PHY 554

Fundamentals of Accelerator Physics
Mon, Wed 6:30 – 7:50 PM Physics, D103

Lecture 1 · Modern Accelerators

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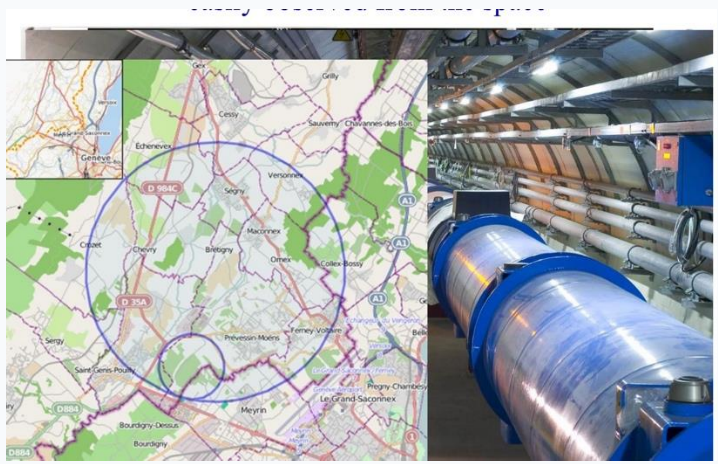


http://case.physics.stonybrook.edu/index.php/PHY554_Fall_2026

What this course is about

Accelerator physics = making charged particles useful

- Create beams: sources, RF acceleration, injection and extraction
- Control beams: magnets, focusing, transverse and longitudinal dynamics
- Preserve beams: emittance, stability, radiation, cooling and collective effects
- Use beams: discovery science, light sources, medicine, industry and emerging technologies

Mental model for the semester

fields → forces → trajectories → beam quality → applications

COURSE FRAME

Goals by the end of the course

- Distinguish major accelerator types and explain what each is optimized for
- Use standard accelerator language: tune, beta function, dispersion, emittance, chromaticity and luminosity
- Set up the basic equations of transverse and longitudinal beam motion
- Explain how RF systems, magnets and radiation shape modern accelerators
- Connect accelerator performance to applications and advanced concepts

Question that students care the most – how grades are given

- Lecture notes are the primary course material; books are useful references, not required prerequisites
- Homework is where the notation becomes operational; collaboration is okay when acknowledged
- Final project/presentation: choose an accelerator-related paper or project and explain the physics clearly
- Participation matters: ask questions, especially when vocabulary is unfamiliar

Class participation	**20%**
Homework	**40%**
Mid-term exam	**20%**
Final presentation / project	**20%**

Semester map

1	**History + overview**	Why accelerators, figures of merit
2	**Transverse motion**	Linear optics, betatron motion, dispersion
3	**RF + longitudinal motion**	Cavities, synchrotron radiation, phase stability
4	**Rings + nonlinear effects**	Chromaticity, resonances, instabilities
5	**Applications + frontiers**	FELs, cooling, plasma and advanced methods

	PHY 554	Lecture	HW	Fundamentals of accelerator physics		Note	HWS	HWS
	Mo/We	6:30PM - 7:50PM		PHYSICS D103			Assigned	Due
	Date			Topic	Teacher			
	Monday, August 24, 2026	Semester starts						
				Introduction				
1	Monday, August 24, 2026	Lecture 1		Introduction to course	YJ			
2	Wednesday, August 26, 2026	Lecture 2		History of Accelerators	YJ			
3	Monday, August 31, 2026	Lecture 3		Simulation toolkits -- installation and test-runs	YJ			
				Transverse motion				
4	Wednesday, September 2, 2026	Lecture 4		Linear betatron motion	YJ			
	Monday, September 7, 2026	Labor day						
5	Wednesday, September 9, 2026	Lecture 5		Floquet transformation	YJ			
6	Monday, September 14, 2026	Lecture 6		Beam emittance and dipole errors	YJ			
7	Wednesday, September 16, 2026	Lecture 7		Transvverse dispersion,	YJ			
8	Monday, September 21, 2026	Lecture 8		Quadrupole field errors, chromaticity	YJ			
				RF				
9	Wednesday, September 23, 2026	Lecture 9		Introduction to RF Acceleration	JM			
10	Monday, September 28, 2026	Lecture 10		RF acceleator fundametals	JM			
				Longitudinal Dynamics				
11	Wednesday, September 30, 2026	Lecture 11		Synchrotron Radiation	JM			
12	Monday, October 5, 2026	Lecture 12		Synchrotron Radiation Source	JM			
13	Wednesday, October 7, 2026	Lecture 13		Longitudinal Dynamics	YJ			
	Monday, October 12, 2026	**Fall break**						
				Storage rings				
14	Wednesday, October 14, 2026	Lecture 14		Beam Dynamics in Electron Storage Ring I	YJ			
15	Monday, October 19, 2026	Lecture 15		Beam Dynamics in Electron Storage Ring II	YJ			
16	Wednesday, October 21, 2026	Lecture 16		Superconducting RF	JM			
	Monday, October 26, 2026			**Mid-term**				
				Nonlinear dynamics				
17	Wednesday, October 28, 2026	Lecture 17		Chromaticities	YJ			
18	Monday, November 2, 2026	Lecture 18		Nonlinear Dynamics	YJ			
				Multi-particle dynamics				
19	Wednesday, November 4, 2026	Lecture 19		Collective effects (CSR?Impedance/wakefield?	DK			
20	Monday, November 9, 2026	Lecture 20		Space charge	DK			
21	Wednesday, November 11, 2026	Lecture 21		Free Electron Lasers, I	JM			
22	Monday, November 16, 2026	Lecture 22		Free Electron Lasers, II	JM			
				Beam Cooling				
23	Wednesday, November 18, 2026	Lecture 23		Electron Cooling	DK			
24	Monday, November 23, 2026	Lecture 24		Stocastic Cooling	DK			
	Monday, November 30, 2026	**Thanksgiving Break**						
25	Wednesday, November 25, 2026	Lecture 25		Coherent electron Cooling	JM			
				Applications				
26	Wednesday, December 2, 2026	Lecture 26		Applications of Accelerators, I	DK			
27	Monday, December 7, 2026	Lecture 27		Applications of Accelerators, II	DK			
28	Wednesday, December 9, 2026	Lecture 28		AI/ML for Accelerators(?)	JM			
	December 9-17			**Final Projects**				

Quick background poll

No one is expected to know everything on this slide.

Math

- ODEs and linear algebra
- Vector calculus
- Complex numbers

Physics

- Classical mechanics
- E&M and Maxwell equations
- Special relativity

Useful later

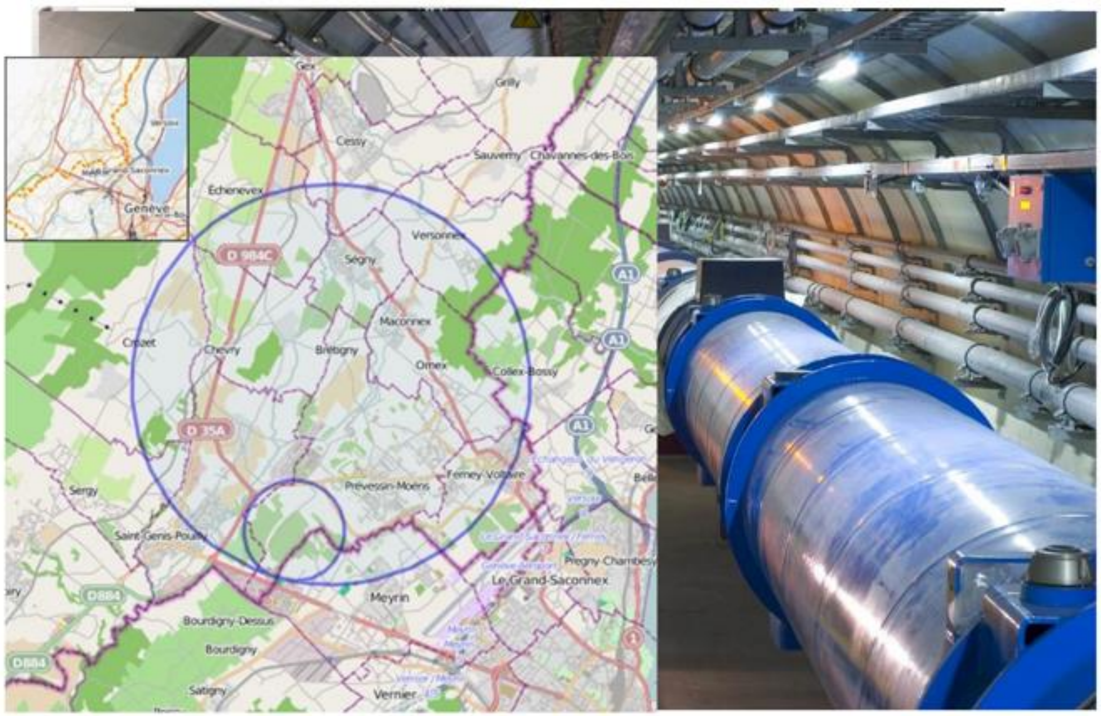
- Hamiltonian mechanics
- Numerical modeling
- Scientific programming

Additional reading materials are available on the course website

Introduction to modern accelerators

- Why accelerators exist and what they are good for
- What particles we accelerate and how beams begin
- Why accelerators are relativistic devices
- Why energy is a central figure of merit
- Why colliders changed high-energy physics
- What limits conventional accelerator progress and motivates new concepts

Accelerators: from tiny devices to city-scale machines



27 km circumference LHC

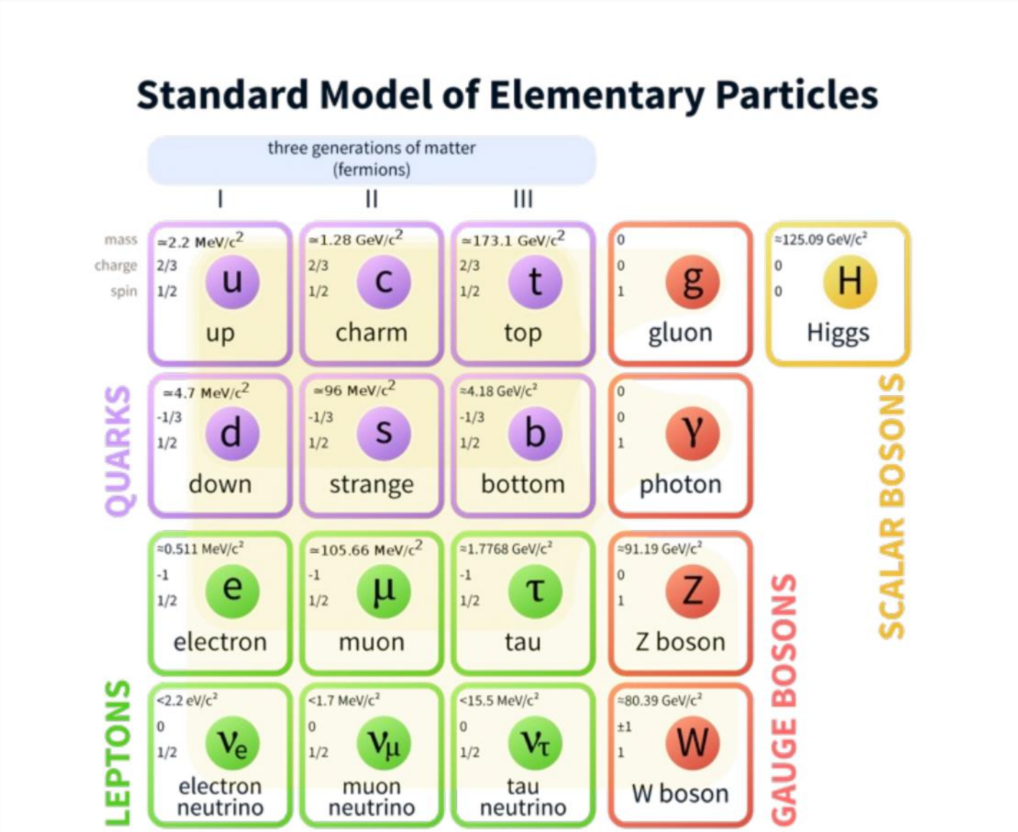
- The underlying idea is simple: electric fields do work on charged particles.
- The engineering scale varies enormously: from electron guns to multi-kilometer rings.
- The physics problem is control: keep particles synchronized, focused and useful.

What has to be controlled in a machine this large?

What accelerators are good for

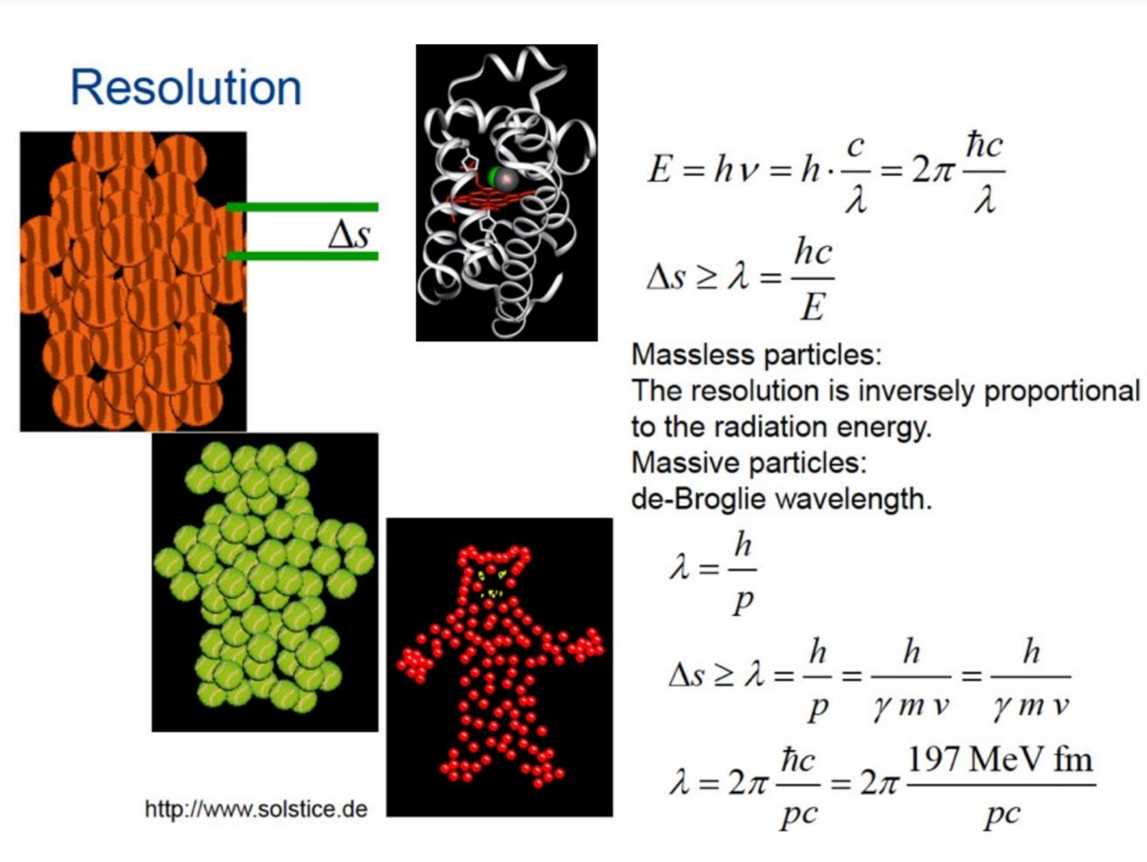
- Fundamental physics: search for new particles and new states of matter
- Nuclear physics: probe nuclei, QCD matter and rare isotopes
- Photon science: X-rays for chemistry, biology and materials
- Medicine and industry: therapy, isotope production, sterilization, ion implantation and inspection

Discovery machines: the particle zoo



- Accelerators helped discover and test the structure of the Standard Model.
- Higher energy gives access to shorter distances and heavier final states.
- But energy alone is not enough: rate, beam quality and detector design also matter.

Light sources: accelerators as microscopes



- Photons and particles act as probes with wavelengths set by energy and momentum.
- Shorter wavelength means finer spatial resolution.
- Modern light sources turn beam quality into brightness, coherence and time resolution.

Bridge to later lectures: "beam quality" becomes a quantitative design target.

What do we accelerate?

Electric fields accelerate charge.

- Common beams: electrons, protons and ions
- Less common but important: positrons and antiprotons
- Specialized facilities can accelerate unstable ions
- Muon colliders are attractive because muons are heavy, but the rest-frame lifetime is only about 2 μs

Takeaway: the particle choice sets the source, acceleration method, radiation effects and applications.

A few useful numbers

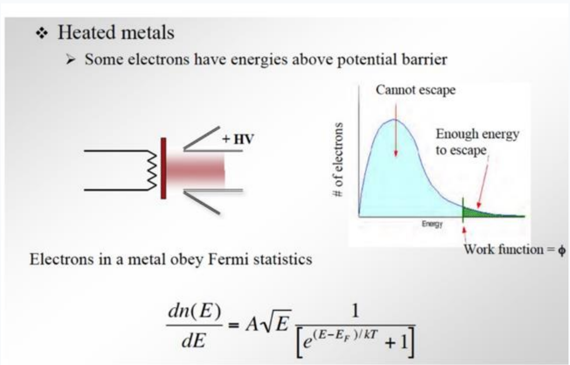
Particle / charge / rest energy / accelerator relevance

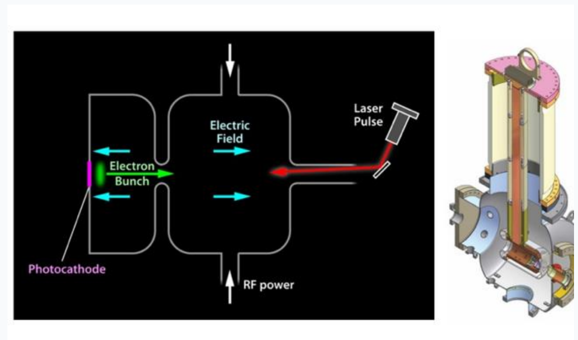
Electron / positron	±e	0.511 MeV	Relativistic at low energy; strong synchrotron radiation
Proton / antiproton	±e	938 MeV	Much heavier; reaches high energy with less radiation
Ion	Ze	≈ A × 931.5 MeV	Charge-to-mass ratio matters for acceleration
1 eV	—	1.602×10^{-19} J	Energy gained by charge e through 1 V

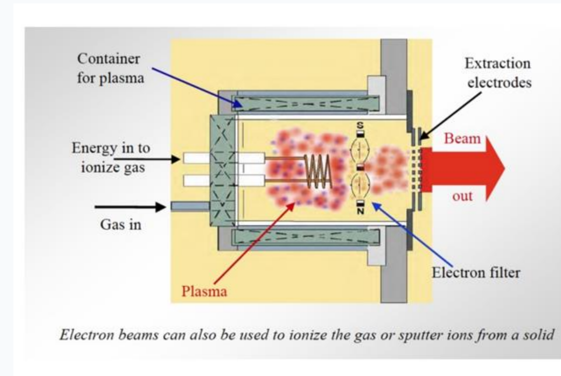
$c = 2.998 \times 10^{8}$ m/s

Use eV, keV, MeV, GeV and TeV as natural accelerator energy units.

Where beams begin: sources



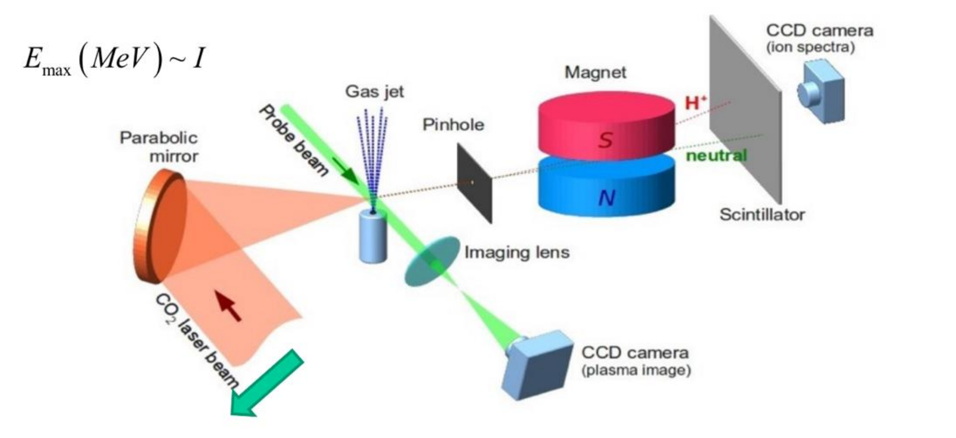




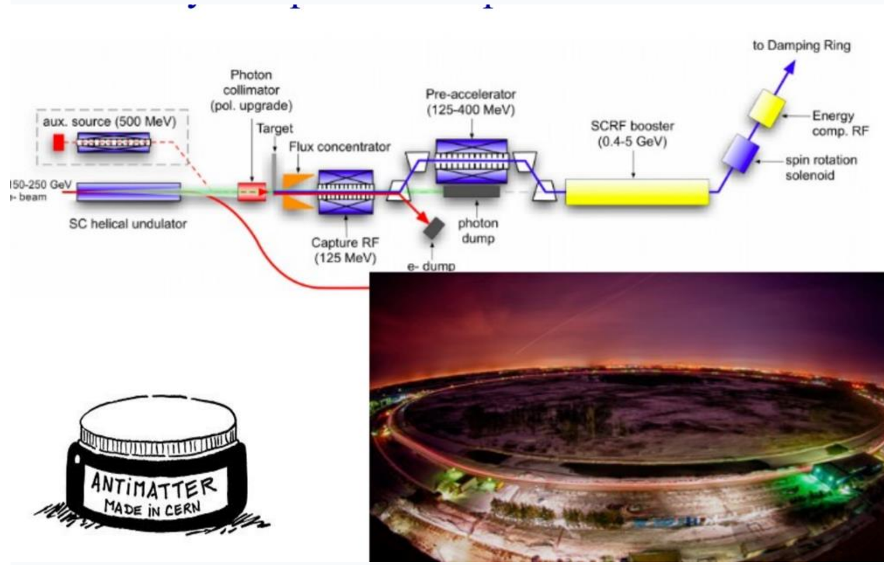
Thermionic **Photo-emission** **Ion source**

- Sources define initial beam current, timing, emittance and species.
- The rest of the accelerator can only preserve or transform what the source provides.

Rare and advanced sources



A monoenergetic proton beam is observed from the interaction of a short-pulse infrared laser with a gas jet target. Electron's pushed out of the gas jet (or metal foil) by high laser pulse , then pull out ions and accelerate them.

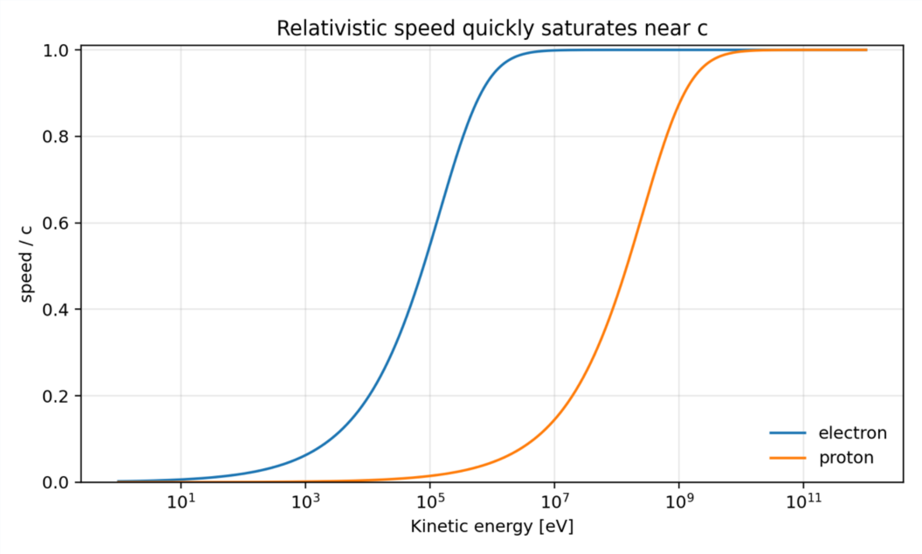


Laser-driven ion acceleration

Positron / antiproton production

Welcome to the relativistic world

- Particle speed quickly becomes a poor figure of merit.
- Energy keeps increasing even when v is already close to c.
- Electrons become relativistic at much lower kinetic energy than protons.
- Accelerator design therefore uses energy, momentum and rigidity—not just speed.



$$\beta = v/c, \quad \gamma = 1/\sqrt{(1 - \beta^2)}$$

Special relativity: the coordinate invariant

Lorentz transformation along x

$$x = \gamma(x' + vt')$$
$$ct = \gamma(ct' + \beta x')$$
$$y = y', \quad z = z'$$

Four-position

$$x\text{^}\mu = (ct, x, y, z)$$

Invariant interval

$$s^2 = c^2t^2 - r^2 = \text{invariant}$$

Only the invariant idea is needed today; detailed tensor notation can wait.

Energy and momentum: the four-vector view

$$p^\mu = (E/c, \vec{p})$$

$$E = \gamma m c^2$$
$$\vec{p} = \gamma m \vec{v}$$
$$\gamma = 1/\sqrt{(1 - v^2/c^2)}$$

Invariant relation

$$E^2 - p^2c^2 = m^2c^4$$

- Energy and momentum, not velocity, become the natural variables.
- This relation is the foundation for center-of-mass energy calculations.

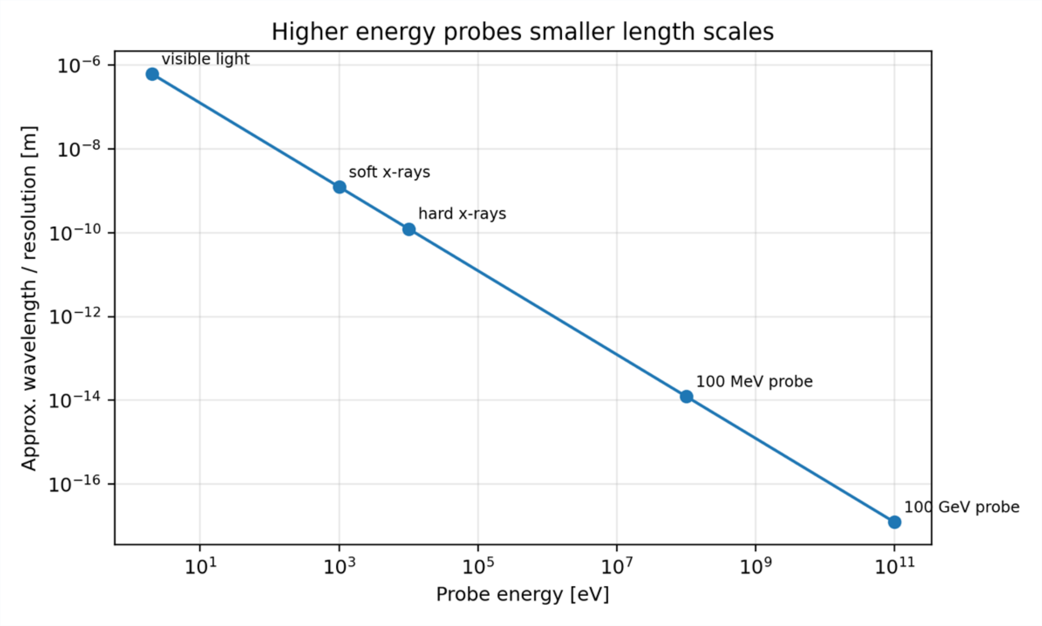
Equation of motion: what fields do

In accelerator physics, fields are the knobs.

$$d\vec{p}/dt = q(\vec{E} + \vec{v} \times \vec{B})$$
$$dE/dt = q\,\vec{E} \cdot \vec{v}$$

- Electric fields change particle energy.
- Magnetic fields bend and focus particles but do no change energy.
- Beam dynamics is the controlled use of these two facts.

Why energy matters I: spatial resolution



Uncertainty / wavelength idea

$$\Delta p \cdot \Delta x \sim \hbar$$
$$\Delta p \sim E/c$$
$$\Delta x \sim \hbar c/E$$

- Higher energy probes smaller length scales.
- The same idea connects photon science and high-energy scattering.

Why energy matters II: creating new mass

At threshold, available energy must at least match rest mass.

$$E_{min} = Mc^2, \qquad M = \Sigma\, m_i$$

- In practice, reactions need extra energy so final particles can separate and conserve momentum.
- The useful question is not "beam energy" alone; it is "available center-of-mass energy."
- This motivates the contrast between fixed-target and collider geometry.

Fixed-target geometry: simple, but inefficient for high mass

Accelerated particle + stationary target

$$M\_eff^2 c^4 = E^2 - P^2 c^2$$

$$\text{For } E_1 \gg m_1 c^2\text{:}\ \ M\_eff\, c^2 \approx \sqrt{(2E_1 m_2 c^2)}$$

- Momentum conservation forces final products to carry common forward motion.
- Large laboratory beam energy does not fully become particle-creation energy.
- Fixed targets remain powerful when intensity, specific reactions or nuclear targets matter.

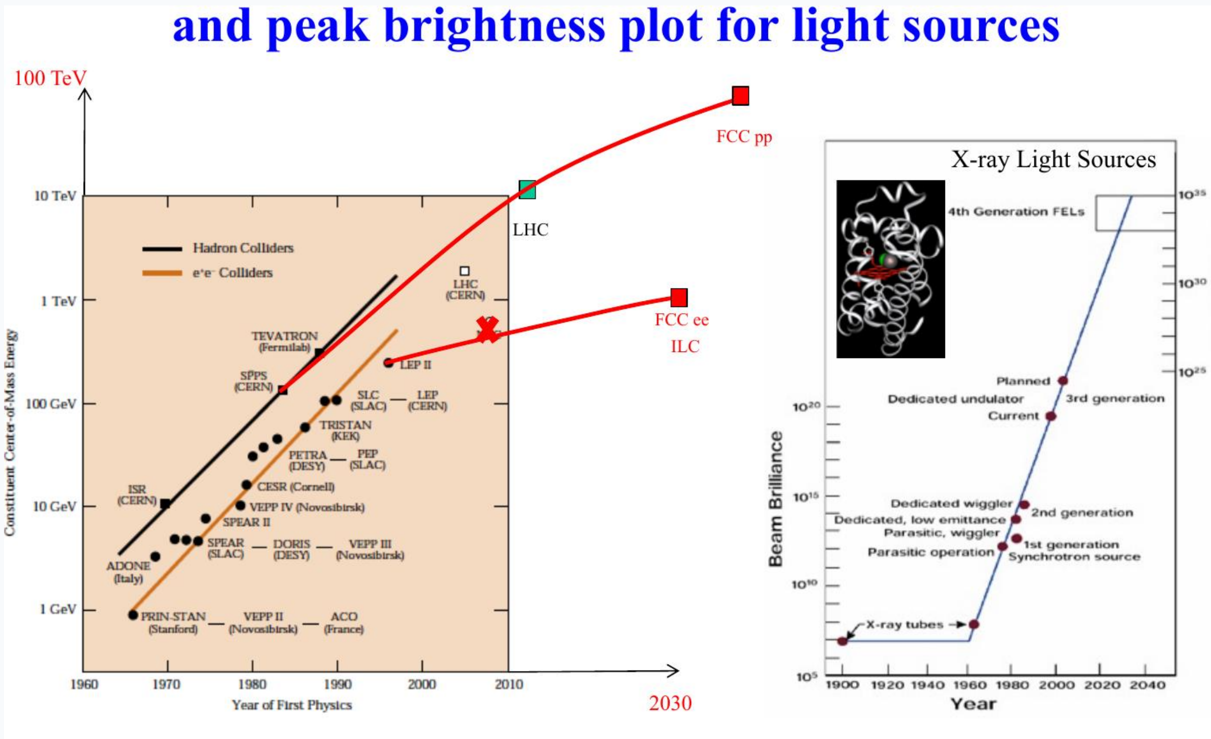
Collider geometry: energy where you want it

Two equal and opposite beams

$$\vec{P}\_total = 0$$
$$E\_CM = E_1 + E_2 = 2\gamma mc^2$$

- Head-on beams maximize center-of-mass energy for particle creation.
- The price is luminosity: two tiny beams must overlap in space and time.
- This is why “energy frontier” and “intensity/luminosity frontier” are different design problems.

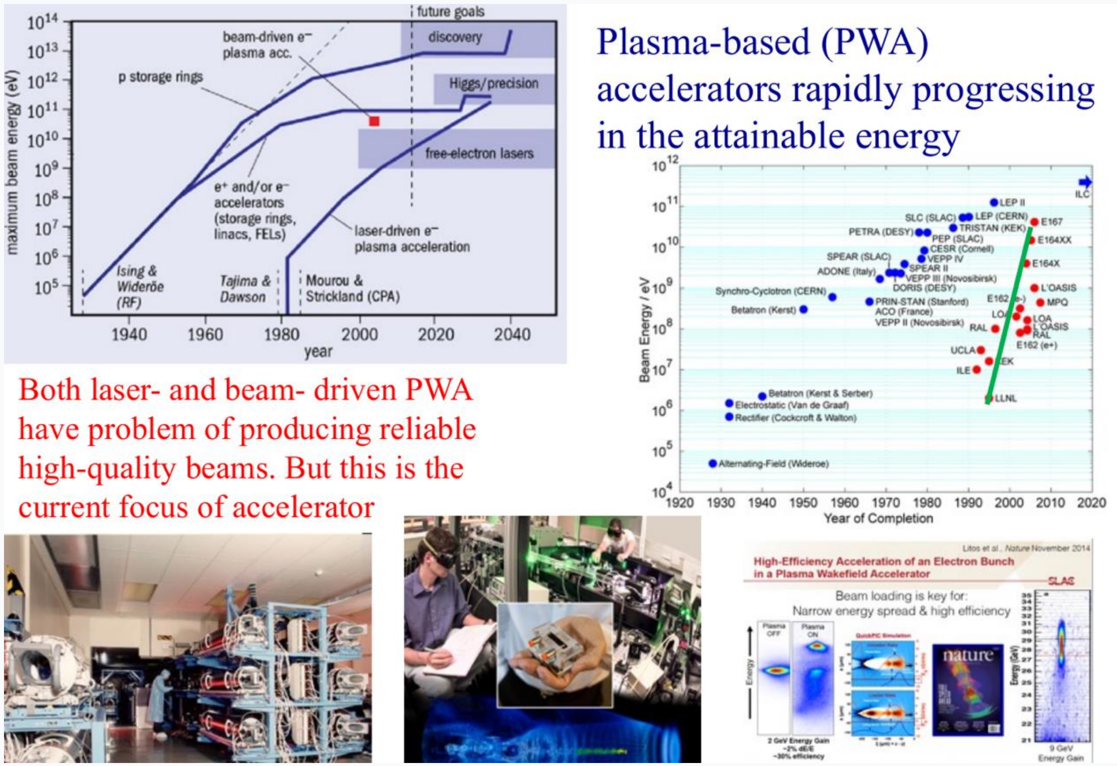
Livingston plots: progress and limits



- Rapid progress often looks exponential on a logarithmic plot.
- Accelerator energy and light-source brightness grew dramatically through the 20th century.
- Today, technology, size and cost constrain conventional scaling.

"Moore's law" analogy: useful as history, dangerous as a guarantee.

Advanced concepts: new gradients, new challenges



- Plasma wakefield acceleration can support much larger gradients than conventional RF structures.
- The central challenge is not just high energy; it is producing reliable, high-quality beams.
- This is an active research frontier, not a solved replacement for conventional accelerators.

Frontier ideas still obey the same beam-dynamics constraints.

What to remember from today

- Most accelerators work with stable charged particles: electrons, protons and ions.
- Energy and momentum are the natural variables because beams are relativistic.
- Electric fields accelerate; magnetic fields bend and focus.
- Energy is a figure of merit because it sets resolution and available mass creation.
- Collider geometry converts beam energy into center-of-mass energy more efficiently than fixed targets.
- Modern limits motivate advanced concepts, but beam quality remains the central constraint.

PHY 554 tradition: no homework after the first class.

Questions (not homework) for your own

- Why don't people use colliders all the time? More specifically, why do some experiments intentionally slam a high-energy beam into a fixed target?
- Besides center-of-mass energy, what figures of merit matter for nuclear and high-energy physics?
- What is the figure of merit for accelerators as light sources?
- How do history and technology shape the accelerators we build?

Suggestion: write down one question you hope this course will answer and try to answer it before the end of semester.