Accelerator Technologies II

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Considered High Energy Frontier Collider

Circular colliders:

- HL-LHC
- FCC (Future Circular Collider)
  - FCC-hh: 100 TeV proton-proton cms energy, ion operation possible
  - FCC-ee: First step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- CEPC / SppC (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 90 - 240 GeV cms
  - SppC : pp 70 TeV cms

Linear colliders

- ILC (International Linear Collider): e^+e^- 250 GeV cms energy, Japan considers hosting project
- CLIC (Compact Linear Collider): e^+e^- 380 GeV - 3 TeV cms energy (also lower possible), CERN hosts collaboration

Other options

- Muon collider, past effort in US, new interest also in Europe and Asia
- Plasma acceleration in linear collider
- Photon-photon collider
- LHeC

Proposed Colliders with at least a CDR

Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.8 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF

European Strategy in a Nutshell

Highest priority is HL-LHC

Beate will give much more detail in the next talk

Highest priority for next collider is a higgs factory

- currently four candidates **FCC-ee, CEPC, ILC or CLIC**

Japan community is considering to host ILC, but process is very slow
China community is considering to host CEPC, but progress very slow
CERN aims to have FCC-ee as next project and later FCC-hh, decision only at next European strategy

But

- No consensus which is the best higgs factory
- No consensus that FCC-ee and ILC/CEPC would be complementary enough to justify both
- Prudently, prepare alternatives
    - e.g. **muon collider**

US unfortunately not pushing for the high-energy frontier, might hopefully change

- Muon collider has been mainly a US development

Future Lepton Colliders

High Energy Leptons: Overview

Past circular and linear electron positron colliders

- LEP (circular) centre-of-mass energy of 205 GeV
- SLC (linear) reached 92 GeV

Studies of future electron-positron colliders

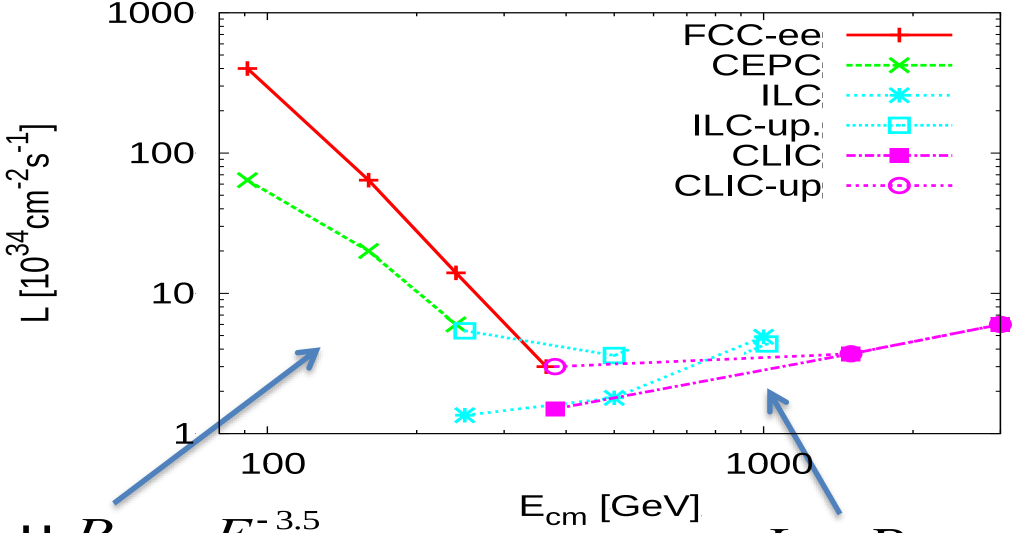
- ILC, superconducting linear collider
- CLIC, normal conducting linear collider
- FCC-ee and CEPC, circular collider

- A (circular) muon collider is being studied

LHeC and FCC-eh quickly covered
Plasma technology is being considered for linear collider, but long way to go
Gamma-gamma collisions are also being considered

Electron-positron Luminosity

Luminosity per facility



$L \propto P_{synrad} E_{cm}^{-3.5}$

$L \propto P_{RF}$

Energy dependence:

At low energies circular colliders look good

- Reduction at high energy due to synchrotron radiation

At high energies linear colliders excel

- Luminosity per beam power roughly constant

Note: The typical higgs factory energies are close to the cross over in luminosity

Linear collider have polarised beams (80% e^-, ILC also 30% e^+) and beamstrahlung

- All included in the physics studies

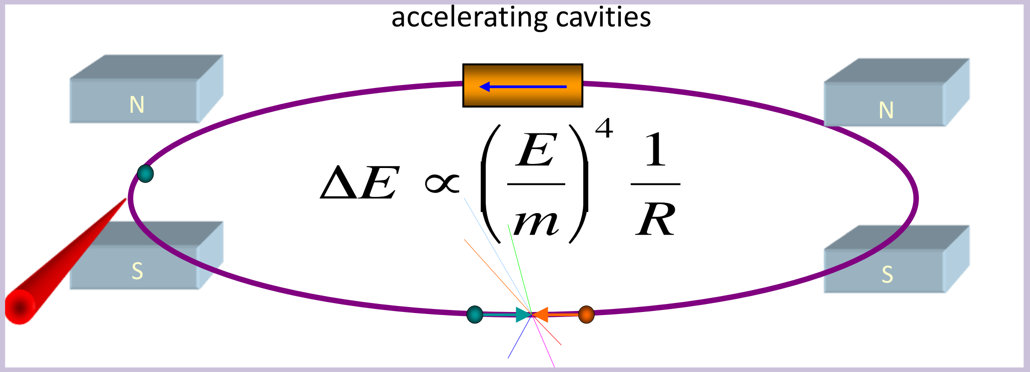
The picture is much clearer at lower or higher energies

Energy Limit

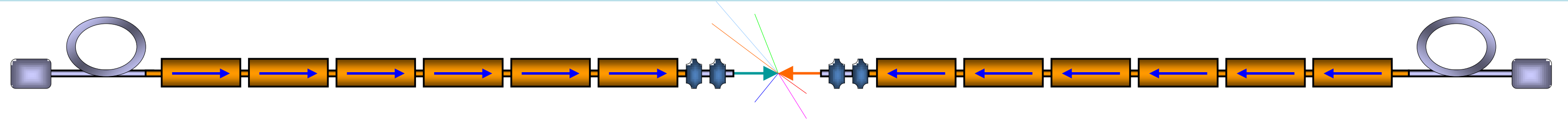
Circular collider

- Accelerate beam in many turns
- Let beam collide many times
- But synchrotron radiation

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



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



Linear electron-positron collider

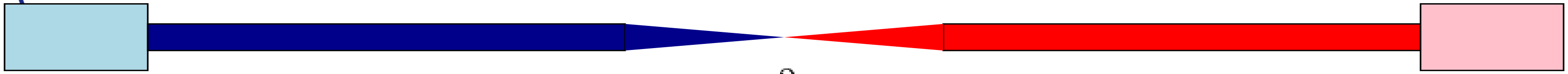
- Essentially no synchrotron radiation
- But have to accelerate beams in one pass
- and only collide once, so small beams

Or use heavier particles in **circular collider**

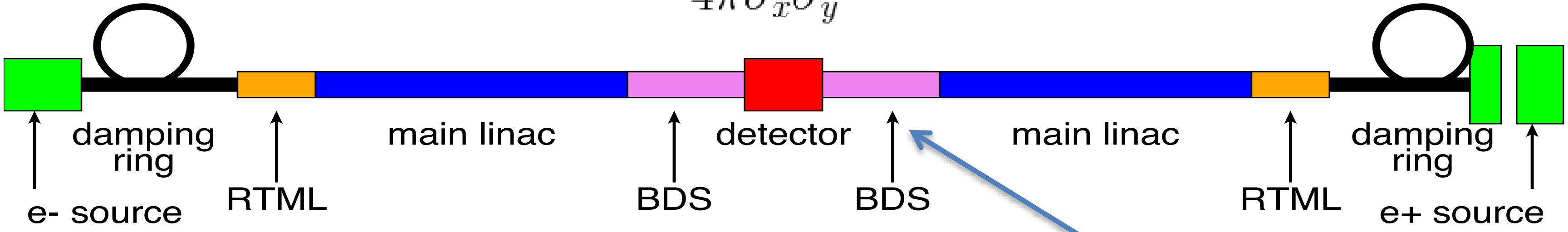
Muons are 200 times heavier than electrons

But they have a short lifetime (2.2 μs)

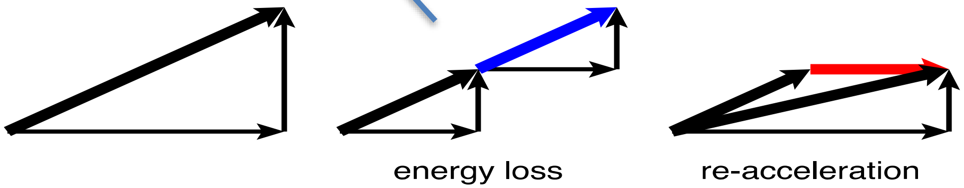
Linear Collider Principle



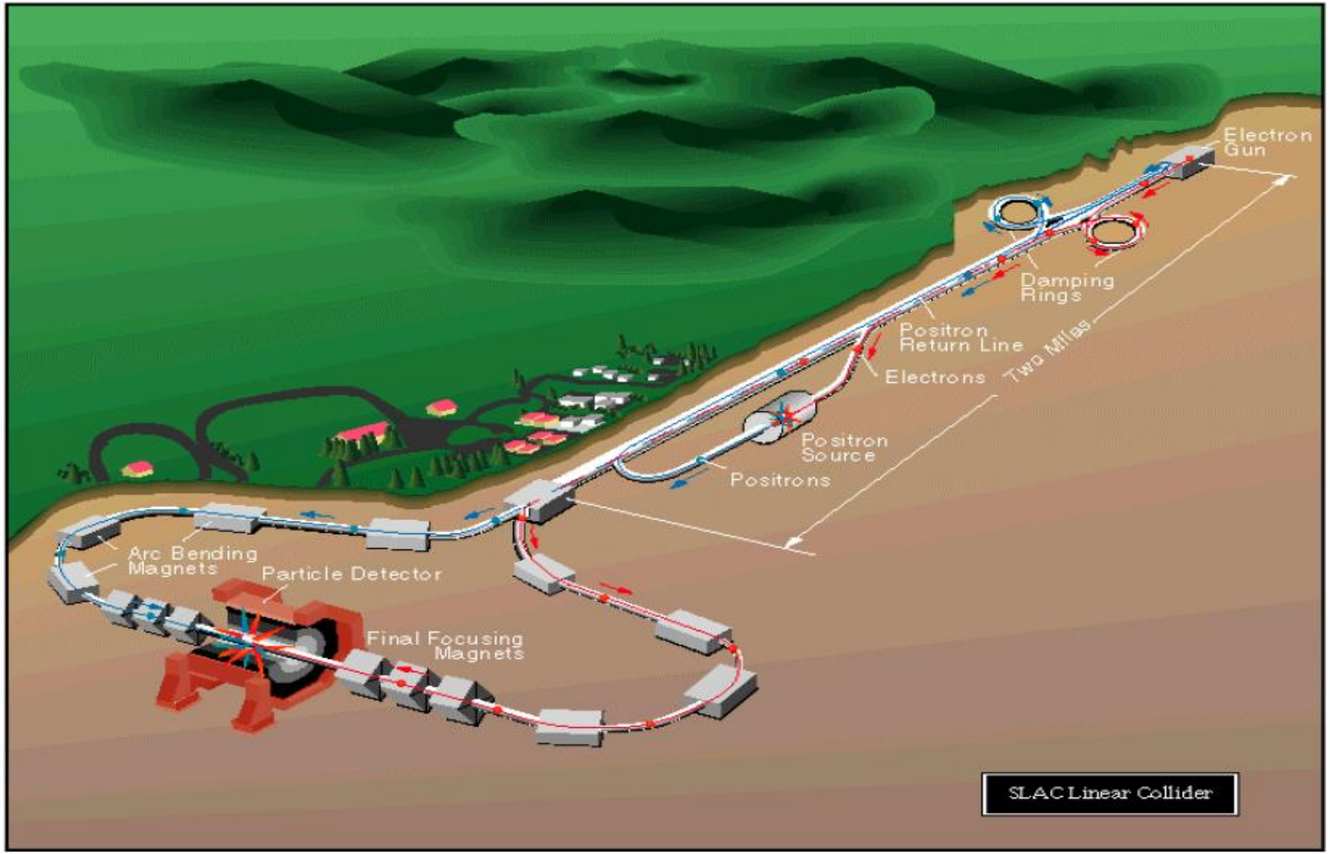
$$\mathcal{L} = \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$



$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$



SLC: The only Linear Collider that existed



Built to study the Z^0 and demonstrate linear collider feasibility

Energy = 92 GeV
Luminosity = 2e30

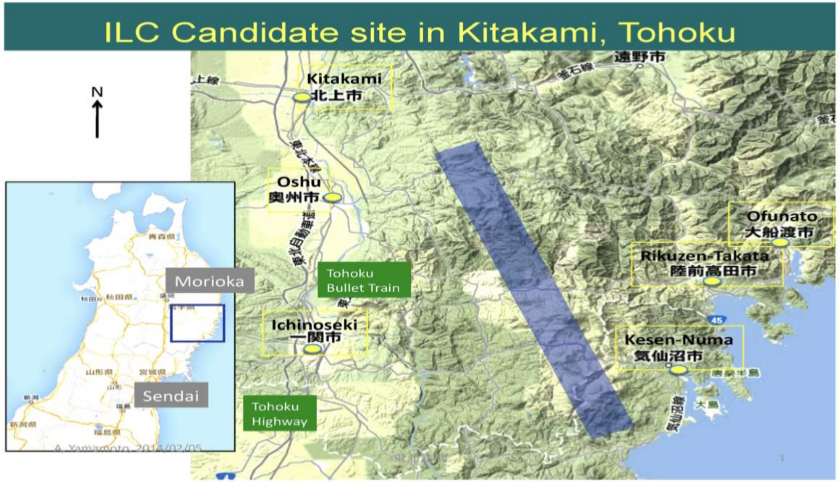
Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

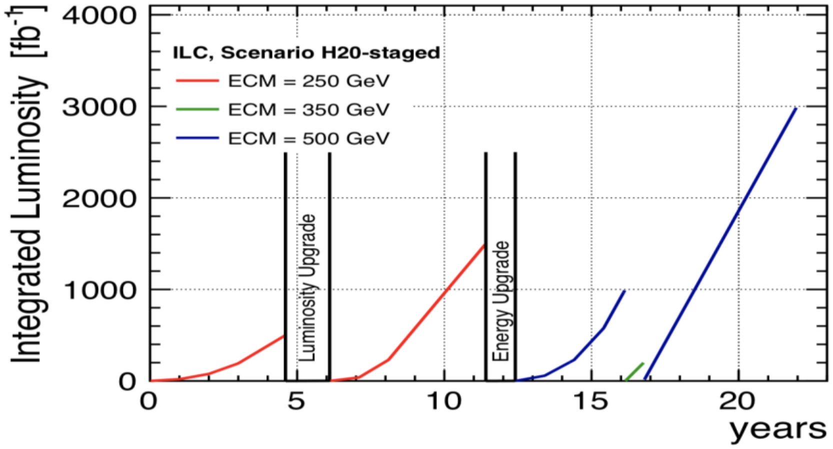
A 10% prototype!

ILC Scenarios

Waiting for Japan to make a commitment

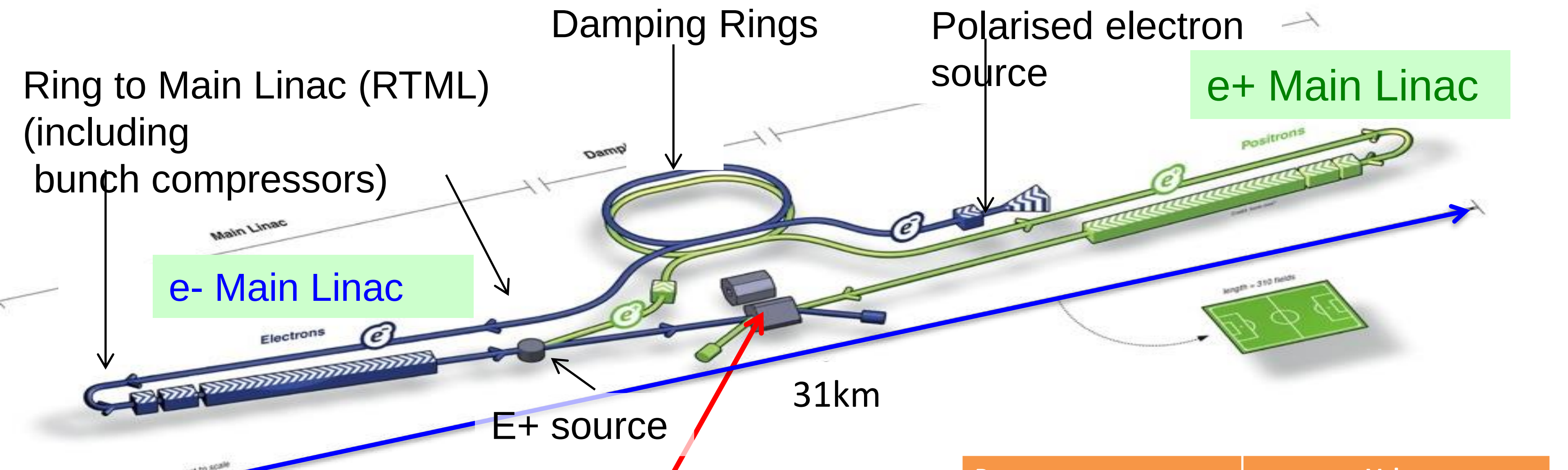
- Site identified and being investigated
- But executive not yet endorsed project
- Process is going on for many years

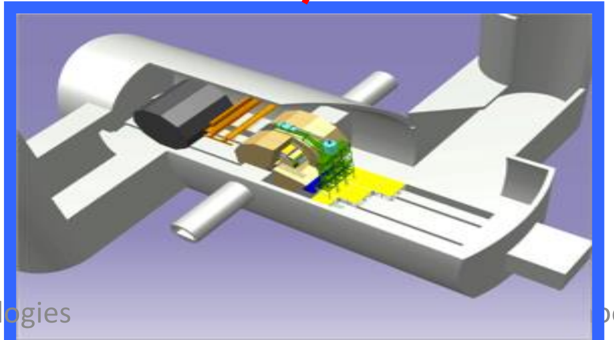




Baseline running example
Note: contains up to 500 GeV, which is not part of current baseline proposal

ILC



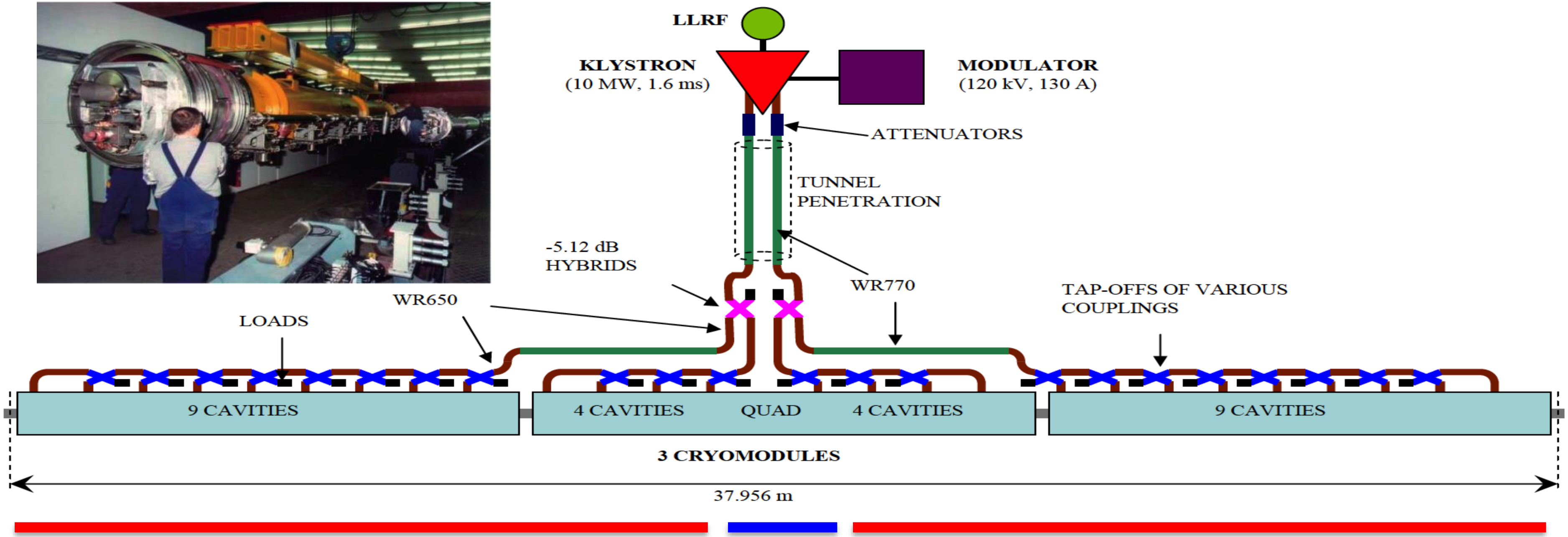


Parameters	Value
C.M. Energy	250 GeV
Peak luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Beam power	5 MW
Beam Rep. rate	5 Hz
E gradient	31.5 MV/m +/-20%

Examples of ILC and CLIC Main Parameters

Parameter	Symbol [unit]	SLC	ILC	CLIC	CLIC
Centre of mass energy	E_{cm} [GeV]	92	250	380	3000
Luminosity	L [$10^{34}cm^{-2}s^{-1}$]	0.0003	1.35	1.5	6
Luminosity in peak	$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]	0.0003	1	0.9	2
Gradient	G [MV/m]	20	31.5	72	100
Particles per bunch	N [10^9]	37	20	5.2	3.72
Bunch length	σ_z [μm]	1000	300	70	44
Collision beam size	$\sigma_{x,y}$ [nm/nm]	1700/600	516/7.7	149/2.9	40/1
Vertical emittance	$\varepsilon_{x,y}$ [nm]	3000	35	30	20*
Bunches per pulse	n_b	1	1312	352	312
Bunch distance	Δz [mm]	-	554	0.5	0.5
Repetition rate	f_r [Hz]	120	5	50	50

Main Linac Unit



Accelerating cavities
O(65%) of linac length

Beam guiding quadrupole
Beam position monitor
Corrector kicker

Accelerating cavities

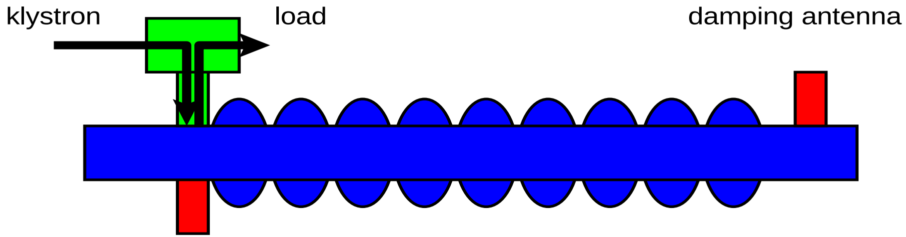
ILC Cavities

Superconducting cavity (Ni at 2 K)

Standing wave structure

RF frequency is 1.3 GHz, 23 cm wavelength

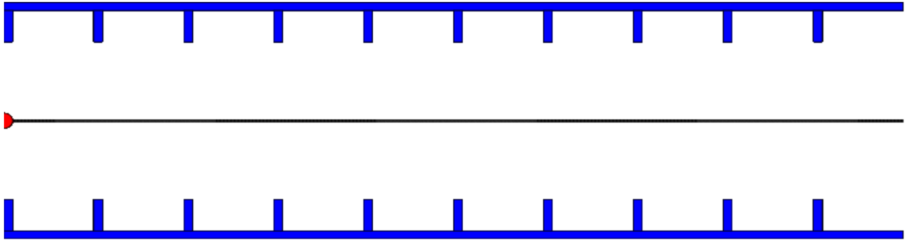
Length is 9 cells = 4.5 wavelengths = 1 m



Pulsed operation:

5 x 1.6 ms pulses per second

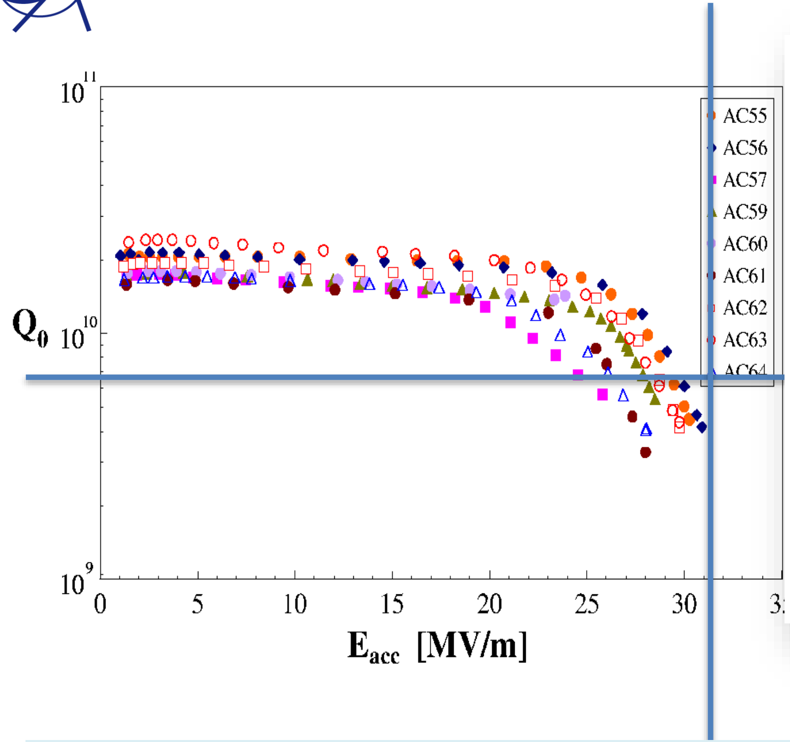
Gradient is 31.5 MV/m

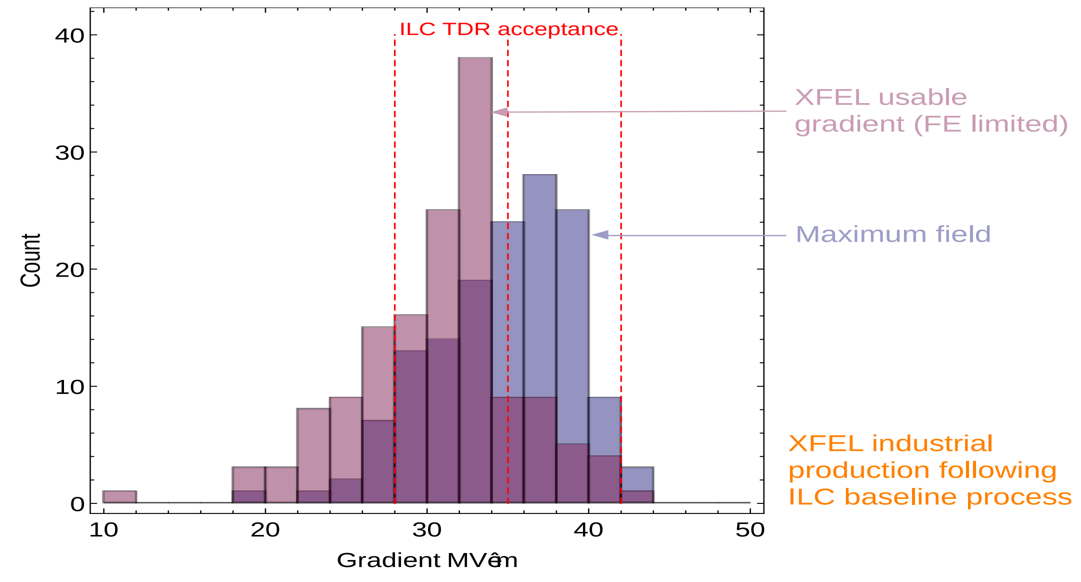


In rings typically

- no pulsing
- lower frequencies (400 MHZ in LHC)
- lower gradient (O(<20 MV/m))

ILC Gradient Limitations





Theoretical gradient limit is 50-60 MV/m

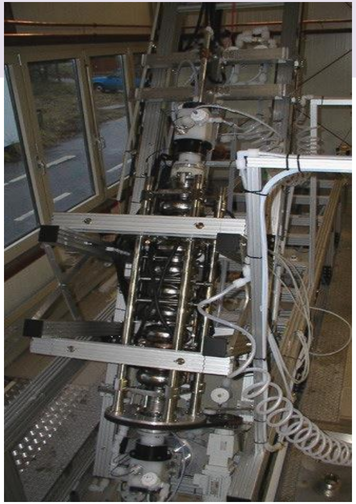
- But can quench at lower gradient
- or Q value decreases

Cavities have different performancies

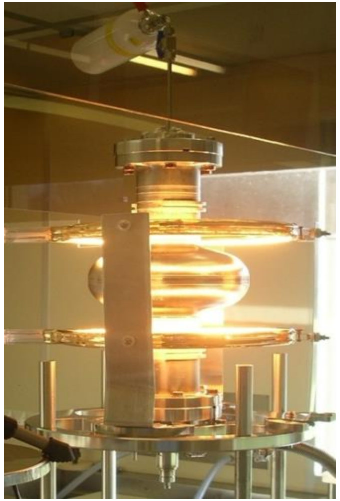
ILC Cavity Treatment

Control of material
Avoid defects
Ensure high quality

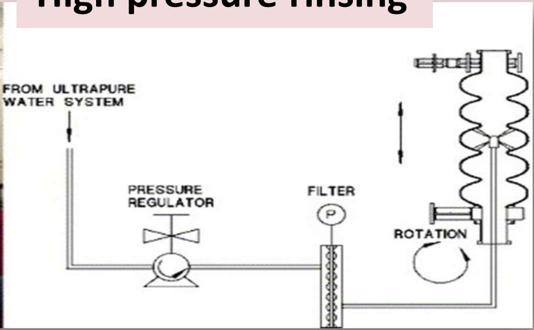
Electropolishing
fill with H_2SO_4, apply current to remove thin surface layer

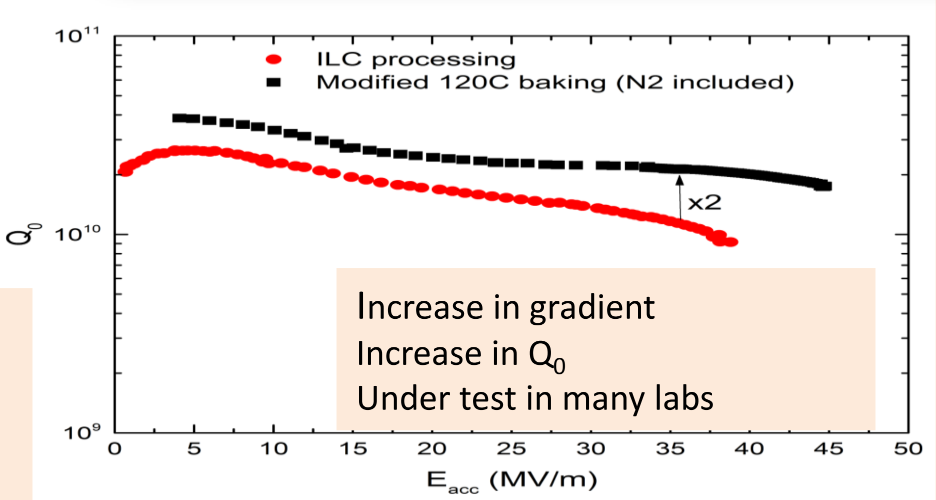


Bakeout



High pressure rinsing

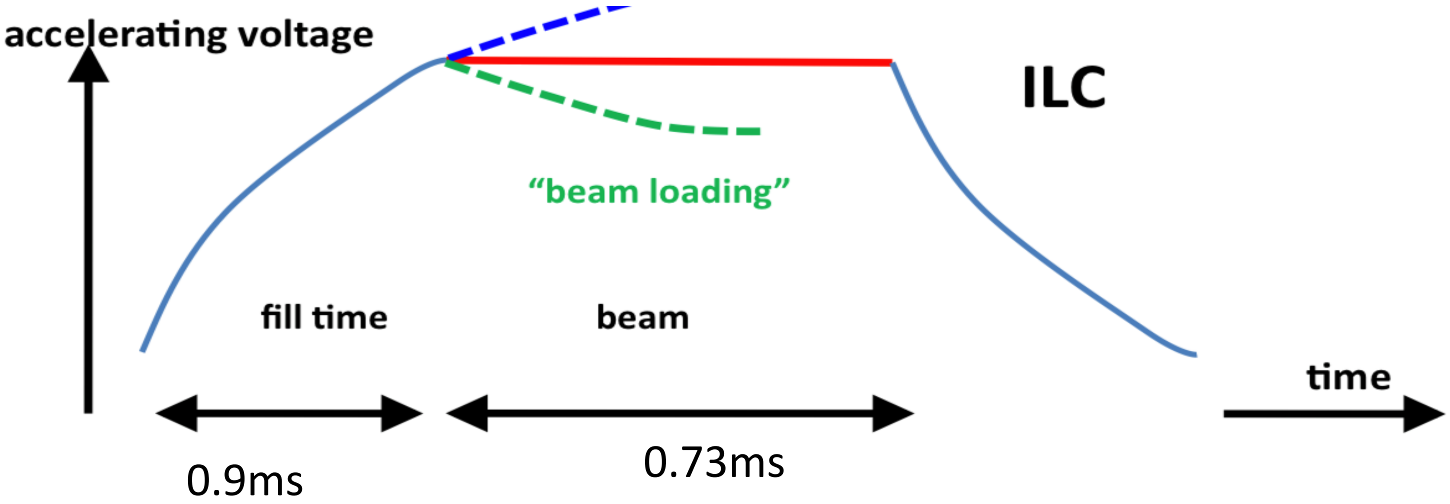




Increase in gradient
Increase in Q_0
Under test in many labs

Novel process found (FNAL):
Nitrogen infusion
Fill cavity at 120°C for a day with low pressure of N_2

Note: Pulsed Operation



5 RF pulses of 1.6 ms per second (1312 bunches in 0.73 ms):

Because field leads to losses in the wall

- About 1 W/m
- With no pulsing losses would be O(100 W/m)

RF power in pulse: 5 MW / (5 x 0.73 ms) = O(1500 MW) = O (150 klystrons)

Note: Cryogenics

Cavities have small losses

$$P_{loss} = const \frac{1}{Q_0} \times G^2$$

About 1W/m

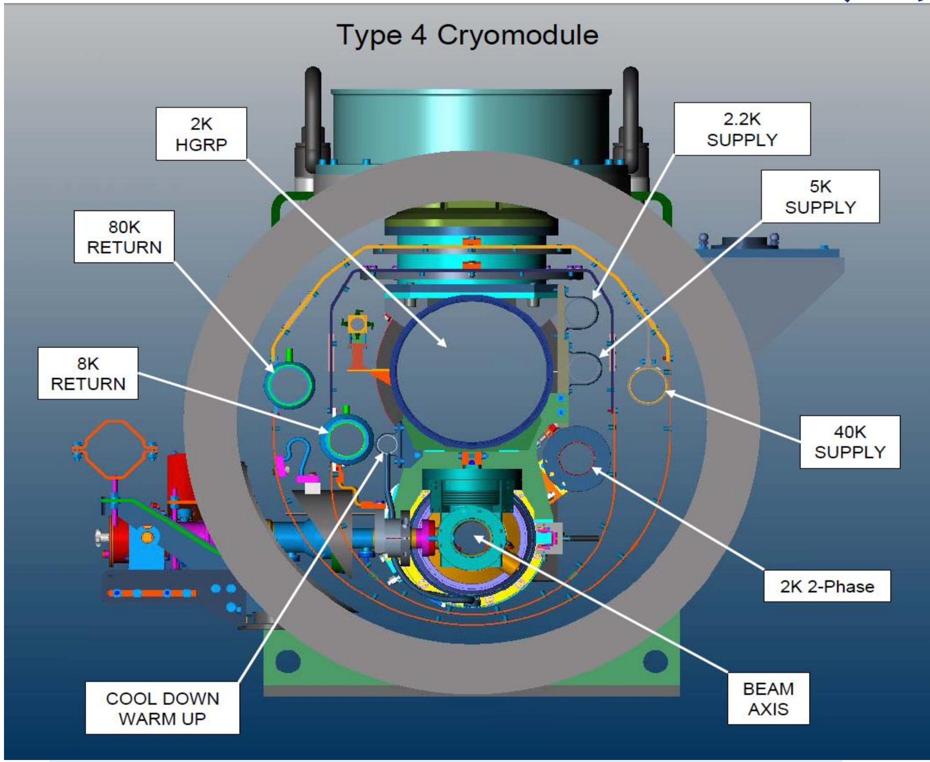
But cooling costly at low temperatures

Remember Carnot:

$$P_{cryo} = \frac{1}{\eta} \frac{T_{room} - T_{source}}{T_{source}} \times P_{loss}$$

$$P_{cryo} \approx 700 \times P_{loss}$$

The typical heat load of 1 W/m
⇒ about 1 kW/m for cryogenics

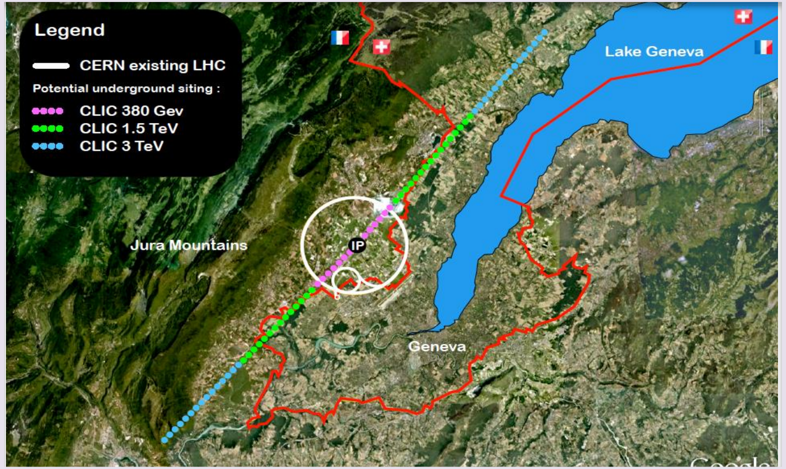


Average RF power: 1.6kW/m (3kW/m)
Power into beam about 0.7kW/m

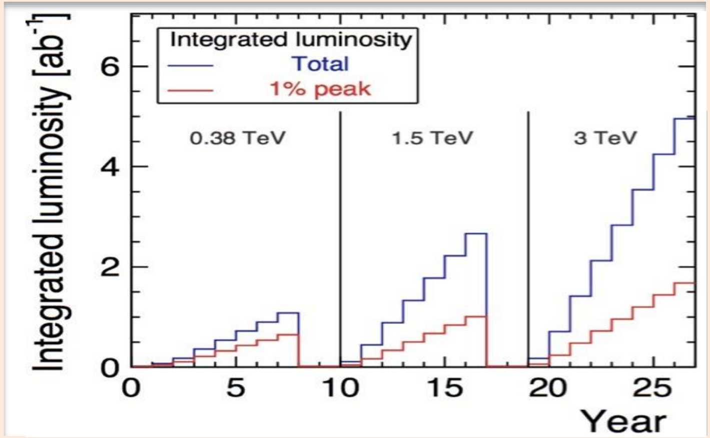
CLIC Staged Scenario

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0

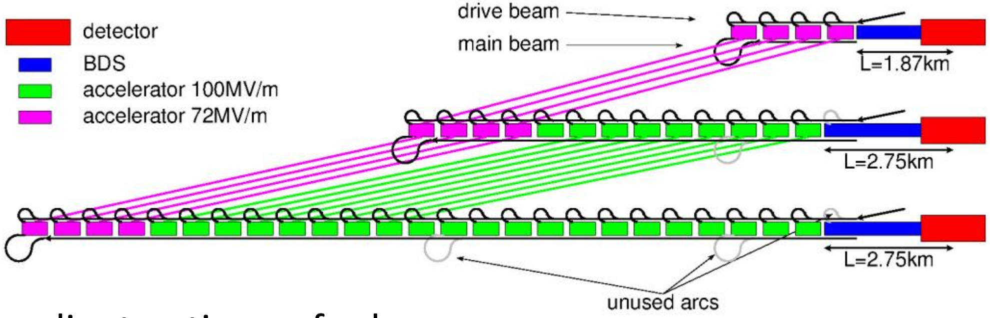
Central complex on Prevessin site



Luminosity targets from Physics Study group
Hopefully input from LHC



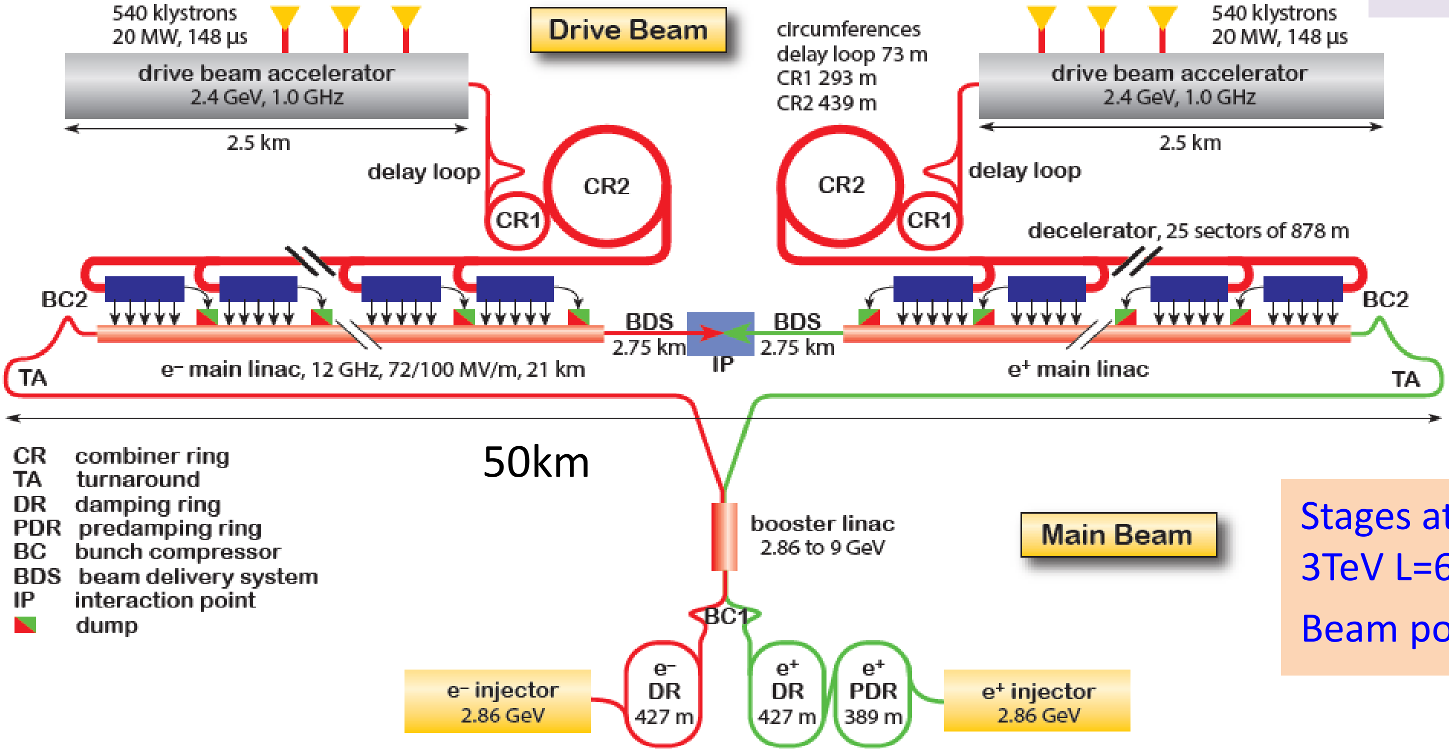
Luminosity evolution



Lower gradient optimum for lower energy

CLIC: The Basis

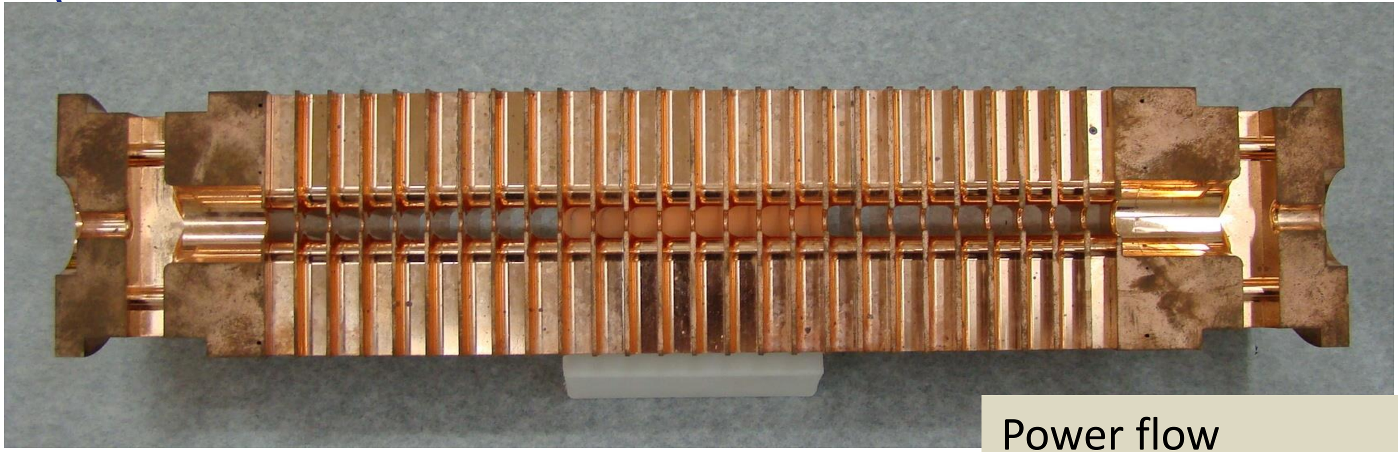
CLIC at 3TeV shown



Stages at E_{cms}=0.38, 1.5 and 3TeV $L=6x10^{34}cm^{-2}s^{-1}$ at 3TeV

Beam power 30MW at 3TeV

CLIC Accelerating Structure



12 GHz, 23 cm long, normal conducting
Loaded gradient 100 MV/m

⇒ Allows to reach higher energies
⇒ 140,000 structures at 3 TeV

But strong losses in the walls

⇒ 50 RF bursts per second
⇒ 240 ns, 60 MW, 312 bunches
⇒ Power during pulse 8.5 x 10^6 MW (3000 x ILC)

Power flow

- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

Average RF power about 3 kW/m
About 1 kW/m into beam

CLIC Gradient Limitations

Breakdowns (discharges during the RF pulse)

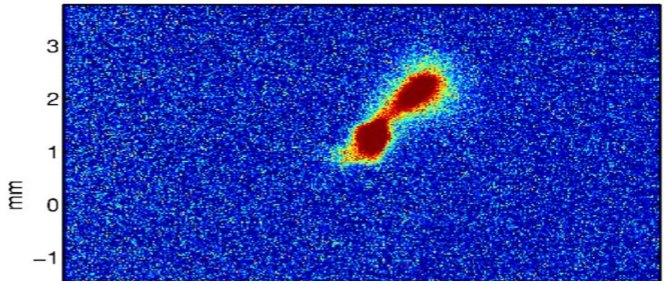
- Require $p \leq 3 \times 10^{-7}\ m^{-1} pulse^{-1}$

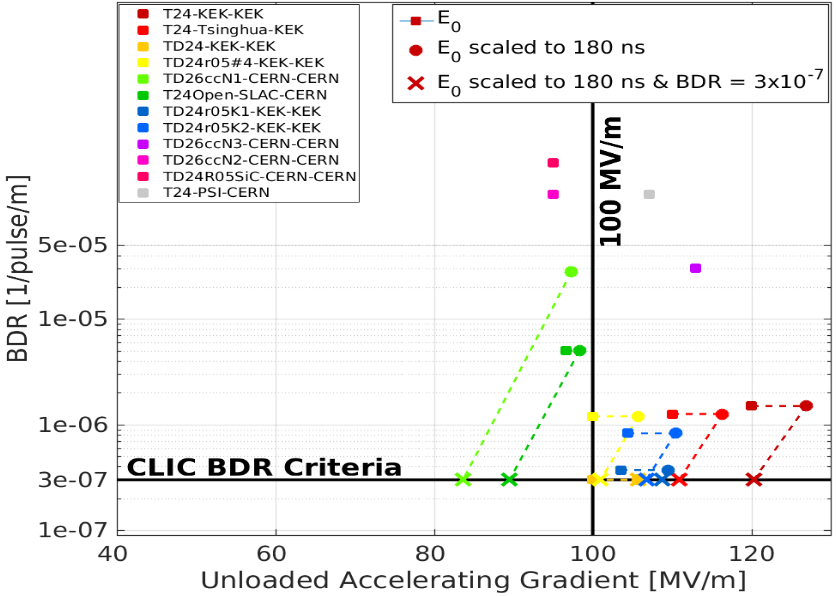
Structure design based on empirical constraints, not first principle

- Maximum surface field
- Maximum temperature rise
- Maximum power flow

R&D programme established gradient O(100 MV/m)

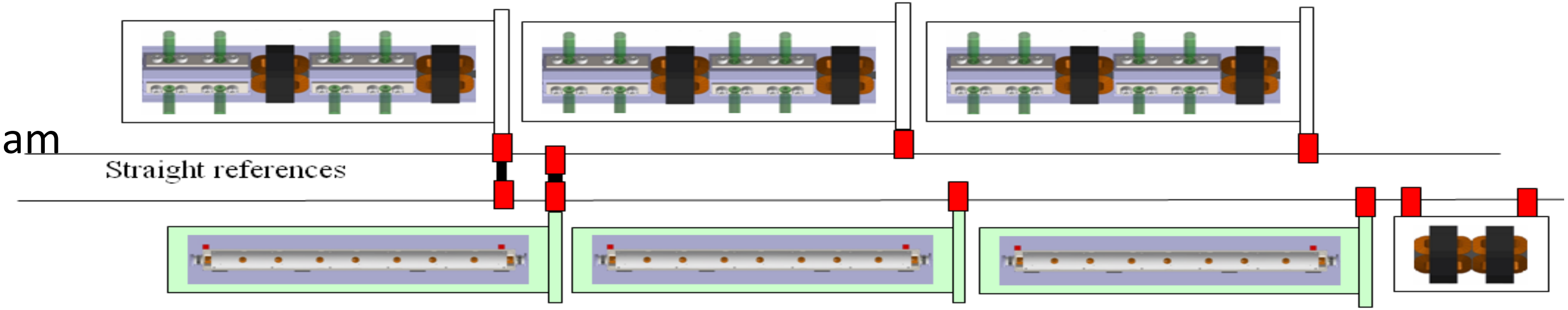
Shorter pulses have fewer breakdowns





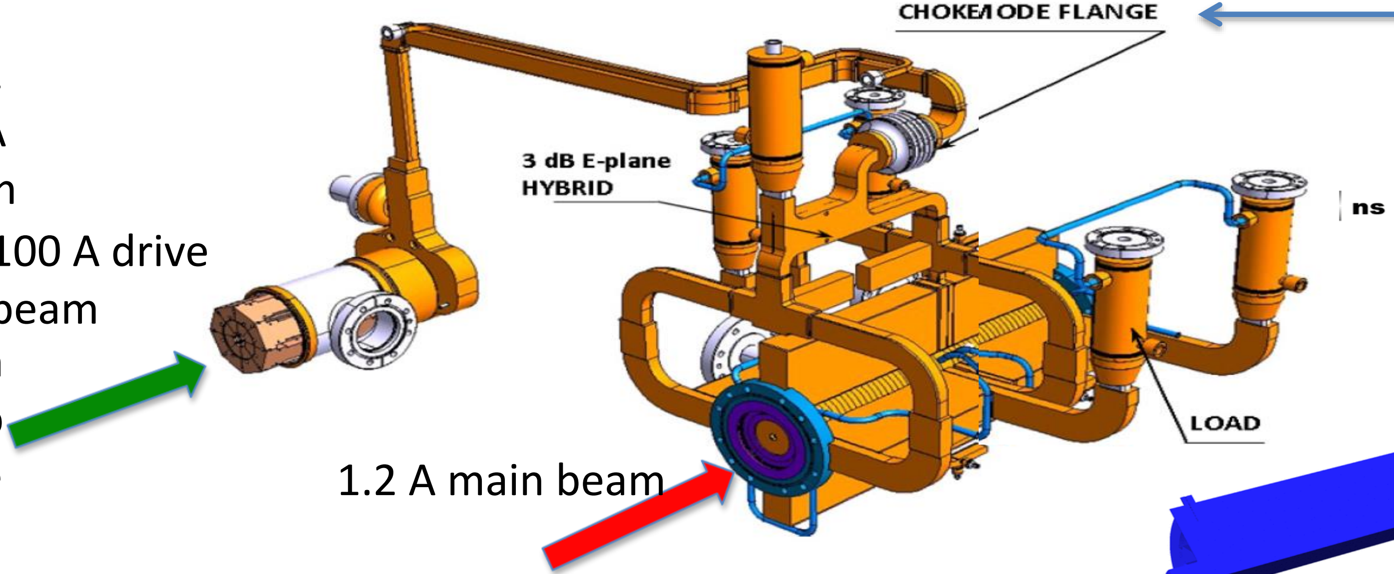
CLIC Two-beam Concept

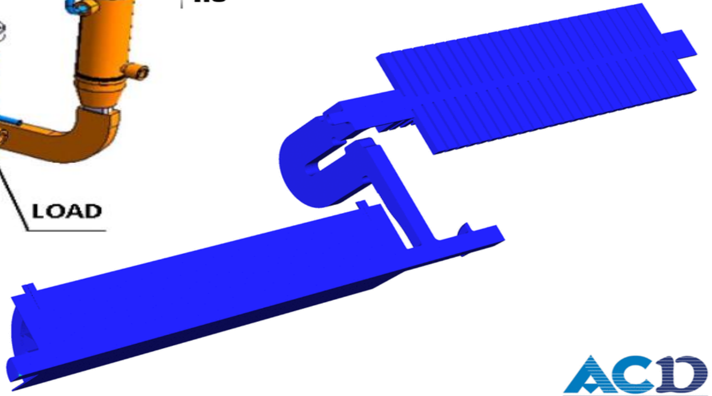
100 A drive beam



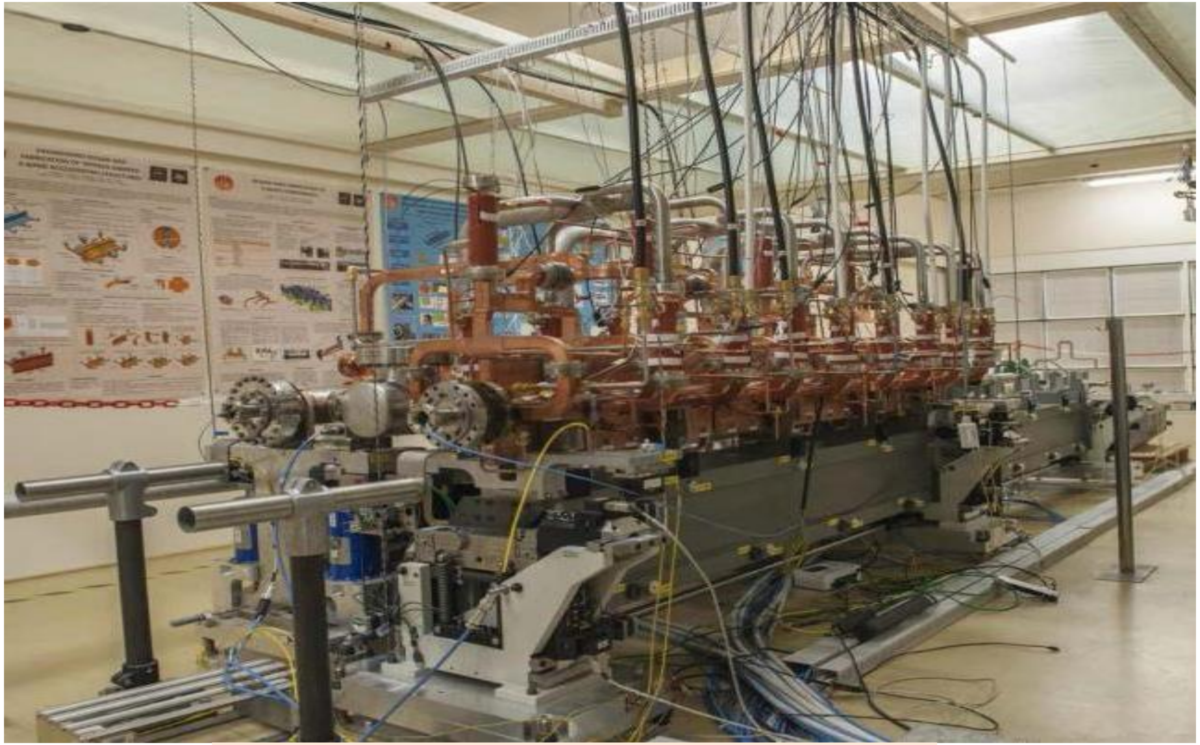
1.2 A main beam

100 A drive beam





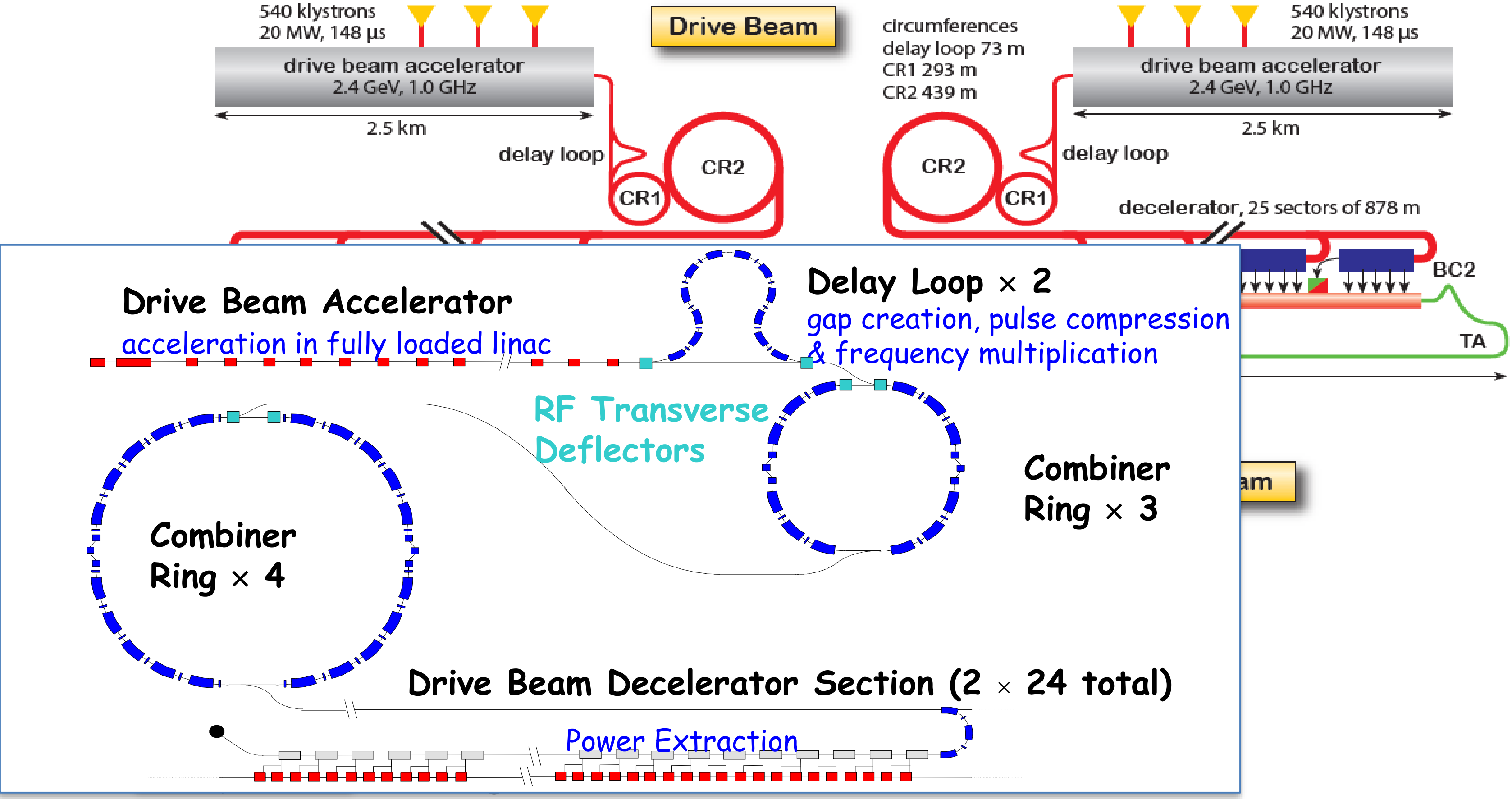
CLIC Two-beam Module



1st module

80 % filling with accelerating structures
11 km for 380 GeV cms
50 km for 3 TeV

CLIC: The Basis



Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

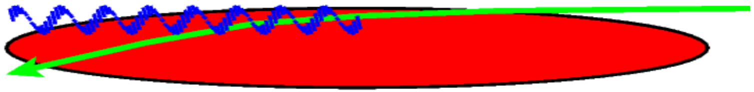
$$\mathcal{L} \propto H_D \quad \frac{N}{\sigma_x} \quad N n_b f_r \quad \frac{1}{\sigma_y}$$

- $\frac{N}{\sigma_x}$: Luminosity spectrum
- $N n_b f_r$: Beam power
- $\frac{1}{\sigma_y}$: Beam Quality (+bunch length)

Need to ensure that one can achieve each parameter

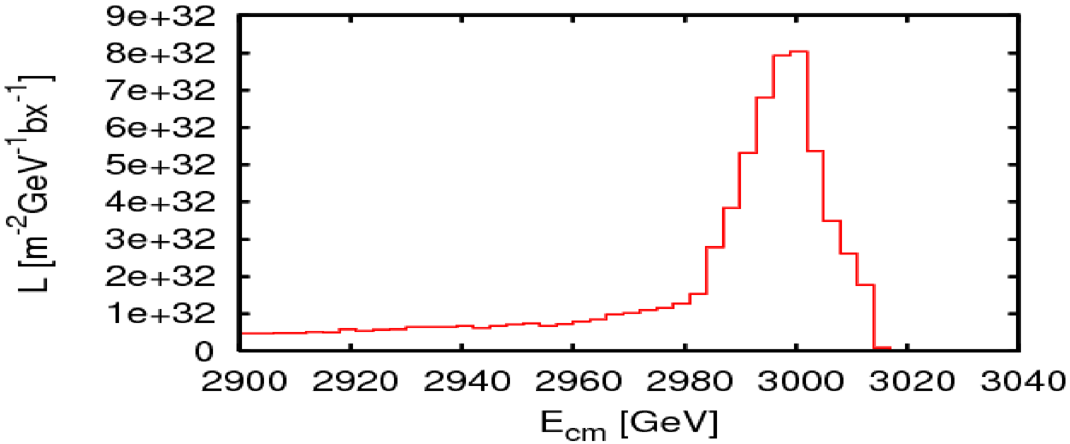
Beam-beam Effect

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



Dense beams focus each other

$\Rightarrow$ emitt beamstrahlung



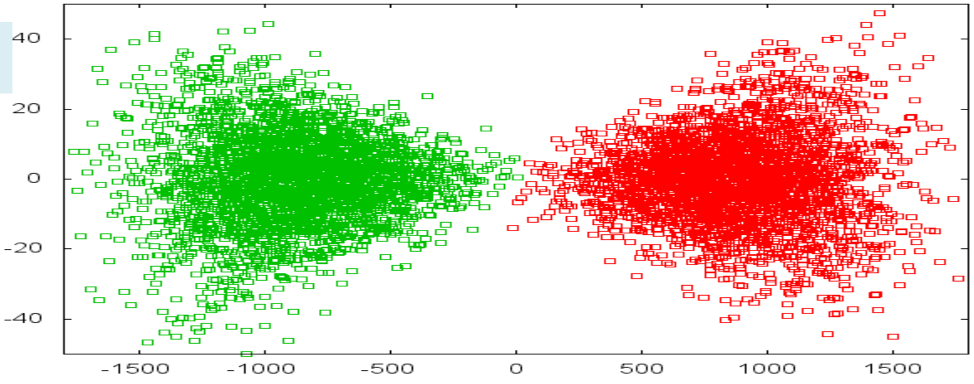
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

Typically aim for O(1)

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

$$\sigma_x \gg \sigma_y \qquad \sigma_x + \sigma_y \approx \sigma_x$$

Beam-beam force on

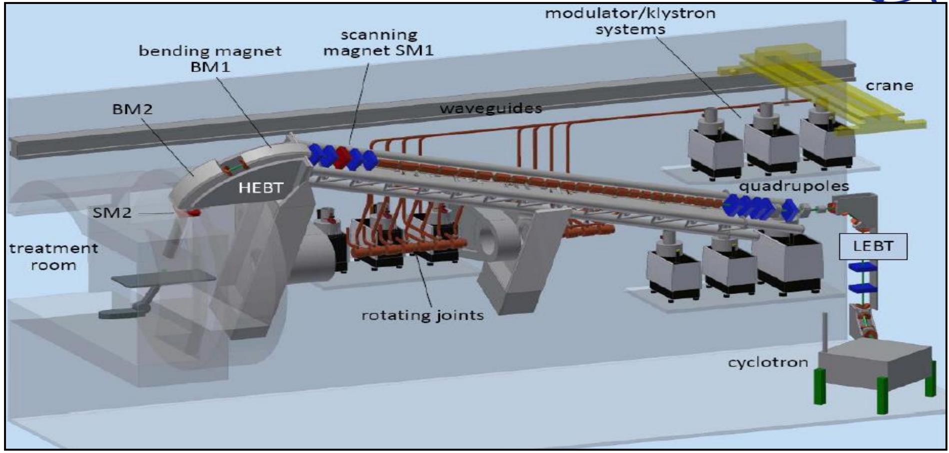


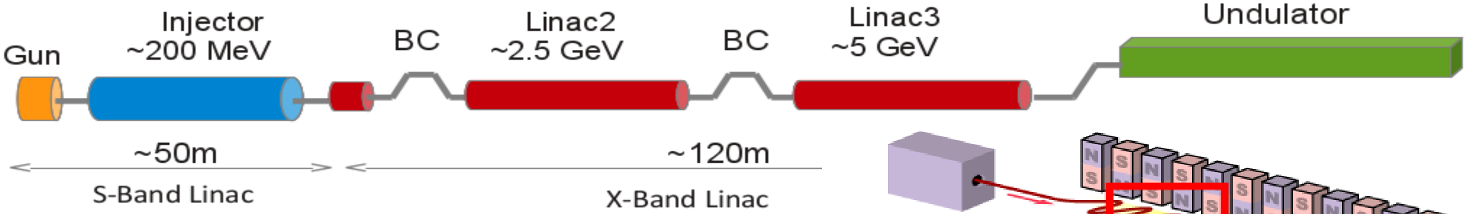
Z direction [µm]

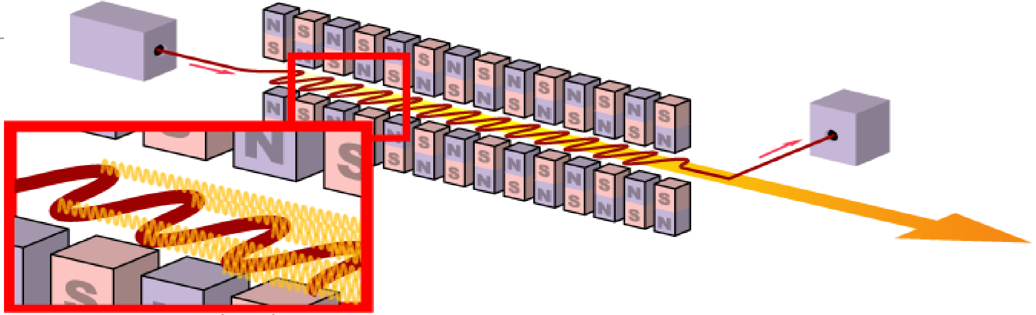
Note: Technology Transfer

The technology developed for linear colliders is useful for other fields, e.g.

- FELs (Examples: European X-FEL in Hamburg, LCLS at SLAC, SACLA in Japan, Swiss FEL, …)
- Medical facilities
- Safety
- Industrial applications



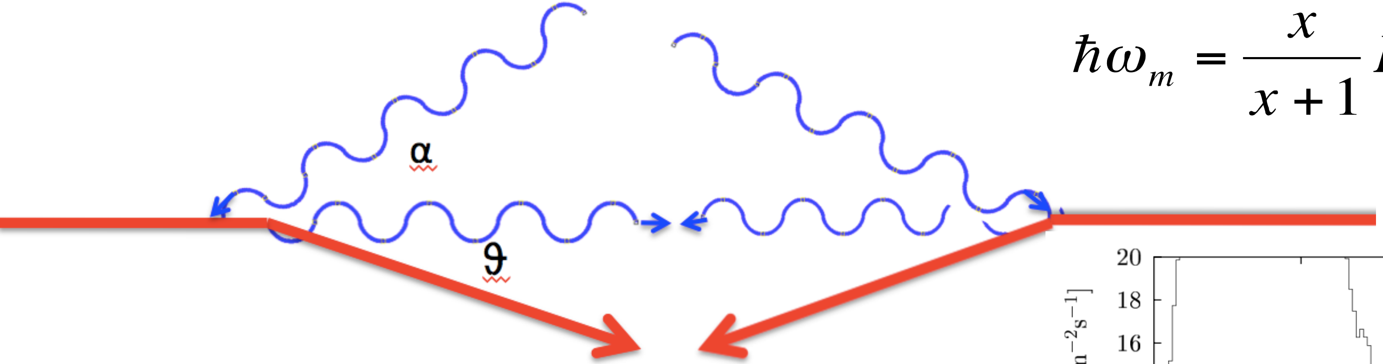




Note: Gamma-gamma Collider Concept

Based on e^-e^- collider

Collide electron beam with laser beam before the IP

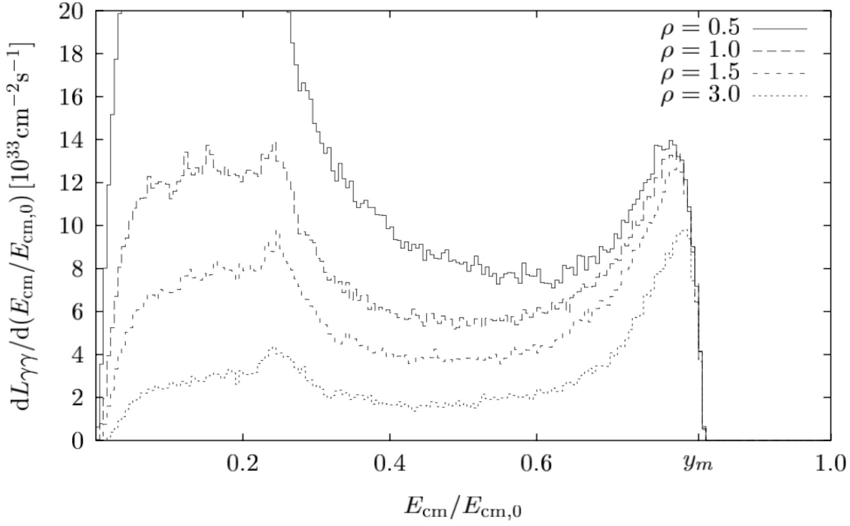


$$\hbar\omega_m = \frac{x}{x+1} E_0 \qquad x = \frac{4E_0\hbar\omega_0}{m^2c^4}$$

Backscattered photons form a spectrum

Practical maximum energy is 83% of electron energy

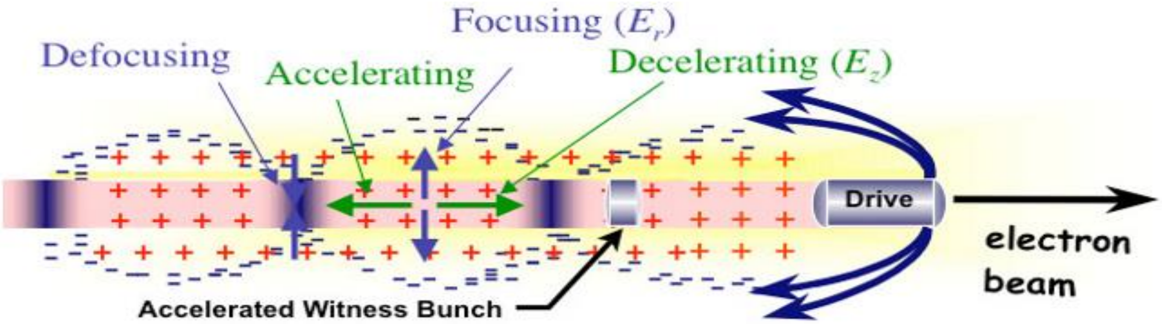
Luminosity



Note: Plasma Accelertion

Plasma can be generated by electron beam, proton beam or laser beam

50 GV/m demonstrated with 42 GeV energy gain



I. Blumenfeld et al, Nature 445, p. 741 (2007)

- Practical solution for efficient acceleration of positrons has to be developed
- Efficiency and beam quality have severe challenges
- Strong plasma focusing is good for beam stability but generates synchrotron radiation
- Application in other fields seem promising, e.g. free electron laser

FCC-ee

FCC-ee

Electron-positron collider in the FCC-hh tunnel

Operation at different energies

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

Synchrotron radiation leads to strong dependence of beam current and luminosity on energy (100 MW limit)

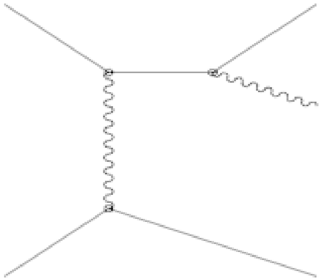
Parameter	Z	WW	ZH	tt
E_{cm} [GeV]	91.2	160	240	365
I [mA]	1390	147	29	5.4
L [10^{34} $cm^{-2}s^{-1}$]	200	25	7	1.4
Years	4	1	3	4
Int. L. [ab^{-1}]	2 x 78	2 x 3.5	2 x 2.7	2 x 0.18

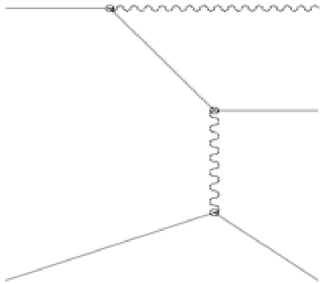
vertical beam size O(30-70 nm)

Short beam lifetime requires top-up injection

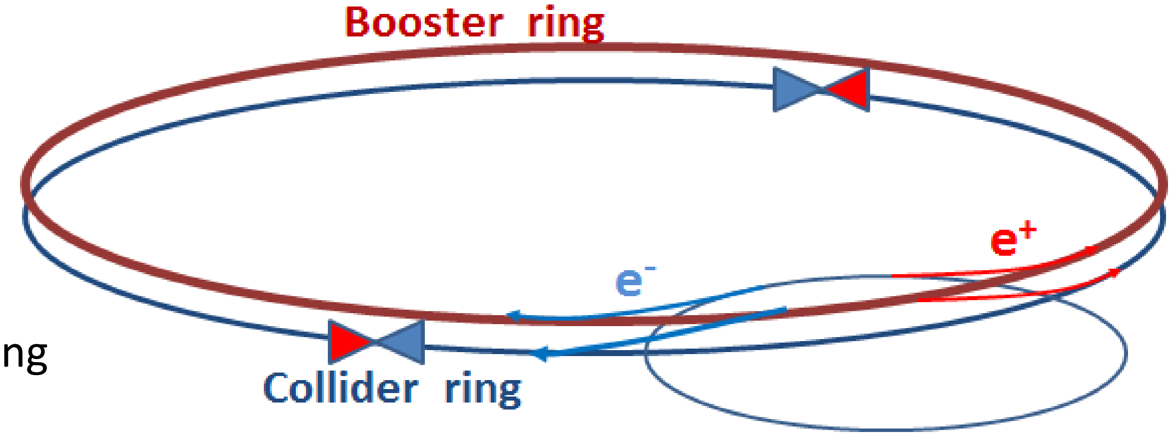
Top-up Injection

Beam lifetime is short (18-200 minutes)
- Bremsstrahlung
- Beamstrahlung
- …





$$\tau_{ee} \propto \frac{I}{L\,\sigma_{ee}\,n_{ip}}$$



Have to refill beam permanently
⇒ top-up injection with booster ring

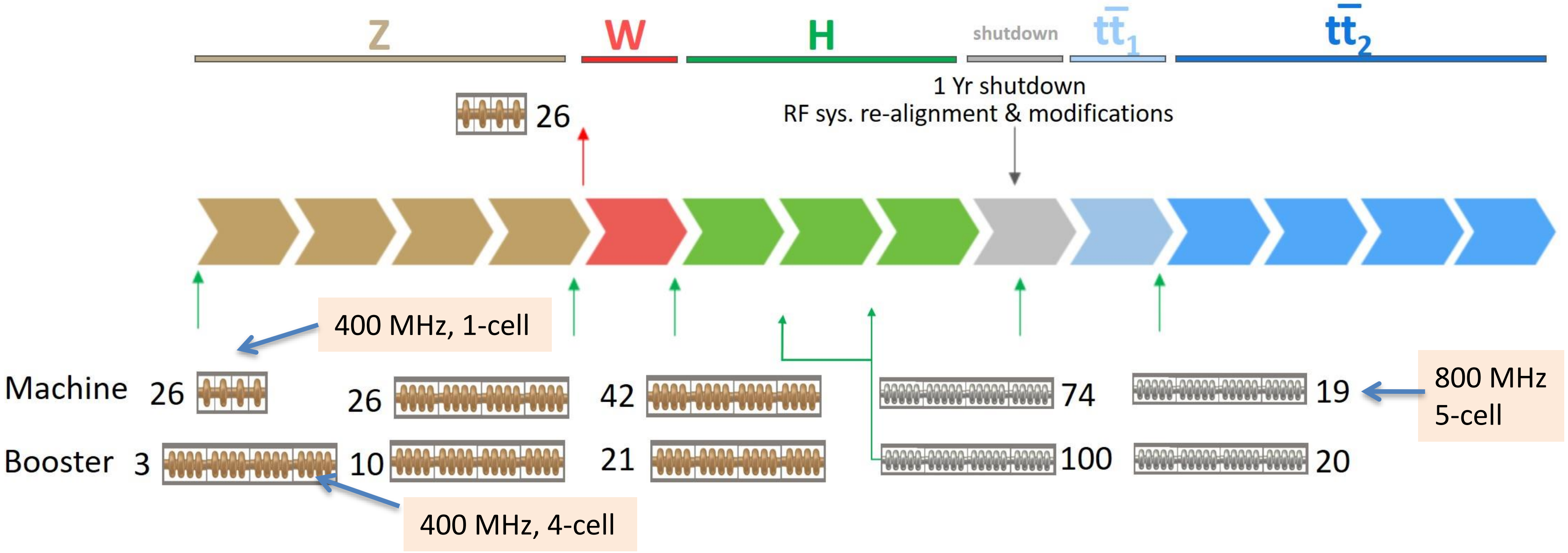
FCC-ee Operational Schedule

5 energy stages

Each year 8 months of operation / 4 months winter shutdown

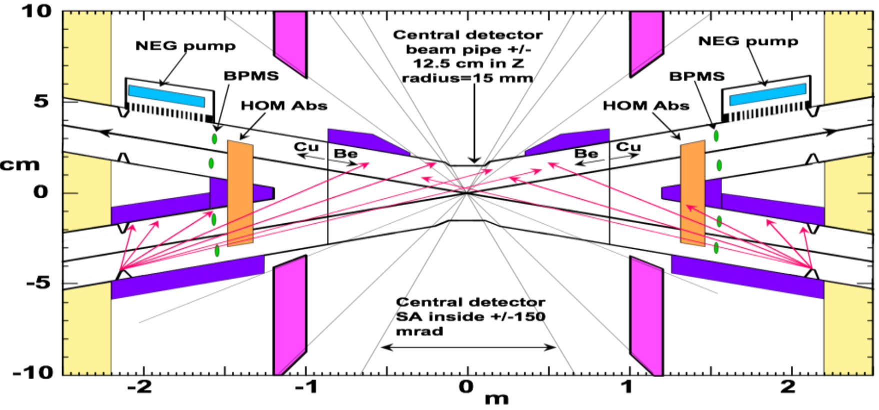
- hardware upgrades during shutdown

Only 1 year-long shutdown to got for top

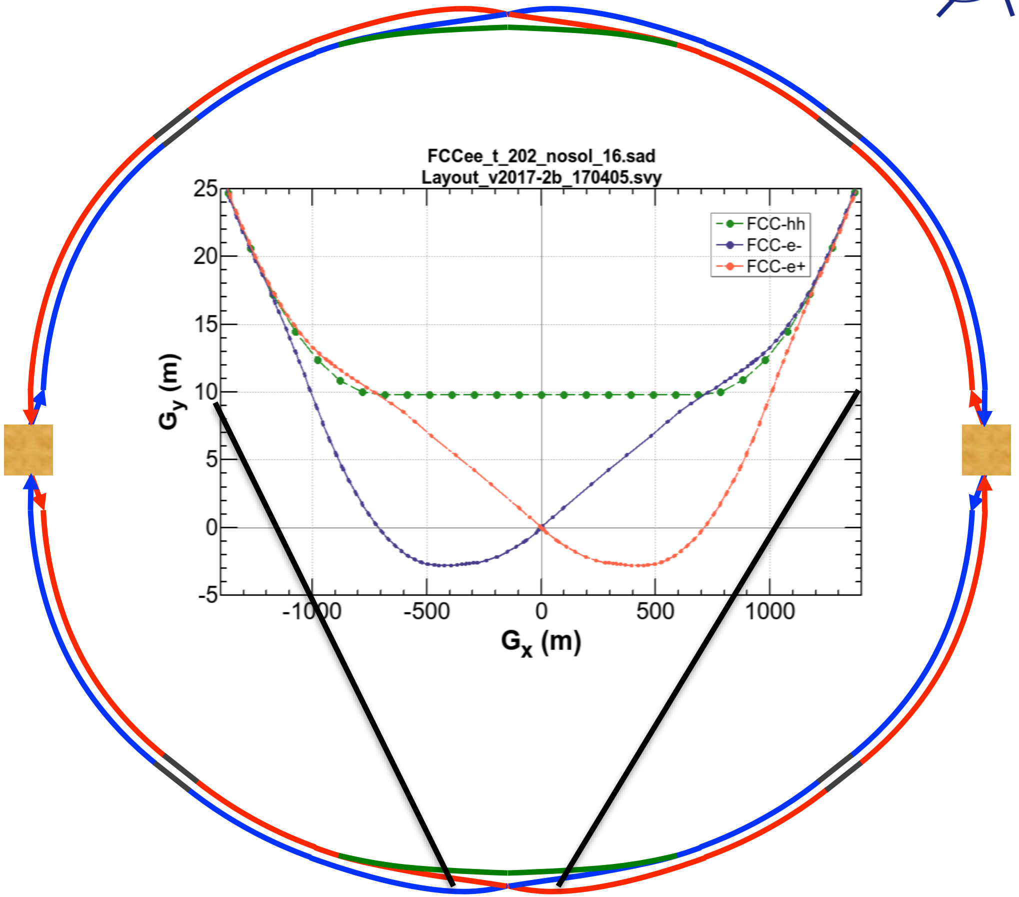


IP Layout

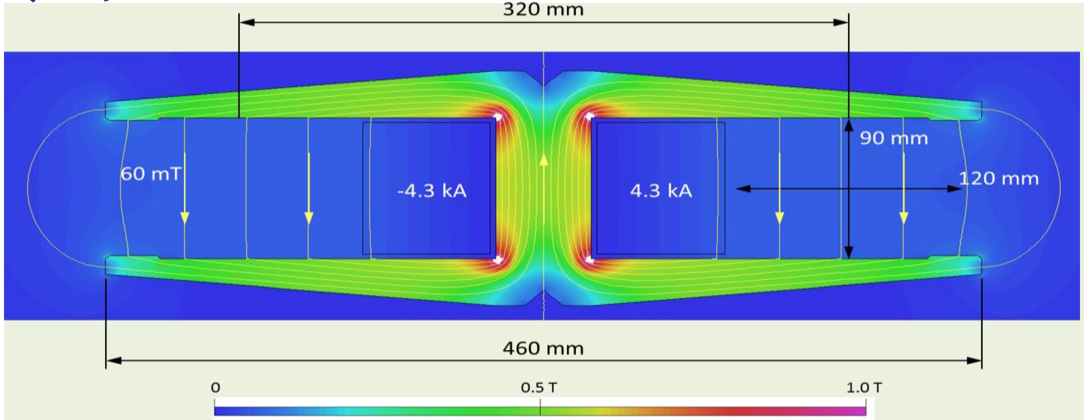
Need a crossing angle at IP
Cannot bend beams close to IP
Requires additional tunnel



Very short beam lifetime requires top-up injection, i.e. booster ring



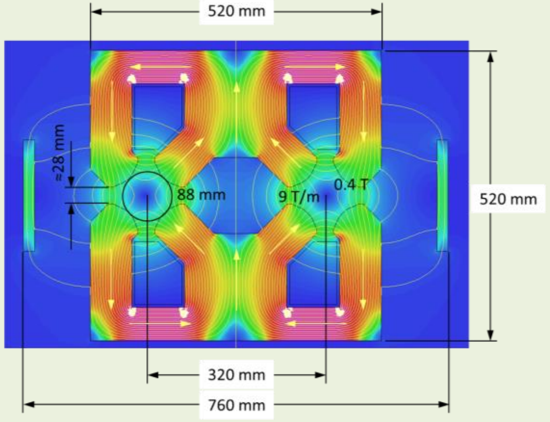
FCC-ee Technologies



Cost effective magnets

Two-in-one design of dipoles and quadrupoles

Optimised windings to reduce cost and power consumption



Optimised RF cavities

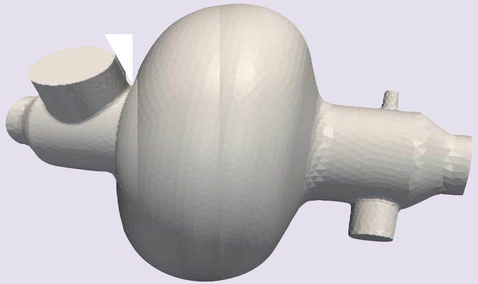
Single cells at low energy:

- Low voltage but high current

Four-cell cavities at high energy:

- Low current but high voltage

High frequency at highest energies



Efficient klystrons, based on design ideas for CLIC

Muon Collider

Comparing Luminosity in MAP vs. CLIC

CLIC is at the limit of what one can do (decades of R&D)

- No obvious way to improve

Muon collider

Power efficient

- Luminosity per beam power increases with energy

Site is **compact**

- 10 TeV comparable to 3 TeV CLIC

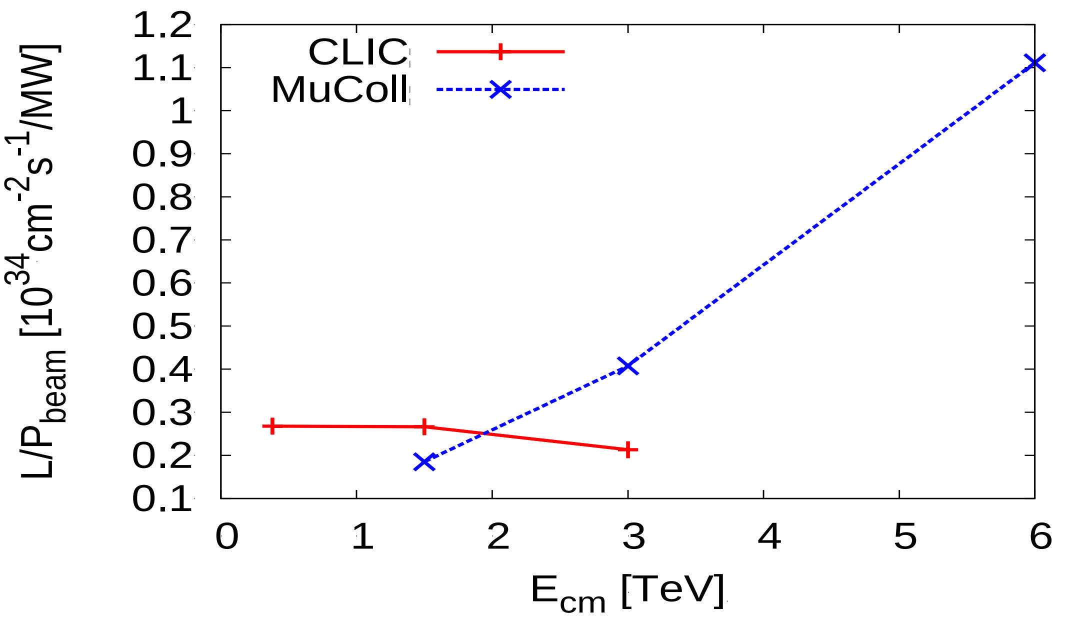
Staging is natural

- acceleration by a factor of a few is done in rings

Appears to promise **cost effectiveness**

- but need detailed study

Other **synergies** exist (neutrino/higgs

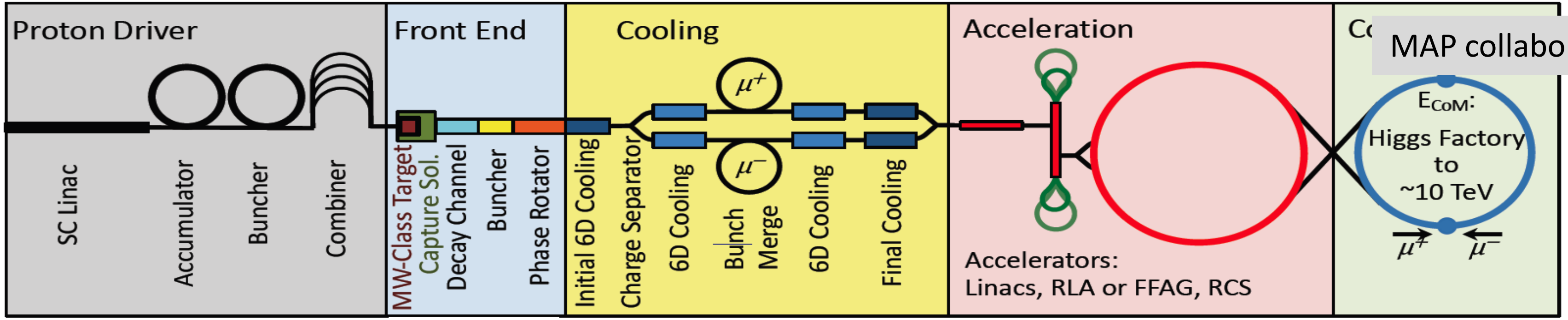


Muon collider promises unique opportunity for a **high-energy, high-luminosity lepton collider**

Main challenge **muons are not stable** (2.2 μs at rest)

Proton-driven Muon Collider Concept

The muon collider has been developed by the MAP collaboration mainly in the US
Muon cooling demonstration by MICE in the UK, some effort on alternative mainly at INFN



MAP collaboration

Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

Acceleration to collision energy

Collision

Protons produce pions
Pions decay to muons

Not as mature as linear collider, but performing study tom make informed decision by 2025

Luminosity Goals

Target integrated luminosities

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

Long-term development

Aim to have muon collider as option for the next European project (or in some other region), if required (e.g. higgs factory somewhere else)

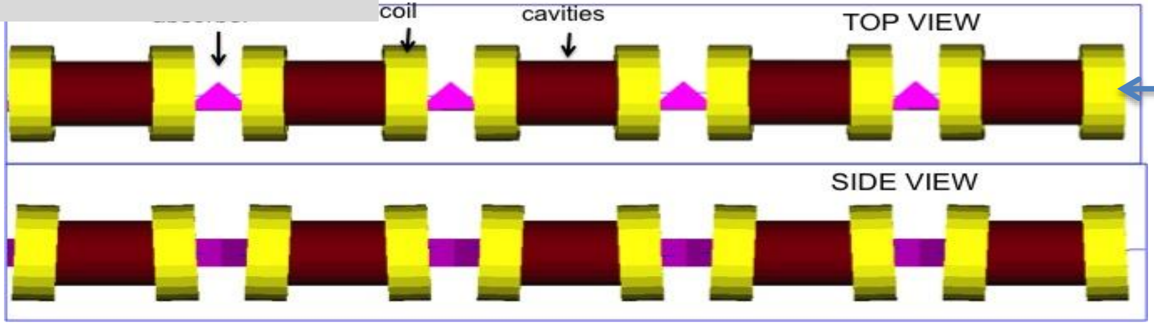
Tentative target parameters Scaled from MAP parameters

Comparison:
CLIC at 3 TeV: 28 MW

Parameter	Unit	3 TeV	10 TeV	14 TeV
L	10^{34} $cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

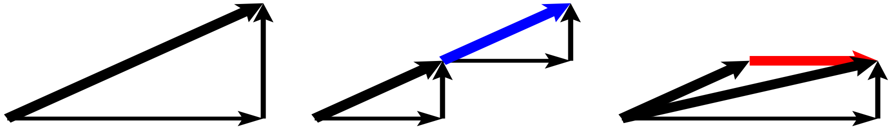
Cooling Concept

MAP collaboration



Limit muon decay, cavities with **high gradient in a magnetic field**
tests much better than design

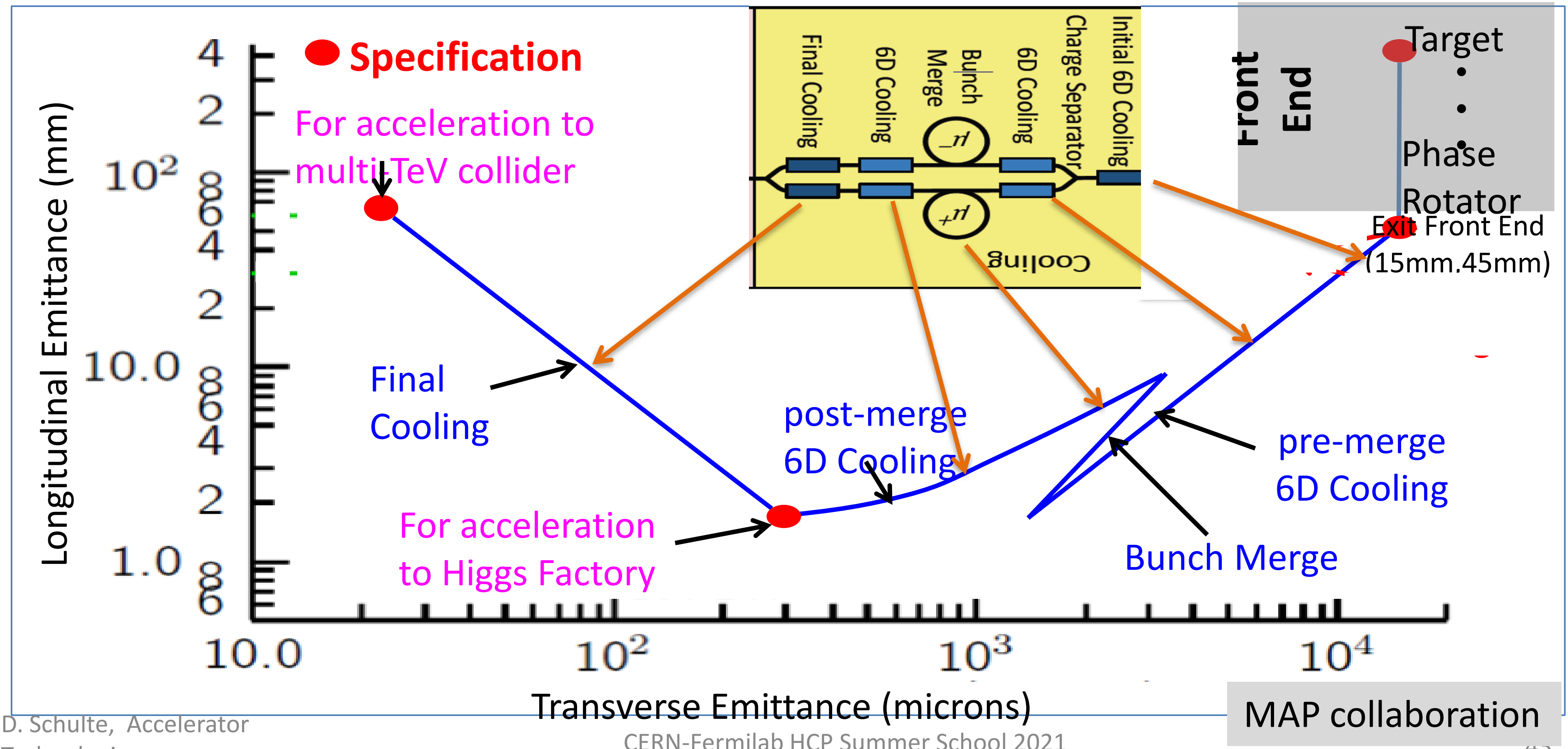
Compact integration to minimise muon loss



Minimise betafunction with **strongest solenoids (40+ T)**
32 T achieved, 40+ T planned

$$\frac{d\epsilon_\perp}{ds} = -\frac{1}{(v/c)^2}\frac{dE}{ds}\frac{\epsilon_\perp}{E} + \frac{1}{2}\frac{1}{(v/c)^3}\left(\frac{14\,\mathrm{MeV}}{E}\right)^2\frac{\beta\gamma}{L_R}$$

Cooling: The Emittance Path



Cooling Challenges and Status

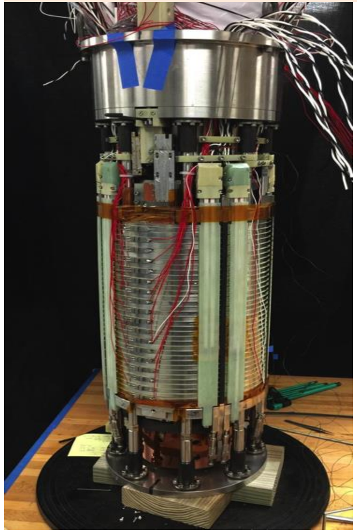
Cavities with very **high accelerating gradient in strong magnetic** field

Very strong solenoids (> 30 T) for the final cooling
- simplified: Luminosity is proportional to the field

Integrated system test

MuCool: >50 MV/m in 5 T field

Two solutions
- Copper cavities filled with hydrogen
- Be end caps

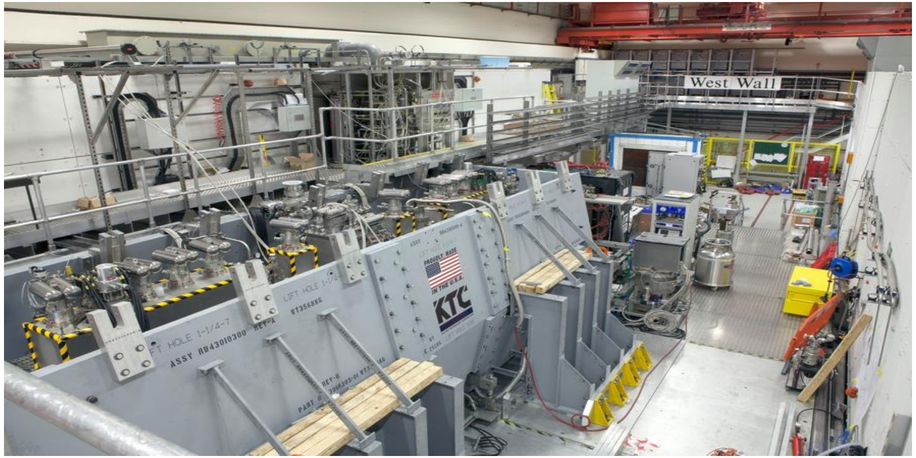


NHFML
32 T solenoid with low-temperature HTS

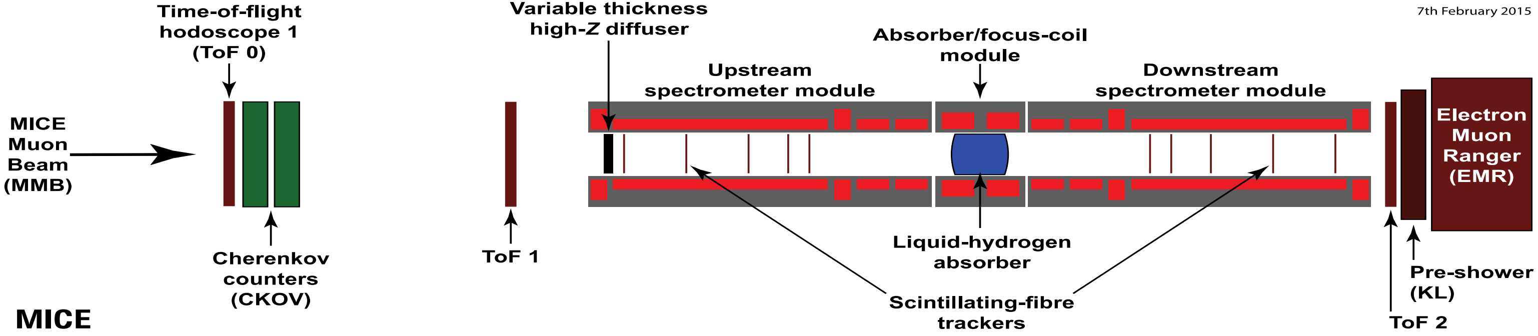
We would like to push even further

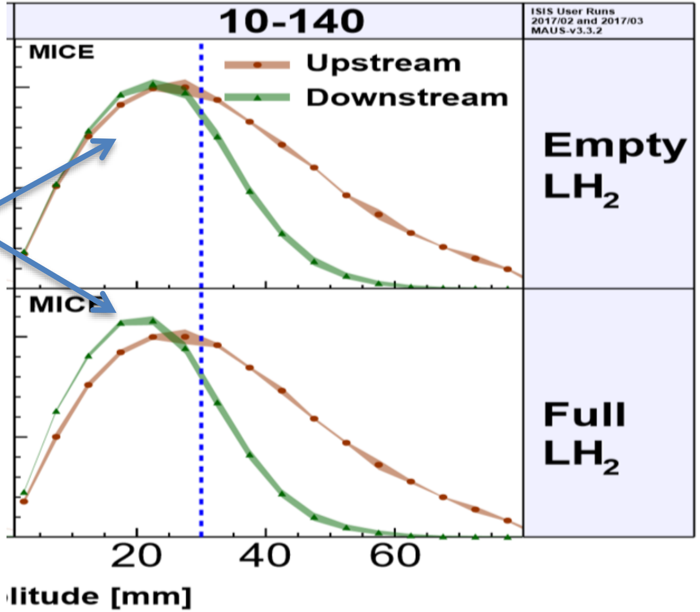
Plans for 40+ T exist

MICE (UK)



MICE (in the UK)





Nature volume 578,

pages 53-59 (2020)

More particles at smaller amplitude after absorber is put in place

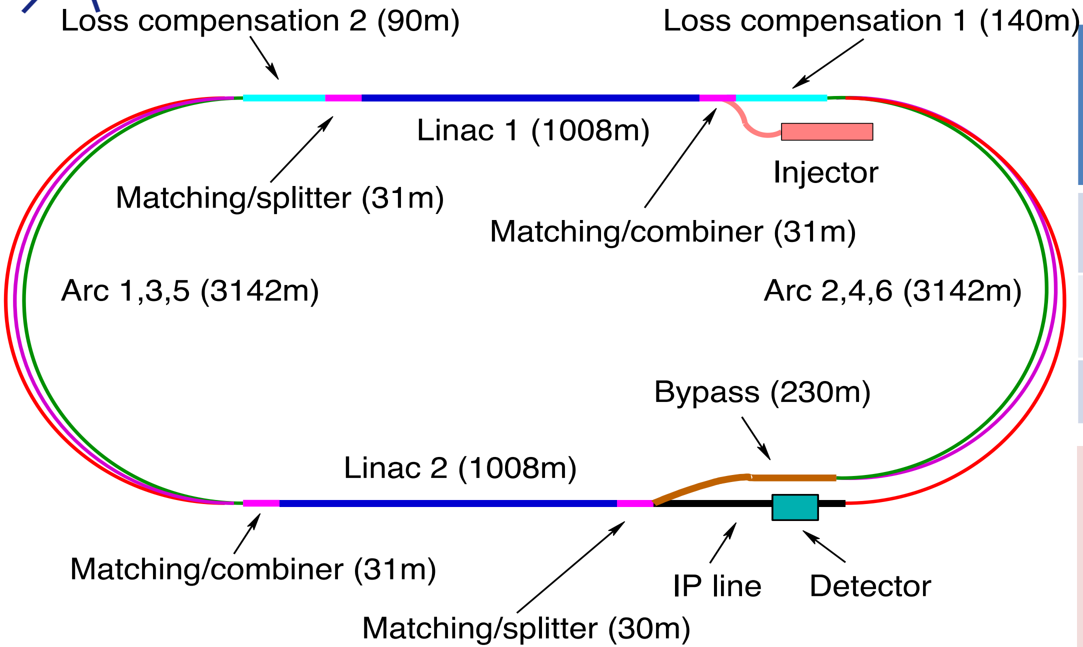
Principle of ionisation cooling has been demonstrated

More complete experiment with higher statistics, more than one stage required

Integration of magnets, RF, absorbers, vacuum is engineering challenge

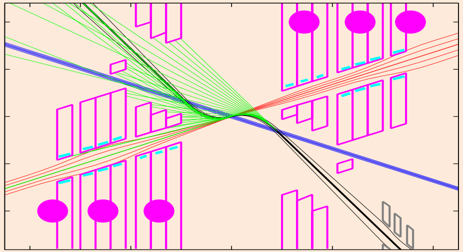
LHeC/FCC-eh

LHeC / FCC-eh



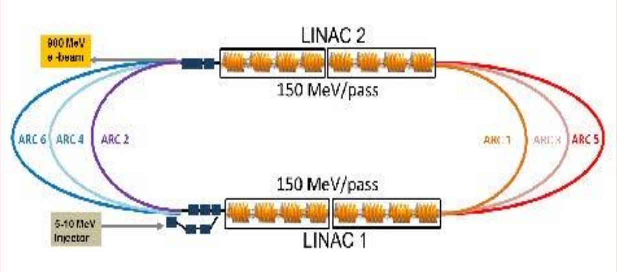
	LHeC CDR	HL-LHeC	HE-LHeC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
L [$10^{33}cm^{-2}s^{-1}$]	1	8	12	15

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



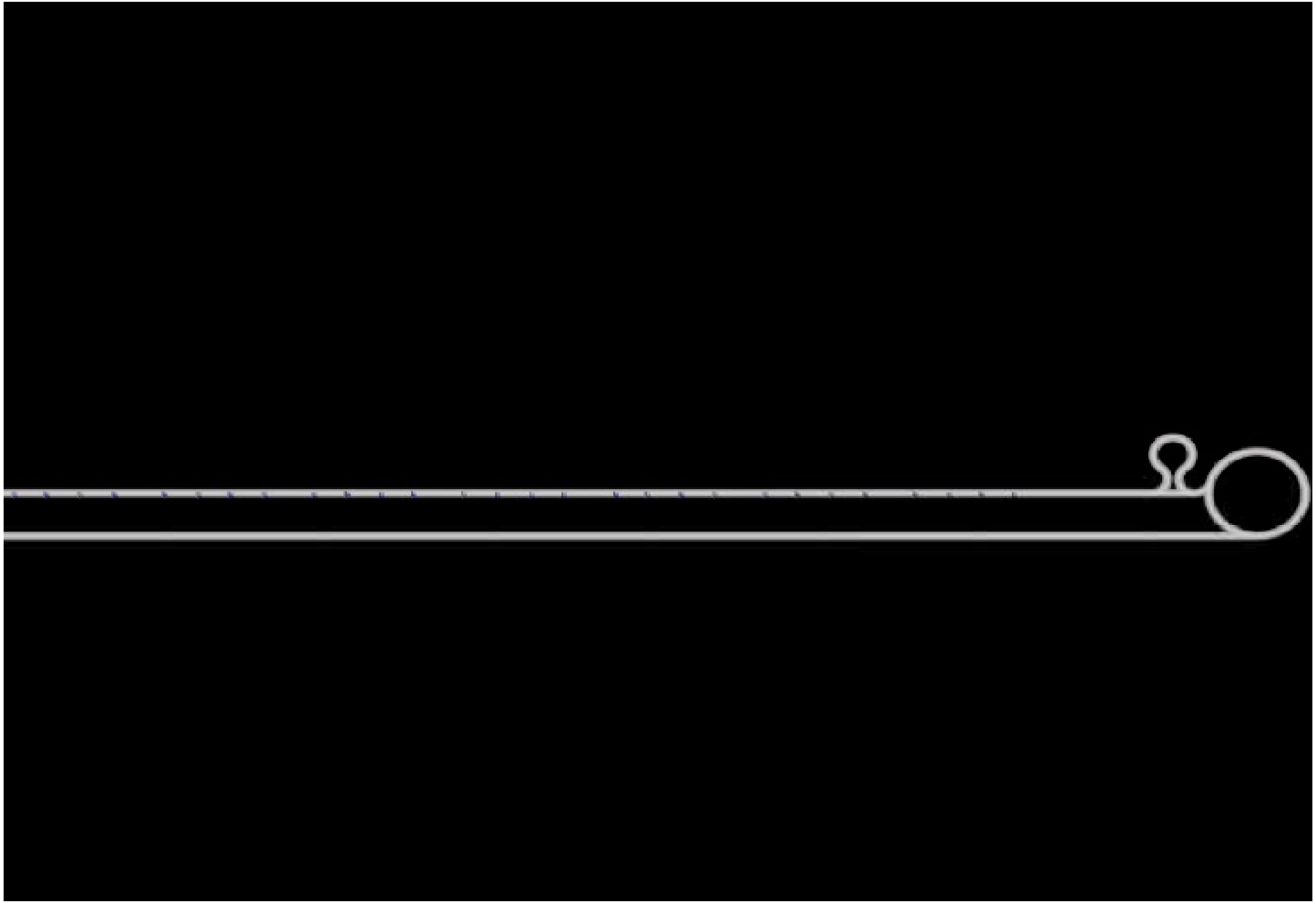
Conclusion and Thanks

- Touched only a small part of the exciting accelerator technologies
- Quite some work ahead to develop and the future colliders
- ILC and CLIC are mature
- FCC-ee and CEPC are being developed
  - FCC-ee for next European Strategy
  - In the long run FCC-hh can follow
- Muon collider is less mature but would offers a long-term lepton path
- Plasma-based colliders are more speculative at this moment
- LHeC would offer electron proton collisions

Many thanks to Reende Steerenberg, Steinar Stapnes, Lucio Rossi, Mark Palmer, Ralph Assmann, Jean-Pierre Delahaye, Lucie Linssen, Steffen Doebert, Alexej Grudiev, Frank Tecker, Walter Wuensch, Stephane Poss, Jan Strube, Joerg Wenninger, M. Benedikt, Frank Zimmermann, Bernhard Holzer, Roberto Kersevan, Ph. Lebrun, …

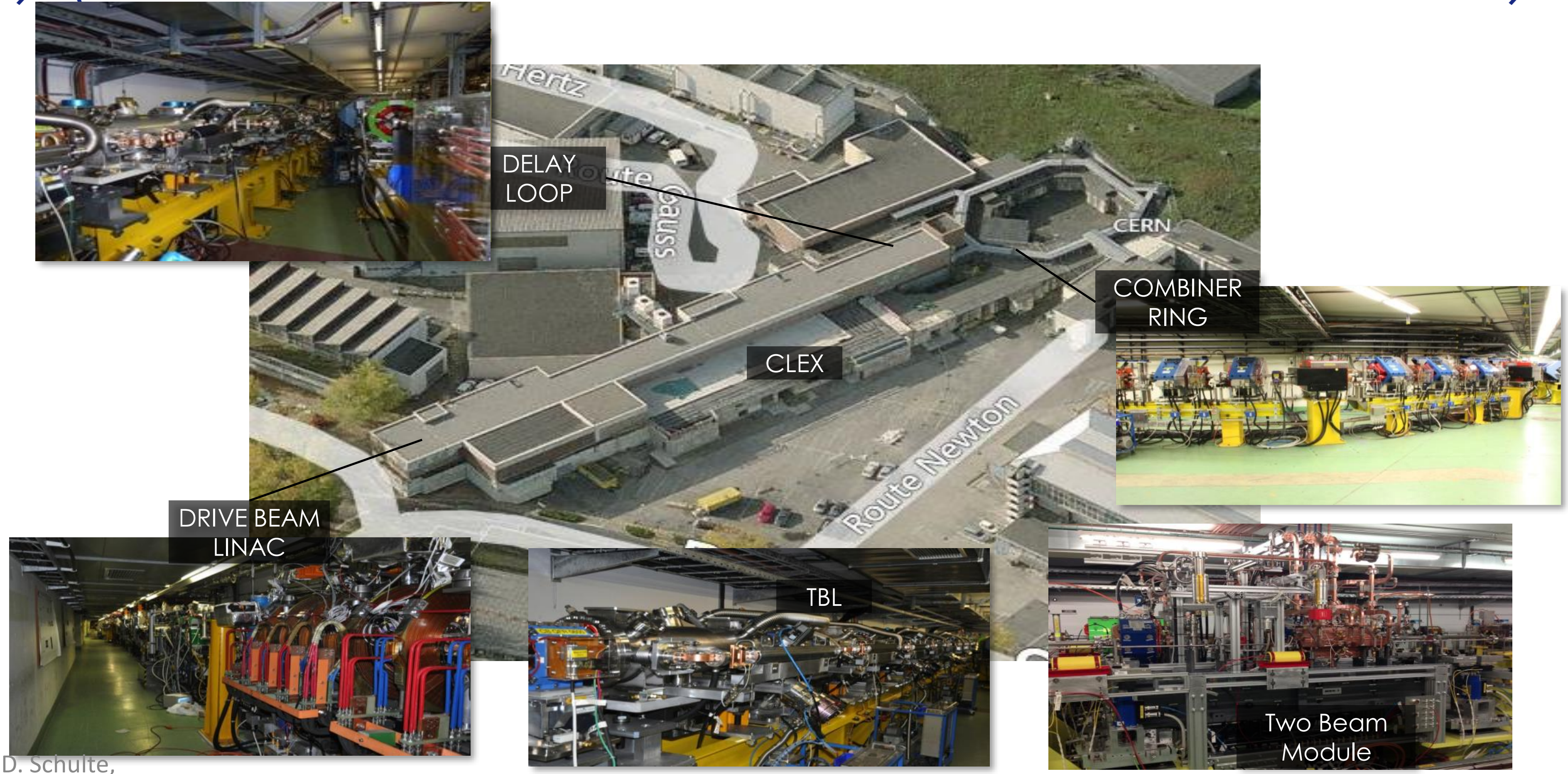
If you can look into the seeds of time, And say which grain w
(Shakespeare)

Reserve



A. Andersson

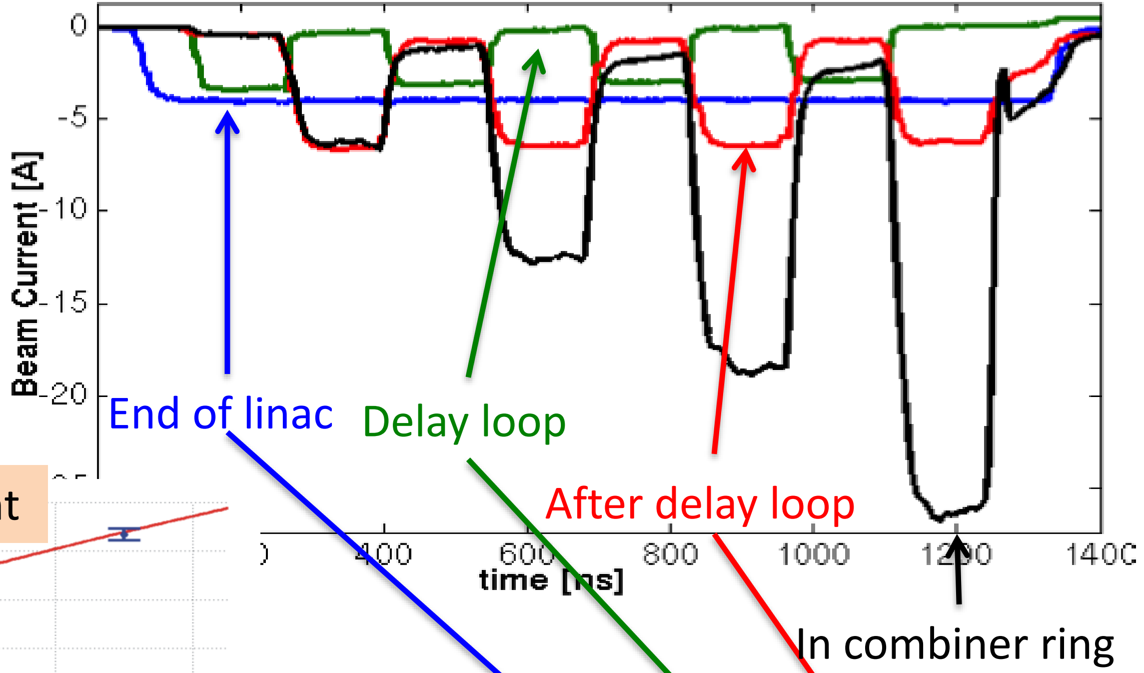
CLIC Test Facility (CTF3)

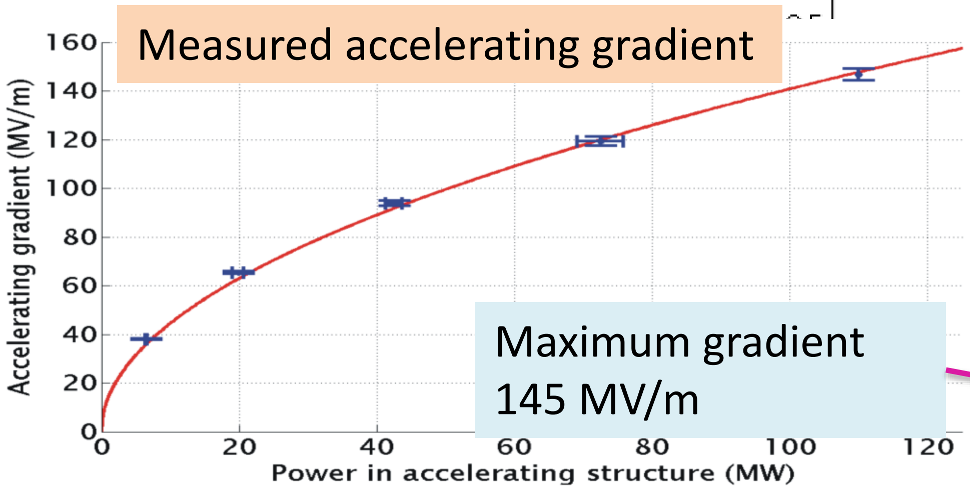


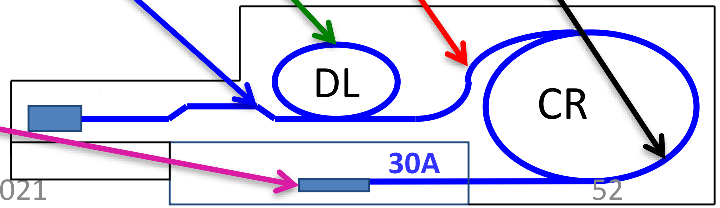
Drive Beam Combination in CTF3

Note: Efficiencies
RF to drive beam >95%
Drive beam to RF >95%

Total efficiency wall plug to main beam is about 10%







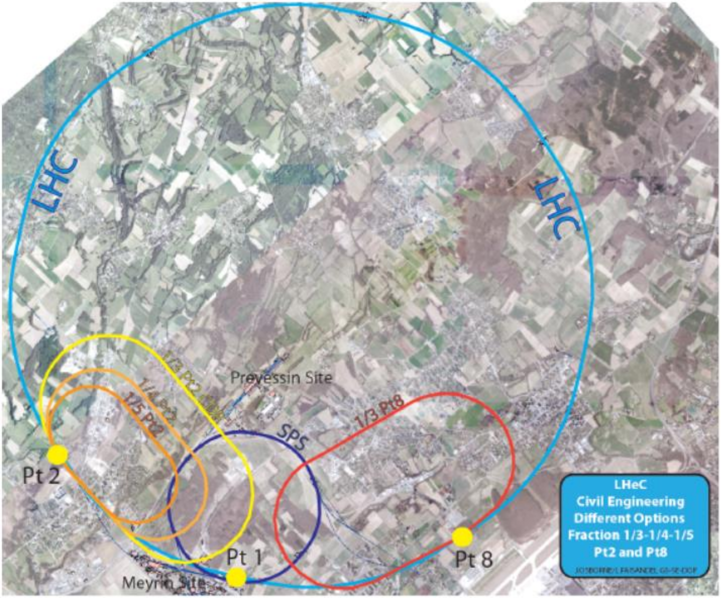
LHeC / FCC-eh Parameters

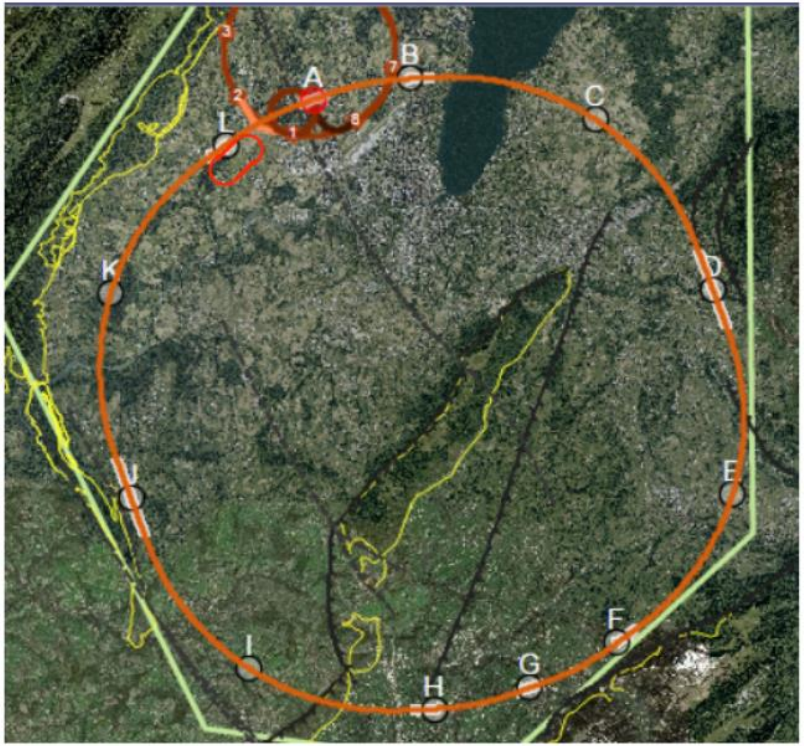
parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	12.5	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.5	1
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2
electrons per bunch [10^9]	1	2.3	3.0	3.0
electron current [mA]	6.4	15	20	20
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor H_{geom}	0.9	0.9	0.9	0.9
pinch factor H_{b-b}	1.3	1.3	1.3	1.3
proton filling H_{coll}	0.8	0.8	0.8	0.8
luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017,
“A Baseline for the FCC-he”

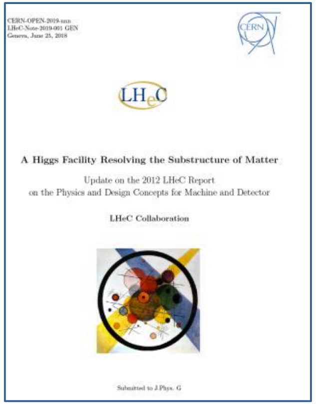
LHeC and FCC-eh Reports

Design of LHeC documented in report 2012, updated planned next year
Design for FCC-eh is similar, except of interaction region





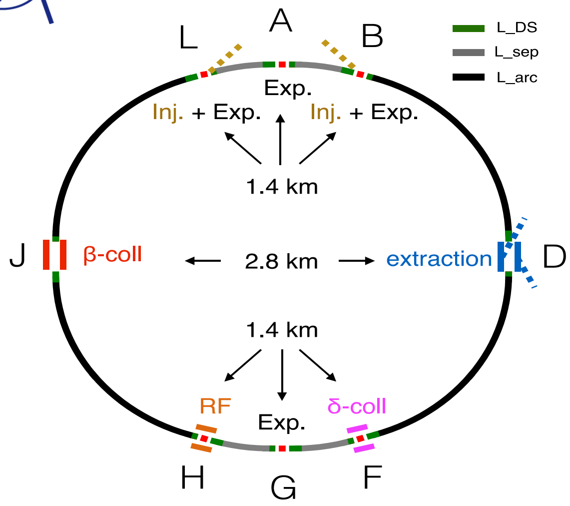
Published 600 pages conceptual design report (CDR) writ
refereed by 24 world experts on physics, accelerator and



Key FCC-ee Parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geom. emit. [nm]	0.27	0.28	0.63	1.46
vert. geom. emit. [pm]	1.0	1.7	1.3	2.9
bunch length w. SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
L per IP [10^{34} $cm^{-2}s^{-1}$]	>200	>25	>7	>1.4
lifetime Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee Layout



Different layout options are being studied
Different optimisation to FCC-hh
but maintaining FCC-hh

Layout	IP	Shafts	circumference	Arc radius of curvature	short arc A-B, F-G, G-H,	long arc B-D, D-F,	straight sections A, G	straight sections B, F, H, L	straight sections D, J
~CDR	2	12	97750	13329	4448	16489	1.4	1.4	2.8
17.08	2	12	96109	12922	5782	14517	1.4	1.4	3.25
19.03	2	12	91350	12380	3864	15582	1.36	1.36	2.69
20.03	4	8	95713	13058	10256	10256	1.45	2.0	1.45

(km)