Overview of Beam Diagnostics

Tom Shea (ORNL)
USPAS and University of New Mexico
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Material adapted from presentations by many people in the accelerator community, particularly: P. Forck, S. Henderson, and S. Cousineau.

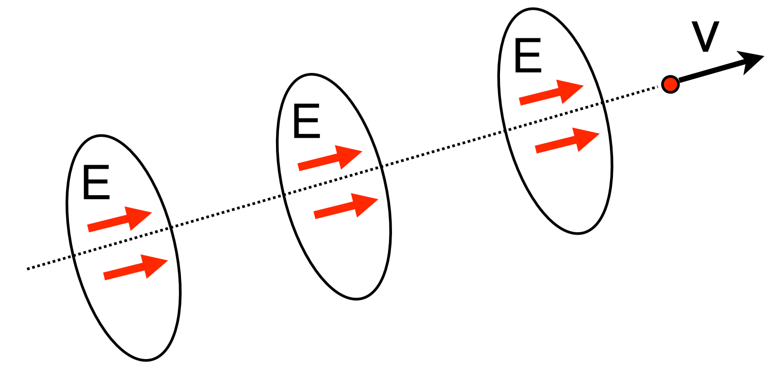
Outline

- Overview of Accelerators
  - History and types of accelerators
  - Performance trends and relevant diagnostics
- Overview of Diagnostics
  - Role and Considerations
  - Physics and Technologies
  - Inventory of diagnostic systems
  - Scale

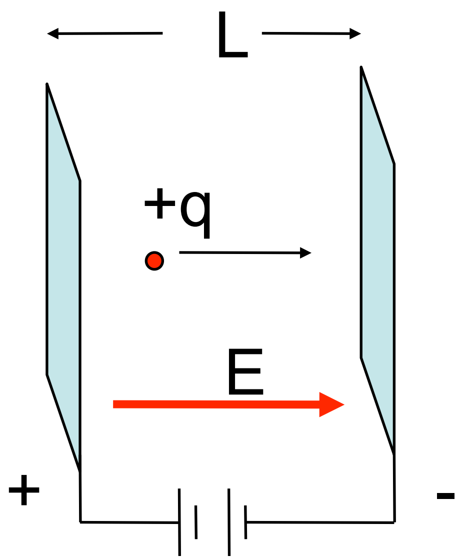
Accelerator Inventory

World wide inventory of accelerators, in total 15,000. The data have been collected by W. Scarf and W. Wiesczycka (See U. Amaldi Europhysics News, June 31, 2000)	
Category	**Number**
Ion implanters and surface modifications	7,000
Accelerators in industry	1,500
Accelerators in non-nuclear research	1,000
Radiotherapy	5,000
Medical isotopes production	200
Hadron therapy	20
Synchrotron radiation sources	70
Nuclear and particle physics research	110

Acceleration Techniques



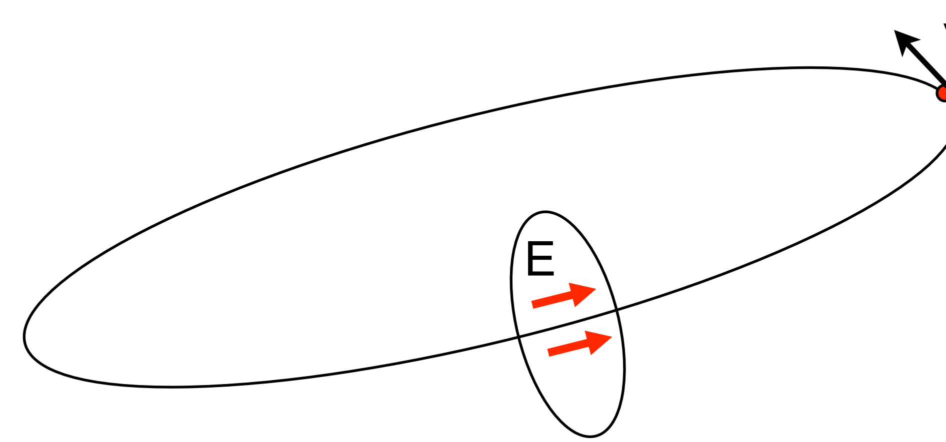
$$\Delta W = qV_0$$



Two approaches for accelerating with time-varying fields (to get above 20 MeV/n or so)

Linear Accelerators

Use many accelerating cavities through which the particle beam passes once: Linacs

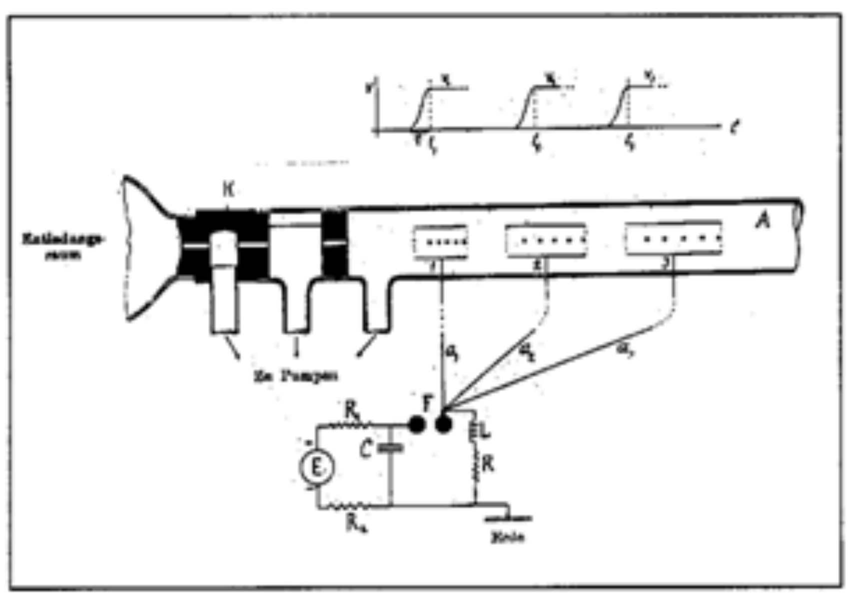


Circular Accelerators

Use one or a small number of Radio-frequency accelerating cavities and make use of repeated passage through them. This approach is realized in circular accelerators: Cyclotrons, synchrotrons and their variants

Linac Concept

- Ising and Wideroe suggested to repeatedly apply a much smaller voltage in a linear accelerator by using time-varying fields
- In this way, a high particle beam energy could be attained by repeatedly applying voltage “kicks”



Ising's idea

R. Wideroe

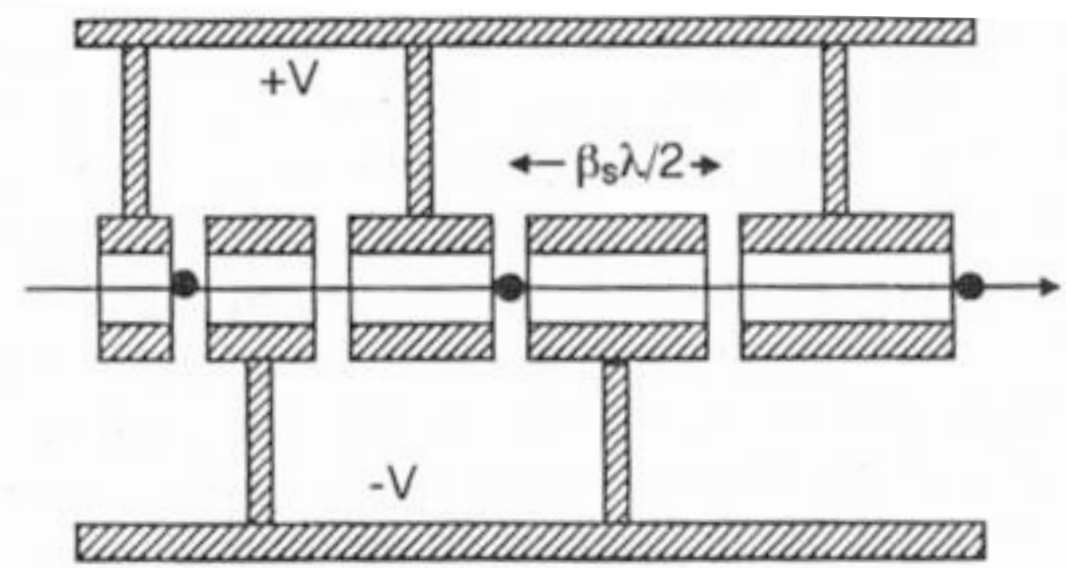


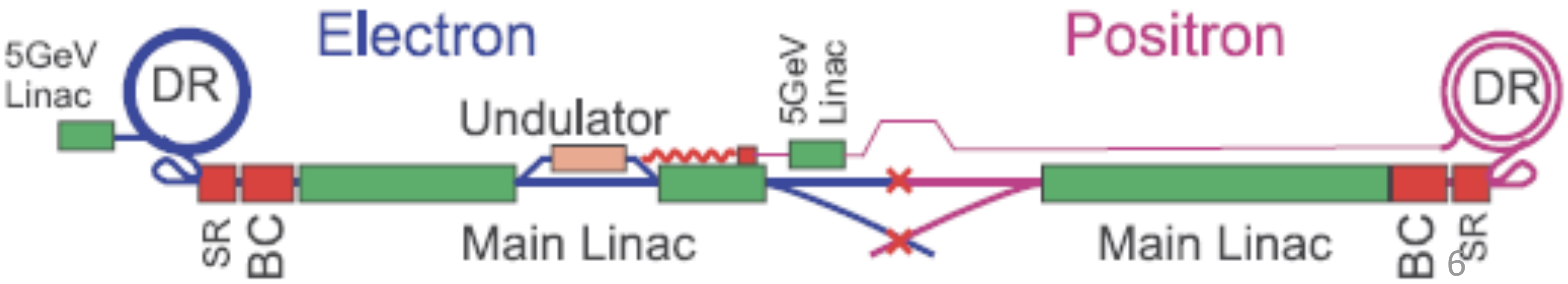
Figure 4.4 Wideröe or Sloan–Lawrence or interdigital structure.

Modern Linacs

- The two largest proton linear accelerators are the LANSCE linac at Los Alamos (800 MeV) and the Spallation Neutron Source Linac at ORNL (1000 MeV)
- Largest linac is at SLAC; One of the largest under consideration is ILC
(31 km total length)
- Electron and hadron linacs now will look similar: most recent and future projects have settled on superconducting cavities.

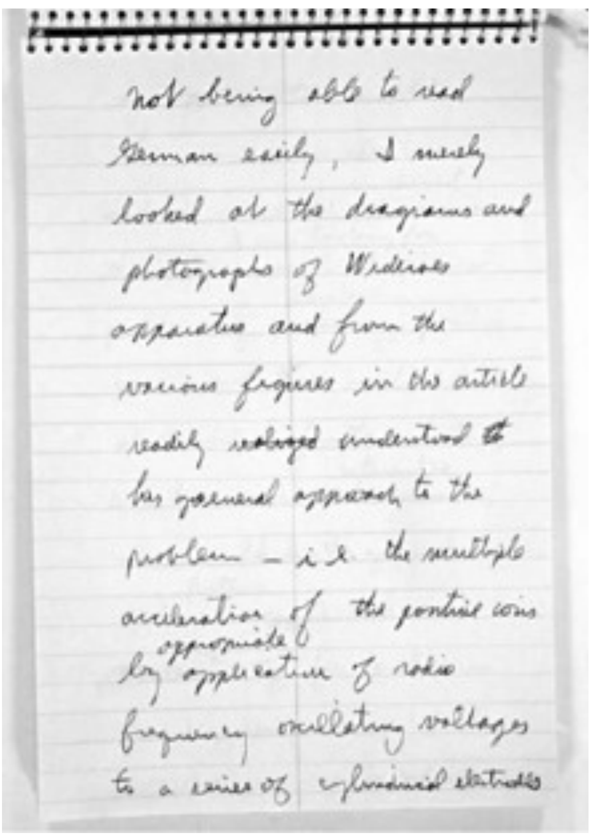
ILC

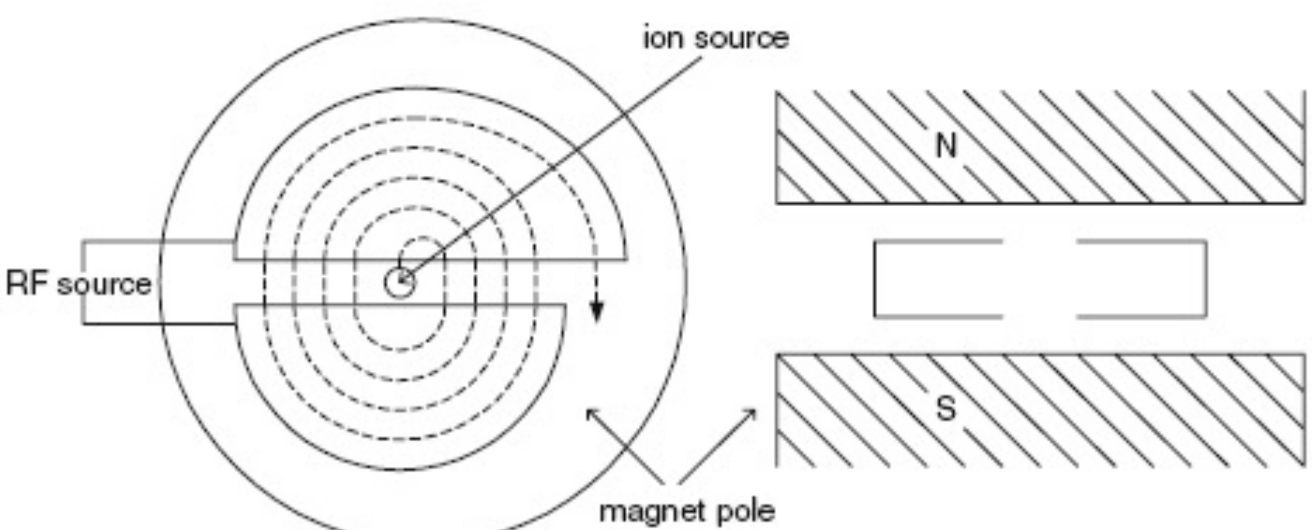
- 500 GeV lepton machine
- peak luminosity of 2e34



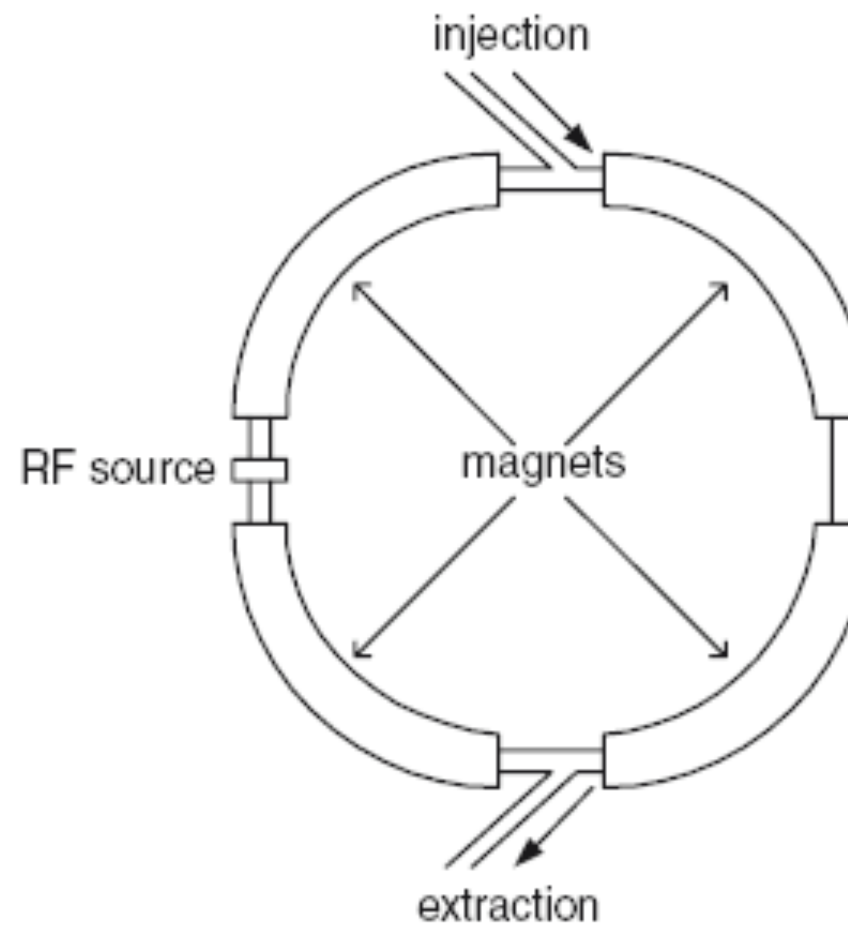
Circular Machines

Lawrence's Application of Wideroe's Idea:
The Cyclotron


not being able to read German easily, I merely looked at the diagrams and photographs of Wideroes apparatus and from the various figures in the article readily understood the general approach to the problem – i.e. the multiple acceleration of the positive ions by appropriate application of radio frequency oscillating voltages to a series of cylindrical electrodes

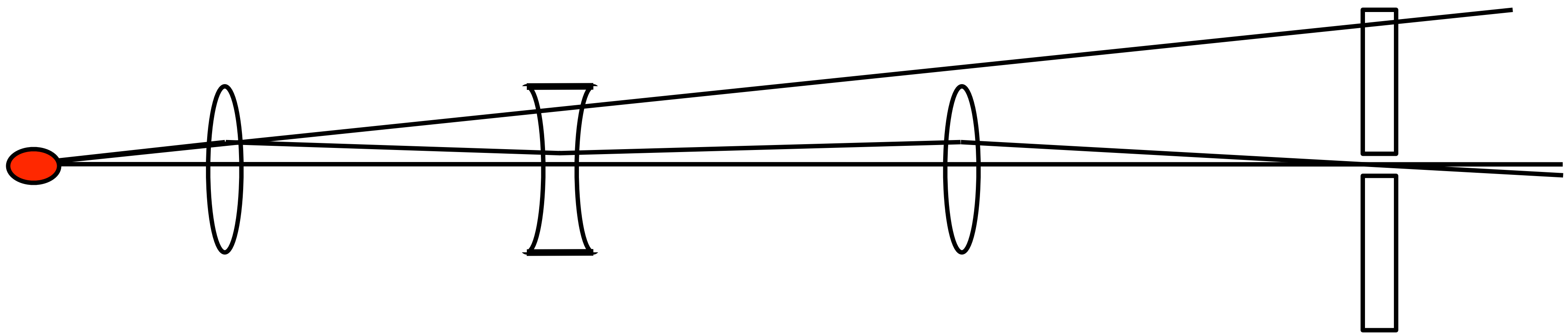


The synchrotron concept - ramped magnets for constant radius - was first proposed in 1943 by the Australian physicist Mark Oliphant.

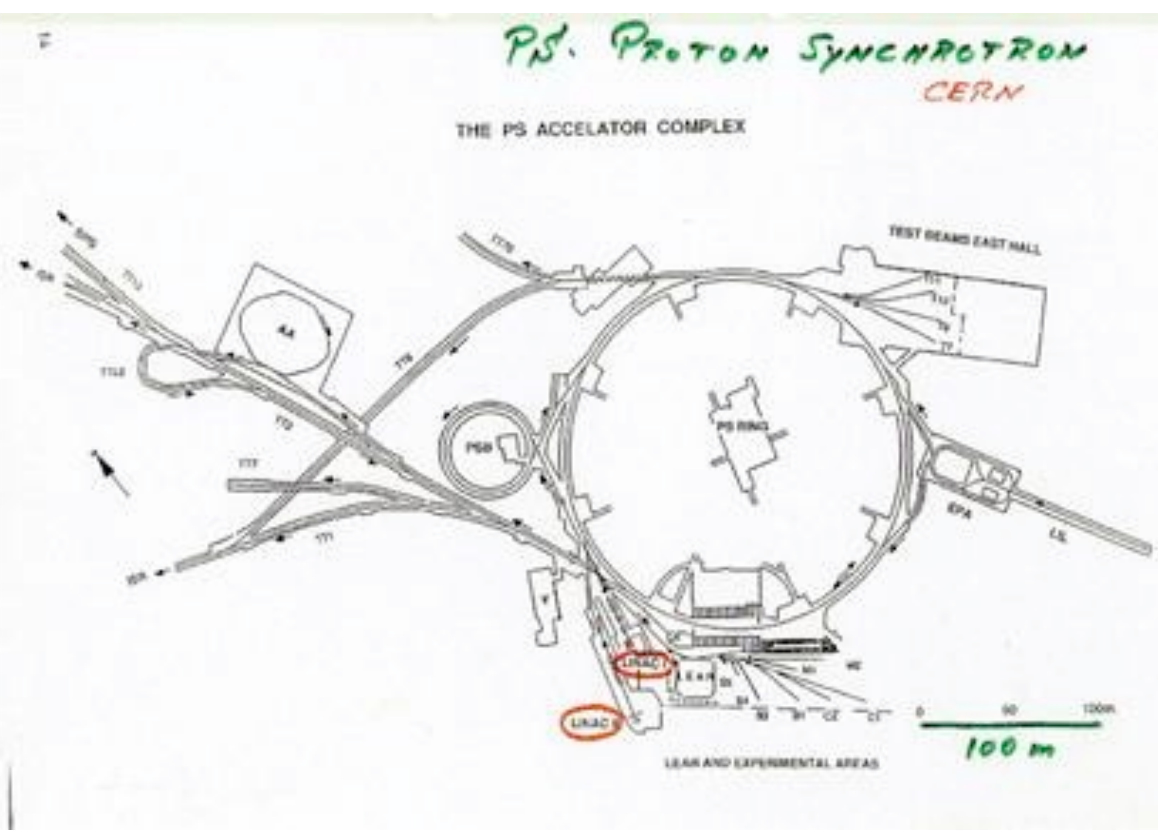


$$\frac{1}{\rho[m]} = 0.3\frac{B[T]}{\beta E[GeV]} = 0.3\frac{B[T]}{cp[GeV]}$$

Strong Focusing Synchrotrons



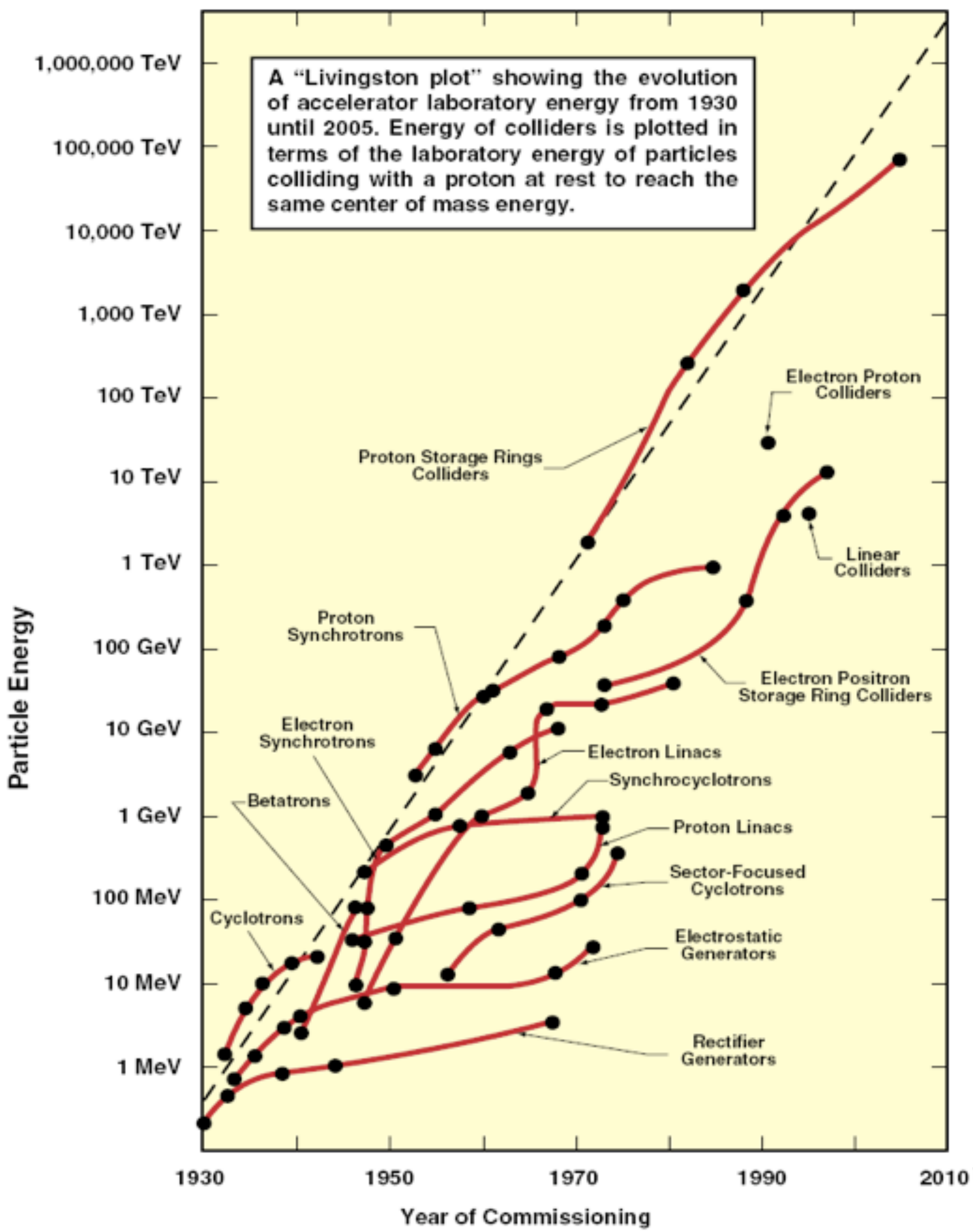
The synchrotron concept was first proposed in 1943 by the Australian physicist Mark Oliphant. “Strong” or “Alternating Gradient” focusing concept first applied to particle accelerators by Courant, Livingston and Snyder. First AG synchrotron: Cornell in 1954.



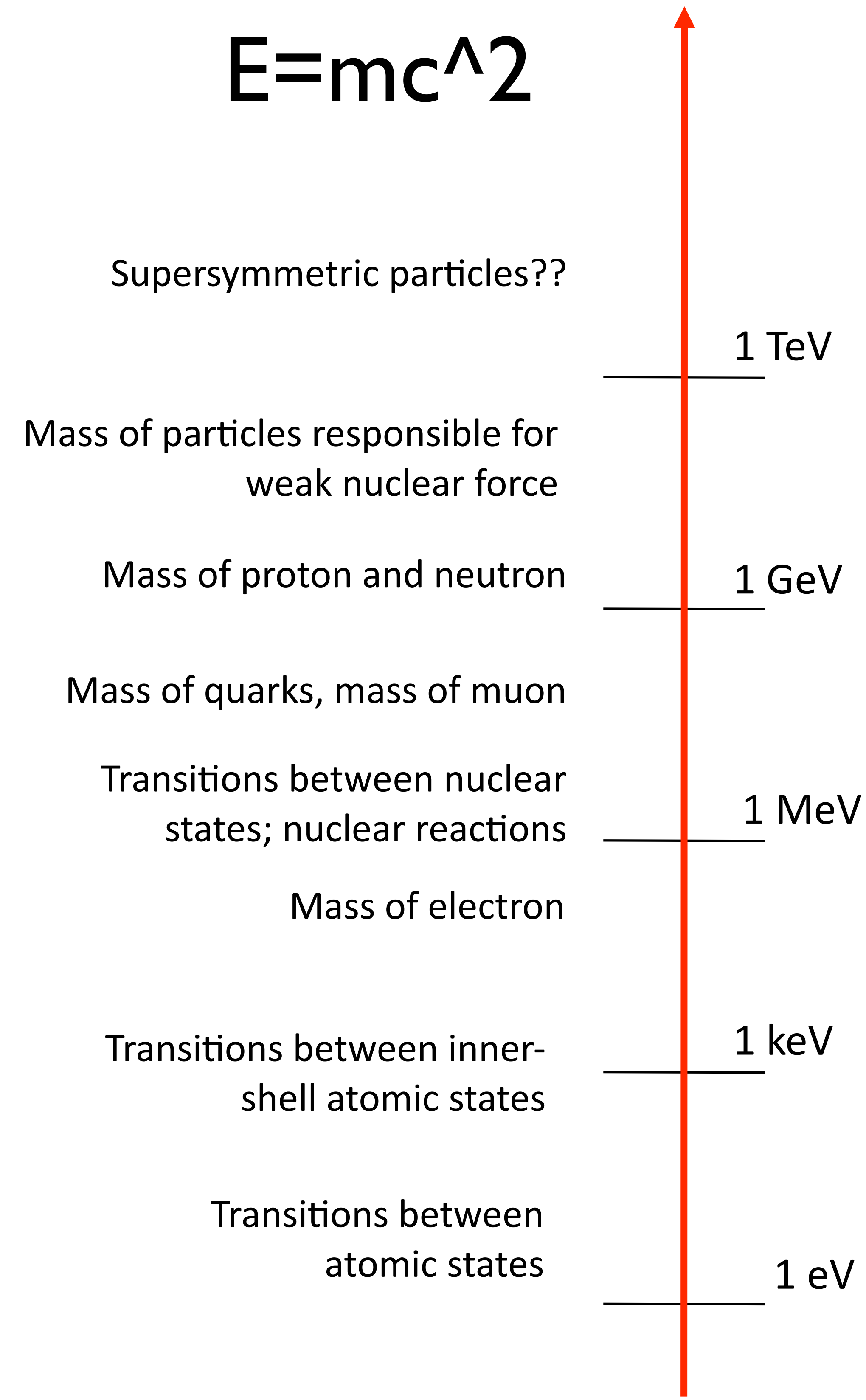
CERN PS (~28 GeV) started operations in 1959.

Brookhaven AGS (~33 GeV) under construction in 1957. Started operations in 1960.

Energy

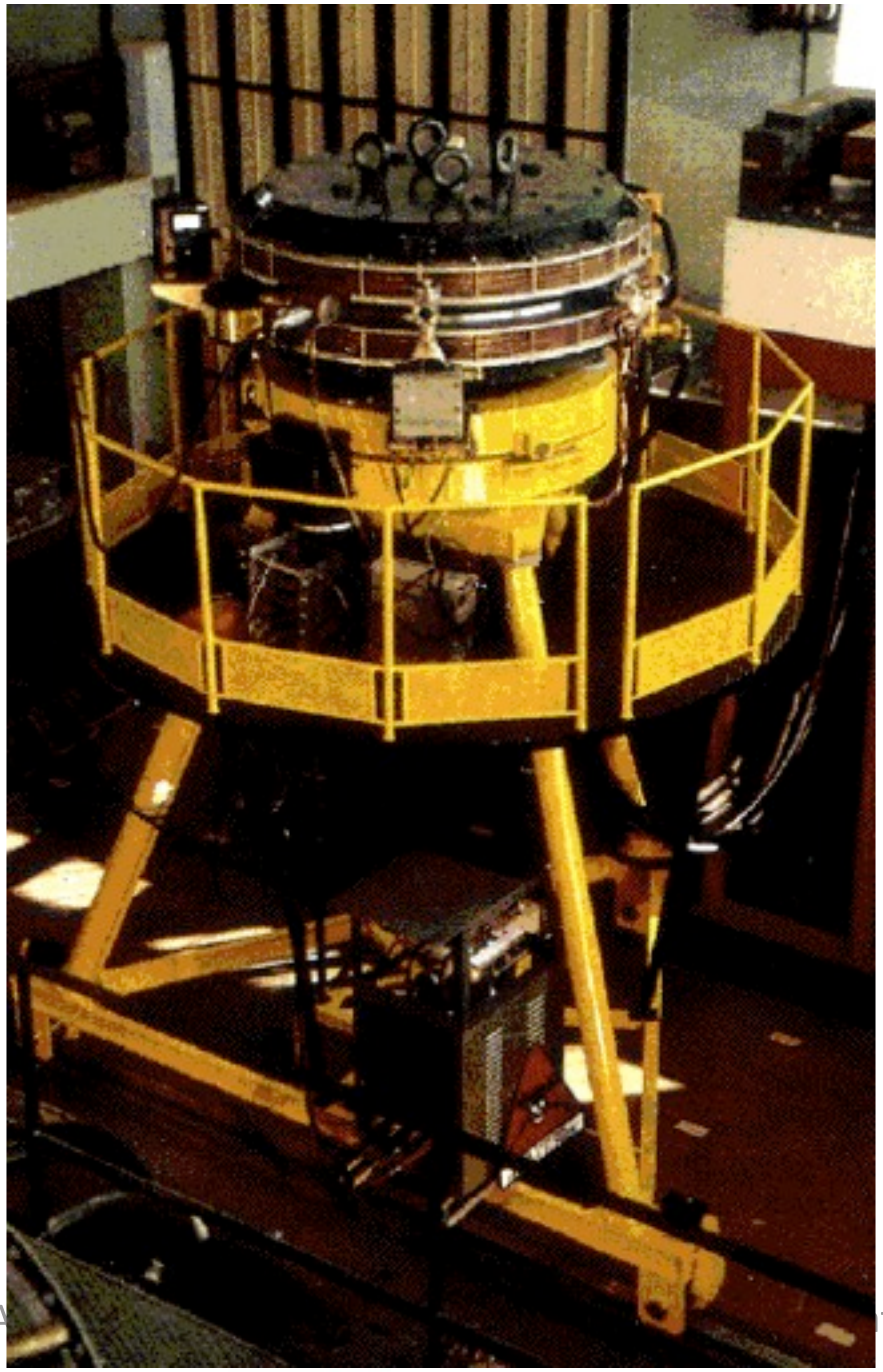

A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.
Particle Energy
1,000,000 TeV
100,000 TeV
10,000 TeV
1,000 TeV
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
1 MeV
1930
1950
1970
1990
2010
Year of Commissioning
Electron Proton Colliders
Proton Storage Rings Colliders
Linear Colliders
Proton Synchrotrons
Electron Positron Storage Ring Colliders
Electron Synchrotrons
Electron Linacs
Synchrocyclotrons
Betatrons
Proton Linacs
Sector-Focused Cyclotrons
Cyclotrons
Electrostatic Generators
Rectifier Generators

E=mc^2


Supersymmetric particles??
1 TeV
Mass of particles responsible for weak nuclear force
Mass of proton and neutron
1 GeV
Mass of quarks, mass of muon
Transitions between nuclear states; nuclear reactions
1 MeV
Mass of electron
Transitions between inner-shell atomic states
1 keV
Transitions between atomic states
1 eV

Colliders

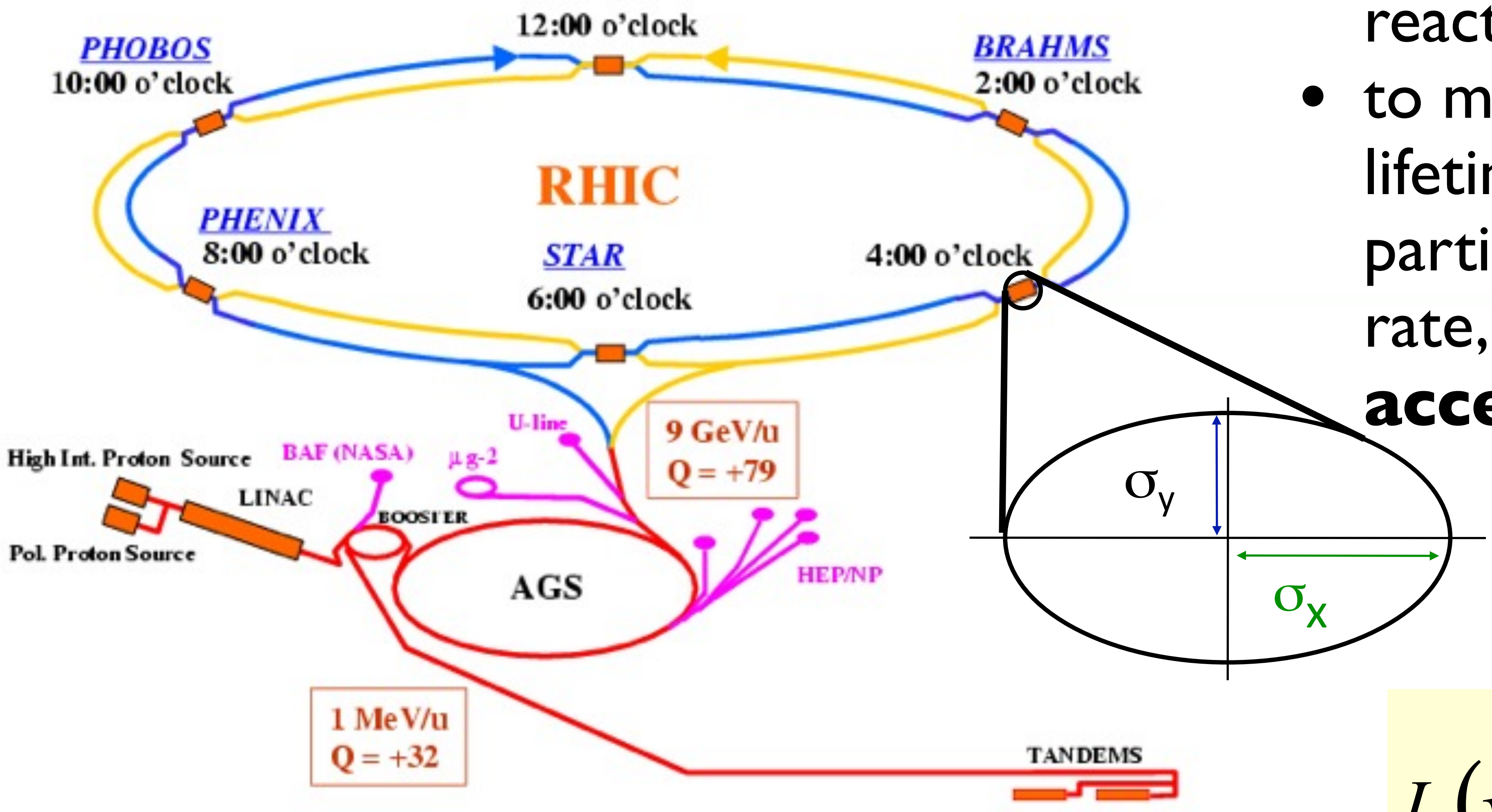
- Circular or linear, common goal is to maximize center-of-mass energy available for particle production



Bruno Touschek built the first successful electron-positron collider, ADA, at Frascati, Italy (1960)

Eventually, went up to 3 GeV

Collider Figure of Merit: Luminosity



- probability of an interesting reaction can be small
- to make a discovery in your lifetime: small bunches, lots of particles per bunch, high bunch rate, reliable operation of **accelerator complex**

for Gaussian beam

$$I_1(x,y) = \frac{n_1}{2\pi\sigma_x\sigma_y} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{y^2}{2\sigma_y^2}}$$

Luminosity = number of interactions per unit area per unit time:

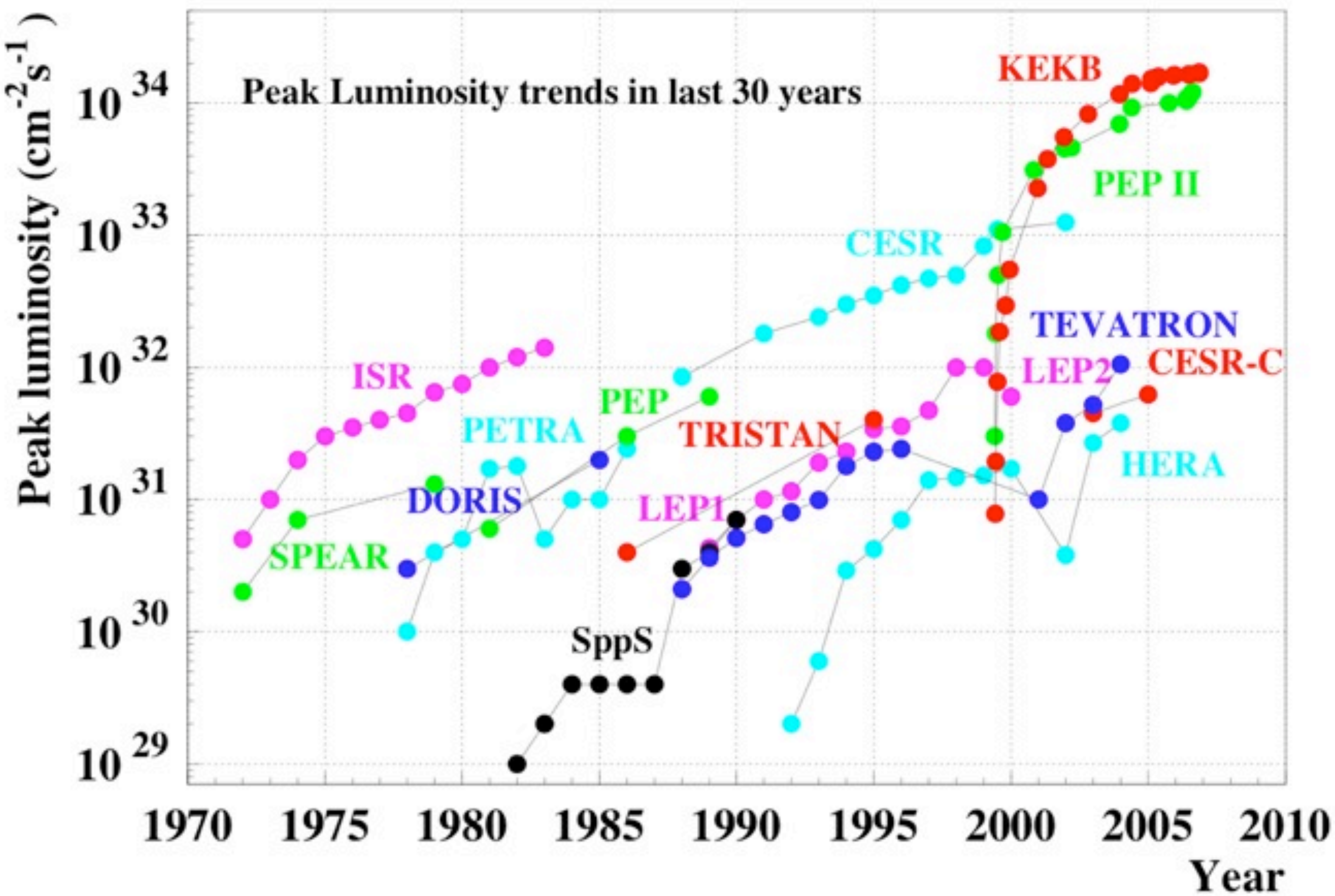
$$L = f\int_{-\infty}^{\infty} dx_1 dy_1 dx_2 dy_2 I_1(x_1,y_1) I_2(x_2,y_2) \delta(x_1 - x_2)\delta(y_1 - y_2)$$

$$= f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

n_1, n_2= particles per bunch

f = frequency of bunch collisions

Luminosity Trends



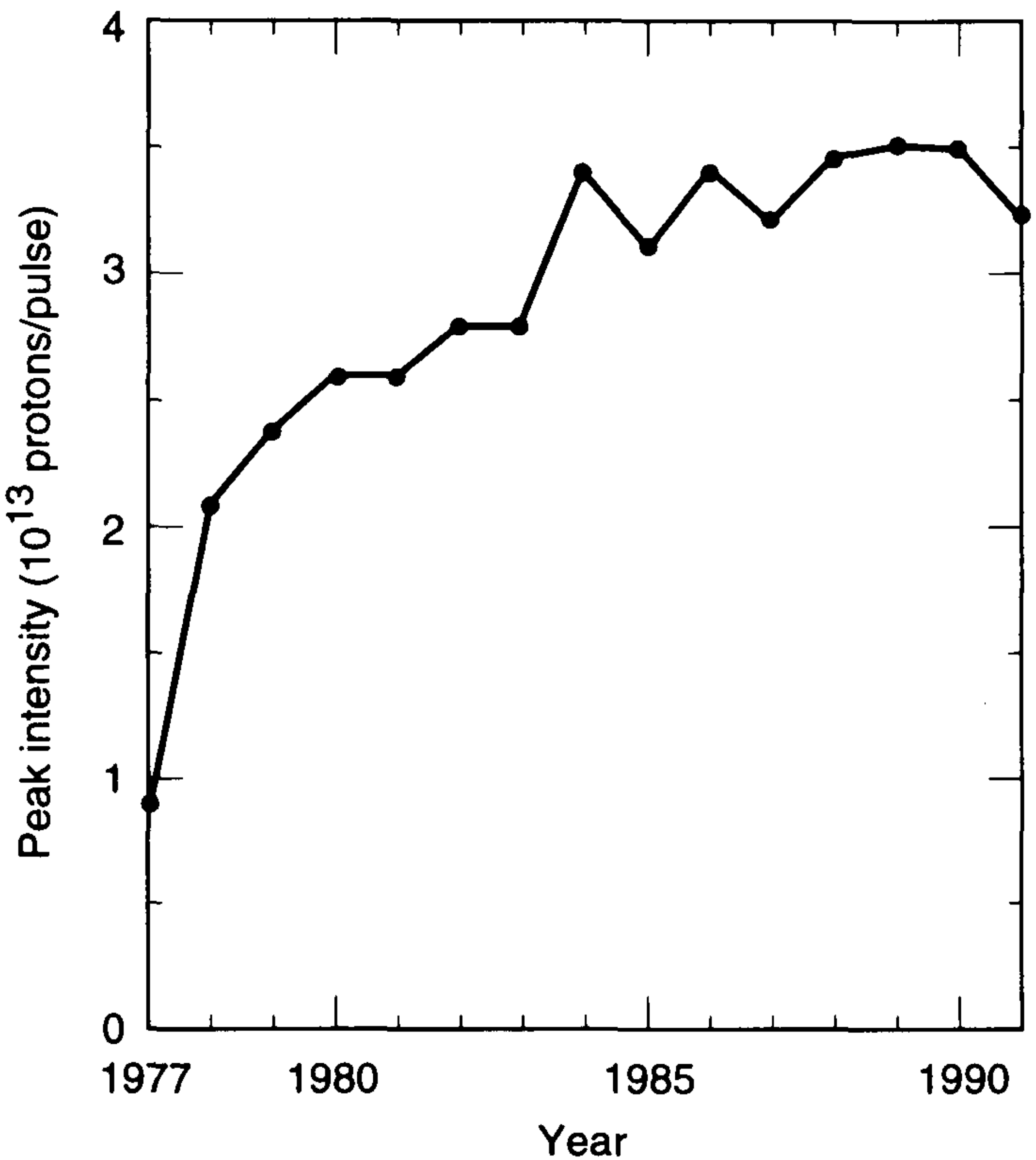
	ILC e- + e+	RHIC		LHC	
		p+p	Au+Au	p+p	Pb+Pb
Maximum beam energy (TeV/u)	0.25	0.25	0.10	7.0	2.76
Luminosity (10^{30} cm^{-2}s^{-1})	$2x10^4$	6	$5x10^{-4}$	104	10^{-3}

Luminosity

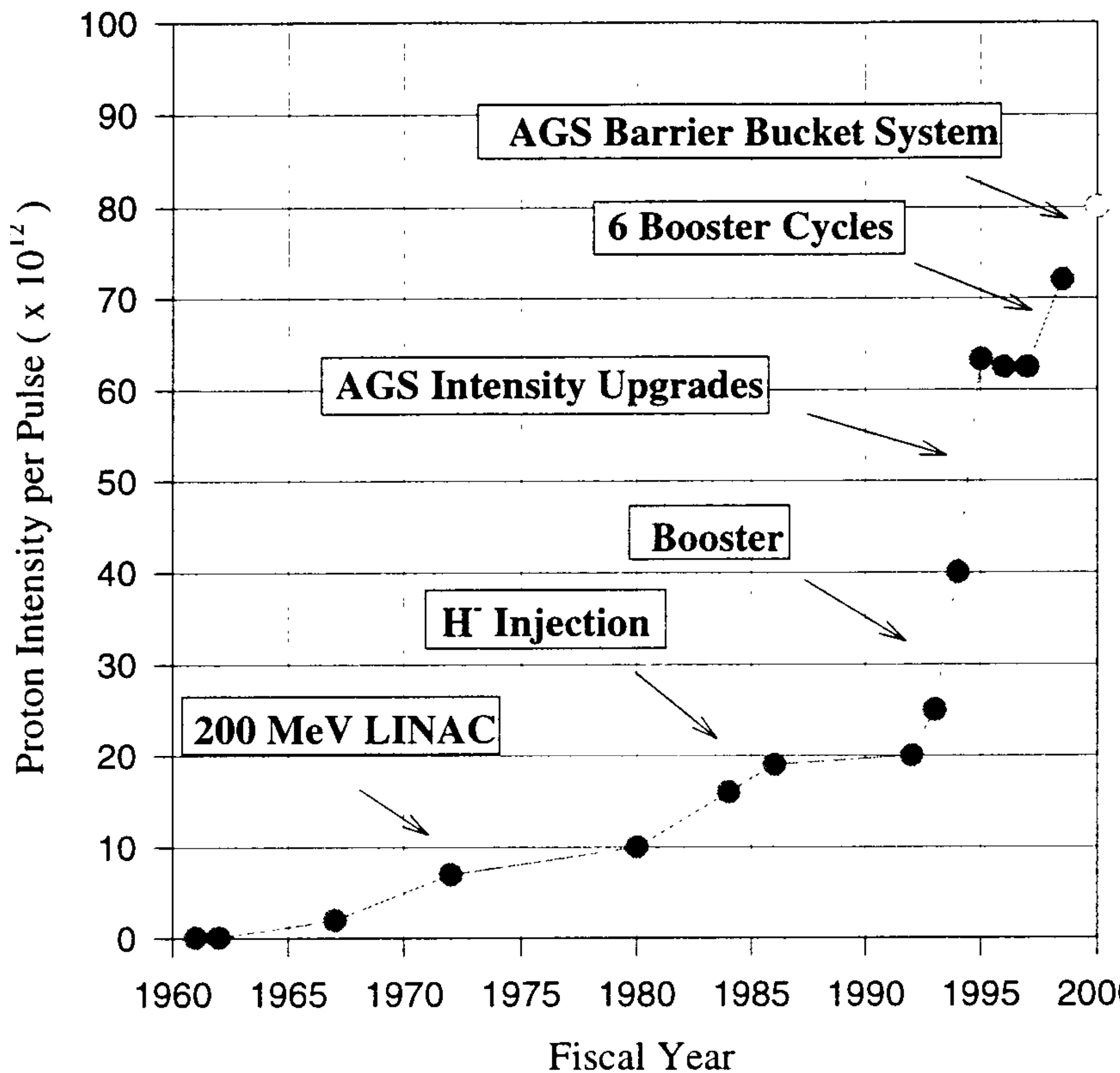
- **Particle counters**
  - Direct indicator of performance
- **Profile (Uli)**
  - and for hadron facilities, **emittance** preservation
- **Position monitors (John)**
  - Near interaction point
  - and for linear colliders:
    - approaching nanometer resolution - **cavity BPMs**
    - feedback within a pulse

Increasing Intensity

PS



AGS

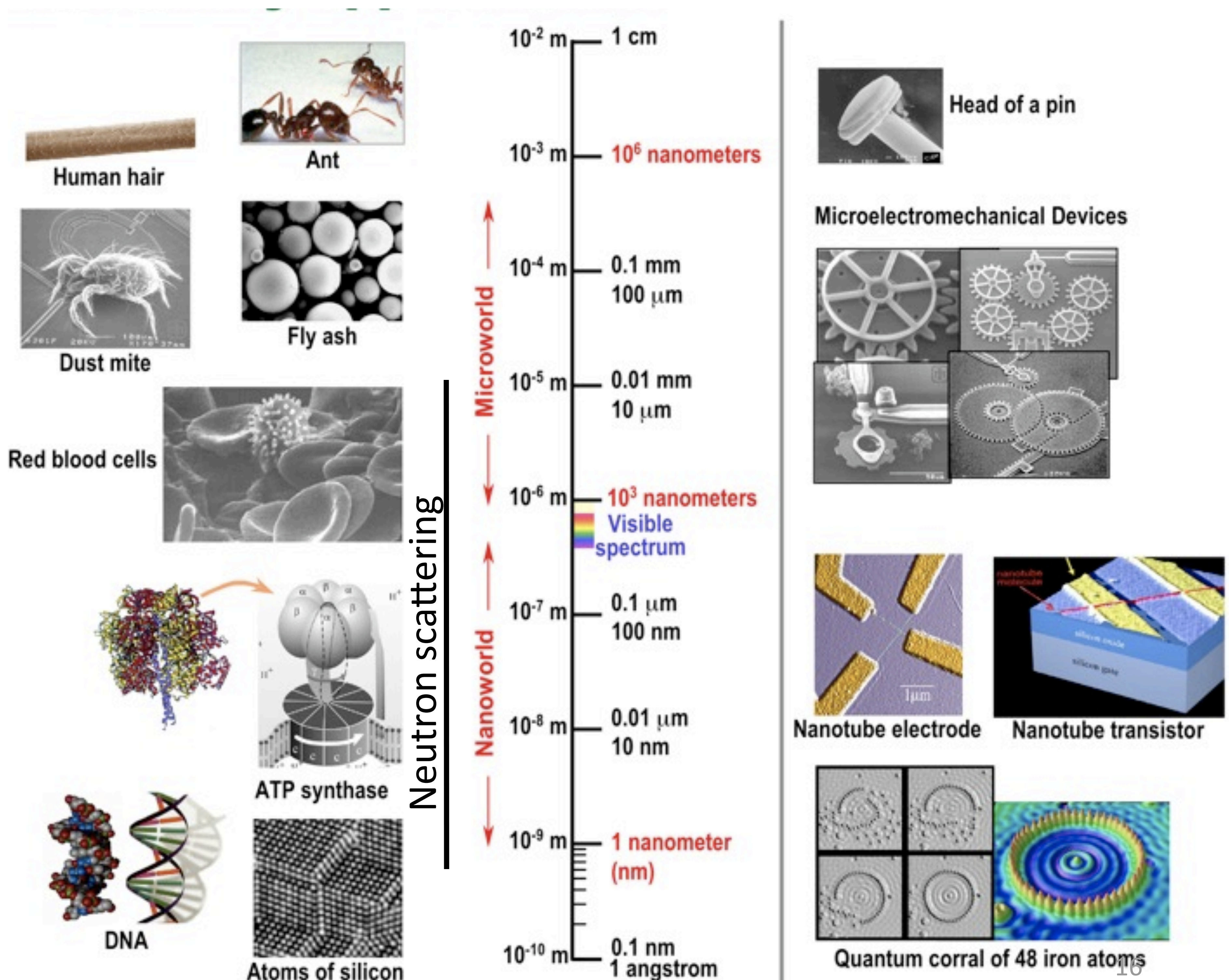


High Intensity

- Demonstrate
  - **Current Monitors, a.k.a BCM (Wim)**
- Enable
  - **Beam Loss Monitor, a.k.a BLM (Sasha)**
    - Intensity limited by loss and attendant activation (~ 1 W/ meter for hands on maintenance)
    - Primary diagnostic input to Machine Protection System
- Survive
  - Non-interceptive devices, particularly **Profile** monitors (Ionization Profile Monitor, **Laser Wire**, etc...)

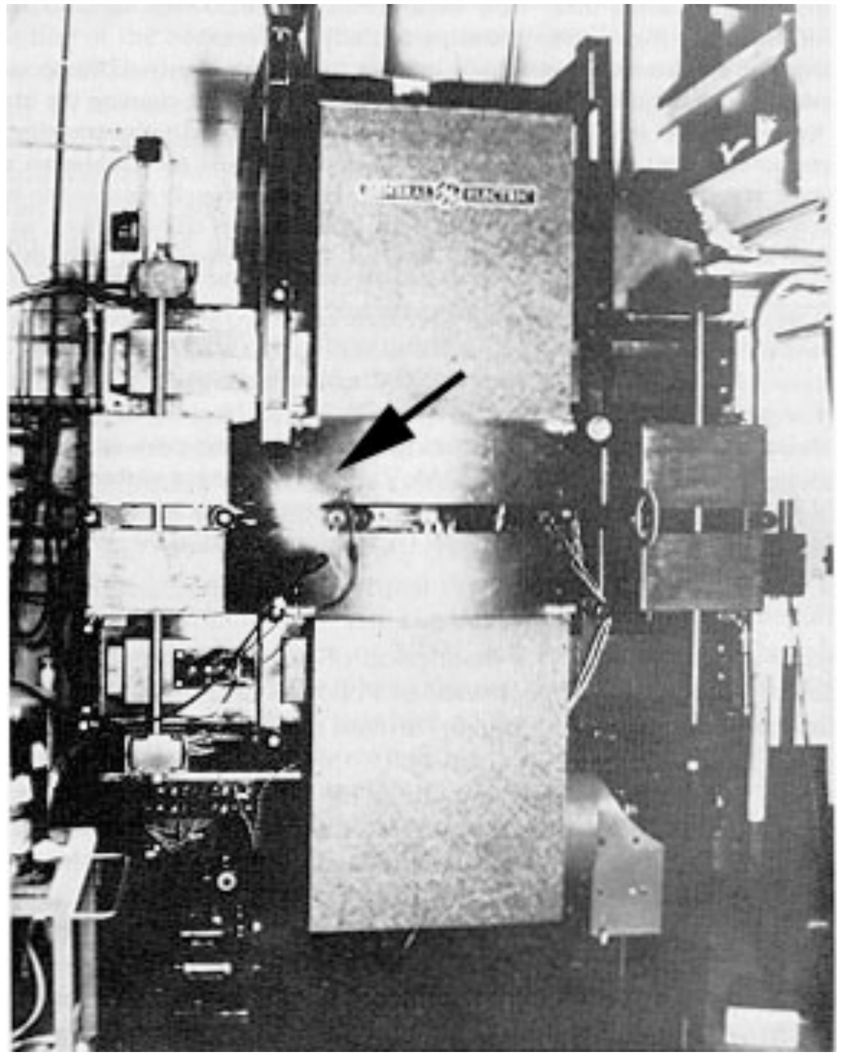
Secondary Beams

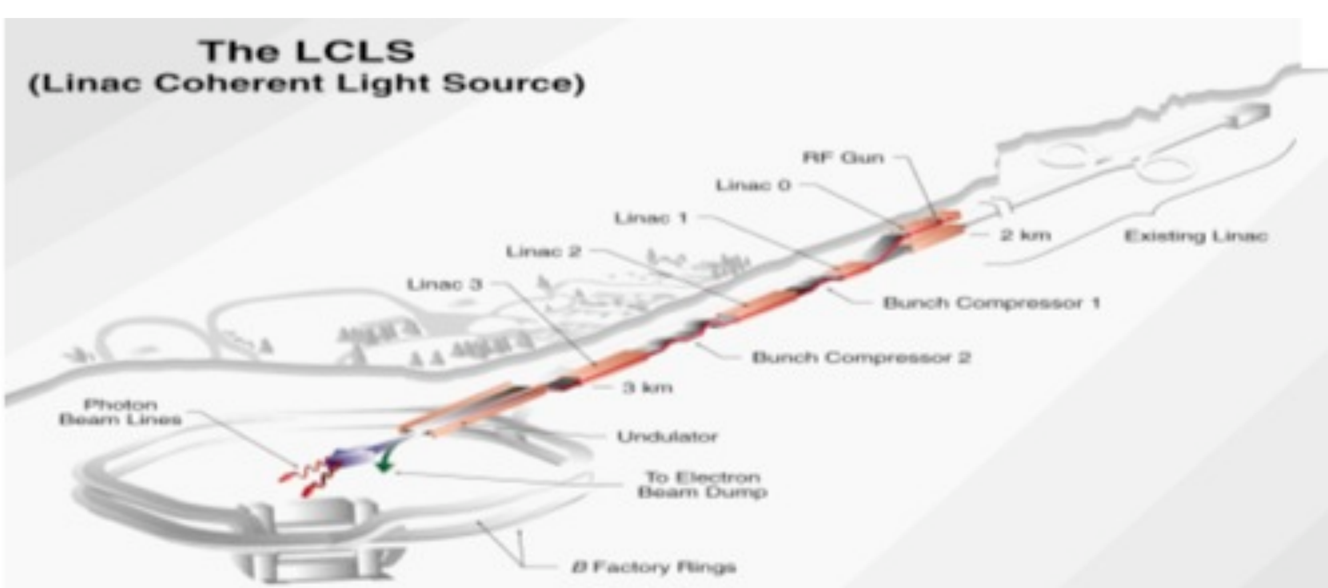
- Secondary beams of photons and neutrons
- Produced at or moderated to wavelengths appropriate for the study of materials and their properties
- Also, neutrinos, radioactive ion beams etc. for physics

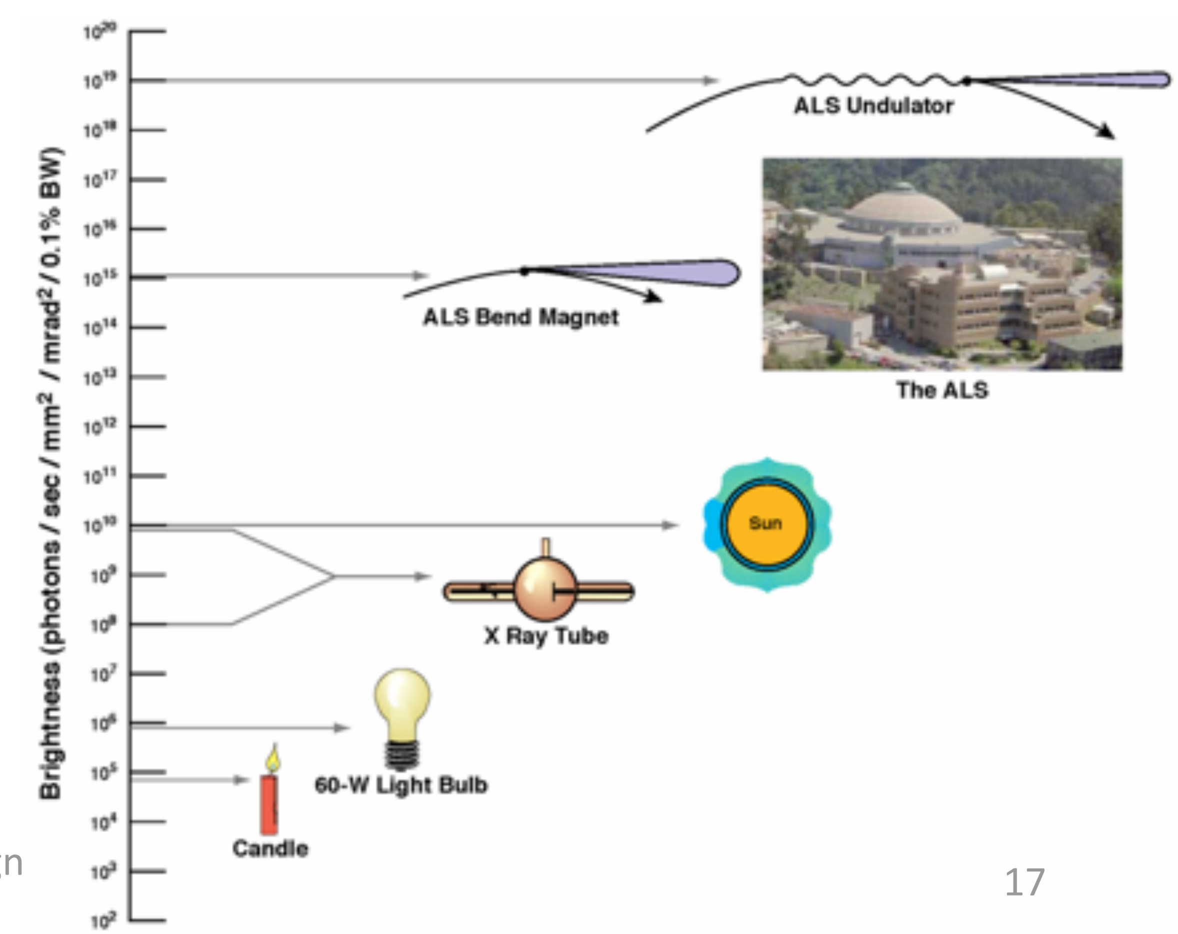


Accelerator–Based Light Sources

70 MeV electron synchrotron at General Electric, Schnectady, NY, 1947

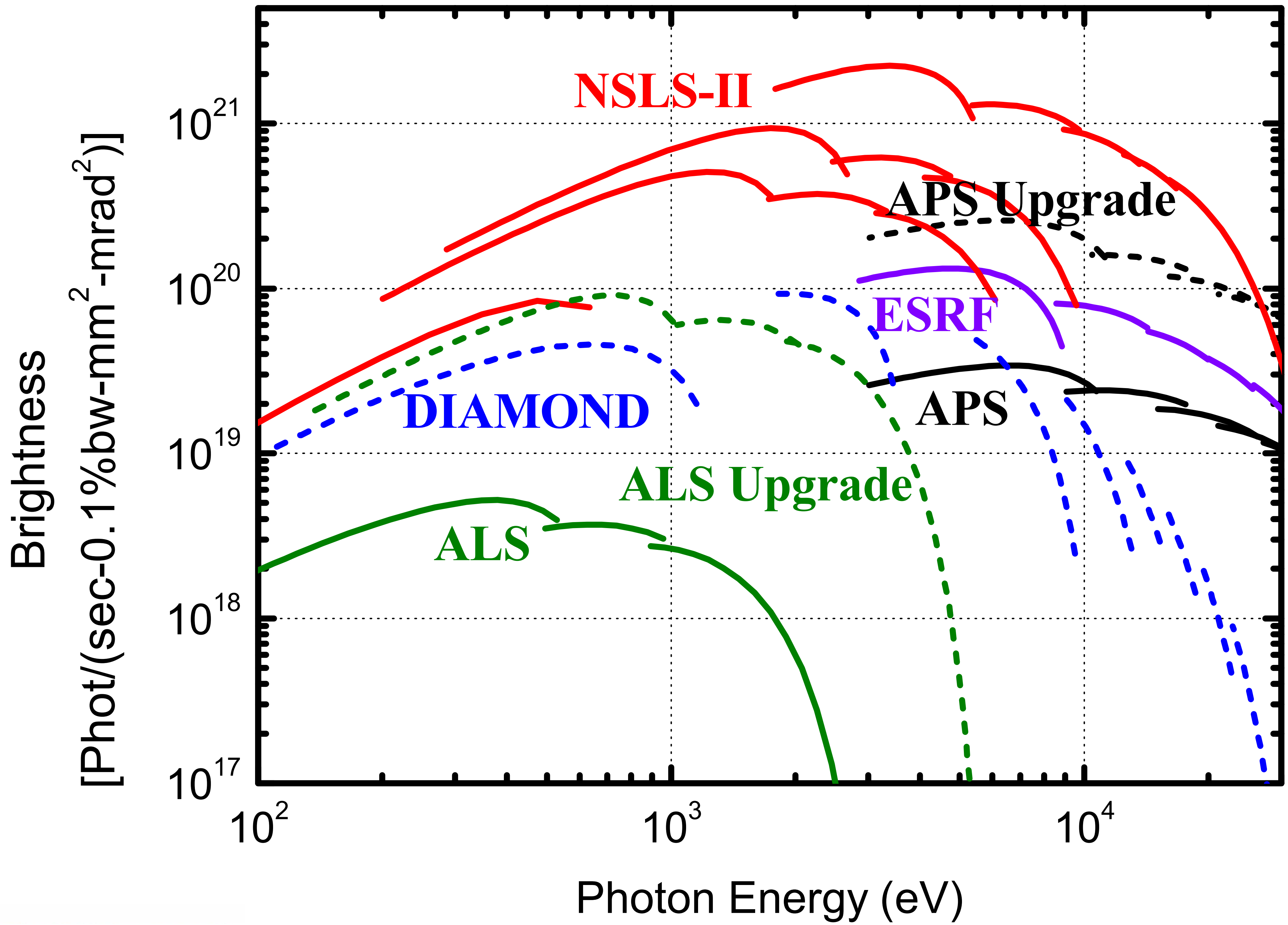






Light Source Brightness

4th generation up here ↑



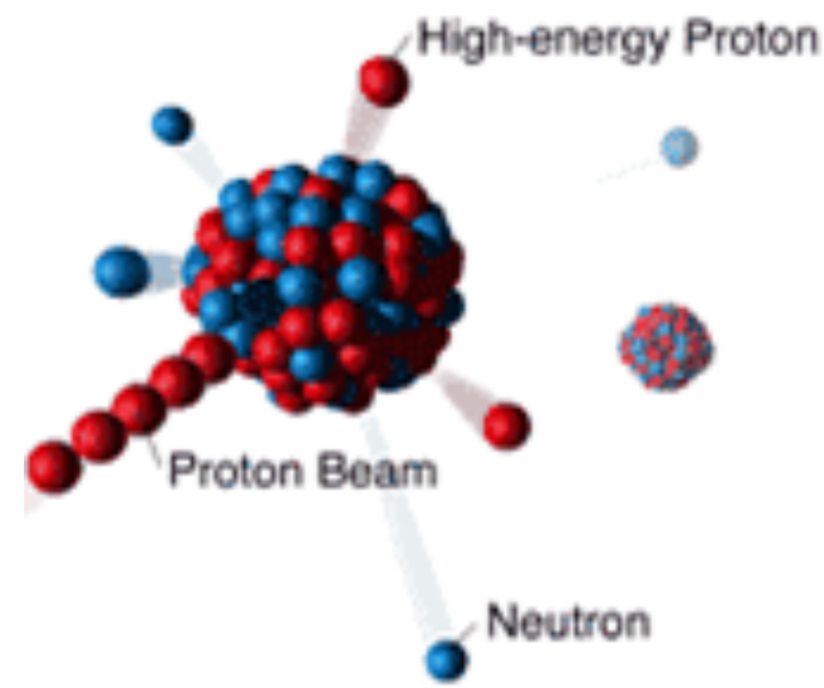
High Photon Brightness

- Brightness -> small electron beam emittance (small size)
  - **Profile monitors (Uli)**
- Position stability
  - ~10% of the small beam size
  - **Position monitors, a.k.a. BPM (John)**
  - orbit feedback

Accelerator-Based Neutron Sources

- High-energy protons are used to generate neutrons from a heavy metal target via the spallation process
- Several labs, ISIS(RAL, UK), LANSCE (Los Alamos), SNS (ORNL), J-PARC (Japan) operate or are building these types of machines
- They use ~1 GeV protons accelerated by linacs or synchrotrons

Spallation Neutron Source, Oak Ridge



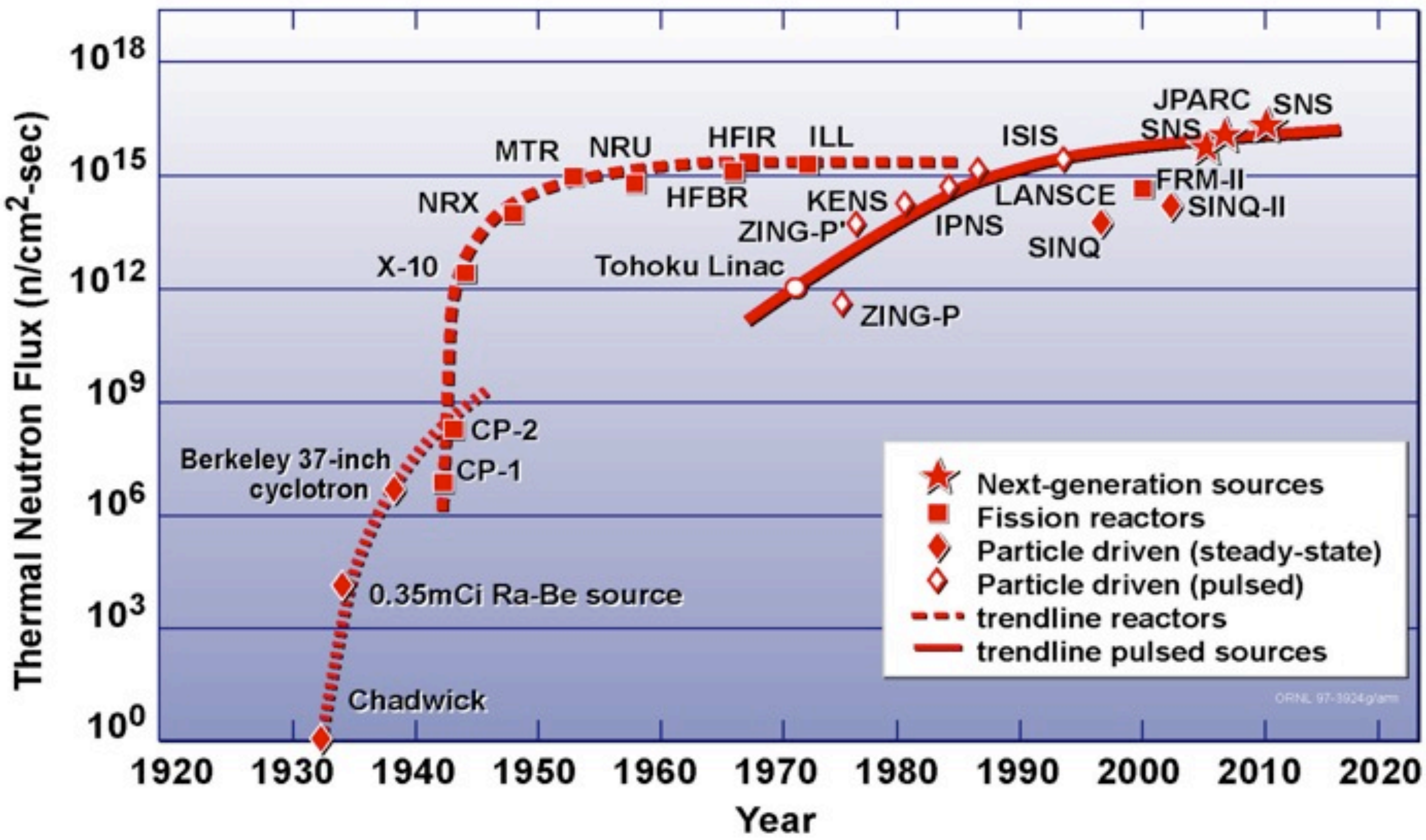
Neutron Source Performance

Reactor-based source:

- neutrons produced by fission reactions
- Continuous neutron beam
- 1 neutron/fission

Accelerator based source:

- 25 neutrons/proton for Hg
- A pulsed beam with precise t_0 allows neutron energy measurement via time-of-flight



(Updated from *Neutron Scattering*, K. Skold and D. L. Price: eds., Academic Press, 1986)

Reactors have reached the limit of heat removal from the core

Pulsed sources have not yet reached their limit and hold out the promise of higher intensities: **Proportional to proton beam intensity on target.**

High Neutron Flux

- High intensity proton facility
  - include usual diagnostics relevant for high intensity machines
- H- in linac
  - allows certain type of **laser profile and laser emittance diagnostic (Tom)**
- Targets (solid and liquid) operate near engineering limits
  - Target **Profile monitor (Uli)**

Role of Diagnostics

- Accelerator performance improvement as a scientific investigation
- 3 approaches, in concert:
  - Numerical (high accuracy simulations)
  - Analytical (reveal scaling laws, fundamental principles)
  - Experimental (key role for diagnostics)

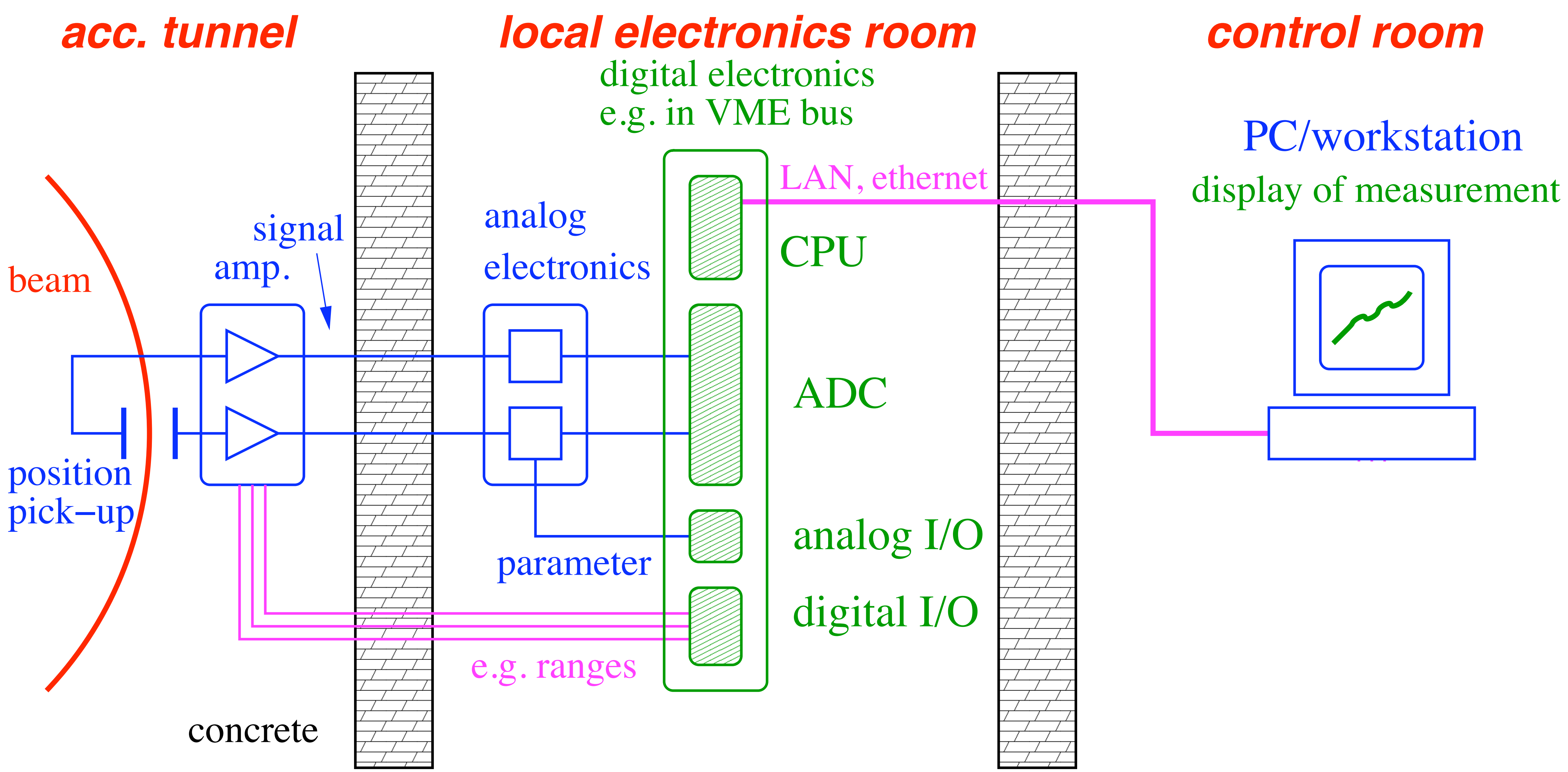
Considerations

- Three types of demands leads to different installations:
  - Quick, non-destructive measurements leading to a single number, simple plots, or machine protect input.
    - Reliable technologies
    - Example: Current measurement by transformers.
  - Daily check, simple diagnosis and mode changes
    - Example: Profile measurement, in some cases destructive
  - Complex diagnosis, commissioning and accelerator development
    - The instrumentation might be destructive and complex.
    - Example: Emittance determination.
- Non-destructive ('non-intercepting') methods are preferred
  - The beam is not influenced
  - The instrument is not destroyed.

Layout

System Integration (Wim)

– also, environmental considerations: electromagnetic interference, radiation, cryogenic environment, ultra-high vacuum, etc.



Underlying Physics (I)

Beam diagnostics covers full spectrum of physics and technology; calls for experts on all these fields

- Accelerator physics for system specification
- Electro-magnetic influence by moving charges:
  - --> classical electro-dynamics, voltage and current measurement, low and high frequencies
  - Examples: Faraday cups, beam transformers, pick-ups
- Emission of photons by accelerated charges:
  - --> optics, optical techniques (from infrared to x-ray)
  - Examples: Synchrotron radiation monitors

Underlying Physics (II)

- Interaction of particles with photons:
  - –→ optics, Lasers, particle detectors
  - Examples: laser scanners, polarimeters
- Coulomb interaction of charged particles with matter:
  - –→ atomic and solid state physics, current measurement, optics, particle detectors
  - Examples: scintillators, viewing screens, ionization chambers, secondary electron monitors, residual gas monitors
- Nuclear- or elementary particle physics interactions
  - –→ nuclear physics, particle detectors
  - Examples: beam loss monitors, polarimeters, luminosity monitors

Diagnostic System Inventory (I)

Beam quantity		**LINAC, transfer line**	**Synchrotron**
current I	*general*	**transformer (dc, pulsed)**	**transformer**
		Faraday cup	
	special	**particle detector**	normalized pick-up signal
position x_{cms}	*general*	**pick-up**	**pick-up**
	special	using profile measurement	cavity excitation (e^-)
profile x_{width}	*general*	**SEM-grid, wire scanner**	**residual gas monitor**
		viewing screen, OTR-screen	**wire scanner**
			synch. radiation (e^-)
	special	grid with ampl. (MWPC)	
trans. emittance	*general*	**slit grid**	**residual gas monitor**
ϵ_{trans}		**quadrupole scan**	**wire scanner**
	special	**pepper-pot**	transverse Schottky pick-up

Diagnostic System Inventory (II)

Beam quantity		**LINAC, transfer line**	**Synchrotron**
momentum	*general*	**pick-up (TOF)**	**pick-up**
p and $\Delta p/p$		magn. spectrometer	
	special		Schottky noise pick-up
bunch width $\Delta\varphi$	*general*	**pick-up**	**pick-up, transformer**
			wall current monitor
	special	**particle detector**	**streak camera (e^-)**
		secondary electrons	
long. emittance	*general*	**buncher scan**	
ϵ_{long}		magn. spectrometer	
	special	TOF application	**pick-up + tomography**
tune, chromaticity	*general*	—	**exciter + pick-up**
Q, ξ	*special*	—	transverse Schottky pick-up
beam loss r_{loss}	*general*	**particle detector**	
polarization P	*general*	particle detector	
	special	Compton scattering with laser	
luminosity $\mathcal{L}$	*general*	particle detector	

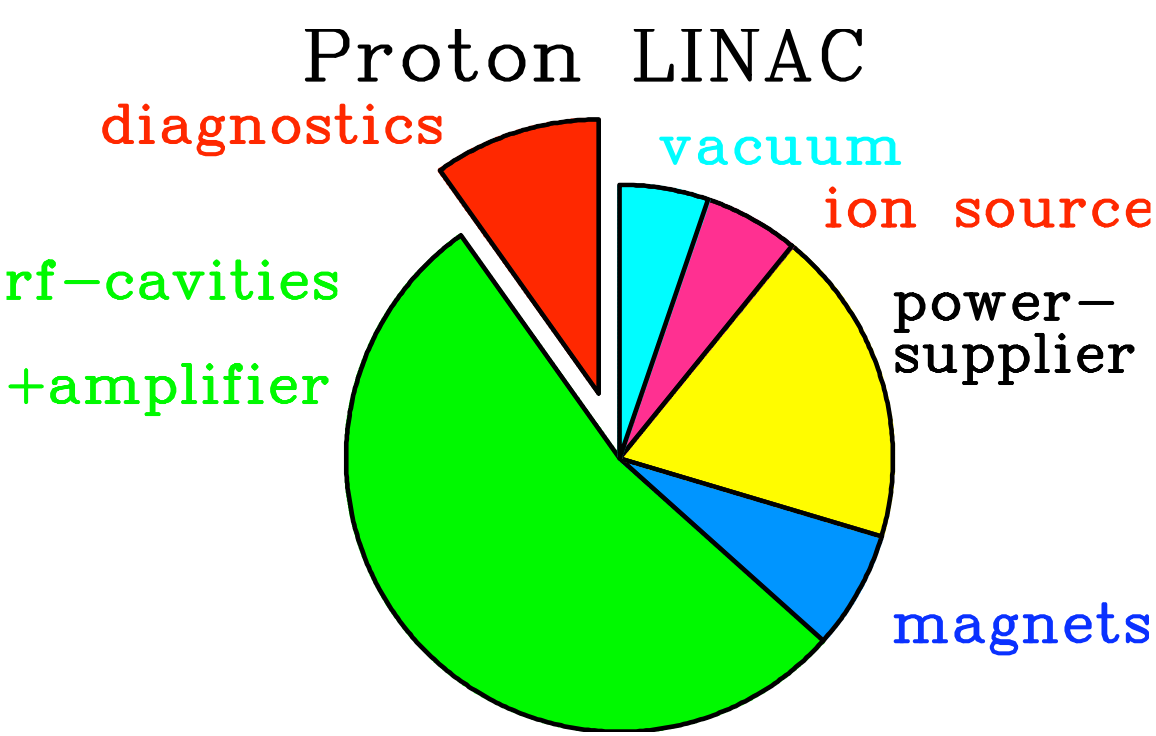
Relative Scale

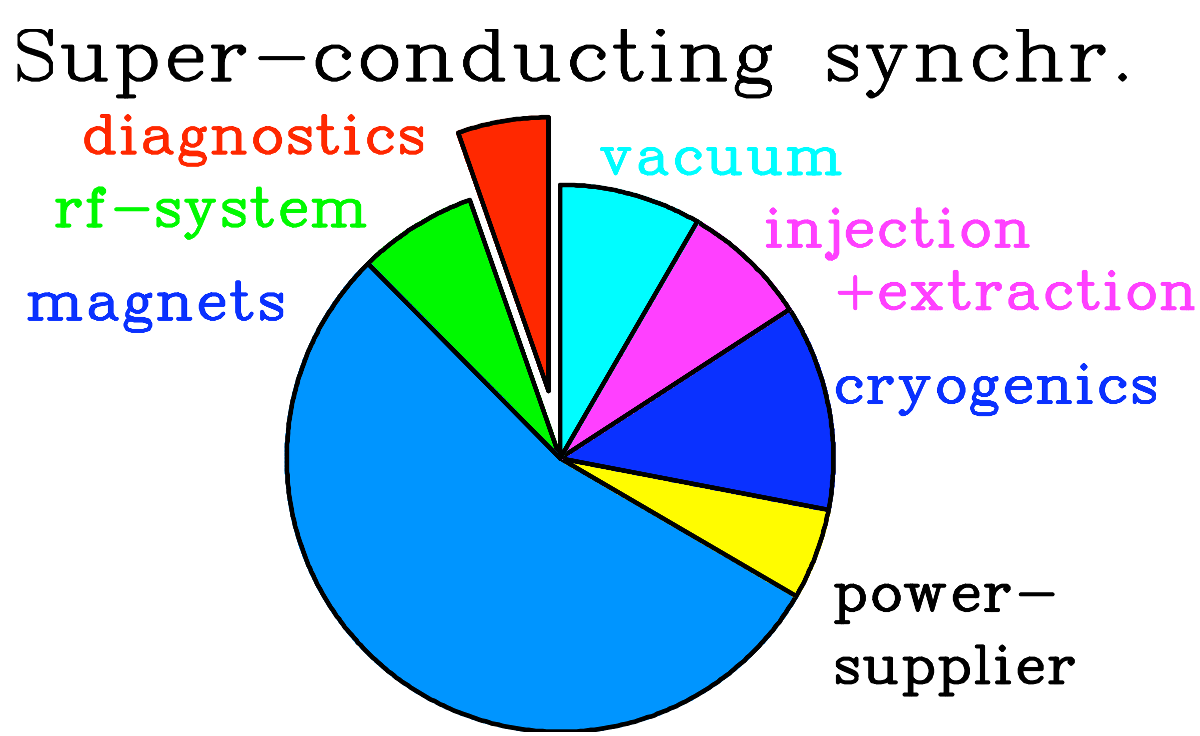
The cost of diagnostic is about 3 to 10 % of the total facility cost:

- ≃ 3 % for large accelerators or accelerators with standard technologies
- ≃ 10 % for versatile accelerators or novel accelerators and technologies.

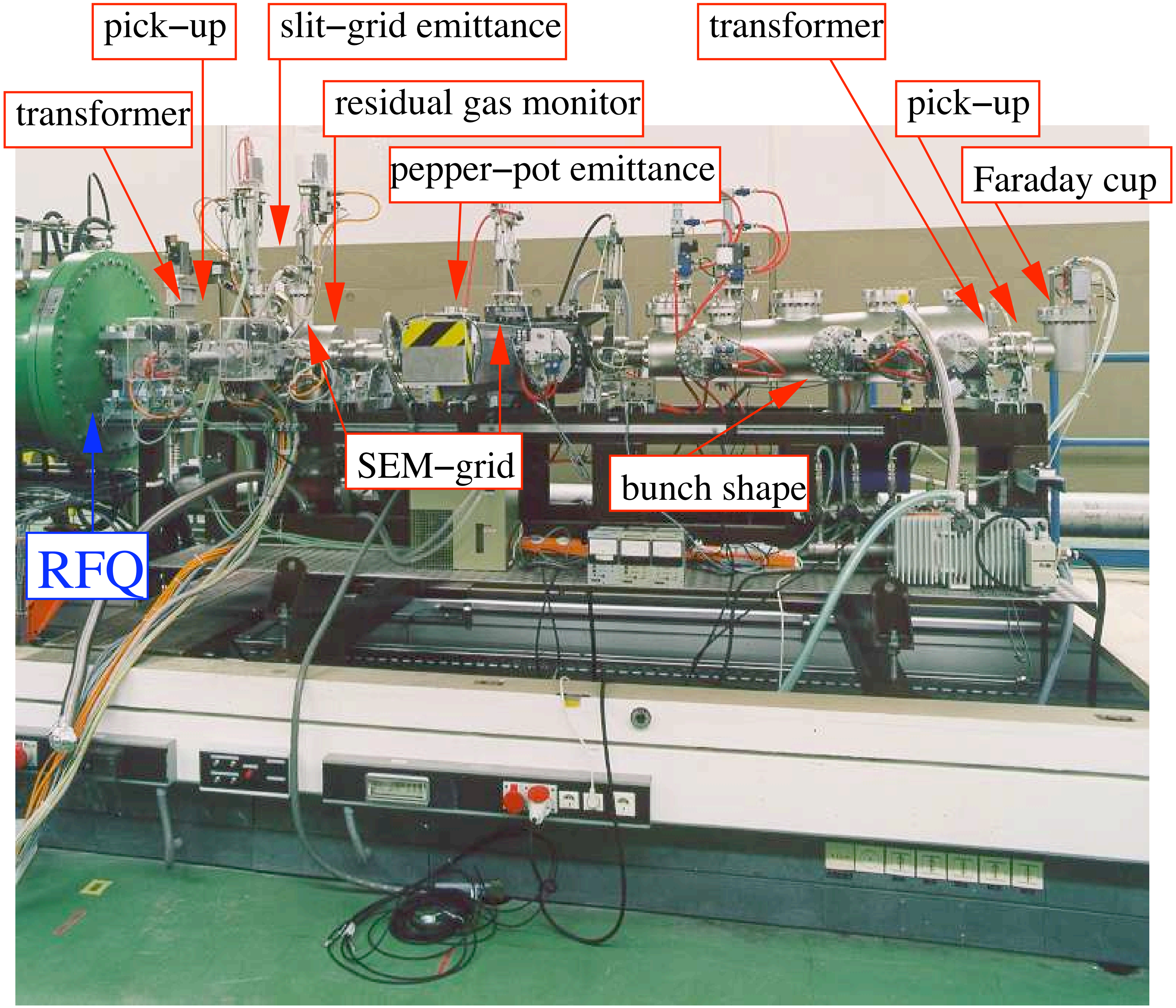
The amount of man-power is about 10 to 20 %:

- Diverse physics and technologies
- High performance data acquisition; complex integration and data analysis
- Accelerator improvements call for new diagnostic concepts.





To Commission a Low Energy Linac



To Commission a Collider

Position monitors	**48 measurement planes in transfer line** **667 planes total in collider rings**
Loss monitors	**120 ion chambers in the transfer line** **400 ion chambers in the collider tunnel**
Ionization profile monitors	One horizontal and one vertical per ring
Collider ring current monitor	One DCCT per ring
Wall current monitors	One per ring
Transverse kickers	Two kicker units per ring (each provides horizontal and vertical deflection)
Schottky cavities	One per ring (each provides horizontal, vertical and longitudinal signals)
Transfer line beam profile monitors	12 phosphor screens muxed into 4 video channels
Transfer line intensity monitors	Five integrating current transformers

Summary

- Sensory system for a particle accelerator
- Critical role in performance improvement
- Plenty of interesting technology
  - this week and beyond...