Mitigation of Coherent Instabilities in Linear Colliders and FCC-hh

D. Schulte

Introduction

Cannot cover all collective instabilities and their mitigation in linear colliders and FCC-hh

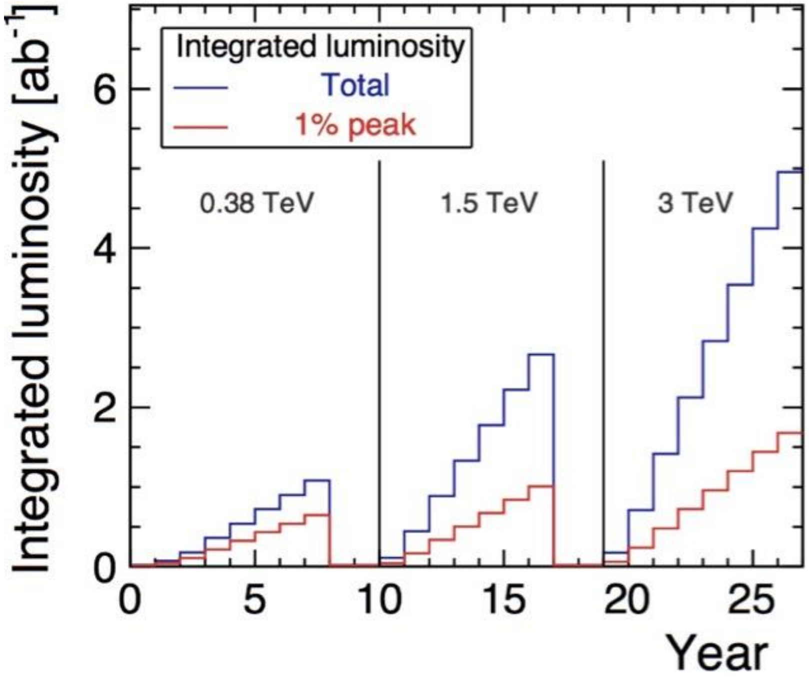
Pick a couple of cases where collective instabilities are mitigated by design choices

Theses cases maybe intellectually less exciting but are critical for the projects and can have an important impact on the project cost and power consumption

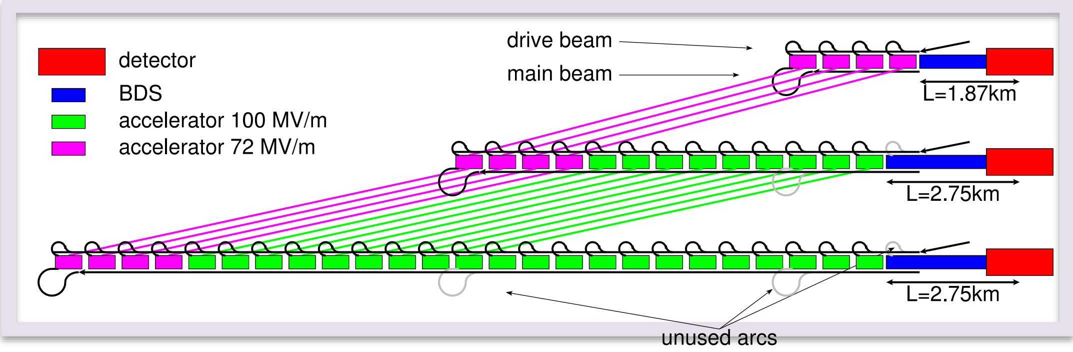
There is some fun in building a complete model of the interdependencies of parameters and choices

- Identifying the actual drivers
- Identifying the limits, their origin and paths for solutions
- Simplifying as much as possible
- …
- But I will not be able to cover this

Staged CLIC Scenario



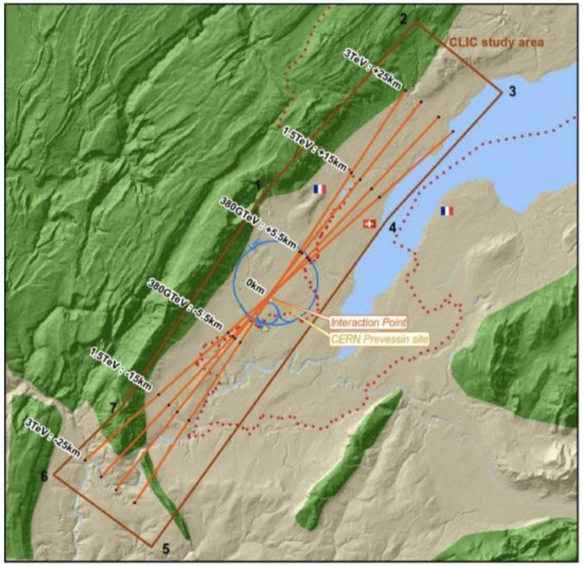
Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0
2	1.5	2.5
3	3.0	5.0



Upgrades from 380 GeV to 3 TeV

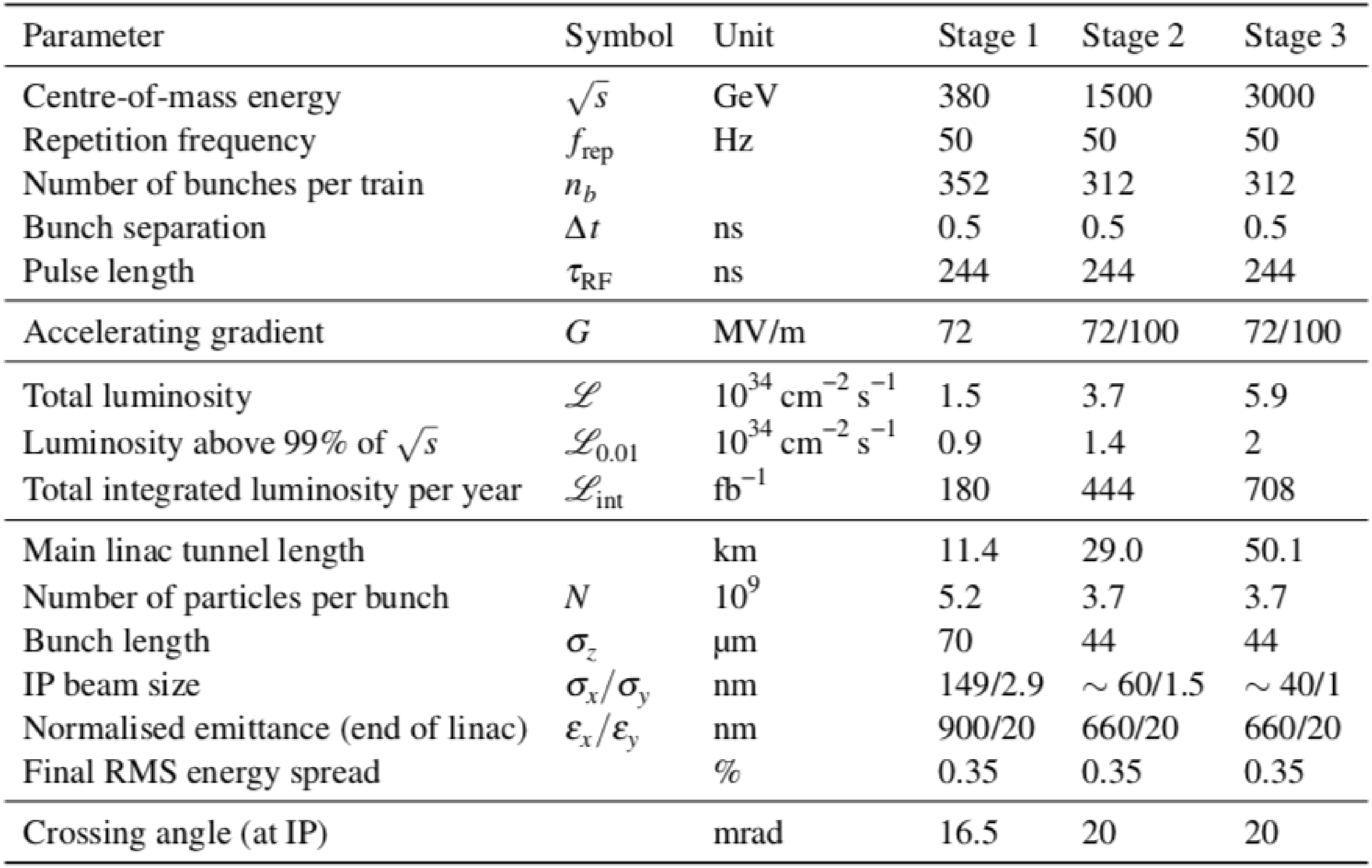
Site exists at CERN

Feasibility established



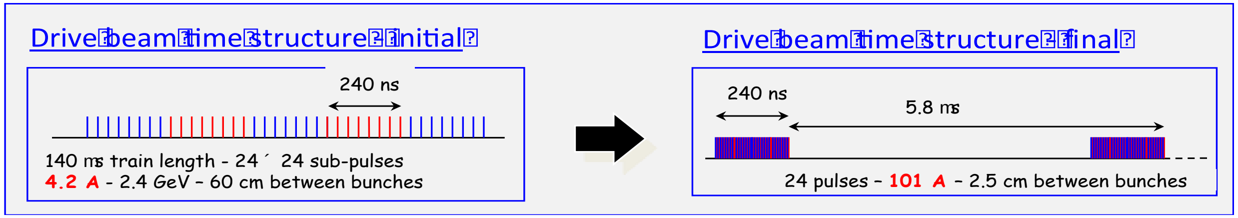
Cost:
380 GeV: 5.9 GCHF
1.5 TeV: + 5.1 GCHF
3.0 TeV: + 7.3 GCHF

Key Parameters



Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{RF}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2} s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2} s^{-1}	0.9	1.4	2
Total integrated luminosity per year	$\mathscr{L}_{\mathrm{int}}$	fb^{-1}	180	444	708
Main linac tunnel length		km	11.4	29.0	50.1
Number of particles per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	$\sim$ 60/1.5	$\sim$ 40/1
Normalised emittance (end of linac)	ϵ_x/ϵ_y	nm	900/20	660/20	660/20
Final RMS energy spread		%	0.35	0.35	0.35
Crossing angle (at IP)		mrad	16.5	20	20

CLIC at 380 GeV


Drive beam time structure - initial

240 ns

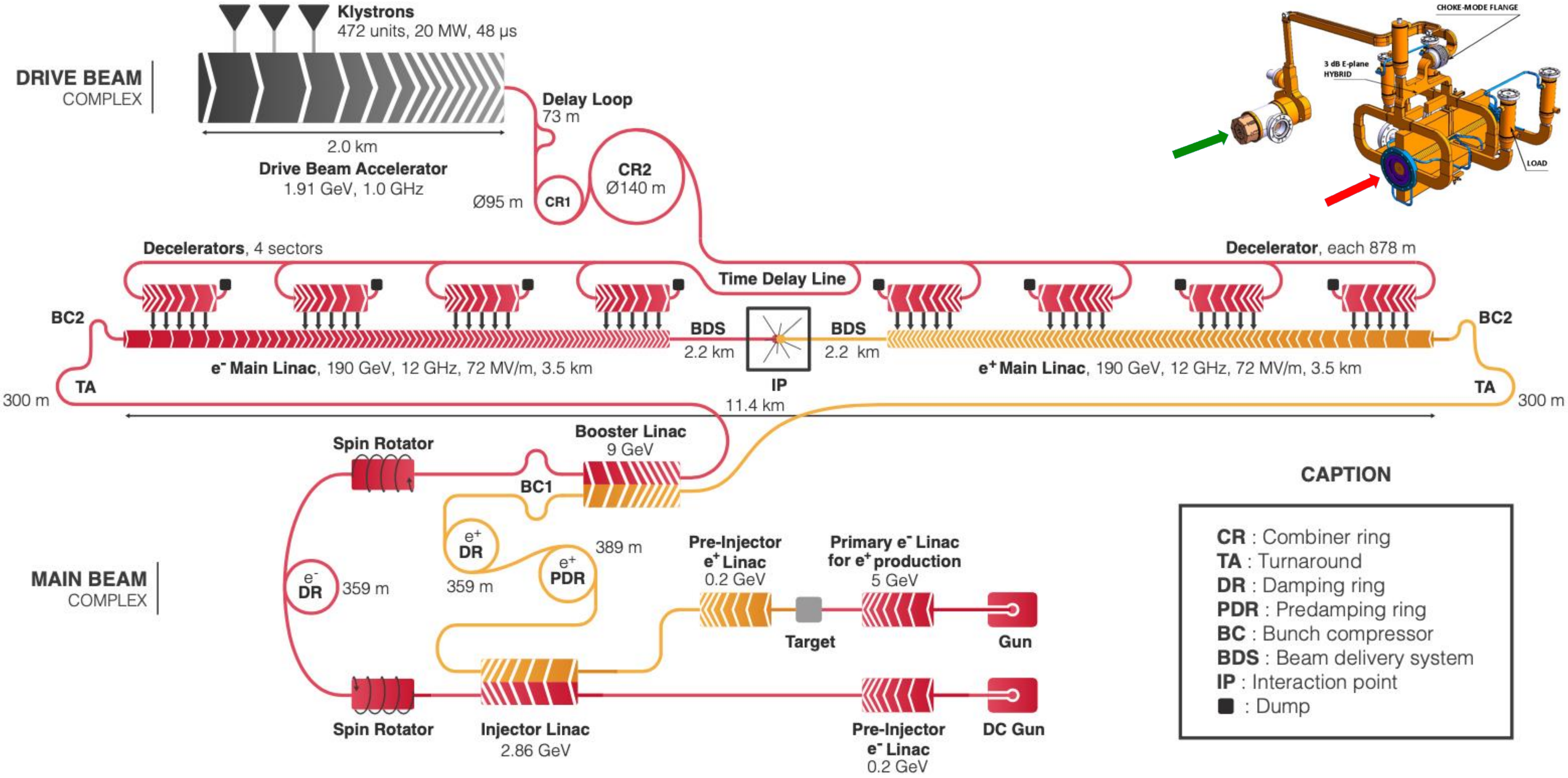
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final

240 ns

5.8 μs

24 pulses – 101 A – 2.5 cm between bunches



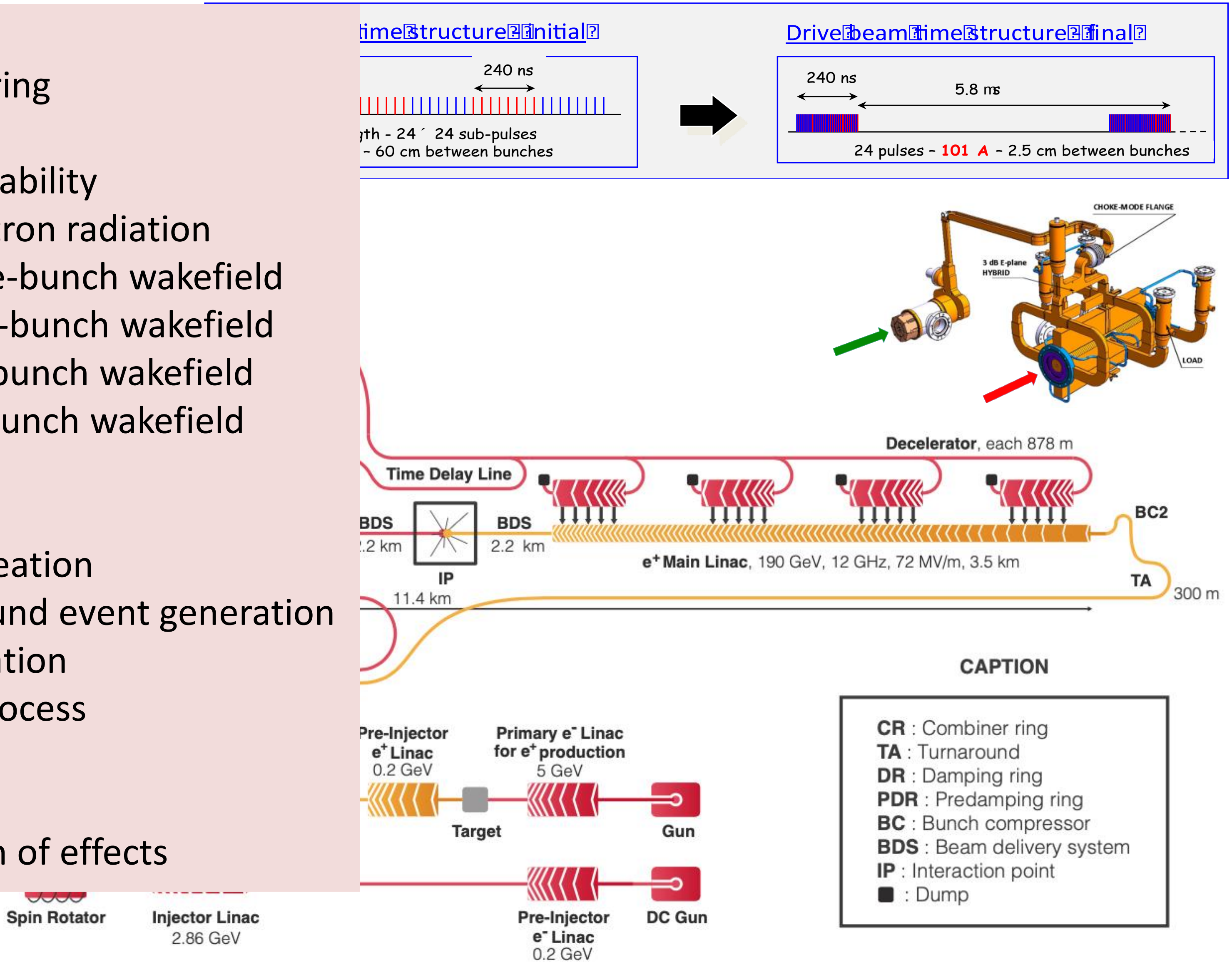
CAPTION

CR : Combiner ring
TA : Turnaround
DR : Damping ring
PDR : Predamping ring
BC : Bunch compressor
BDS : Beam delivery system
IP : Interaction point
■ : Dump

CLIC at 380 GeV

Space charge
Intra-beam scattering
Electron cloud
Fast beam-ion instability
Coherent synchrotron radiation
Longitudinal single-bunch wakefield
Longitudinal multi-bunch wakefield
Transverse single-bunch wakefield
Transverse multi-bunch wakefield
Pinch effect
Beamstrahlung
Incoherent pair creation
Hadronic background event generation
Coherent pair creation
Trident cascade process
…

Often combination of effects



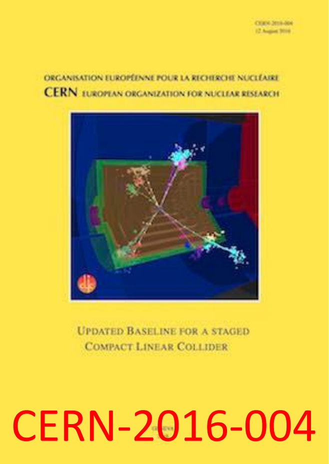
CLIC Optimisation

Collective effects and instabilities play a decisive role in the overall design

Single- and multi-bunch beam break-up in linac is key in parameter choice

Scan 1.7 billion cases:

- Fix **structure design parameters**: **a_1,a_2,d_1,d_2,N_c,ϕ,G**
- Determine **main linac beam parameters** (limited by stability)
- Calculate **luminosity** (including performance of other systems)
- Calculate **cost** and **power**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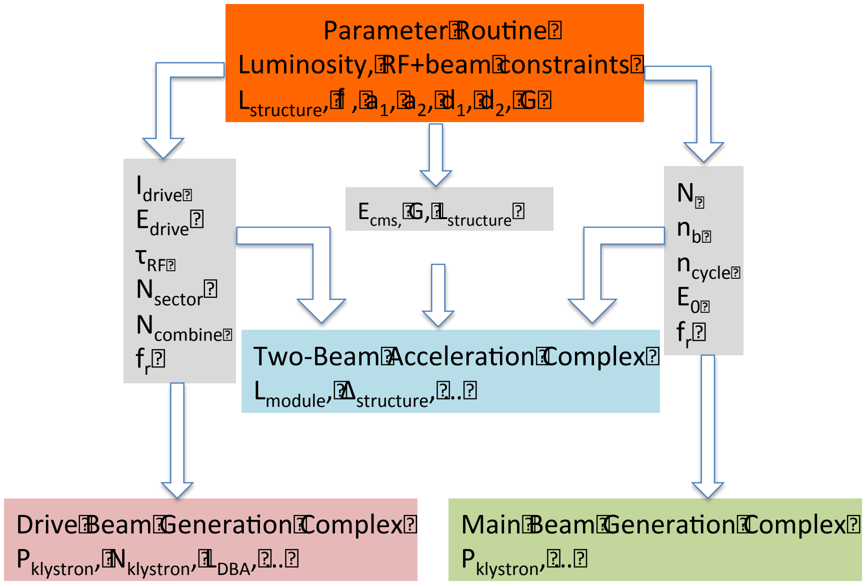
UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

CERN-2016-004


Parameter Routine
Luminosity, RF+beam constraints
$L_{structure}$, ϕ, a_1, a_2, d_1, d_2, G

I_{drive}
E_{drive}
τ_{RF}
N_{sector}
$N_{combine}$
f_r

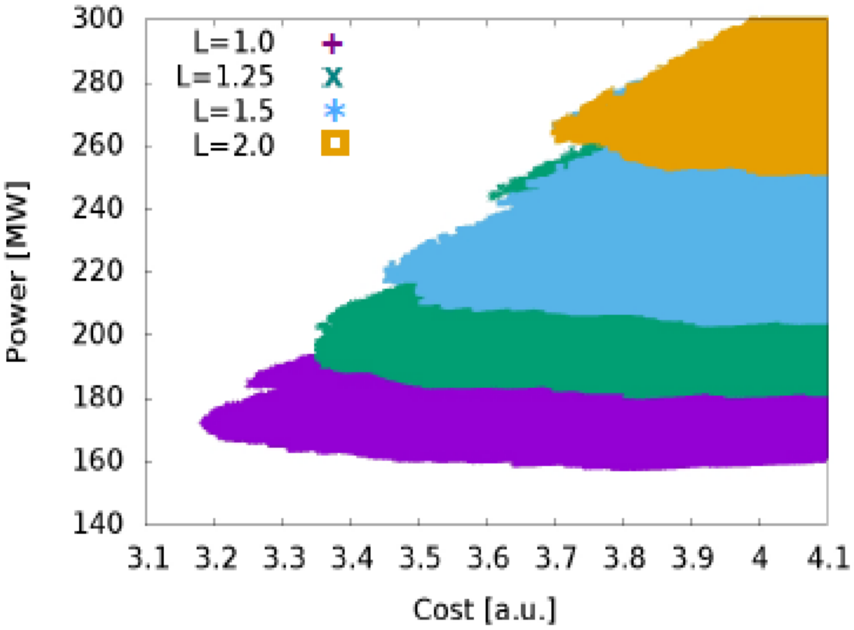
E_{cms}, G, $L_{structure}$

N
n_b
n_{cycle}
E_0
f_r

Two-Beam Acceleration Complex
L_{module}, $\Delta_{structure}$, …

Drive Beam Generation Complex
$P_{klystron}$, $N_{klystron}$, L_{DBA}, …

Main Beam Generation Complex
$P_{klystron}$, …



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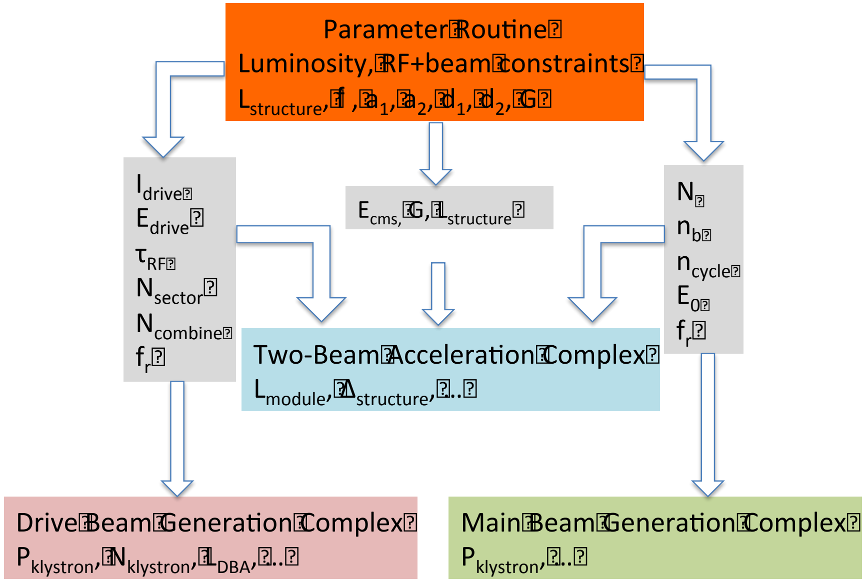

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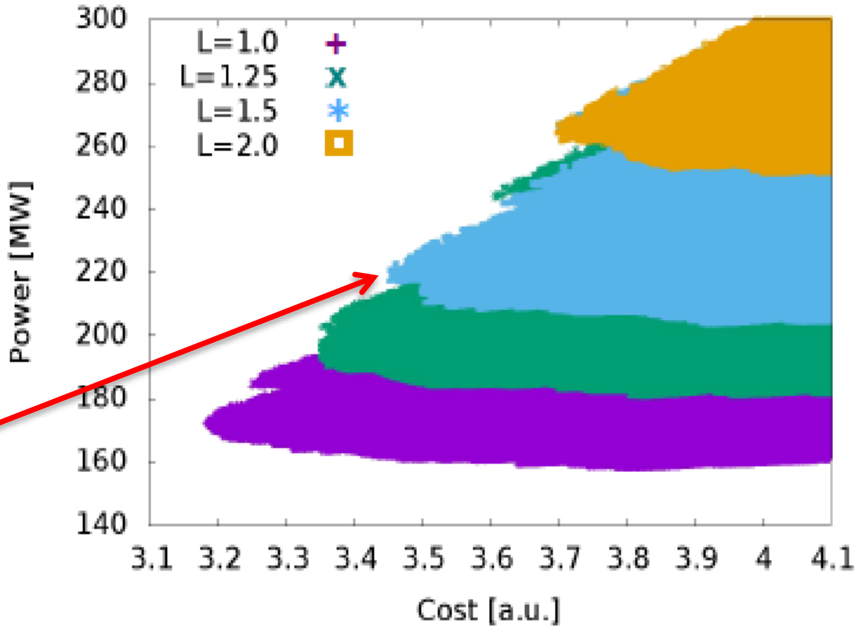

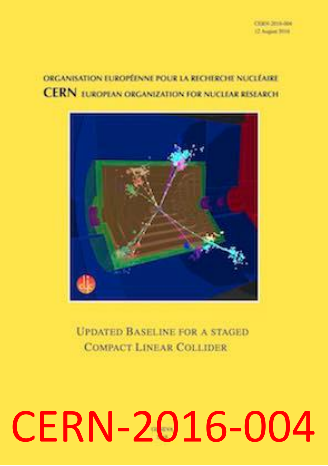

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UPDATED BASELINE FOR A STAGED
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CERN-2016-004

This is the one we picked

Luminosity Drivers

At low (sub-TeV) energies

Can re-write normal luminosity formula

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

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

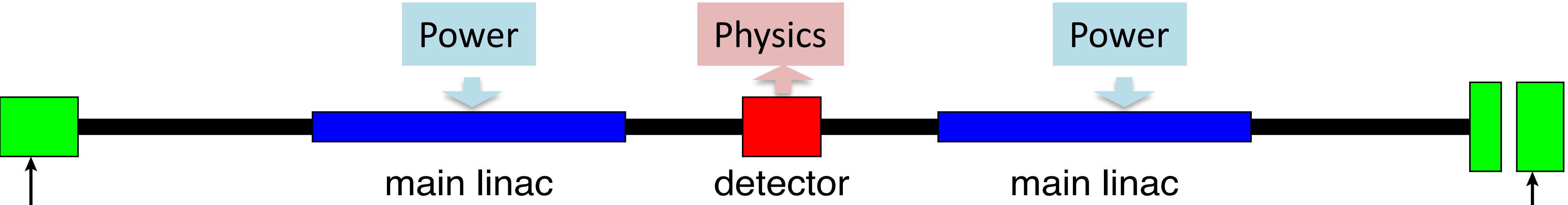
H_D : pinch enhancement, typically 1-2
N : number of particles per bunch
n_b : number of bunches per train
f_r : number of trains per second
$\sigma_{x,y}$: transverse beamsizes

Luminosity Spectrum
(CE at IP)

Beam current
(CI in ML)

Beam Quality
(CE everywhere)

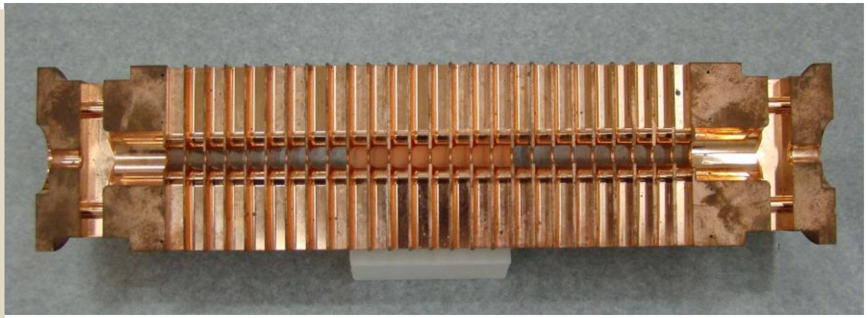
Main Linac, Bunch Charge and Length



e- source

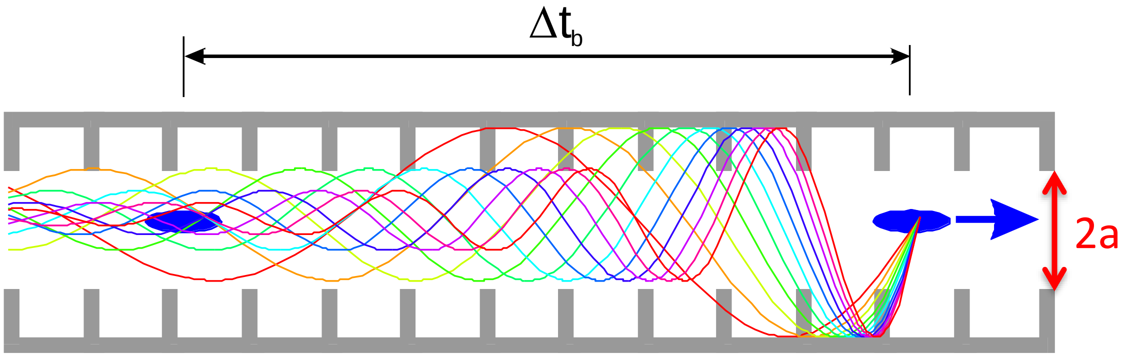
e+ source

Copper allows G=100 MV/m
But strong losses in the walls
- ⇒ 50 RF bursts per second
- ⇒ 240 ns, 60 MW, 312 bunches



Power flow (roughly)
- 1/3 lost in cavity walls
- 1/3 in filling the structure and into load
- 1/3 into the beam

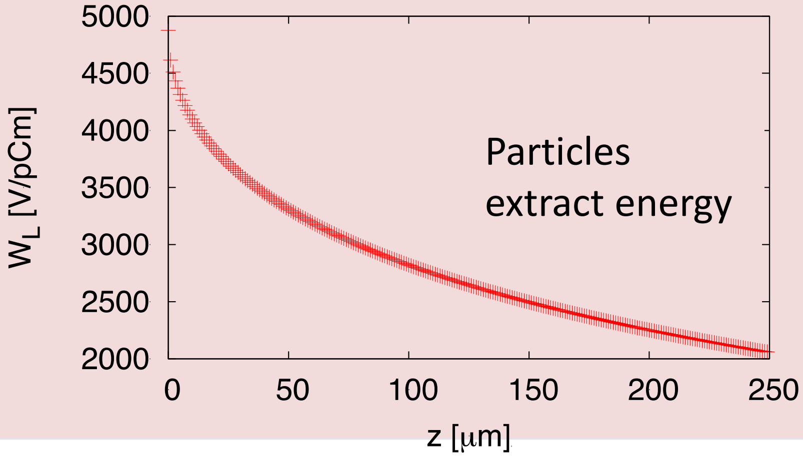
High gradient is small iris aperture radius **a**
But beam is less stable at small **a**
For luminosity need to find limit that is just stable



Main current limit
- Single-bunch beam break-up
- Multi-bunch beam break-up

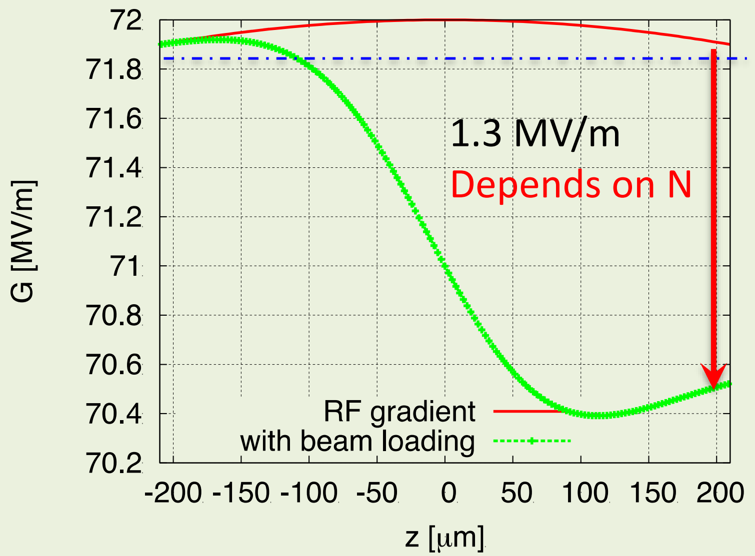
Bunch Length and Energy Spread

Need small energy spread for focusing at IP:
1% full energy spread (0.35% RMS)

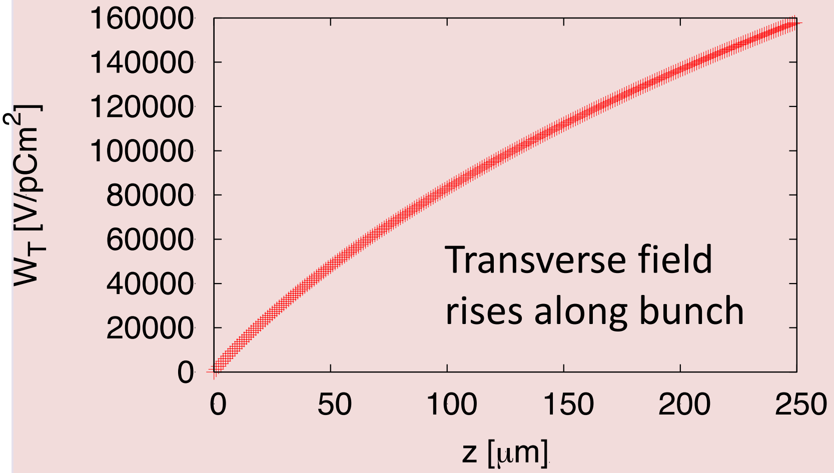


Particles extract energy

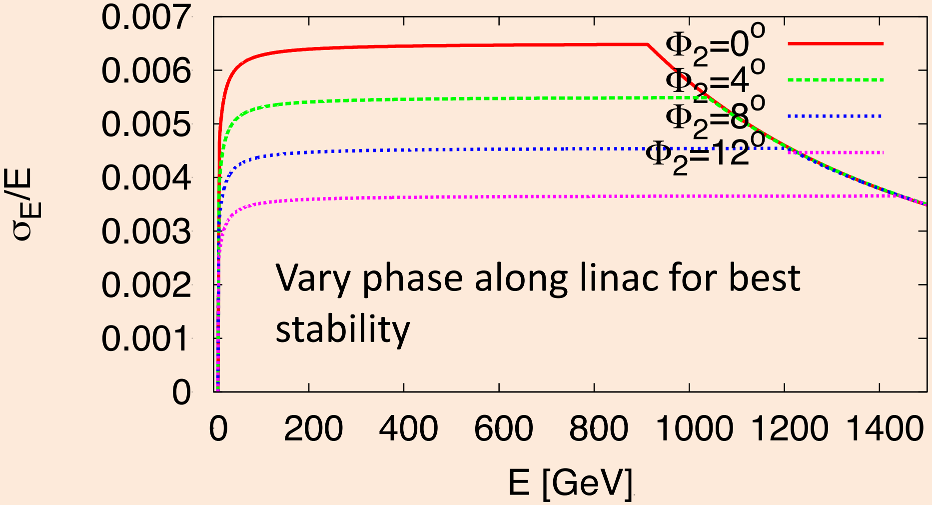
On-crest



1.3 MV/m
Depends on N



Transverse field rises along bunch



Vary phase along linac for best stability

Bunch Length and Energy Spread

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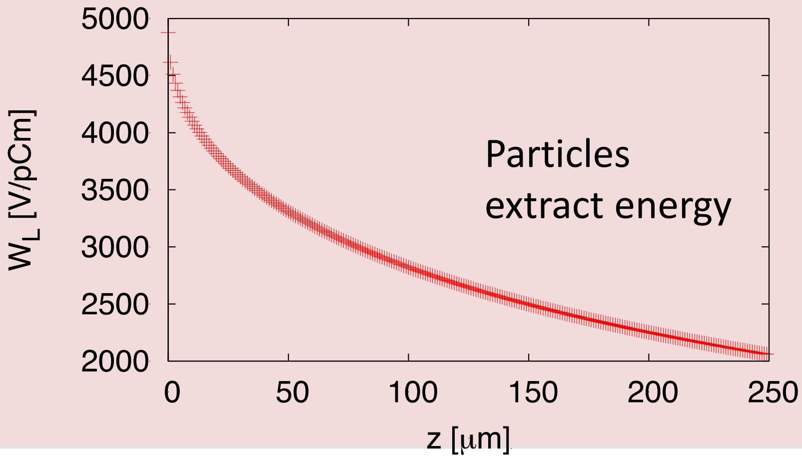
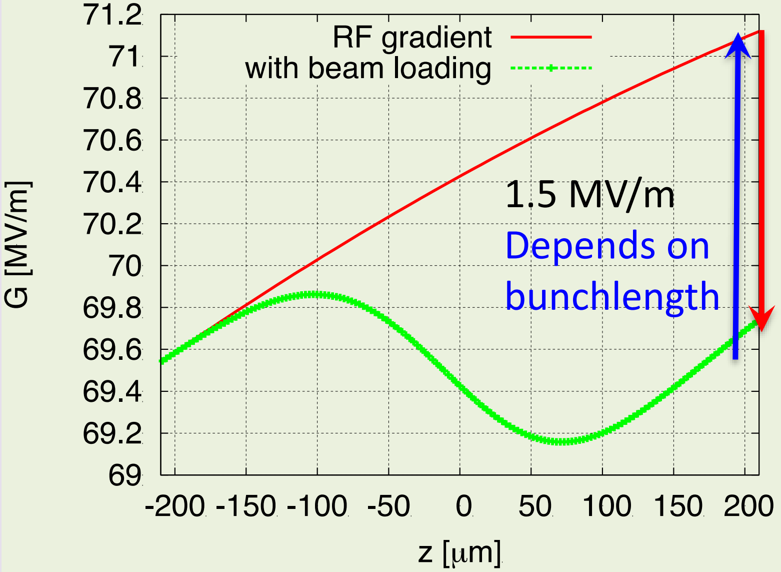
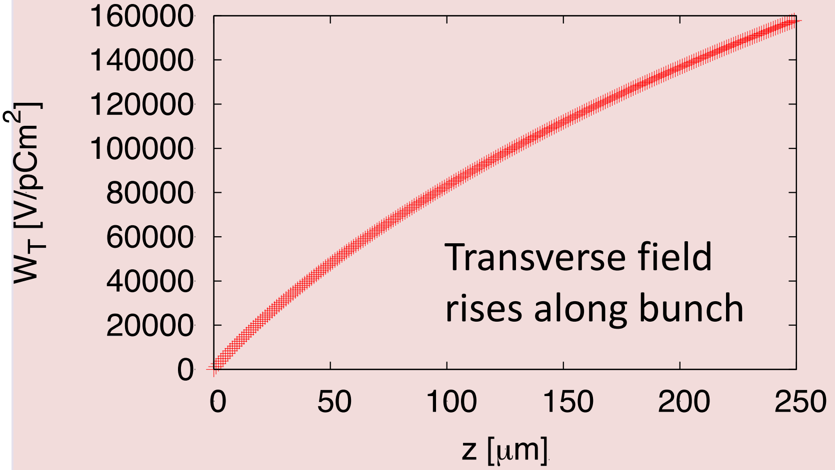


Particles extract energy


Off-crest (12°)

1.5 MV/m

Depends on bunchlength



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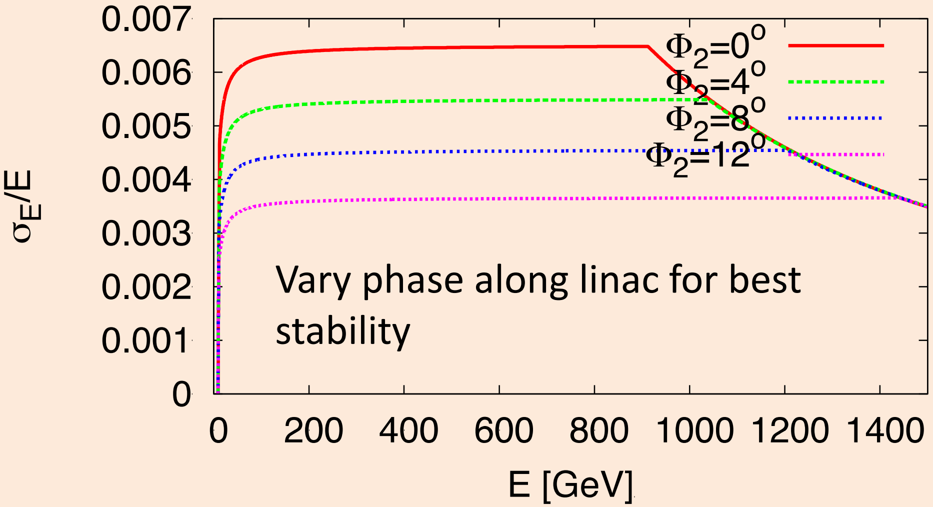
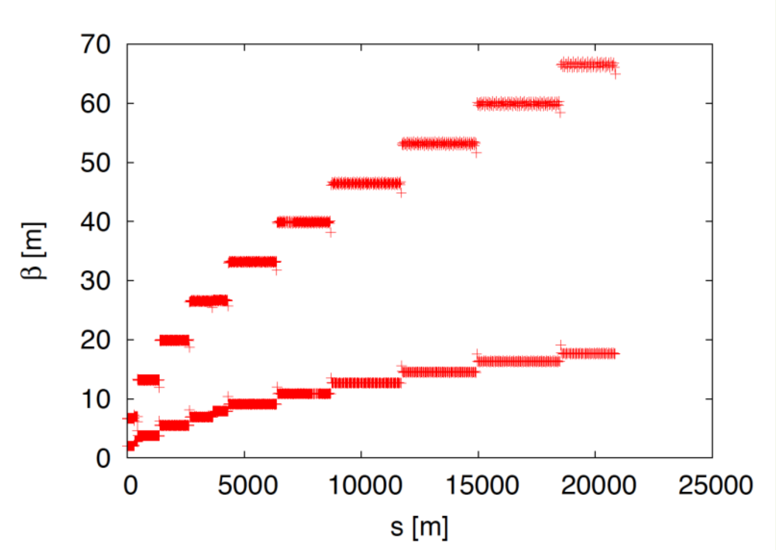


Vary phase along linac for best stability

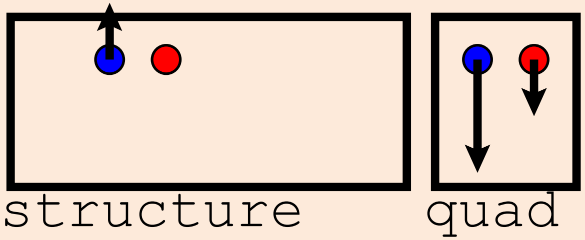
Beam Stability

Check stability

Fill 10 % of linac with quads,
scale ®∝ $E^{1/2}$, □√ = const



BNS damping (Balakin, Novokhatsky and Smirnov) stabilises beam

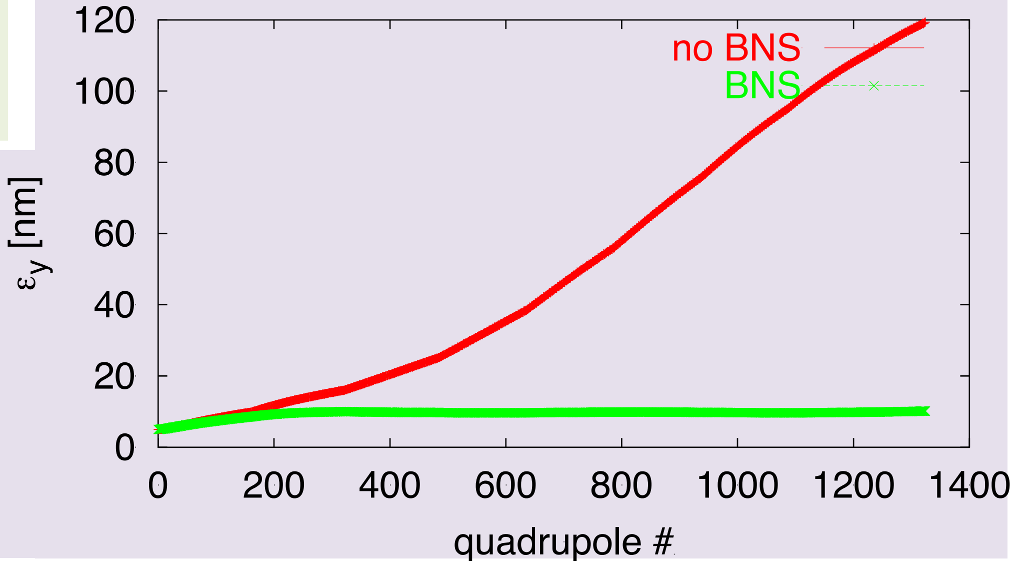


Requires strong focusing

$$\delta \approx -\frac{\beta^2}{E} N e^2 W_\perp(\Delta z)$$

For increasing charges
⇒ Adjust (increase) bunch length
Until not stable

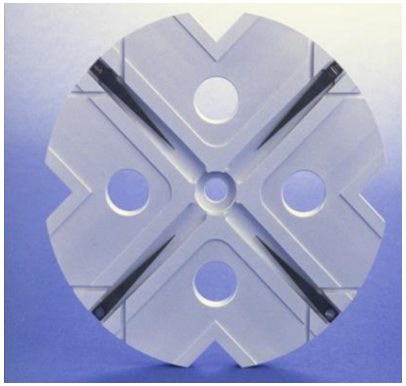
Then back off to have margin

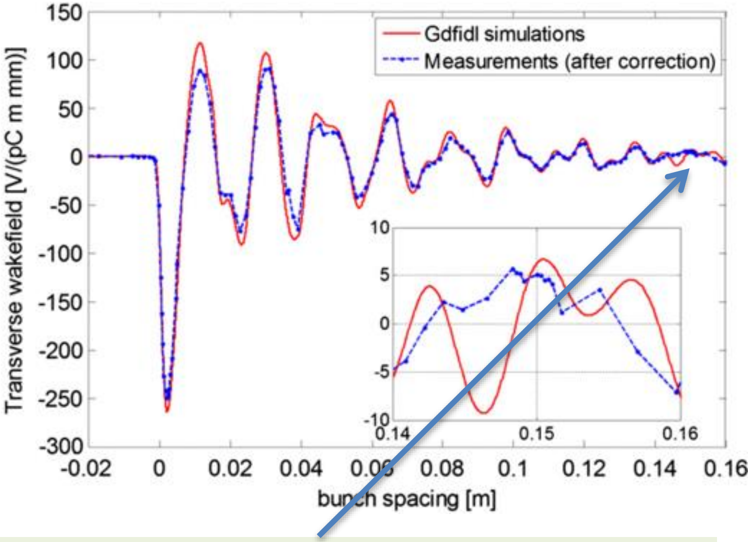


Multi-bunch Limit

Wakefield amplitudes are large

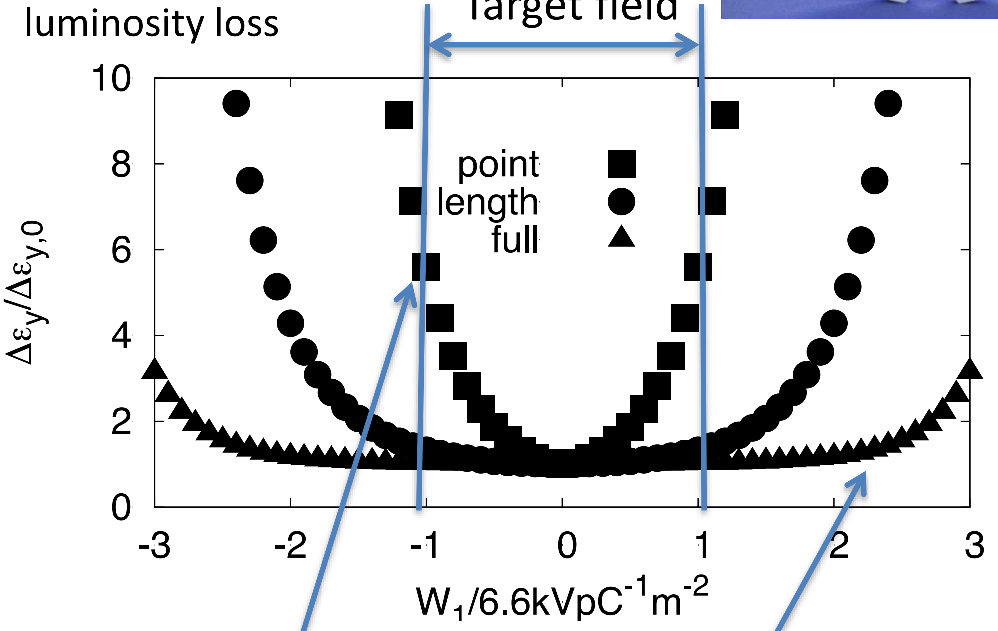
- Strong damping (Q=O(10))
- Detuning (each cell is different)





Chose smallest spacing consistent with maximum wakefield
6 buckets, i.e. 0.5ns

Amplification of luminosity loss



Monochromatic bunches OK, but no margin

Fully real simulation:
Energy spread stabilises, very acceptable

Number of bunches limited by acceptable RF pulse length

But chose value that is sufficient for luminosity

Impact of Technologies

Main linac beam break-up mitigation:

Even more effective damping allows to increase current
- But how?

Reduced impedance due to novel design
- But how?
- Superconducting technology allows much larger apertures (due to limited loss) but lower gradients
- Do dielectric materials allow larger apertures?

Could imagine feedback or feed-forward correction along the train
- But need very high bandwidth
- Can one imagine any feedback of feed-forward within a bunch?

RF quadrupoles can produce BNS damping
- Need to vary field a lot over the bunch
- Timing jitter will give transverse kicks

Stronger quadrupoles and smaller betafunction
- But need solution for magnets and alignment/stability

FCC(-hh)

FCC (Future Circular Collider): Proposal for project at CERN
- CDR for EU strategy end 2018

FCC-hh
- pp collider
  - 100 TeV cms
  - 20 ab^{-1} per experiment
- Ion option
- Defines infrastructure

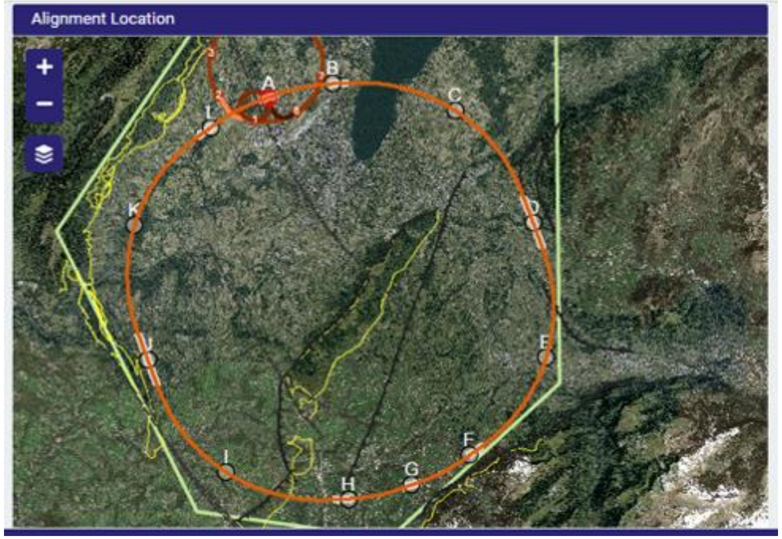
FCC-ee
- Potential e$^+$e$^-$ first stage
- Now seems like quite probable first step

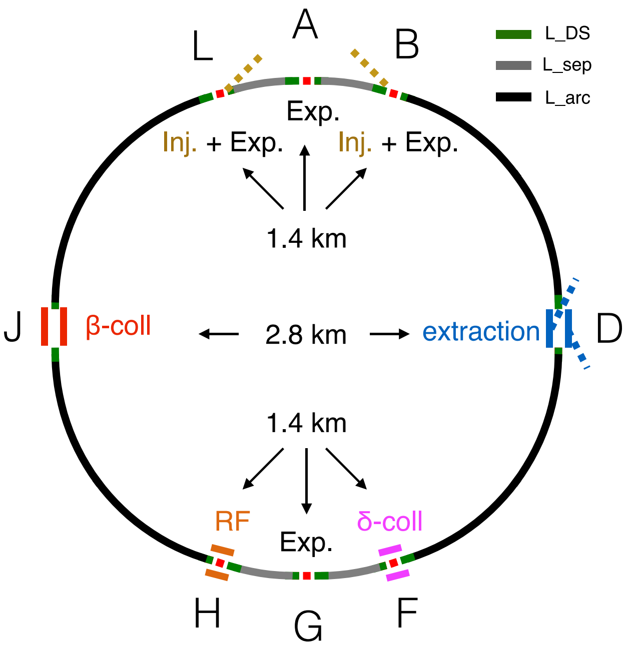
FCC-eh
- additional option

HE-LHC
- LHC with high field magnets

Site studies in Geneva basin
- Can use LHC as injector

CDR available
- FCC-hh technically feasible
- Magnets to be demonstrated





Cost

FCC-ee 11.6 GCHF

FCC-hh = FCC-ee + 17 GCHF
FCC-hh = 24 GCHF

Parameters and Luminosity

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

$$\sigma^2 \propto \beta\epsilon$$

$$\mathcal{L} \propto \frac{N}{\epsilon}\frac{1}{\beta} N n_b f_r$$

Limit from beam-beam

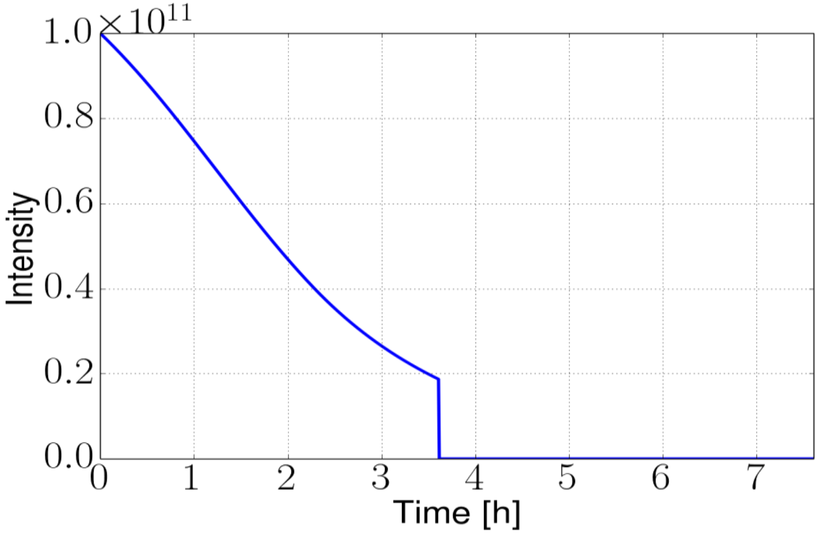
Limit from synchrotron radiation

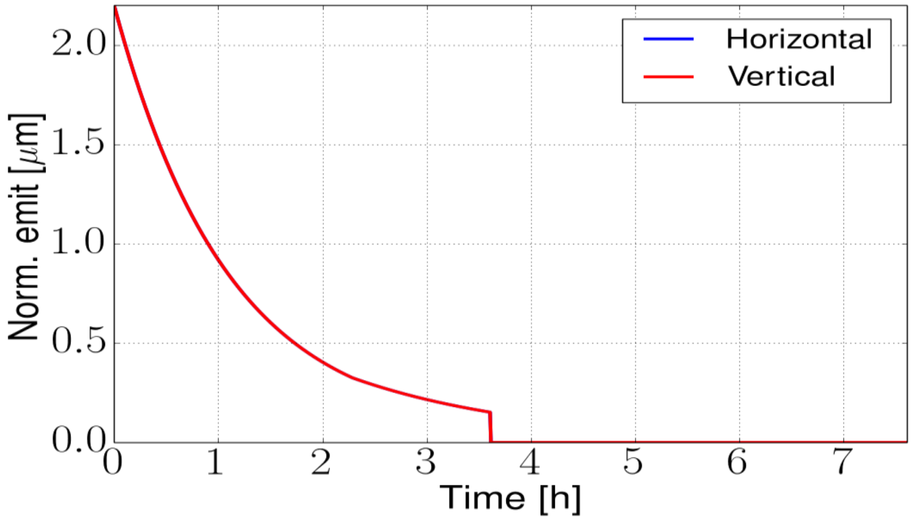
Limit from collimation / optics

5 MW -> 100 MW for cooling

	FCC-hh Initial	**FCC-hh Nominal**
Luminosity L [10^{34}cm^{-2}s^{-1}]	5	< 30
Background events/bx	170	< 1020
Bunch distance Δt [ns]	25	
Bunch charge N [10^{11}]	1	
Fract. of ring filled η_{fill} [%]	80	
Norm. emitt. [μm]	2.2(0.44)	
Max ξ for 2 IPs	0.01 (0.02)	< 0.03 (< 0.026)
IP beta-function β [m]	1.1	0.3
IP beam size σ [μm]	6.8	3.5
RMS bunch length σ_z [cm]	8	
Crossing angle [σ□]	12	Crab. Cav.
Turn-around time [h]	5	4

Luminosity During the Run





S. Arsenyev, X- Buffat

Main loss mechanism is luminosity

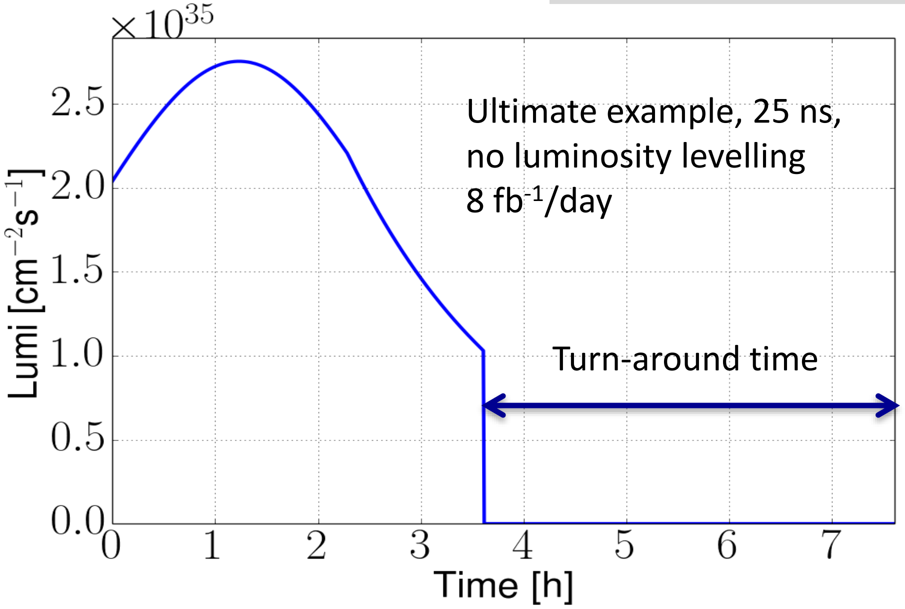
⇒ This is what we want

⇒ Beam is burned quickly

⇒ Another reason to have enough charge stored

Achieve 72% of absolute maximum integrated luminosity (full 3×10^{34} $cm^{-2}s^{-1}$, then refill)

⇒ Turn-around time is important limitation for collider



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

Turn-around time

Impedances

S. Arsenyev et al.

Impedance at injection mainly from beamscreen

⇒ But key ingredient of magnet cost

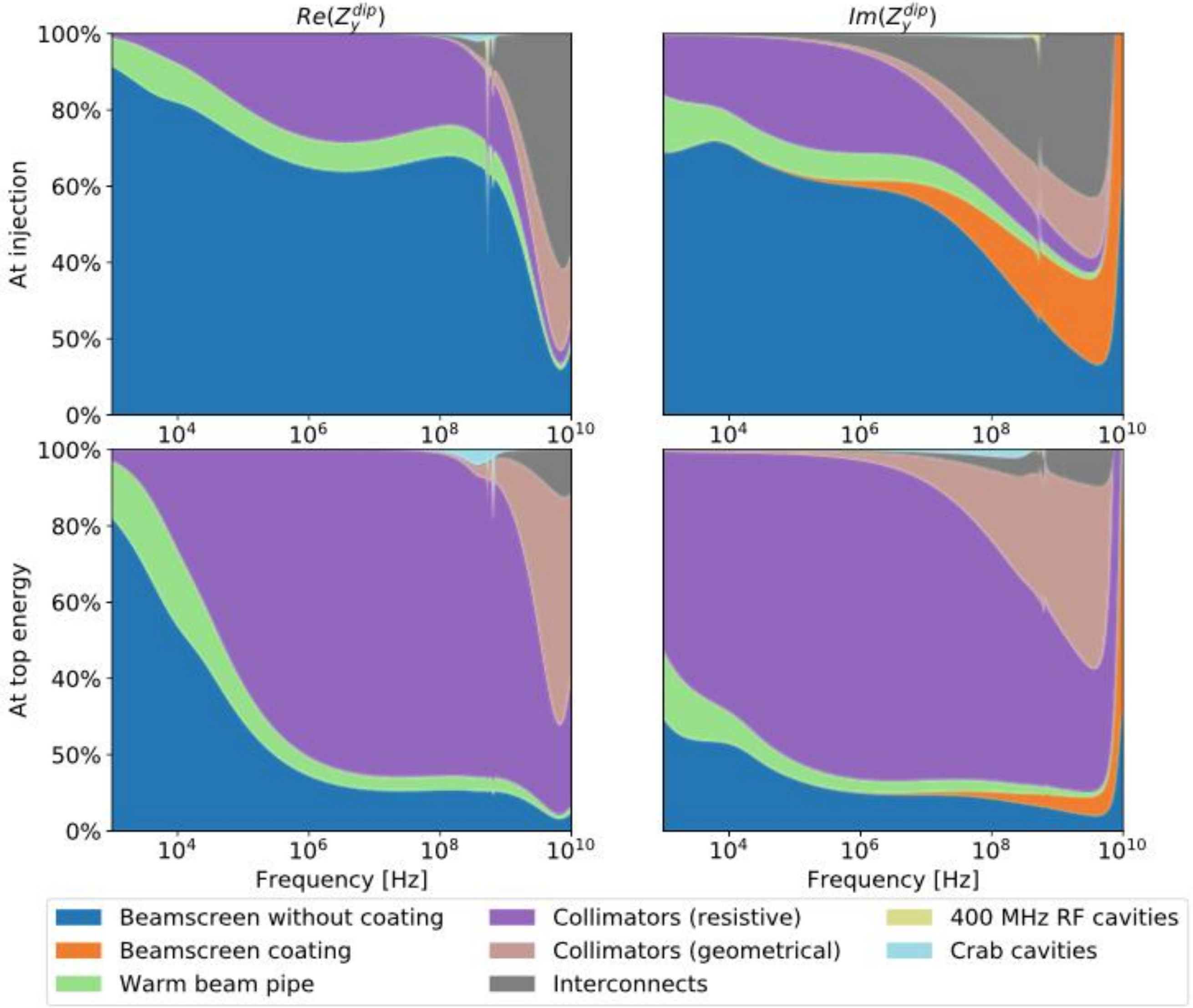
⇒ Use highest practical injection energy

⇒ And optimised design

At top energy mainly from collimators

⇒ Collimator apertures and material

⇒ Correct scaling of experimental and betatron insertion lengths



Beamscreen Considerations

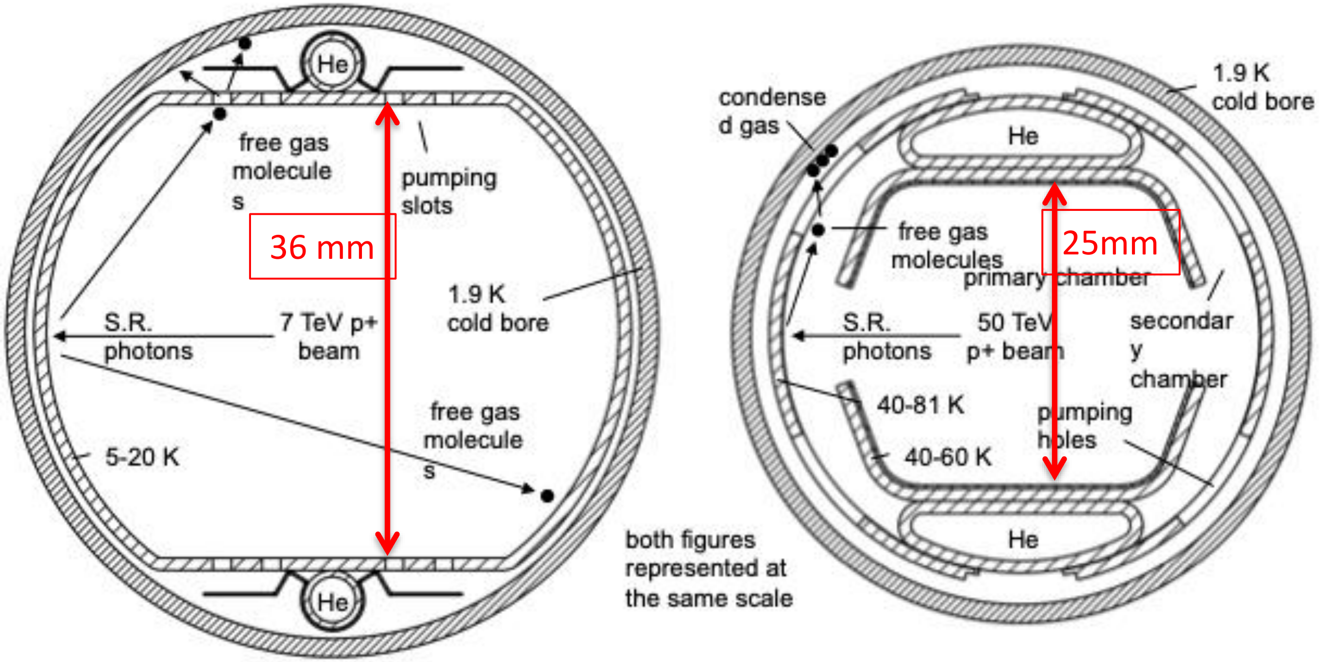
- Protect magnets from 30 W/m synchrotron radiation
- Povide good vacuum, suppress electron cloud, robust against quench, …
- Trade-off with beam stability

Strategy:

- Highest practical injection energy for stability, i.e. 3.3 TeV
- Reduce resistive impedance by copper coating
- Chose minimum aperture with stable beam
- Reduce geometric impedance by shielding the pumping holes
- Reduce electron cloud by ante-chamber and surface treatment

LHC beamscreen

FCC-hh beamscreen



R. Kersevan, C. Garion, et al.

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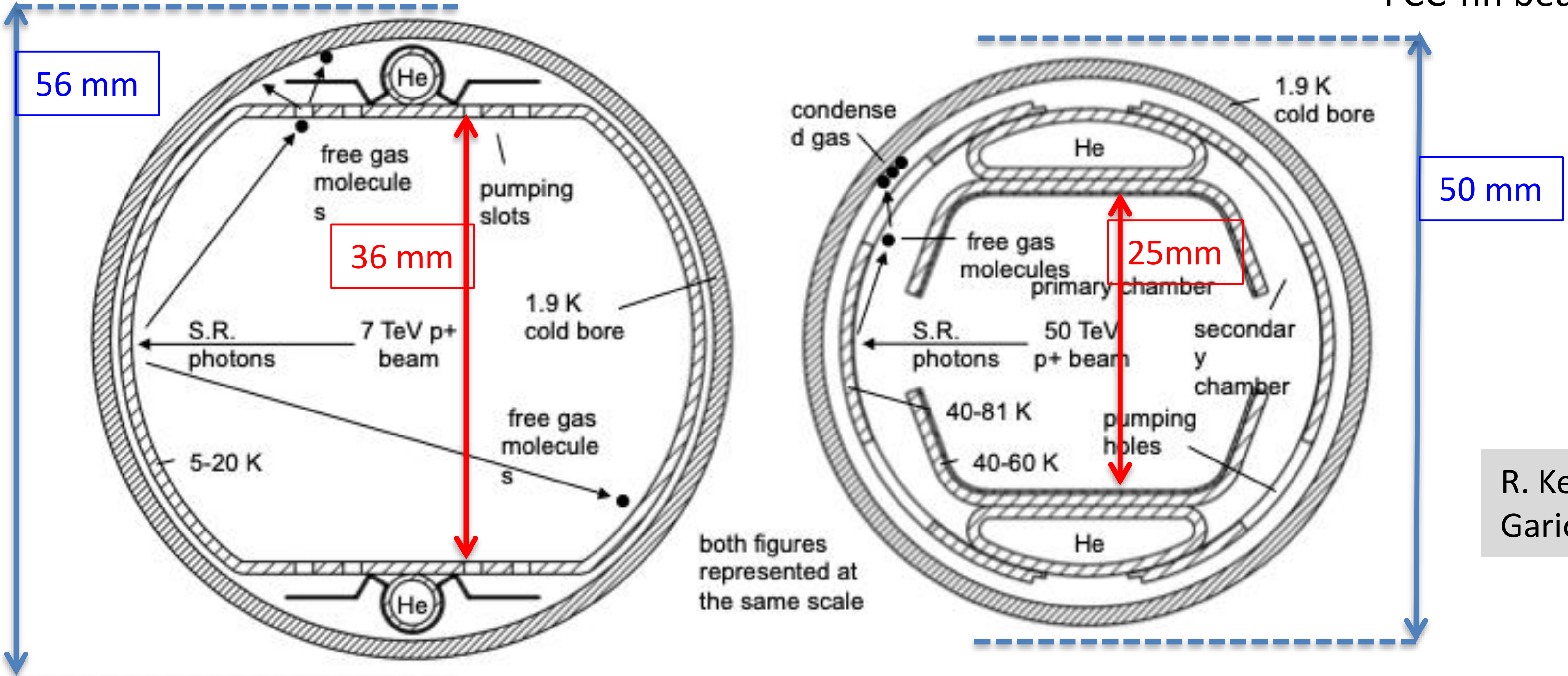
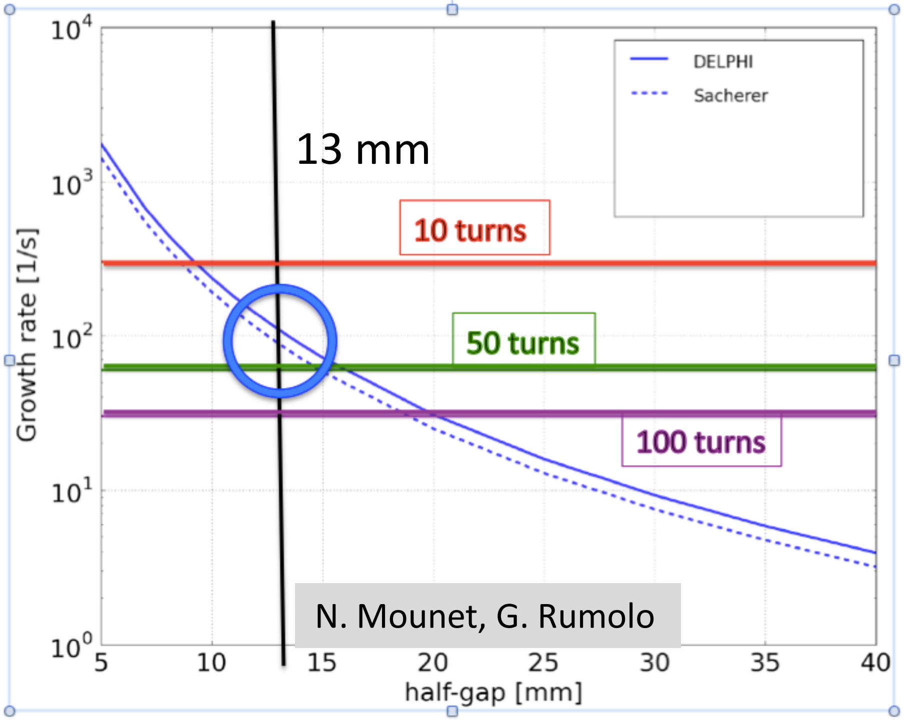


R. Kersevan, C. Garion, et al.

Beamscreen Radius

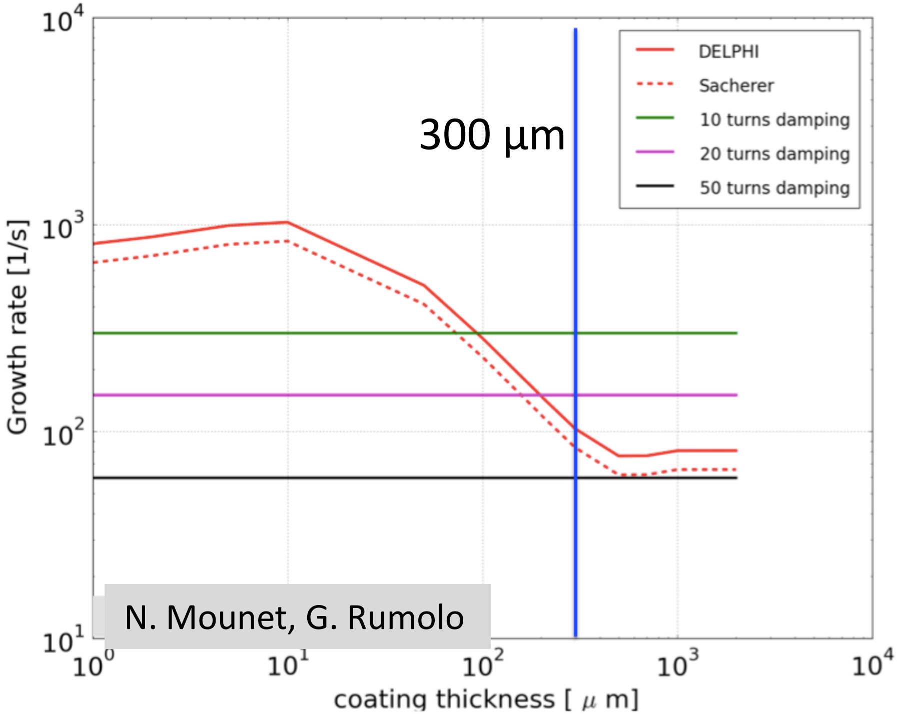
Identify minimum radius of copper tube that is acceptable



N. Mounet, G. Rumolo

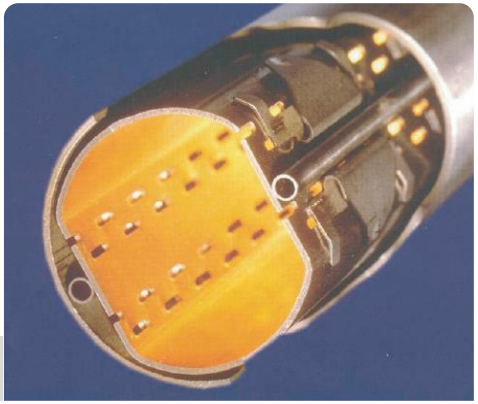
Identify minimum thickness of copper coating
Skin depth of lowest relevant frequency
$F = F_{rev}\ (1-\Delta Q)$, chose $\Delta Q < 0.5$

Note: hard for quench



N. Mounet, G. Rumolo

Hide pumping holes (they would limit charge to $1.5\text{x}10^{11}$ => not enough margin)



X. Buffat et al.

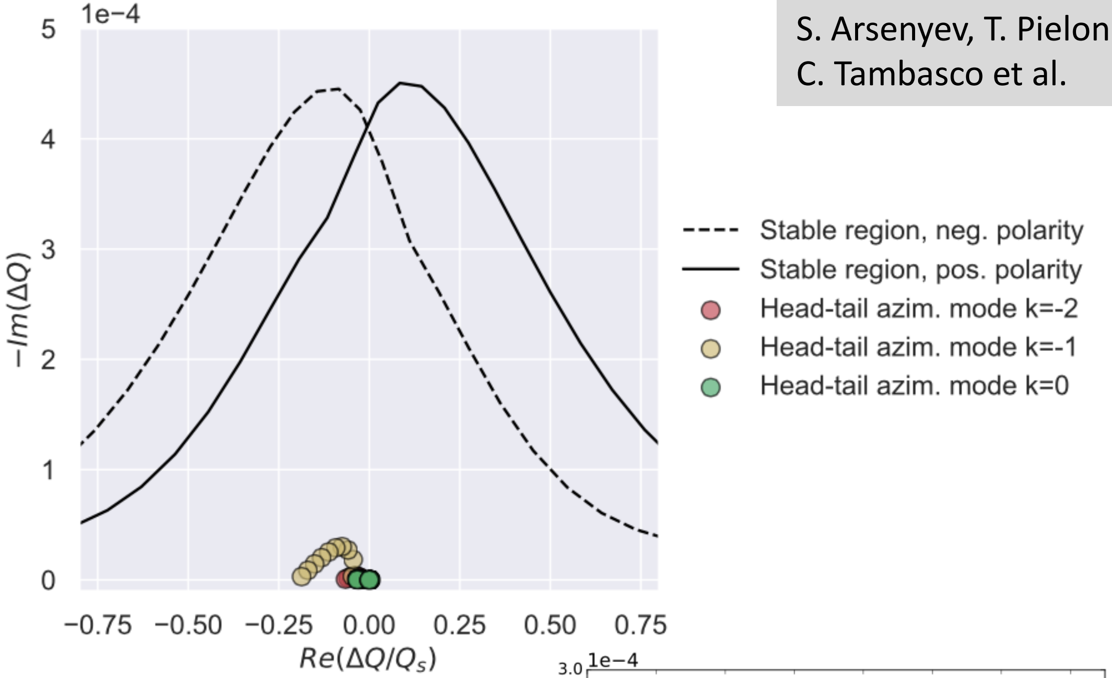
Multi-Bunch Instability

S. Arsenyev, T. Pieloni, C. Tambasco et al.

At injection curing rigid bunch mode with octupoles would spoil dynamic aperture, at top energy would need many octupoles

$\Rightarrow$ Cure it with feedback

Feedback reasonable (at injection 20 turns damping to cure 65 turns rise time, at flat top 150 vs. 460)



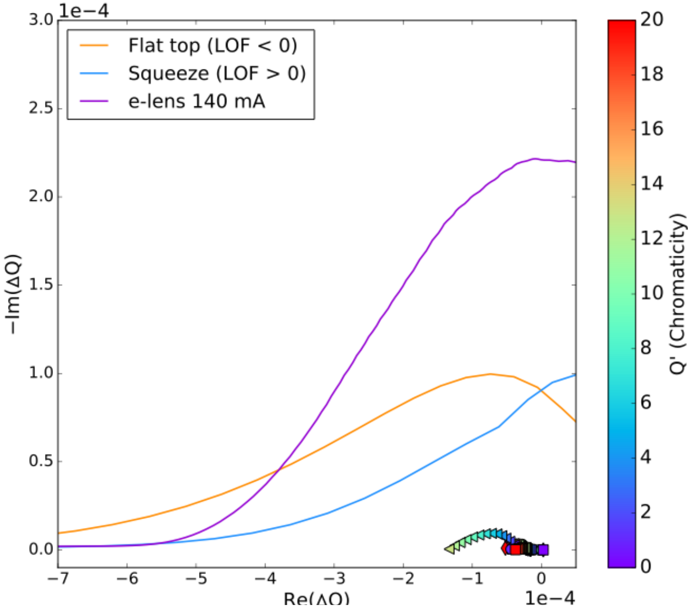
Stabilise higher modes with octupoles

Worst case is non-zero chromaticity

$\Rightarrow$ Perform a scan to identify it

Or use electron lens, RF quadrupoles, intra-bunch feedback

Note: low noise required tolerance of beam jitter tolerance 10^{-4} of beam size



Collision Considerations

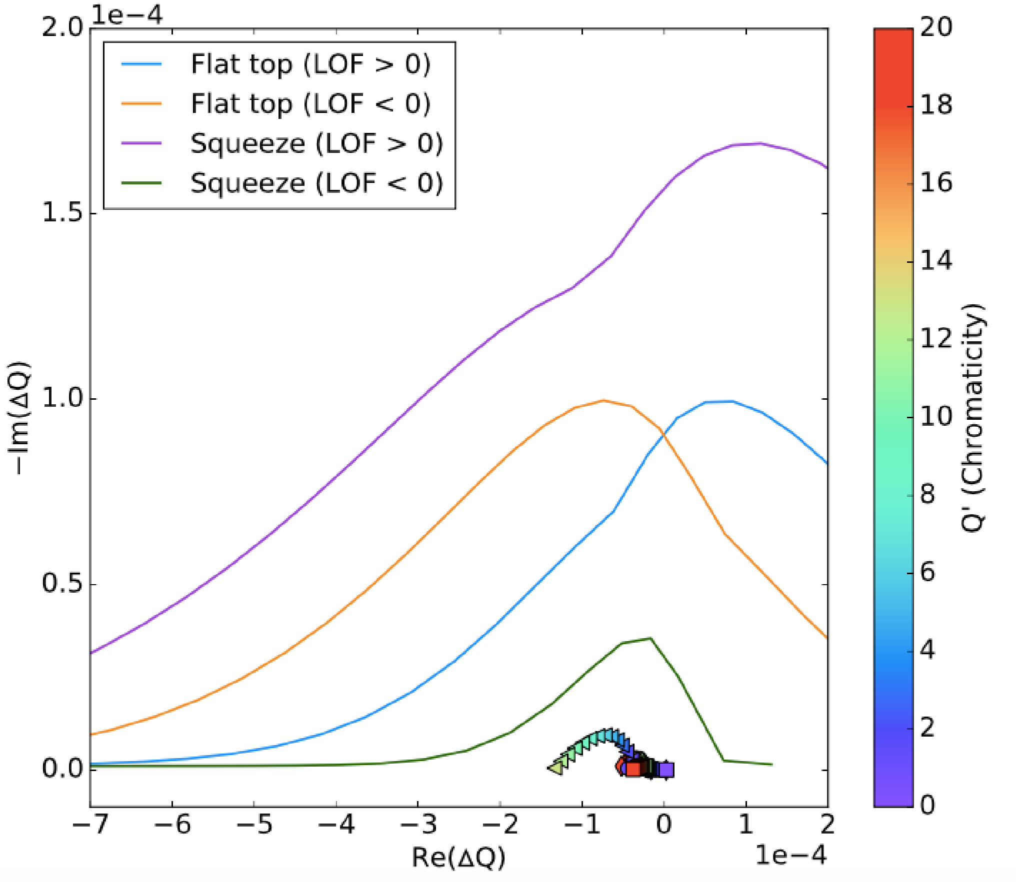
- Depending on polarity octupoles add or subtract from beam-beam effect
- Enhanced stability but reduced dynamic aperture
- Or reduced stability and larger dynamic aperture

Solution is collide and squeeze

But if we go out of collision during the run?

Other options might be easier to use

- But more study required to make sure we fully understand implications



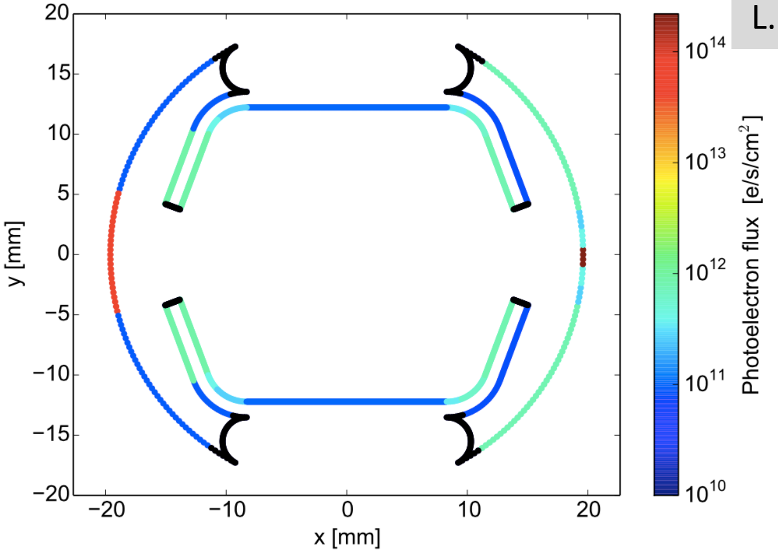
T. Pieloni,
C. Tambasco et al.

Electron Cloud Instability

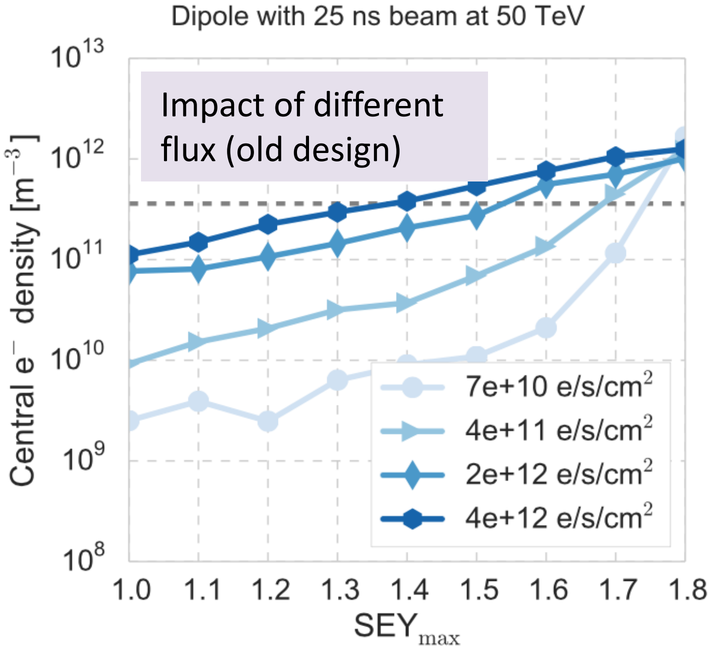
Well known instability (and heat source)

Use three countermeasures
- Beamscreen geometry
- Surface treatment
- Beam parameters

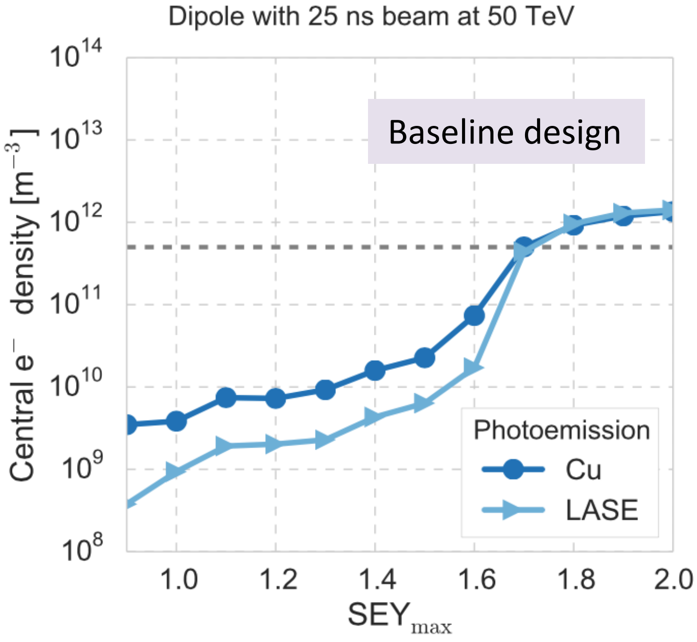
Already direct photo-production of electrons can render beam unstable
- Beamscreen design minimises reflection of photons into main chamber



L. Mether



Impact of different flux (old design)



Baseline design

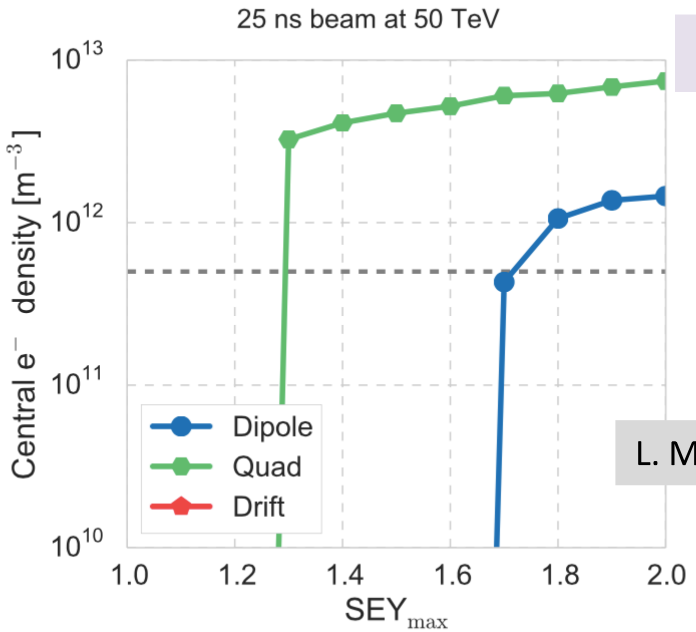
Design looks robust

Electron Cloud Instability II

Beam stability ensured by coating or laser treatment for nominal 25 ns spacing

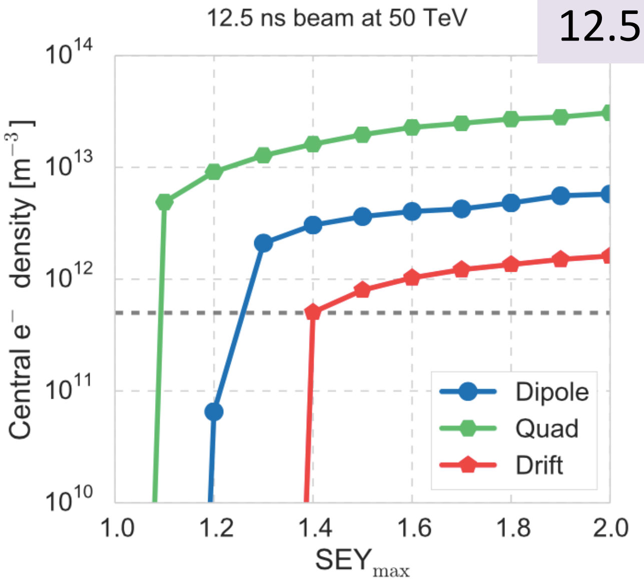
But little / no margin for 5 and 12.5 ns
⇒ Important impact on parameter choice

Better ecloud suppression or mitigation of instability would be very important

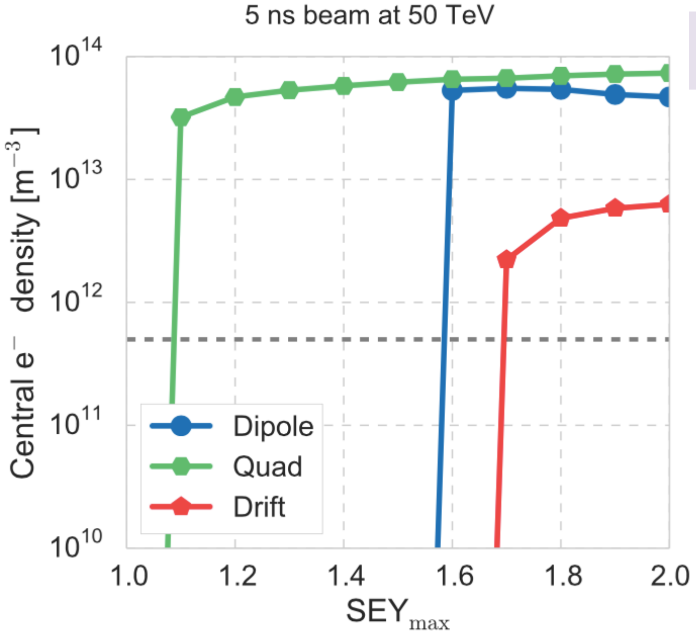

25 ns beam at 50 TeV

25 ns

L. Mether


12.5 ns beam at 50 TeV

12.5 ns


5 ns beam at 50 TeV

5 ns

Potential Improvements

Collective instability mitigation is consistent with improved current technology

- Because it has been built into the design …

Improvements would enable design changes

- Currently, main limitation is electron cloud, which prevents < 25 ns bunch spacing
  - Electron cloud mitigation could remove this limit
    - Better coating
    - Solenoids, clearing electrodes, …
- Better beam stability could allow for larger beam current or smaller magnet aperture or lower injection energy
  - Increase of beam current would lead to more integrated luminosity
  - But current also limited by synchrotron radiation and damage potential

  - Lower injection energy or smaller aperture could reduce project cost
  - But aperture limitation from dynamic aperture not too different for the moment
- Beam-beam limit seems OK
  - But more margin is always welcome

Conclusion

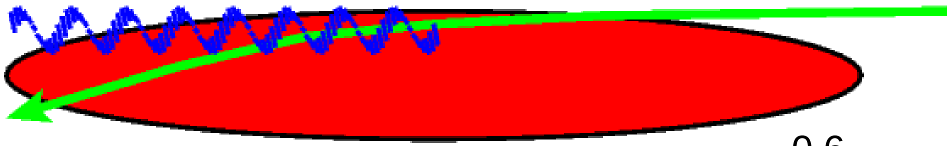
- Collective instabilities are parameter drivers for FCC-hh and linear colliders

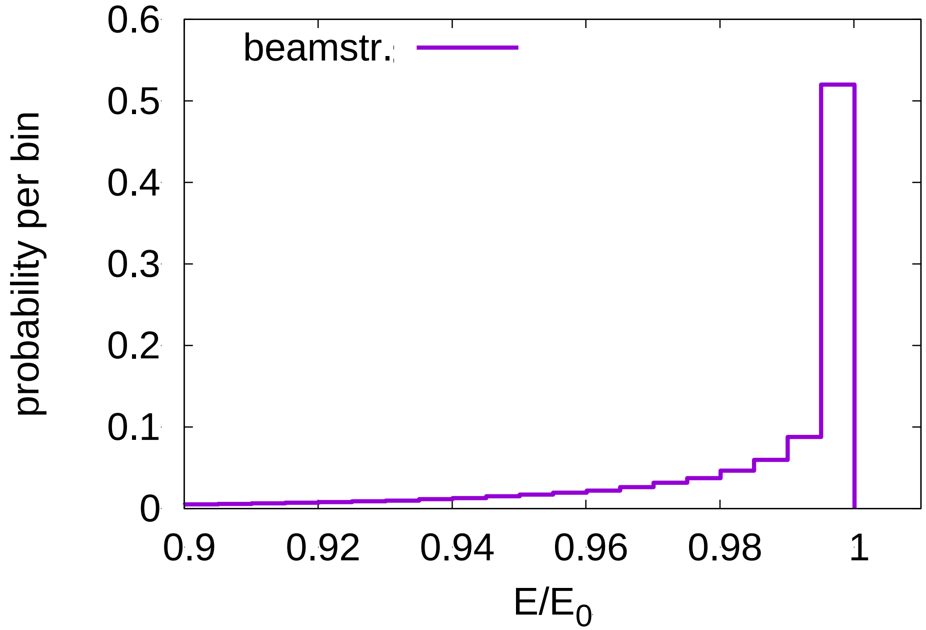
- They are in part mitigated by technical means
  - Feedback
  - Electron-cloud coatings
  - Low impedance design
  - Damping
  - …

- In part they are mitigated by parameter choices
  - CLIC: Bunch charge and length, bunch spacing
  - Bunch size at CLIC IP
  - FCC-hh: Bunch spacing, magnet aperture

Reserve

Beamstrahlung





Number of photons dominates $L_{0.01}/L$

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

$$+$$

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

$$\sigma_x \gg \sigma_y$$

$$\sigma_x + \sigma_y \approx \sigma_x$$

$$\rightarrow$$

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

$$\boxed{\propto n_\gamma}$$

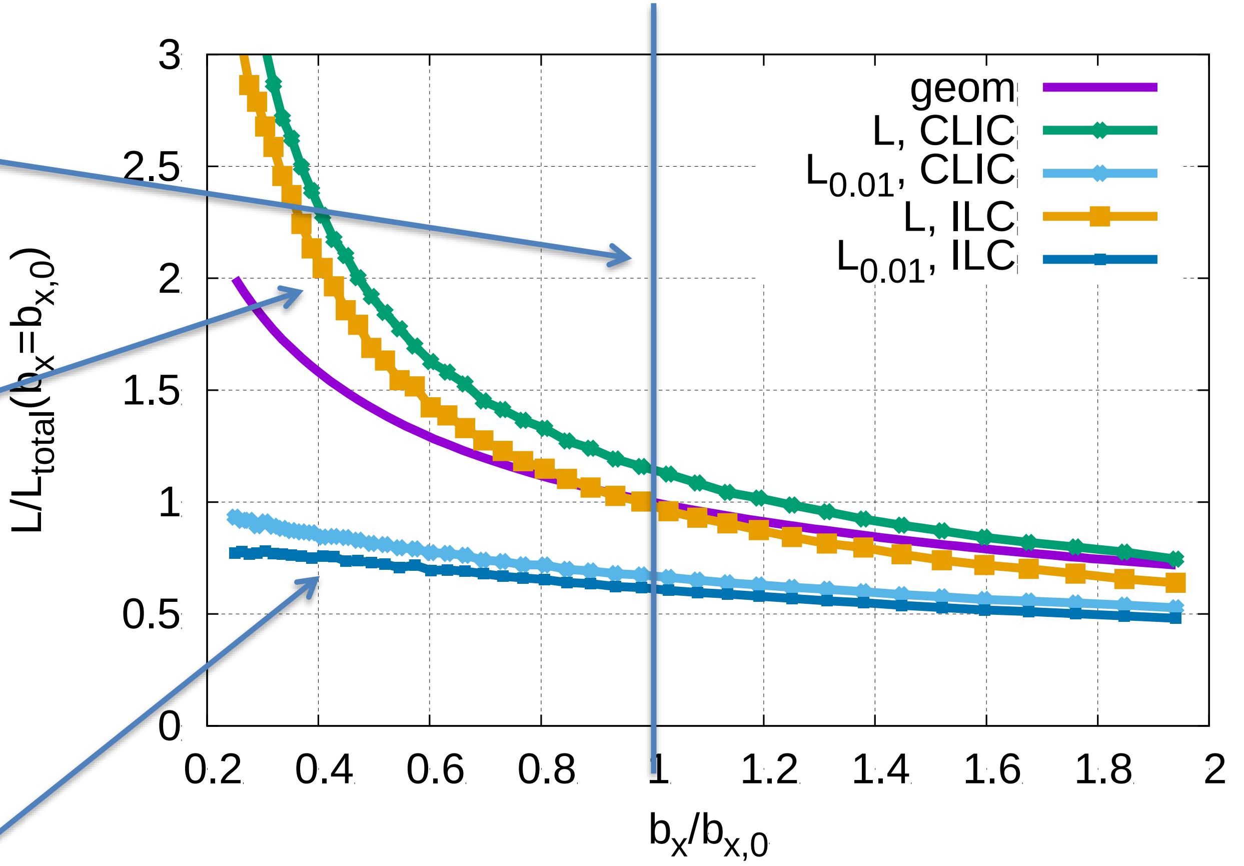
Luminosity Spectrum

Design value
$L_{0.01}/L$=60%

The total luminosity L varies strongly with beta-function

But $L_{0.01}$ does not change so much

Hard to push beta-functions
That low



So tend to use $L_{0.01}/L$=60% as criterion

Reasonable compromise for most physics studies

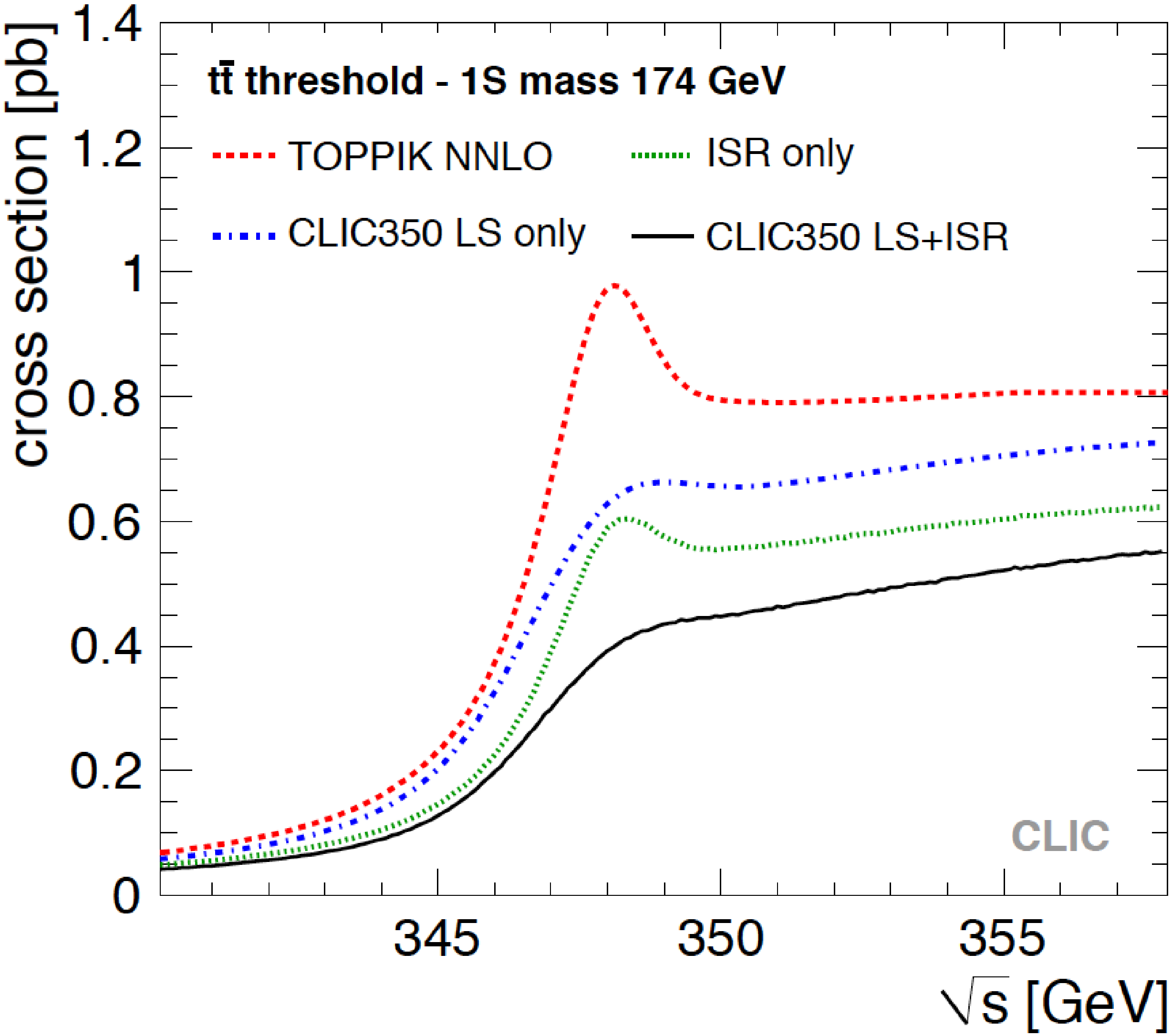
Top Production at Threshold

K. Seidel et al. **arXiv:1303.3758**

Top production at threshold is strongly affected by beam energy spread and beamstrahlung

For $L_{0.01} > 0.6$ L impact of beamstrahlung is comparable to ISR

But depends on physics



Note: Luminosity Drivers

In the classical regime

$$\mathcal{L} \propto H_D\, n_\gamma\, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$$

In the quantum regime

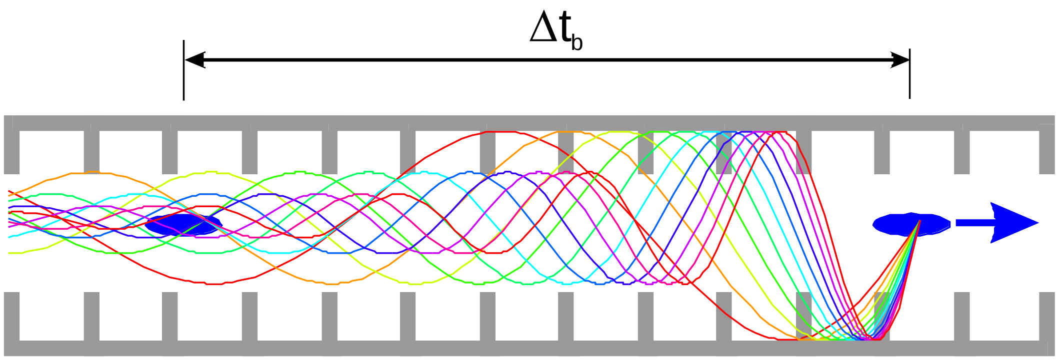
$$\mathcal{L} \propto H_D \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}}\, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$$

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

CLIC Main Linac Pulse Optimisation

Power to beam $$P'_{beam} = IG$$

Power lost in structure $$P'_{loss} = \frac{G^2}{R'}$$



$$\frac{P'_{beam}}{P'_{loss}} = \frac{R'}{Q} Q \frac{I}{G}$$

Maximise current:

- Maximise bunch charge
- Minimise distance between bunches

Go to the limit! See in the following

High R'/Q (small iris **a**) helps for maximum gradient
Less power needed to generate gradient

But high R'/Q (small **a**) is bad for beam stability

Low gradient G makes machine expensive

Well, it is copper …

Need to compromise between R'/Q, G and I

For Reference: Simplified Treatment

Assume

- $W_z(s) = W_z = \mathrm{const}$
- uniform bunch with length $L \ll \lambda$
- and use linear approximation

Field seen by first particle

$$G_H = G\cos\left(\phi - \frac{L}{2}\frac{2\pi}{\lambda}\right) \approx G\left(\cos(\phi) - \frac{L}{2}\frac{2\pi}{\lambda}\sin(\phi)\right)$$

Field seen by last particle

$$G_T = G\cos\left(\phi + \frac{L}{2}\frac{2\pi}{\lambda}\right) \approx G\left(\cos(\phi) + \frac{L}{2}\frac{2\pi}{\lambda}\sin(\phi)\right) - NeW_z$$

We require (this automatically solves the equation for all other particles)

$$G_H = G_T$$

which leads to

$$L = \frac{NeW_z}{G}\frac{\lambda}{2\pi\sin(\phi)}$$

Impedance Effect Scalings

Or: Why was a potential problem to be expected?

Impedance effects scale as

Low. Freq. Multi-bunch $\frac{Z_\perp \beta C}{E} I$

Single bunch $\frac{Z_\perp \beta C}{E} N$

Resistive wall impedance $Z_\perp \propto \frac{\sqrt{\rho}}{b^3}$

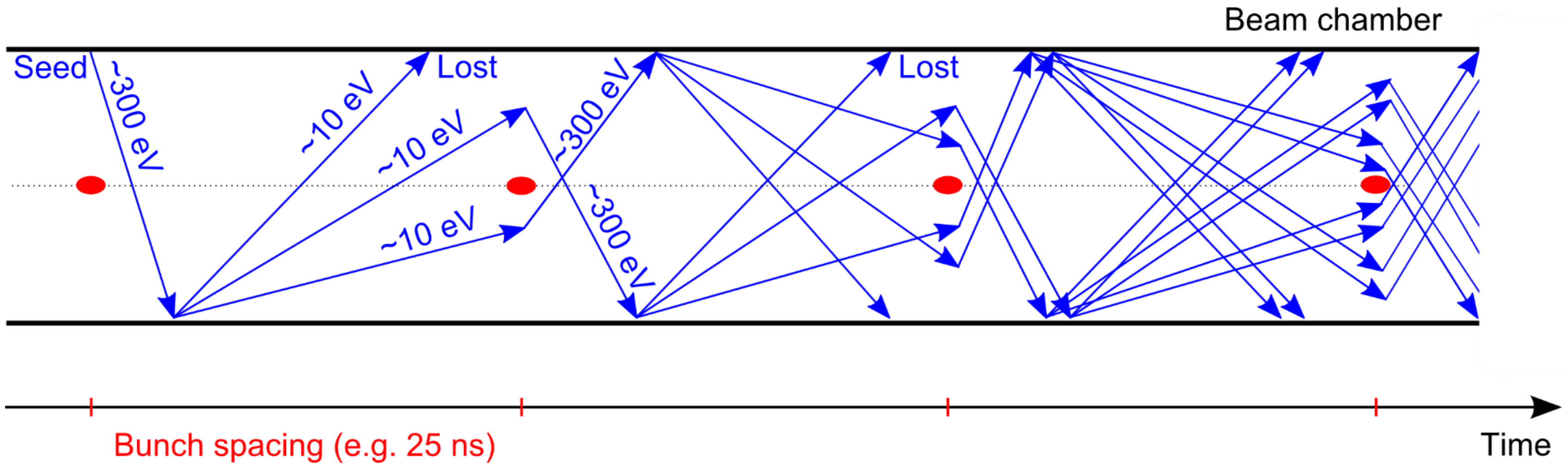
Ratio of FHC to LHC impedance effect scale

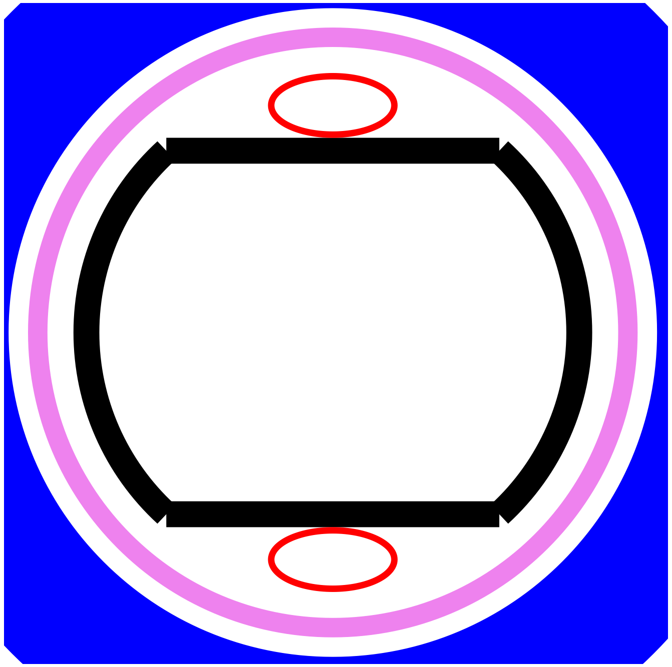
$$R_{FHC/LHC} = \left(\frac{b_{LHC}}{b_{FHC}}\right)^3 \sqrt{\frac{\rho_{FHC}}{\rho_{LHC}}} \frac{C_{FHC}}{C_{LHC}} \frac{\beta_{FHC}}{\beta_{LHC}} \frac{E_{LHC}}{E_{FHC}} \frac{I_{FHC}}{I_{LHC}}$$

Example at 50K and 25ns spacing

$$R_{FHC/LHC} \approx \left(\frac{18}{13}\right)^3 \sqrt{\frac{0.8}{0.24}} \frac{100}{27} \frac{132}{66} \frac{0.46}{3} \frac{1}{1.7} \approx 3.3$$

Electron Cloud Effects





Still a potential performance limitation for LHC

- Heat load
- Beam instability

Twice as many photons as in LHC

At 100 times the energy (4.3keV vs. 44eV)

- Similar to B-factories

Surface properties important like photoelectron yield, secondary emission yield, reflectivity, …

⇒ Experimental input critical

Electron Cloud Effects

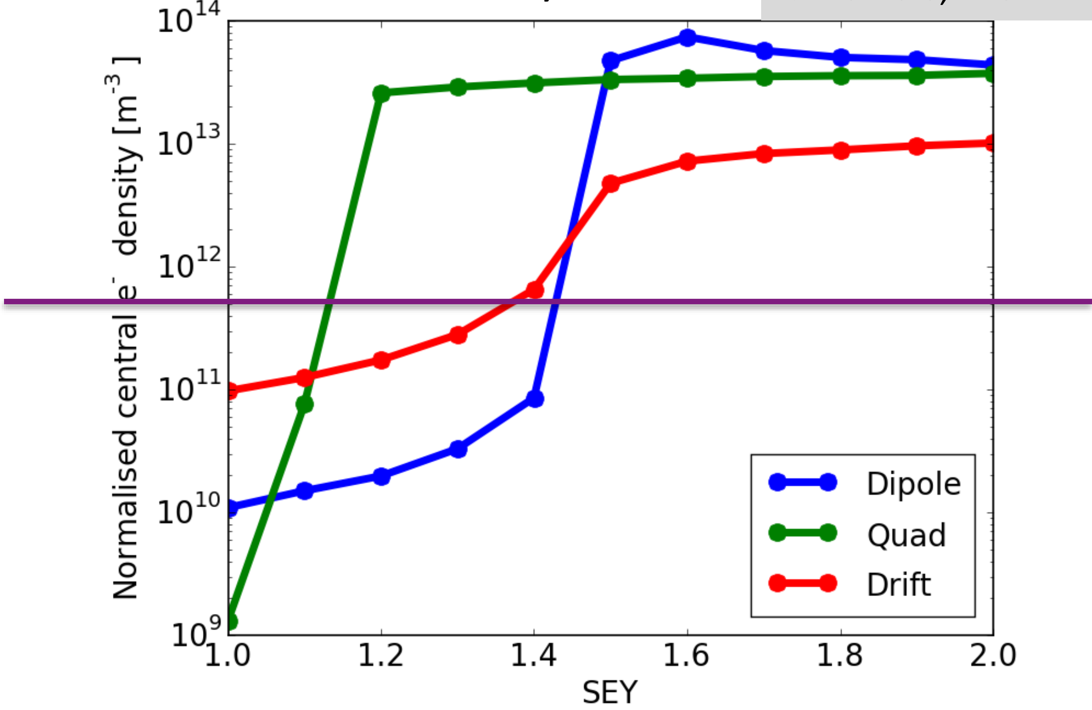
Simulations for 5ns shown

Required:
- Photoelectron yield <0.02
- Secondary emission yield δ_m<1.2
- Not much margin

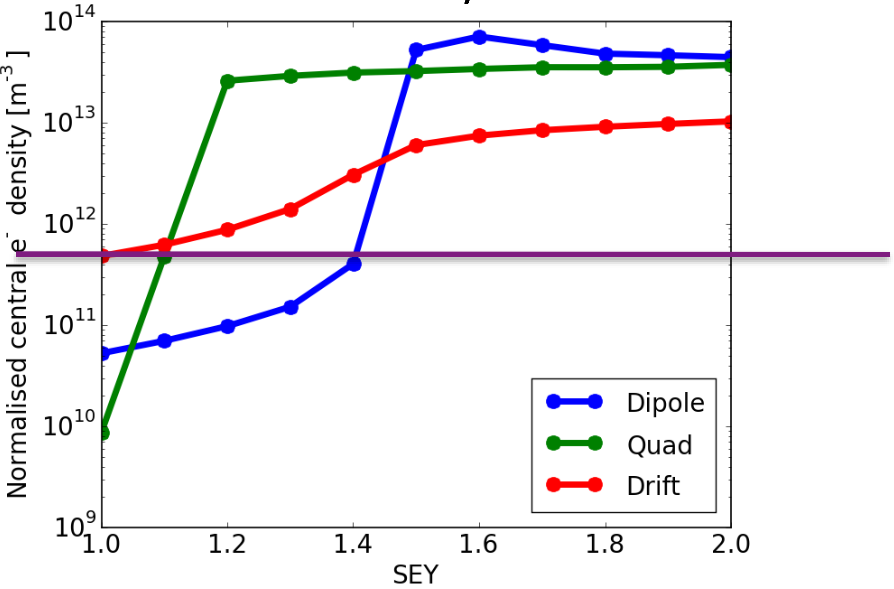
25ns is better

L. Mether,
G. Rumolo, K. Ohmi

Photoelectron yield 0.02



Photoelectron yield 0.1



⇒ Need mitigation methods

⇒ Need to measure surface properties

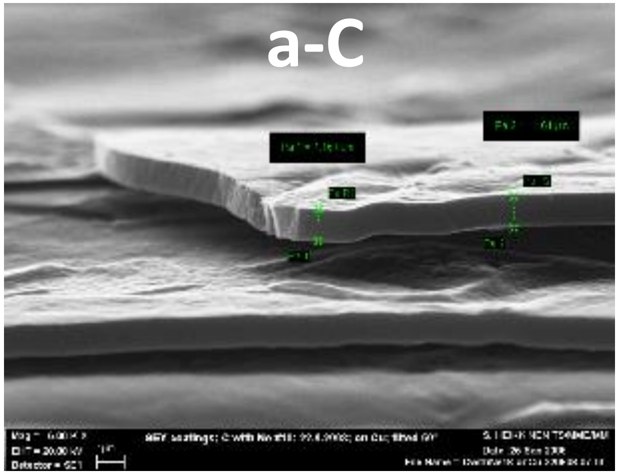
Mitigation Methods

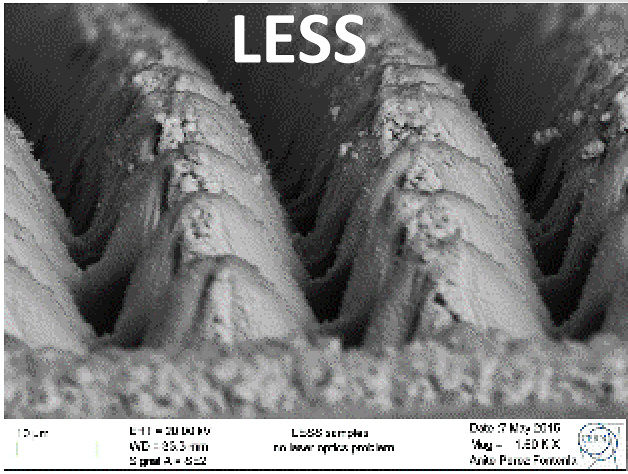
Developments for LHC are critical

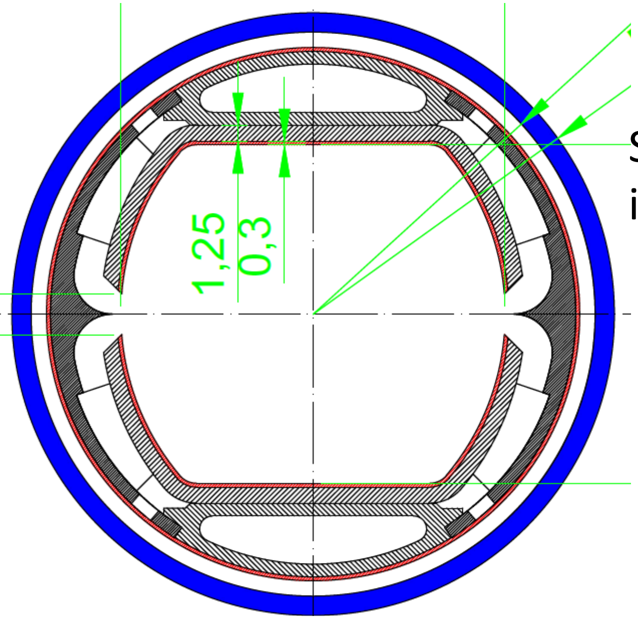
- Carbon coating
- Laser treatment of surface

Can also learn from B-factories

P. Costa Pinto et al.

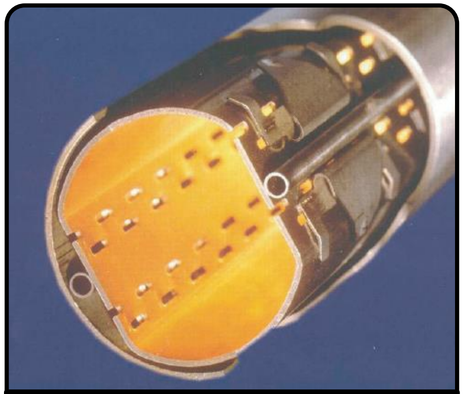






Simulation of exact geometry is important, may help

Prototype and experiments in EuroCirCol WP 4



Cryo Beam Vacuum

Low Emittance Transport Challenges

- Beam stability

  Incoming beam can jitter (have small offsets) and become unstable

  Structure design, lattice design, choice of beam parameters

- Static imperfections

  Errors of reference line, elements to reference line, elements. . .

  Excellent pre-alignment, lattice design, beam-based alignment, beam-based tuning

- Dynamic imperfections

  Element jitter, RF jitter, ground motion, beam jitter, electronic noise,. . .

  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

Luminosity Drivers

$$\mathcal{L} \propto \frac{N}{\epsilon}\frac{1}{\beta}N n_b f_r$$

Maximise the beam current

Risks:

- High stored energy and losses
- Impedance and electron cloud
- Aperture should be minimised for dipole cost
- High synchrotron radiation load due to high beam energy

Squeeze the beam as much as possible
Harder than in HL-LHC (scaling with energy)
More collision debris due to higher luminosity and energy

Limited by beam-beam effects,
emittance growth and particle losses

Somewhat more difficult than HL-LHC
due to longer L^*

For integrated luminosity:

- Fast turn-around critical for luminosity
- Minimise time for stops etc.
- High availability with more components than LHC
- Maximising current also maximises time between new fills