Future Linear Colliders

for Particle Physics

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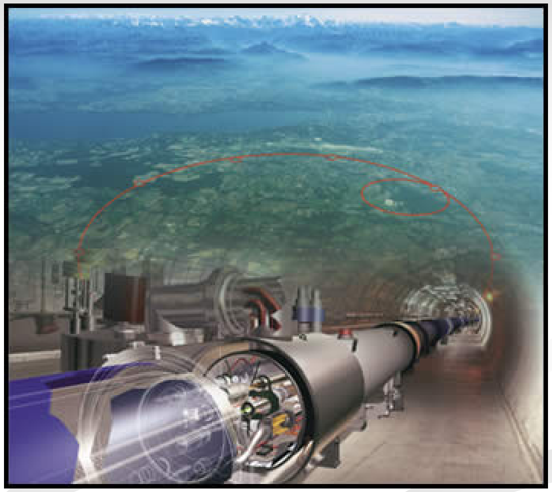
Starting point: LEP and LHC

This decade: both LEP and LHC

LEP: 1989 - 2000



LHC: 2007-

- Why more colliders?
- What will they look like?

Part I

A Future Linear Collider – Why and How

The three main parameters

Accelerators for Particle Physics are characterized by:

	LEP	LHC
Particle type(s)	$\mathbf{e^+}$ and $\mathbf{e^-}$	**p,** ions (**Pb, Au**)
Collision energy ($\mathbf{E_{cm}}$)	**209 GeV** (max)	p: **14 TeV** at p (~ 2-3 TeV mass reach, depending on physics) Pb: 1150 TeV
Luminosity ($\mathcal{L}$)	Peak: $\mathbf{10^{32}\ cm^{-2}s^{-1}}$ Daily avg last years: 10^{31} cm^{-2}s^{-1} Integrated: ~ 1000 pb^{-1} (per experiment)	Peak: $\mathbf{10^{34}\ cm^{-2}s^{-1}}$ (IP1 / IP5)

Particle type

Hadron versus lepton collisions

- Can be elementary particle (lepton) or composite object (hadron)
  - LEP: e^+e^- (lepton)
  - LHC: pp (hadron)

- Hadron collider:
  - Hadrons easier to accelerate to high energies
  - Parton collisions $\Rightarrow$ intrinsic parton energy spread $\Rightarrow$ large discovery range

- Lepton collider (LC):
  - well-defined E_{CM}
  - well-defined polarization (potentially)

    -> **data analysis are in many caser simpler** (single events can be readily analyzed)

    -> are better at **precision measurements** of many parameters

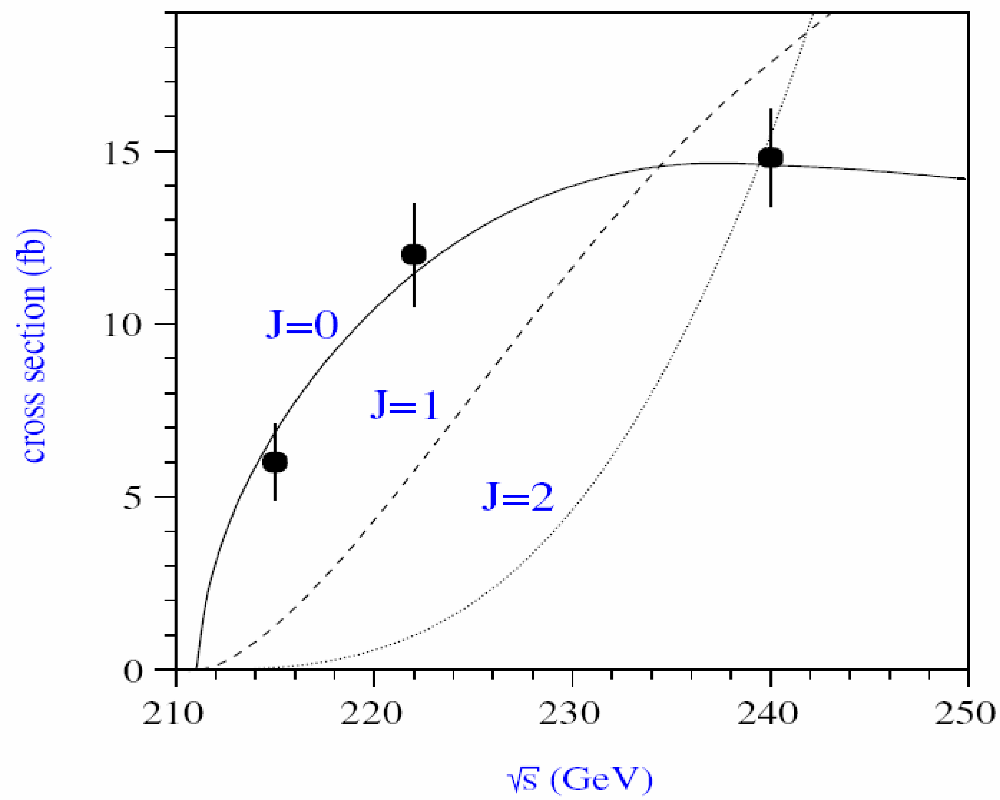
LHC and LC synergies: Higgs

- LHC might discover one, or more, Higgs particles, with a certain mass
- However, discovery and mass is not enough
- Are we 100% sure it is really a SM/MSSM Higgs Boson?
  - What is its spin?
  - Exact coupling to fermions and gauge bosons?
  - What are its self-couplings?
- So, are these properties exactly compatible with the SM/MSSM Higgs?

Confidence requires a need for precision

Higgs: Spin Measurement

- The SM Higgs must have spin 0
- In a lepton collider we will know E_{cm}
- A lepton collider can measure the spin of any Higgs it can produce

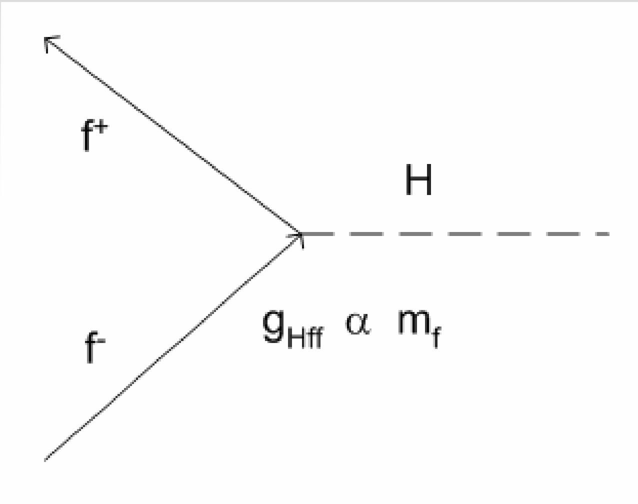


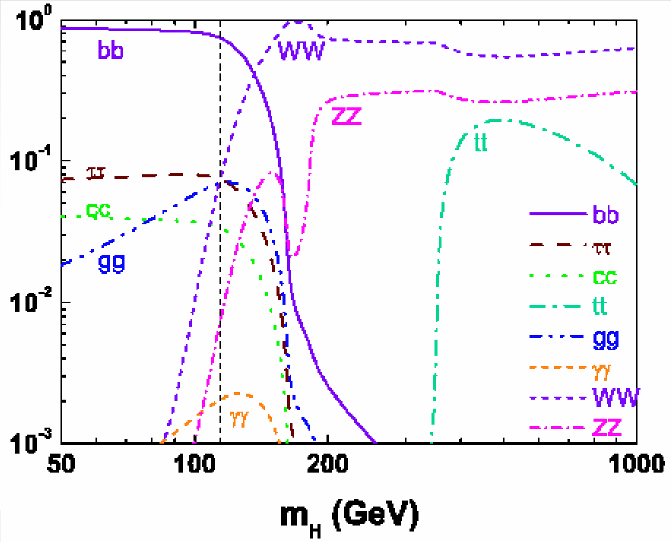
$e^+e^- \rightarrow HZ$ **(mH=120 GeV, 20 fb–1)**

Slide: B. Barish

Higgs: fermion couplings

- SM predicts $g_{Hff} / g_{Hf'f'} = m_f / m_{f'}$





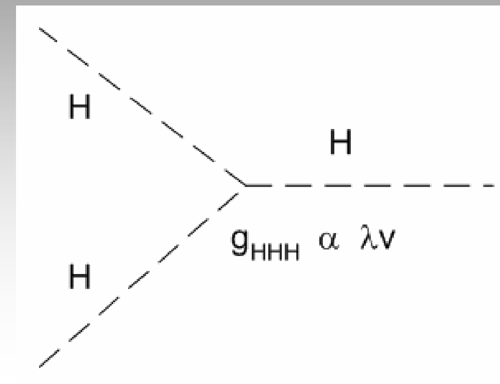
- Must be checked for all particle species ⇒ need to measure also rare decays like H -> $\mu^+\mu^-$
- Some couplings might be measured by LHC
- But sufficient **precision** can only be reached in a lepton collider

Higgs: self-couplings

The Higgs potential (M&S notation):

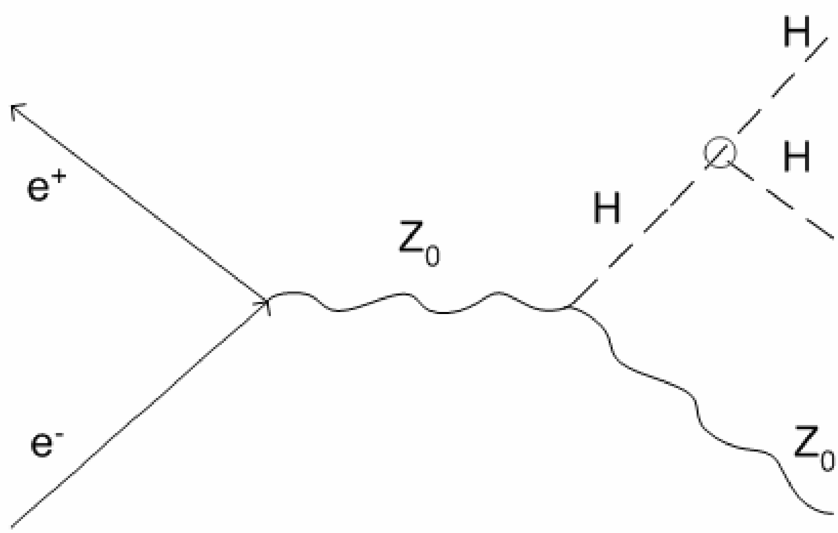
$$V(\sigma) = \frac{1}{2}m_H^2\sigma^2 + \lambda v \sigma^3 + \frac{1}{4}\lambda\sigma^4$$

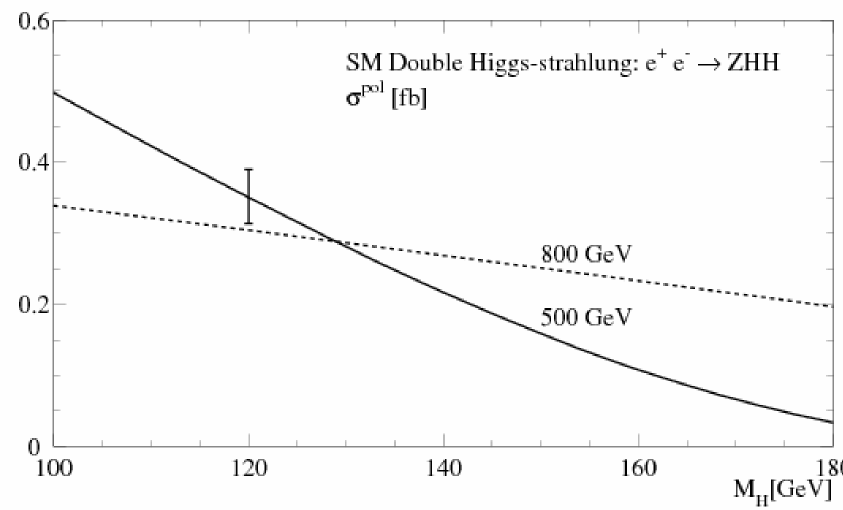
$$v = \sqrt{\frac{-\mu^2}{\lambda}} = \frac{m_H}{\sqrt{2\lambda}}$$



- SM predicts $g_{HHH}\ \alpha\ \lambda$

- Can be measured with polarized lepton collision via $e^+e^- \to HHZ$





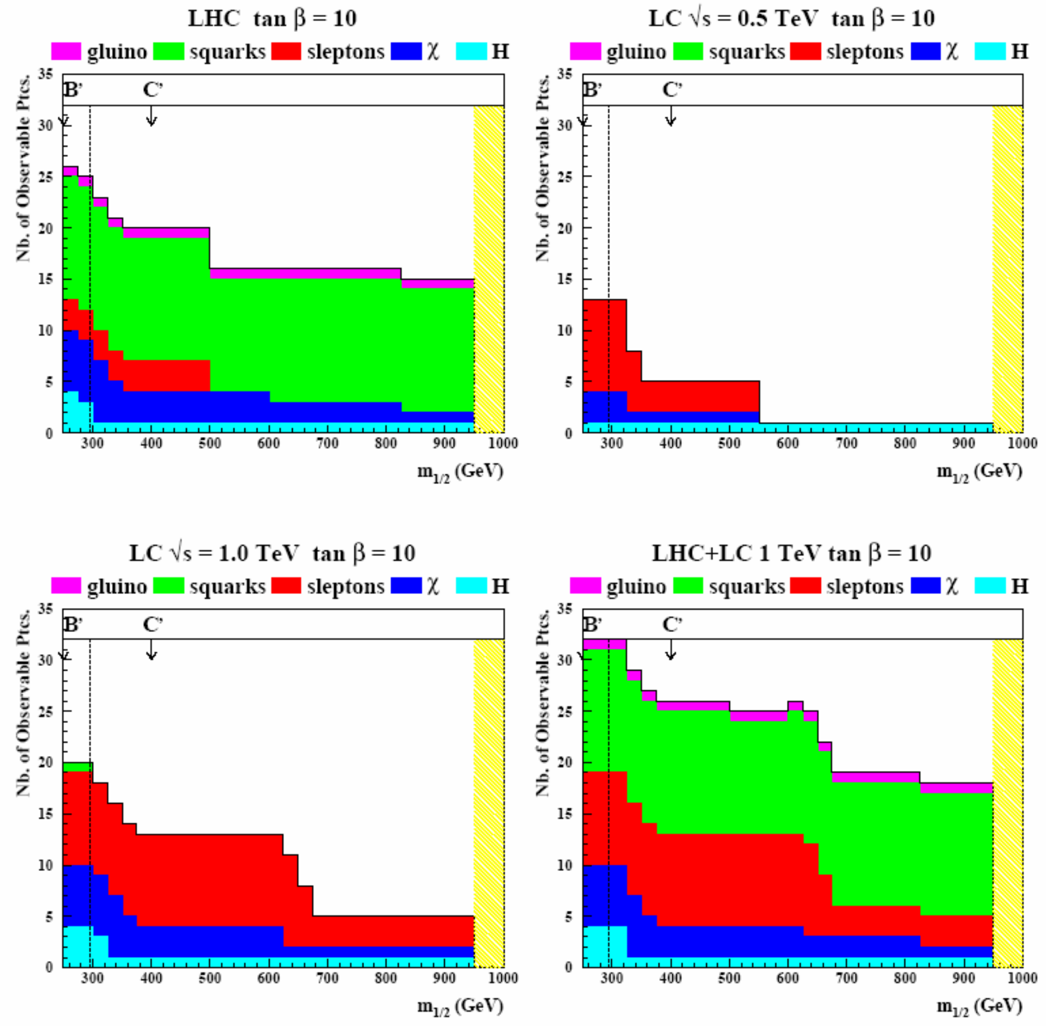
(Graph: M.M.Mühlleitner)

SUSY

- if (SUSY) LHC will most probably detect a large subset of sparticles, but might also miss a set (depending on energy)

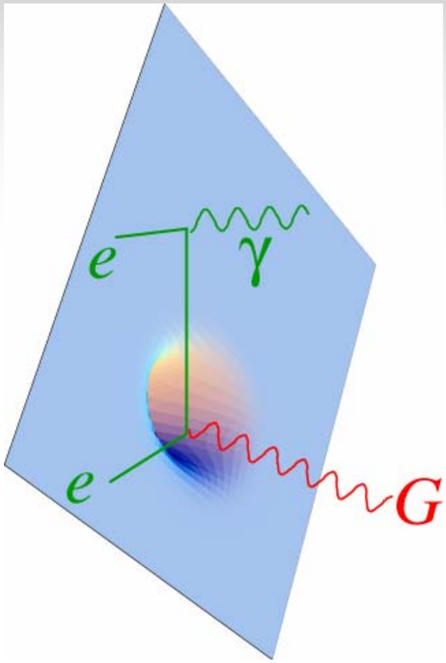
- A multi-TeV LC will complement the LHC spectrum of discoveries

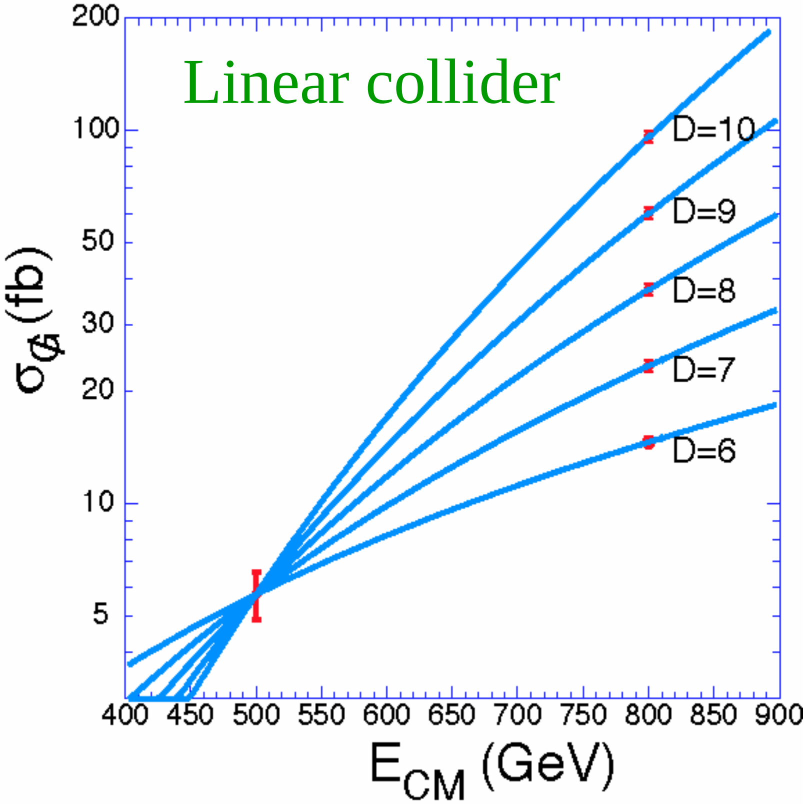
- LHC better squark-detection and a lepton collider better slepton-detection



Extra dimensions

- Applicable for both LHC and LC, but **exact D** is easier to deduct with LC

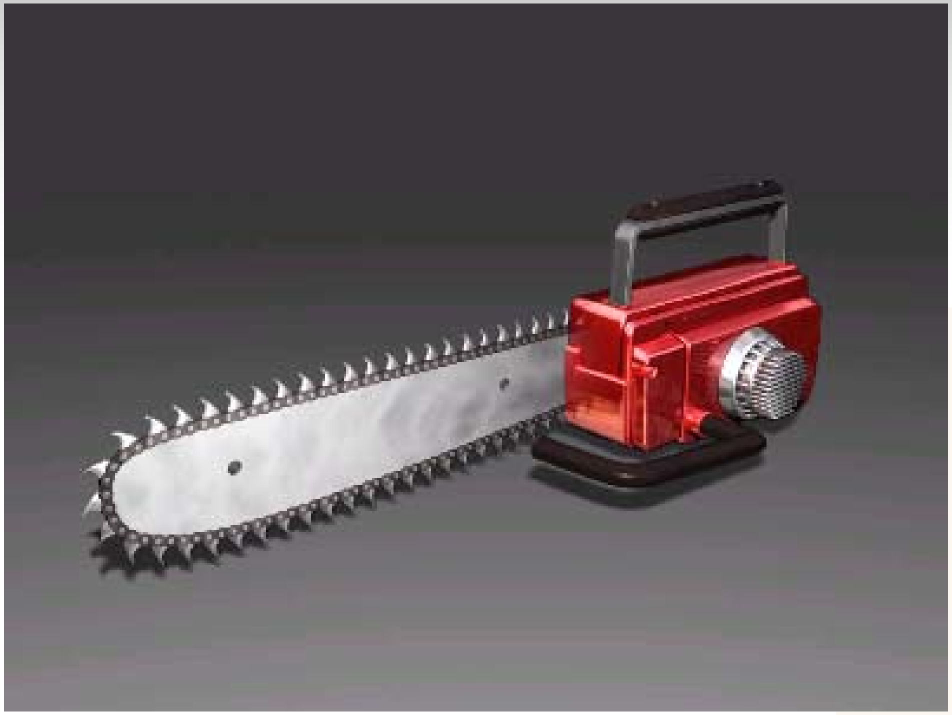




"New space-time dimensions can be mapped by studying the emission of gravitons into the extra dimensions, together with a photon or jets emitted into the normal dimensions"

Slide: B. Barish

The Chainsaw and the Scalpel



LHC

Lepton collider

LHC + LC = SYNERGY

Collision energy

Limitations LEP and LHC

- We want E_{cm} as high as possible for new particle accelerators
- circular colliders ⇒ particles bended ⇒ two limitations occurs:

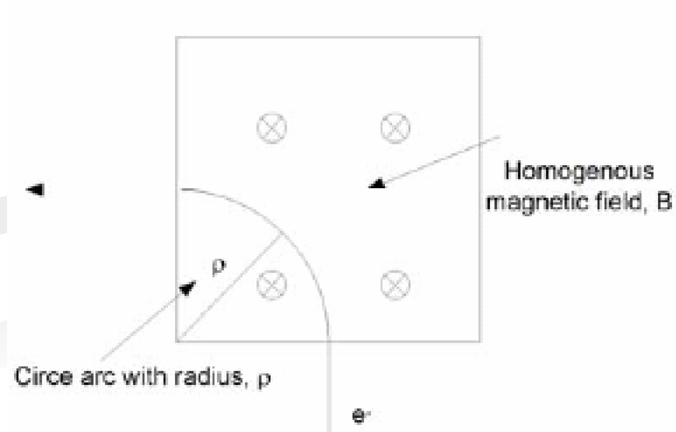
I) synchrotron radiation energy loss

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

$P \propto E^4$ ⇒ **Limited LEP to E_{cm}**=209 GeV (RF energy replenishment)
$P \propto m_0^{-4}$ ⇒ changing to p in **LHC** ⇒ **P no longer the limiting factor**

II) Magnetic rigidity

$$B\rho = \frac{p}{e}$$



Technological limit of bending magnet field strength
⇒ **Limits LHC to E_{cm}=14 TeV** ($\propto$ B)
⇒ Superconducting magnets needed

Synchrotron radiation energy loss

- Main problem LEP: synchrotron radiation loss:

- Though-experiment: we want P_s=P_{LEP} and E_{cm}=2 TeV. *What options do we have?*

$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

$$P_{S,LEP} = K \frac{1}{m_e^4} \frac{E_{LEP}^4}{R_{LEP}^2} \approx K \frac{1}{m^4} \frac{(10E_{LEP})^4}{R^2}$$

$$\Rightarrow R = 100 R_{LEP} (\frac{m_e}{m})^2$$

Option 1

$$\Rightarrow R = 100 R_{LEP} (\frac{m_e}{m})^2$$

- *If we keep $m=m_{e,}$ $\Rightarrow$ R=2700 km (!)*

- *If we insist on an e^-e^+ synchrotron at this energy with LEP's power consumption the size will ridicoulous*

- *$\Rightarrow$ **NOT feasible**, neither economically, practically nor "culturally"*

Option 2

$$\Rightarrow R = 100 R_{LEP} (\frac{m_e}{m})^2$$

- *Other idea: $m=m_{u,}$ $\Rightarrow$ R ~ 100 m (not the limiting factor anymore)*

a Muon Collider

- *Gives basically the same physics as an electron collider for the same E_{CM}, without the radiation loss*

- *Only a small catch: τ_u=2.10^{-6}s*
  - *Time-dilation helps a little bit, e.g. at E_u=0.5 TeV τ_{LAB}=1.10^{-2}s*

$\Rightarrow$ but we still have to accelerate and collide VERY fast

In addition: problems with neutrino radiation

- serious studies has been done, but NOT feasible with today's technology

Option 3

$$\Rightarrow R = 100 R_{LEP} (\frac{m_e}{m})^2$$

- *We go back to: $m=m_e$, but let $R \rightarrow \infty$*

- *Forget bending all together, accelerate along a **linear accelerator***

- *Today: the **ONLY feasible** way to do TeV-scale lepton-lepton collisions*

Luminosity

What is luminosity?

- If we know the cross-section of a process, **how often will this process take place**? Must depend on the number of particle colliding, the beam size etc..

$$R = \sigma \times \mathcal{L} \; [s]$$

- Luminosity: proportionality factor that collects the relevant beam properties, independent of physics

Circular collider:

$$L = f \times (N^2 / 4\pi\sigma_x\sigma_y)$$

- Cross-sections for interesting events are very small, e.g. $\sigma(gg \rightarrow H) = 23$ pb [at $s^2_{pp} = (14\ \mathrm{TeV})^2$, $m_H = 150\ \mathrm{GeV}/c^2$]

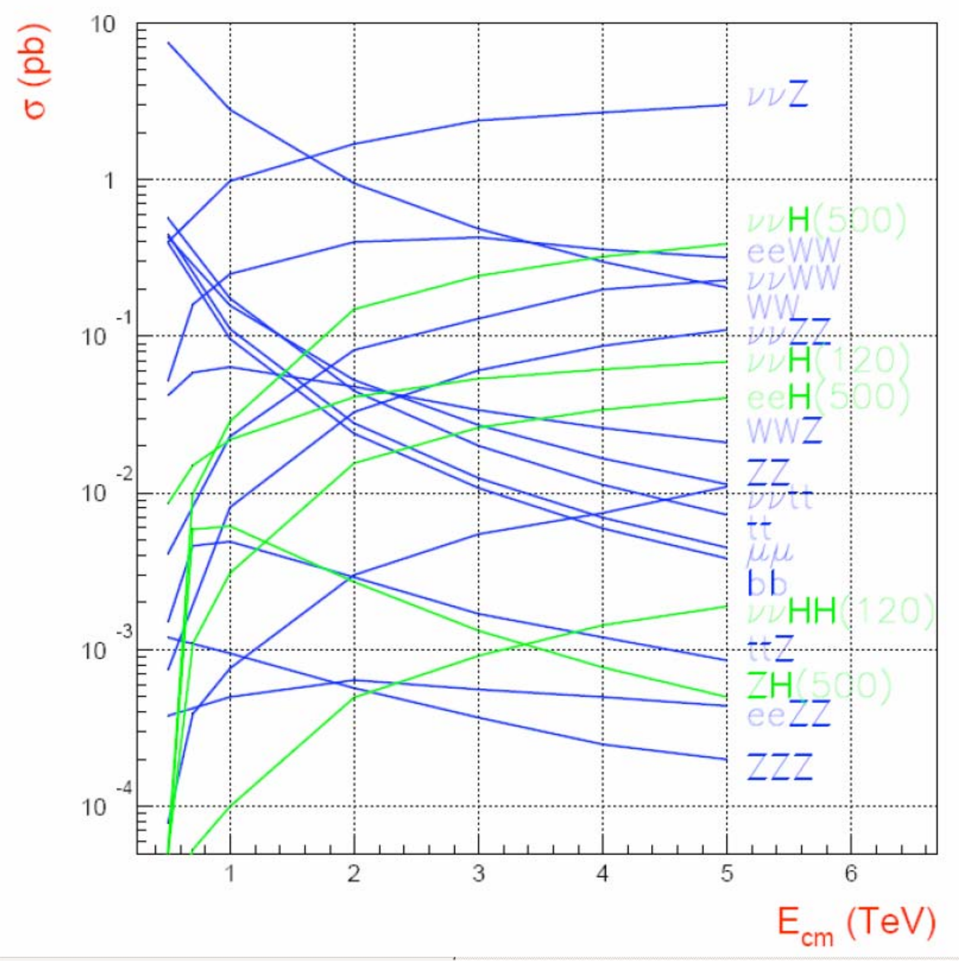
$\Rightarrow$ **large luminosity is very important**

Energy dependence of $\mathcal{L}$

Cross section falls with E_{CM}

(True for s-channel annihilation cross sections, opposite for some Higgs couplings)

Still, s-channels must be compensated by $\mathcal{L}$



E.g. E_{CM} =3 TeV,

$\mathcal{L}$=10^{34}cm^{-2}s^{-1} is needed

- several OM higher than LEP

Recent history (summary)

- From this, recent history is clear:
  - LEP: precise lepton collisions
  - reached energy limit
  - LHC allows much higher E_{cm} while reusing LEP tunnel
  - LHC will:
    - probe new energy ranges,
    - will do great discoveries
    - but cannot do all the precision measurements desired

Near future (prediction)

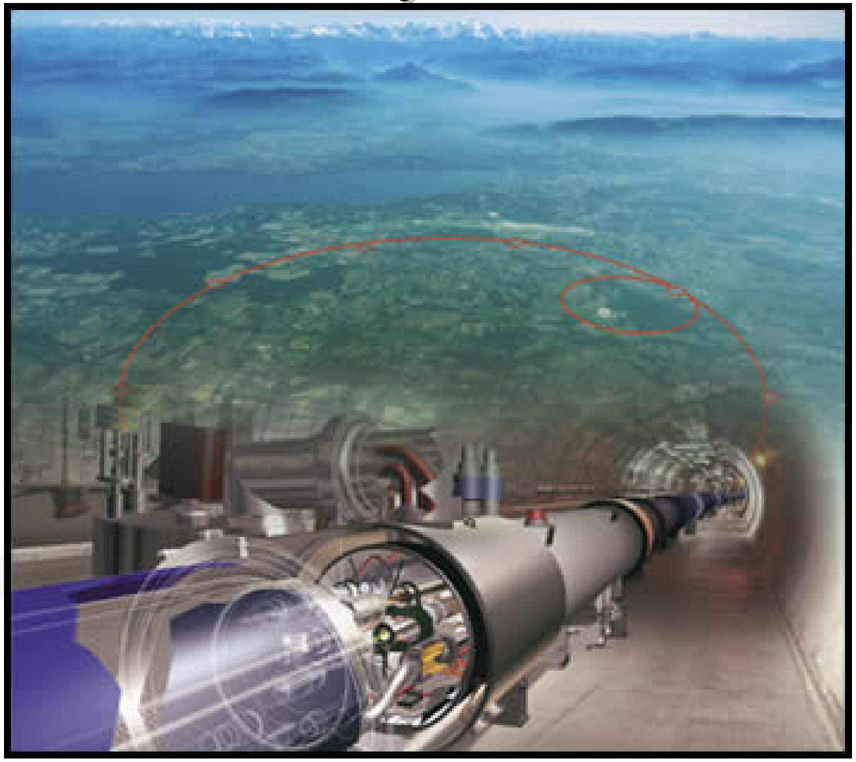
- A new linear e^-e^+ collider in the order of energy the LHC is desired
- Energy range: ~ 1 TeV - but to be determined by LHC results
- Luminosity: must be substantially higher than LEP

...LHC results

- Actual prospects of physics can only be defined by the discoveries of the LHC
- Future collider projects are therefore, as everyone else, eagerly following the preparation and soon first results of LHC data-analysis

First step towards a future linear collider:

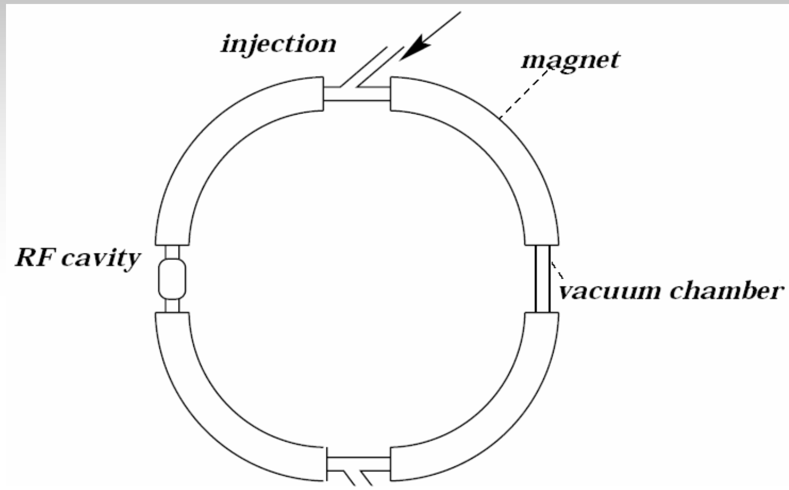
a successful LHC

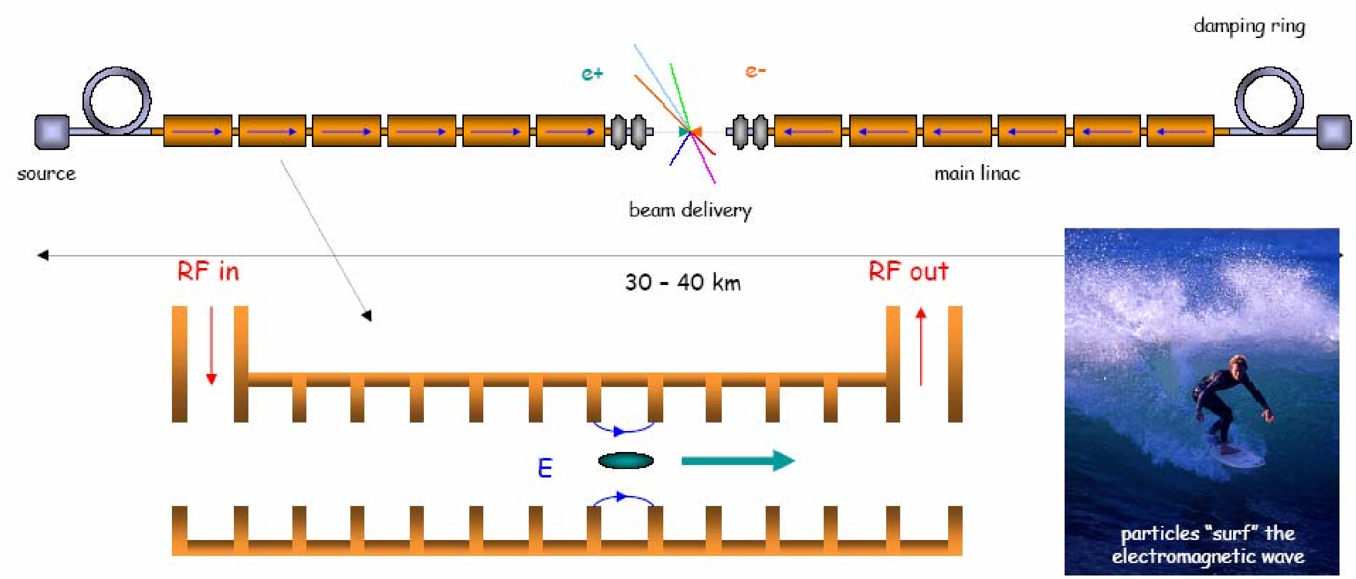


Part II a

Linear Colliders – general aspects

Linacs versus rings





The three main parameters

	Rings	Linacs
Particle type(s)	ions, p/$\overline{p}$, $e^{+/-}$	ions, p/$\overline{p}$, $e^{+/-}$
Collision energy	accelerating cavities reused	accelerating cavities used once
Luminosity	■ bunches collided many times ■ several detectors simultaneously	■ each bunch collide only once ■ only one detector in use at a given time

1^{st} challenge: E_{COM}

- Accelerating cavities used once
- The length of the linac is then given by
  1. E_{COM}
  2. Accelerating gradient [V/m]
- E.g. for E_e=0.5 TeV and an average gradient of g=100 MV/m we get: l=E[eV] / g[V/m] = 5 km
  - Needs two linacs (e^+ and e^-) and a long final focus section ~ 5 km ⇒ total length for this example 15 km
- There are technological limits to the gradients

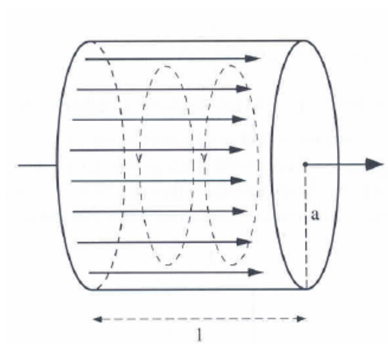
  ⇒ 1^{st} main challenge of future linacs: keep them short enough !

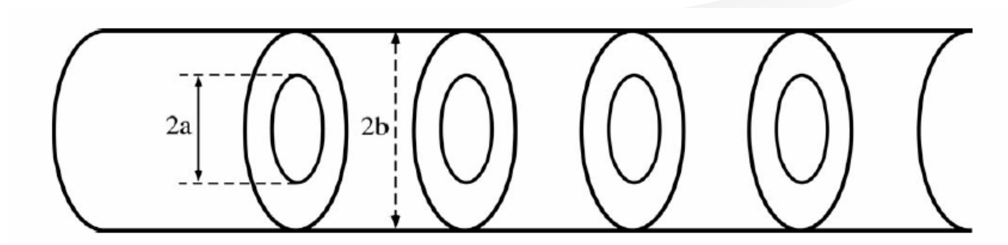
(as for rings, too long distances becomes simply too costly and impractical

⇒ **maximize gradient** (what is a linac to first order? Lot's of cavities)

Standard acceleration techniques

- Particles are accelerated (in rings or linacs) by electromagnetic fields (RF)
- Either inside a standing-wave cavity or in traveling-wave structures

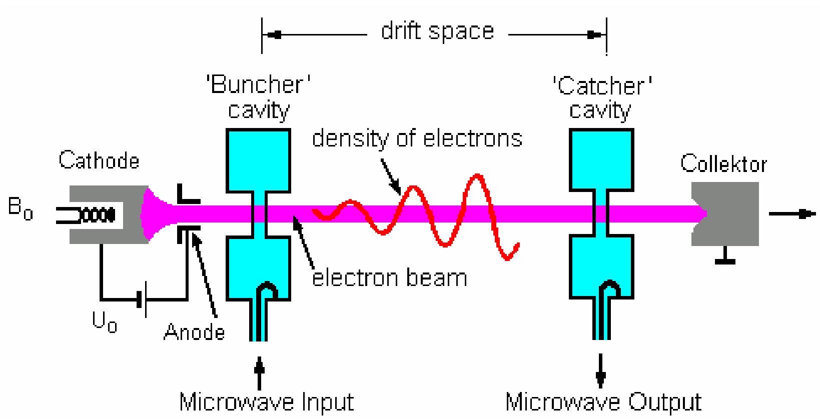




- Common for both is the need to couple in the RF-field, with a RF-power up to several MW

Standard acceleration technique

- Standard way to generate the cavity field:
  - a Klystron generates the RF-field
  - transferred via a wave-guide to the cavity
- What is a Klystron?
  - Electrons continuously emitted from a cathode and accelerated
  - A small RF-signal (P_{RF} ~ W) is coupled into a cavity point A and modulates the electron velocity
  - The beam drifts from A towards B and while being gradually more bunched
  - At cavity at B couples out the induced field (P_{RF} ~ MW)

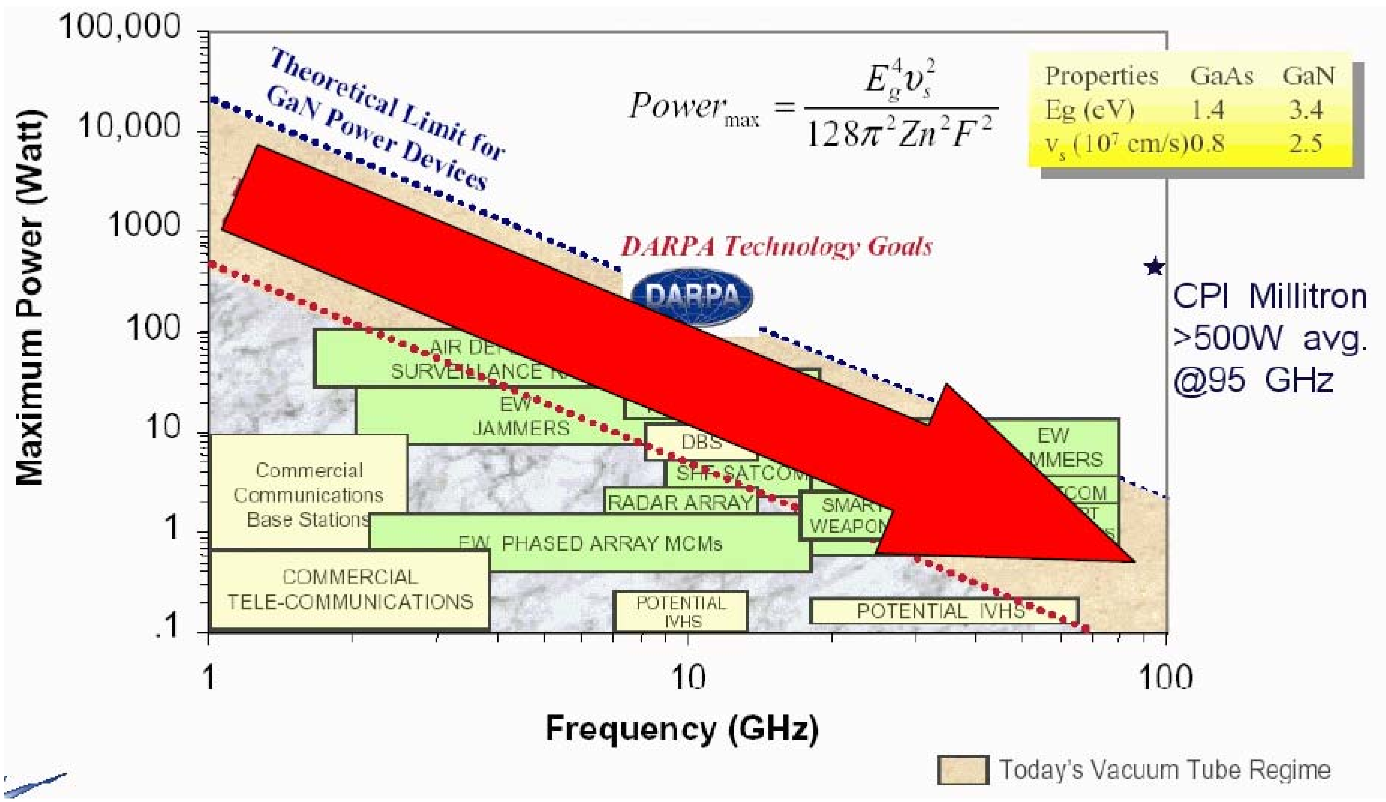


Limitations of a Klystron

- In general, the output power of the klystron is $P = n.U.I_{klystron}$

-> technological limit on P, for high frequencies

-> e.g peak power (in pulses) limited to several 10s MW for 3 GHz (frequency up -> sizes go down -> current density goes up)

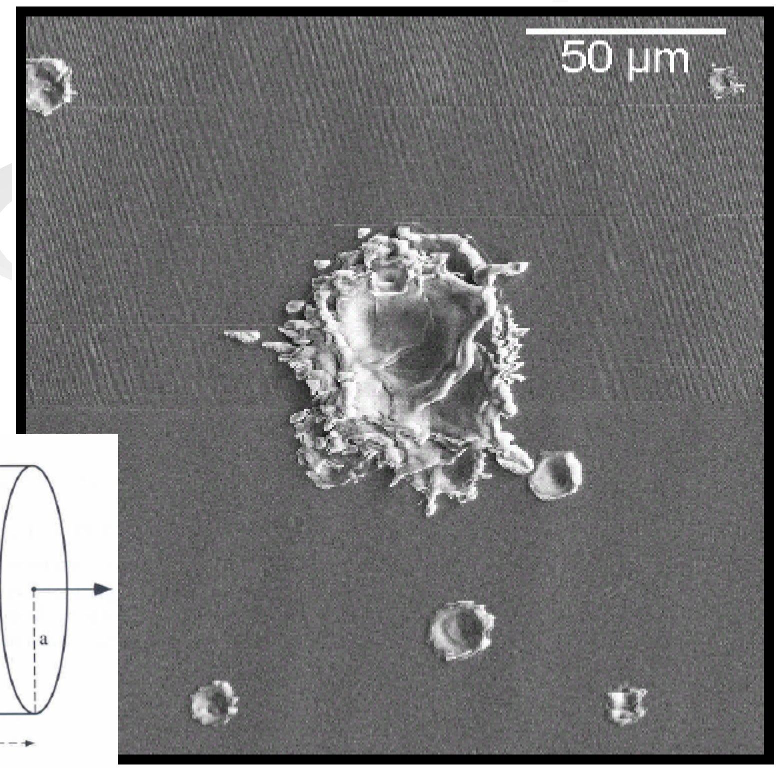


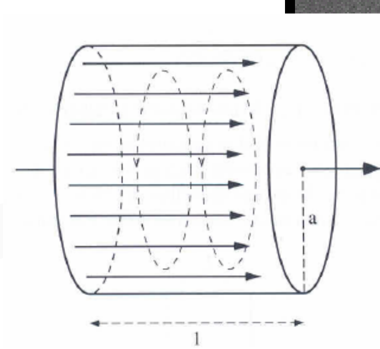
Gradients and breakdown

- Gradient (V/m = E) is also limited (independent of Klystron limitations)
- Breakdown/discharge: sudden dissipation of field energy into material
- No clear theory, but most likely triggered by field emission, followed by larger currents

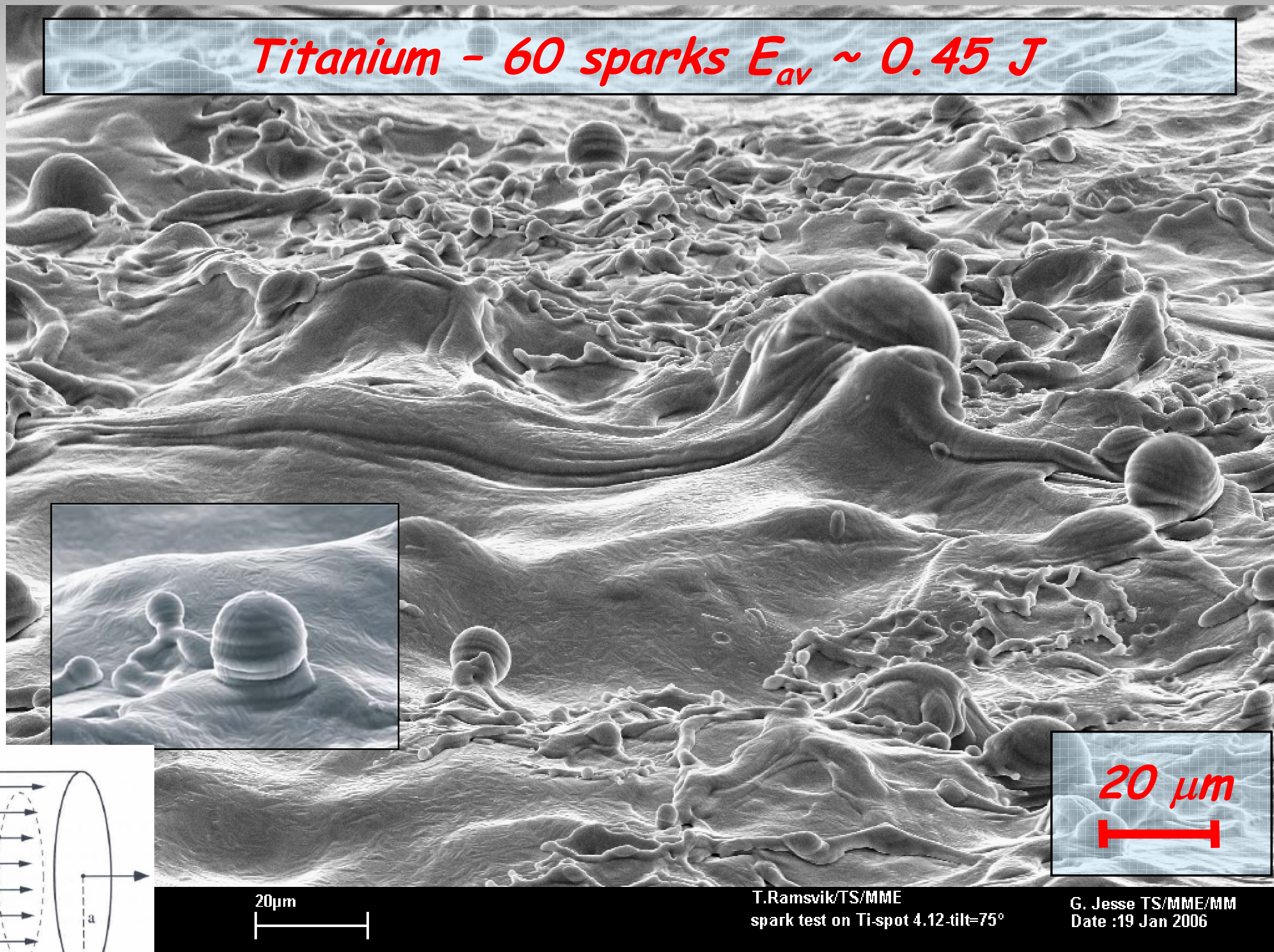
- Trips accelerating structure (bad), and melts it down (worse)

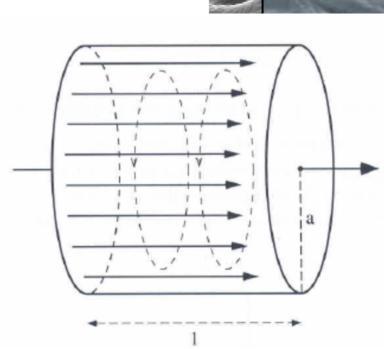
- A lot of new research needed to improve the current situation





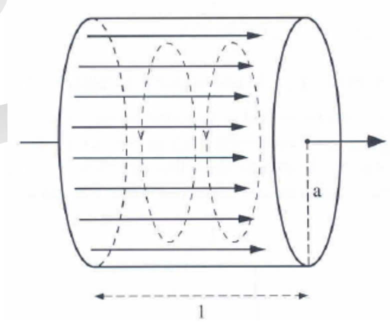
DC Breakdown tests (T. Ramsvik)



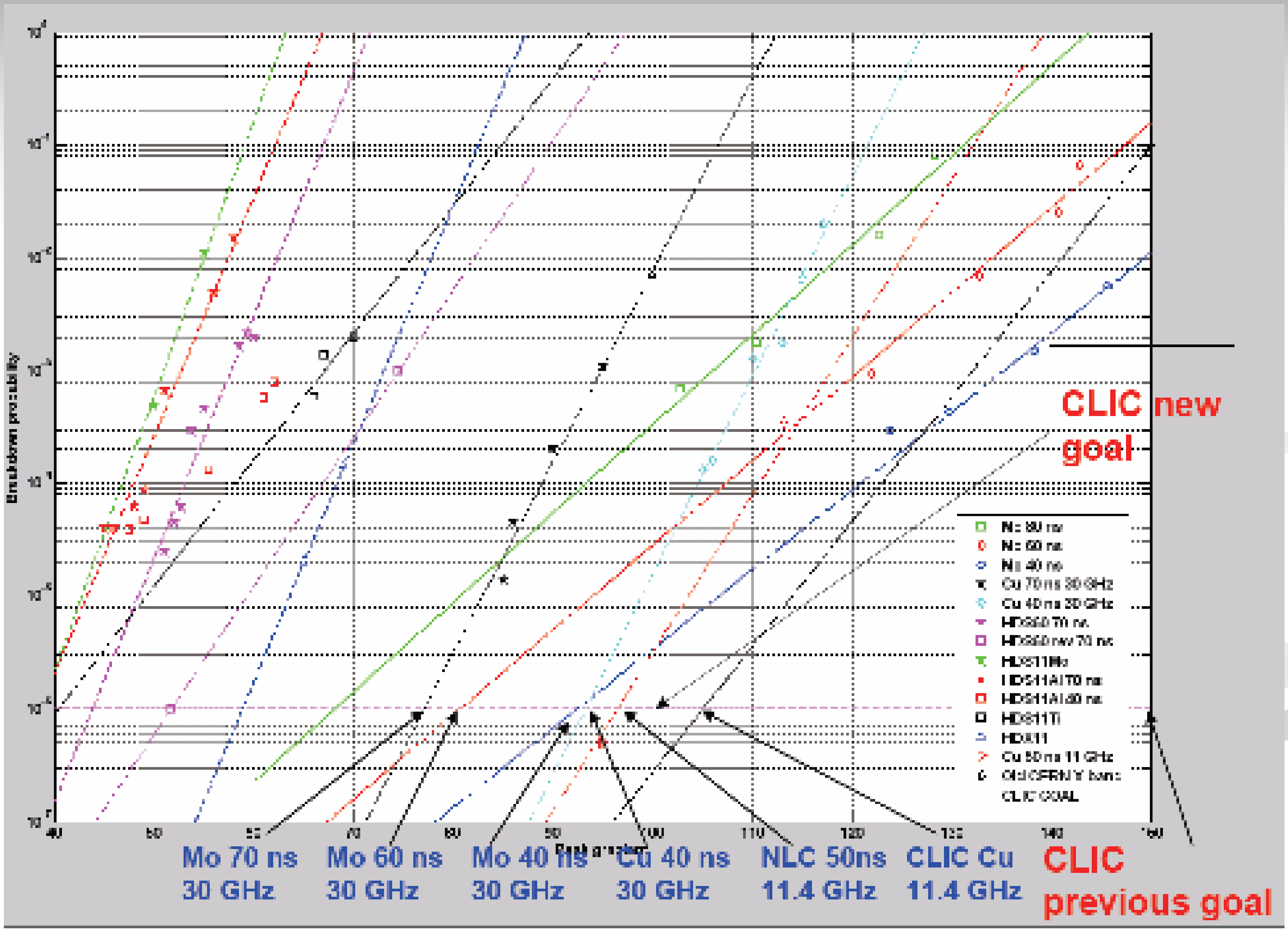


Trip rate

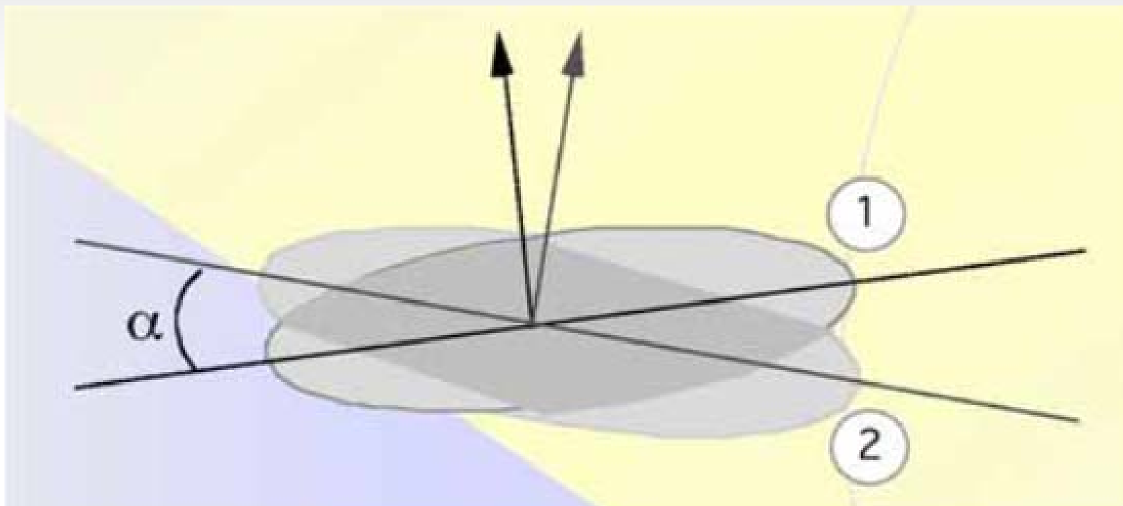
- Important number for linear colliders: **trip rate**
- One trip in one accelerating structure might (worst case) imply that the whole pulse is useless for physics
- Target: 1% loss in luminosity $\Rightarrow$ 0.05 breakdown per hour $\Rightarrow$ pulse trip rate of 10^{-6}
- **Limits NC gradient to ~ 100 MV/m (for f >~ 10 GHz) - and *to be proven***
- (Current) RF-frequency compromise trip rate / power consumption / other: **12 GHz**



Results of breakdown rate tests



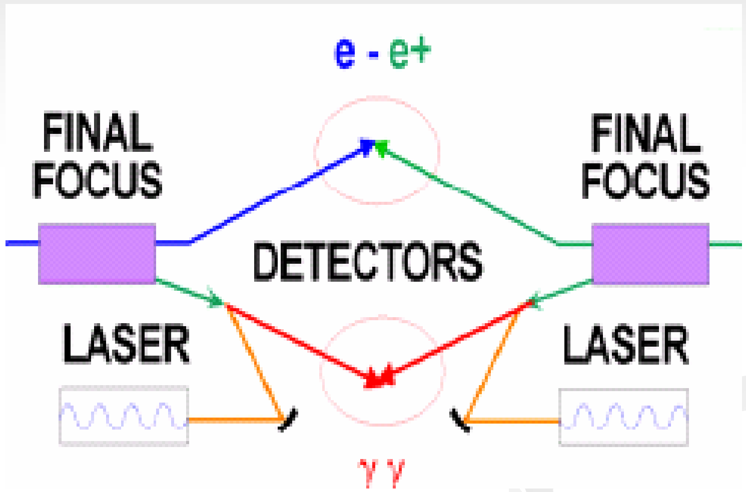
2^{nd} challenge: $\mathcal{L}$



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

Intermezzo: ...what about detectors?

- Linear collider: typically two detectors



- But only one in use at a given time

$\Rightarrow$ Higher $\mathcal{L}$

2nd challenge: $\mathcal{L}$

$$\mathcal{L} = f_r \frac{N^2 n_b}{4\pi\sigma_x\sigma_y} \times H_D \times \alpha_{corr} \propto \eta P \times \frac{N}{\sigma_x} \times \sigma_y$$

- Three fundamental limitations for $\mathcal{L}$
  - η – given by RF-system, to be maximized
  - N/σ_x – optimum from beam-beam interaction
  - **σ_y – to be minimized**

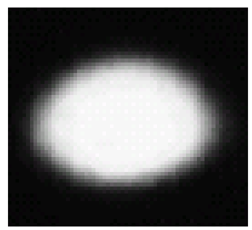
$\mathcal{L}$: Size requirement σ_y?

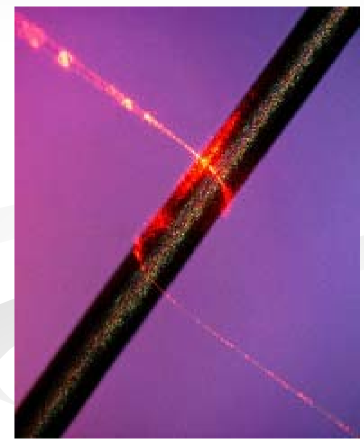
(Example design value for E_{cm} = 3 TeV, 10^{35} $cm^{-2}s^{-1}$)

σ_x=60 nm, σ_y=0.7nm (!)

7Å ! Vertical bunch-width of a water molecule!

(LEP: width of a human hair)



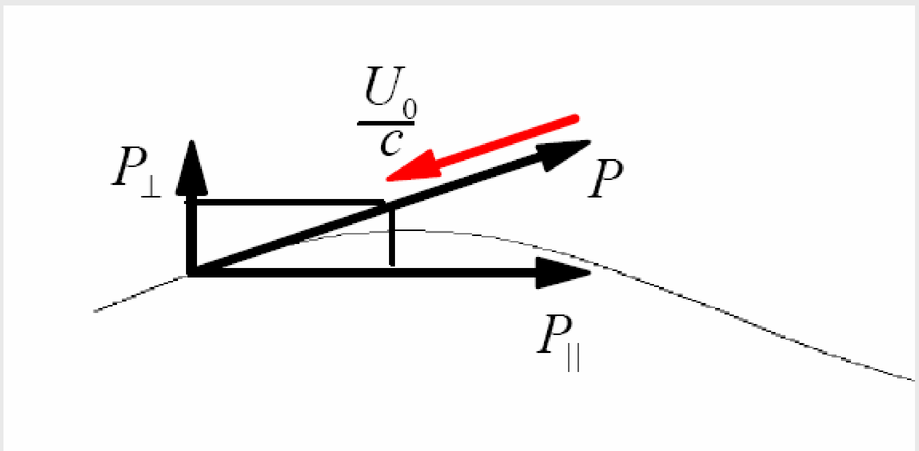


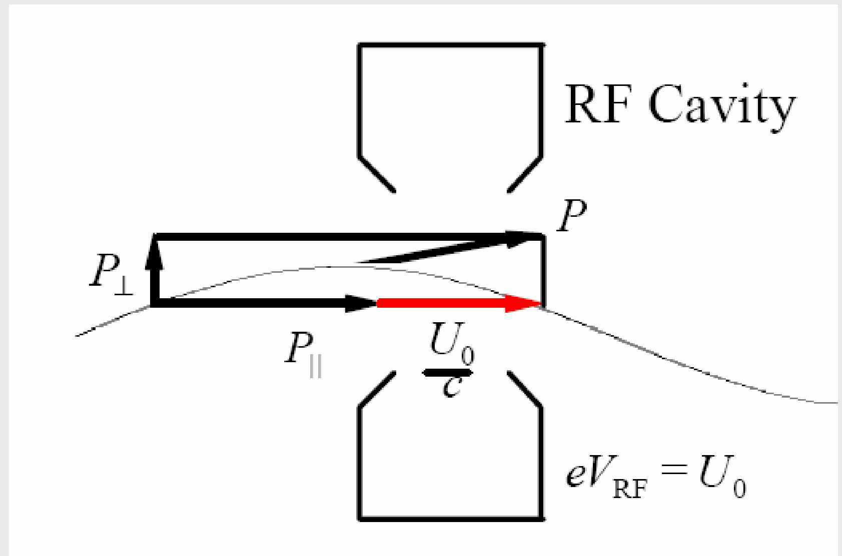
- Future linear colliders: truly **nanobeams**

- $\sigma_y = \sqrt{(\beta_y \varepsilon_y)} \Rightarrow \varepsilon_y$ quantity to be minimized
  - (The accelerator beta functions β will be at their minimum in the interaction point)

$\mathcal{L}$: How do we *generate* low ε_y?

Radiation damping





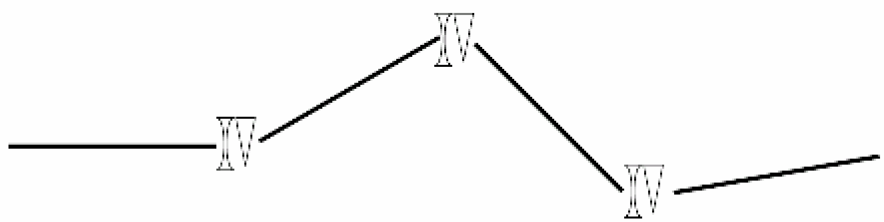
In linear colliders:

- dedicated damping rings before main linac

$\mathcal{L}$: How do we *keep* low ε_y?

(Example design value for E_{cm} = 3 TeV, 10^{35} $cm^{-2}s^{-1}$)

- Pre-alignment of components: 10 μm (LHC: 100 μm)
  - allows test beam to go through
- Beam-based alignment for dynamic alignment of components
  - remaining imperfections detected using beam, and *effect on the beam* is corrected



- Active stabilization (beam-based feedback) of magnets: 1 nm

Summary: the next *big* thing

The Future Linear Collider

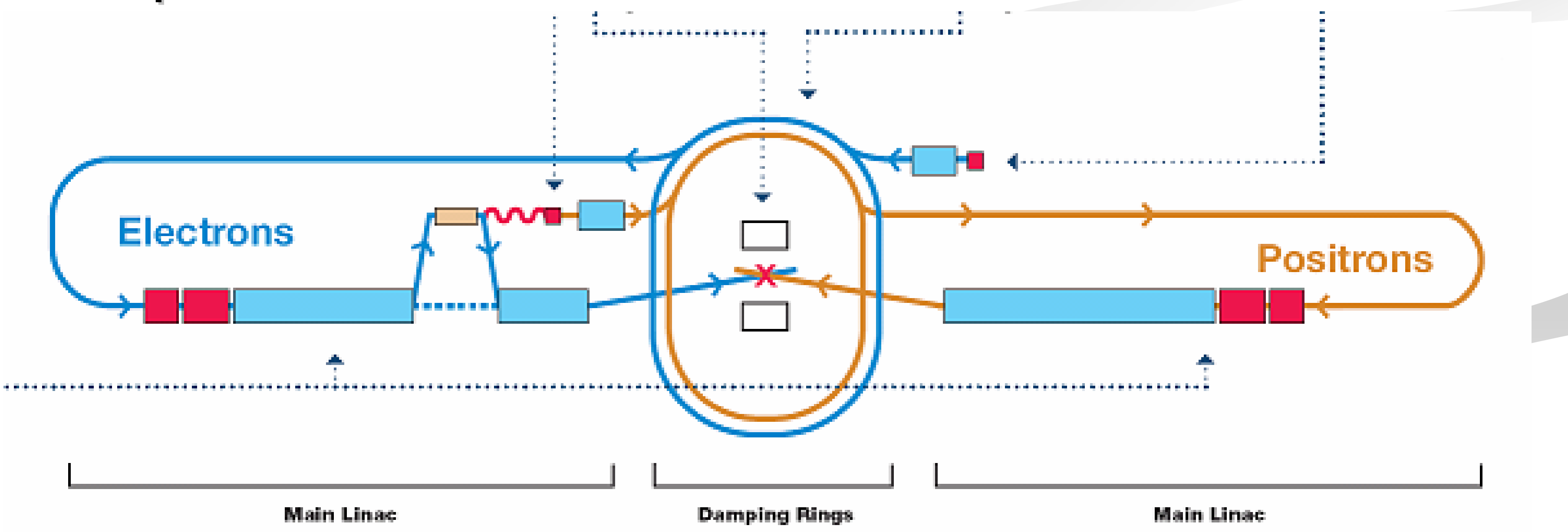
A linear high $\mathcal{L}$ e^+e^- collider of more than 30 km length, with nanometer precision scales

Part II b

Designs and ongoing efforts for linear colliders

The ILC collaboration

- ILC: International Linear Collider
- A global collaboration is currently doing the "Global Design Effort" (GDE) in order to have a detailed design ready for 2010
- Lots of ongoing research in Europe, USA and Japan



ILC design choices

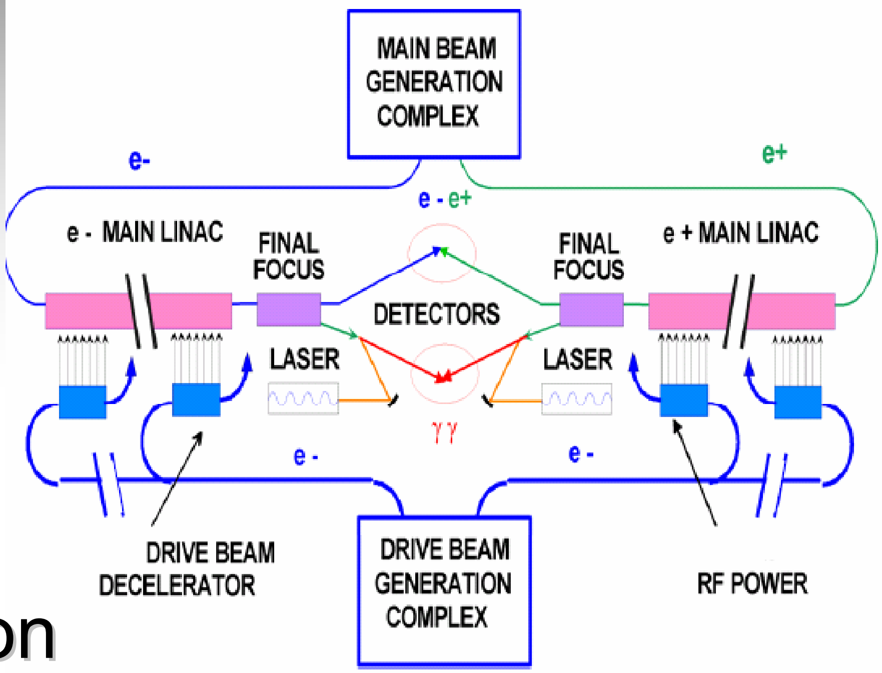
- Klystron-based main linac
- Superconducting RF-cavities at 1.3 GHz
- Gradient 35 MV/m
  - Hard physics limit: critical magnetic field strength for superconductivity (abs. maximum of ca. 50 MV/m)
  - Production/technology limitations forces practical gradient lower (cavity rejection factor leads to optimum of ca. 35 MV/m)
- Advantages
  - Low power consumption (one klystron can feed 36 cavities)
  - Low frequency gives large beam-pipe -> strongly reduced wake fields
  - Gradient is proven
- Disadvantages
  - Low gradient $\Rightarrow$ max 1 TeV (50 km)

The CLIC collaboration

- CLIC:

Compact Linear Collider

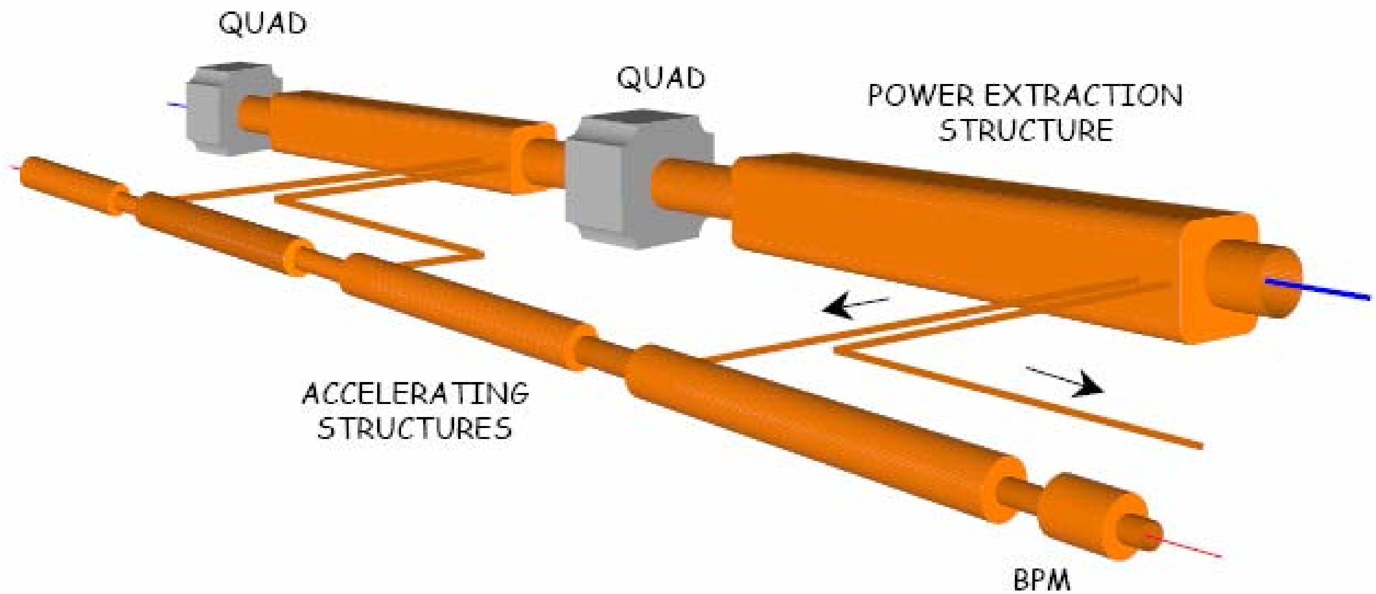
- Normal conducting cavities
- Gradient 100 MV/m
  - Limited by breakdown



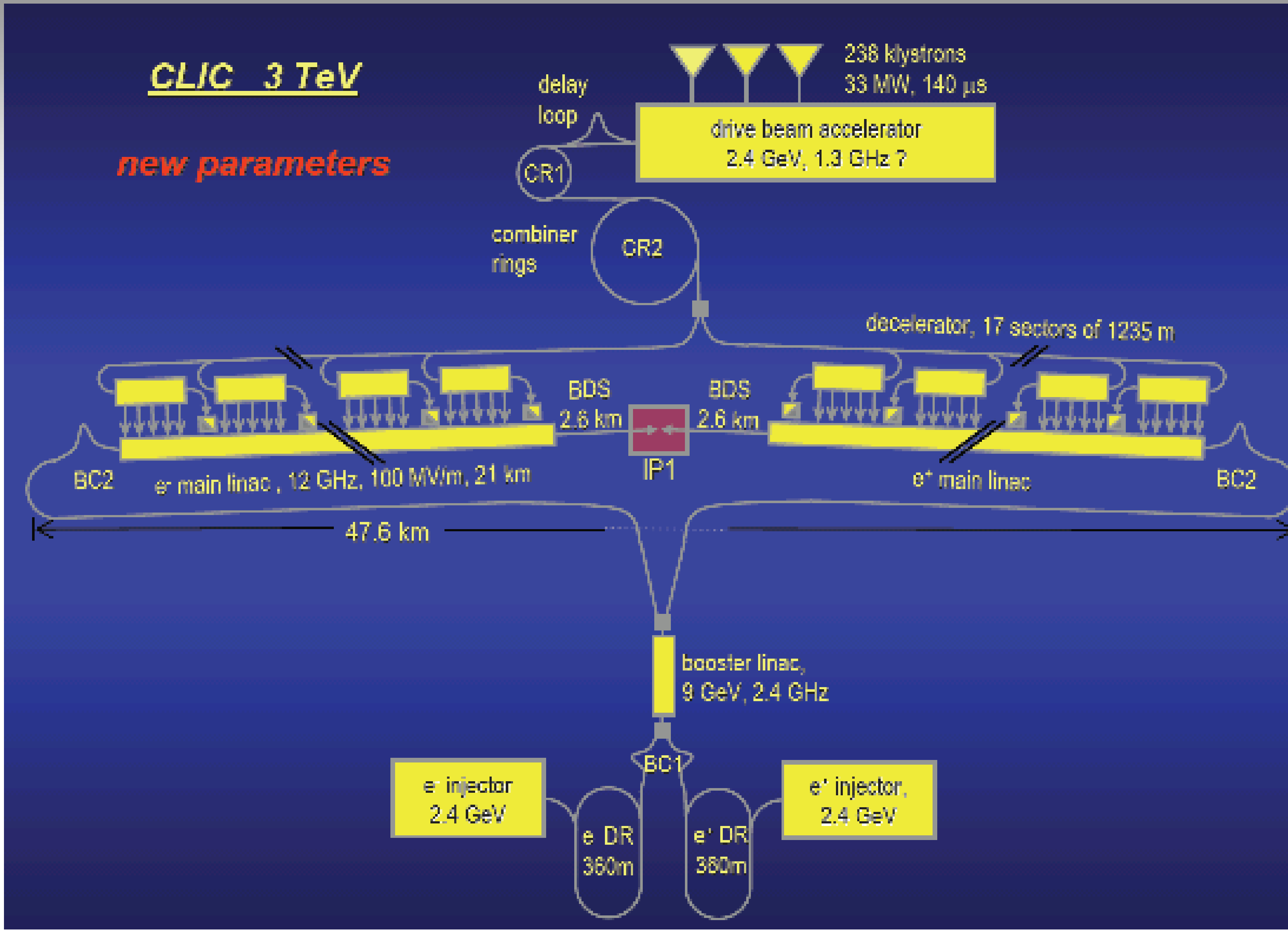
- Two-beam based acceleration
  - Instead of Klystrons use an e^- drive beam to generate power
  - For high-energy: klystrons (> 10000 needed) will be more costly, and must be extremely fail-safe
  - Power is easier to handle in form of beam ⇒ short pulses easier
  - Depending on final CLIC parameters klystrons might not even be feasible (too high POWER wrt. RF)

Two-beam accelerator scheme

- Power extracted from one beam (the drive beam) to provide power main beam
- Special Power Extraction Transfer Structure (PETS) technology
- Particles generate wake fields ↔ leaves behind energy



CLIC


CLIC 3 TeV
new parameters
delay loop
238 klystrons
33 MW, 140 µs
drive beam accelerator
2.4 GeV, 1.3 GHz ?
CR1
combiner rings
CR2
decelerator, 17 sectors of 1235 m
BDS
2.6 km
BDS
2.6 km
IP1
BC2
e- main linac , 12 GHz, 100 MV/m, 21 km
e+ main linac
BC2
47.6 km
booster linac,
9 GeV, 2.4 GHz
BC1
e- injector
2.4 GeV
e+ injector,
2.4 GeV
e- DR
360m
e+ DR
360m

Main differences CLIC and ILC

	CLIC	ILC
Gradient and length (1 TeV)	100 MV/m 22 km (but, optimized for 3 TeV, 48 km)	35 MV/m 50 km
Temperature	Warm (cavities and magnets at room temperature)	Cold (superconducting cavities, magnets at room temperature)
State of technology	Feasibility study on-going	No major outstanding items to prove. Detailed design on-going

The European strategy *for particle physics*

- CLIC strongly supported by the CERN Council and management, as well as in the European strategy for particle physics:

4. In order to be in the position to push the energy and luminosity frontier even further it is vital to strengthen the advanced accelerator R&D programme; *a coordinated programme should be intensified, to develop the CLIC technology and high performance magnets for future accelerators, and to play a significant role in the study and development of a high-intensity neutrino facility.*

Global collaboration

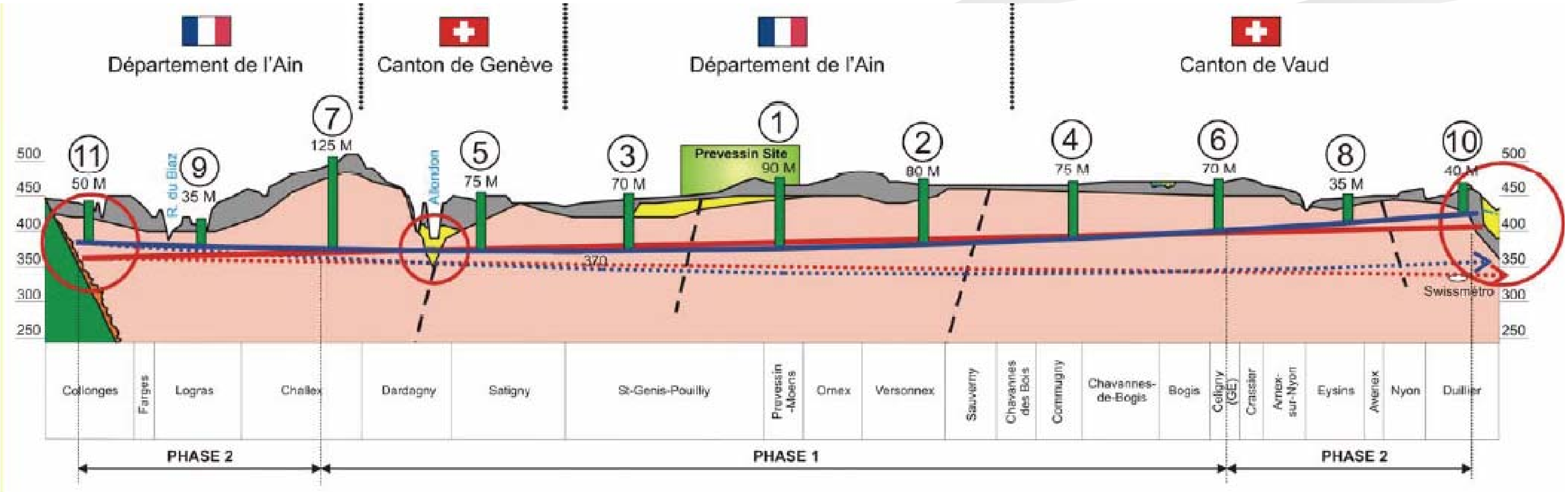
Be it ILC or CLIC the project will under any circumstances be a global collaboration

ILC official cost estimate: 6.7 B$

(w/o detectors or manpower)

Site?

- Global project -> interests in Europe, USA, Asia
- Depends on many factors, not least political
- But, studies are being done also for CERN



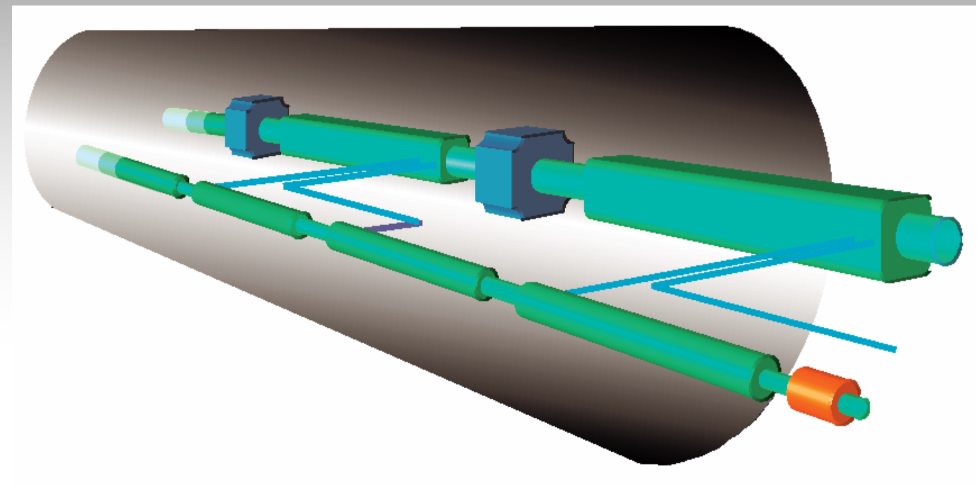
CLIC Main Parameters (3/2007)

- **Particle type: e^- and e^+**

- **E_{cm} = 3 TeV**
- Gradient: 100 MV/m
- Length: 47.6 km

- **Luminosity: 3×10^{34} $cm^{-2}s^{-1}$**
- Particles per bunch: 3×10^9
- Pulse repetition rate: (100 – 250) Hz
- Beam size at IP: σ_x = 60 nm , σ_y = 0.7 nm

- Cost: not yet established
- Site: not yet established



CLIC

Novel two-beam acceleration: the future of linear accelerators?

(NB: all parameters might be subject to change)

Part III

Beam Physics in Linear Colliders

Intermezzo

Norske storheter innen akseleratorfysikk

Rolf Wideröe

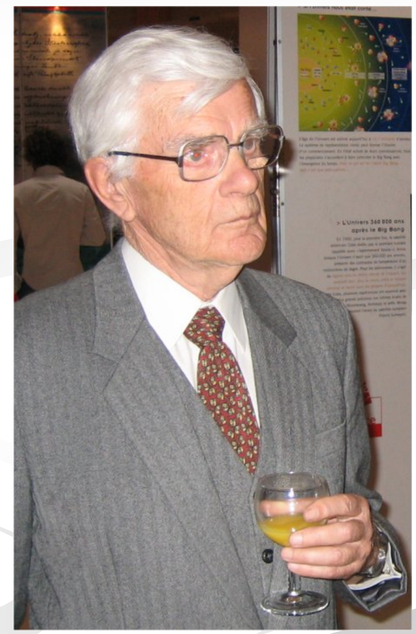
Pioneer både for betatronprinsippet og for lineære akseleratorer!

Odd Dahl

Leder av CERN PS prosjektet (en viktig del av LHC-komplekset den dag i dag!)

Bjørn Wiik

Professor og direktør ved Europas nest største akseleratorsenter! (DESY i Hamburg)

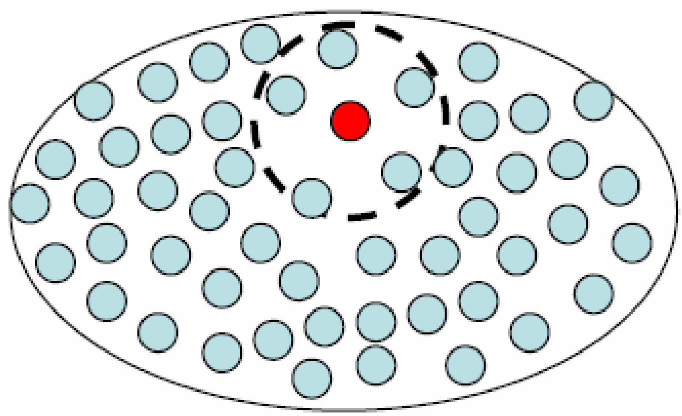


Kjell Johnsen

Involvert i en rekke CERN-prosjekter, og leder av CERN's gruppe for akseleratorforskning!

Beam Physics and *collective effects*

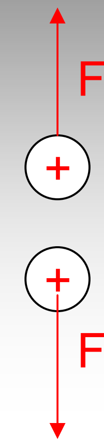
- Accelerators deal with charged, relativistic particles, interacting with the external world - just like detectors
- Difference: large number and density of particles
- Leads us to a branch of Beam Physics called "collective effects"



"the influence of the collective electromagnetic fields from many particles"

$\mathcal{L} \propto N^2$, $\mathcal{L}$ large $\Rightarrow$ N large $\Rightarrow$ Collective effects very important for CLIC/ILC

Collective effect 1: Space Charge



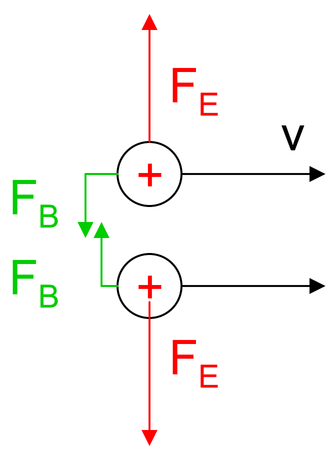
- Most intuitive collective effect: equal charges repel each other
- Imagine then N=10^{10} equal particles per bunch...!

- don't have to imagine; gauss law's gives (uniform cylinder):

$$E_r = \frac{Ne}{2\pi\varepsilon_0 a^2 L} r$$

- However: accelerate these particles and stay in the lab frame. Moving charges ⇒ current ⇒ magnetic field:

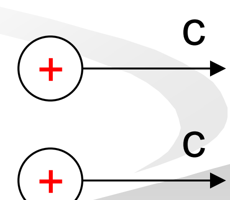
⇒



⇒ Combined Gauss' and Ampere's law gives

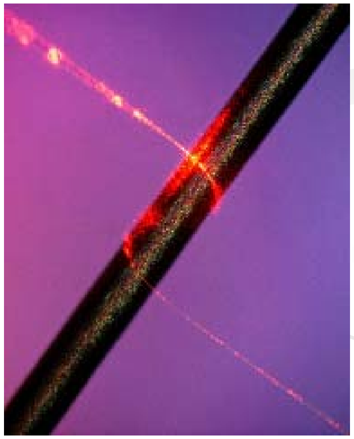
$$F_r = \frac{1}{\gamma^2} \frac{Ne^2}{2\pi\varepsilon_0 a^2 L} r$$

⇒



Space charge cancellation

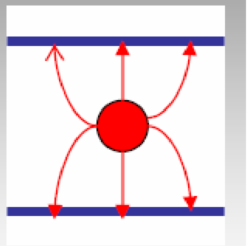
- Luckily, in HEP particle accelerators we always have $v \rightarrow c$
- The $1/\gamma^2$ cancellation is very important effect in all particle accelerators
- **Without it: no nanobeams** (neither LEP or LHC beams)



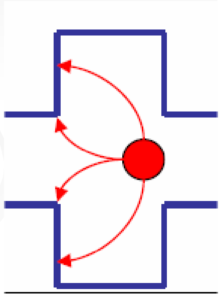
- NB: $1/\gamma^2$ cancellation does only hold under certain conditions (not in bends, beam-beam etc)

Collective effect 2: Wake fields

- Straight motion c, in a smooth perfectly conducting beam pipe, field-lines moves at uniform speed (think: image currents) – steady state, no loss



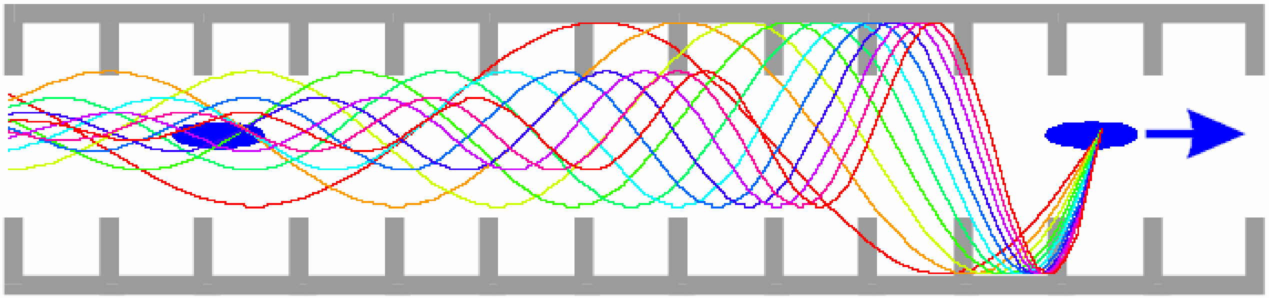
- Irregularity, e.g. a cavity: field lines are trapped left behind



- The field left behind will influence:

  1) rear part of bunch (single bunch effect)

  2) following bunches (multi-bunch effect)

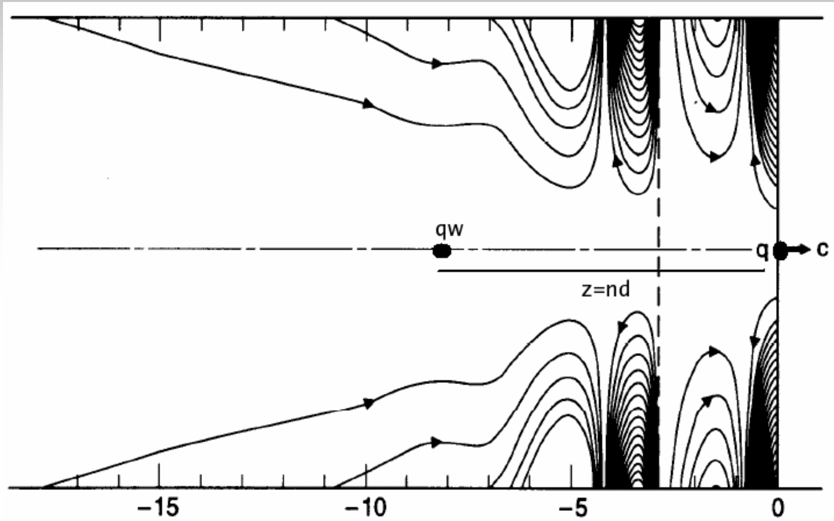


Wake fields

- In general the induced field has both longitudinal (∥) and transverse (⊥) components
- Longitudinal: $F_{\parallel}$ acts on trailing particles (and source particles): **energy kick**
- Transverse: $F_{\perp}$ acts on trailing particle: **transverse kick**

Wake functions

- Even for the simplest cases the trailing field becomes complicated:



Resistive wall wake field (A. Chao/K. Bane): constant cross section

- Fortunately we are usually no interested in the field, but its effect on a test particle. And, “even better”, the effect along a defined structure or path length.

- We define the following **normalized** quantities (1st order terms):

$$\int_0^L F_{\parallel}(z)ds \approx -q_s q_w w_{\parallel}(z)$$

$$\int_0^L F_{\perp}(z)ds \approx -\Delta y q_s q_w w_{\perp}(z)$$

- With v=c: w's **characteristic of structure only**:

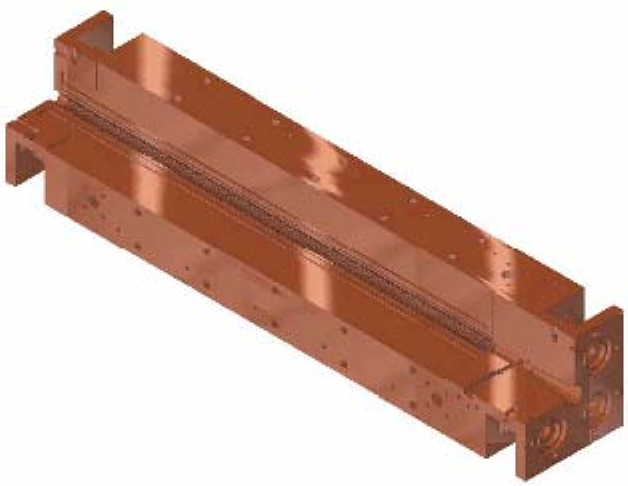
* great: can now use EM-simulations (Maxwell) to calculate wake function

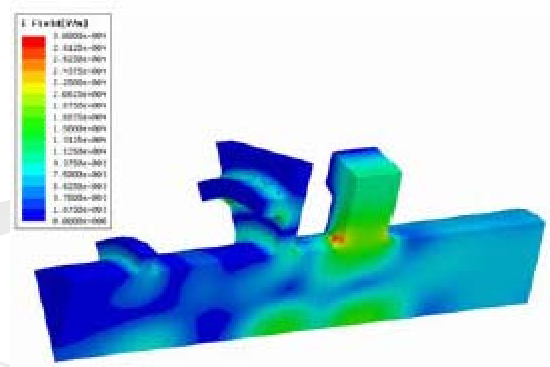
* then: can plug the results only into our simulation packages as Green’s functions for any charge distribution

CLIC: drive beam power generation

Longitudinal wake $F_{\parallel}$ (**desired**):

- extracts energy from the drive beam
- the field travels to the end of the cavity
- coupled out and transported in waveguides to the main linac accelerating cavities





Transverse wake $F_{\perp}$ (**undesired**, but Maxwell insists):

- Inflicts kicks on the drive beam

One PETS produces steady-state power of ~ 100 MW (!) when the drive beam goes through

Collective effect 3: Coherent Synchrotron Radiation

- Radiated power in part one: assumes (the normal case) that the phase of radiation from particles is independent -> Incoherent Synchrotron Radiation:

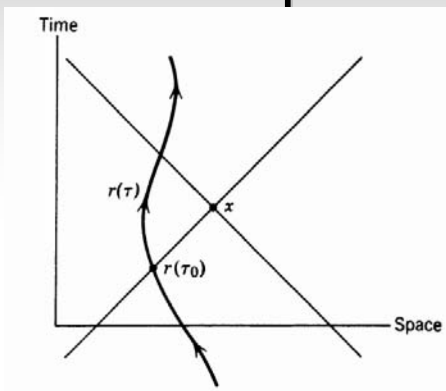
$$P_S = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

- However, for the bunch length $\sigma < \lambda_{rad}$ the particles will radiate coherently at thies frequencies (think: the whole bunch a point charge)
  - Power will be radiated $\propto N^2$ (instead of N)

- For these analyses: need to start with the full Lienard-Wiechert equation

A quick reminder:

- Radiation by moving charges can be described by the Lienard-Wiechert potentials:



Retarded field (Jackson)

$$V(t) = \frac{e}{4\pi\varepsilon_0}[\frac{1}{r(1-\mathbf{n}\cdot\beta}]_{ret}$$

$$\mathbf{A}(t) = \frac{\mu_0 e}{4\pi}[\frac{\beta c}{r(1-\mathbf{n}\cdot\beta}]_{ret}$$

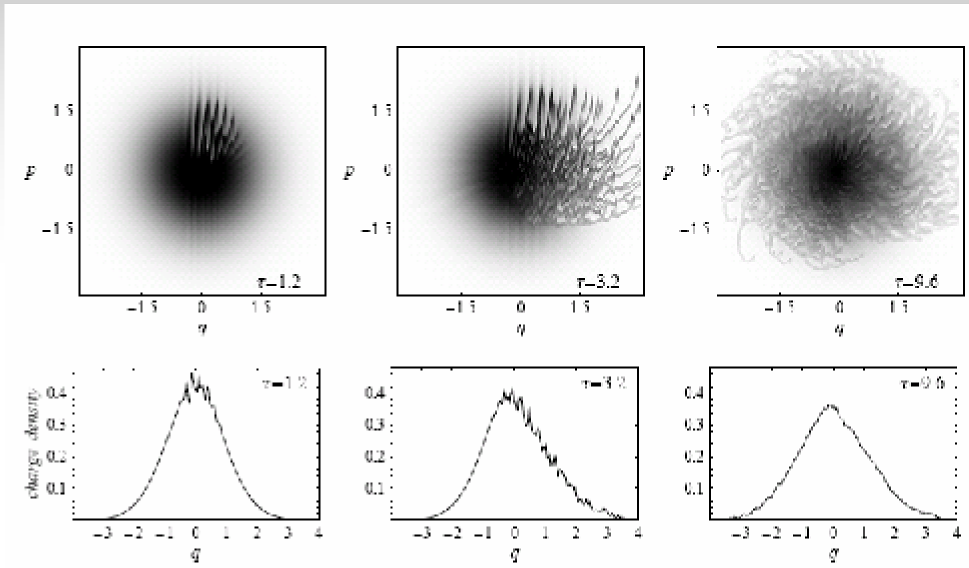
- Looks "harmless", but all RHS values are at the time of the photon-emission, t_{ret}=t-R(t_{ret})/c, while LHS is at time t

- one "feature" affects leading particles as well as trailing

- the mathematics (and physical interpretations) can become quite involved $\Rightarrow$ will show some effects

Effect of CSR

- CSR effects: break up bunch completely



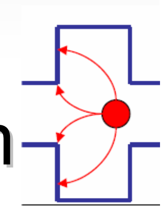
- Coherence only for short bunches ($\sigma < \lambda_{rad}$) and high E ($\propto E^4$)
- CLIC drive beam needs short pulses, and has high energy and current $\Rightarrow$ this CSR radiation regime not yet fully understood and tested out

Putting it all together

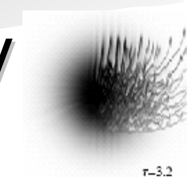
- Space charge cancellation allows σ_y=0.7 nm

- Wake field generates power - but also transverse forces

- Effect of transverse wake forces depends on magnetic rigidity – higher energy ⇒ stiffer beam ⇒ better transverse stability



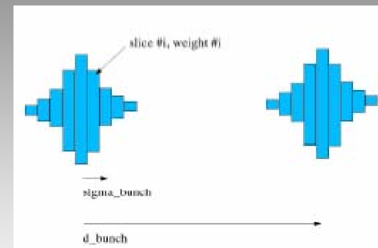
- But, synchrotron radiation increase with energy ⇒ so a compromise must be found

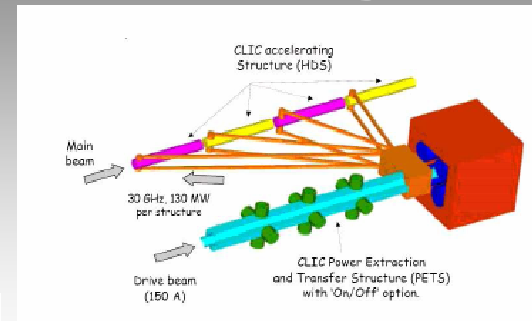


- For instance for: CLIC Drive Beam: I≈100 A, E_0 ≈ 2.5GeV, σ=1 mm

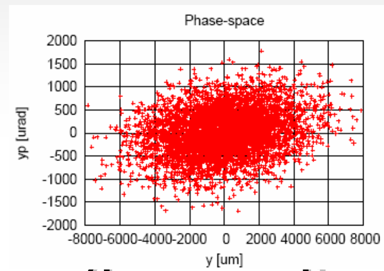
My work involves among other things calculation and simulation of all the above effects – Beam Dynamics

How do we work with Beam Physics

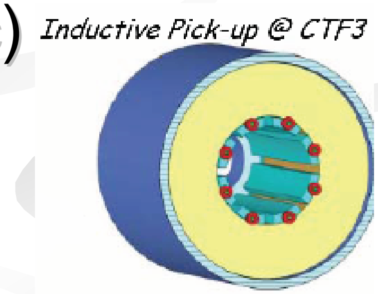




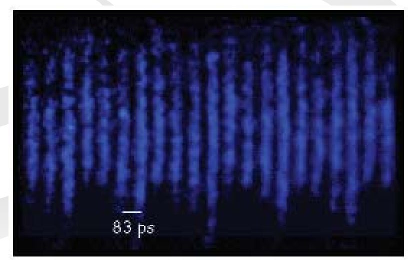
- **Modeling**
- **Simulation**
  - Particle tracking
  - Electromagnetic effects



- **Design of instrumentation** (beam diagnostic)
  - Nanoinstrumentation



- **Measurement**
  - Only a subset of interesting parameters can in fact be measured with any precision

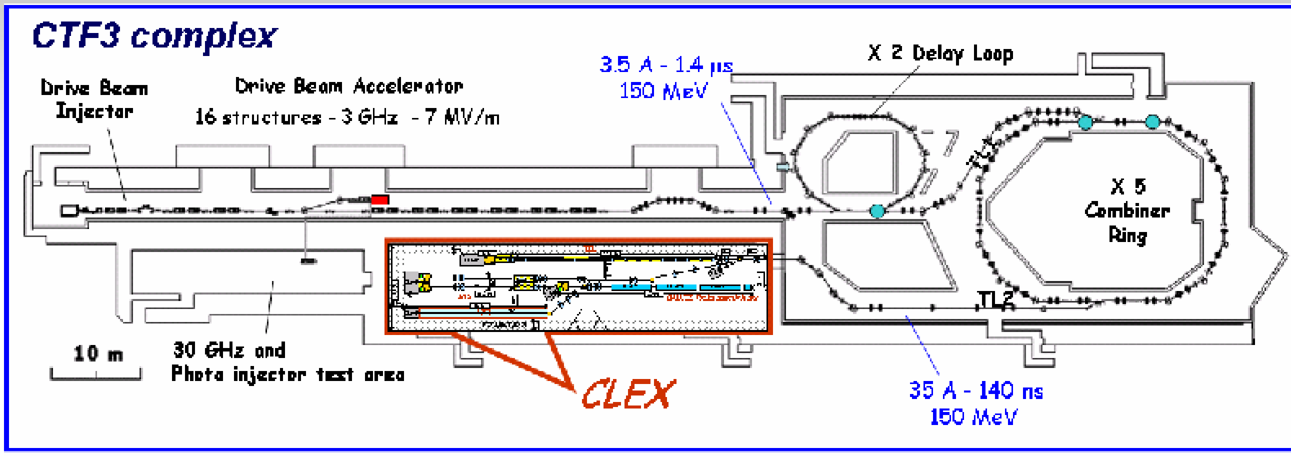


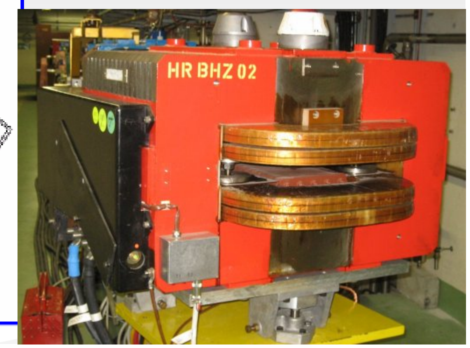
- **Analysis**
  - Beam dynamics

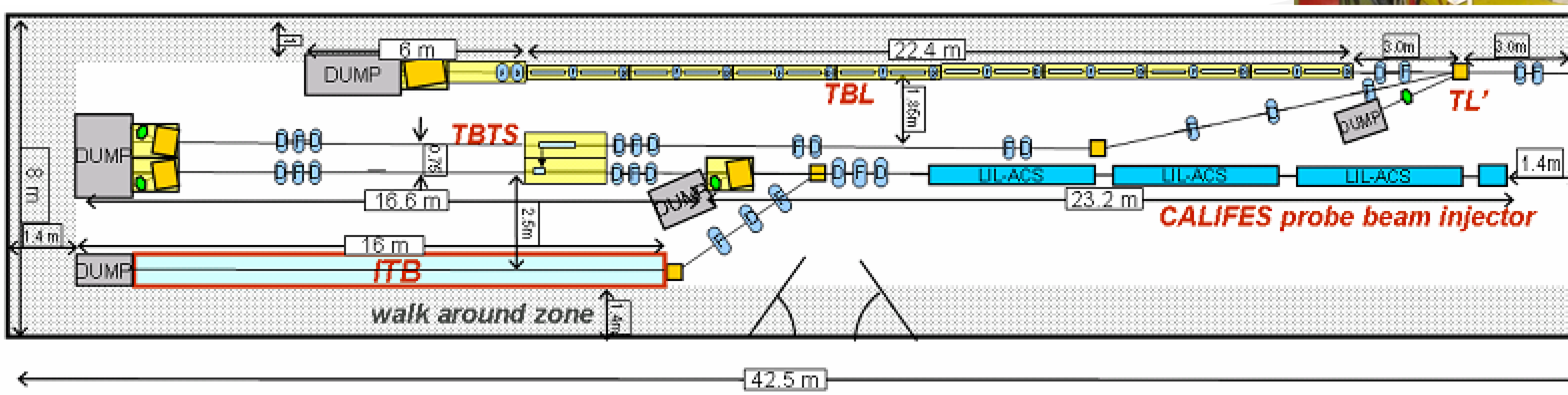
...GOTO 10...

CLIC Test Facility 3

- Experiments performed in CLIC Test Facility 3 (CTF3)

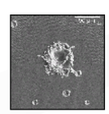


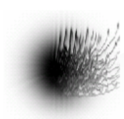




Important CLIC feasibility studies that will be performed in CTF3:

- Drive Beam power production
- Stable accelerating gradient
- Bunch compression and transport of short bunches

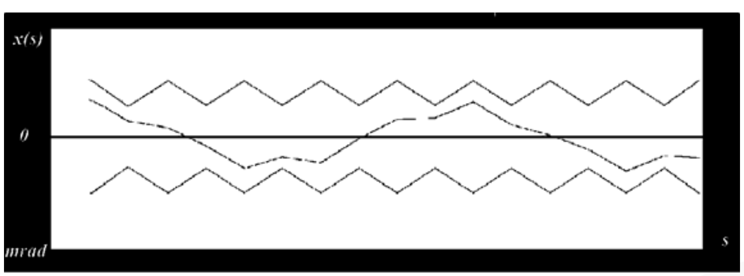


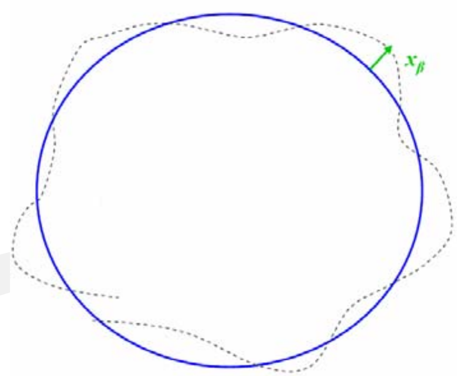


Just a reminder

- How do all we have talked about relate to accelerator lectures in e.g. FYS 4550 ??

- Typical for acc. physics: everything is dynamics!
  - everything oscillates, in all degrees of freedom
    - 6D phase-space dynamics
  - All dynamic motion in a strong focusing environment (betatron motion)





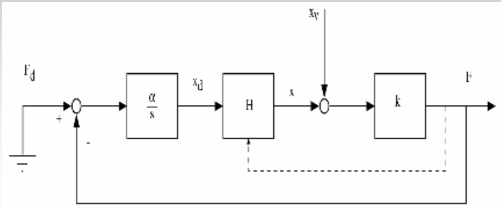
- Comes "on top" on the collective effects

Other research topics

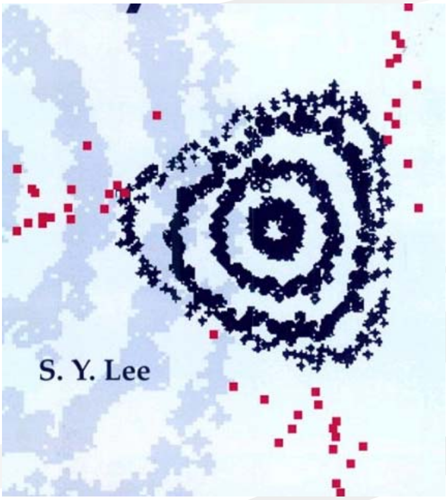
- Plenty of other research topics to reach a the technology level and physics understanding needed for Future Linear Colliders
  - Nanobeams
    - Nanoinstrumentation
    - Movers (BBA, Kalman)
    - Stabilizing quadrupoles to the 0.5 nm
  - Intra-beam scattering and electron clouds
- ...not discussed further

Accelerator physics and other fields

- Model-independent analysis of accelerator physics ↔ **cybernetics**



- (Circular) accelerators: phase-space trajectories with non-linear elements – **one of the best test-beds for Chaos-theory** and other non-linear dynamics phenomena



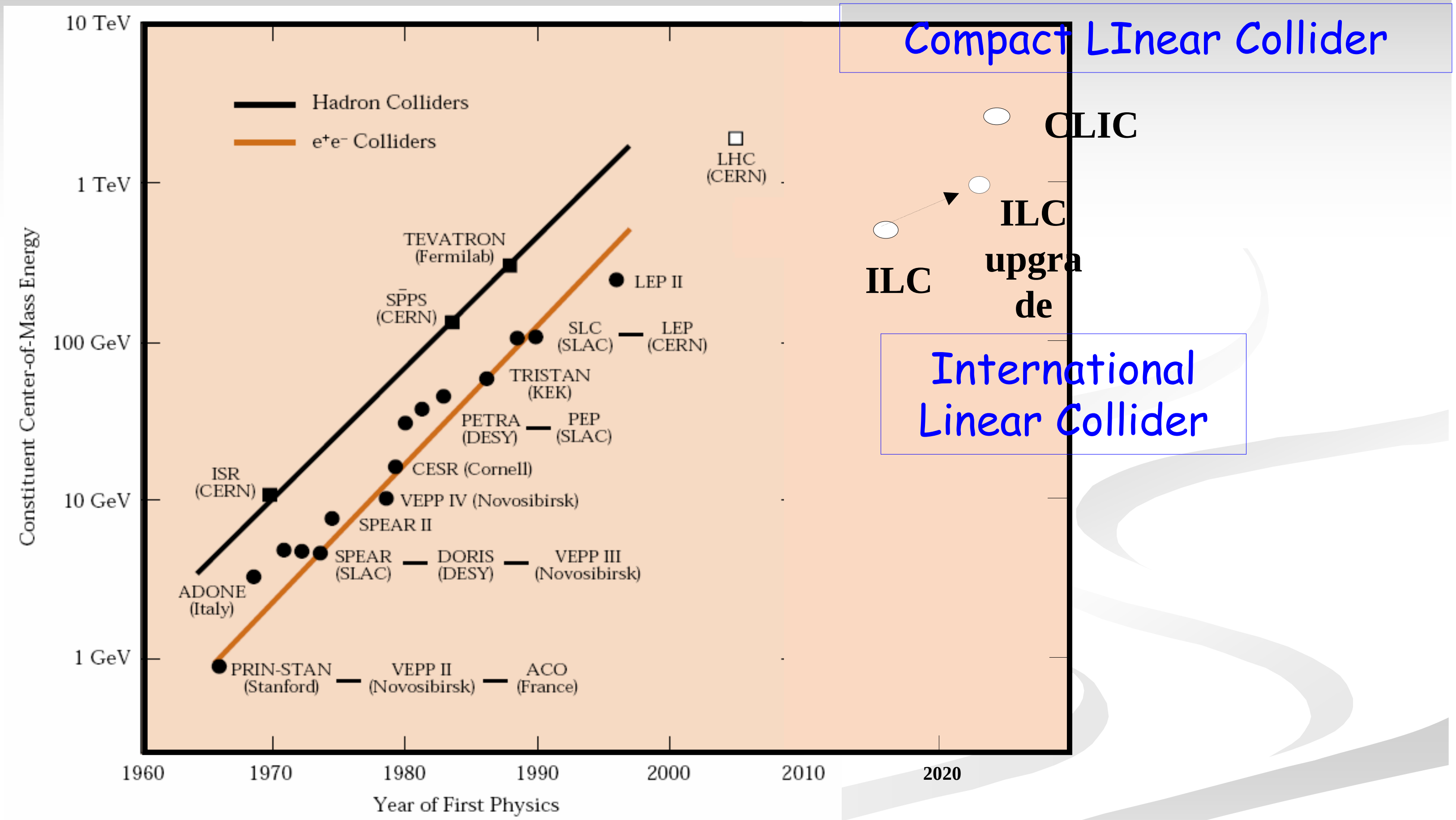
Measured 3rd order resonance in phase-space

Conclusions

Summary

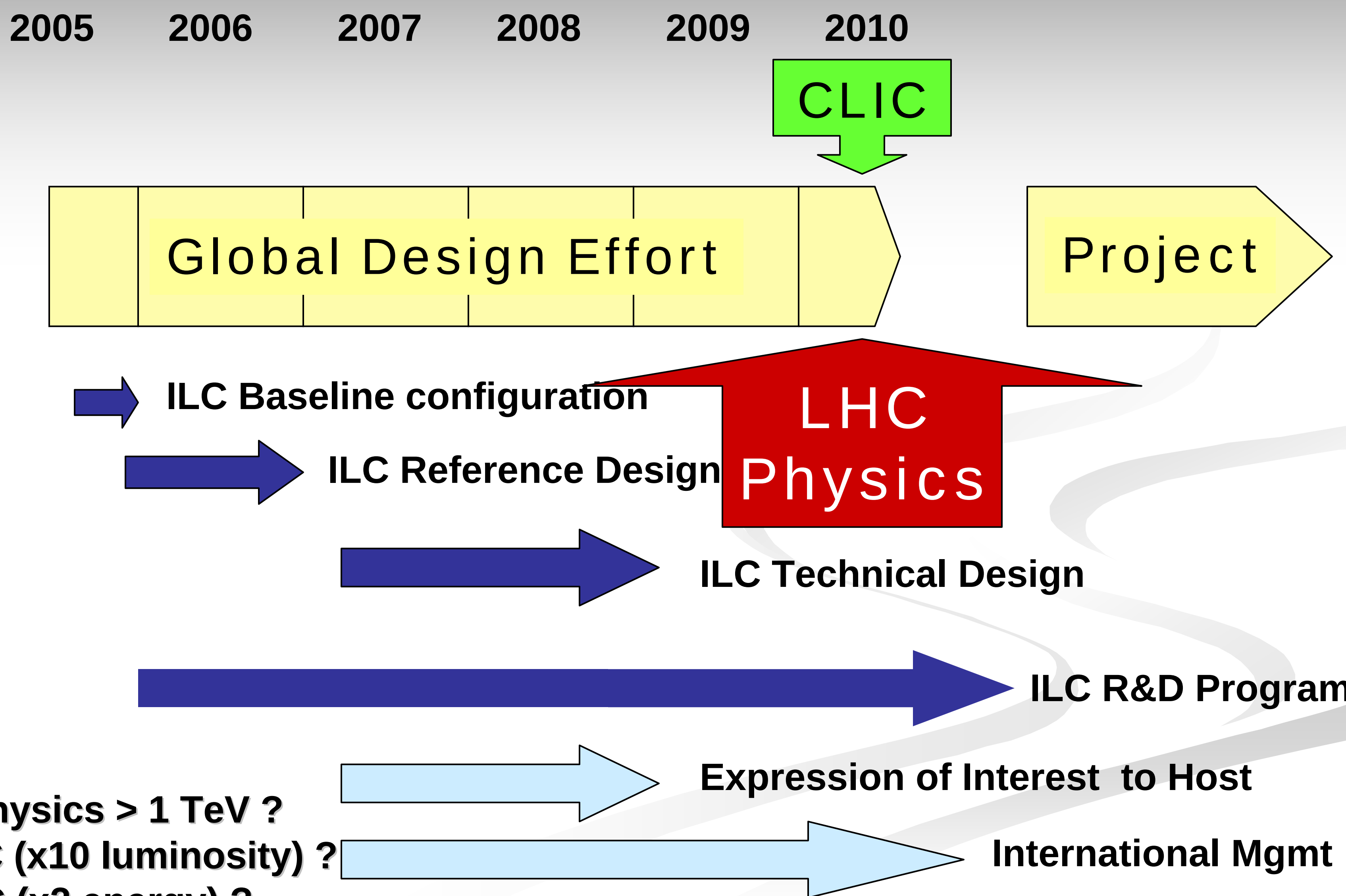
- The need for the LC: **Particle Physics**
- Hard limitations for the LC: **Technology and material science**
- The design of the LC: **Classical Physics +** some quantum phenomena

Historical perspective revisisted



Slide: J. P. Delahaye

The ILC GDE Plan and Schedule



LHC physics > 1 TeV ?
* SLHC (x10 luminosity) ?
* DLHC (x2 energy) ?

Slide: B. Barish

Acknowledgements

- A big thanks to the CLIC team and Prof. S. Stapnes for all help in preparing this presentation

- Figures are borrowed from a number of CLIC and ILC sources, including
  - CLIC Notes
  - CLIC Presentations and academic trainings
  - linearcollider.org
  - CERN strategy group reports
  - CAS lectures