Lecture 0

Introduction

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What to Learn in This Course ?

Accelerator Science

(Generation of energetic particles/radiation)

Physics of charged particle beams

Physics of accelerator systems

Textbooks

- Main textbooks:
  - J. B. Rosenzweig, *Fundamentals of Beam Physics* (Oxford, 2003)
  - A. Seryi , *Unifying Physics of Accelerators, Lasers and Plasma* (CRC Press, 2015)

- References:
  - M. Conte and W. M. MacKay, *An Introduction to the Physics of Particle Accelerators* (World Scientific, 2008)

* All of the above books are available as ebook (pdf) in the UNIST library.

Introductory Remarks

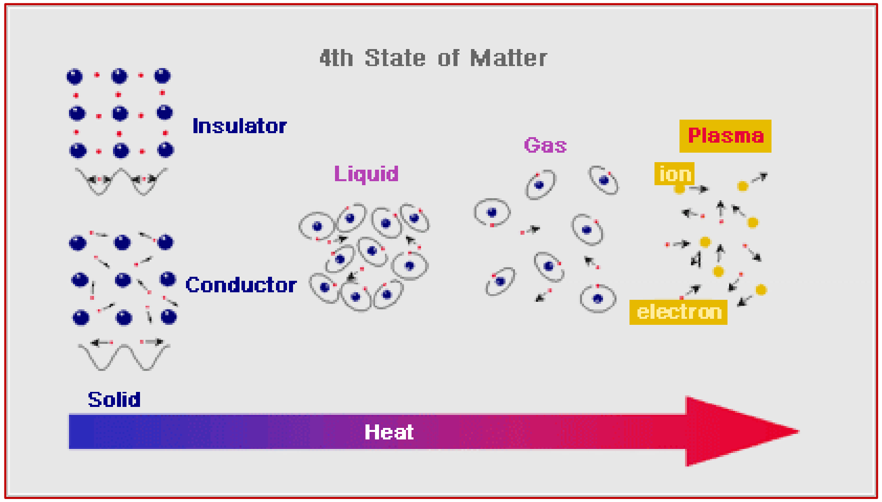
- Accelerator physics is a branch of applied physics that deals with all the physics issues associated with accelerators.
- The goal is the production of energetic particle beams for other applications (~beam physics).
- Particle beams are collections of charged particles all travelling in nearly the same direction with nearly the same speed (possibly relativistic).

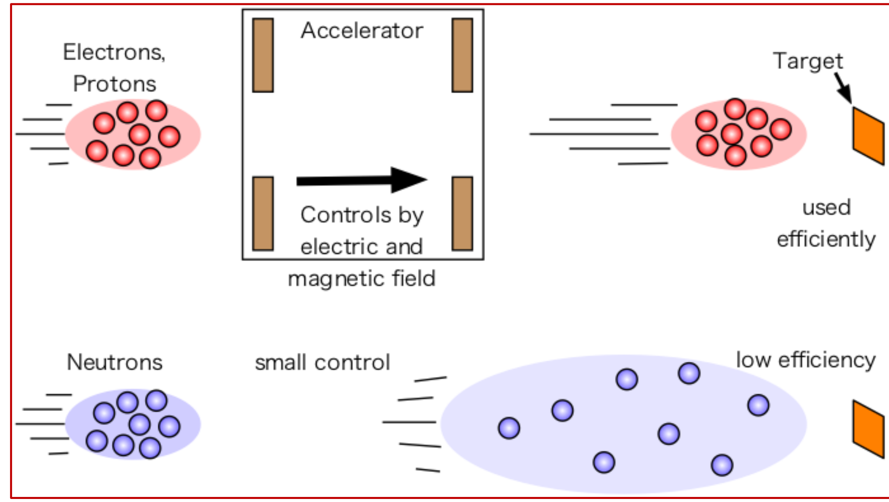
- Accelerator physics encompasses broad disciplines, ranging from engineering and technology to diagnostics/controls, to experimental physics, to computer science, to computational and theoretical physics.
- Accelerator physics assumes basic knowledge in electromagnetism, classical mechanics, and special theory of relativity. Also basic understanding on magnet/RF/microwave engineering would be helpful.

- In general, charged particles are focused and bent by use of magnets, and accelerated by use of electromagnetic waves in cavities.
- Accelerator physics studies motions of charged particles under the influence of electromagnetic fields within the context of classical physics.

Intense Beams

- Much of modern accelerator physics is concerned with intense beams that have very strong self-forces, and display characteristics of plasmas (ionized gases).





To a large degree, accelerator physics and plasma physics are quite similar. Both involve nonlinear dynamics (single-particle effects) and collective instabilities (multi-particle effects). However, there is an important difference:

$$\text{beam self fields} > \text{external applied fields} \qquad \text{(plasma)}$$

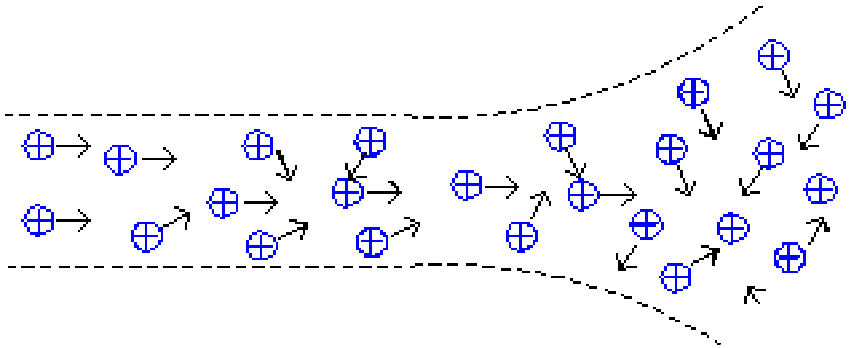
$$\text{beam self fields} \ll \text{external applied fields} \qquad \text{(accelerators)}$$

[From A. Chao (SLAC)]

Macroscopic Self-Fields

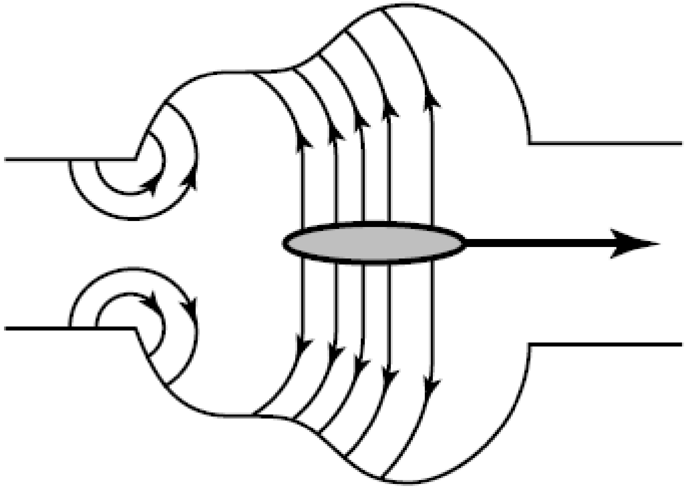
- Macroscopic self-fields are most often termed space-charge when they arise from the near-field of the beam's charge distribution and wake-fields when they arise from the beam's collectively radiated fields.

Space charge effects → Nonlinearity, resonance, coupling

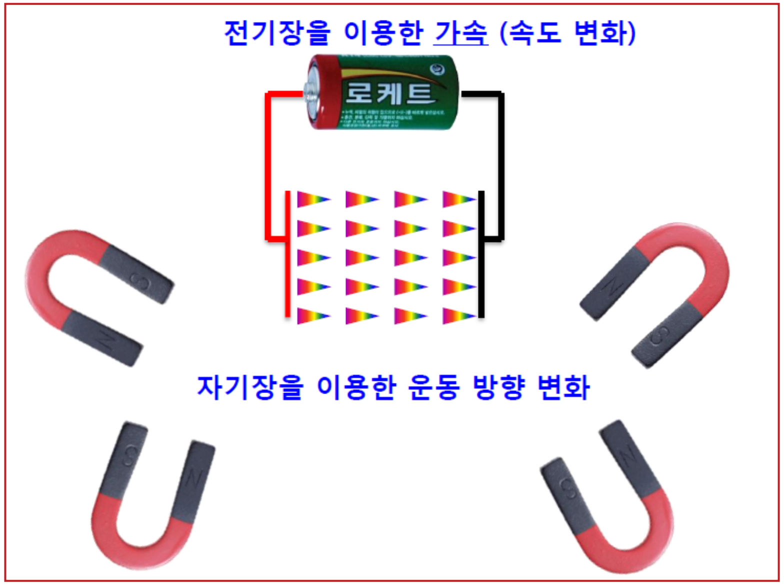


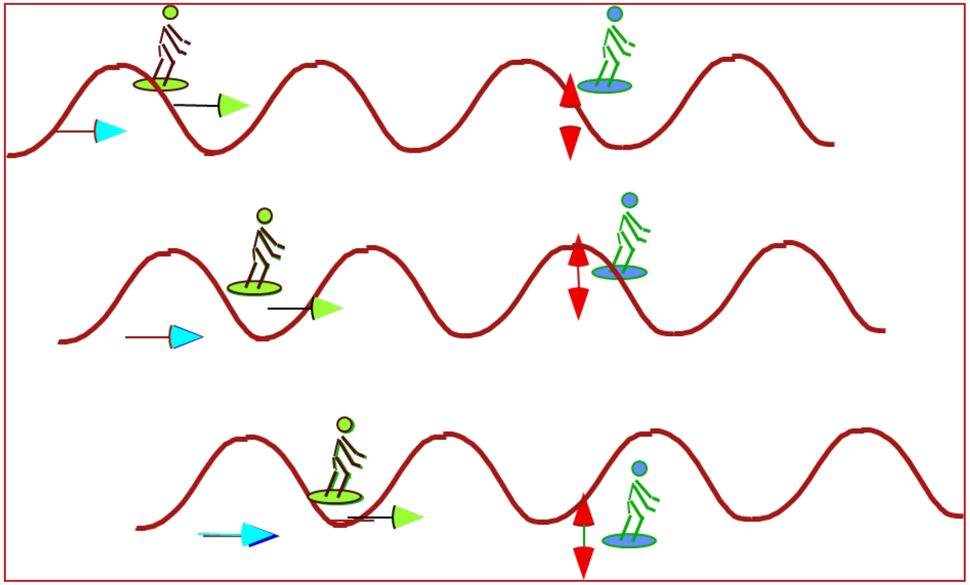
Pipe with Structure

→ Wakefields



Overview of Accelerators





Influence of Accelerator Science

Phys. Perspect. 13 (2011) 146–160

1422-6944/11/020146-15
DOI 10.1007/s00016-010-0049-y

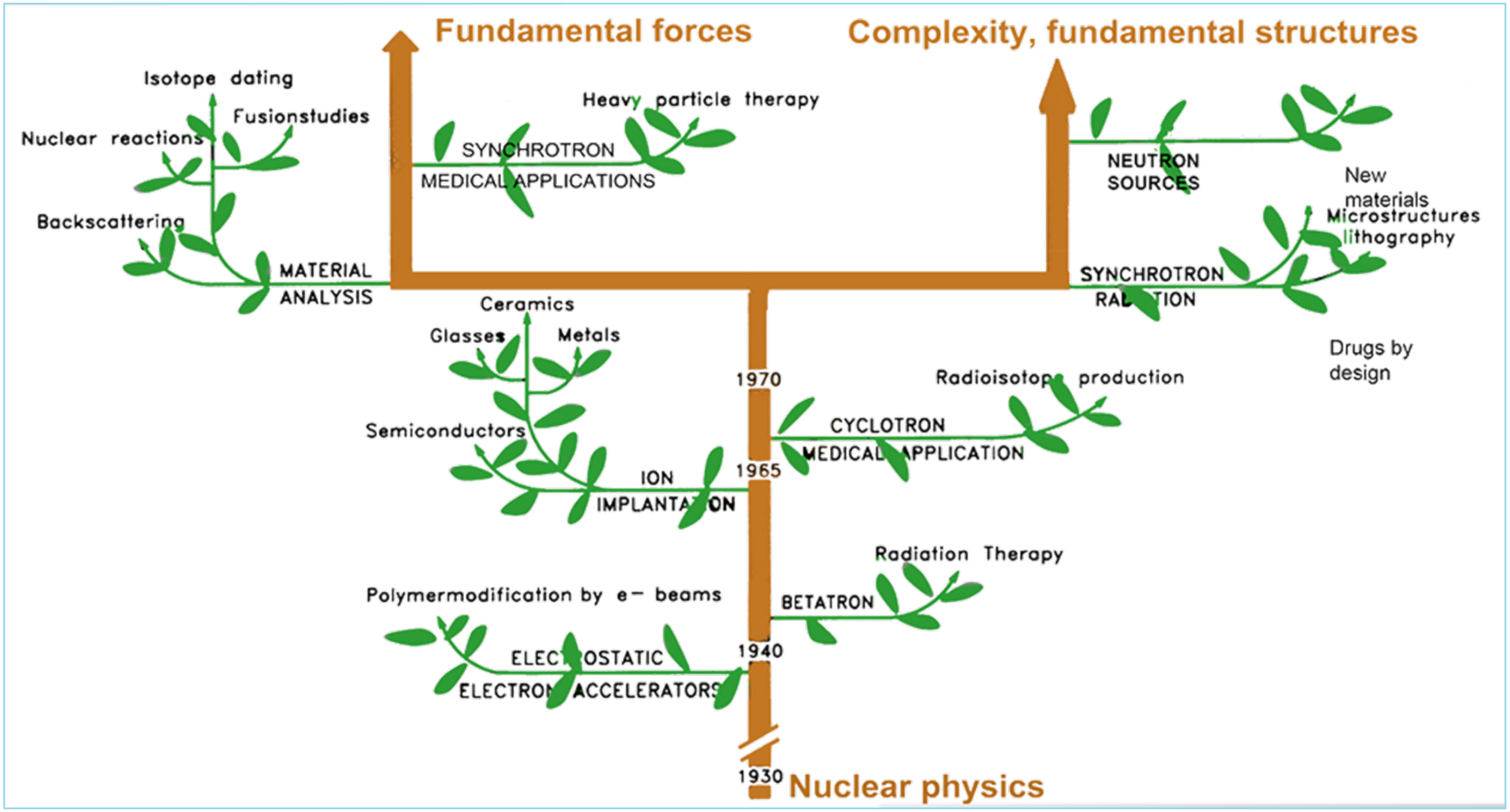
Physics in Perspective

The Influence of Accelerator Science on Physics Research

Enzo F. Haussecker and Alexander W. Chao*

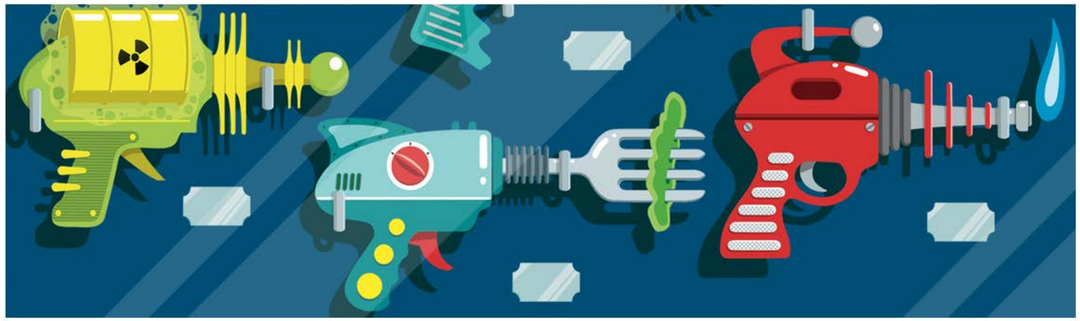
"It is estimated that accelerator science has influenced almost 1/3 of physicists and physics studies, and on average contributed to physics Nobel Prize-winning research every 2.9 years."

From Basic Science Research to Applications



10 Reasons Why You Can't Live Without a Particle Accelerator

http://nautil.us/issue/14/mutation/10-reasons-why-you-cant-live-without-a-particle-accelerator



MATTER | PARTICLE PHYSICS

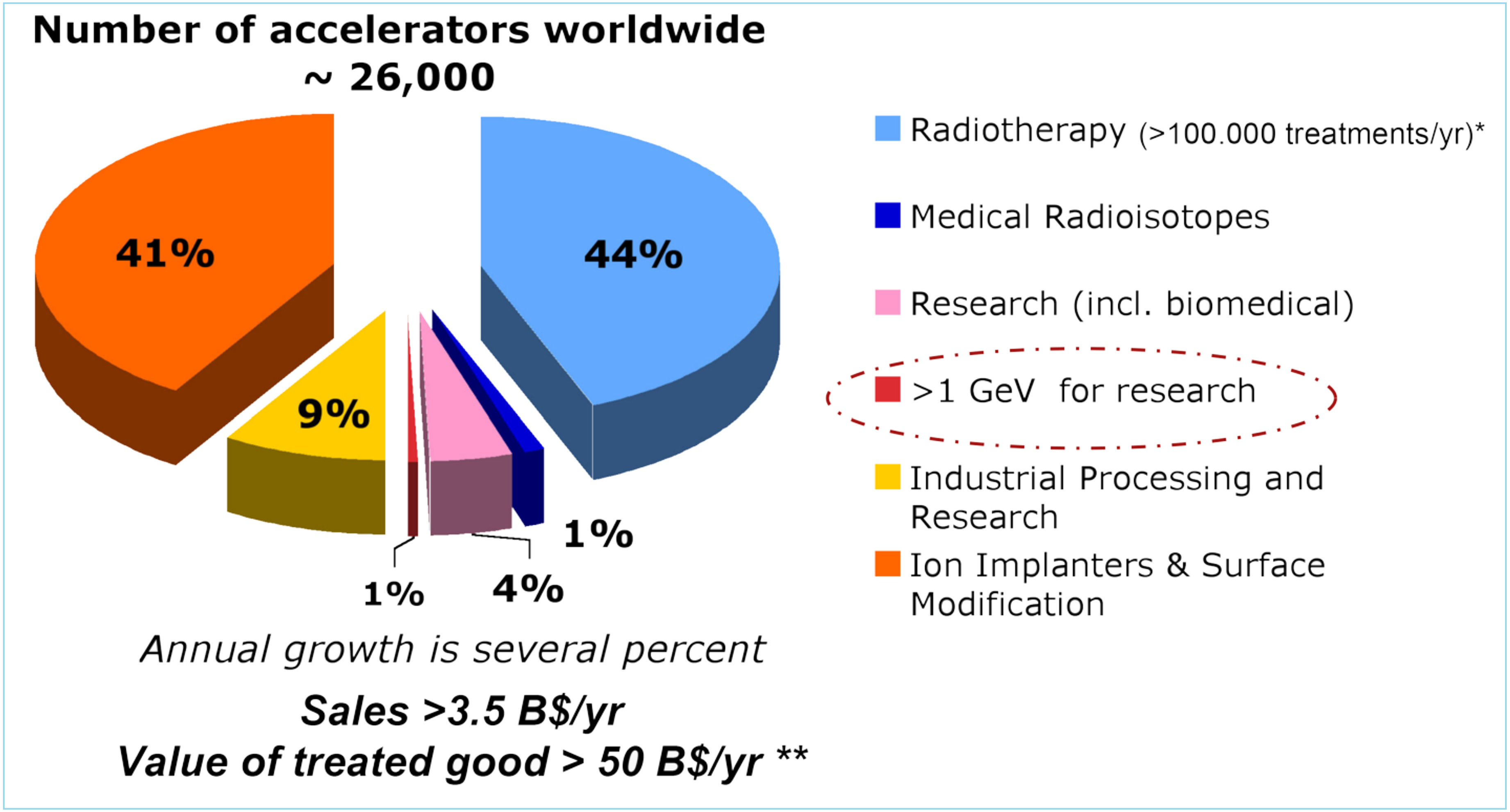
10 Reasons Why You Can't Live Without A Particle Accelerator

Particle accelerators can make you healthy and wealthy.

BY LINA ZELDOVICH
ILLUSTRATIONS BY JAMES WALTON
JUNE 12, 2014

1. Is your milk carton sealed? An accelerator did it.
2. A lot of natural gas is wasted. Accelerators can fix that problem.
3. Want your spinach *E. coli* free? Accelerators may have cleaned it.
4. Can coal be a clean fuel? Yes, if you attach an accelerator to the smokestack.
5. Antibiotics harm fish? Accelerators can turn pharmaceuticals into fertilizer.
6. Your new computer has arrived. Thank an accelerator for building it.
7. Accelerators make us live longer. They kill cancer.
8. Can nuclear reactors be accident-proof? Yes, if particle accelerators control them.
9. The world still runs on oil. Accelerators can find it.
10. Accelerators keep watch for weapons of mass destruction.

Accelerators are Big Business



The Hottest Job in Physics ?

http://www.symmetrymagazine.org/article/the-hottest-job-in-physics

The hottest job in physics?

04/26/16 | By Troy Rummler

Accelerator scientists are in demand at labs and beyond.

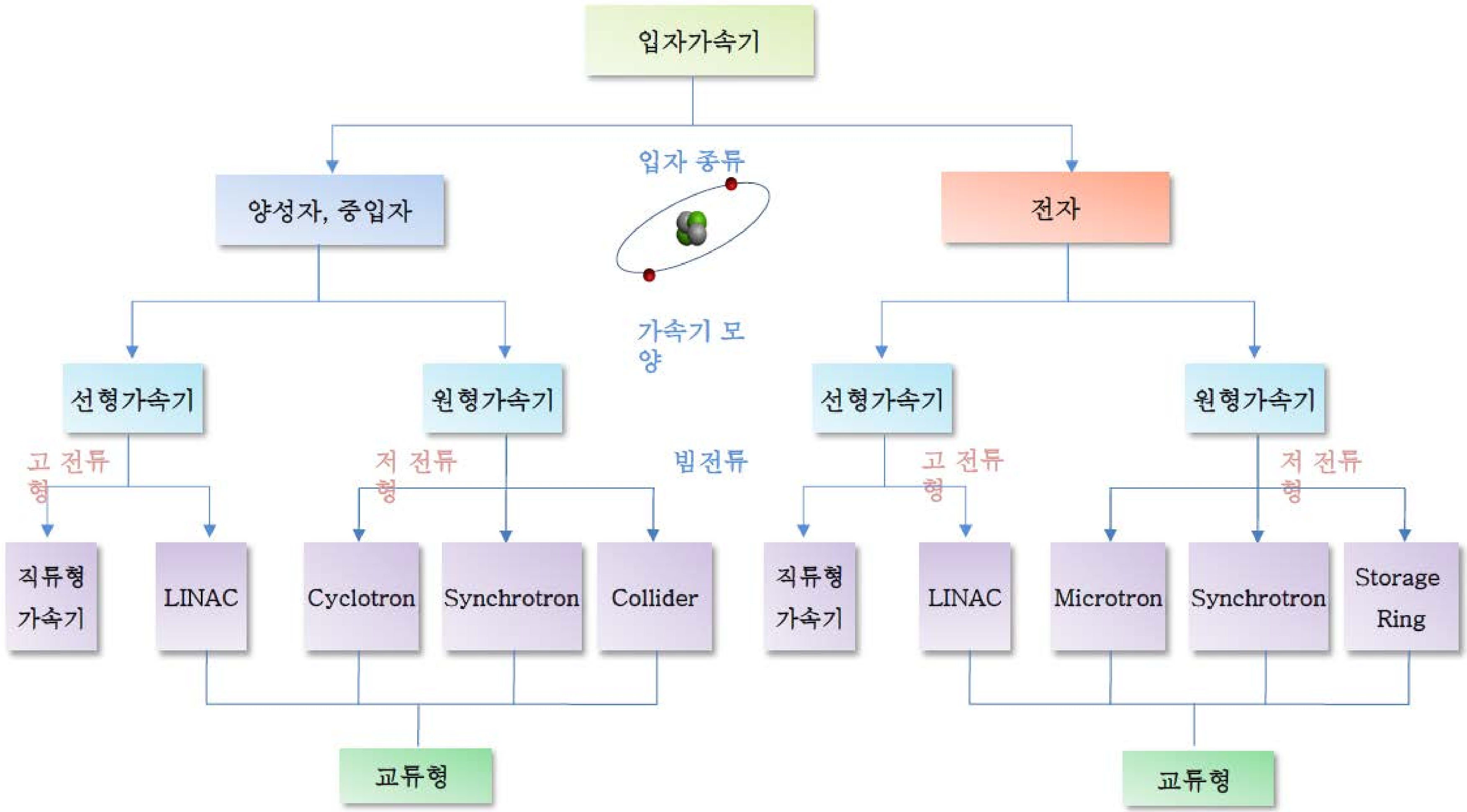
While the supply of accelerator physicists in the United States has grown modestly over the last decade, it hasn't been able to catch up with demand fueled by industry interest in medical particle accelerators and growing collaborations at the national labs.

"Accelerator [science] has many applications, ranging from high energy physics, nuclear physics, and material and medical sciences," Cai says. Both within the field of high-energy physics and beyond, the high demand illustrates the immense value of accelerator scientists and of the institutions helping to train them.

"There are few universities offering disciplines in the field of accelerators," Cai says. "Most importantly, many people think it is [only] an engineering field." Similar concerns were raised in responses to a 2015 Request for Information posted by DOE on the issue of too few accelerator physicists. Multiple respondents pointed out that many research awards don't include work with accelerators.

"The real increase has been in medical accelerators, with a number of new companies getting into the proton therapy business," says Robert Hamm, CEO of R&M Technical Enterprises, an accelerator consulting group. "This has been the most significant factor in the industrial demand for accelerator physicists."

Types of “Conventional” Accelerators



Pros VS Cons of Accelerators

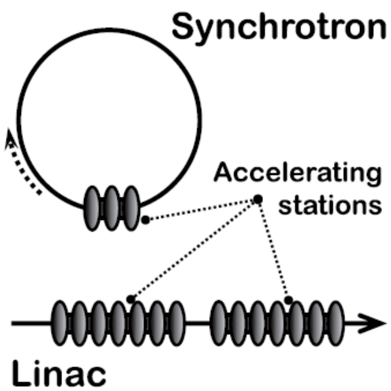


FIGURE 5.6
Synchrotron and linac.

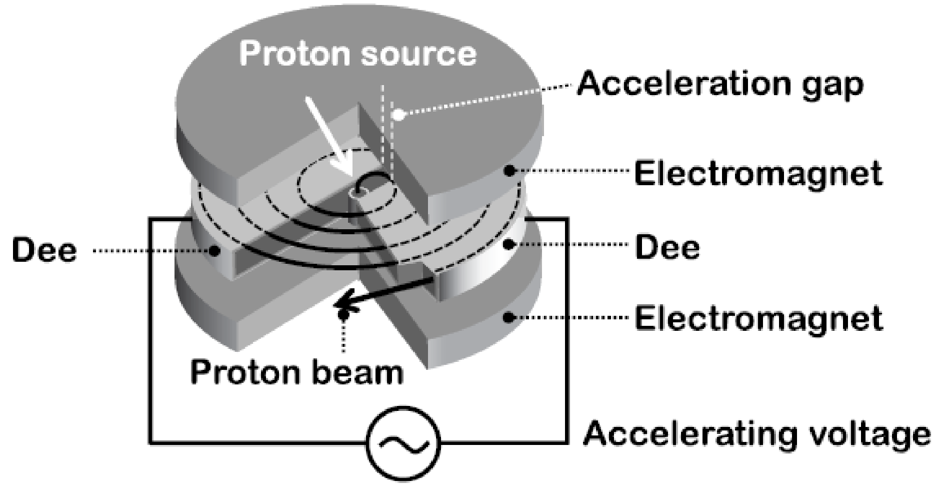
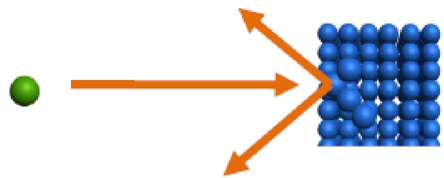
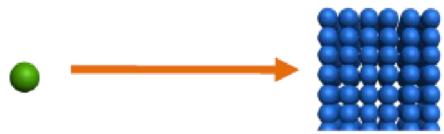
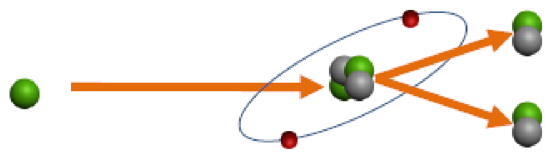
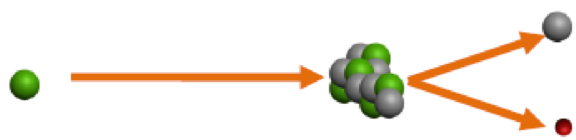
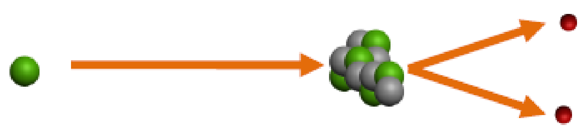


FIGURE 9.7
Schematic of a cyclotron.

형태 분류	장 점	단 점
선형가속기	연속적인 형태로 가속하기 때문에 대 전류 입자 가속이 **가능** (= 입자의 개수 늘릴 수 있음)	에너지를 높일 수록 가속관이 점점 더 길어짐
싱크로트론	입자를 반복 가속할 수 있어 에너지를 높이는데 유리함 (CERN의 LHC 는 약 7 TeV/u)	같은 궤도를 돌며 가속하기 때문에 연속적이지 못하여 대 전류 입자 가속이 **불가능**
사이클로트론	• 대 전류 입자 가속 **가능** • 입자의 반복 가속 **가능**	제작 가능한 전자석 크기의 기술적 제한으로 에너지를 높이기 어려움

Interactions of Accelerated Beams with Matters

입자에너지		기본반응	주요연구
~ 1KeV		**Sputtering** 물질표면의 원자를 낱개로 분리	박막가공 나노가공
~ 10KeV		**Implantation** 물질 속에 투여하여 물질구조와 성질변화	표면 개질 나노결정 반도체 도핑
~ 100MeV		**Nuclear Reaction** 물질의 원자핵과 반응하여 새로운 원소 생성	신종 유전자원 RI 생산 방사선 치료기기
~ 10GeV		**Spallation** 무거운 원자핵을 쪼개서 가벼운 원자 또는 중성자 생성	중성자원 신종 RI 생산
~ 100GeV		**소립자 연구** 원자핵 속의 양성자 중성자를 쪼개 소립자 생성	신종 소립자 탐색 핵 및 고에너지 물리

Various Actions of Accelerated Beams

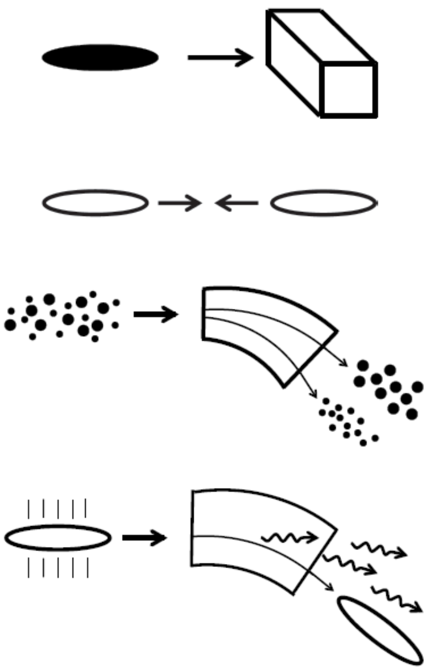


FIGURE 1.4
Uses of accelerated beams — sending to target, colliding with another beam, characterization of the beam or separation into species, generation of useful radiation.

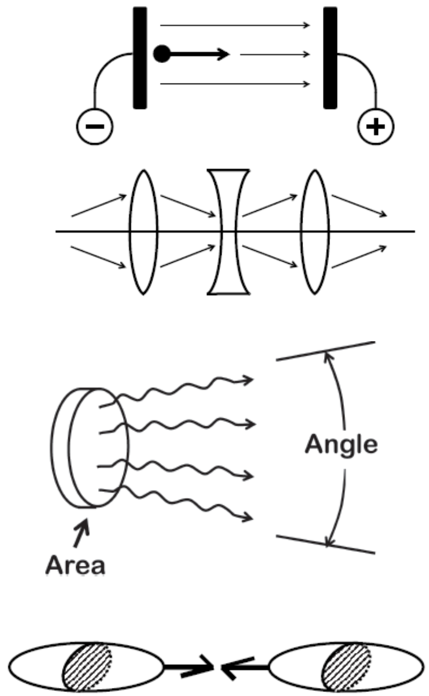


FIGURE 1.5
Actions on accelerated beams — acceleration, focusing, generation of radiation, colliding.

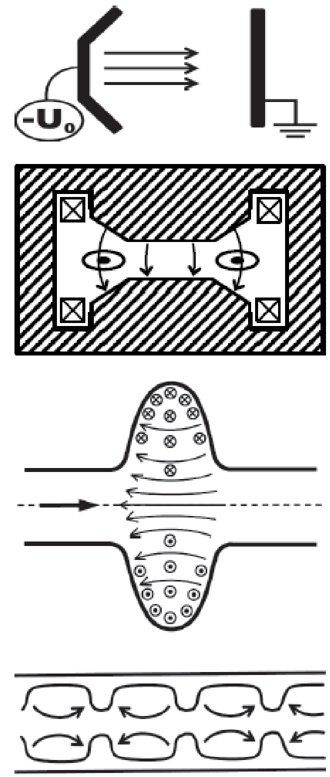


FIGURE 4.13
Electrostatic and betatron acceleration. RF cavity and RF structure.

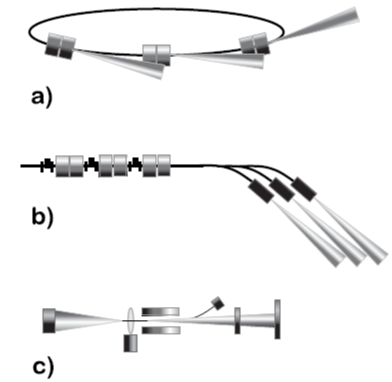


FIGURE 6.19
Light sources' evolution.

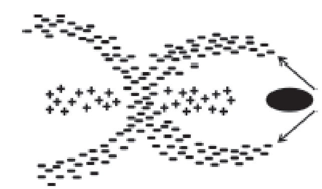
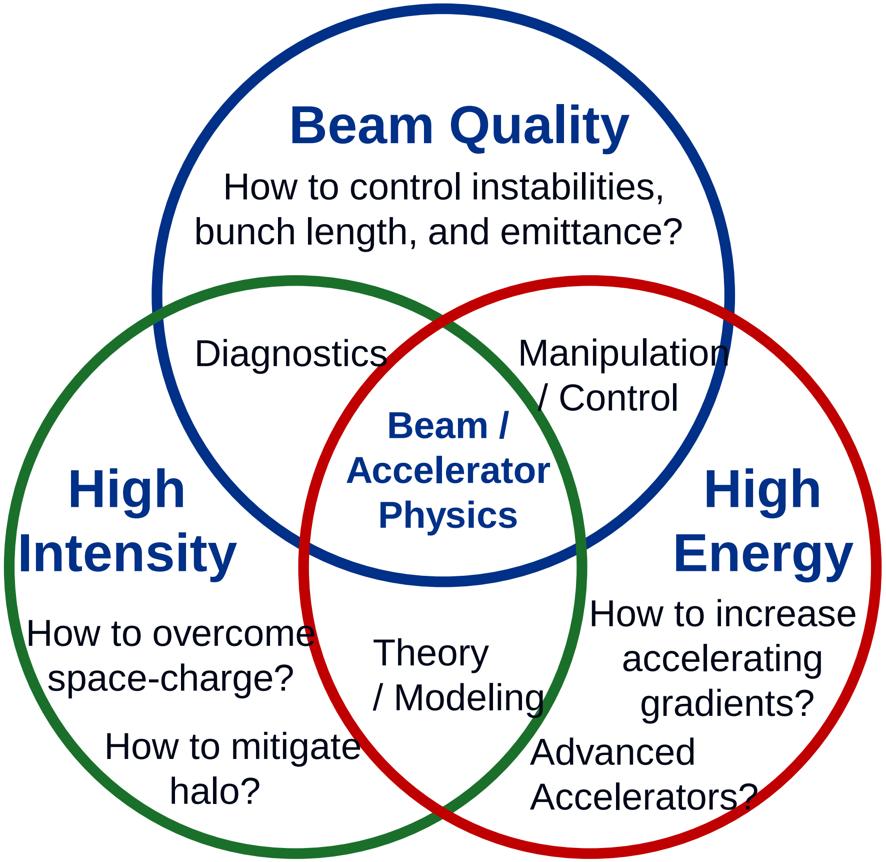


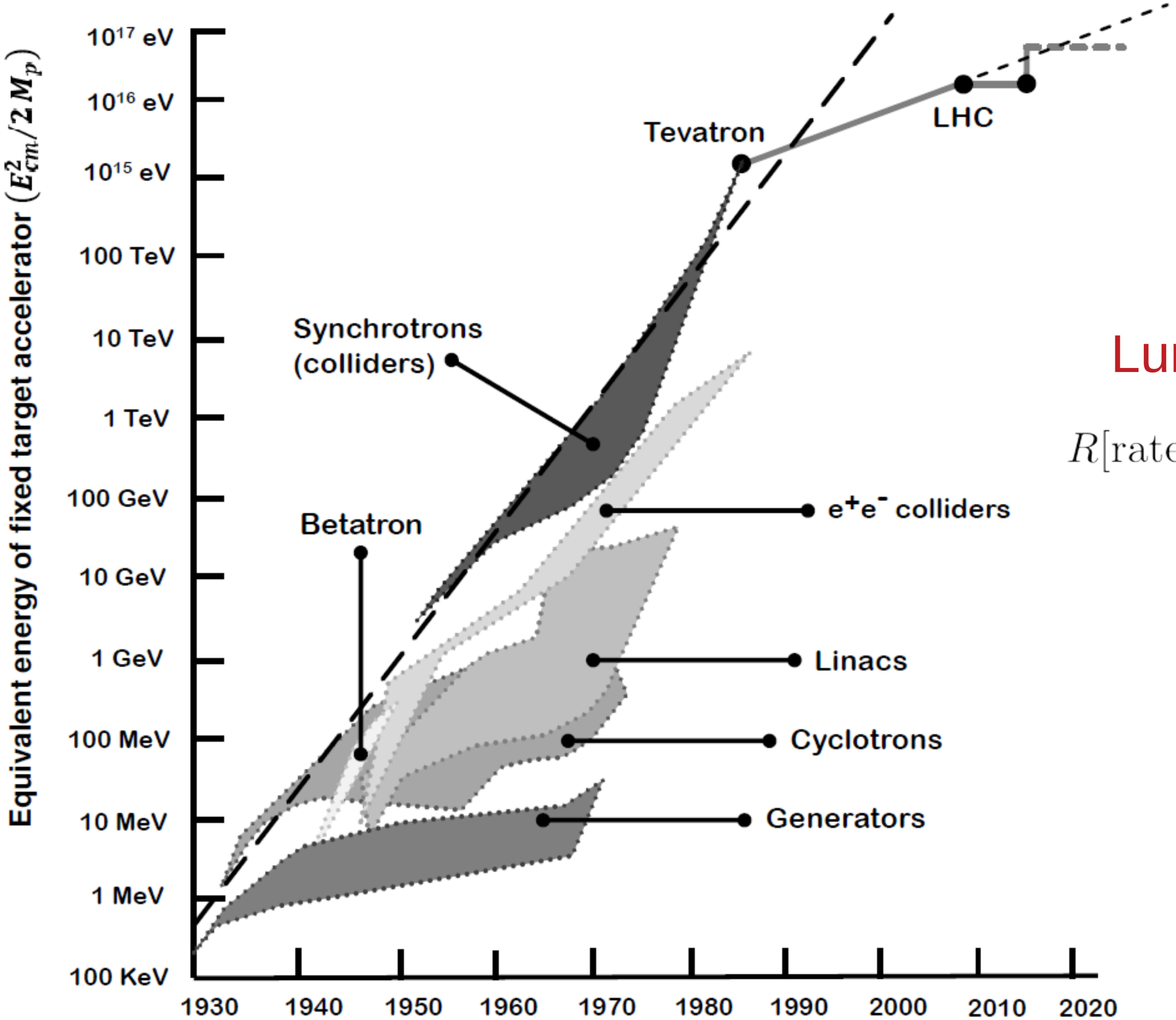
FIGURE 1.15
Plasma acceleration concept.

[From "*Unifying Physics of Accelerators, Lasers and Plasma*"]

Frontiers of Modern Accelerators



Energy Frontier

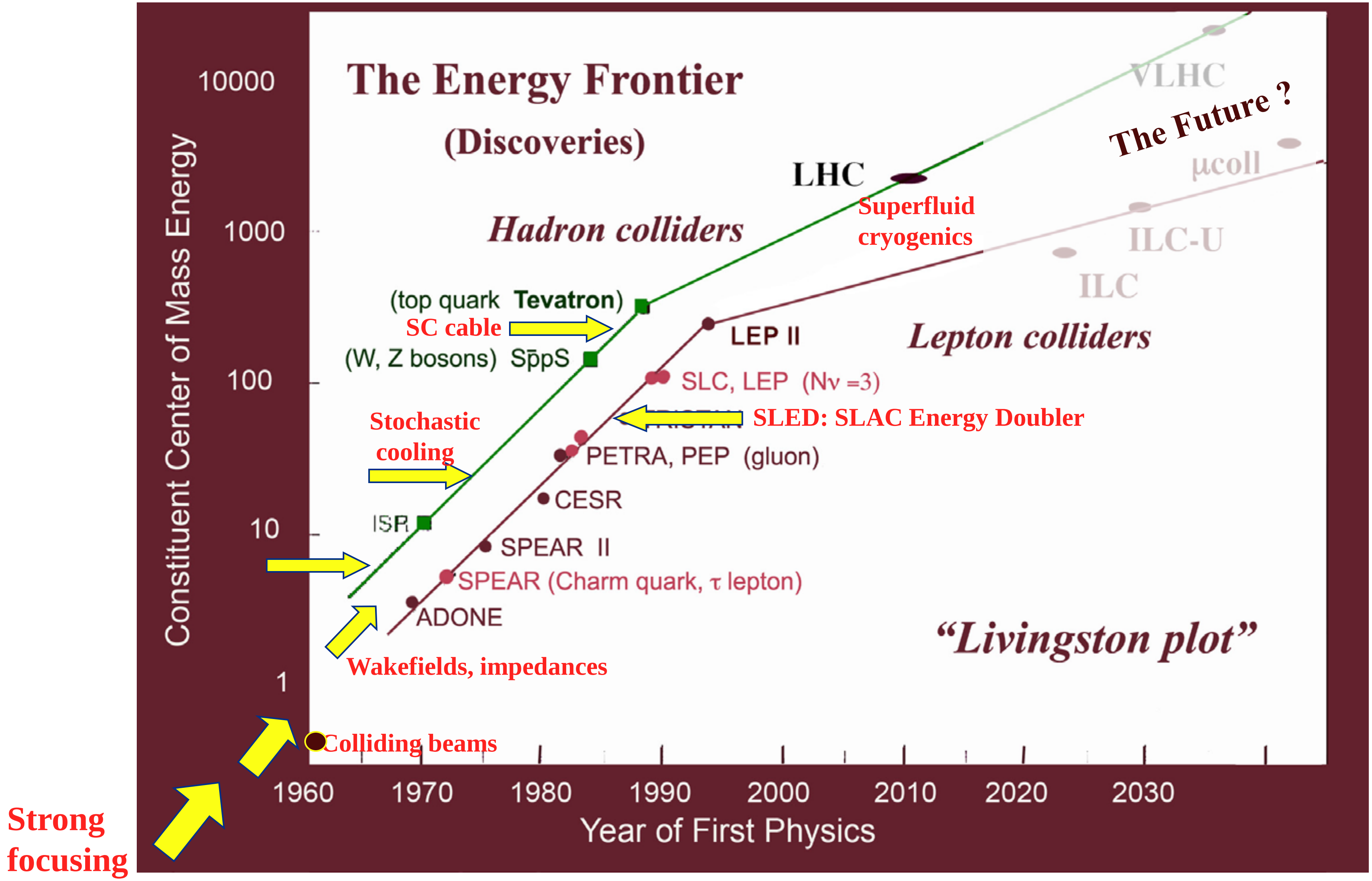


Luminosity:

$$R[\text{rate}] = \sigma_{\text{physics}}(E)[\text{cm}^2] \times L[\text{cm}^{-2}\text{s}^{-1}]$$

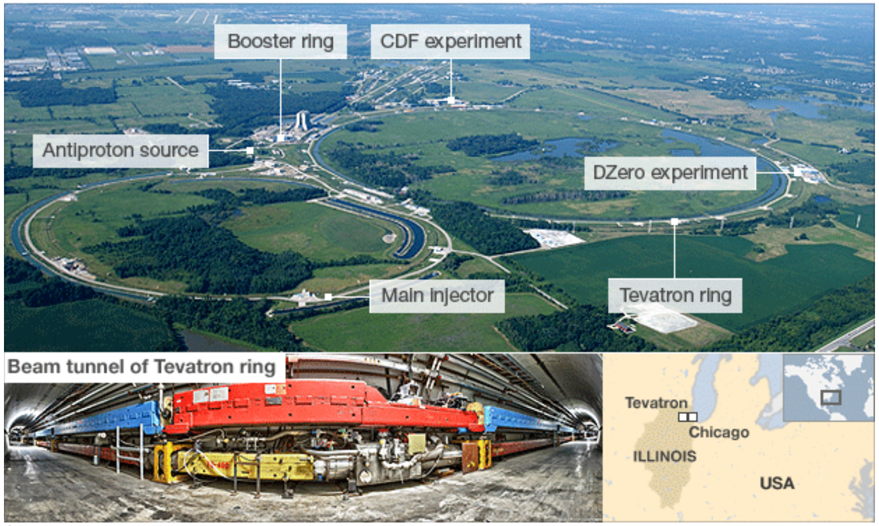
$$L \approx \frac{f_c N_1 N_2}{4\pi\sigma_x\sigma_y}$$

Energy Frontier

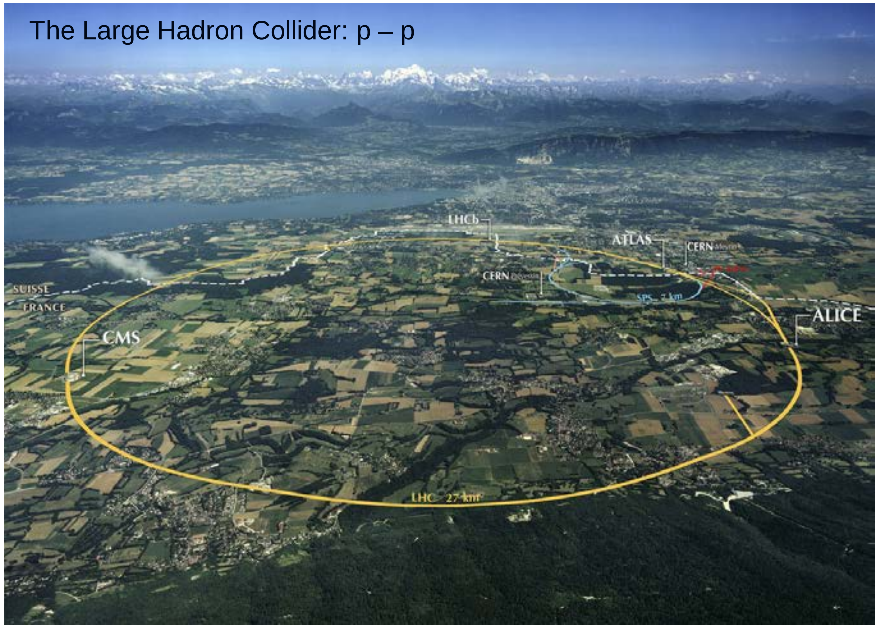


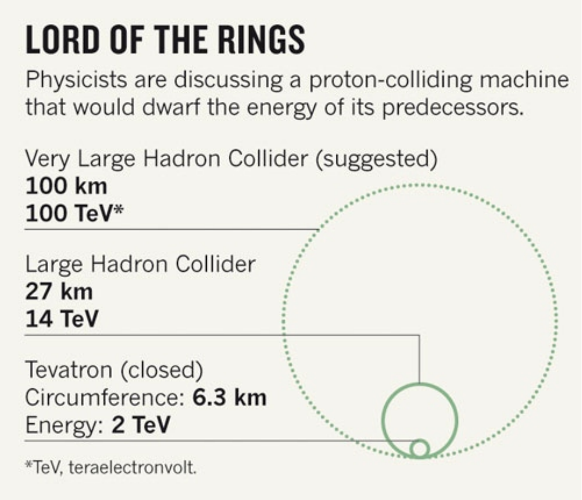
Energy Frontier

The Tevatron Collider: p – pbar



Source: Fermilab





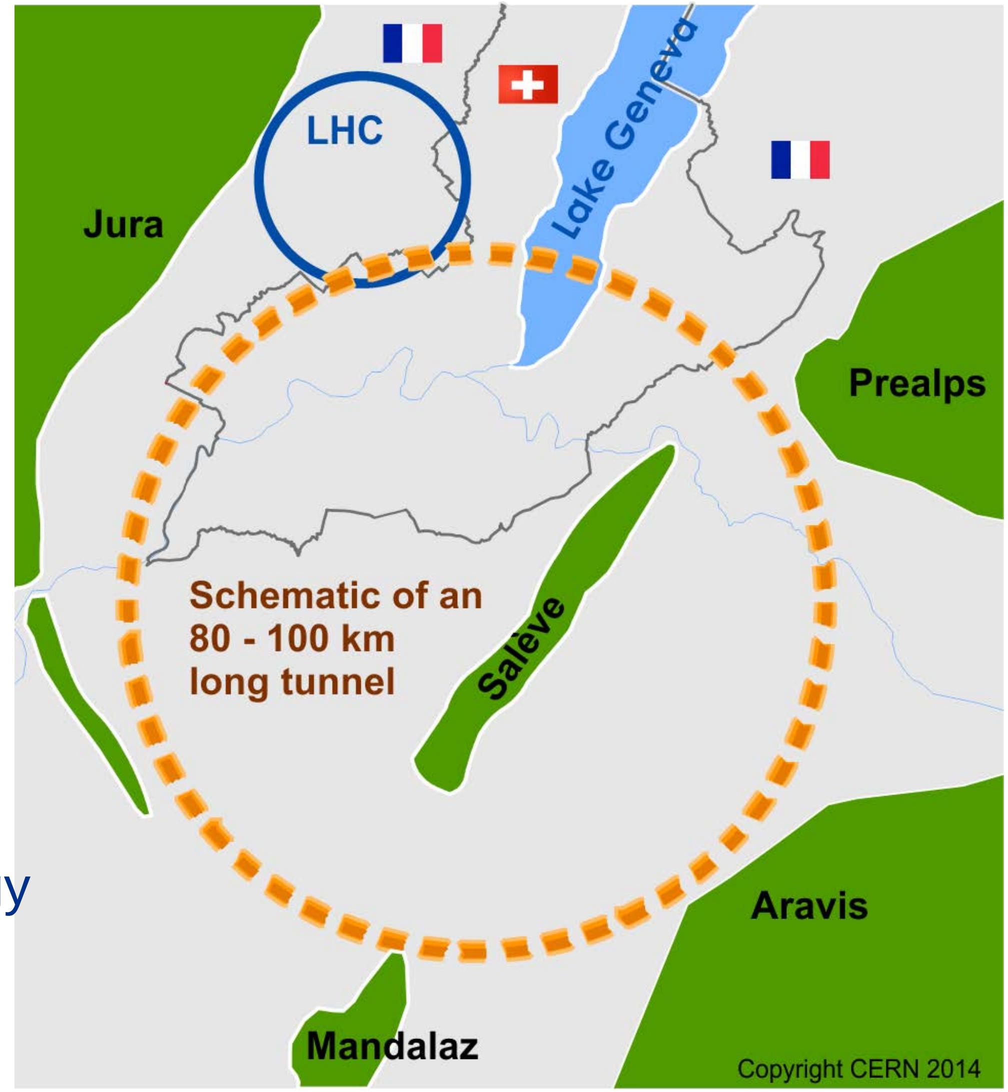
Future Circular Collider

International FCC collaboration (CERN as host lab) to study:

- *pp*-collider (*FCC-hh*)
  → main emphasis, defining infrastructure requirements

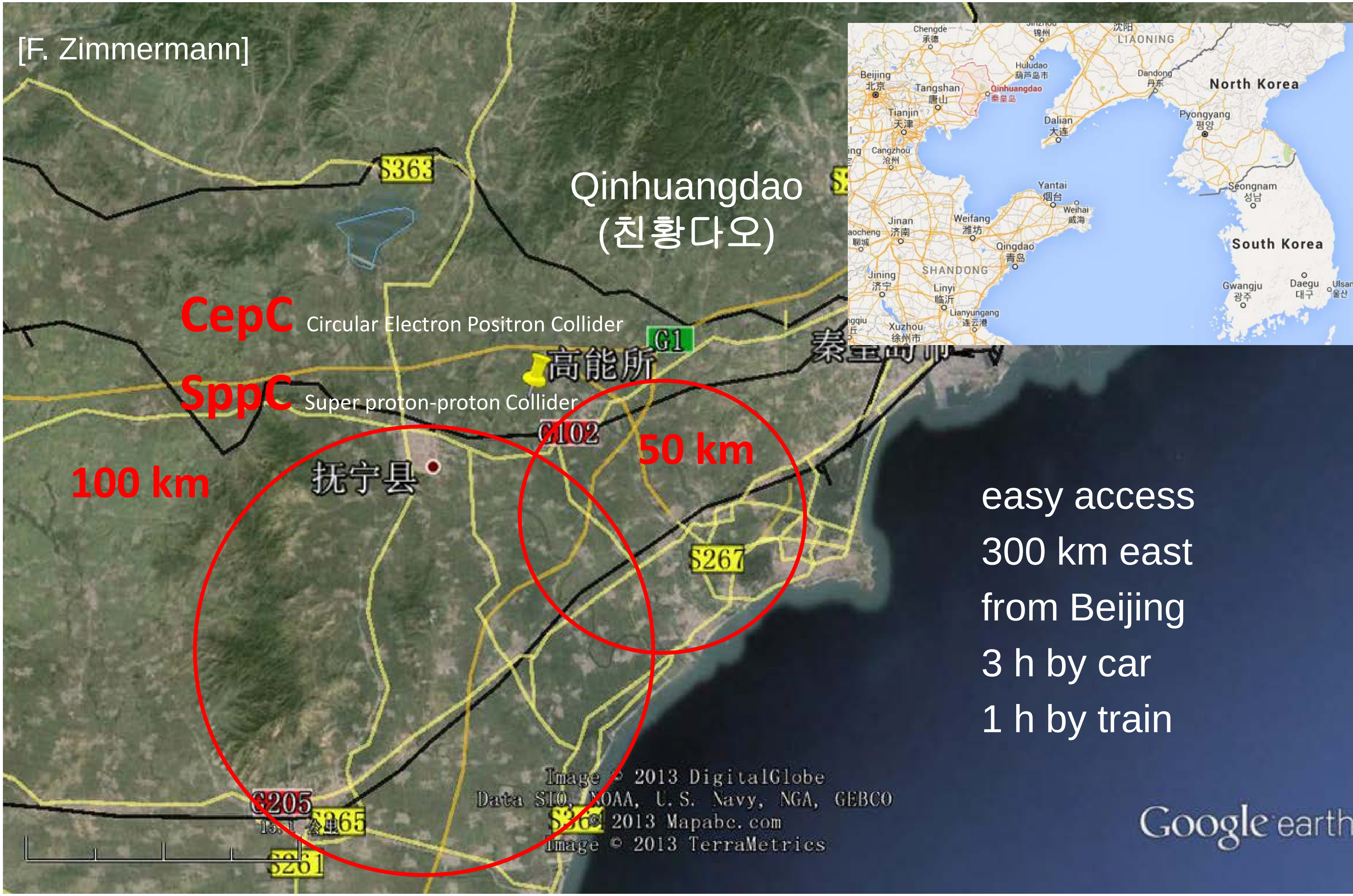
~16 T ⇒ 100 TeV *pp* in 100 km

- e^+e^- collider (*FCC-ee*) as potential intermediate step
- *p-e* (*FCC-he*) option
- *HE-LHC* with *FCC-hh* technology
- CDR and cost review by 2018



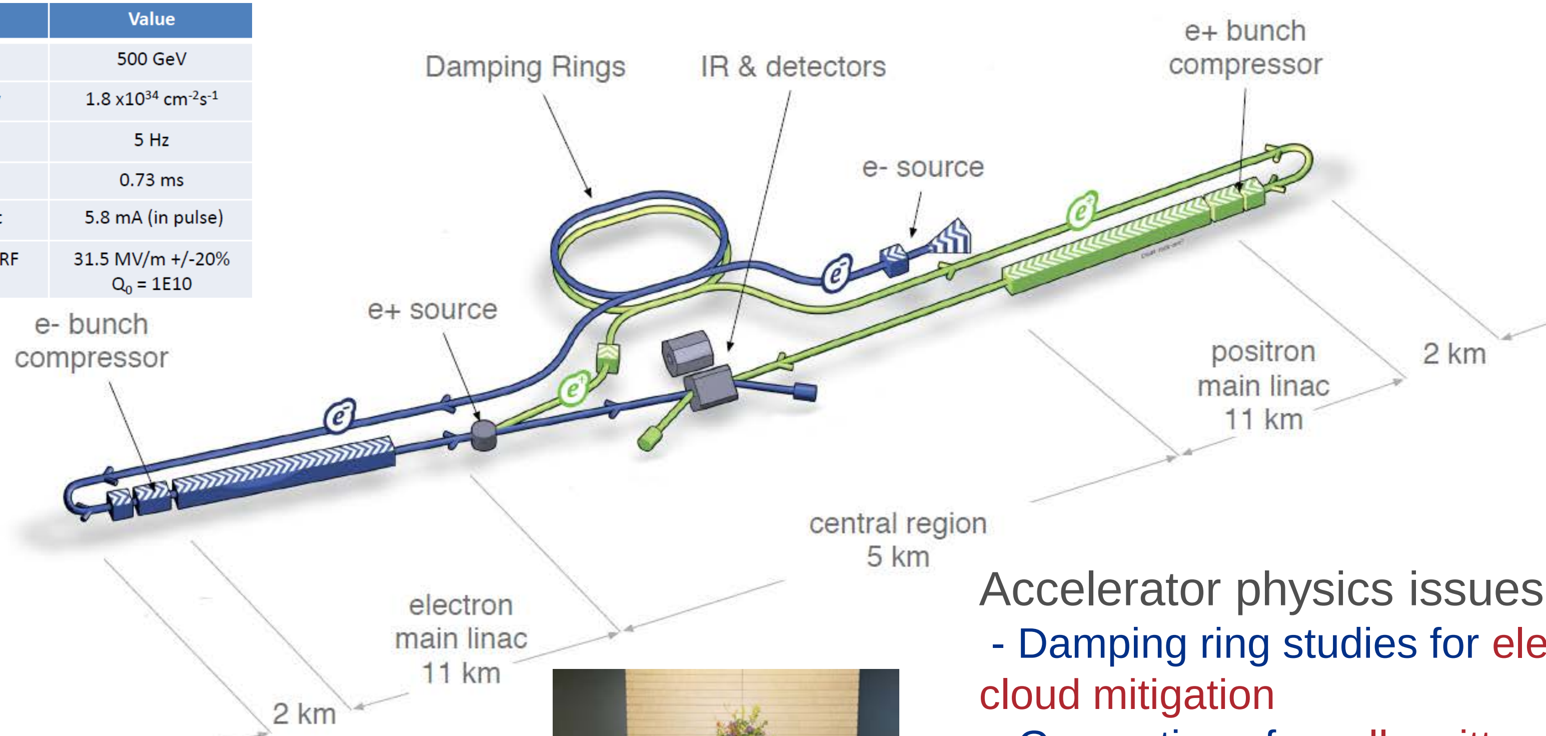
[F. Zimmermann]

CAS-IHEP's 50 km (baseline) Proposal



International Linear Collider

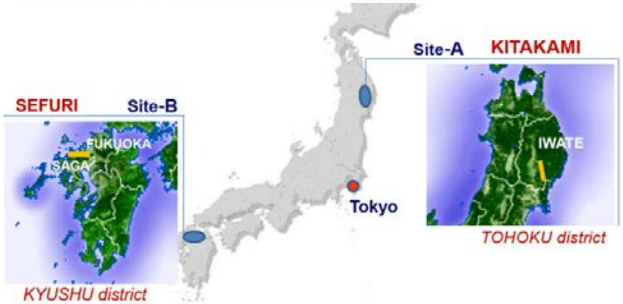
Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10



Accelerator physics issues:

- Damping ring studies for electron-cloud mitigation
- Generation of small emittance beams, preservation, and focusing to nm-beamsize

Japan has expressed strong support for hosting the ILC

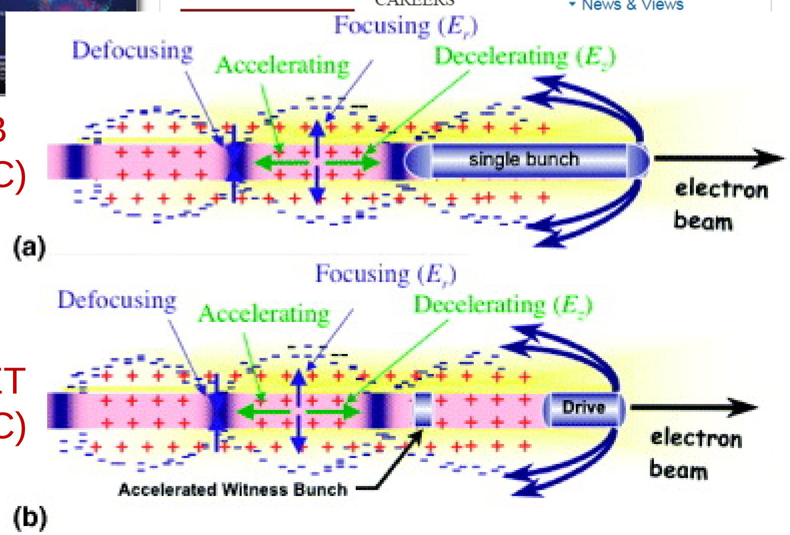


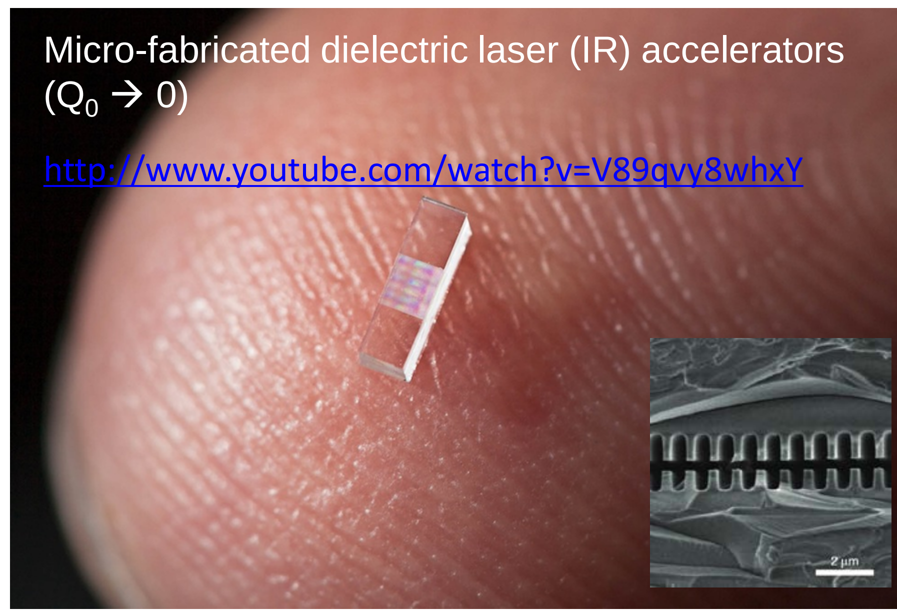
- 1.3 GHz SCRF technology

Energy Frontier: Advanced Accelerators

FFTB (SLAC)

FACET (SLAC)





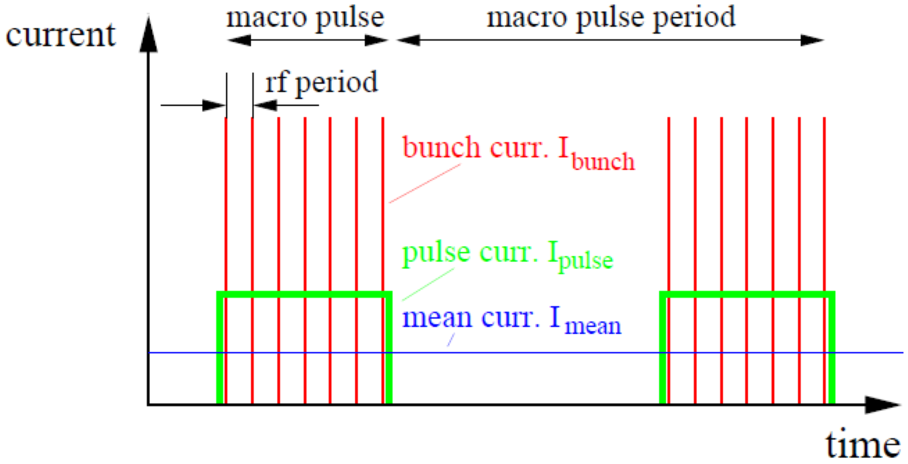
Transformer ratio limit → Proton-driven → AWAKE (CERN)

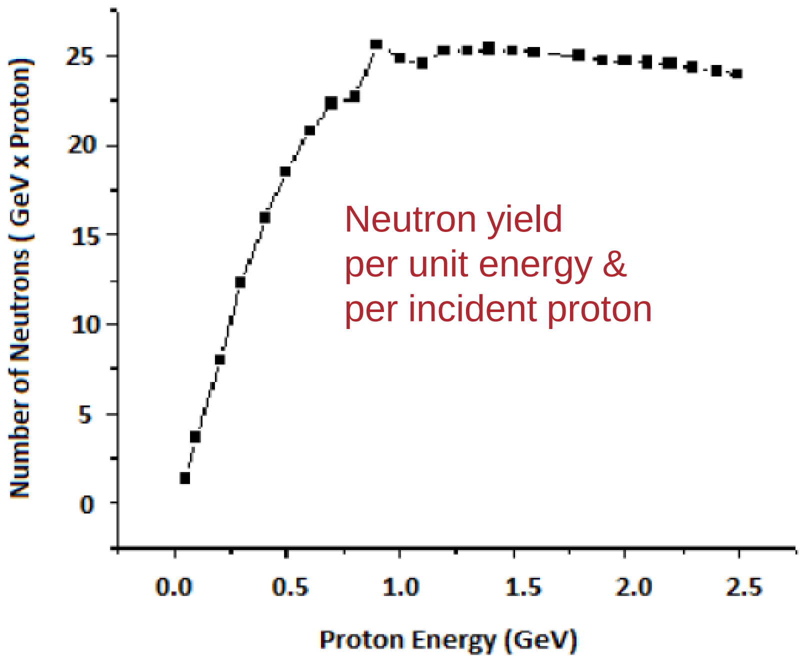
Intensity (Power) Frontier

Power:

$$P[\mathrm{MW}] = I_{\mathrm{pulse}}[\mathrm{mA}] \times E[\mathrm{GeV}] \times \mathrm{Duty}[\%]$$

$$\mathrm{Duty} = f_{\mathrm{rep}} T_{\mathrm{pulse}}$$

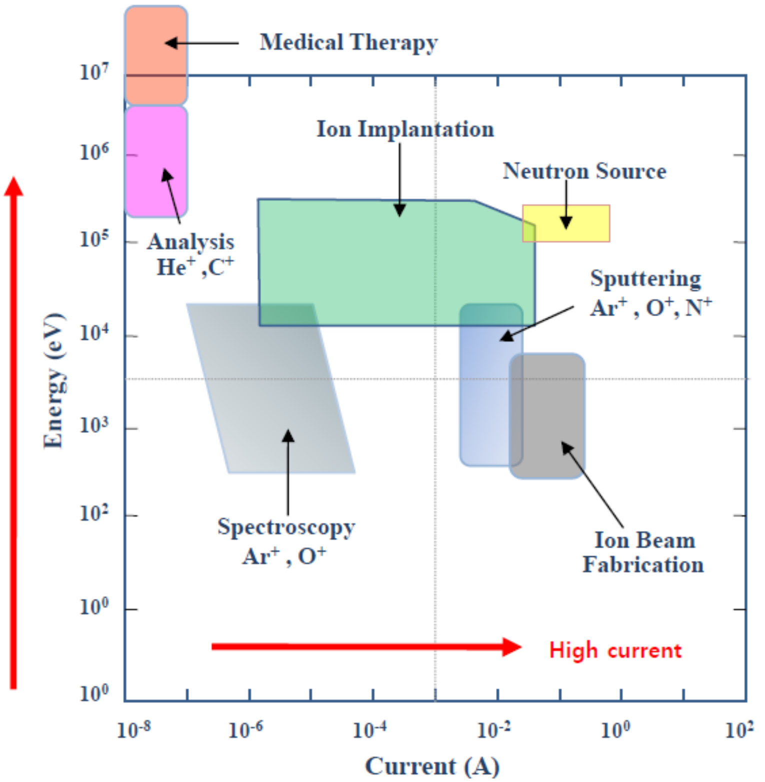




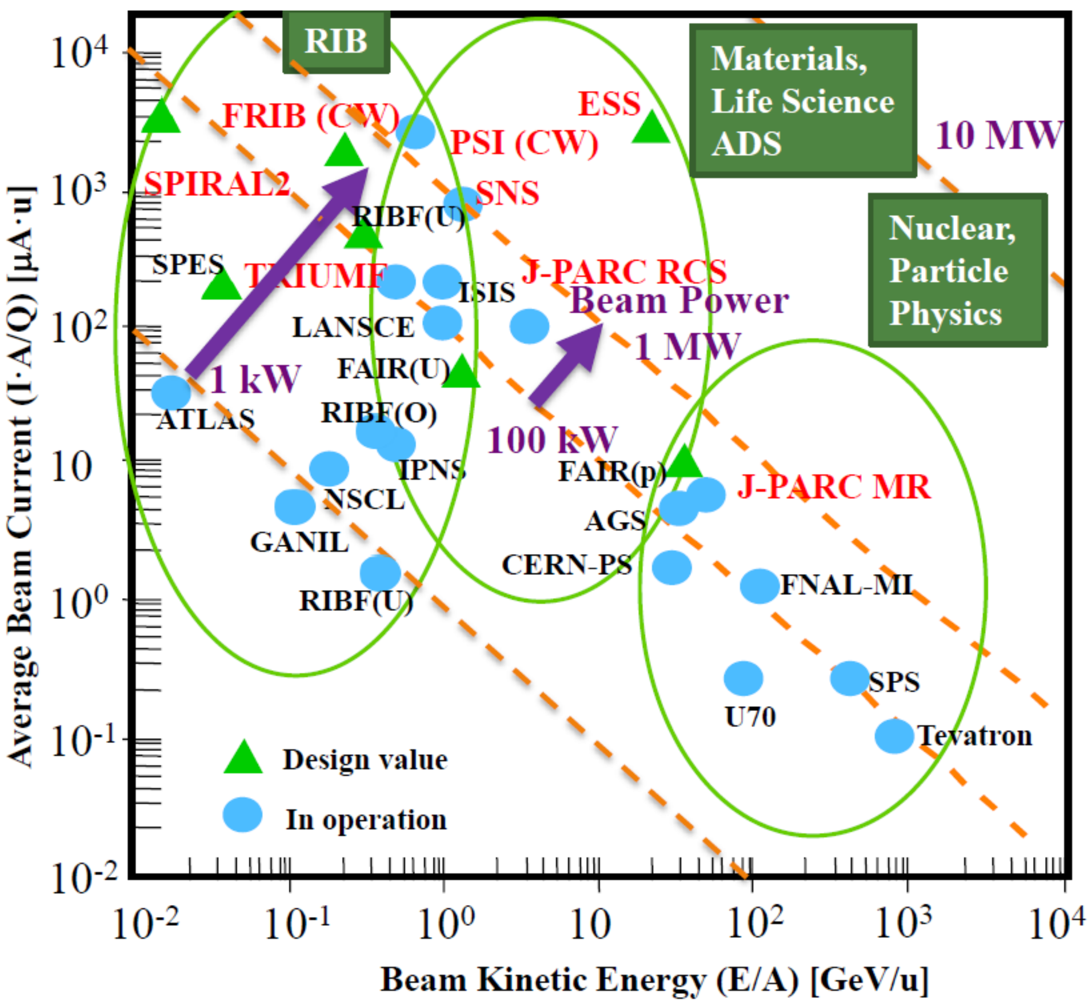
Neutron yield
per unit energy &
per incident proton

Intensity (Power) Frontier

Low energy applications:

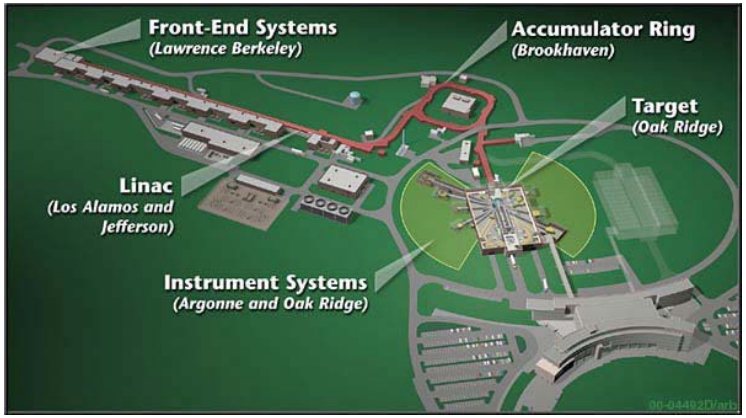


High energy applications:



Intensity Frontier: Neutron Sources

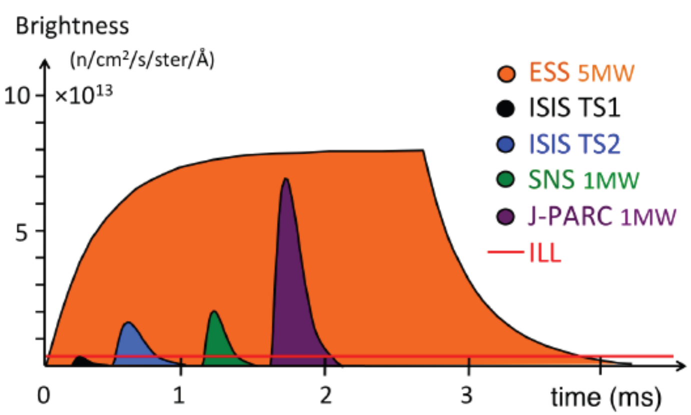
- Spallation Neutron Source (SNS/ORNL)

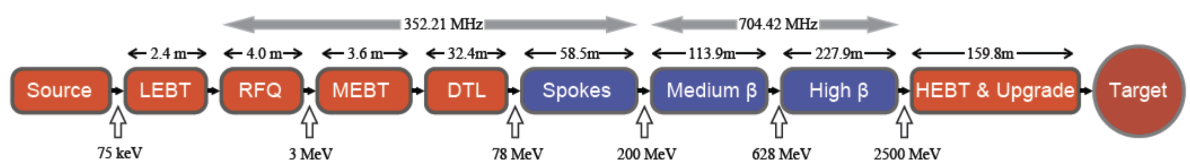


A stepping stone to other high power facilities

- 1 GeV superconducting H- linac
- 26 mA average linac macropulse current
- 1 ms long linac macropulse / 1 μs ring revolution time
- Accumulator ring with ~1000 turn charge exchange injection
- A short-pulse neutron source (1.4 MW,700 ns pulse on target)

- European Spallation Source (ESS)





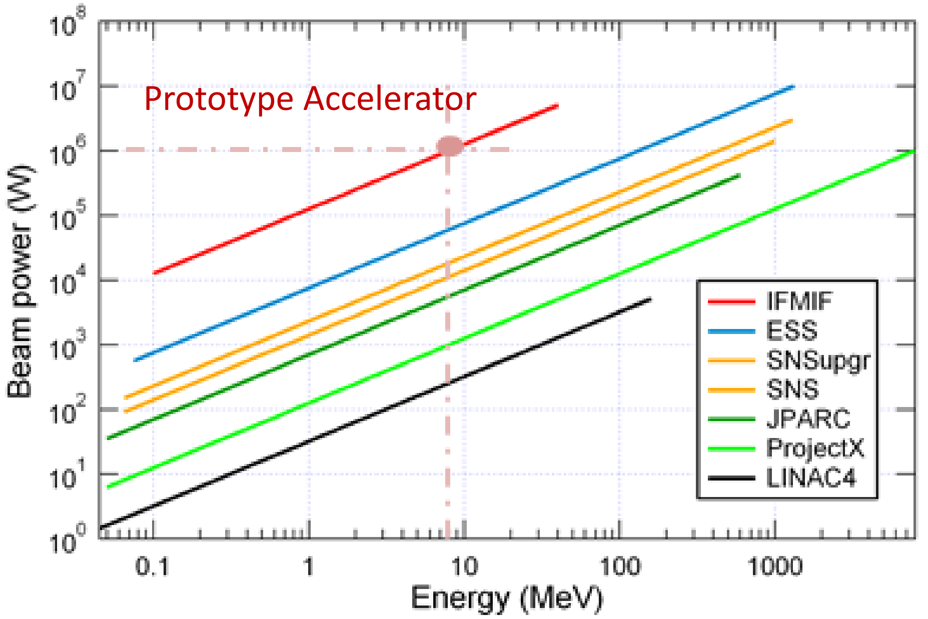
Parameter	Unit	Value
Energy	GeV	2.5
Current	mA	50
Pulse length	ms	2.86
Pulse repetition frequency	Hz	14
Average power	MW	5
Peak power	MW	125

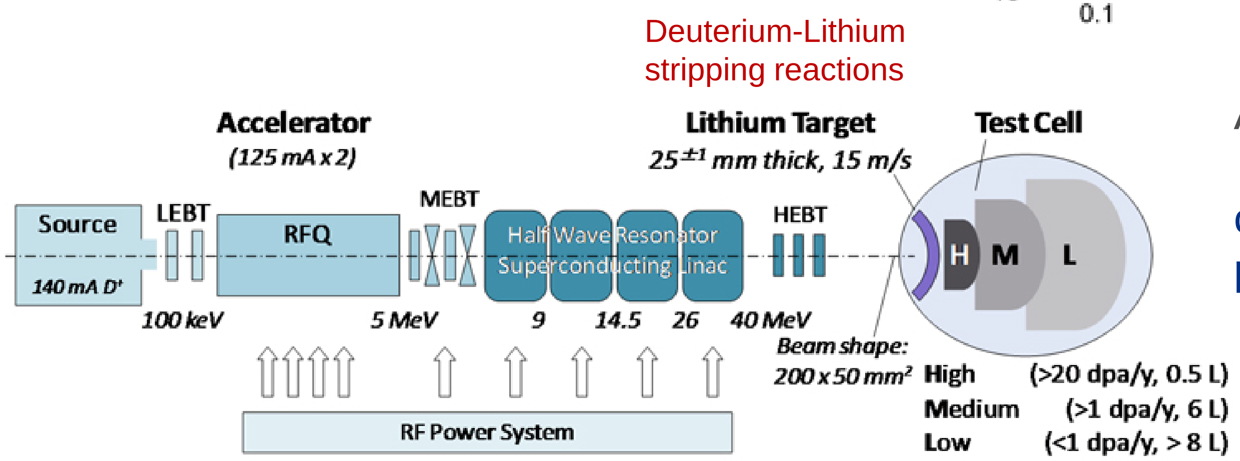
No ring → Proton beam

Accelerator physics issues:
- Emittance growth
- Beam halo/Beam loss
- Space-charge resonances

Intensity Frontier: Fusion Material Irradiation

- IFMIF is an essential facility in the world fusion program.
- It will become a fusion relevant neutron source.





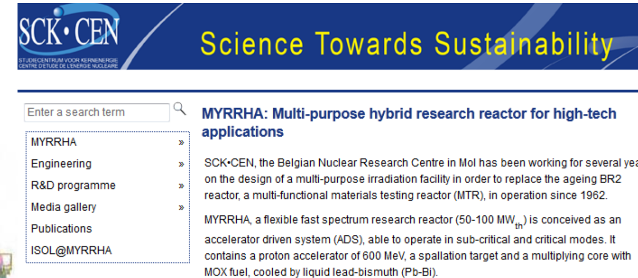
Accelerator physics issues:
- Significantly higher beam currents than any existing or planned machines (125 mA CW)
- Space-charge issues
- Deuterium beam operation

Intensity Frontier: Accelerator Driven System

High power CW proton linac
(~1 GeV, >20 mA, CW)

LBE(Lead–Bismuth Eutectic) target
(~30 neutron/p)

Reactor core
(keff < 1, wide range of fuel)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Science Towards Sustainability

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- ISOL@MYRRHA

MYRRHA: Multi-purpose hybrid research reactor for high-tech applications

SCK•CEN, the Belgian Nuclear Research Centre in Mol has been working for several years on the design of a multi-purpose irradiation facility in order to replace the ageing BR2 reactor, a multi-functional materials testing reactor (MTR), in operation since 1962.

MYRRHA, a flexible fast spectrum research reactor (50-100 MW_{th}) is conceived as an accelerator driven system (ADS), able to operate in sub-critical and critical modes. It contains a proton accelerator of 600 MeV, a spallation target and a multiplying core with MOX fuel, cooled by liquid lead-bismuth (Pb-Bi).


Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

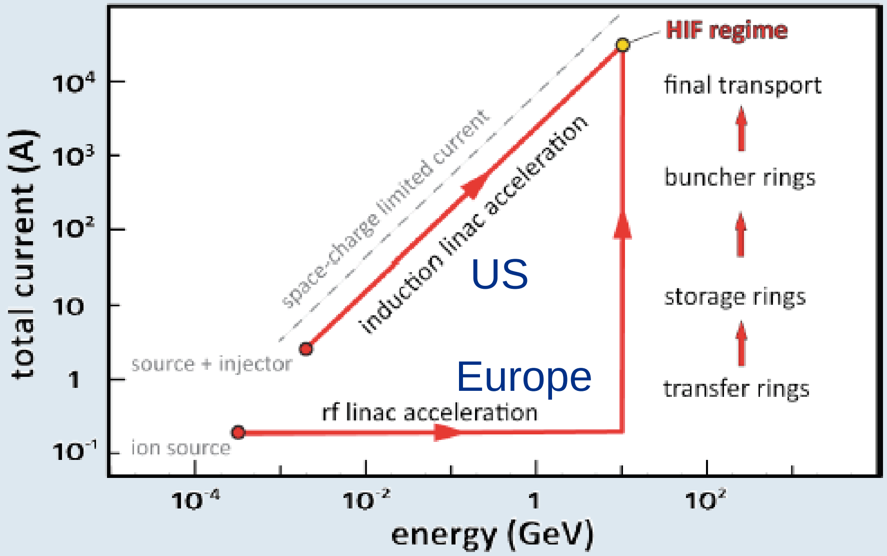
H. Aït Abderrahim[h], J. Galambos[d], Y. Gohar[a], S. Henderson[c*], G. Lawrence[e], T. McManamy[d], A. C. Mueller[g], S. Nagaitsev[c], J. Nolen[a], E. Pitcher[e*], R. Rimmer[f], R. Sheffield[e], M. Todosow[b]

Accelerator physics issues:

- Minimize beam trips (<50/year for t>5 min) to reduce thermo-mechanical stresses on target and reactor
- Long-term operation of high-power CW front-end
- Beam halo/Beam loss (<1 W/m)
- High dynamic range (>10^6), high-resolution measurement of beam particle distributions

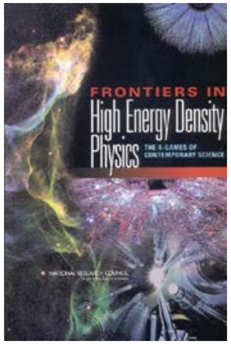
Intensity Frontier: Heavy Ion Fusion

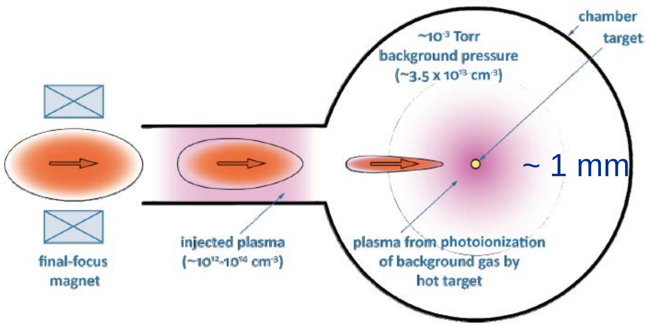
- Heavy ion accelerator (~10 GeV) can deposit enough energy (>10 keV) for D-T fusion
- High rep. rate and high efficiency
- Robust final optics
- But, could be very expensive



	NDCX-II	GSI-SIS18	LHC	HIF driver
Ion energy	1.2→ 6 MeV (Li+)	70 GeV (U^{28+})	14 TeV (p)	10 GeV (Pb^+)
Beam power	0.1 to 1 GW (50Ax2MeV →150Ax6MeV)	350 MW (in 130 ns)	1 TW (100 μs dump)	4 TW / beam X100 beams (in 8.2 ns)
Beam energy	0.08 to 0.25 J	45 J	100 MJ (total dump)	6 MJ
Space charge $\Delta\phi$/KE (final)	High 5 x 10^{-2}	Very Low 10^{-9}	Negligible	High to low 10^{-1} to 10^{-5}
Ion range	Low (~ 3 μm foil) 0.0001 g/cm^2	High (> WDM target) 10 g/cm^2	Way too high for IFE 10,000 g/cm^2	IFE target requirement 0.03 -1 g/cm^2

Accelerator physics issues:
- Space-charge dominated beam
- Beam compression
- Driver for high energy density physics

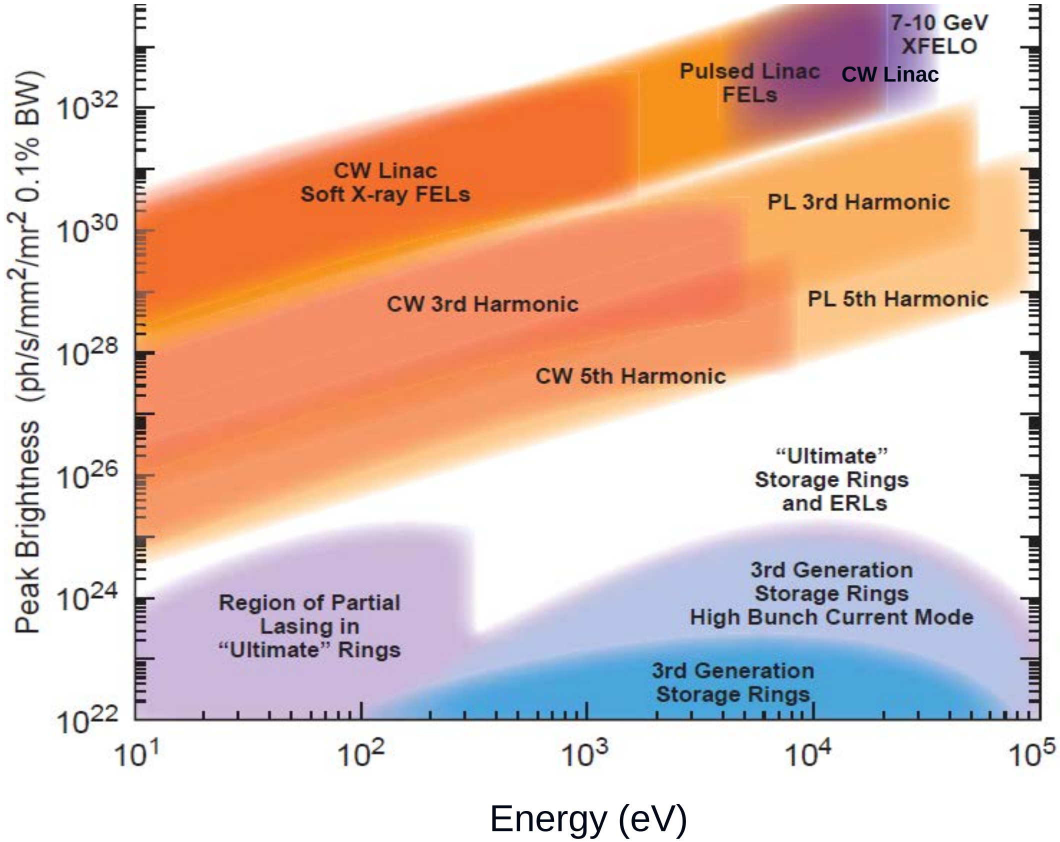




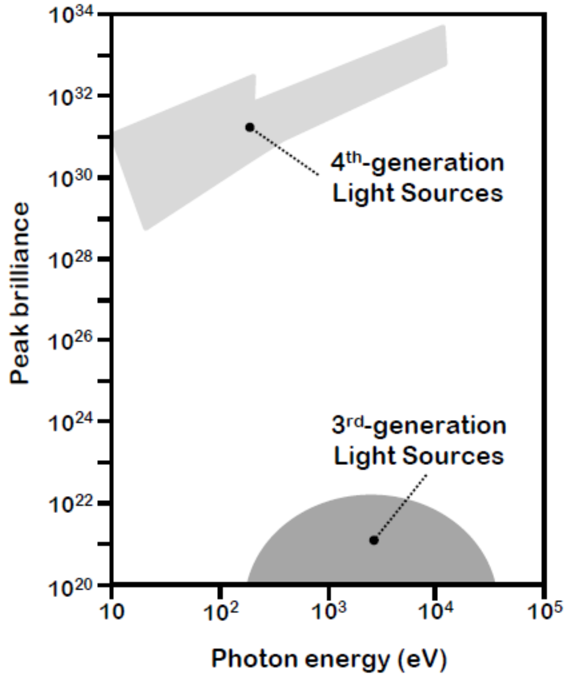
Quality Frontier

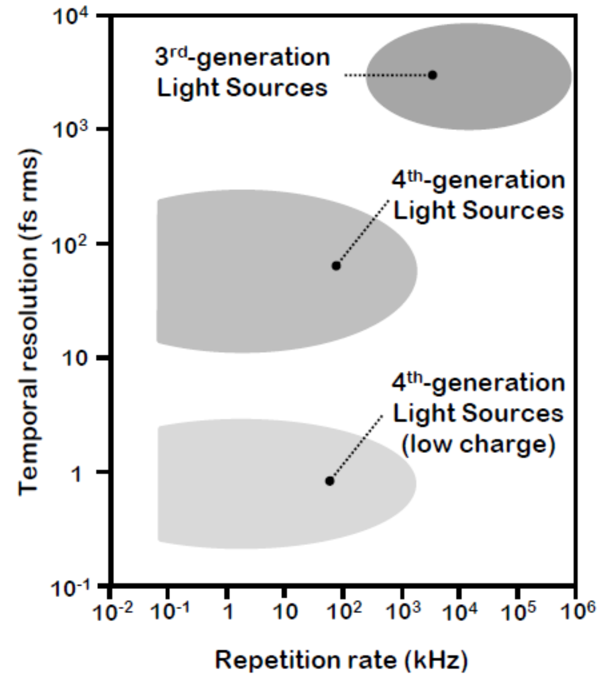
Brightness (Brilliance):

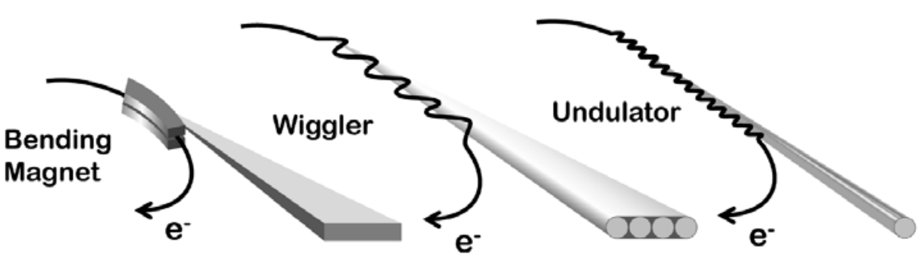
$$B[\#/\mathrm{s}/\mathrm{mm}^2/\mathrm{mr}^2/0.1\%\mathrm{BW}] = \frac{d^4 N_{photon}}{dt dS d\Omega (d\lambda/\lambda)} \propto \frac{N_{beam}}{\epsilon_x \epsilon_y}$$

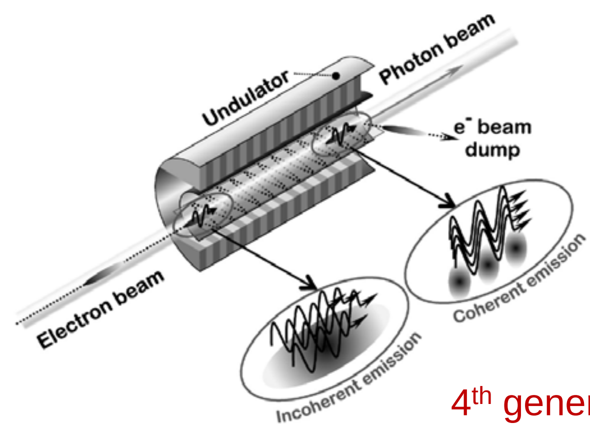


Quality Frontier





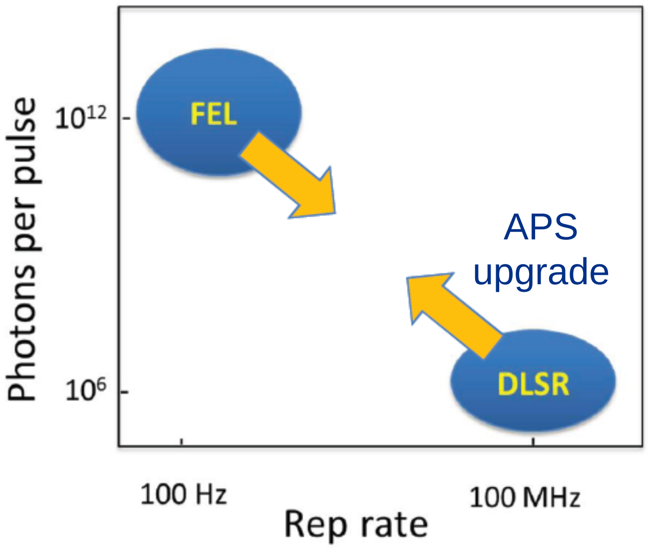




3rd generation

4th generation

Quality Frontier: Ultimate Storage Ring



NATURE | NEWS

Ultimate upgrade for US synchrotron

Argonne lab banks on beam-bending magnets in bid for world's most focused X-ray light source.

Eugenie Samuel Reich

10 September 2013

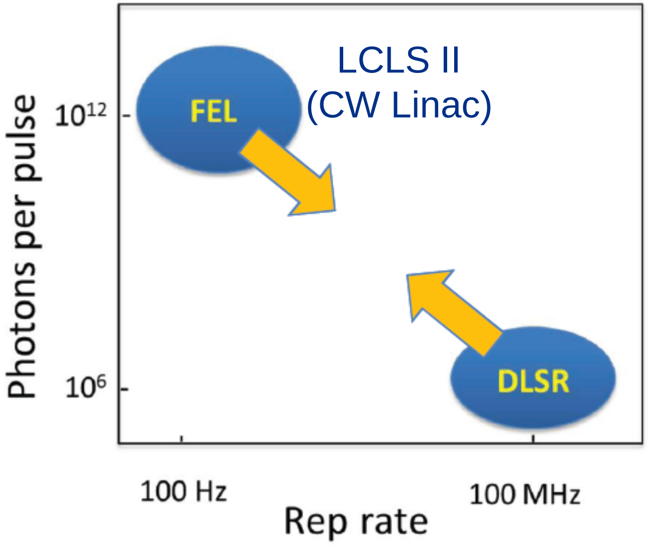
$$\epsilon_y \leq \epsilon_x \approx \frac{\lambda}{4\pi}$$

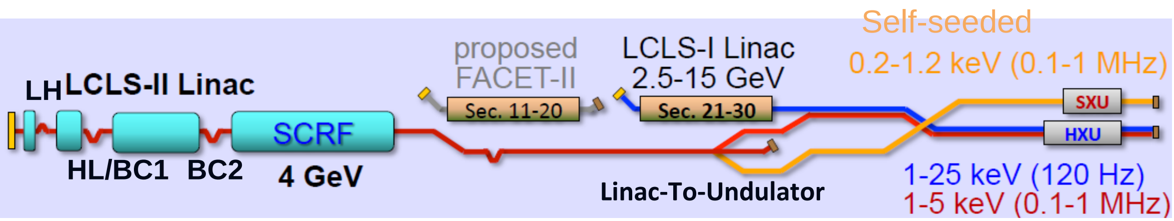
Quantum fluctuation
~ Radiation damping

+ Dispersion

Accelerator physics issues: Low emittance & High current
- Multi-Bend Achromat (MBA) lattices with compact magnet design (MAX IV, Sweden)
- Coupling control
- Chromatic aberration and Non-linearity due stronger focusing
- Intra Beam Scattering (IBS)
- Transverse (resistive wall, ion trapping, TMCI) and Longitudinal (cavity HOMs) beam instabilities

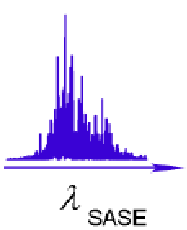
Quality Frontier: Advanced FEL's

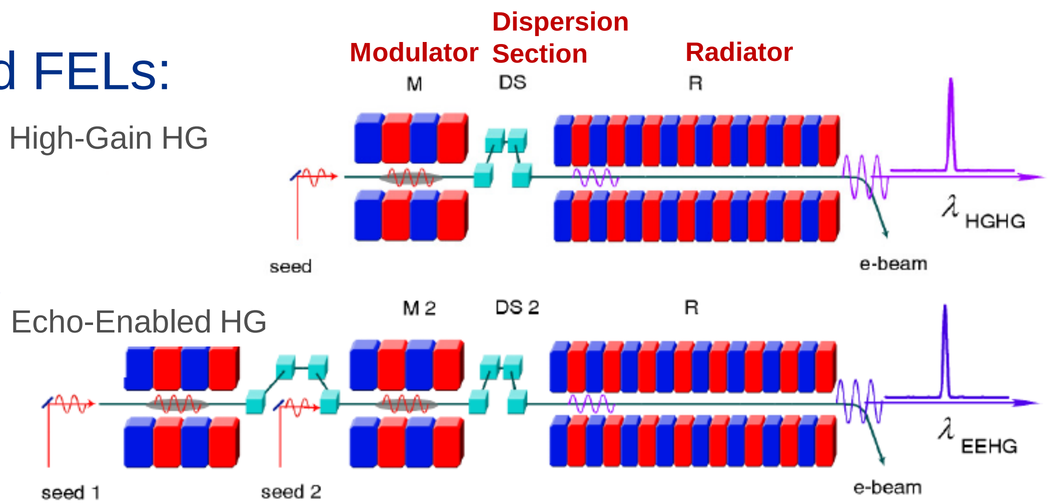




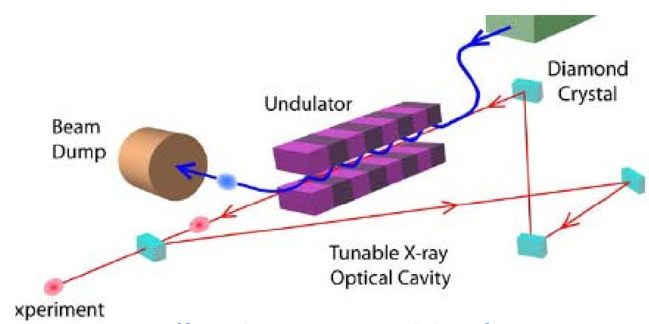
- Replacing first kilometer of the normal conducting S-band linac by 4 GeV SCRF linac (ILC technology, 35 x 1.3 GHz CM and 3 x 3.9 GHz CM for HL)

- Seed FELs:





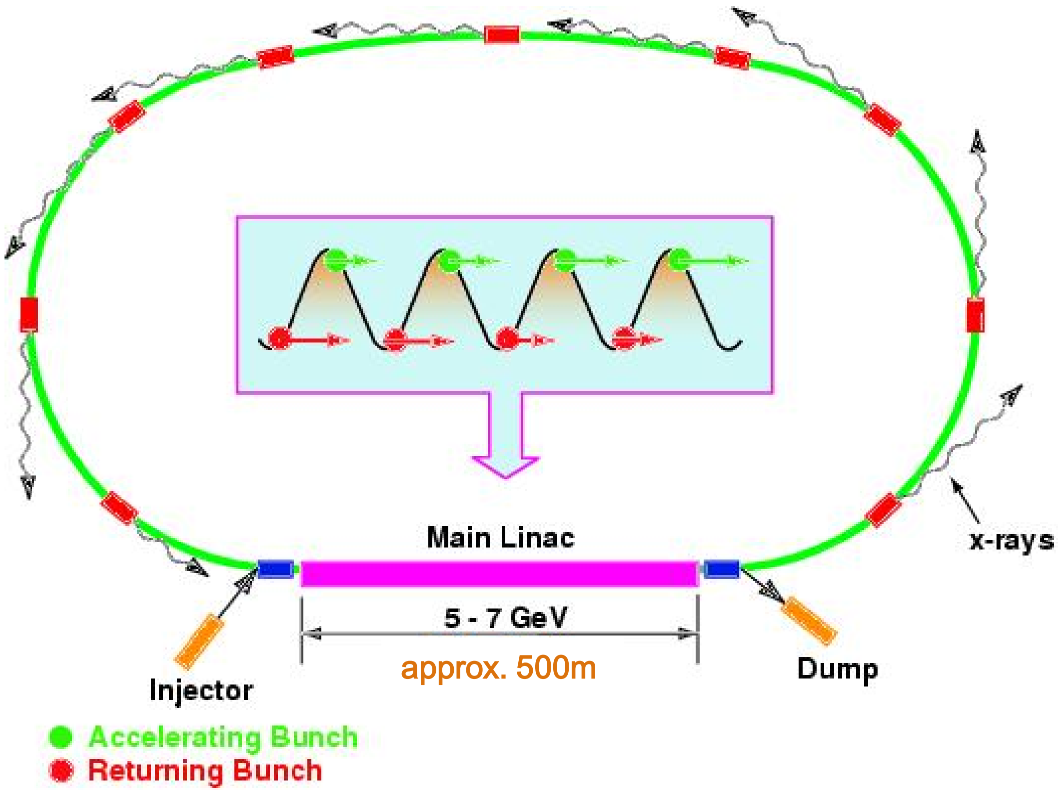
- XFEL Oscillator:



Full coherence with ultra-pure spectrum (Kwang-Je Kim)

Quality Frontier: 5th Generation Light Source ?

Energy Recovery Linac (ERL)



- High average brilliance
- Full spatial coherence
- fs to ps pulses

XFEL

- Many experiments
- Ready tunability
- High flux
- Stability
- High-energy x-rays

Storage Ring

- Flexible pulse characteristics
- 10^9 pulses/s
- Narrow energy spread
- Flexible machine parameters
- Drive XFELO, high rep-rate XFEL

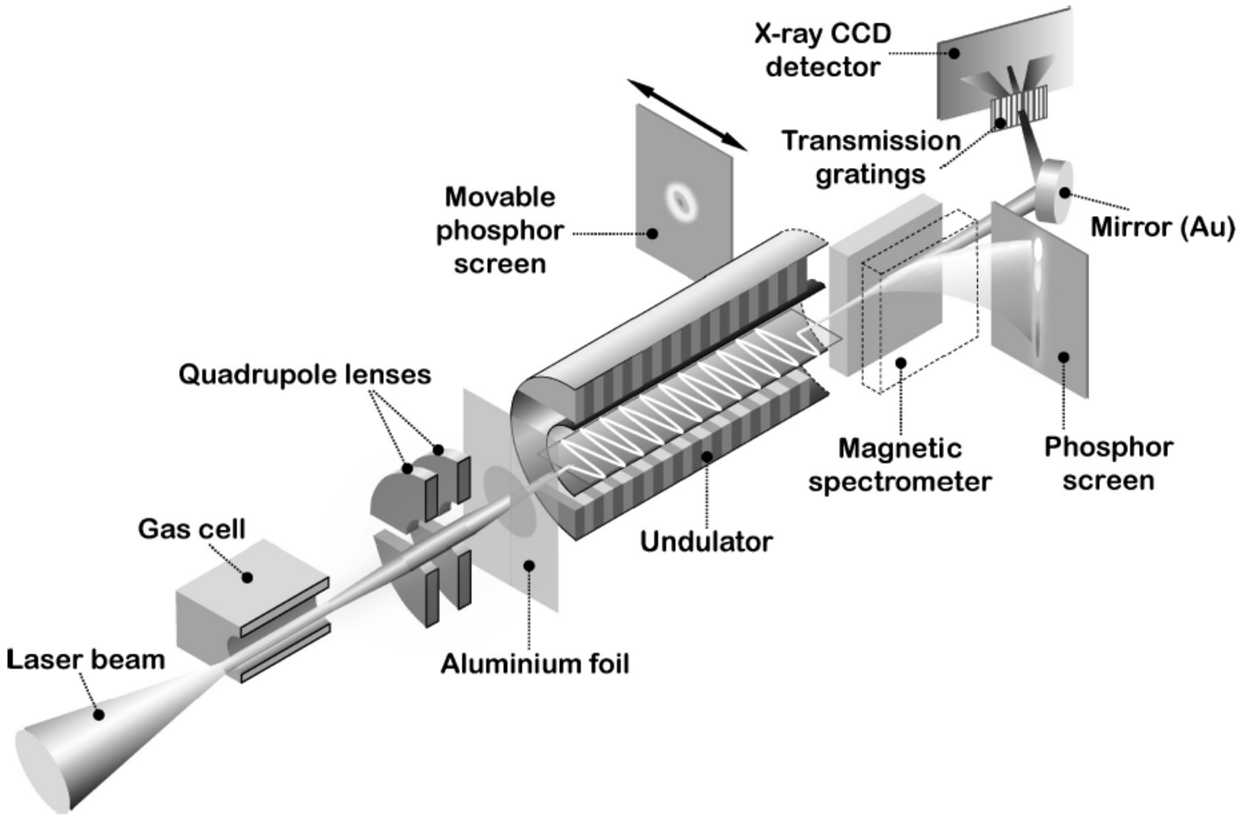
ERL

Energy recovered during deceleration is used to accelerate new bunches.

[Joel D. Brock]

Quality Frontier: Advanced FEL's

- A compact light source driven by an LPWA:

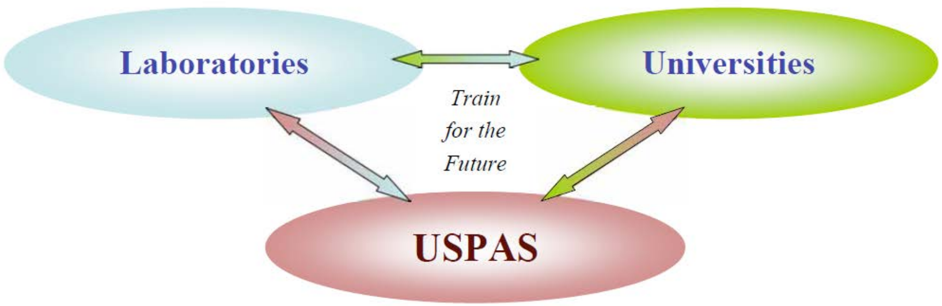


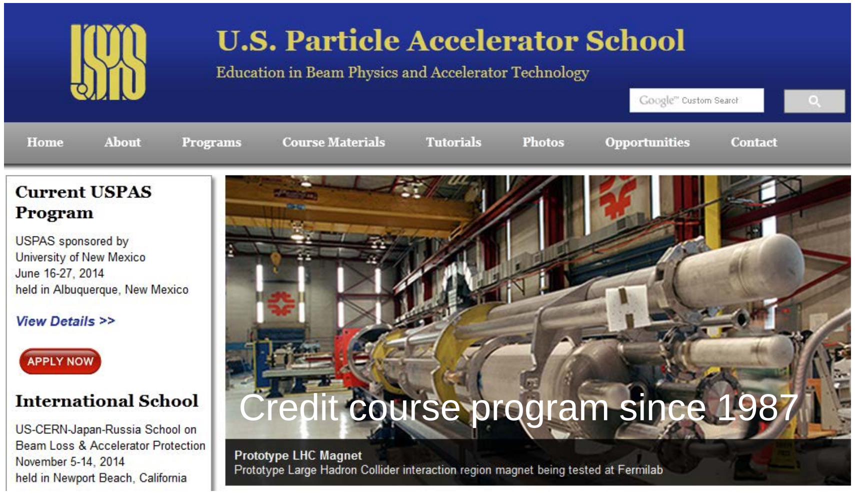
Challenges: Repetition rate (~ Hz yet), Energy spread, only a few GeV yet

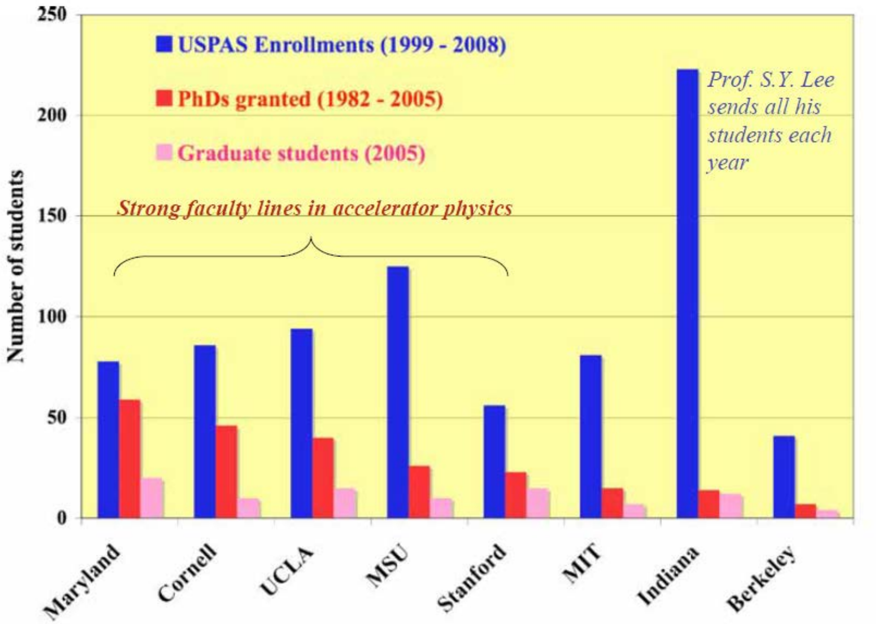
How to Pursue Accelerator/Beam Physics at UNIST?

Accelerator/Beam Physics Education

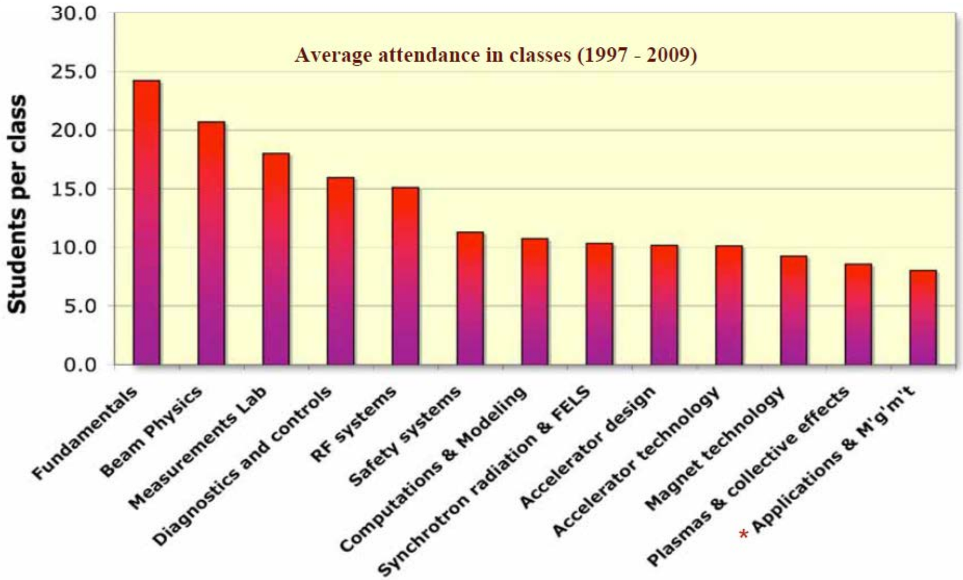
→ Mediated by Particle Accel. School







+ U. Chicago/IIT/NIU

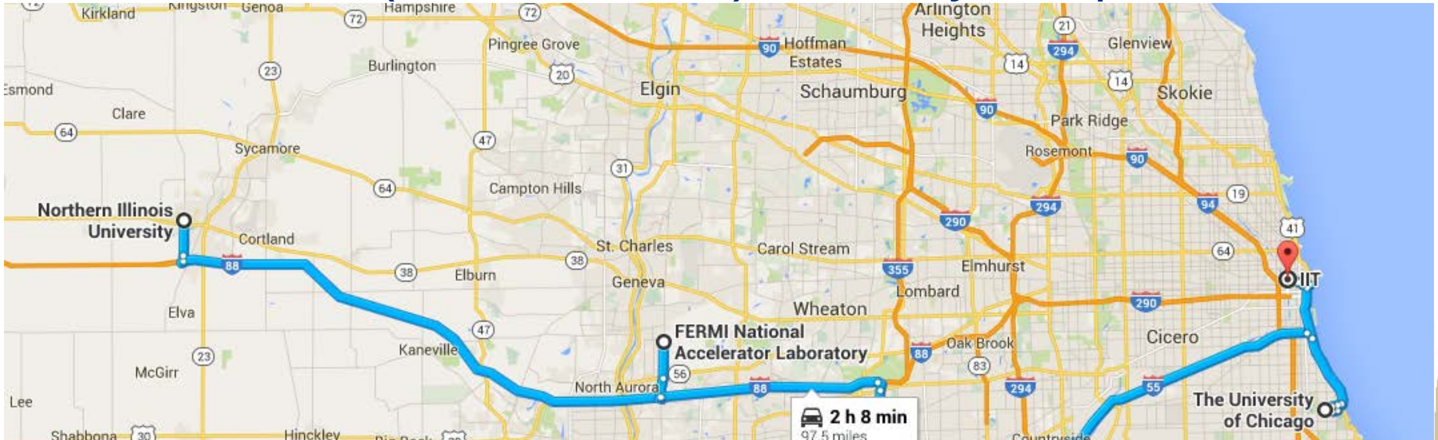
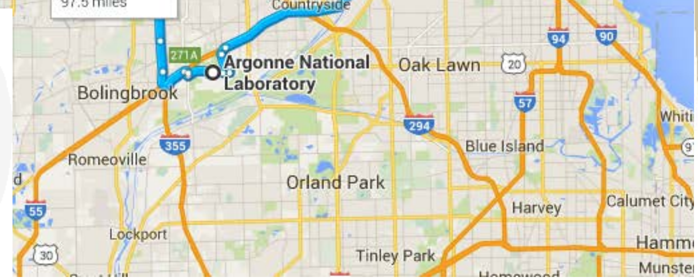


[From William A. Barletta]

KOPAS

Learn more about KoPAS
Korea Particle Accelerator School
(KoPAS 2015)
제3회 국제가속기학교
July 28(Tue) - 31(Fri), 2015
2015년 7월 28일(화) - 31일(금)
Venue : Institute for Basic Science(IBS), Daejeon
장소 : 대전 기초과학연구원
Organizing Committee
· Dr. Sunchan Jeong (Director, IBS/RISP, Korea)
· Dr. Dong O Jeon (IBS/RISP, Korea)
· Prof. Do-Won Kim (Kangnung N. Univ., Korea)
· Prof. William A. Barletta (USPAS/MIT, USA)
· Prof. Young-Kee Kim (Univ. of Chicago, USA)
Lecturers
Prof. Jean Delayen
Dr. John Byrd
Dr. Yujong Kim
Prof. Moses Chung
7.28
Introduction to Accelerator Physics
· Basics of Electromagnetism, Dynamics and Relativity
· Transverse Linear Optics, Phase Space, Betatron Oscillation
· Transverse Emittance & Transverse Beam Parameters
7.29
Introduction to Accelerator Physics
· Basics of RF System
· Basics of RF Cavity
· Longitudinal Phase Space, Synchrotron Oscillation & Longitudinal Beam Parameters
· Lattice Design and Transverse & Longitudinal Beam Dynamics
7.30
Focus Topics
· Space-charge Effects
· Basics of Instabilities
· Basics of Superconducting RF Cavity
7.31
Focus Topics
· Basics of Synchrotron Radiation
· Basics of Beam Diagnostics
※ There is no registration fee to all participants.
※ Deadline of registration : July 17, 2015
※ The schedules for 'Focus Topics' are TENTATIVE.
※ http://indico.risp.re.kr/indico/event/kopas2015
41 Nb
RAON
기초과학연구원
U.S. Particle Accelerator School
미래창조과학부
국제과학비즈니스벨트
문의 IBS 중이온가속기건설구축사업단 Tel : +82-42-878-8857 / E-mail : kopas@ibs.re.kr

[Example] Close connection between Universities (UC, NIU, IIT) and Accelerator labs. (Fermilab, ANL) – Facility/Manpower etc.

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UC

Faculty

Kwang-Je Kim Argonne lab / U.Chicago (Physics)	Young-Kee Kim U.Chicago (Physics)	Sergei Nagaitsev Fermilab / U.Chicago (Physics)
		

[Example] Close connection between UNIST and Accelerator labs. (PAL, KOMAC, KHIMA) – Facility/Manpower etc.

PLS II
(Pohang Light Source)

PAL XFEL
(Pohang Accelerator Lab. X-ray Free Electron Laser)

RISP
(Rare Isotope Science Project)

KHIMA
(Korea Heavy-Ion Medical Accelerator)

KOMAC
(Korea Multi-purpose Accelerator Complex)

Beam Parameters

Parameter	KOMAC	PAL-XFEL	RISP	KHIMA
Species	Proton	Electron	Proton ~ Heavy ion	Proton & Carbon
Energy	100 MeV	10 GeV	200 MeV/u for U^{79+}	110 ~ 430 Mev/u for ^{12}C
Beam current	20 mA (1.33 ms)	3 kA (0.2 nC/100 fs)	8 pμA For U^{79+}	100 ~ 235 eμA for ^{12}C (before injection)
Rep. Rate	60 Hz	60 Hz	CW	4~ 5 Hz
Accelerator Structure	Vane-type RFQ + 350 MHz DTL	S-band Linac (2.856 GHz) + 3 Bunch Compressor	RFQ + SCRF Linac: QWR (81.25 MHz), HWR (162.5 MHz), SSR (325 MHz) + Cyclotron for ISOL	RFQ+ IH-DTL + Synchrotron
Research Areas	Nano, Bio, IT, Space, Radiation, Medical etc.	Atomic/Molecular, Condensed matter, Surface/cluster, Material science, Chemistry/Biology, Non-equilibrium plasma, Warm-dense plasma	Nuclear physics, Bio-medical science, Material science, Neutron science	기존 방사선 치료에 잘 반응하지 않는 종양 머리에 암이 발생하는 두경부암, 뼈에 암이 생기는 골육종, 전립선암, 수술이 불가능한 직장암, 폐암, 간암, 피부가 검은 색으로 변하는 흑색종