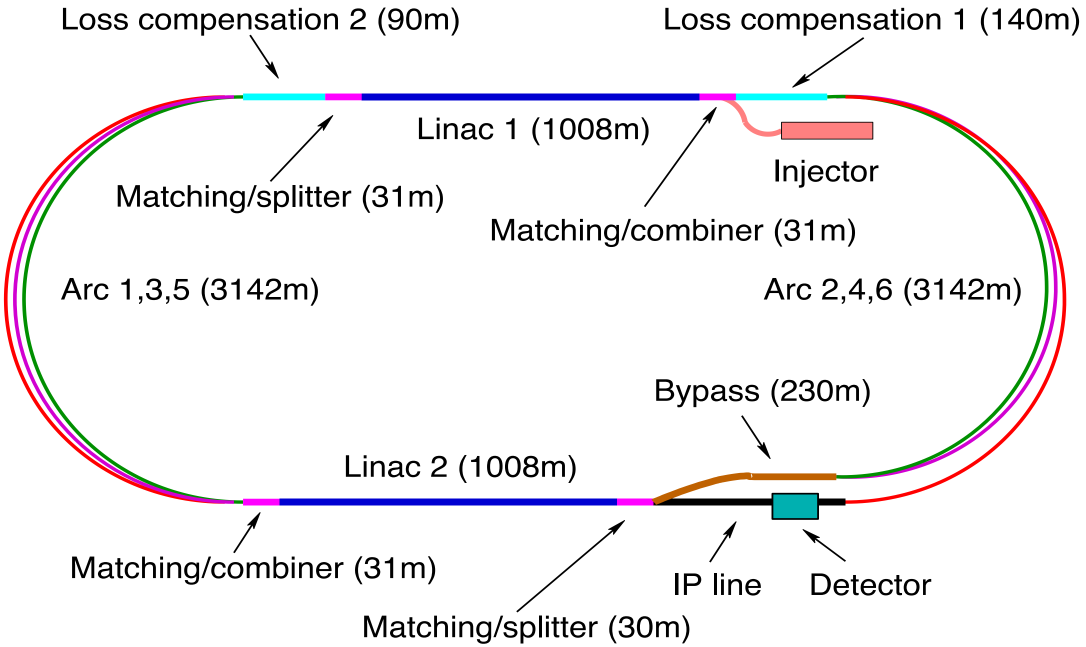
The drive beam concept has been demonstrated in CTF3
e.g. 150 MV/m acceleration

Next step is to build real drive beam facility



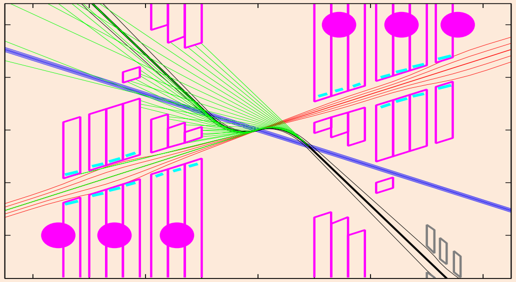
D. Schulte

Note: LHeC / FCC-he



	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
L [10^{33} $cm^{-2}s^{-1}$]	1	8	12	15

Interaction region
design ongoing



M. Klein et al

Development of accelerator technology
E.g. RF power required to control cavities
Test facility (PERLE) planned in Orsay