Experimental Methods of Particle Physics

Particle Accelerators

Andreas Streun, PSI
andreas.streun@psi.ch

https://ados.web.psi.ch/empp-streun

Particle Accelerators

1. Introduction
2. Accelerator basics and types
3. Single particle dynamics
4. Multi-particle dynamics
5. Longitudinal beam dynamics
6. Synchrotron radiation
7. Luminosity
8. Muons and neutrinos

1. Introduction

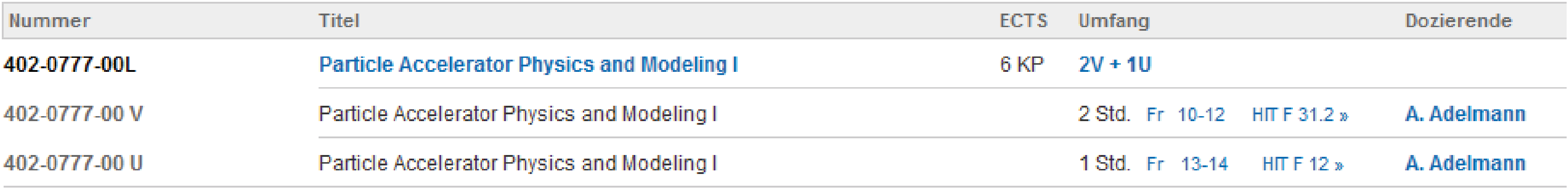
- Books & webs
- Why accelerators?
- Particles
  - Particles of interest
  - Particle wavelength and momentum
  - Particles to accelerate
  - Particle production
- A beam of particles
  - Beam quality
  - Accelerator peformance
- Particle Physics experiments
  - Center-of-mass energy
  - Luminosity

Books & Webs & Lectures

- K. Wille, Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen, Teubner Studienbücher, Stuttgart 1992.
- K. Wille, The physics of particle accelerators, Oxford university press, 2005.
- S. Y. Lee, Accelerator Physics, World Scientific, Singapore 1999
- H. Wiedemann, Particle Accelerator Physics I+II, Springer, Berlin Heidelberg New York 2007.
- Proceedings of The CERN Accelerator School http://cas.werb.cern.ch/cas/

- A. W. Chao and M.Tigner, Handbook of Accelerator Physics and Engineering, World Scientific, Singapore 1998.
- Proceedings of the Accelerator Conferences http://www.jacow.org/

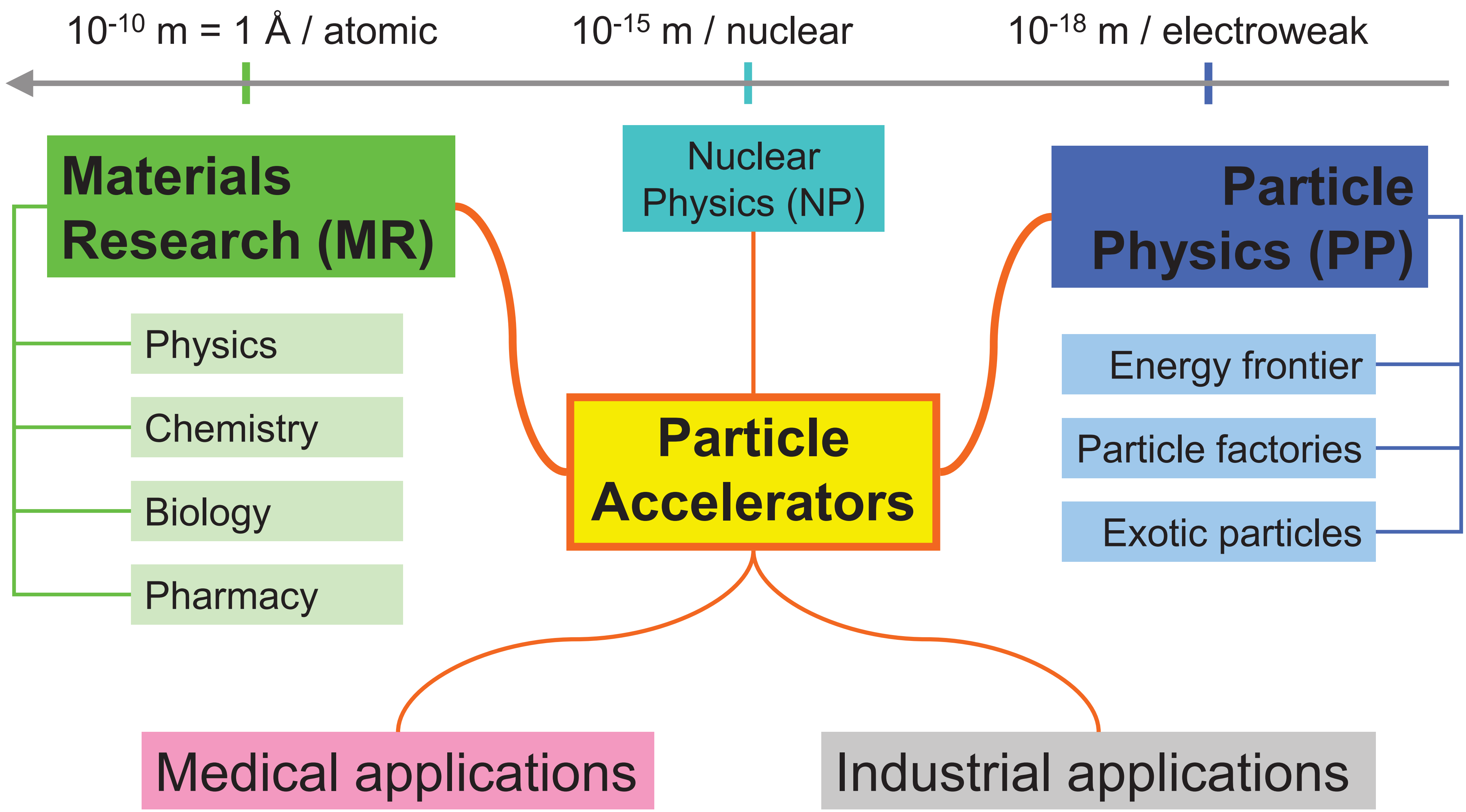
- ETH 2-semester lecture on accelerators and modeling



Nummer	Titel	ECTS	Umfang	Dozierende
402-0777-00L	Particle Accelerator Physics and Modeling I	6 KP	2V + 1U	
402-0777-00 V	Particle Accelerator Physics and Modeling I		2 Std. Fr 10-12 HIT F 31.2 »	A. Adelmann
402-0777-00 U	Particle Accelerator Physics and Modeling I		1 Std. Fr 13-14 HIT F 12 »	A. Adelmann

Why accelerators? → I. Applications

length scale



10^{-10} m = 1 Å / atomic

10^{-15} m / nuclear

10^{-18} m / electroweak

Materials Research (MR)

- Physics
- Chemistry
- Biology
- Pharmacy

Nuclear Physics (NP)

Particle Physics (PP)

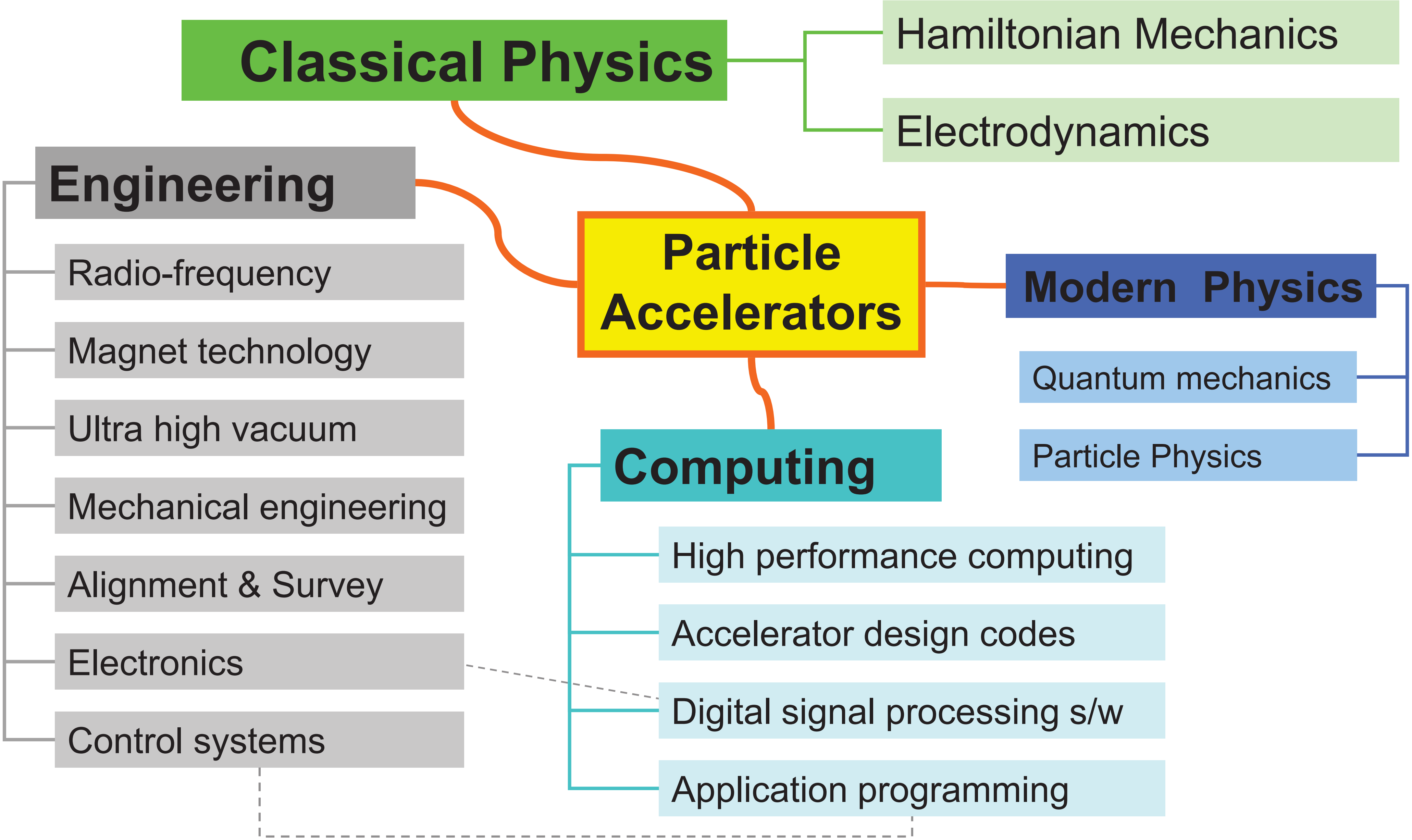
- Energy frontier
- Particle factories
- Exotic particles

Particle Accelerators

Medical applications

Industrial applications

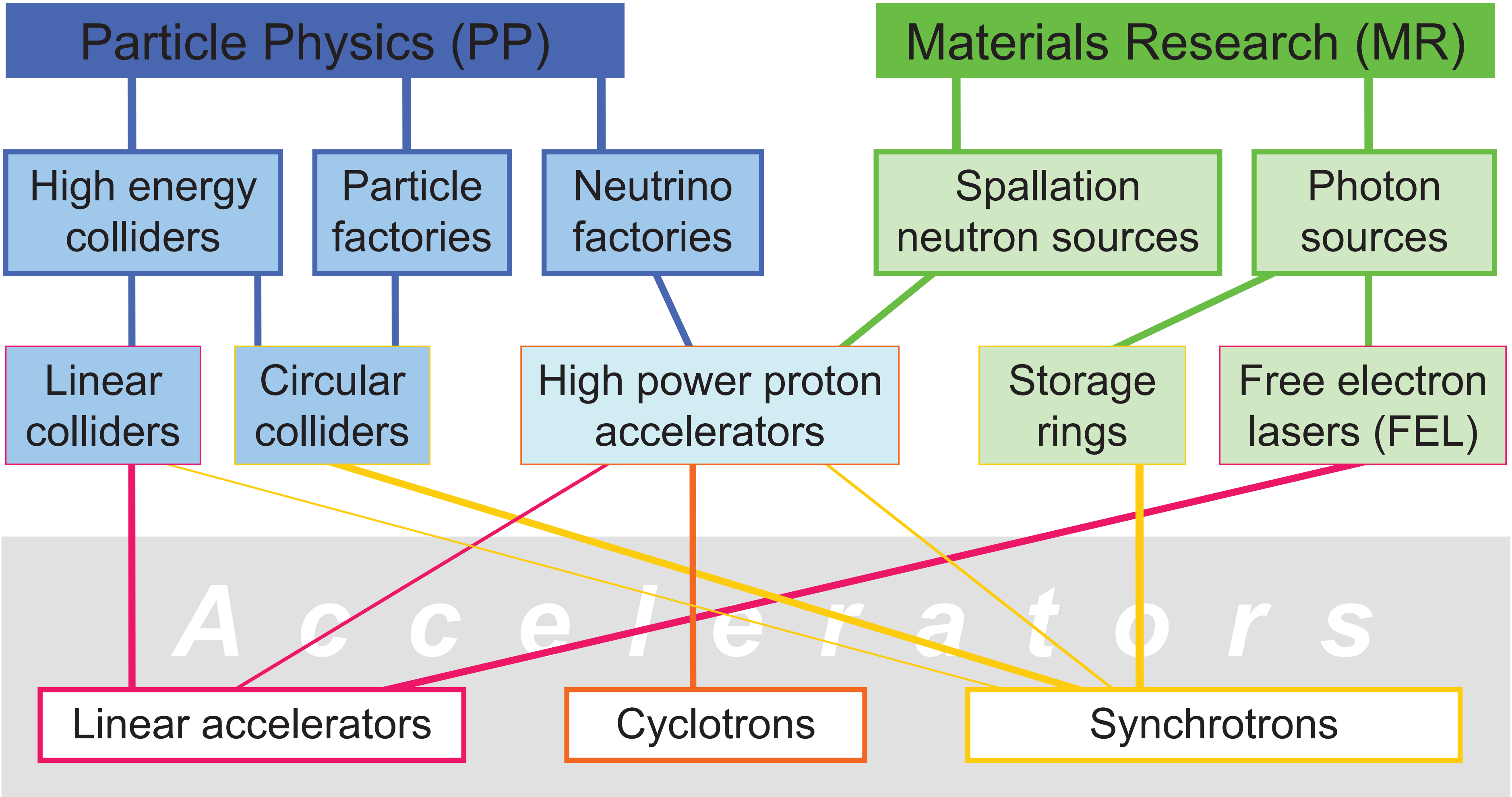
Why accelerators? → II. Connections



Particle Accelerators

- **Classical Physics**
  - Hamiltonian Mechanics
  - Electrodynamics
- **Engineering**
  - Radio-frequency
  - Magnet technology
  - Ultra high vacuum
  - Mechanical engineering
  - Alignment & Survey
  - Electronics
  - Control systems
- **Modern Physics**
  - Quantum mechanics
  - Particle Physics
- **Computing**
  - High performance computing
  - Accelerator design codes
  - Digital signal processing s/w
  - Application programming

Why accelerators? → III. common PP & MR interests



PP & MR scientists: ⇨ understand potential and limitations of accelerators
⇨ help to specify future machines

Particles of interest (PP)

Particle Physics: *interested in **all** particles!*

presently: particular interest in

- new and unknown particles:
  $W^{\pm}$ (80.4 GeV), Z (91.2 GeV), H^{0} (126 GeV), ...?
  produced in $e^{+}e^{-}$ or pp or $p\bar{p}$ collision
  ⇨ highest energies: e.g. **LEP**, **LHC**
- meson pairs (e.g. $K_S K_L$, $B^0\bar{B}^0$) *at high rate*
  ⇨ meson factories: e.g. **KEK-B**, **DAΦNE**.
- muons ($\mu^{\pm}$) and neutrinos (ν_e, ν_μ)
  ⇨ long baseline experiments: e.g. **CNGS**, **JPARC**
  ⇨ muon accelerator and neutrino factory projects

Particles of interest (MR)

Materials Research: *neutral* particles

⇨ high penetration depth in materials

- Neutrons (*n*)
  - penetrate high Z materials
  - depth not a steep function of Z
  - have a magnetic moment and a spin
  - explore structure and dynamics of materials
  - rather low ***flux*** (= particles per time and area)
- Photons (γ)
  - available at (very!) high flux
  - penetrate well low Z materials
  - have polarization
  - complementary to neutrons (“surface vs. bulk”)

Particle wavelength

Size of structure ⇔ Size of probe

MR ⇨ $\lambda \sim 10^{-10}$ m

NP ⇨ $\lambda \sim 10^{-15}$ m

PP ⇨ $\lambda \sim 10^{-18}$ m

De-Broglie wavelength

$$\boxed{\lambda = \frac{h}{p}}$$

Planck constant

$$h = 6.63 \cdot 10^{-34}\ \mathrm{Js} = 4.14 \cdot 10^{-15}\ \mathrm{eV \cdot s}$$

Particle momentum

$$p = m \cdot v = m_o c \cdot \beta\gamma$$

$$\xrightarrow{v \ll c}$$

non – relativistic

$$p = m_o v$$

$$\xrightarrow{v \approx c}$$

high relativistic

$$p = m_o c \cdot \gamma = E / c$$

Recall: momentum & energy

norm. velocity $\beta = v / c$

Lorentz factor $\gamma = E / m_o c^2$

rest energy $E_o = m_o c^2$

Momentum

- $p = m \cdot v = m_o c \cdot \beta\gamma$
- non-relativistic $p = m_o v$
- high relativistic $p = m_o c \cdot \gamma = E/c$

Total energy

- $E = mc^2 = m_o c^2 \gamma = \sqrt{(m_o c^2)^2 + (pc)^2} = E_{kin} + m_o c^2$

Kinetic energy

- $E_{\mathrm{kin}} = m_o c^2 (\gamma - 1) = q \cdot U =$ charge × voltage.
- E_{kin} in units of eV is equivalent to the accelerating voltage for a particle with charge $q = 1\mathrm{e}$ $(\mathrm{p}, \mathrm{e}^+, \mathrm{Na}^+, \mu^+ \ldots)$
- non-relativistic $E_{\mathrm{kin}} = \tfrac{1}{2} m_o v^2$
- high relativistic $E_{\mathrm{kin}} = pc$

useful relations:

$$\beta = \sqrt{1 - \frac{1}{\gamma^2}} \qquad \gamma = \frac{1}{\sqrt{1 - \beta^2}} \qquad \beta\gamma = \sqrt{\gamma^2 - 1}$$

Examples: momentum and wavelength

MR: **1Å** **neutron** ($m_o c^2 = 940.8$ MeV, $m_o = 1.68 \cdot 10^{-27}$ kg)

⇨ $p = 12.4$ keV/c
⇨ $v = 3960$ m/s $<< c$
⇨ $E_{\text{kin}} = 0.08$ eV ⇨ $<E_{\text{kin}}> = kT$ ⮷
⇨ temperature equivalent $T = 930$ K

MR: **1Å** **photon** (no rest mass)

⇨ $v = c$, $E_\gamma = pc = 12.4$ keV → X-ray

NP: **10^{-15} m** **electron** ($m_o c^2 = 511$ keV)

⇨ $p = 1.24$ GeV/c
⇨ $v = 0.999'999'915\, c = c - 90$ km/h !
⇨ $E_{\text{kin}} = pc = 1.24$ GeV

PP: **10^{-18} m** **proton** ($m_o c^2 = 938.3$ MeV)

⇨ $p = 1.24$ TeV/c
⇨ $v = 0.999'999'7\, c$
⇨ $E_{\text{kin}} = pc = 1.24$ TeV (→ **LHC** 7 TeV)

Particles to accelerate

Requirements for acceleration:

charge $q \neq 0$ *and* lifetime $\tau \geq \approx 1\ \mu s$

- ✓ standard: electron e^- and proton p
- ✓ antiparticles: positron e^+ and antiproton $\overline{p}$
- ✓ ions: ${}^A_Z X^{q/e}$: ${}^1_1\mathrm{H}^+ = p$, ${}^1_1\mathrm{H}^-$, ${}^4_2\mathrm{He}^{2+} = \alpha$ … ${}^{238}_{92}\mathrm{U}^{n+}$ …
- ✓ muons: μ^+, μ^- $\tau = 2.2\ \mu s$
- ✗ pion $\pi^\pm$ ($\tau = 26$ ns), neutron n, neutrino ν, photon γ …

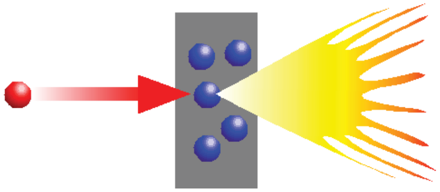
	m_o[kg]	m_o[MeV/c^2]	m_o[u]	q [e]	τ
e^+/e^-	$9.109 \cdot 10^{-31}$	0.511		± 1	∞
$p/\bar{p}$	$1.672 \cdot 10^{-27}$	938.3	1.007	± 1	∞
ions			$\approx A$	$\ldots -1, +1 \ldots +Z$	different
μ^+/μ^-		106.7		± 1	2.2 μs

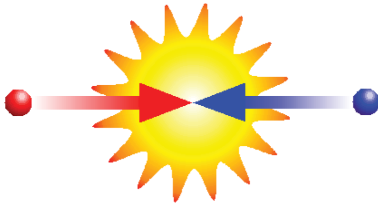
$1e = 1.602 \cdot 10^{-19}$ As $\quad$ $1u = 931.5$ MeV $= \frac{1}{12}$ mass of ${}^{12}_{6}$C

Particle Production

how to get the particles of interest
from the particles that can be accelerated

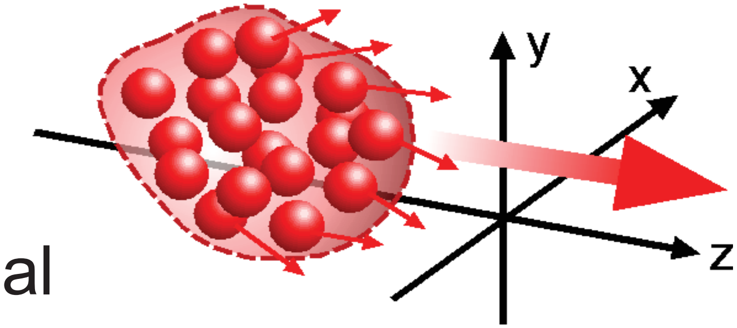
how ***many*** *?*





Principle	**Products**	**Performance**
Beam on target electrons e^- protons p spallation target	pairs e^+e^-, $p\bar{p}$ mesons $\pi \rightarrow \mu \rightarrow \nu$ neutrons n	Flux ⇩ chapter **8**
Colliding beams leptonic e^+e^- hadronic pp	*anything...* mesons $K\bar{K}$, $B\bar{B}$... Higgs H^o	Luminosity ⇩ chapter **7**
Synchrotron radiation electrons e^-	photons γ	Brightness ⇩ chapter **6**

A beam of particles



Particle **beam** ($\boldsymbol{n}$, $\boldsymbol{\mu}$, $\boldsymbol{\gamma}$, $\boldsymbol{e^-}$, $\boldsymbol{p}$ ...)

= ensemble of **N** particles in 6-dimensional phase space ($x, y, z; p_x, p_y, p_z$)

1st order

Beam centroid

mean values $< r_i >$

- beam momenta p_x, p_y, p_z

  moving along "z"

  $\rightarrow p_z \approx p >> p_x, p_y$
- beam location $z\ (t)$
- beam positions x, y
- beam angles $x' \approx p_x/p,\ y'$

2nd order

Beam distribution

rms values $\sigma_i^2 = < r_i^2 >$
and correlations $< r_i\, r_j >$

- momentum spread $\sigma_{\Delta p/p}$
- "bunch length" $\sigma_{\Delta z}$
- beam sizes σ_x , σ_y
- beam divergences $\sigma_{x'} , \sigma_{y'}$
- ... correlations ...

Beam quality → I. phase space density

Criterion for beam quality (n , μ , γ, e^-, p ...) :

density in 6-d phase space

⇨ performance of experiment

→ flux, luminosity, brightness,

⇨ threshold phenomena

→ coherence, non-linearity...

Theorem of Liouville:

(holds under several conditions....)

"The 6-d phase space density is an invariant." or

"The 6-d phase space occupied by a beam behaves like an incompressible liquid."

Beam quality → II. Emittance

Decoupling of 6-d phase space density into **3 × 2** dimensions (this is often ≈ possible):

longitudinal ×	horizontal ×	vertical
$\Delta p/p, \; \Delta z$	x, p_x (or x')	y, p_y (or y')

momentum spread

pulse (bunch*) length

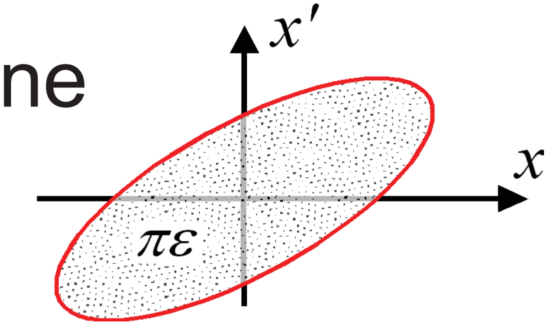
transverse emittances $\varepsilon_x, \varepsilon_y$

2-d phase space area:

$$\varepsilon_x^2 = \langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2$$

invariant along beam transport line

⇨ chapter **4**



* beams are usually “bunched”, not continuous
⇨ chapter **2**

Beam quality → III. Accelerator performance

- Momentum p
  (high relativistic: energy $E = pc$)
- Momentum spread $\sigma_{\Delta p/p}$
- Bunch length $\sigma_{\Delta z}$
- Emittances $\varepsilon_x , \varepsilon_y$
- Beam **current** $I = q \cdot dN/dt$
- Higher orders...
  (non-Gaussian, halo, tails etc.)

→

6-d phase space density

⇩

Experiment performance:

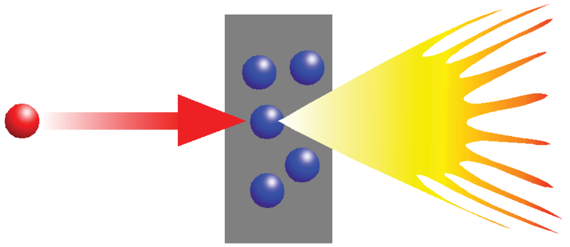
Luminosity (PP)

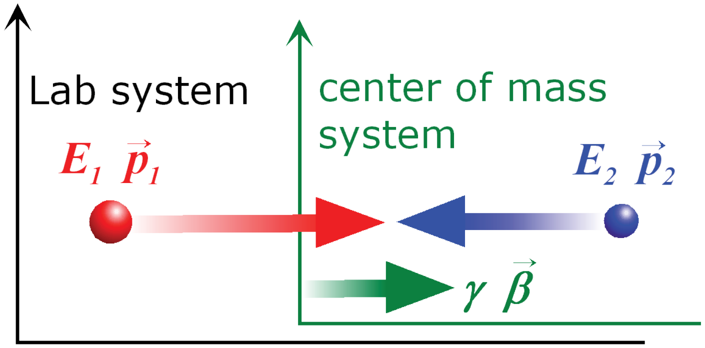
Brightness (MR)

- Polarization (spin orientation)
- Time structure: [continuous or] “bunched” → repetition rate
- Stability: position, angle, momentum, timing...
  jitter as function of frequency

PP-experiment → I. Center-of-mass energy

Beam on target





Colliding beams

$\vec{p}_2 = 0 \quad E_1 = E$

$E_{\rm cm} \approx \sqrt{2E\, m_2 c^2}$

$$E_{\rm cm} = \sqrt{(E_1+E_2)^2 - (\vec{p}_1 c + \vec{p}_2 c)^2}$$

$$\vec{\beta} = \frac{\vec{p}_1 c + \vec{p}_2 c}{E_1+E_2} \qquad \gamma = \frac{E_1+E_2}{E_{\rm cm}}$$

$\vec{p}_2 = -\vec{p}_1 \quad E_1 = E_2 = E$

$E_{\rm cm} = 2E$

Beam on target

- Antiparticles: e^+, $\bar{p}$
- Mesons for experiments: π, K . . .
- Muons and neutrinos: $\mu\ \ [\to \nu_\mu]$
- Spallation neutrons: n

Colliding beams

- possibility of pure leptonic production $e^+ \to\leftarrow e^-$
- highest energies (e.g. LHC $E_{\rm cm} = 14$ TeV)
- high luminosity particle factories: Φ, B . . .
- variable boost $\vec{\beta}$ from $E_1 \neq E_2$ (→ B-factories)

PP-experiment → II. Luminosity

Layout of experiment

- Required energy E_{cm} [and boost $\vec{\beta}$] $\longrightarrow$ $E_1,\ E_2$
- Required precision p $\longrightarrow$ Events $N \approx \frac{1}{p^2}$ $\left(p = \frac{\Delta N}{N} \quad \Delta N \approx \sqrt{N}\right)$
- Efficiency of experiment ϵ (Observation inside detector, branching ratio etc.)
- Scheduled time of measurement T $[\mathrm{s}]$

$\Longrightarrow$ Particle production rate $R\ [\mathrm{s}^{-1}] = \frac{N}{\epsilon T}$

- Production cross section σ $[\mathrm{cm}^2$, or $\mathrm{barn} = 10^{-24}\,\mathrm{cm}^2]$

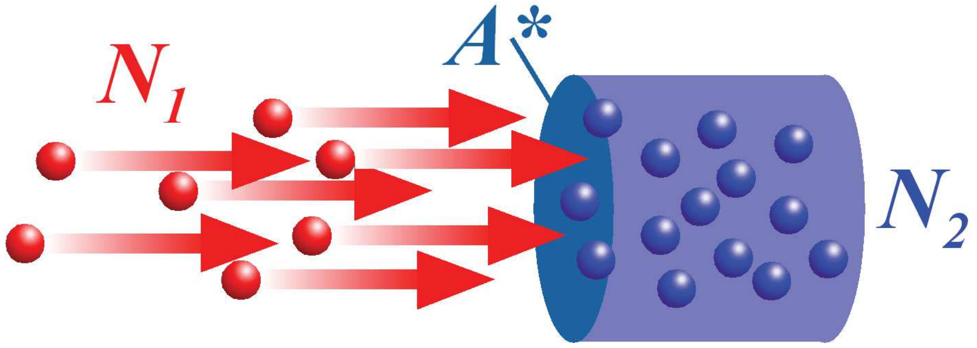
$\Longrightarrow$ $\boxed{R = \sigma \mathcal{L}}$ *Luminosity* $\mathcal{L}\ [\mathrm{cm}^{-2}\mathrm{s}^{-1}]$

Luminosity = sum of all possible encounters per time and area

$$\mathcal{L} = \frac{N_1}{T} \times \frac{N_2}{A^*}$$

(A^* common interaction area)

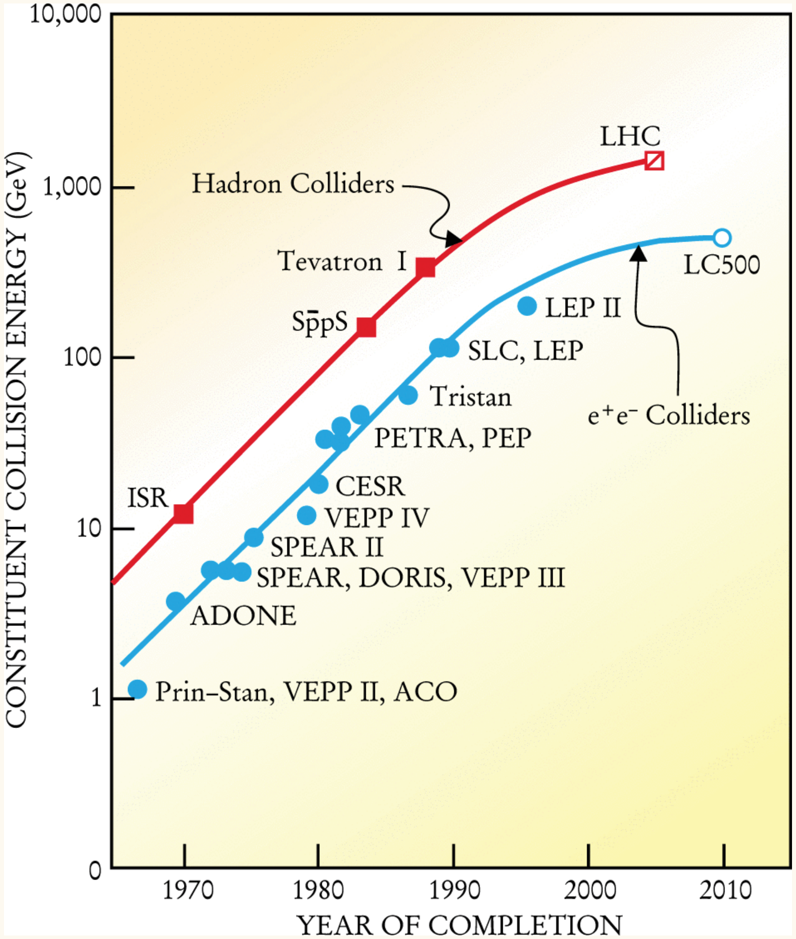
$\mathcal{L}$ = particle current of beam 1
× particle density of beam 2



Requirements for PP-machines

- high beam currents: N_1, N_2, T
- focus at collision: A^*
- (highest ↔ given) beam energies: E_1, E_2 $\longrightarrow$ E_{cm} $[,\vec{\beta}]$

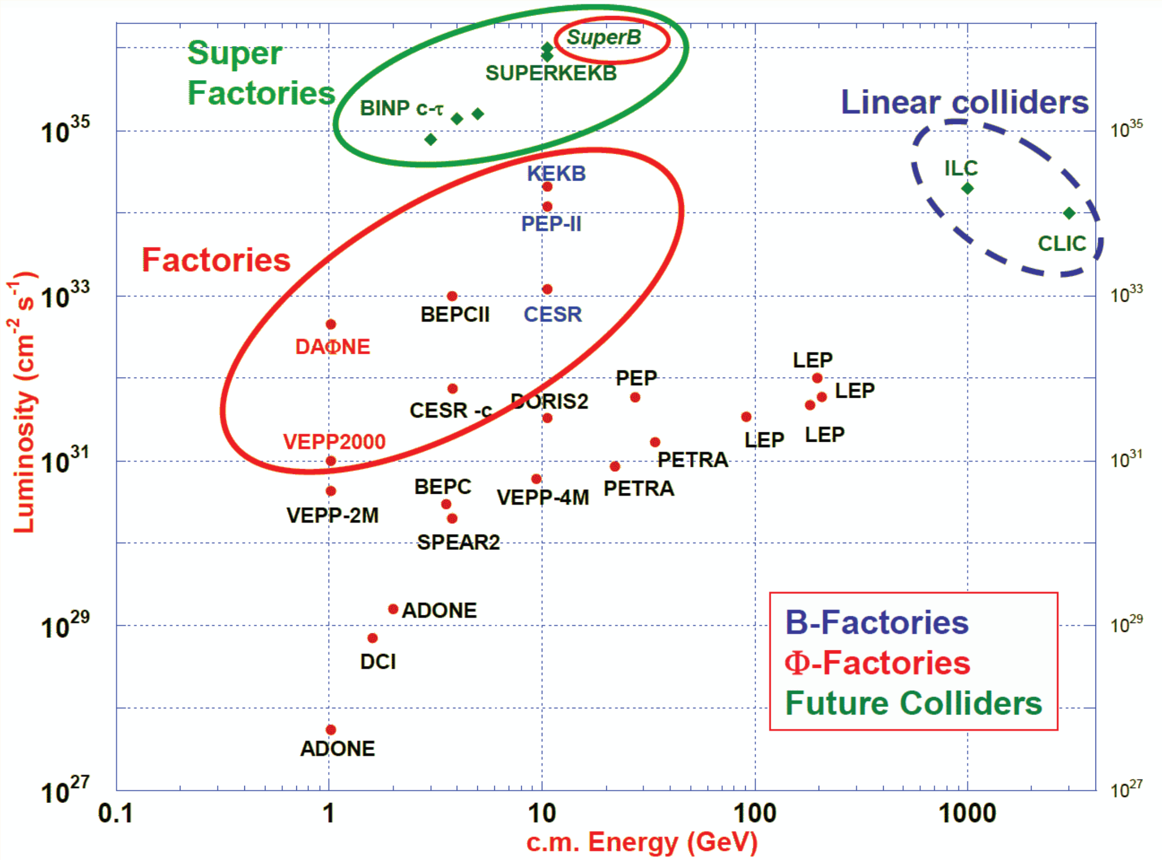
$\Longrightarrow$ challenges for accelerators.



"Livingston plot"

Progress of center of mass energy

M. L. Tigner, Does accelerator based particle physics have a future? Physics Today 54.1 (2001)



Luminosities of e^+e^--colliders