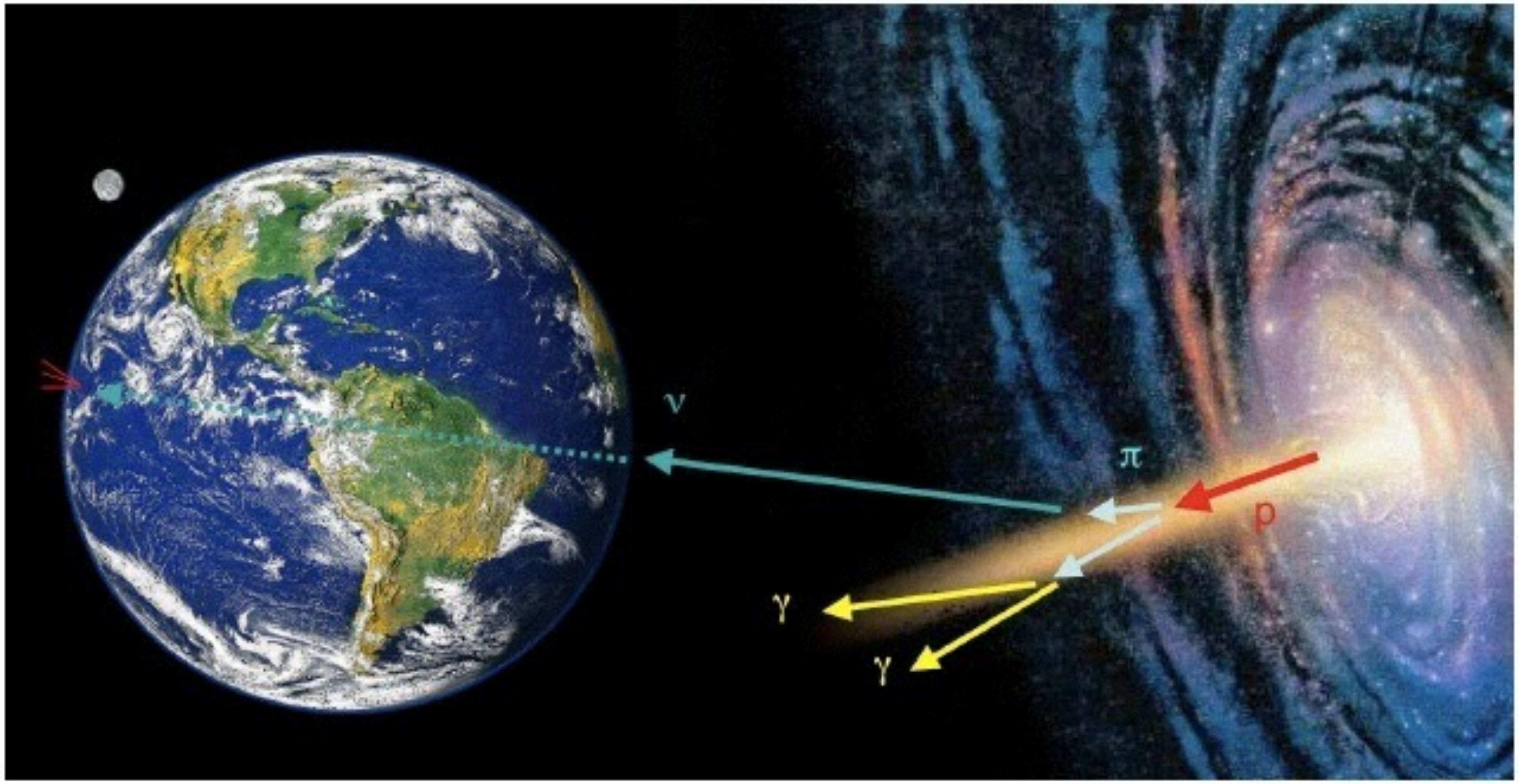
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



02. Ground-based Accelerators

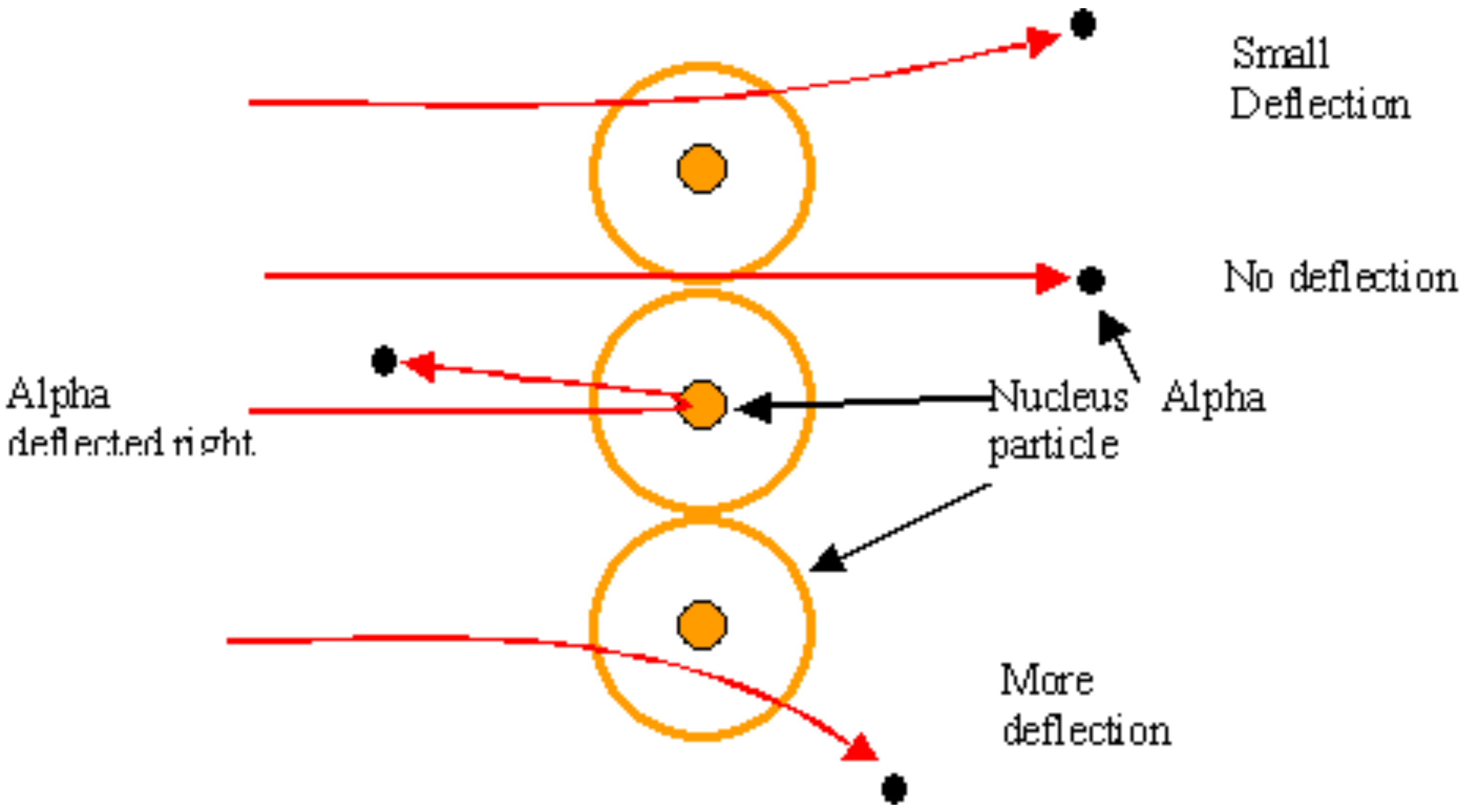
18.04.2016

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

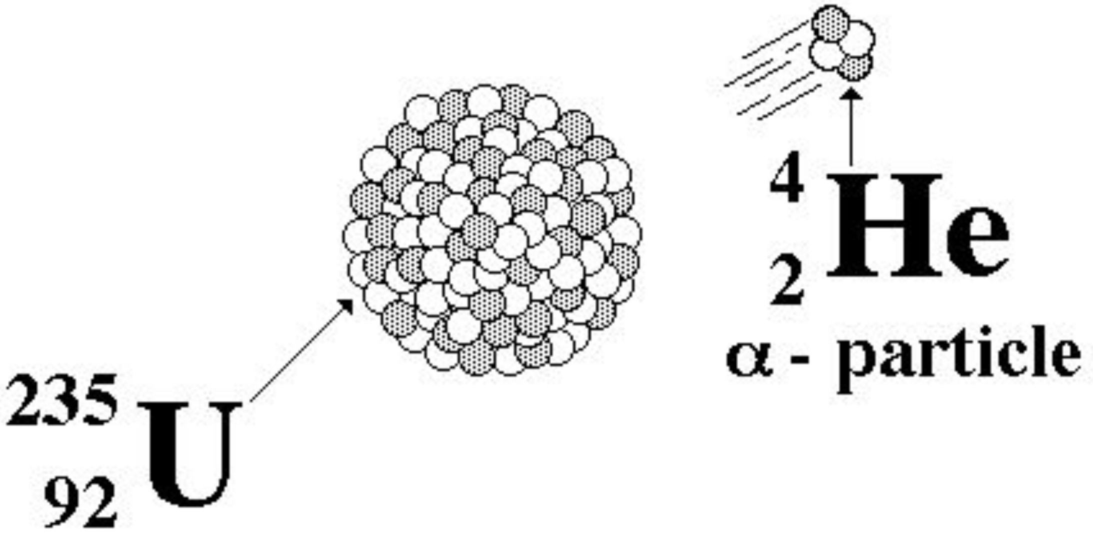
Prof. Dr. Siegfried Bethke
Dr. Frank Simon

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

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

1 GeV probes the size of the proton!

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

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

1 GeV probes the size of the proton!

- To create new, previously unknown particles, you need energy

$$E = mc^2$$

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

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

1 GeV probes the size of the proton!

- To create new, previously unknown particles, you need energy

$$E = mc^2$$

- 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
- ...

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
- ...

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

Frank Simon (fsimon@mpp.mpg.de)

Historical Overview

- 1928: R. Wideroe reports the operation of the first linear accelerator (Ka 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

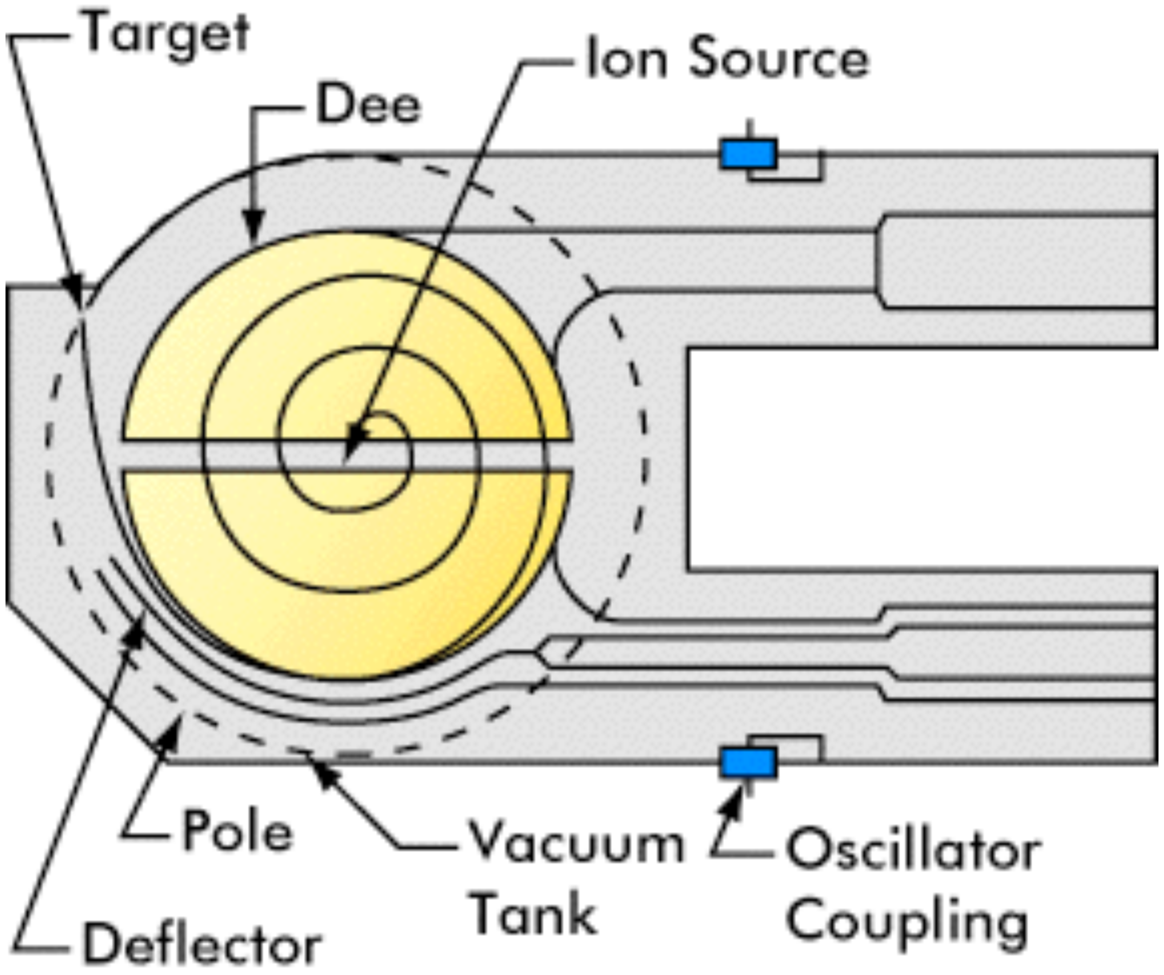
- The underlying equations: Maxwell-Equations

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

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

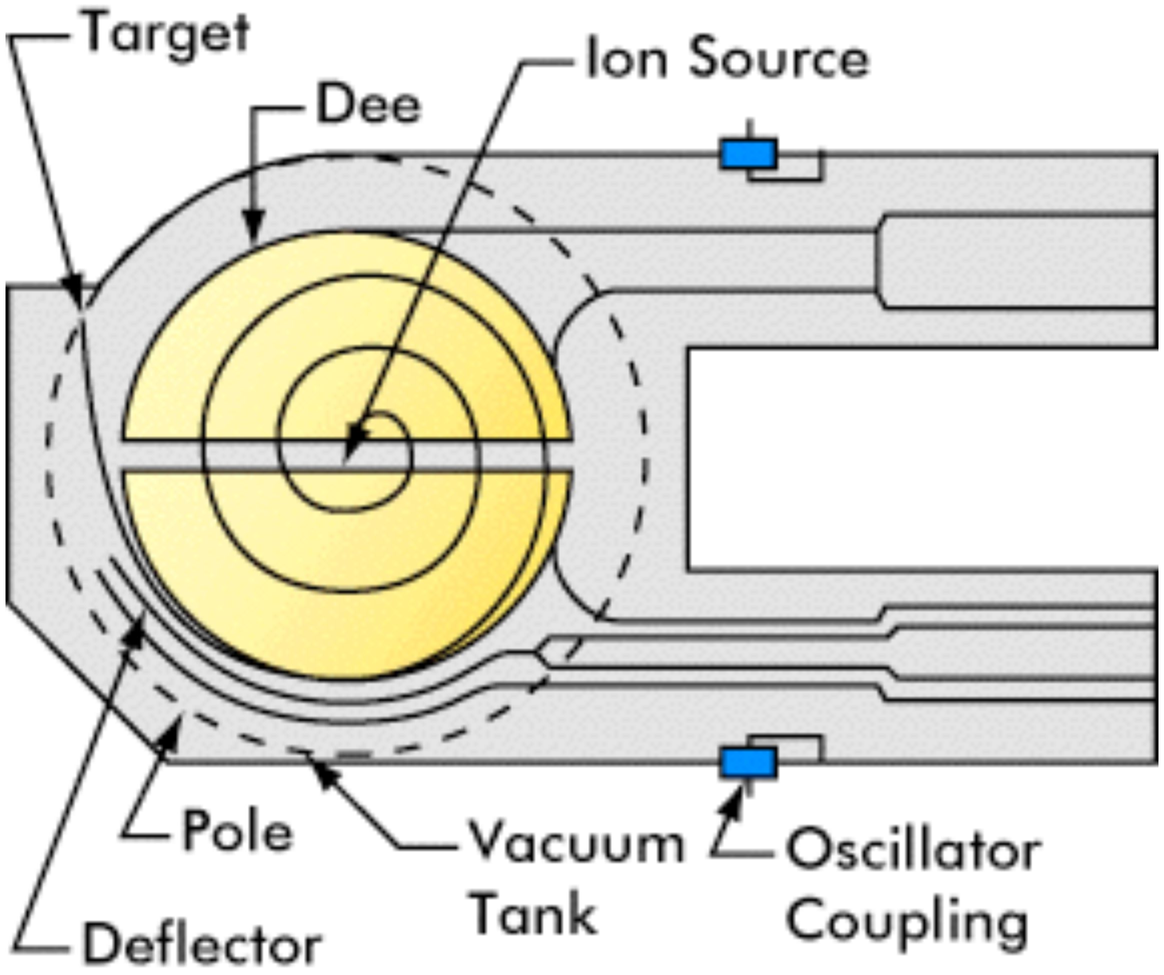
n.b.: The Lorentz-force is non-conservative for time-dependent fields!

Basic Accelerator Types: Cyclotron, Linac

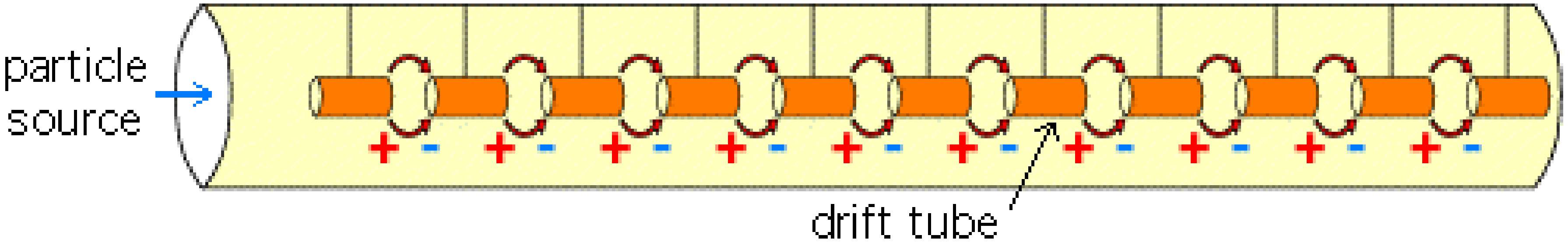


- Cyclotron:
    - Magnetic field to bend particles
    - Alternating electric field for acceleration

Basic Accelerator Types: Cyclotron, Linac

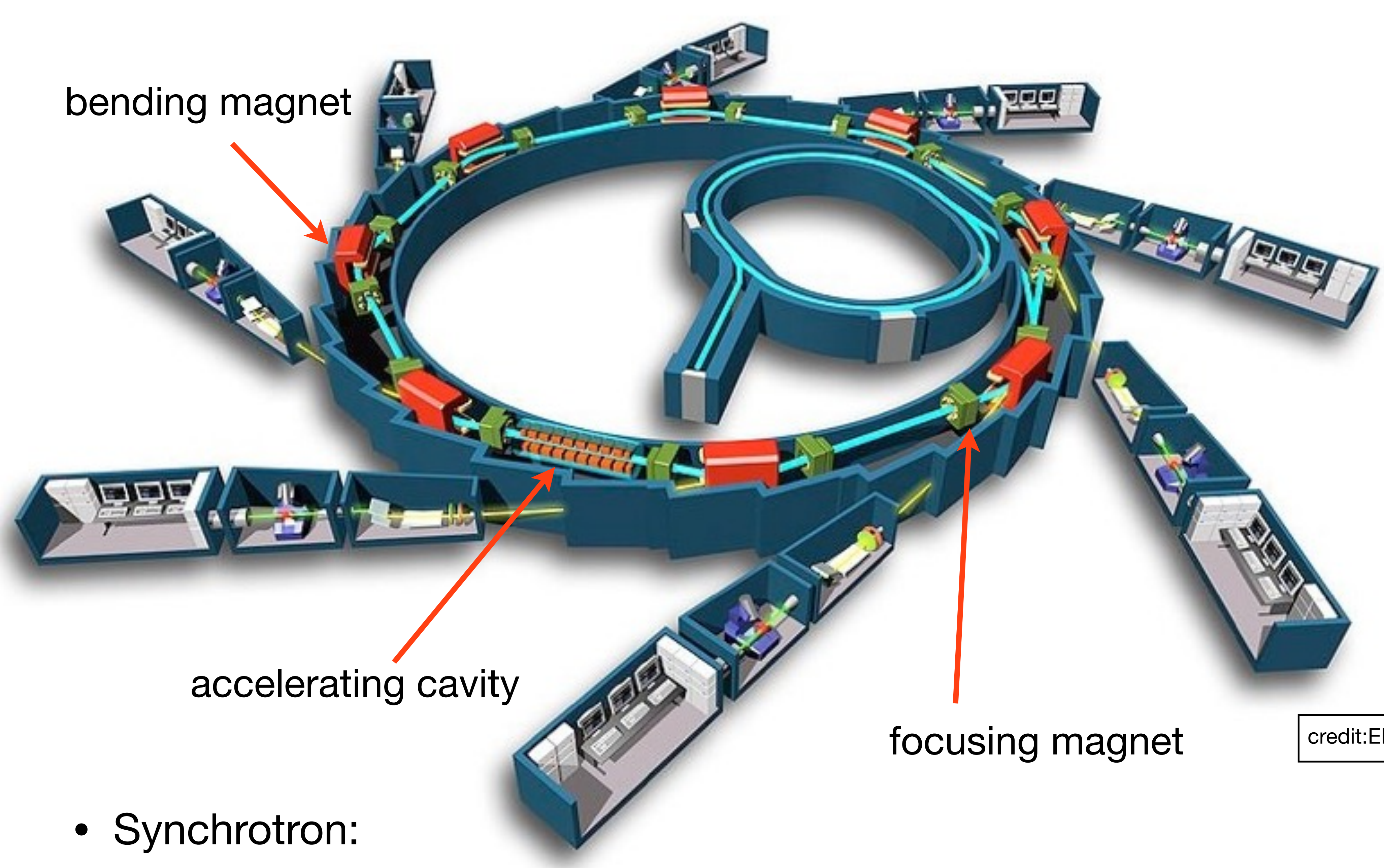


- Cyclotron:
    - Magnetic field to bend particles
    - Alternating electric field for acceleration



- Linear accelerator:
    - Alternating electric field for acceleration

Basic Accelerator Types: Synchrotron



credit:EPSIM 3D/JF Santarelli, Synchrotron Soleil

- 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!

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

Lorentz force acts on moving charge

It forces the particle on a circular track:

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

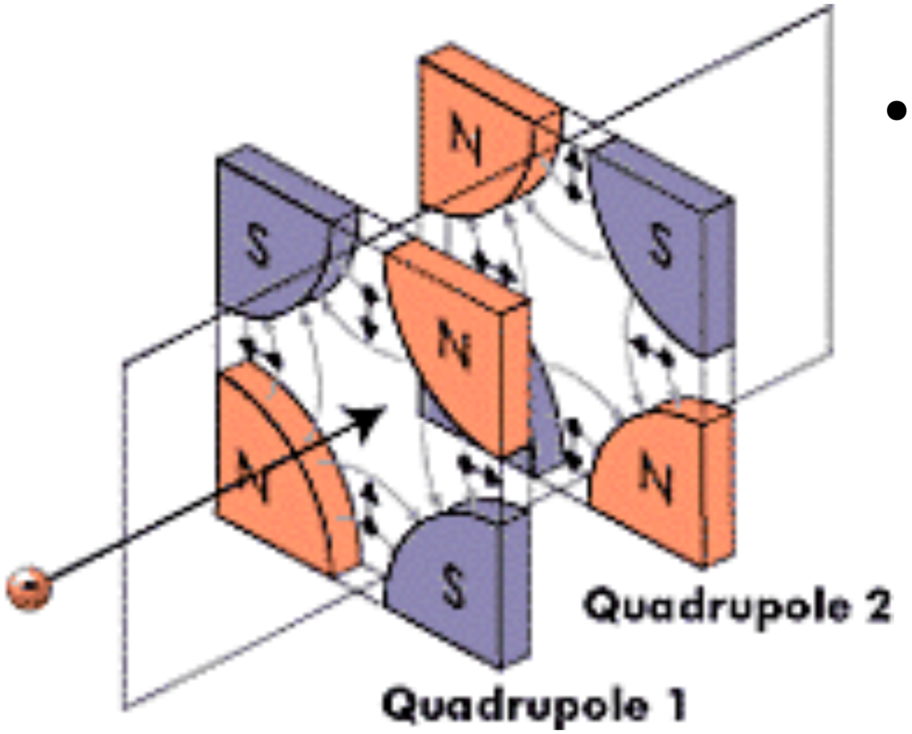
Often, the term “stiffness” is used:

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

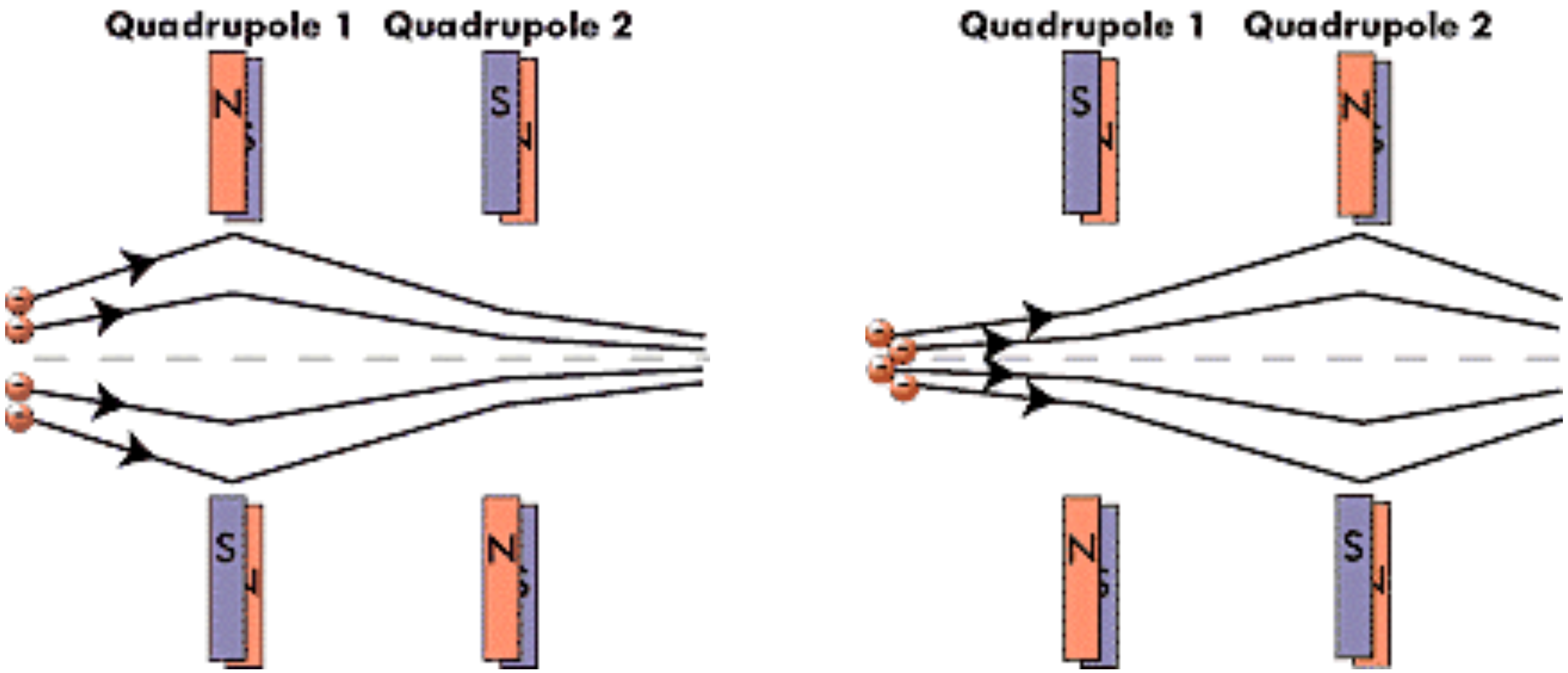
LHC : (Bρ)~23000 Tm

Strong Focusing

- Strong Focusing, or Alternating Gradient Synchroton: 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 loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

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

- Energy loss of electrons per turn in a storage ring

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

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

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

- Energy loss of electrons per turn in a storage ring

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

- Energy loss of protons

$$\Delta E = 7.8 \times 10^{-6}\frac{E^4[\mathrm{TeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

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

- Energy loss of electrons per turn in a storage ring

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

- Energy loss of protons

$$\Delta E = 7.8 \times 10^{-6}\frac{E^4[\mathrm{TeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

- Example: 100 GeV electrons in LHC-tunnel (ρ ~ 4.3 km), e.g. LEP: ΔE ~ 2 GeV

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

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

- Energy loss of electrons per turn in a storage ring

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

- Energy loss of protons

$$\Delta E = 7.8 \times 10^{-6}\frac{E^4[\mathrm{TeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

- Example: 100 GeV electrons in LHC-tunnel (ρ ~ 4.3 km), e.g. LEP: ΔE ~ 2 GeV
- Example: 7 TeV protons in LHC-tunnel (ρ ~ 4.3 km): ΔE ~ 4.4 keV

Limits for Ring Accelerators: Synchrotron Radiation

- Charged particles loose energy when accelerated:

$$P = \frac{1}{6\pi\epsilon_0}\frac{e^2a^2}{c^3}\gamma^4 \qquad a = \frac{v^2}{\rho}$$

ρ: bending radius

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

- Energy loss of electrons per turn in a storage ring

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

- Energy loss of protons

$$\Delta E = 7.8 \times 10^{-6}\frac{E^4[\mathrm{TeV}^4]}{\rho[\mathrm{km}]}\mathrm{MeV}$$

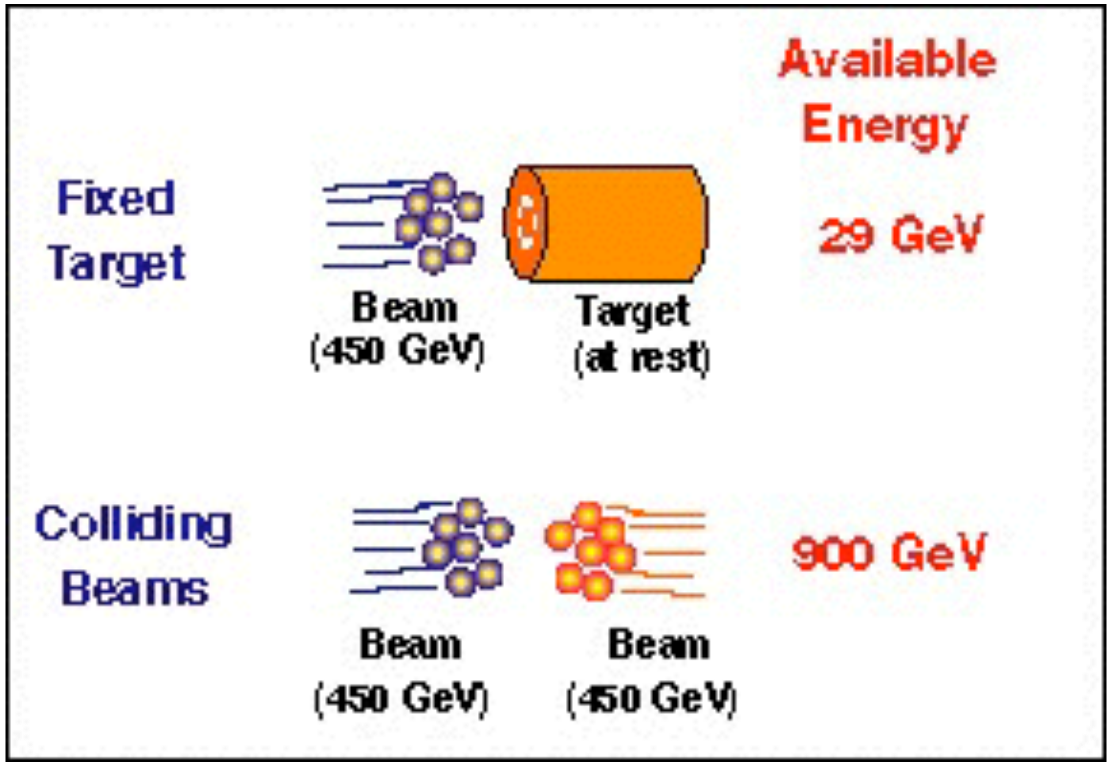
- Example: 100 GeV electrons in LHC-tunnel (ρ ~ 4.3 km), e.g. LEP: ΔE ~ 2 GeV

- Example: 7 TeV protons in LHC-tunnel (ρ ~ 4.3 km): ΔE ~ 4.4 keV

➾ 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

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

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

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

Key Collider Parameters

- Event Rate $$R = L \cdot \sigma$$

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

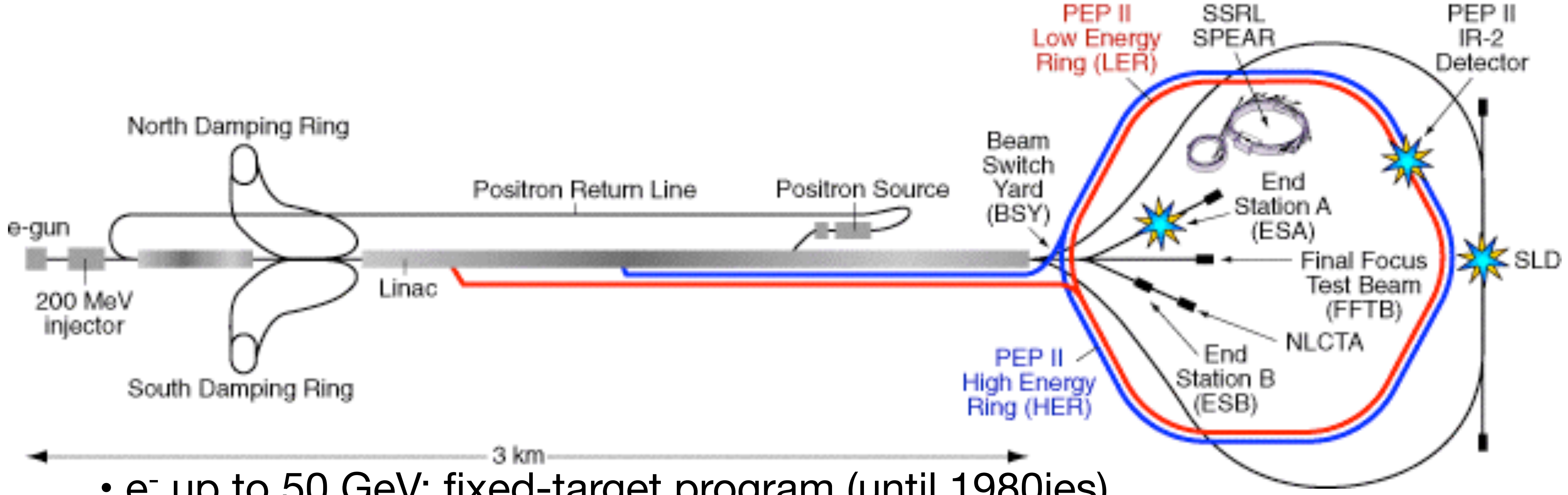
f: Collision frequency
n_i: Number of particles in bunch i
σ_x: horizontal beam size
σ_y: vertical beam size

... assuming a gaussian beam profile and perfect overlap

- 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)

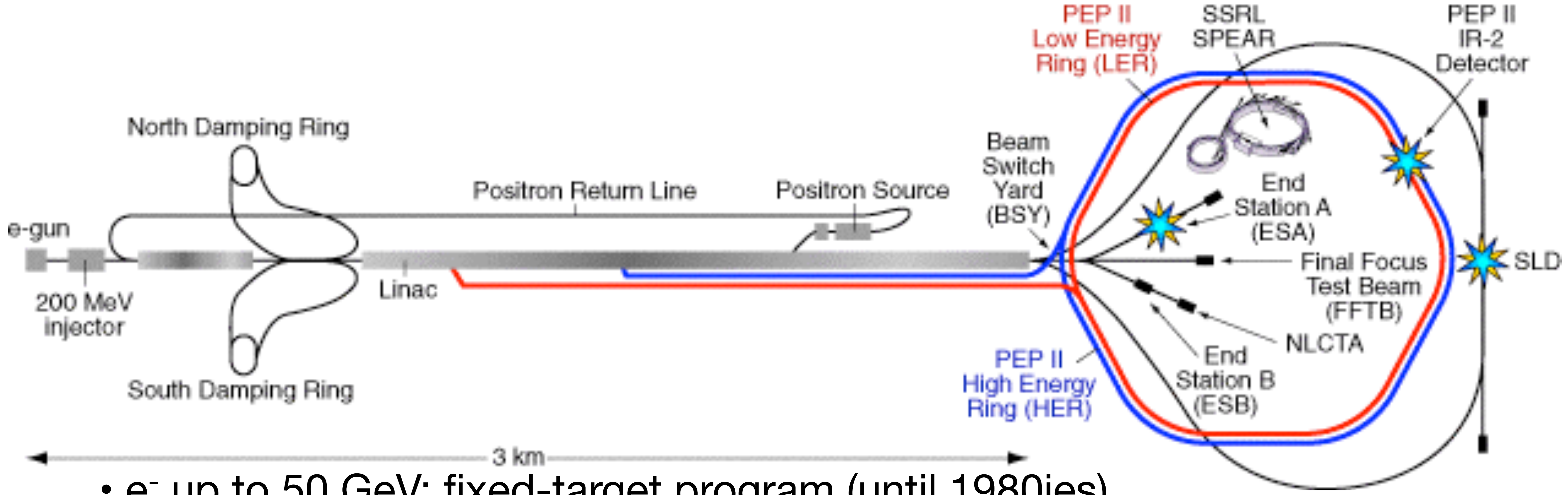
$$L = f \frac{n_1 n_2}{4\sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}}$$

SLAC Linear Collider SLC



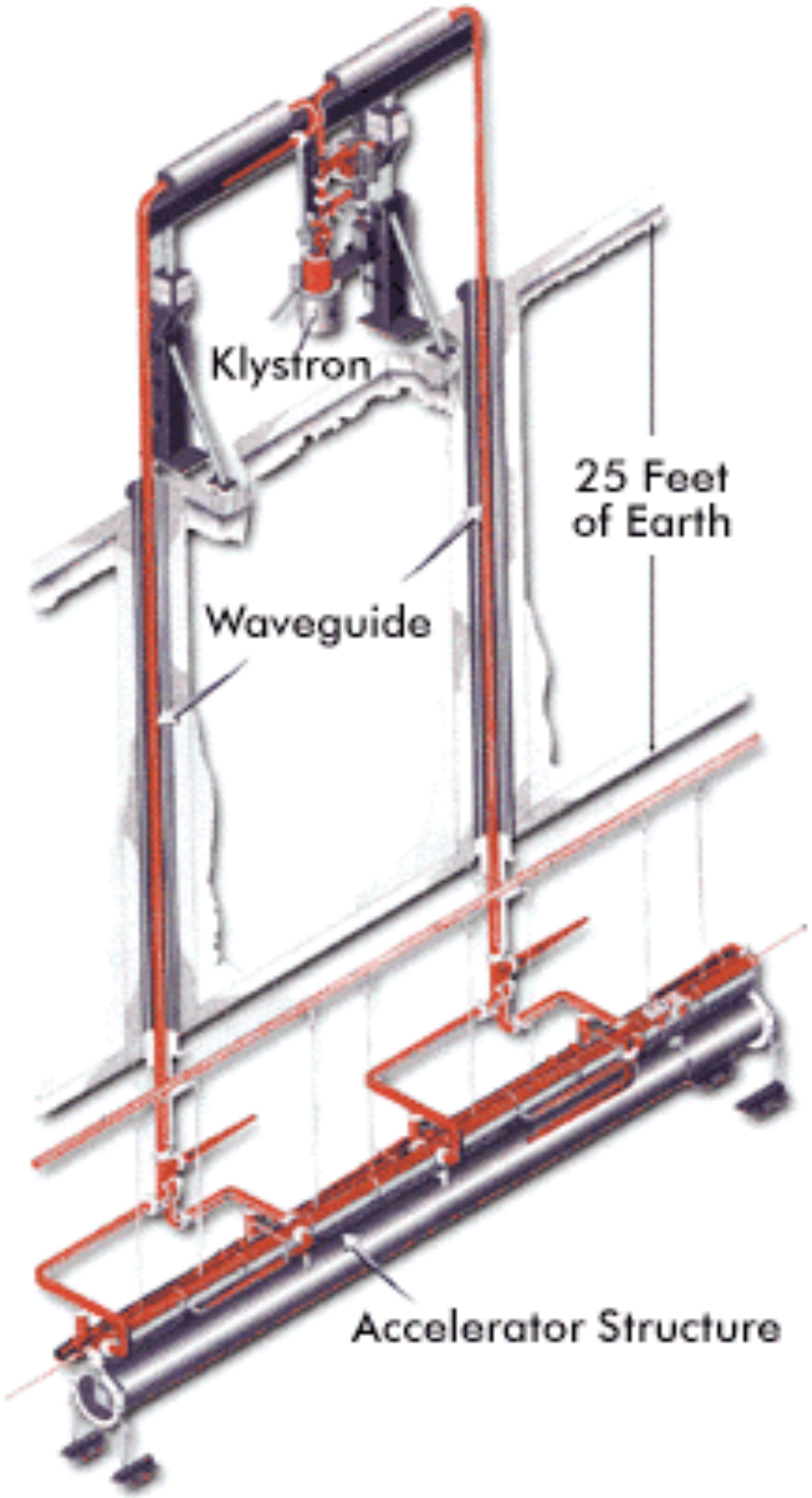
- e^- up to 50 GeV; fixed-target program (until 1980ies)
- e^- und e^+ for PEP-I storage ring (E_{cm} = 29 GeV; early 1980ies)
- e^- und e^+ for SLC collider ($E_{cm} = M_Z$ ~ 91 GeV; 1989 - 1999)
- e^- und e^+ for PEP-II storage ring (E_{cm} ~10 GeV; 1999 - 2008)

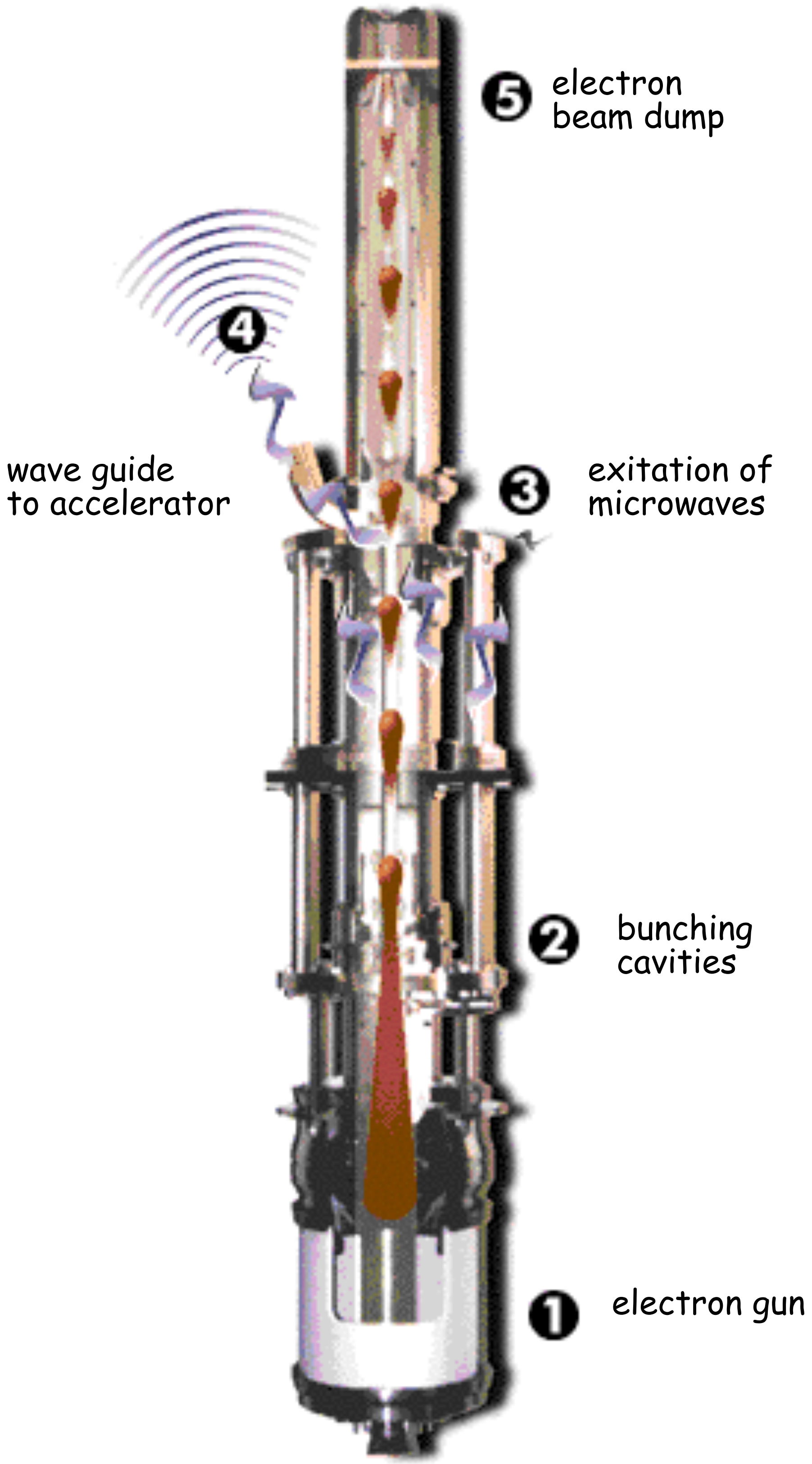
SLAC Linear Collider SLC



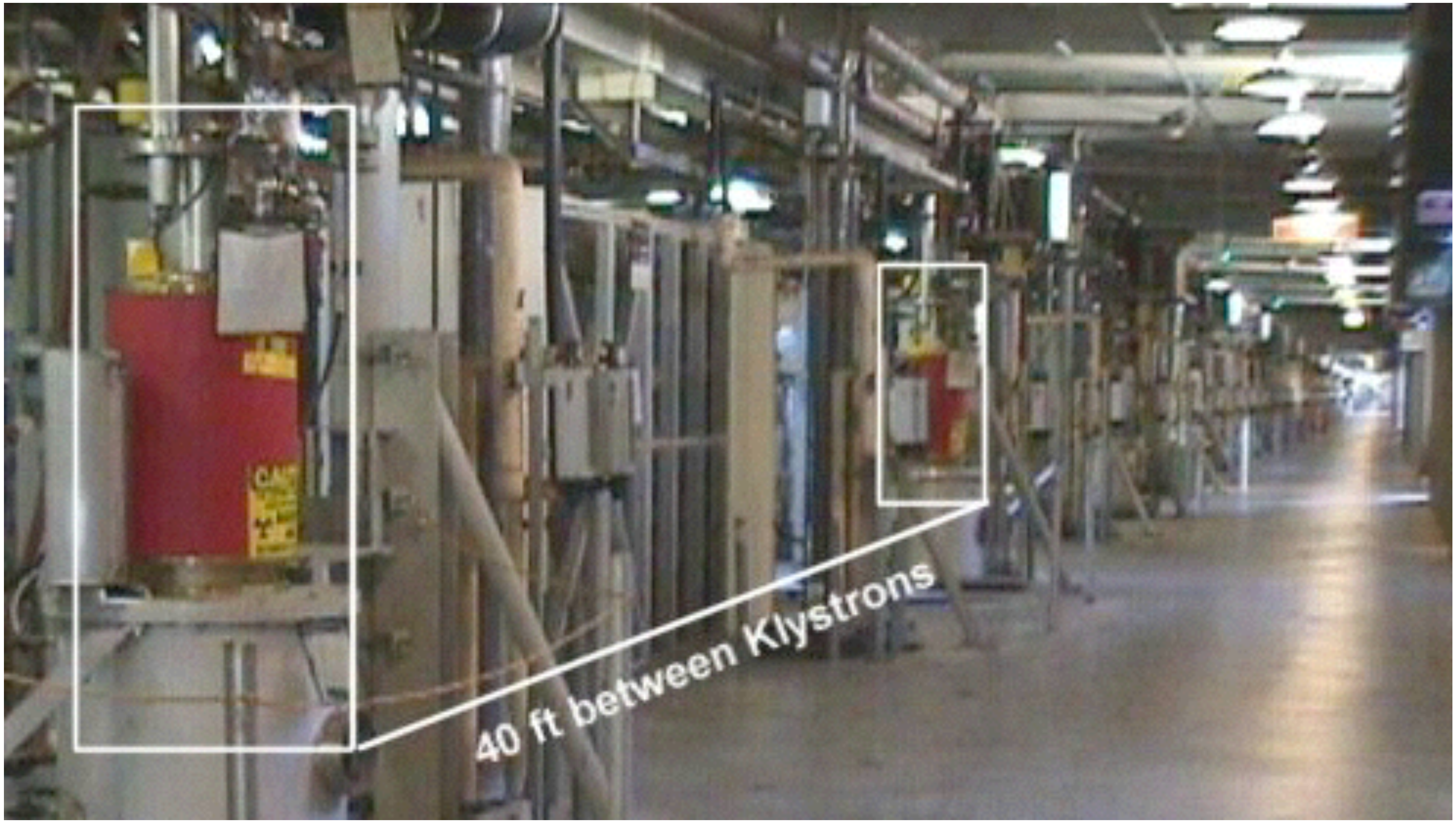
- e^- up to 50 GeV; fixed-target program (until 1980ies)
- e^- und e^+ for PEP-I storage ring (E_{cm} = 29 GeV; early 1980ies)
- e^- und e^+ for SLC collider ($E_{cm} = M_Z$ ~ 91 GeV; 1989 - 1999)
- e^- und e^+ for PEP-II storage ring (E_{cm} ~10 GeV; 1999 - 2008)

Powering Accelerators: Klystrons





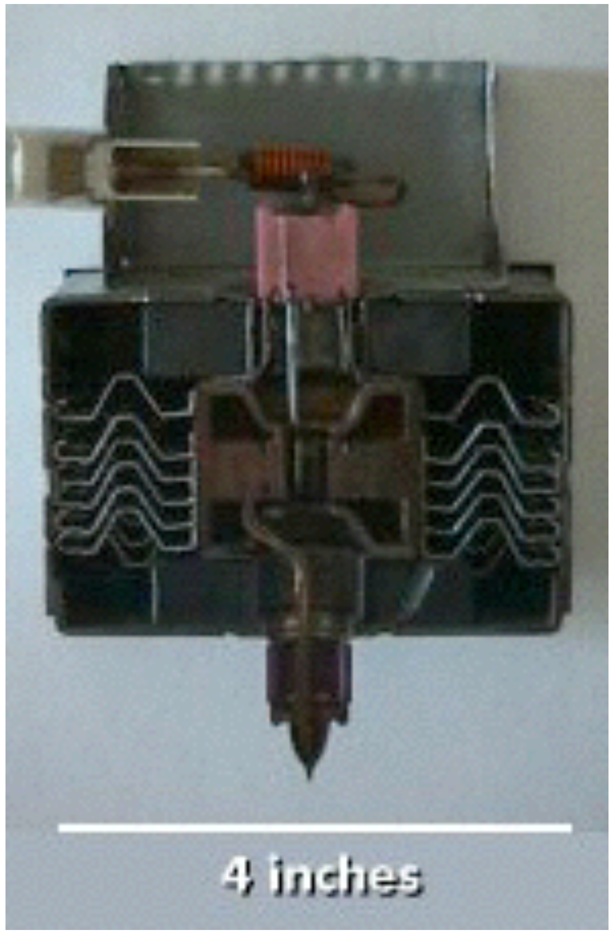
Klystrons



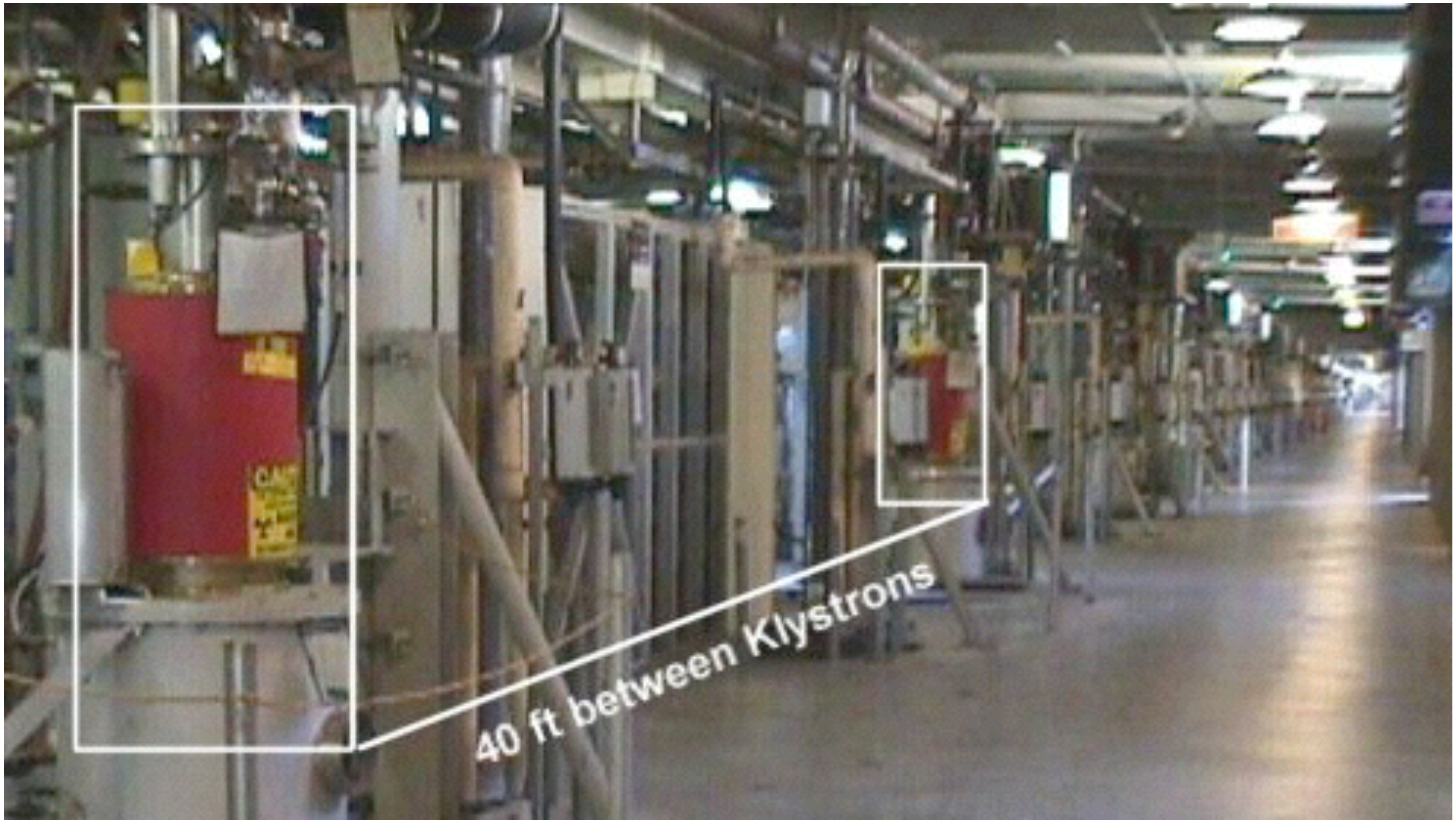
Microwave generator
in a Microwave Oven

SLAC Klystron Gallery

Klystrons



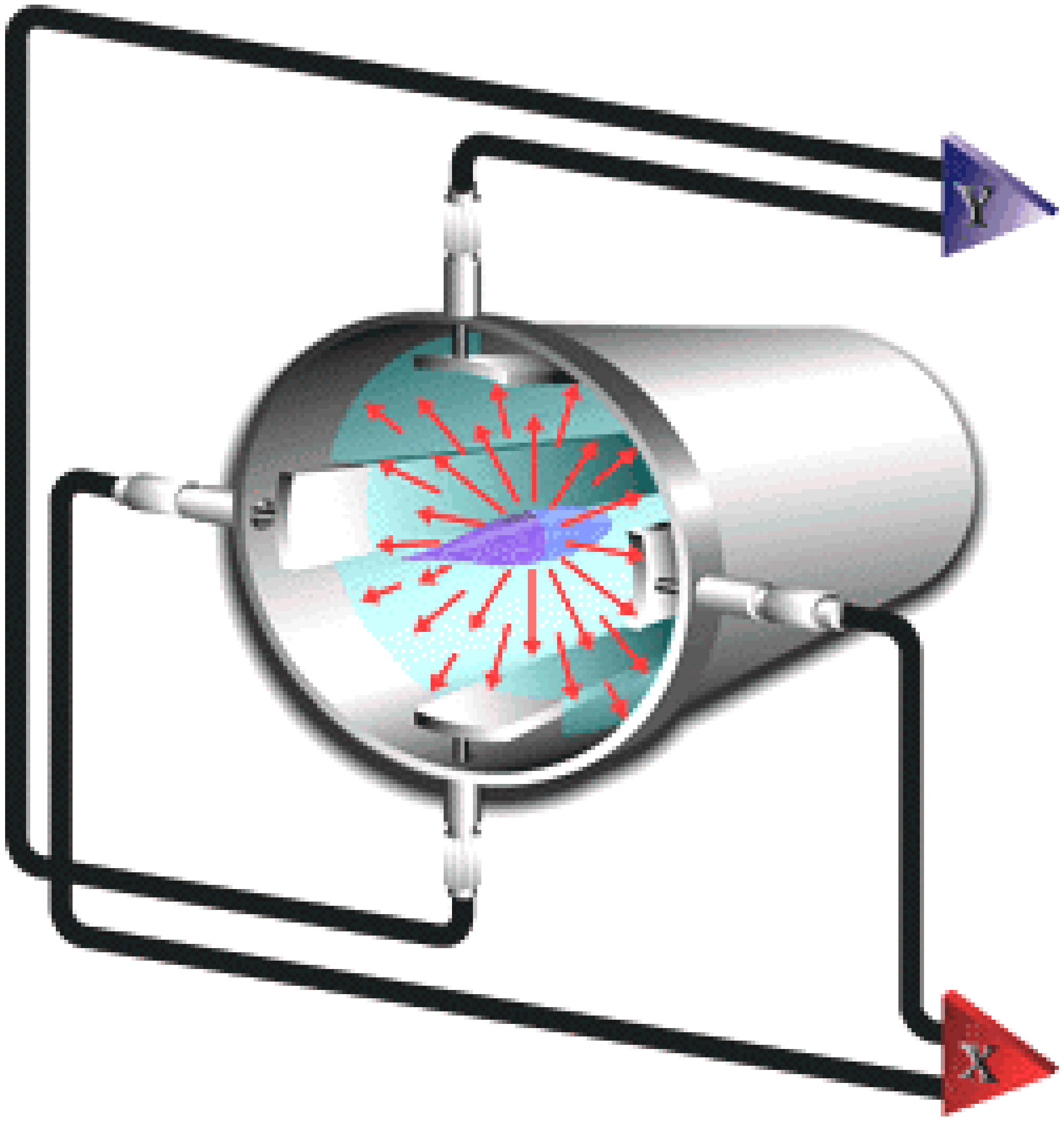
Microwave generator in a Microwave Oven



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

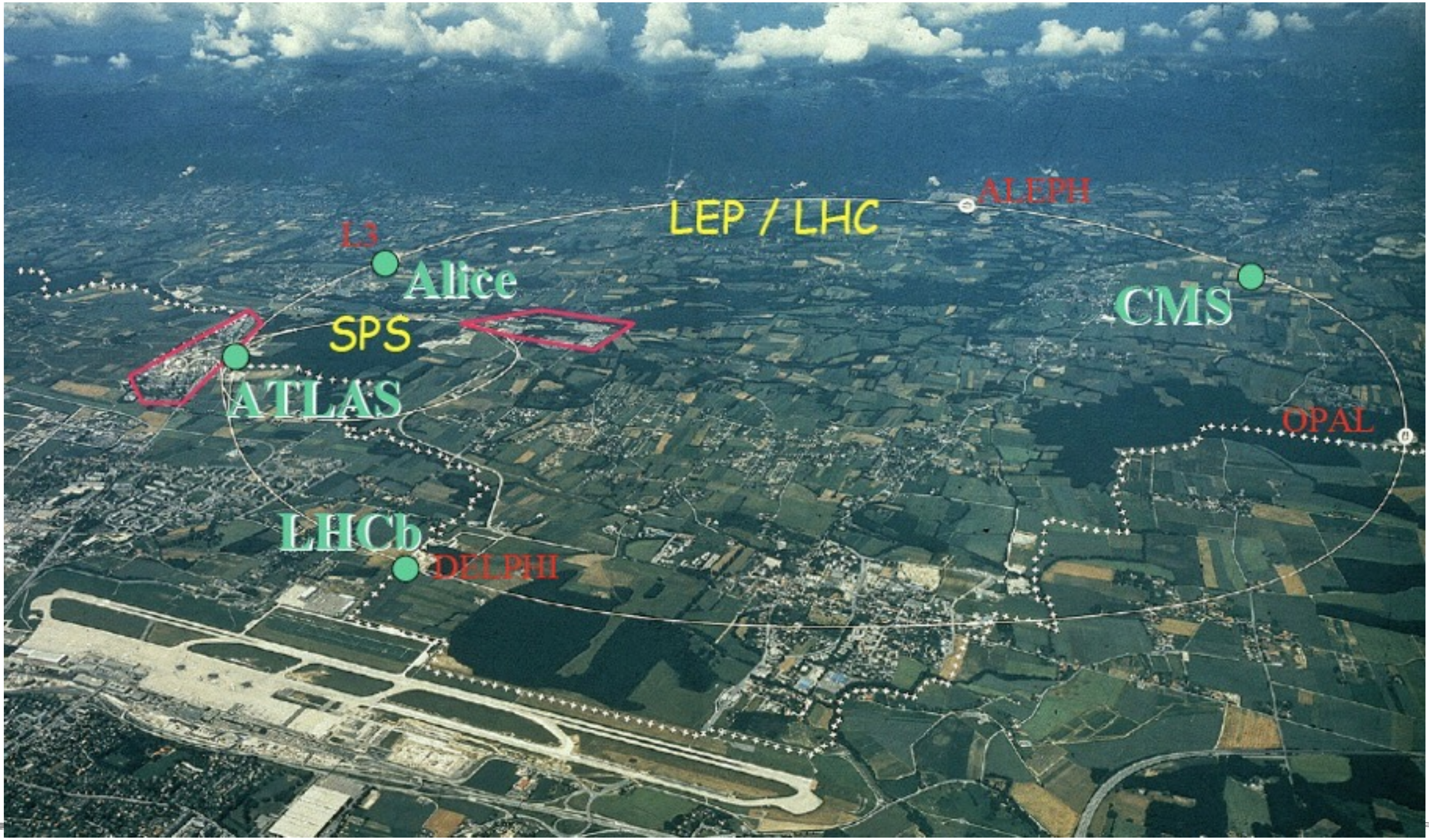
- DESY Hamburg: Petra (e^+e^-), Hera (ep)

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

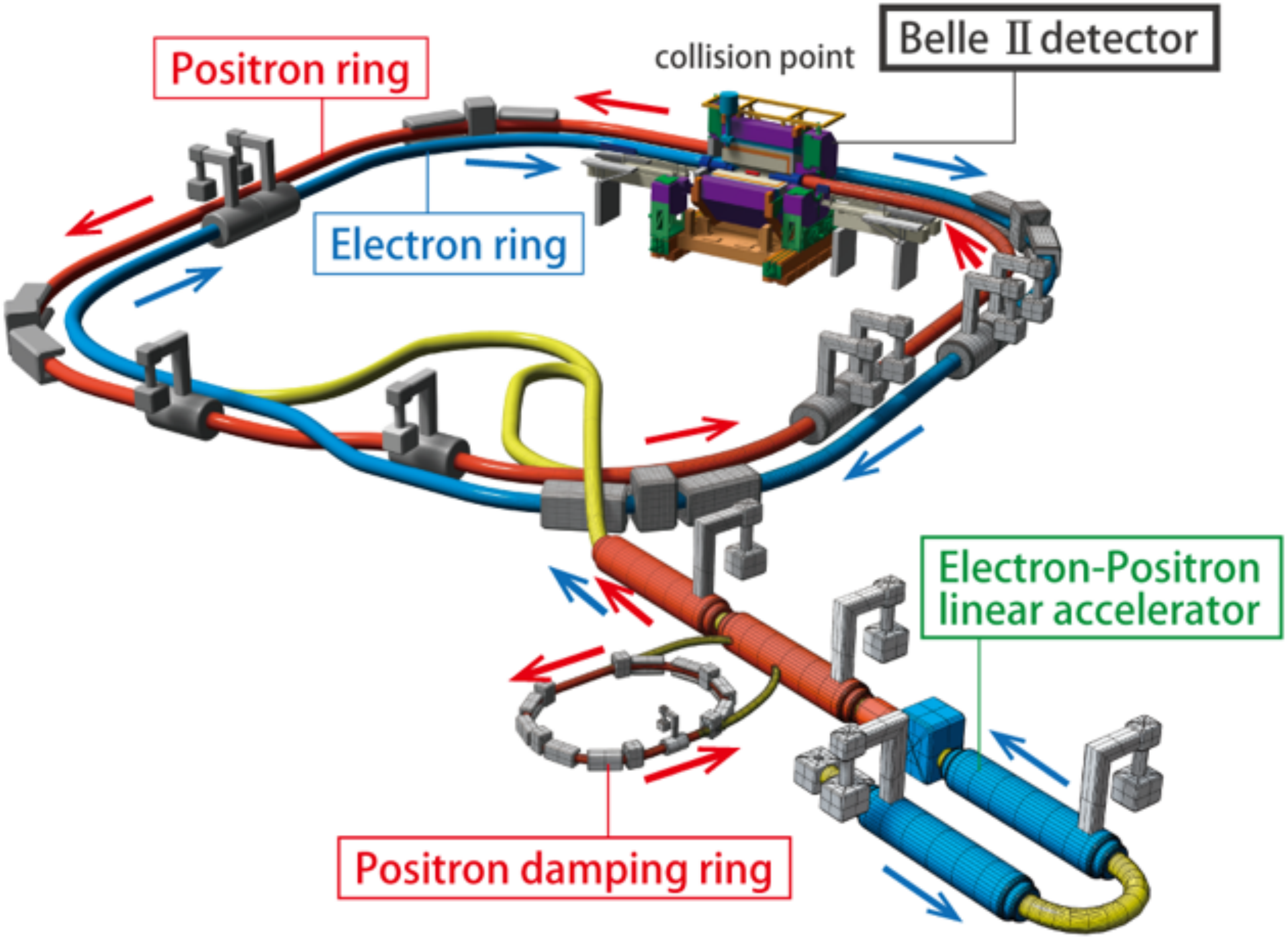
Now: Home of the LHC

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

Foto: CERN

The Latest Addition: SuperKEKB

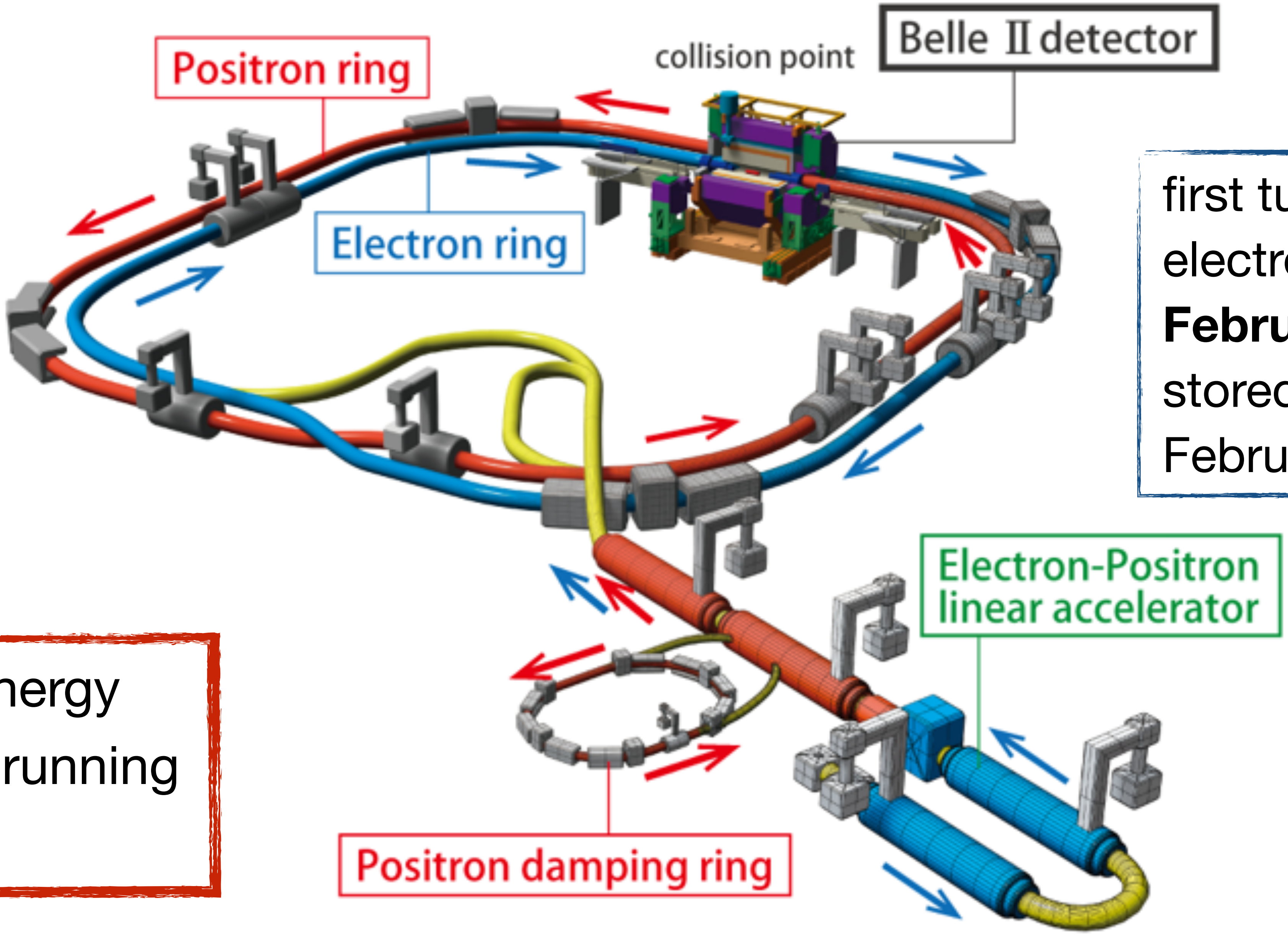
- Asymmetric e^+e^- collider: 7 GeV on 4 GeV to produce boosted Υ(4s) at a center of mass energy of 10.58 GeV, decays into entangled B mesons
  - Used to study CP violation, indirect searches for New Physics



The Latest Addition: SuperKEKB

- Asymmetric e^+e^- collider: 7 GeV on 4 GeV to produce boosted Υ(4s) at a center of mass energy of 10.58 GeV, decays into entangled B mesons
  - Used to study CP violation, indirect searches for New Physics

first turns of positrons: **February 8** stored beam on February 10

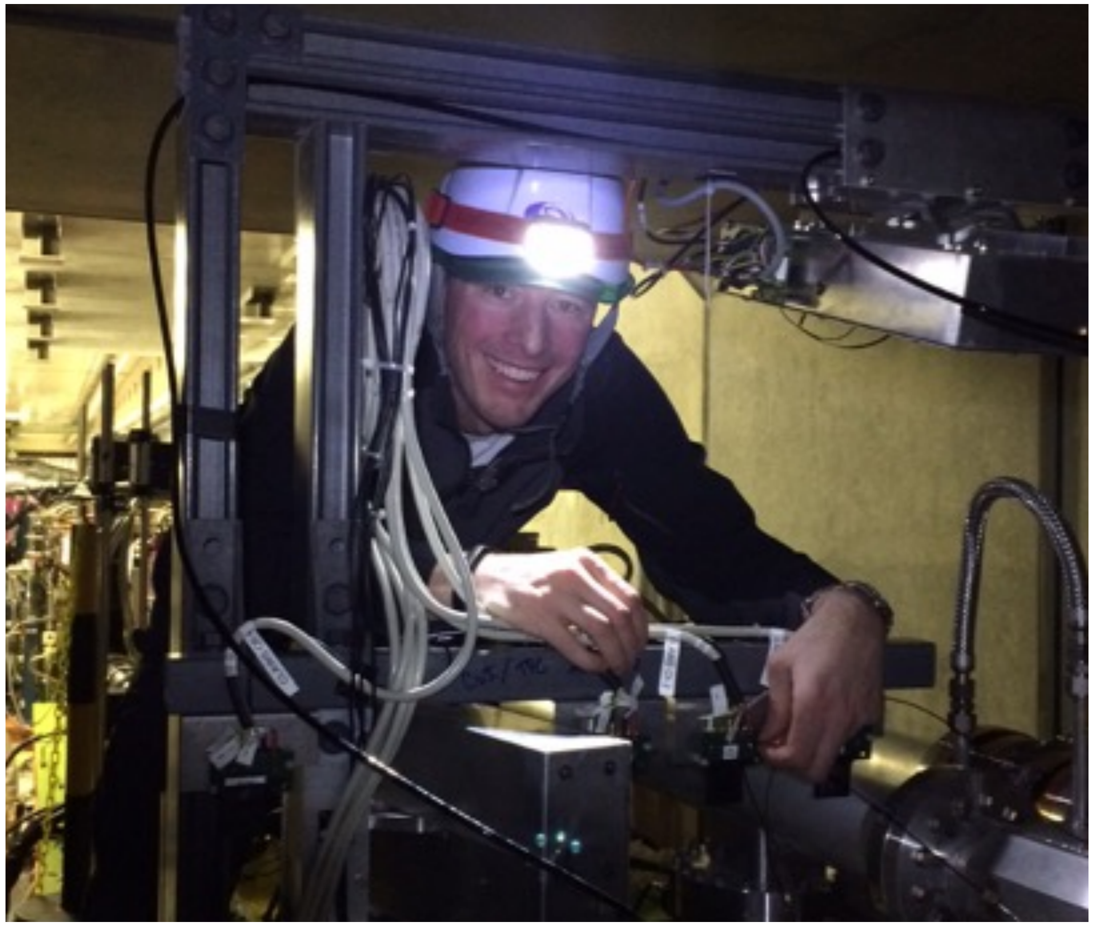


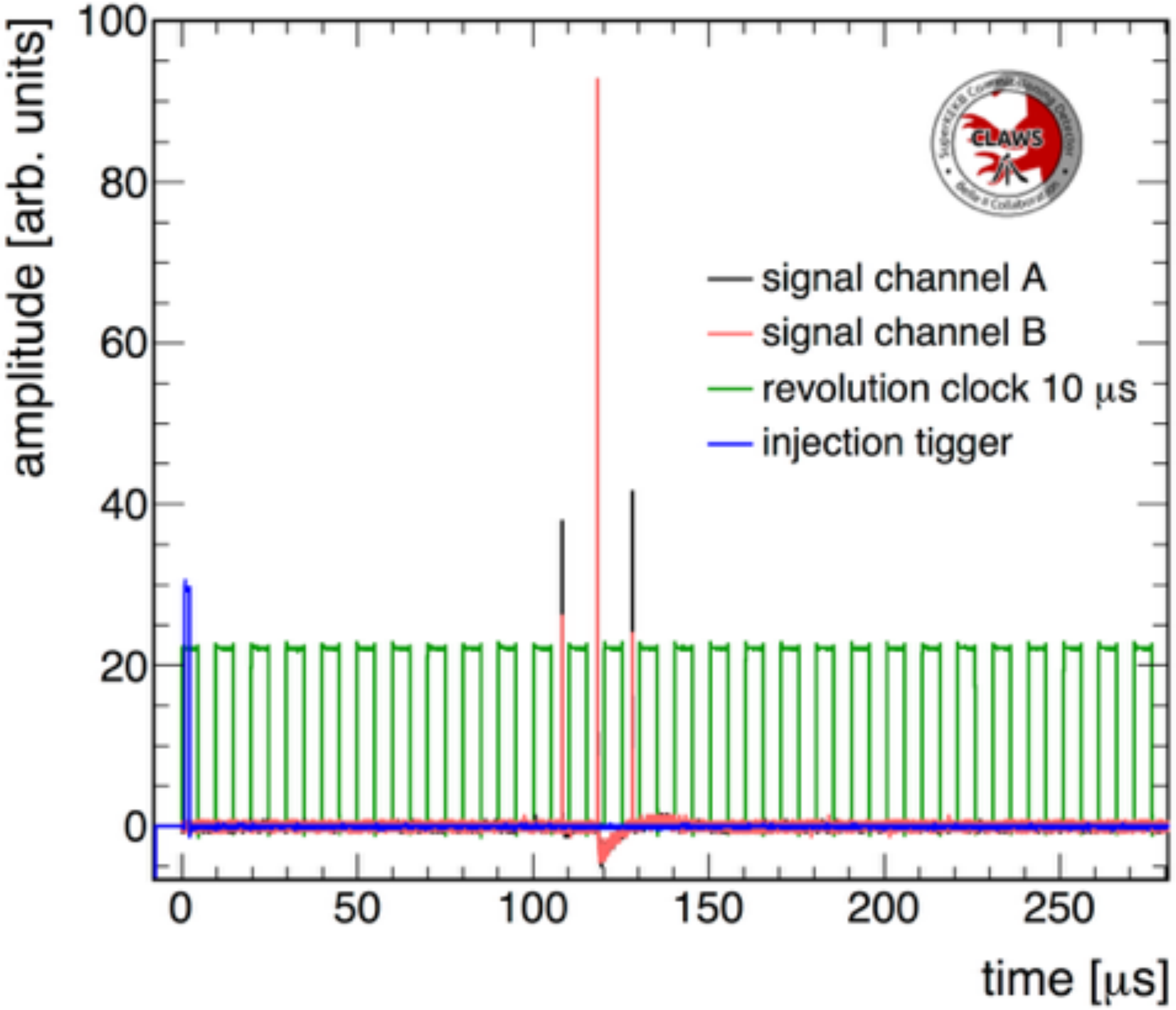
first turns of electrons: **February 24** stored beam on February 26

The first high-energy collider to start running after LHC!

SuperKEKB Startup: With MPP Detectors

- A small scintillator system was installed at the SuperKEKB interaction point to monitor background levels prior to the installation of the Belle-II detector
  - Saw the first particles from the accelerator (interactions of electrons with remaining gas in the beam pipe)



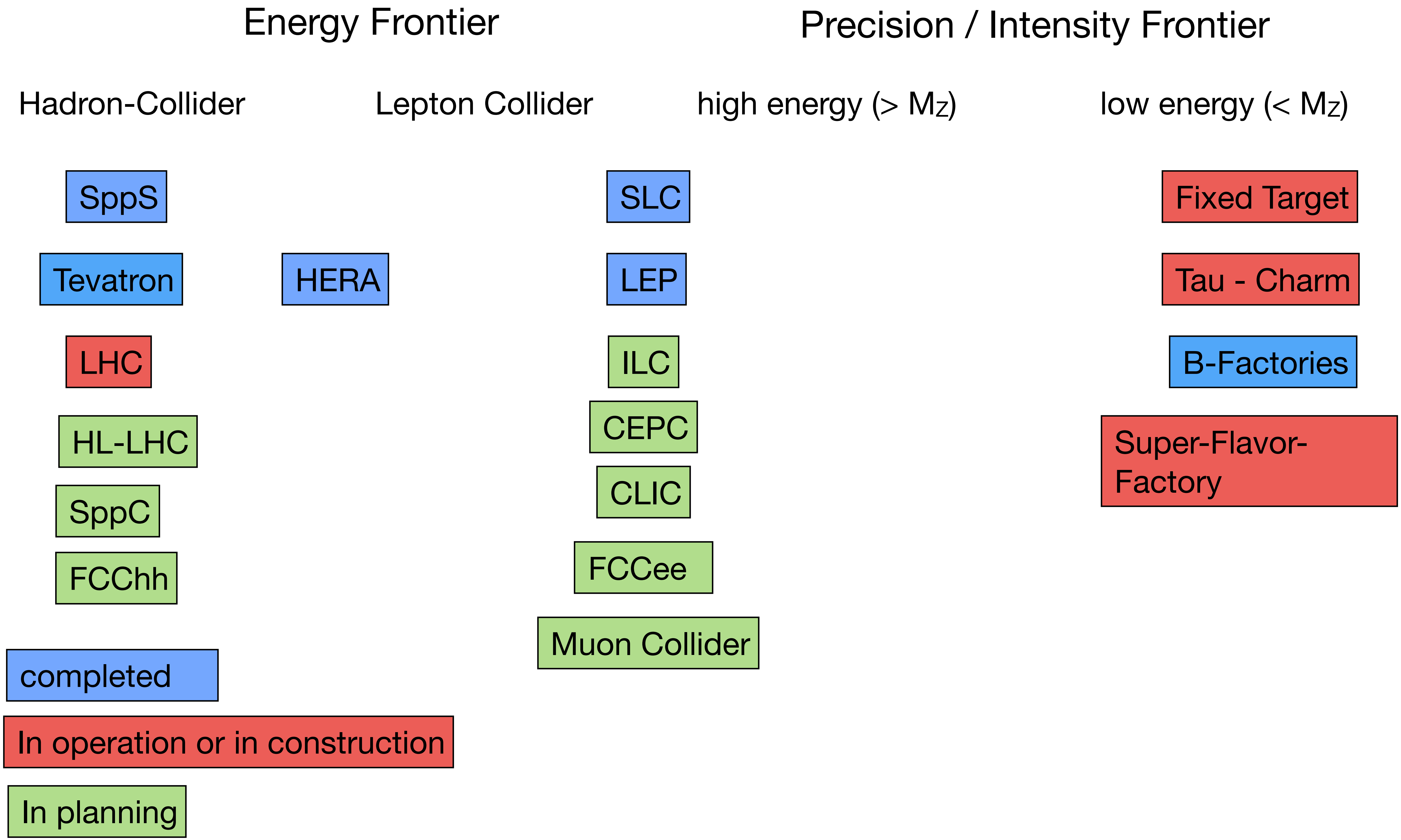


Collider Parameters - Overview

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*	3×10^{30}
LEP (CERN)	1989 – 2000	$e^+ e^-$	104	26.7	10^{32}
ILC (??)	2030+ (?)	$e^+ e^-$	250 (500)	*15 + 15*	2×10^{34}
KEKB (KEK)	1999 - 2010	$e^+ e^-$	8 x 3.5	3.0	2×10^{34}
PEP-II (SLAC)	1999 -	$e^+ e^-$	9 x 3.1	2.2	10^{34}
SuperKEKB	2016- (?)	e^+e^-	7 x 4		8×10^{35}
HERA (DESY)	1991 -	e p	30 x 920	6.3	8×10^{31}
S$p\bar{p}$S (CERN)	1981 – 1990	$p\bar{p}$	315	6.9	6×10^{30}
TEVATRON (Fermilab)	1987 - 2011	$p\bar{p}$	1000	6.28	2×10^{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 (> M_Z)

low energy (< M_Z)

SppS

Tevatron

LHC

HL-LHC

SppC

FCChh

HERA

SLC

LEP

ILC

CEPC

CLIC

FCCee

Muon Collider

Fixed Target

Tau - Charm

B-Factories

Super-Flavor-Factory

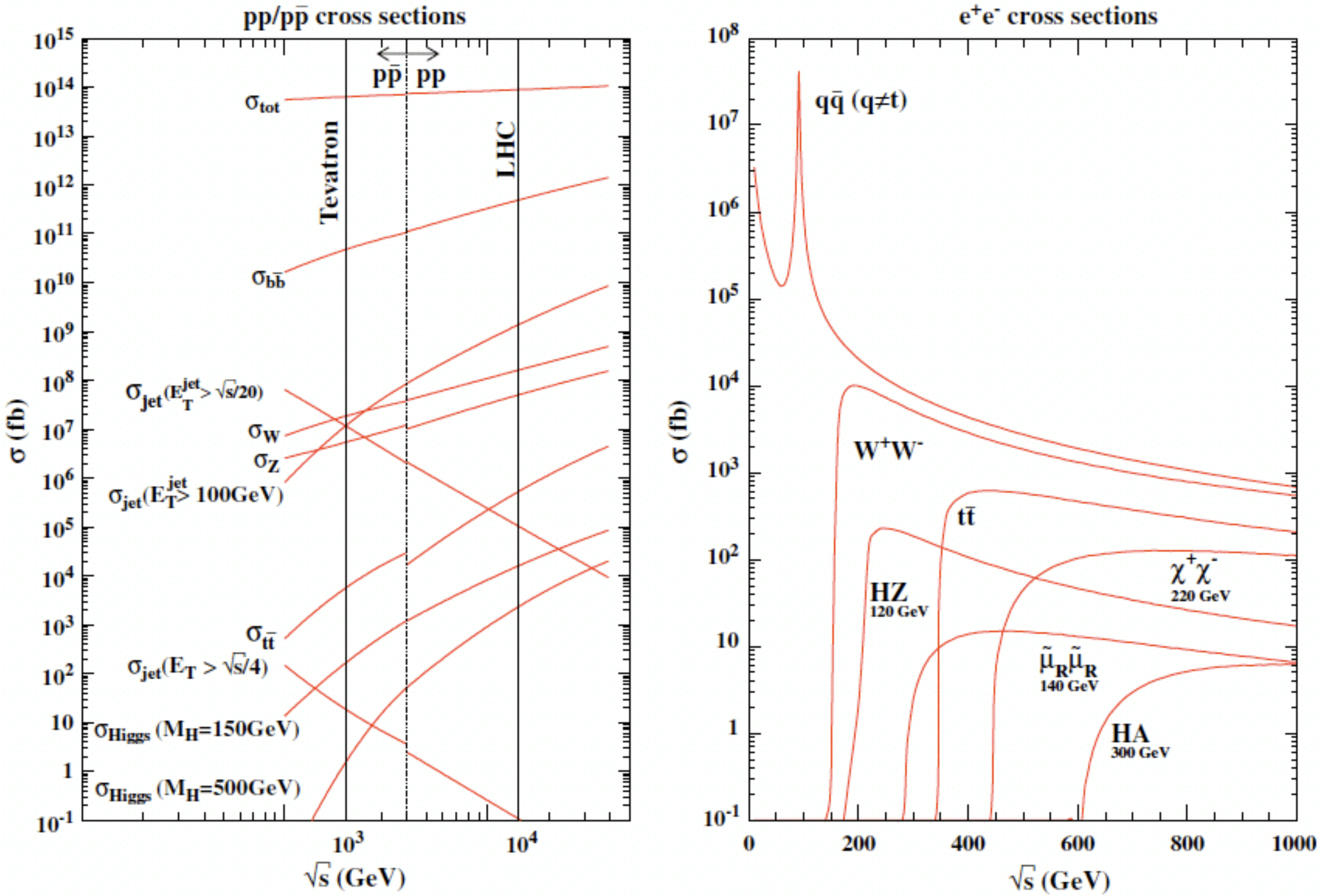
completed

In operation or in construction

In planning

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

- Solutions for the problem of synchrotron radiation:
  - 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)

High Energy Lepton Colliders

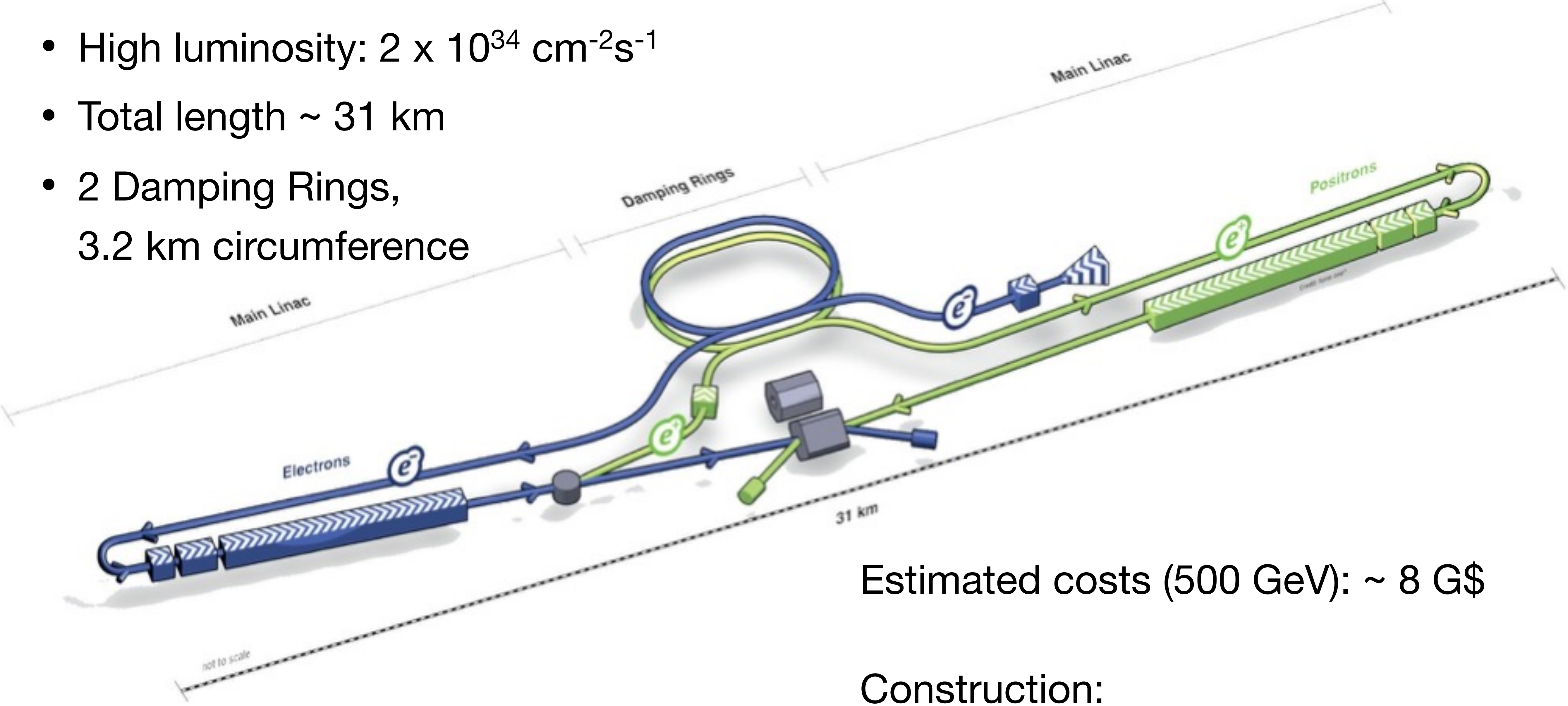
- Solutions for the problem of synchrotron radiation:
  - No curves: Linear accelerators for electrons
  - High mass: muons instead of electrons

- 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)

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 x 10^{34} $cm^{-2}s^{-1}$
- Total length ~ 31 km
- 2 Damping Rings,
  3.2 km circumference

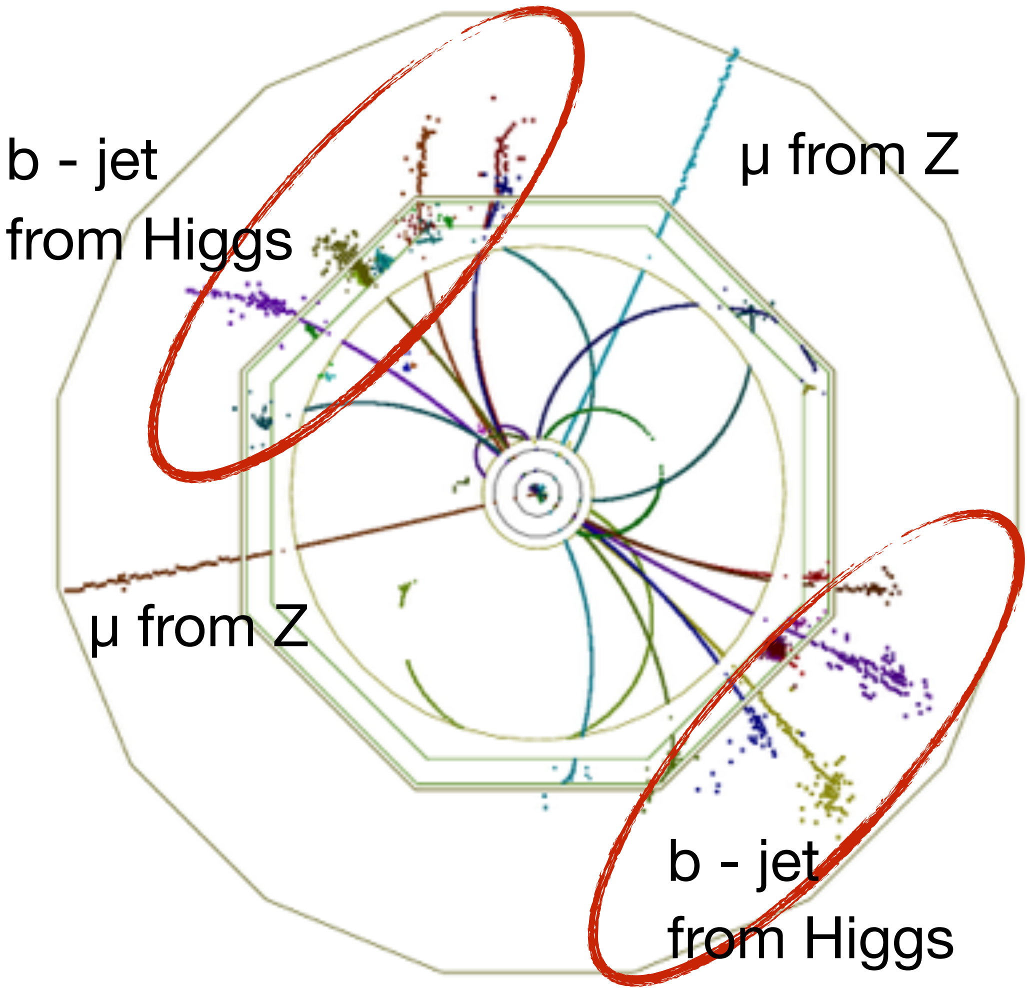


Estimated costs (500 GeV): ~ 8 G$

Construction:
~ 9 years until commissioning

One Physics Example: Higgs

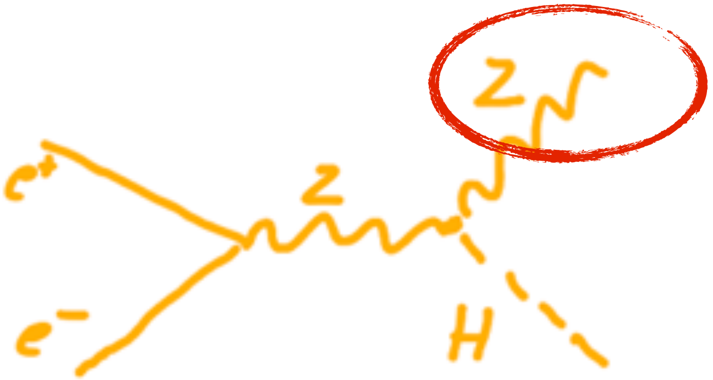
- A flagship measurement: Model-independent coupling of Higgs to Z
- Obtained from recoil mass measurement of reconstructed Z boson, independent of Higgs decay



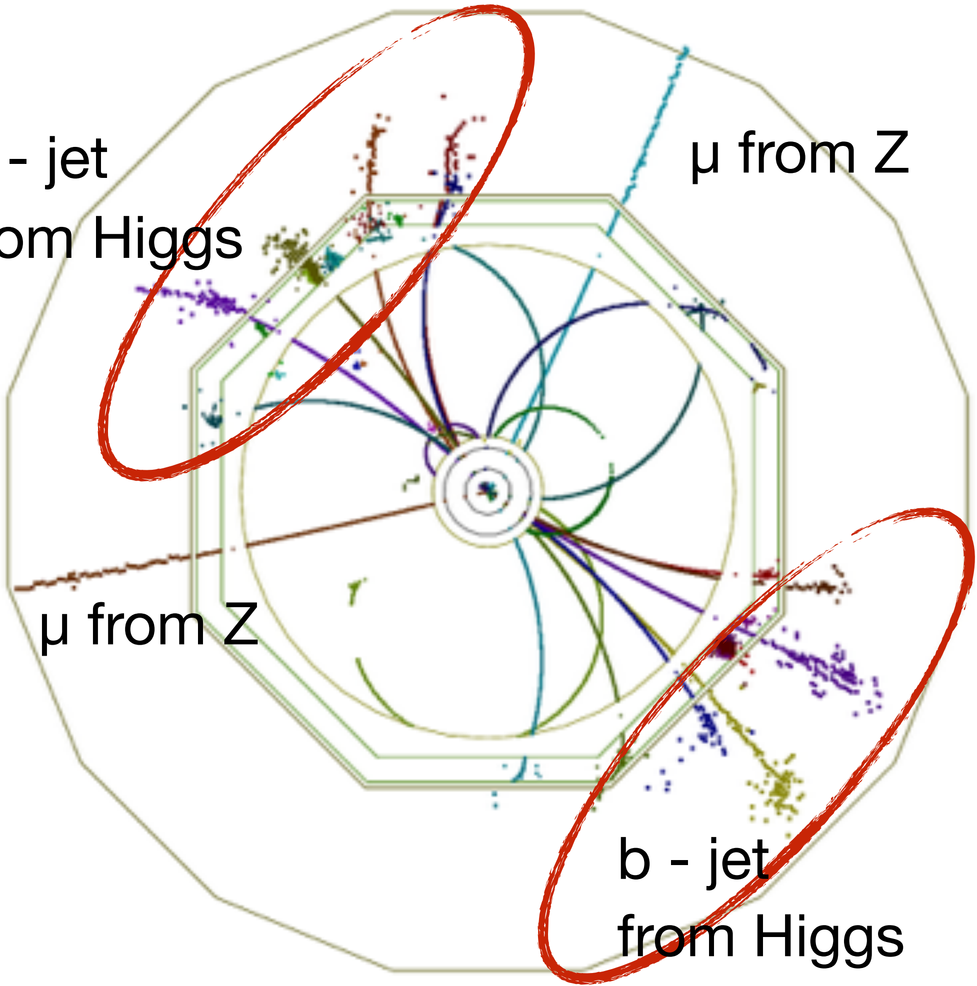
$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

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



$$\boxed{m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}}$$


b - jet
from Higgs

μ from Z

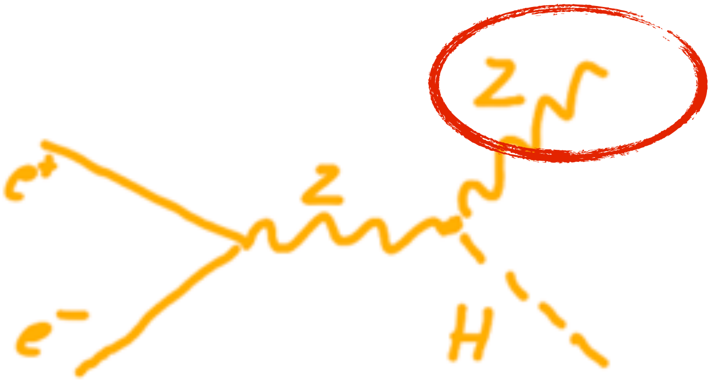
μ from Z

b - jet
from Higgs

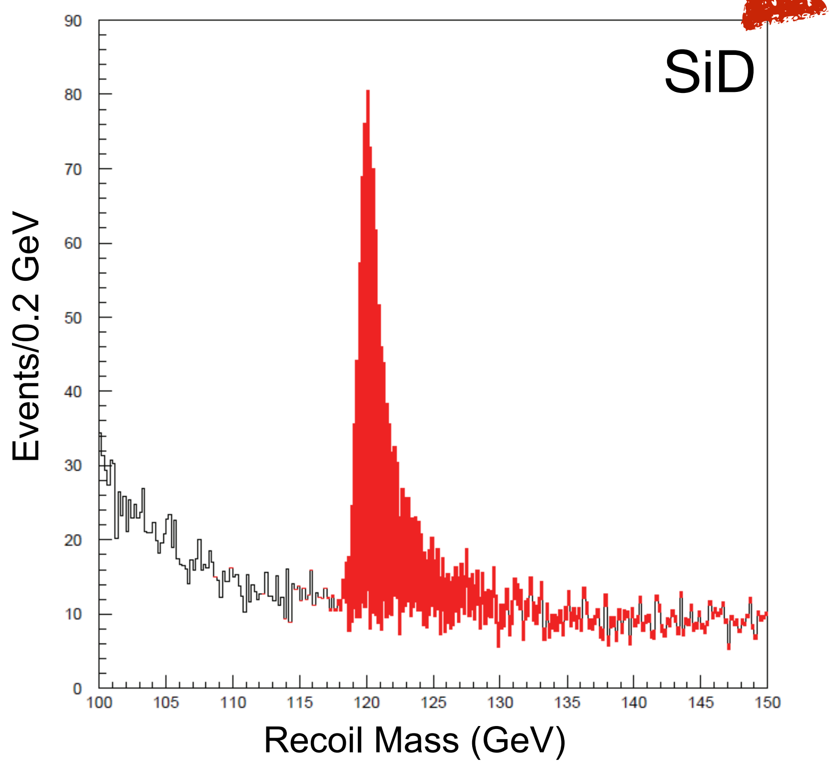
$e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

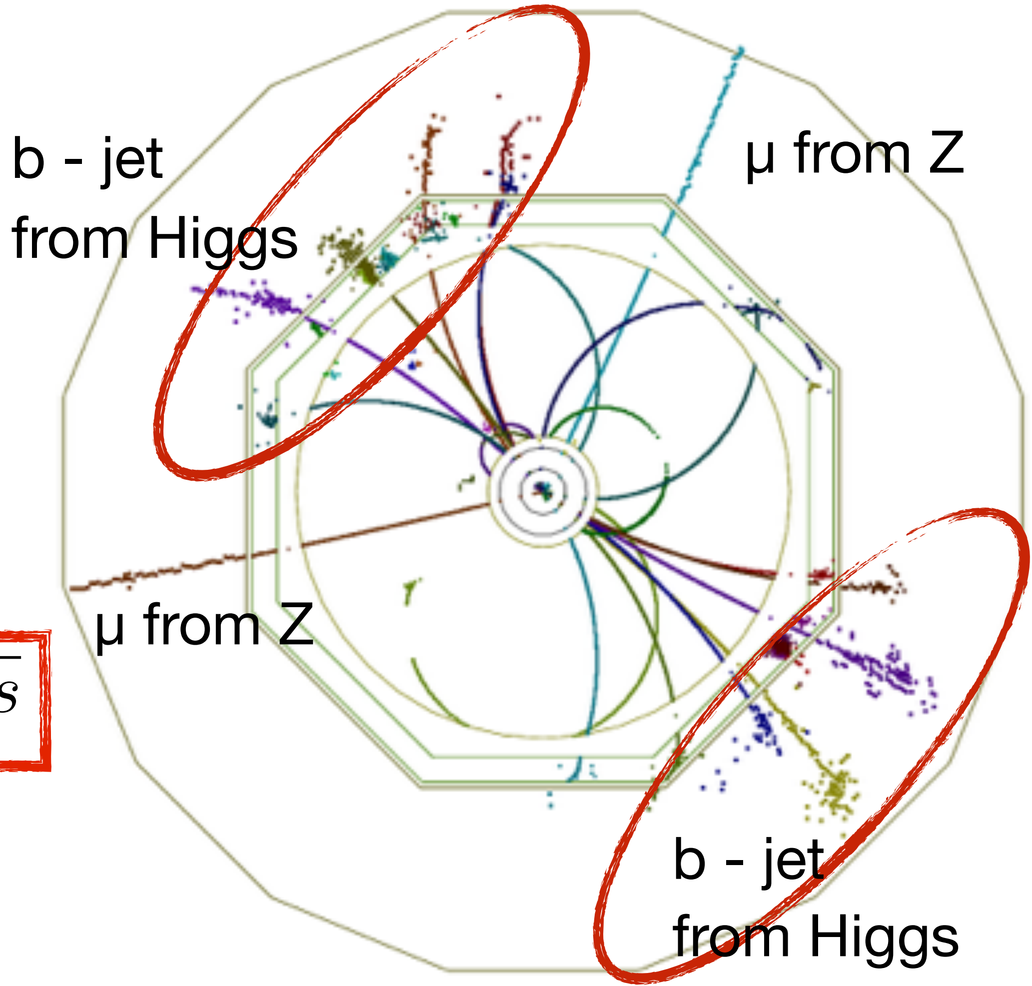
One Physics Example: Higgs

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



$$\boxed{m_{rec}^2 = s + m_Z^2 - 2E_Z\sqrt{s}}$$





$e^+e^- \to ZH \to \mu^+\mu^- b\bar{b}$ ILD, 250 GeV

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

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

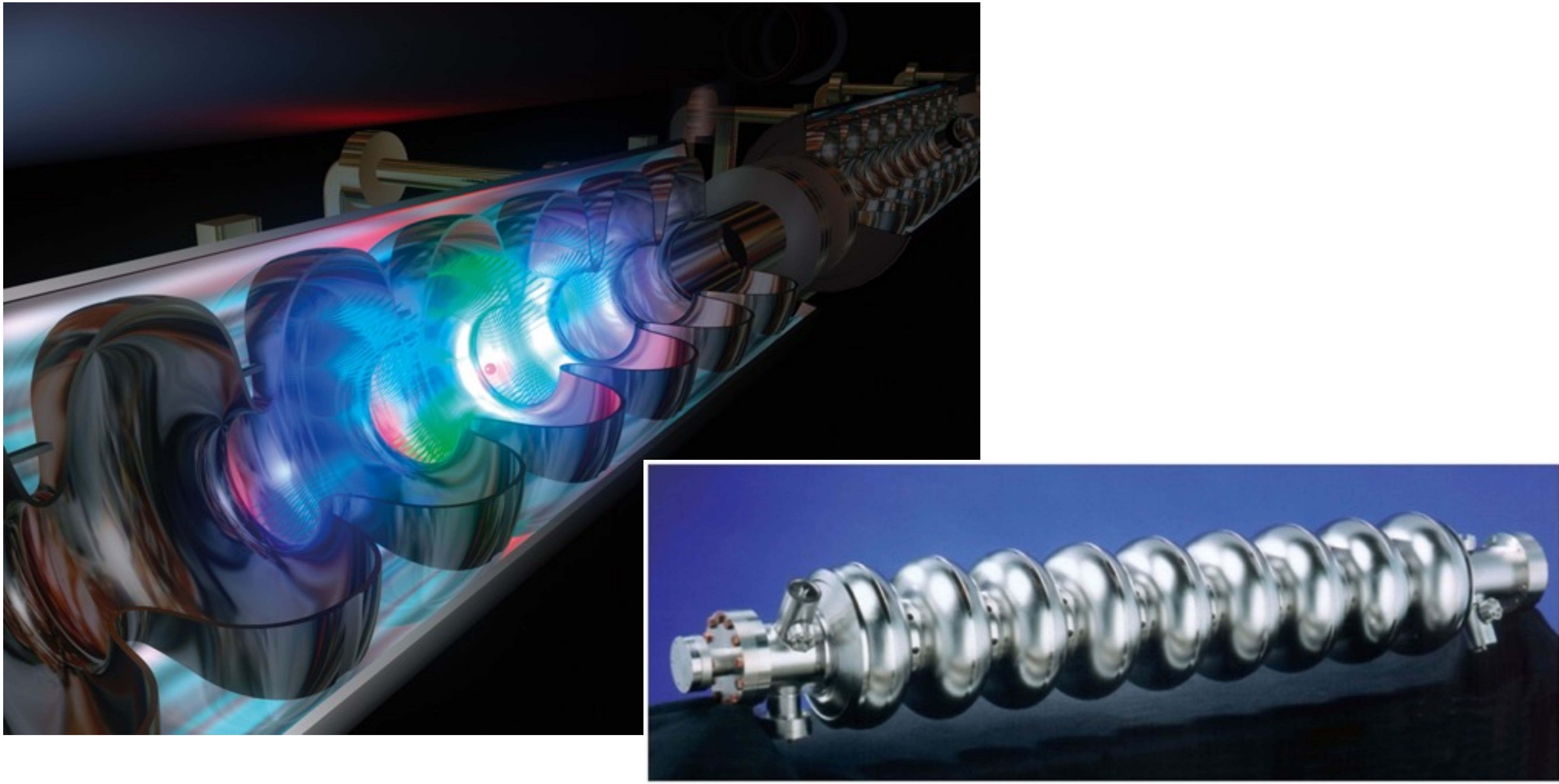
Advantages:

- 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

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

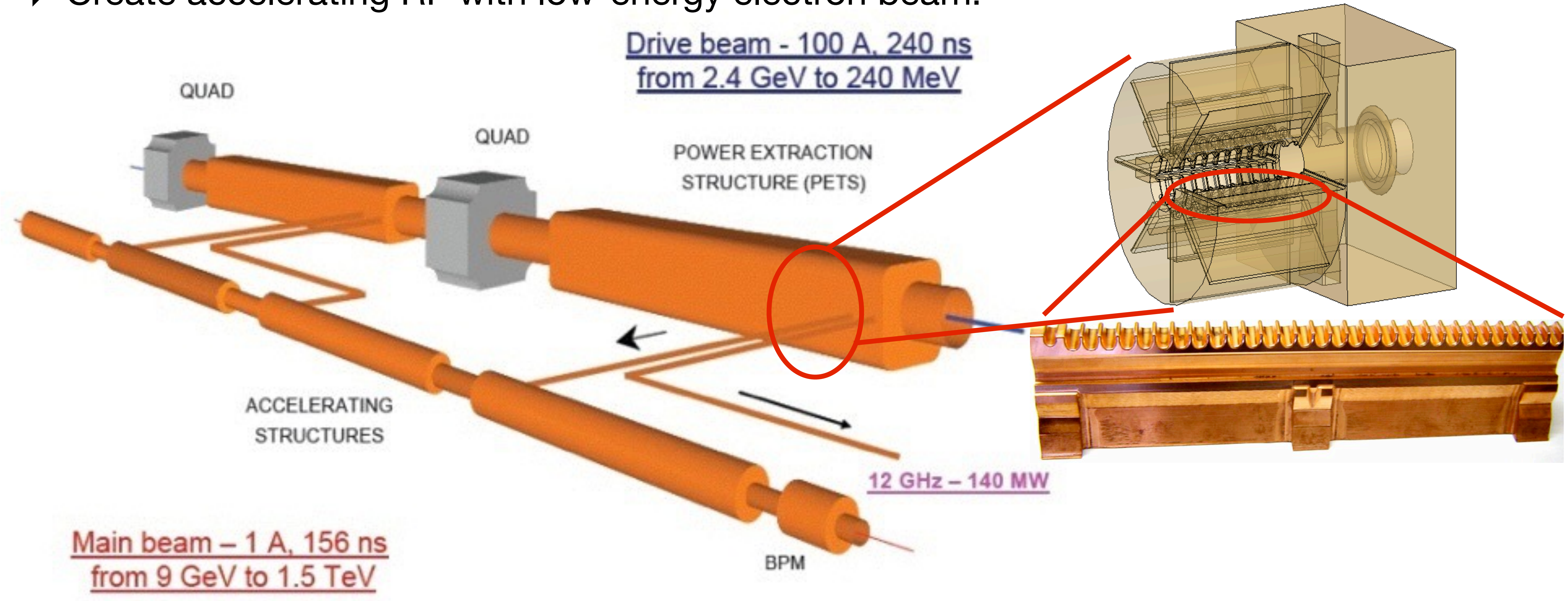
Accelerating Structures for the ILC



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

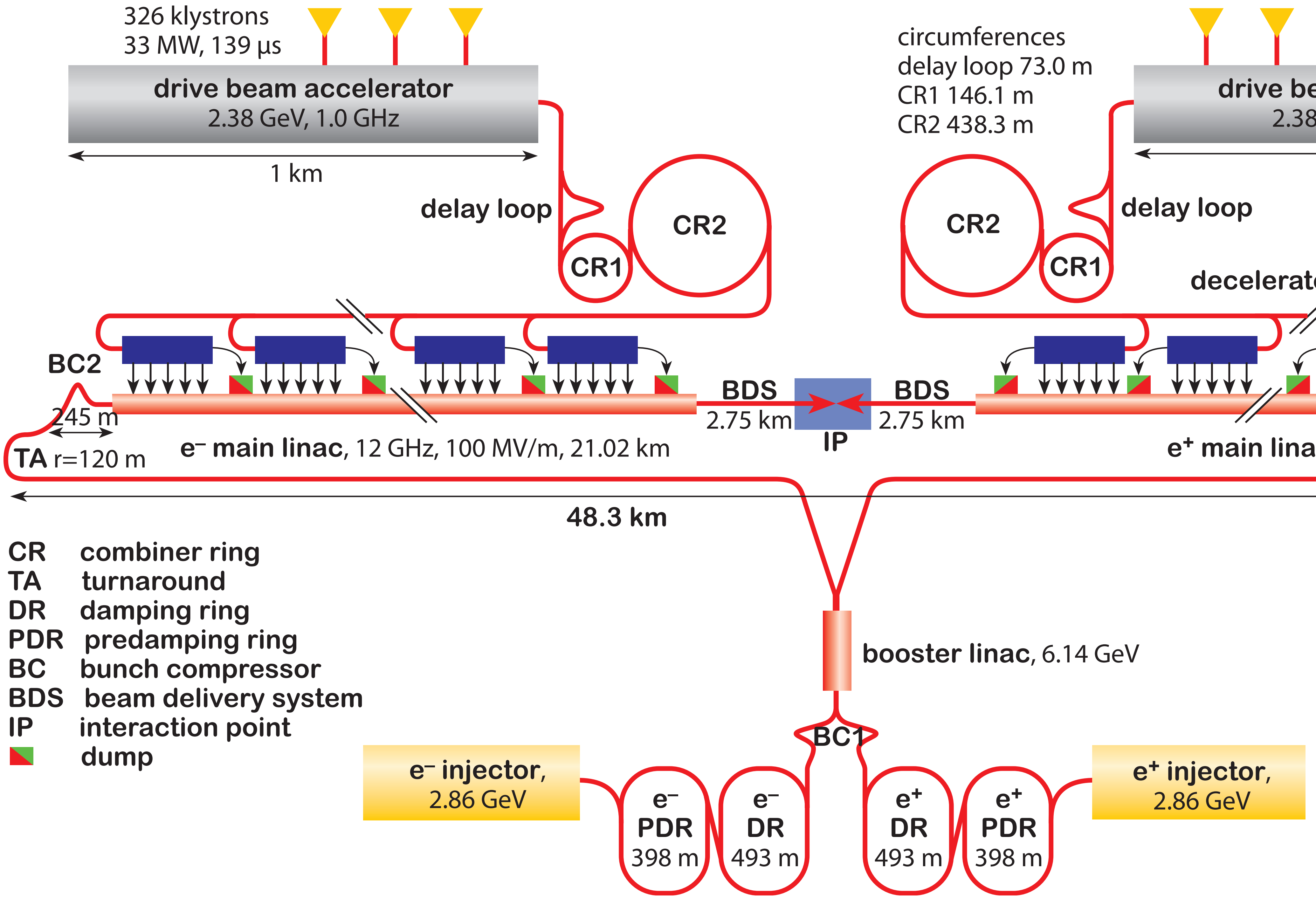
The Path to Higher Energies: 2 Beam Acceleration

- 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 ~ 1GHz, not 12 GHz)
    - Create accelerating RF with low-energy electron beam!

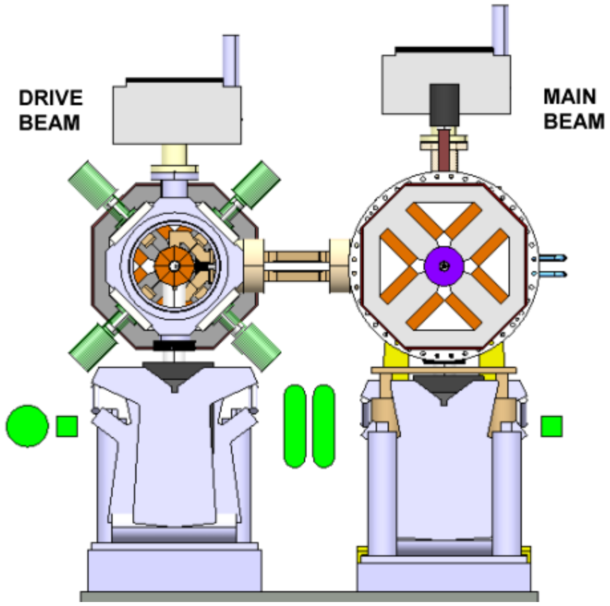


CLIC: “Compact” Linear Collider

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



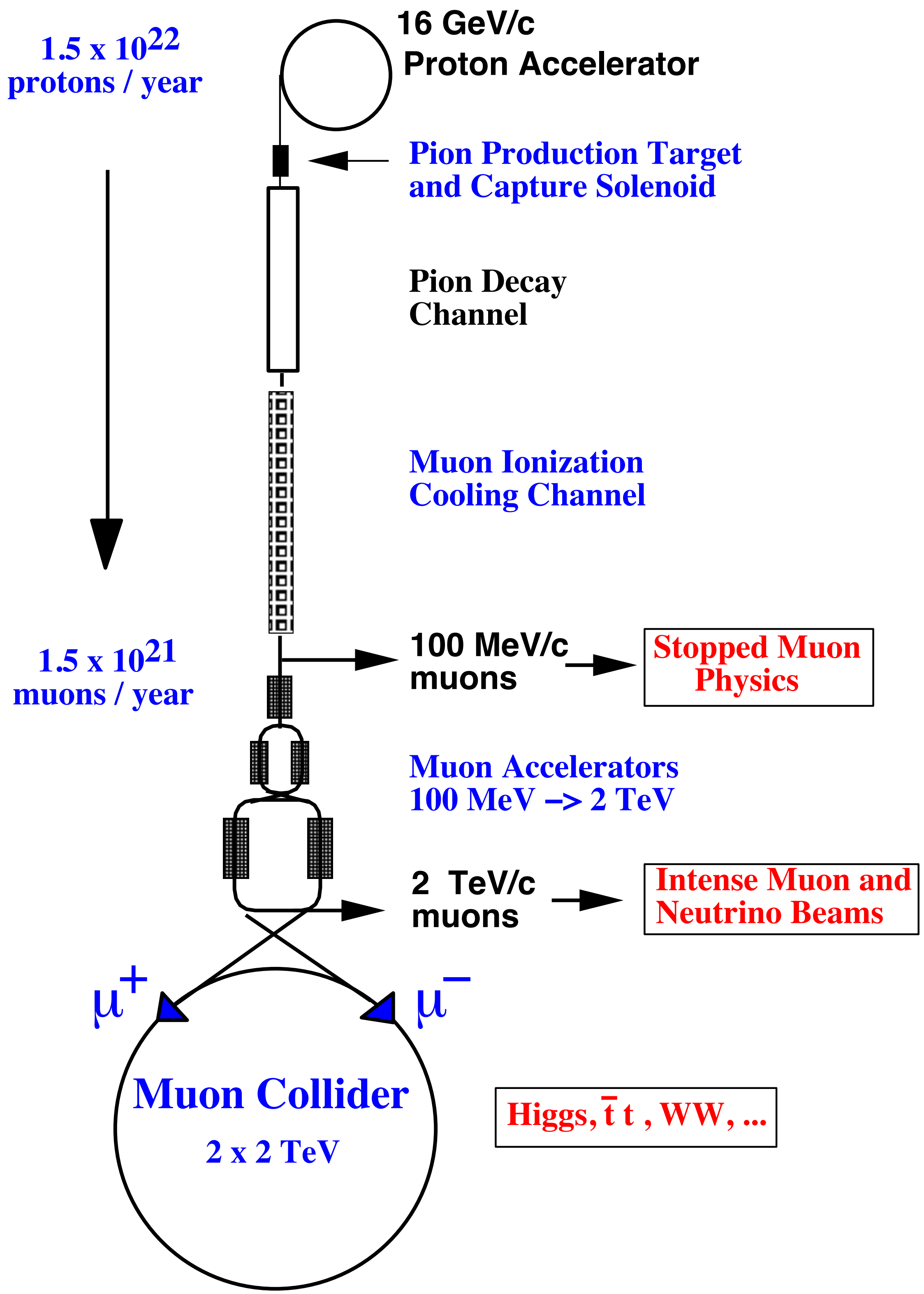
CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**



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!

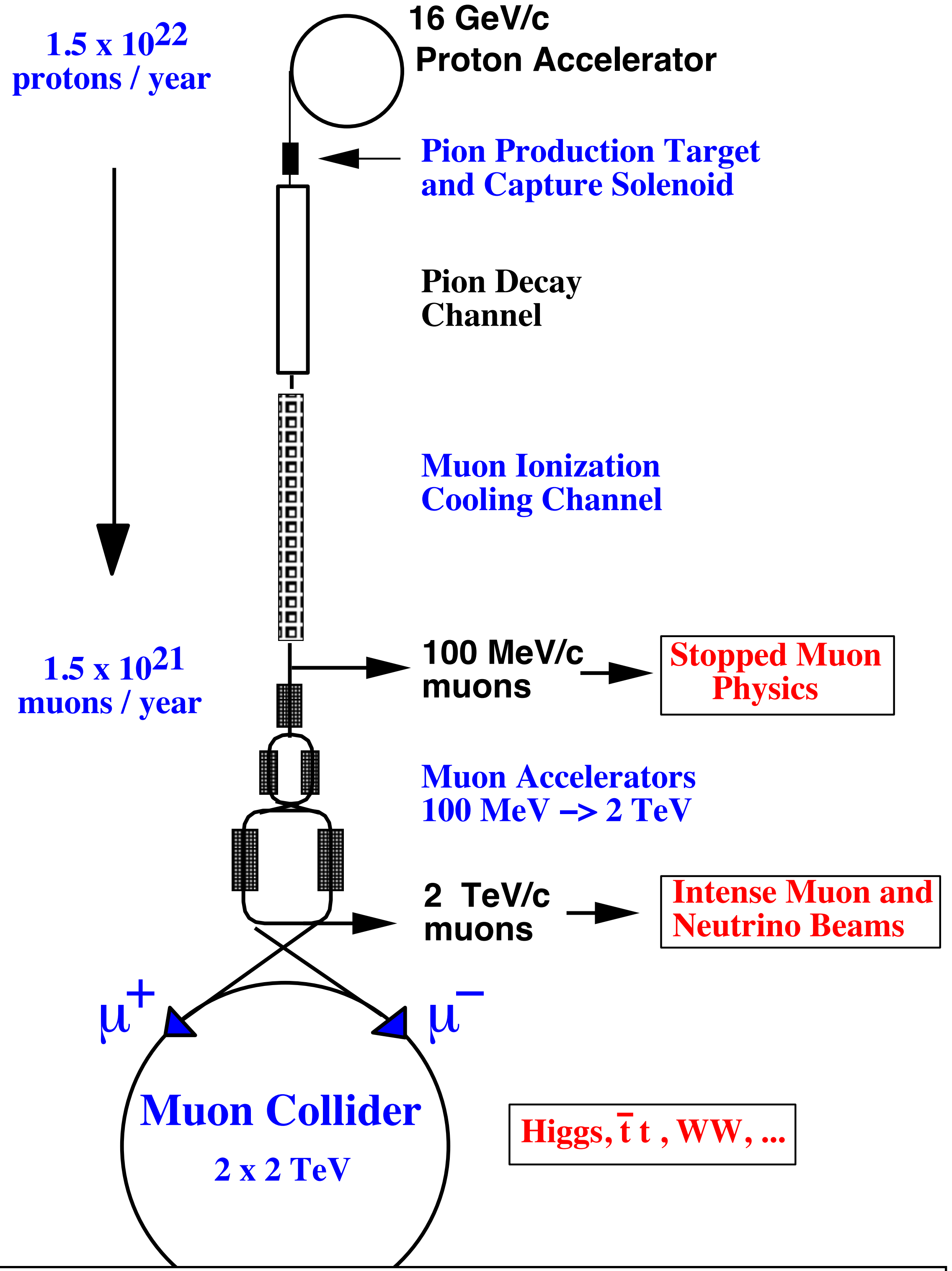


Beyond Electrons: Muon Collider

- 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!

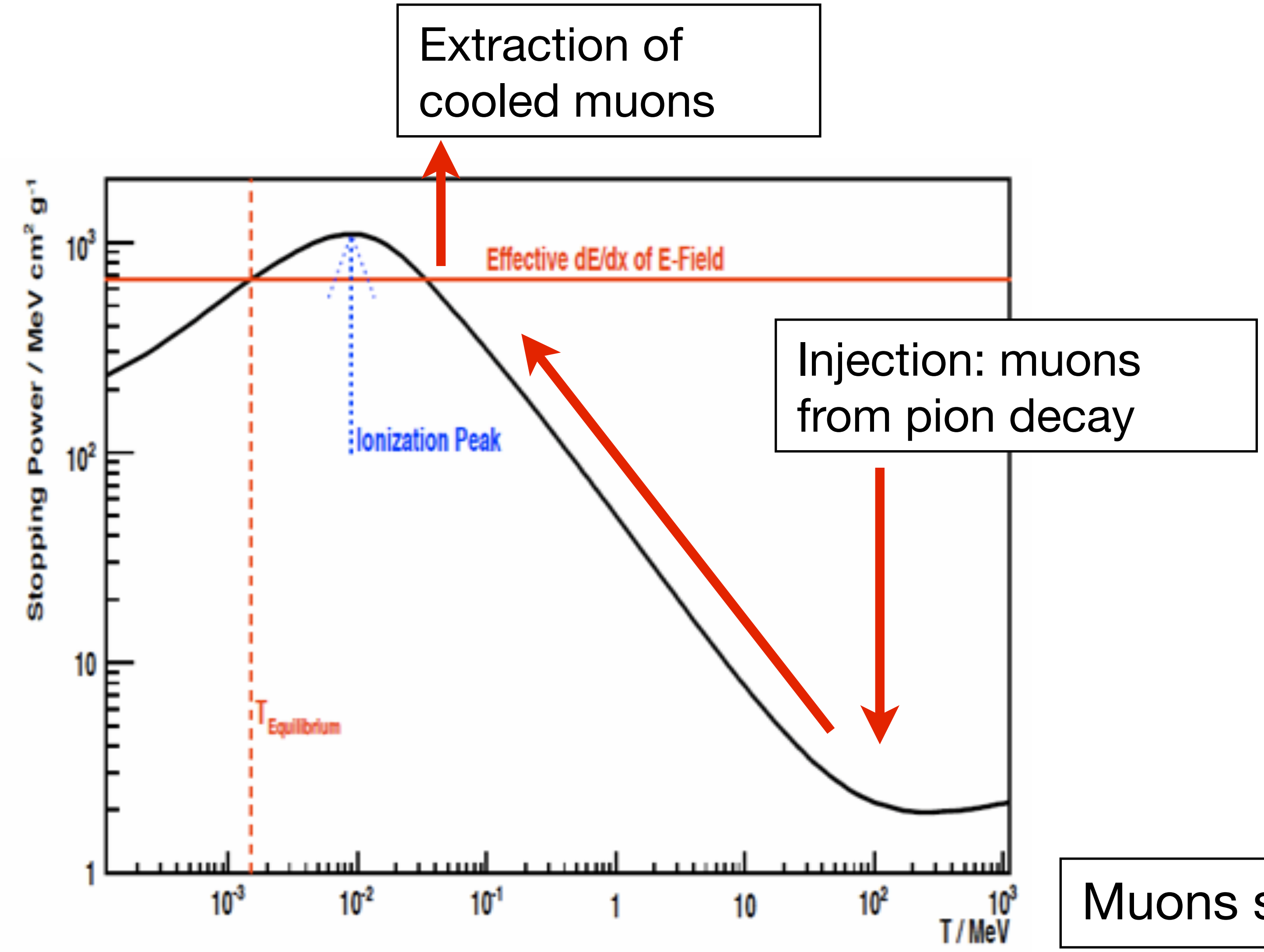


Muons survive ~ 1000 revolutions in the collider

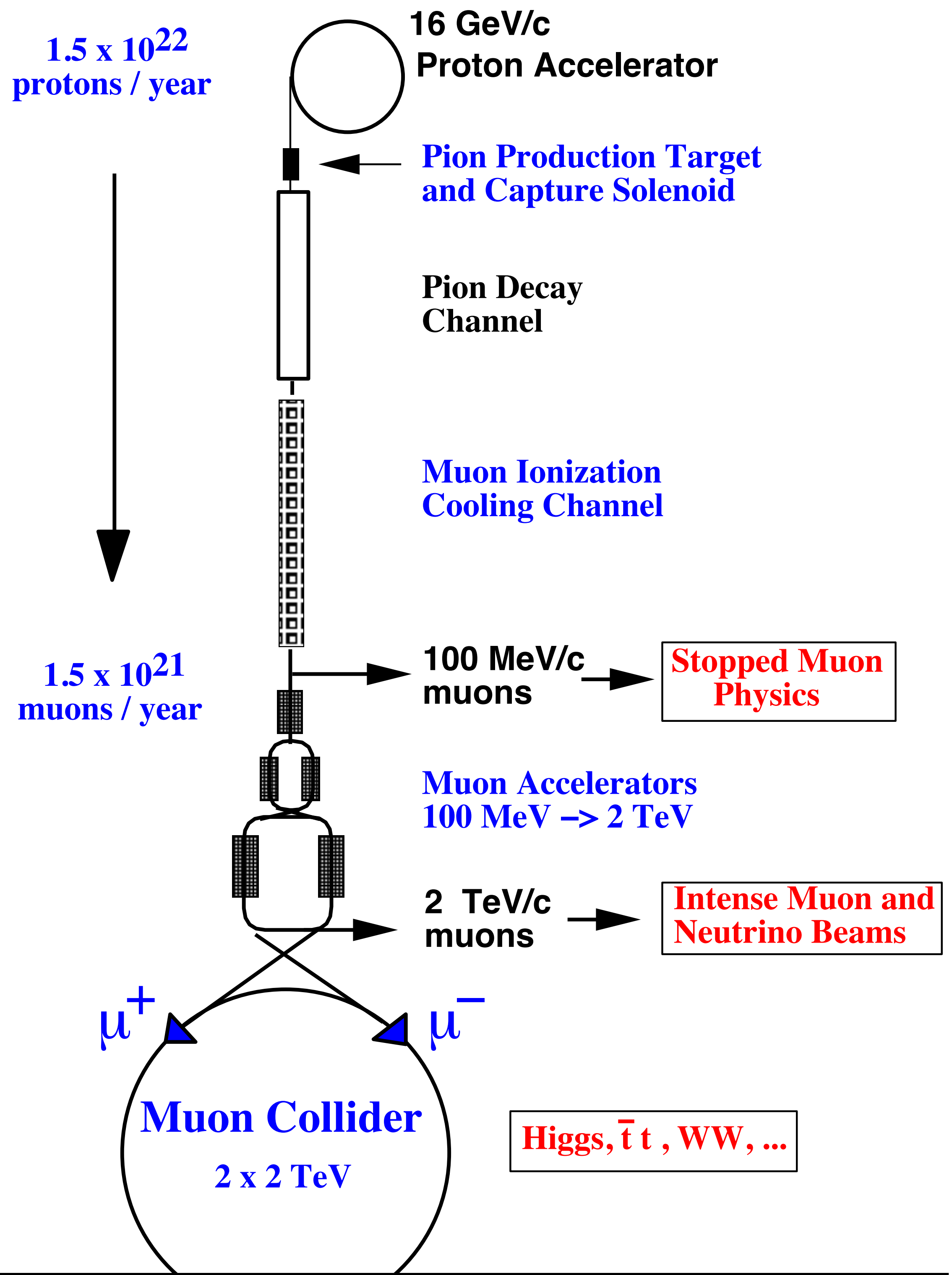
Beyond Electrons: Muon Collider

- 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!


Extraction of cooled muons

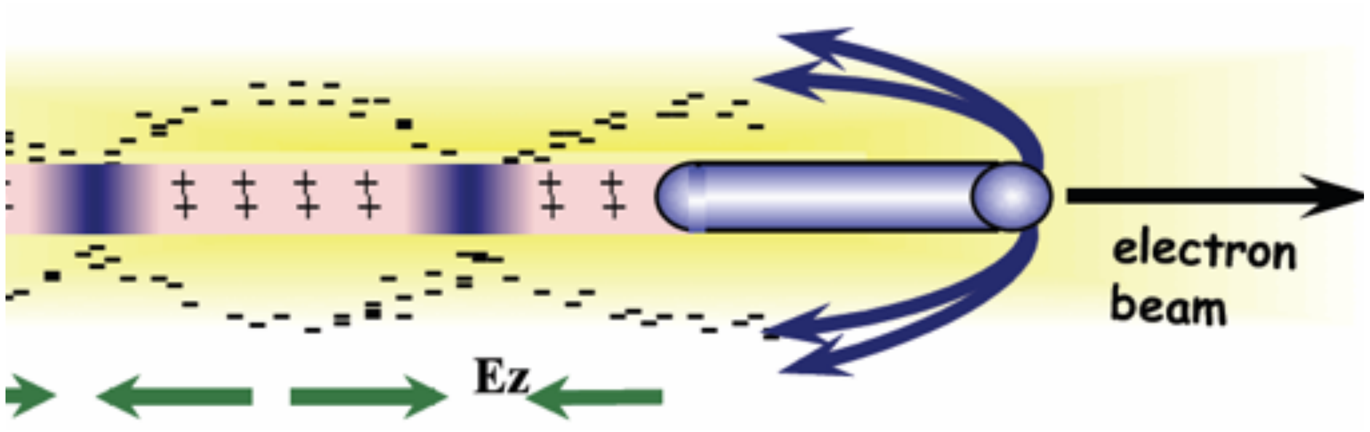
Injection: muons from pion decay



Muons survive ~ 1000 revolutions in the collider

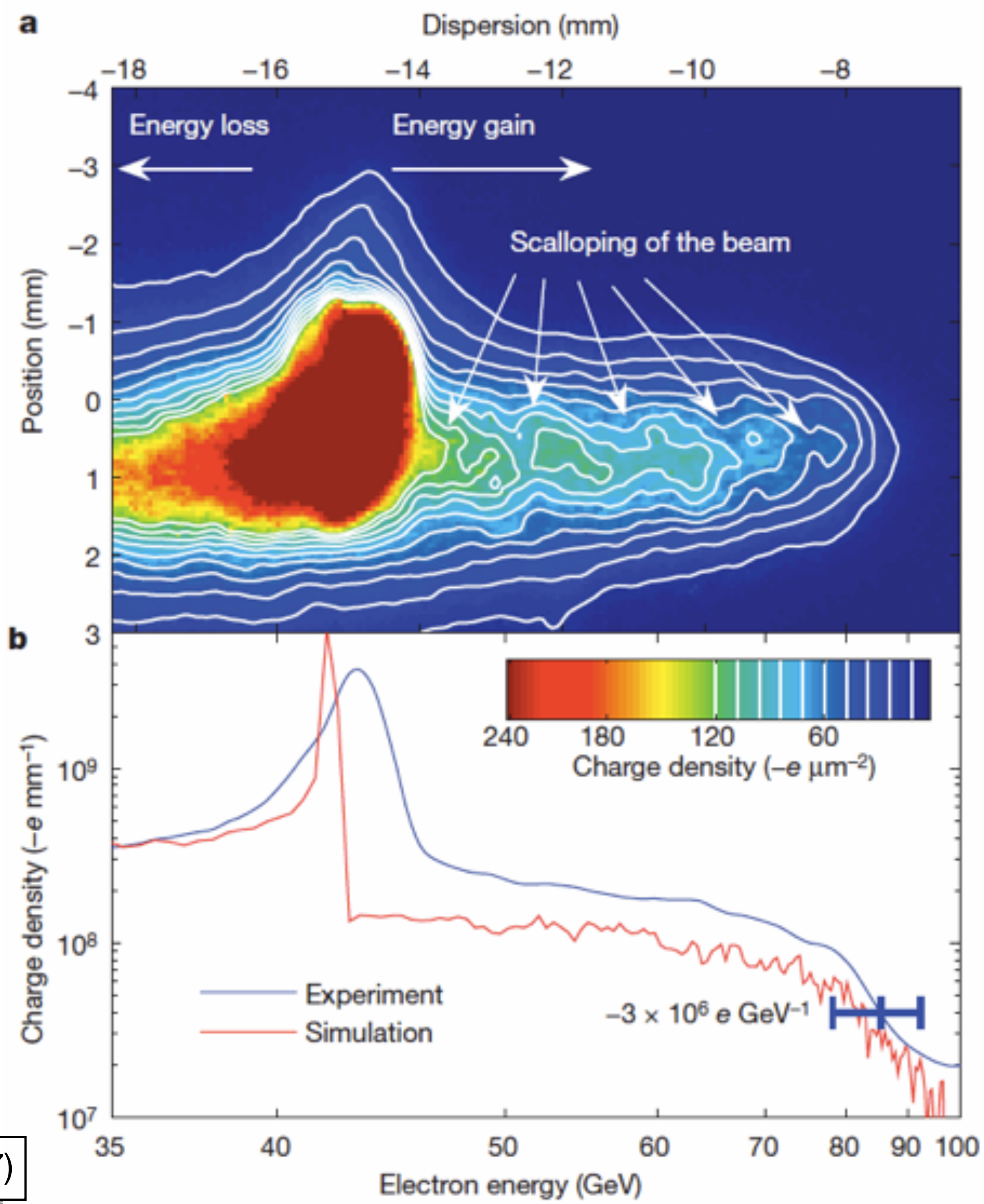
Plasma Wakefield Acceleration

- 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



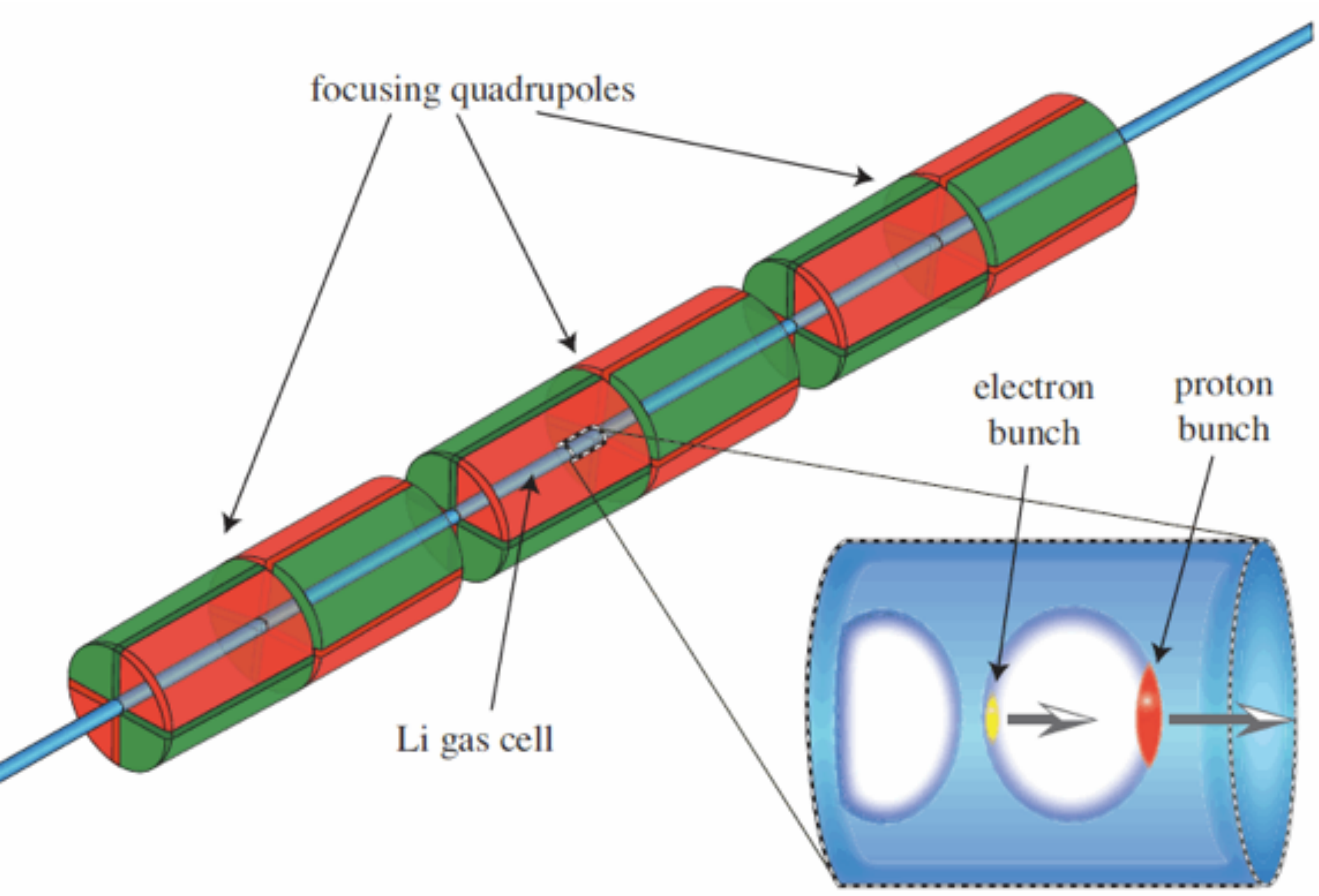
- Demonstration of high energy acceleration of electrons at SLAC: E-164X
- doubling of beam energy observed: 40 GeV energy gain over less than 1 m of plasma -> **~50 GV/m**

Nature 445, 741 (2007)

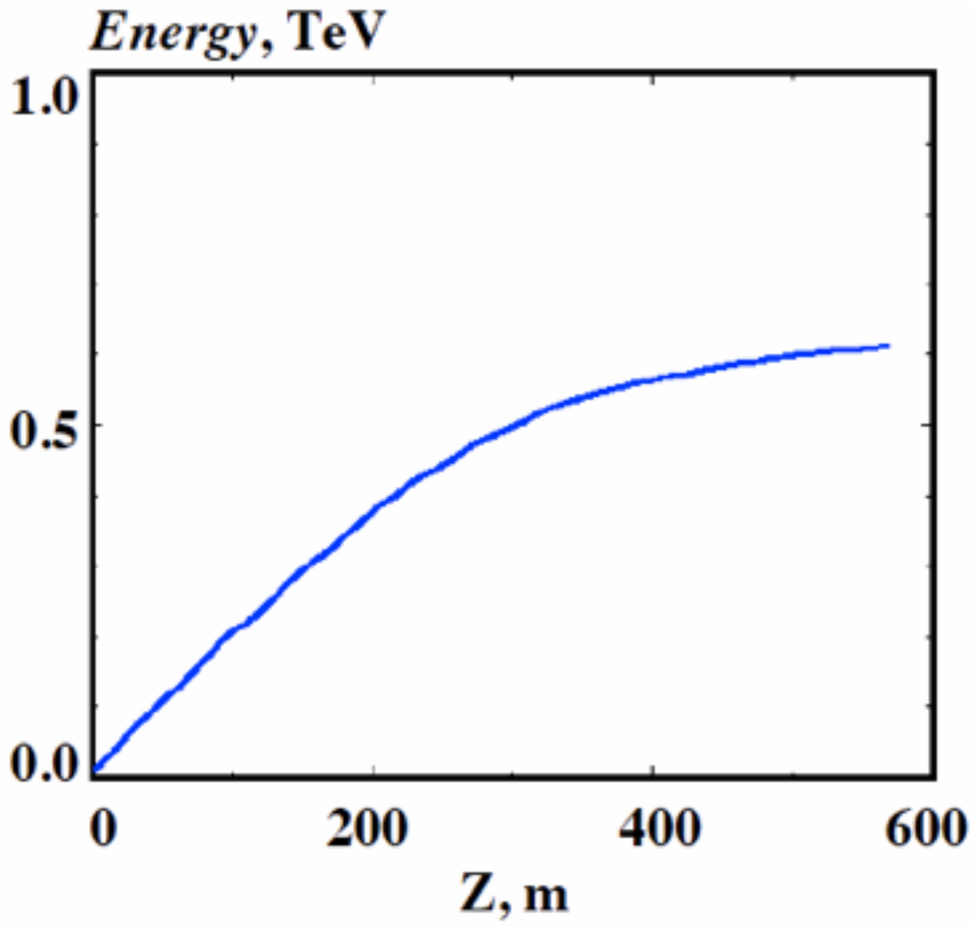


Plasma Wakefield Acceleration

- Need to get the energy into the plasma
  - Lasers - used for extreme gradients over very short distances (~ 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
  - Lasers - used for extreme gradients over very short distances (~ mm)

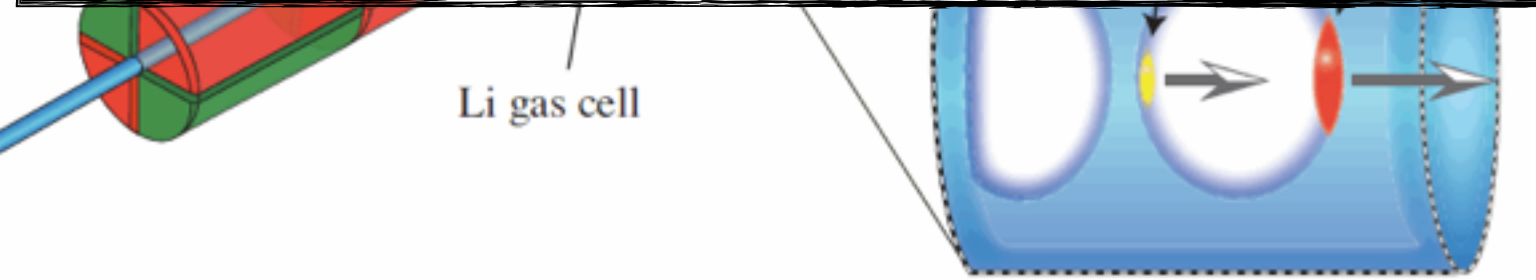
Key challenges (so far unsolved) for all techniques:

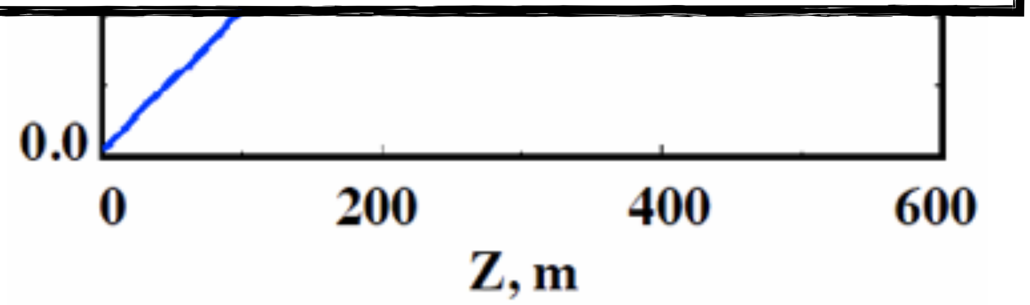
How to get very sharp energy distributions, high repetition rate, high currents and good focusing?

How to accelerate positrons with a comparably high gradient?

Or, in short:

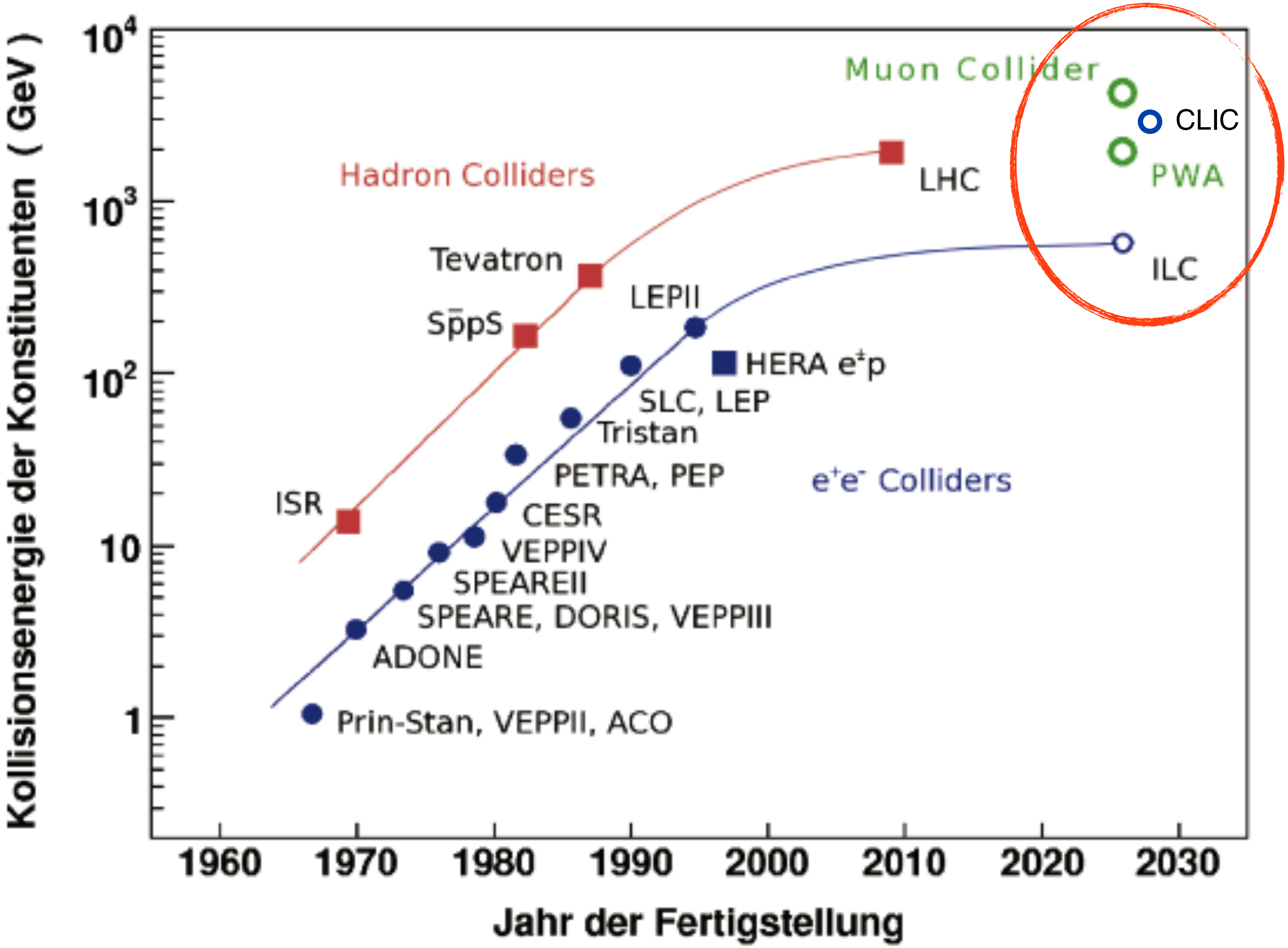
How to get high luminosity for a collider?





The Development of Collider Energies

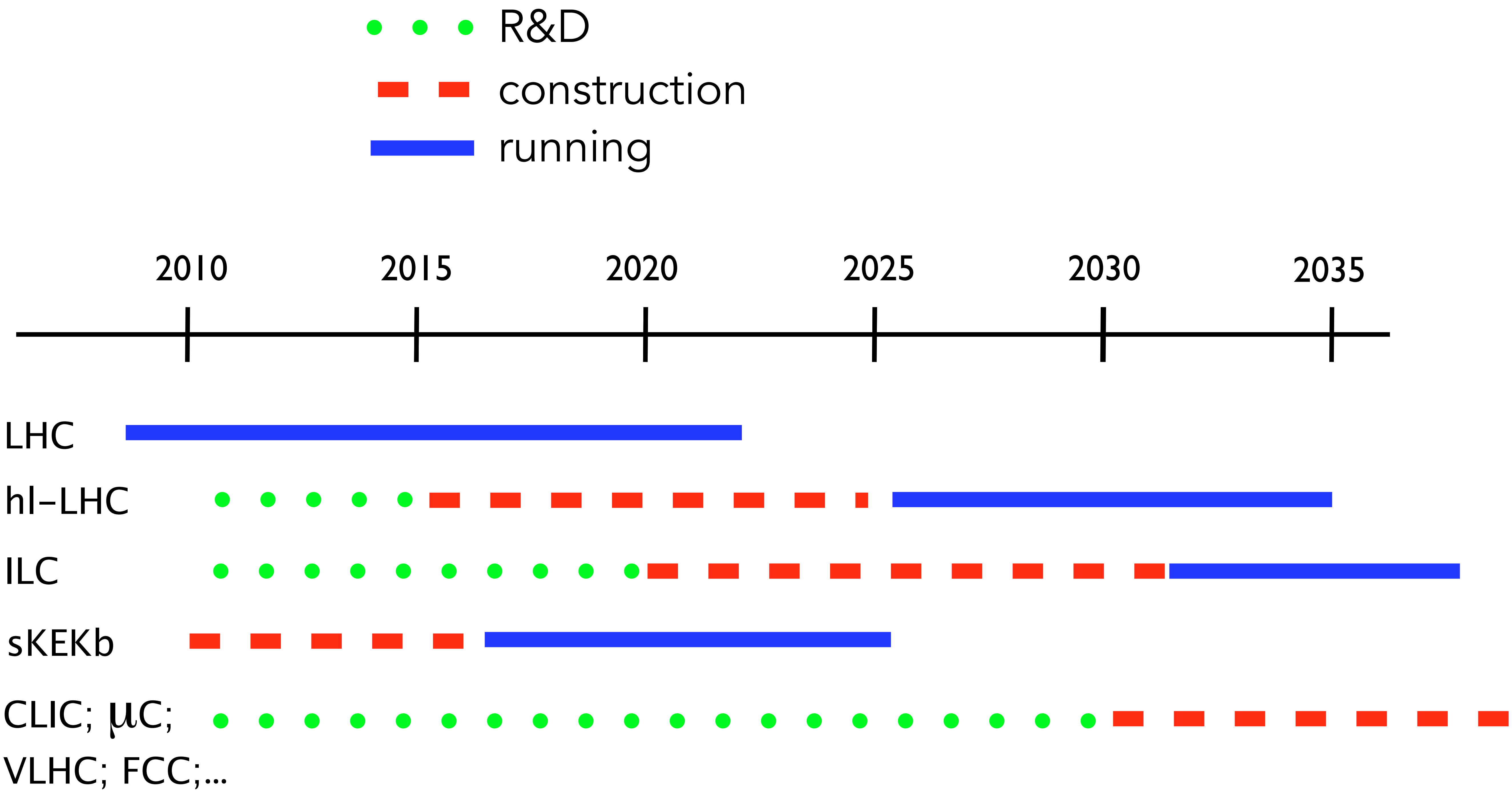
- “Livingston Plot”



discussed projects & speculation

Possible Time Line

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



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

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

Next Lecture: 25.04., “Detectors”, F. Simon