Introduction to Accelerator Physics

Part 4

Pedro Castro / Accelerator Physics Group (MPY)

Introduction to Accelerator Physics
DESY, 29th July 2014

Differences between proton and electron accelerators

HERA (Hadron Electron Ring Accelerator) tunnel:

proton accelerator

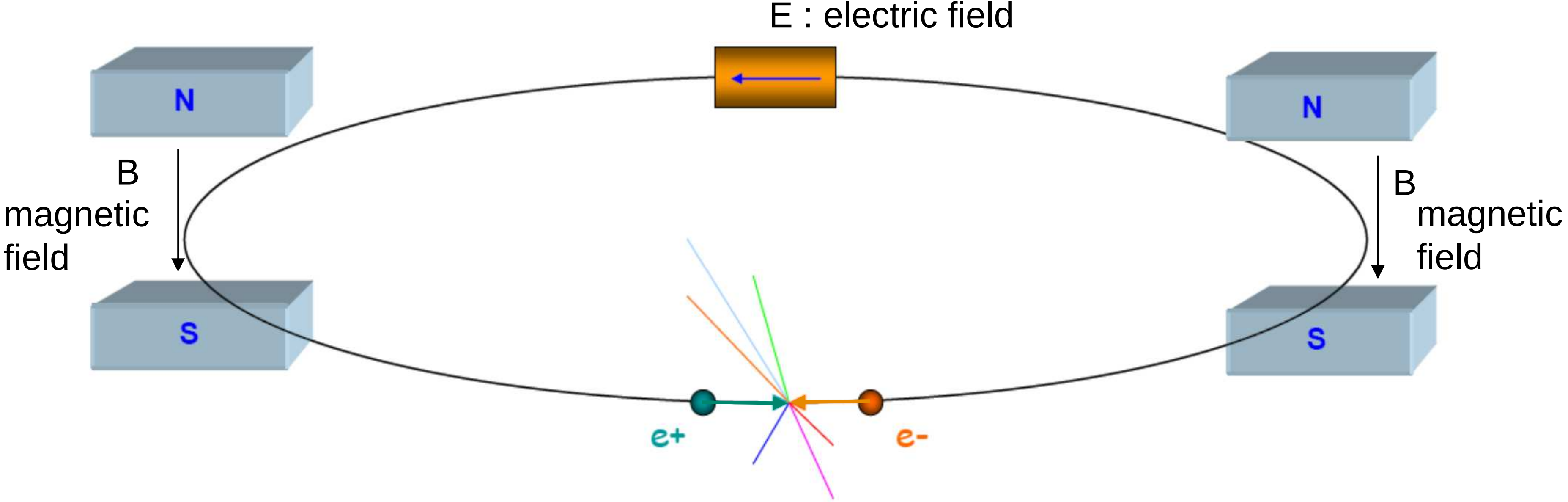
920 GeV

electron accelerator

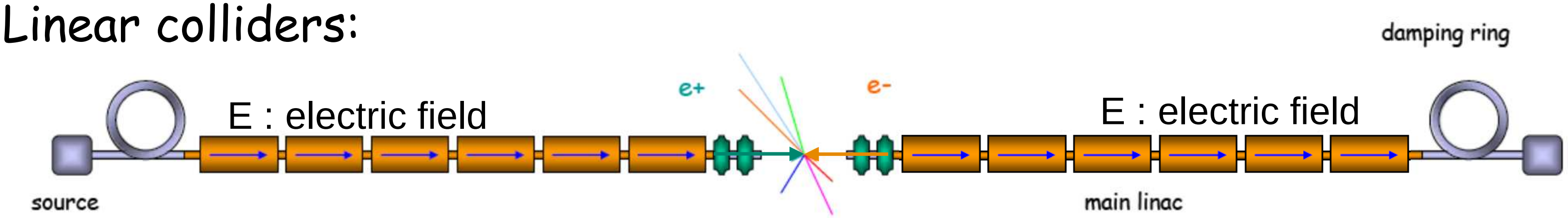
27.5 GeV

Which collider is better?

Circular colliders:

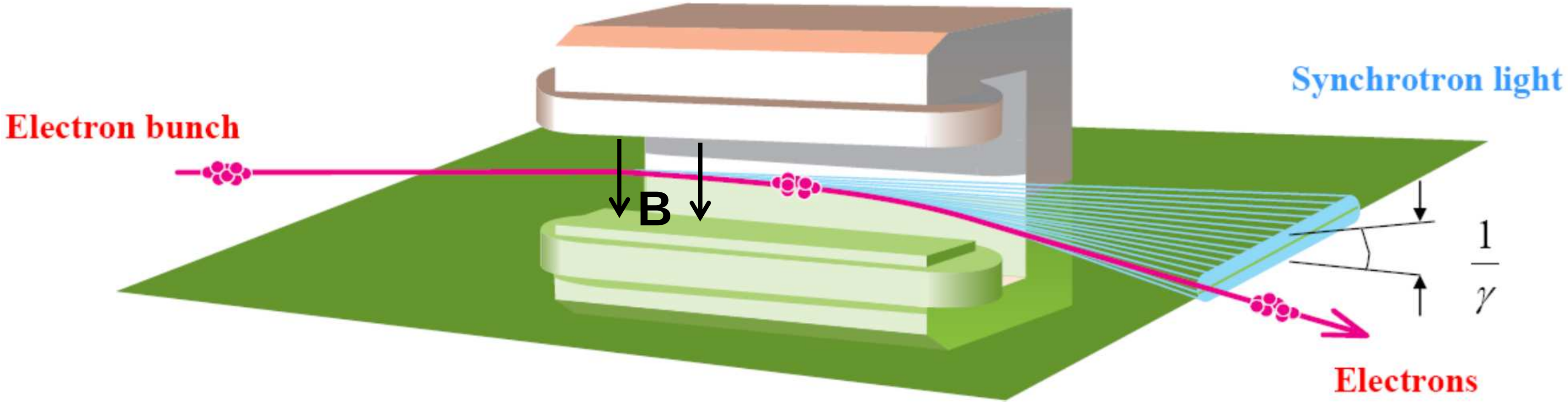


Linear colliders:



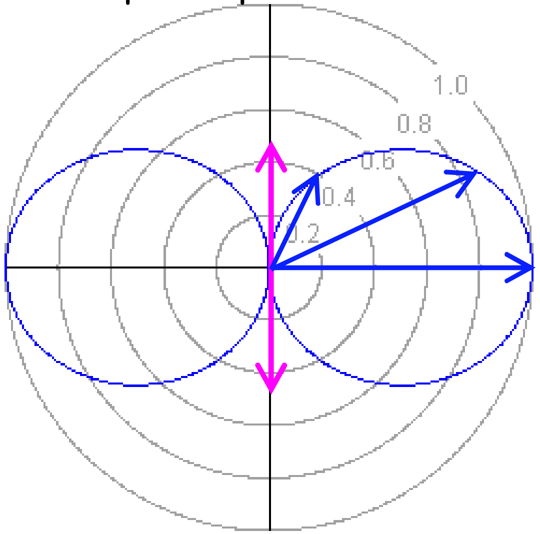
Synchrotron radiation

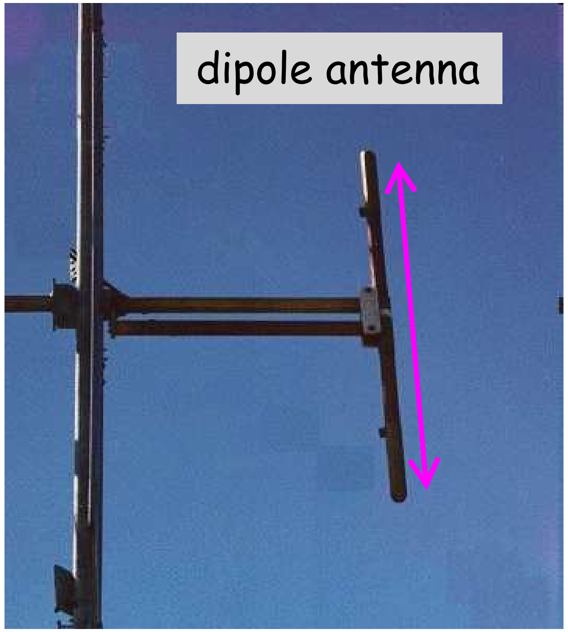
Dipole magnet

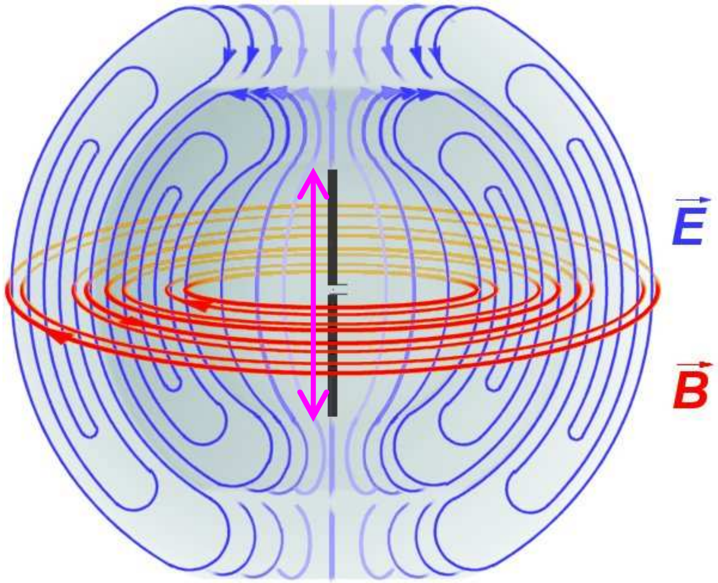


Radio antenna

radiation power pattern:







Radiation of a dipole antenna

local oscillator:

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

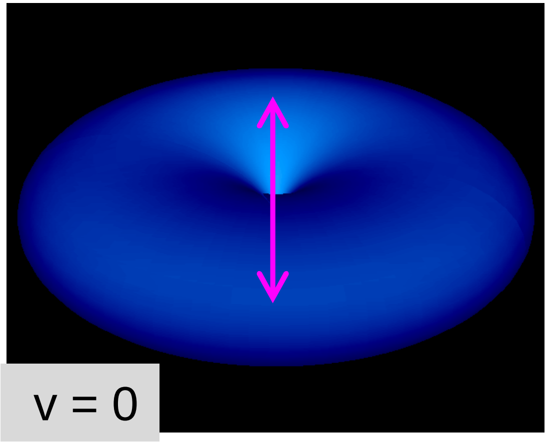
$$(\text{oscillation amplitude}: a < \lambda)$$

moving oscillator:

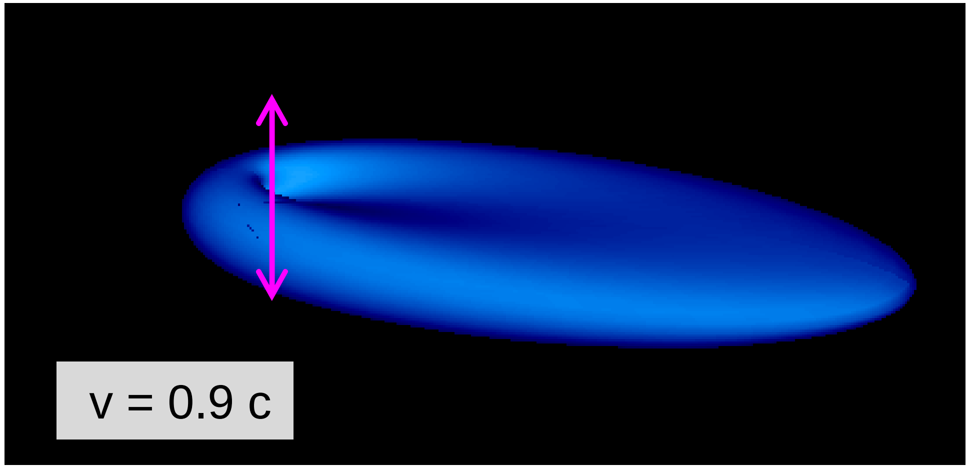
$$P = \frac{q^2 a^2}{12\pi\varepsilon_0 c^3}\gamma^4\omega^4$$

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

Radiation of an oscillating dipole

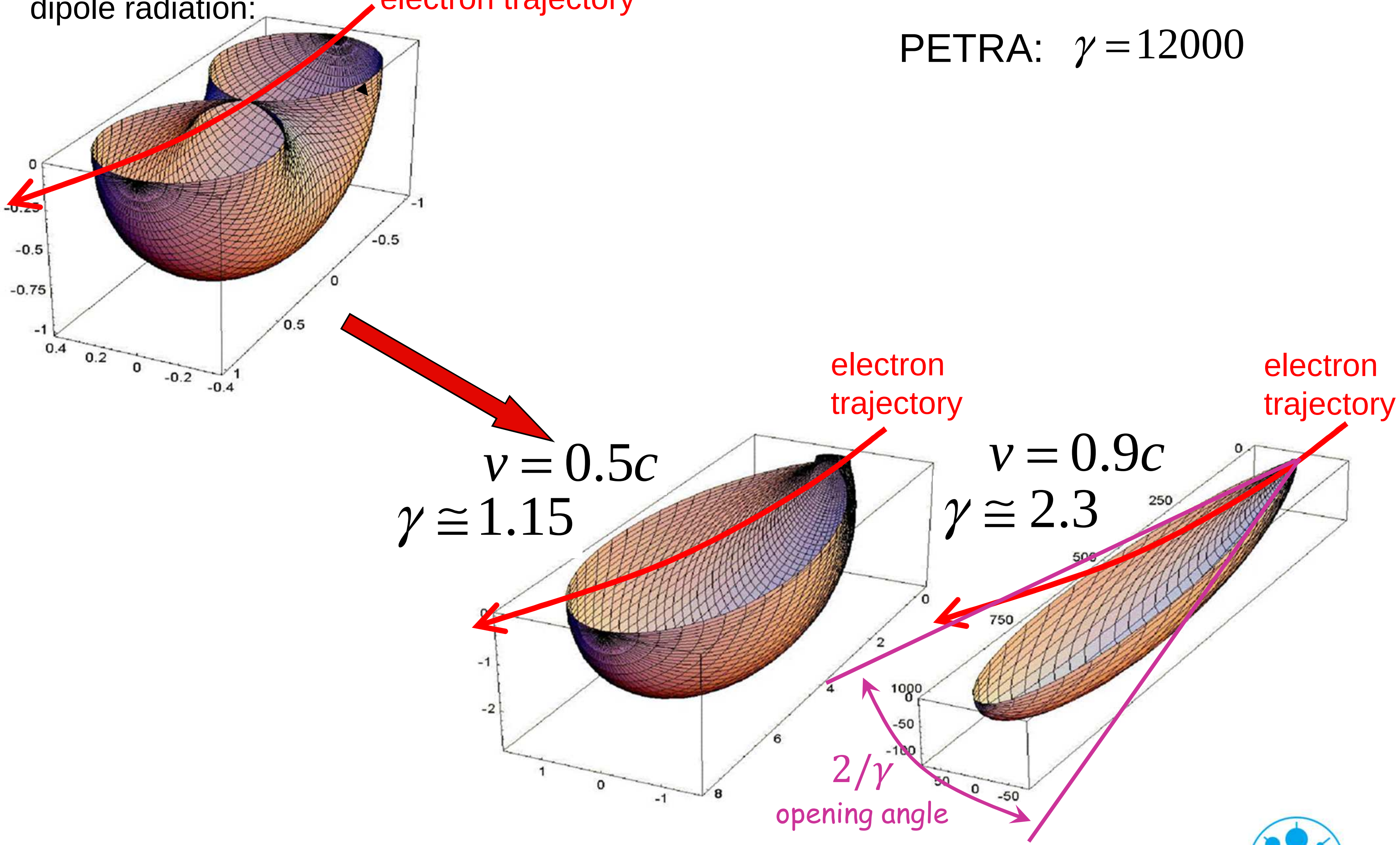


Radiation of a moving oscillating dipole



Radiation of a oscillating dipole under relativistic conditions

dipole radiation:



electron trajectory

PETRA: $\gamma = 12000$

$v = 0.5c$

$\gamma \cong 1.15$

electron trajectory

$v = 0.9c$

$\gamma \cong 2.3$

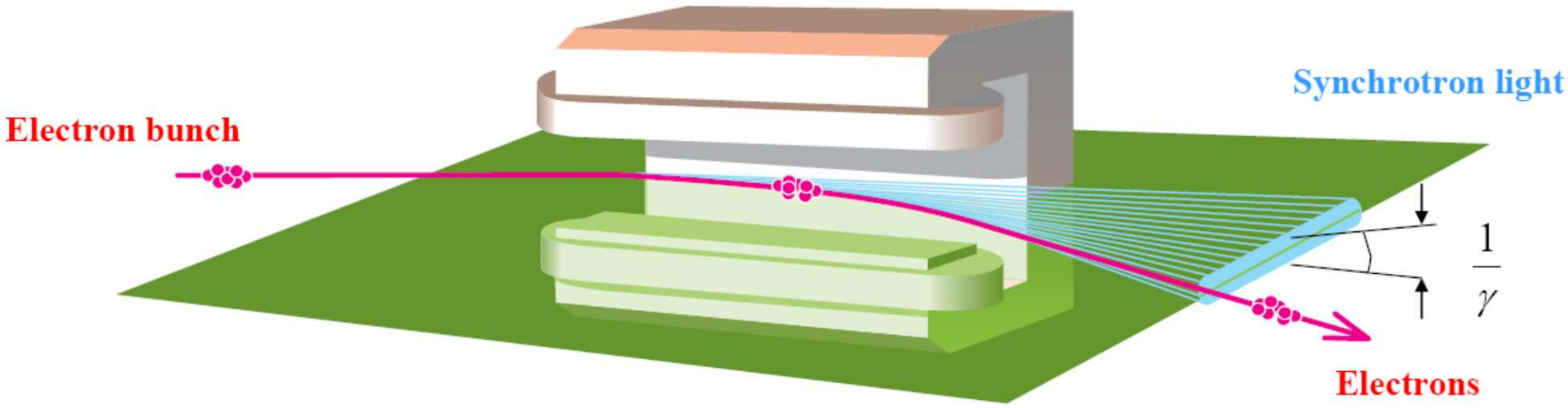
electron trajectory

$2/\gamma$

opening angle

Synchrotron radiation

Dipole magnet



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

$$\left(\frac{2\pi r}{c}\right)\times \qquad P = \frac{c\,q^2}{6\pi\varepsilon_0}\,\frac{\gamma^4}{r^2}$$

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

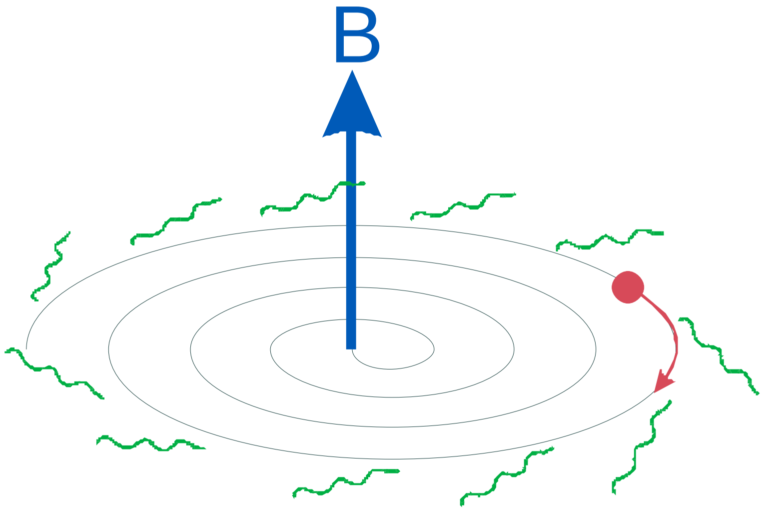
$$\frac{1}{r} = \frac{q\,B}{p}$$

vacuum permitivity

Synchrotron radiation

Total energy loss after one full turn:

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



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

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:

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

HERA electron ring:

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

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

$$\gamma = 54000$$

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

same ←→

HERA proton ring:

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

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

$$\gamma = 980$$

the limit is the max. dipole field = 5.5 Tesla

$$\frac{1}{r} = \frac{qB}{p} \quad \Rightarrow \quad p_{max} = RqB_{max}$$

need acceleration = 87 MV per turn

Synchrotron radiation

Total energy loss after one full turn:

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

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

x5 →

LEP collider:

$r = 2800\ \text{m}$

$E = 105\ \text{GeV}$

$\gamma = 205000$

$\Delta E_{turn} \cong 4\ GeV\ (4\%)$

need 4 GV per turn !!

Summing-up

Basics of synchrotron radiation

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

International Linear Collider (ILC)

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

(not to scale)

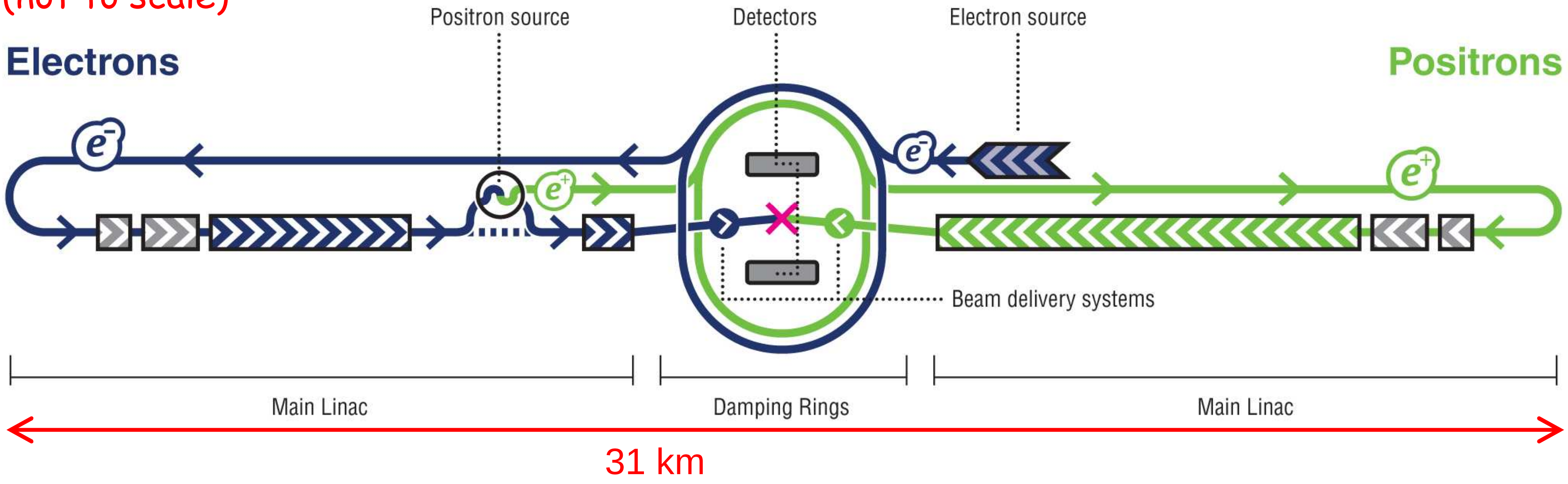
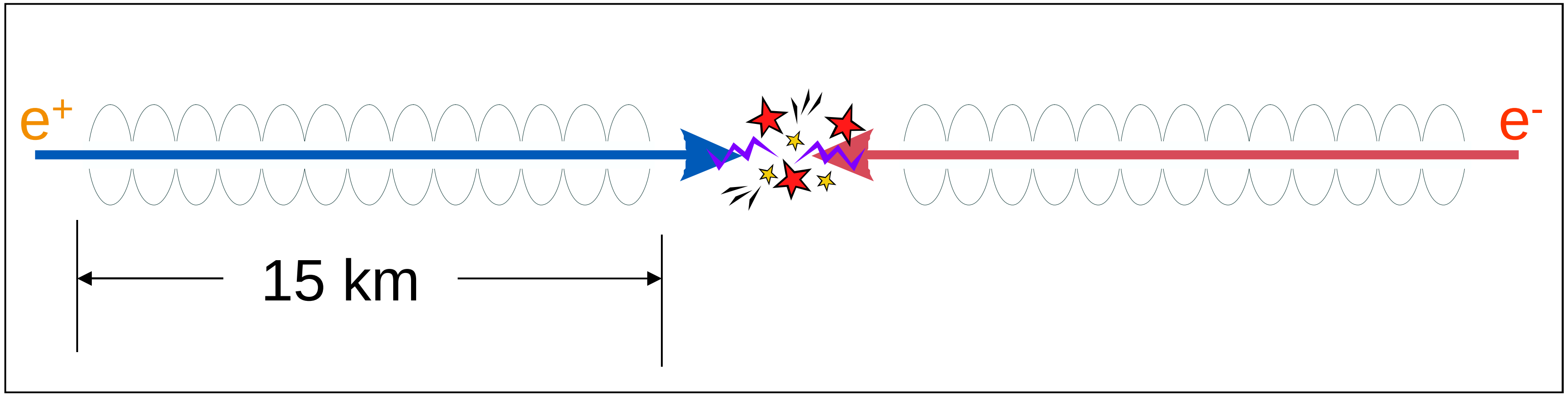
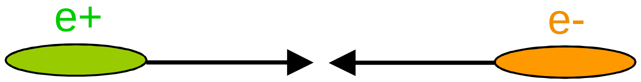


Figure of merit: Luminosity





<u>production rate</u> of a given event (for example, Z particle production):

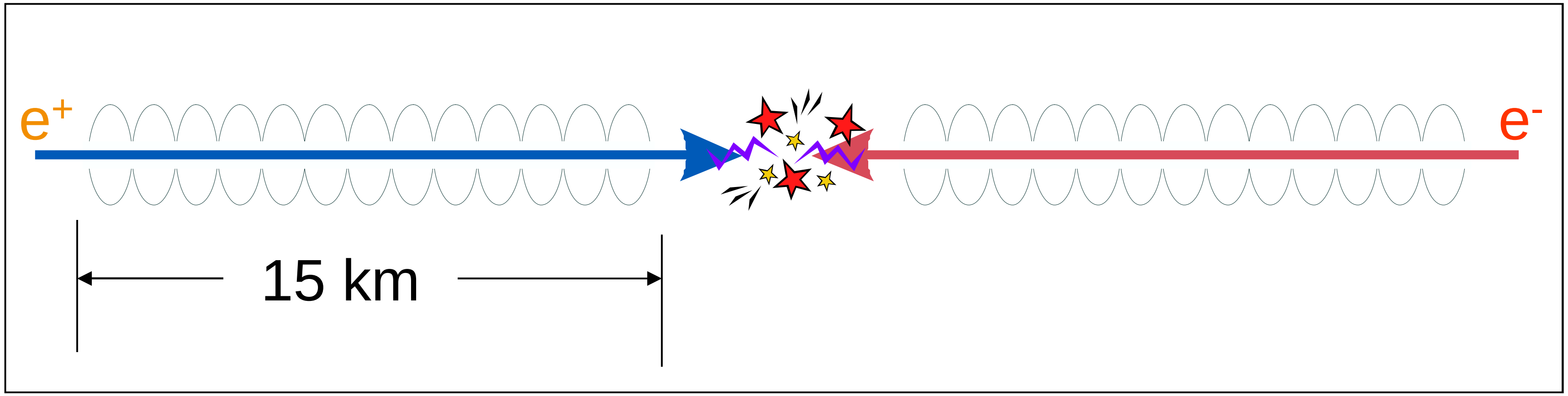
$$R_Z = \frac{dN_z}{dt} = \Sigma_z \cdot L$$

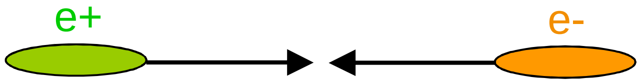
number of events

luminosity (independent of the event type)

cross section of Z production

Luminosity





number of colliding bunches per second

number of positrons per bunch

number of electrons per bunch

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

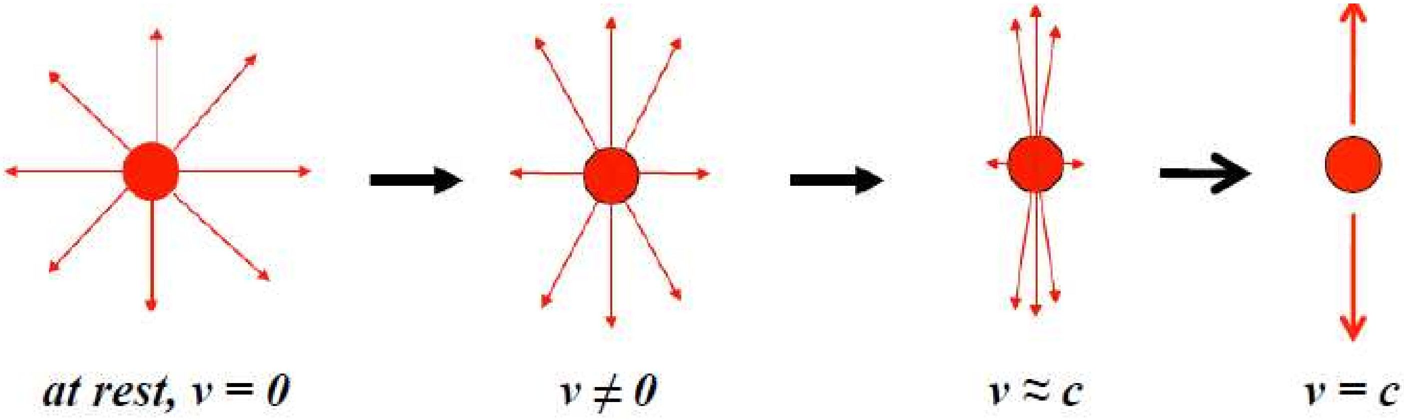
luminosity

beam-beam enhancement factor

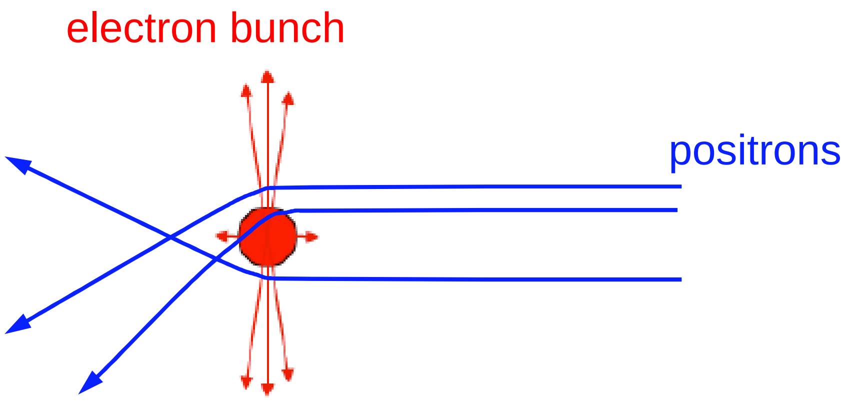
transverse bunch sizes (at the collision point *)

Luminosity enhancement factor H_D due to focusing of opposite beam

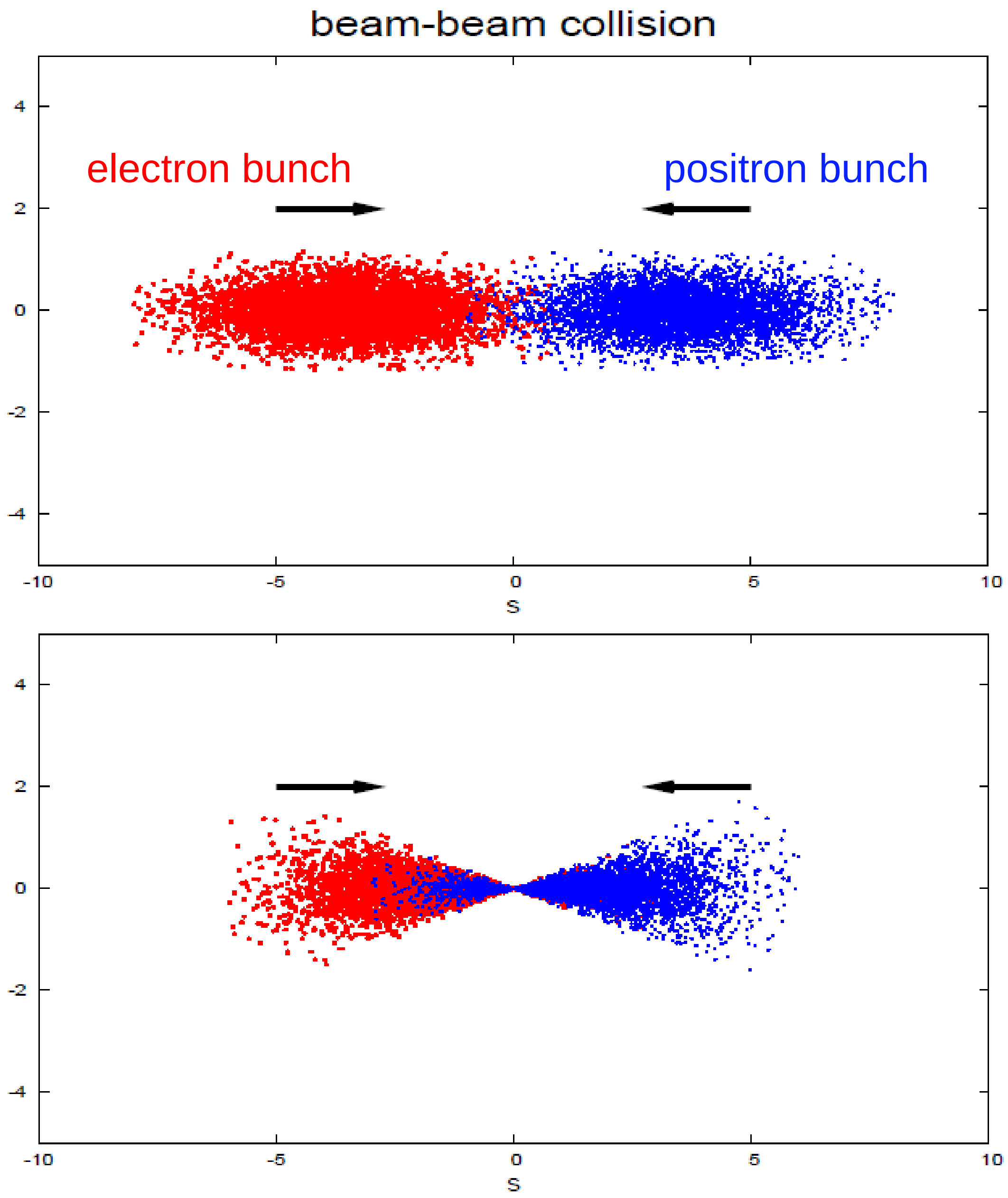
electric field of a charged particle (or bunch)



opening angle of field lines $= \pm 1/\gamma$



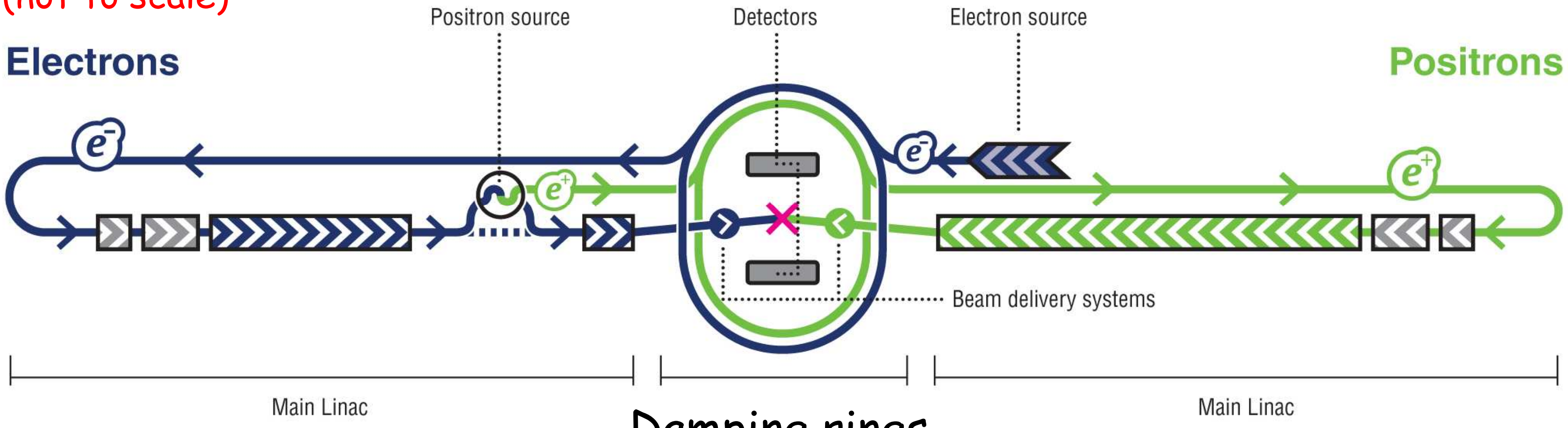
Luminosity enhancement factor H_D due to focusing of opposite beam



International Linear Collider (ILC)

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

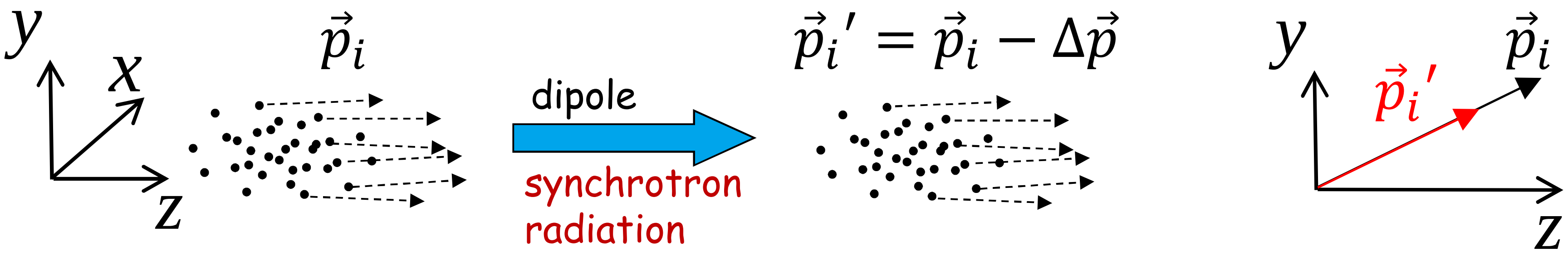
(not to scale)



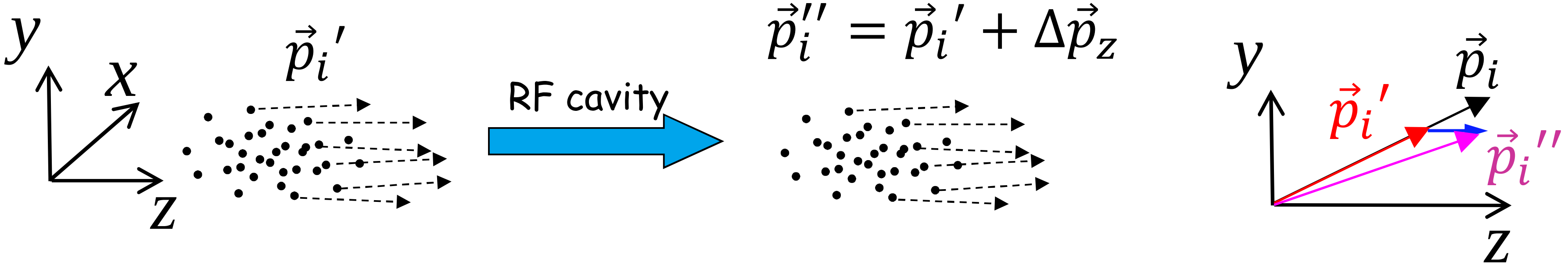
Damping rings

Damping rings

Radiation damping:

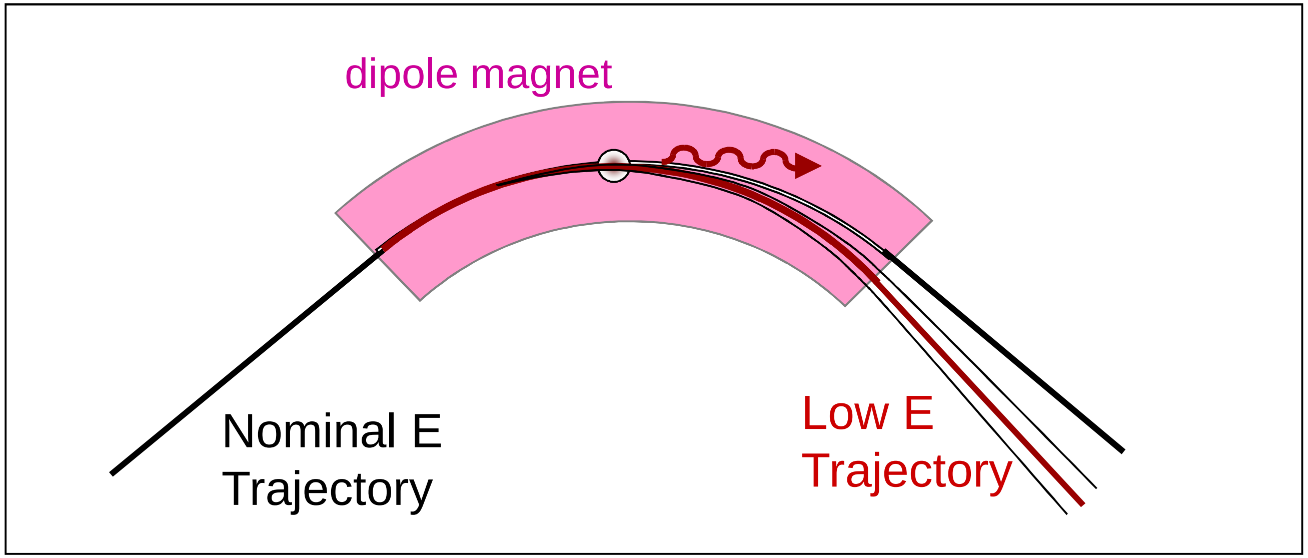


Longitudinal acceleration:



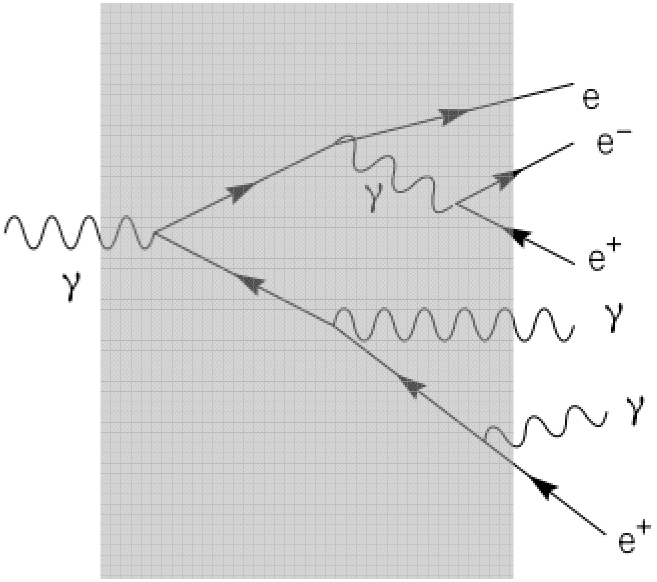
acceleration (only in z direction) $\frac{p_x}{|\vec{p}|}$ and $\frac{p_y}{|\vec{p}|}$ get smaller

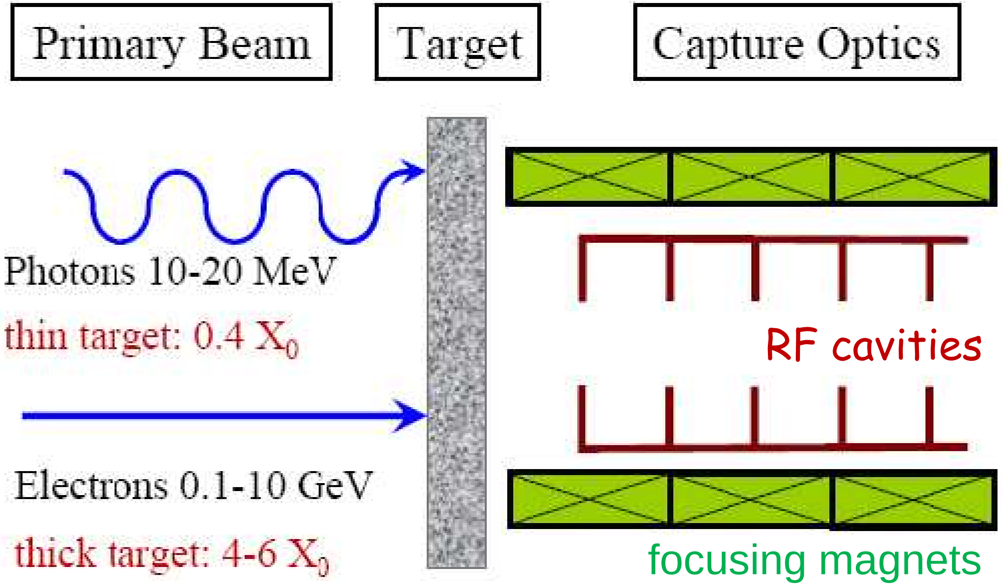
Quatum excitation



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

Positron source





Primary Beam

Target

Capture Optics

Photons 10-20 MeV

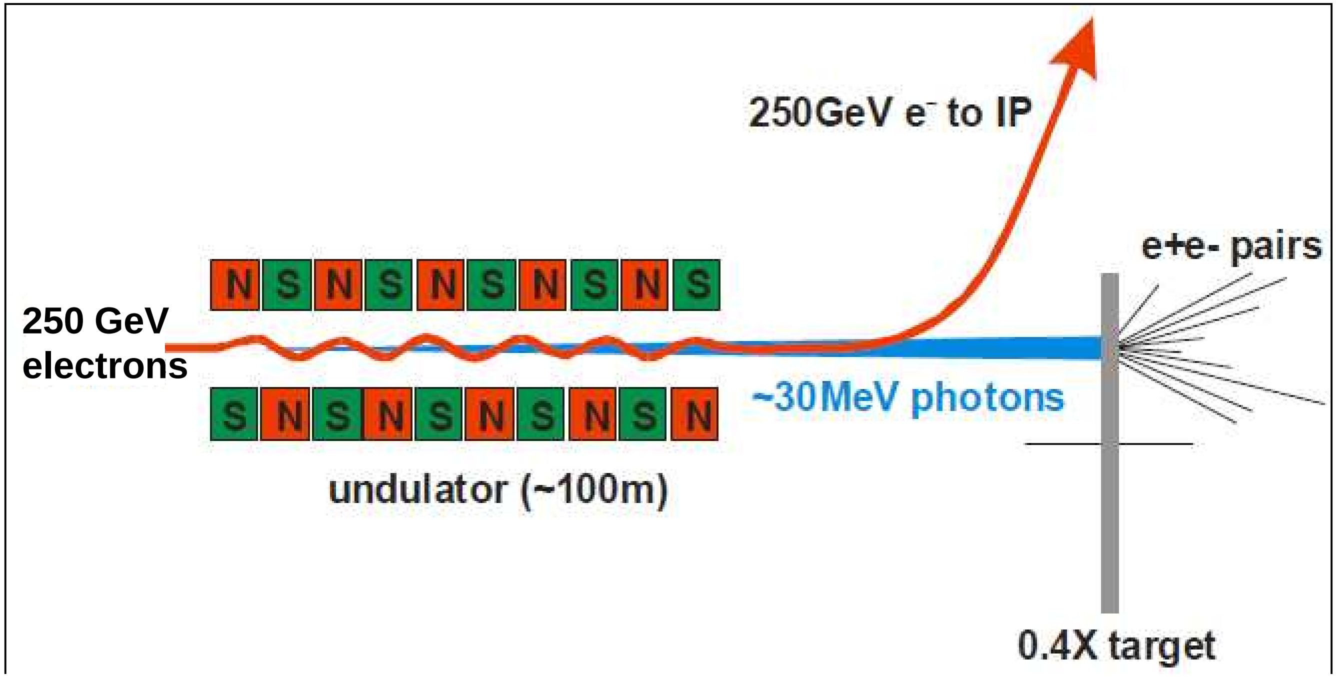
thin target: 0.4 X_0

Electrons 0.1-10 GeV

thick target: 4-6 X_0

RF cavities

focusing magnets



250GeV e$^-$ to IP

e+e- pairs

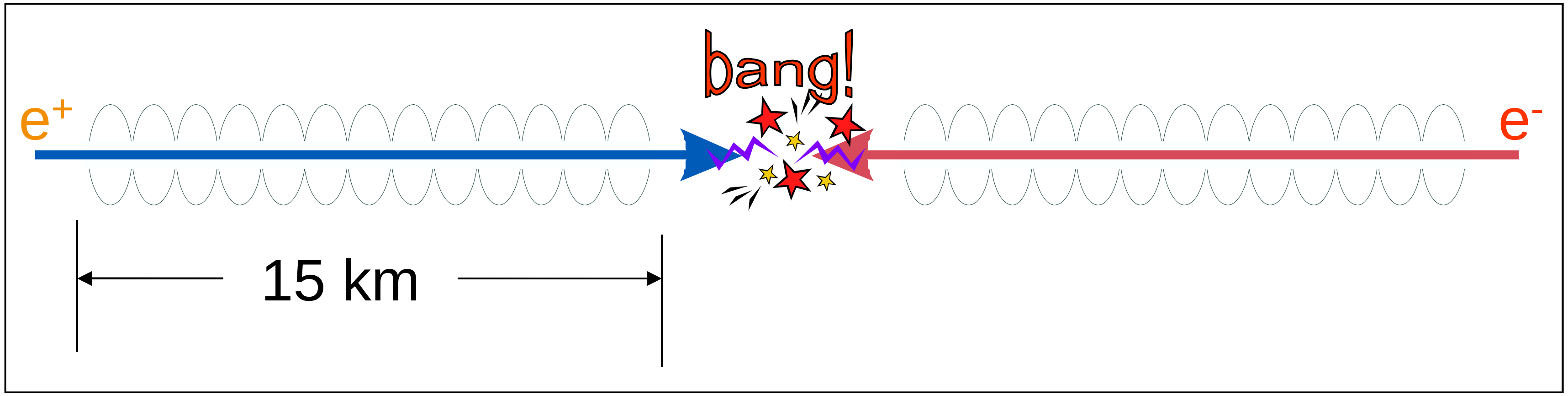
250 GeV electrons

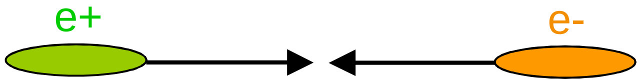
~30MeV photons

undulator (~100m)

0.4X target

Luminosity





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

beam power

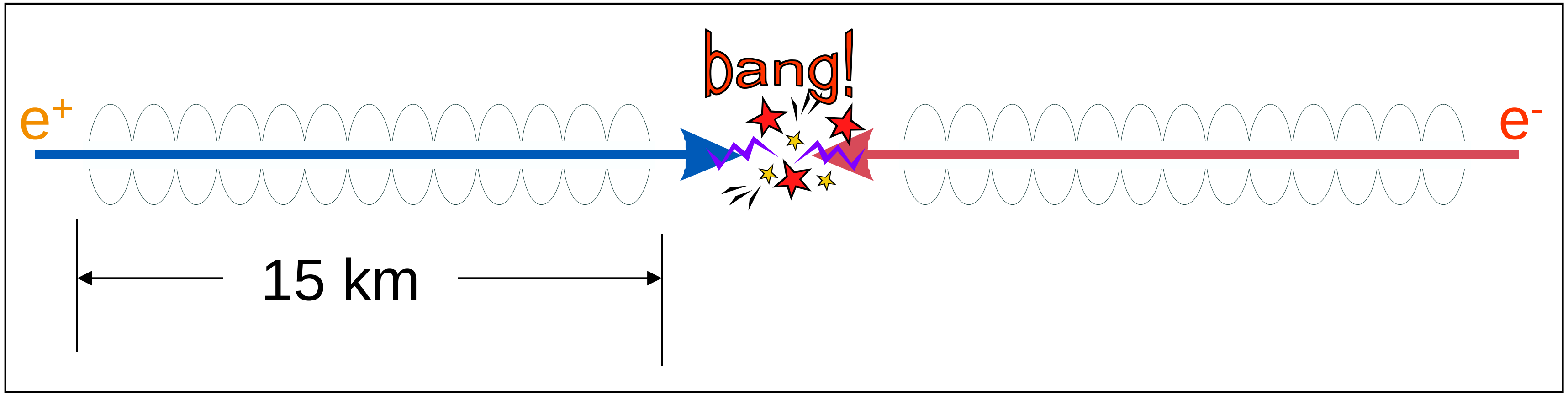
RF power

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

conversion efficiency

Project for a future e-e+ collider: ILC

The International Linear Collider

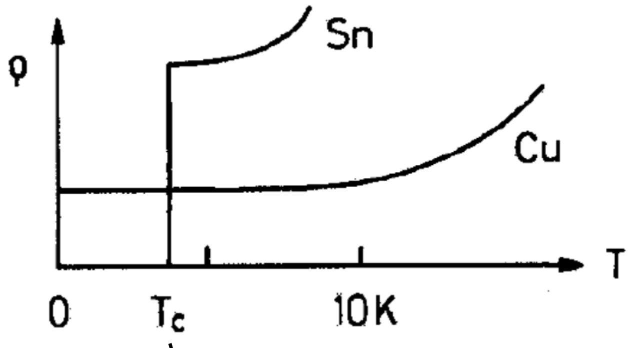


Colliding beams with $E_{CM} = 500$ GeV

using superconducting cavities for acceleration:

Advantages of RF superconductivity

resistance



for DC currents !

critical temperature (Tc):

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:

dynamic losses

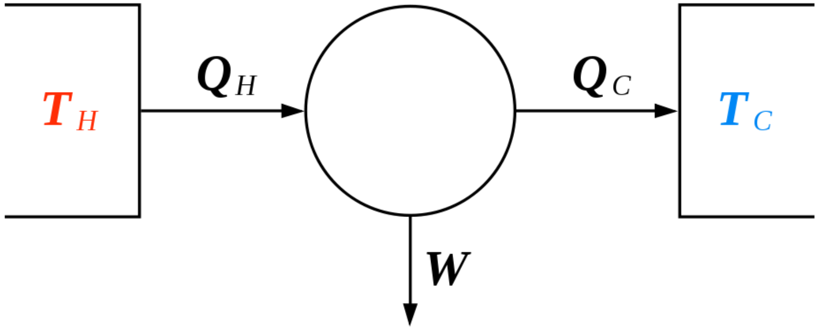
	superconducting cavity	normal conducting cavity
for E = 1 MV/m	0.4 + 1 W / m at 2 K	60 kW / m

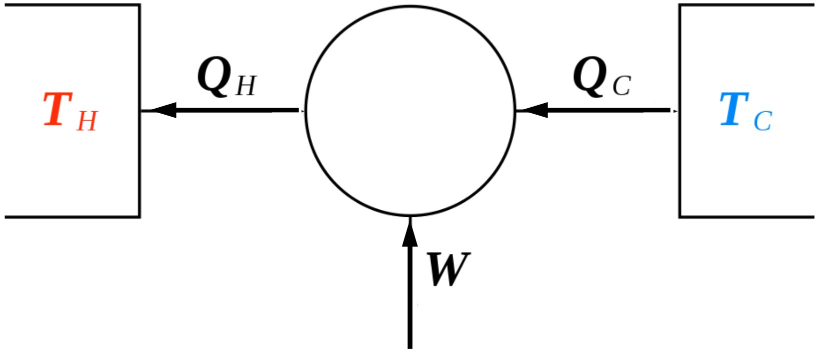
dissipated at the cavity walls

static losses

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	0.4 W/m	60 kW / m
	electric power		RF power lost

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
for E = 1 MV/m	1 kW/m 0.4 W/m	60 kW / m	
for E = 1 MV/m	1 kW/m 0.8 W/m	120 kW / m	including RF generation efficiency (50%)

e-power

e-power for RF

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
for E = 1 MV/m	1 kW/m 0.4 W/m	60 kW / m	
	e-power	RF power	
for E = 1 MV/m and 20 mA beam	1 kW/m 0.4 W/m + 20 kW/m	60 kW / m + 20 kW / m	
$\eta_{RF \to beam}$	~ 100 %	~ 25 %	

$$P_{beam} = \eta_{RF \to beam} \, P_{RF}$$

Advantages of RF superconductivity

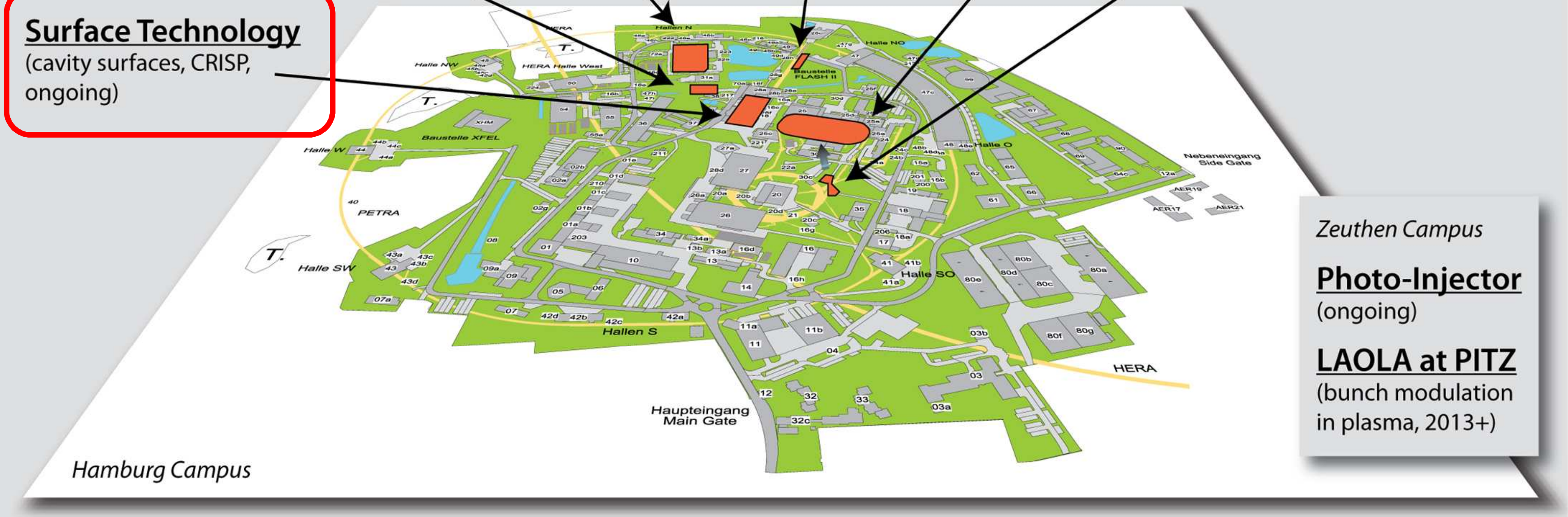
Example: comparison of 500 MHz cavities:

	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
for E = 1 MV/m	1 kW/m 0.4 W/m	60 kW / m	
	e-power	RF power	
for E = 1 MV/m and 20 mA beam	1 kW/m 0.4 W/m + 20 kW/m	60 kW / m + 20 kW / m	
for E = 1 MV/m and 20 mA beam	1 kW/m 40 kW/m	160 kW / m	including RF generation efficiency (50%)

e-power for RF

reduction factor of 4 in (electrical) power

Accelerator Research at DESY



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

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

Surface Technology
(cavity surfaces, CRISP, 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)

Hamburg Campus

Zeuthen Campus

Photo-Injector
(ongoing)

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

Accelerator Research at DESY

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

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

FEL Seeding
(sFLASH, FLASH2 seeding, ongoing)

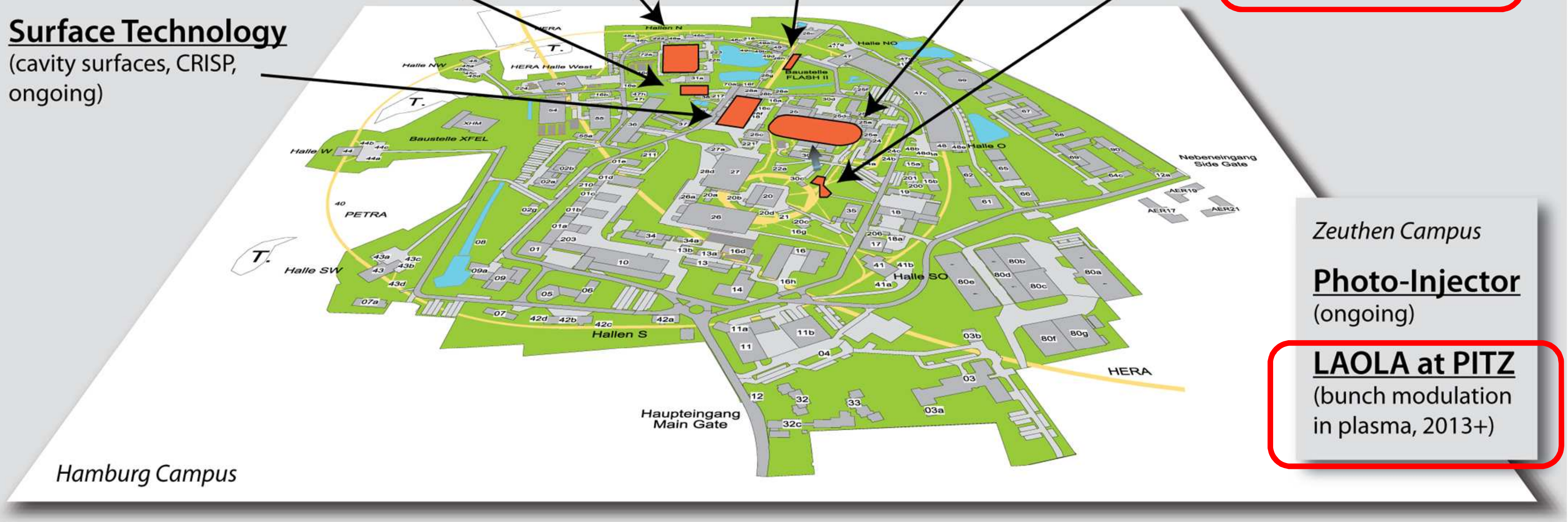
LAOLA at FLASH2
(beam-driven plasma acceleration, 2016+)

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)

Surface Technology
(cavity surfaces, CRISP, ongoing)



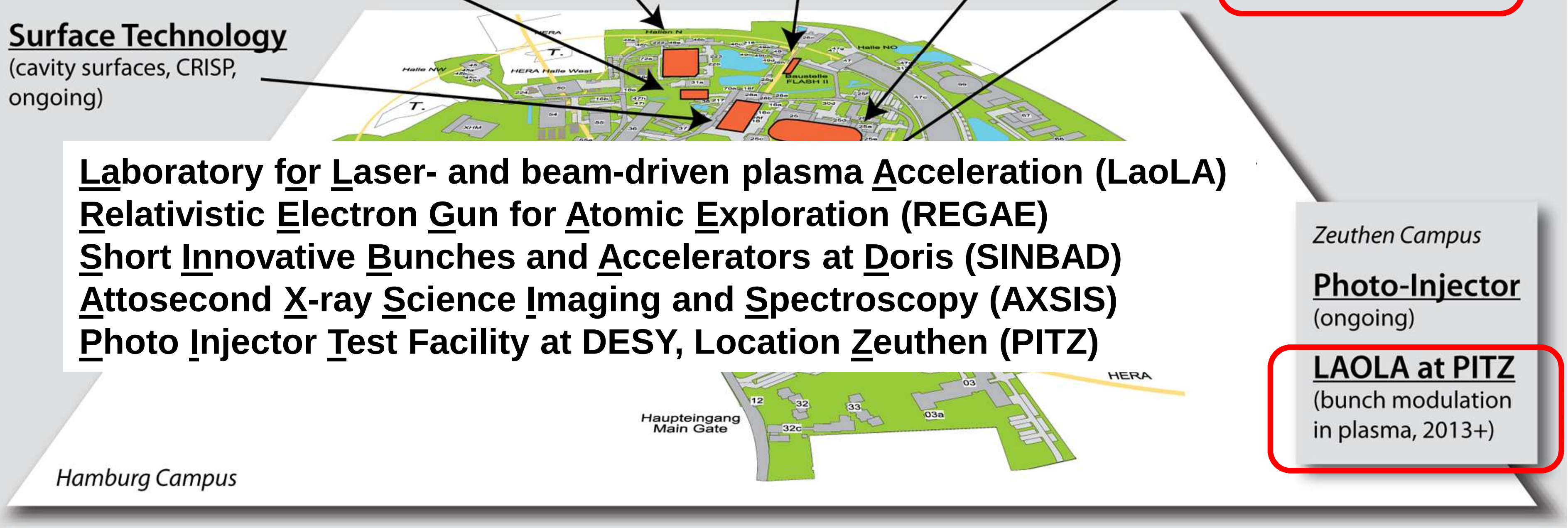
Hamburg Campus

Zeuthen Campus

Photo-Injector
(ongoing)

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

Accelerator Research at DESY



FEL Seeding
(sFLASH, FLASH2 seeding, ongoing)

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

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

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

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

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

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

Surface Technology
(cavity surfaces, CRISP, ongoing)

Laboratory f**o**r **L**aser- and beam-driven plasma **A**cceleration (LaoLA)
Relativistic **E**lectron **G**un for **A**tomic **E**xploration (REGAE)
Short **In**novative **B**unches and **A**ccelerators at **D**oris (SINBAD)
Attosecond **X**-ray **S**cience **I**maging and **S**pectroscopy (AXSIS)
Photo **I**njector **T**est Facility at DESY, Location **Z**euthen (PITZ)

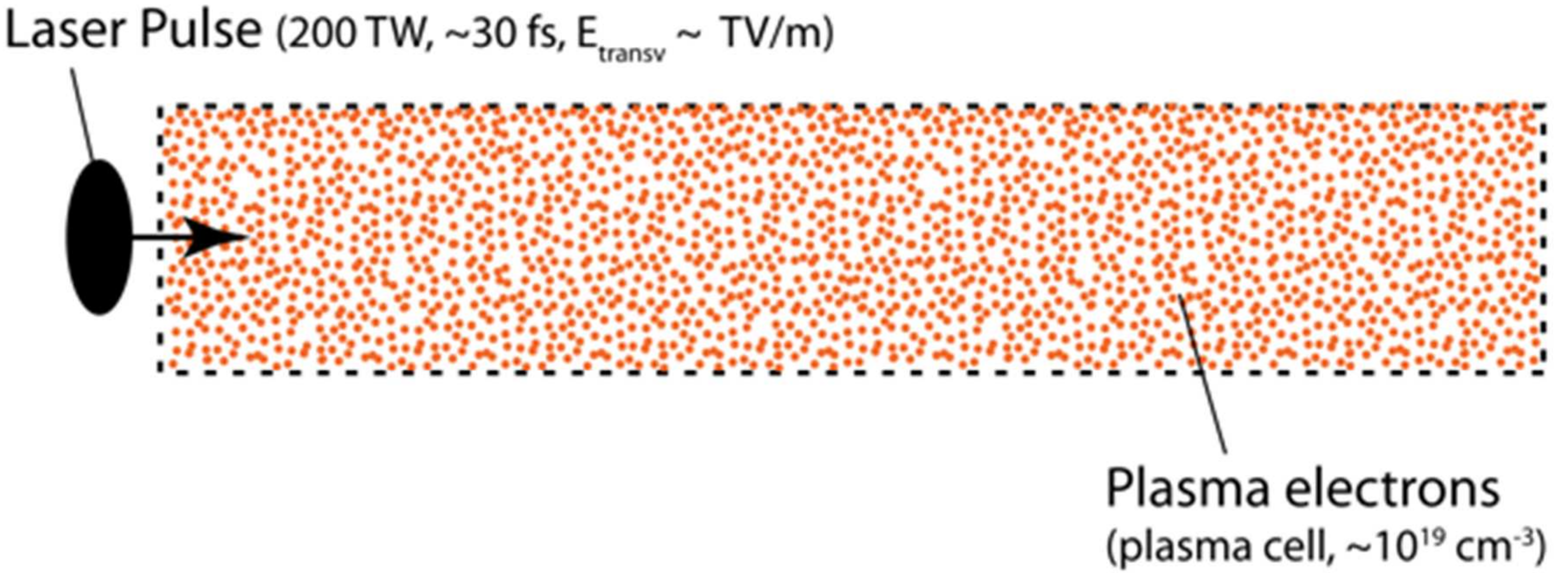
Zeuthen Campus

Photo-Injector
(ongoing)

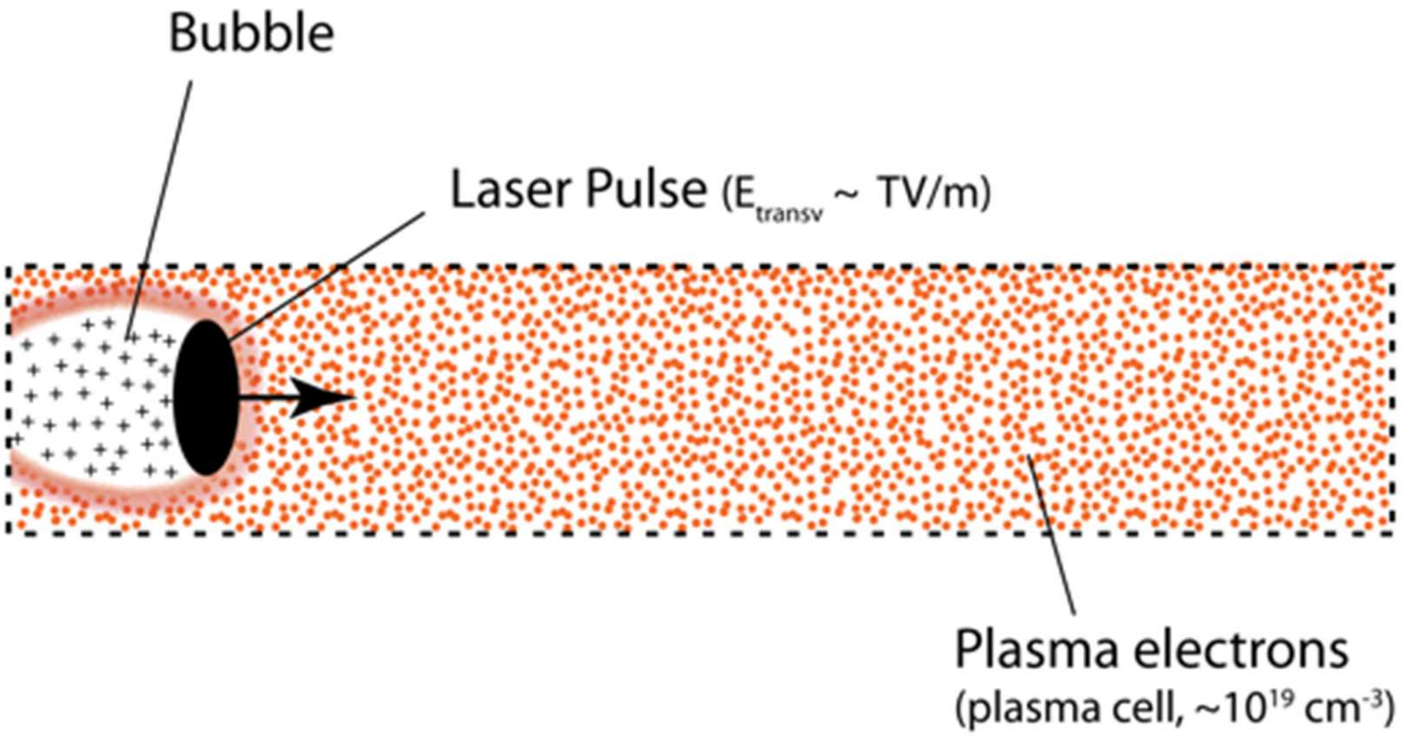
LAOLA at PITZ
(bunch modulation in plasma, 2013+)

Hamburg Campus

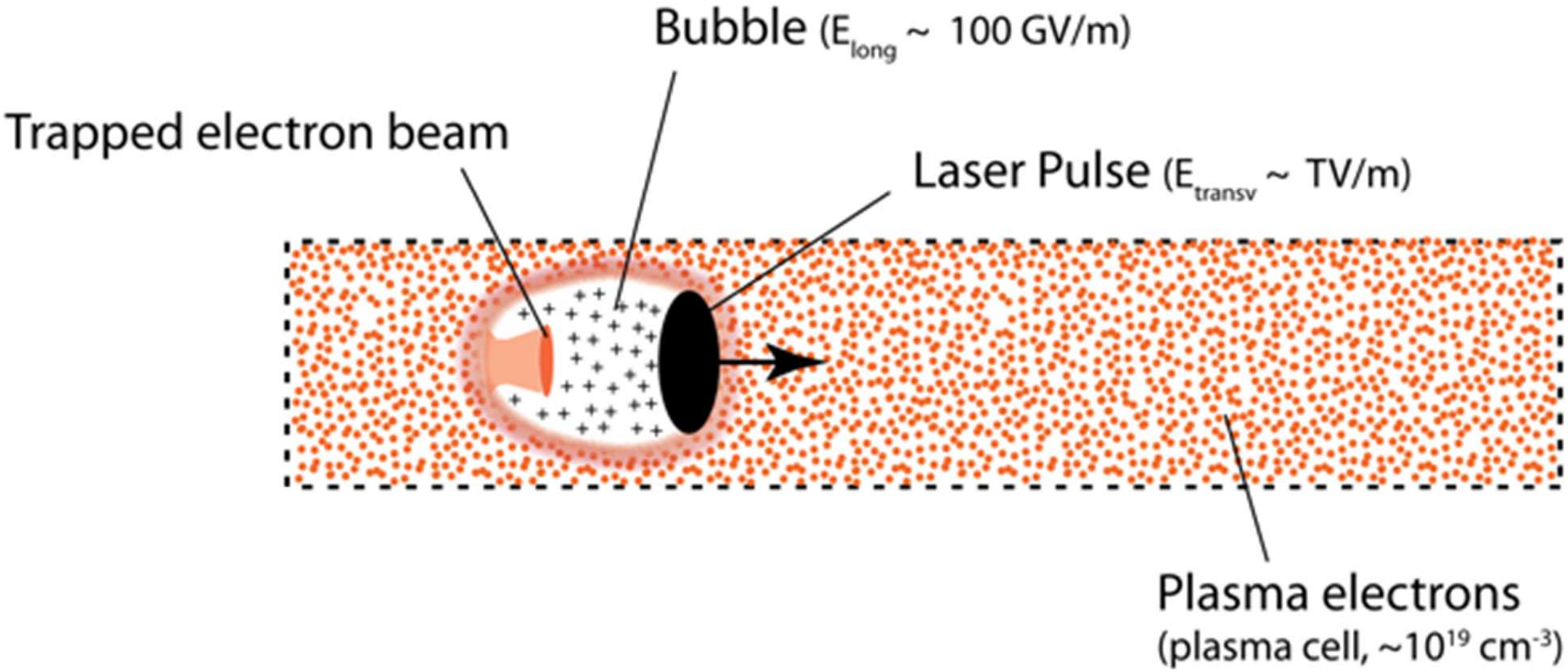
Laser-driven plasma wakefield acceleration



Laser-driven plasma wakefield acceleration



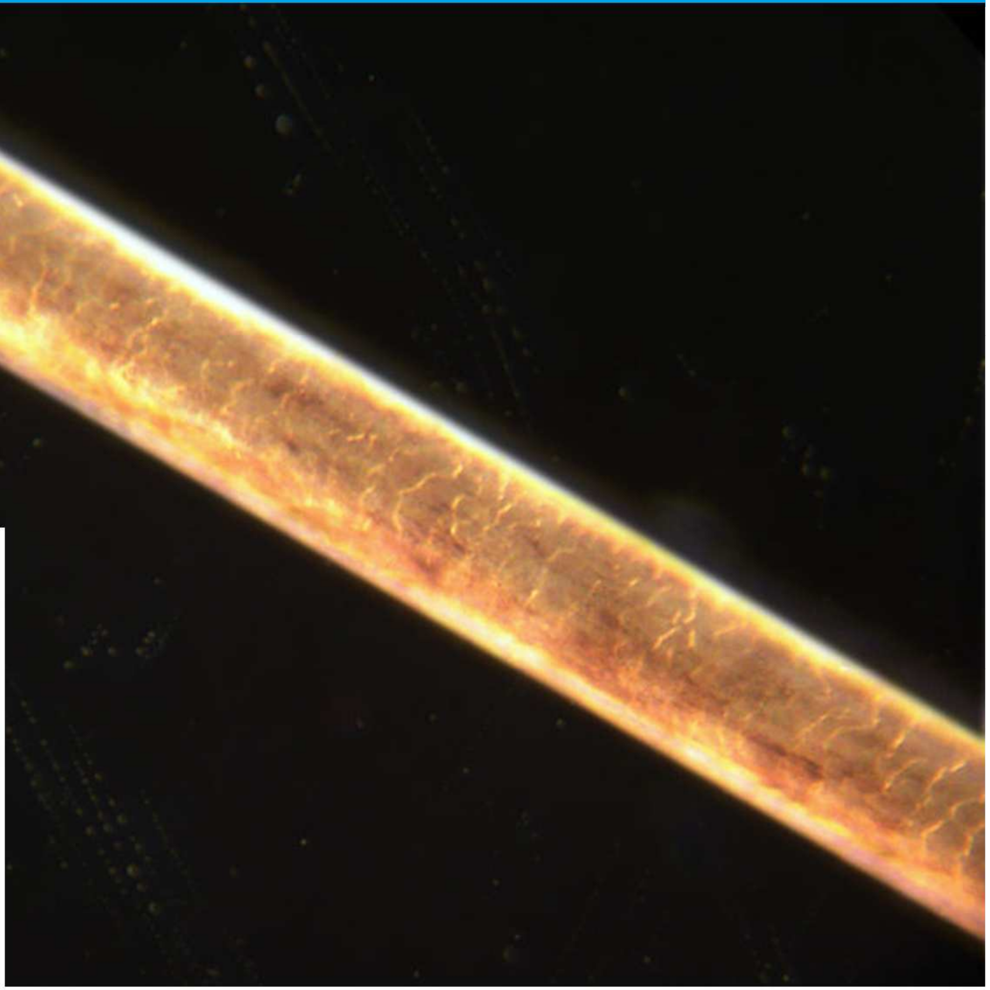
Laser-driven plasma wakefield acceleration

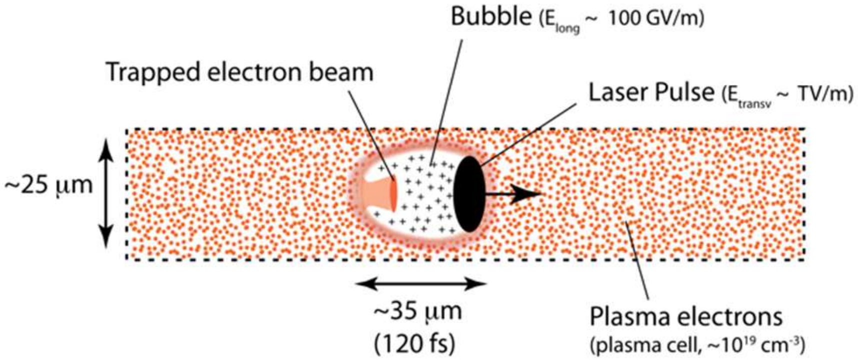


Acceleration (and focusing) within a hair width …

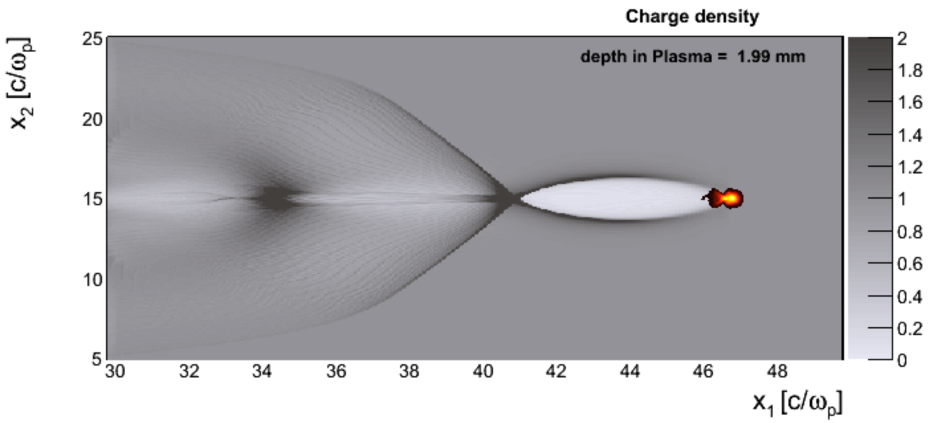
E_{long} **100 GV/m**

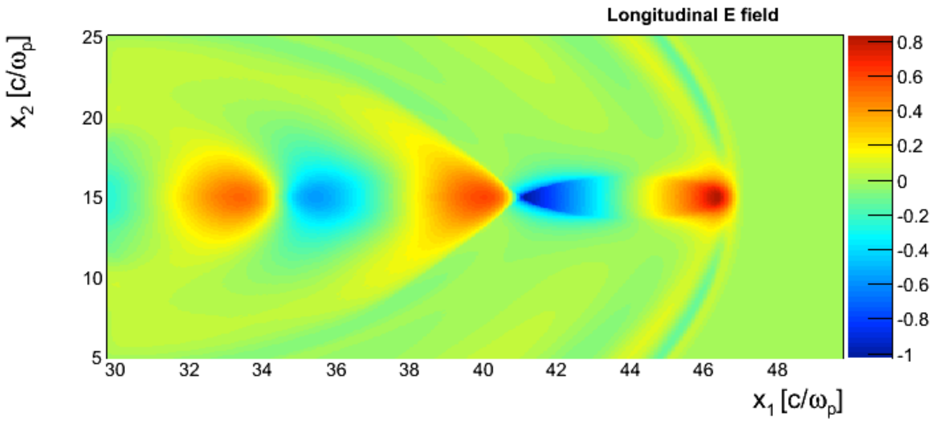
g_{transv} **300 MT/m**

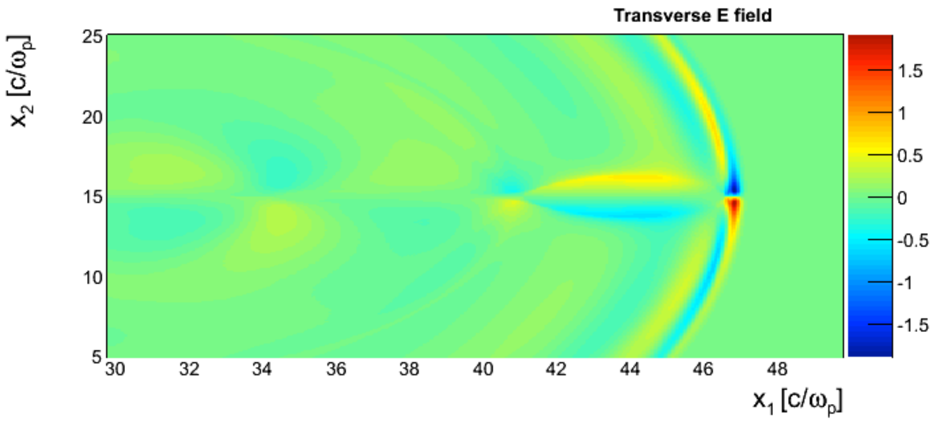


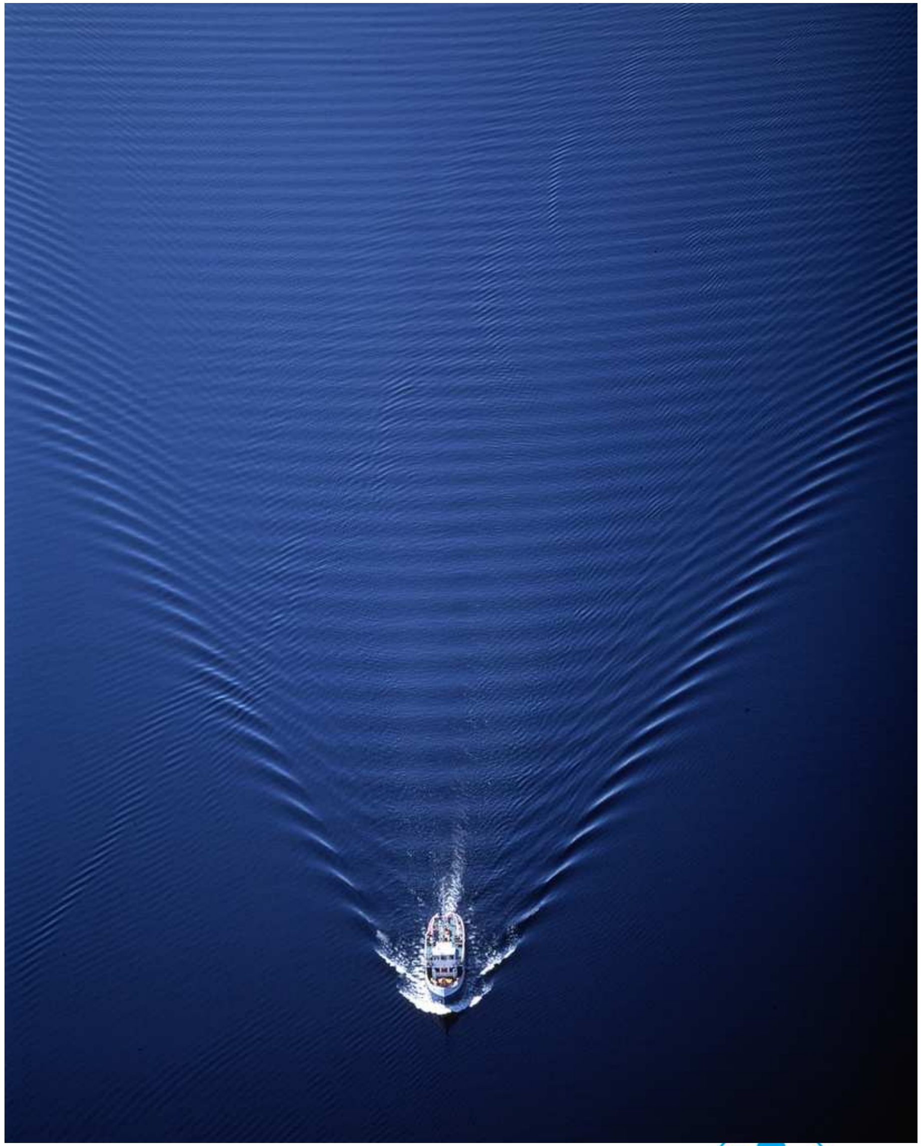


Simulations

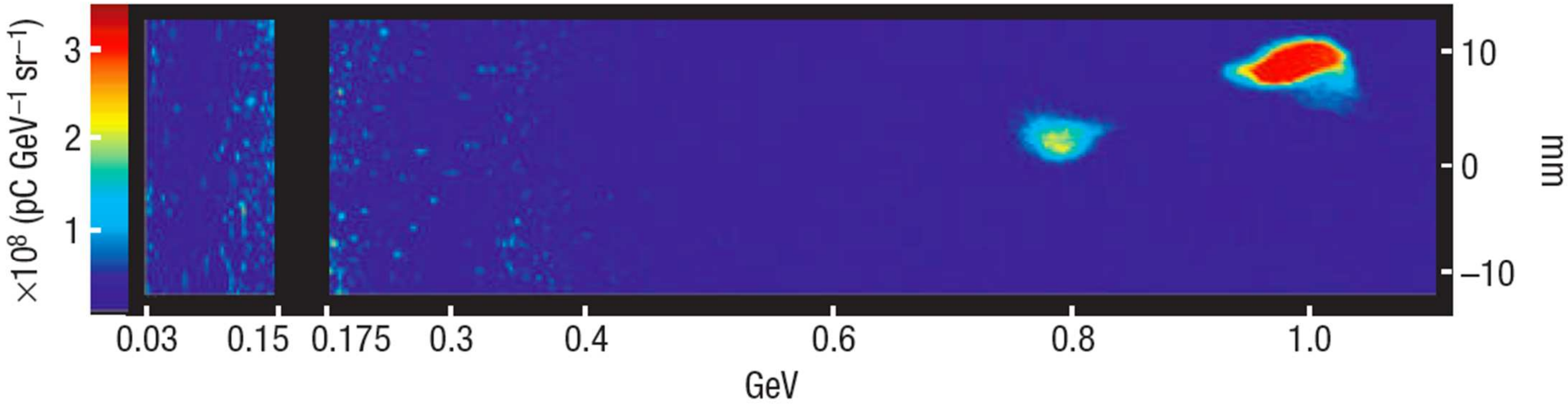

Charge density

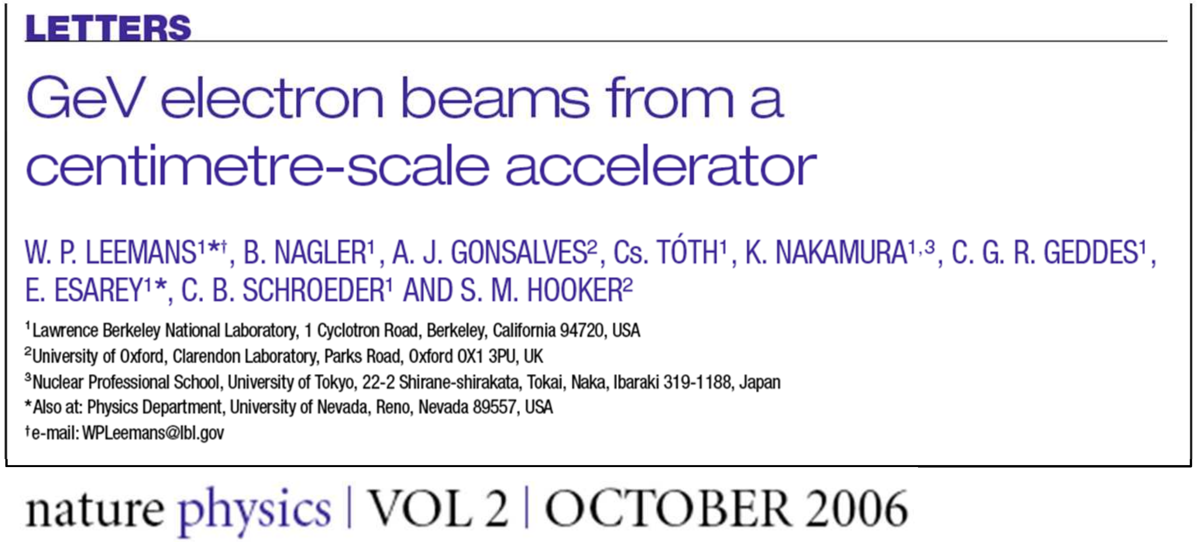

Longitudinal E field


Transverse E field



Breakthrough in the lab





LETTERS

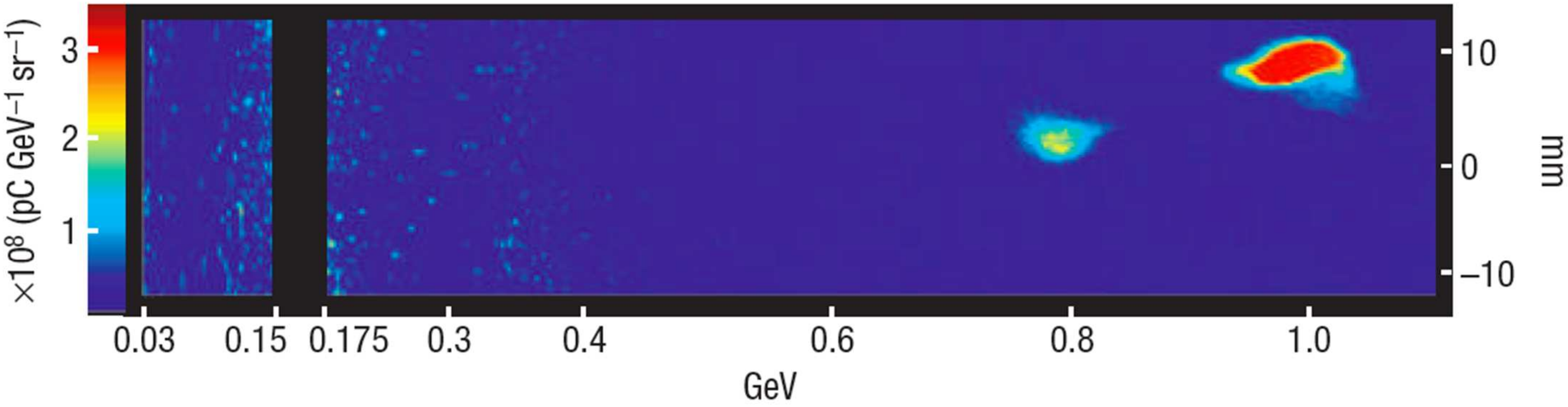
GeV electron beams from a centimetre-scale accelerator

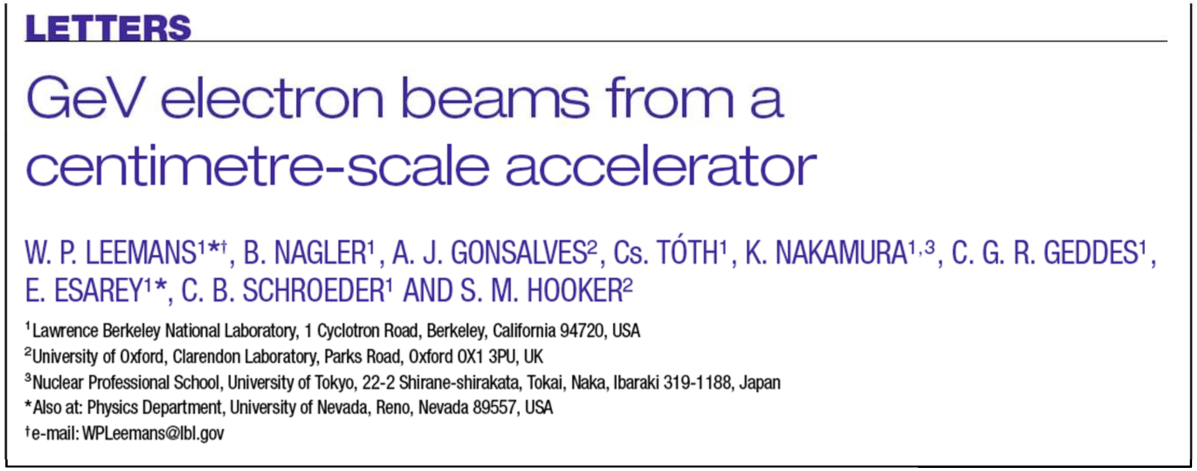
W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2] University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3] Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA
†e-mail: WPLeemans@lbl.gov

nature physics | VOL 2 | OCTOBER 2006

Breakthrough in the lab





LETTERS

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

[1] Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720, USA
[2] University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[3] Nuclear Professional School, University of Tokyo, 22-2 Shirane-shirakata, Tokai, Naka, Ibaraki 319-1188, Japan
*Also at: Physics Department, University of Nevada, Reno, Nevada 89557, USA
†e-mail: WPLeemans@lbl.gov

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 laser-driven plasma wakefield acceleration

- plasma <u>self-injection</u> is very unstable in energy, timing …
- very low efficiency “wall-plug power” to “beam power”

(reminder: power efficiency in RF cavity accelerators)

beam power

RF power

$$P_{beam} = \eta_{RF \to beam} \; P_{RF}$$

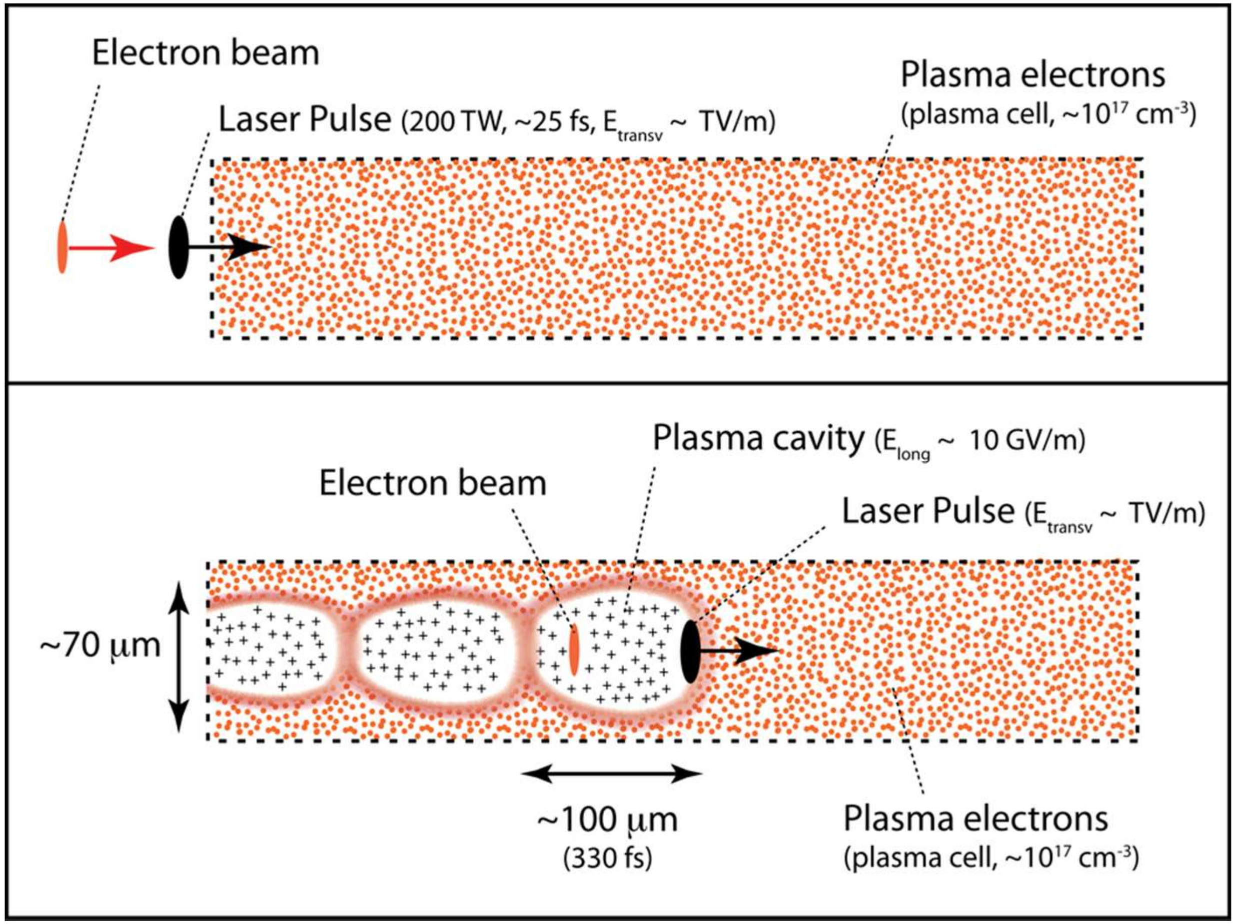
conversion efficiency

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

Challenges of laser-driven plasma wakefield acceleration

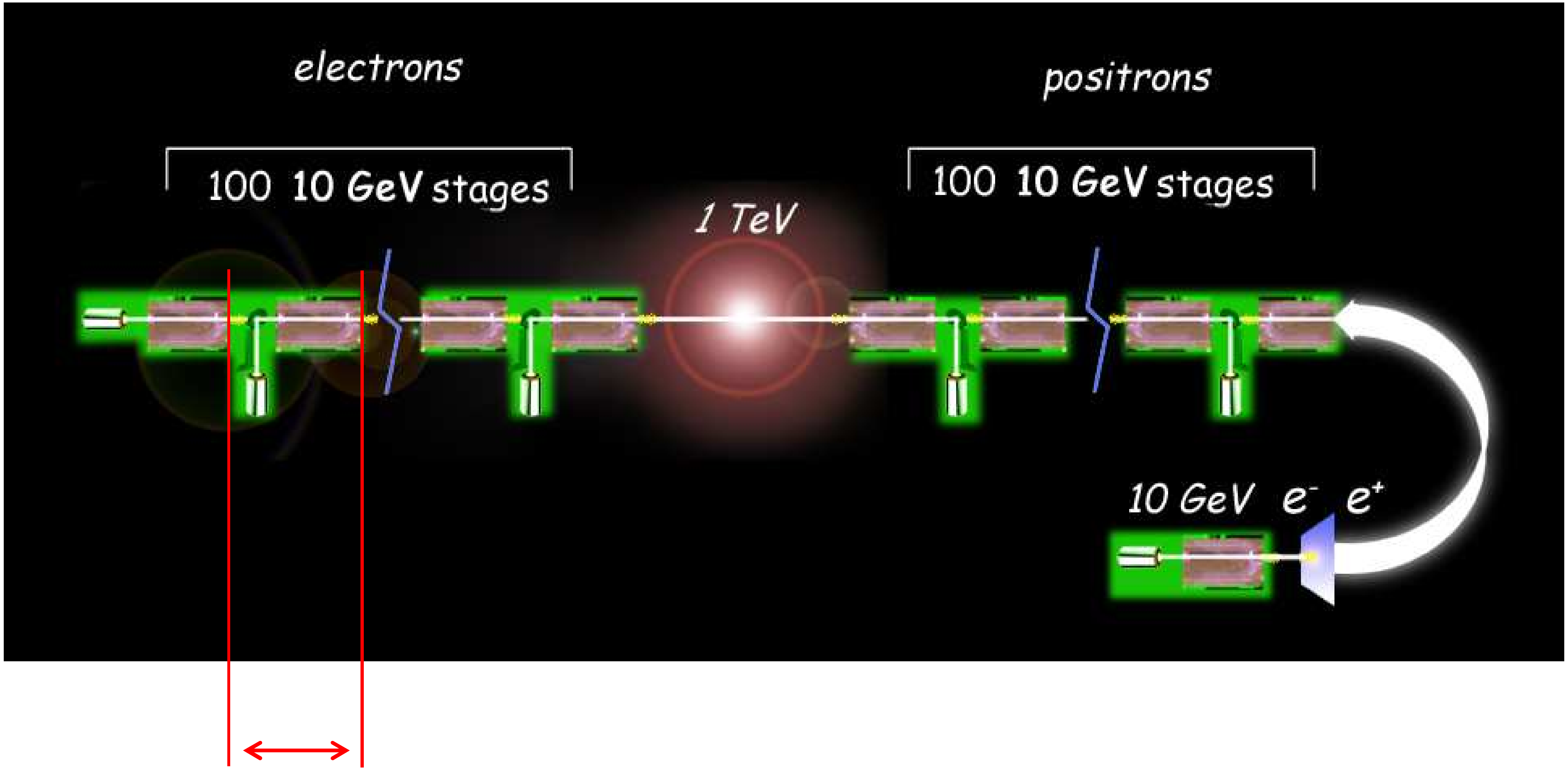
- plasma self-injection is very unstable in energy, timing …
- very low efficiency “wall-plug power” to “beam power”
- maximum energy limitation at 1 GeV or few GeV (in self-injection mode)
- multiple-stage plasma acceleration not yet demonstrated

Challenges of laser-driven plasma wakefield acceleration



not yet proven !

Linear collider based on plasma wakefield acceleration



cell length ?

Circular colliders (synchrotrons):

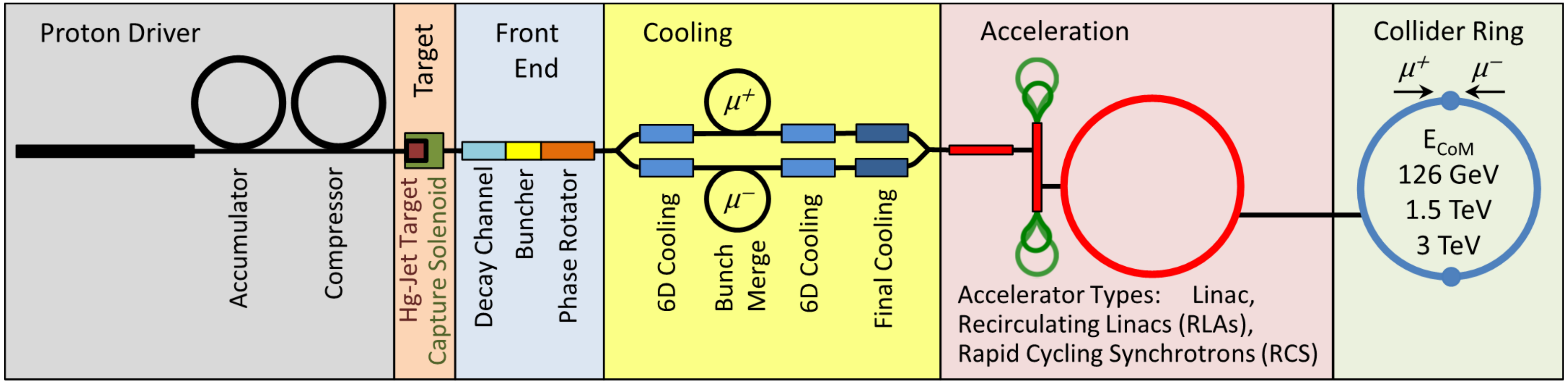
particle type	limitation
proton synchrotrons $938\ \mathrm{MeV}/c^2$	dipole magnet
electron synchrotrons $0.511\ \mathrm{MeV}/c^2$	synchrotron radiation
muon synchrotrons $105.7\ \mathrm{MeV}/c^2$	mean lifetime: $\tau = 2.2\ \mu s$? $\tau^* = \gamma\,\tau = 21\ ms$ at $\mathrm{E} = 1\ TeV$ travel 6300 km 1000 turns in a synchrotron with $B = 7\ T$

Circular colliders (synchrotrons):

particle type	limitation
- proton synchrotrons $938\ \mathrm{MeV}/c^2$	dipole magnet
- electron synchrotrons $0.511\ \mathrm{MeV}/c^2$	synchrotron radiation
- muon synchrotrons $105.7\ \mathrm{MeV}/c^2$	mean lifetime: $\tau = 2.2\ \mu s$ $p \rightarrow \pi \rightsquigarrow \mu$ (muon beams produced as tertiary beams)

Muon collider principle

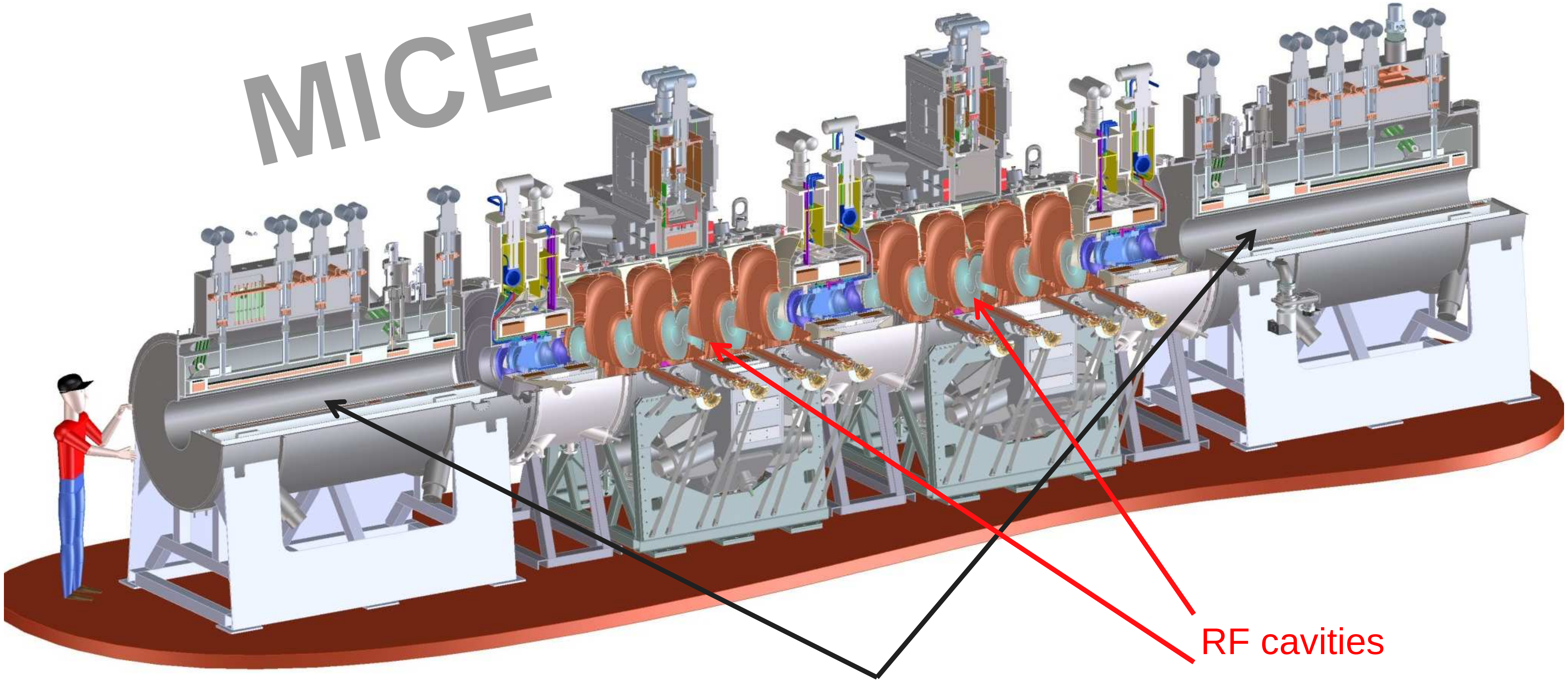
Muon collider block diagram



Collider:
E_{cm} = 3 TeV
circumference = 4.5 km
$L = 3\times10^{34}$ cm^{-2}s^{-1}

MICE at FERMILAB (Chicago)

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



RF cavities

focusing
with solenoids

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 wakefield acceleration
- muon collider

Thank you for your attention

pedro.castro@desy.de