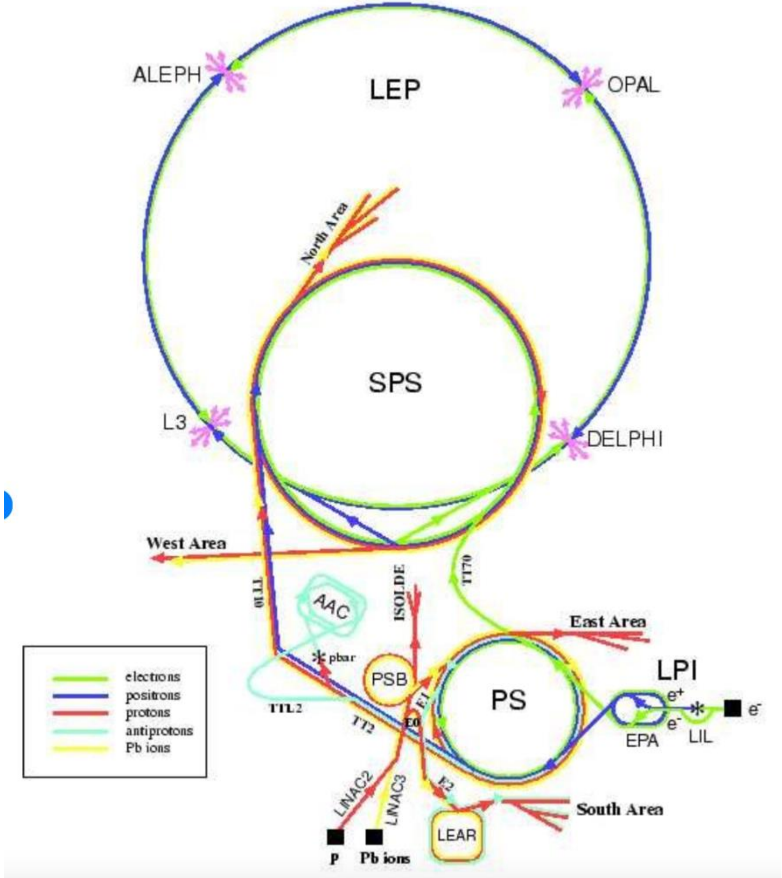
# Accelerator Physics and Challenges for Future Colliders II

## Electron-positron Colliders

D. Schulte, CERN

# LEP and LHC


LEP
ALEPH
OPAL
L3
DELPHI
SPS
North Area
West Area
East Area
South Area
TT10
TT70
TTL2
TT2
ISOLDE
AAC
pbar
PSB
PS
E0
E1
E2
LPI
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Pb ions
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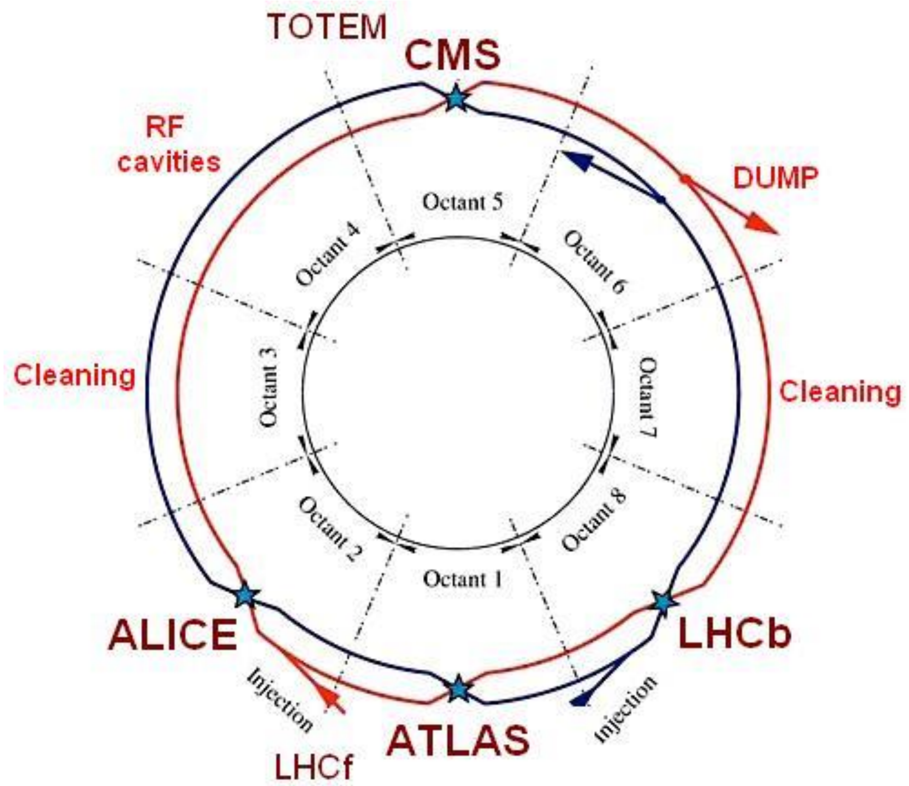

TOTEM
CMS
RF cavities
DUMP
Cleaning
Cleaning
Octant 1
Octant 2
Octant 3
Octant 4
Octant 5
Octant 6
Octant 7
Octant 8
ALICE
LHCb
ATLAS
LHCf
Injection
Injection

# 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

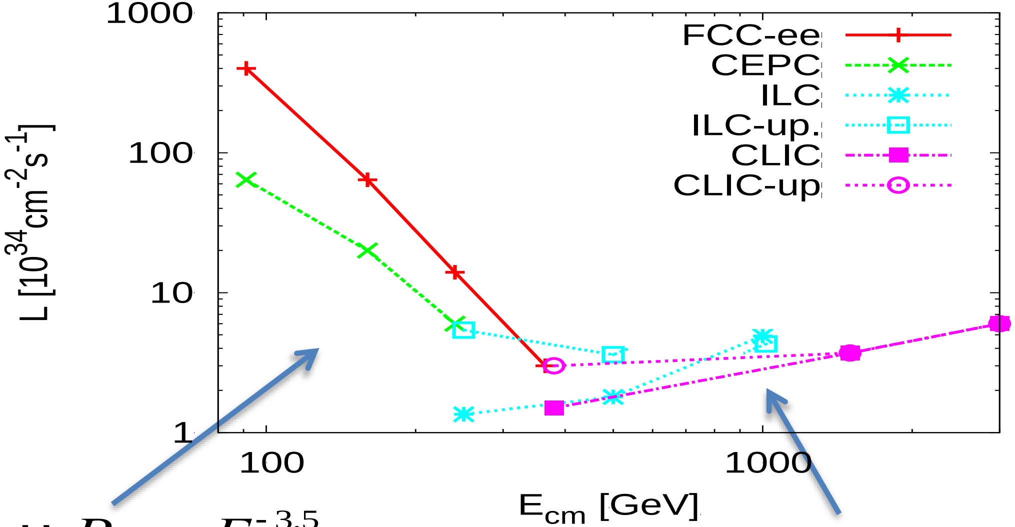
- ILC, superconducting linear collider
- CLIC, normal conducting linear collider
- FCC-ee and CEPC, circular collider

- 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**



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

$L \mu P_{RF}$

**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

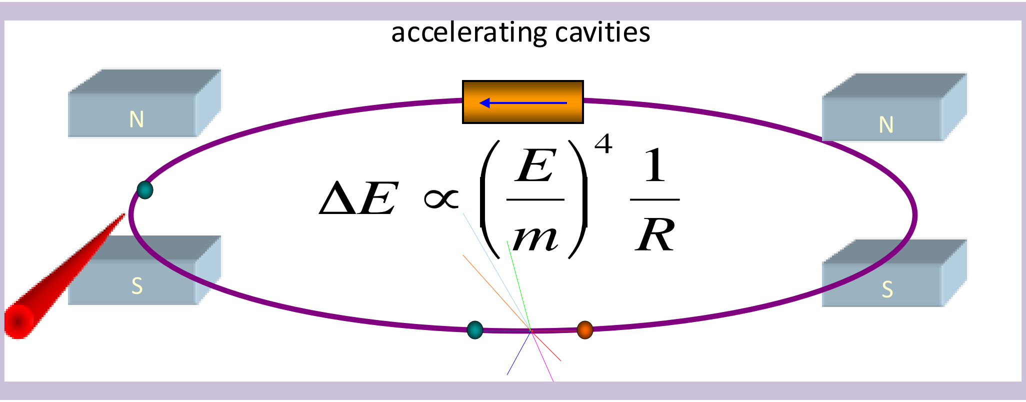
The picture is much clearer at lower or higher energies

# Energy Limit

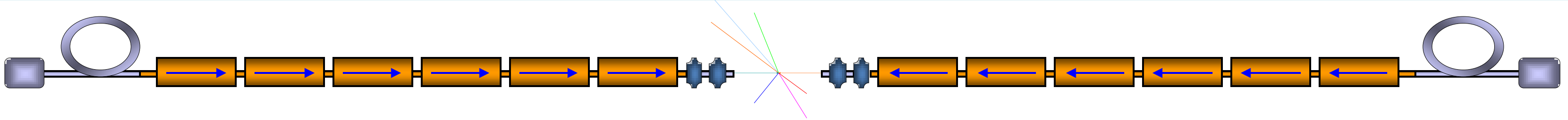
Circular collider

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

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



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

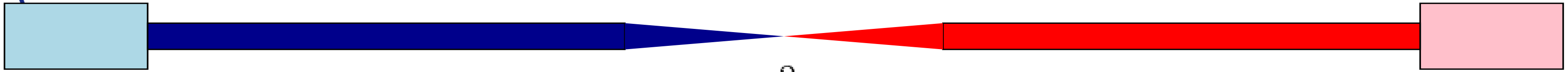


**Linear electron-positron collider**

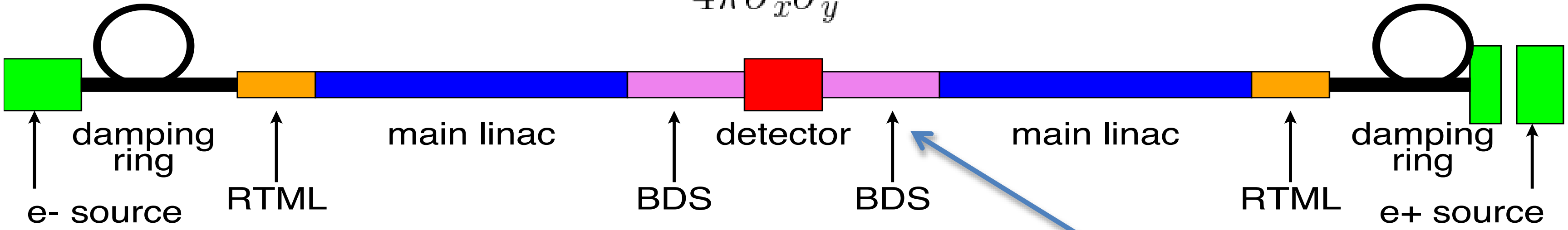
- Essentially no synchrotron radiation
- But have to accelerate beams in one pass
- and only collide once, so small beams

Or use heavier particles in **circular collider**
**Muons** are 200 times heavier than electrons
But they have a short lifetime (2.2 µs)

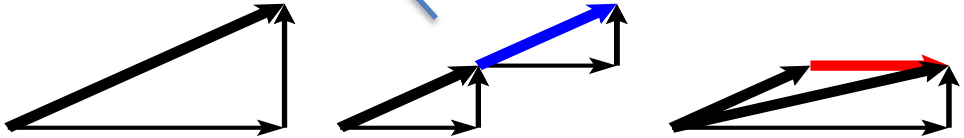
# Linear Collider Principle



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



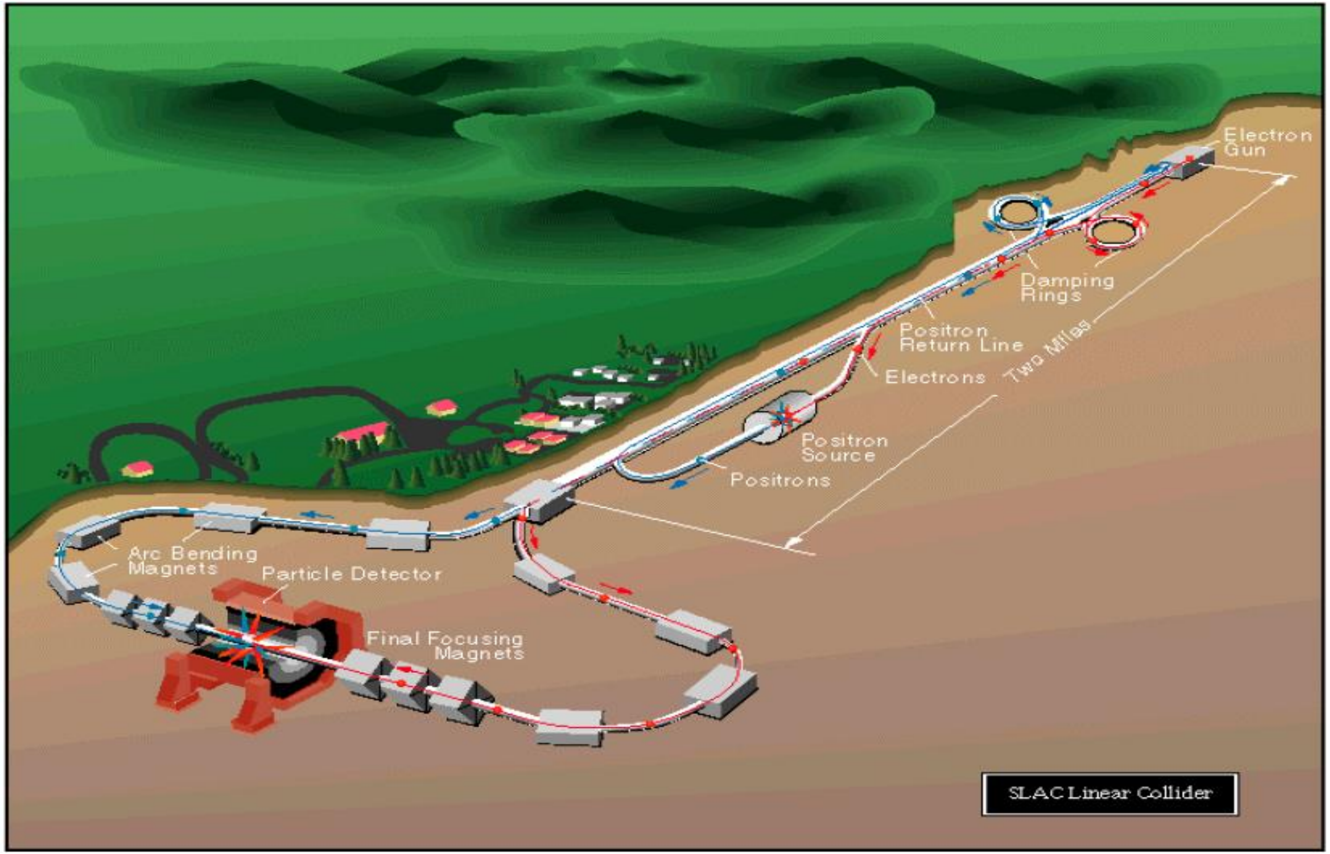
$$\sigma_{x,y} = \sqrt{\frac{\beta_{x,y}\epsilon_{x,y}}{\gamma}}$$



energy loss

re-acceleration

# SLC: The only Linear Collider that existed



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

Energy = 92 GeV

Luminosity = 2e30

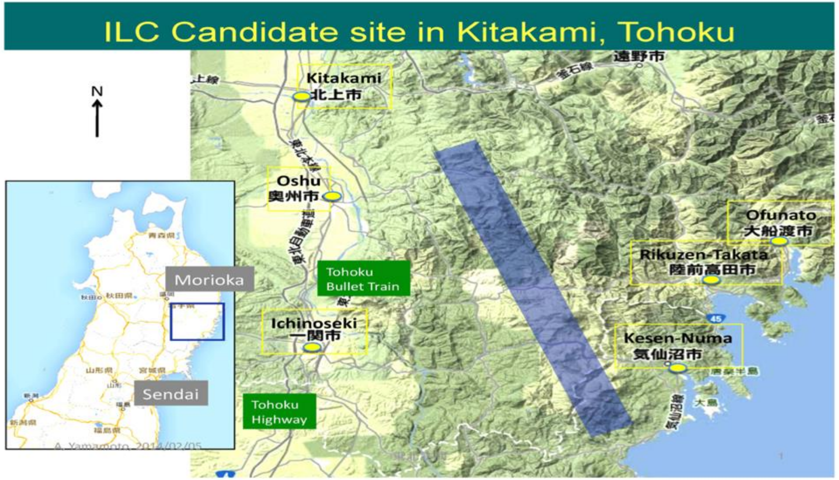
Has all the features of a 2nd gen. LC except both e+ and e- used the same linac

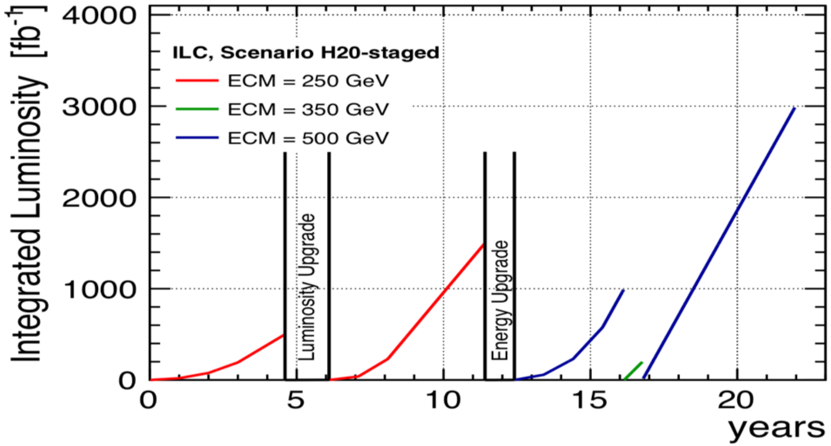
A 10% prototype!

# ILC Scenarios

Waiting for Japan to make a commitment

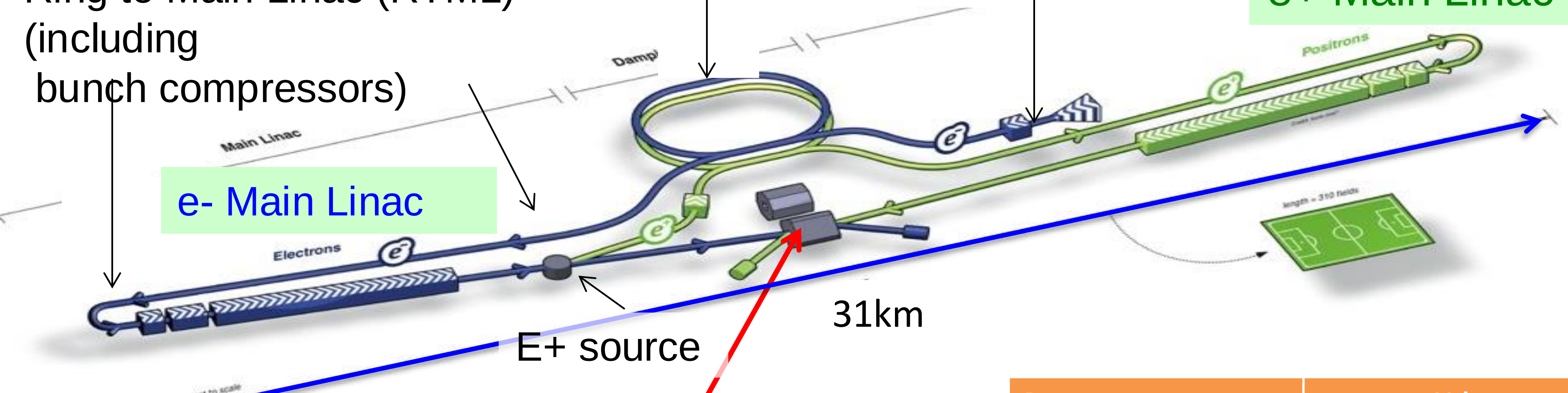
- Site identified and being investigated
- But executive not yet endorsed project
- Process is going on for many years





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

# ILC



Damping Rings

Polarised electron source

Ring to Main Linac (RTML) (including bunch compressors)

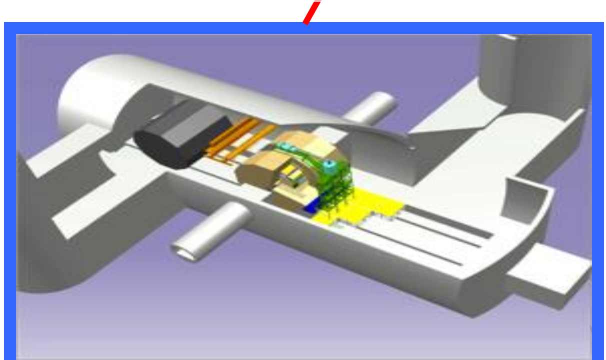
e+ Main Linac

e- Main Linac

31km

E+ source

ILC Scheme | © www.form-one.de

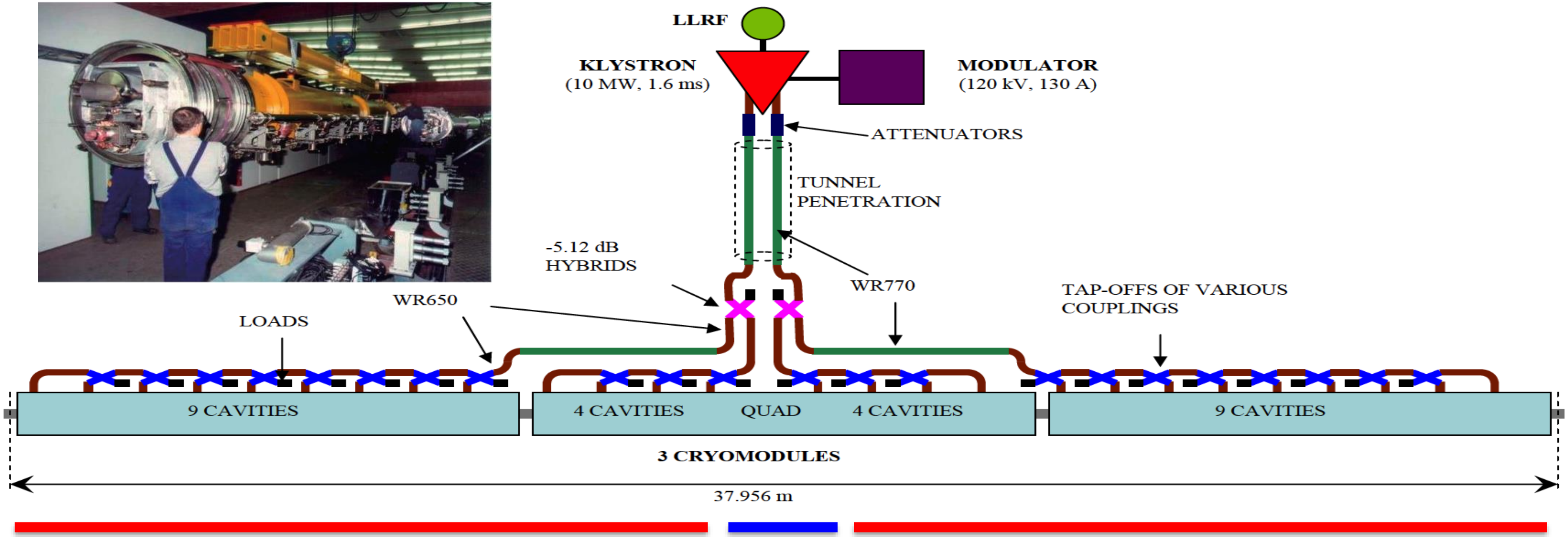


| Parameters | Value |
|---|---|
| C.M. Energy | 250 GeV |
| Peak luminosity | 1.35 x$10^{34}$ cm$^{-2}$s$^{-1}$ |
| Beam power | 5 MW |
| Beam Rep. rate | 5 Hz |
| E gradient | 31.5 MV/m +/-20% |

# 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 | $\sigma_z$ [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

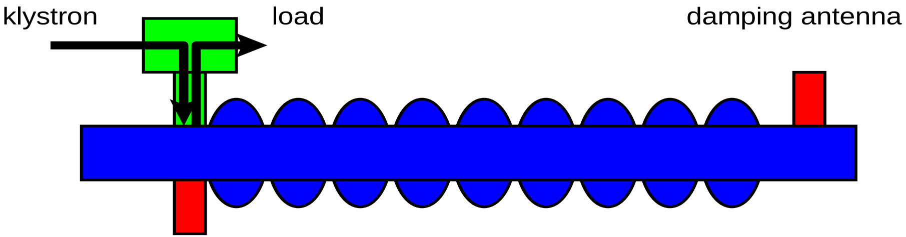
# ILC Cavities

Superconducting cavity (Ni at 2 K)

Standing wave structure

RF frequency is 1.3 GHz, 23 cm wavelength

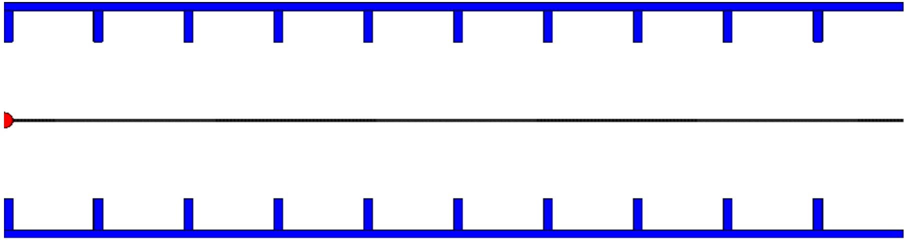
Length is 9 cells = 4.5 wavelengths = 1 m



Pulsed operation:

5 x 1.6 ms pulses per second

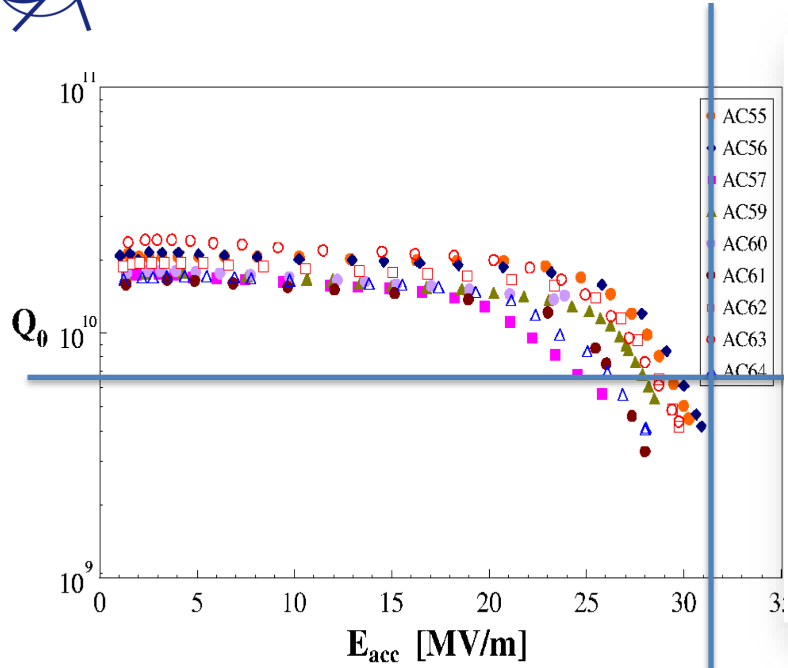
Gradient is 31.5 MV/m

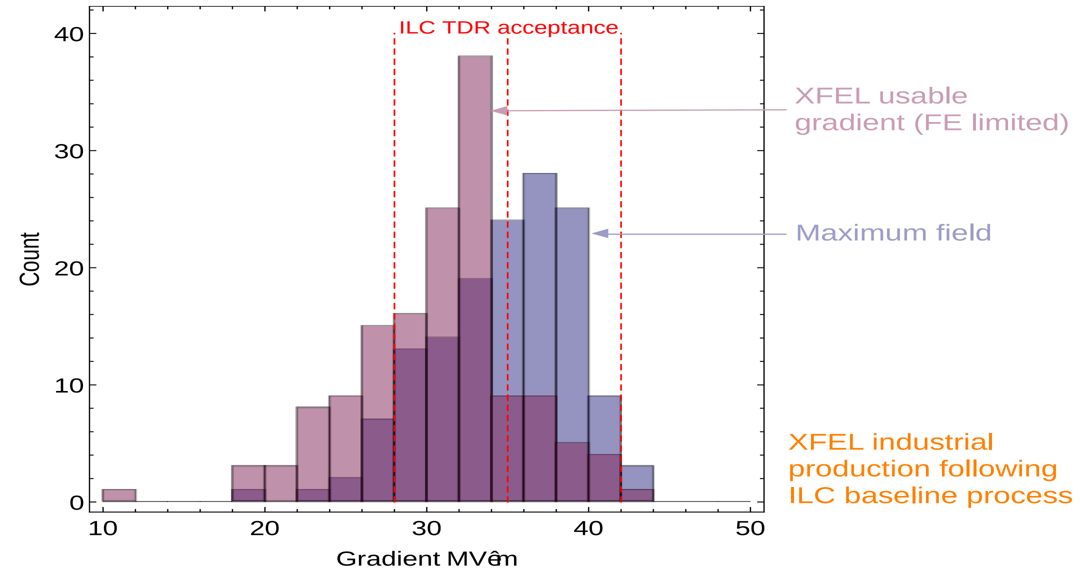


In rings typically

- 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

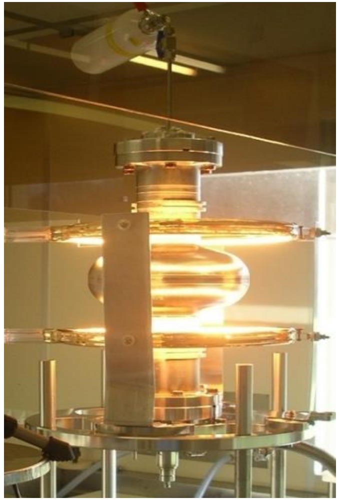
Cavities have different performancies

# ILC Cavity Treatment

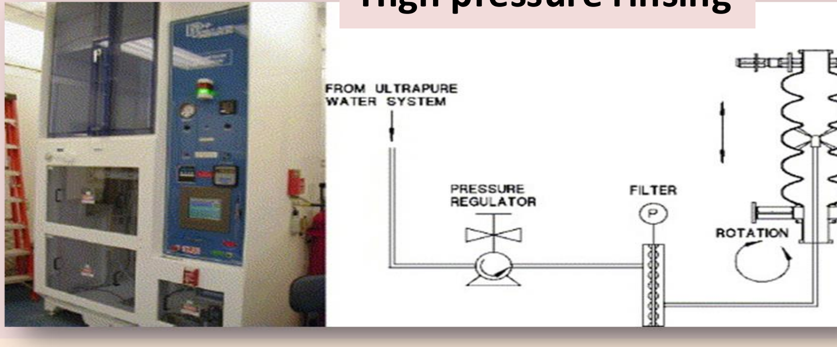
**Control of material**
Avoid defects
Ensure high quality

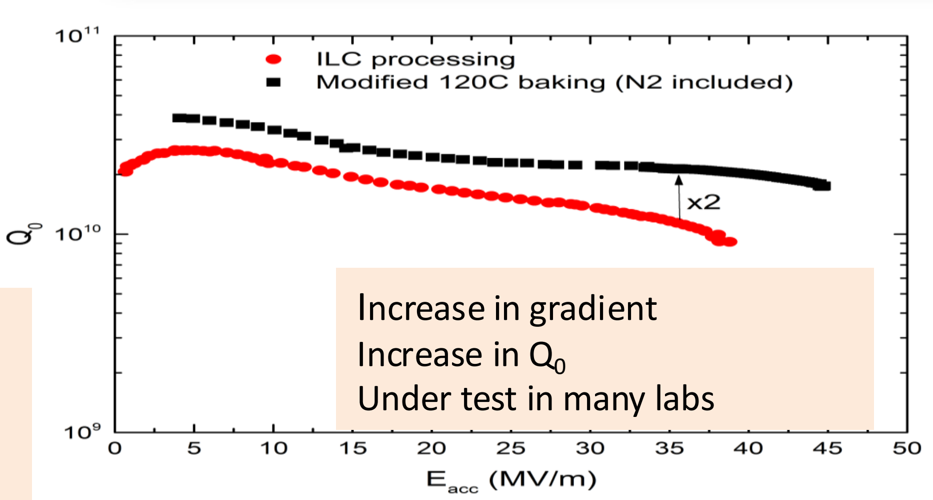
**Electropolishing**
fill with $H_2SO_4$, apply current to remove thin surface layer

**Bakeout**



**High pressure rinsing**

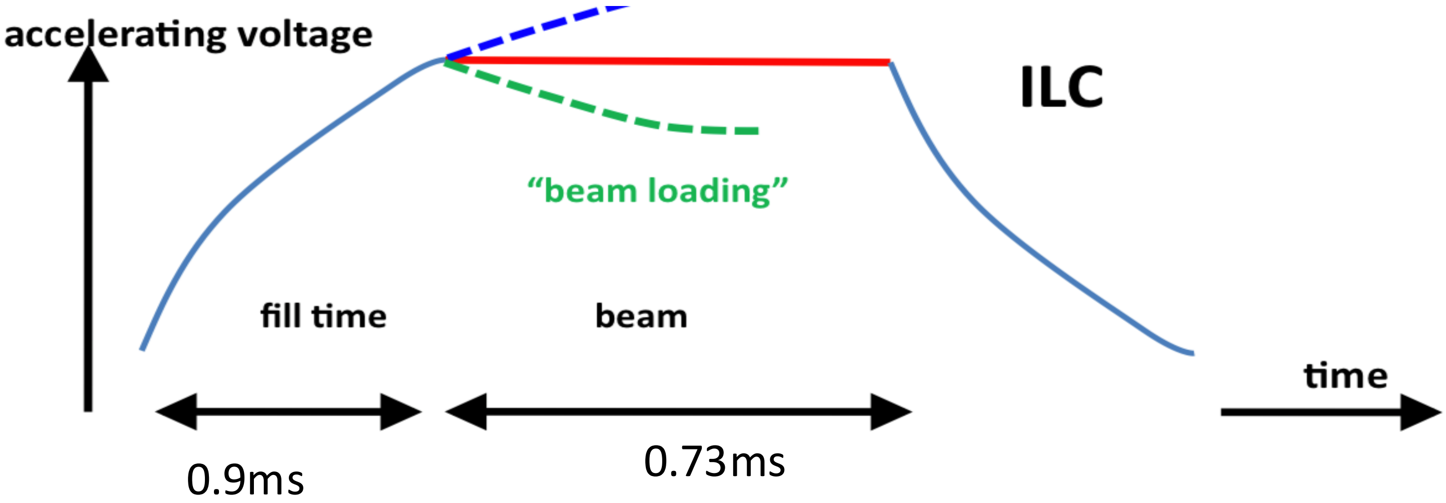




Increase in gradient
Increase in $Q_0$
Under test in many labs

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

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

About 1W/m

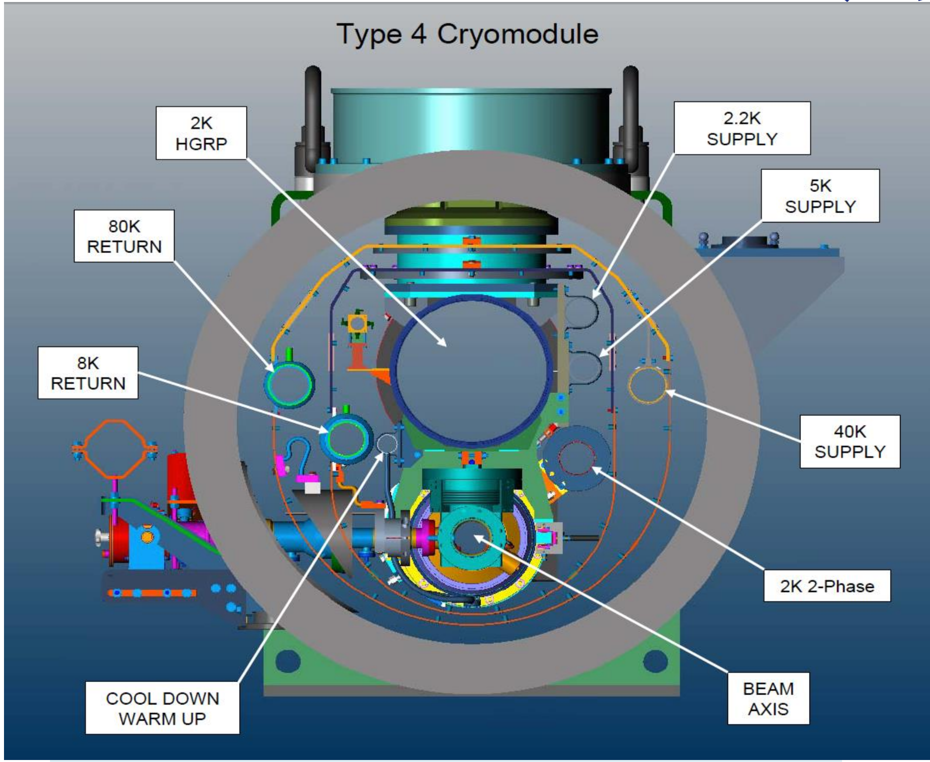
But cooling costly at low temperatures

Remember Carnot:

$$P_{cryo} = \frac{1}{h} \frac{T_{room} - T_{source}}{T_{source}} ´ \; P_{loss}$$

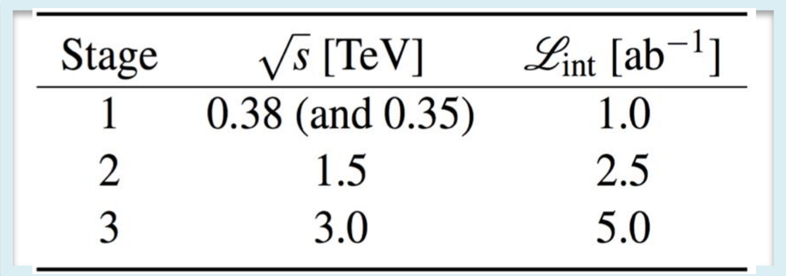
$$P_{cryo} » 700 ´ \; P_{loss}$$

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

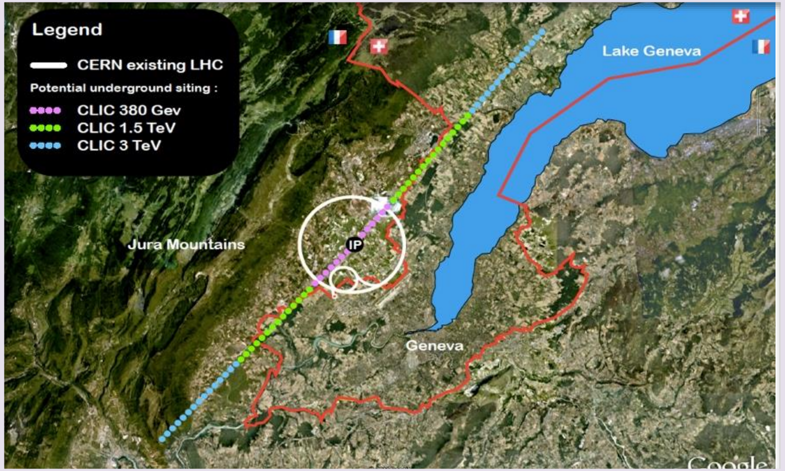
# CLIC Staged Scenario



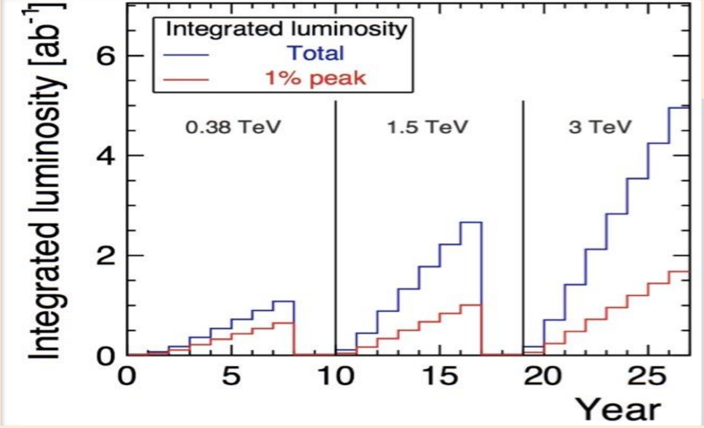
| Stage | $\sqrt{s}$ [TeV] | $\mathscr{L}_{\text{int}}$ [ab$^{-1}$] |
|---|---|---|
| 1 | 0.38 (and 0.35) | 1.0 |
| 2 | 1.5 | 2.5 |
| 3 | 3.0 | 5.0 |

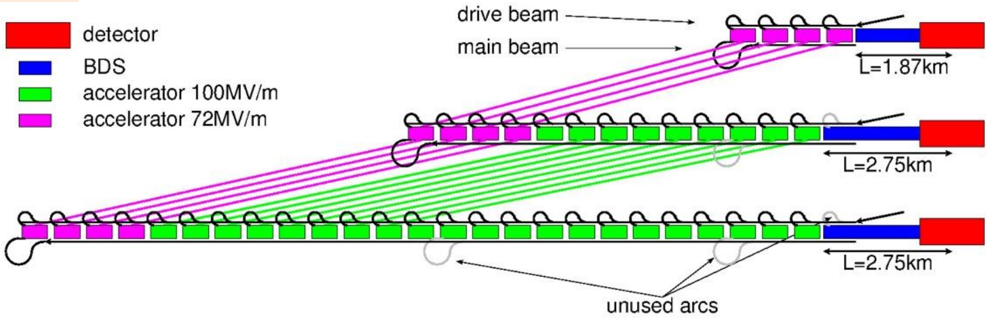
Luminosity targets from Physics Study group
Hopefully input from LHC

Central complex on Prevessin site



Luminosity evolution

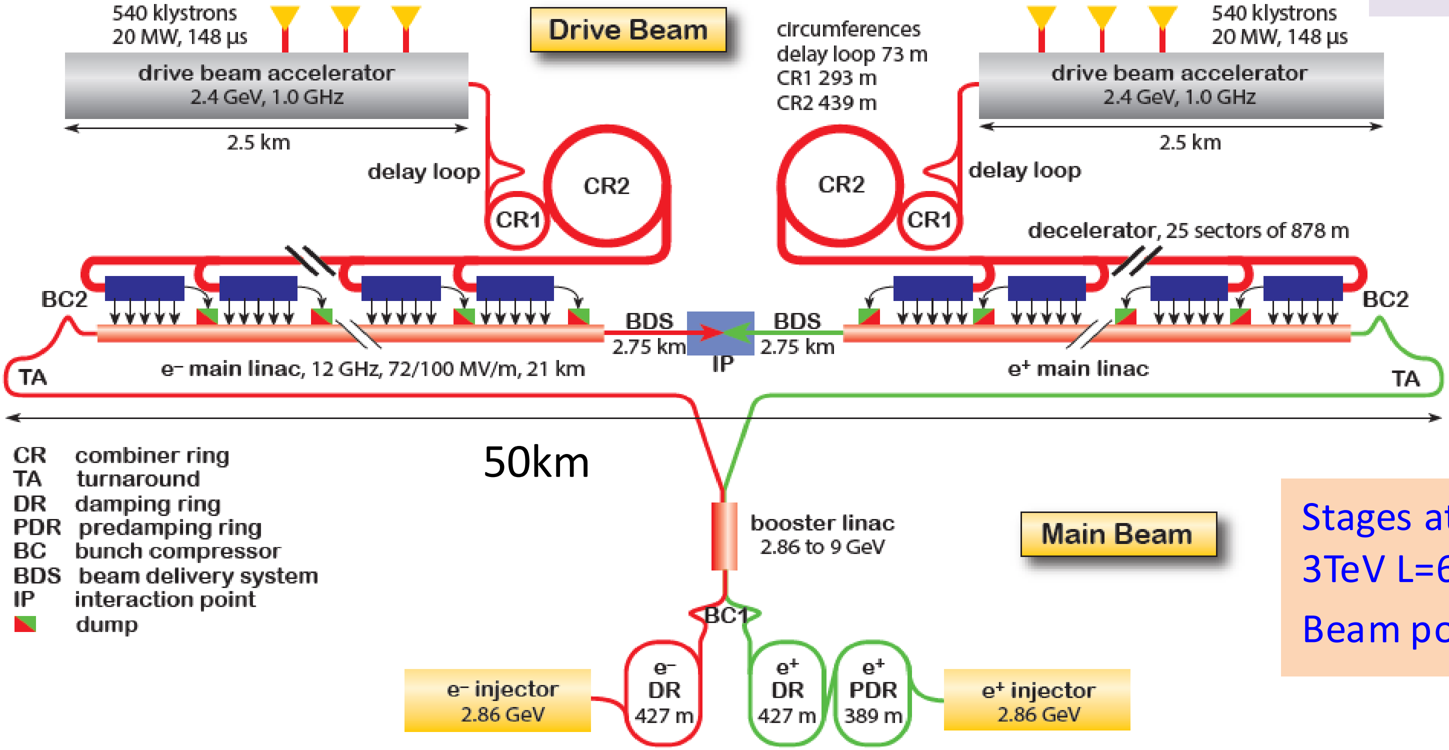




Lower gradient optimum for lower energy

# CLIC: The Basis

CLIC at 3TeV shown

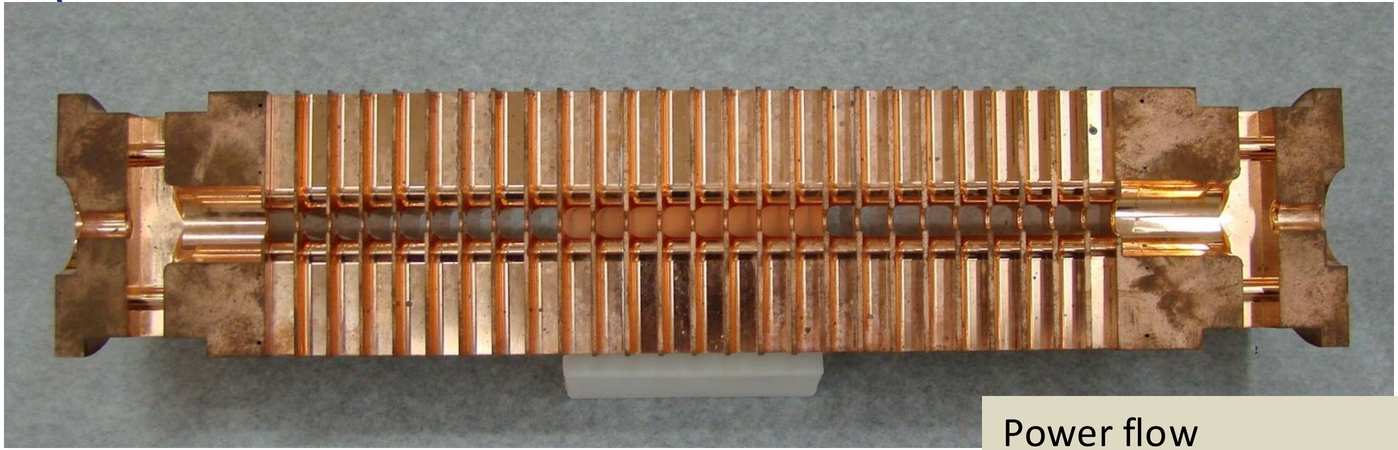


| | |
|---|---|
| CR | combiner ring |
| TA | turnaround |
| DR | damping ring |
| PDR | predamping ring |
| BC | bunch compressor |
| BDS | beam delivery system |
| IP | interaction point |
| 🟥 | dump |

Stages at $E_{cms}$=0.38, 1.5 and 3TeV L=$6\times10^{34}$ $cm^{-2}s^{-1}$ 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

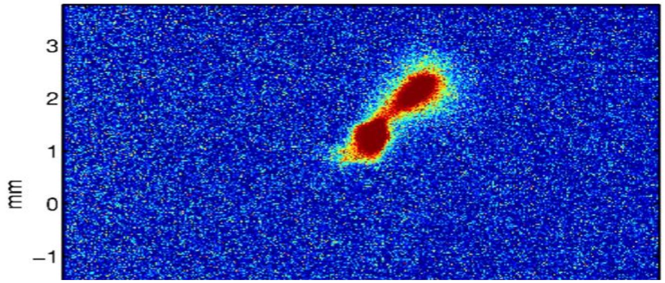
Average RF power about 3 kW/m

About 1 kW/m into beam

# CLIC Gradient Limitations

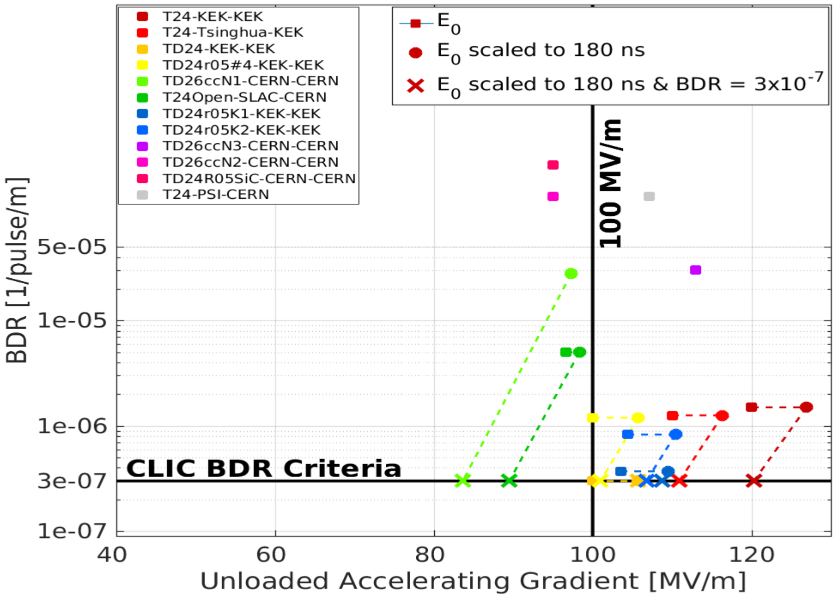
Breakdowns (discharges during the RF pulse)

- Require $p \leq 3 \text{ x } 10^{-7}\ \mathrm{m}^{-1}\mathrm{pulse}^{-1}$



Structure design based on empirical constraints, not first principle

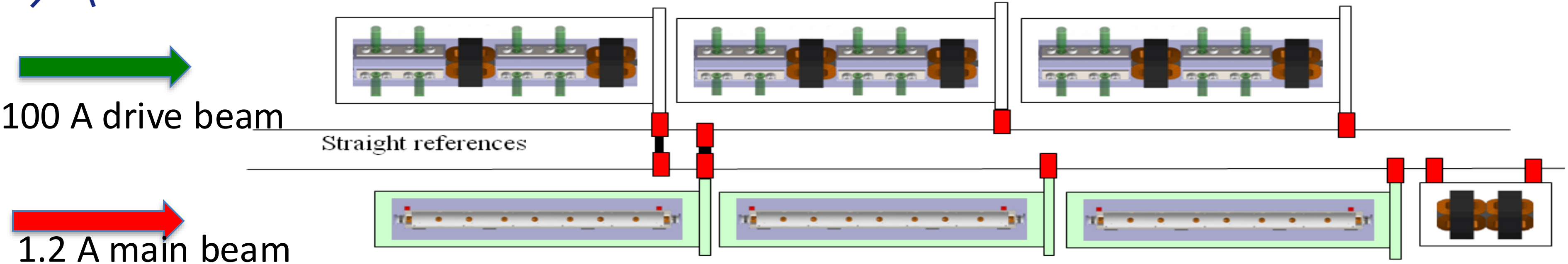
- Maximum surface field
- Maximum temperature rise
- Maximum power flow



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

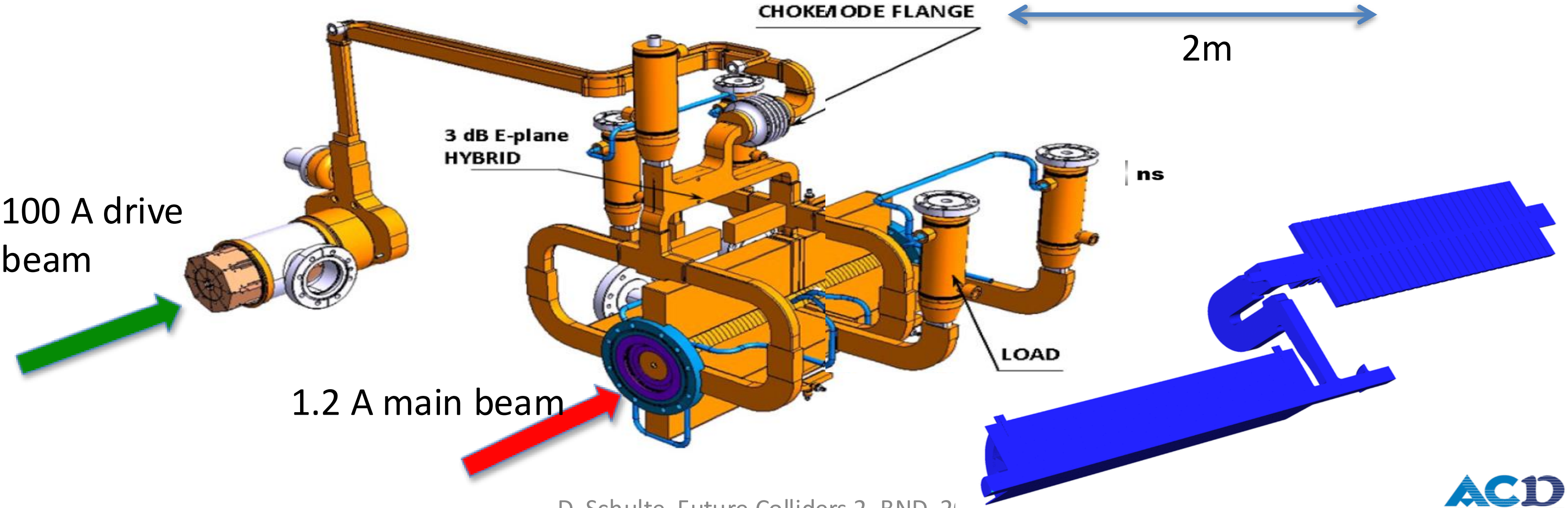
Shorter pulses have fewer breakdowns

# CLIC Two-beam Concept



100 A drive beam

1.2 A main beam



100 A drive beam

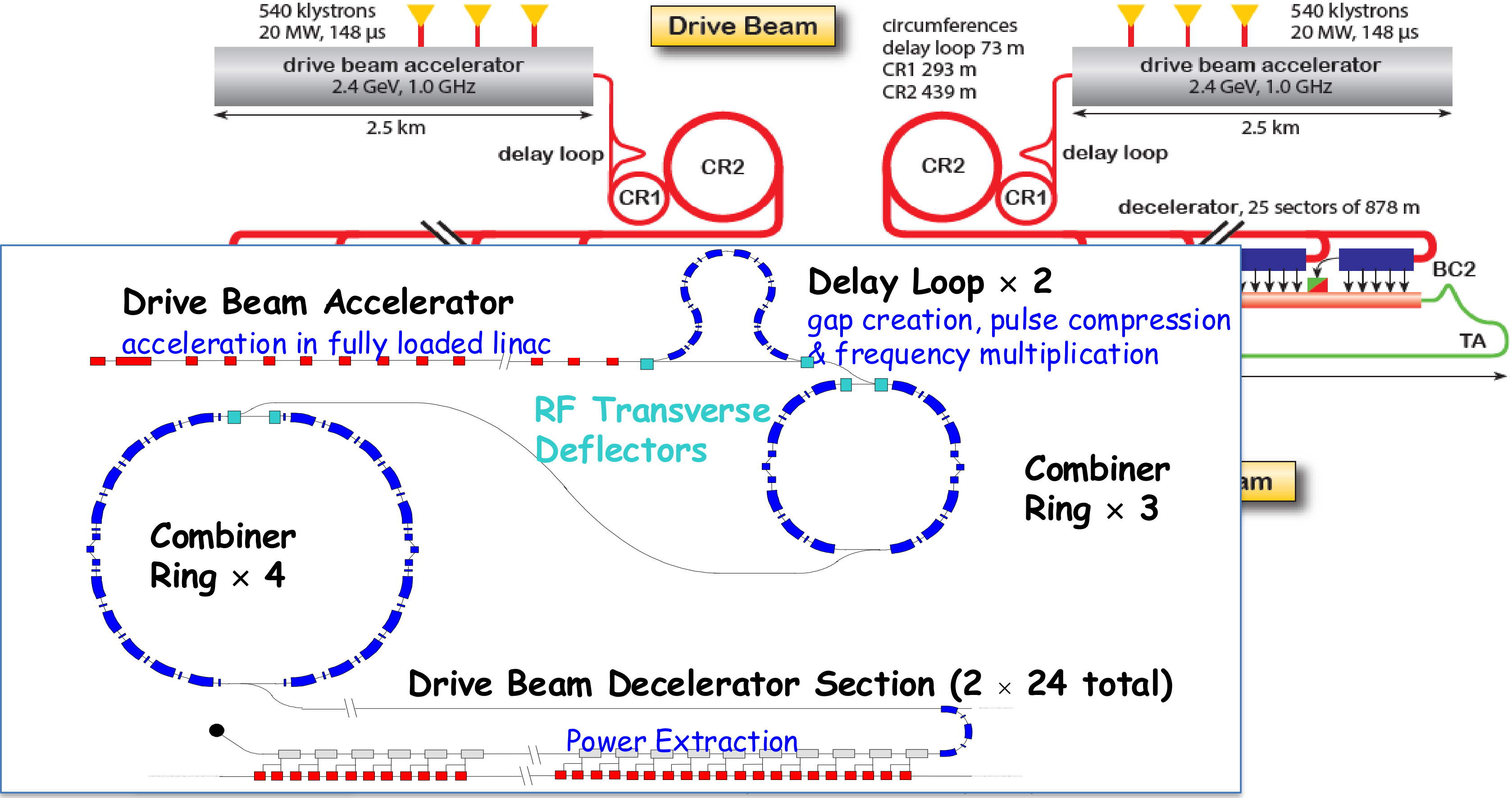
1.2 A main beam

# 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



**Drive Beam Accelerator**

acceleration in fully loaded linac

**Delay Loop × 2**

gap creation, pulse compression & frequency multiplication

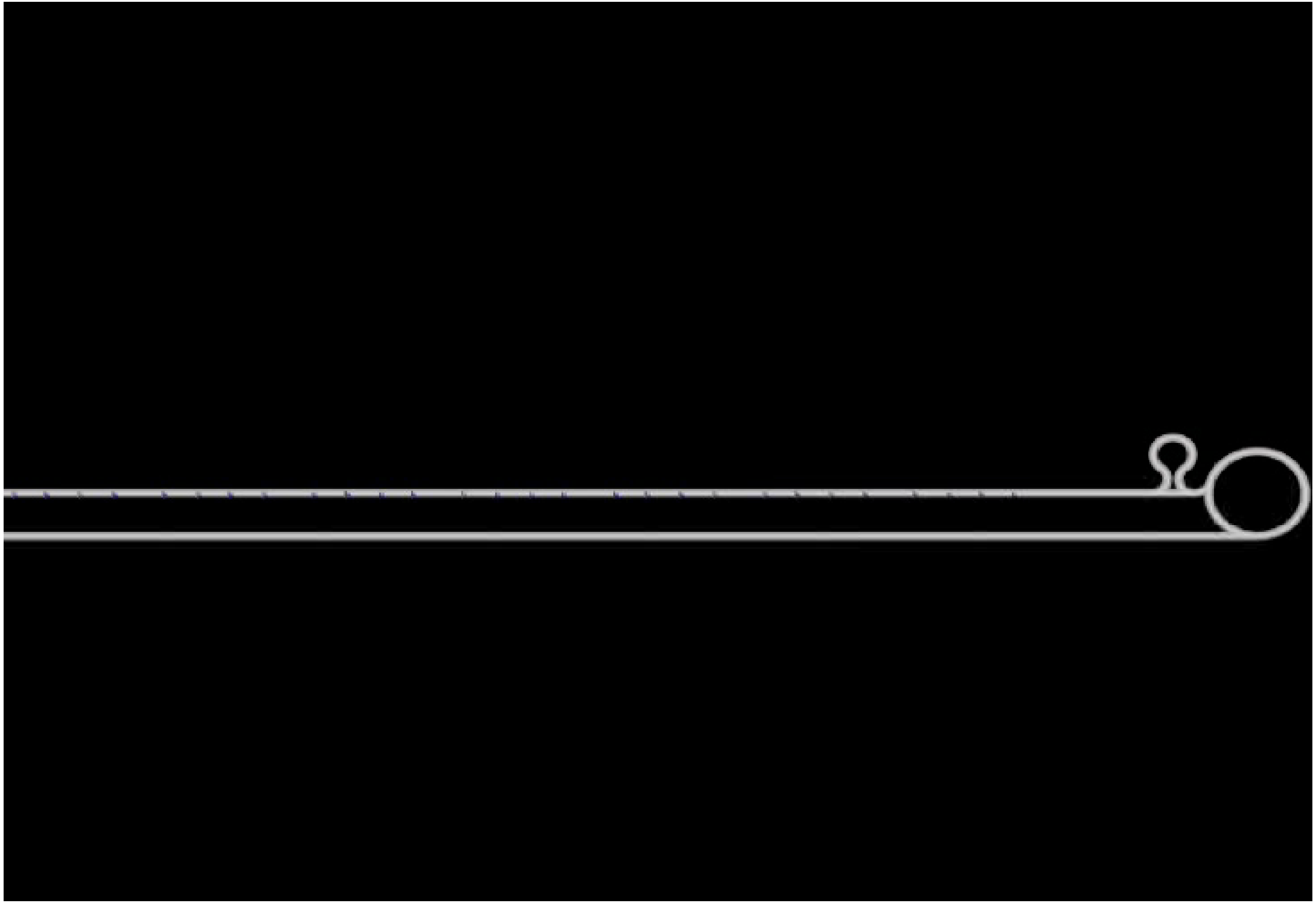
RF Transverse Deflectors

**Combiner Ring × 3**

**Combiner Ring × 4**

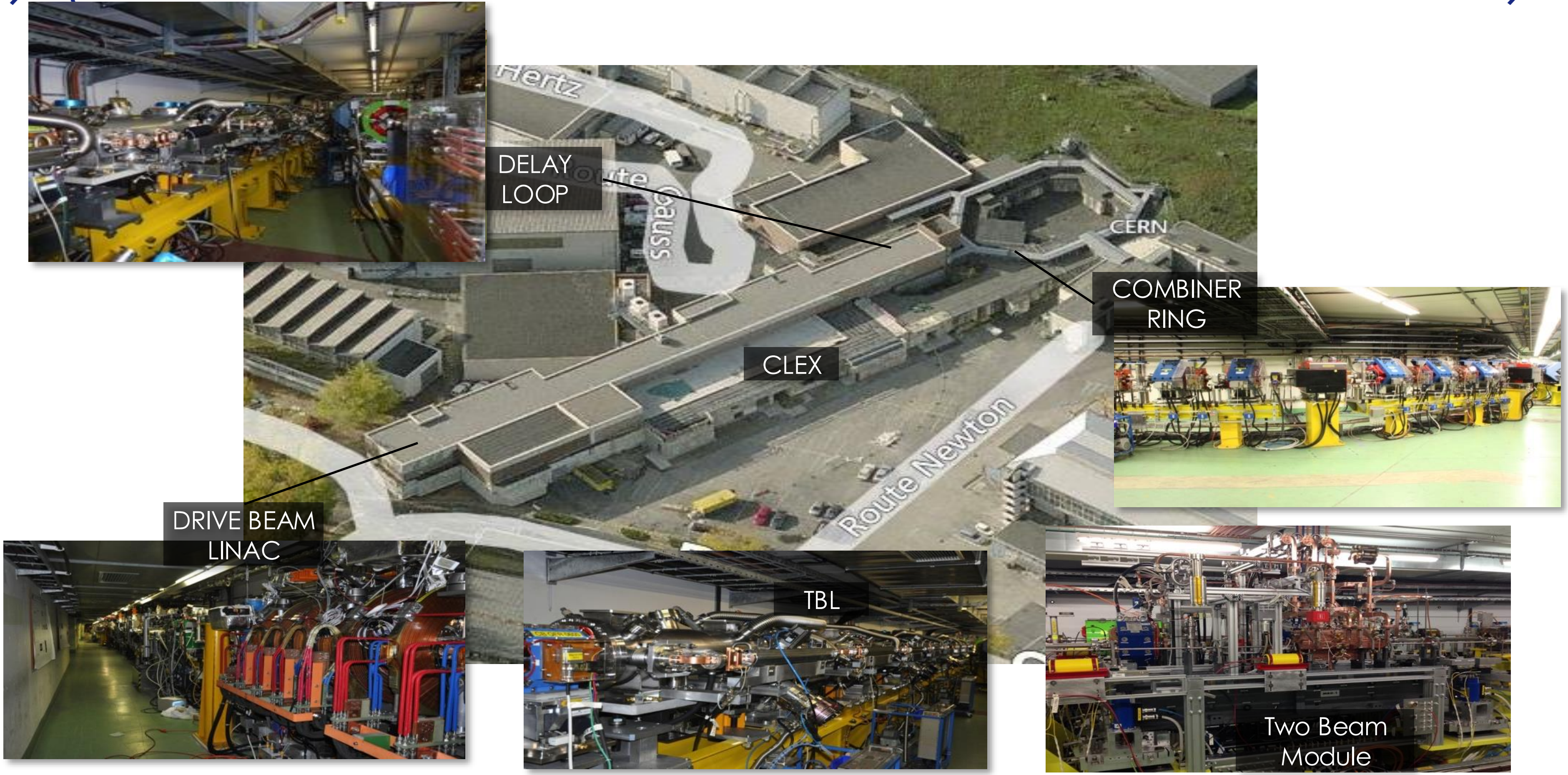
**Drive Beam Decelerator Section (2 × 24 total)**

Power Extraction



A. Andersson

# CLIC Test Facility (CTF3)



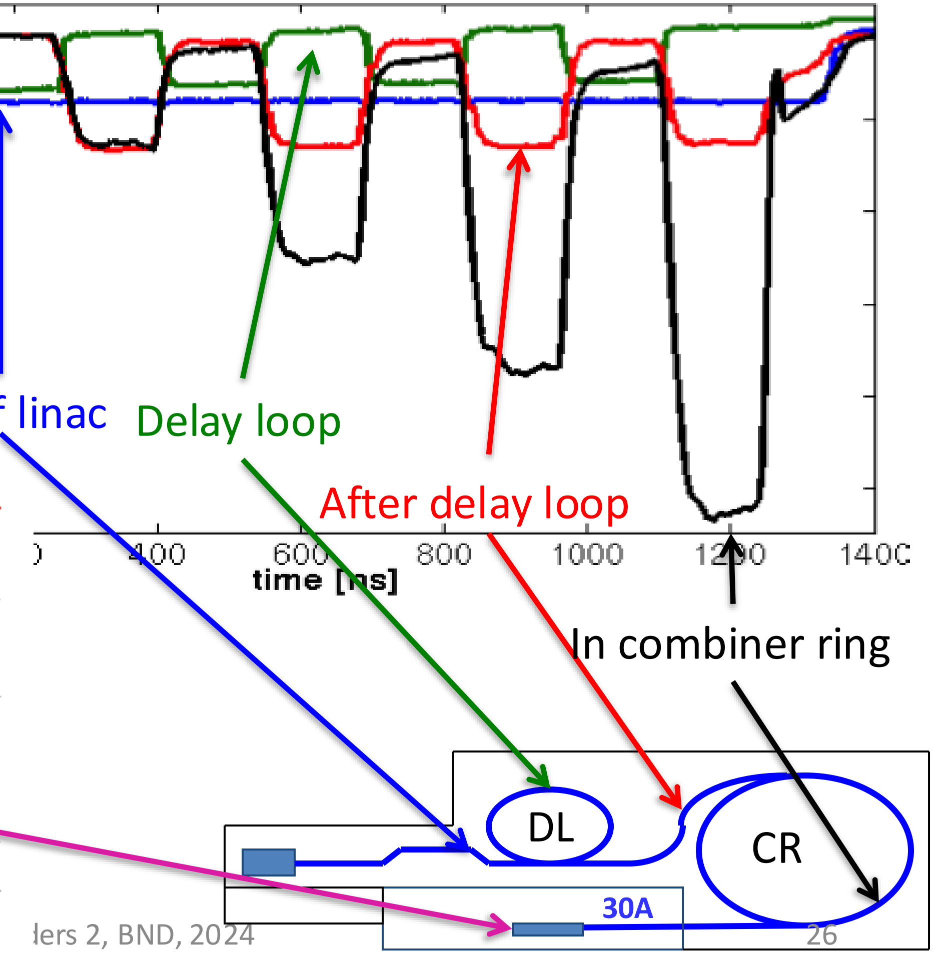
# Drive Beam Combination in CTF3

Note: Efficiencies

RF to drive beam >95%

Drive beam to RF >95%

Total efficiency wall plug to main beam is about 10%

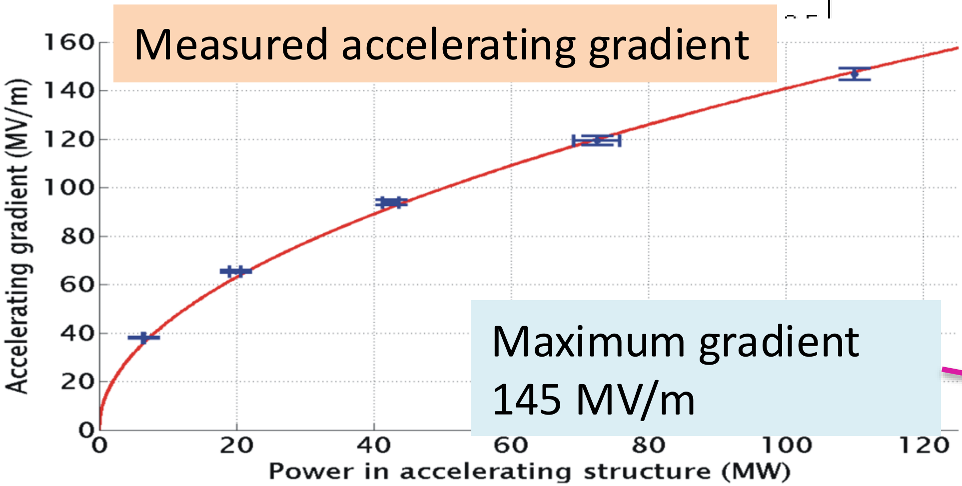


End of linac

Delay loop

After delay loop

In combiner ring



Measured accelerating gradient

Maximum gradient 145 MV/m

# Luminosity and Parameter Drivers

Can re-write normal luminosity formula

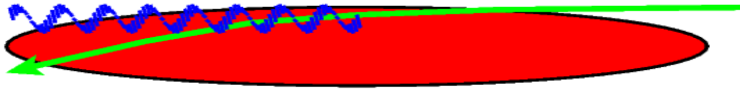
$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

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

Need to ensure that one can achieve each parameter

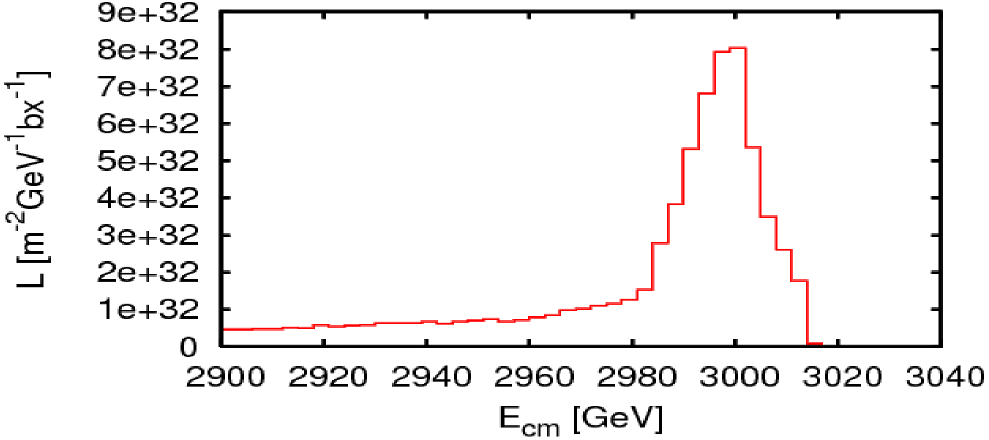
# Beam-beam Effect

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



Dense beams focus each other

$\Rightarrow$ emitt beamstrahlung



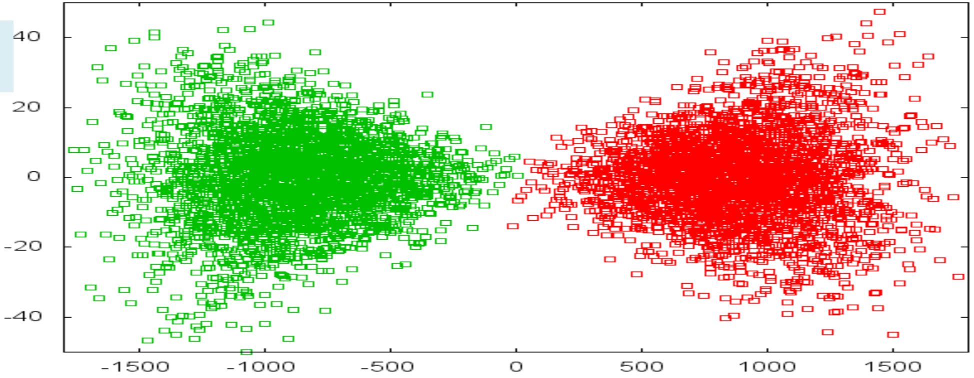
$$\mathcal{L} \propto \frac{N}{\sigma_x \sigma_y}$$

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]

# Luminosity and Beam Quality

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

$$\sigma_y = \sqrt{\beta_y \epsilon_y / \gamma}$$

Damping ring main source of horizontal emittance
But value is OK, as we will see

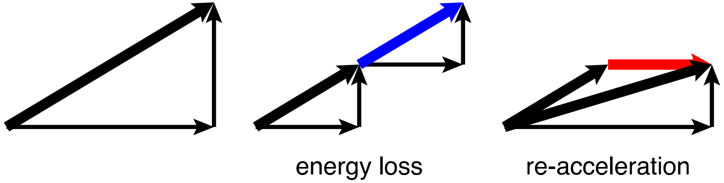
| | $\Delta\epsilon_x$ [nm] | $\Delta\epsilon_y$ [nm] | | |
|---|---|---|---|---|
| | Total contribution | Design limits | Static imperf. | Dynamic imperf. |
| Damping ring exit | 700 | 5 | 0 | 0 |
| End of RTML | 150 | 1 | 2 | 2 |
| End of main linac | 50 | 0 | 5 | 5 |
| Interaction point | 50 | 0 | 5 | 5 |
| sum | 950 | 6 | 12 | 12 |

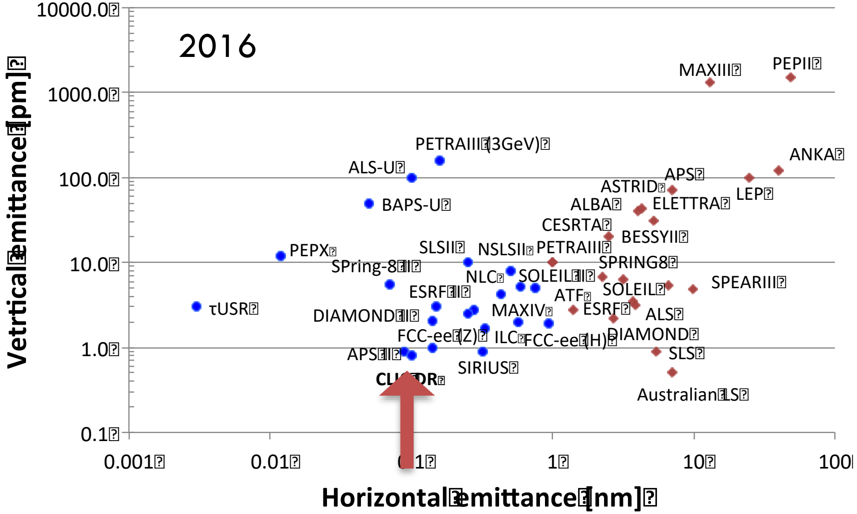
Imperfections are the main source of final vertical emittance

Require 90% likelihood to meet static emittance growth target

# Damping Rings

Cool the beams from the sources





Important progress in collaboration with light source community

Studies of lattice and collective effects show that emittance targets can be reached for 3TeV

Currently optimising for 380 GeV

✓

# Main Linac: Low Emittance Preservation

Beam stability

- incoming beam can jitter (have small offsets) and become unstable
- lattice design, choice of beam parameters

Static imperfections

- errors of reference line, elements to reference line, elements. . .
- excellent pre-alignment, beam-based alignment, beam-based tuning

Dynamic imperfections

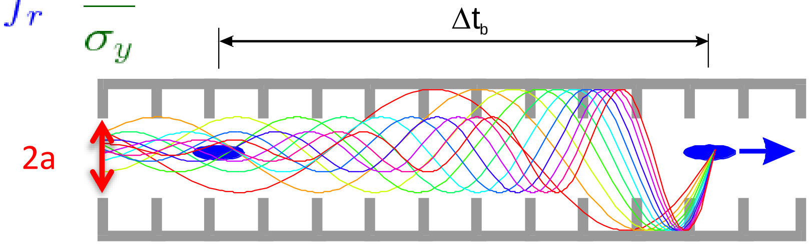
- Ground motion, cooling water induced jitter, RF jitter, electronic noise, magnetic fields, . . .
- lattice design, BNS damping, component stabilisation, feedback, re-tuning, re-alignment

- Combination of dynamic and static imperfections can be severe

- Lattice design needs to balance dynamic and static effects

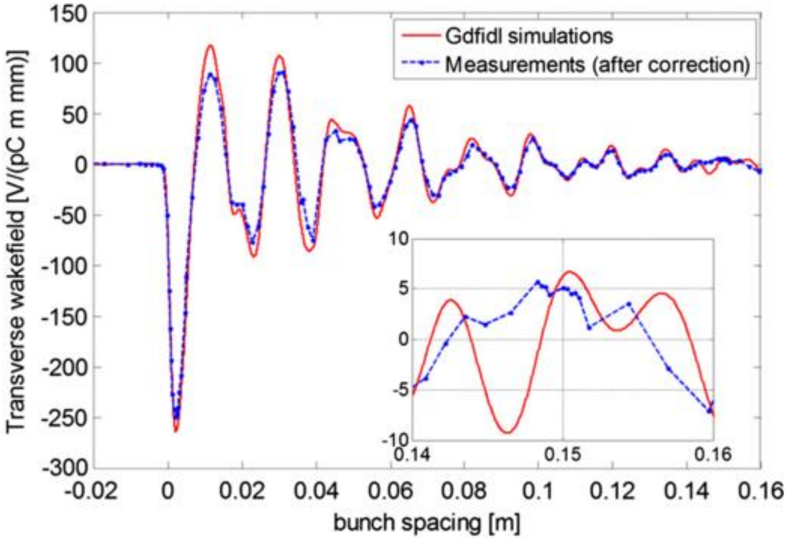
# Wakefields and Beam Current

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



Goal: maximise beam current
⇒ Maximise bunch charge
⇒ Minimise distance between bunches

Limits are given by wakefields:
With an offset particles produce transverse wakefields
⇒ The head kicks the tail, force is defocusing
⇒ Can render beam unstable

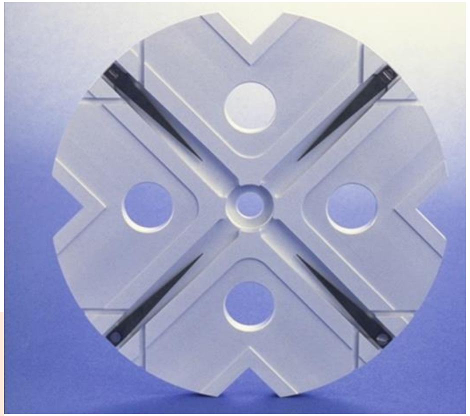


RF team loves small aperture **a**

- Less power
- Easier to reach gradient

Beam team hates small aperture **a**

- More wakefields
- Beam less stable

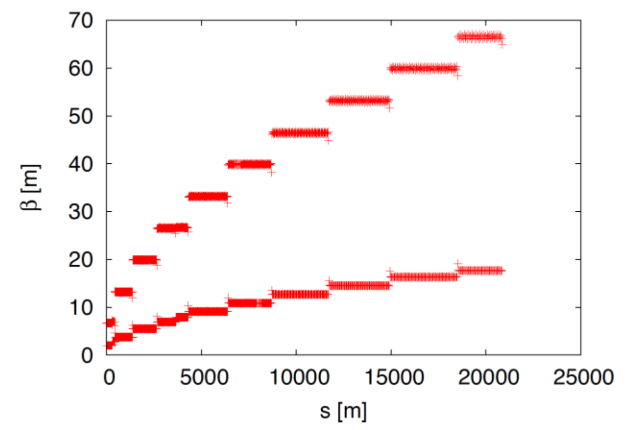


Multi-bunch wakefields minimised by damping and detuning

# Tricks of the Beam Physics

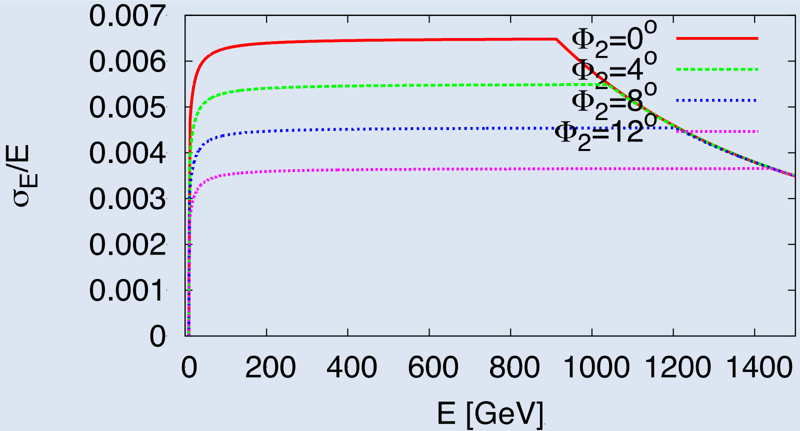
Make the focus strong again

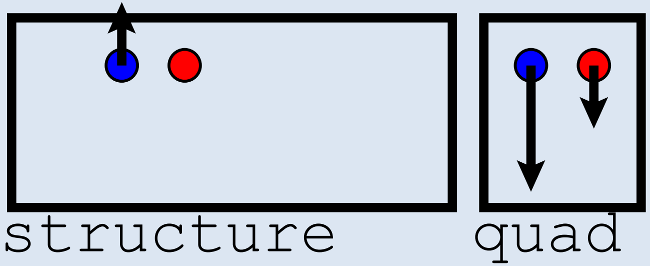
- Use O(10%) of the linac for magnets
- Leads to small beta-function
- Makes the beam stable (strong spring for an oscillator)



For single bunch use BNS damping (Balakin, Novokhatsky and Smirnov)

- Introduce energy chirp that compensates transverse wakefields



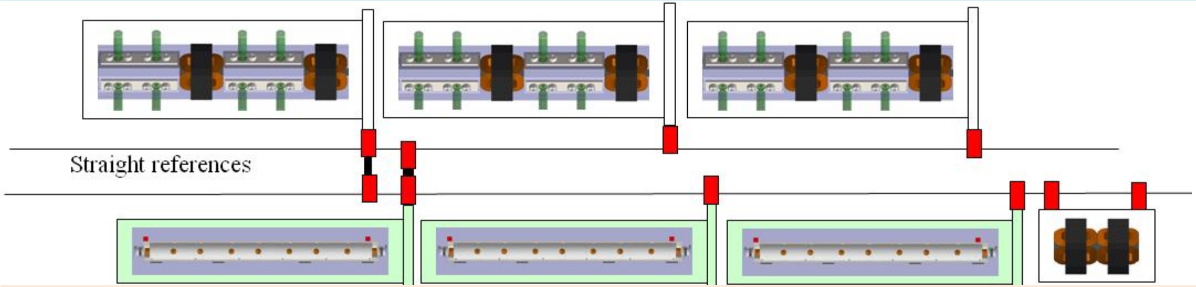


# Static Imperfections: Main Linac Alignment

1) Align components accurately on the supporting girders

2) Establish reference system with overlapping wires, has some error but is not critical

3) Align modules remotely to the wires using their sensors and movers

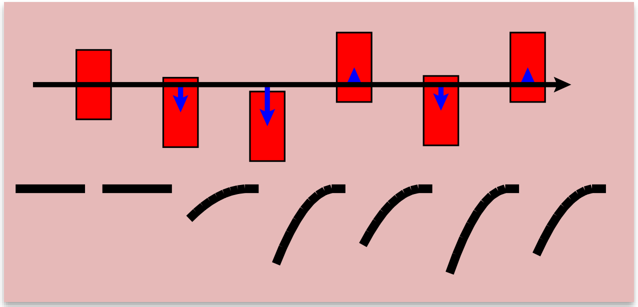


The error for this is most critical misalignment of components is of the order O(10μm)

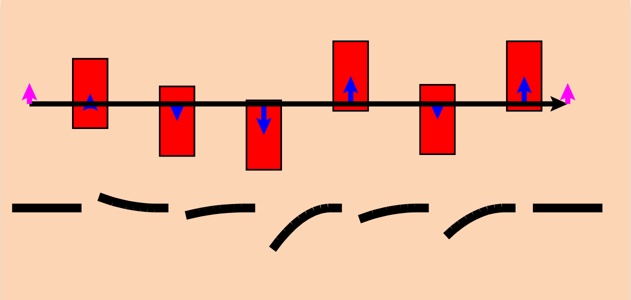
4) Use sophisticated beam-based alignment such as dispersion free steering (DFS, i.e. different energy beams) to align components
In particular to align BPMs

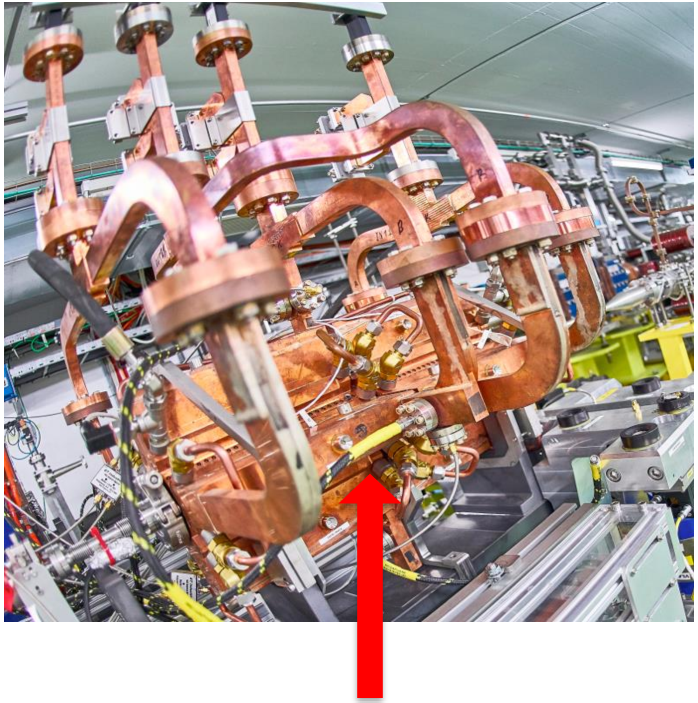
# RF Alignment

Structures scattered on girder
⇒ Wakefield kick



5) Measure beam offset with wakefield monitor
Move girder to remove mean offset
⇒ No net wakefield kick





Wakefield monitor:
Measure wakefield in damping waveguide

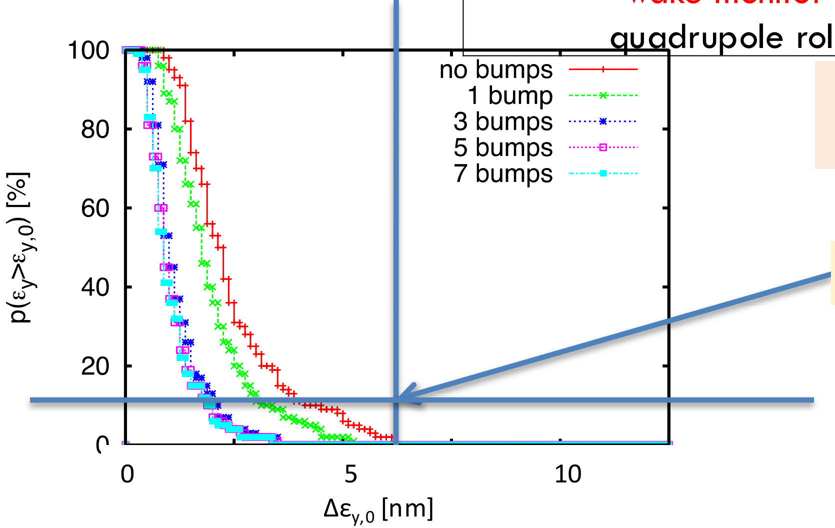
Limit mainly from
- wakefield monitor accuracy (3.5 µm)
- reproducibility of wakefield
- tiny variation of betatron phase along girder

# Main Linac Emittance Growth (3 TeV)

Emittance growth for different imperfections

Using sophisticated beam-based methods

| imperfection | with respect to | symbol | value | emitt. growth |
|---|---|---|---|---|
| BPM offset | wire reference | $\sigma_{BPM}$ | 14 $\mu$m | 0.367 nm |
| BPM resolution | | $\sigma_{res}$ | 0.1 $\mu$m | 0.04 nm |
| accelerating structure offset | girder axis | $\sigma_4$ | 10 $\mu$m | 0.03 nm |
| accelerating structure tilt | girder axis | $\sigma_t$ | 200 $\mu$radian | 0.38 nm |
| articulation point offset | wire reference | $\sigma_5$ | 12 $\mu$m | 0.1 nm |
| girder end point | articulation point | $\sigma_6$ | 5 $\mu$m | 0.02 nm |
| wake monitor | structure centre | $\sigma_7$ | 3.5 $\mu$m | 0.54 nm |
| quadrupole roll | longitudinal axis | $\sigma_r$ | 100 $\mu$radian | $\approx$ 0.12 nm |



Note: The tight tolerances are the price for the strong focusing,
Which allowed high beam current

Goal: less than 10% above $\Delta\varepsilon_y = 5$ nm

Further improvement using tuning bumps

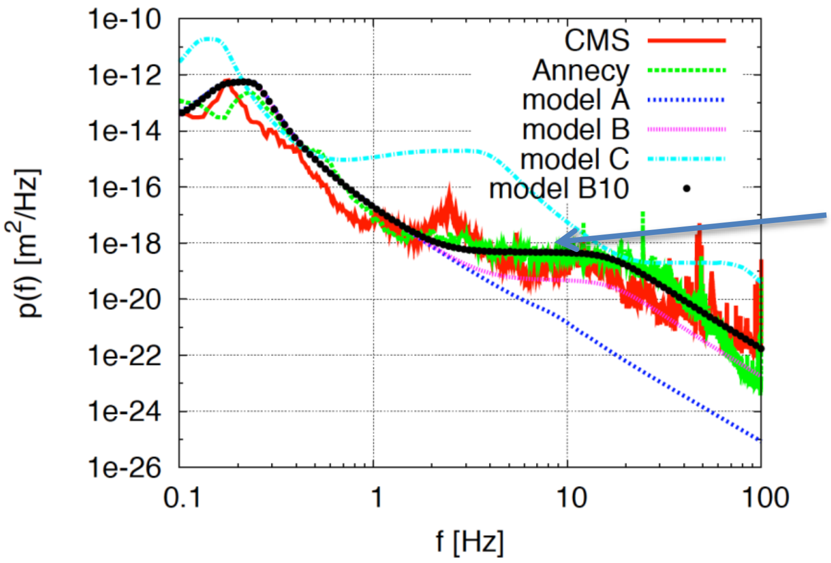
# Example: Ground Motion

In CLIC can reduce dynamic effects at frequencies lower than a few Hz

$\Rightarrow$ Andrei Seryi
Friday 2.3.

In ILC can use a bunch-bunch feedback system

- But be careful, bunch-to-bunch noise will be amplified
- e.g. the damping ring extraction kicker kicks each bunch separately, so it will induce noise

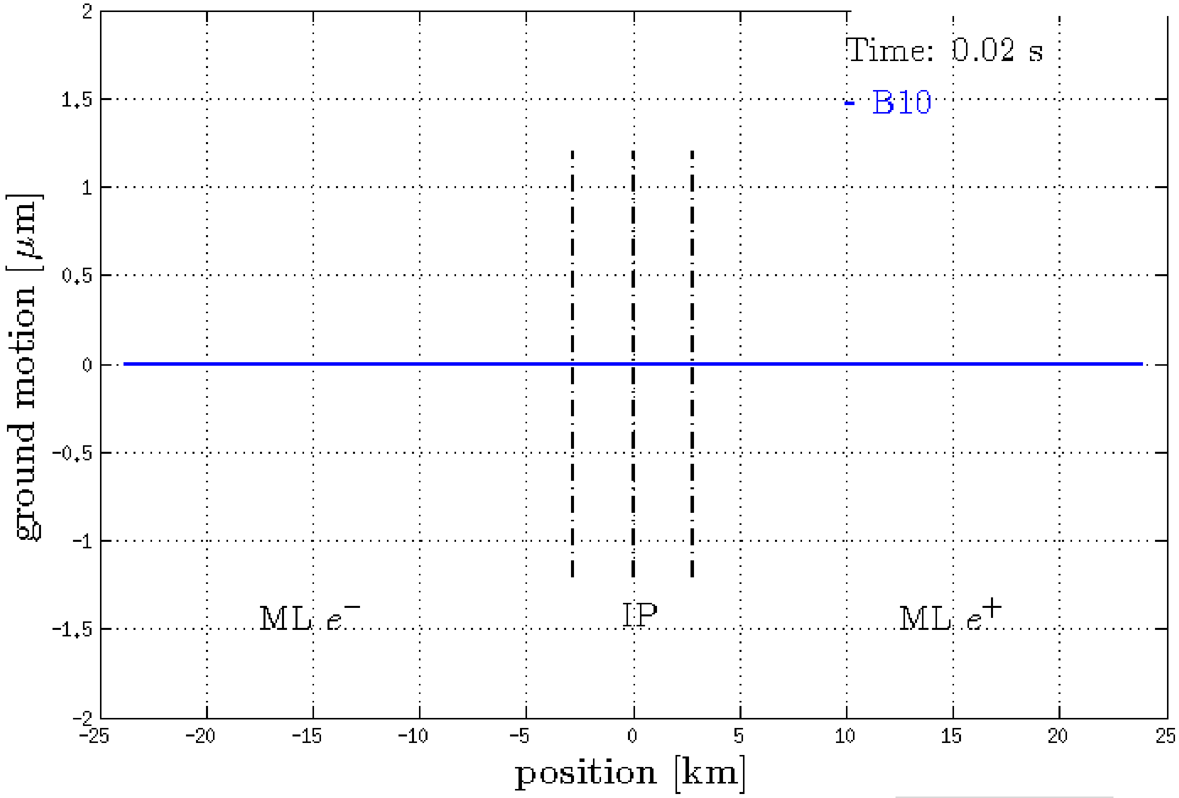


We spot a problem:

Frequencies cannot be mitigated by beam feedback

# Example Issue: Ground Motion

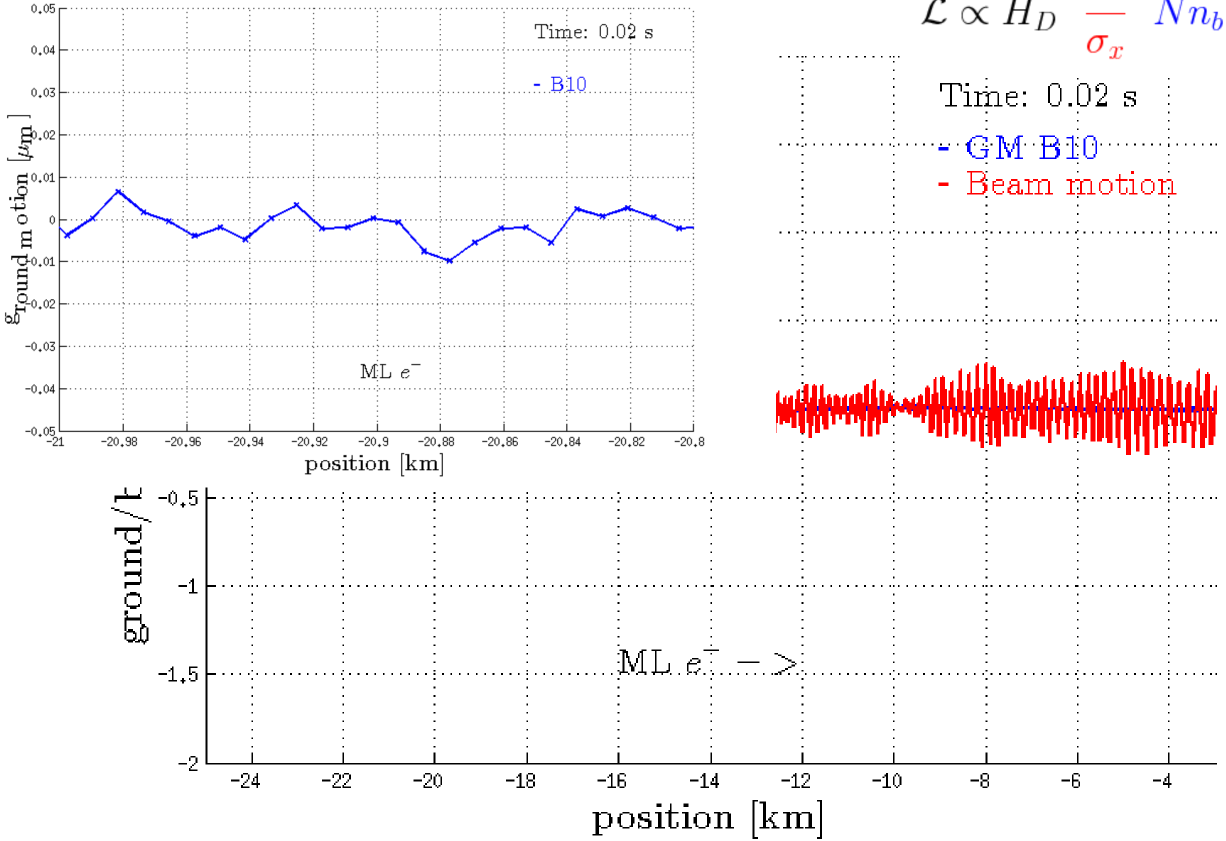
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

# Resulting Beam Jitter

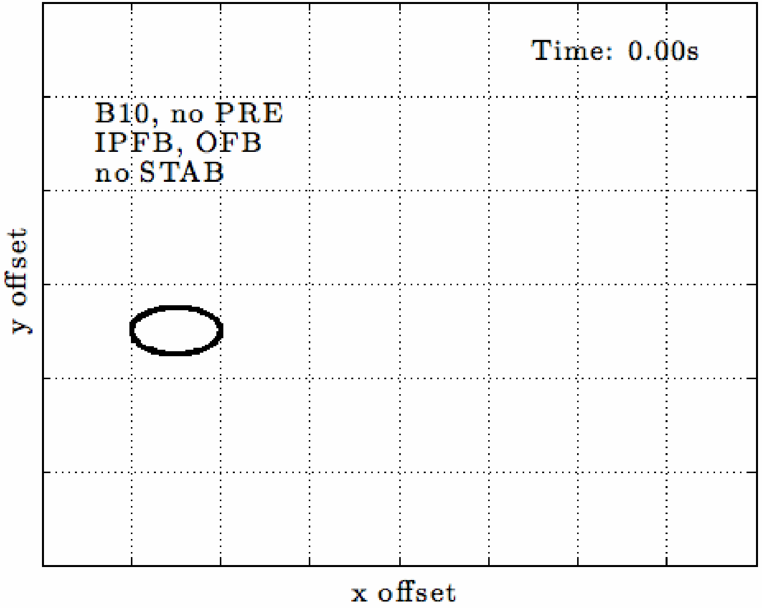
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y}$$



J. Pfingstner

# Beams at Collision

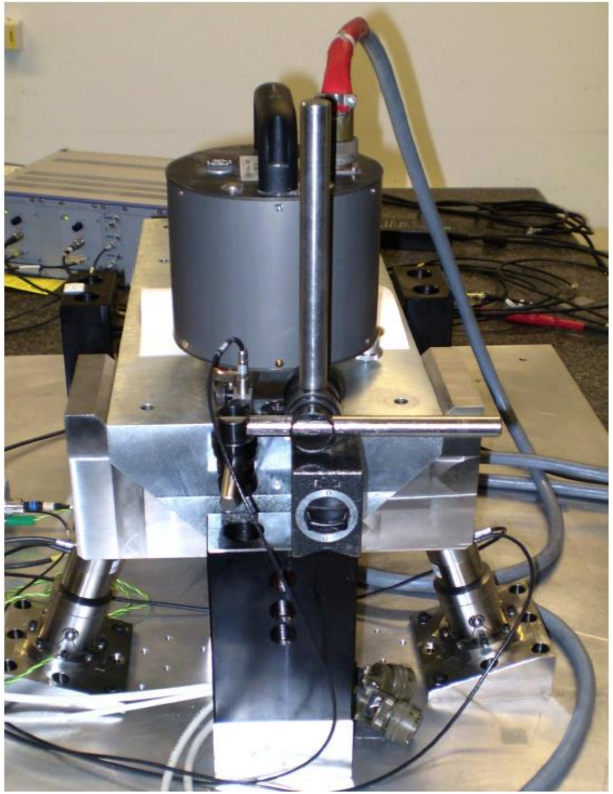
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



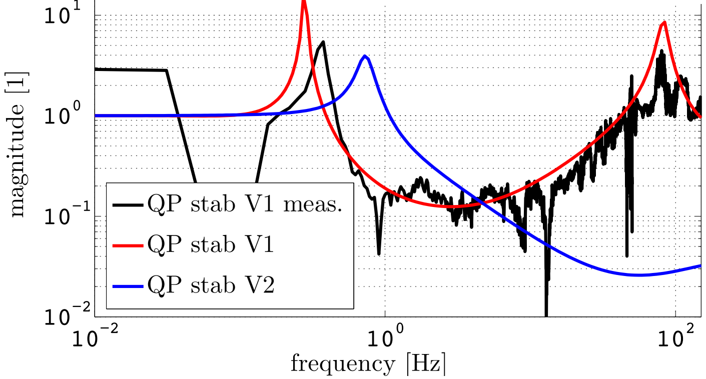
J. Pfingstner

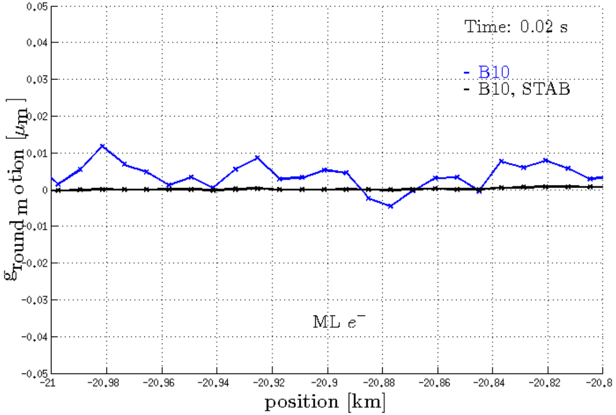
# Stabilisation System

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



K. Artoos et al.

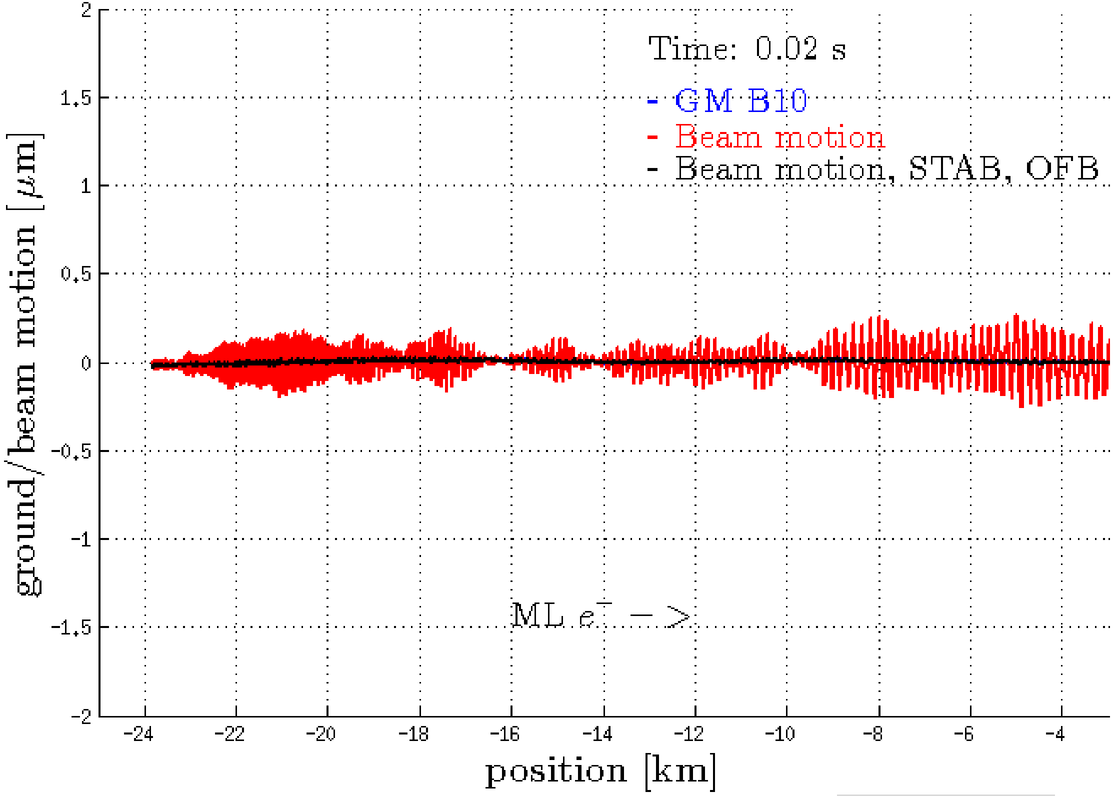




J. Snuverink, et al.

# Impact of Stabilisation on Beam

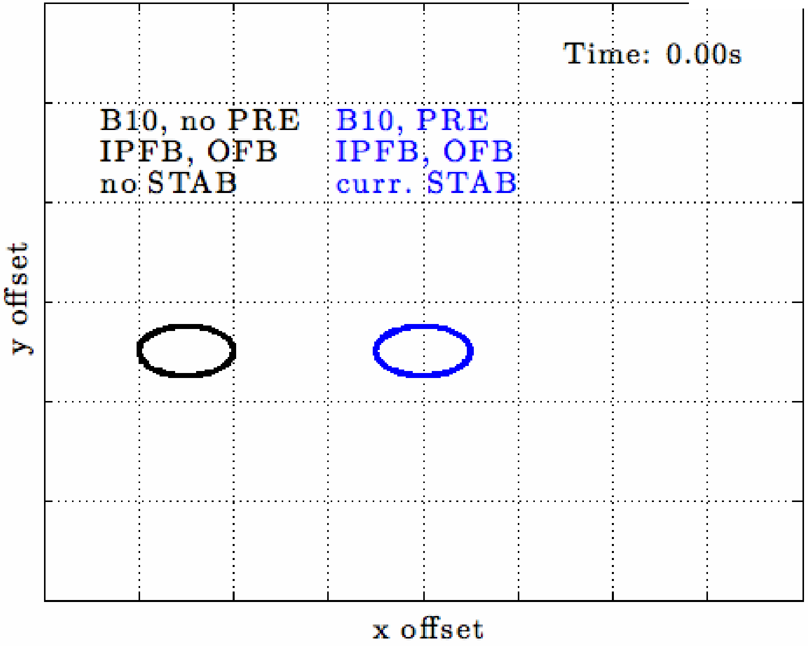
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

# Beam at Collision

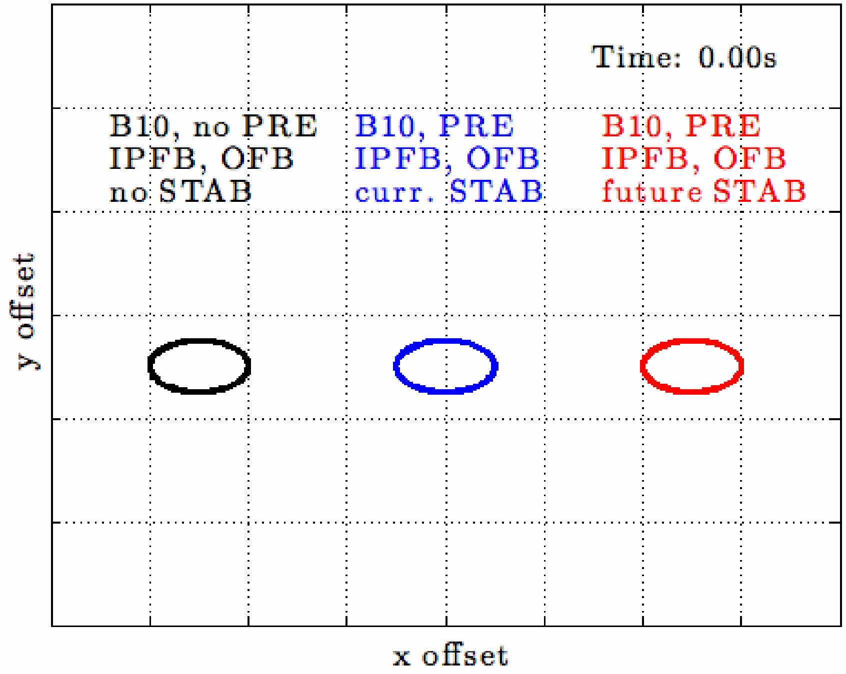
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$



J. Pfingstner

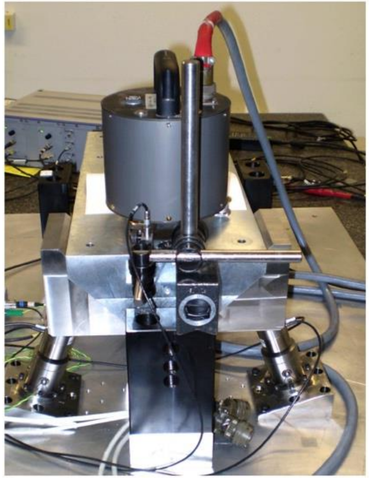
# Beam at Collision

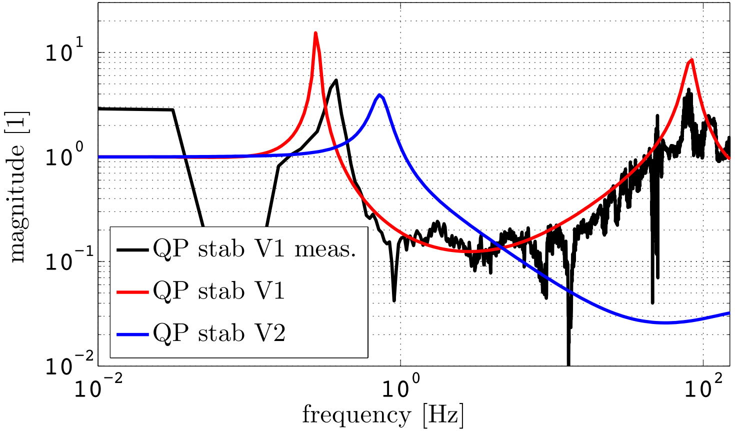
$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \boxed{\frac{1}{\sigma_y}}$$

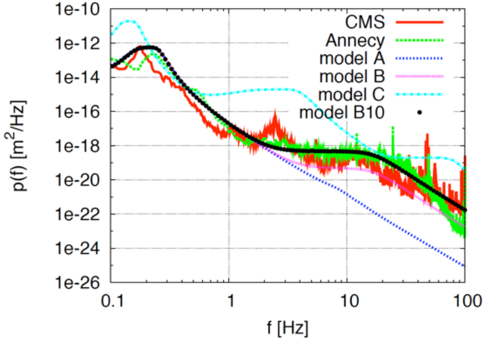


J. Pfingstner

# Active Stabilisation Results







Code

Machine model
Beam-based feedback

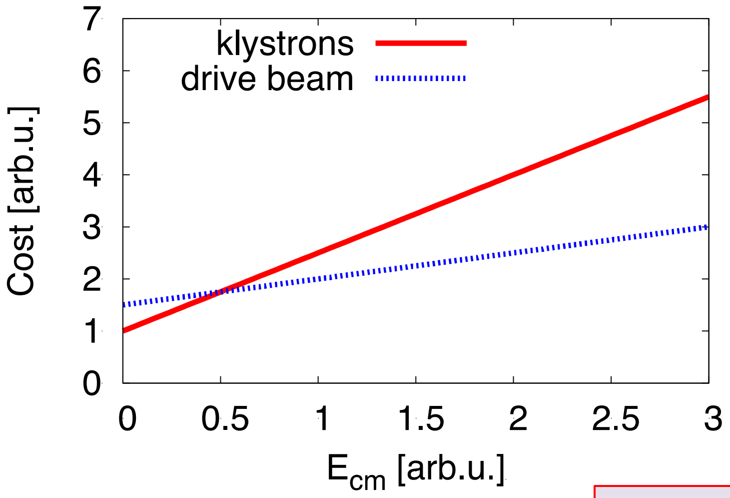
Luminosity achieved/lost [%]

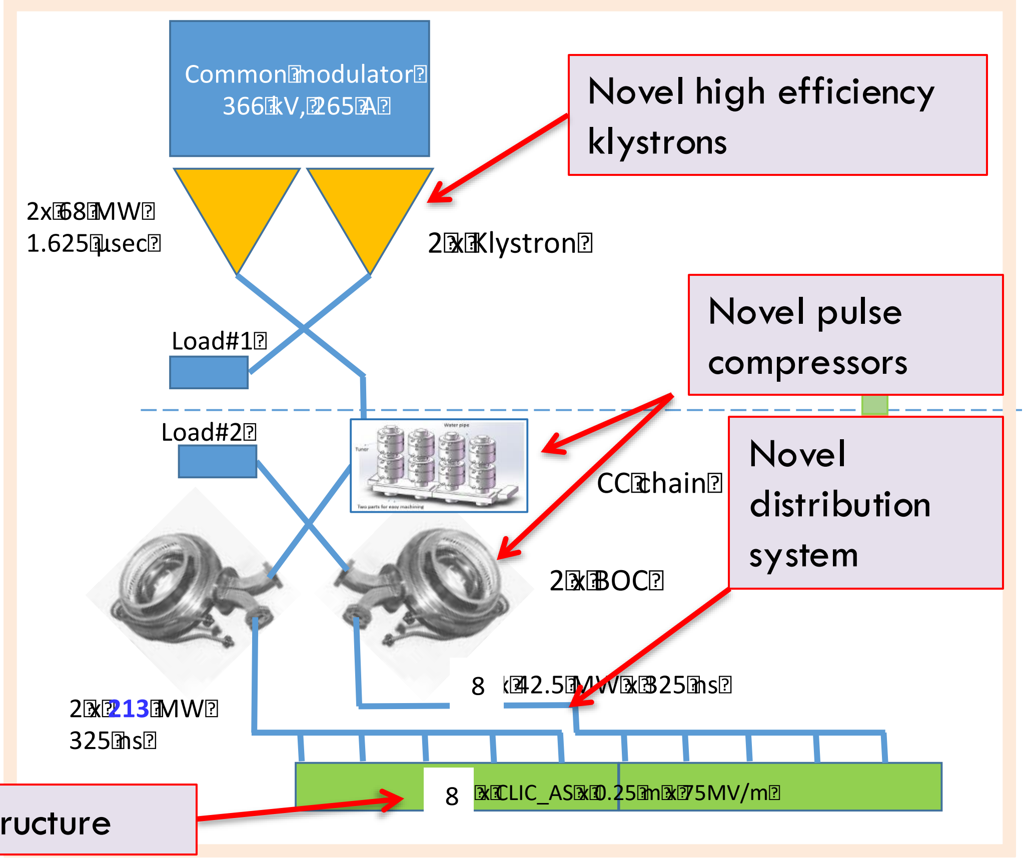
| | B10 |
|---|---|
| No stab. | 53%/68% |
| Current stab. | 108%/13% |
| Future stab. | 118%/3% |

Close to/better than target

# Klystron-based Alternative

Develop klystron-based alternative
Expect comparable cost for first energy stage
But increases faster for high energies





Novel high efficiency klystrons

Novel pulse compressors

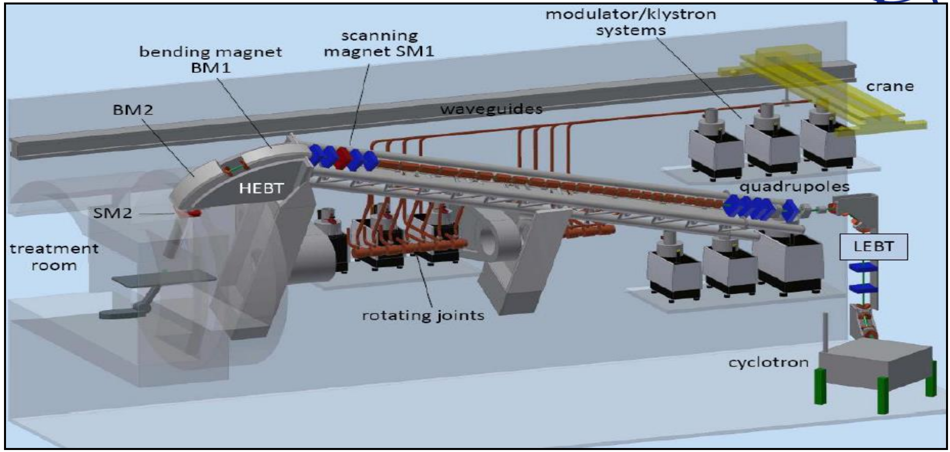
Novel distribution system

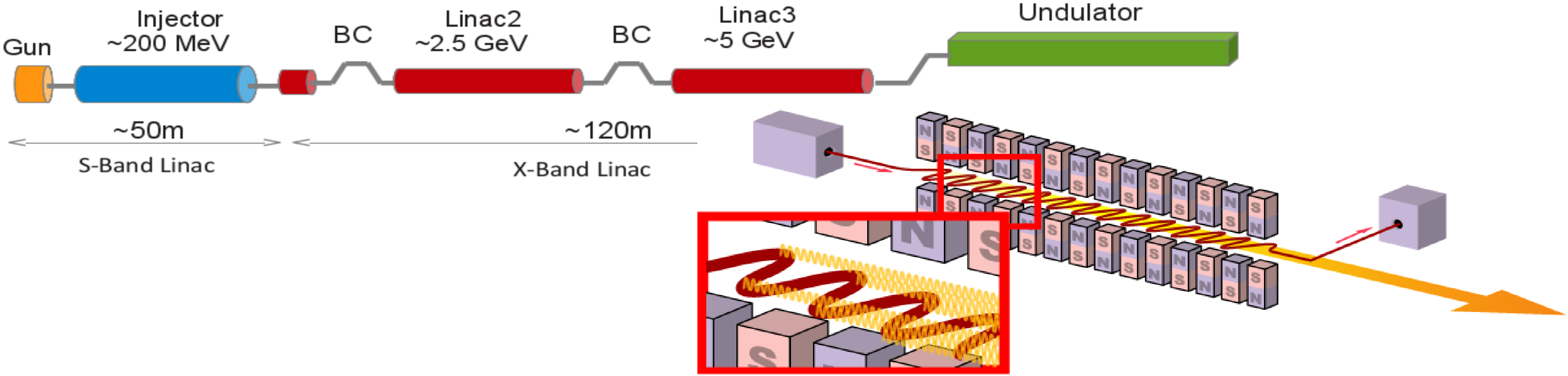
Optimised structure

# 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





# FCC-ee

# FCC-ee Design Considerations

Consistent with later implementation of hadron collider

- Long tunnel

Option for two or four high-luminosity experiments

- Use four-fold symmetry

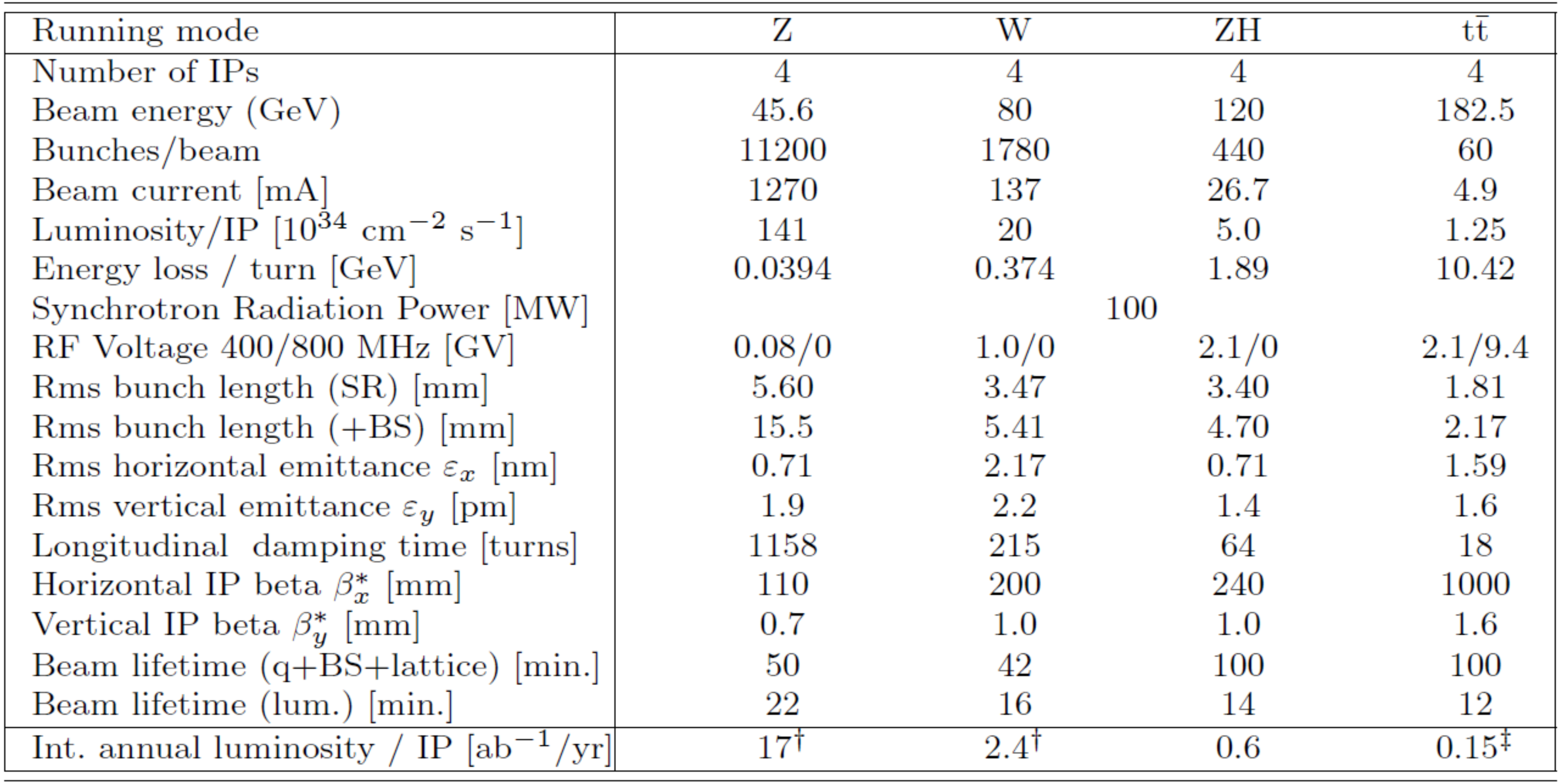
Synchrotron radiation is an important power consumer

- Limit radiation to 100 MW (sum of both beams)

Basic feasibility

- Implementation close to CERN (civil engineering, geology, …)
- Cost, power consumption, $CO_2$ footprint, …
- Technical risk, …

# Key Parameters



| Running mode | Z | W | ZH | $t\bar{t}$ |
|---|---|---|---|---|
| Number of IPs | 4 | 4 | 4 | 4 |
| Beam energy (GeV) | 45.6 | 80 | 120 | 182.5 |
| Bunches/beam | 11200 | 1780 | 440 | 60 |
| Beam current [mA] | 1270 | 137 | 26.7 | 4.9 |
| Luminosity/IP [$10^{34}$ cm$^{-2}$ s$^{-1}$] | 141 | 20 | 5.0 | 1.25 |
| Energy loss / turn [GeV] | 0.0394 | 0.374 | 1.89 | 10.42 |
| Synchrotron Radiation Power [MW] | 100 | | | |
| RF Voltage 400/800 MHz [GV] | 0.08/0 | 1.0/0 | 2.1/0 | 2.1/9.4 |
| Rms bunch length (SR) [mm] | 5.60 | 3.47 | 3.40 | 1.81 |
| Rms bunch length (+BS) [mm] | 15.5 | 5.41 | 4.70 | 2.17 |
| Rms horizontal emittance $\varepsilon_x$ [nm] | 0.71 | 2.17 | 0.71 | 1.59 |
| Rms vertical emittance $\varepsilon_y$ [pm] | 1.9 | 2.2 | 1.4 | 1.6 |
| Longitudinal damping time [turns] | 1158 | 215 | 64 | 18 |
| Horizontal IP beta $\beta_x^*$ [mm] | 110 | 200 | 240 | 1000 |
| Vertical IP beta $\beta_y^*$ [mm] | 0.7 | 1.0 | 1.0 | 1.6 |
| Beam lifetime (q+BS+lattice) [min.] | 50 | 42 | 100 | 100 |
| Beam lifetime (lum.) [min.] | 22 | 16 | 14 | 12 |
| Int. annual luminosity / IP [ab$^{-1}$/yr] | 17$^\dagger$ | 2.4$^\dagger$ | 0.6 | 0.15$^\ddagger$ |

# Synchrotron radiation in FCC-ee

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

Beam particles emit important synchrotron radiation

- At 182.5 GeV (maximum energy), loss of 9 GeV or ~5% per turn

Design choice: limit radiation power to 50 MW per beam, 100 MW total

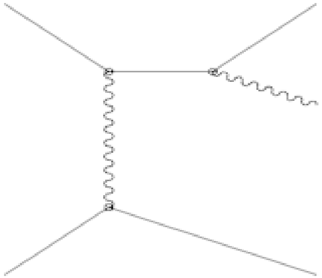
- Superconducting cavities can transfer almost all power to the beam
- But RF power sources have some inefficiency
  - Need about 160 MW from the grid
- Also cryogenics system is required to maintain cavity superconducting
- Not critical for magnet and beampipe cooling – normal-conducting magnets

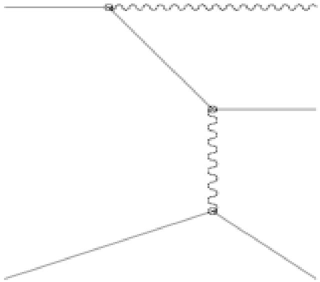
| Parameter | Z | WW | ZH | tt |
|---|---|---|---|---|
| $E_{cm}$ [GeV] | 91.2 | 160 | 240 | 365 |
| $\triangle$E [GeV] | 0.0394 | 0.374 | 1.89 | 10.42 |
| I [mA] | 1270 | 137 | 27 | 4.9 |
| L [$10^{34}$ $cm^{-2}s^{-1}$] | 141 | 20 | 5 | 1.25 |

# Beam Lifetime

Beam lifetime is short (18-200 minutes)

- Bremsstrahlung
- Beamstrahlung
- …





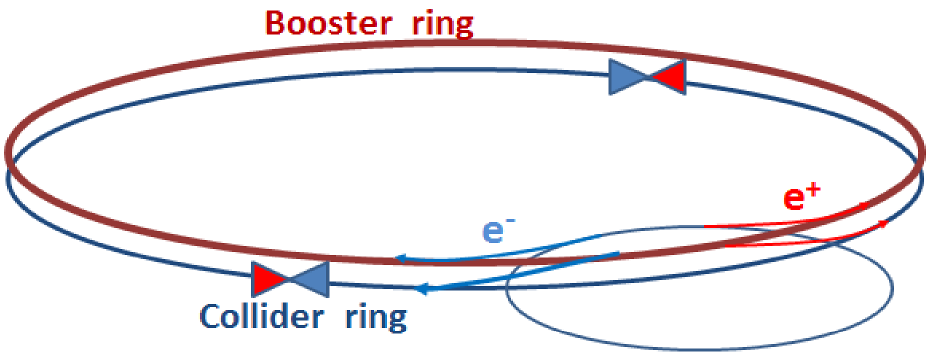
| Parameter | Z | WW | ZH | tt |
|---|---|---|---|---|
| $E_{cm}$ [GeV] | 91.2 | 160 | 240 | 365 |
| L [$10^{34}$ $cm^{-2}s^{-1}$] | 141 | 20 | 5 | 1.25 |
| Beam lifetime [60s] | 50 | 42 | 100 | 100 |
| L lifetime [60s] | 22 | 16 | 14 | 12 |

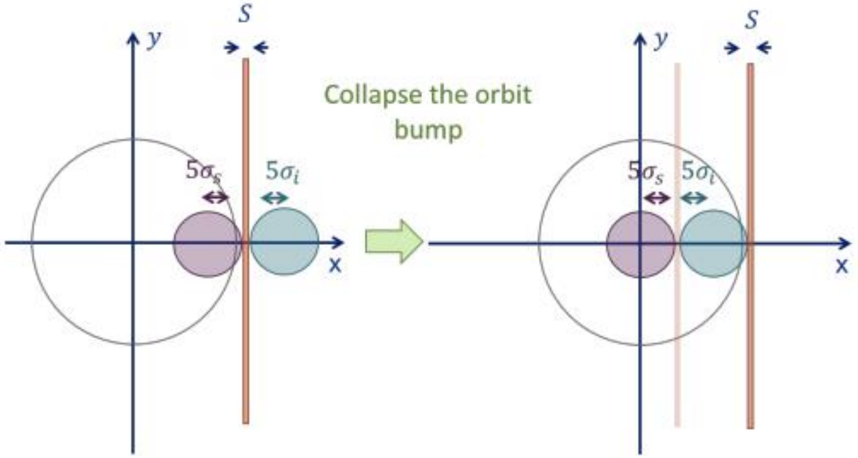
Short beam lifetime requires top-up injection

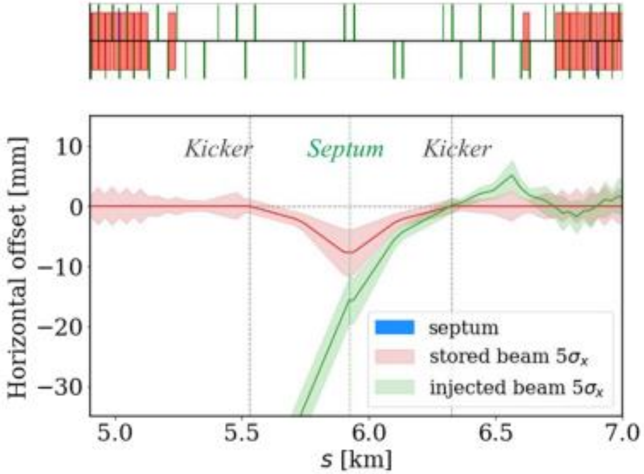
# Top-up Injection

Inject small bunches next to circulating bunches

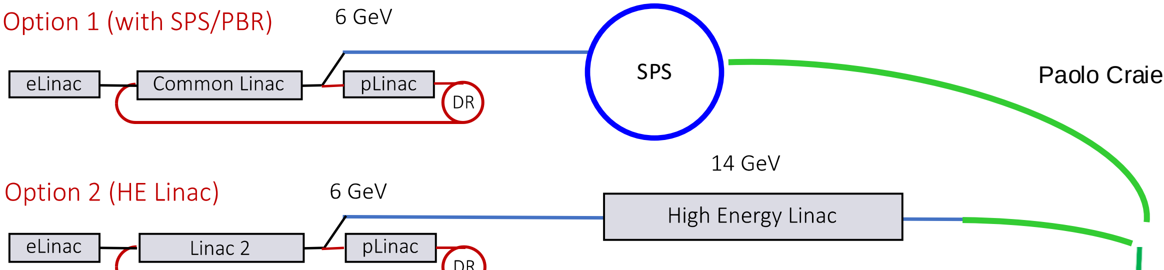
They will merge due to synchrotron damping







# Layout Considerations



Paolo Craievich

**Double ring** e+e- collider

**Two or four experiments**

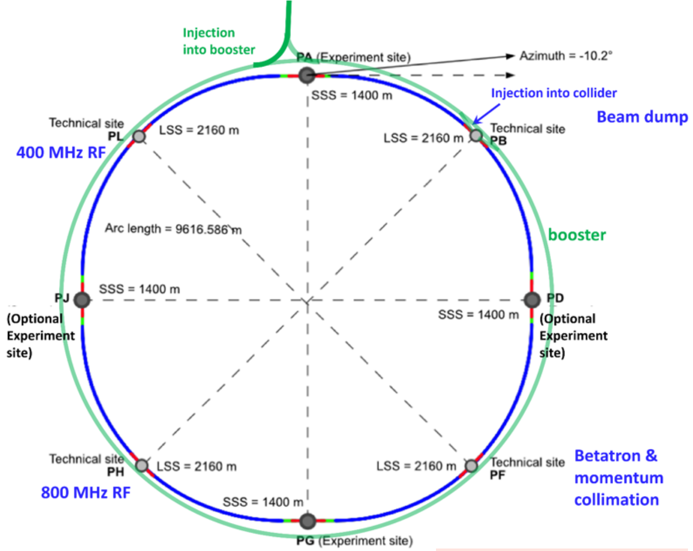
- **Asymmetric Interaction Region layout and optics** to limit synchrotron radiation towards the detector
- Horizontal crossing angle of 30 mrad and crab waist collision scheme

**Perfect 4-fold superperiodicity allowing 2 or 4 IPs;**

**Synchrotron radiation power 50 MW/beam** at all beam energies

**Top-up injection** scheme for high luminosity

Implies **booster synchrotron in collider tunnel**



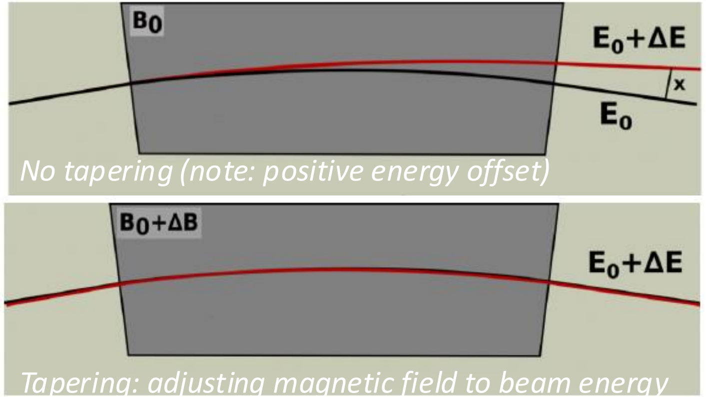
K. Oide, J. Gutleber

M. Hofer ICHEP 2022

# Lattice Tapering

Lattice needs to take into count particle energy loss along arc

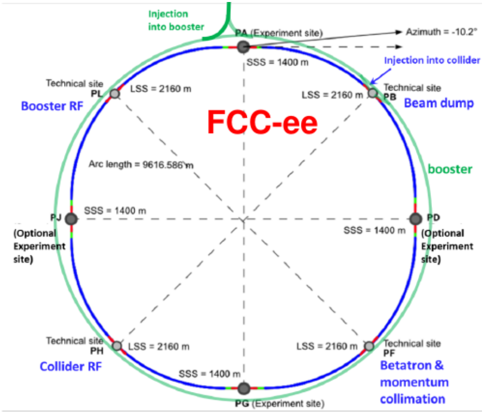
- Magnet strength depends on position in the arc
- “Tapering”
- Requires the two beams to be in different beampipes

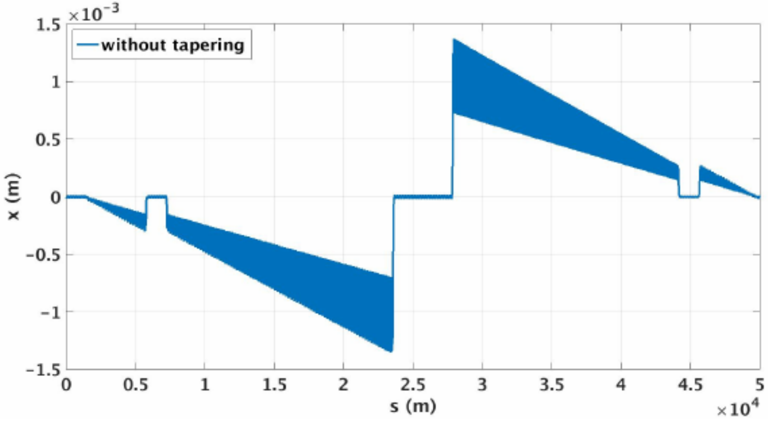


*No tapering (note: positive energy offset)*

*Tapering: adjusting magnetic field to beam energy*

*B. Härer, A. Doblhammer, and B.J. Holzer, IPAC16, THPOR003*



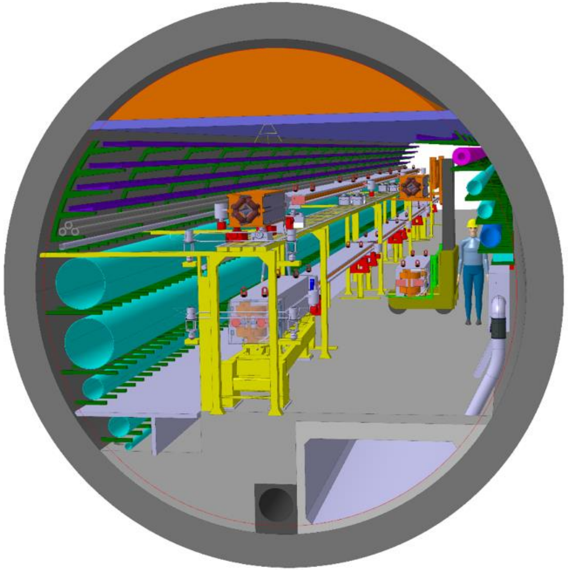


# Arc Half-cell Mock-up

Project aim

- Arc half-cell: most recurrent assembly of mechanical hardware in the accelerator (~1500 similar FODO cells in the FCC-ee)
- Mock-up → Functional prototype(s) → Pre-series → Series
- Building a mock-up allows optimizing and testing fabrication, integration, installation, assembly, transport, maintenance
- Working with demonstrators of the different equipment, and/or structures with equivalent volumes, weights, stiffness

F. Carra et al



*Arc perspective view, F. Valchkova-Georgieva*

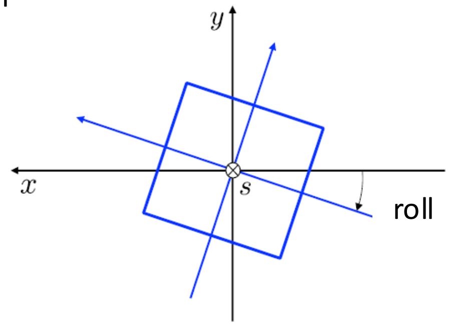
# Optics Correction Strategy

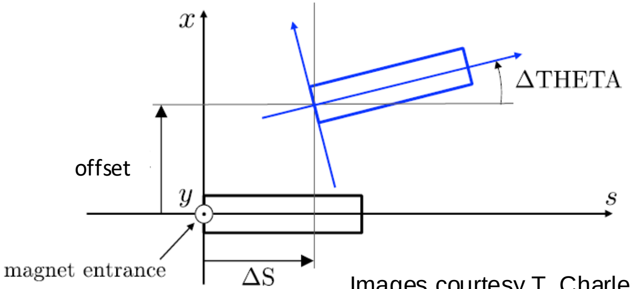
Motivation

- ➢ Evaluate specifications of the main **magnets misalignment** of the High Energy Booster arcs cells **and of magnets field error**
- ➢ Definition of the **orbit correction strategy and of correctors specifications** for the booster

Orbit correction using beam position monitors reading

| errors | Case | Plane | 3 x Analytical RMS | 3 x Mean RMS/seeds |
|---|---|---|---|---|
| MQ offset = 150 µm<br>MB field err = $10^{-3}$<br>MB roll = 300 µrad<br>BPM offset = 150 µm<br>MS offset = 150 µm<br>BPM resolution = 50 µm | Residual orbit [µm] | x | 188 | 174 |
| | | y | 192 | 188 |
| | Correctors stengths [mTm] | x | 16 | 17 |
| | | y | 16 | 17 |





Images courtesy T. Charles

Improvements and related work to do:

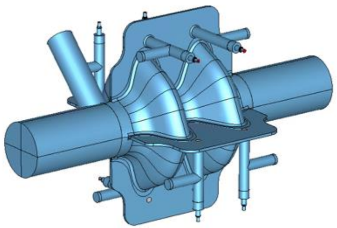
- ➢ Other methods than SVD - AI ?
- ➢ Demonstrate full emittance **tuning**
- ➢ Study the impact of booster support vibrations on emittance (dynamic imperfections)
- ➢ Study the impact of energy ramp during the booster cycle

# RF Cavities

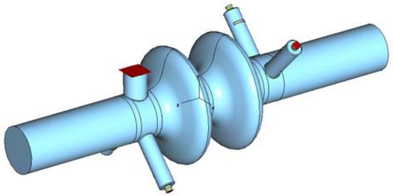
We need to replenish energy loss by synchrotron radiation:

- Superconductive RF is most efficient way

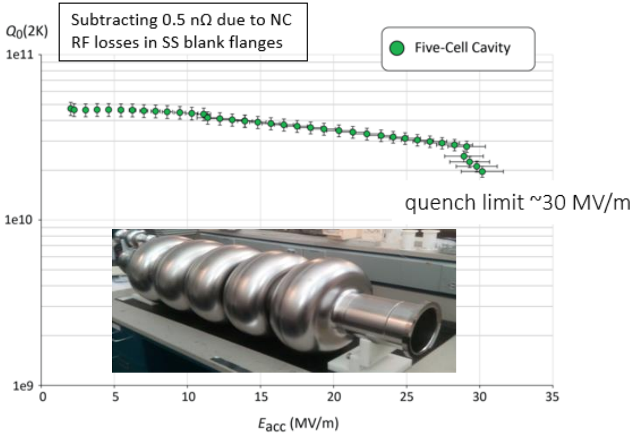
- **SRF technology building on LHC studies and collaborative R&D** (F. Peauger et al.)
  - 5-cell 800 MHz cavity without damping built and tested at 2K by Jefferson lab with excellent results
  - 400 MHz cavities based on LHC studies of Cu-coated Nb cavities at 4.5K
  - Alternative slotted waveguide elliptical cavity with f=600 MHz



SWELL 2-cell 600 MHz cavity for Z, W, H

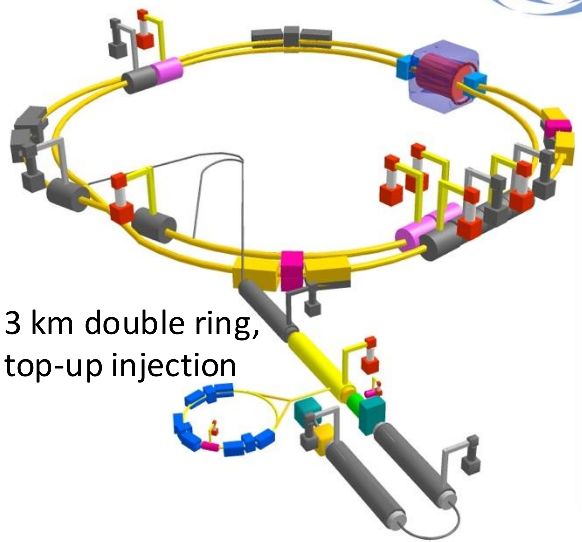


Model for 2-cell 400 MHz for WW and ZH



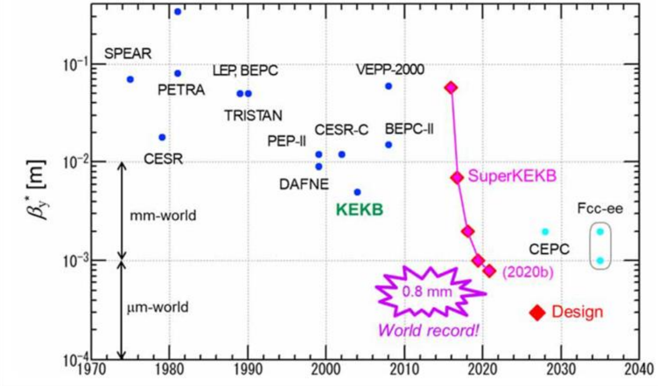
- **RF placement optimized for infrastructure requirements** (F. Valchkova-Georgieva et al)

# Super KEKb

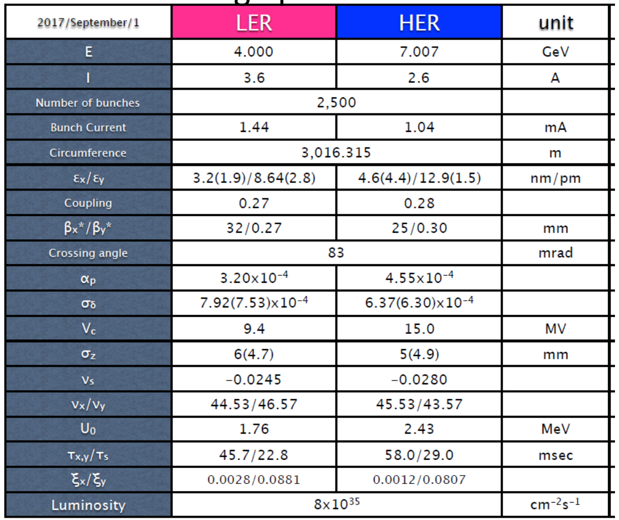


3 km double ring,
top-up injection

**world's highest luminosity**
**$4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ & lowest $\beta^*$**



Design parameters



| 2017/September/1 | LER | HER | unit |
|---|---|---|---|
| E | 4.000 | 7.007 | GeV |
| I | 3.6 | 2.6 | A |
| Number of bunches | 2,500 | | |
| Bunch Current | 1.44 | 1.04 | mA |
| Circumference | 3,016.315 | | m |
| $\varepsilon_x/\varepsilon_y$ | 3.2(1.9)/8.64(2.8) | 4.6(4.4)/12.9(1.5) | nm/pm |
| Coupling | 0.27 | 0.28 | |
| $\beta_x^*/\beta_y^*$ | 32/0.27 | 25/0.30 | mm |
| Crossing angle | 83 | | mrad |
| $\alpha_p$ | $3.20 \times 10^{-4}$ | $4.55 \times 10^{-4}$ | |
| $\sigma_\delta$ | $7.92(7.53) \times 10^{-4}$ | $6.37(6.30) \times 10^{-4}$ | |
| $V_c$ | 9.4 | 15.0 | MV |
| $\sigma_z$ | 6(4.7) | 5(4.9) | mm |
| $\nu_s$ | −0.0245 | −0.0280 | |
| $\nu_x/\nu_y$ | 44.53/46.57 | 45.53/43.57 | |
| $U_0$ | 1.76 | 2.43 | MeV |
| $\tau_{x,y}/\tau_s$ | 45.7/22.8 | 58.0/29.0 | msec |
| $\xi_x/\xi_y$ | 0.0028/0.0881 | 0.0012/0.0807 | |
| Luminosity | $8 \times 10^{35}$ | | cm$^{-2}$s$^{-1}$ |

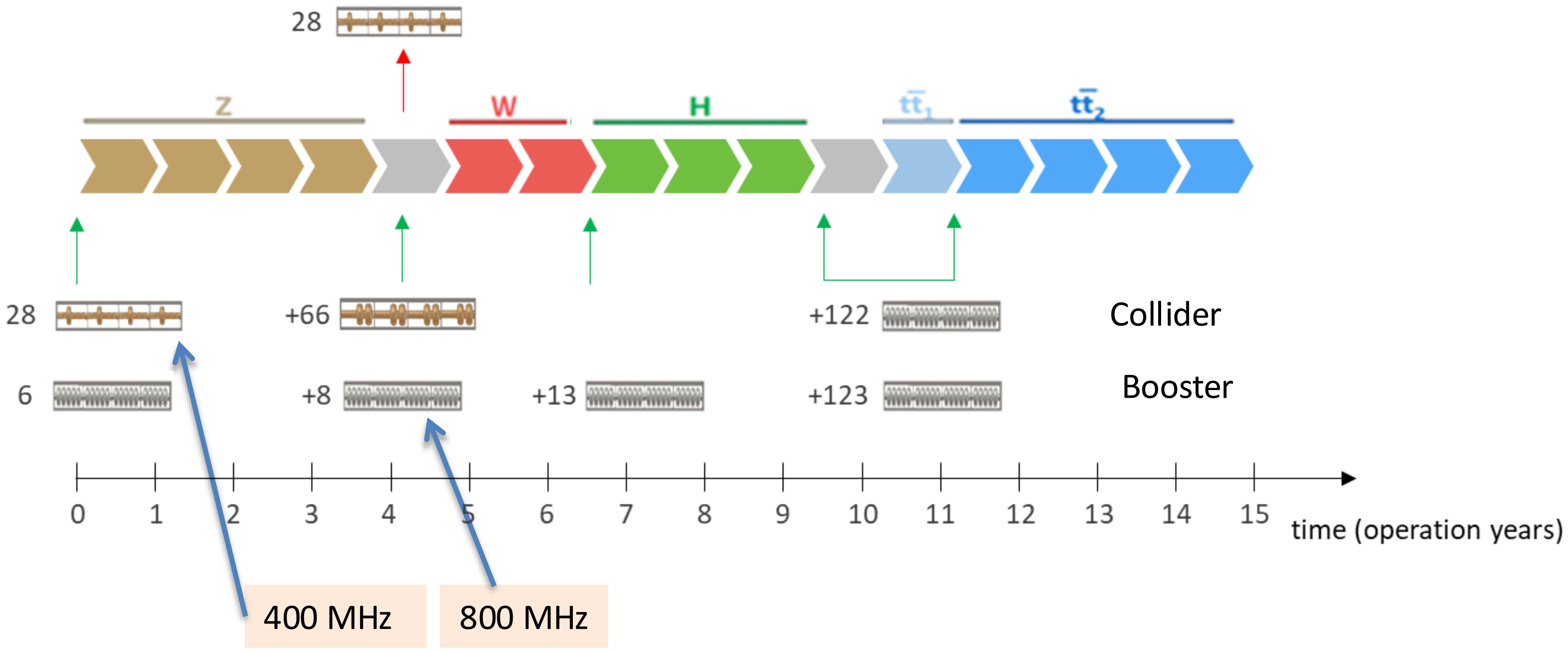
- $b_y^*$ = 0.8 mm demonstrated
- Collision with large crossing angle compensated by sextupoles schemes (as in DAFNE and as foreseen in FCC-ee)
- Design luminosity not reached so far due to intensity limitation (fast beam losses) in Super KEKB

# FCC-ee Operational Schedule

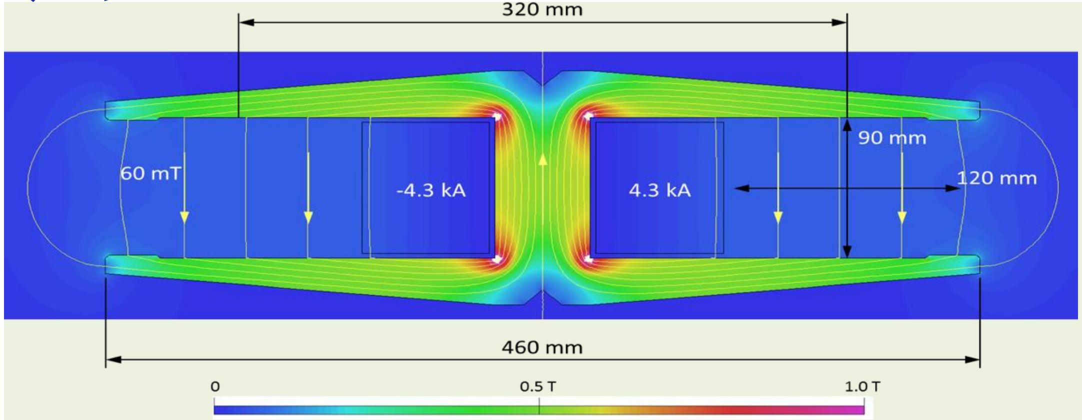
5 energy stages

Each year 8 months of operation / 4 months winter shutdown

- hardware upgrades during shutdown



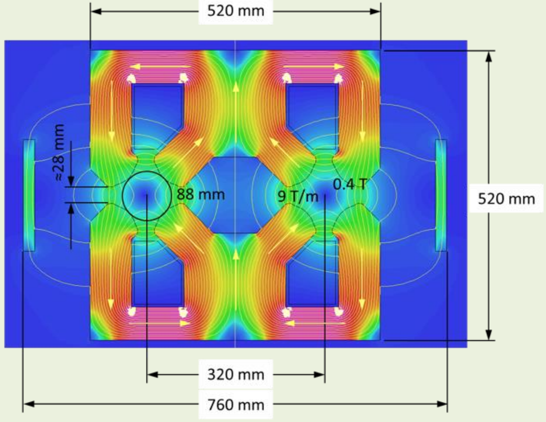
# FCC-ee Technologies



**Cost effective magnets**

Two-in-one design of dipoles and quadrupoles

Optimised windings to reduce cost and power consumption



**Optimised RF cavities**

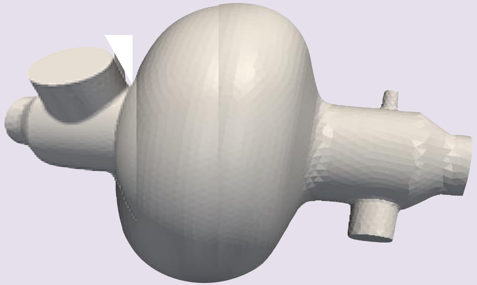
Single cells at low energy:

- 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

# Vacuum and Beamscreen

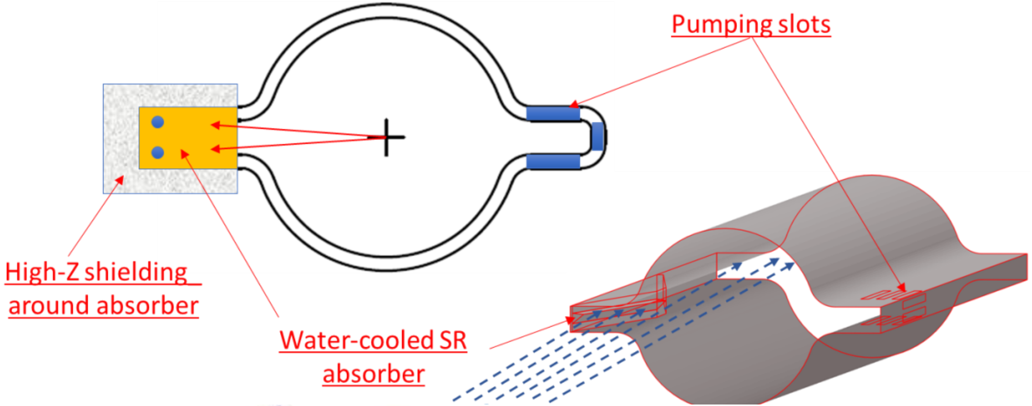
Absorbers intercept radiated photons (currently: ~6 m spacing)

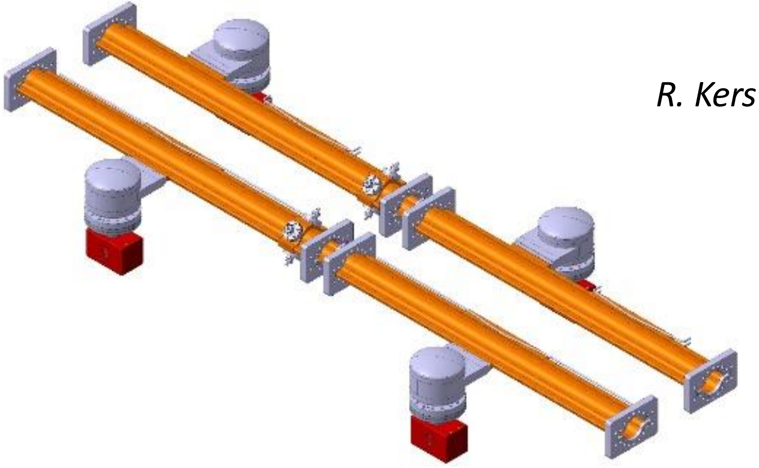
- ”winglets” in the plane of the orbit to capture photons

Continuous impact of photons can cause heating, outgassing and bad vacuum

Challenging beam screen design

- Use NEG (Non Evaporable Getter) pumps next to photon absorbers – pump away emitted gas molecules





*R. Kersevan*

# Electron Cloud

Electrons are set free by ionisation and the synchrotron radiation photons

They are accelerated by the positively charged beam and hit the beam pipe on the other side

They can produce more than one secondary

- They can also be reflected

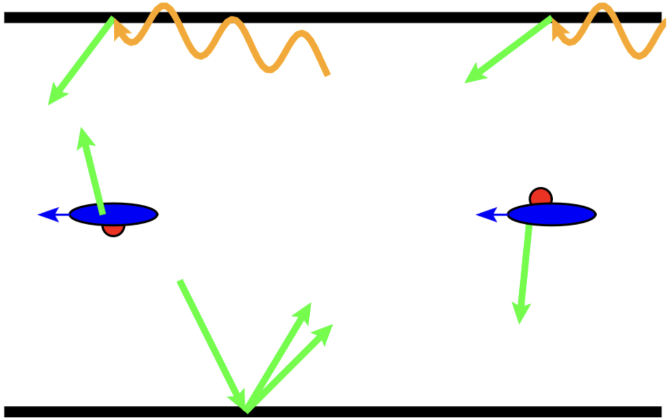
This can lead to an exponential build-up

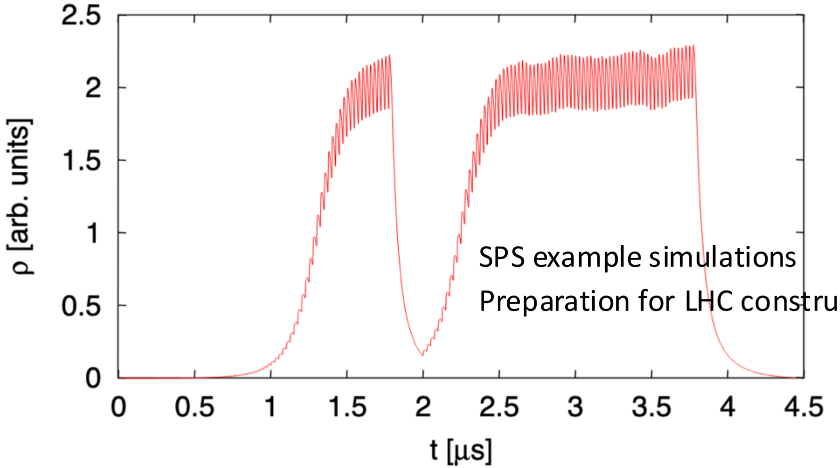
- Limited by the beam current

A high density of electrons at the beam will render it unstable

- Bunches give a kick to the cloud that gives a kick to the next bunches …

This is a limitation in the LHC





SPS example simulations

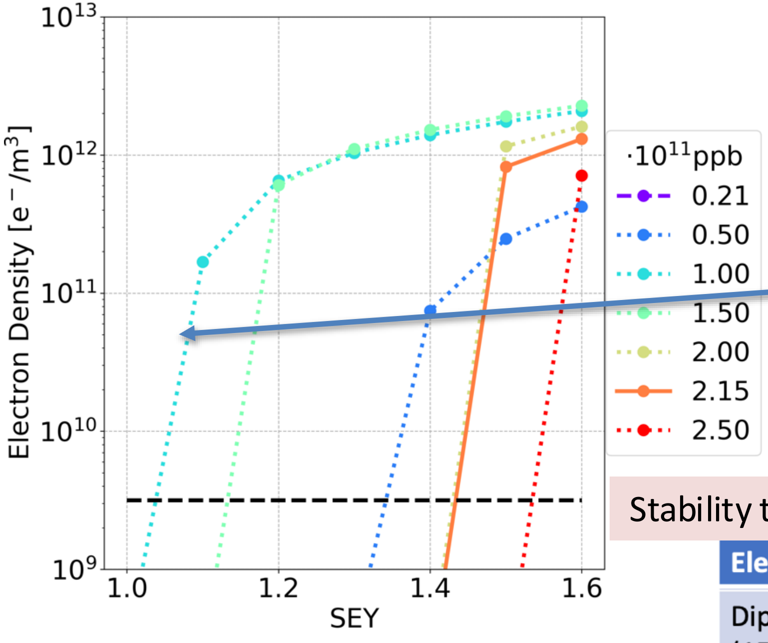
Preparation for LHC construction

# Multipacting Limit

Need to study all different magnet configurations,
Diopoles, quadrupoles, sextupoles, …

Two limits:

- Beam stability
- Heat load



Intermediate bunch intensities impose tightest requirements (as in the LHC)

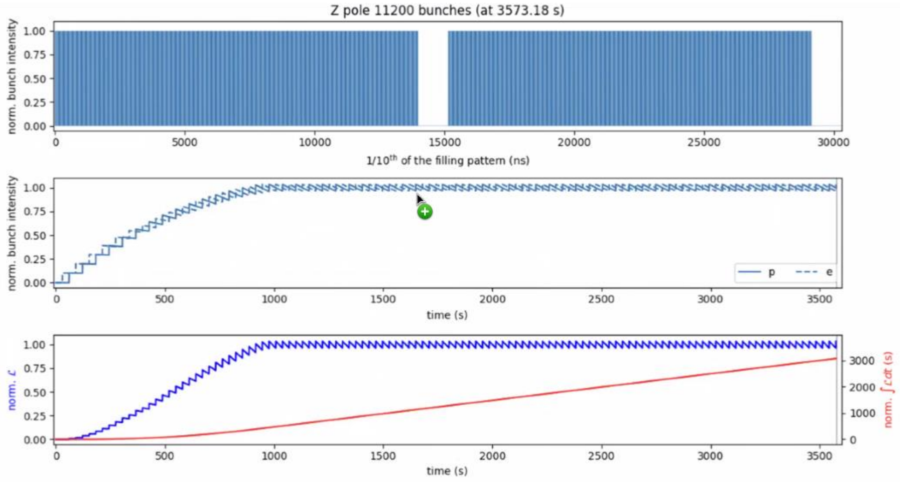
Stability threshold

L. Sabato, EPFL

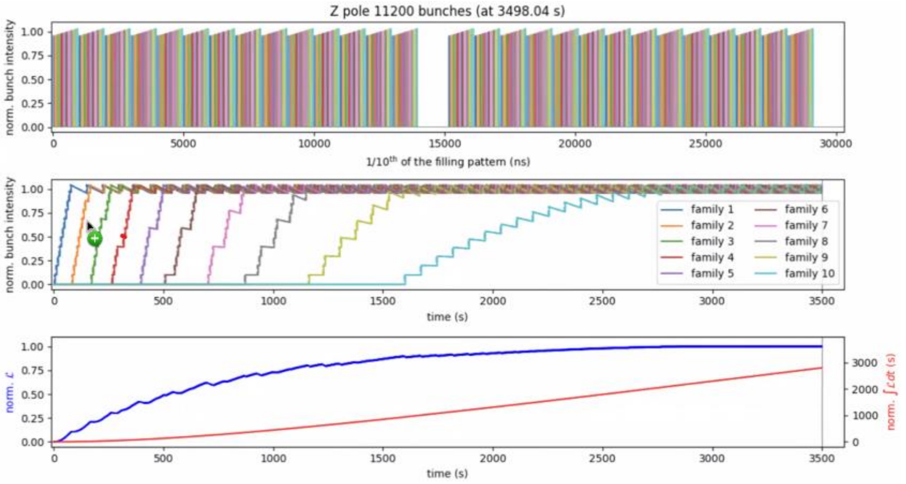
| Element | SEY Threshold | 20 ns | 25 ns | 50 ns |
|---|---|---|---|---|
| Dipole (15.2 mT) | nominal intensity | 1.3 | 1.4 | > 1.6 |
| | all intensity below nominal one | 1.0 | 1.0 | 1.3 |

# Potential Solution

“CDR scheme”



“Carli-Bartosik scheme”



Initially do not fill all bunches

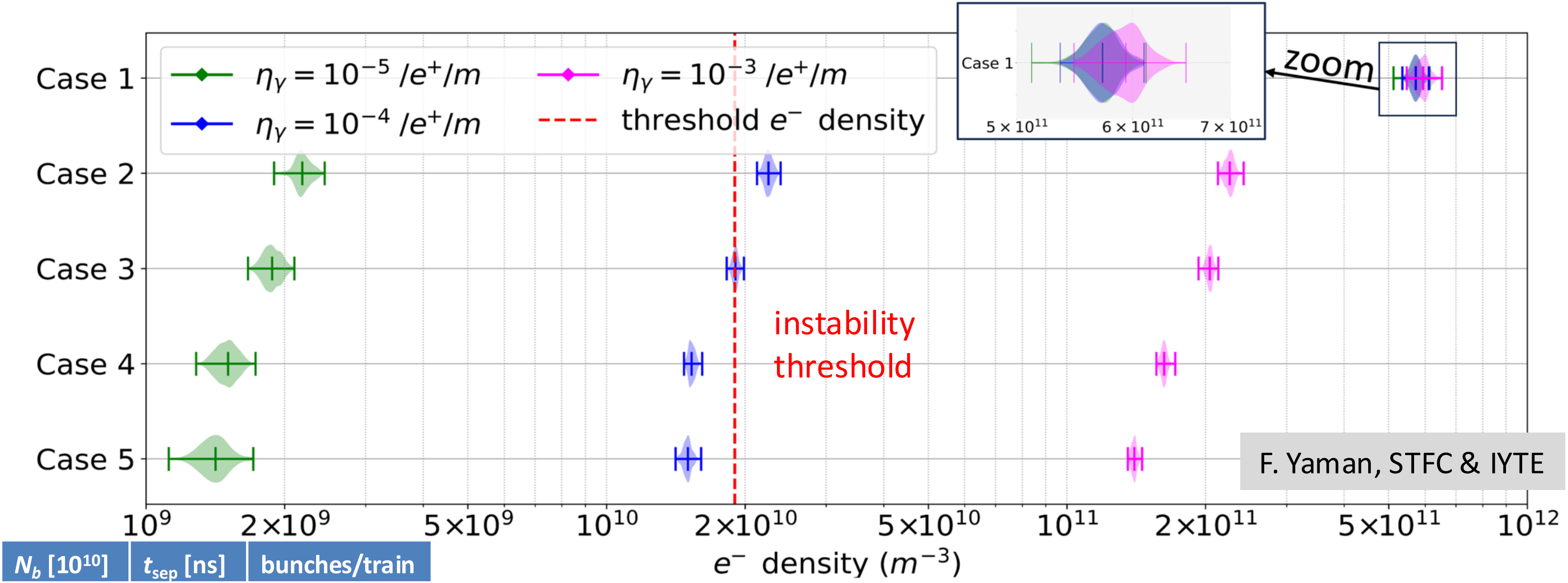
Just fill a few to the full level

- Electron cloud build-up reduced due to train length

Then add a few more bunches

H. Bartosik, C. Carli, L. Mether, F. Zimmermann

# Photon Capture Requirement



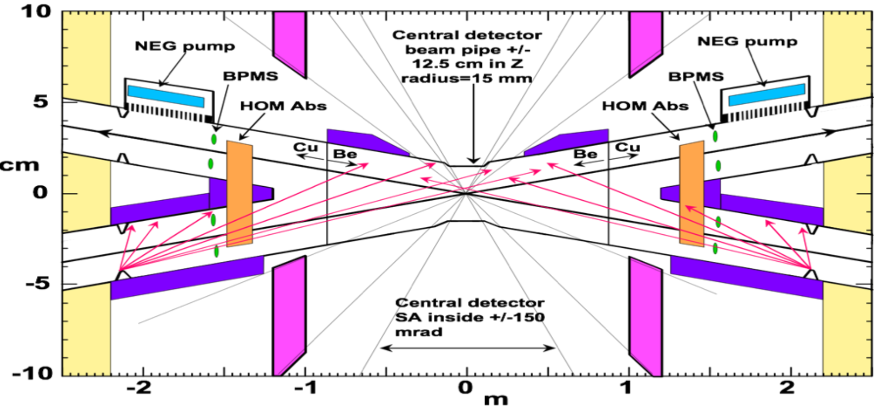
| Scenario | $N_b$ [$10^{10}$] | $t_{sep}$ [ns] | bunches/train |
|---|---|---|---|
| Case 1 | 15 | 25 | 320 |
| Case 2 | 21.5 | 25 | 280 |
| Case 3 | 21.5 | 25 | 560 |
| Case 4 | 24.3 | 25 | 255 |
| Case 5 | 43.0 | 50 | 280 |

**Need $\eta_\gamma$ below $10^{-4}$/e⁺/m**

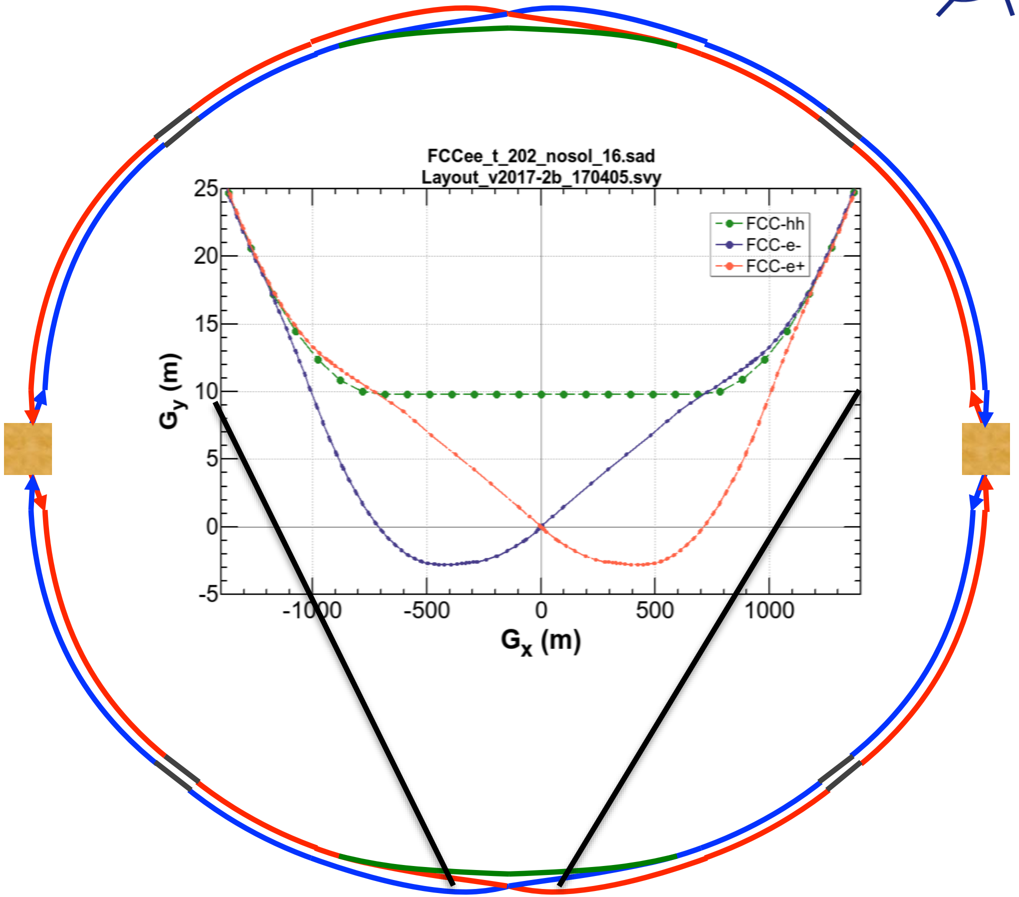
**Antechamber with photon stops must absorb 99% of the photons**

# 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



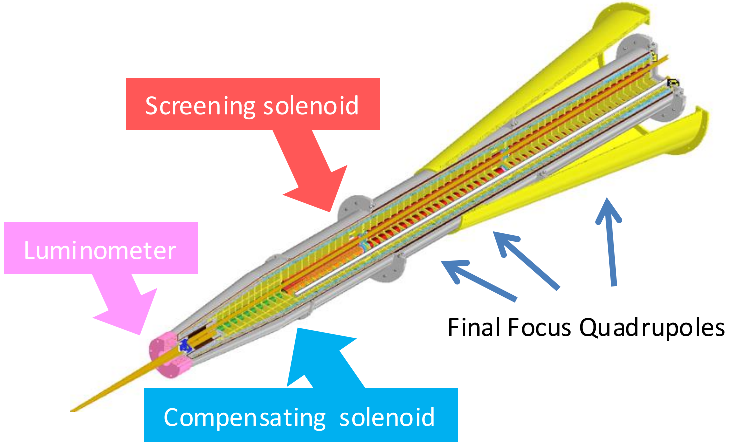
# MDI

**Canted-Cosine-Theta magnets**

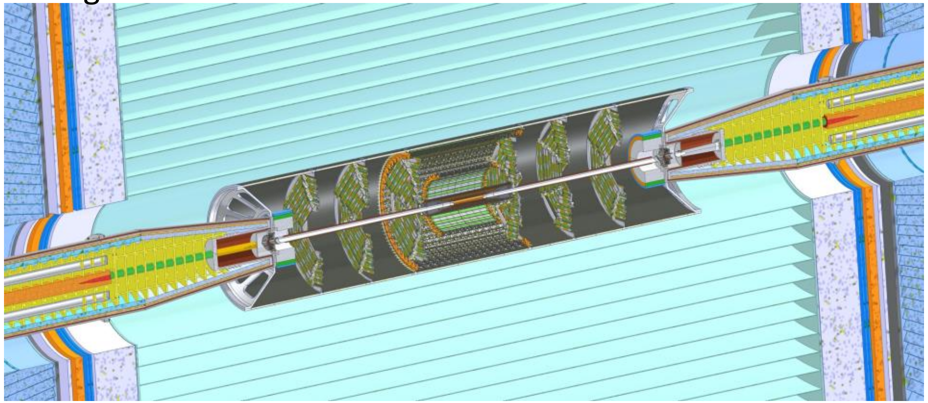
- Elegant 2-layer design for inner quadrupoles
- Working to fit within 100 mrad stay-clear cone
- Prototype built and warm-tested
- Complex integration of SC quadrupoles, LumiCal, shielding, diagnostics…
- Mock-up under discussion

**FCC-ee interaction region**

- L* = 2.2 m
- The 10 mm central radius is for ± 9 cm from the IP.
- The two symmetric beam pipes with radius of 15 mm
- are merged at 1.2 m from the IP
- Low impedance vacuum chamber
- Synchrotron Radiation Background and photon dumps



Integration within the detector



# Beamstrahlung

Beamstrahlung also important in FCC-ee

| Bunch Energy [GeV] | Beamstrahlung Parameter $\Upsilon$ | Photons per particle $n_\gamma$ | Average photon energy [MeV] $< E_\gamma >$ | Total photon beam power [kW] |
|---|---|---|---|---|
| 45.6 | 1,81 x $10^{-4}$ | 0,148 | 2 | 390 |
| 182.5 | 9,12 x $10^{-4}$ | 0,242 | 67 | 88 |

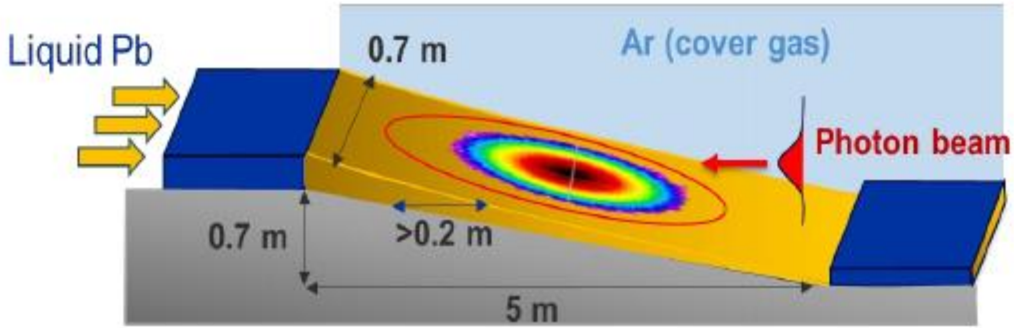
A lattice design challenge

- A few particles lose much energy
- Ring lattice needs large momentum acceptance
- Goal is to maintain particles with 2% in the beampipe

A potential damage challenge

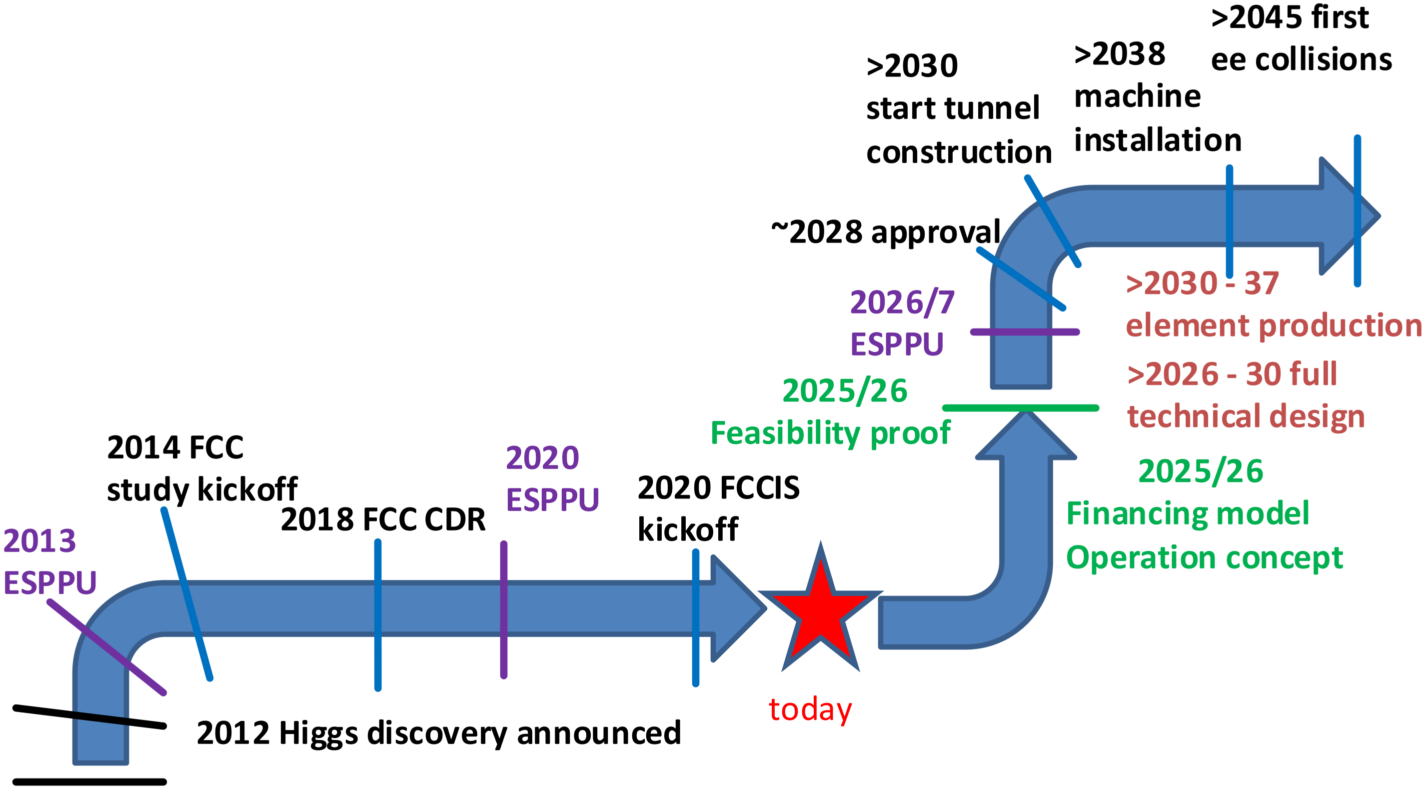
- Radiated photon power up to 400 kW
- Hit downstream vacuum chamber in localised spot
- Engineering challenge to dispose of heat without material damage
- Different solutions under study: solid graphite absorber (might break), absorber with flowing liquid Pb

*M. Calviani et al.*



# Timeline Considerations

Goal is to start physics
soon after HL-LHC finishes



2012 Higgs discovery announced

2013
ESPPU

2014 FCC
study kickoff

2018 FCC CDR

2020
ESPPU

2020 FCCIS
kickoff

today

2025/26
Feasibility proof

2025/26
Financing model
Operation concept

2026/7
ESPPU

>2026 - 30 full
technical design

~2028 approval

>2030
start tunnel
construction

>2030 - 37
element production

>2038
machine
installation

>2045 first
ee collisions

# Reserve

# FCC-ee

Electron-positron collider in the FCC-hh tunnel

Operation at different energies

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

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

| Parameter | Z | WW | ZH | tt |
|---|---|---|---|---|
| $E_{cm}$ [GeV] | 91.2 | 160 | 240 | 365 |
| $\triangle$E [GeV] | 0.0394 | 0.374 | 1.89 | 10.42 |
| I [mA] | 1270 | 137 | 27 | 4.9 |
| L [$10^{34}$ $cm^{-2}s^{-1}$] | 141 | 20 | 5 | 1.25 |
| Beam lifetime [60s] | 50 | 42 | 100 | 100 |
| L lifetime [60s] | 22 | 16 | 14 | 12 |

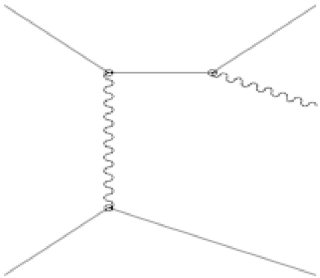
Short beam lifetime requires top-up injection

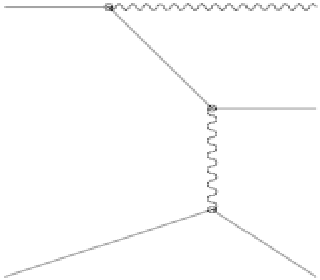
vertical beam size O(30-70 nm)

# Beam Lifetime

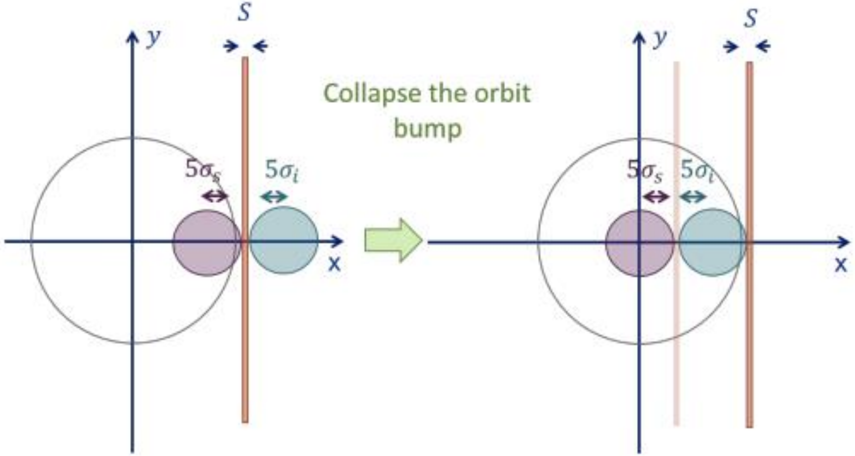
Beam lifetime is short (18-200 minutes)

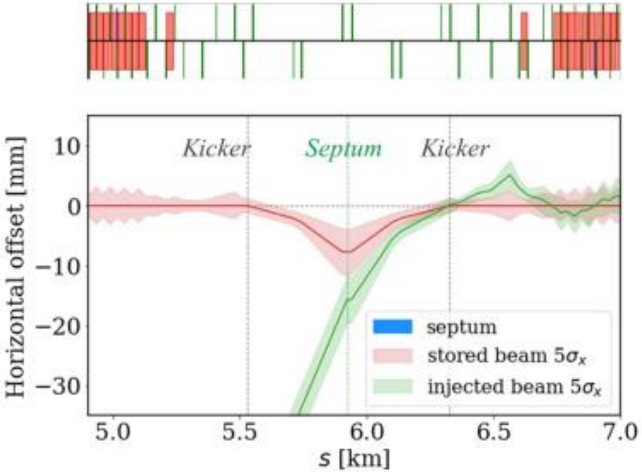
- Bremsstrahlung
- Beamstrahlung
- …





$$\tau \propto \frac{I}{\quad}$$

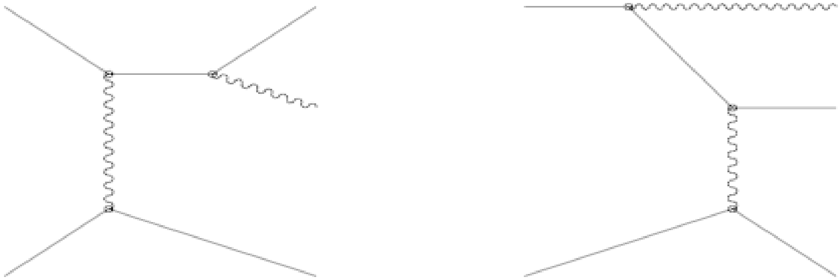




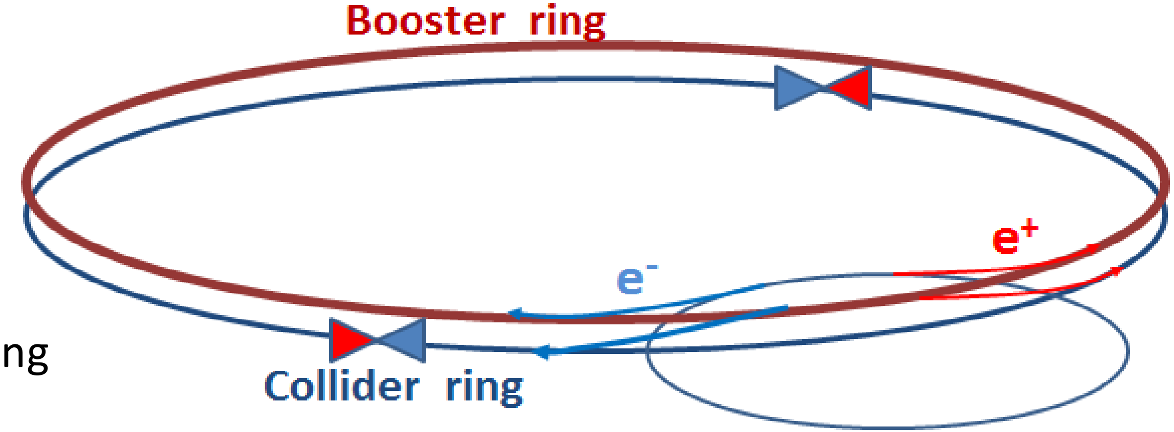
# Top-up Injection

Beam lifetime is short (18-200 minutes)

- Bremsstrahlung
- Beamstrahlung
- …



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



Have to refill beam permanently

$\Rightarrow$ top-up injection with booster ring

# Future Lepton Colliders