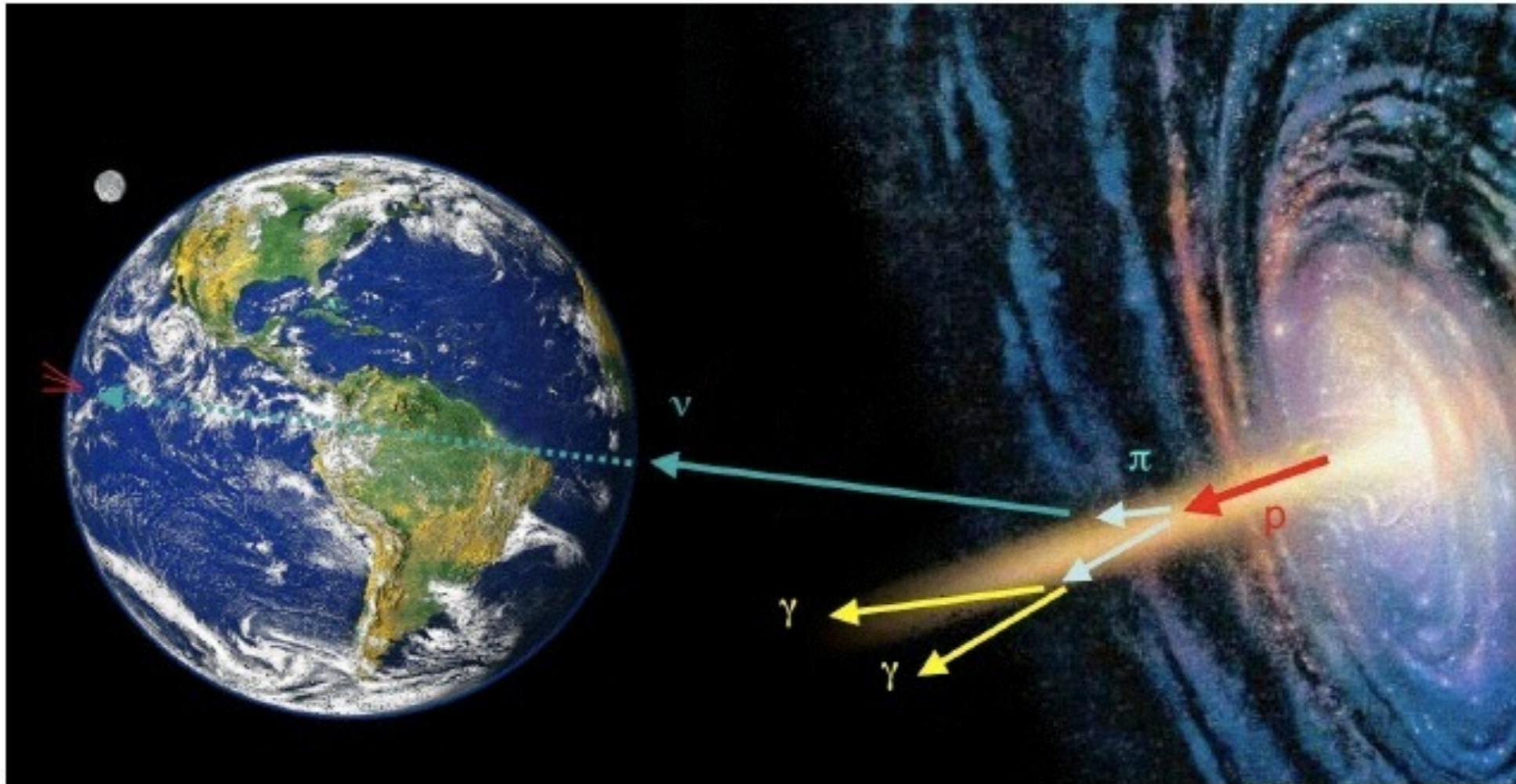


Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



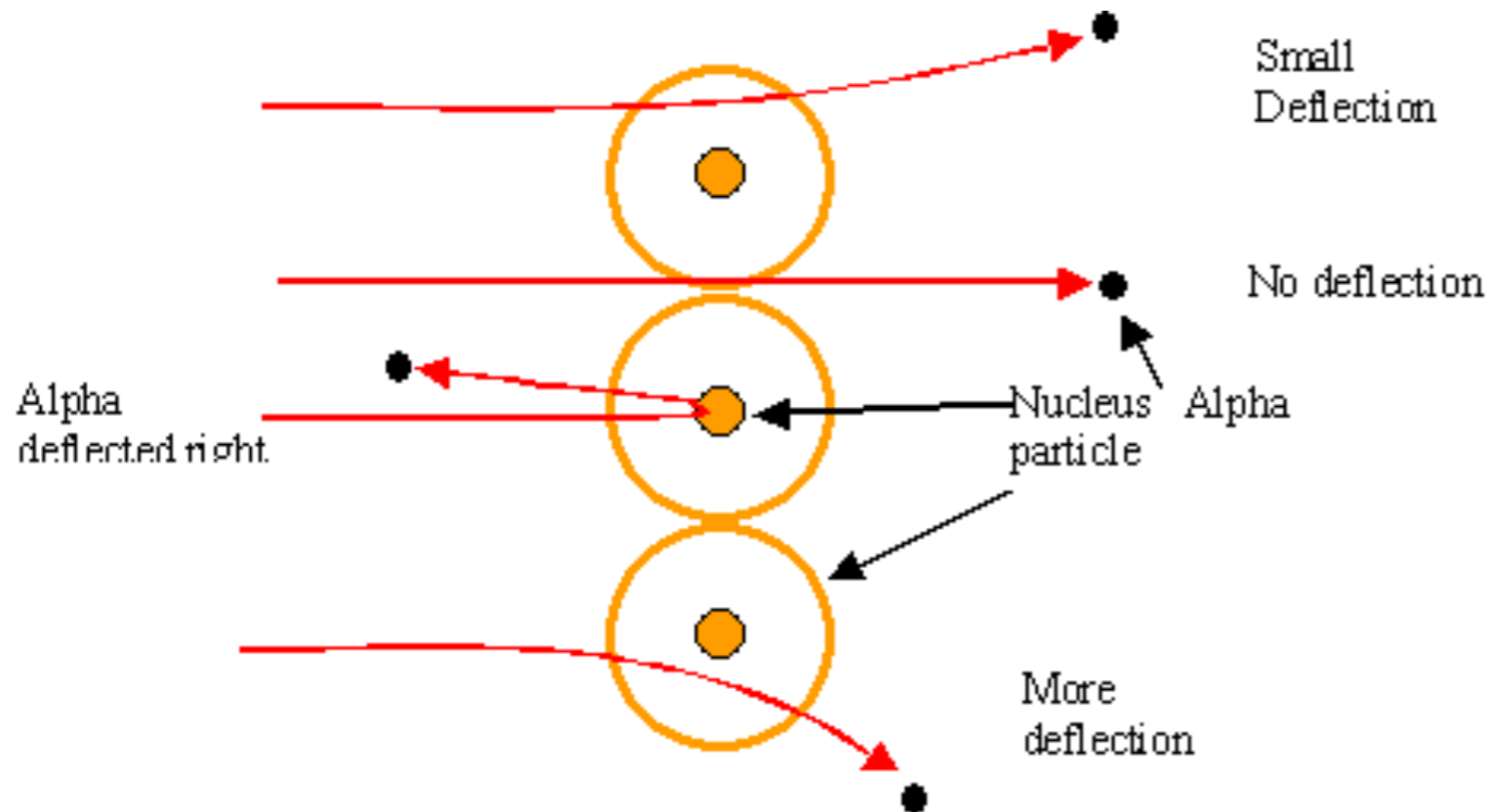
02. Ground-based Accelerators

14.04.2014

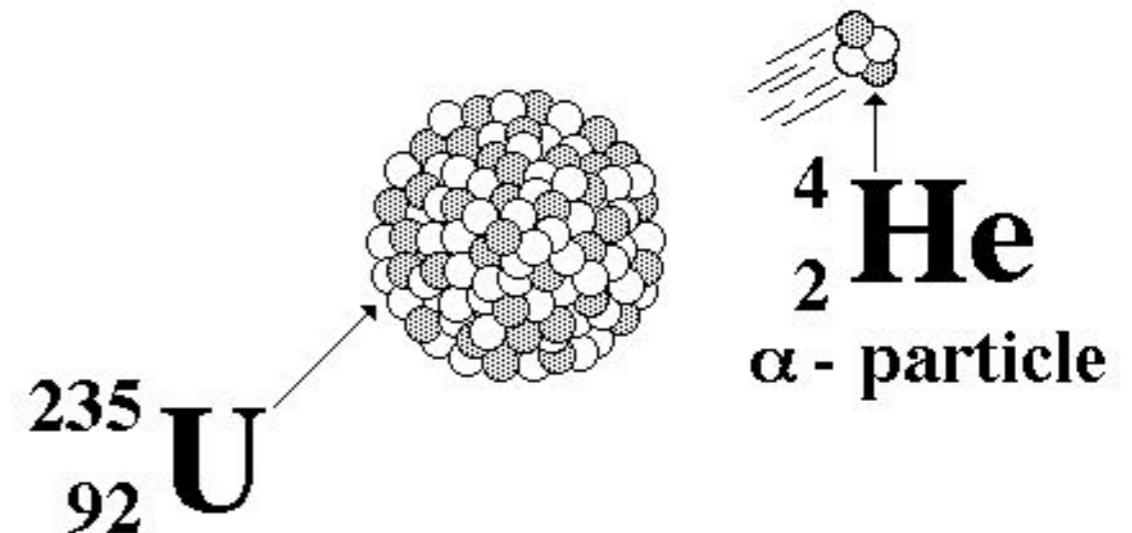


100 Years ago: How it started

- 1911 Rutherford discovered the atomic nucleus by experiments with α particles on a thin Gold foil



- Uranium as natural “accelerator”
MeV - scale particles from
radioactive decay



Motivation for Accelerators

- Initially, accelerators were only used for basic research:
To look into the structure of matter, you need short wavelengths, e.g. high energies

$$\lambda = \frac{h}{p} \approx \frac{(1.2 \text{ fm})}{p \text{ (in GeV/c)}}$$

1 GeV probes the size of the proton!

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$$E = mc^2$$

- If you are looking for something that is rare (small cross-section!), you need

Intensity

Applications

- Basic research in high energy physics
- Sources of synchrotron radiation for material science, chemistry, biology
- Radiation Therapy
- Production of radio isotopes for medical diagnostics
- Ion implantation in semiconductor industry
- ...

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Bill Barletta in Physics Today, 02/2010: Estimated 26 000 accelerators world-wide **1%** are research machines with energies above 1 GeV; about **44%** are for radiotherapy, **41%** for ion implanters and surface modification of materials, **9%** for industrial processing and research, **4%** for biomedical and other lower-energy research, and **1%** for making medical radioisotopes

Historical Overview

- 1928: R. Wideroe reports the operation of the first linear accelerator (K_a and Na-ions)
- 1931: Van de Graaff constructs the first high voltage generator
- 1932: Lawrence and Livingston present first proton beams from a 1.2 MeV Cyclotron
- 1939: Hansen, Varian and Varian invent the Klystron
- 1941: Kerst and Serber introduce the Betatron
Touschek and Wideroe invent the principle of ring accelerators
- 1947: Alvarez develops the first proton linear accelerator
- 1950 Christofilos formulates the concept of strong focusing



E.O. Lawrence

Accelerator Basics



The Basics of Particle Acceleration

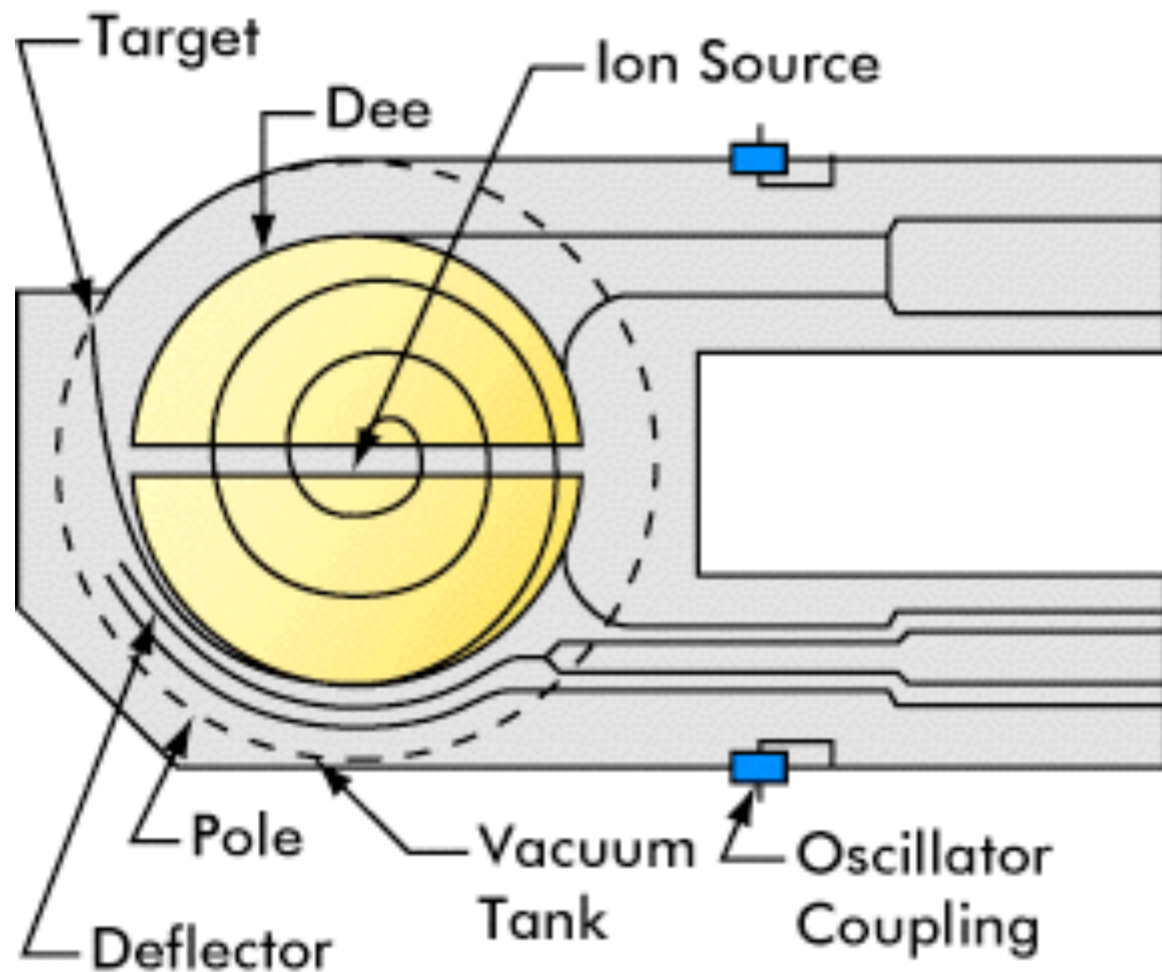
- The underlying equations: Maxwell-Equations

Differentialform	Integralform
$\operatorname{div} \vec{D} = \rho_{\text{frei}}$	$\oint \vec{D} \cdot d\vec{A} = Q$
$\operatorname{div} \vec{B} = 0$	$\oint \vec{B} \cdot d\vec{A} = 0$
$\operatorname{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t}$	$\oint \vec{E} \cdot d\vec{s} = -\frac{d}{dt} \int \vec{B} \cdot d\vec{A}$
$\operatorname{rot} \vec{H} = \vec{j} + \frac{\partial \vec{D}}{\partial t}$	$\oint \vec{H} \cdot d\vec{s} = I + \frac{d}{dt} \int \vec{D} \cdot d\vec{A}$

The key: Lorentz-Force $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$

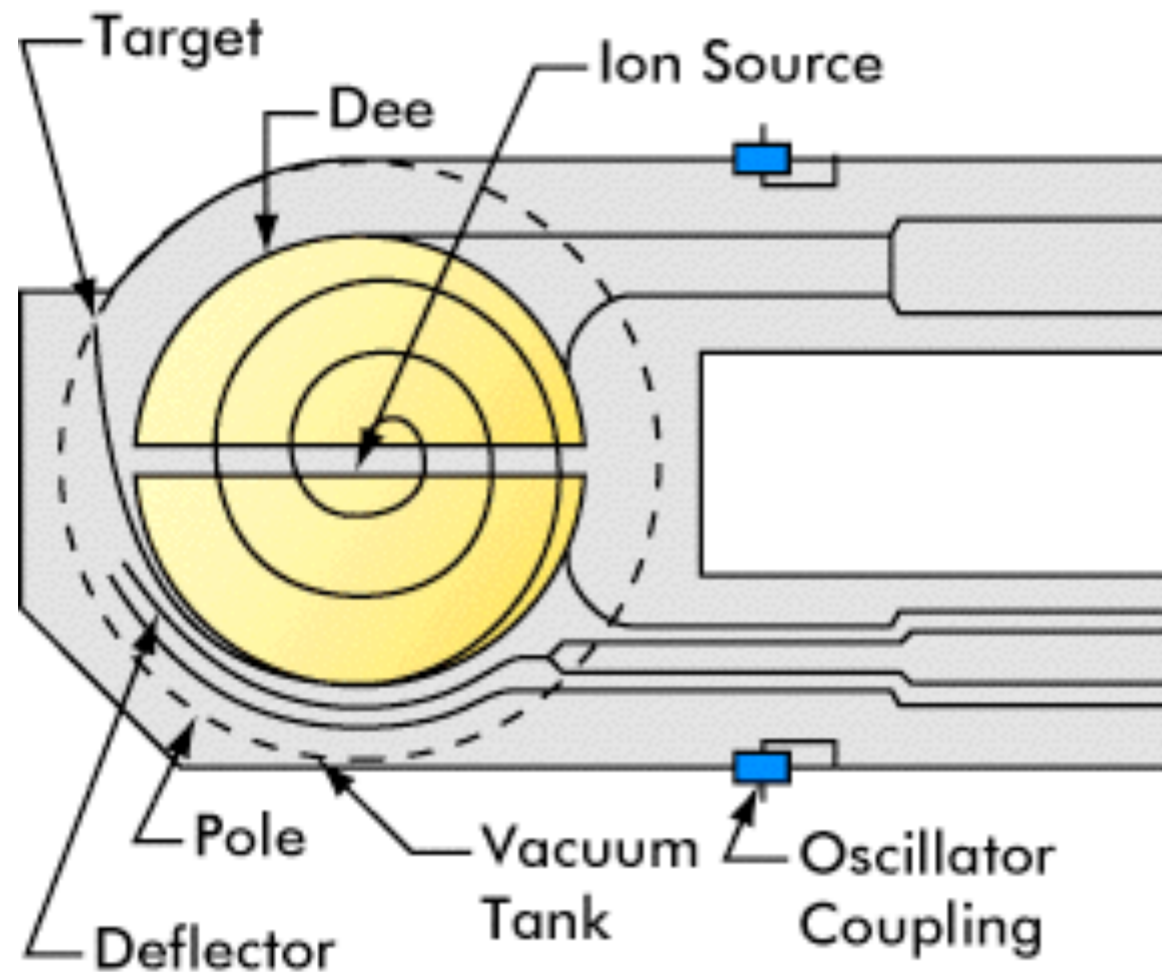
n.b.: The Lorentz-force is non-conservative for time-dependent fields!

Basic Accelerator Types: Cyclotron, Linac

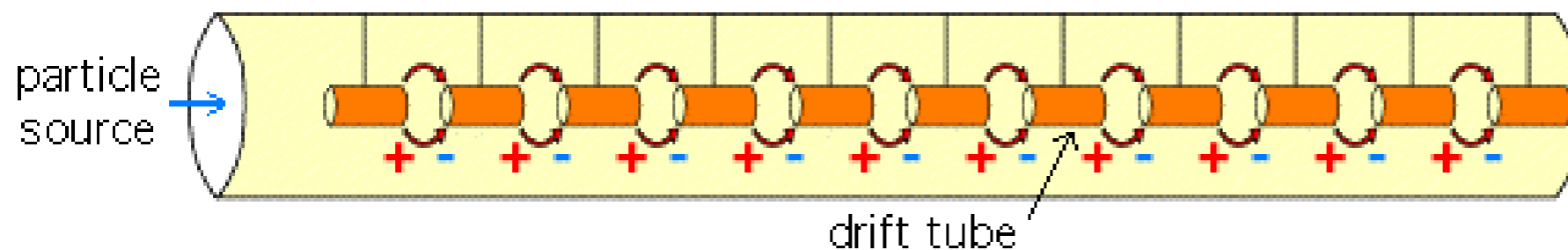


- Cyclotron:
 - Magnetic field to bend particles
 - Alternating electric field for acceleration

Basic Accelerator Types: Cyclotron, Linac



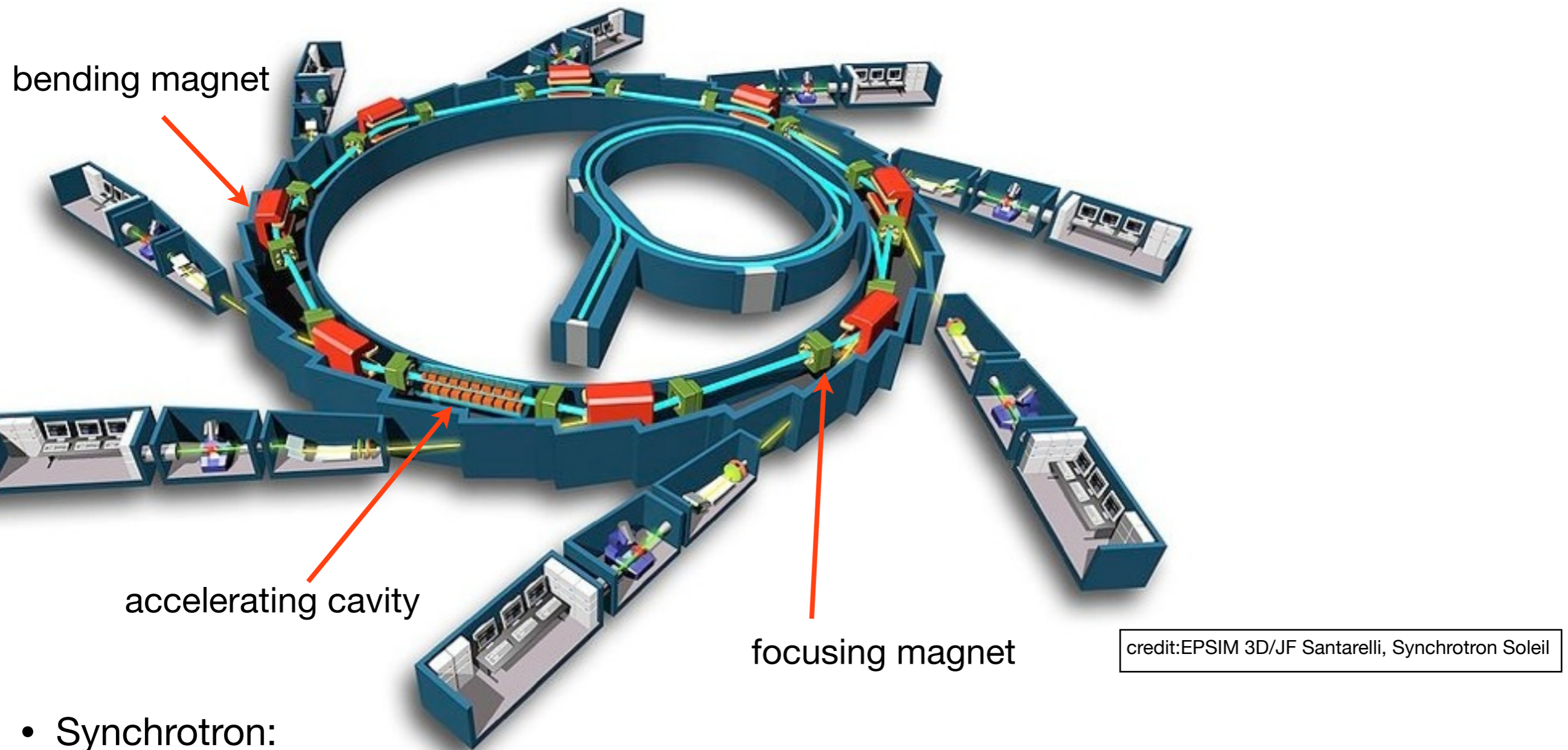
- Cyclotron:
 - Magnetic field to bend particles
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- Linear accelerator:
 - Alternating electric field for acceleration



Basic Accelerator Types: Synchrotron



- Synchrotron:

- Magnetic bending field gets ramped up with particle energy: Particles can stay on fixed path
- Magnetic field only needed locally
- Same accelerating cavities get passed many times

Keeping on Track: Bending Power

- Strong dipole magnets keep particles on their track in a synchrotron
Magnetic field and radius define energy!

$$\vec{F} = \frac{d\vec{p}}{dt} = q(\vec{v} \times \vec{B})$$

Lorentz force acts on moving charge

It forces the particle on a circular track:

$$\rho = \frac{p}{qB} \quad \Rightarrow \quad \rho[\text{m}] \approx \frac{p[\text{MeV}/c] / 300}{B[\text{T}]}$$

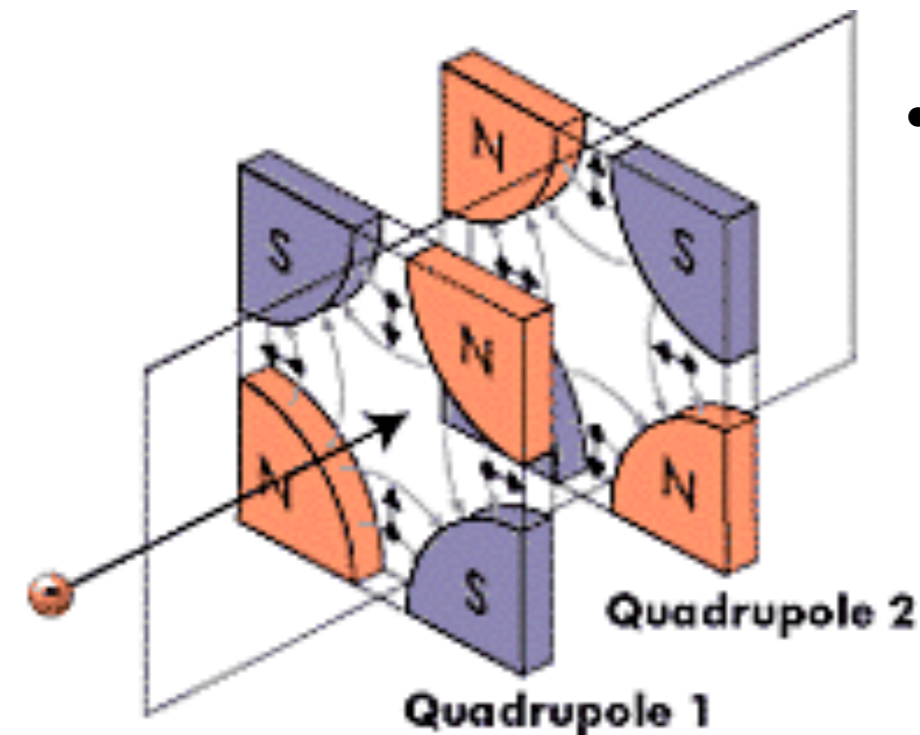
Often, the term “stiffness” is used:

$$(B\rho) = \frac{p}{q} \Rightarrow (B\rho)[\text{Tm}] \approx \frac{p[\text{MeV}/c]}{300}$$

LHC : $(B\rho) \sim 23000 \text{ Tm}$

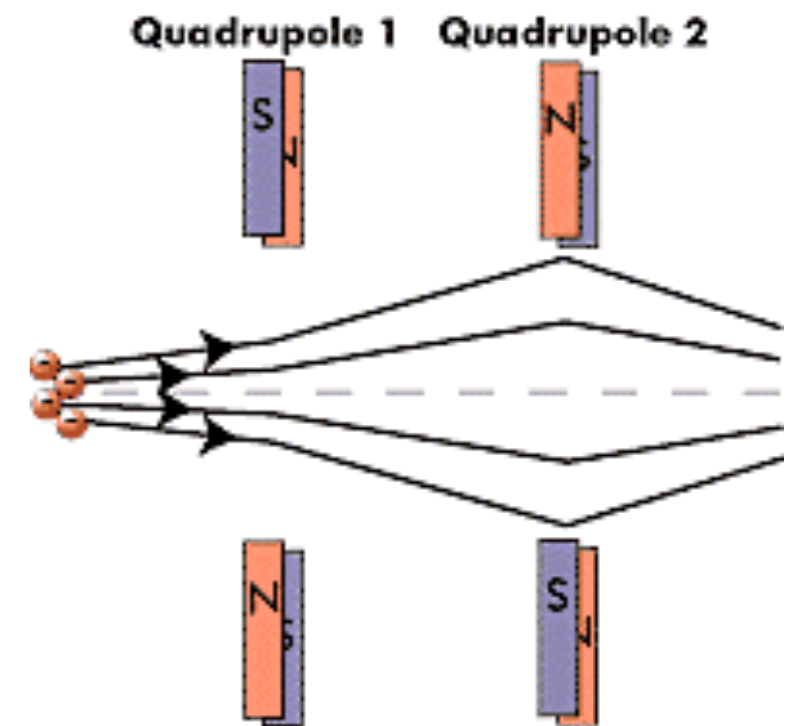
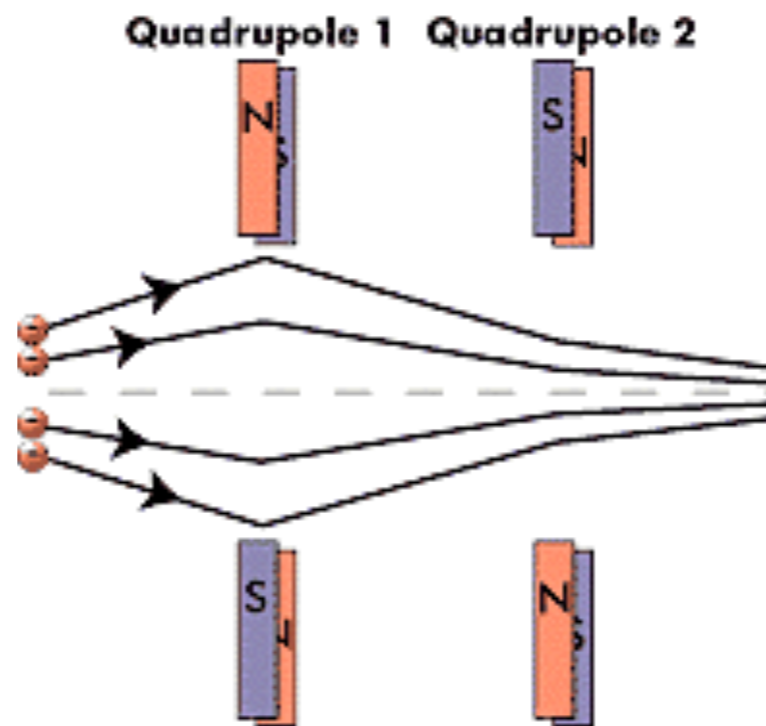
Strong Focusing

- Strong Focusing, or Alternating Gradient Synchrotron: Breakthrough that allowed to reach high energies of 10 GeV and more



- Two crossed quadrupole fields have a net focusing effect, if they are placed at the right distance d (smaller than the focal length) - Just like a lens system in optics!

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 f_2}$$



Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles lose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0} \frac{e^2 a^2}{c^3} \gamma^4 \quad a = \frac{v^2}{\rho} \quad \rho: \text{bending radius}$$

scales with γ^4 , at constant energy with $1/m^4 \Rightarrow$ Electrons lose 10^{13} times more energy than protons!

- Energy loss of electrons per turn in a storage ring

$$\Delta E = 8.85 \times 10^{-5} \frac{E^4 [\text{GeV}^4]}{\rho [\text{km}]} \text{MeV}$$

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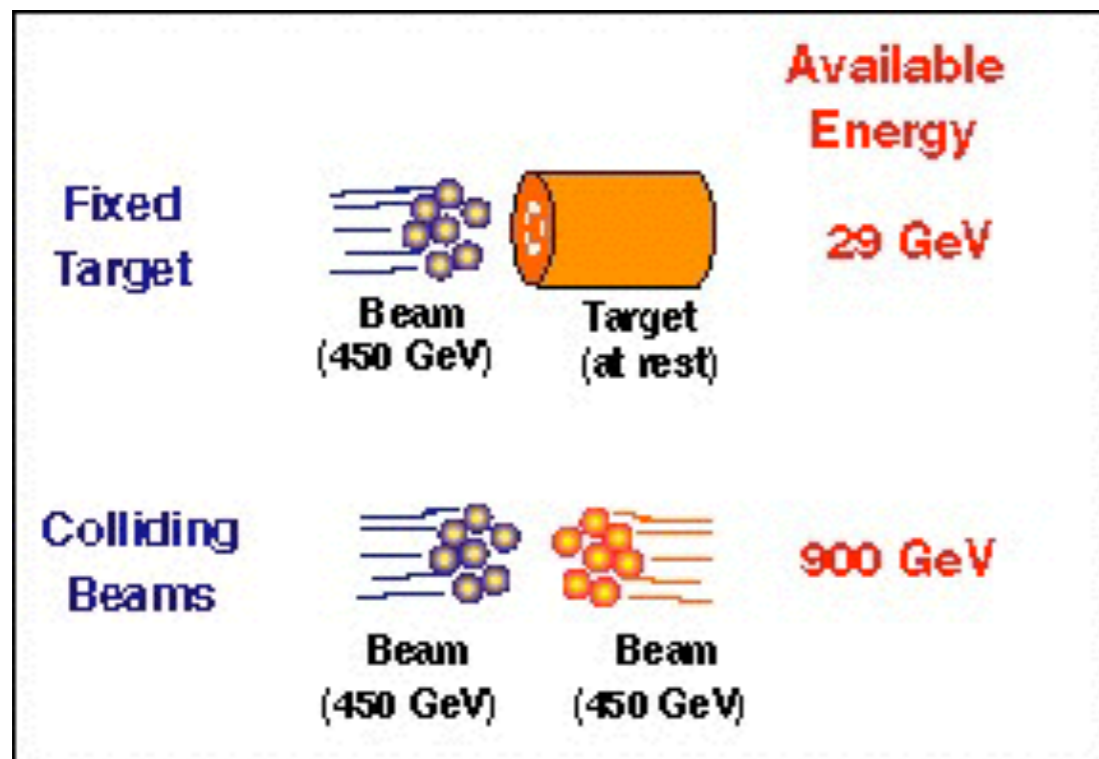
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\Rightarrow Highest energies are not possible with electrons using synchrotrons!

High Energies: Colliders

- The first experiments with accelerators were fixed-target experiments:
(Relatively) easy to manage: Shoot a beam at a target
- Much higher energy can be obtained in collider mode:
Two beams collider, the center of mass can be at rest in the laboratory



For colliding protons

$$E_{\text{cm}} = \sqrt{2(\gamma + 1)}m_p c^2$$

$$E_{\text{cm}} = 2E = 2\gamma m_p c^2$$

Key Collider Parameters

- Event Rate

$$R = L \cdot \sigma$$

- Luminosity

$$L = f \frac{n_1 n_2}{4\pi\sigma_x \sigma_y}$$

f: Collision frequency

n_i : Number of particles in bunch i

σ_x : horizontal beam size

σ_y : vertical beam size

... assuming a gaussian beam profile and perfect overlap

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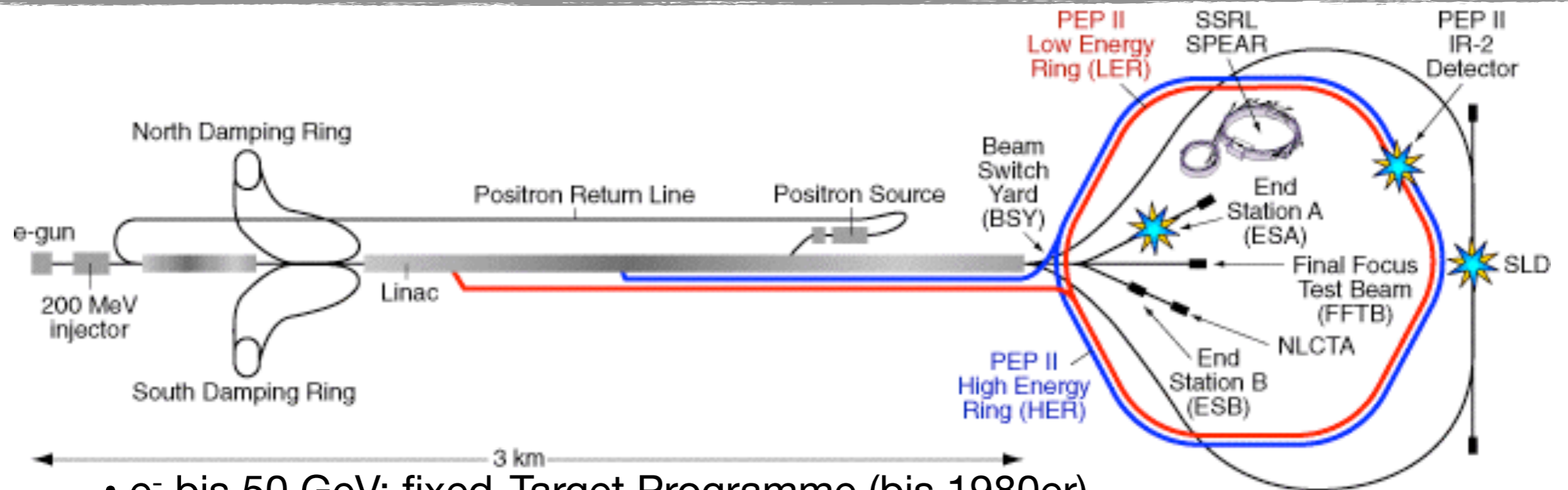
σ_y : vertical beam size

... assuming a gaussian beam profile and perfect overlap

- Luminosity is often expressed in terms of the “ β function” at the collision point and in terms of “emittance”
 - β^* is related to the beam optics
 - ε is related to the beam quality, and gives the phase space of the beam particles (units length * angle)

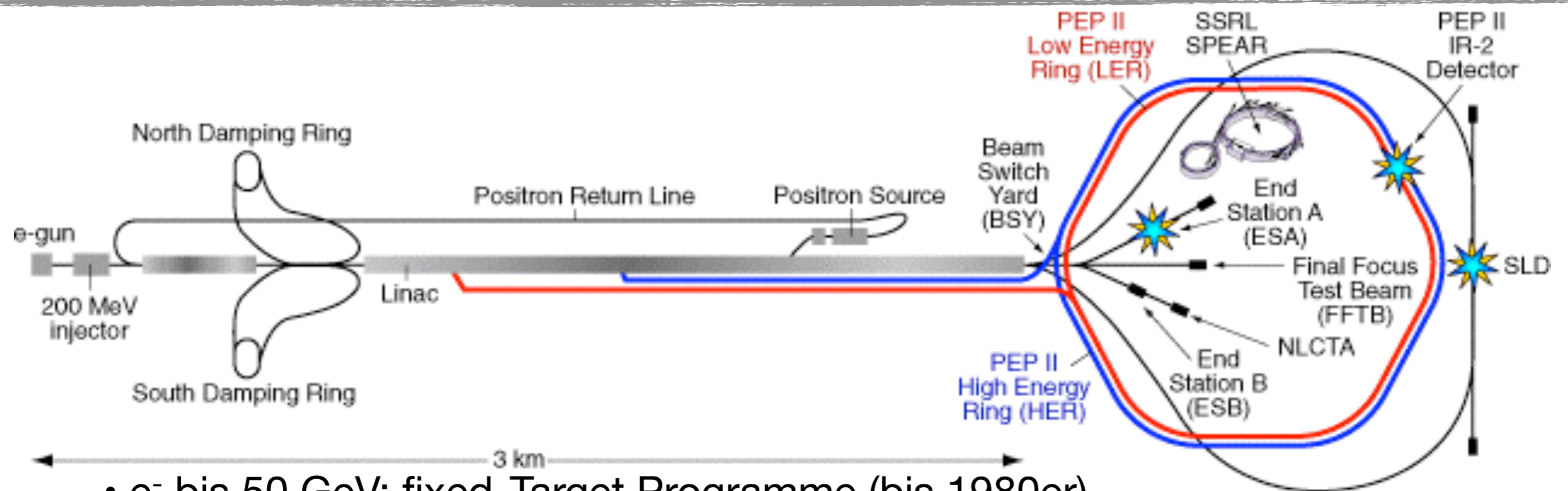
$$L = f \frac{n_1 n_2}{4\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$$

SLAC Linear Collider SLC



- e^- bis 50 GeV; fixed-Target Programme (bis 1980er)
- e^- und e^+ für PEP-I Speicherring ($E_{cm} = 29$ GeV; frühe 1980er)
- e^- und e^+ für SLC collider ($E_{cm} = M_Z \sim 91$ GeV; 1989 - 1999)
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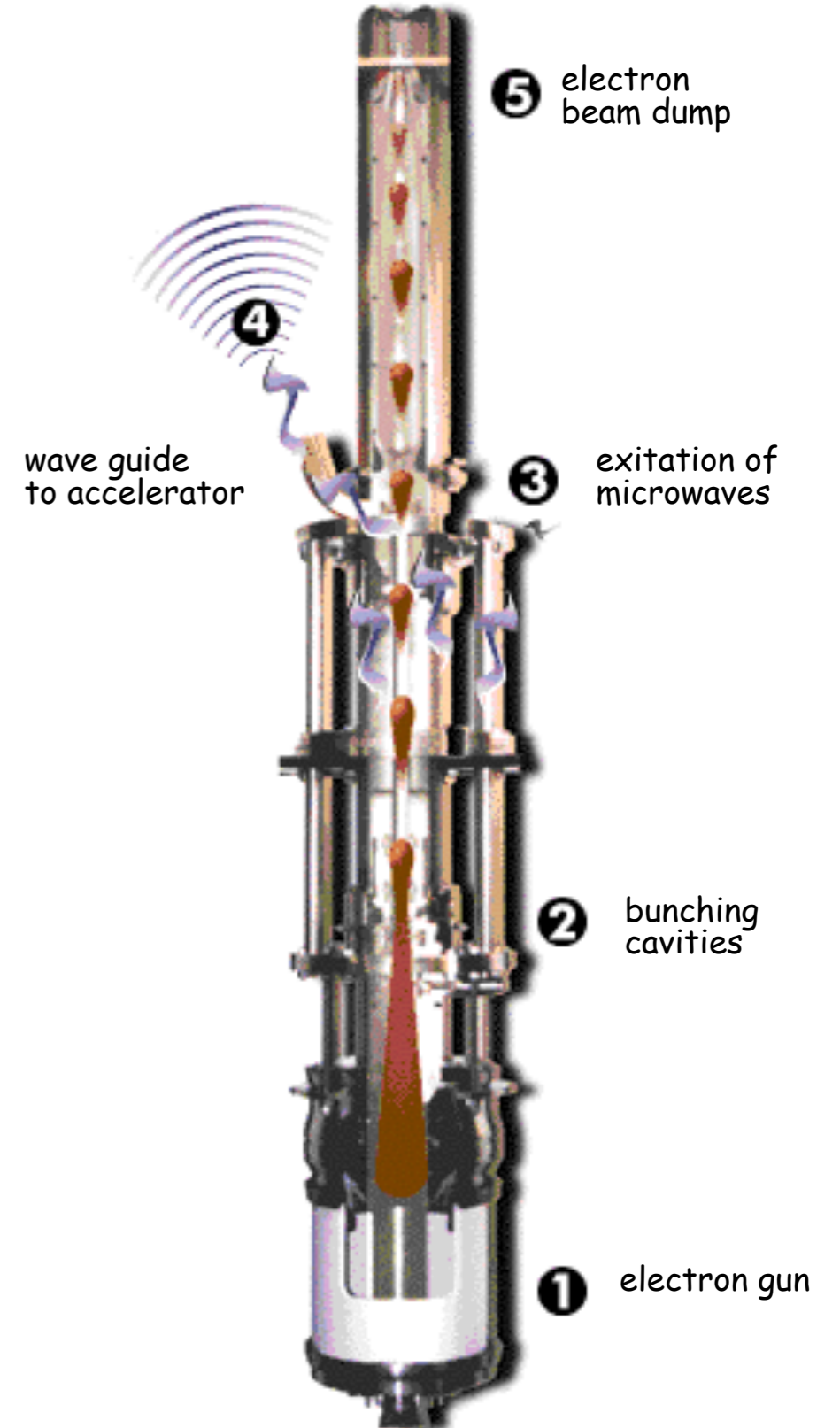
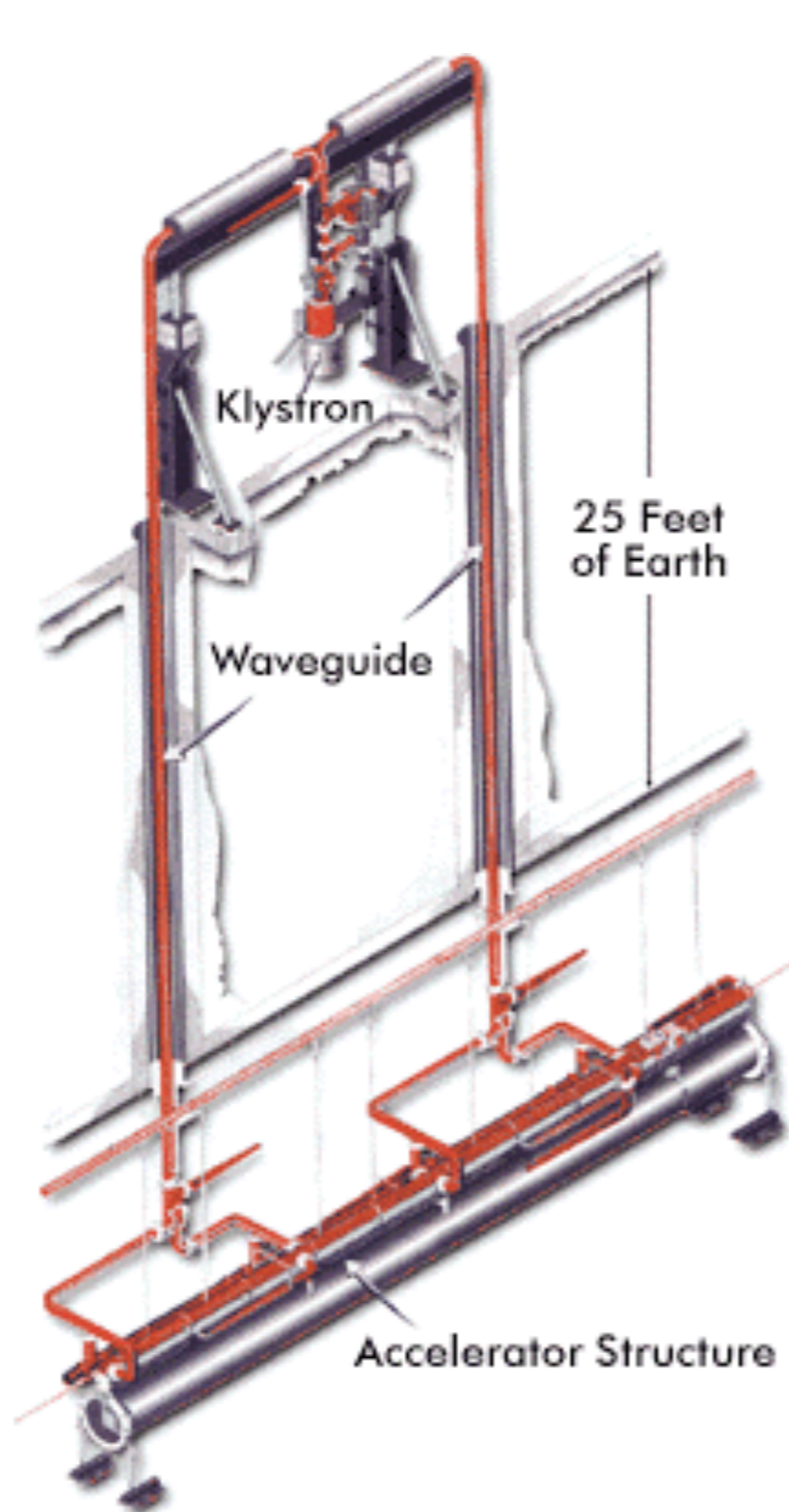
SLAC Linear Collider SLC



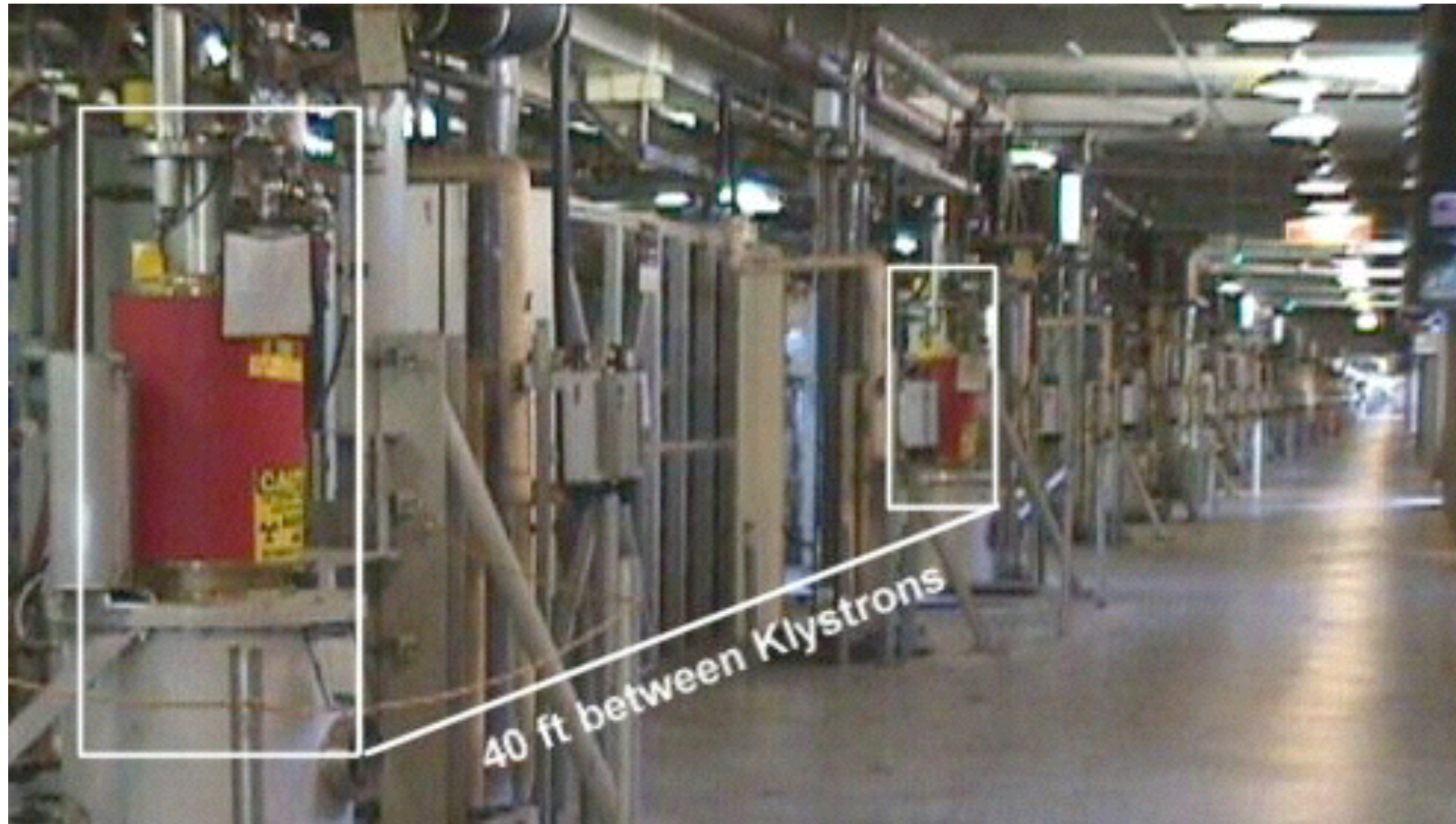
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Powering Accelerators: Klystrons



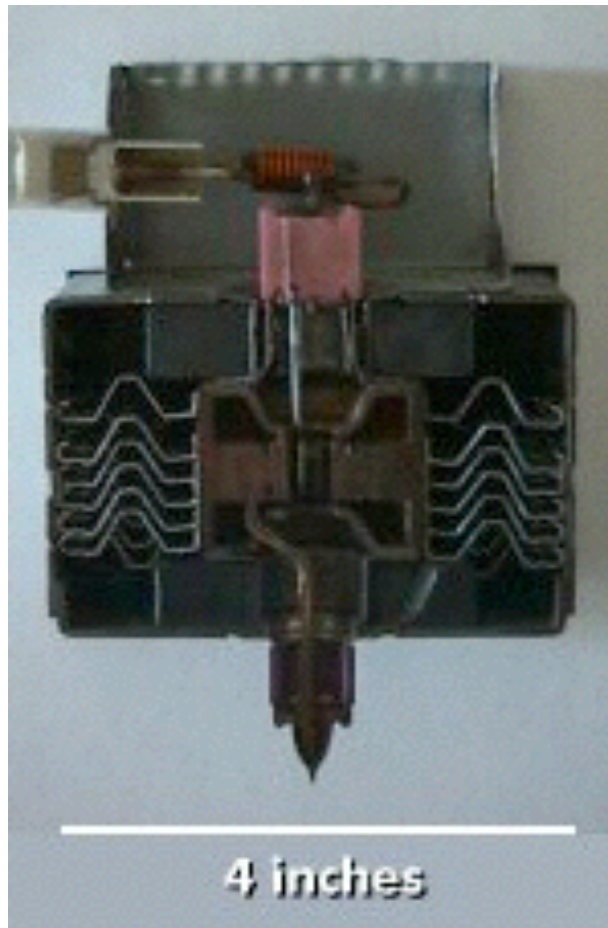
Klystrons



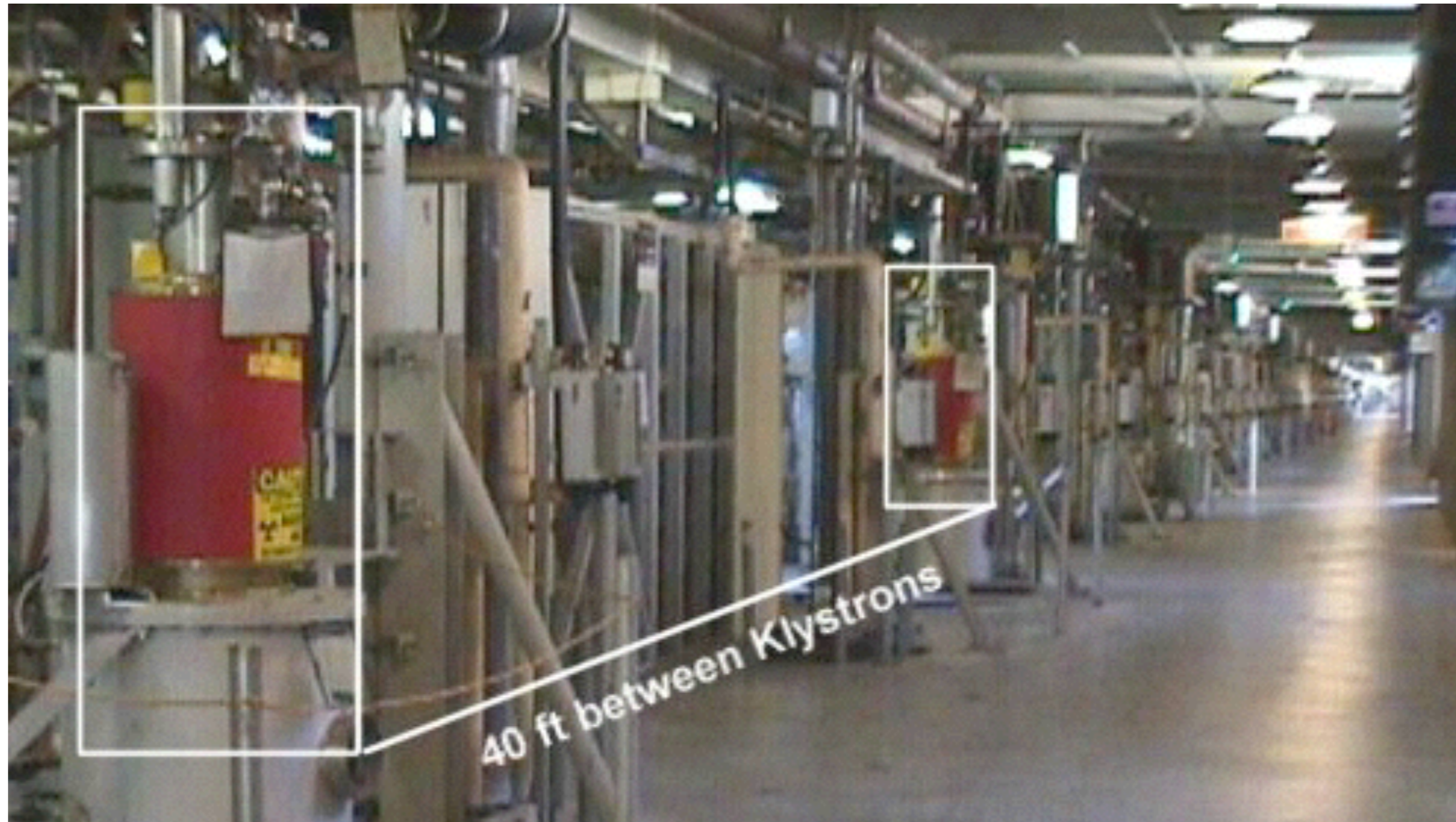
Microwave generator
in a Microwave Oven

SLAC Klystron Gallery

Klystrons



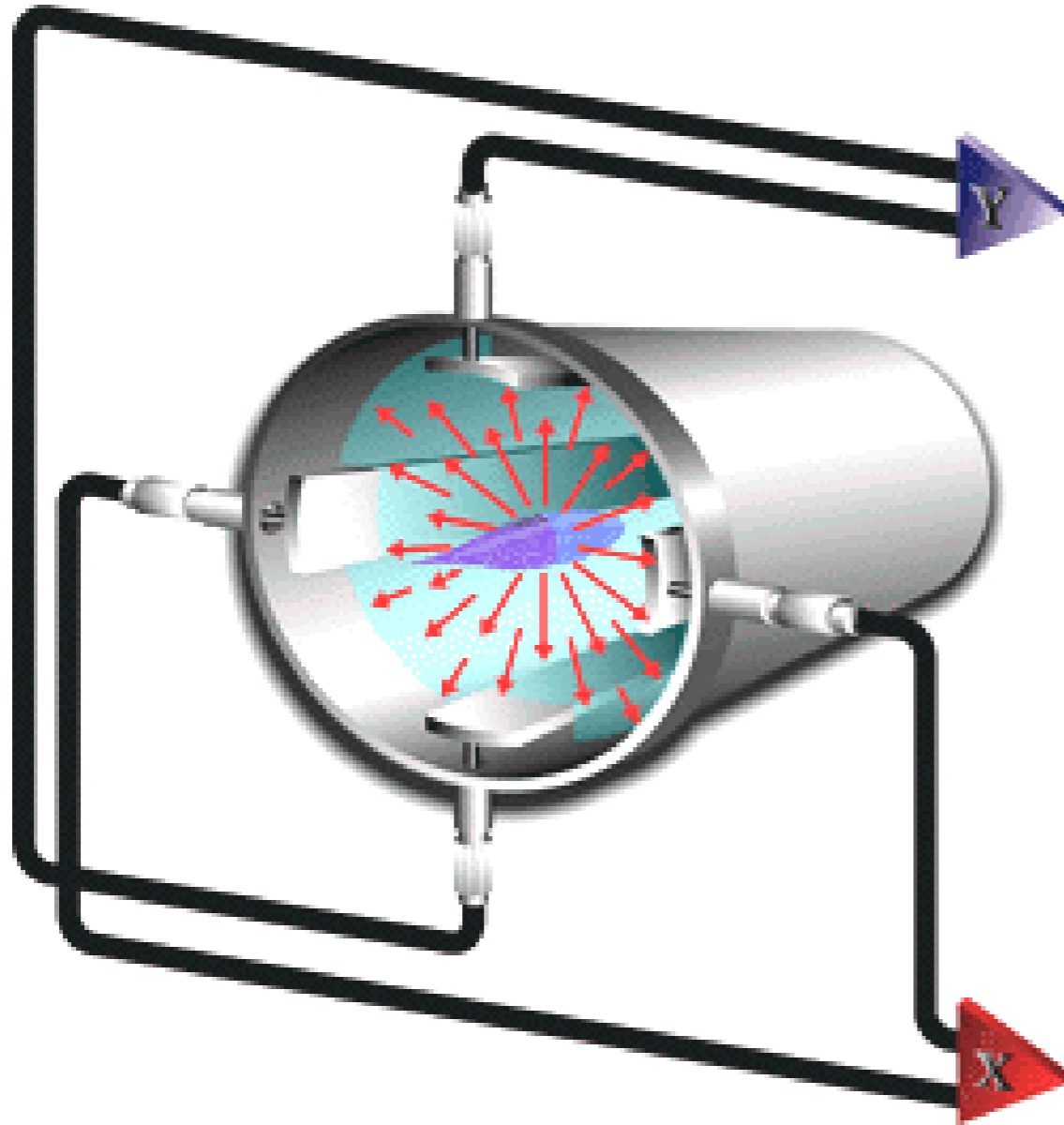
Microwave generator
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SLAC Klystron Gallery

Diagnosing the Beam

- Important for steering of the beams: Know where the particles are!



- Beam position monitors:
Pick-up electrodes provide
spatial information

Past Electron Colliders: DESY

- DESY Hamburg: Petra (e^+e^-), Hera (ep)

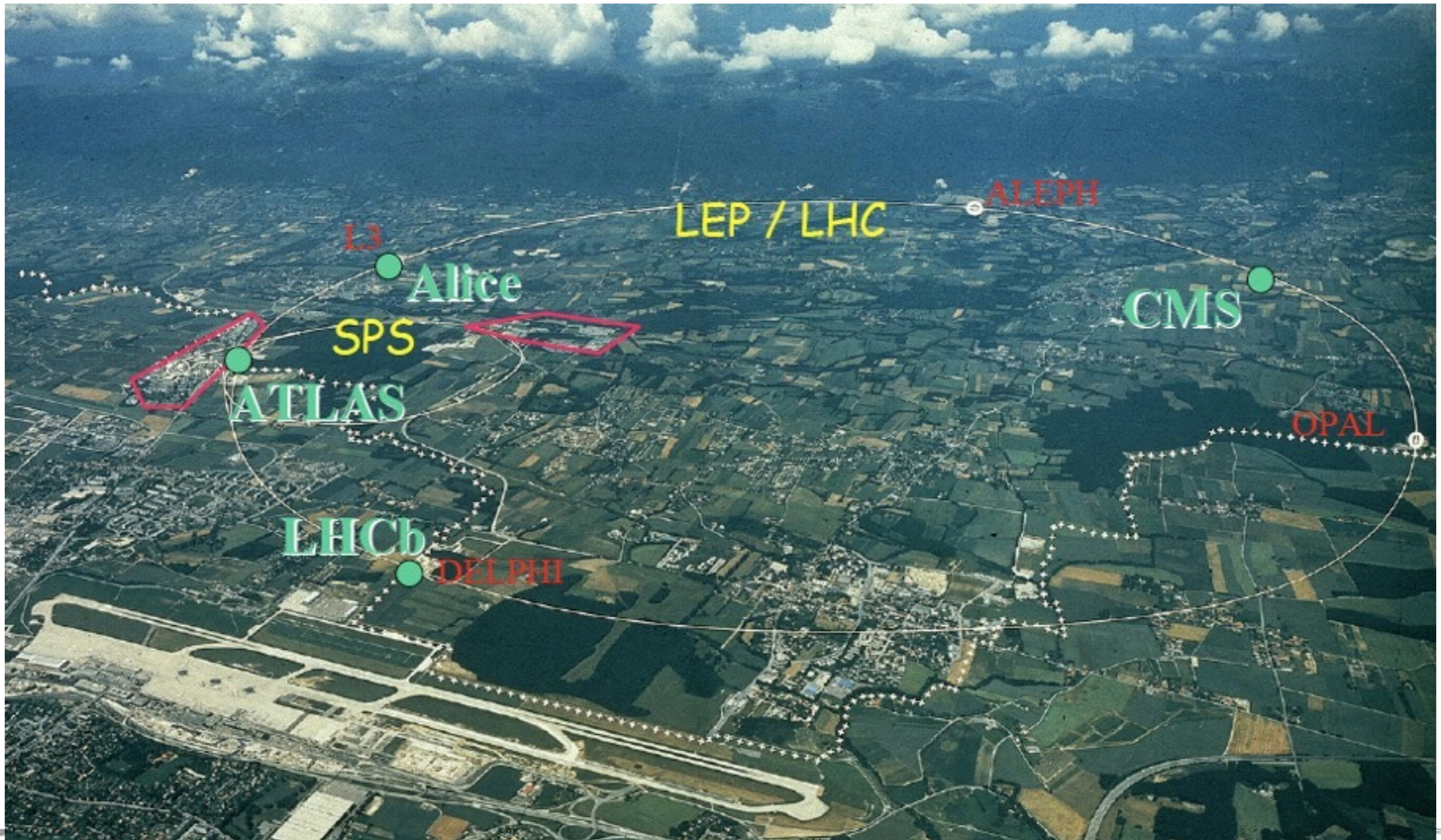


Petra (1976-1986)
up to 19 GeV per
beam

discovery of the
gluon in 1979

Past Electron Colliders: LEP (1989 - 2000)

- Up to now the highest energy collider for leptons: Up to 209 GeV center of mass energy



The LEP Tunnel



- Focusing quadrupoles
- Main dipoles

Foto: CERN

The LEP Tunnel



- Focusing quadrupoles
- Main dipoles

Now: Home of the LHC

Much higher energy for protons: Limited by dipole magnet strength, LEP was limited by accelerating cavity power (synchrotron radiation!)

Foto: CERN

Collider Parameters - Overview

Collider	start – end date	beam type	max. beam energy (GeV)	circumference or length (km)	L (cm ⁻² s ⁻¹)
PETRA (DESY)	1978 - 1986	e ⁺ e ⁻	23.4	2.304	10 ³⁰
SLC (SLAC)	1989 – 1999	e ⁺ e ⁻	50	1.45 + 1.47	3x10 ³⁰
LEP (CERN)	1989 – 2000	e ⁺ e ⁻	104	26.7	10 ³²
ILC (??)	2025+ (?)	e ⁺ e ⁻	250 (500)	15 + 15	2x10 ³⁴
KEKB (KEK)	1999 - 2010	e ⁺ e ⁻	8 x 3.5	3.0	2x10 ³⁴
PEP-II (SLAC)	1999 -	e ⁺ e ⁻	9 x 3.1	2.2	10 ³⁴
SuperKEKB	2016- (?)	e ⁺ e ⁻	7 x 4		8 x10 ³⁵
HERA (DESY)	1991 -	e p	30 x 920	6.3	8x10 ³¹
Spp̄S (CERN)	1981 – 1990	p p̄	315	6.9	6x10 ³⁰
TEVATRON (Fermilab)	1987 - 2011	p p̄	1000	6.28	2x10 ³²
LHC (CERN)	2009 -	pp	7000	26.7	10 ³⁴

Future Accelerators



Current and Future Accelerator Projects in HEP

Energy Frontier

Precision / Intensity Frontier

Hadron-Collider

Lepton Collider

high energy ($> Mz$)

low energy ($< Mz$)

SppS

SLC

Fixed Target

Tevatron

HERA

LEP

Tau - Charm

LHC

ILC

B-Factories

HL-LHC

CLIC

Super-Flavor-
Factory

FCChh

Muon Collider

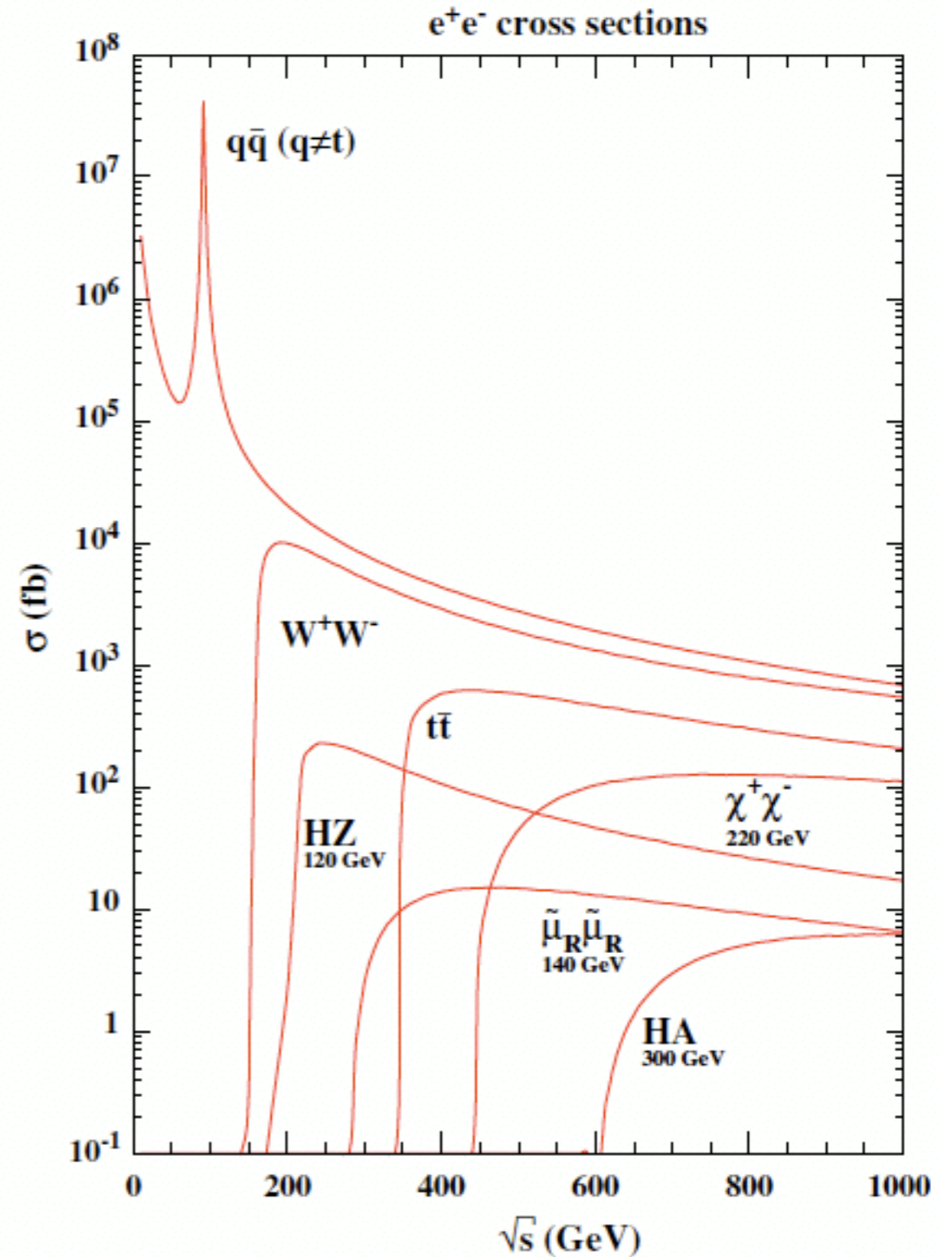
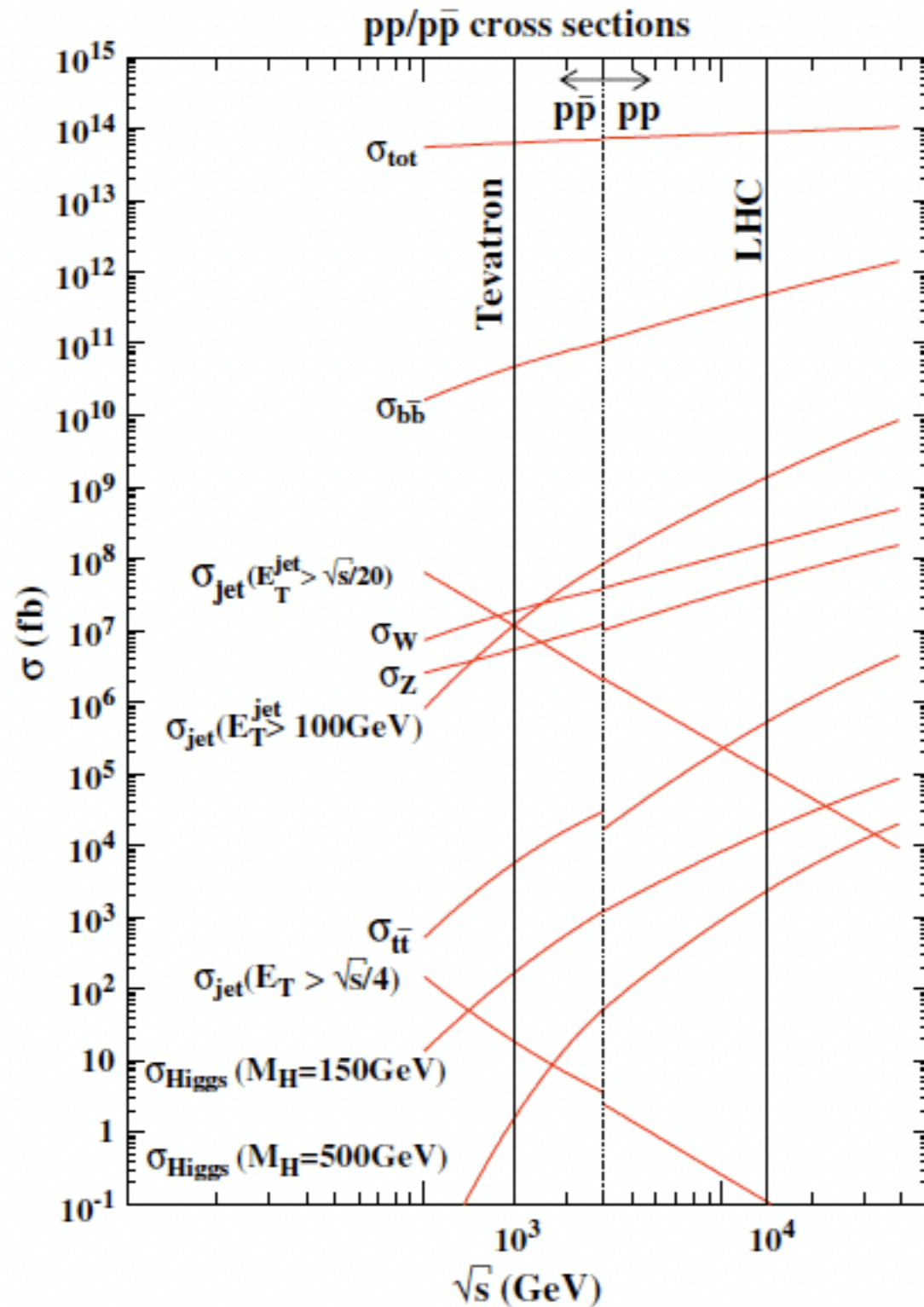
Abgeschlossen

In Betrieb oder im Bau

In Planung

Proton vs. Lepton-Colliders

G. Weiglein et al. / Physics Reports 426 (2006) 47–358



High Energy Lepton Colliders

- Solutions for the problem of synchrotron radiation:
 - No curves: Linear accelerators for electrons
 - High mass: muons instead of electrons

High Energy Lepton Colliders

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 - No curves: Linear accelerators for electrons
 - High mass: muons instead of electrons
- Both options are being studied, both have pros and cons:
 - Linear Collider: Energy has to be reached in a single shot, requires many accelerating cavities, no re-use of particles after collision
 - Muon Collider: Muons are unstable and can only be stored for short times. Capturing and “cooling” of the Muons, so that they can be used in a storage ring is far from trivial (remember: Muons are tertiary particles: Produced from pions decaying in flight, the pions are produced by shooting protons at a target)

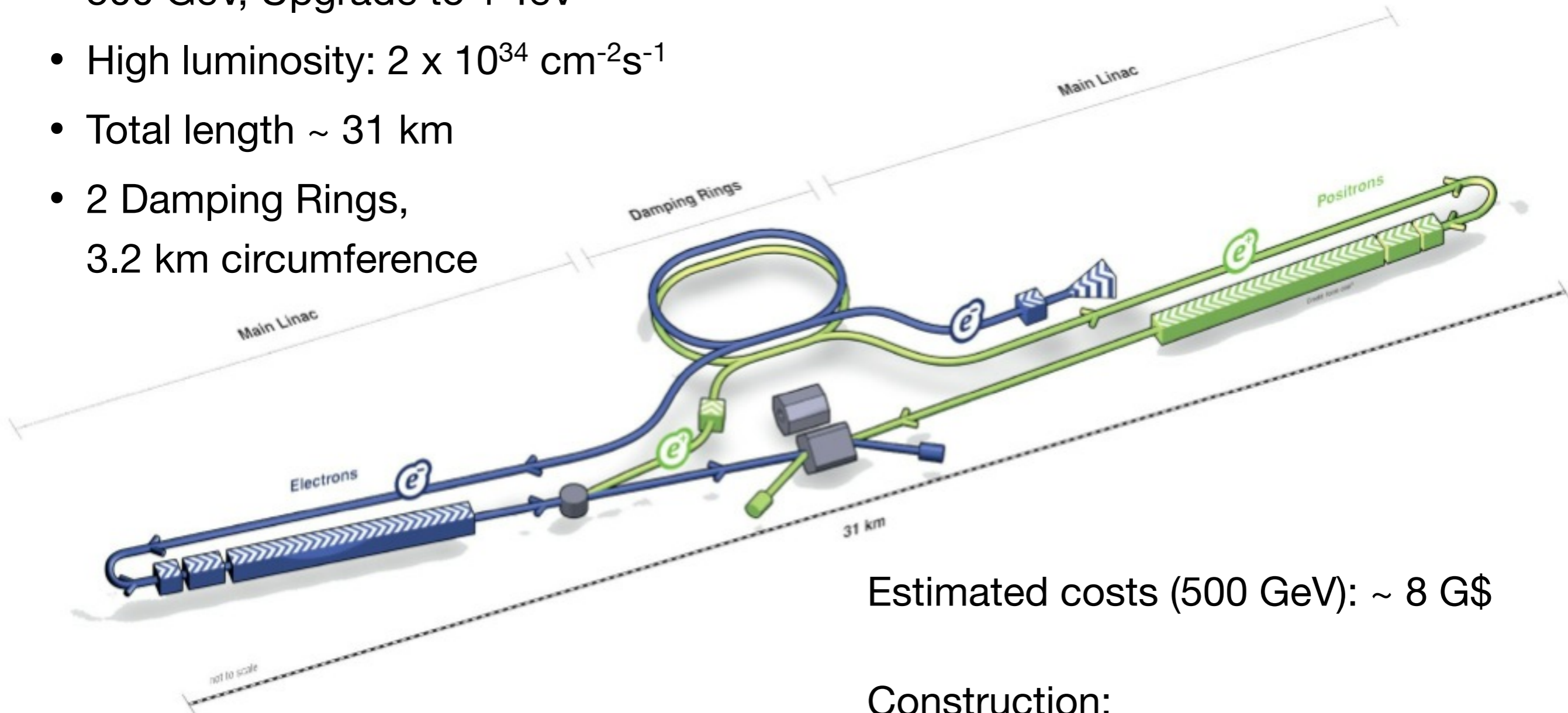
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The Linear Collider concept is already very mature, while many issues for a Muon Collider still need to be solved

The International Linear Collider ILC

- Planned e^+e^- Collider with a center of mass energy of 500 GeV, Upgrade to 1 TeV
- High luminosity: $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Total length $\sim 31 \text{ km}$
- 2 Damping Rings, 3.2 km circumference



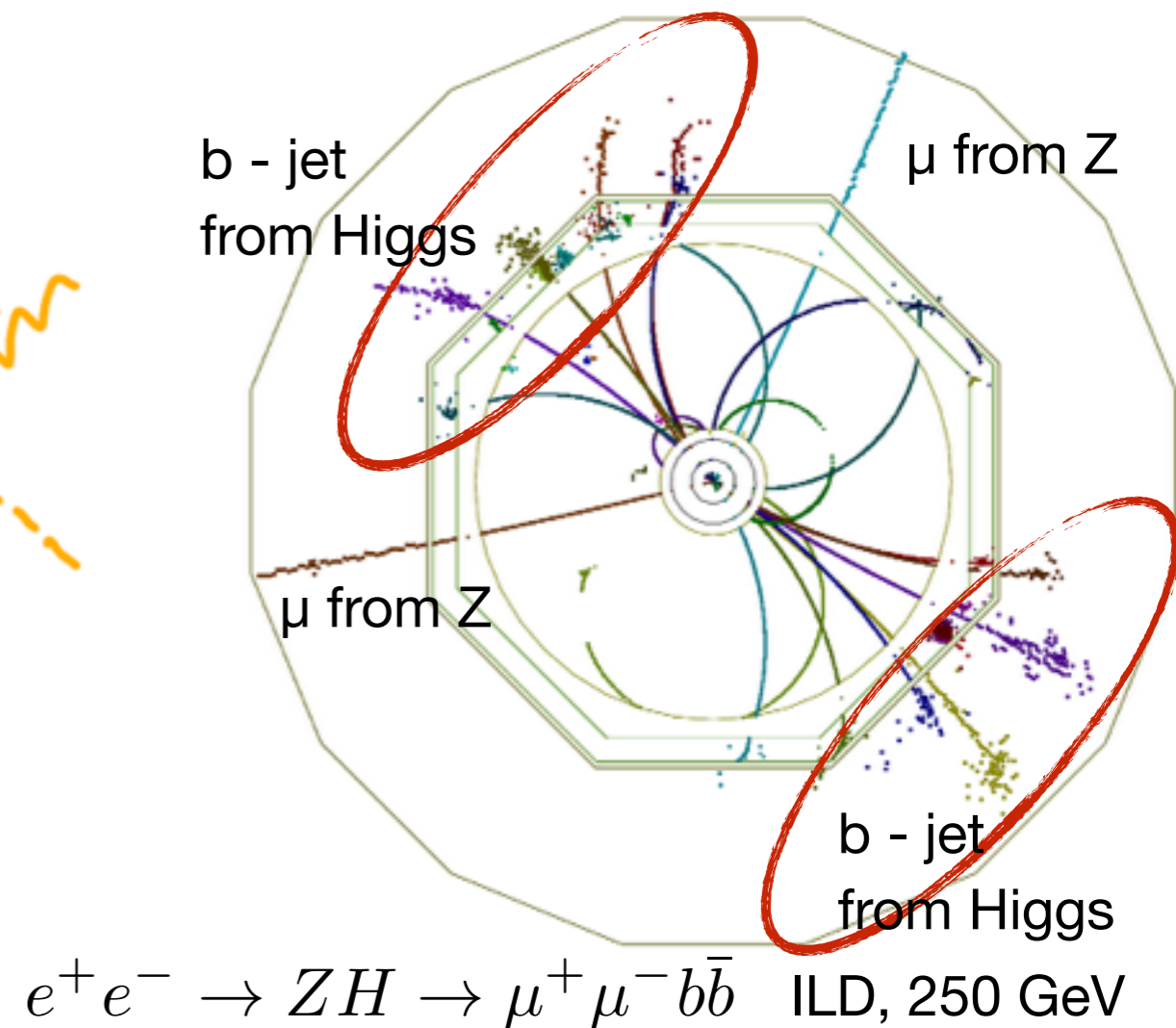
Estimated costs (500 GeV): $\sim 8 \text{ G\$}$

Construction:

~ 9 years until commissioning

One Physics Example: Higgs

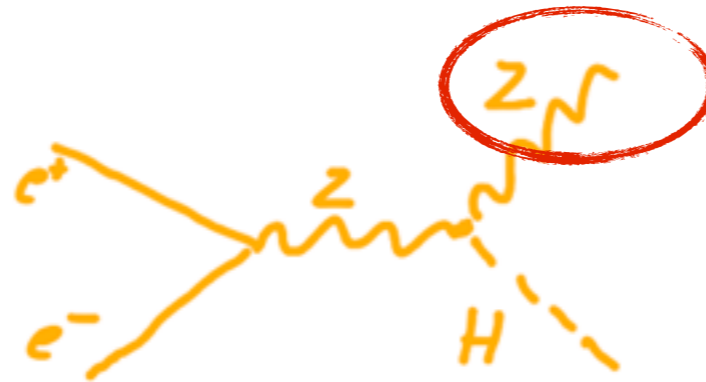
- A flagship measurement: Model-independent coupling of Higgs to Z
- Obtained from recoil mass measurement of reconstructed Z boson, independent of Higgs decay



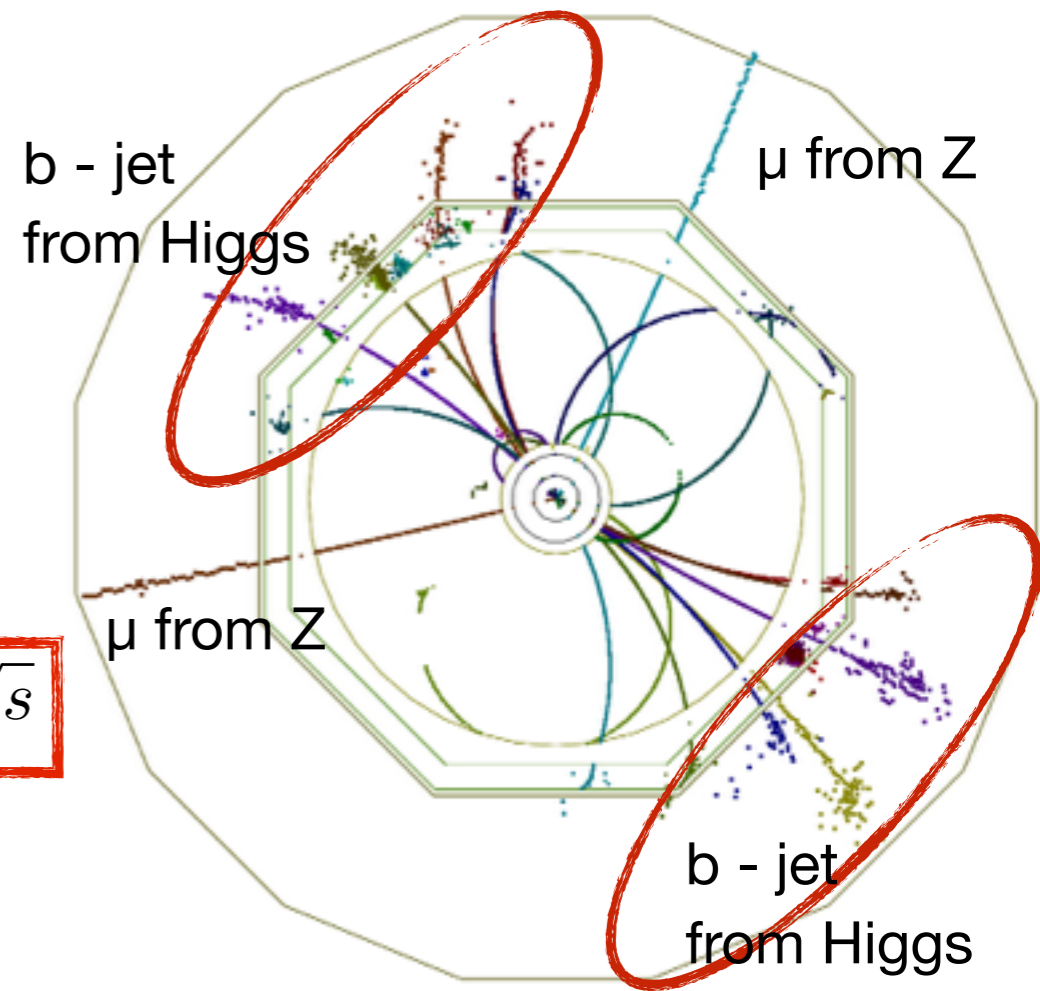
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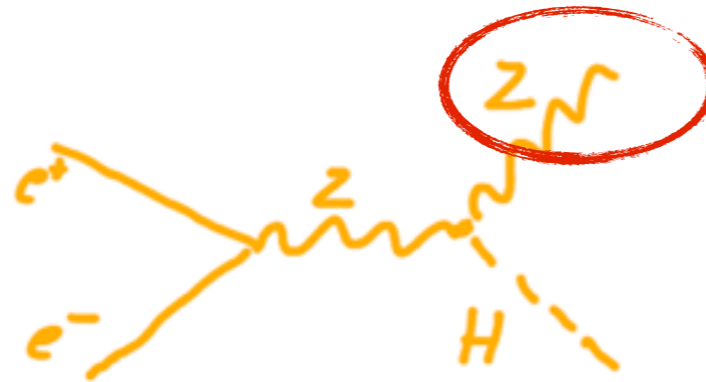
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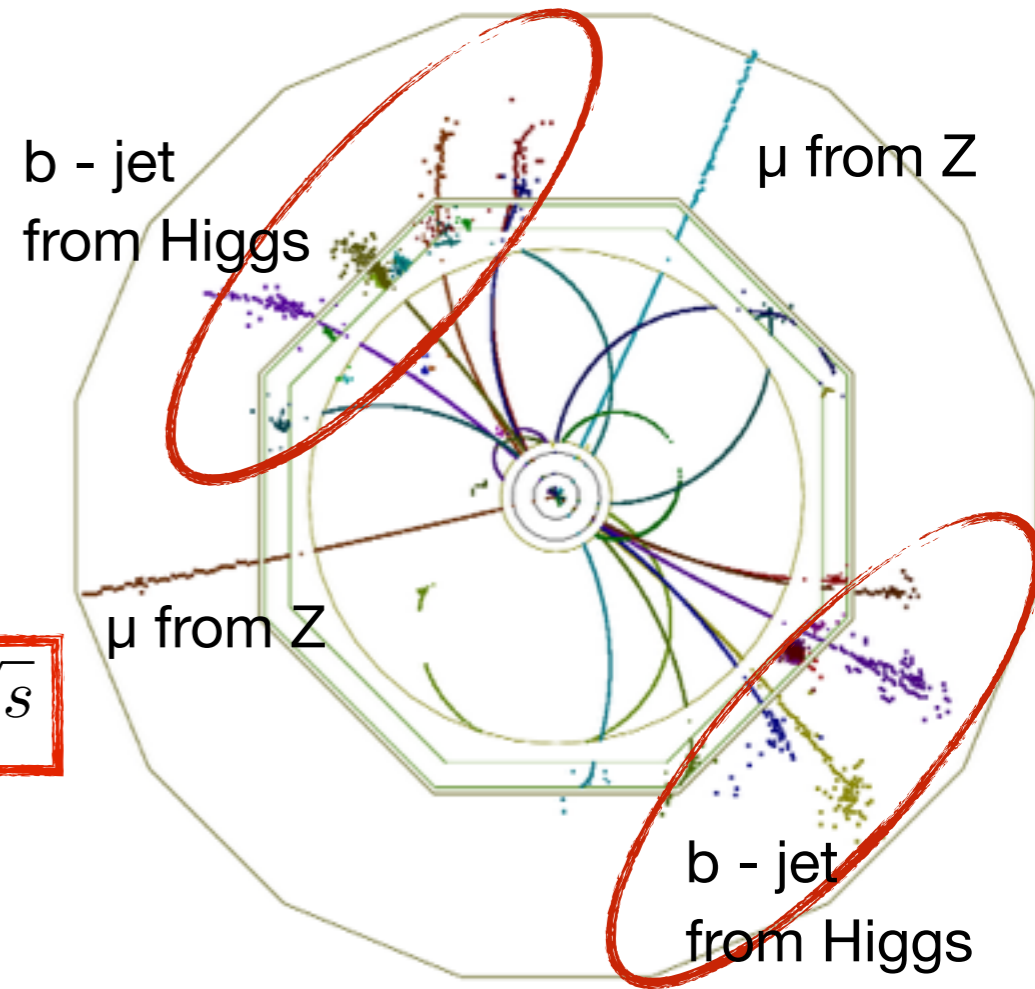
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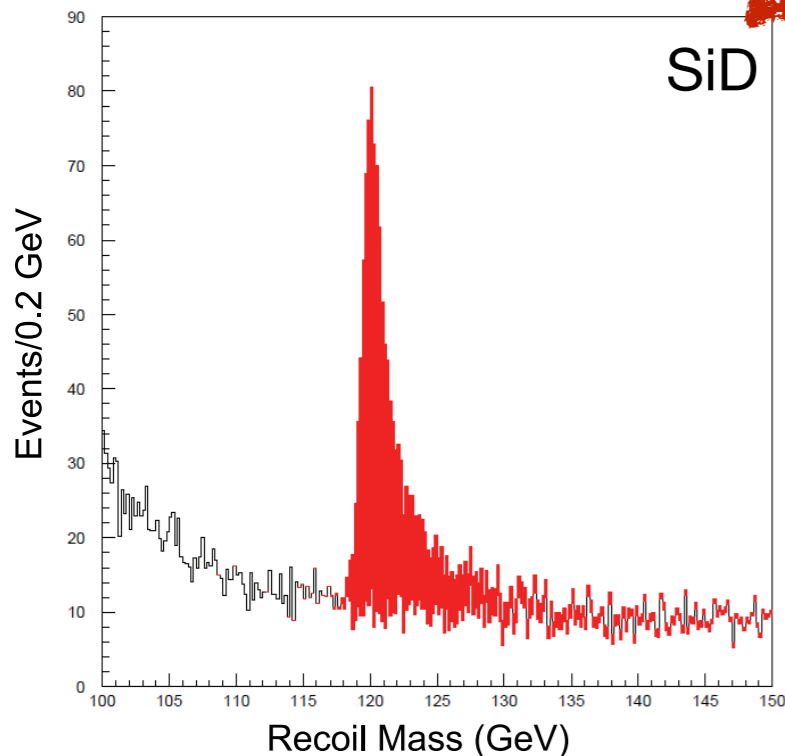
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Detect production of Higgs without reconstructing it:
Free of model assumptions - can constrain non-Standard-Model decays of the Higgs

Accelerating Structures for the ILC

- The key figure of merit: The acceleration gradient
 - ▶ Determines the length of a linear accelerator to reach a certain energy

The solution for ILC: Superconducting cavities

Advantages:

- No energy losses in the resonator walls: Efficient acceleration, long pulses possible
- relatively low frequency: 1.4 GHz
 - High stability because of manageable tolerances
 - Simple RF (radio frequency) generation

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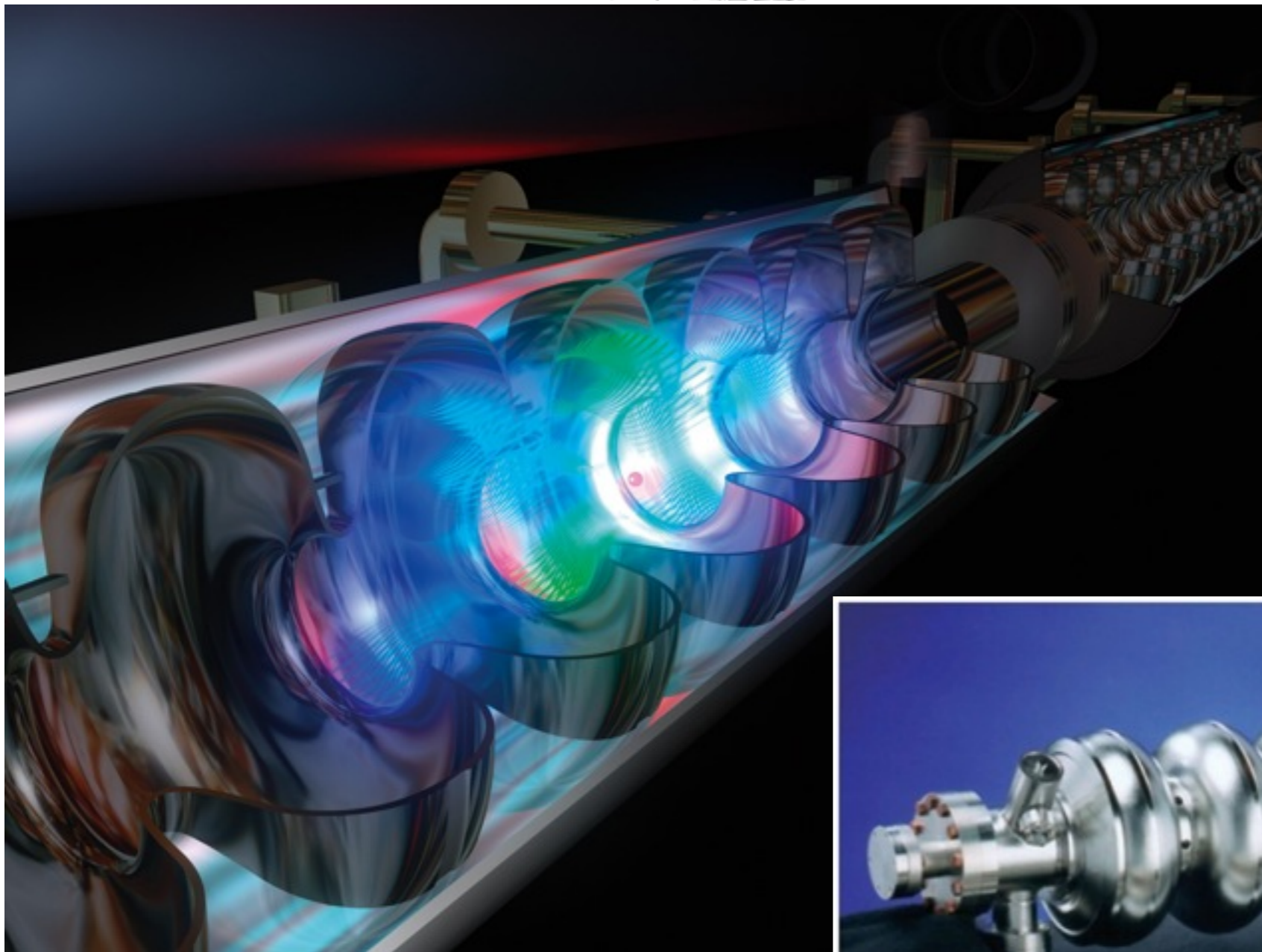
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Alternatives: Normal-conducting (copper) cavities

- No cryogenics required
- Can achieve higher acceleration gradients (with very high frequencies)
- but: extremely small tolerances, high frequency => challenging RF generation, short pulses to keep losses tolerable
 - NLC-Design: 11.4 GHz, to reach sufficient acceleration gradients

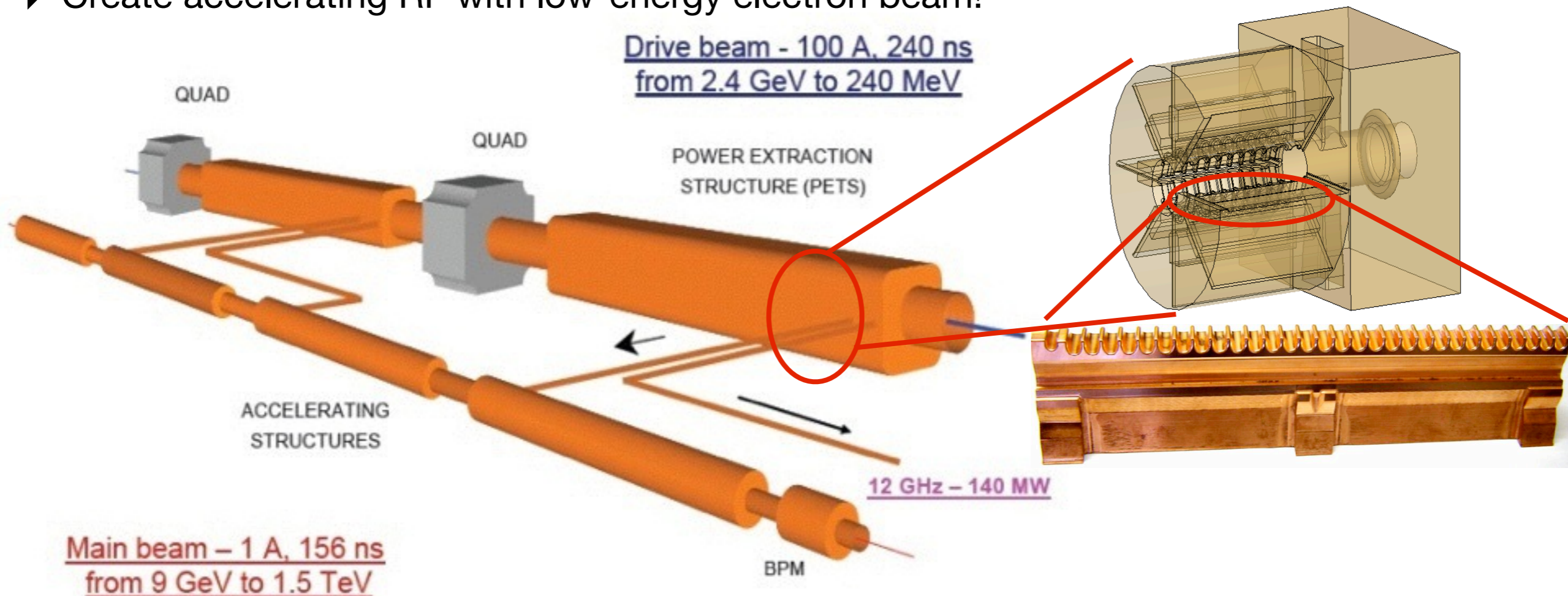
Accelerating Structures for the ILC



- Gradient ~ 31.5 MV/m - ILC technology has already reached gradients > 40 MV/m for some test modules

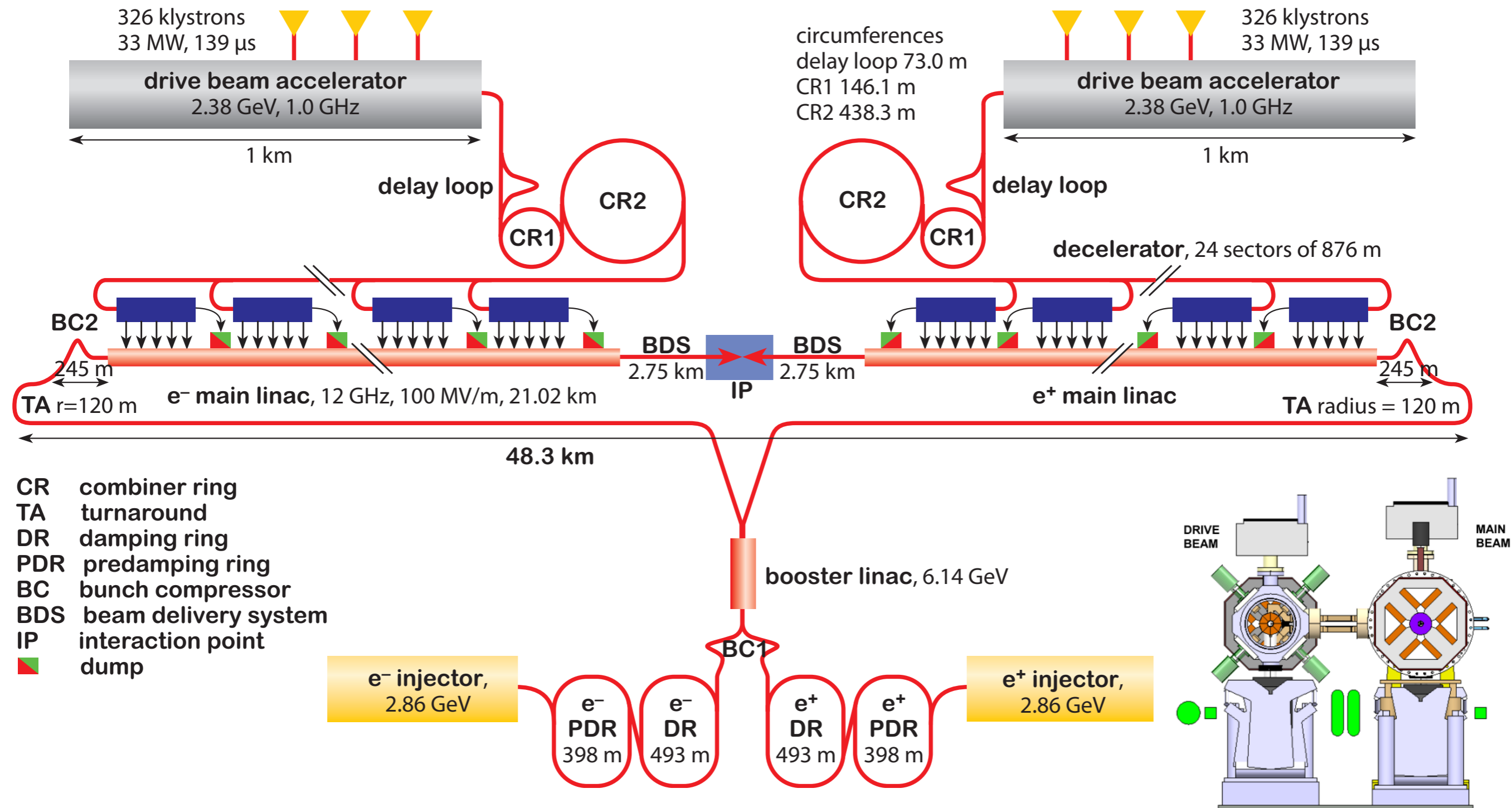
The Path to Higher Energies: 2 Beam Acceleration

- Das Issue: For energies of ~ 3 TeV the ILC technology is not practical: Length of the accelerator > 100 km
 - ▶ Higher acceleration gradients are needed - achievable with normal-conducting structures and high frequencies (12 GHz) - CLIC: 100 MV/m
 - ▶ To reach a satisfactory accelerator efficiency, a new way to create the RF is needed (standard Klystrons are good at ~ 1 GHz, not 12 GHz)
 - ▶ Create accelerating RF with low-energy electron beam!



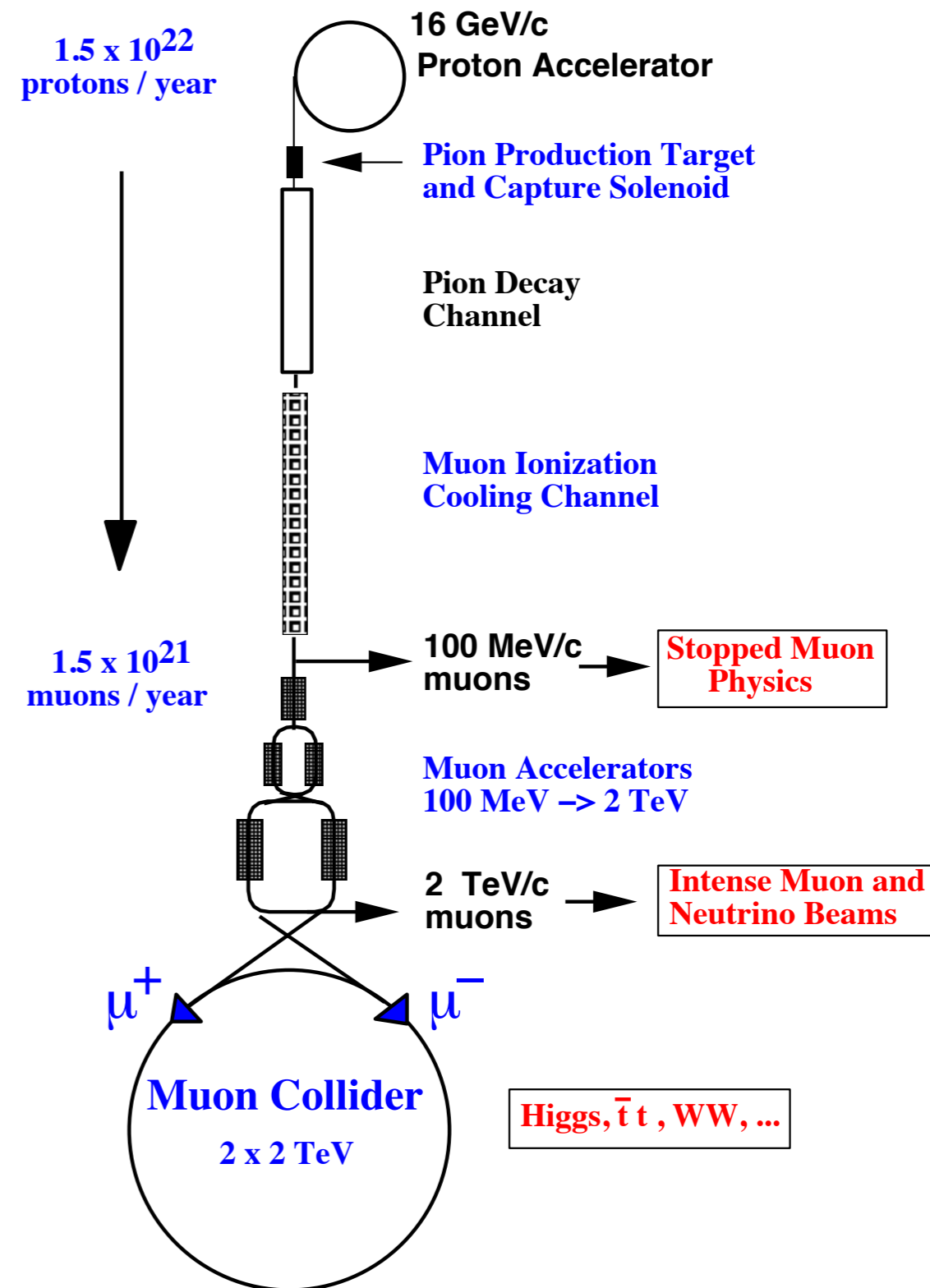
CLIC: "Compact" Linear Collider

- 3 TeV center of mass energy, 2 beam acceleration; Luminosity up to $6 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$



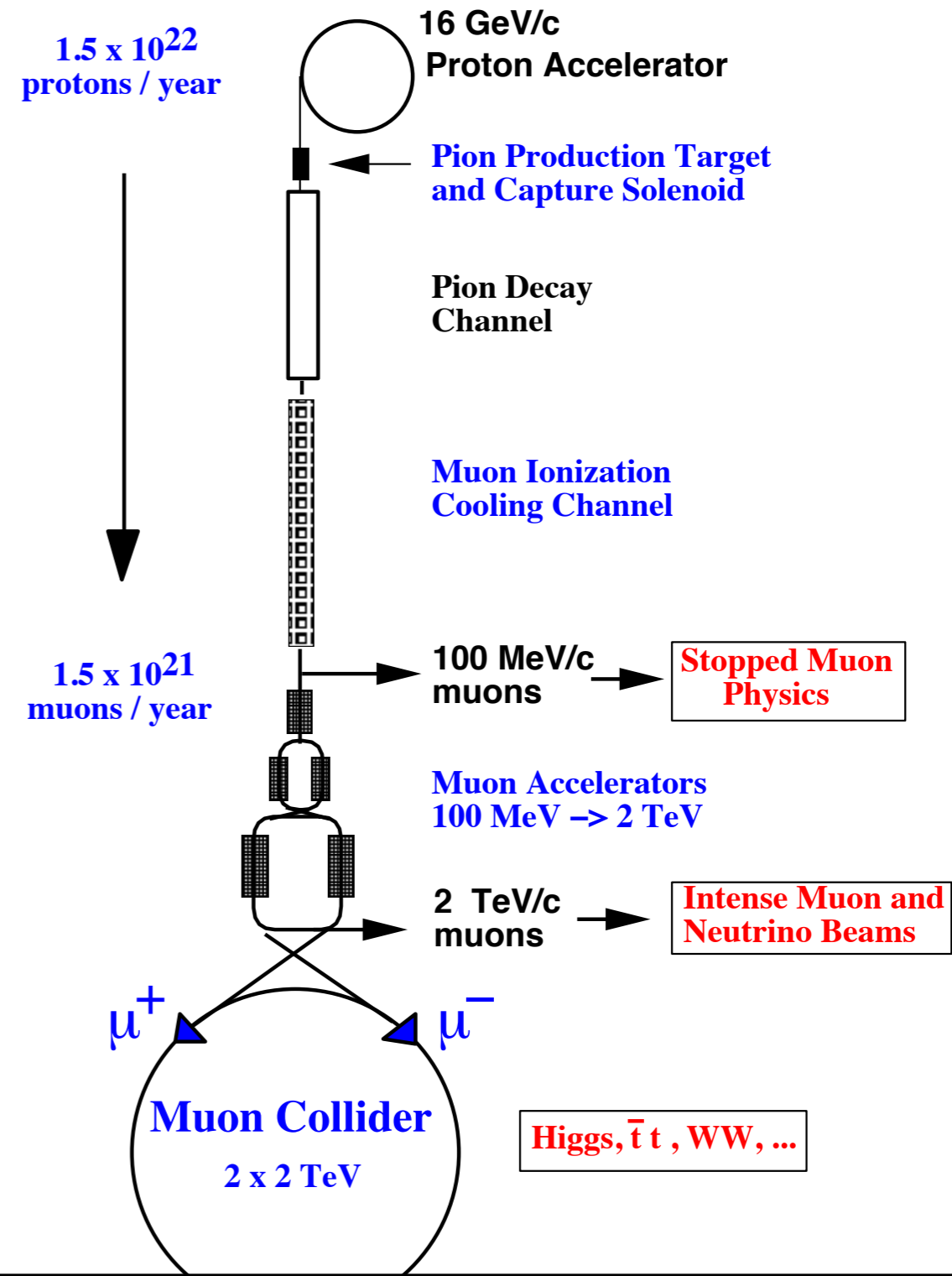
Beyond Electrons: Muon Collider

- Storage ring for muons: Synchrotron radiation ok
- The challenge: Getting muons into the ring
Requires reduction of the phase space (after pion decay) by a factor of 10^5 bis 10^6
- ▶ Cooling!



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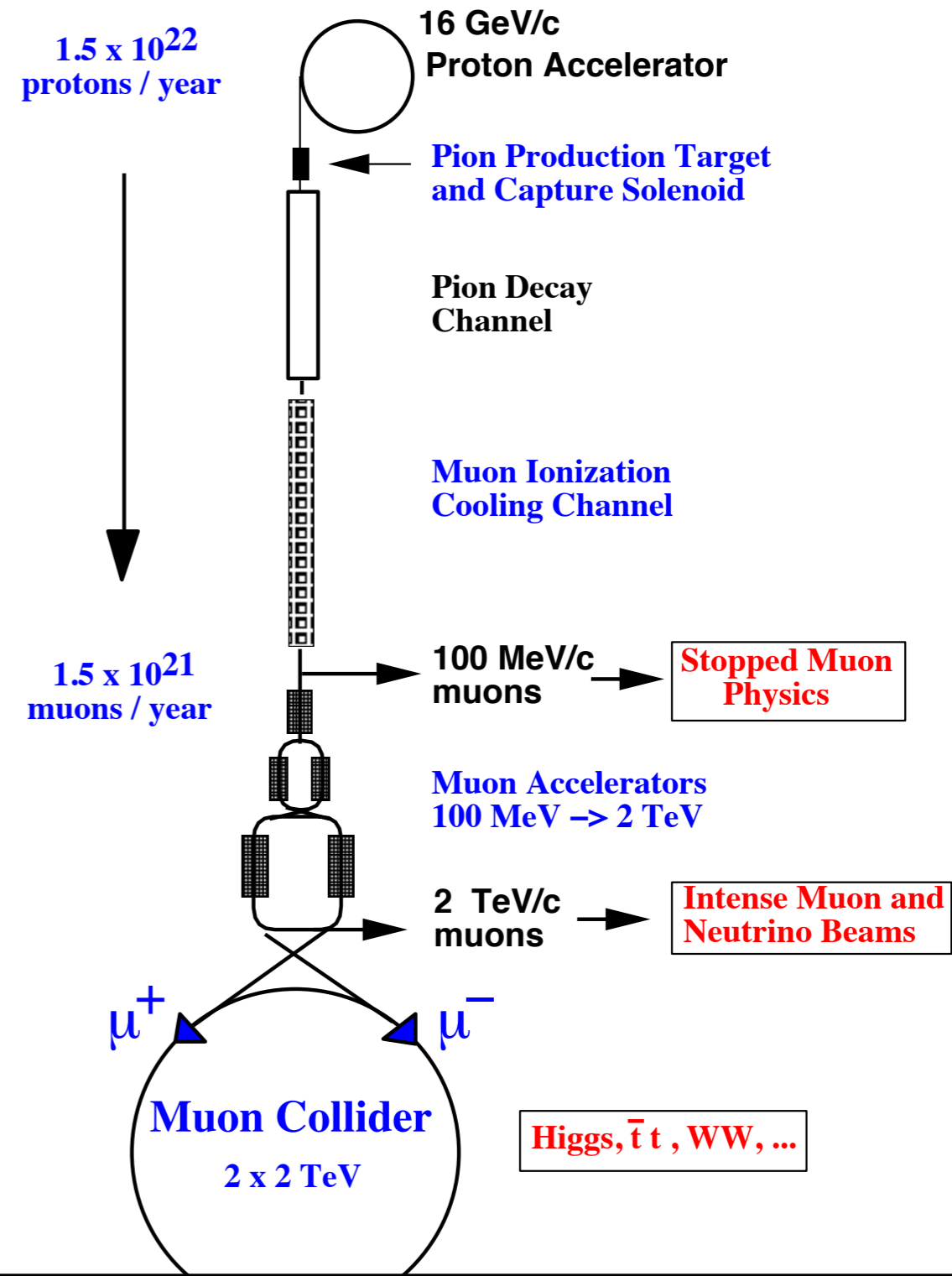
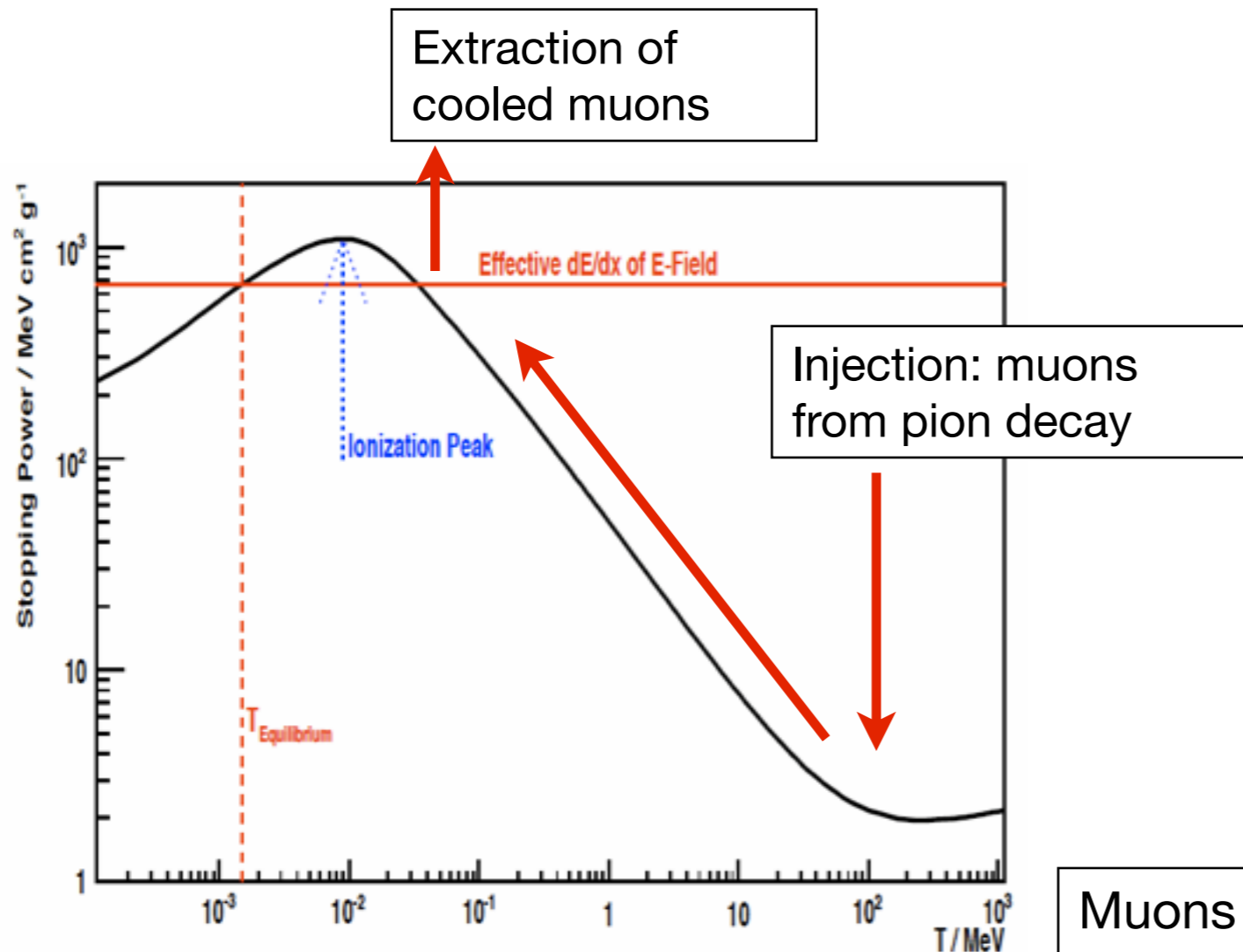


Muons survive ~ 1000 revolutions in the collider



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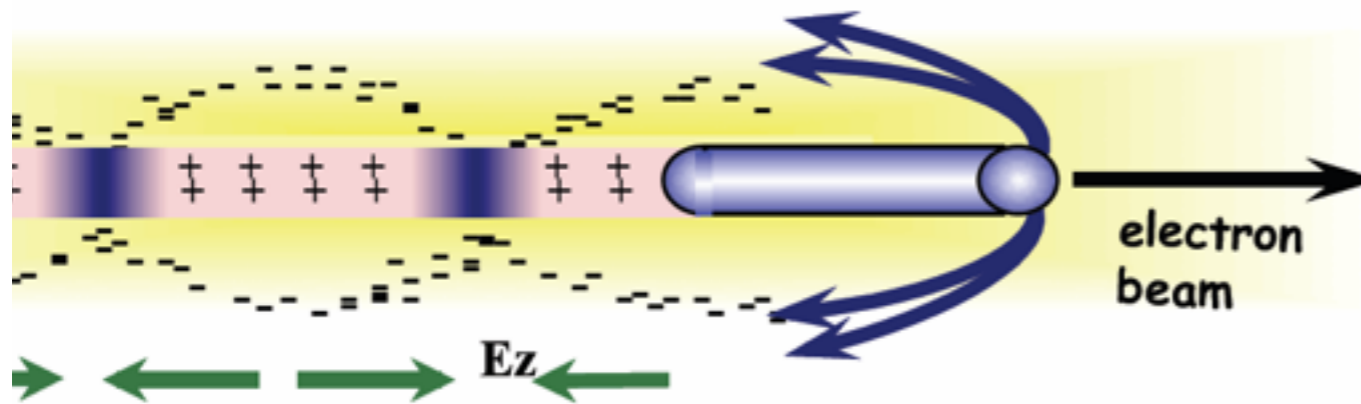


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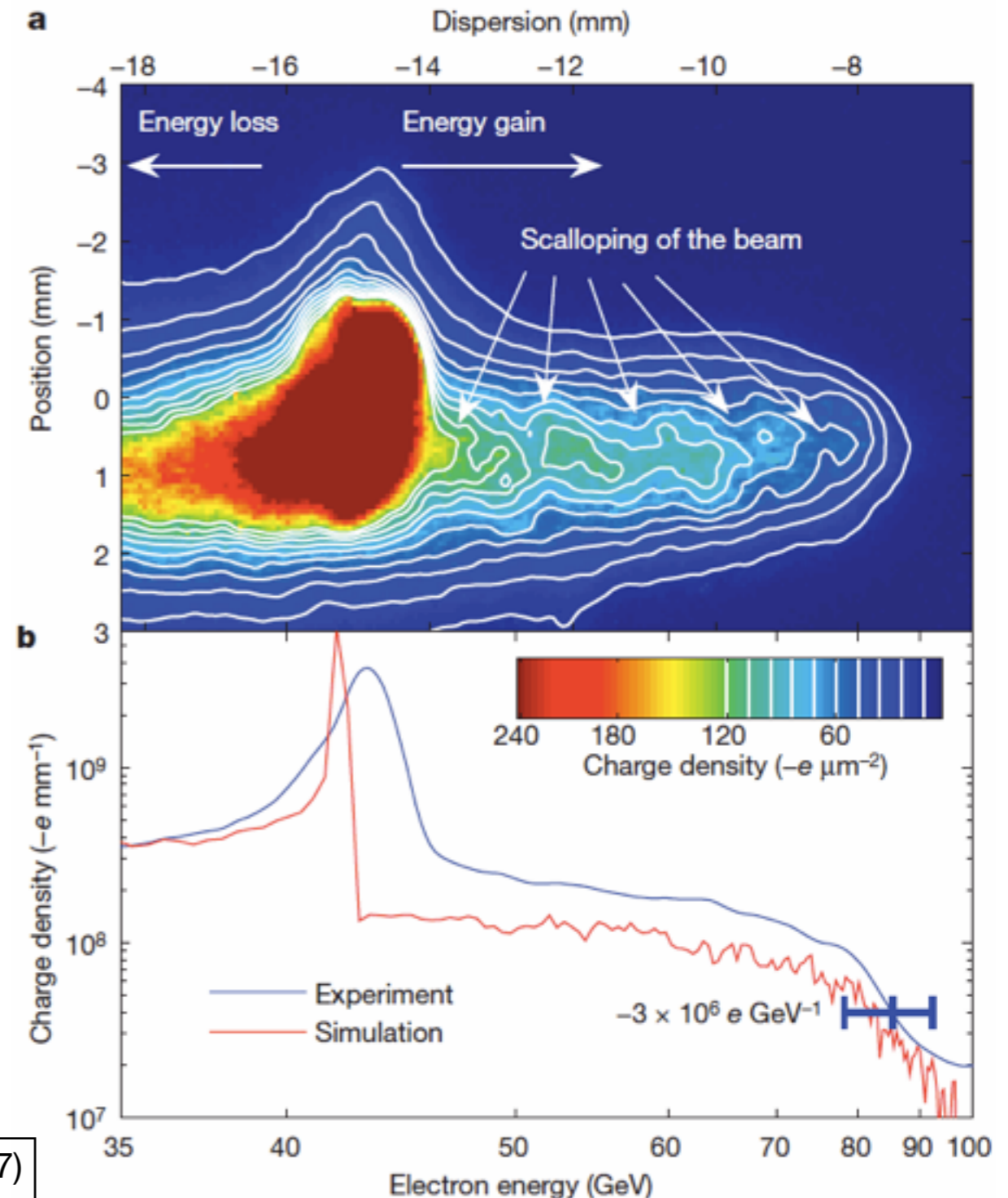
Plasma Wakefield Acceleration

- For high-energy linear colliders: Need much higher acceleration gradient to go significantly beyond ~ 1 TeV beams
 - Conventional accelerating structures limited at ~ 100 MV/m or below



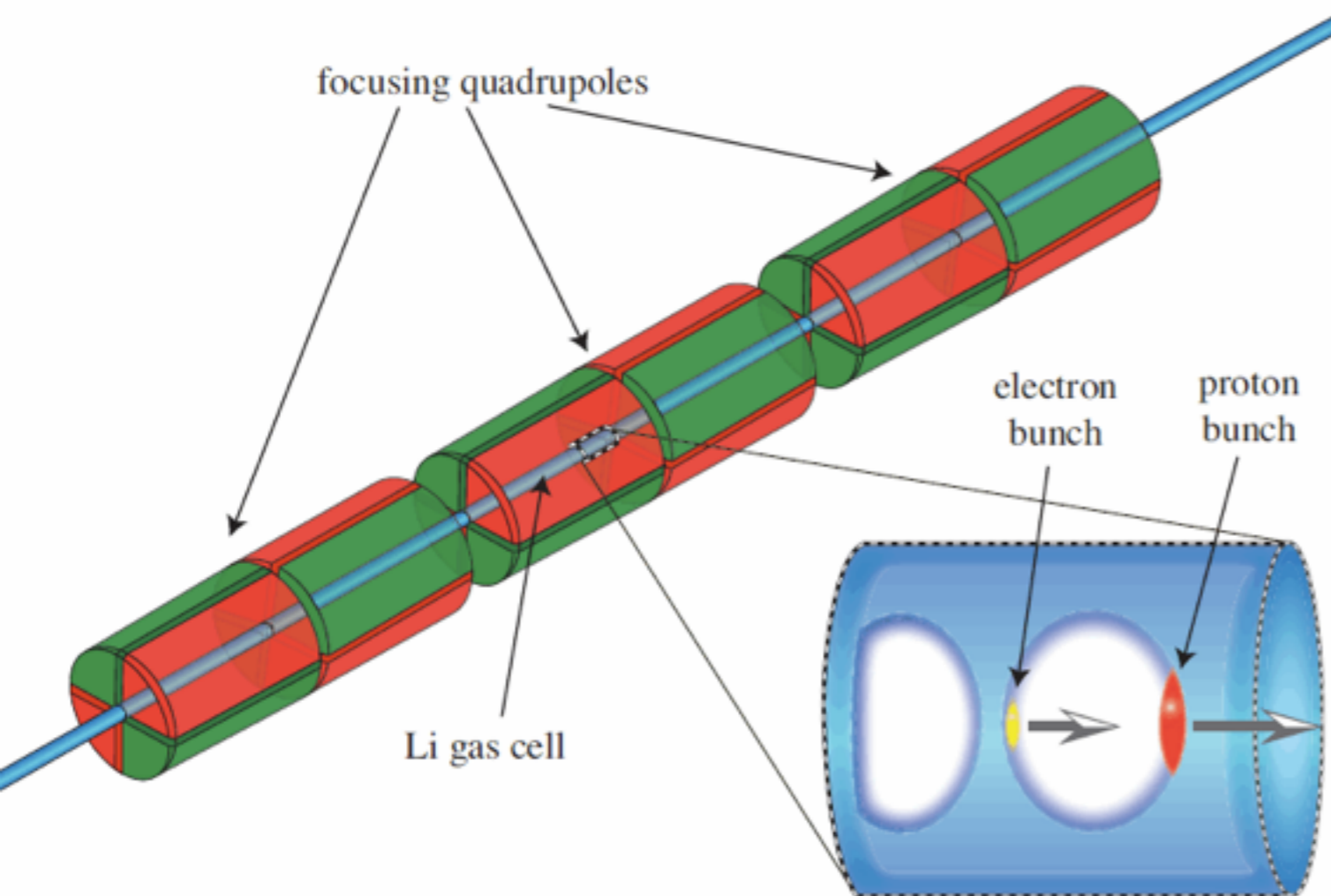
- Demonstration of high energy acceleration of electrons at SLAC: E-164X
- doubling of beam energy observed: 40 GeV energy gain over less than 1 m of plasma $\rightarrow \sim 50$ GV/m

Nature 445, 741 (2007)

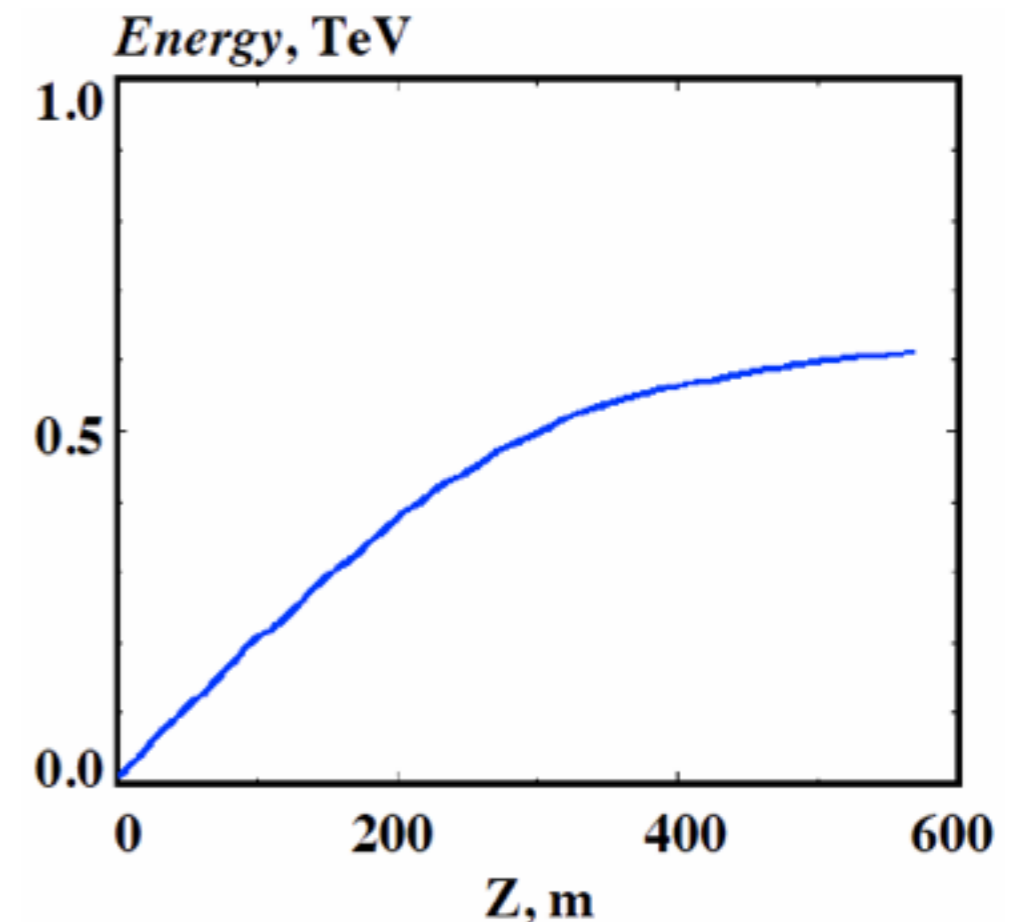


Plasma Wakefield Acceleration

- Need to get the energy into the plasma
 - Lasers - used for extreme gradients over very short distances (\sim mm)
 - Beams - Much higher power - Long acceleration distances possible
 - ▶ Idea followed at MPP: Use protons to drive plasma: Very high energy available!



Simulation with 1 TeV
proton beam



Plasma Wakefield Acceleration

- Need to get the energy into the plasma
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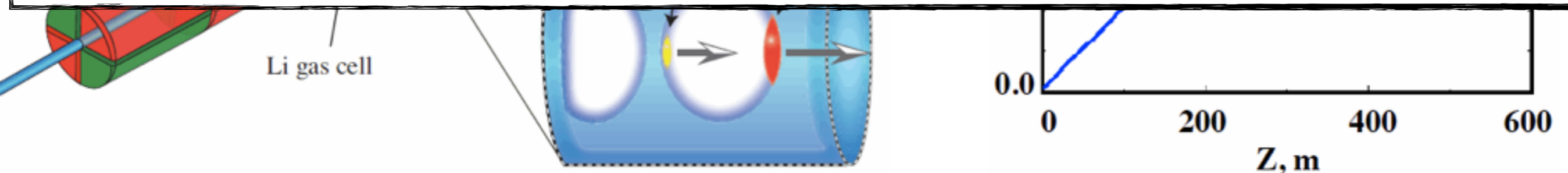
Key challenges (so far unsolved) for all techniques:

How to get very sharp energy distributions, high repetition rate, high currents and good focusing?

How to accelerate positrons with a comparably high gradient?

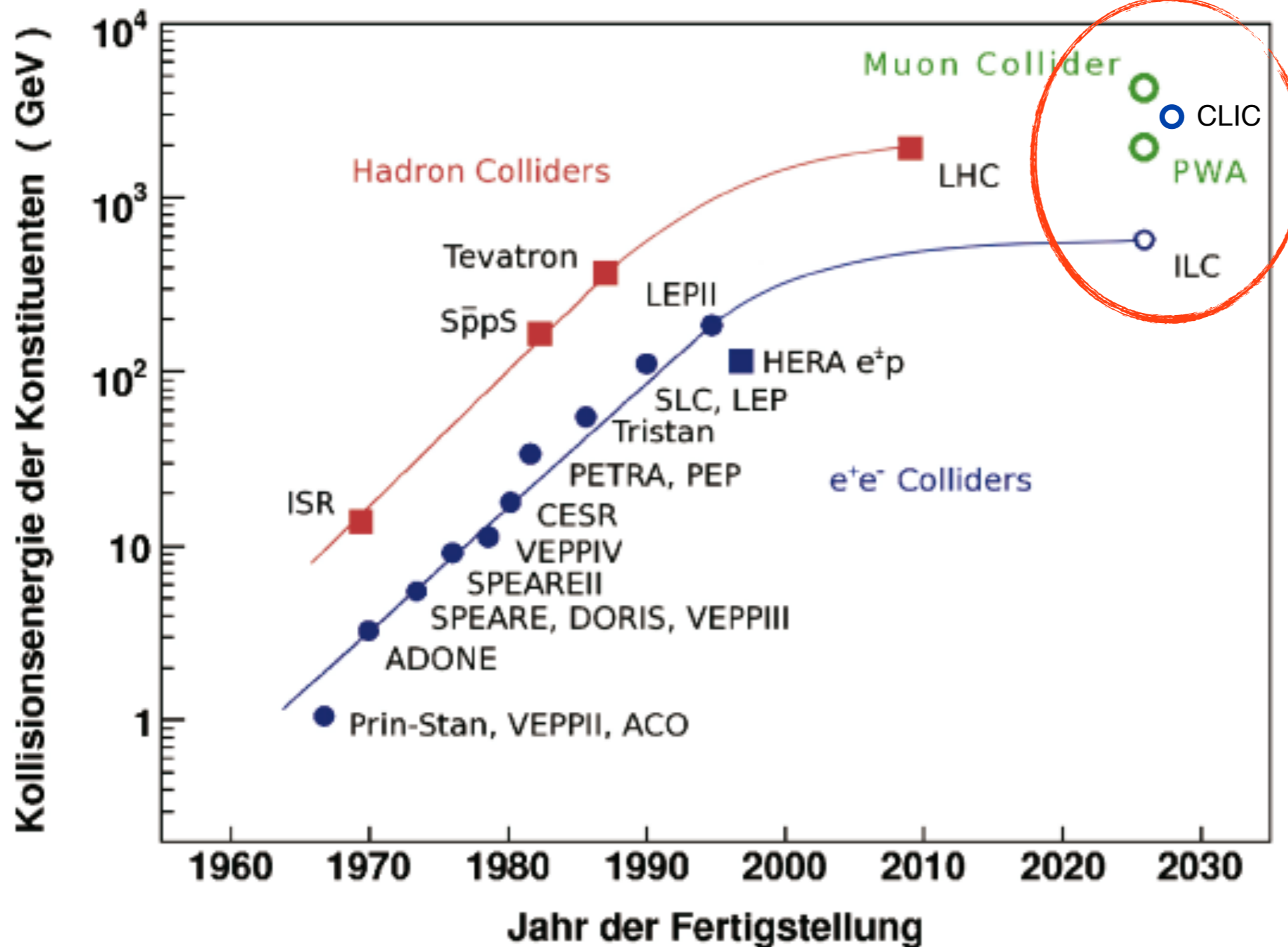
Or, in short:

How to get high luminosity for a collider?



The Development of Collider Energies

- “Livingston Plot”



discussed projects
& speculation

Global Planning

The image shows the cover of a report titled 'The European strategy for particle physics'. The title is written in a white, serif font on a red horizontal band. The background of the cover is a dark blue with a radial light effect emanating from the bottom center, suggesting particle tracks or a detector. The top part of the cover shows a blurred image of what appears to be a particle detector or accelerator component.

The European strategy
for particle physics

update 2012/13

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The European strategy for particle physics

update 2012/13

1. the highest priority is to fully exploit the physics potential of the [LHC](#) ... and organize towards a luminosity upgrade by around 2022 ([hl-LHC](#)).

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4. European participation in a global (long baseline) **neutrino** programme.

Possible Time Line

- Adapted from recent workshops etc, mixed with own interpretations and expectations



2010

2015

2020

2025

2030

2035

LHC



hl-LHC



ILC



sKEKb



CLIC; μ C;



VLHC; FCC;...

Summary

- Accelerators are key instruments in particle physics - with many applications beyond fundamental research
- Two basic concepts are in use today
 - Linear accelerators
 - Synchrotrons
- A high-energy e^+e^- linear collider is a likely future project in HEP
 - Other projects are developed as well
- Accelerator technology is constantly developed further
 - Current concepts: Superconducting cavities, two-beam acceleration schemes
 - Possible future technology: Plasma wakefield acceleration

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Next Lecture: 28.04., “Detectors”, F. Simon