creating the initial state you dream of,
the collider system

Outline

The goal

The acceleration techniques

Linear, why ?

Energy and luminosity challenges
nasty consequences

end of lecture 1

Collider elements

Polarisation

e^-e^- option

$\gamma\gamma$ option

$e\gamma$ option

The goal

Build an accelerator

- with enough energy to reach a valuable physics
- to collect all the physics reachable
  in a reachable time, around 15 years.

That supposes an adequate luminosity.

$\Delta E \times \mathcal{L} \sim \text{cst}$

The acceleration techniques, a remainder

electrostatic

RF cavities, modes, losses, dependence in ω

superconducting / warm accelerators

plasma accelerators

Study of the techniques to accelerate particles

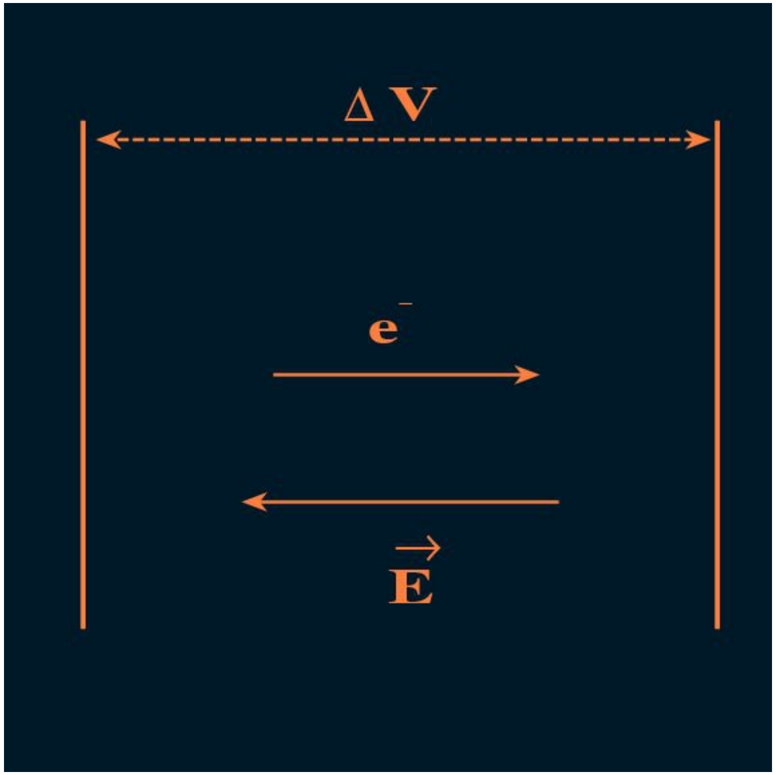
Apply to a particle of charge e an electric field E.
It generates on the particle a force F = eE = ma
and the particle supports an acceleration

$$a = \frac{eE}{m}$$

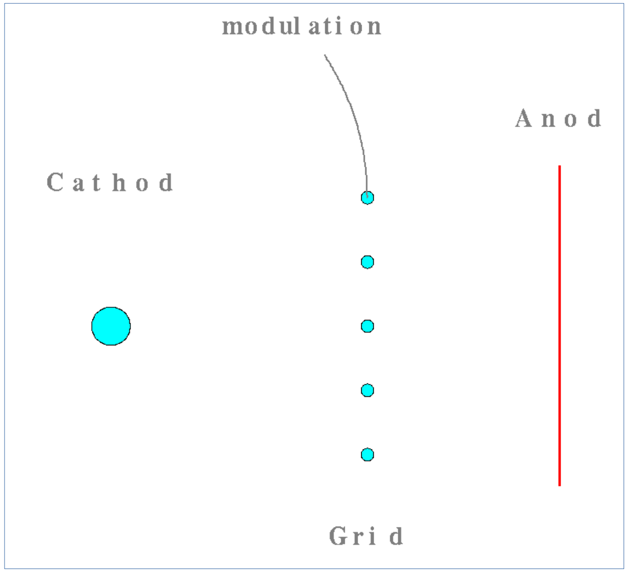
After a length L, the energy acquired by the particle is the work of the force
E = eEL where EL if the voltage difference V
E = eV

Method I.

Apply to the particles, here electrons, a static voltage.
The electron acqires the energy eΔV.
We have an electrostatic accelerator.
Beware of the limitations dues to breakdowns



This will be used for polarised sources, see later.



Do you know what a triod is?
a classical source of electrons is just that.

Method II.

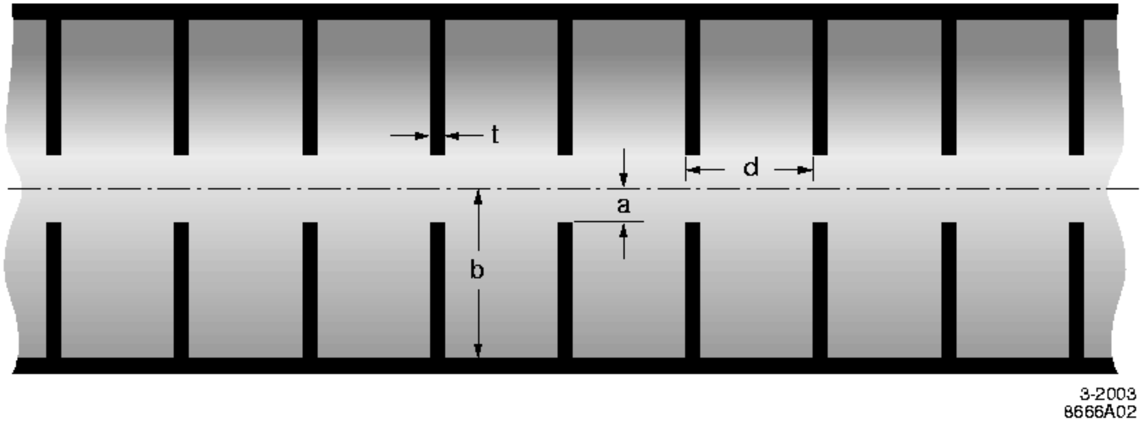
Can we apply a time-dependent field, an electromagnetic wave ?

In the absence of boundary conditions, the solutions to Maxwell equations are plane waves where E and B are orthogonal to the plane wave direction of propagation. Not very convenient.

Is it possible to impose boundary conditions such that the E field becomes aligned with the propagation direction ?

In a cylindrical wave guide, YES but unfortunately the phase speed becomes > c !!

OK when introducing boundary conditions in z.



Existence of oscillation modes

Maxwell equations

$\nabla \cdot$ is the divergence

$\nabla \times$ is the curl

$$\nabla \cdot \vec{D} = \rho \qquad \vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$$

$$\nabla \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = \vec{0}$$

with

$$\vec{B} = \mu \vec{H}$$

$$\vec{D} = \epsilon \vec{E}$$

In the absence of electric charges and currents $\nabla \cdot \vec{D} = 0 \qquad \vec{\nabla} \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{0}$

$$\vec{\nabla} \times (\vec{\nabla} \times \vec{E}) \equiv \vec{\nabla}(\vec{\nabla} \cdot \vec{E}) - \vec{\nabla}^2 \vec{E} = -\vec{\nabla} \times \frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla}^2 \vec{E} = \frac{\partial}{\partial t}(\vec{\nabla} \wedge \vec{B})$$

$$\vec{\nabla}^2 \vec{E} = \mu \frac{\partial}{\partial t}(\vec{\nabla} \times \vec{H}) \qquad \vec{\nabla}^2 \vec{E} = \mu \frac{\partial^2 \vec{D}}{\partial t^2}$$

wave equation

$$\vec{\nabla}^2 \vec{E} - \mu \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

and also

$$\vec{\nabla}^2 \vec{H} - \mu \epsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0$$

$$F^{\mu\nu} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_x \\ E_z & -B_y & B_x & 0 \end{pmatrix}$$

Lorentz invariants : $E \cdot B \quad E^2 - B^2$

energy $\frac{1}{2} F^{\mu\nu} F_{\mu\nu} = E^2 + B^2$

$$\partial_\mu F^{\mu\nu} = j^\nu$$

where j^ν is the electric current $j^\mu = (\rho, \vec{j})$

Current conservation is obvious: $\partial_\nu j^\mu = \partial_\nu \partial_\mu F^{\mu\nu} = 0$

The other group of equations is obtained by duality: noting that there is no magnetic charge or current $\vec{B} \rightarrow \vec{E} \quad , \quad \vec{E} \rightarrow -\vec{B}$

$$\partial_\mu \epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma} = 0$$

where $\varepsilon^{\mu\nu\rho\sigma}$ is the order 4 totally antisymetric tensor (Levi Civita).

Looking for a free wave solution of

$$\vec{\nabla}^2 \vec{E} - \mu \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = 0$$

$$\vec{\nabla}^2 \vec{H} - \mu \epsilon \frac{\partial^2 \vec{H}}{\partial t^2} = 0$$

We take the z axis along the propagation direction and look for a plane wave solution.

$$\vec{E} = \vec{E}_0 \exp[i(\omega t - kz)]$$

$$\vec{H} = \vec{H}_0 \exp[i(\omega t - kz)]$$

The absence of boundary conditions,
a homogeneous and isotropic vacuum,
requires that E_0 et H_0 are constants.

Applying the wave equation to the electric field

$$\nabla^2 \vec{E} = k^2 \vec{E} = \mu \epsilon \frac{\partial^2 \vec{E}}{\partial t^2} = \mu \epsilon \omega^2 \vec{E}$$

$$k^2 = \mu \epsilon \omega^2 \rightarrow \frac{\omega}{k} = \frac{1}{\sqrt{\mu \epsilon}}$$

It is a plane wave with phase speed equal to $1/\sqrt{\mu\varepsilon}$,
in the vacuum it propagates at the speed c.

Applying Maxwell equations to this solution:

$$\vec{\nabla}\cdot\vec{E}=\frac{\partial \vec{E}}{\partial z}=-ikE_{0,z}\exp\left[i\left(\omega t-kz\right)\right]=0$$

either k or E_{0z} have to be 0

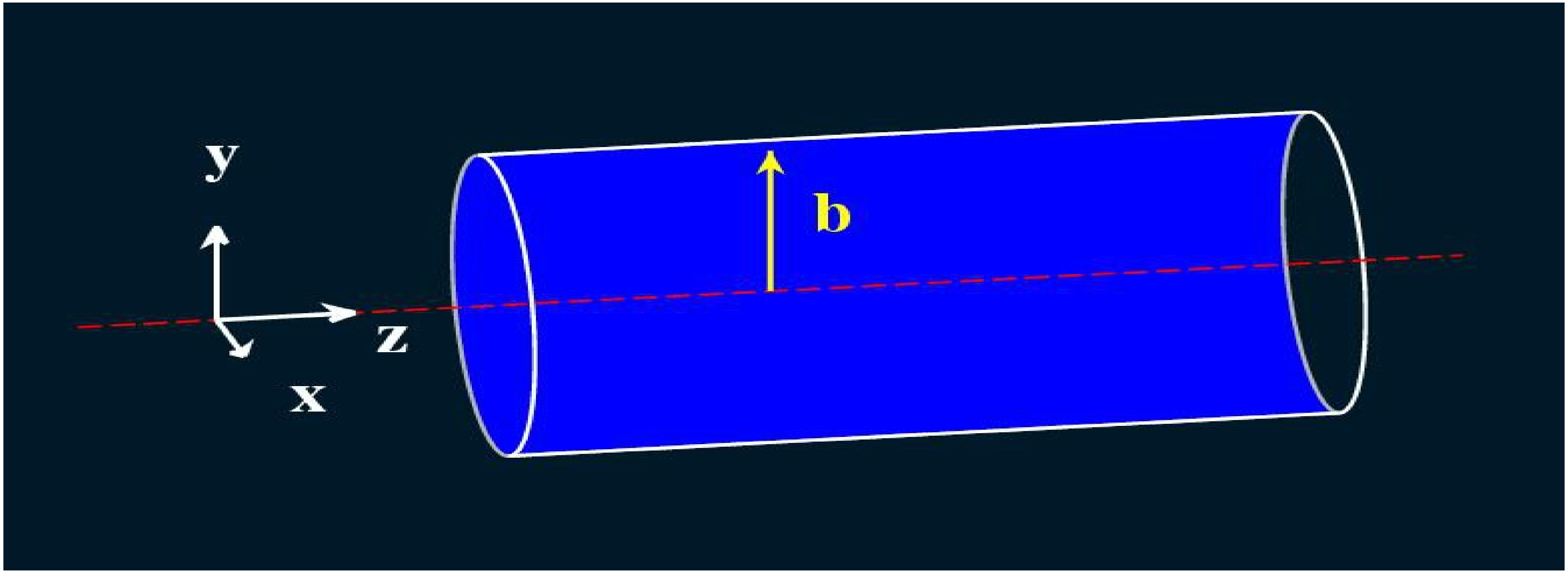
k = 0   no wave

E_{0z} = 0 the field is perpendicular to the direction of propagation!!

Looking for a solution with boundary conditions

We introduce boundary conditions in x and y in order to compensate the z derivative of the field by non zero derivatives in x and y.

We take a conducting tube with axis z and radius b.



We look for solutions like:

$$\vec{E} = \vec{E}_0 \exp[i(\omega t - kz)]$$

$$\vec{H} = \vec{H}_0 \exp[i(\omega t - kz)]$$

where E_0 et H_0 depend on x and y
or going to semipolar coordinates
on ρ and θ but not on z and t

we have then

$$\frac{\partial}{\partial z} = -ik, \frac{\partial^2}{\partial z^2} = -k^2$$

$$\frac{\partial}{\partial t} = +i\omega, \frac{\partial^2}{\partial t^2} = -\omega^2$$

At the boundary (r=b), the normal component of B and the tangential component of E are continuous. If the conductor is perfect the fields are zero inside and when $r \to b$ H_r, E_z and $E_\theta \to 0$

Since $E_\theta = 0$, the θ component of the magnetic field curl vanishes.
and we have :

$$E_\theta = 0$$

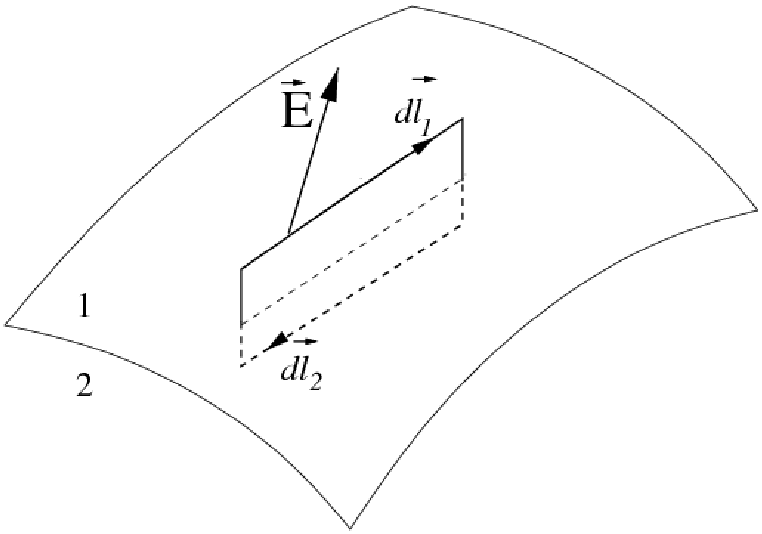
$$E_z = 0$$

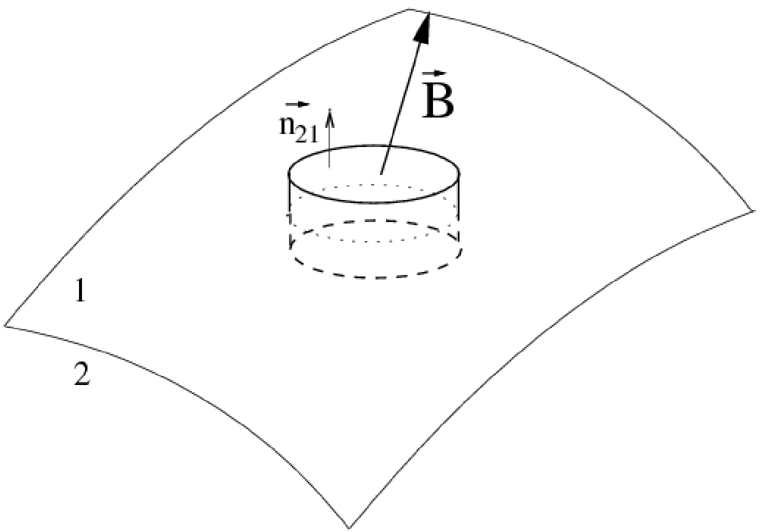
$$H_r = 0$$

$$\frac{\partial H_z}{\partial r} = 0$$

@ r = b

Speaking of continuity





$$\int_C \vec{E}\cdot\vec{dl} = \iint_S (\vec{\nabla}\times\vec{E})\cdot\vec{dS} = -\frac{\partial}{\partial t}\iint_S \vec{B}\cdot\vec{dS}$$

$$\iint_S B\cdot\vec{dS} = -\frac{\partial}{\partial t}\iiint_V \vec{\nabla}\cdot\vec{B}\,d\tau$$

Stokes theorem

Rewriting the z component of the wave equation as

$$\nabla_\perp^2 E_z - k^2 E_z + \mu \epsilon \omega^2 E_z = 0$$

defining

$$k_c^2 \equiv \mu \epsilon \omega^2 - k^2$$

$$\nabla_\perp^2 E_{0,z} + k_c^2 E_{0,z} = 0$$

where J_n are Bessel functions of the first type

$$E_{0,z} = \sum_{n=0}^{\infty} a_n J_n(k_c r) \cos(n\theta + \theta_n)$$

1. n is an integer because the field is monovalued
--cos[n(θ+2π)] = cos nθ   if n is integer.
2. to impose $E_z \rightarrow 0$ @ r=b, $k_c b = z_{np}$, where z_{np} is the p^{th} zero of J_n.

Notice that it implies $k_c>0$ and

$$E_{0,z} = \sum_{p=1}^{\infty} \sum_{n=0}^{\infty} a_{np} J_n(k_{c,np} r) \cos(n\theta + \theta_{np})$$

Notice that

$$k_{c,np} = \frac{z_{np}}{b} = \sqrt{\mu \epsilon \omega^2 - k^2}$$

$$\omega_{c,np} = \frac{1}{\sqrt{\mu \epsilon}} \frac{z_{np}}{b}$$

Hence k=0 corresponds to a non-zero ω:

Cut frequency

mass

$\omega > \omega_C$: k real is possible, the wave is a complex exponential

$\omega < \omega_C$: k is imaginary, the wave decreases exponentialy with z, it can not propagate – evanescent wave!

Phase and group wave speeds:

$$v_{gr} = \frac{\partial \omega}{\partial k} = \frac{1}{\sqrt{\mu \epsilon}} \frac{\sqrt{\omega^2 - \omega_c^2}}{\omega} < c$$

$$v_{ph} = \frac{\omega}{k} = \sqrt{\frac{1}{\mu \epsilon} + \frac{\omega_c^2}{k^2}} > c$$

Since particles move with a speed <c

they will dephase against the field

no acceleration is possible!

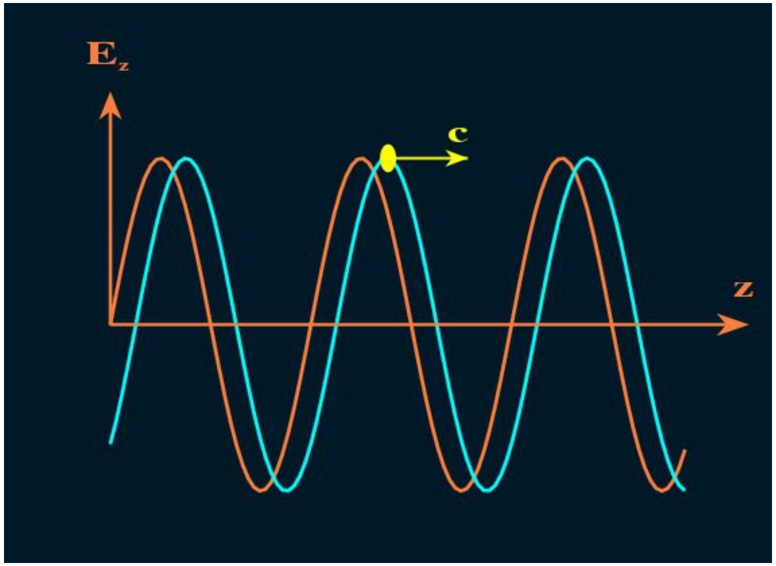
We have to introduce z boundaries

multicavities acceleration.

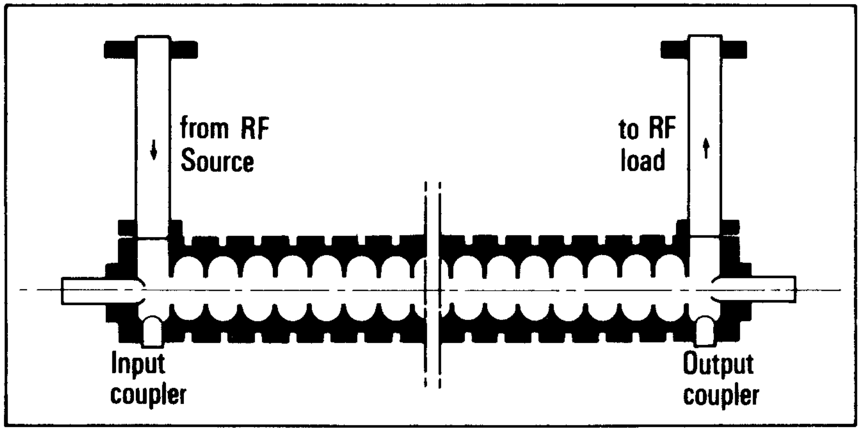
Use of progressive (travelling)
or standing waves

Progressive wave :
phase speed c
the particle bunches see a constant field

$$E_z = E_0 \cos(\varphi)$$

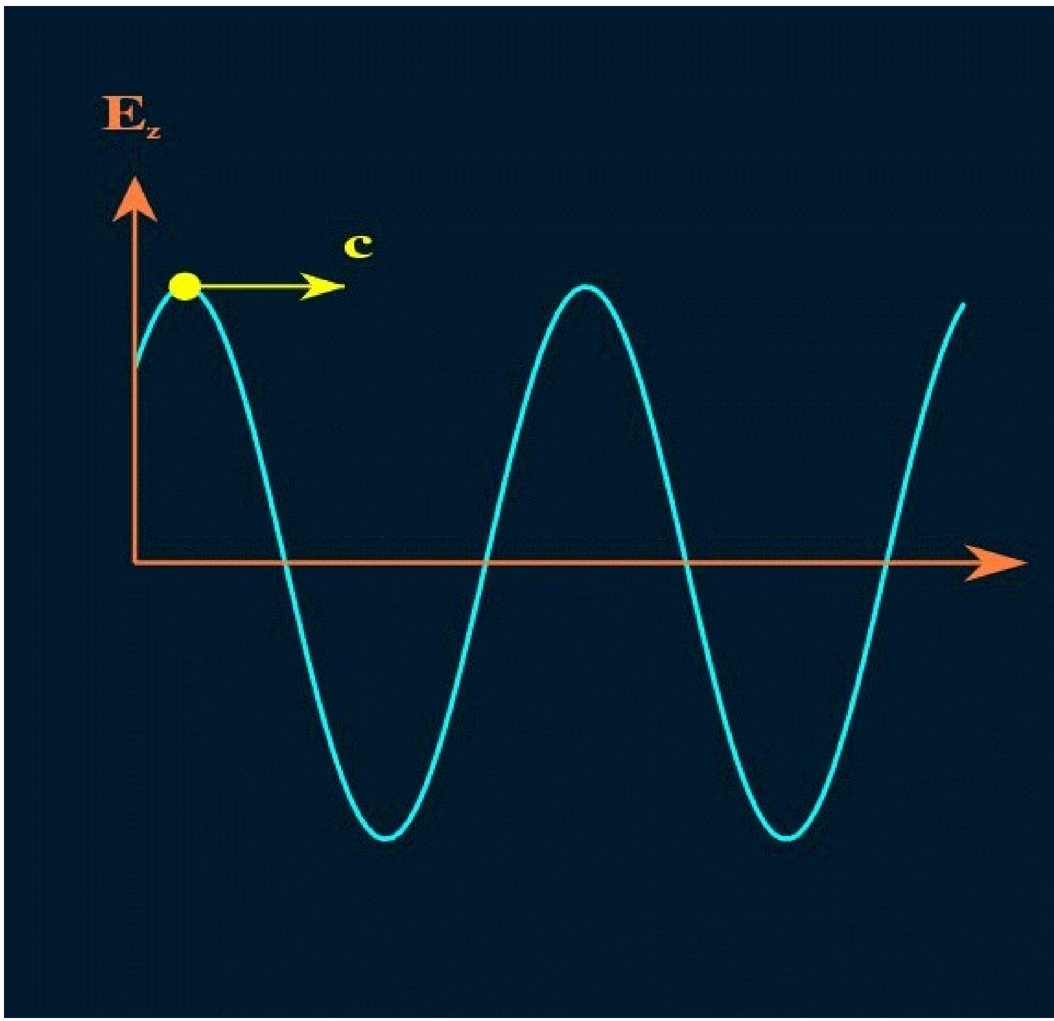


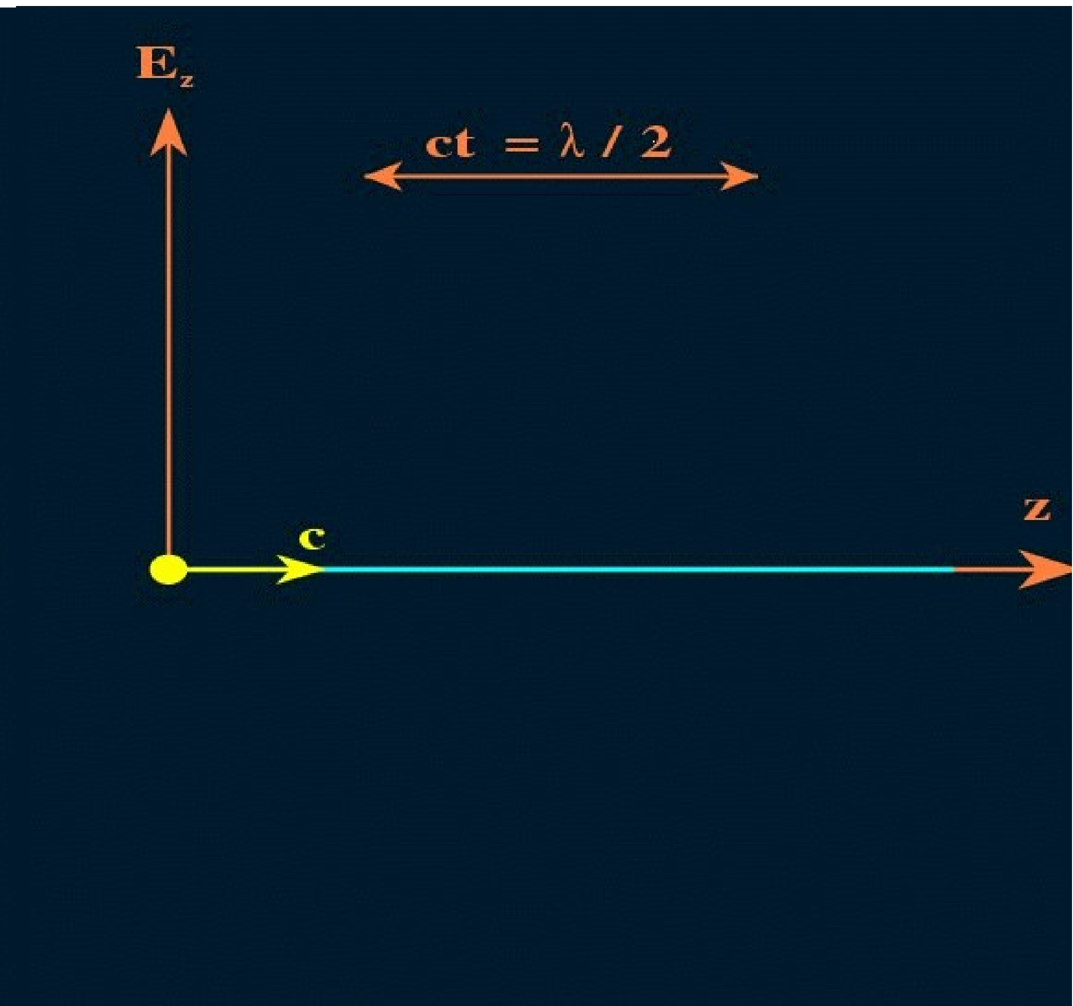
if not for the energy absorbed by the beam
(beam loading)

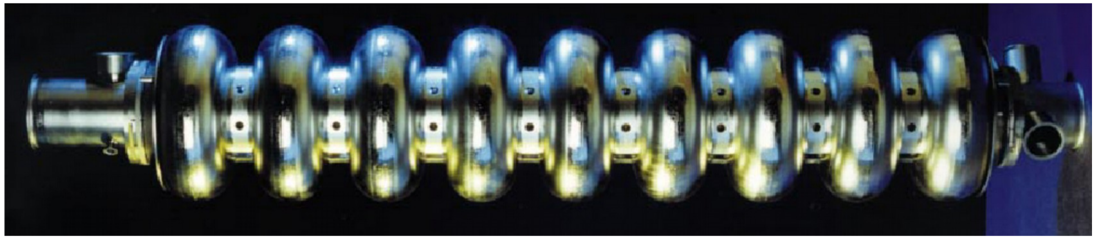


progressive/travelling wave

stationary/standing wave



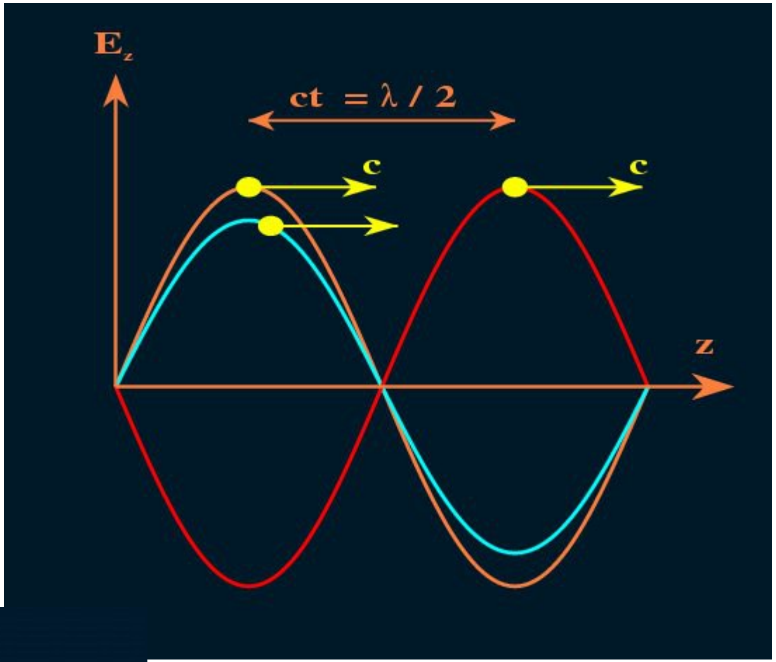




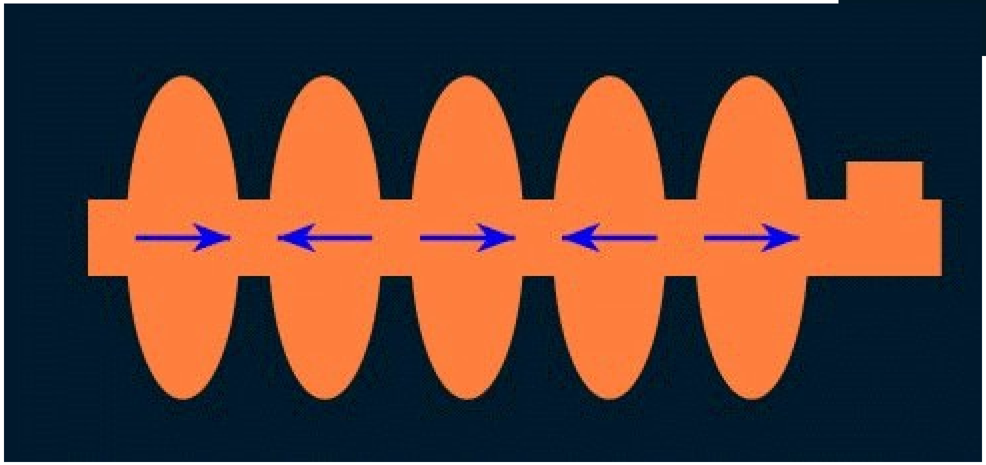
Stationary or standing wave

Resonant cavity :
the particles see the field :

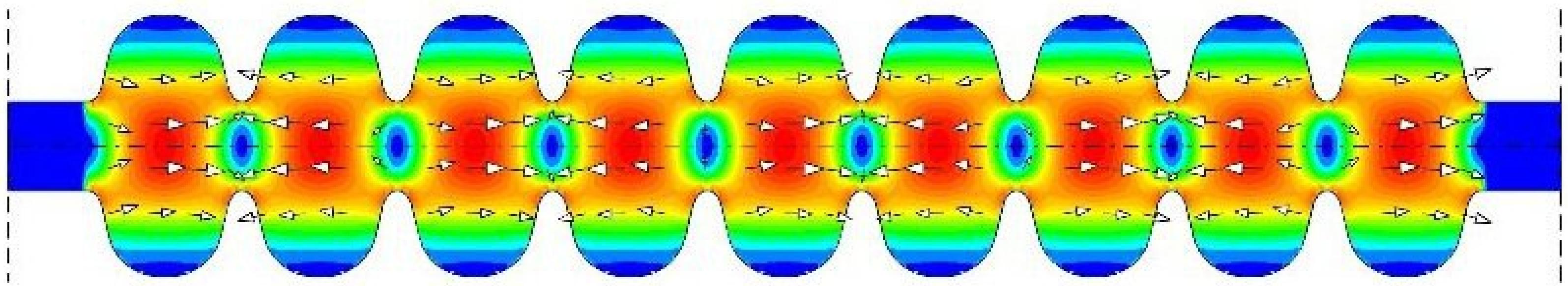
$$E_z = E_0 \sin(\omega t + \varphi)\sin(kz)$$
$$= E_0 \sin(kz + \varphi)\sin(kz)$$



Polarity reverses every T/2



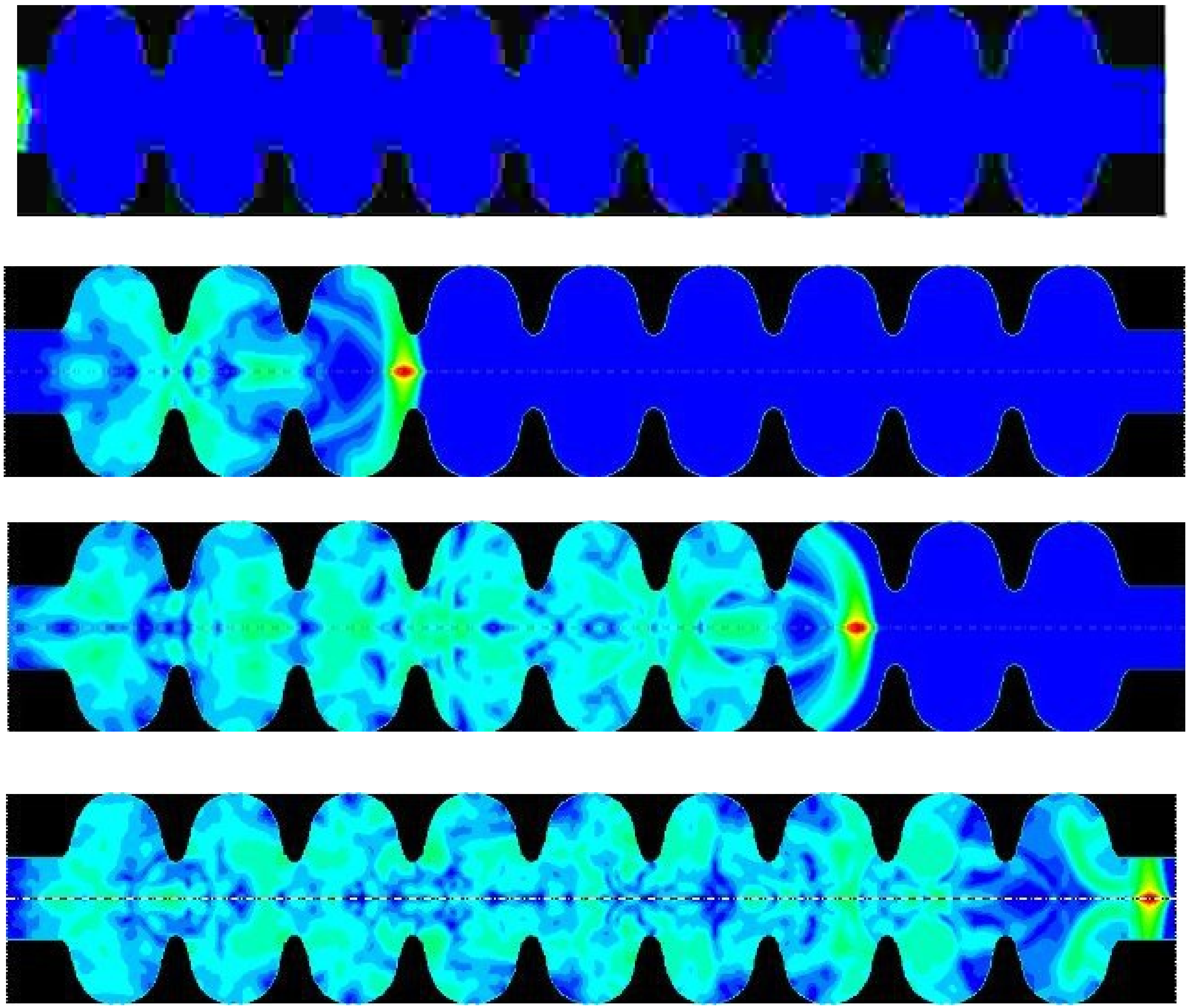
A standing wave is less efficient by a transit factor T=sin(ψ/2)/(ψ/2) where ψ is the transit angle, wave phase variation during the particle transit in the cavity.



Electric field in a TESLA cavity for the fundamental mode π at 1.3 GHz (S).

The beam passing through induces in the cavity a decelerating field

Wake fields in the RF structures



Wake fields induced by the beam passing through the cavities

The wake fields have long lifetimes
$\tau = 2Q/\omega_{RF} \sim 1s$

The out of axis bunchs generate dipole fields which deflect the following bunchs $\Rightarrow$
attenuation $\tau < 100\ \mu s$

Important quantities / RF mode standing waves

Voltage gain along the axis — values for EXFEL ILC

$U = \int dz\, E_z\, (z, t=z/c)$ — 20 — 31.5 MV

Stored energy: W

geometrical factor : $R/Q = U^2 / \omega_{RF}\, W$ ~ 1 kΩ

$$\frac{U^2}{\omega_{RF} W} \approx \frac{T^2 L}{b} \sqrt{\frac{\mu}{\epsilon}}$$

optimal transit angle 134°

Power dissipated:

P_Ω corresponds to the ohmic losses

$$P = dW/dt = P_\Omega + P_{beam}$$

Quality factor $Q_0 = \omega_{RF}\, W / P_\Omega$ $\sim 10^{10}$

(Shunt Impedance $R = U^2 / P$)

The size of the cavities is about the wave length

The power transferred to the beam is in ω^2,
it is more efficient to go to higher frequencies
super 1.3 GHZ (S), warm 11.4 GHz (X), CLIC 30 GHz, (plasma 3THz).

RF power when accelerating

The RF power is provided by klystrons: $Q_{ext} = \omega_{RF} W/P_{RF}$

The RF power is dissipated in the beam
and in the resistive losses

	$P_{RF} = P_{beam} + P_\Omega$	valeurs TESLA
	$P_{beam} = U\, I_{beam}$	230 kW = 25MV . 9mA
with	$P_\Omega = \omega_{RF} W/Q_0 = U^2/R$	2,5 mW

NB $P_\Omega \sim R_S$ surface resistance

R_S (Nb @ 2 K) $\simeq$ R_S (Cu @ 300 K) 10^{-6}

$P_\Omega \ll P_{beam}$ for Nb , $P_\Omega \simeq P_{beam}$ for Cu

The difference between warm and superconducting

Energy loss: $P_{in} = P_{beam} + P_{\Omega} + P_{out}$

For superconducting P_{Ω} ~ zero.
In stationary mode P_{out} zero.

For warm as P_{out} is dominated by P_{Ω} (2/3 de Pin),
progressive waves with constant gradient,

for cold it is more favourable to use standing waves.

If P_{Ω} nul, the wave stays longer, long pulse, 1ms against μs.

A cavity quality is measured by its « Q » value
fraction of the stored energy lost in the walls
in 2π times the RF period.

Running cost: electric consumption

$$P_{total} = (P_{beam} + P_{\Omega}) / \eta_{RF} + P_{\Omega} / \eta_{cooling}(T)$$

Beam power: $P_{beam} = E_{CM} \times N_{part} = E_{CM} /e\, I_{beam} = N_{cavity}\, U\, I_{beam}$

Ohmic losses: $P_{\Omega} = N_{cavity}\, U^2 / R = E_{CM} /e\, N_{cavity}\, R$

A cooling is necessary to maintain the Linac at the temperature T
In a cryogenic machine the ohmic losses are dissipated in a refrigerator providing the temperature T :
Efficiency (Carnot)
$\eta_{cooling}$ (T) ~ (T/300) / 4 = 1/300 @ LEP (4K)

1/600 @ ILC (2K)

radiofrequency

time structure

In a superconducting accelerator with cavities $Q \sim 10^{10}$

The RF stays long and should be used fully.
At a given power it will be better to have few trains per second
with numerous bunchs properly spaced.
RF beam efficiency at ILC 44 %

In a warm accelerator
the RF pulses are short, few bunches well packed in numerous trains.

good transfer efficiency, higher fields.

shorter accelerators

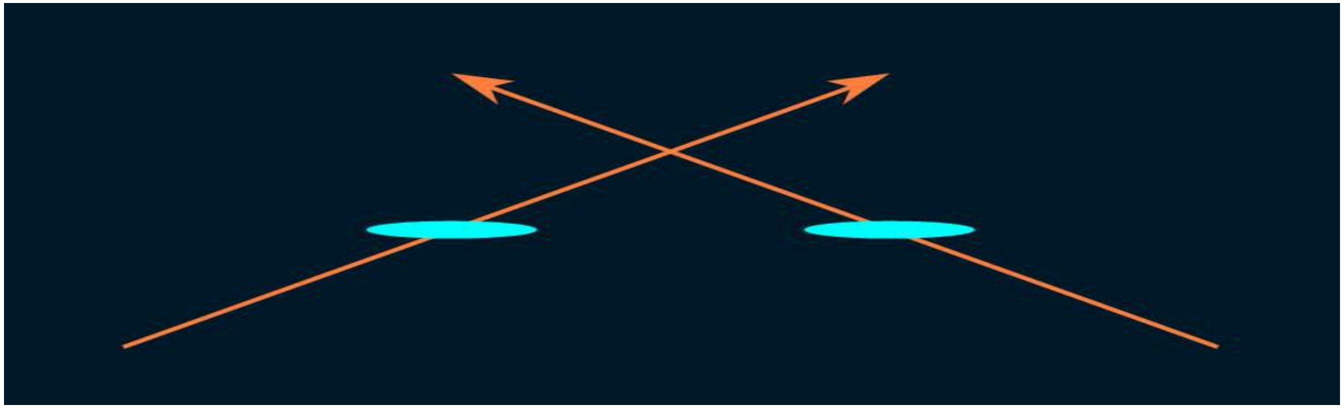
Remark: all the stored energy can not be used for accelerating due to beam loading
the last bunchs would be submitted to very reduced fields.

Time structure:
in ILC 5 RF pulses 1 ms long per second, every 200 ms (5H)
in each pulse a train of about 3000 bunches separated by 300 ns.

Warm accelerator, 100 pulses per second, containing 150 bunches separated by 1.4 ns, about 40 cm.

This implies that the two beams cross at angle to avoid crossing at more than one point
This induces a loss in luminosity which can be corrected by a crab crossing
which degrades in turn the interaction point knowledge.

~idem at CEPC



The choice for ILC has been the superconducting accelerator
CLIC is a warm accelerator.

This is linked to the gradients
expected for superconducting cavities
today about 1/2 of warm cavities

ILC has two prototypes :
the EXFEL in construction at DESY
LCLS II in design

ILC power consumption 160 MW to 210 to 300
500 L upgrade 1 TeV

Superconducting cavities

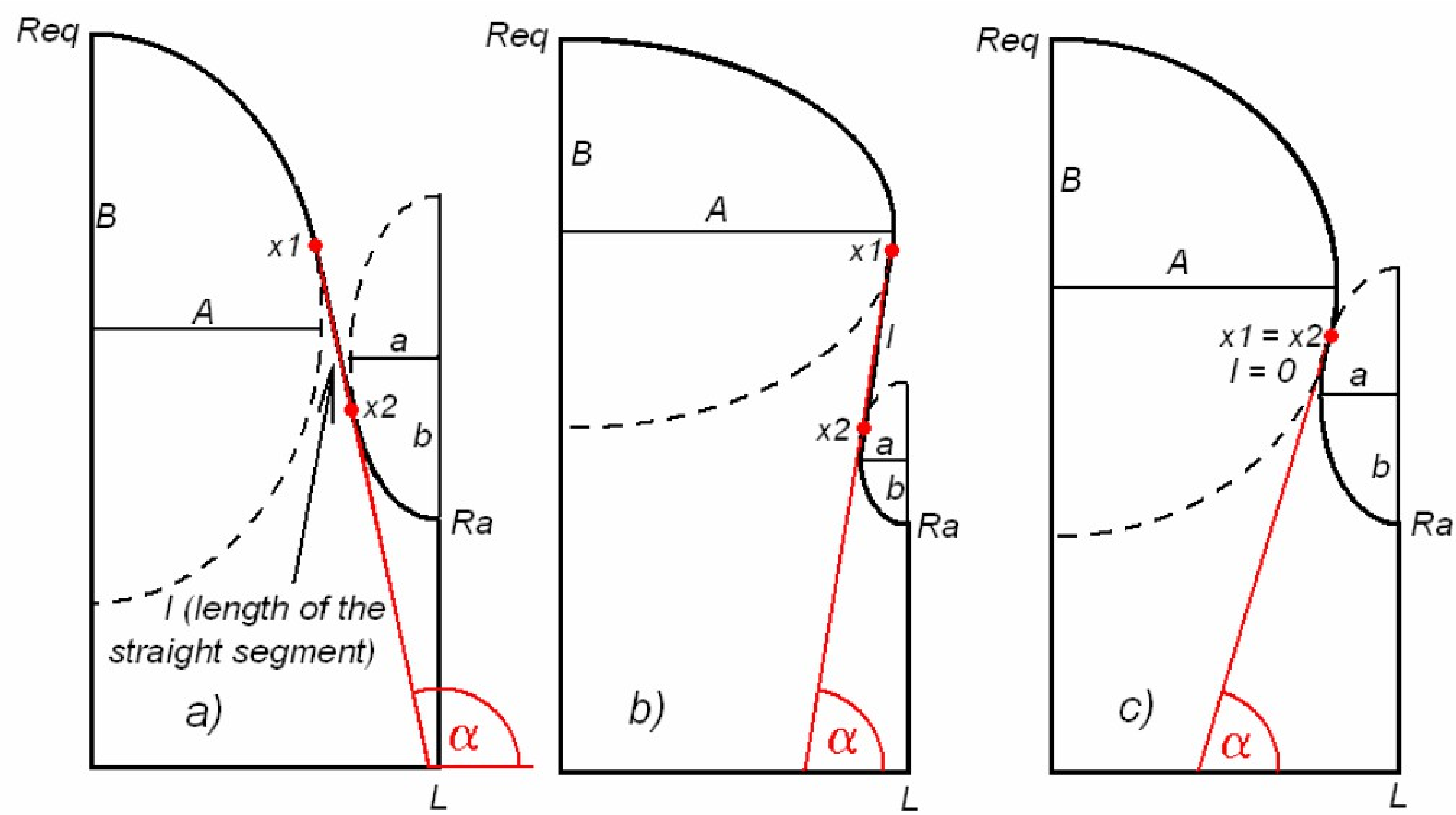
Those used at LEP reached 6 to 7 MV/m, much too low for a linear accelerator.
But they were running in a continuous mode.
TDR : ILC 500 GeV needs 31.5 MV/m +- 20 % Q_0=0.8 10^{10}

The technology has much improved for the voltage and the Q.
Industrial cavities reach 45 MV/m currently,
this is not so far from the « theoretical limit » close to 50 MV/m, linked to the field on the surface which induces the return of the niobium to its normal state.

from $H_\theta < H_c$ = 200mT for the massive Niobium

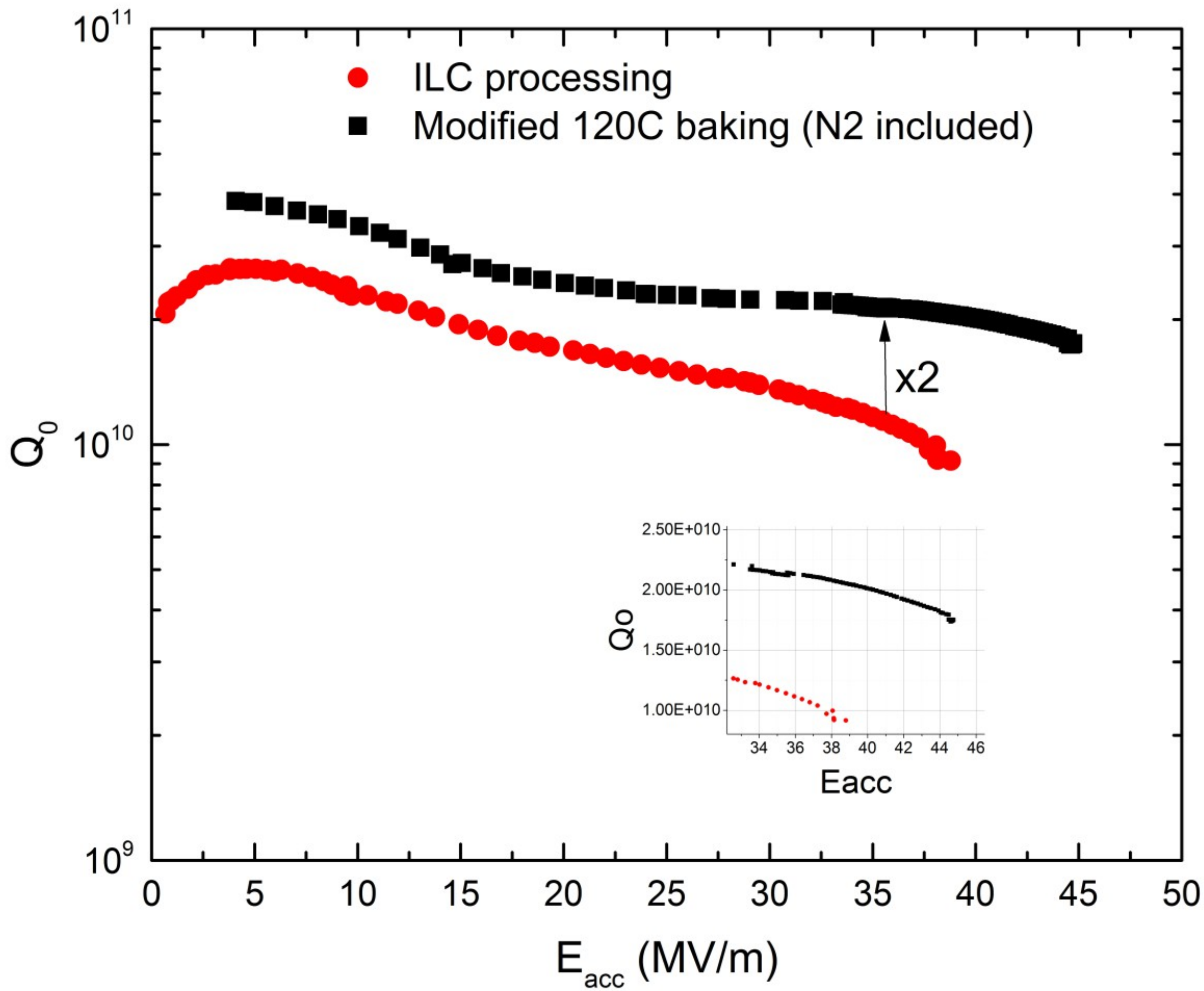
LC goal for 1 TeV : 40-45 MV/m Q_0=1-2 10^{10}

It is essentially a question of the state of the surface
which can be improved by different techniques like RF burning,
electropolishing in presence of nitrogen…
but also : Large grain niobium
new shape for cavities
coating of Nb2Sn or MgB2 (47 % increase)



Shemelin PAC 2007

“standard” 120C bake vs “N infused” 120C bake

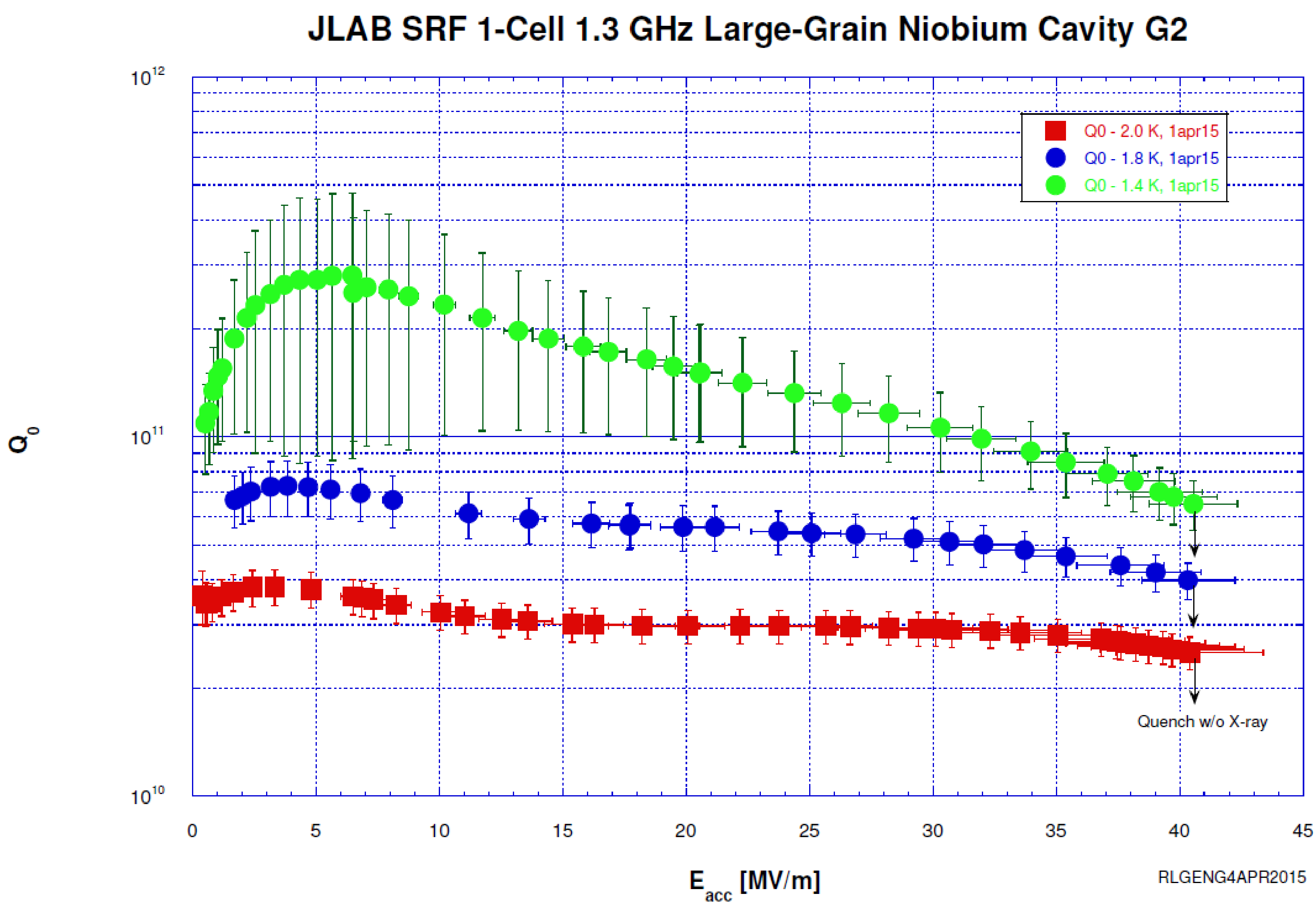


- Achieved:

45.6 MV/m ▭ 194 mT
With Q ~ 2e10!

- Q at ~ 35 MV/m ~ 2.3e10!
- ILC specs: Q=0.8e10 @ 35MV/m

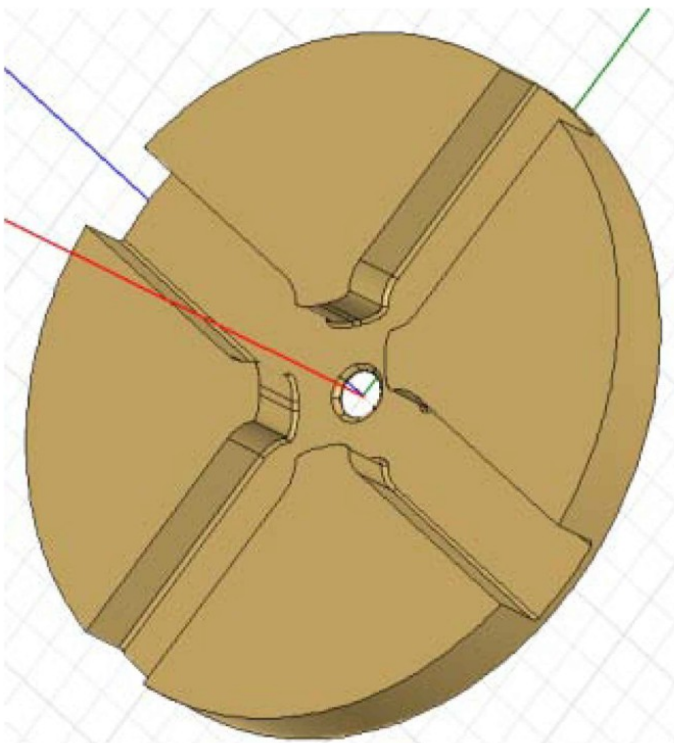
Increase in Q factor of two, increase in gradient ~15%

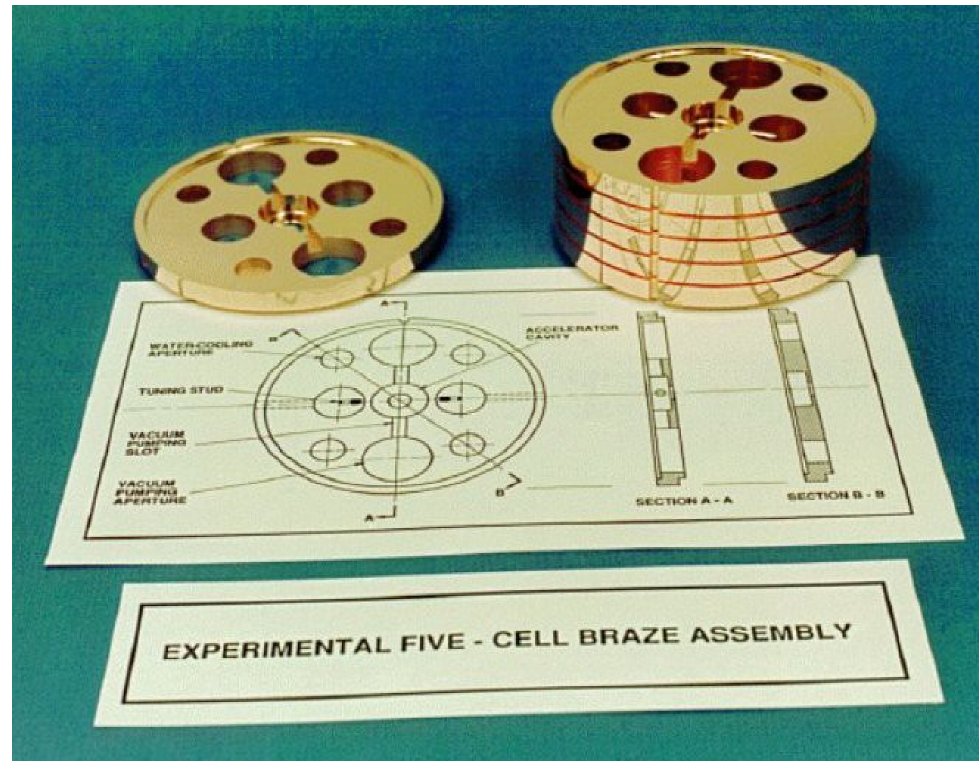


Geng et alii IPAC 2015

Accelerating cavities for the american project NLC
the wavelength is reduced by a factor 10 from ILC.

CLIC accelerating cavity





Generating RF : the klystrons

A continuous beam (<500 kV, < 500 A) is emitted by an electron gun.

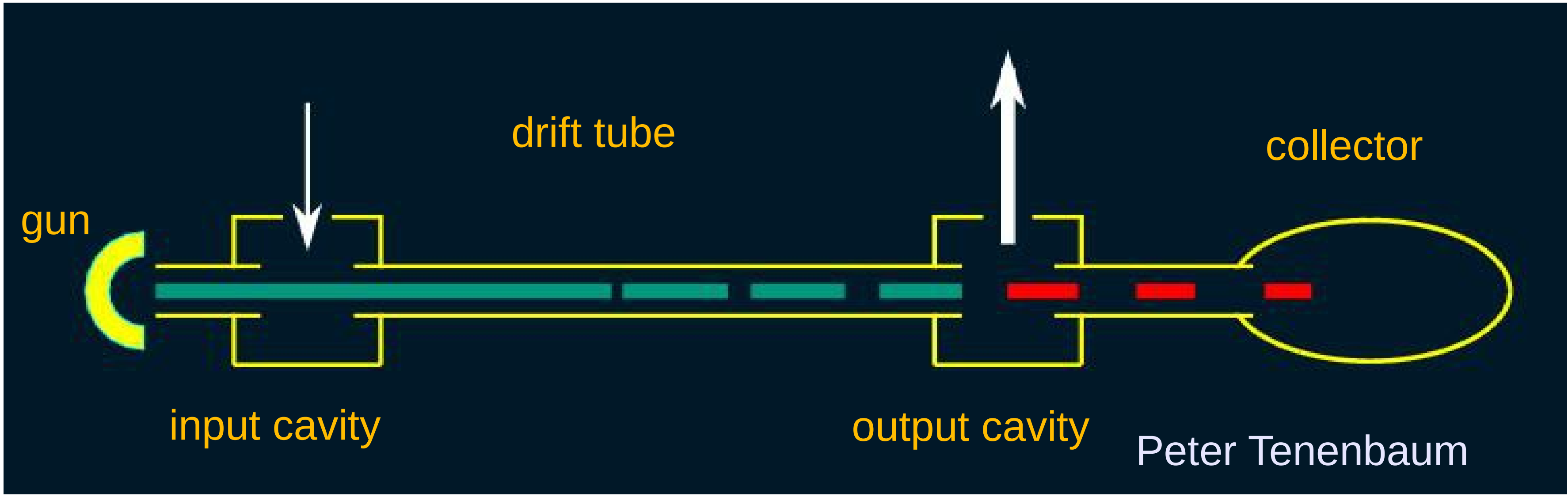
A low power signal, at a chosen frequency, excites the input cavity

The particles are accelerated or decelerated according to the phase when they enter the input cavity.

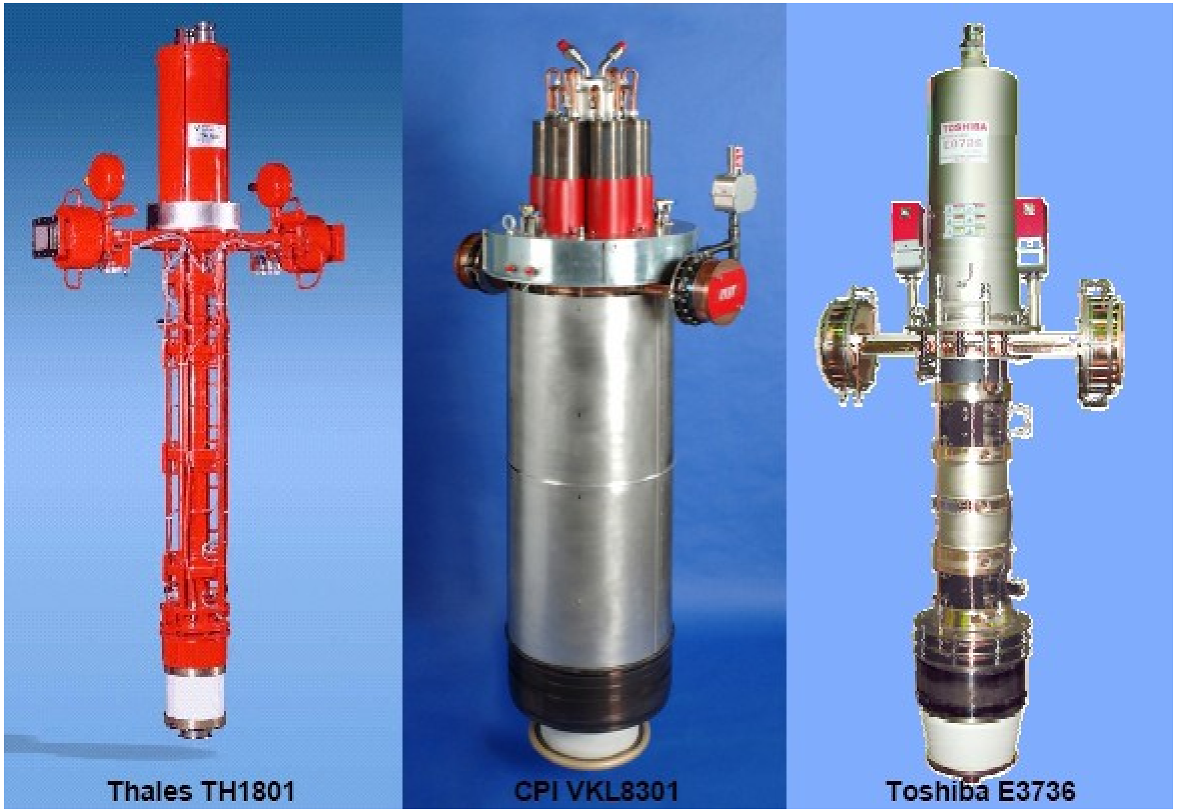
The speed modulation is transformed by the drift in the tube in a time modulation (the beam is pulsed at the pilote frequency)

The pulsed beam excites the output cavity at the chosen frequency (beam loading)

The beam is finaly stopped in the collector.



Accelerators



Multibeam klystrons
going these days from 66 % efficiency toward 90 %

To reach really higher energies the next electron accelerator should be linear!

Radiative losses:

a charged particle with energy *E* following an orbit of radius R looses the energy: $\delta E = 6\,10^{-15} R^{-1} \gamma^4$

where *R* is in meters and *E* in MeV

Example:

a 100 GeV electron and a 1km radius

m_e = 0.5 MeV, γ = 2 10^5

$$\delta E = 6.10^{-15} 10^{-3} 16.10^{20} \approx 10\,GeV$$

Radius such that $\delta E = E$

that does not mean that the beam stops in one turn

$E^3 \approx 10^7 R$ with *E* in GeV and *R* in km

i.e. 100 m for 100 GeV, 100 km for 1 TeV
the earth radius for 4TeV !!

R increases like E^3 when in a linear accelerator L increases like E
as the cost is ≃ L (or 2πR) at some energy the linear becomes cheaper.

The proton, 2000 times heavier, radiates much less (about 10^{13}),
the muon also

Motion of a charged particle in a magnetic field

$$P^\mu = mU^\mu = m\gamma(c, \vec{v})$$

X^μ is the time-position 4-vector
U^μ is the speed 4-vector
P^μ is the energy-momentum 4-vector

$$U^\mu = \frac{dX^\mu}{d\tau}$$

$$P^\mu = mU^\mu = m\gamma(1, \beta^\mu)$$

equation of motion $\frac{dP^\mu}{d\tau} = qF^{\mu\nu}U_\nu$

in the absence of electric field the spatial part writes $m\gamma\frac{d\vec{v}}{d\tau} = m\gamma^2\frac{d\vec{v}}{dt} = q\gamma\left(\vec{v}\wedge\vec{B}\right)$

Writing with complex numbers the motion in the plane orthogonal to B

$$\frac{dv}{dt} = -i\frac{qB}{m\gamma}v$$

writing $\omega = \frac{qB}{m\gamma}$

$$\frac{dv}{v} = -i\omega dt$$

$$v = v_0 e^{-i\omega t}$$

$$x = x_0 + i\frac{v_0}{\omega}e^{-i\omega t}$$

The trajectory is a circle with radius

$$R = \frac{v}{\omega} = \frac{m\gamma v}{qB} = \frac{p}{qB}$$

$$p = qRB$$

in SI, p is in VC/c, qRB in CmT
if the charge is in electrons: p (eV) = c R(m) B(T)

$$p(GeV) = 0.3B(T)R(m)$$

$$U^\mu = (\gamma c, \gamma \vec{v}) \qquad U^2 = \gamma^2 c^2 (1-\beta^2)^2 = c^2$$

Acceleration 4-vector $\quad A^\mu = \frac{dU^\mu}{d\tau} \qquad U^2 = c^2 \Rightarrow U_\mu \frac{dU^\mu}{d\tau} = 0 \Rightarrow U_\mu A^\mu = 0$

writing $\quad \vec{a} = \frac{d\vec{v}}{dt} \qquad A = \left(\frac{d\gamma}{d\tau} c, \frac{d\gamma}{d\tau} \vec{v} + \gamma \frac{d\vec{v}}{d\tau}\right) \qquad d\tau = \frac{1}{\gamma} dt$

Synchrotron radiation

power radiated by a charge q with *A* for acceleration 4-vector

$$\wp = \frac{q^2 A^2}{6\pi\epsilon_0 c^3}$$

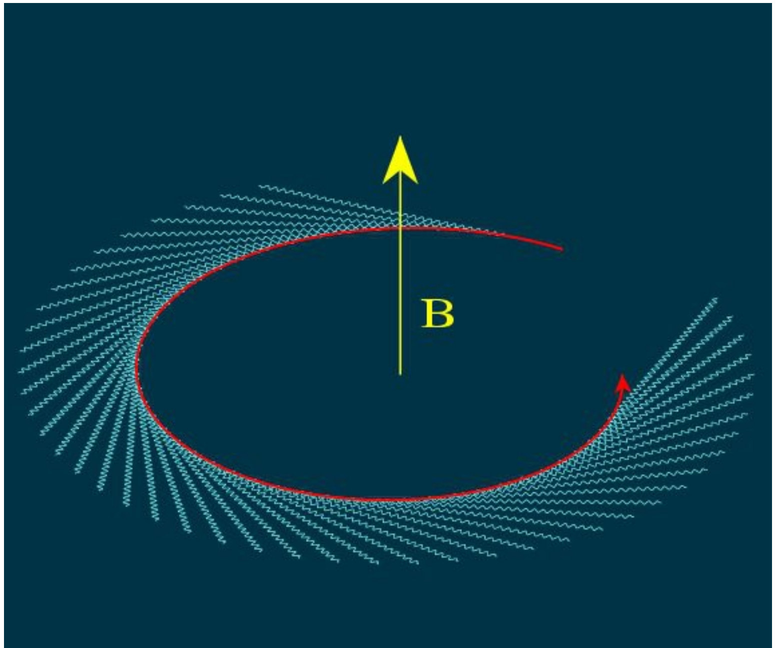
In a uniform rotation

$$A = (0, \gamma^2 \vec{a})$$

$$\vec{a} = \frac{v}{\rho}\vec{v} \wedge \vec{n}$$

$$A^2 = \frac{\gamma^4 \beta^4 c^4}{\rho^2}$$

$$\wp = \frac{q^2}{6\pi\epsilon_0}\frac{\gamma^4\beta^4 c}{\rho^2}$$



$$\wp \propto E^4 \rho^{-2}$$

time for a turn: $\frac{2\pi\rho}{\beta c}$

energy radiated per turn

$$\wp_r = -\frac{q^2\beta^3}{3\epsilon_0}\gamma^4\rho^{-1}$$

factor to convert in MeV:

$$\frac{1.6\,10^{-19}}{3\;\;8.8\,10^{-12}}10^{-6} = 6\,10^{-15}$$

Synchrotron radiation

Expressing the radiated power as a function of E (energy) and B for an electron

$$\rho^{-1} = \frac{eB}{p} = \frac{ecB}{\beta E}$$

$$\wp = \frac{e^2}{6\pi\epsilon_0}\gamma^4\beta^4 c \frac{e^2 c^2 B^2}{\beta^2 E^2}$$

in relativistic regime (β=1),

$$\wp \propto E^2 B^2$$

and for a revolution (T = 2$\pi\rho/\beta$c),

$$\wp_r \propto E^3 B$$

This is a purely classical approach which does not take into account the quantum mechanics aspects

synchrotron radiation spectrum
critical frequency

Reference: Introduction à la relativité,
André Rougé, Editions de l'Ecole polytechnique

What about cost?

The cost for building increases like L hence E

The proportionality factor depends on the acceleration gradient
from 35 at ILC to 100 MV/m at CLIC

The running cost depends on the power consumption

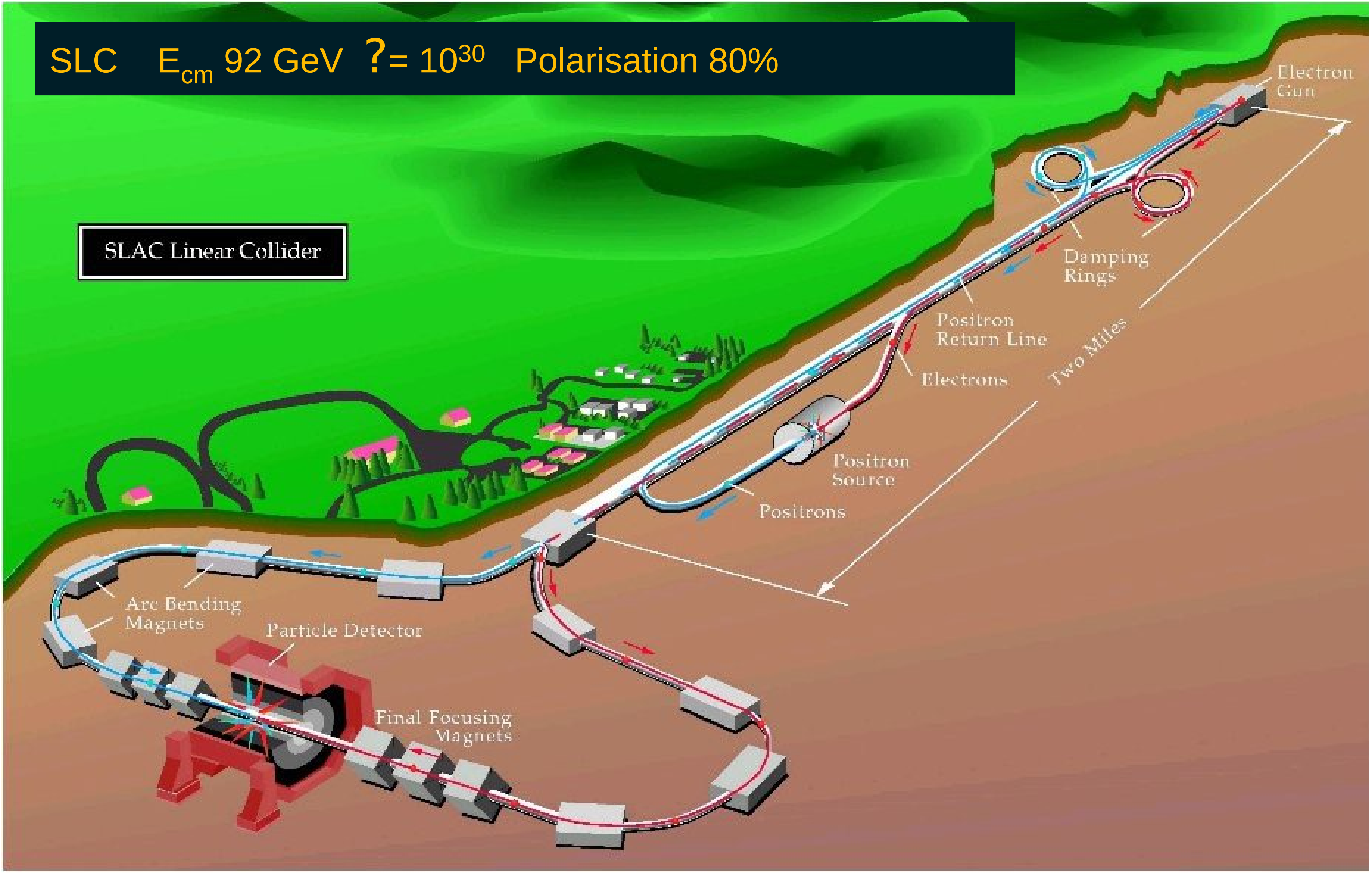
Beam power: 5 x 3000 bunches of 10^{10} electrons of 500 GeV
few tens of MW.

Balance between construction and running costs

The ancestor, a proof of feasability

SLAC

SLC E_{cm} 92 GeV ?= 10^{30} Polarisation 80%



And the progress to be made

	SLC	LC	
E_{cm}	100	500-1000	GeV
P_{beam}	0.04	5-20	MW
σ^*_y	500	1-5	nm
dE/E_{bs}	0.03	3-10	%
$\mathcal{L}$	0.0003	3	10^{34} cm^{2} s^{-1}

$\mathcal{L}$ is a number characteristic of the collider which, multiplied by the cross section σ gives the number of events per second: $N = L\,\sigma$

dimension $[\,T^{-1}\,L^{-2}\,]$ or E^3, current (non SI) units $cm^{-2}\,s^{-1}$

$$\mathcal{L} = \frac{I_1 I_2}{A} H_D$$

I_i is the current in the beam i,
A is the beam section at the interaction point
H_D an amelioration factor (pinch effect).

In the case of a pulsed beam with gaussian profile

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

where n_b is the bunch number,
N the number of electrons per bunch
f_{rep} the repetition frequency
σ_x et σ_y the lateral and vertical size of the beam.

one size at least is very small to limit the disruption at the collision
few nm at LC

The luminosity per bunch crossing is a Lorentz invariant:

J_1 and J_2 are the 4-vector current densities of the 2 beams

$$J_1 = \rho_1(x)\gamma(x)(1,\vec{\beta}_1(x))$$

$$\int \mathscr{L}\, dt = \int \left[(J_1 \cdot J_2)^2 - J_1^2 J_2^2 \right]^{1/2} d^4x$$

For relativistic beams (β = 1)

$\int \mathscr{L}\, dt$ is the overlap between the spatial distributions of the two beams :

$$\int \mathscr{L}\, dt \simeq 2\rho_1(x)\rho_2(x)\, d^4x$$

For two identical and gaussian beams

$$\int \mathscr{L}\, dt \simeq \frac{N^2}{4\pi\sigma_x^* \ \sigma_y^*} \qquad \mathscr{L} \simeq n_b f_{rep} \frac{N^2}{4\pi\sigma_x^* \ \sigma_y^*}$$

with n_b = # bunchs / pulse , f_{rep} = # pulse / s

Integrated luminosity

is measured in cm^{-2}
we are still at the time of CGS

or more usually in fb^{-1}

$1\ fb = 10^{-15}\ 10^{-24}\ cm^2$
which is much smaller than a barn.
« it's as big as a barn »

The notion of emittance

The emittance measures the volume or spread of a bunch of particles in its phase space $\epsilon = \Delta_x \Delta_{p_x} \Delta_y \Delta_{p_y} \Delta_z \Delta_{p_z}$

In the absence of couplings between planes
we can consider independently the x emittance
idem for y and z

$$\epsilon_x = \Delta_x \Delta_{p_x}$$

When the beam is accelerated P_z growths
the emittance goes down.
The normalised emittance we will use further is defined to stay constant as

$$\epsilon^* = \beta \gamma \epsilon$$

at high energy it becomes $\epsilon_x = \Delta_x \Delta_{\theta_x}$

$$\theta_x = \frac{p_x}{p}$$

Disruption in linear and circular.

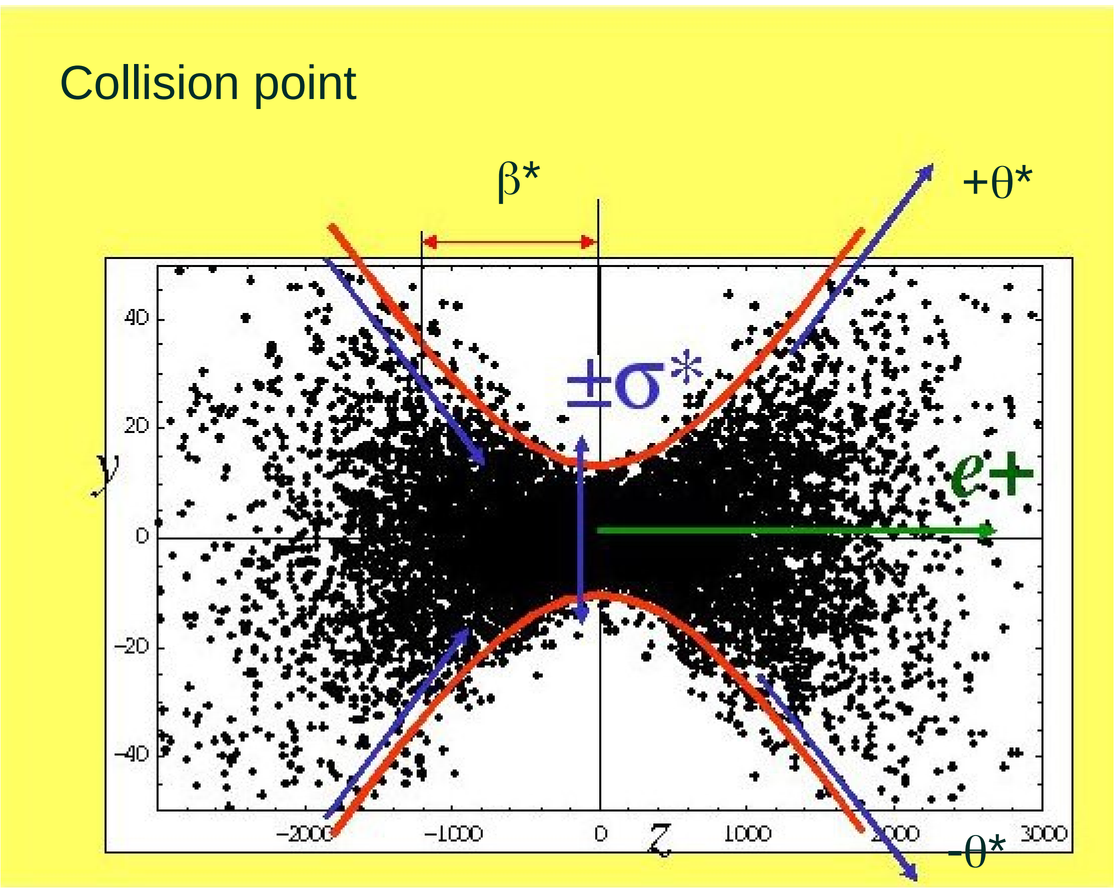
Few effects which degrade the collider performances

Hourglass effect

Beamstrahlung

The hourglass effect

At the focal point or interaction point ,
the emittance is $\varepsilon = \sigma^* \times \theta^* =$ beam invariant
the depth of the focus is $\beta^* = \sigma^* / \theta^* = \sigma^{*2} / \varepsilon$



The hourglass effect requires

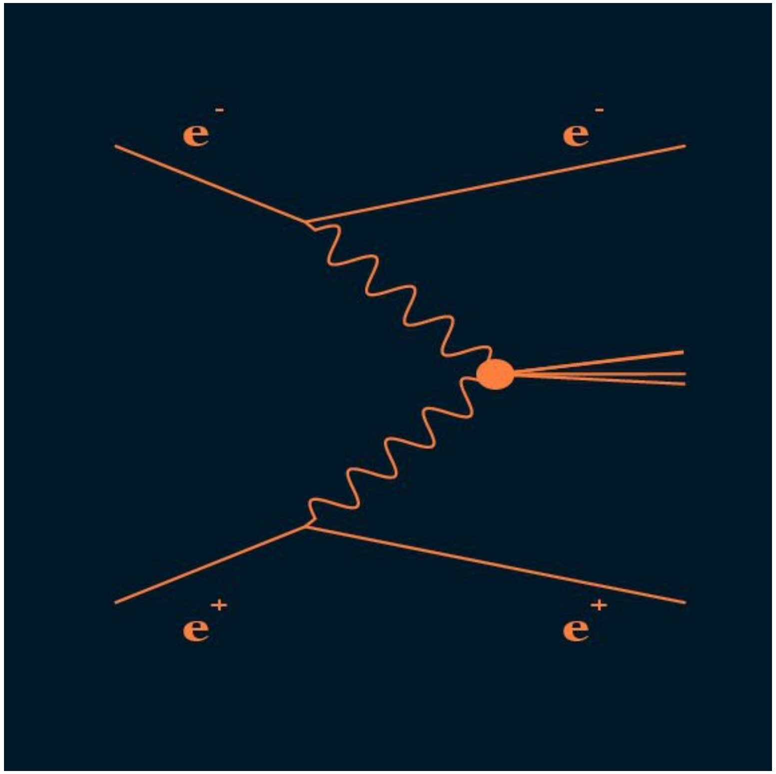
$$\sigma_z \leq \beta^* .$$

Reducing σ^* does not help except if ε or σ_z are much smaller!

The vertical σ is currently at ~ 1nm
what is the ultimate σ ?

During the collisions
the particles see the field of the particles of the other beam and can emit photons by bremsstrahlung

collisions $\gamma\gamma$.



At the linear collider the bunchs are so dense that the particles radiate in the macroscopic magnetic field from the opposite bunches.

mean energy loss: $\left\langle \frac{\Delta E}{E} \right\rangle \propto \frac{1}{\sigma_z (\sigma_x{}^* + \sigma_y{}^*)^2}$
for a small disruption

$$\langle B \rangle = B_S \times \frac{5 r_e^2 N}{6 \alpha_e \sigma_z (\sigma_x{}^* + \sigma_y{}^*)}$$

Compton length : $\lambda = \frac{h}{mc}$

where $B_S = m_e^2 c^2 / e = 4.4\ 10^9$ *T (Schwinger field)*

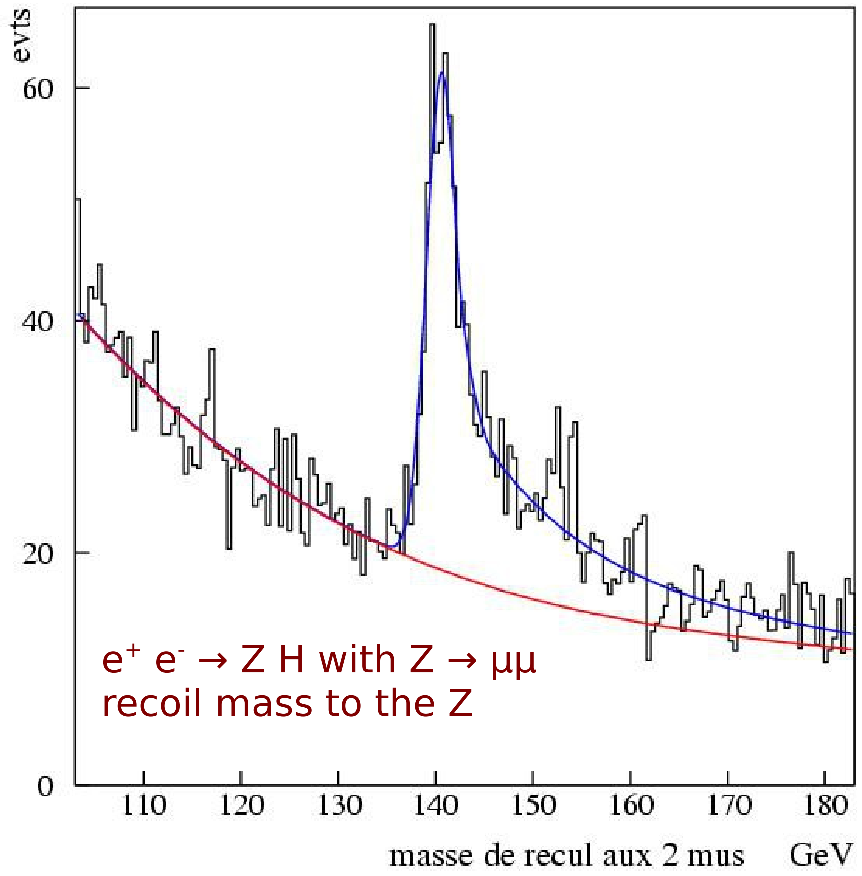
$e E_S \frac{1}{m} = m$ applied to an electron its work on a Compton length equals the mass

⟨B⟩ = 0.32 T @ LEP, 60 T @ SLC , 360 T @ TESLA

Notice the s_z^{-1} term. Could be terrible for plasma acceleration but QM effects.

Consequences

This radiation induces a reduction of the energy in the collision CM giving an energy spectrum extending to lower energies.



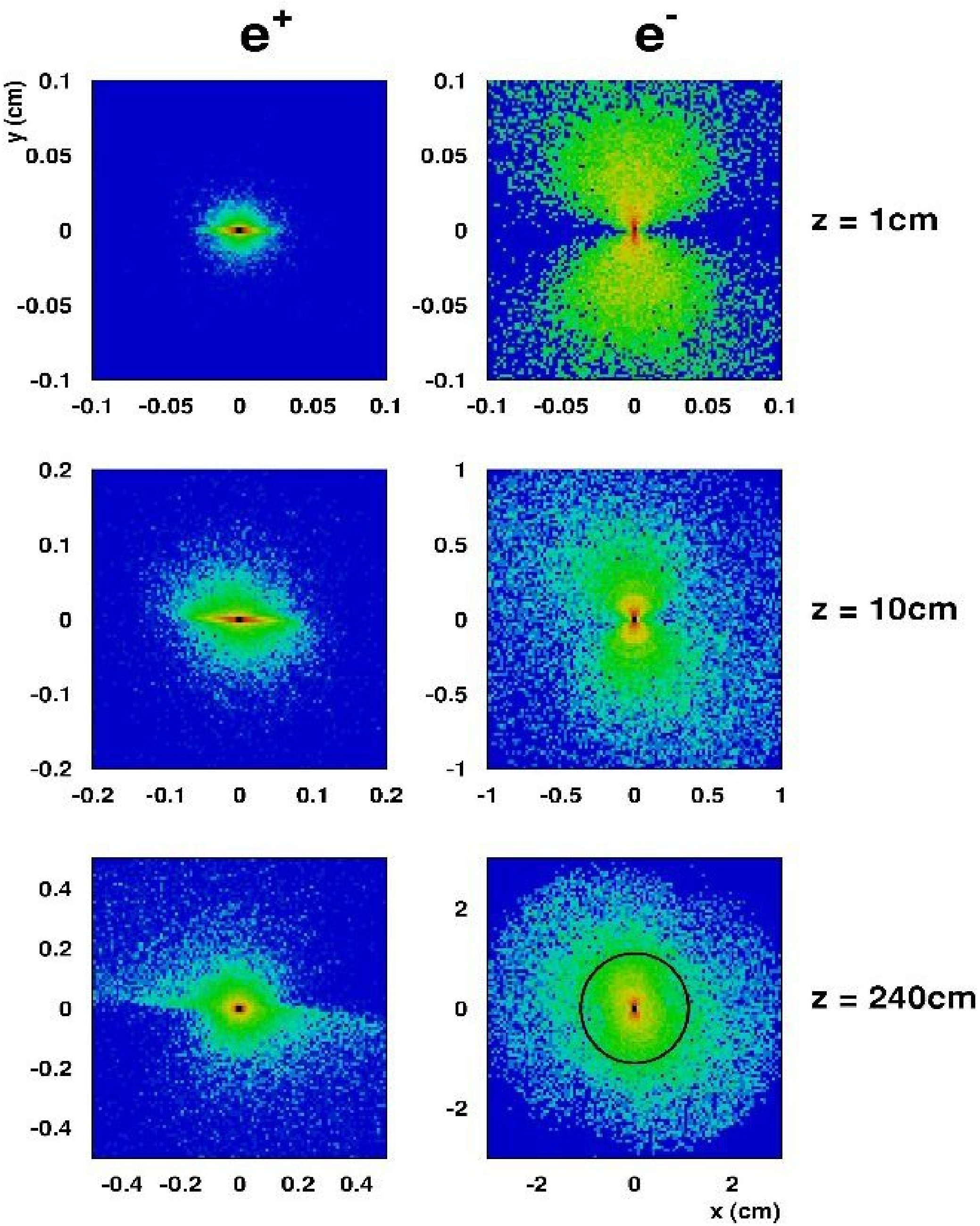
AND

The beamstrahlung gammas induce an important background creating a cloud of e^+e^- pairs and minijets backscattering on the forward calorimeters up to the vertex detector.

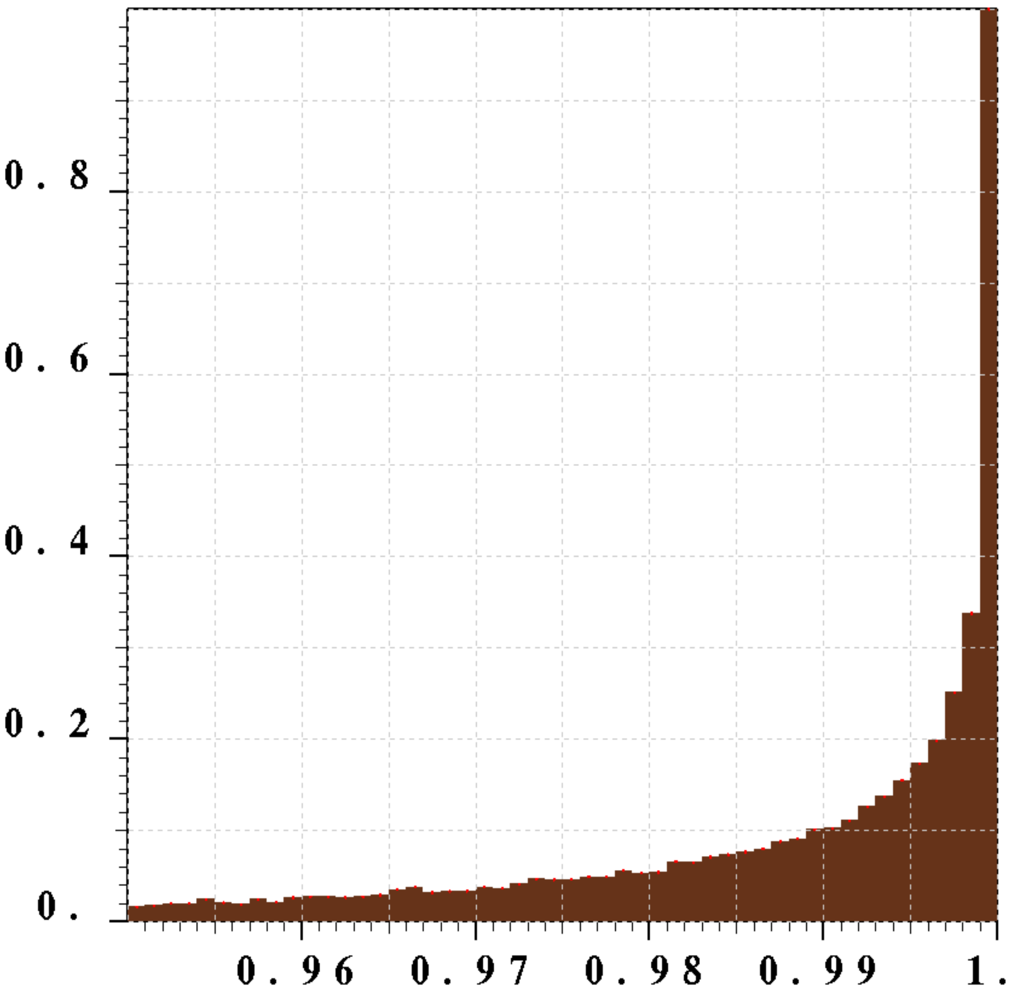
The detection of particles emitted very forward becomes delicate.

pair halo

Observe the behaviour
of the positrons / electrons

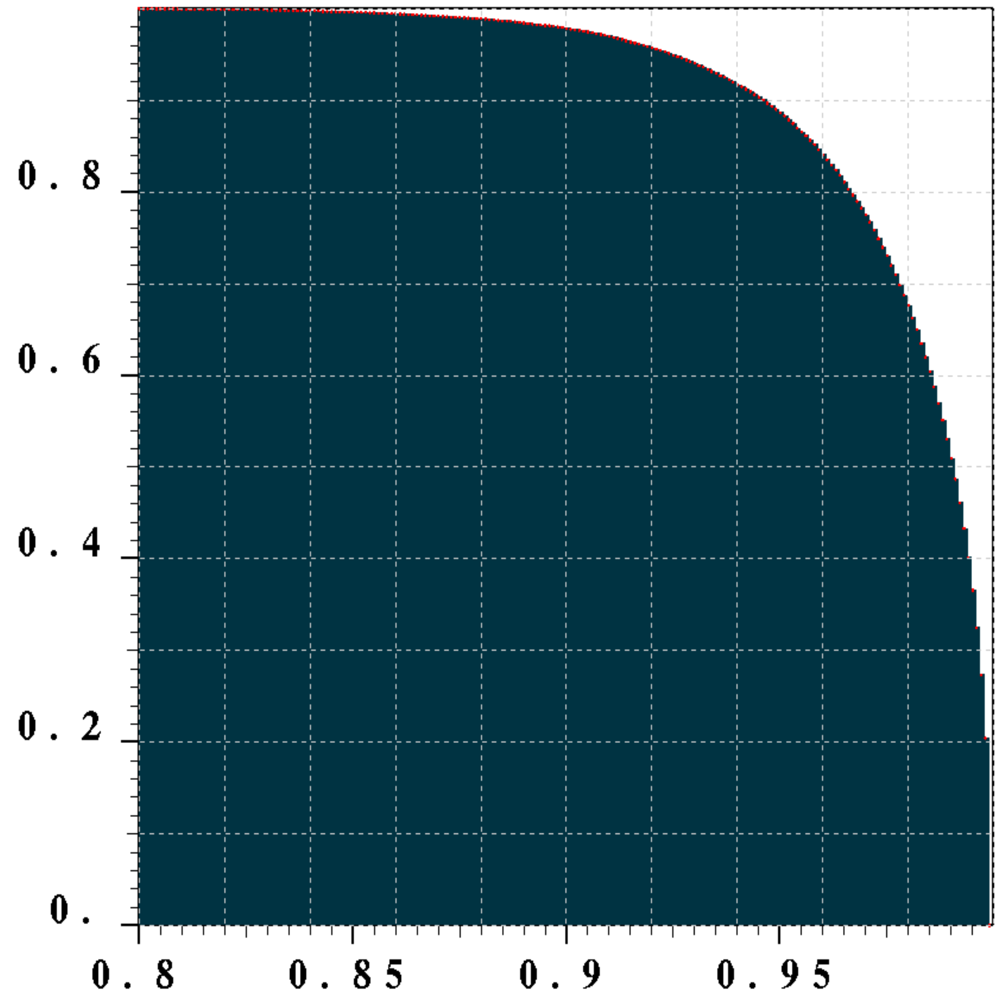


Beam energy spectrum



fraction of beam energy

Integrated beam energy spectrum



fraction of beam energy

Differential energy spectrum

Beam fraction with an energy greater than a fraction of the nominal energy

The luminosity challenge at the linear collider:

keep the power consumption at a reasonable level e.g. few hundreds of MW

It would be politically incorrect
to reach the power of a nuclear plant ~ 1 GW

In a circular accelerator the bunchs recirculate and we have « just » to reinject the energy lost in the turn,
for example at the LEP the bunchs were recirculating at a frequency of 44 kHz.
what if the energy loss becomes heavy ?

For the linear, the power consumption is directly proportional to the repetition frequency.

Then to increase the luminosity we rather play with the interaction zone size, hence the beam emittance.

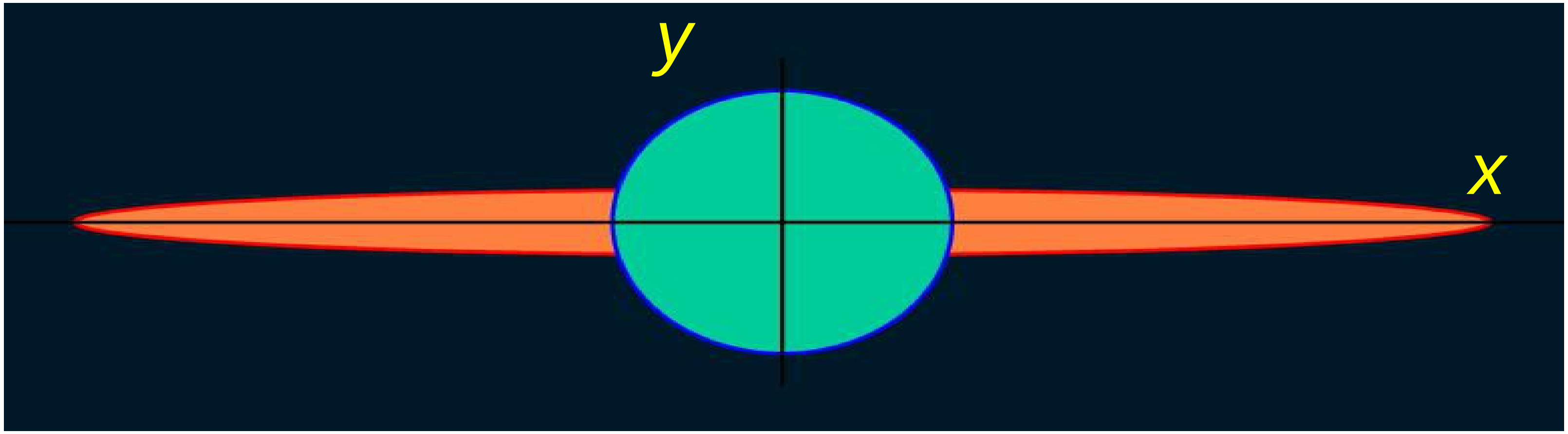
By making $\sigma_y^* \ll \sigma^*_x$ the beamstrahlung strength
i.e. $\langle \Delta E/E \rangle$, is made independent of σ_y^*.
The luminosity is then increased by reducing σ_y^*.

Other way of looking at this :
maximising $(\sigma_x^* + \sigma^*_y)$ at constant luminosity $(\sigma_x^* \times \sigma^*_y)$

leads to flat beams with:
$\sigma_x^* \ll \sigma^*_y$ or $\sigma_y^* \ll \sigma^*_x$

⇒ 'razor blades' with $R = (\sigma_x^* / \sigma^*_y) \simeq 100$

The particles of one beam are sensitive only
to the field created by the opposite beam in their vicinity



End of the first lecture

Summary of what we saw up to know

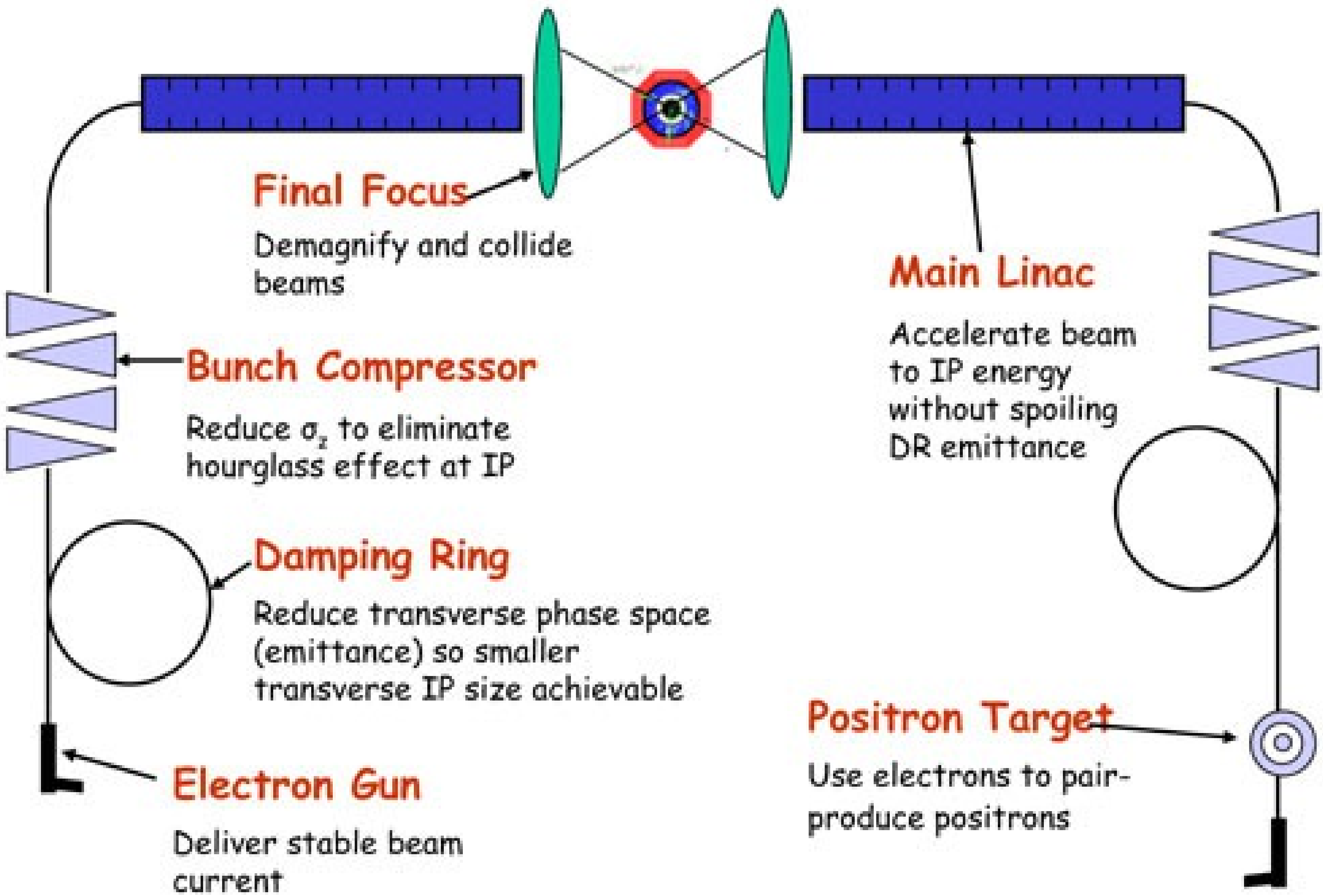
How to accelerate charged particles
How cavity structures bring the RF in phase with accelerated particles
Travelling or standing waves
Warm or super conducting cavities
Why this collider has to be linear
Notion of luminosity
Notion of emittance
Beamstrahlung
that concerns the main linac

Now we go for :

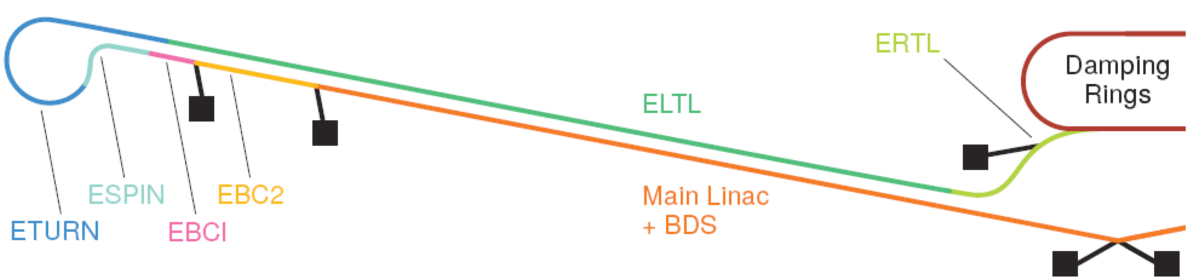
structure of the collider complex
sources : electrons and positrons
damping rings
beam delivery system
alignment
luminosity, polarisation measurements
options e- e-, γγ
cost
plasma acceleration

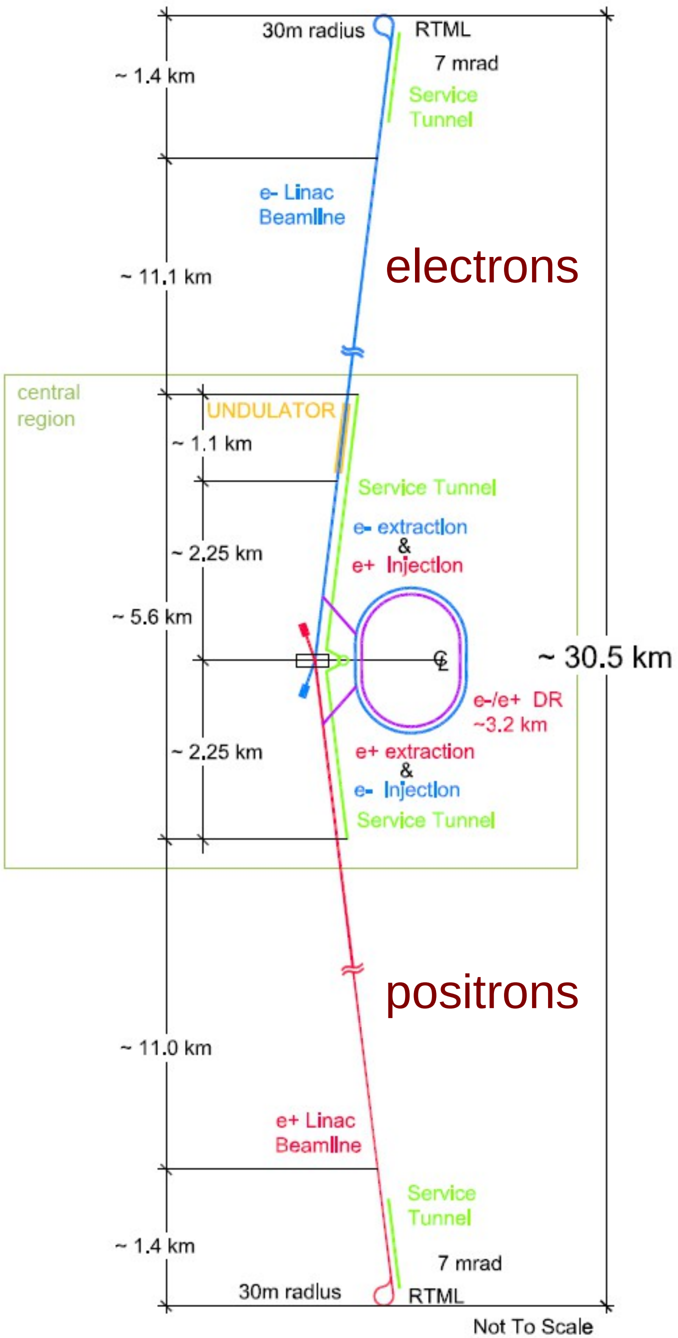
TESLA

LC conceptual scheme



schematic layout of ILC in the TDR





Looking at the other parts of the collider

We have to:

produce the electrons	electron source
produce the positrons	positron source
reduce the emittance	cooling (damping) rings
focalise the beams at the interaction point	beam delivery system final focus

Requirements :

produce long trains (RF) of bunches	1ms @ 5-10 Hz 3000 bunches
with high charge	few nC or 10^{10} particles
with an excellent emittance	$\varepsilon_{n\ x,y} \sim 10^{-6}, 10^{-8}$ m
and polarised (electrons and positrons)	

Principle

laser photo-injector :

circularly polarised photons on a GaAs strained cathode

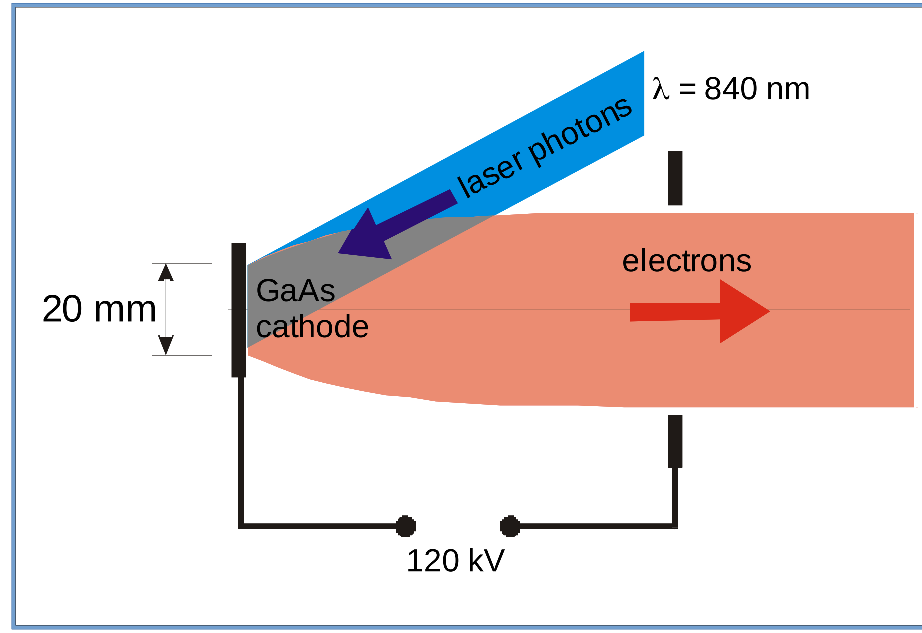
to differentiate the energy levels of the two spin states

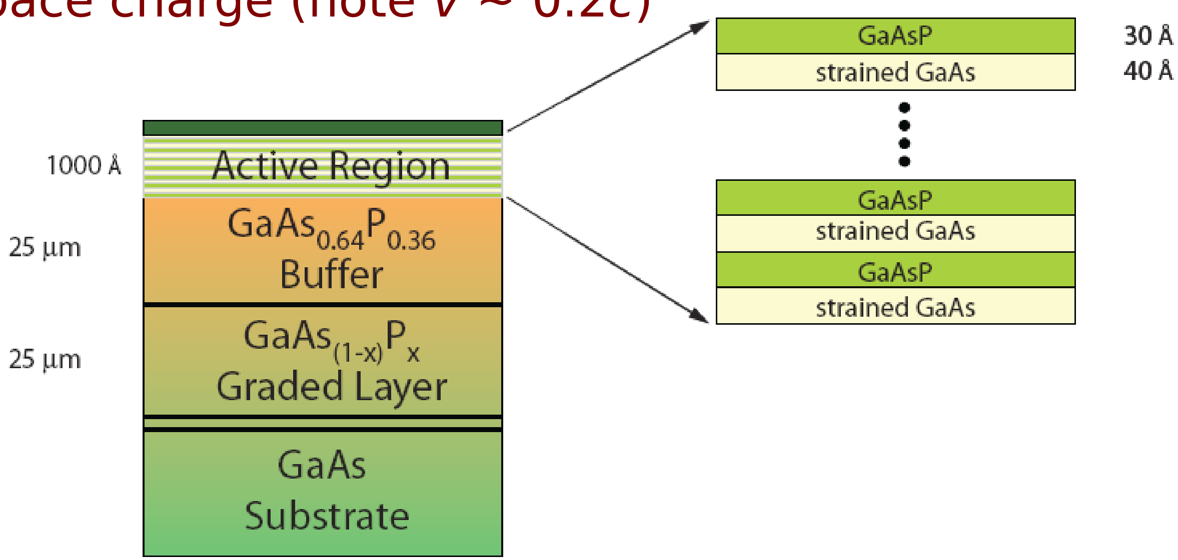
⇒ longitudinaly polarised e-

the laser pulse is modulated to provide the required time structure

a strong vacuum is required for GaAs ($<10^{-11}$ mbar)

the beam quality is dominated by the space charge (note $v \sim 0.2c$)





$$\epsilon_n \approx 10^{-5} m$$

we have to gain a

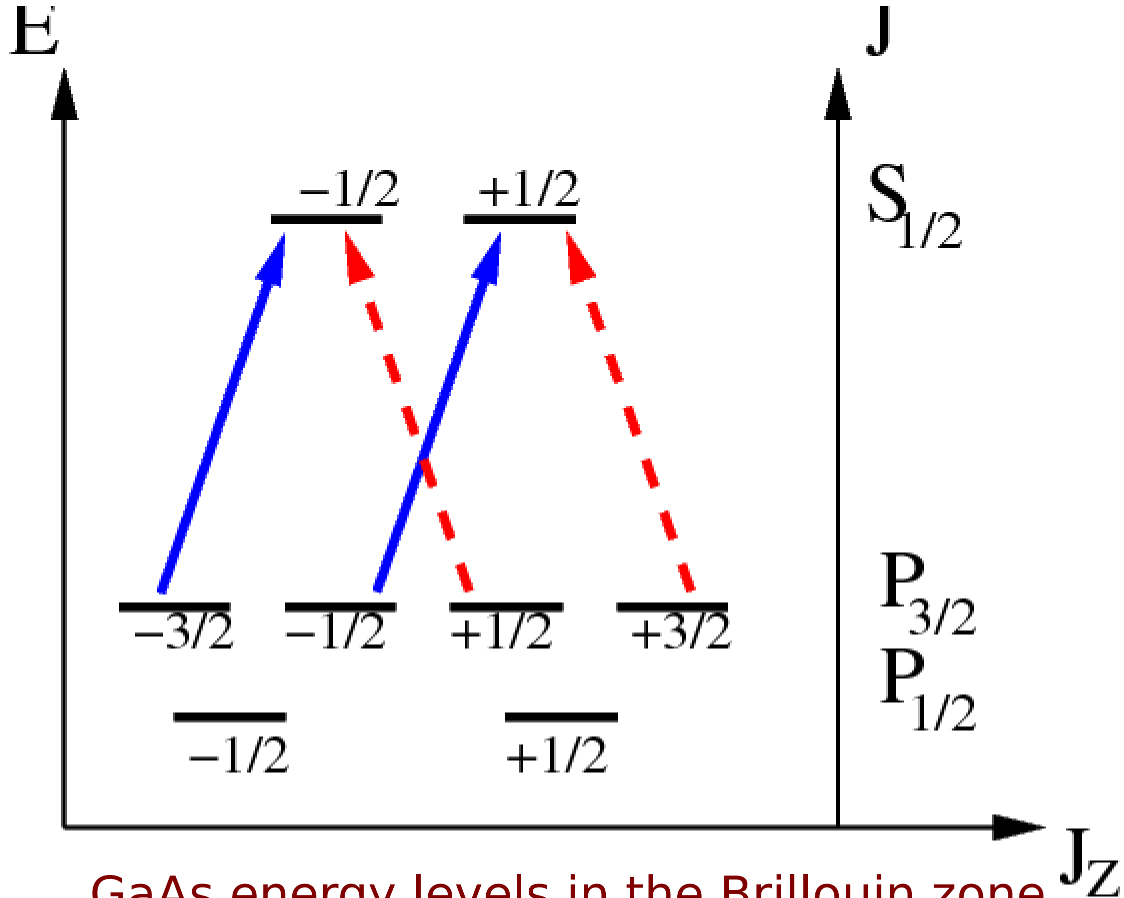
factor 10 in the plane x

factor ~500 in the plane y

Transition -3/2 → -1/2
or -1/2 → +1/2
the first one is 3 times
more probable

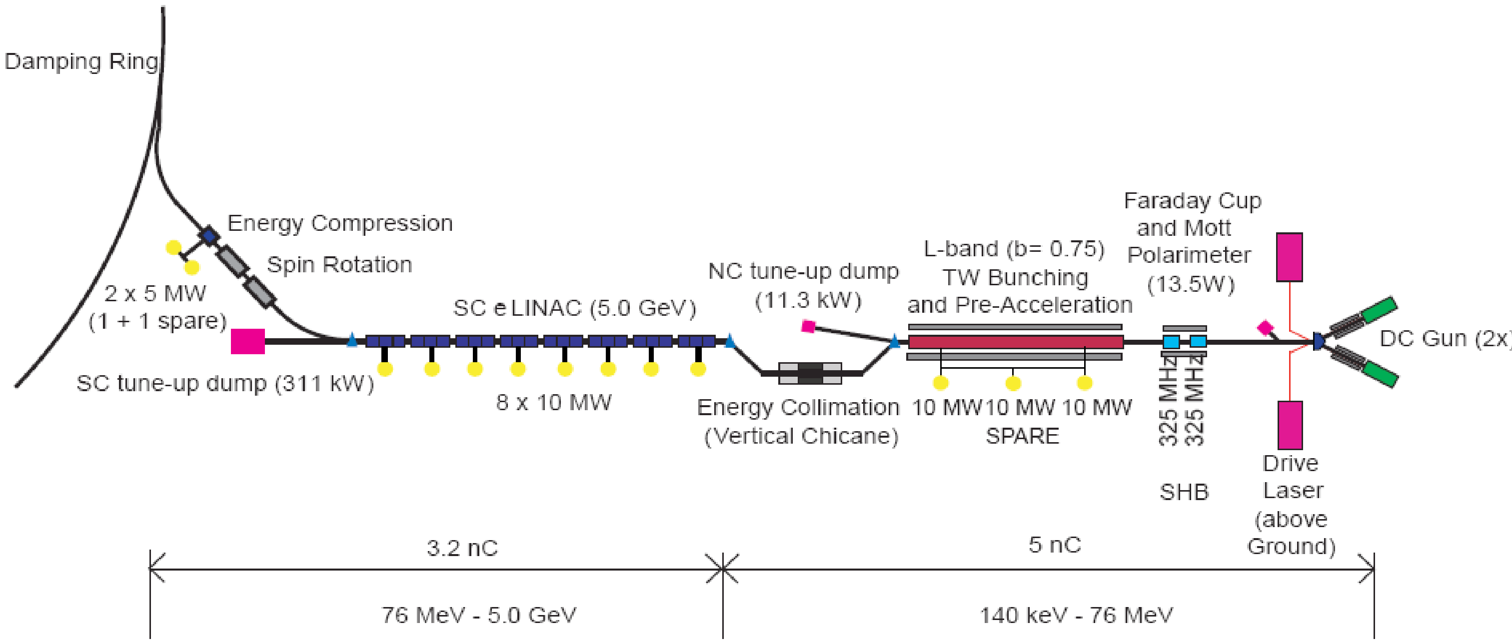
$$P = \frac{P^+ - P^-}{P^+ + P^-} = \frac{1-3}{1+3} = 0.5$$

The strain differentiate
the 3/2 and ½ levels
in theory could reach
100 % polarisation



GaAs energy levels in the Brillouin zone

Actual scheme for electron source from gun to damping rin

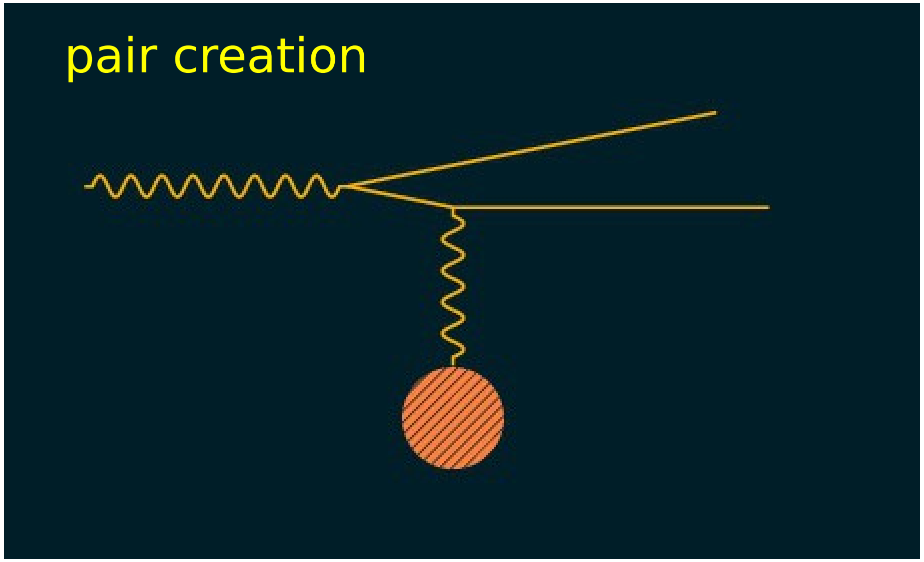


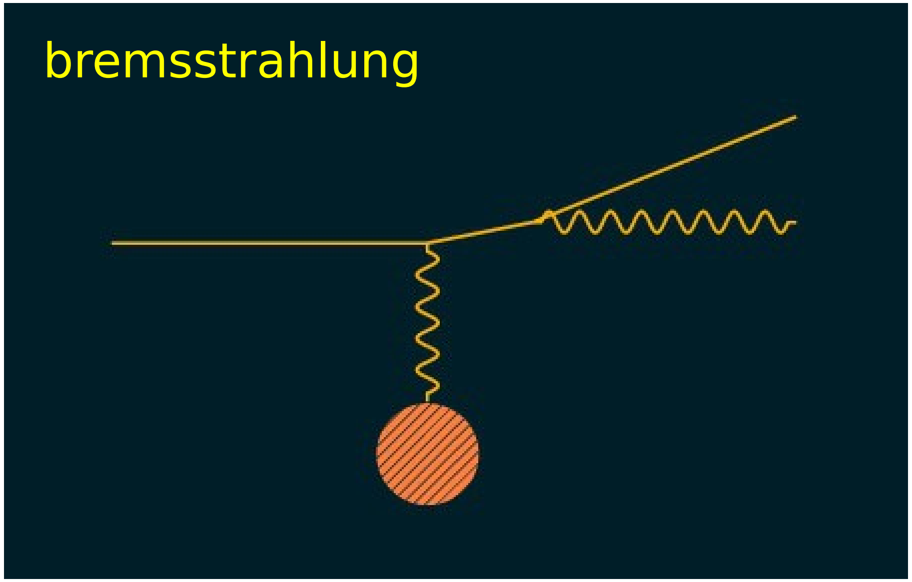
positron source

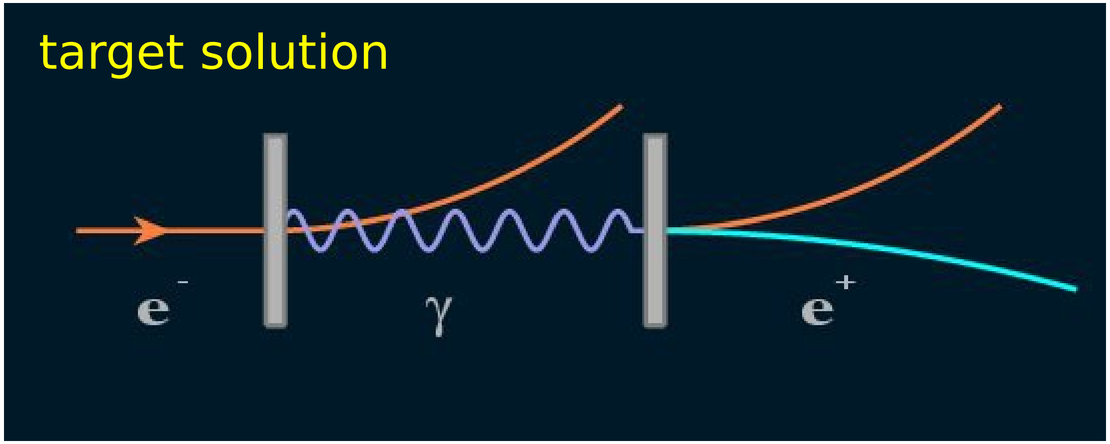
e^+e^- pairs production
by converting photons on a target
keeps partly the photon polarisation

the photons having been produced by
- Bremsstrahlung of electrons on a target
- through an undulator (baseline in ILC)
- by backward Compton scattering,

the last two solutions providing polarised photons.

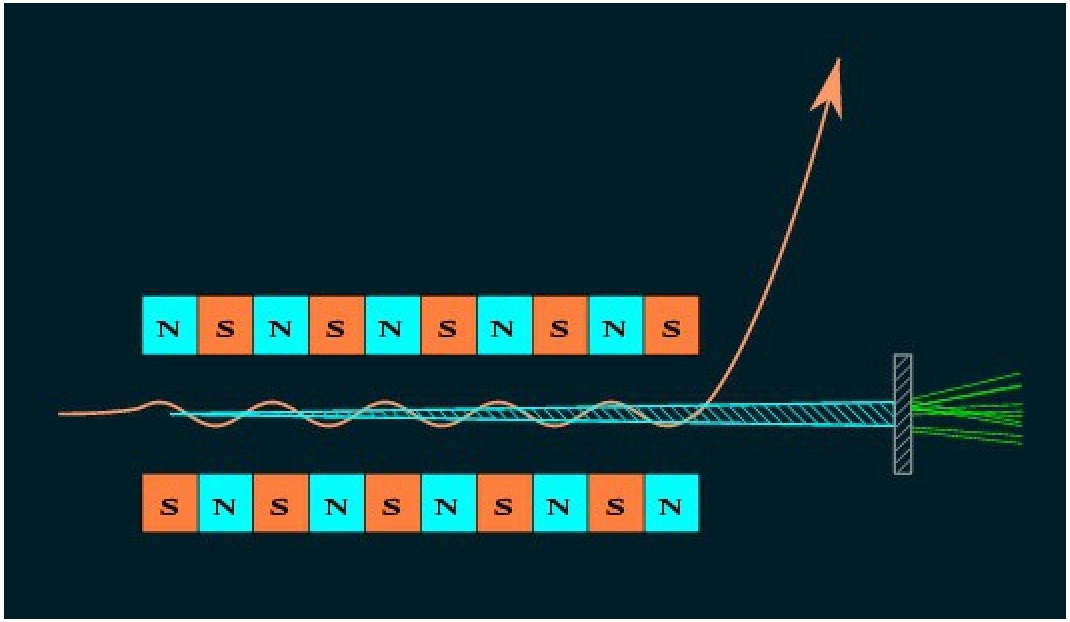






positron source

undulator



set of opposite magnets

The coherent synchrotron radiation in the undulator generates photons of around 30 MeV

a $0.4X^0$ target produces e^+ e^- pairs

a thin target reduces the scattering for a better emittance, which stays way too high. 10^{-2} m

less power left in the target 5 kW

but need an electron energy > 150 GeV!

And the circular polarisation ? helical undulator

Weiszäcker-Williams

Static structure providing a periodical field, electrical or magnetic :

k is the spatial frequency, the wave length is then

$$\lambda = \frac{2\pi}{k}$$

$$E_x = 0, \quad E_y = E_0 \cos kz, \quad E_z = 0$$

in the laboratory

an electron comes in with the speed : $\beta = \frac{p_e}{E_e}$

In the electron frame:

$$B_x' \sim E_y' = \gamma E_0 \cos k(\gamma z' + \beta \gamma t')$$

at high energy (β=1) it is a plane wave of frequency $k\gamma$
or an ensemble of photons with energy $k\gamma$ polarised linearly or circularly depending on the geometry of the undulator

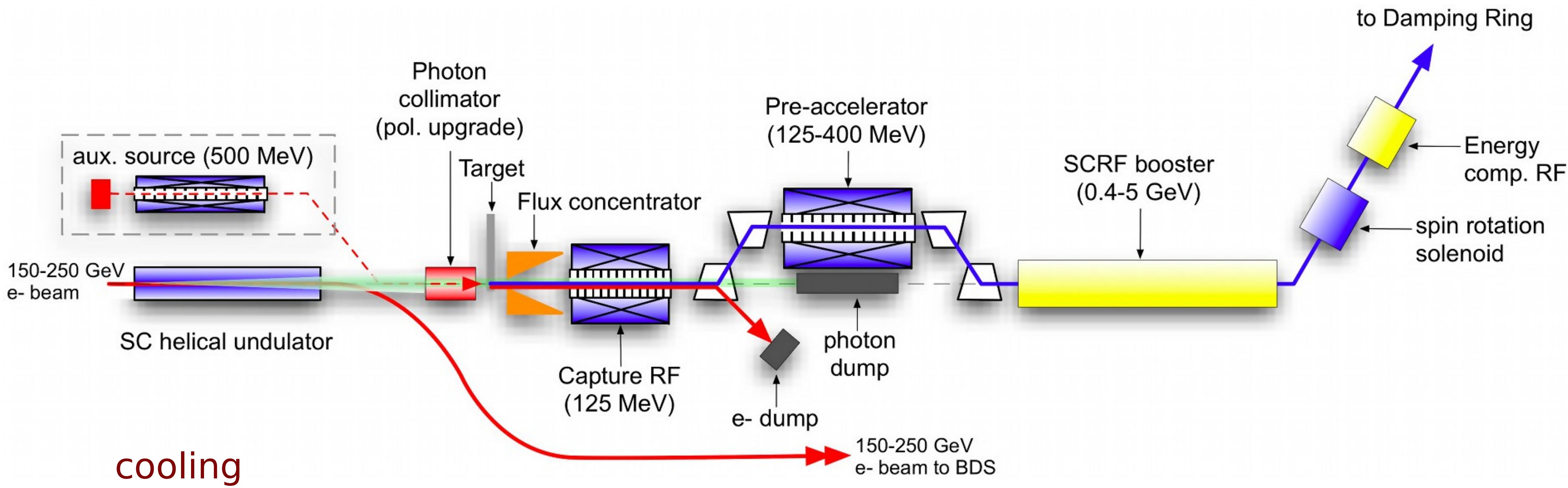
Backscattering — If the photon energy is << m_e ,
the backscattered photons have an energy $k\gamma$ or $\gamma\lambda^{-1}$

Going back to the laboratory,
the photons take a boost γ and their energy is $\gamma^2 \lambda^{-1}$

Example: with a structure pitch of 1cm, electrons of 150 GeV ($\gamma = 3\ 10^5$)
1cm ≃ $5 10^{-4}$ eV hence E_γ = 45 MeV

Accelerators

positron source



cooling

Problem : we need photons of about 30 MeV to generate positrons energetic enough to resist the Coulomb forces
the pitch of undulators is imposed by technology ~ 1cm
then the electron energy in the undulator has to be high enough

too high for running at the Z !

Remark : plasma undulator

Emittance: a size times an angular dispersion ; dimension L $\epsilon_x \; ; \; \epsilon_y$
conservation of emittance along the accelerator: Liouville's theorem

Rings in which the bunch train is stored
for a time T (~20-200 ms)
to reduce the emittance under the concomitant action of the synchrotron emission
and the acceleration by the RF.

initial emittance
(~0.01m for e^+)

$$\epsilon_f = \epsilon_{eq} + (\epsilon_i - \epsilon_{eq}) e^{-2T/\tau_D}$$

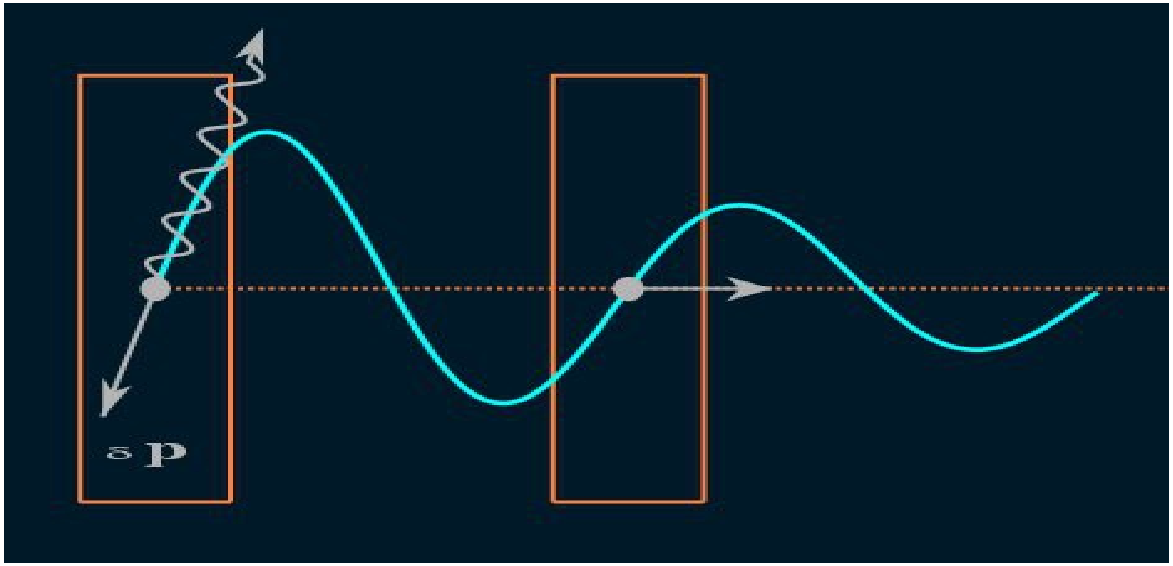
final emittance

emittance at equilibrium

damping time

vertical damping

the slope y' is not modified
by the photon emission



δp restored by RF in such a way that

$$\Delta p_Z = \delta p_z.$$

due to the adiabatic cooling

$$y' = dy/ds = p_y/p_Z,$$

and the amplitude is reduced by:

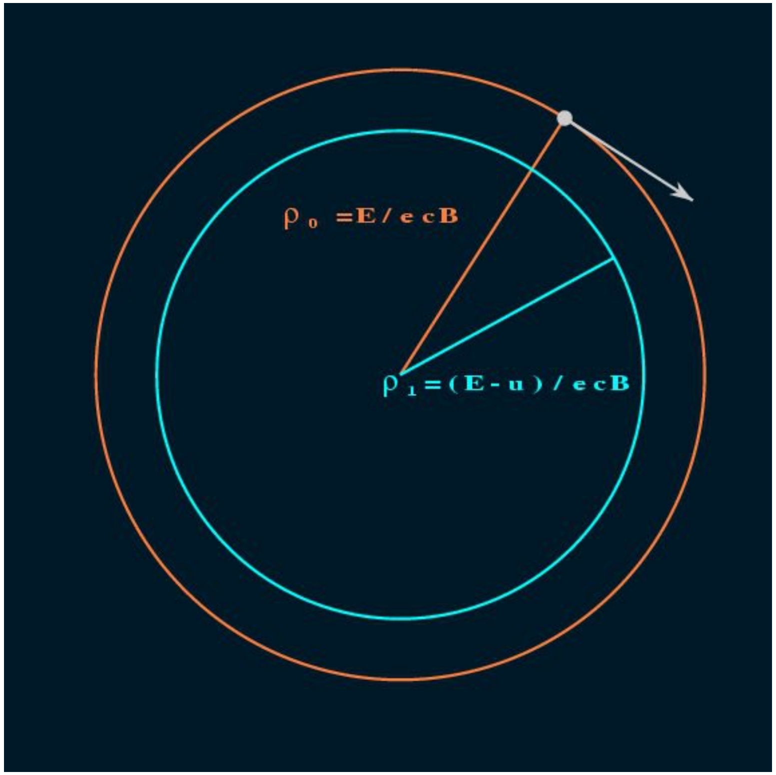
$$\delta y = -\delta p\, y'$$

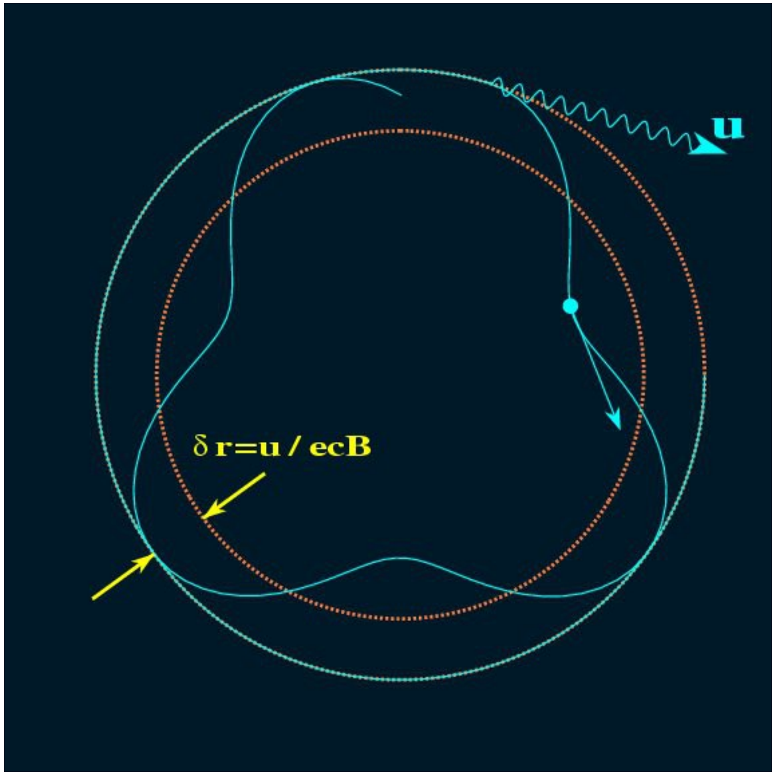
We have to integrate over all β phases :

$$\tau_D \approx \frac{2E}{\langle \wp_\gamma \rangle} \quad \text{with} \quad \wp_\gamma \propto E^4 \rho^{-2} \quad \text{hence} \quad \tau_D \propto E^{-3} \rho^2$$

LEP: E ~ 90 GeV, P_γ ~ 15000 GeV/s, τ_D ~ 12 ms

horizontal damping





The particles undergo then β oscillations around the new closed orbite $\rho_1 \Rightarrow$ emittance increase

$$\frac{d\epsilon_x}{dt} = Q$$

The equilibrium is reached when

$$\frac{d\epsilon_x}{dt} = 0 = Q - \frac{2}{\tau_D}\epsilon_x$$

$\tau_D \propto E^{-3}\rho^2$ suggests high-energy and small ring. But

required RF power: $$P_{RF} \propto \frac{E^4}{\rho^2} \times n_b N$$

equilibrium emittance: $$\epsilon_{n,x} \propto E^2 \rho^{-1}$$

example:

Take $E \approx 2$ GeV

$B_{bend} = 0.13$ T $\Rightarrow$ $\rho \approx 50$ m

$\langle P_\gamma \rangle = 27$ GeV/s [28 kV/turn]

hence $\tau_D \approx$ 148 ms - few ms required!!!

Increase $\langle P_\gamma \rangle$ by ~30 using wiggler magnets

Remember: $8 \times \tau_D$ needed to reduce e^+ vertical emittance.

Store time set by f_{rep}: $$t_s \approx n_{train} / f_{rep}$$

radius: $$\rho = \frac{n_{train} n_b \Delta t_b c}{2\pi}$$

The horizontal emittance ε_x^{eq} is set by the dispersion of trajectories with random energies around the ring .

The vertical emittance ε_y^{eq} is set by the random angle of γ emission, and by x-y coupling due to defects .

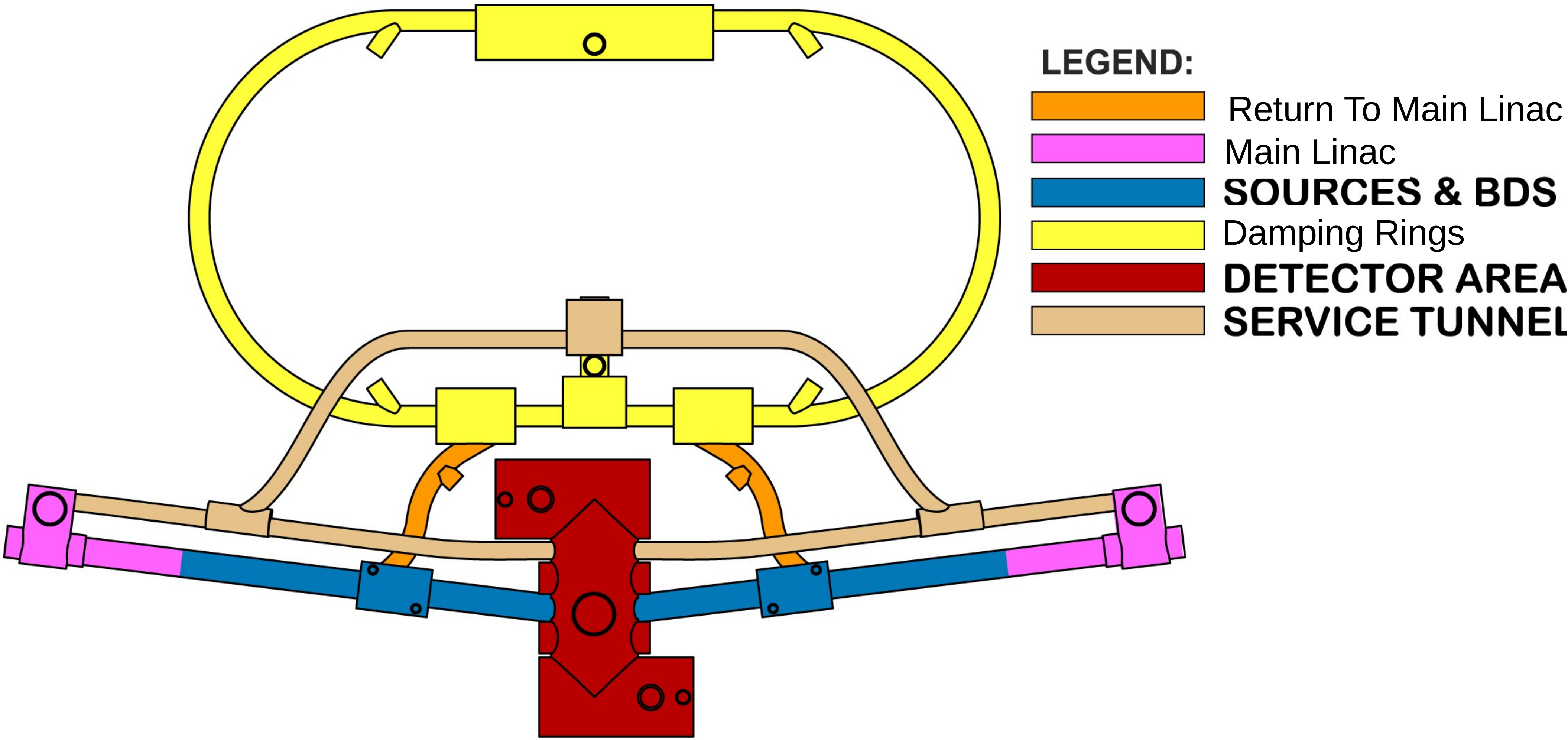
⇒ The damping rings produce naturally flat beams !

... and the quantum excitations

In fact

The emission of photons is not a continuous process,
the radiation is emitted by discrete quanta
which number and energy spectrum follow statistical laws.
The emission process can be modelled as a series of "kicks"
which excite longitudinal and transverse oscillations.

Accelerators

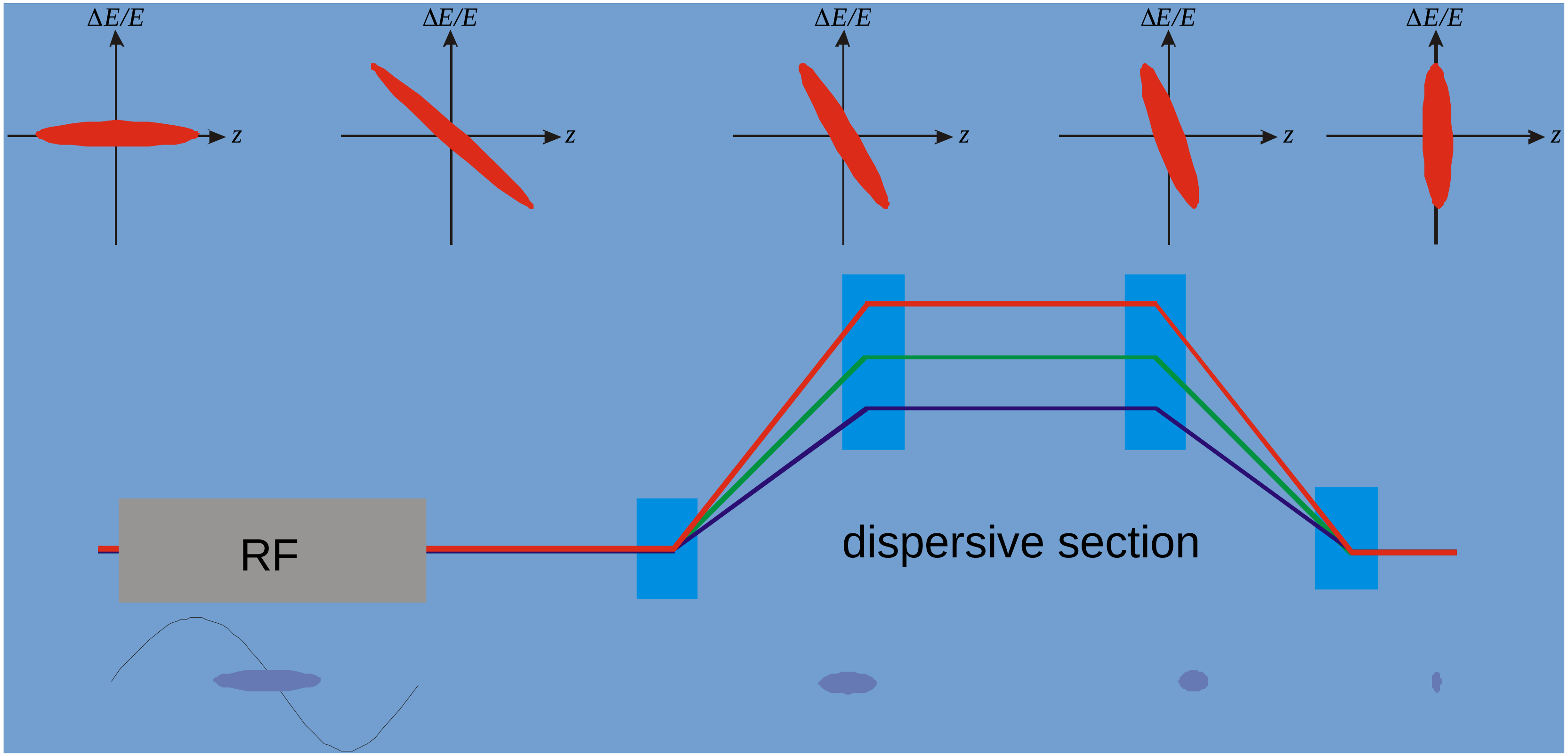


Bunch compression

The length of the bunchs coming out of the damping rings
~ few mm
at the interaction point it has to be in the range 100-300 μm

evolution of
the longitudinal
phase space

rotation in phase space
we trade
the chromaticity
for the length

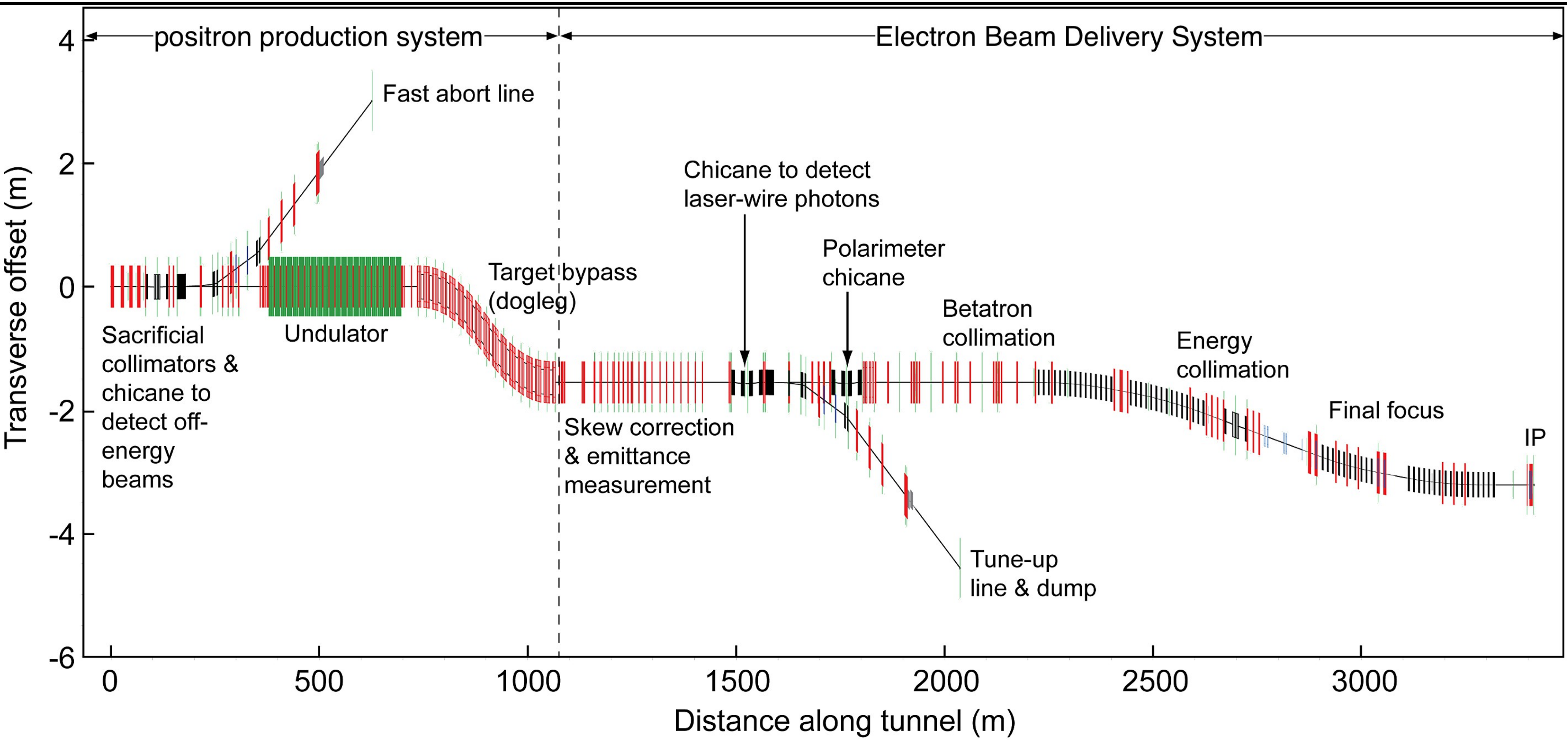


Accelerators

Final focus

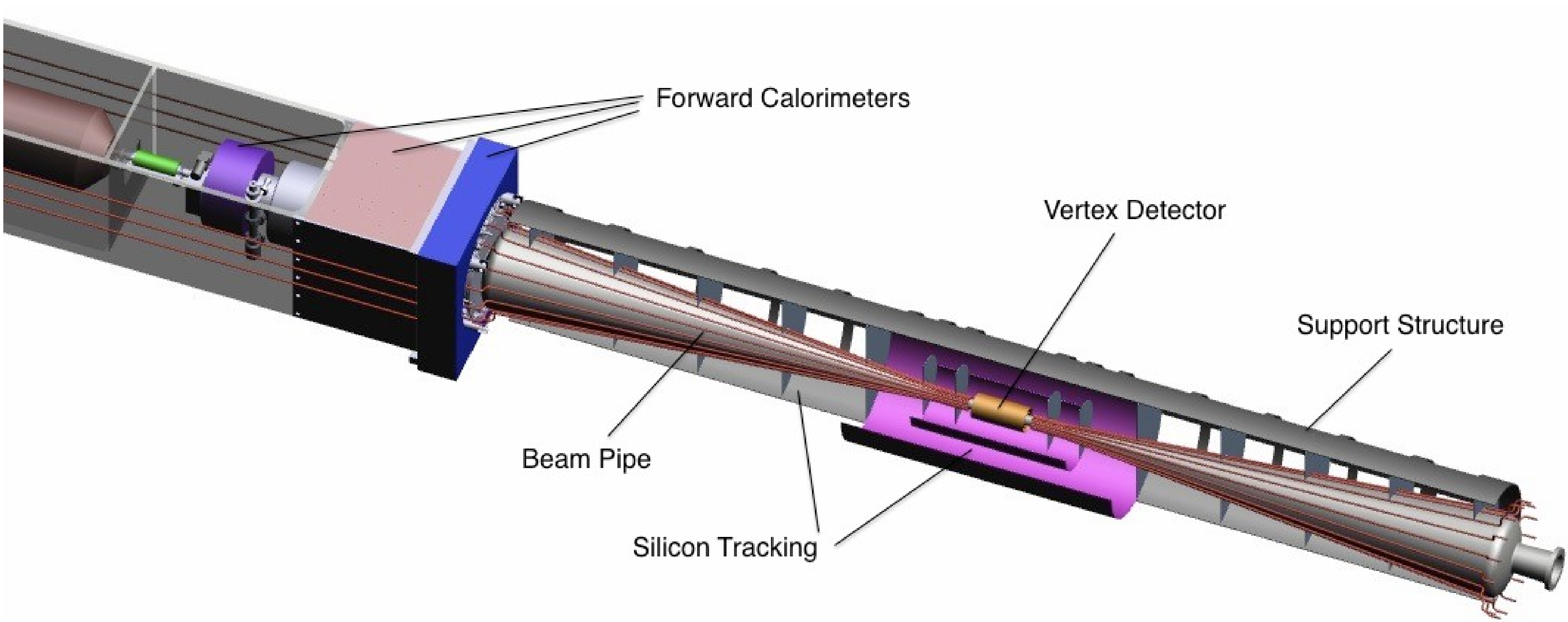
Chromatic corrections

In order to focus efficiently
it is necessary for the energy spread
(chromaticity) to be very small before collision



In view of the distance between bunches 300x 0.3 m
the beams cross at an angle of 14mrad

normalised emittances 10000 /35nm
bunch length 300µm
horizontal beam size 500 nm
vertical beam size 6 nm at 500 GeV ($\gamma=10^6$)



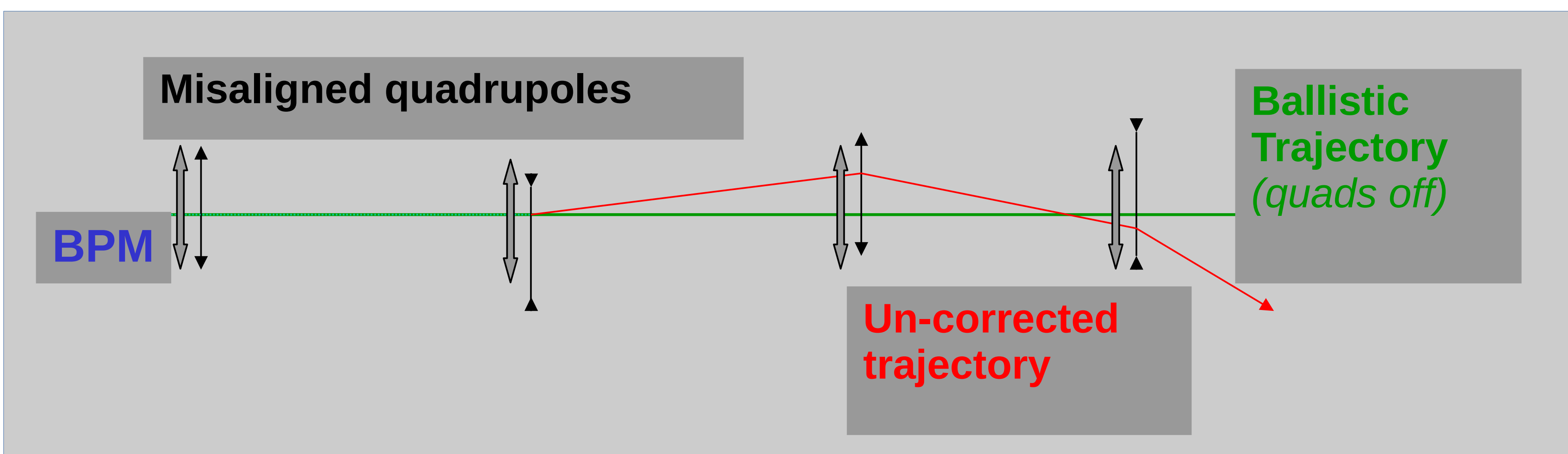
Stability

- Beams with very small emittance
- Very strict tolerances on the components
  - Quality of the fields
  - Alignment
- Question on vibrations and ground motion
- Active stabilisation
- Feed-back systems

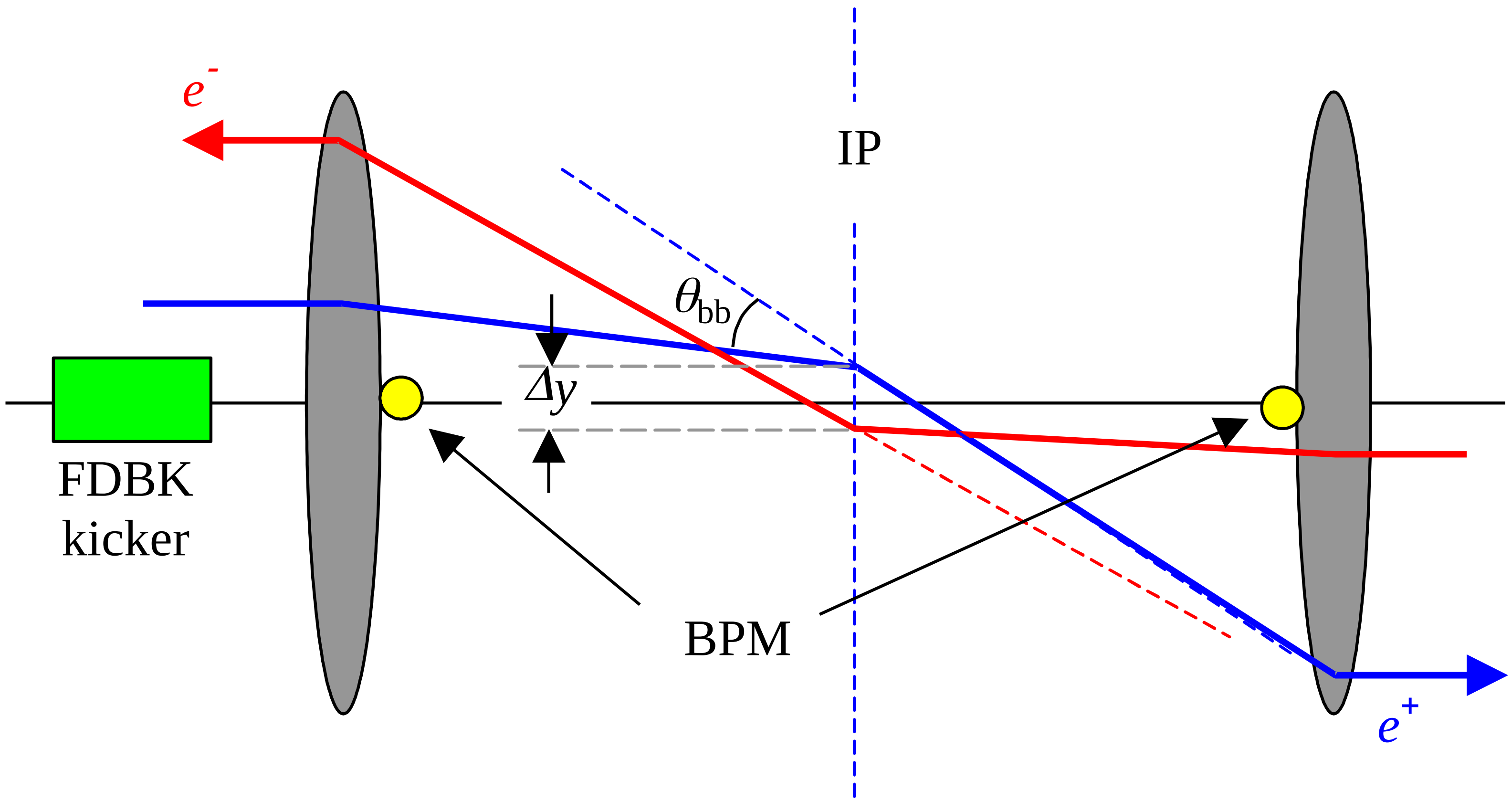
much worse for CLIC

Alignment using the beam

- The alignment tolerances vary like ω_{RF}^3, and are below 1µm.
- The laser systems offer an alignement precision ~ 100 µm
- The beam itself is used to define straight lines passing through very precise beam position monitors (BPM)
- The magnetic centre of the quadrupoles and the electric centre of the RF cavities are measured and moved.



Beam-Beam orbit feedback

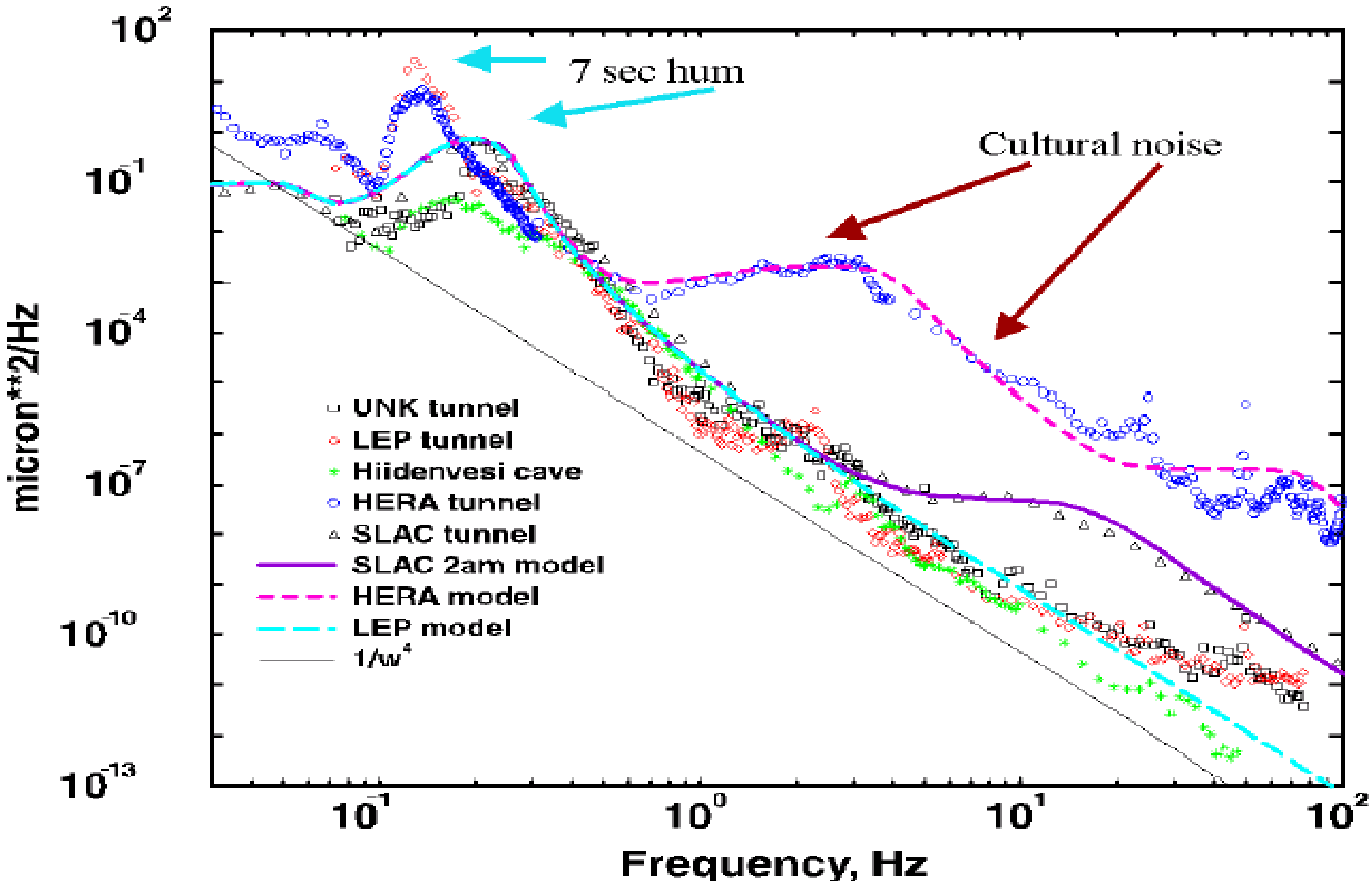


use strong beam-beam kick to keep beams colliding

Generally, orbit control (feedback) will be used extensively in LC

The first bunches determine the corrections for the rest of the train

Spectrum of ground motion

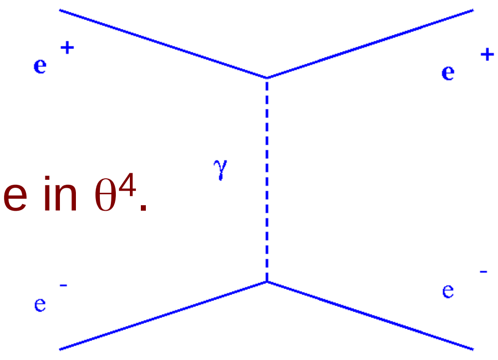


Vibration damping, for the accelerator (QD0), and for the detector (platform)

Luminosity measurement

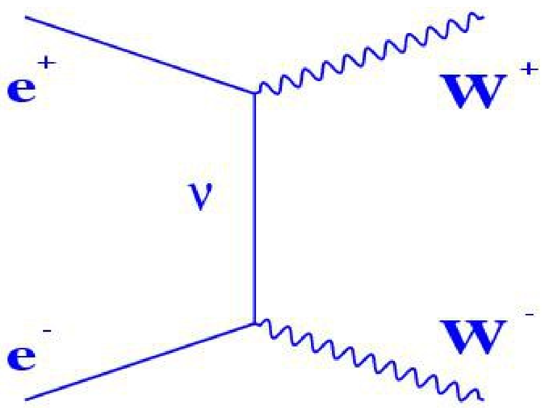
Using reference reactions well known and computed theoretically

Usually the BhaBha scattering



but it is very sensitive to the measurement of the polar angle in θ^4.

Use of WW



Note: The Bhabha acolinearity measurement provides the beamstrahlung spectrum

Polarisation

Essential ingredient for numerous physics subjects
especially at the GigaZ to measure A_{LR}

The electrons can be polarised at 80% or better

electron gun with a GaAs cathod lit by a laser
in a reasonnable electric field (no RF)

Positrons could be polarised at 30-60% depending
on the length of the undulator 147 - 220m

undulator plus damping ring

It is essential to know it with a very good precision

Polarimeter before and after interaction point by Compton scattering
+ measurement from the data utilise WW in the forward direction

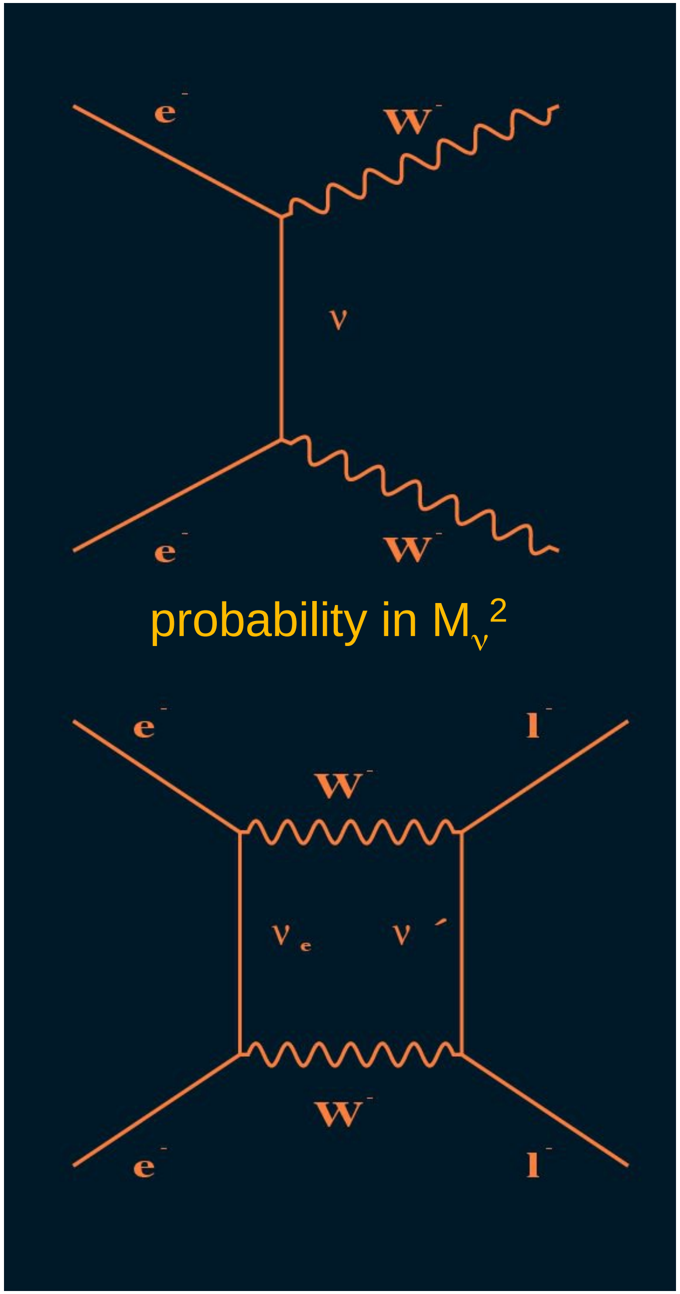
Reference: Klaus Mönig LC-PHSM-2004-012

Option $e^- e^-$

Luminosity reduced by a factor 3 (pinch effect)

No technical probleme

double beta inverse



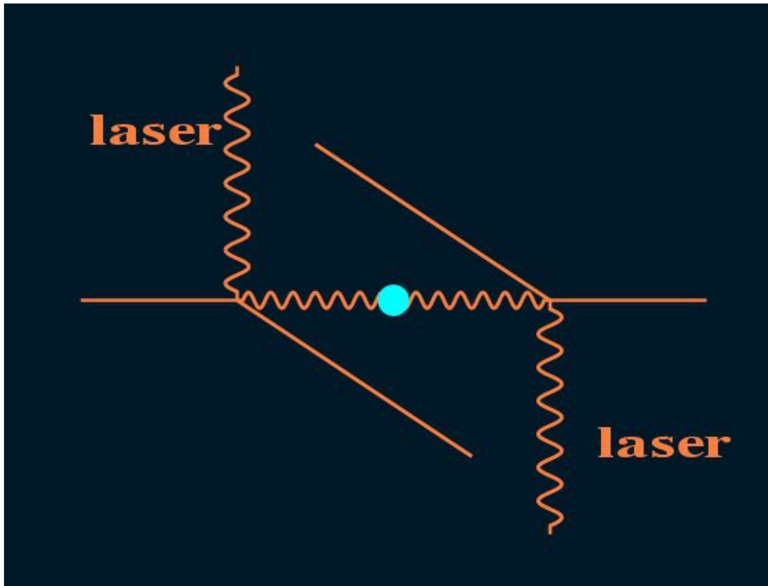
With a left polarisation study
LNV leptonic number violation
LFV leptonic flavour violation

W^- W^- scattering isospin 2

doubly charged Higgs

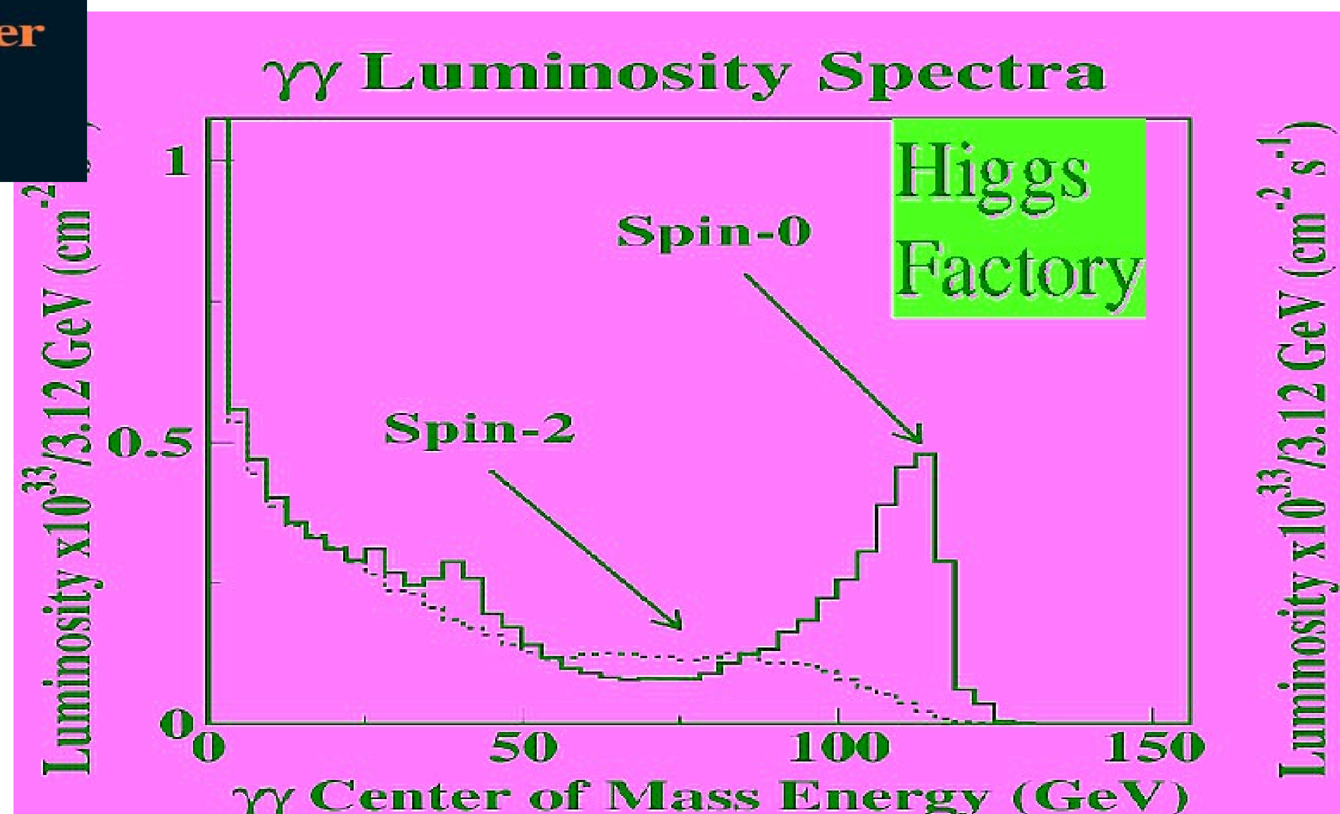
Møller scattering to explore Z'

Option γγ

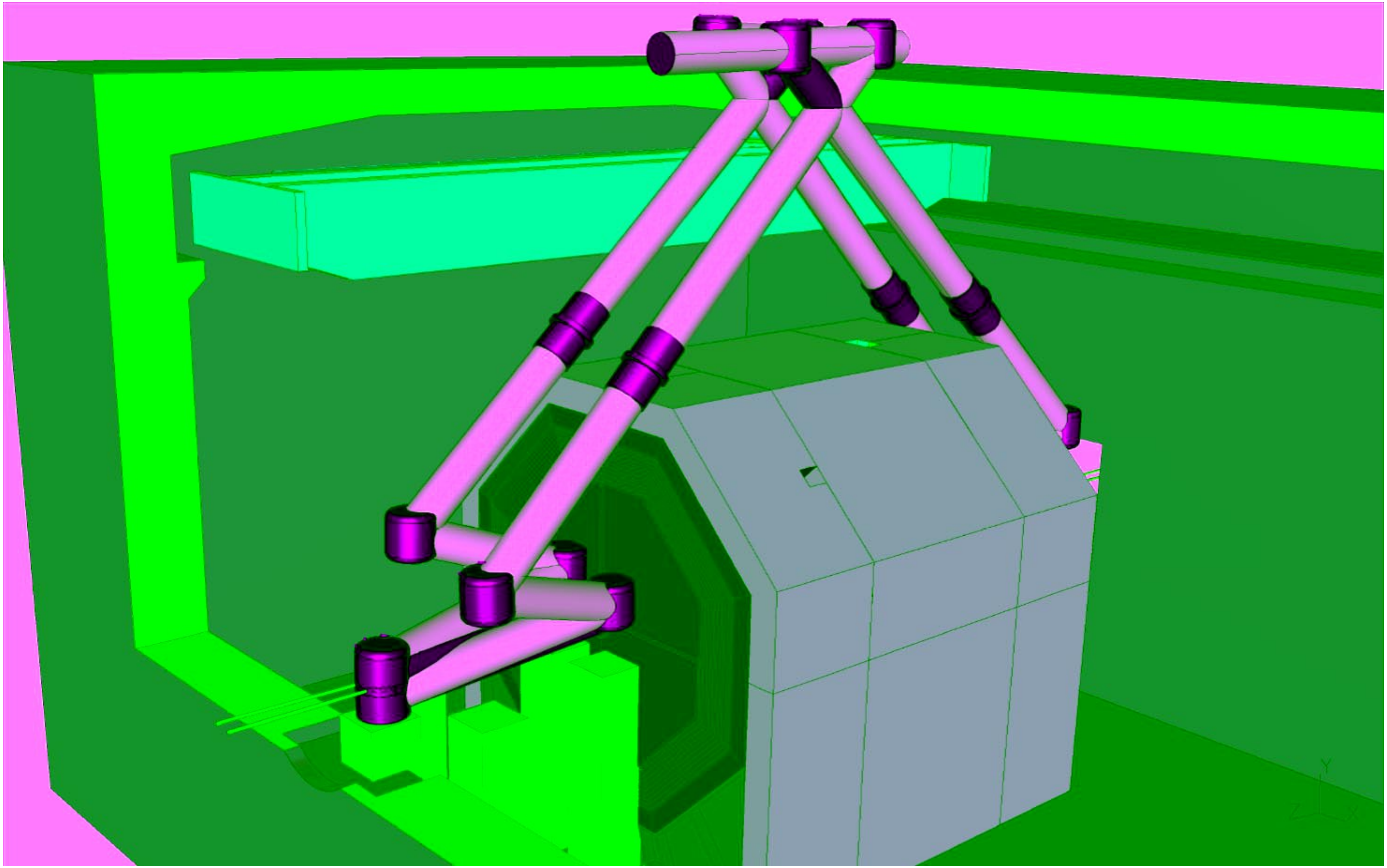


Can be provided with two electron beams
no need of positrons

Probleme of the laser power:
recycling cavity

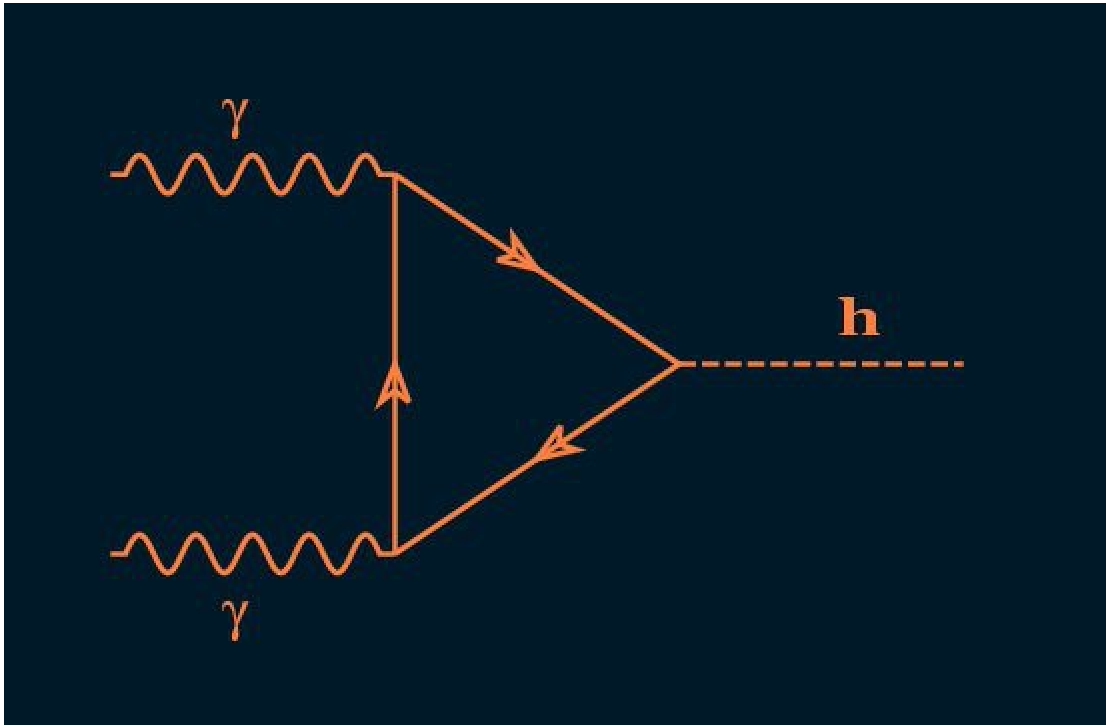


Option γγ



Option γγ

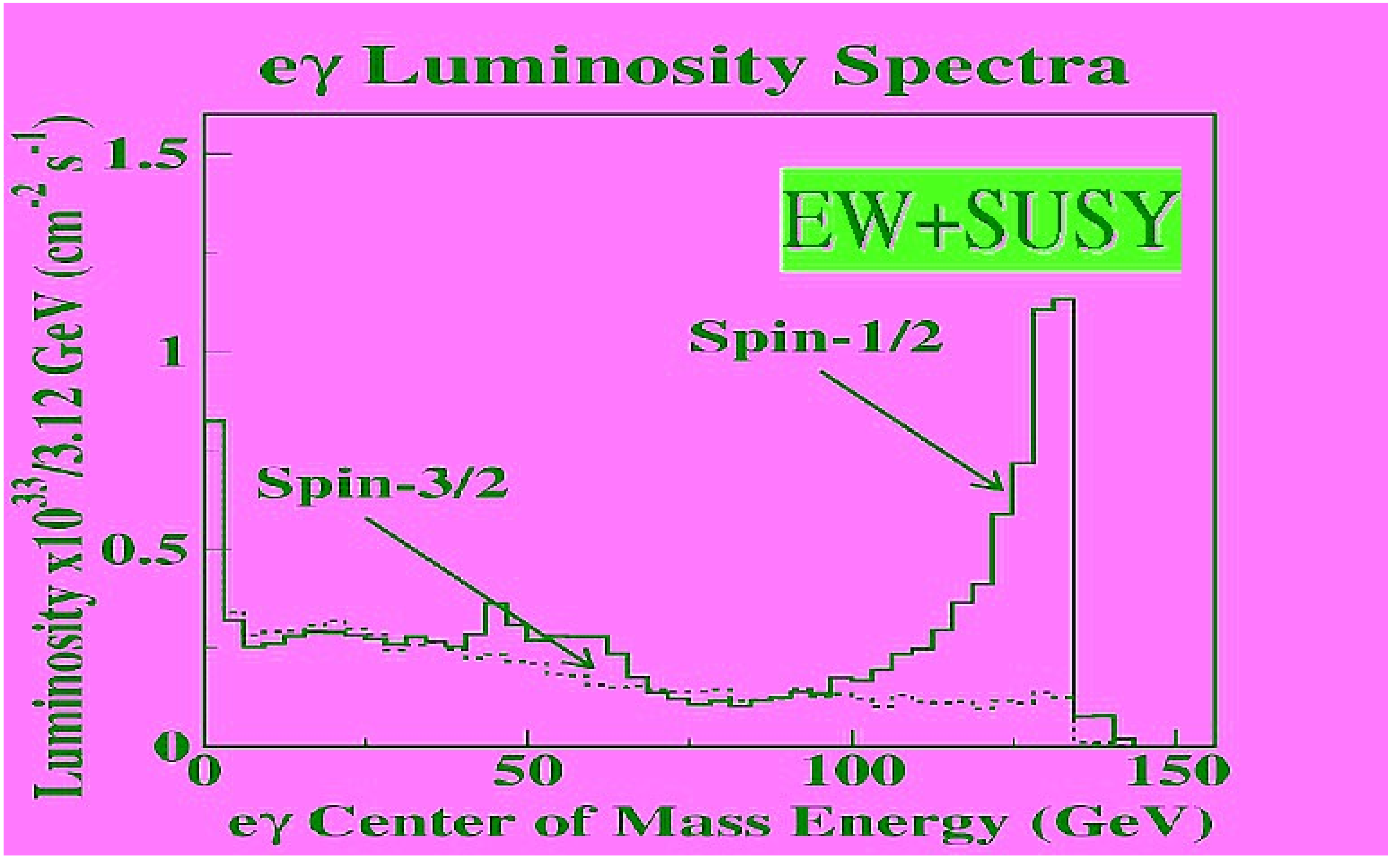
Higgs factory, (X750 factory ?)



21000 H (120) per year
for TESLA at 160 GeV
that was before the Higgs discovery

Γ_γ measured at 2% per year
provides 4% on the $Ht\bar{t}$ coupling.

Option eγ


eγ Luminosity Spectra
EW+SUSY
Spin-1/2
Spin-3/2
Luminosity x10^33/3.12 GeV (cm^-2 s^-1)
1.5
1
0.5
0
0
50
100
150
eγ Center of Mass Energy (GeV)

Accelerators

Cost

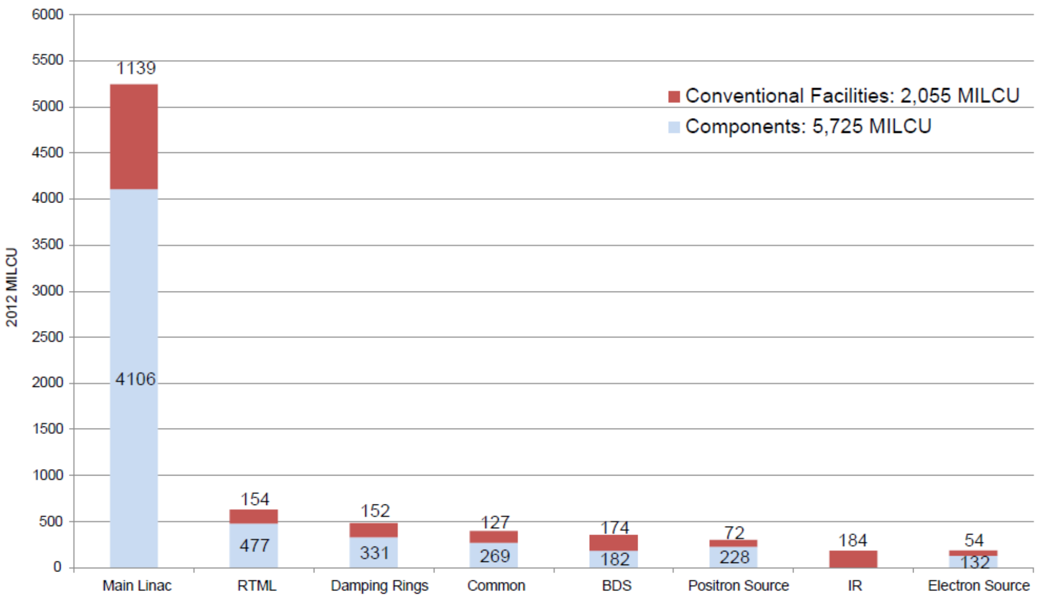


Figure 15.8. Distribution of the ILC value estimate by system and common infrastructure, in ILC Units. The numbers give the TDR estimate for each system in MILCU.

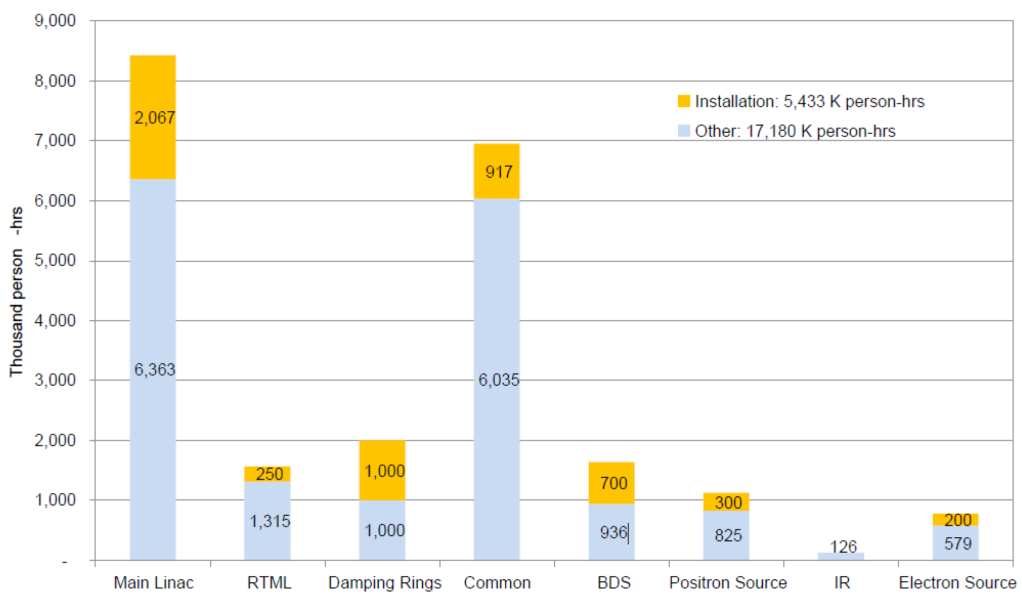
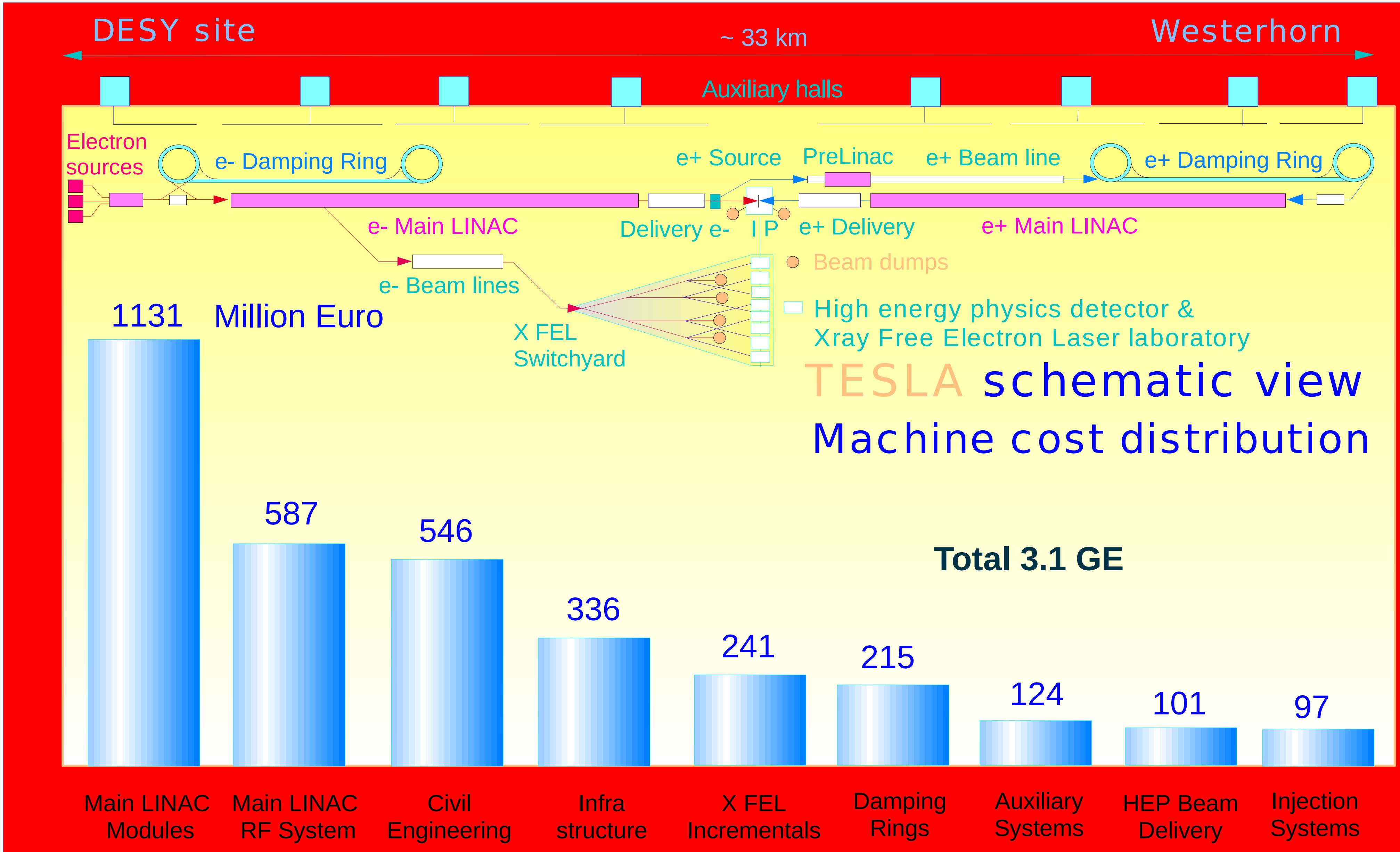


Figure 15.10. Distribution of the ILC Labour estimate by accelerator system. The numbers give the TDR estimate for each system in thousand person-hrs.


DESY site
~ 33 km
Westerhorn
Auxiliary halls
Electron sources
e- Damping Ring
e+ Source
PreLinac
e+ Beam line
e+ Damping Ring
e- Main LINAC
Delivery e-
I P
e+ Delivery
e+ Main LINAC
Beam dumps
e- Beam lines
X FEL Switchyard
High energy physics detector &
Xray Free Electron Laser laboratory
TESLA schematic view
Machine cost distribution
1131
Million Euro
587
546
336
241
215
124
101
97
Total 3.1 GE
Main LINAC Modules
Main LINAC RF System
Civil Engineering
Infra structure
X FEL Incrementals
Damping Rings
Auxiliary Systems
HEP Beam Delivery
Injection Systems

Plasma accelerators

with « classical » accelerators we can dream of reaching about 100 MeV/m
with problems of structure degradation.
going farther ?

We can consider creating accelerating structures of short wavelength
in an already disrupted medium : a plasma.

In an ionised gas the speed of the move for ions is much lower
than for electrons, as their mass ratio,
at a certain scale we can consider the ions as static, the electrons
oscillating collectively at the plasma frequency

$$\omega_p^2 = \frac{4\pi N Z e^2}{m}$$

gaseous target, electronic density 10^{16} to 10^{19} cm^{-3}
λ_p ~300 to 10µm

Exciting a longitudinal wave
the plasma wave propagates at a phase speed equal to the laser group speed
creating very high electric fields, about 1000 times those
in a « classical » accelerator

Charged particles injected at the right place of the wave are submitted to accelerating and focusing forces.

How to excite plasma waves ?
By a short and powerfull laser shock, few tens of fs,
>50 TW > 1 J   few tens of fs.

1ns = 3 10^{5} µm
1fs = 3 10^{-1} µm ~ 1 optical wavelength

laser pulses at 1fs are white

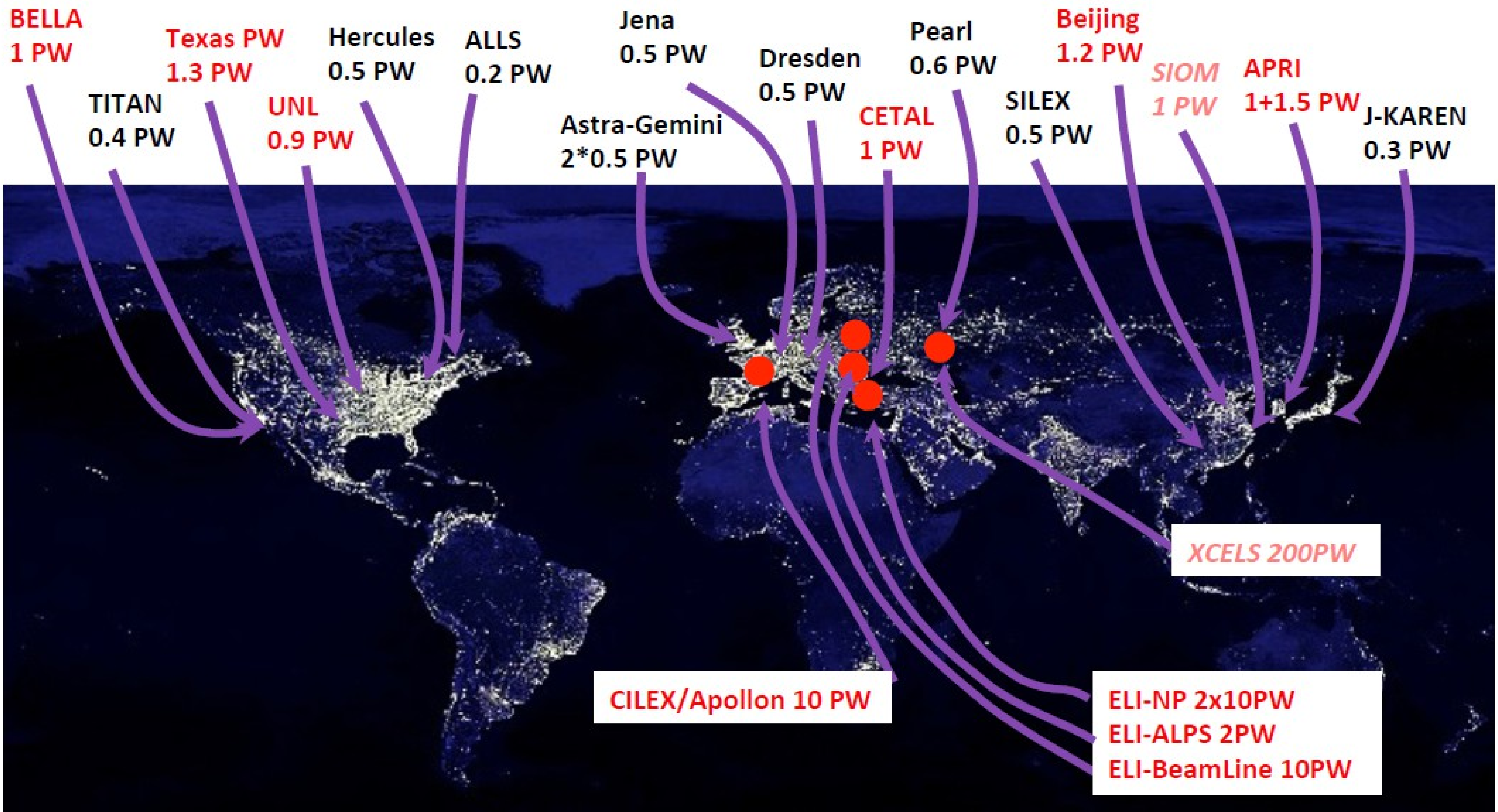
By a pulse of electrons, experiments at SLAC doubling the beam energy for the tail of the bunch.

By a pulse of protons, experiment AWAKE at CERN.

A bunch of particles entering the gas cell
looses its energy to the gas as a plasma wave (a clever beam dump)
which in turn transfers its energy to the second beam.

Accelerators

Proliferation of the PW and UHI laser systems in the world (>10^{20} W/cm²)

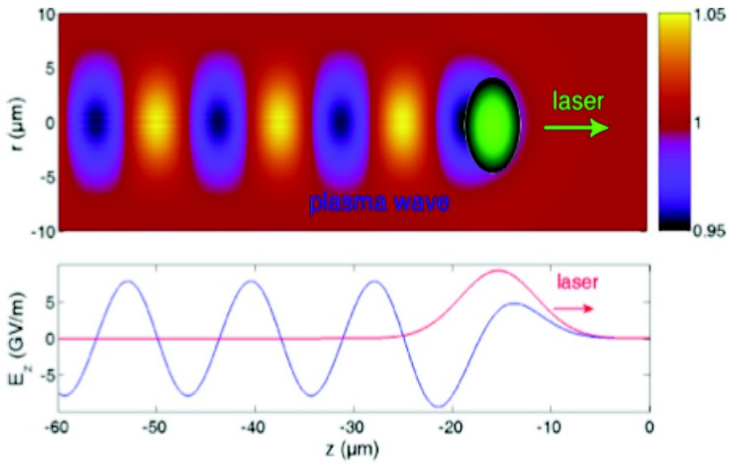


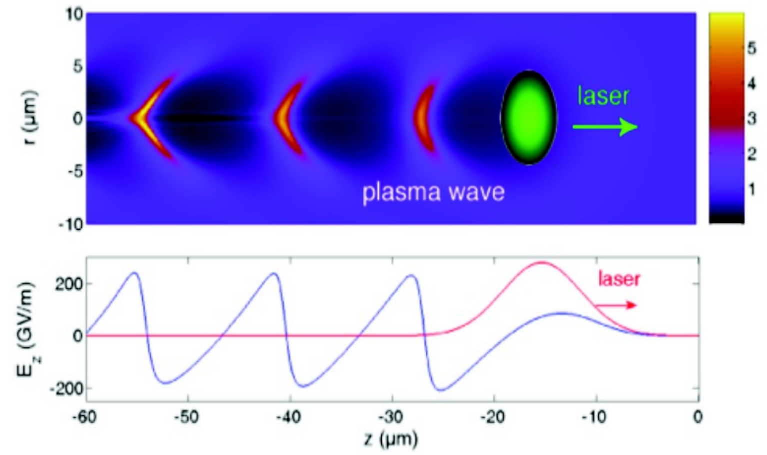
Many installations with 1-10 PW lasers are under development in the world with a focus on particle acceleration, the record is a 4GeV acceleration in a 10cm long plasma on BELLA at the LBNL.

Laser Wake Field Acceleration

courtesy of Arnd Specka

longitudinal electric field accelerating
transverse electric field focussing





quasi-linear regime
- longitudinal plasma wave
- external injection
- laser pulse O(100fs)
- plasma density 10^{16} to 10^{17} cm^{-3}

non linear regime (bubble)
- electric central wakefield
- self-injection
- laser pulse O(20fs)
- plasma density 10^{18} to 10^{19} cm^{-3}

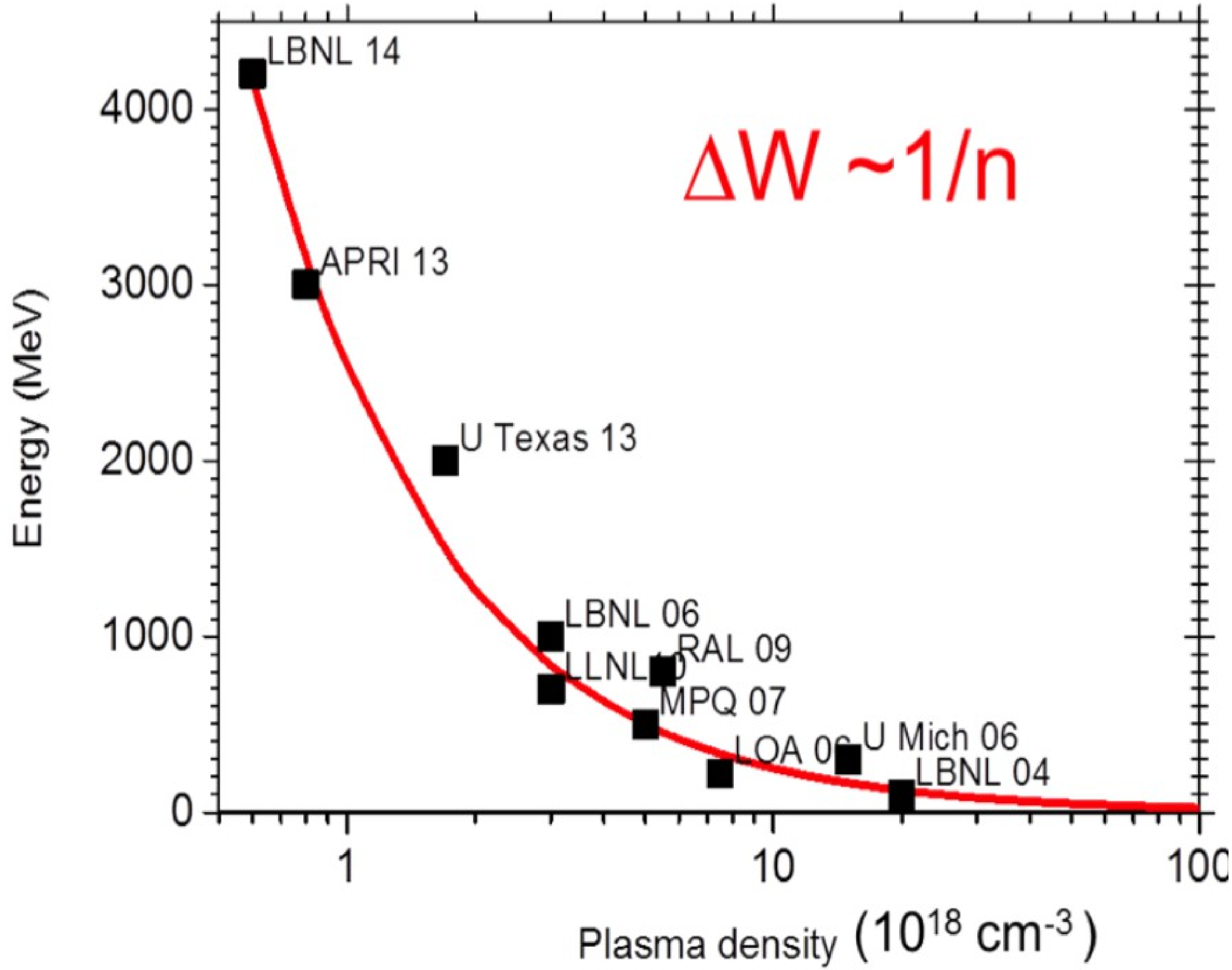
But the devil is in the details : few problems

the phase speed depends on the plasma density, at a point $\gamma_{el} > \gamma_p$
the acceleration also
the speed is lower than c and grows by reducing the density $L_{max} \propto n_0^{-3/2}$
then the acceleration goes down.
Like in RF accelerators we need then cells and a multistage accelerator

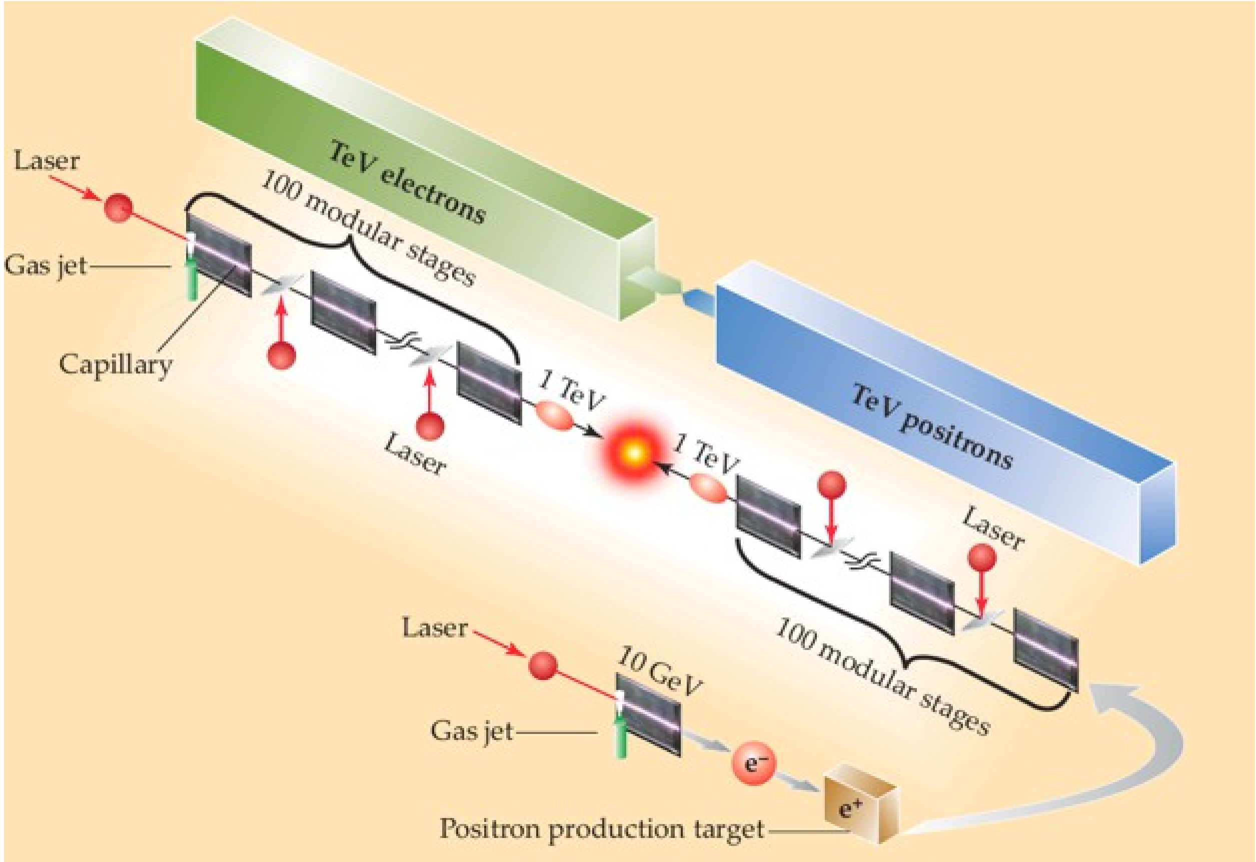
The laser beam is focussed in the plasma but diverges (Rayleigh length) and,
except if we introduce some guidance (autofocus, capillaries, discharges...) ,
the acceleration length is limited (10cm max up to now)

But the main issue is the energy yield.
The beam energy in a current laser is about 0.025 % of the plug energy !!!
recall that the total yield from the plug of an ILC is about 17 %
plus the efficiency of the transfer to the plasma
plus the efficiency of the transfer to the particle beam, beam loading.

Fibre lasers pumped with diodes are efficient, up to 50 %
but of low power
need for coherent bundles of fibres.



In order to gain in energy per stage :
reduce the plasma density
increase the laser power



A TeV collider in a few hundreds of meters
Leemans & Esarey Physics Today 2009

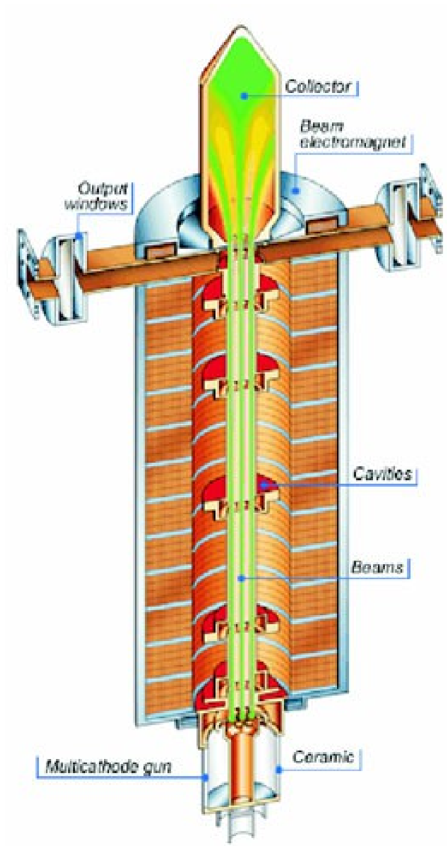
A lot to develop to reach that

Eupraxia : an intermediate step, a reliable accelerator at 5 GeV

End of the section on accelerators

TESLA Multi Beam Klystrons

Three Thales TH1801 Multi Beam Klystrons have been produced and tested



MBKs reduce HV and improve the efficiency: lower space charge.

Seven beams, 18.6 A, 110 kV, produce 10 MW with 70% eff.

Cathodes are still the weak point

Operational experience

Achieved efficiency	65%
RF pulse width	1.5 ms
Repetition rate	5 Hz
Operation experience	> 5000 h

10% of operation time at full spec's

A new design proposed by Toshiba looks more robust and should reach 75% efficiency

Accelerators

Time structure

Superconducting linac

long RF pulse: 1 ms

300 km

5 per second for reason of power consumption, could go to 10

bunchs every 300 ns i.e. 3000 bunchs per train

Strong consequences on the detector

Warm

short RF pulse

100 Hz

bunches every 1.4 ns i.e. 200 bunchs per train

Accelerators

Parameter	X	L	X	L
C. M. Energy/Energy Reach [TeV]	0.5/0.625	0.5/0.625	1/1.3	1/1
Loaded rf gradient [MV/m]	52	28	52	35
2-linac total length [km]	13.4	27.0	26.8	42.5
$\gamma\epsilon_x$(IP) [μm-rad]	3.6	9.6	3.6	9.6
$\gamma\epsilon_y$(IP) [μm-rad]	0.04	0.04	0.04	0.04
$\mathcal{L}_g\,[10^{33}cm^{-2}s^{-1}]$	14.2	14.5	22.2	22.7
D_y	12.9	22.0	10.1	17.3
H_D	1.46	1.77	1.41	1.68
$\mathcal{L}\,[10^{33}cm^{-2}s^{-1}]$	20.8	25.6	31.3	38.1
Number of main linac klystrons	4520	603	8984	1211
Number of main linac RF structures	18080	18096	35936	29064
Peak RF power per structure [MW]	56	0.28	56	0.35
Average power per beam [MW]	6.9	11.3	13.8	22.6
Linac AC to beam efficiency [%]	6.6	17.0	7.1	15.3
Site Operating AC power [MW]	260	179	454	356