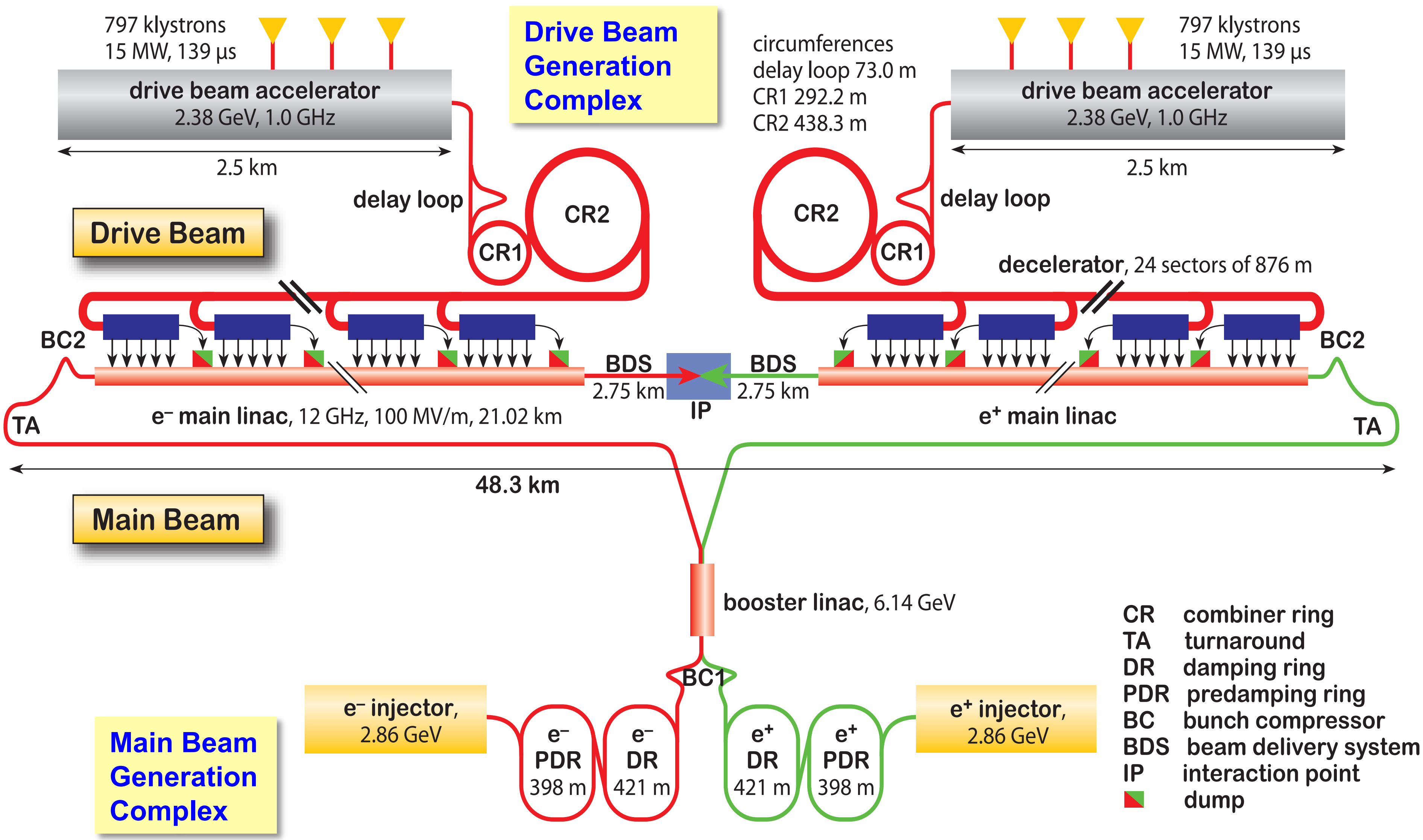
Introduction to the CLIC Accelerator and to the Sources of Beam-induced Background

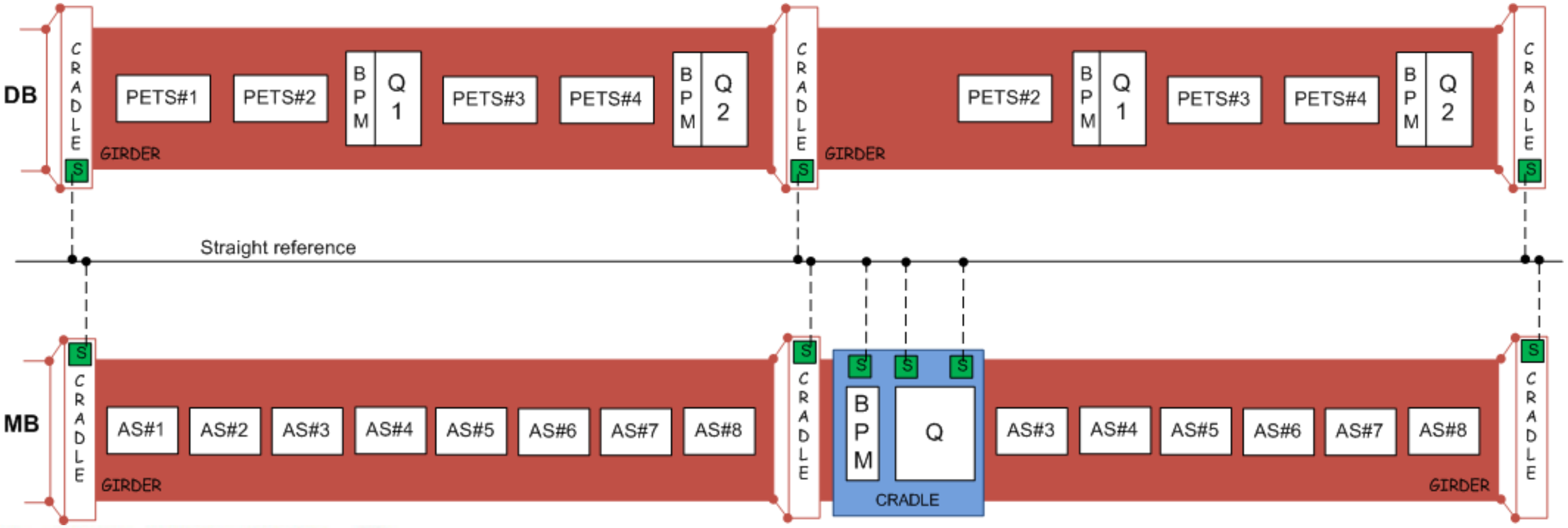
D. Schulte for the CLIC team

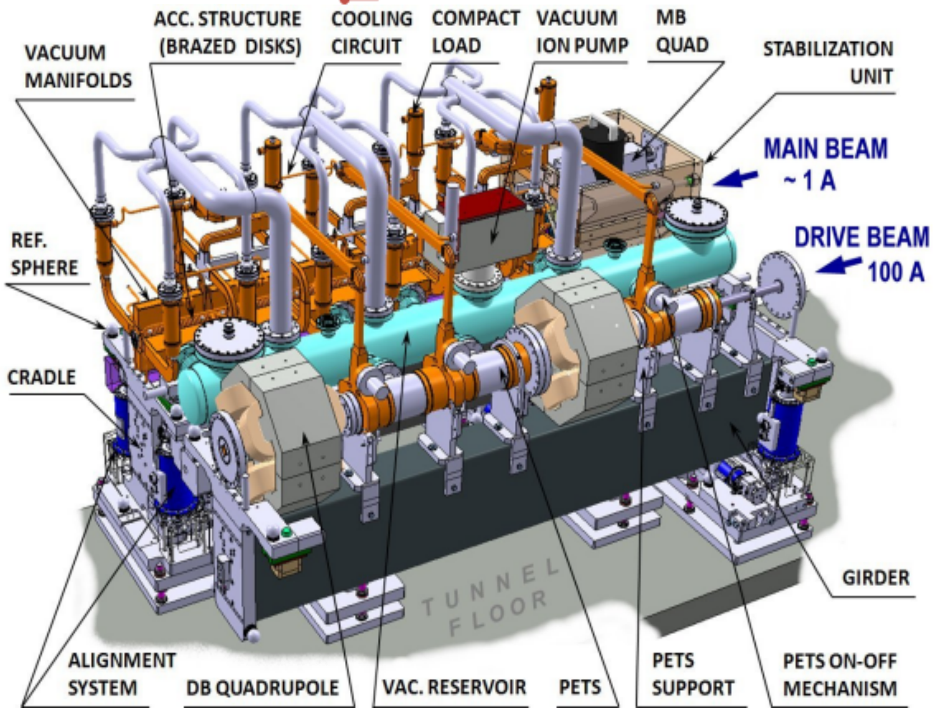
Layout at 3 TeV

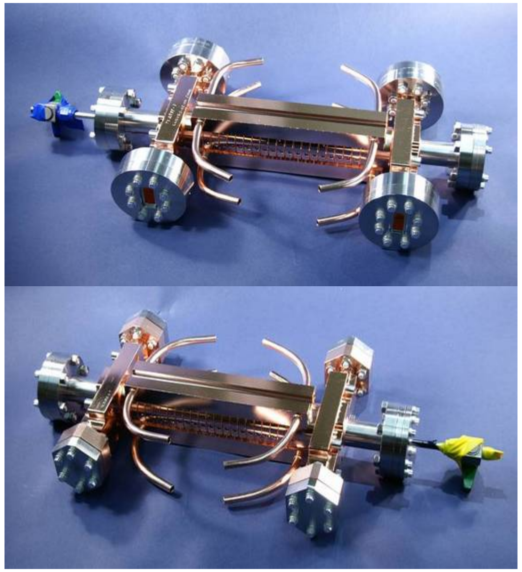


Vol 1, 2.2.1

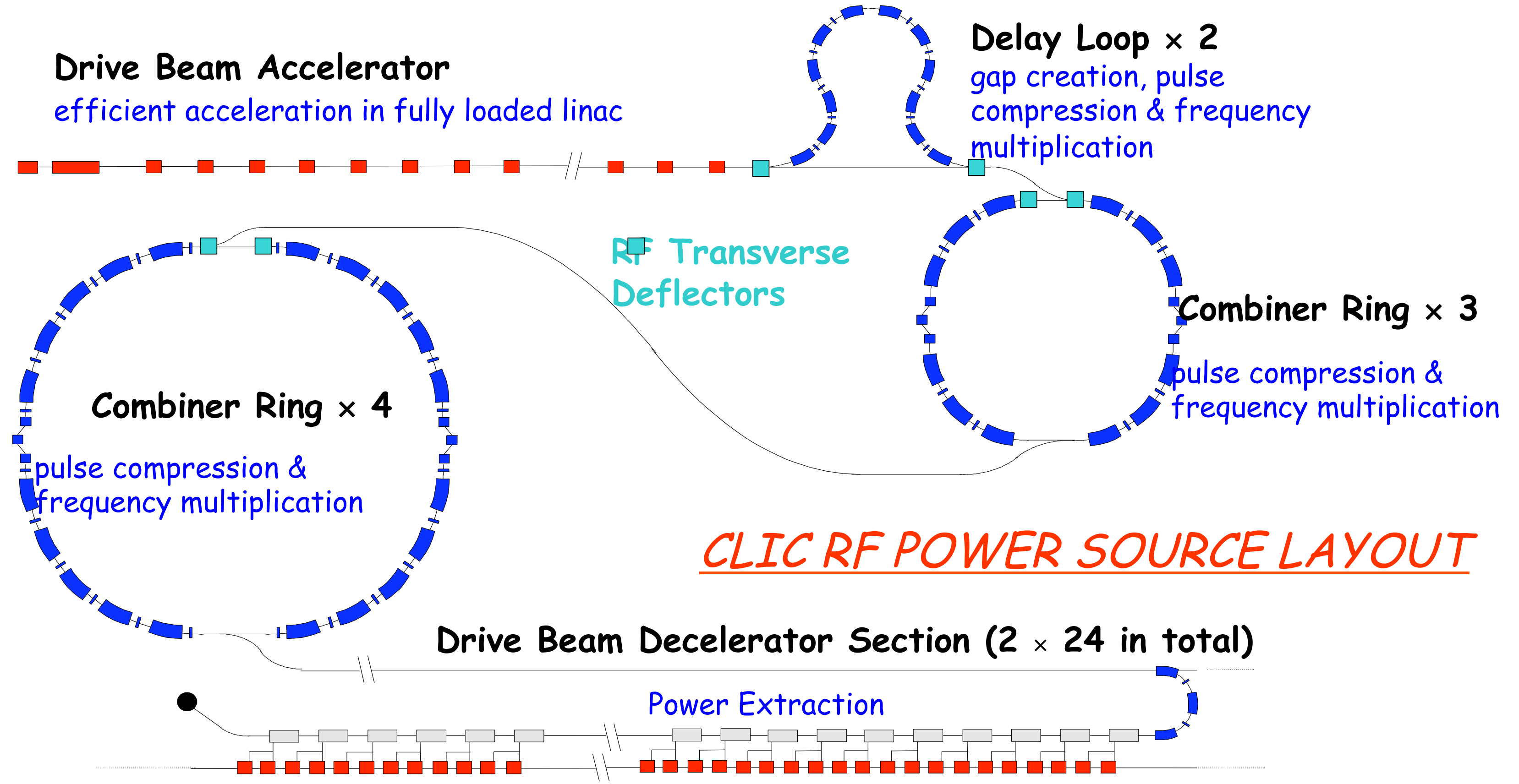
Two Beam Acceleration



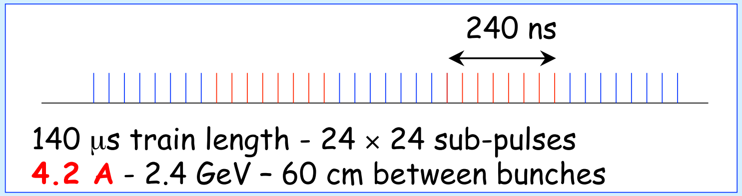




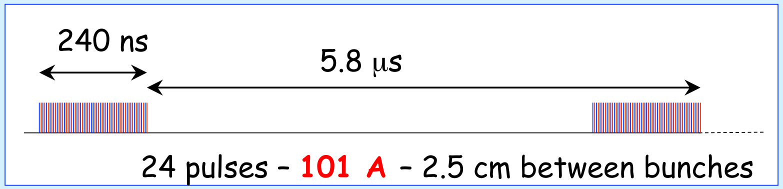
CLIC Power Source Concept



Drive beam time structure - initial



Drive beam time structure - final



Current CLIC Energy Stages

parameter	symbol		
centre of mass energy	E_{cm} [GeV]	500	3000
luminosity	$\mathcal{L}$ $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2
gradient	G [MV/m]	80	100
site length	[km]	13	48.3
charge per bunch	N $[10^9]$	6.8	3.72
bunch length	σ_z [μm]	70	44
IP beam size	σ_x/σ_y [nm]	200/2.26	40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20
bunches per pulse	n_b	354	312
distance between bunches	Δ_b [ns]	0.5	0.5
repetition rate	f_r [Hz]	50	50
est. power cons.	P_{wall} [MW]	240	560

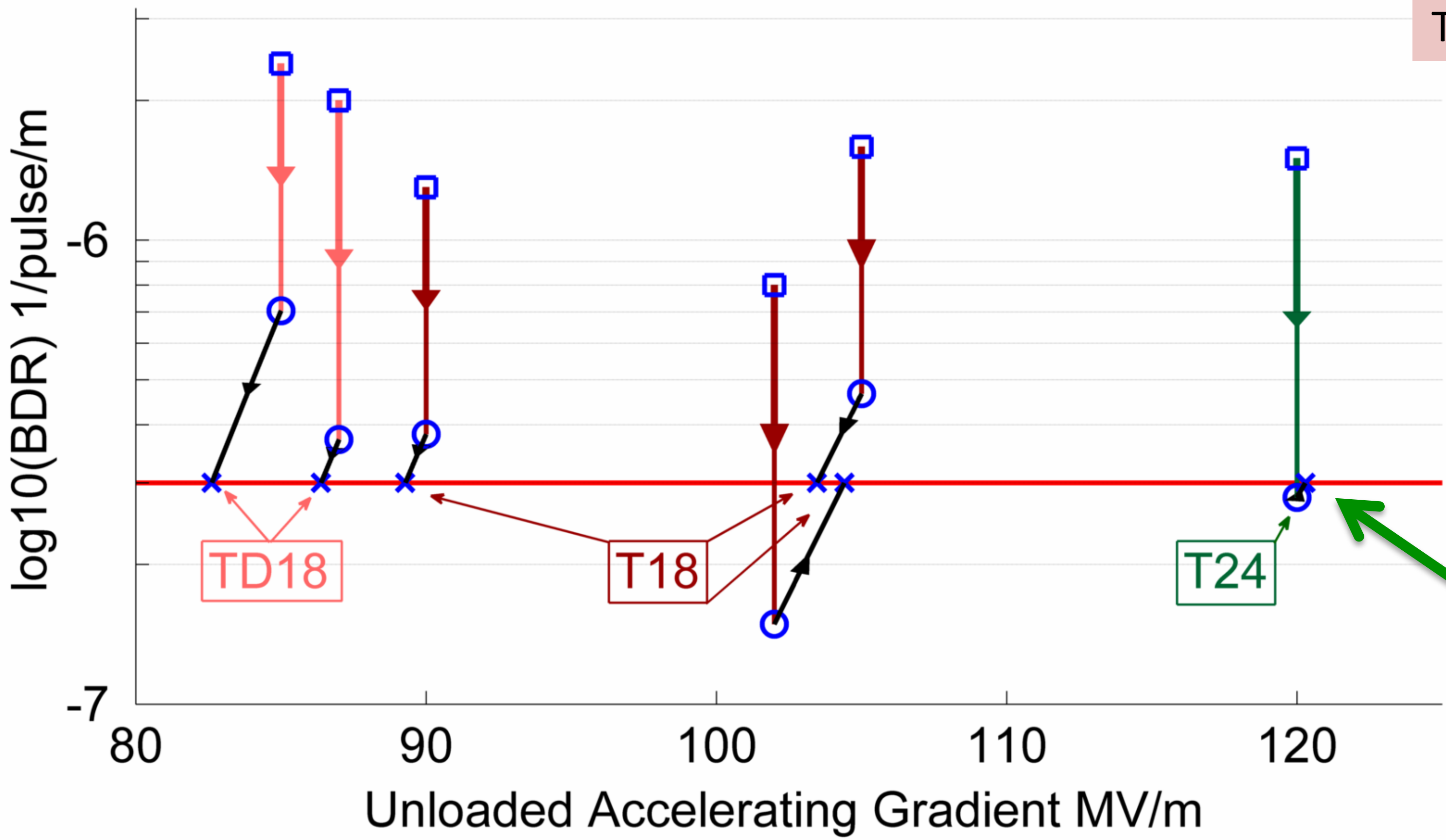
Key Design Issues

Main linac gradient	–	Accelerating structure
Drive beam scheme	–	Drive beam generation
	–	PETS
	–	Two beam module
	–	Drive beam deceleration
Luminosity	–	Main beam emittance generation and preservation, focusing
	–	Alignment and stabilisation
Operation and Machine Protection System (robustness)		
Detector (experimental conditions)		

Machine issues covered in volume 1

Achieved Gradient

Tests at KEK and SLAC



Measurements scaled according to

$$p \propto G^{30}\tau^{5}$$

Some input power as 100MV/m loaded

	Simple early design to get started	More efficient fully optimised structure
No damping waveguides	T18	T24
Damping waveguides	TD18	TD24 = CLIC goal

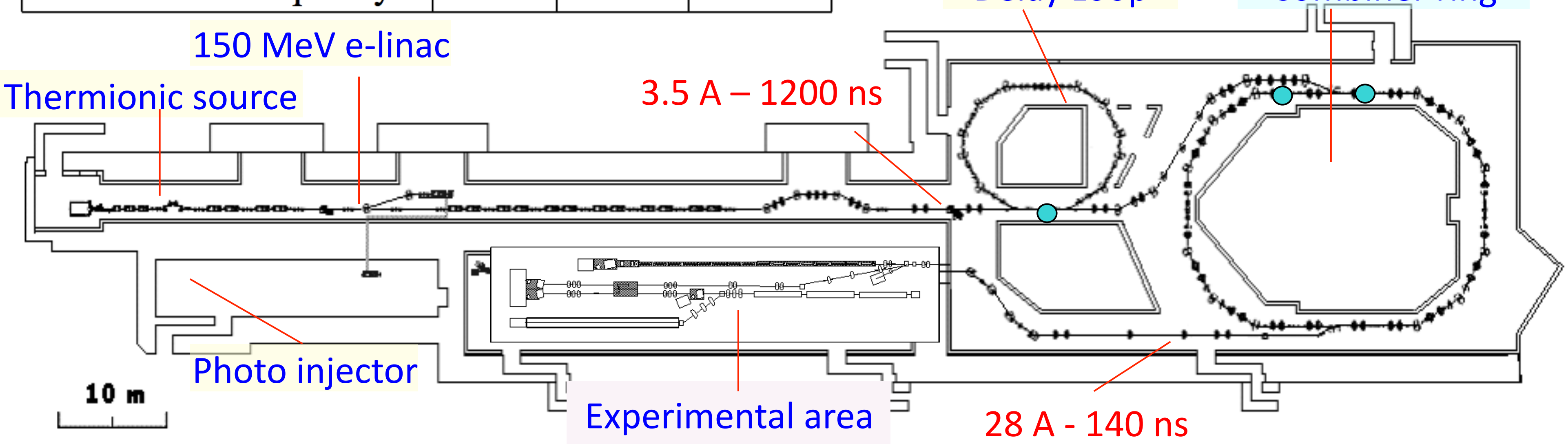
CLIC RF team
N. Shipman

TD24: September 15th @ KEK
mid-November @ SLAC
Soon @ CERN

CLIC Test Facility (CTF3)

parameter	unit	CLIC	CTF3
accelerated current	A	4.2	3.5
combined current	A	101	28
final energy	MeV	2400	$\approx$ 120
accelerated pulse length	μs	140	1.2
final pulse length	ns	240	140
acceleration frequency	GHz	1	3
final bunch frequency	GHz	12	12

Recycled infrastructure
- made it affordable
- causes lots of headache



Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

Luminosity spectrum

Beam current

Beam Quality (+bunch length)

In the quantum regime for beamstrahlung

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

Luminosity and Parameter Drivers

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

Maximum peak:

$$n_\gamma \approx 2$$

Efficiency
Scales as:

$$\eta_{RF->beam} \propto \frac{N}{\Delta z}$$

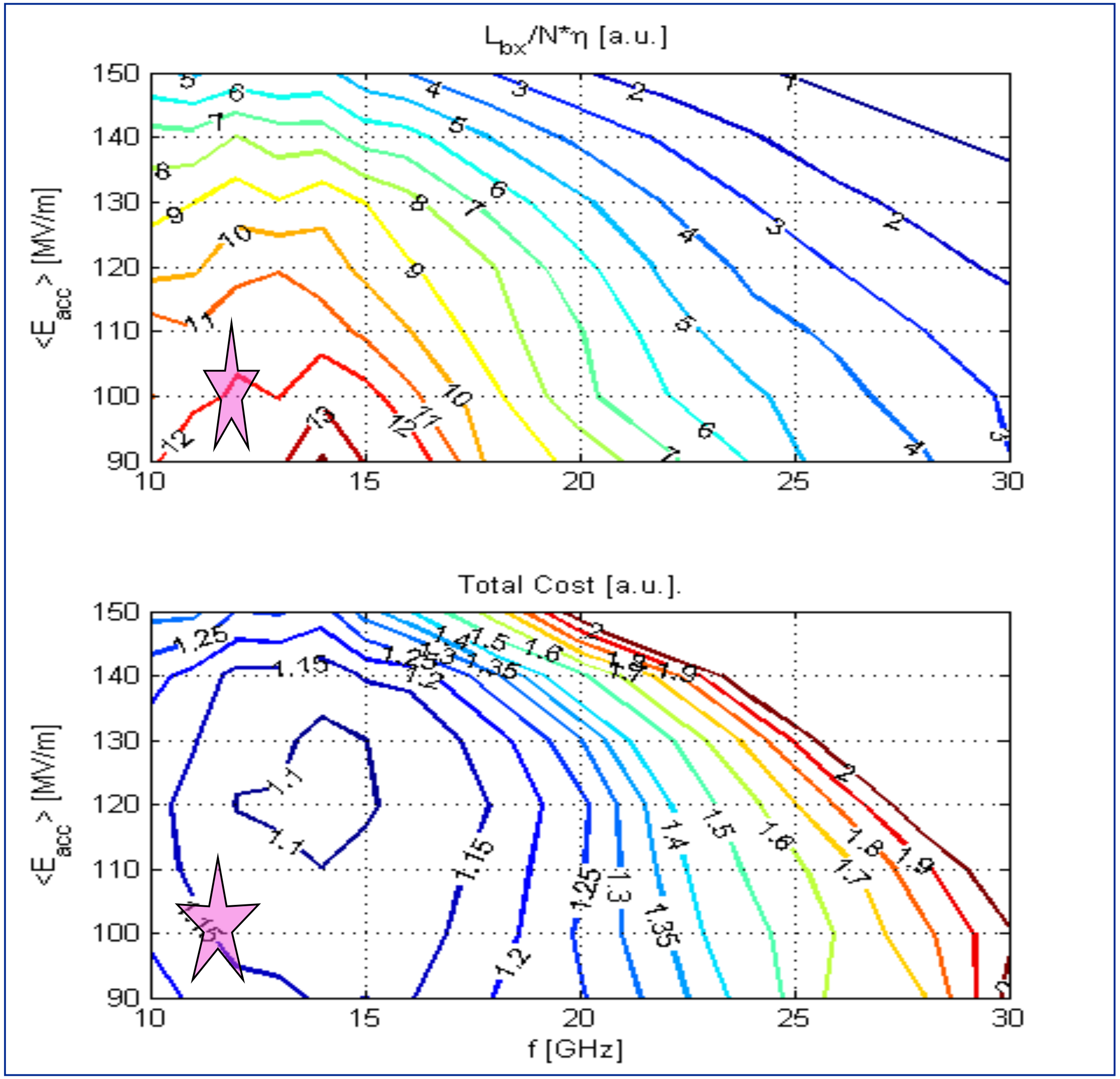
Minimum beam size:

$$\sigma_y \approx 1\,\mathrm{nm}$$

3TeV Parameter Optimisation

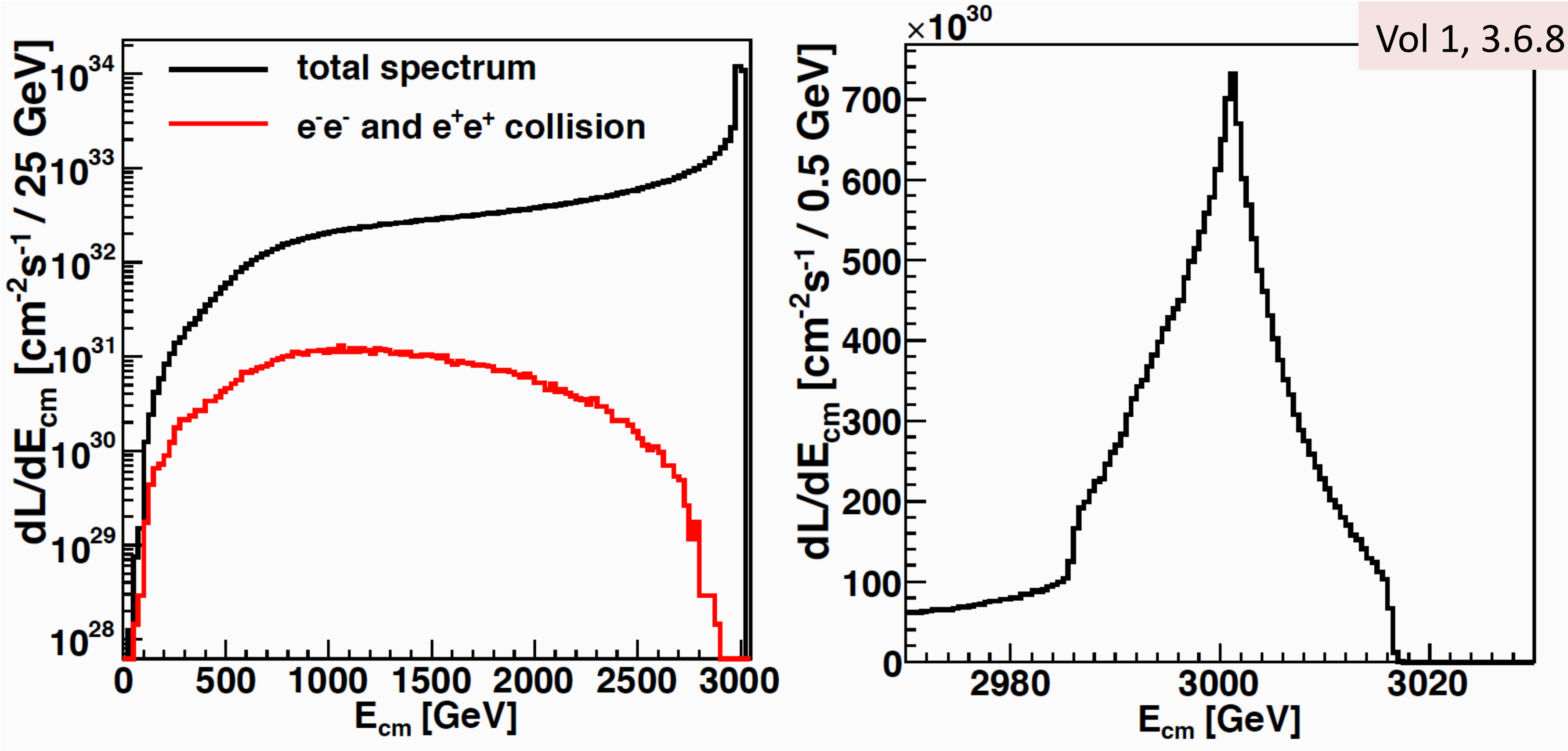
Optimisation:

- Minimise cost for fixed luminosity $L_{0.01}$
- Physics constraint
  - $L_{0.01} > 0.3$ L
- No constraints on background
  - Regarded as perturbation



Luminosity Spectrum

Vol 1, 3.6.8.1

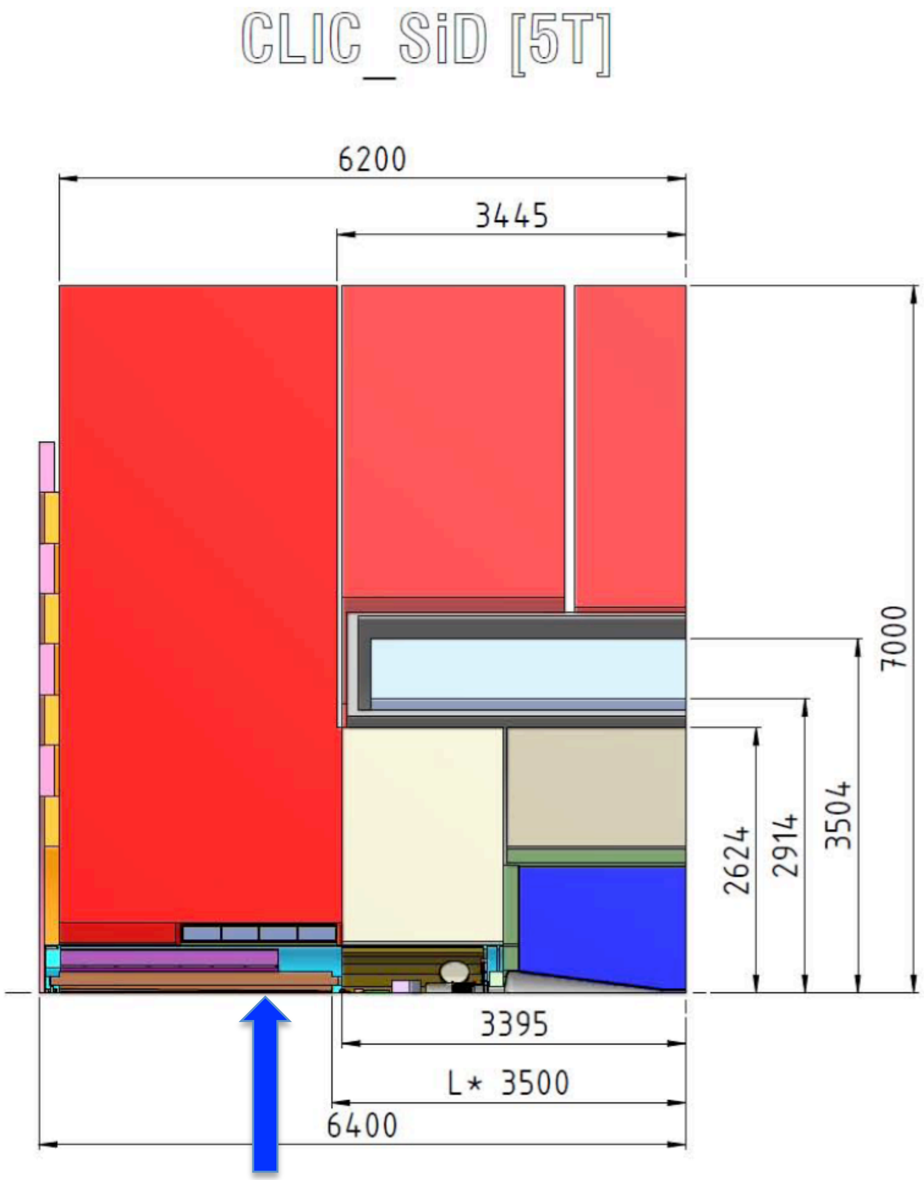


Includes beam energy spread (ML RF) and beamstrahlung (n_γ=2.1)

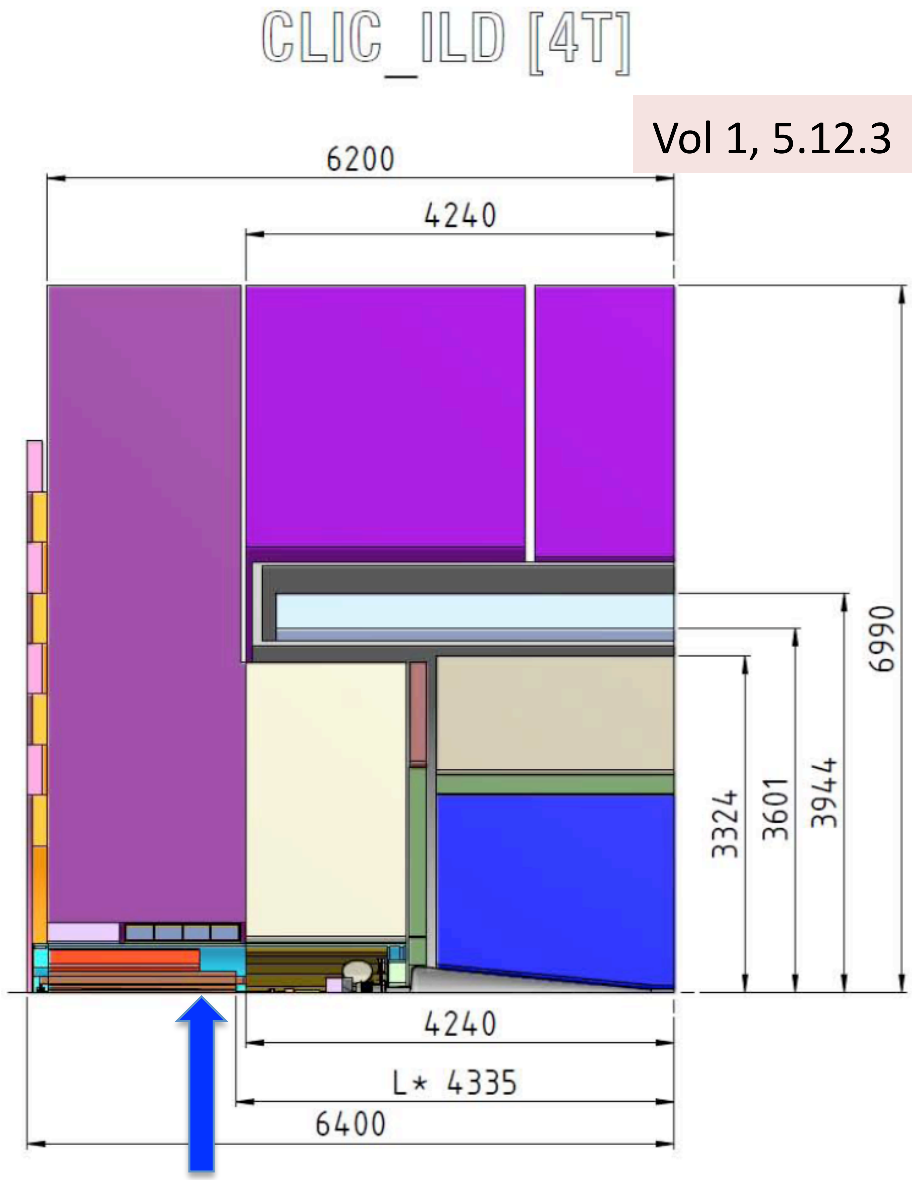
$L_{0.01}$=2 10^{34} $cm^{-2}s^{-1}$ L=5.9 10^{34} $cm^{-2}s^{-1}$

Provided file with full correlations for CALYPSO

MDI



Vol 1, 5.12.3



Choice of L*

Longer L* would be beneficial
- detector design
  - angular coverage
  - shielding solenoid
- final quadrupole stabilisation

But it reduces luminosity

-> use 3.5m/4.3m as a baseline

-> all studies performed at 3.5m, some at 4.3m

Vol 1, *2.5.3.7*

L* [m]	total luminosity $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	peak luminosity $[10^{34}\text{cm}^{-2}\text{s}^{-1}]$
3.5	6.9	2.5
4.3	6.4	2.4
6	5.0	2.1
8	4.0	1.7

Luminosity includes 20% overhead for imperfections

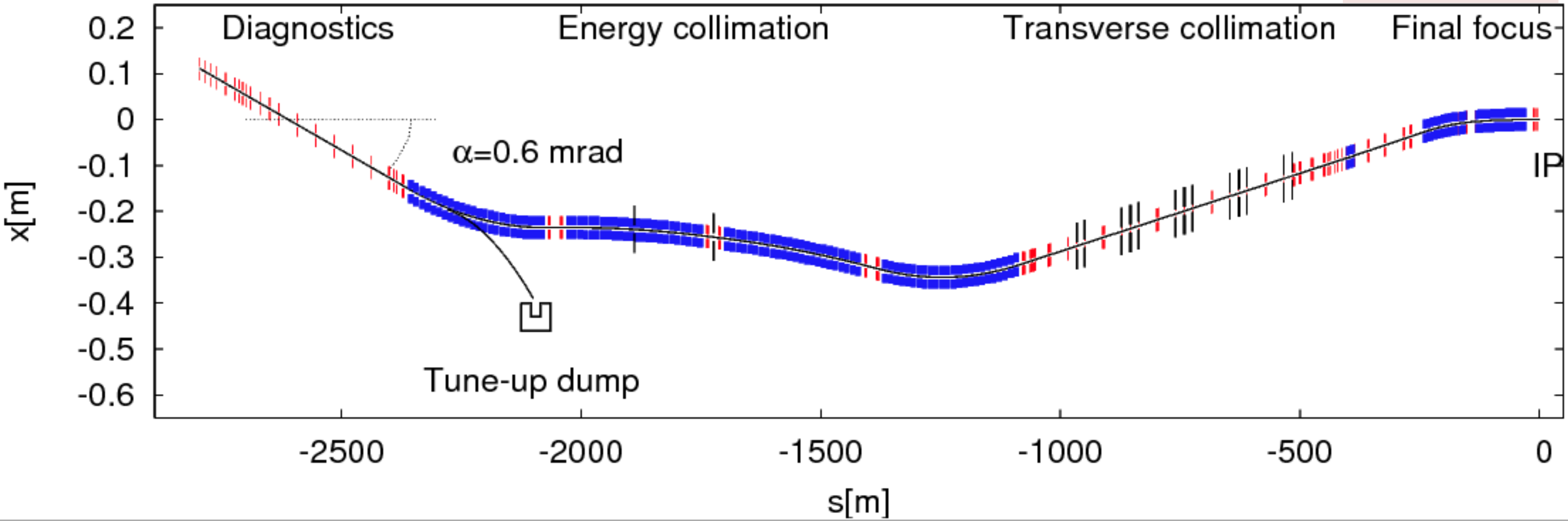
More effort in the future to understand trade-off

Background Sources

- Machine produced background before IP
  - beam tails from linac and BDS
    - beam-gas, beam-black body radiation scattering
  - synchrotron radiation of beam in BDS/final doublet
  - Muons
- Beam-beam background around IP
  - beam particles
  - beamstrahlung
  - coherent pair creation
  - incoherent pair creation
  - hadron production
  - secondary neutrons
- Spent beam background
  - backscattering of particles in dump line
  - especially neutrons

BDS Design

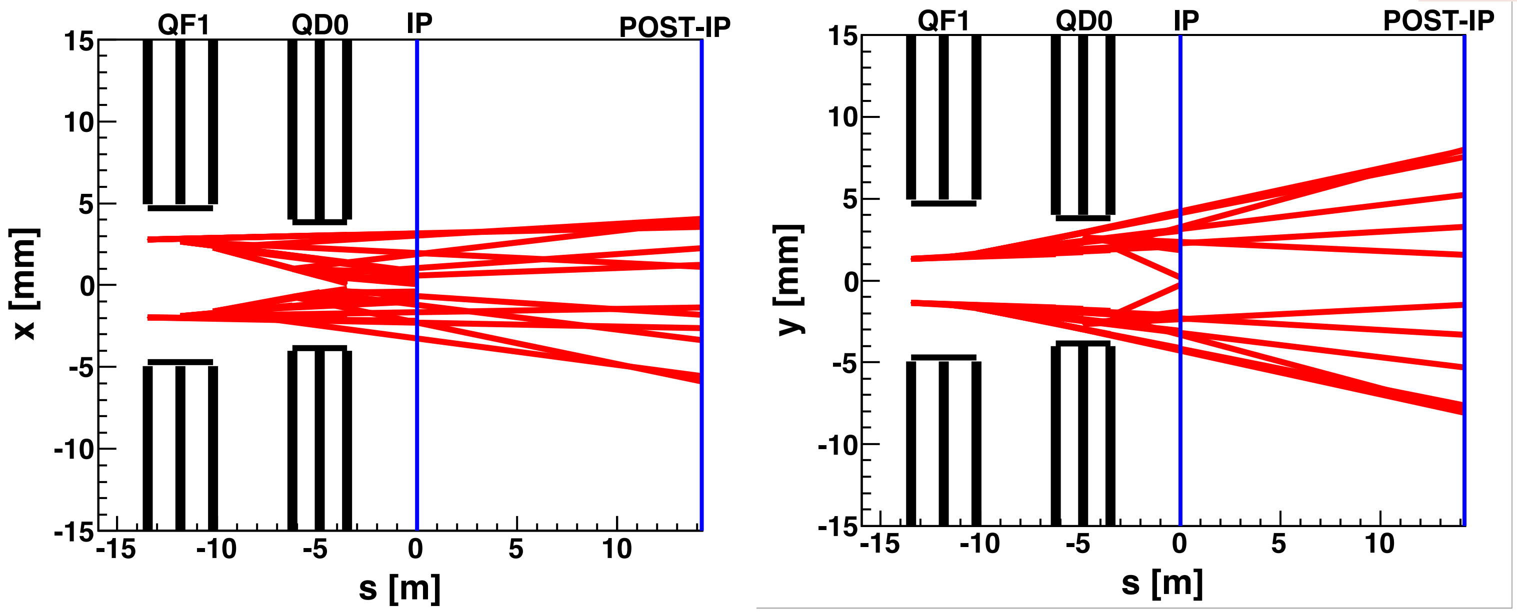
Vol 1, ***2.5.3***



- Collimation protects machine and detector from errand beams and tails
  - collimates at $|\Delta E|>1.5\%$, $|\Delta x|>10\sigma_x$, $|\Delta y|>55\sigma_y$
- Final focus system squeezes the beam for IP
- Instrumentation includes energy and polarisation measurement

Collimation System

Vol 1, 3.6.8.3

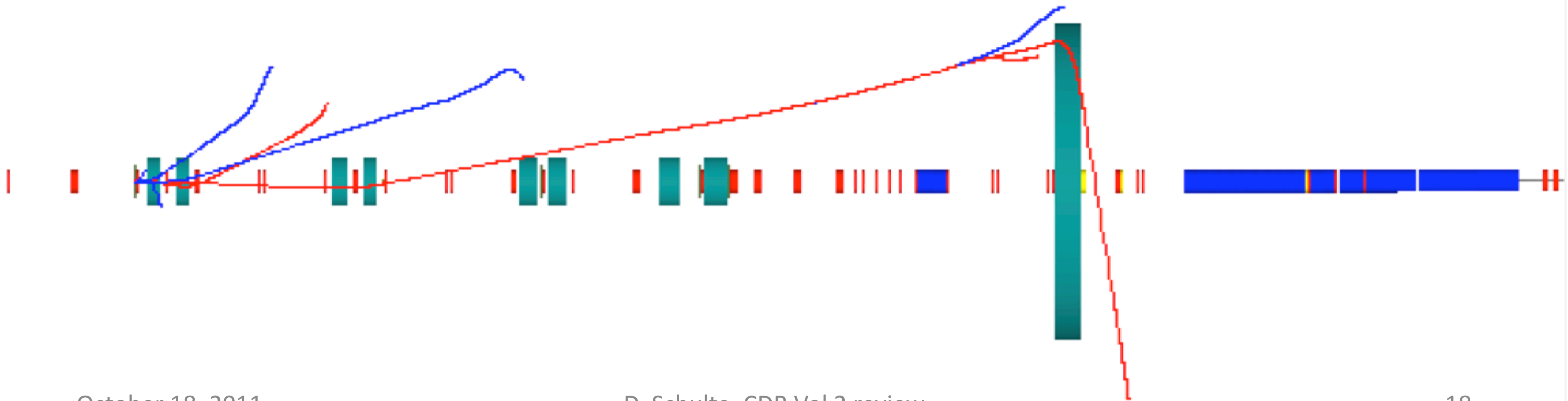


• Removes particles which can produce synchrotron radiation in the final doublet that can generate tertiary background

• Will generate secondary muons

Muons

- Target muons/bunch crossing < 1
  - muons per lost particle ~ 10^{-4}
  - allowed loss ~10^{-6}
- Muon spoilers gain factor 10, i.e. allowed loss ~10^{-5}
  - further reduction may be possible
- Main halo generation is elastic beam-gas scattering in the BDS
  - expected loss $7\ 10^{-8}$, i.e. 0.05 muons with no spoilers
  - Other sources to be reviewed



Beam-beam Background Calculation

- Beam-beam simulations are performed with GUINEA-PIG(++)

- Luminosity and background is stored in data base

- Values are given for 120% of nominal luminosity
  - i.e. not using luminosity budget for dynamic effects

- Dynamic effects reduce luminosity and most background
  - Background effects mostly scale with luminosity
  - except for beamstrahlung and coherent pairs, but they do not produce direct detector background
  - More detailed study as operation models become available

Spent Beam Content

Spent beam particles

Beamstrahlung

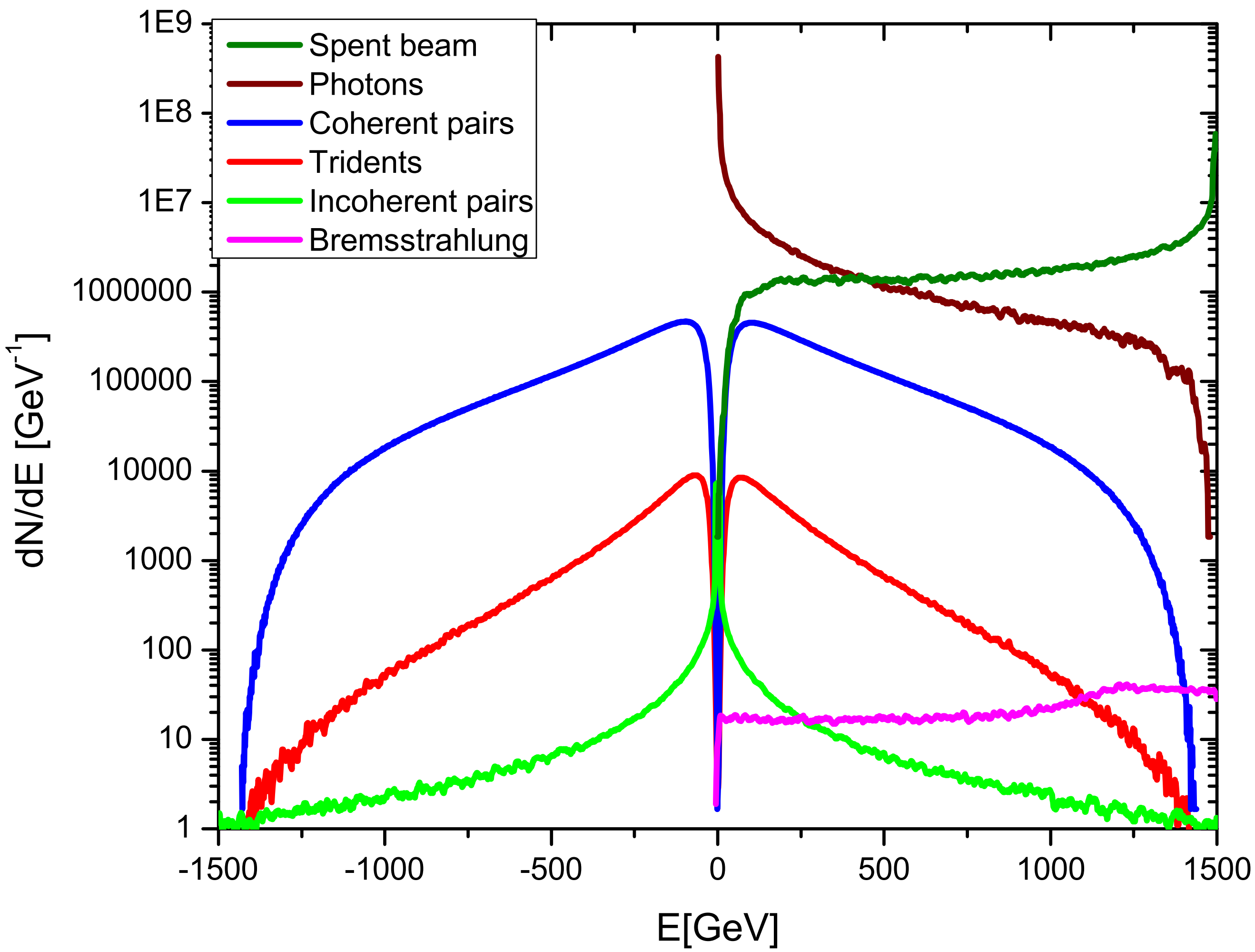
Coherent pairs

Trident cascade pairs

Incoherent pairs

Hadrons

...



In strong fields photons can turn into e^+-e^- pairs (coherent pair production)

Total 7 10^8 particles

J. Esberg

Spent Beam Divergence

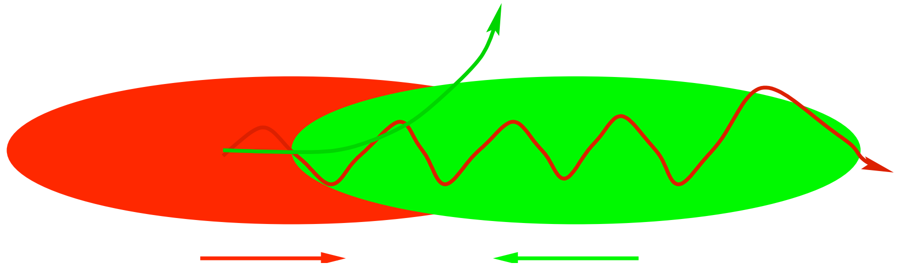
Beam particles are focused by oncoming beam

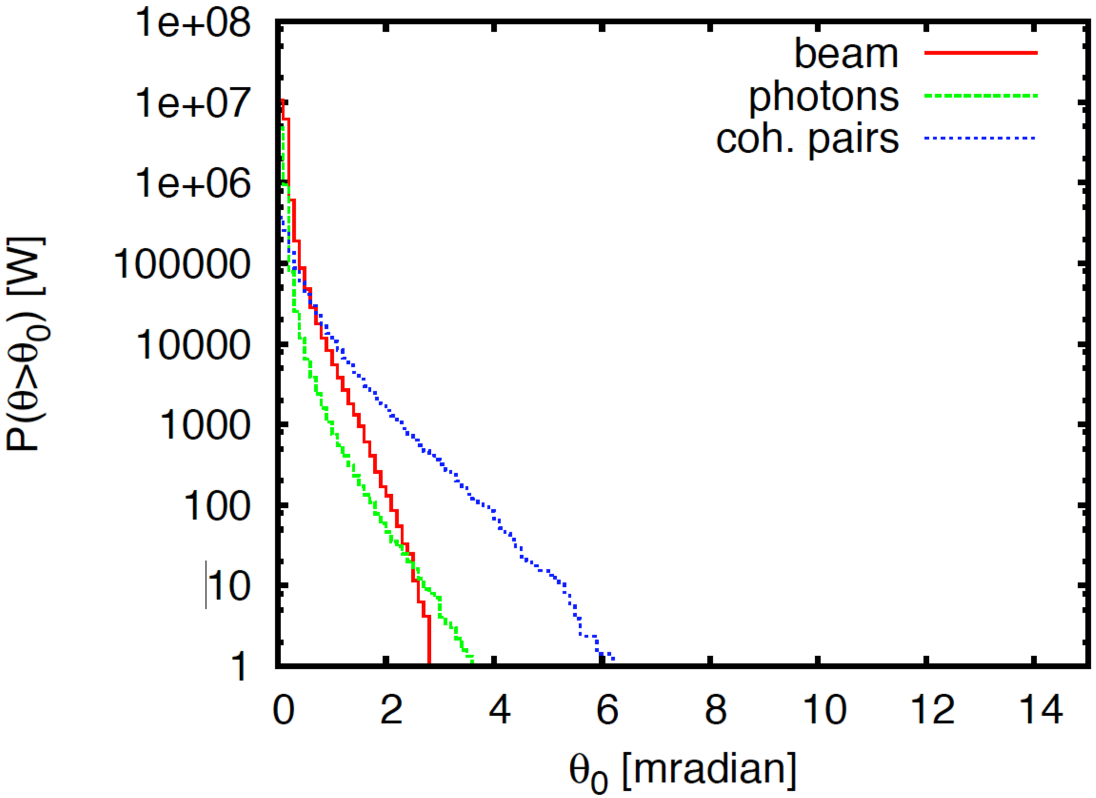
Photons are radiated into direction of beam particles

Coherent pair particles can be focused or defocused by the beam

-> Extraction hole angle should be significantly larger than 6mradian

-> 20mradian crossing angle





$$1\,\mathrm{W} \approx 400\,\mathrm{TeV/bx} \approx 300\,\mathrm{beamparticles/bx}$$

Crossing Angle

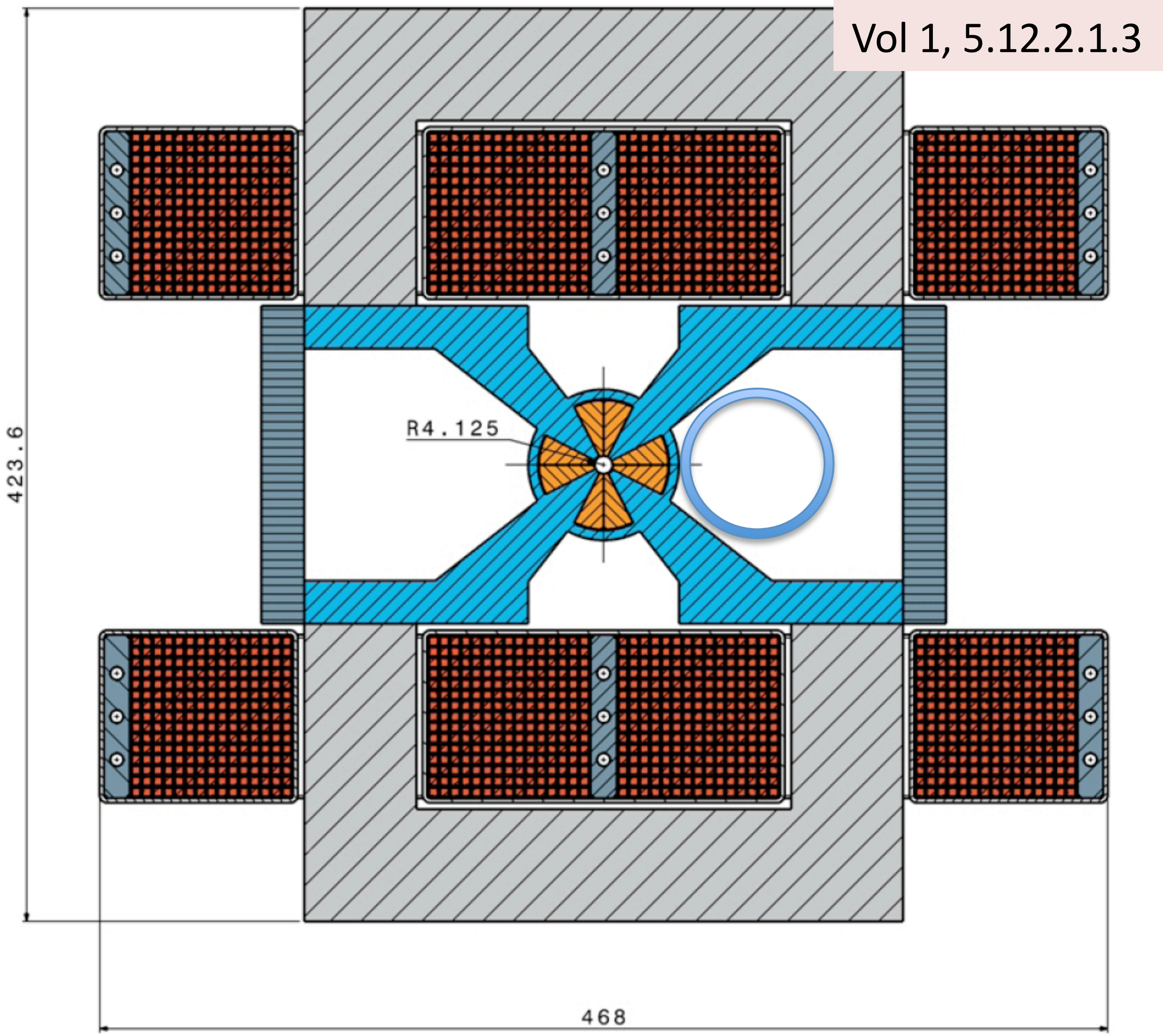
Space needed by QD0:
35mm@ 3.5m = 10mradian

Space for spent beam:
35mm @ 3.5m = 10mradian

Multi-bunch kink instability
is very small:

$$\Delta y = \frac{\Delta y_0}{1 - n_c \frac{4Nr_e}{\gamma\theta_c^2}\frac{\partial y}{\partial \Delta y}}$$

$\Delta y = 1.06\ \Delta y_0$



Incoherent Pairs

GUINEA-PIG used

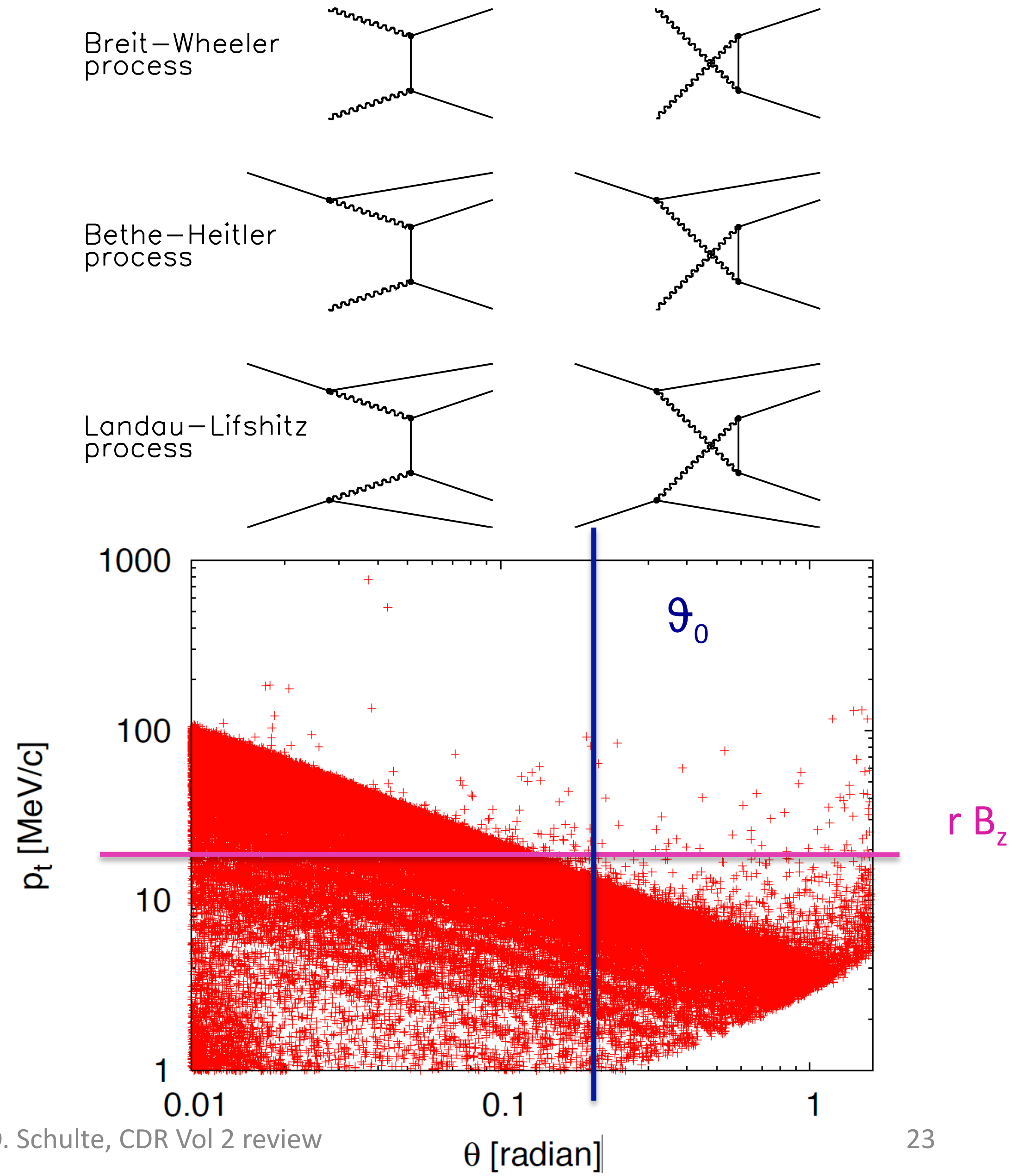
- Calculation with virtual photon approximation (Q^2_{max} choice confirmed by benchmarking Ph. Bambade et al.)

- Beam size effect is included

300,000 particles produced

Average energy is 70GeV

Strong deflection by the beam
- smaller deflection observed with CAIN, under study



Hadronic Background

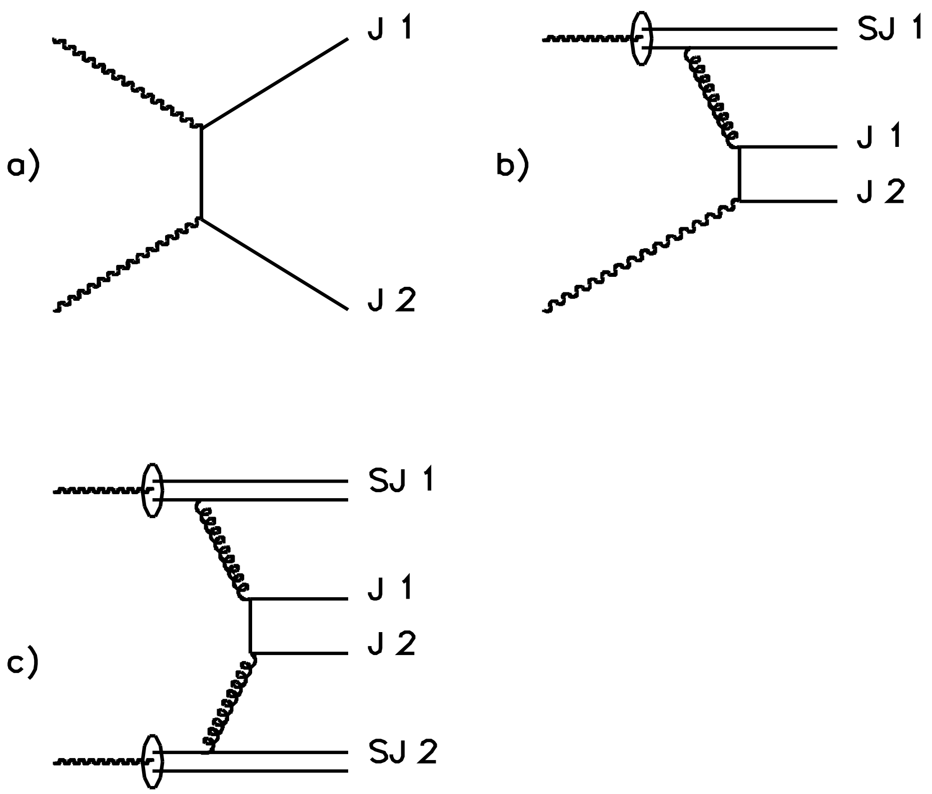
Based on equivalent photon approximation with

Q^2_{max} = max(1GeV^2,(s/100)$^{0.43}$)

3.2 events per bunch crossing

Events are simulated with PYTHIA 6.4.20

Benchmarked with SLAC generator (T. Barklow et al.)



$$\sigma_{\gamma\gamma}(s_{\gamma\gamma}) = 211\ \text{nb}\left(\frac{s_{\gamma\gamma}}{\text{GeV}^2}\right)^{0.0808} + 215\ \text{nb}\left(\frac{s_{\gamma\gamma}}{\text{GeV}^2}\right)^{-0.4525}$$

Background Summary

parameter	units		
E_{cms}	[TeV]	0.5	3.0
L_{total}	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.3	5.9
$L_{0.01}$	$[10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	1.4	2.0
n_γ		1.3	2.1
$\Delta E/E$		0.07	0.28
N_{coh}	$[10^5]$	2×10^{-3}	6.8×10^3
E_{coh}	$[10^3\ \mathrm{TeV}]$	0.015	2.1×10^5
N_{incoh}	$[10^6]$	0.08	0.3
E_{incoh}	$[10^6\mathrm{GeV}]$	0.36	22.6
$n_\perp$		20.5	45
$n_{Had}(W_{\gamma\gamma} > 5GeV)$		0.2	2.8
$n_{Had}(W_{\gamma\gamma} > 2GeV)$		0.3	3.2

Energy Flexibility of 3TeV Machine

E/E_0	n_b	$n_{\mathcal{L}}$	$Q_p/Q_{p,0}$
1.0	312	1.0	1.0
0.75	472	1.5	1.12
0.667	552	1.77	1.18
0.5	792	2.54	1.27
0.375	1112	3.56	1.34
(0.333)	(1272)	(4.08)	(1.36)

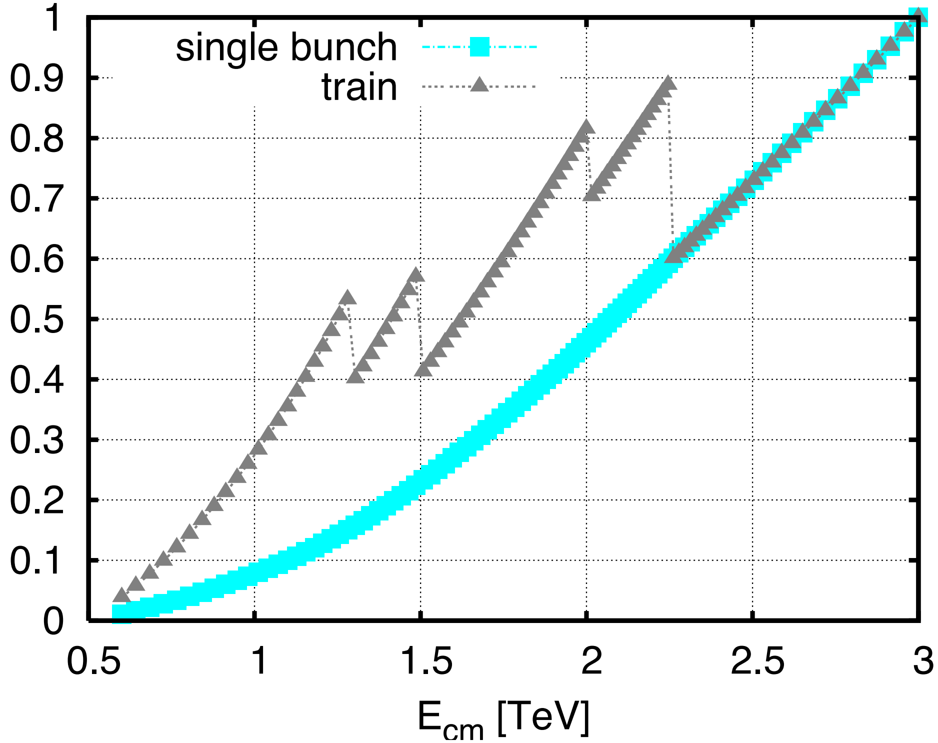
E maximum centre-of-mass energy for operation mode

n_b number of bunches per main beam pulse

$n_{\mathcal{L}}$ resulting increase in luminosity

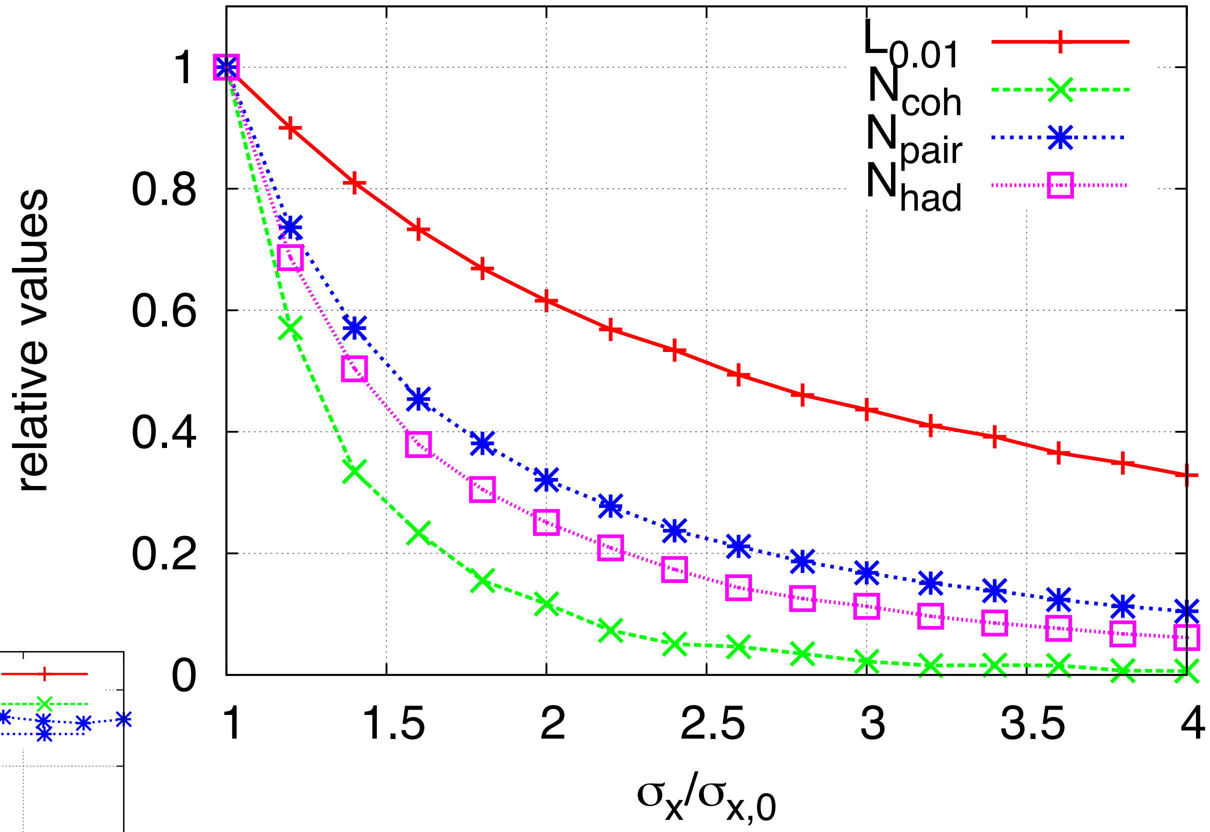
$Q_p/Q_{p,0}$ maximum charge per pulse compared to nominal case

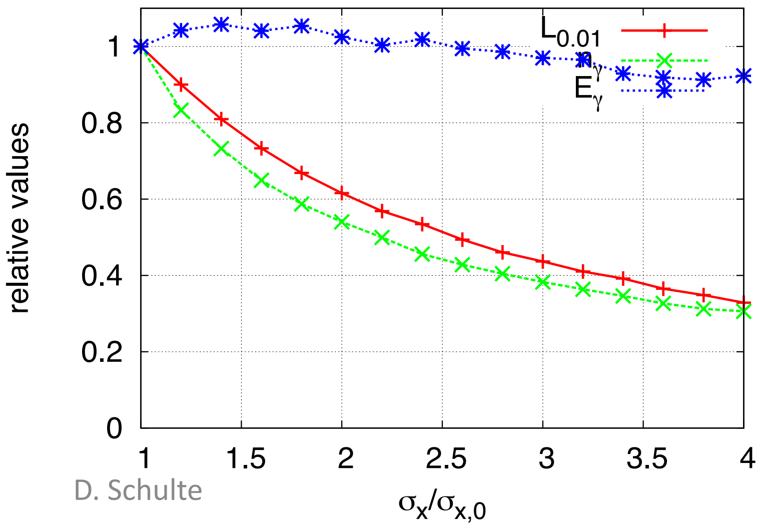
Vol 1, 8



Background and Luminosity

Increasing σ_x
- most efficient way
- best ration background/luminosity





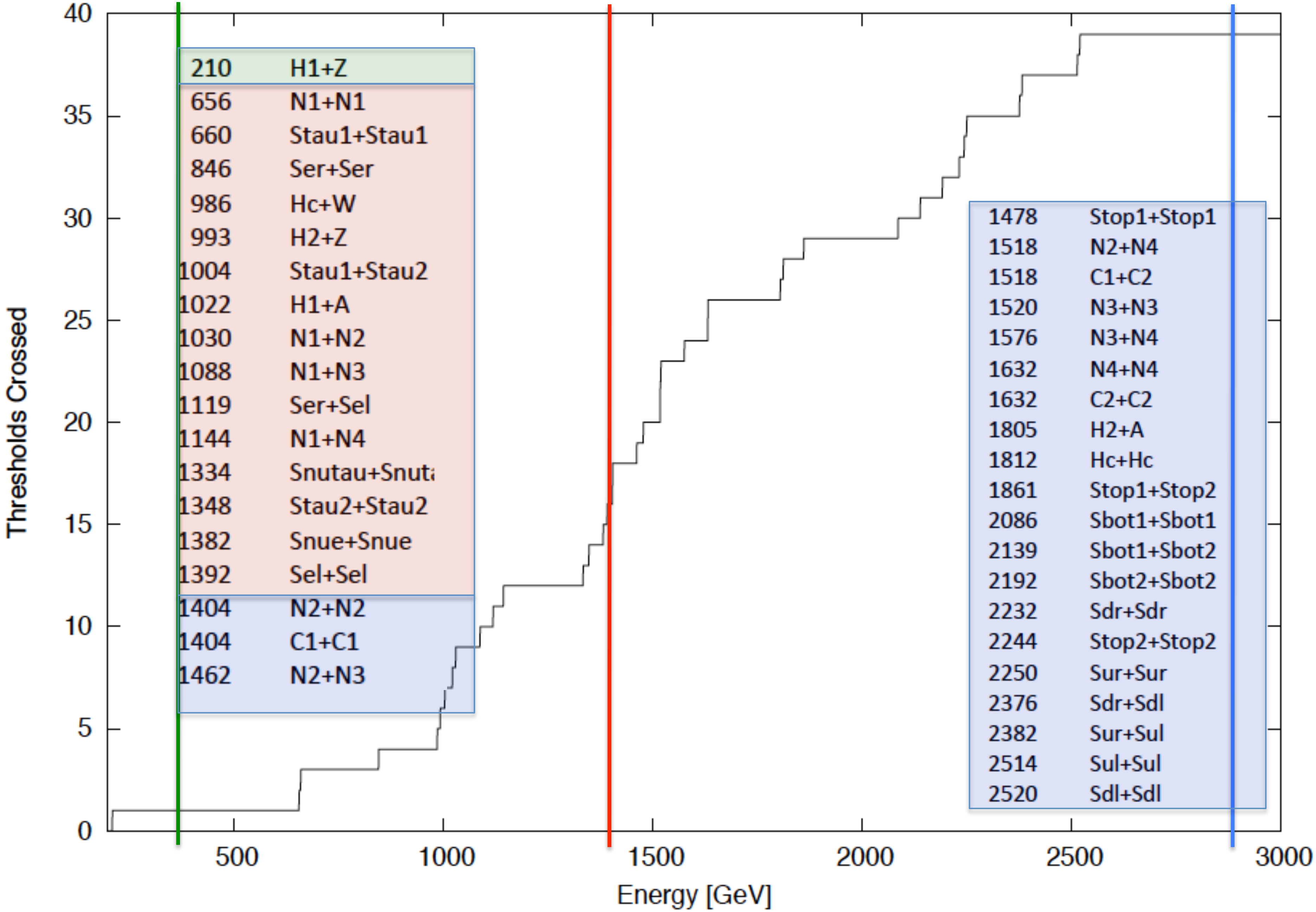
Beamstrahlung photon energy unchanged but number goes down

Potential New CLIC Staged Parameters

parameter	symbol			
centre of mass energy	E_{cm} [GeV]	350	1400	2900
gradient	G [MV/m]	80	80/100	80/100
DB sectors		4	12	24
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	1.54	3.6	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.0	1.5	2
gradient	G [MV/m]	80	100	100
site length	[km]	11	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	70	44	44
IP beam size	σ_x/σ_y [nm]	236/2.7	?/?	41/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	260	360	580

First stage ML structures are re-used

Thresholds Crossed as a function of Energy (GeV)



Conclusion

CLIC 3TeV design is quite advanced
- feasibility demonstration almost finished

Good understanding of
- luminosity spectrum
- beam-beam background
- muon background
- synchrotron radiation in final doublet

Staged design foreseen to adjust to LHC findings
- choice energy stages
- further optimisation of the design

Reserve Slides

Polarisation

No detailed integrated studies

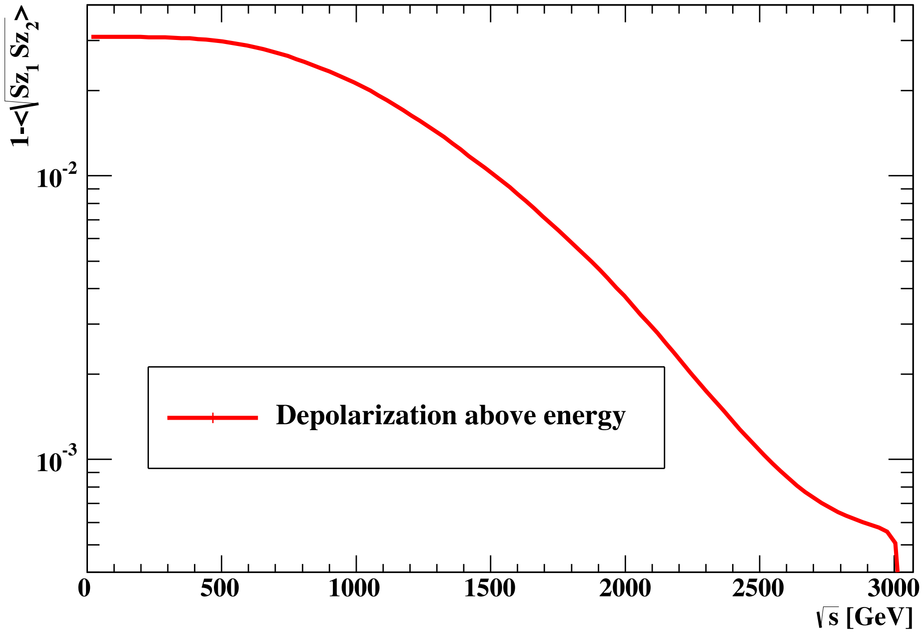
- but some considerations/calculations
- e.g. spin rotators and figure eight turn-around for electrons
- depolarisation in IP (GUINEA-PIG++)

Expect >80% electron polarisation at source

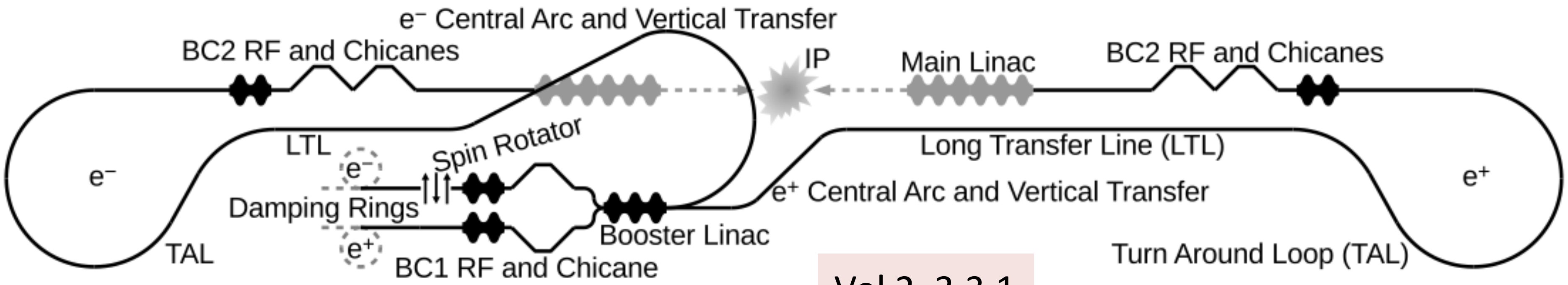
- 87% have been demonstrated at SLAC

No polarised positrons in baseline

- could use ILC helical undulator source
- but have other options



J. Esberg, preliminary



Vol 2, 3.3.1

Staged Approach: Potential Parameters

Will be in Vol 1, 9.3

E_{cm} n_b N	[TeV] $[10^9]$	1.0 312 3.72	1.5 312 3.72	2.0 312 3.72	2.4 312 3.72	3.0 312 3.72
L $L_{0.01}$	$[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$ $[10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	2.2 1.0	3.75 1.45	5.0 1.8	5.7 1.98	5.7 2.0
n_γ $\Delta E/E$	 %	1.7 17	1.95 22	2.1 26	2.1 27	2.0 27
N_{coh} E_{coh}		$1.73 \cdot 10^7$ $2.51 \cdot 10^9$	$1.39 \cdot 10^8$ $2.81 \cdot 10^{10}$	$3.61 \cdot 10^8$ $9.10 \cdot 10^{10}$	$5.33 \cdot 10^8$ $1.56 \cdot 10^{11}$	$6.49 \cdot 10^8$ $2.29 \cdot 10^{11}$
N_{incoh} E_{incoh}		$1.2 \cdot 10^5$ $2.21 \cdot 10^6$	$2.2 \cdot 10^5$ $7.01 \cdot 10^6$	$3.0 \cdot 10^5$ $1.40 \cdot 10^7$	$3.4 \cdot 10^5$ $1.98 \cdot 10^7$	$3.3 \cdot 10^5$ $2.46 \cdot 10^7$
n_{had}		0.6	1.4	2.27	2.78	2.85

N_{had} for $W_{\gamma\gamma}$ > 5GeV

Beamstrahlung Optimisation

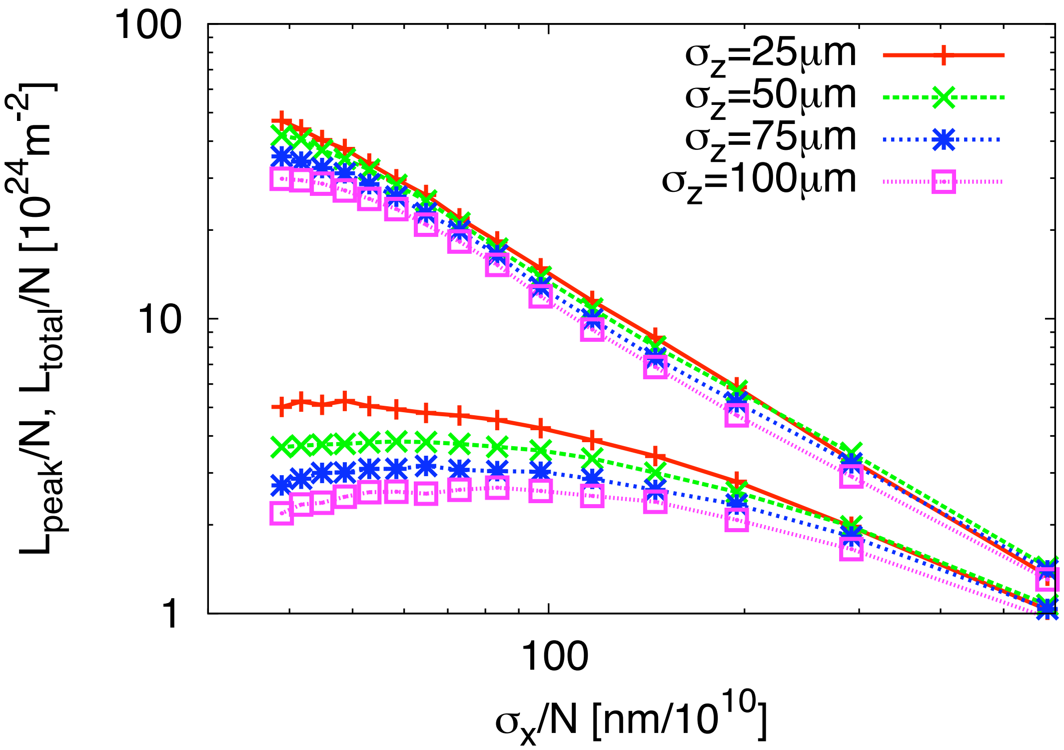
For low energies (classical regime) number of emitted photons

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

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

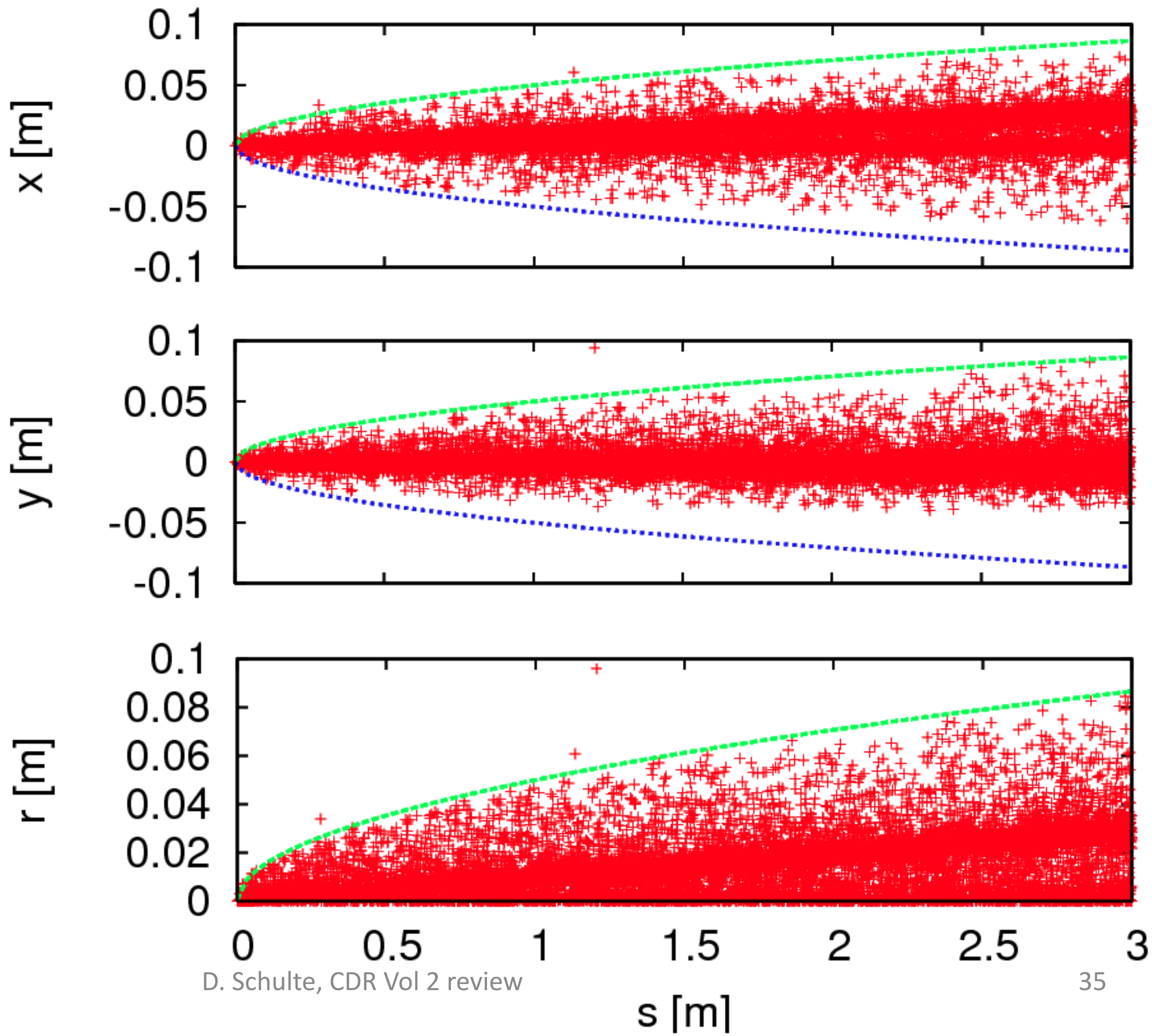
Hence use $\sigma_x \gg \sigma_y$

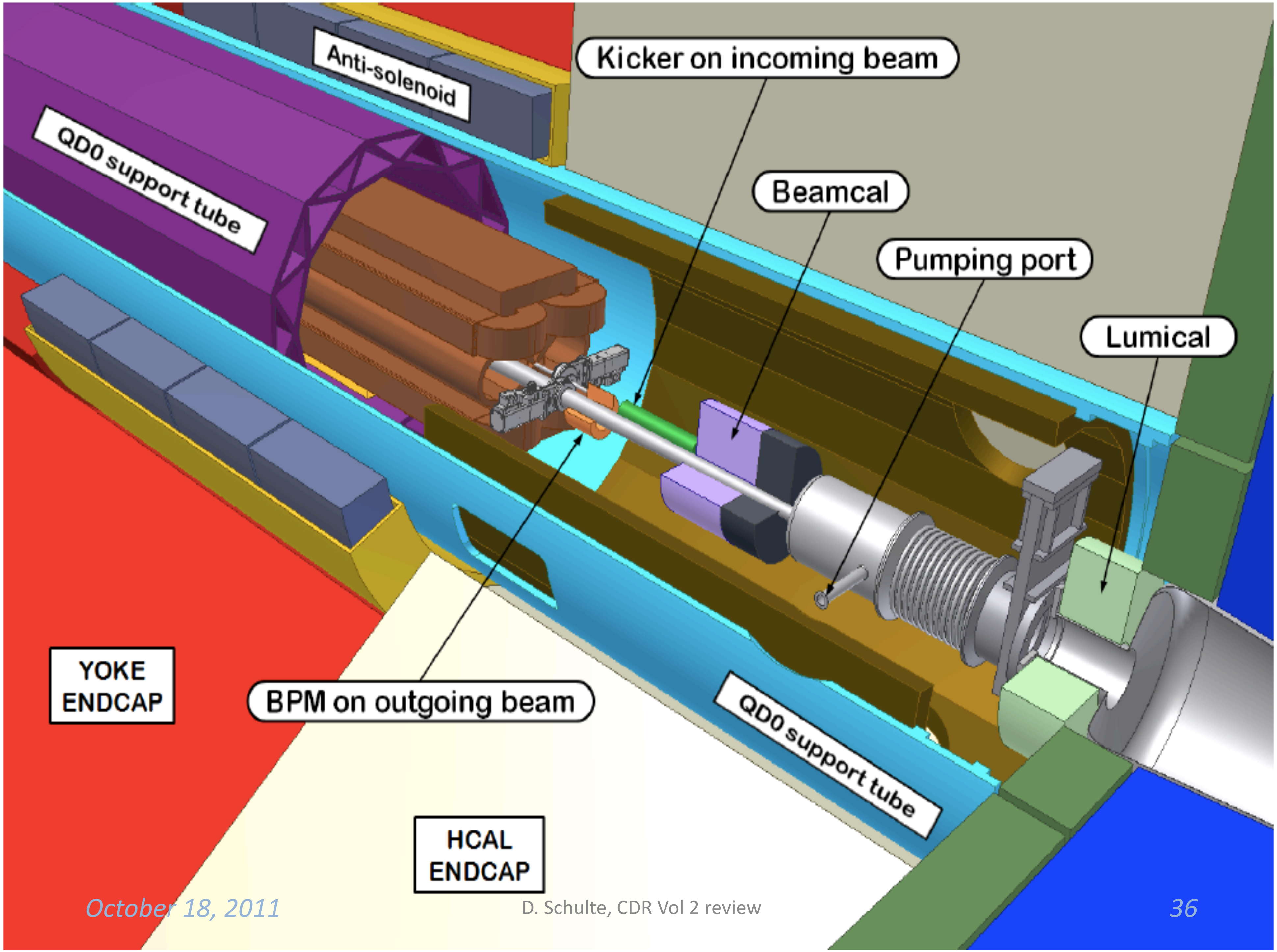
$$\sigma_x + \sigma_y \approx \sigma_x$$



For CLIC at 3TeV (quantum regime)

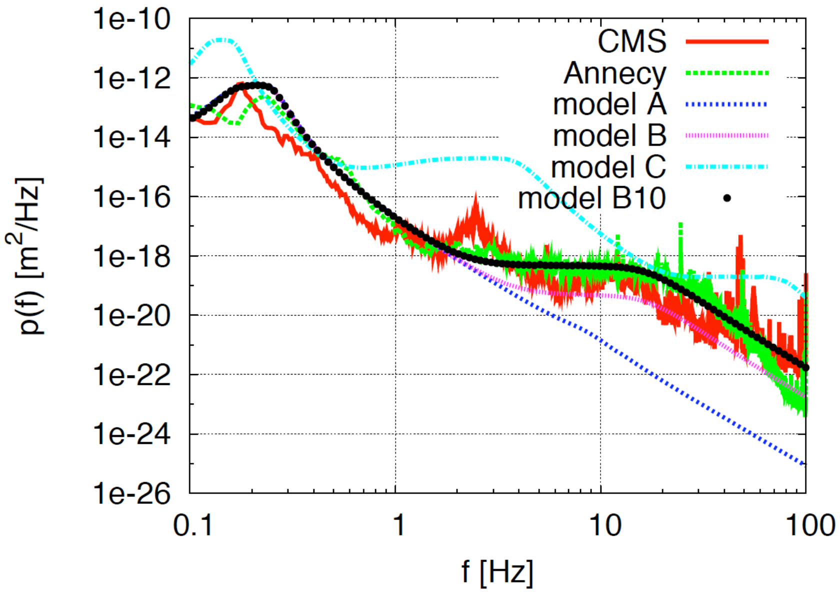
$$\mathcal{L} \propto \frac{N}{\sigma_x}\frac{\eta}{\sigma_y} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}}\frac{\eta}{\sigma_y}$$

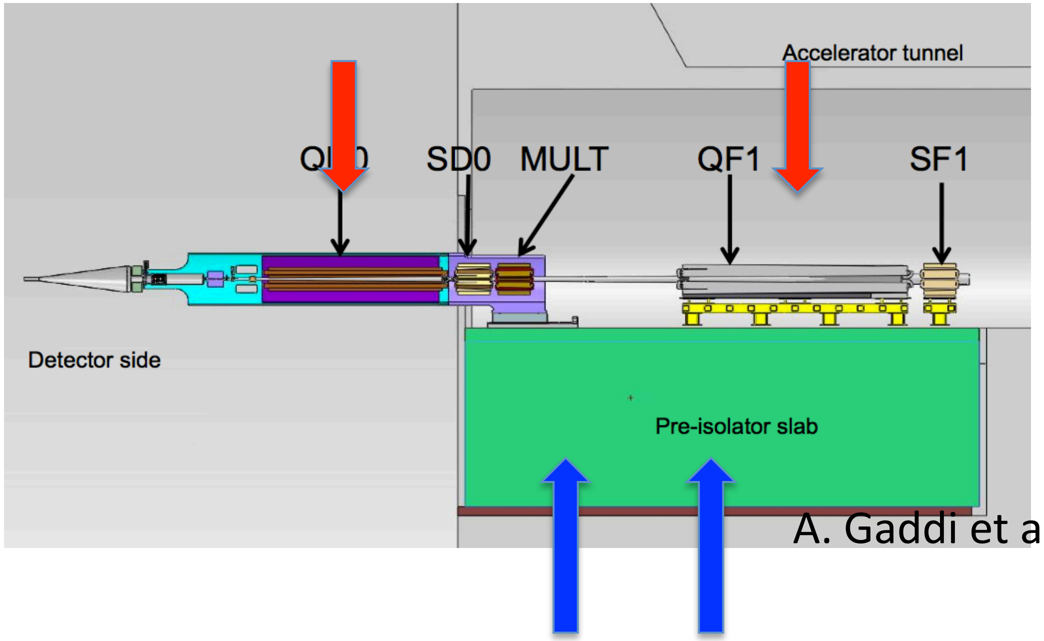

0.1
0.05
0
-0.05
-0.1
x [m]
y [m]
0.08
0.06
0.04
0.02
r [m]
0
0.5
1
1.5
2
2.5
3
s [m]



Anti-solenoid
QD0 support tube
Kicker on incoming beam
Beamcal
Pumping port
Lumical
YOKE ENDCAP
BPM on outgoing beam
QD0 support tube
HCAL ENDCAP

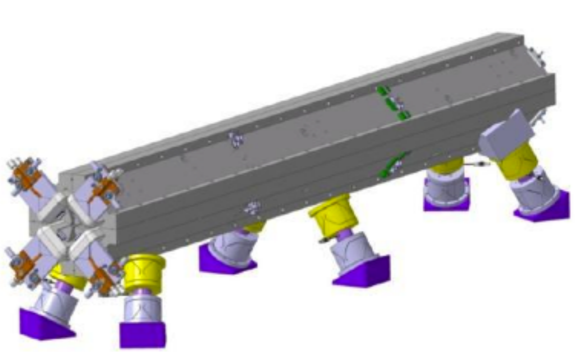
Ground Motion

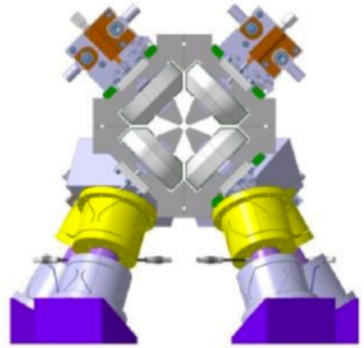




A. Gaddi et al.

Natural ground motion can impact the luminosity
-> develop stabilisation for beam guiding magnets





K. Artoos et al.

Beam-Beam Effect

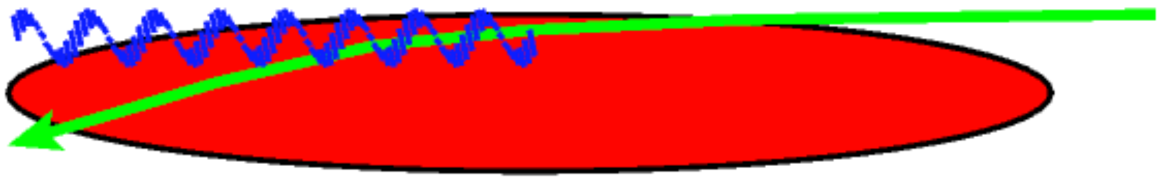
Bunches are squeezed strongly to maximise luminosity

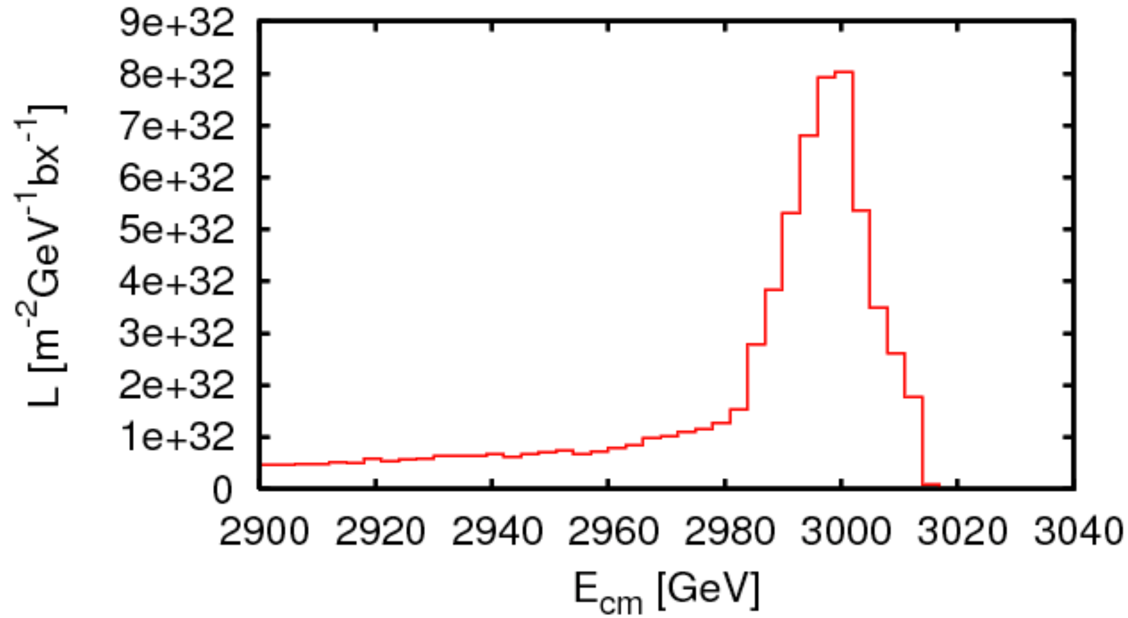
Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons (O(1)) (beamstrahlung)

They collide with less than nominal energy





Luminosity and Parameter Drivers

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

Luminosity spectrum

Beam current

Beam Quality (+bunch length)

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

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

Beamstrahlung

Beamstrahlung is described by the beamstrahlung parameter

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E_0} \propto \frac{N\gamma}{(\sigma_x + \sigma_y)\sigma_z}$$

Classical regime (0.5TeV) $\Upsilon \ll 1$	$\mathcal{L} \propto H_D\, n_\gamma\, \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$
Quantum regime (3TeV) $\Upsilon \gg 1$	$\mathcal{L} \propto H_D \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \eta_{RF->beam} \frac{P_{RF}}{E_{cm}} \frac{1}{\sigma_y}$

Required $L_{0.01}$> 0.3 L

Spent Beam Content

Spent beam particles

Beamstrahlung

Coherent pairs

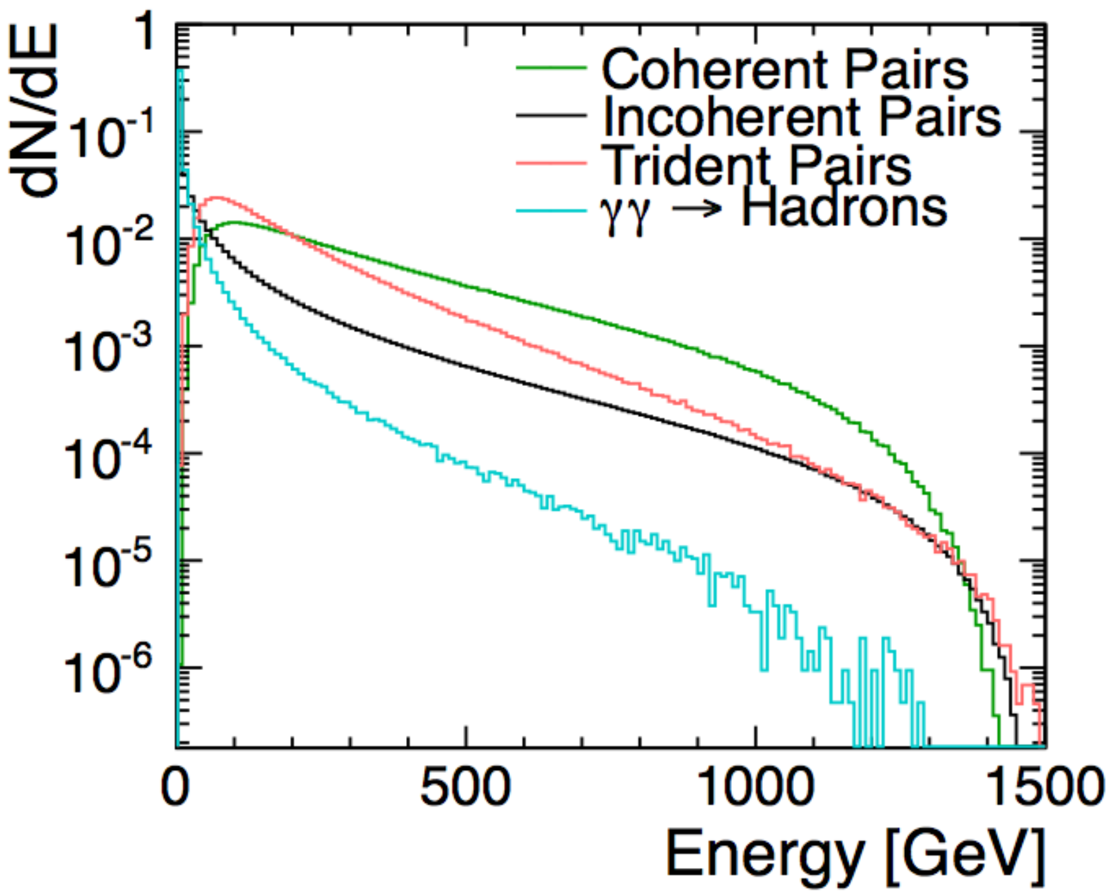
Trident cascade pairs

Incoherent pairs

Hadrons

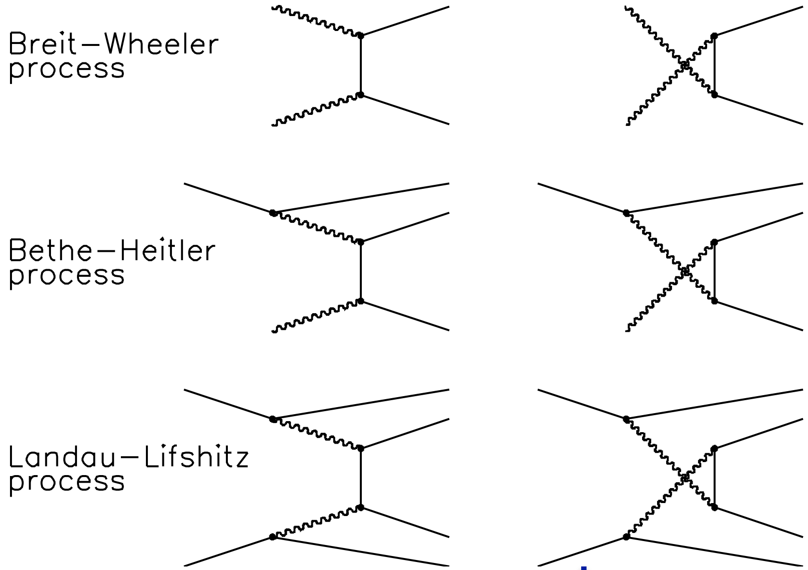
...

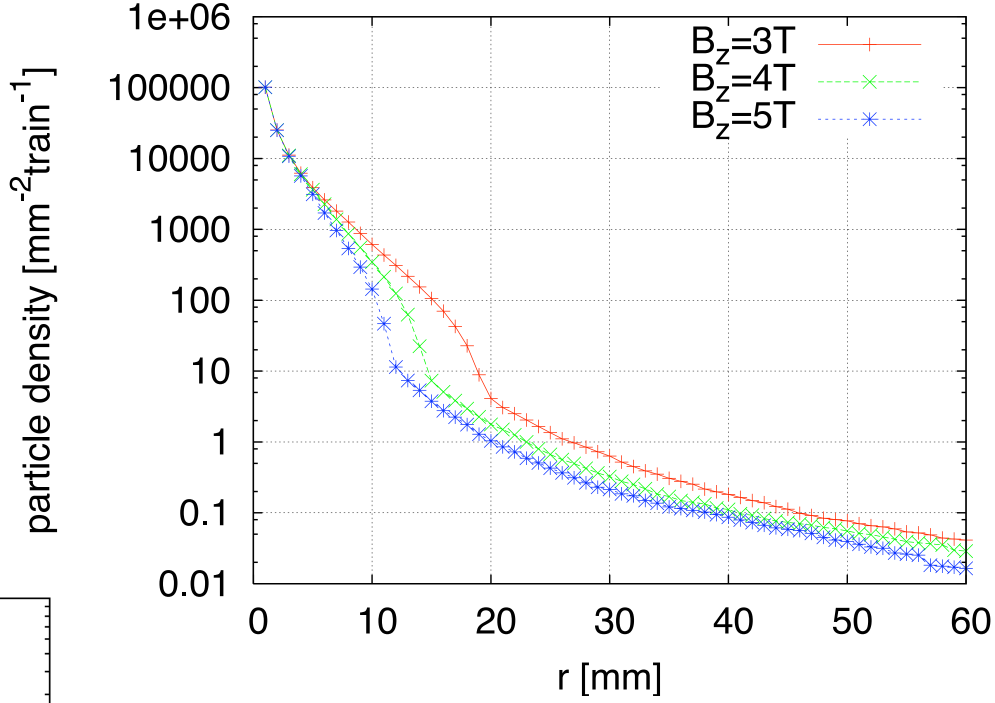
In strong fields photons can turn into e^+-e^- pairs (coherent pair production)
Total 7 10^8 particles

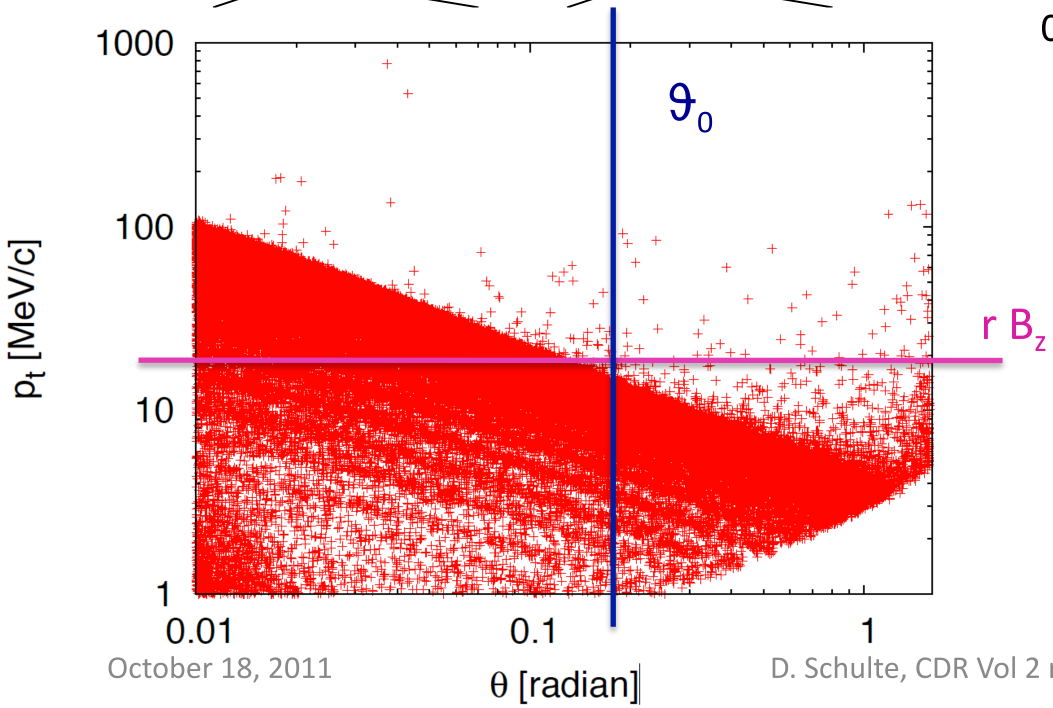


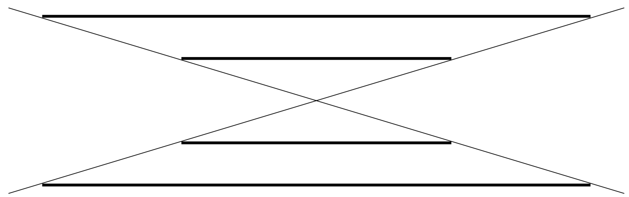
Spectra are normalised

Incoherent Pairs







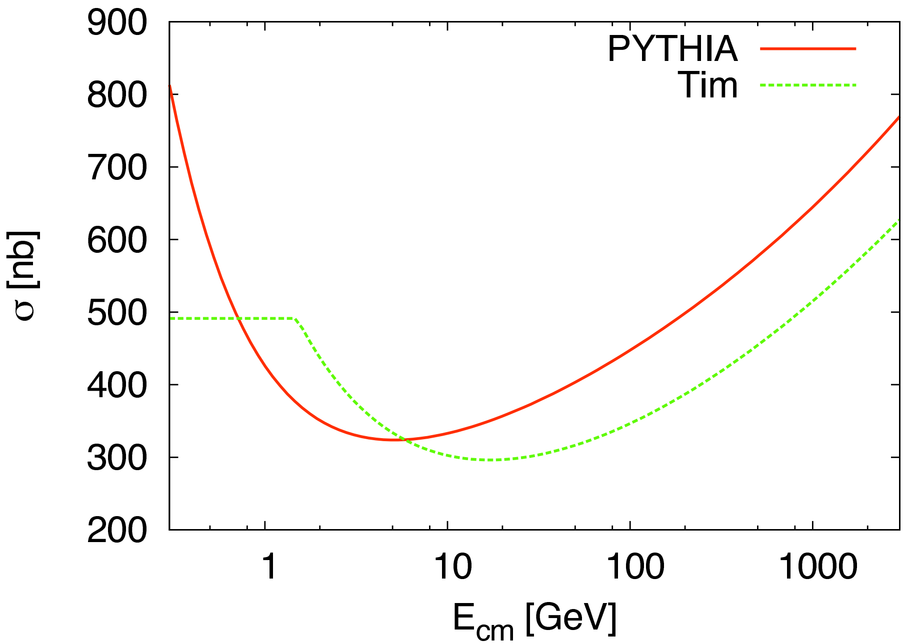


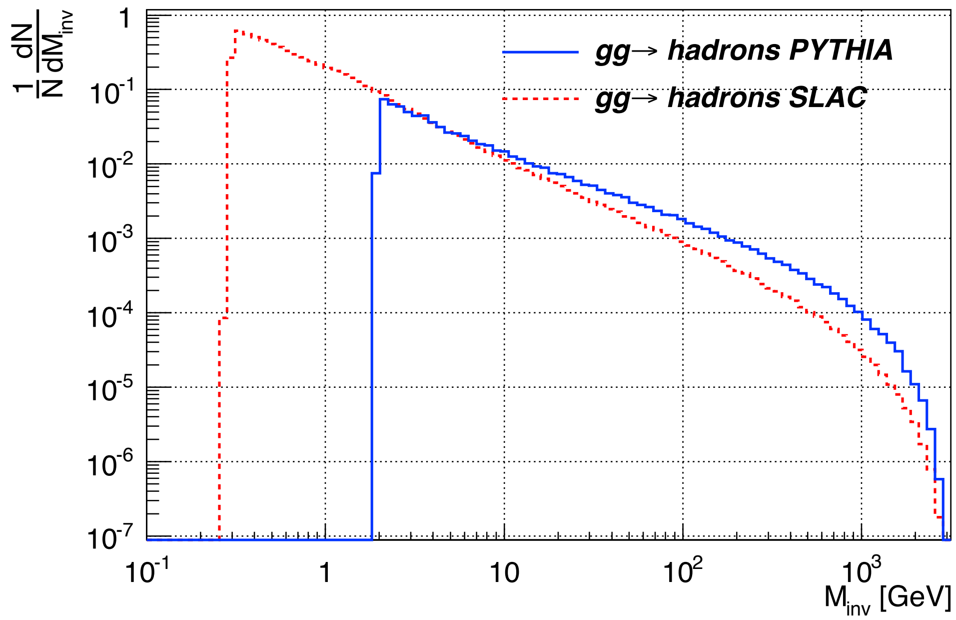
Simplified study at r=30mm :

~1 direct hit per mm^2 per train

(expect 3 hits per particle)

Cross Section Comparison





PYTHIA (G. A. Schuler, T. Sjöstrand)

$$\sigma_{\gamma\gamma}(E_{cm}^2) = 211\ \text{nb}(E_{cm}^2\text{GeV}^{-2})^{0.0808} + 215\ \text{nb}(E_{cm}^2\text{GeV}^{-2})^{-0.4525}$$

SLAC (T. Barklow)

$$\sigma_{\gamma\gamma}(E_{cm}^2) = 200\ \text{nb}(1 + 0.0063[\ln(E_{cm}^2\text{GeV}^{-2})]^{2.1} + 1.96(E_{cm}^2\text{GeV}^{-2})^{-0.37})$$

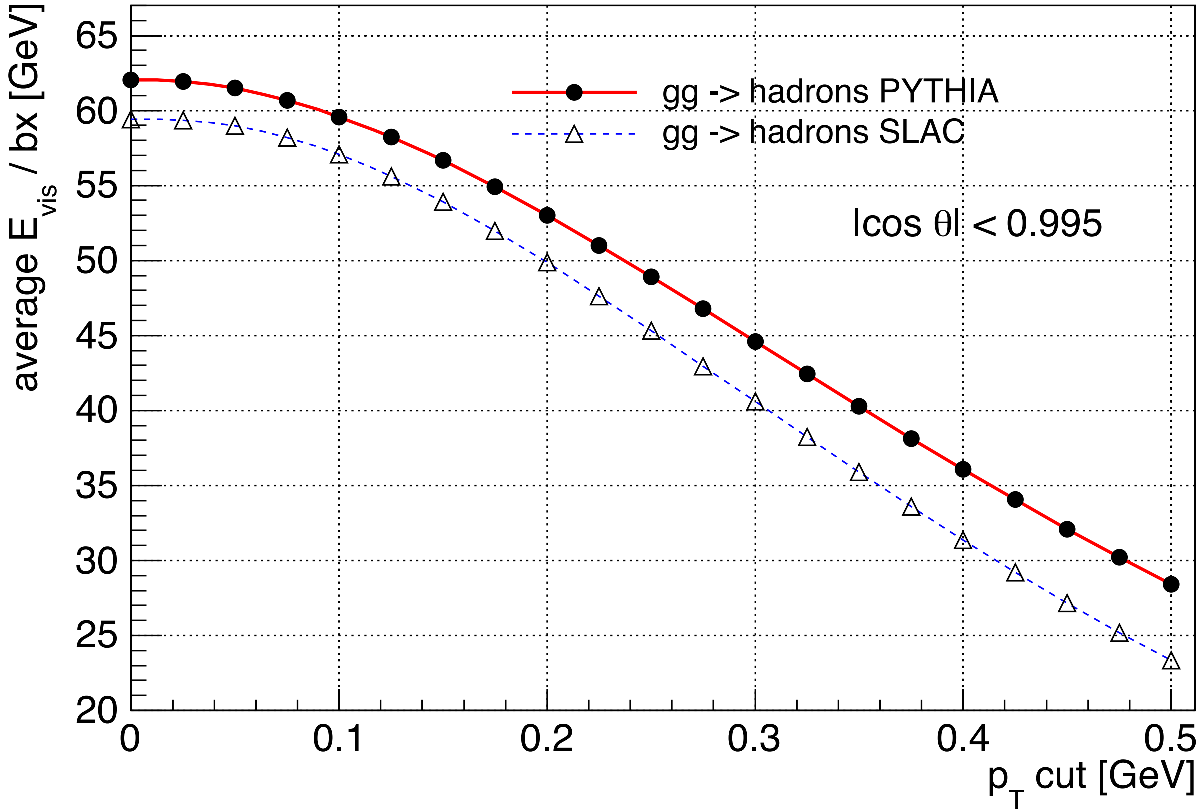
Hadronic Event Comparison

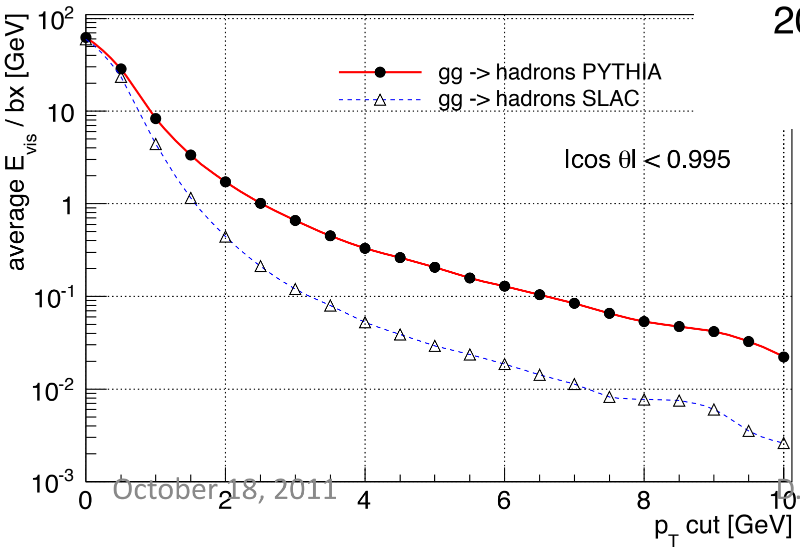
Good agreement for visible
Energy per bunch crossing

HADES is conservative at high PT

3.2 events per bx
2.8 with E_{cm}>5GeV

4.1 events per bx
2.25 with E_{cm}>5GeV





Tail Population

Cross section for elastic scattering:

$$\sigma(\theta \geq \theta_0) \approx \frac{4\pi Z^2 r_e^2}{\gamma^2 \theta_0^2}$$

Cut angle for n sigma:

$$\theta_0^2 = \frac{n^2 \epsilon}{\beta\gamma}$$

Results in:

$$\sigma \approx \frac{4\pi Z^2 r_e^2 mc^2}{n^2 \epsilon} \frac{\beta}{E}$$

Total probability is:

$$p \approx \sum \rho_i Z_i^2 \frac{4\pi r_e^2 mc^2}{n^2 \epsilon} \int_0^L \frac{\beta}{E} ds$$

Tail Population II

$$p \approx \sum \rho_i Z_i^2 \frac{4\pi r_e^2 mc^2}{n^2\epsilon} \int_0^L \frac{\beta}{E} ds$$

Unbaked vacuum (1nTorr)
40% H_2, 40% H_2O, 10% CO, 10%CO_2
average Z^2=53.6
density=3.2 10^{22}molecules/Torr

Hence:

$$p \approx 8.64 \times 10^{-17}\,\mathrm{m}^{-1} \frac{1}{n^2\epsilon} \int_0^L \frac{\beta}{E} ds$$

Tightest constraint is 55 σ_y:

Main linac $\int_0^L \frac{\beta}{E} ds \approx 1000\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$ p=1.43 10^{-9}

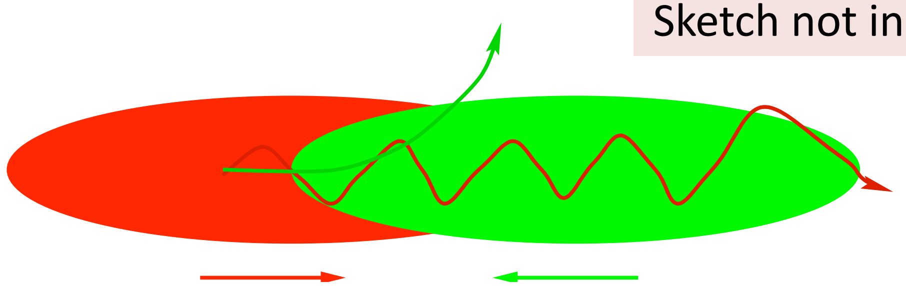
BDS horizontal $\int_0^L \frac{\beta_x}{E} ds \approx 832\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$ p=1.19 10^{-9}

BDS vertical $\int_0^L \frac{\beta_y}{E} ds \approx 48667\,\frac{\mathrm{m}^2}{\mathrm{GeV}}$ p=6.95 10^{-8}

For both sides together:
~530 particle/bunch

Spent Beam Divergence

Sketch not in CDR



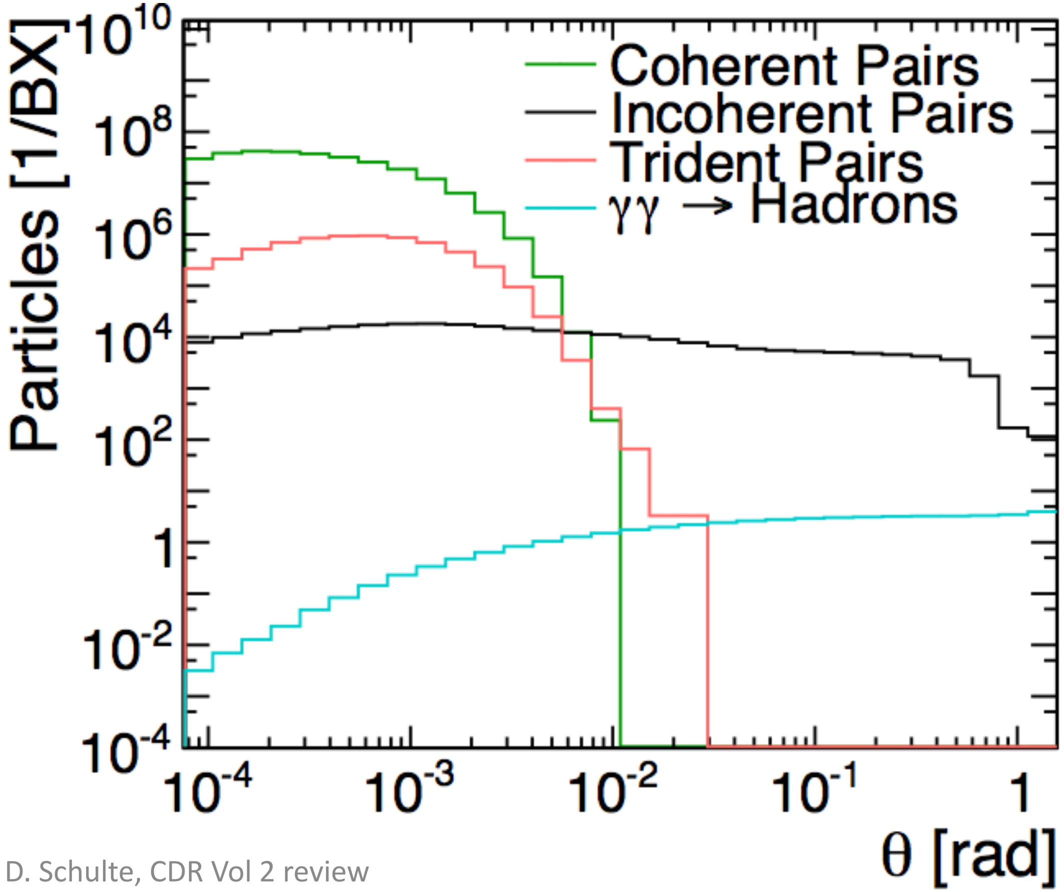
Beam particles are focused by oncoming beam

Photons are radiated into direction of beam particles

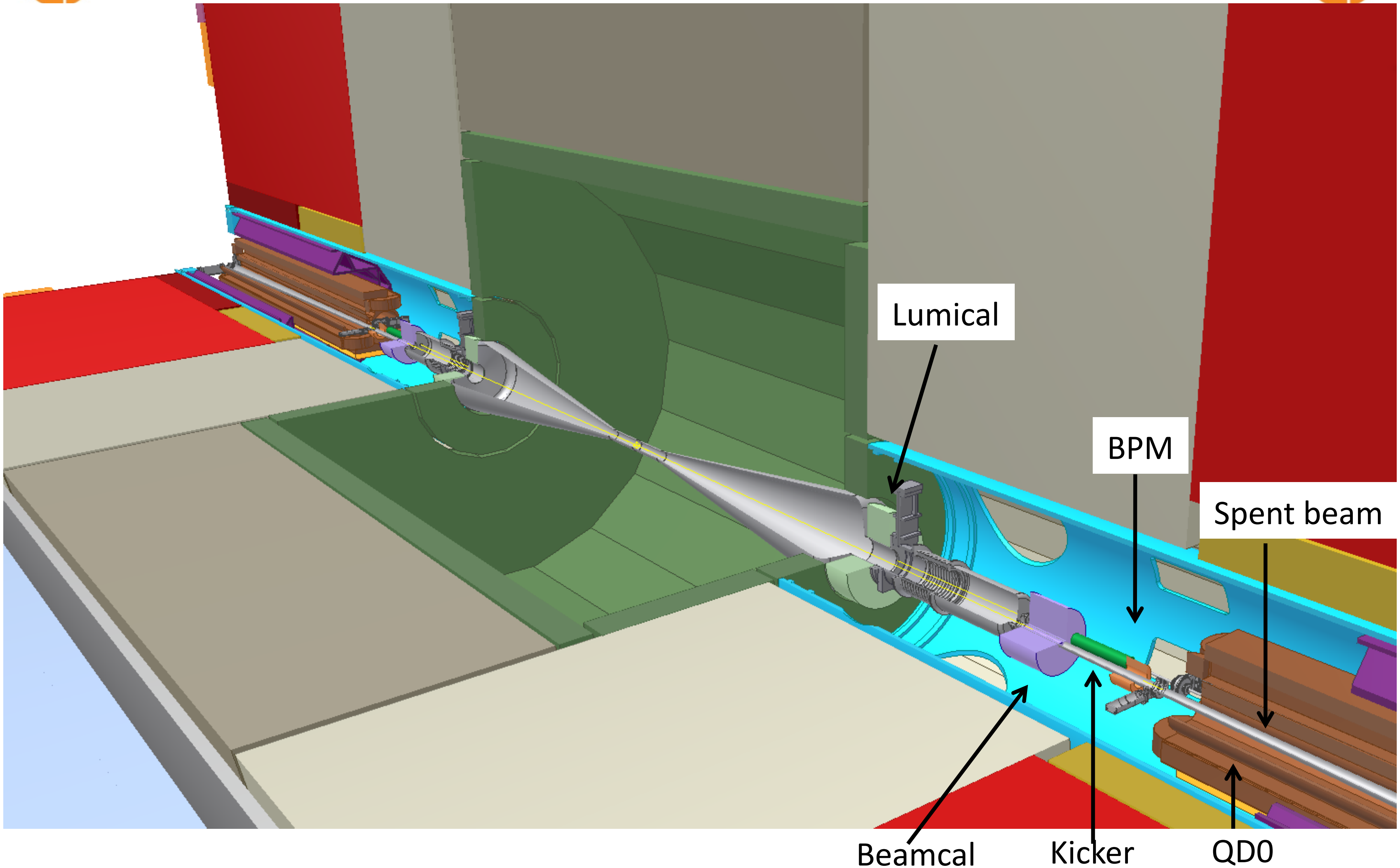
Coherent pair particles can be focused or defocused by the beams

-> Extraction hole angle should be significantly larger than 6mradian

-> 20mradian crossing angle

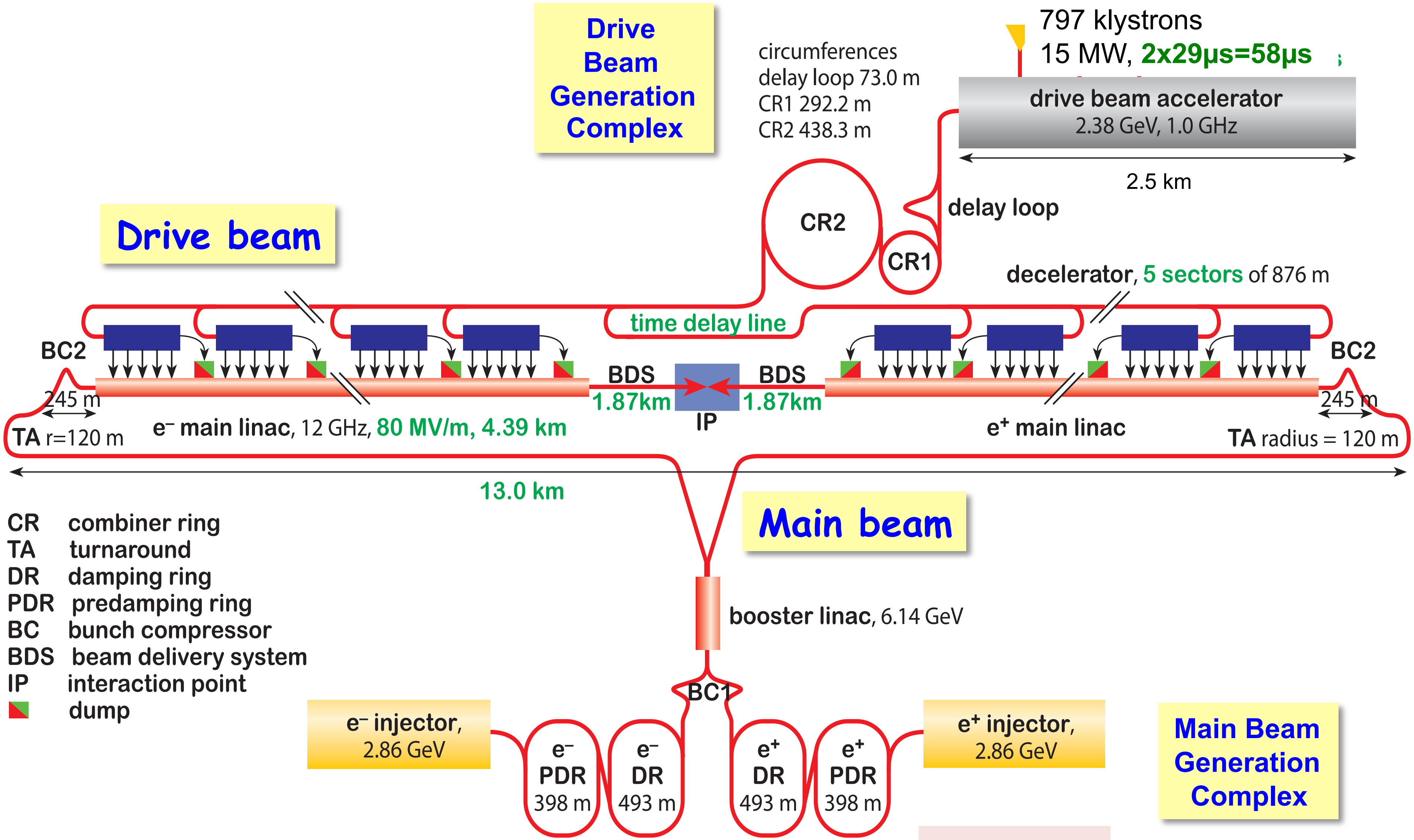


Integration of QD0 magnets and IP Feedback systems in IR



For details see Hubert Gerwig, Konrad Elsener and Andre Sailer

Layout for 500 GeV



Vol 1, 2.2.1

Luminosity and Parameter Drivers

Can re-write normal luminosity formula

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

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

Luminosity spectrum

Beam current

Beam Quality (+bunch length)

In the classical limit for beamstrahlung

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