Introduction to Accelerator Physics

Part 2

Pedro Castro / Accelerator Physics Group (MPY)
Introduction to Accelerator Physics
DESY, 22nd July 2013

HELMHOLTZ ASSOCIATION

DESY

Differences between proton and electron accelerators

HERA (Hadron Electron Ring Accelerator) tunnel:

proton accelerator

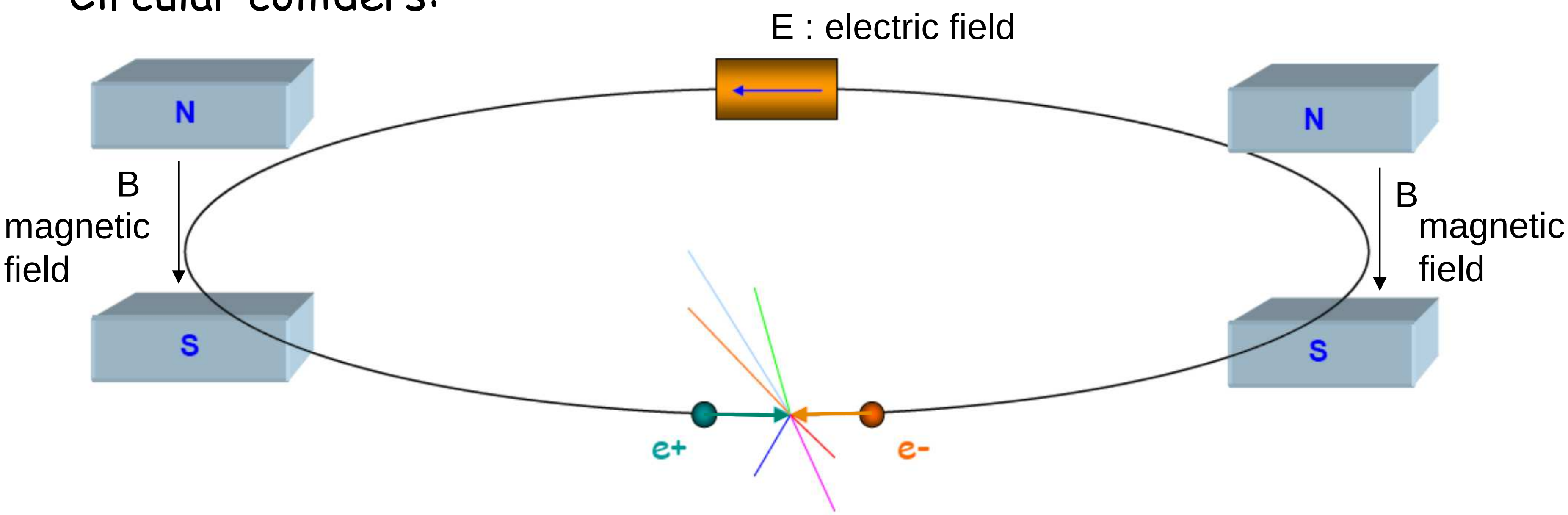
920 GeV

electron accelerator

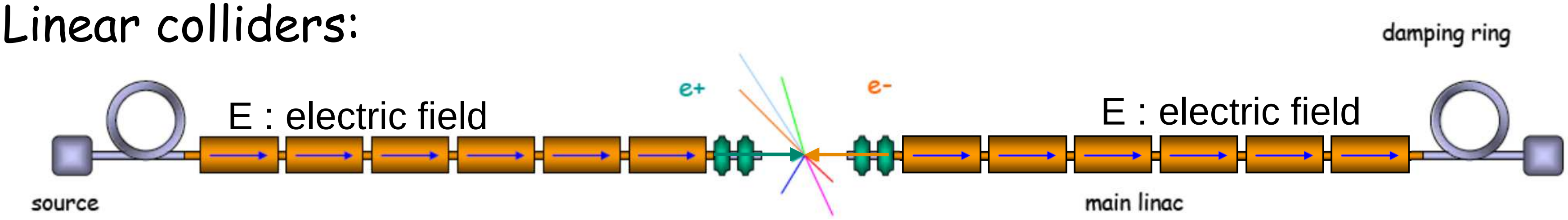
27.5 GeV

Which collider is better?

Circular colliders:

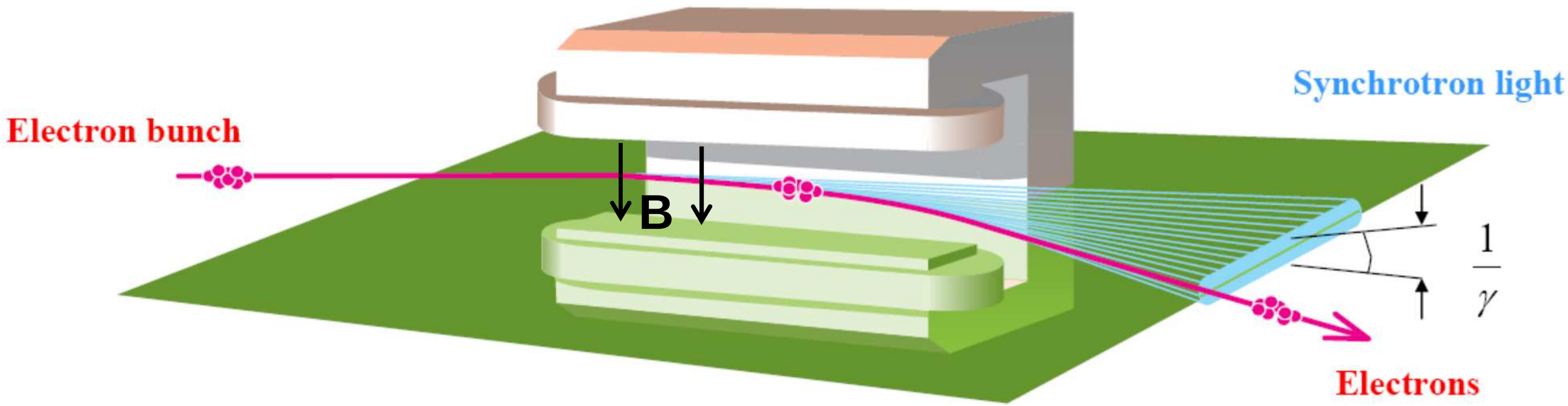


Linear colliders:



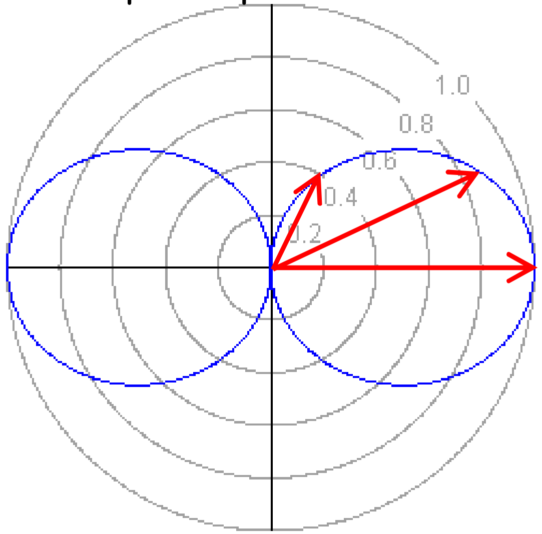
Synchrotron radiation

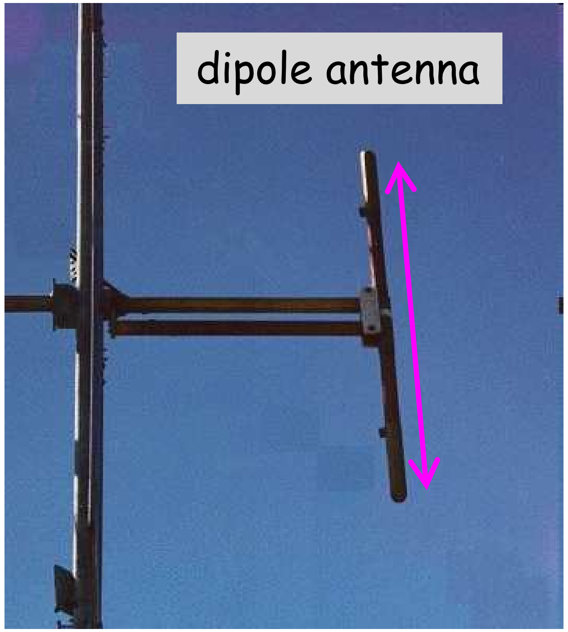
Dipole magnet

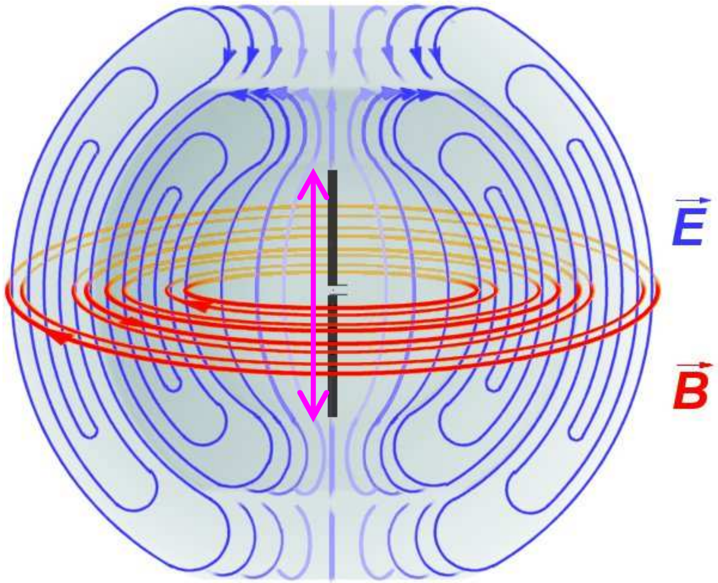


Radio antenna

radiation power pattern:







Radiation of a dipole antenna

local oscillator:

$$P = \frac{q^2 a^2}{12\pi\varepsilon_0 c^3}\omega^4$$

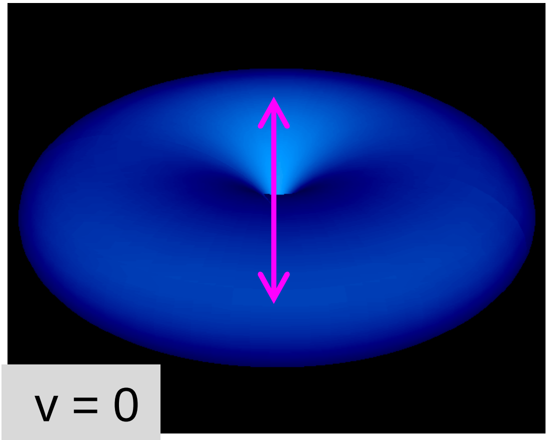
$$(\text{oscillation amplitude} : a < \lambda)$$

moving oscillator:

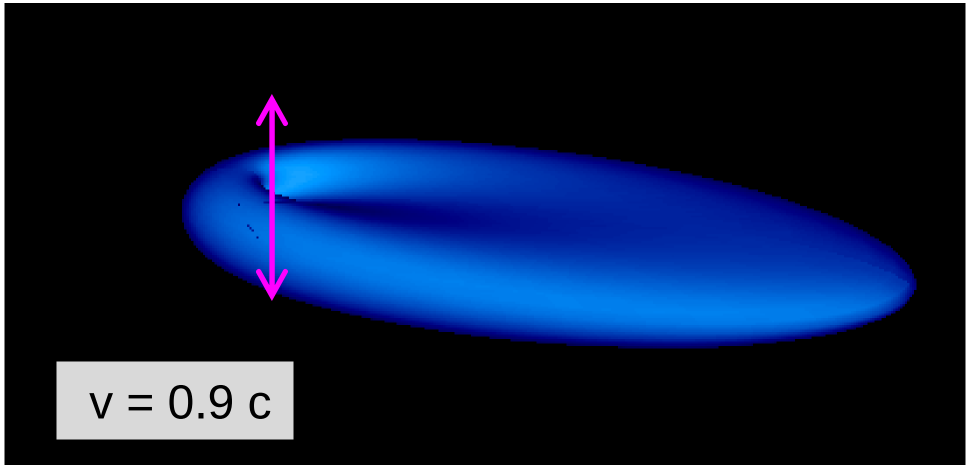
$$P = \frac{q^2 a^2}{12\pi\varepsilon_0 c^3}\gamma^4\omega^4$$

$$\gamma = \frac{E}{m_0 c^2}$$

Radiation of an oscillating dipole

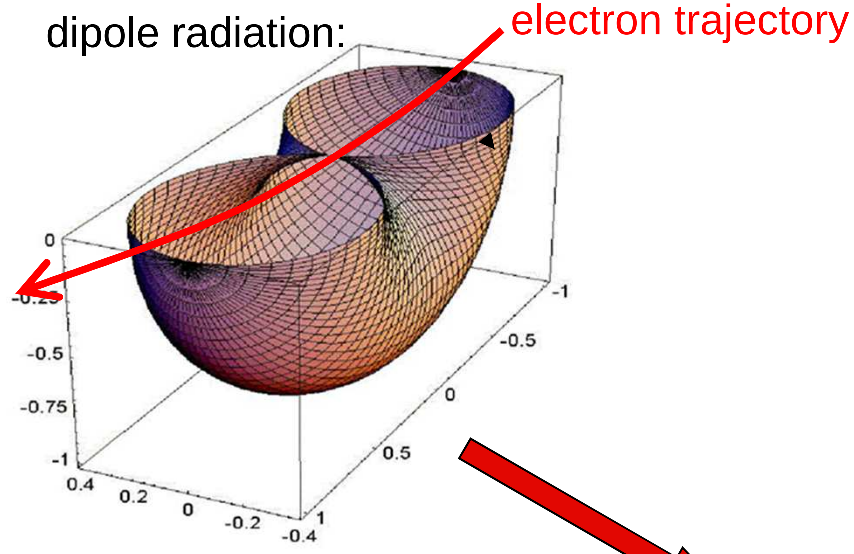


Radiation of a moving oscillating dipole

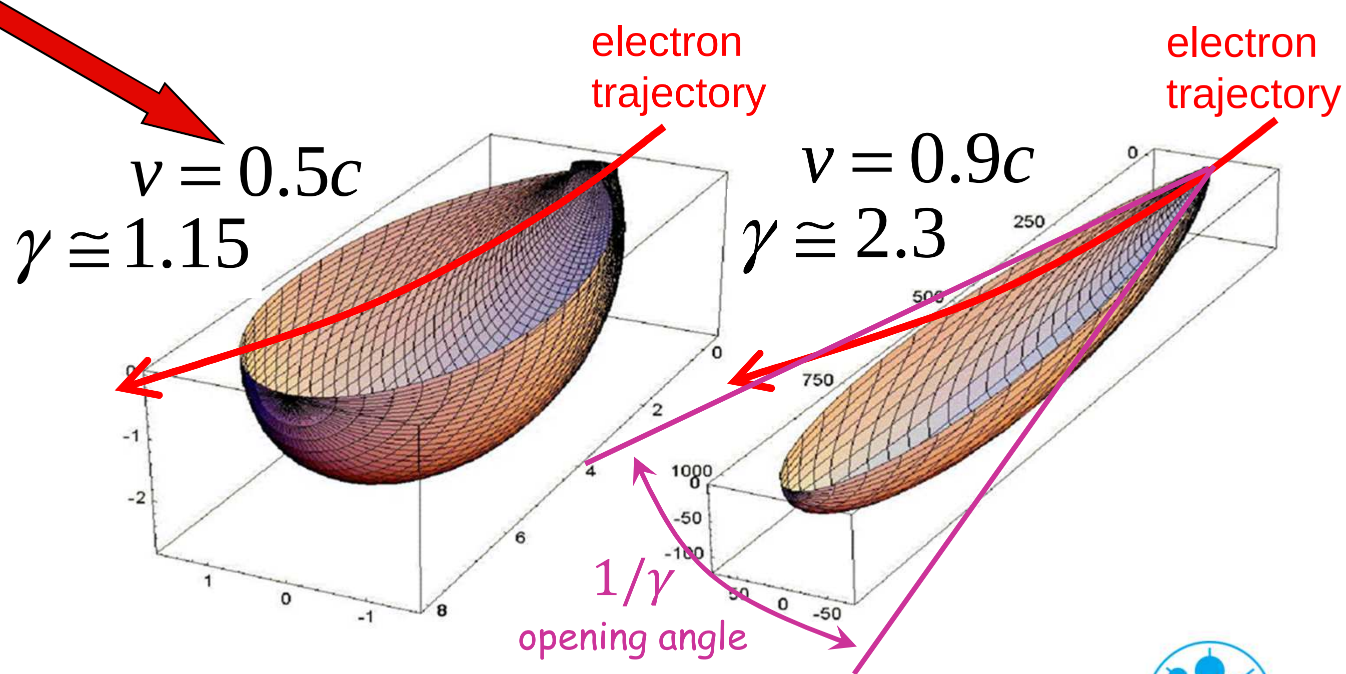


Radiation of a oscillating dipole under relativistic conditions

dipole radiation:

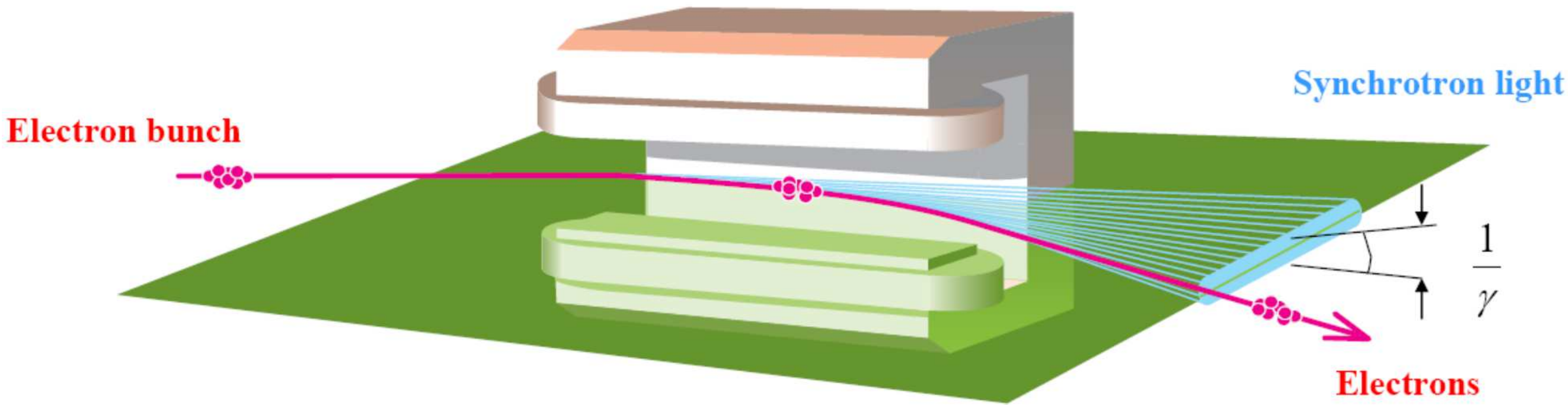


PETRA: $\gamma = 12000$



Synchrotron radiation

Dipole magnet



Power radiated by one electron in a dipole field *B*:

$$P = \frac{c\,q^2}{6\pi\,\varepsilon_0}\,\frac{\gamma^4}{r^2}$$

$$\gamma = \frac{E}{m_0 c^2}$$

$$\frac{1}{r} = \frac{q\,B}{p}$$

vacuum permitivity

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0} \frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032 \times 10^{-18} \frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$$r = 580\ \text{m}$$

$$E = 27.5\ \text{GeV}$$

$$\gamma = 54000$$

$$\Delta E_{turn} = 87\ \text{MeV}\ (0.3\%)$$

need acceleration = 87 MV per turn

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$$r = 580 \text{ m}$$

$$E = 27.5 \text{ GeV}$$

$$\gamma = 54000$$

$$\Delta E_{turn} = 87 \text{ MeV } (0.3\%)$$

need acceleration = 87 MV per turn

same

HERA proton ring:

$$r = 580 \text{ m}$$

$$E = 920 \text{ GeV}$$

$$\gamma = 980$$

$$\Delta E_{turn} \cong 10 \text{ eV } (10^{-9}\%)$$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\text{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\text{turn}}[\text{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\text{m}]}$$

HERA electron ring:

$$r = 580 \text{ m}$$

$$E = 27.5 \text{ GeV}$$

$$\gamma = 54000$$

$$\Delta E_{turn} = 87 \text{ MeV } (0.3\%)$$

same ⟷

HERA proton ring:

$$r = 580 \text{ m}$$

$$E = 920 \text{ GeV}$$

$$\gamma = 980$$

the limit is the max. dipole field = 5.5 Tesla

$$R = \frac{mv}{qB} = \frac{p}{qB} \quad \Longrightarrow \quad p_{max} = RqB_{max}$$

need acceleration = 87 MV per turn

$$\frac{1}{r} = \frac{qB}{p}$$

Synchrotron radiation

Total energy loss after one full turn:

$$\Delta E_{\mathrm{turn}} = \frac{q^2}{3\varepsilon_0}\frac{\gamma^4}{r} \quad \Rightarrow \quad \Delta E_{\mathrm{turn}}[\mathrm{GeV}] = 6.032\times 10^{-18}\,\frac{\gamma^4}{r[\mathrm{m}]}$$

HERA electron ring:

$$r = 580\ \mathrm{m}$$
$$E = 27.5\ \mathrm{GeV}$$
$$\gamma = 54000$$
$$\Delta E_{turn} = 87\ \mathrm{MeV}\ (0.3\%)$$

need acceleration = 87 MV per turn

x5 →

LEP collider:

$$r = 2800\ \mathrm{m}$$
$$E = 105\ \mathrm{GeV}$$
$$\gamma = 205000$$
$$\Delta E_{turn} \cong 4\ GeV\ (4\%)$$

need 4 GV per turn !!

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International Linear Collider (ILC)

Colliding beams with Ecm = 500 GeV (update to 1 TeV possible)

(not to scale)

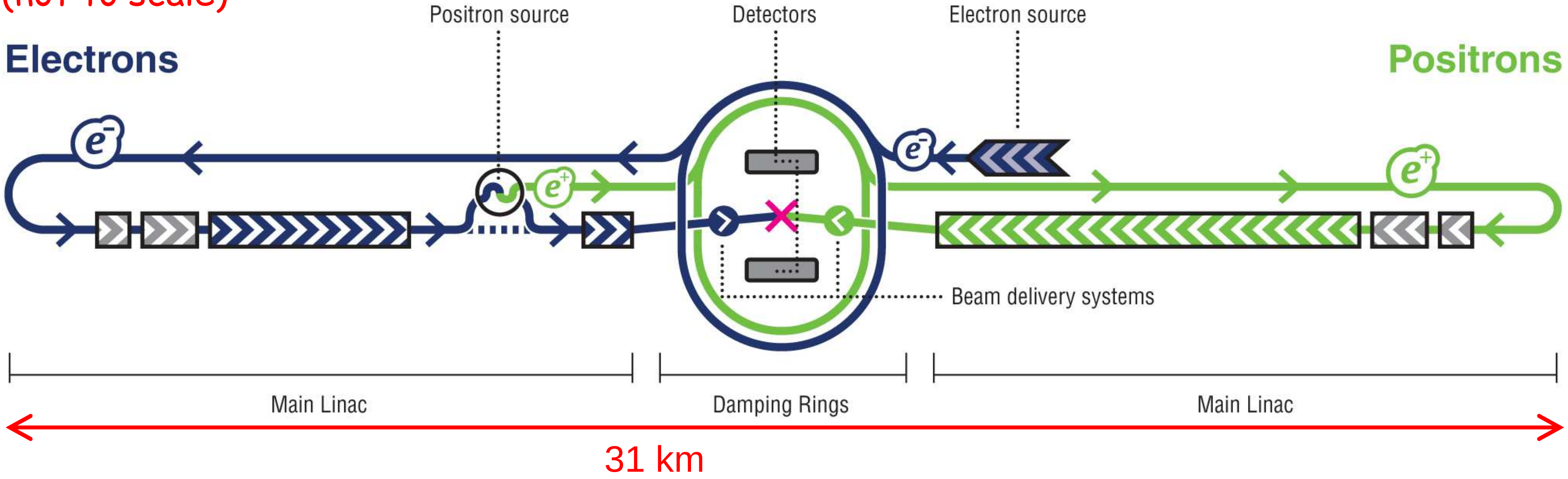

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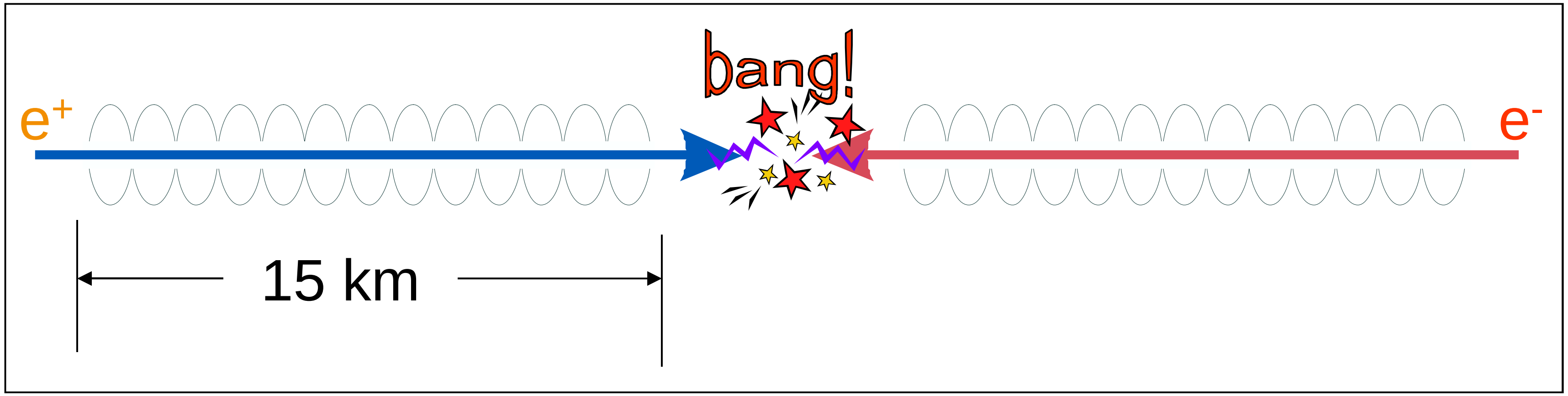
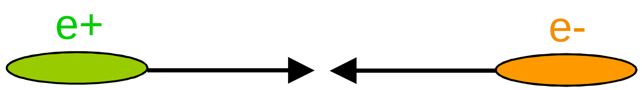
Figure of merit: Luminosity





production rate of a given event (for example, Z particle production):

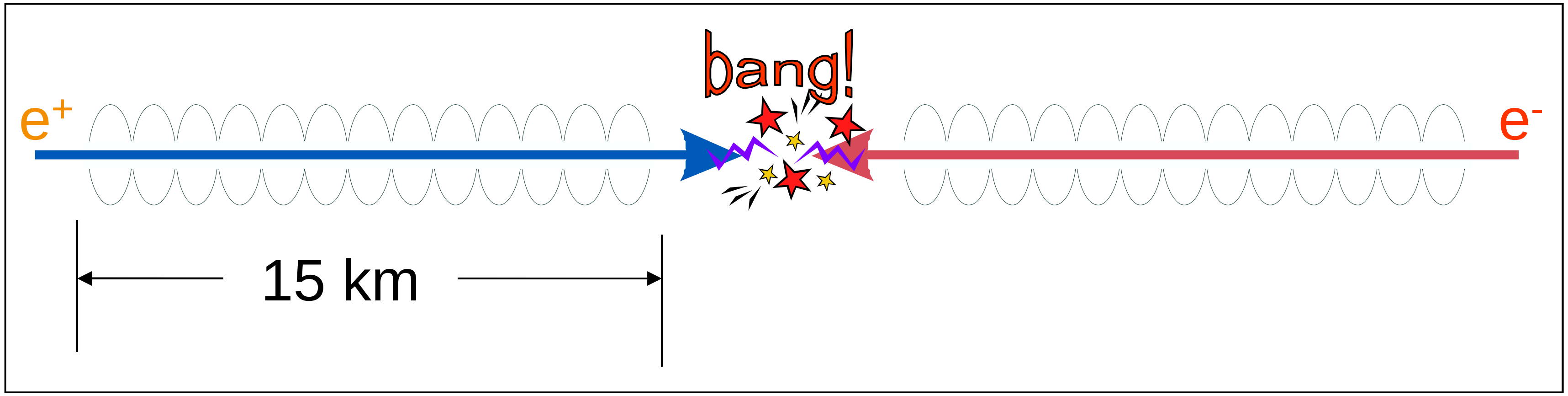
$$R_Z = \frac{dN_z}{dt} = \Sigma_z \cdot L$$

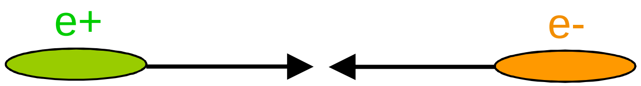
number of events

luminosity (independent of the event type)

cross section of Z production

Luminosity





$$R_Z = \Sigma_z \cdot L = \Sigma_z \cdot \frac{f_b N_{e+} N_{e-}}{4\pi \sigma_x \sigma_y}$$

number of colliding bunches per second (f_b)

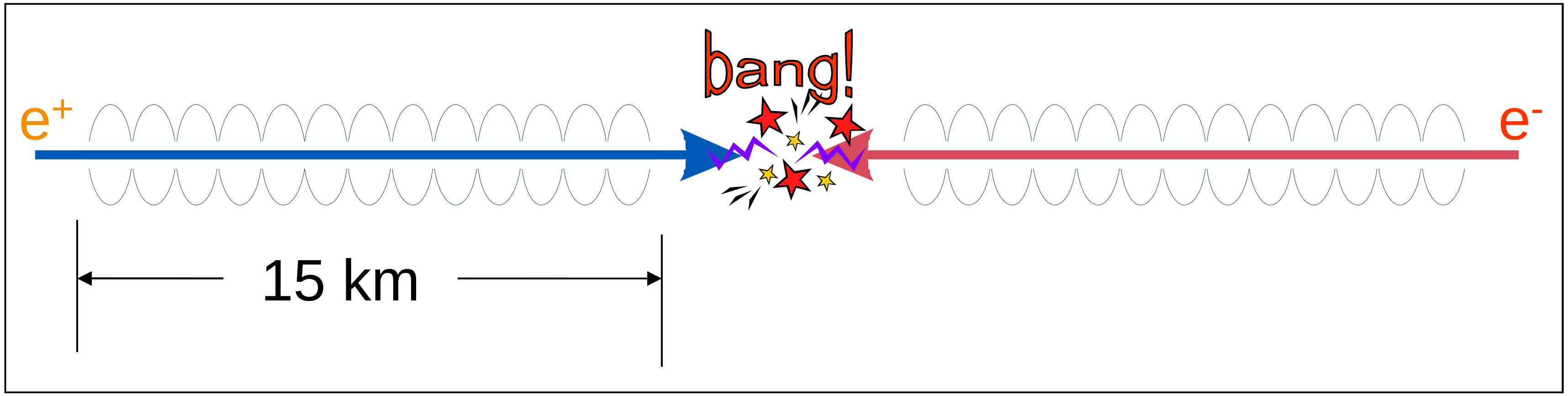
number of positrons per bunch (N_{e+})

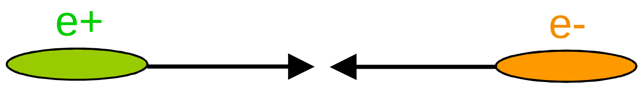
number of electrons per bunch (N_{e-})

luminosity (L)

transverse bunch sizes (at the collision point) (σ_x, σ_y)

Luminosity





number of colliding bunches per second

number of positrons per bunch

number of electrons per bunch

$$R_Z = \Sigma_z \cdot L = \Sigma_z \cdot \frac{f_b N_{e+} N_{e-}}{4\pi \sigma_x^* \sigma_y^*} \cdot H_D$$

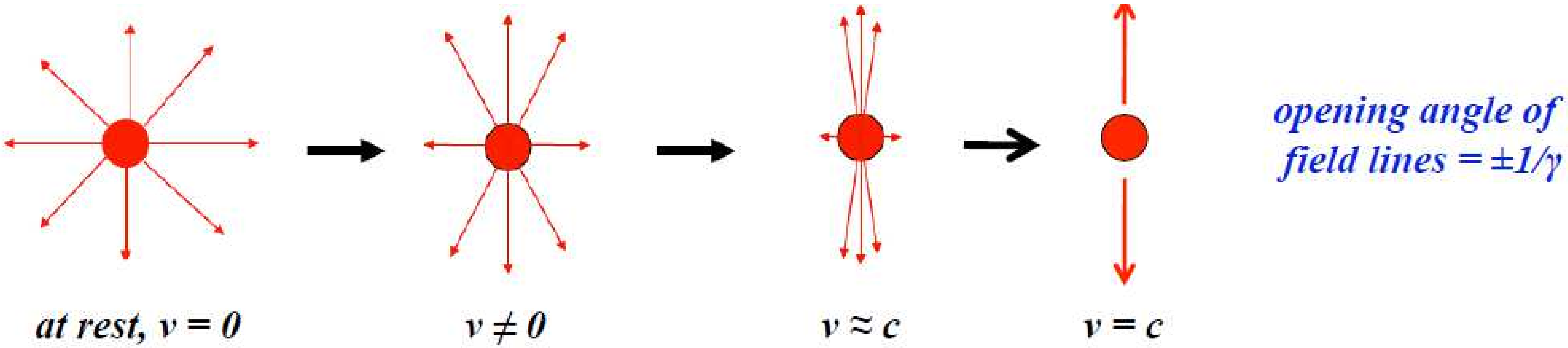
luminosity

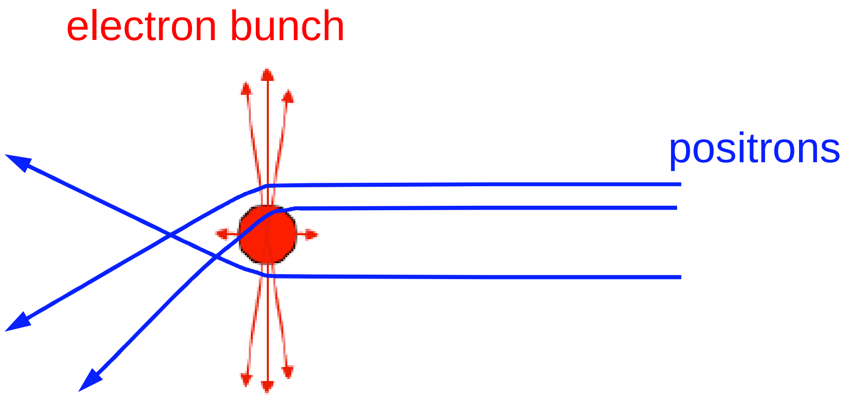
beam-beam enhancement factor

transverse bunch sizes (at the collision point *)

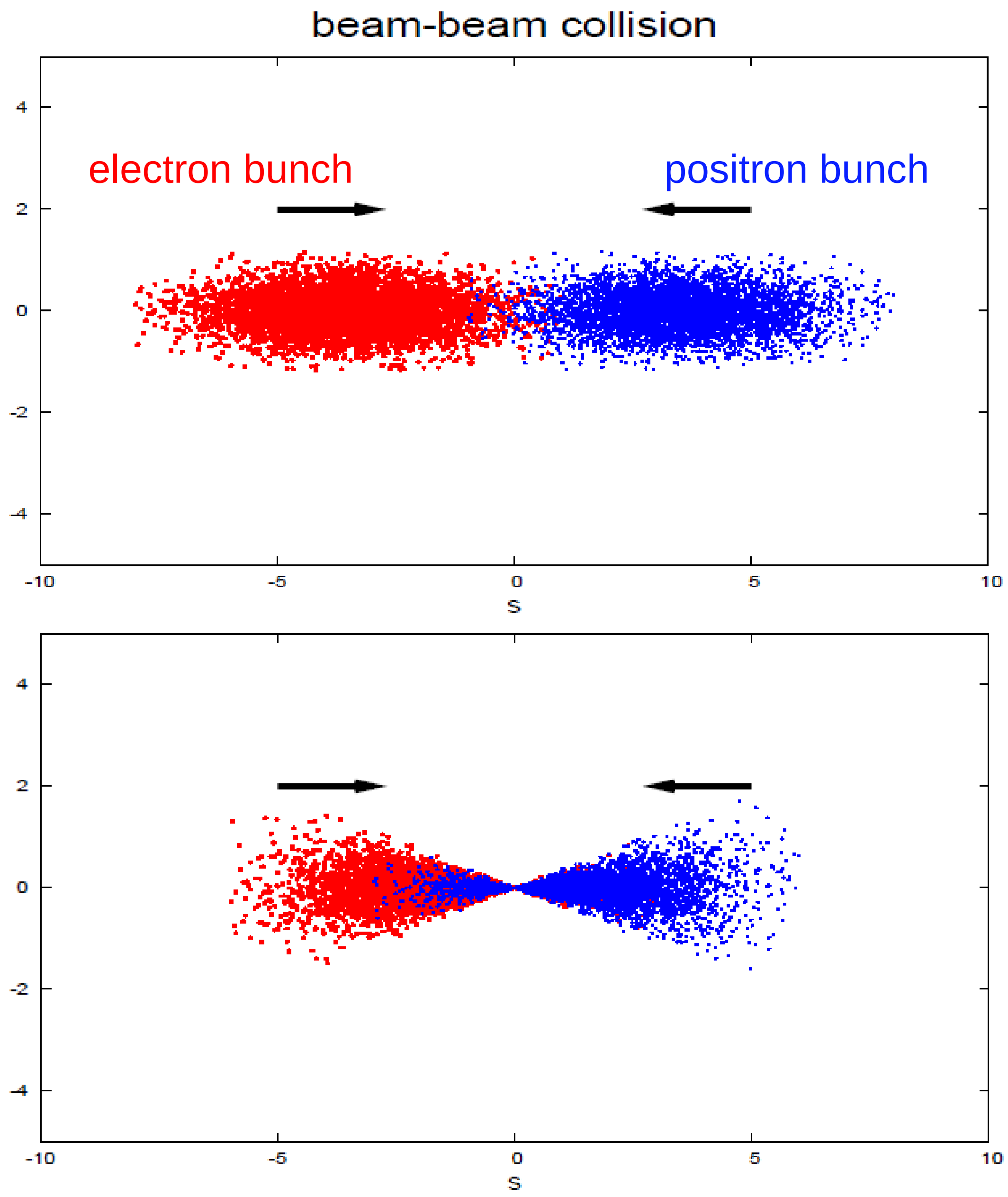
Luminosity enhancement factor H_D due to focusing of opposite beam

electric field of a charged particle (or bunch)





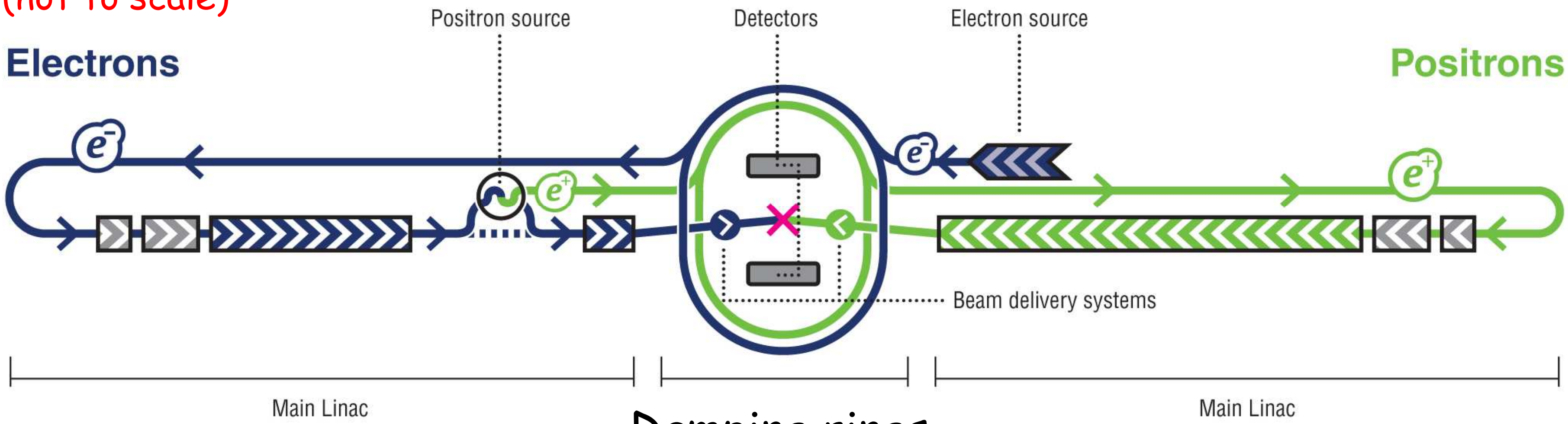
Luminosity enhancement factor H_D due to focusing of opposite beam



International Linear Collider (ILC)

Colliding beams with Ecm = 500 GeV (update to 1 TeV possible)

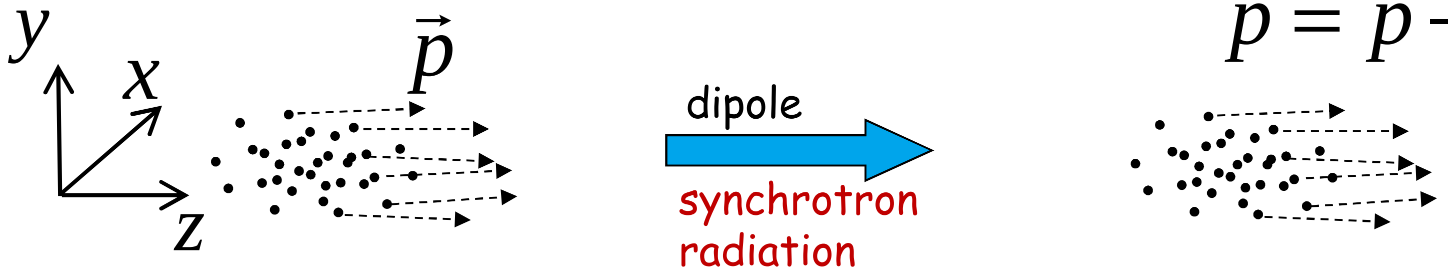
(not to scale)



Damping rings

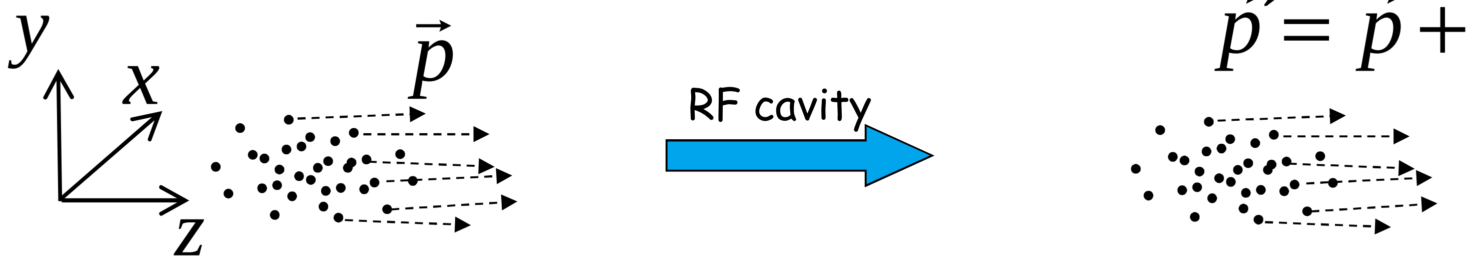
Damping rings

Radiation damping:



$$\vec{p}' = \vec{p} - \Delta\vec{p}$$

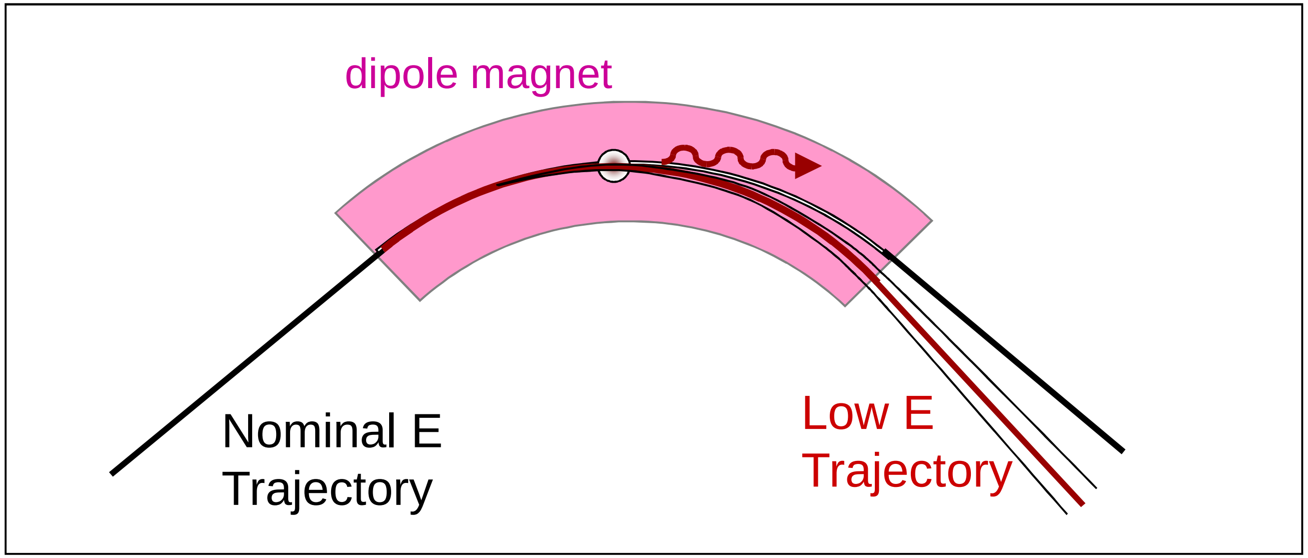
Longitudinal acceleration:



$$\vec{p}' = \vec{p} + \Delta\vec{p}_z$$

acceleration (only in z direction) $\dfrac{p_x}{|\vec{p}|}$ gets smaller

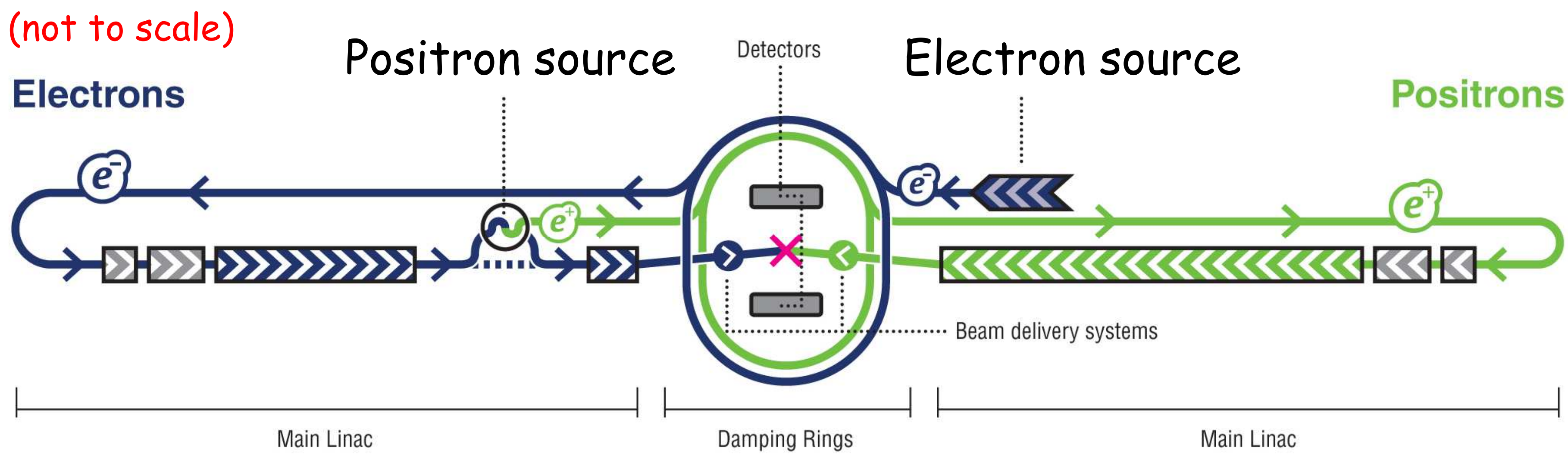
Quatum excitation



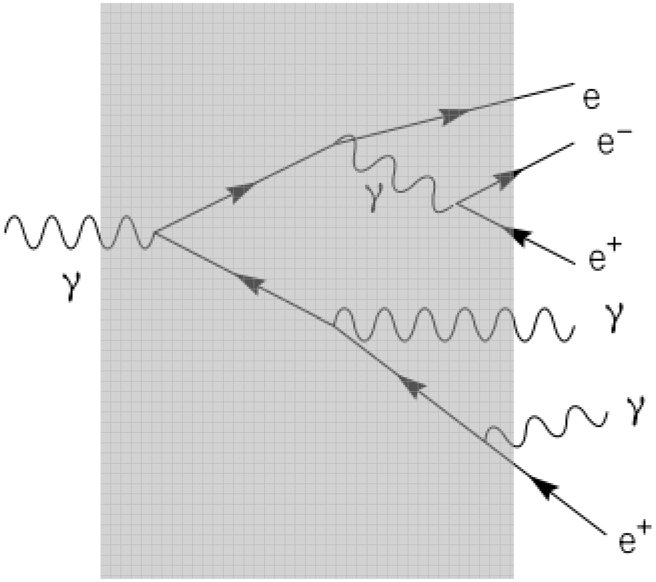
- Quantum excitation
  - Radiation is emitted in discrete quanta
  - Number and energy distribution etc. of photons obey statistical laws
  - ➔ Increase beam size

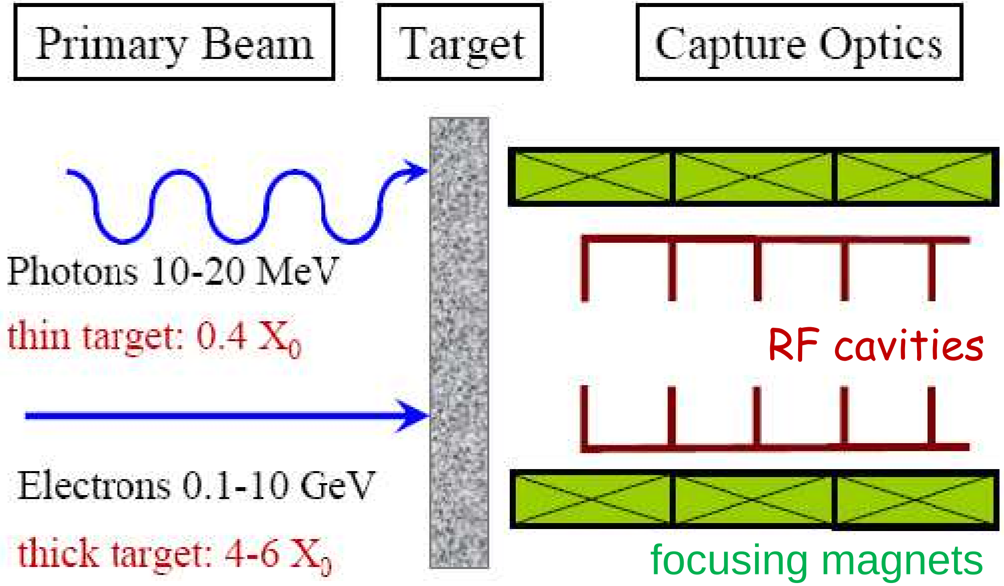
International Linear Collider (ILC)

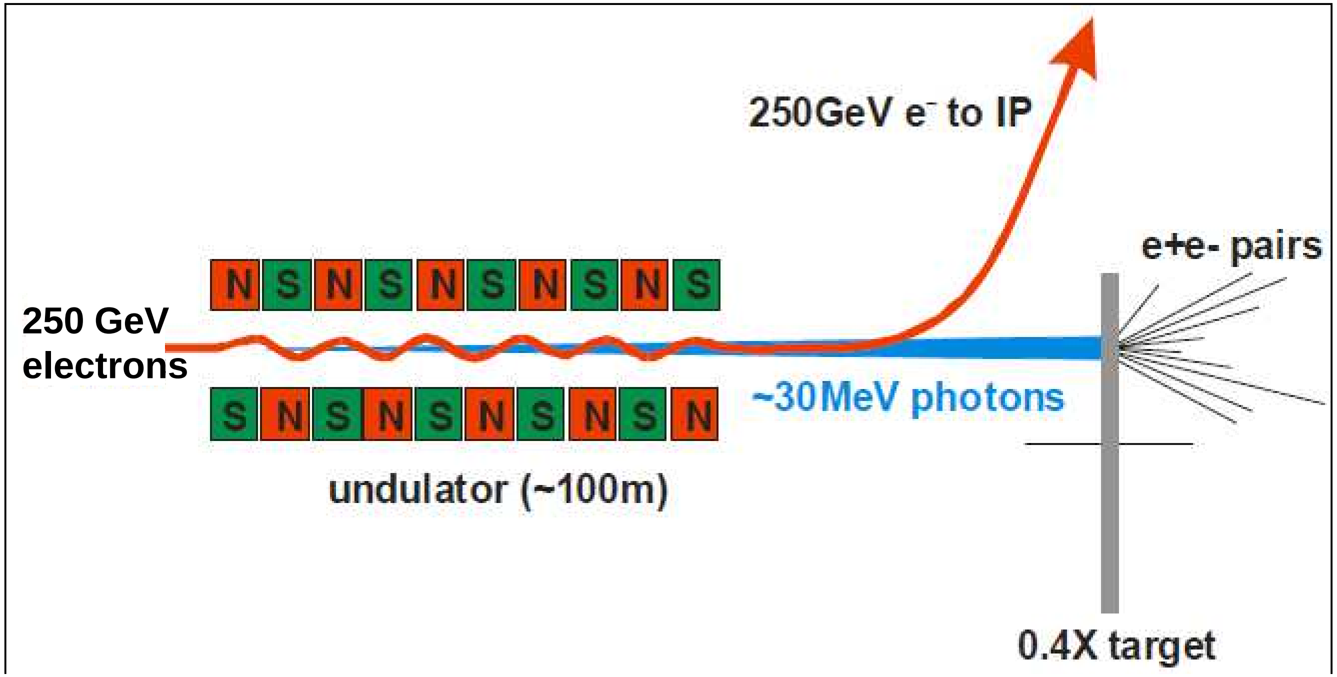
Colliding beams with Ecm = 500 GeV (update to 1 TeV possible)



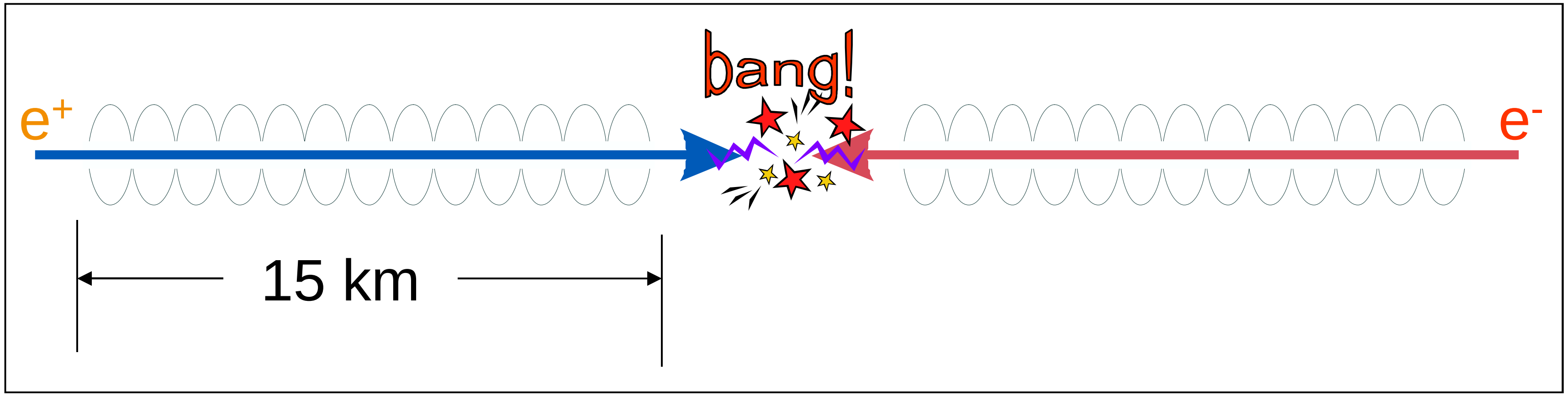
Positron source

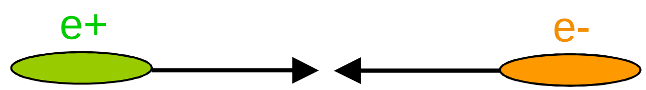






Luminosity





$$L = \frac{f_b N^2}{4\pi \sigma_x^* \sigma_y^*} \cdot H_D = \frac{\eta_{RF \to beam} P_{RF} N}{4\pi \sigma_x^* \sigma_y^* E_{cm}} \cdot H_D$$

beam power

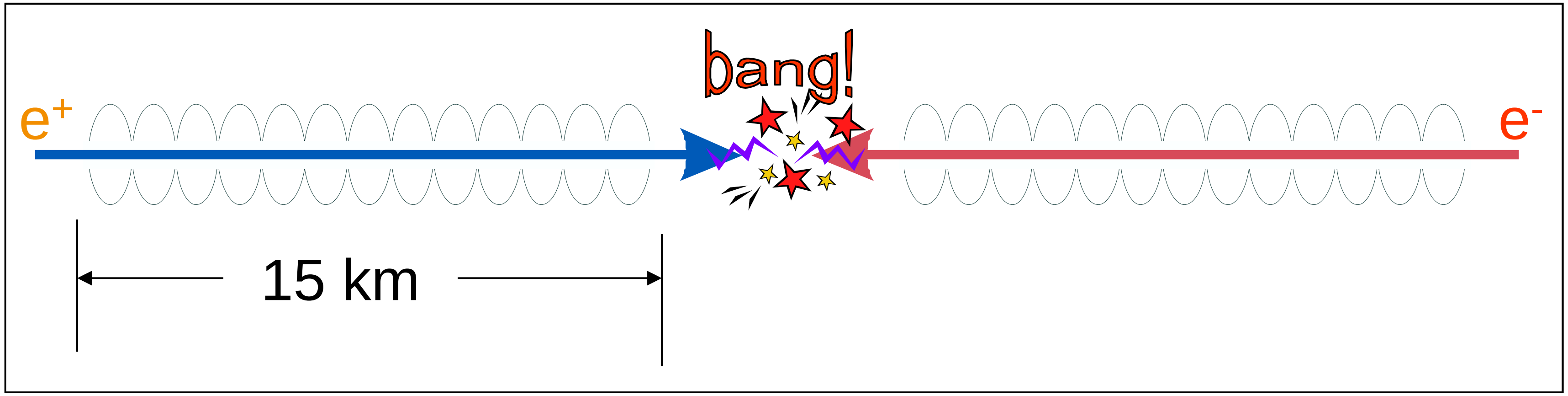
RF power

$$f_b N E_{cm} = P_{beam} = \eta_{RF \to beam} P_{RF}$$

conversion efficiency

Project for a future e-e+ collider: ILC

The International Linear Collider

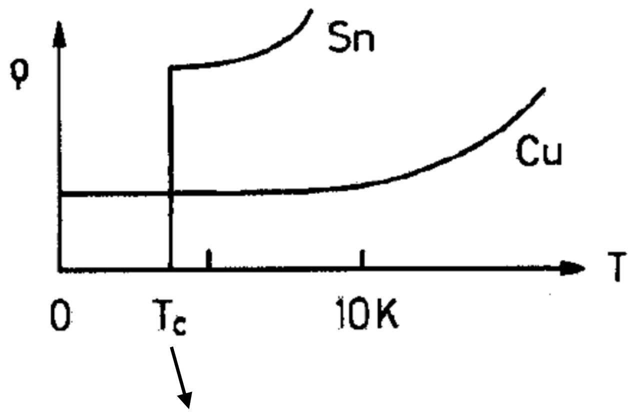


Colliding beams with $E_{CM} = 500$ GeV

using superconducting cavities for acceleration:

Advantages of RF superconductivity

resistance



critical temperature (Tc):

for DC currents !

at radio-frequencies, there is a "microwave surface resistance"

which typically is <u>5 orders of magnitude</u> lower than R of copper

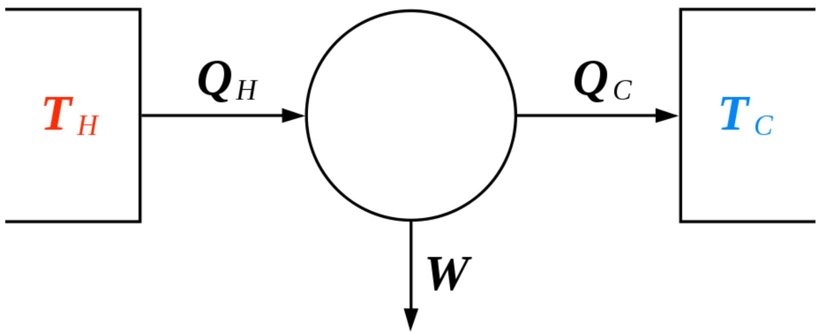
Advantages of RF superconductivity

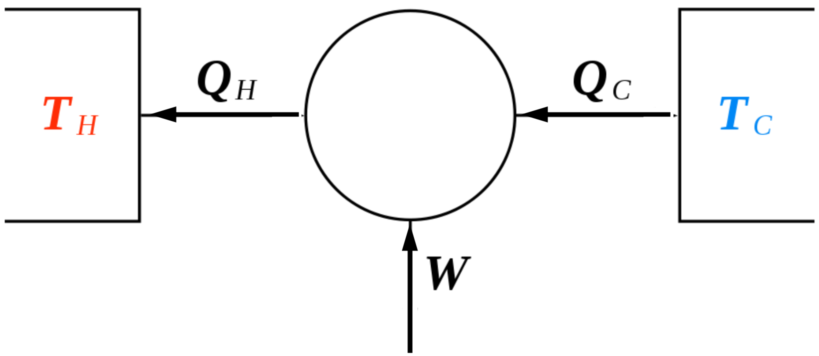
Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	0.4 + 1 W / m at 2 K	60 kW / m	dissipated at the cavity walls

2nd law of Thermodynamics

"Heat cannot spontaneously flow from a colder location to a hotter location"





max. efficiency	most common applications
$\eta_c = \frac{T_H - T_C}{T_H}$	thermal power stations, cars, …
$\eta_c = \frac{T_C}{T_H - T_C}$	air conditioners, refrigerators, …

Carnot efficiency:

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	0.4 + 1 W / m at 2 K	60 kW / m	dissipated at the cavity walls

Carnot efficiency: $\eta_c = \frac{T}{300-T} = 0.007$ x cryogenics efficiency 20-30%

for E = 1 MV/m	1 kW / m	60 kW / m

for E = 1 MV/m	1 kW / m	120 kW / m	including RF generation efficiency (50%)

reduction factor of >100 in (electrical) power

Advantages of RF superconductivity

Example: comparison of 500 MHz cavities:

	superconducting cavity	normal conducting cavity	
for E = 1 MV/m	0.4 + 1 W / m at 2 K	60 kW / m	dissipated at the cavity walls
Carnot efficiency: $\eta_c = \frac{T}{300-T} = 0.007$		x	cryogenics efficiency 20-30%
for E = 1 MV/m	1 kW / m	60 kW / m	
for E = 1 MV/m and 20 mA beam	21 kW / m	80 kW / m	total RF power needed
for E = 1 MV/m	42 kW / m	160 kW / m	including RF generation efficiency (50%)

reduction factor of 4 in (electrical) power

Accelerator Research at DESY

HELMHOLTZ ASSOCIATION

SC Technology
(R&D on CW, cryo module test bench, ongoing)

Surface Technology
(cavity surfaces, CRISP, ongoing)

SC Processes
(large series production & testing of sc cavities and modules, AMTF, ongoing)

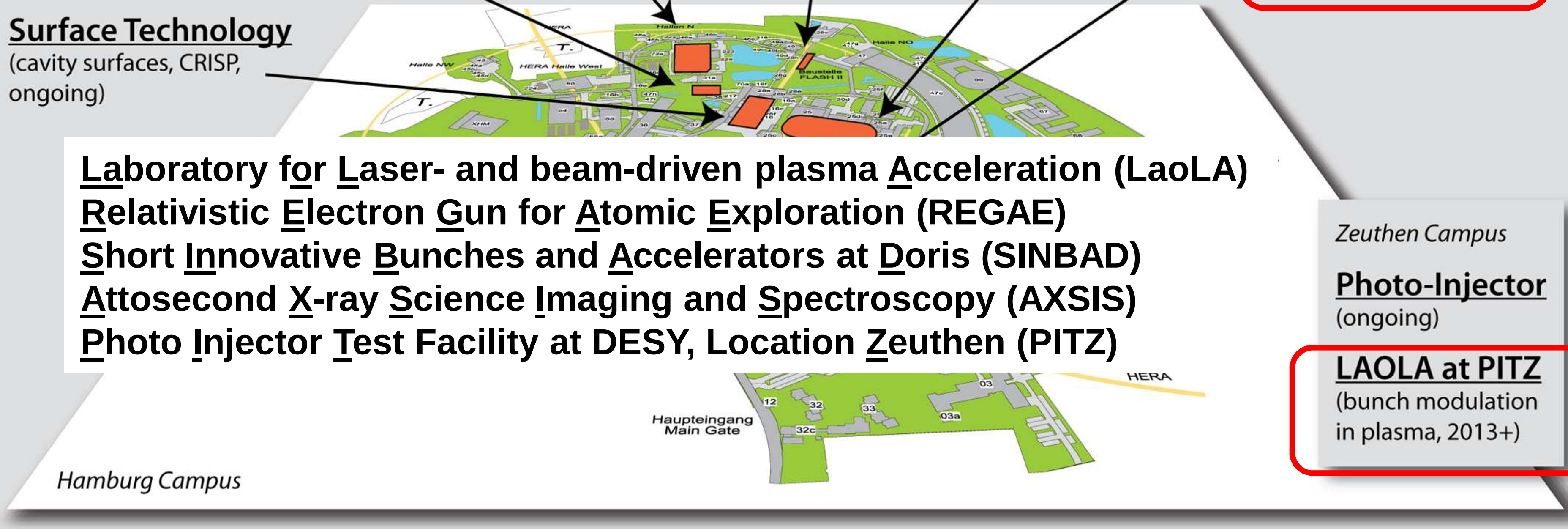
FEL Seeding
(sFLASH, FLASH2 seeding, ongoing)

LAOLA at FLASH2
(beam-driven plasma acceleration, 2016+)

SINBAD (ultra-short bunches, LAOLA, proto-type table-top FEL, 2017+)

AXSIS (atto-second bunches, ICS, 2014+)

LAOLA at REGAE
(laser-driven plasma acceleration, 2013-2016)



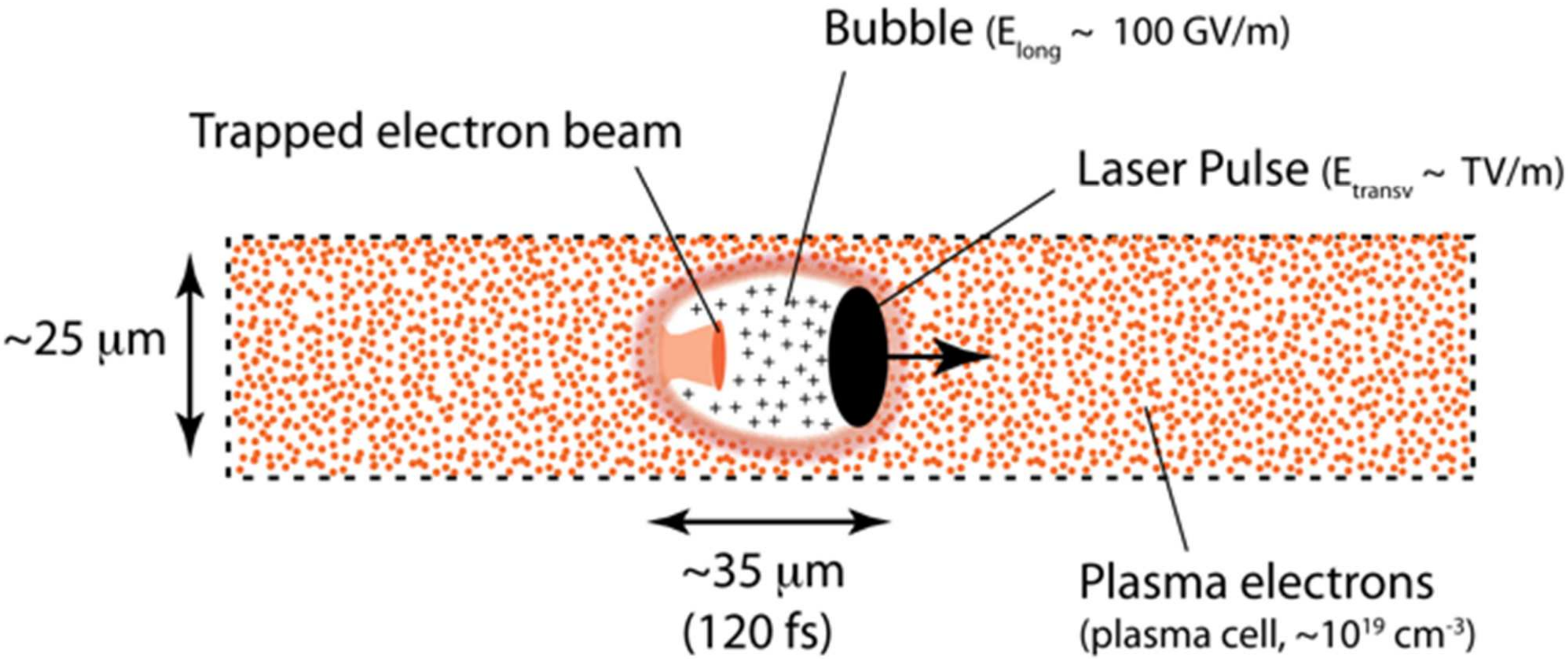
Laboratory for Laser- and beam-driven plasma Acceleration (LaOLA)
Relativistic Electron Gun for Atomic Exploration (REGAE)
Short Innovative Bunches and Accelerators at Doris (SINBAD)
Attosecond X-ray Science Imaging and Spectroscopy (AXSIS)
Photo Injector Test Facility at DESY, Location Zeuthen (PITZ)

Zeuthen Campus

Photo-Injector
(ongoing)

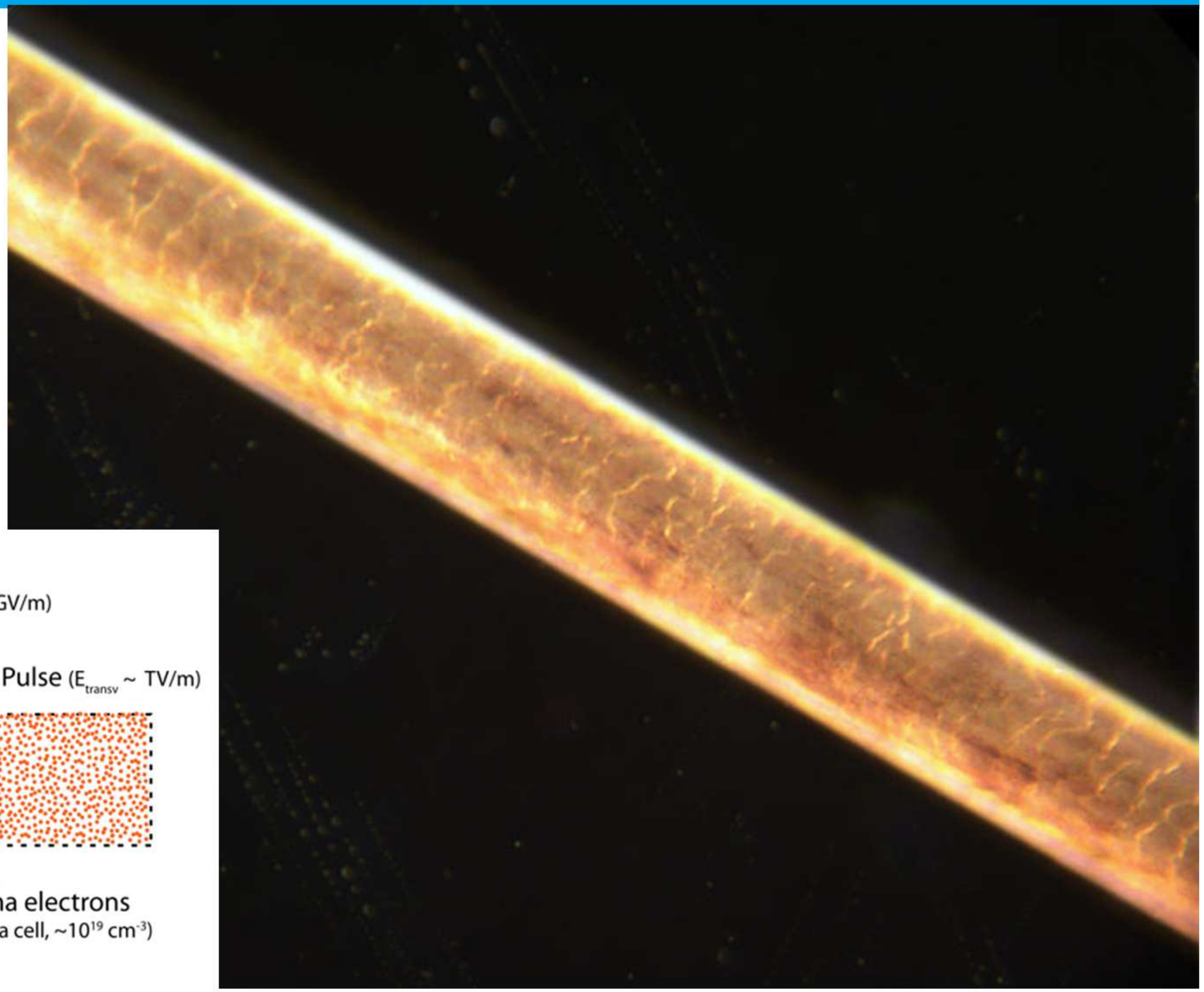
LAOLA at PITZ
(bunch modulation in plasma, 2013+)

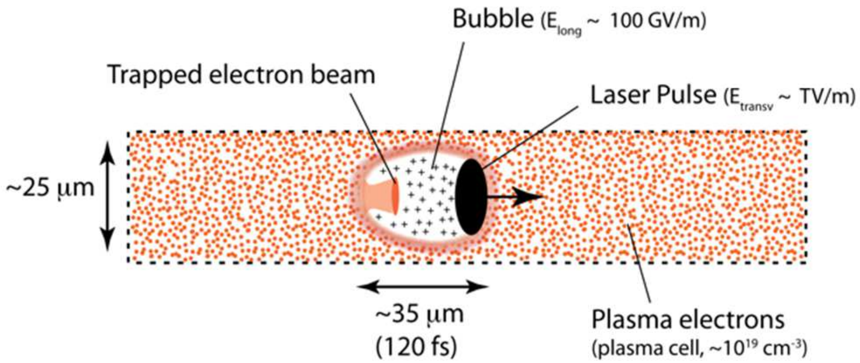
Laser-driven plasma acceleration



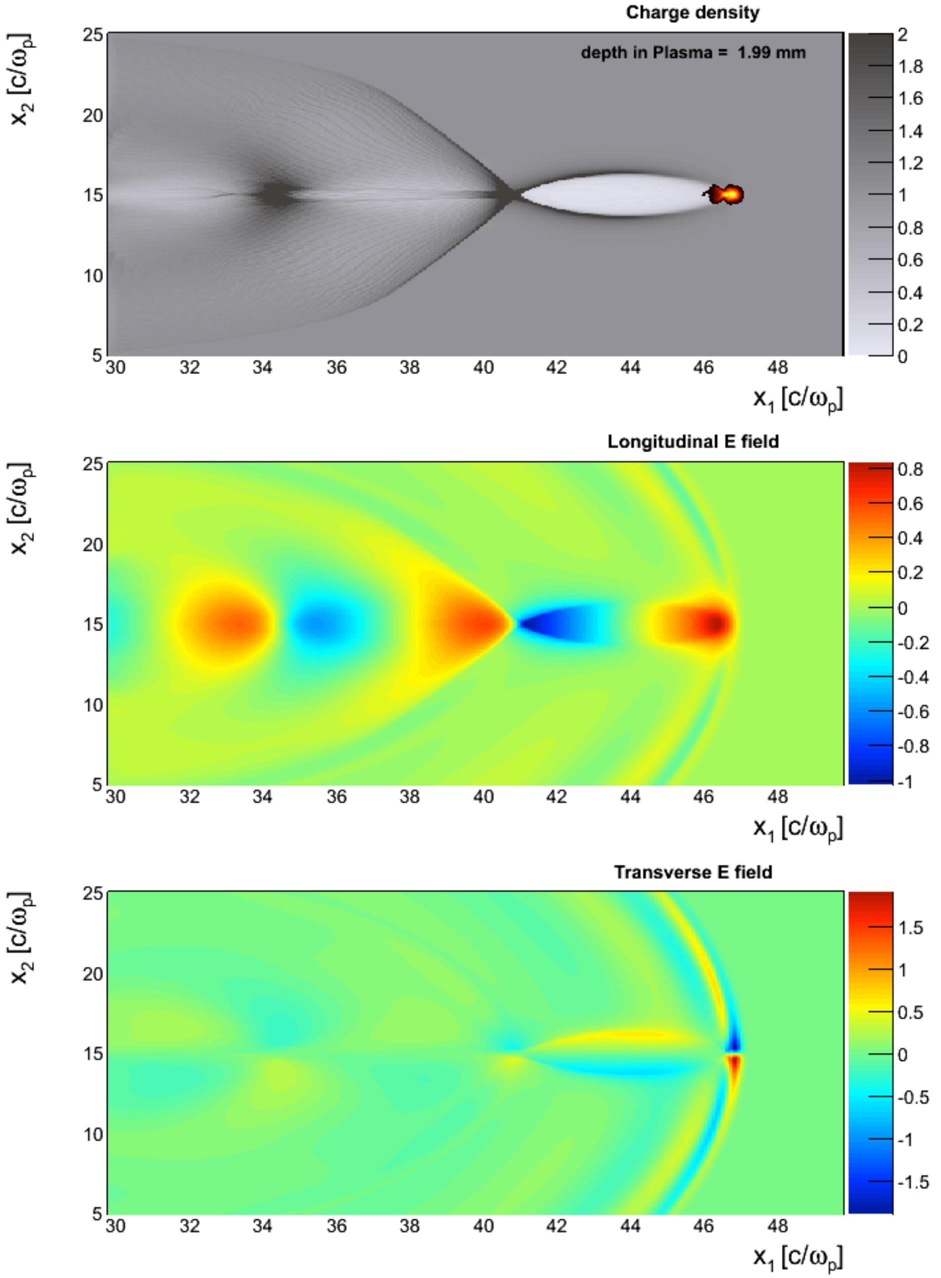
Acceleration (and focusing) within a hair width …

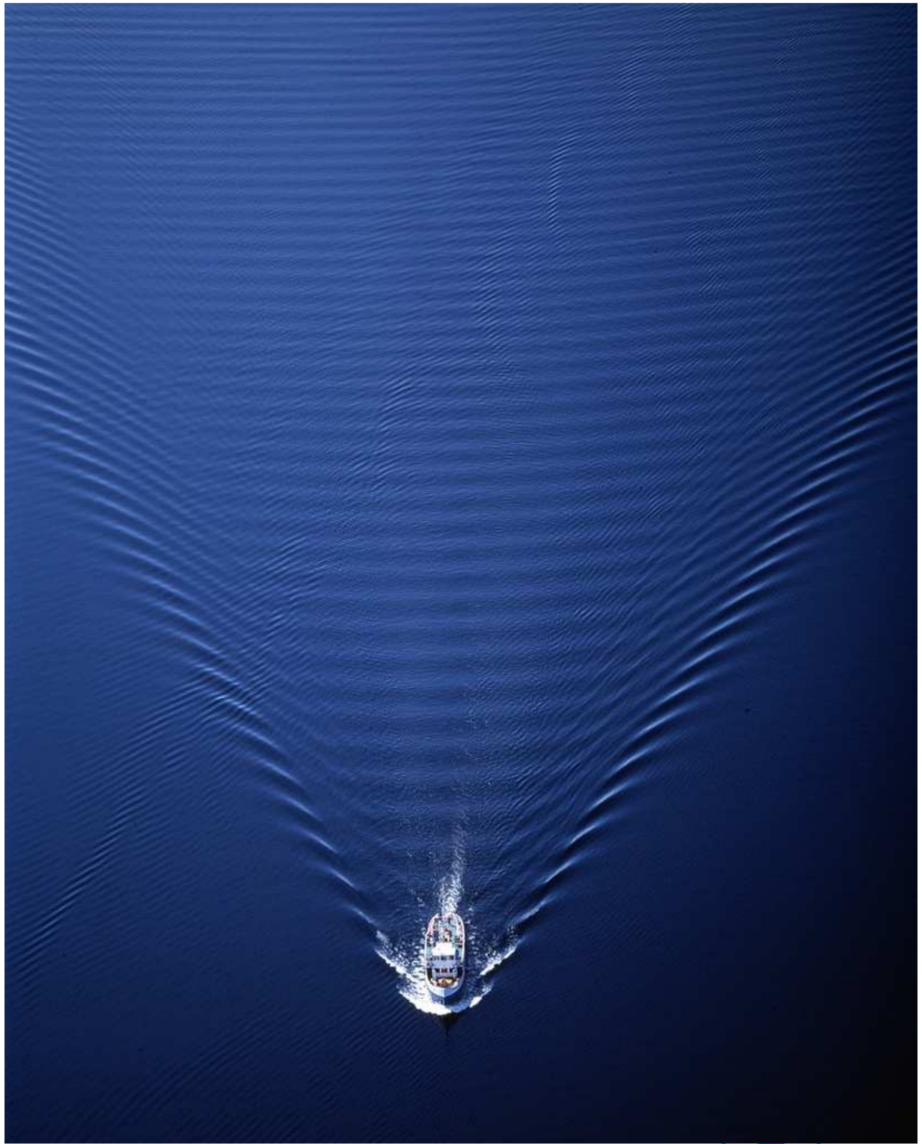
E_{long}	**100 GV/m**
g_{transv}	**300 MT/m**



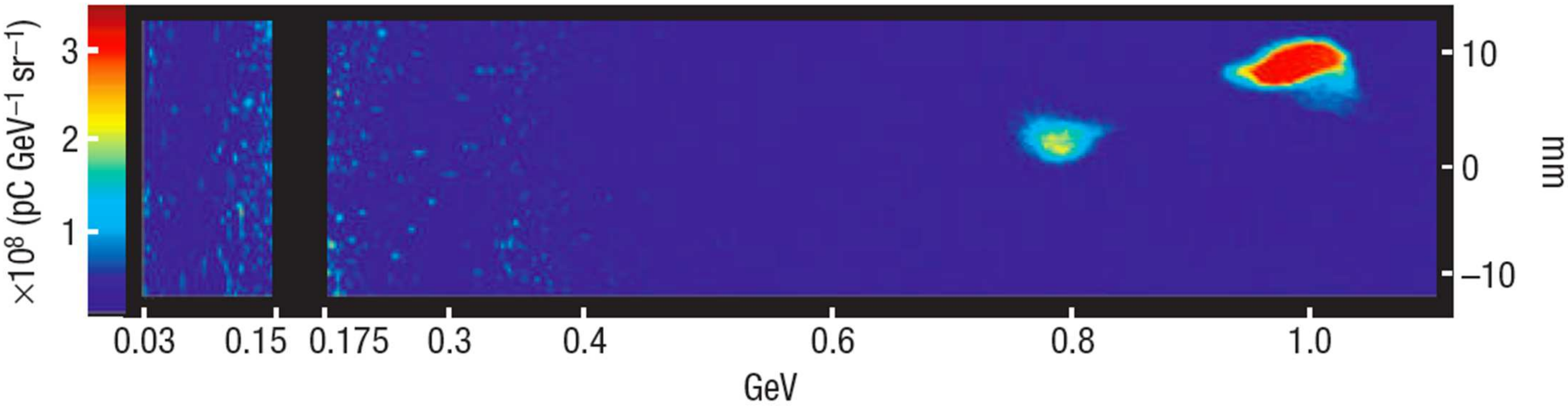


Simulations





Breakthrough in the lab



LETTERS

GeV electron beams from a centimetre-scale accelerator

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nature physics | VOL 2 | OCTOBER 2006

2-3 orders of magnitude higher acceleration fields than conventional RF cavities

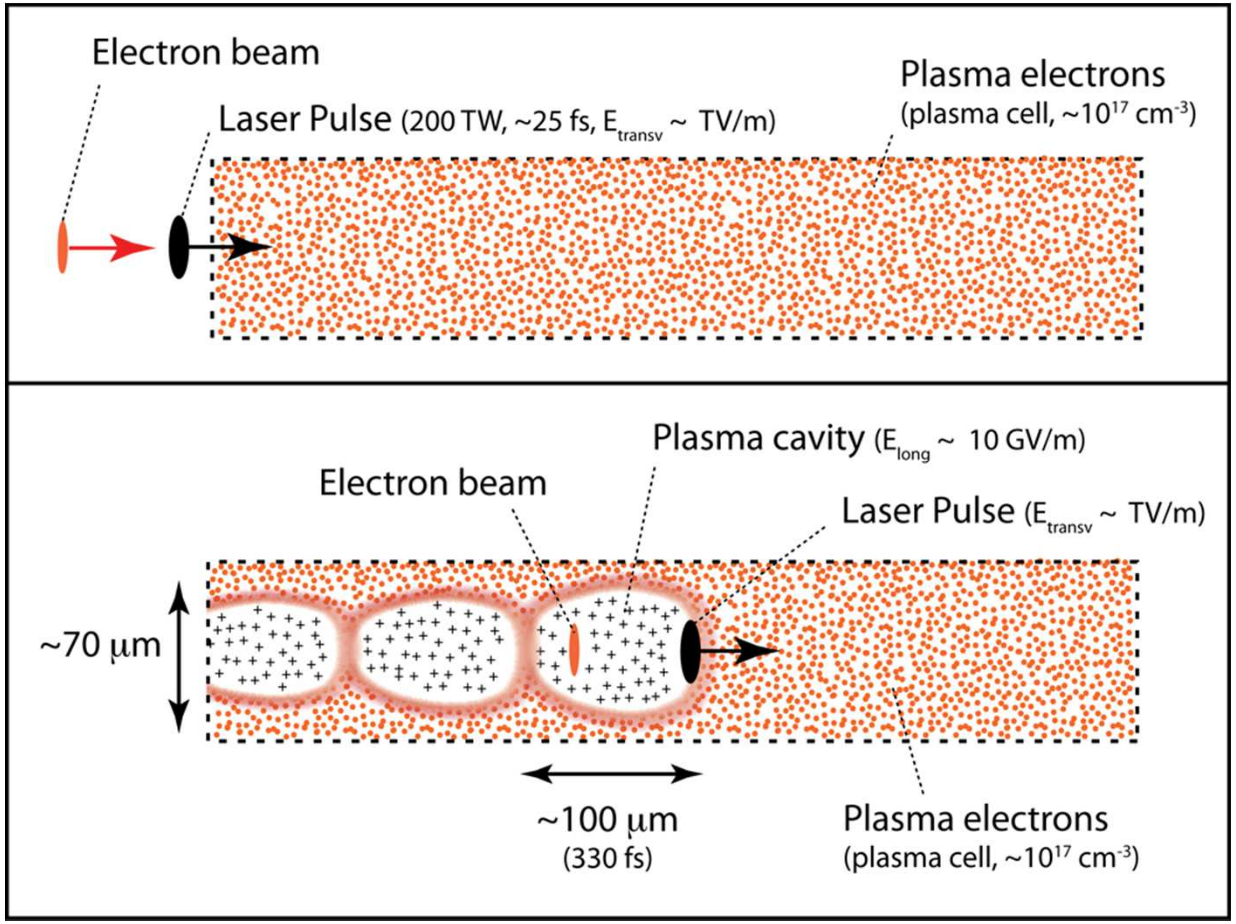
smaller and cheaper accelerators are possible

Challenges of plasma acceleration

Maximum energy limitation at 1 GeV or few GeV

Plasma self-injection is very unstable in energy, timing …

Challenges of plasma acceleration



not yet proven !

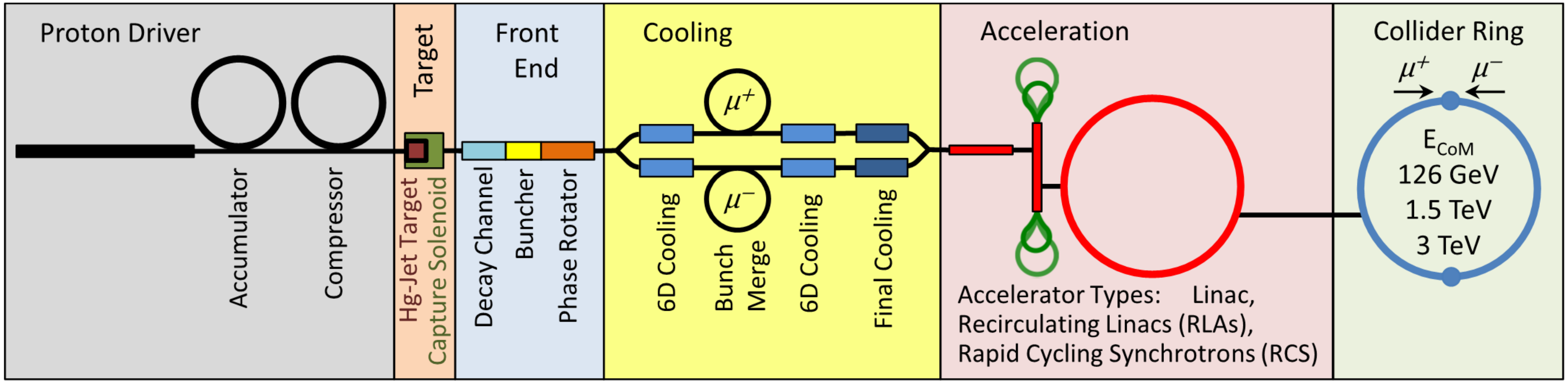
Circular colliders (synchrotrons):

particle type	limitation
• proton synchrotrons 938 $\mathrm{Me}V/c^2$	dipole magnet
• electron synchrotrons 0.511 $\mathrm{Me}V/c^2$	synchrotron radiation
• muon synchrotrons 105.7 $\mathrm{Me}V/c^2$	mean lifetime = 2.2 μs ?

Muon beams produced as tertiary beams: $p \rightarrow \pi \rightsquigarrow \mu$

Muon collider principle

Muon collider block diagram



Collider:

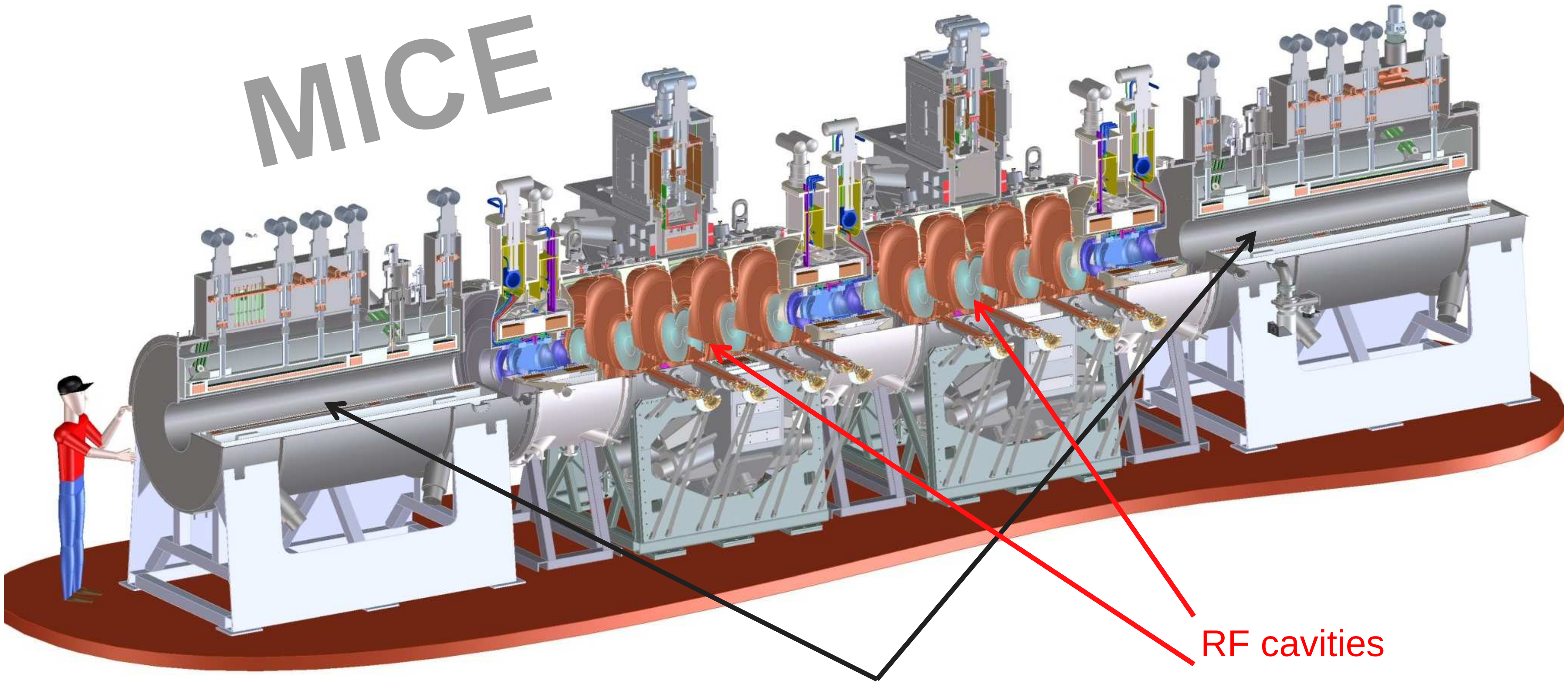
E_{cm} = 3 TeV

circumference = 4.5 km

$L = 3{\times}10^{34}$ cm^{-2}s^{-1}

MICE at FERMILAB (Chicago)

The Muon Ionization Cooling Experiment (MICE)
→ demonstrate the method and validate simulations



Summing-up

Basics of synchrotron radiation

particle type	limitation
• proton synchrotrons	dipole magnet
• electron synchrotrons	synchrotron radiation

International Linear Collider (ILC):

- luminosity eq.
- damping rings
- positron source
- power efficiency in superconducting cavities

Two very promising (and challenging) research areas in accel. physics:

- laser-driven plasma acceleration
- muon collider

Thank you for your attention

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