## Accelerator Physics: Present and Future

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### Outline

- What is accelerator ?
- What is accelerator physics ?
- Frontiers of accelerator physics
  - ✓ A powerful particle smasher
  - ✓ A bright photon source

If time permits

- ✓ An intense neutron driver
- Accelerator projects in Korea
- Conclusions



## 가속기란?



#### What is the Accelerator?



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가속기 =

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### 가속기 = 하전입자 + 전기장 + 자기장

#### Cockcroft-Walton accelerator









#### **RF** Acceleration





#### 입자속도~파동속도

#### 입자속도<< 파동속도



#### Prinzip einer Methode zur Herstellung von Kanalstrahlen hoher Voltzahl.

Von GUSTAF ISING.

Mit 2 Figuren im Texte.

Mitgeteilt am 12. März 1924 durch C. W. OSEEN und M. SIEGRAHN.

Die folgenden Zeilen beabsichtigen eine Methode zu skizzieren, welche im Prinzip erlaubt, mit einer zu Verfügung stehenden müssigen Spannung Kanalstrahlen (ev. Kathodenstrahlen) beliebiger Voltzahl zu erzeugen. Dies soll dadurch Wideröe (1928)

The **Rolf Wideroe Prize** is awarded every third year by the Accelerator Group of the European Physical Society (EPS), in memory of Rolf Widerøe, to individuals in recognition of outstanding work in the field of accelerator physics.<sup>[1]</sup>



### **Magnetic Fields due to Currents**

- → Permanent magnet (ex, Undulator)
- → Electromagnet





#### → 또는 초전도 전자석



#### **Zoo of Accelerators**





#### **Things Accelerators Can Do**





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### **Things Accelerators Can Do**





Phys. Perspect. 13 (2011) 146–160 © 2011 Springer Basel AG (outside the USA) 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."



### **Accelerators Are Big Business**





## 가속기 물리학이란?



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### **Accelerator Physics: From Wikipedia**

Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle beams and their interaction with accelerator structures by electromagnetic fields. Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle beams and their interaction with accelerator structures by electromagnetic fields. It is also related to other fields: • Microwave engineering (for acceleration/deflection structures in the radio frequency range). • Optics with an emphasis on geometrical optics (beam focusing and bending) and laser physics (laser-particle interaction of the particle interaction of t		CIPEDIA Encyclopedia	Q	Create acco	unt	Log in •••
Article       Talk       Read       Edit       View histor         From Wikipedia, the free encyclopedia       Image: Corresponding inline citations. Please help to improve this article by introducing more precise citations. (January 2020) (Learn how and when to remove this template message)       Image: Corresponding inline citations. Please help to improve this article by introducing more precise citations. (January 2020) (Learn how and when to remove this template message)         Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle accelerators. As such, it can be described as the study of motion, manipulation and observation of relativistic charged particle beams and their interaction with accelerator structures by electromagnetic fields.         It is also related to other fields:         • Microwave engineering (for acceleration/deflection structures in the radio frequency range).       • Optics with an emphasis on geometrical optics (beam focusing and bending) and laser physics (laser-particle interaction of the particle)	≅ Accelera	tor physics		ŻĄ	18 la	inguages 🗸
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<ul> <li>This article includes a list of general references, but it lacks sufficient corresponding inline citations. Please help to improve this article by introducing more precise citations. (January 2020) (Learn how and when to remove this template message)</li> <li>Accelerator physics is a branch of applied physics, concerned with designing, building and operating particle accelerators. As such, it can be described as the study of motion, manipulation and observation of relativistic charged particle beams and their interaction with accelerator structures by electromagnetic fields.</li> <li>It is also related to other fields:</li> <li>Microwave engineering (for acceleration/deflection structures in the radio frequency range).</li> <li>Optics with an emphasis on geometrical optics (beam focusing and bending) and laser physics (laser-particle interaction of the particle)</li> </ul>	From Wikipedia, the free	encyclopedia				
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Plasma physics, for the description of intense beams.



### **Accelerator Physics: From chatGPT**

What is accelerator physics?

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Accelerator physics is a branch of physics that deals with the design, construction, and operation of particle accelerators. Particle accelerators are machines that accelerate charged particles to high energies using electromagnetic fields. They are used for a wide range of applications, including fundamental research in particle physics, materials science, and medical applications such as cancer treatment.

Accelerator physics involves the study of the behavior of particles as they are accelerated, including their interactions with electromagnetic fields, their trajectories, and the effects of relativistic motion. It also involves the design and optimization of the accelerator structures, the control of the particle beams, and the development of diagnostic techniques to measure beam parameters.

Accelerator physics is a highly interdisciplinary field that draws on concepts from electromagnetism, quantum mechanics, relativity, and engineering. It is a rapidly evolving field, with new technologies and techniques constantly being developed to push the limits of particle acceleration and advance our understanding of the universe.



### **Accelerator Physics: ~Beam Physics**

• Particle beams are collections of charged particles all travelling in nearly the same direction with nearly the same speed (possibly relativistic).



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





### **Intense Beams**

Dominant for low energy

 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



#### (cf., scattering effect)

(cf., plasma wakefield)



### **Accelerator VS Plasma Physics**

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

beam self fields > external applied fields ( plasma) ,

beam self fields  $\ll$  external applied fields (accelerators).

This difference means *perturbation techniques* are applicable to accelerators with

unperturbed motion = external fields (magnets, RFcavities), perturbation = self fields, wakefields.

In fact, in accelerator physics, a first order perturbation often suffices. This makes accelerators much cleaner physical system to study compared to typical plasma systems, although the mathematics and physics tools are quite similar.

#### [From A. Chao]



### **Beam as a Nonneutral Plasma**



An Introduction to the

#### PHYSICS OF NONNEUTRAL PLASMAS

Moses Thanks for being one of my best students! by Ronald C. Davidson Ron Davidin







The Nobel Prize in Physics 1984 Carlo Rubbia, Simon van der Meer

Share this:

#### Simon van der Meer - Facts



#### Simon van der Meer

Born: 24 November 1925, the Hague, the Netherlands

Died: 4 March 2011, Geneva, Switzerland

Affiliation at the time of the award: CERN, Geneva, Switzerland

Prize motivation: "for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Field: experimental particle physics

Prize share: 1/2

#### Discovered the W and Z Particles

According to modern physics, there are four fundamental forces in nature. The weak interaction, responsible for e.g. the beta-decay of nuclei is one of them. According to the theory forces are mediated by particles: the weak interaction by the so called heavy bosons W, Z, about 100 times more massive than the proton. Simon van der Meer developed a method to accumulate a large number of energetic antiprotons in an accelerator ring. These were used in experiment where antiprotons and protons of high energy were brought to collide. In these experiments W and Z particles were discovered in 1983. "Accelerator physics—a field where often work of the highest quality is buried in lost technical notes or even not published; one has only to think of Simon van der Meer's Nobel prize work on stochastic cooling unpublished in any refereed journal."

#### attitude at some laboratories:

"... if you have time to write papers you do not have enough real work to do..."



"We publish in concrete and steel!", John B. Adams

(CERN director)



## 가속기 물리학의 최전선



### **Frontiers of Accelerator Physics**

→ Science goals/Society needs push limits of accelerator performance





Three main aspects in this talk:

- Particle/Nuclear physics: A powerful particle smasher
- Photon science: A bright photon source
- Neutron science: An intense neutron driver



### **Important Figure of Merit**

• Particle collider: Energy & Luminosity

$$R = \sigma_{physics}(E) [\text{cm}^{2}] \times L[\text{cm}^{-2}\text{s}^{-1}]$$
$$L \approx \frac{f_{c}N_{1}N_{2}}{4\pi\sigma_{x}\sigma_{y}}$$

• Light source: Brightness

$$B[\#/s/mm^{2}/mr^{2}/0.1\%BW] = \frac{d^{4}N_{photon}}{dtdSd\Omega(d\lambda/\lambda)}$$
$$\propto \frac{N_{ebeam}}{\varepsilon_{x}\varepsilon_{y}}$$

Neutron source: Power

$$P[\mathsf{MW}] = I_{pulse}[\mathsf{mA}] \times E[\mathsf{GeV}] \times duty[\%]$$
$$duty = f_{rep}T_{pulse}$$





#### **Accelerator: A powerful particle smasher**

#### Rutherford scattering experiment using alpha particles in 1909





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The Tevatron Collider: p – pbar (Both beams share the same beam pipe and magnet aperture)





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#### Accelerator: A bright photon source

Profile Monitor YAGS:DMP1:500 11-Apr-2009 0





#### **Accelerator: An intense neutron driver**





## 강력한 입자/핵 분쇄기로서의 가속기: Energy



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### Large Hadron Collider Upgrade

#### → Present LHC will reach its limits in the early 2020s



#### Accelerator physics issues:

- Impedance, Electron cloud, Intra-beam scattering, Beam-Beam
- Crab cavities, Halo collimation, Magnet





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### **Beyond LHC: Lord of the rings**

#### **COLLISION COURSE**

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



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### **Future Circular Collider (FCC)**

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

• *pp*-collider (*FCC-hh*)

~16 T  $\Rightarrow$  100 TeV *pp* in 100 km

- e<sup>+</sup>e<sup>-</sup> collider (FCC-ee) as potential intermediate step
- p-e (FCC-he) option
- HE-LHC with FCC-hh technology
- CDR and cost review by 2018→2019

~25 조원

https://fcc-cdr.web.cern.ch/



[F. Zimmermann]



### China's Proposal: CepC and SppC



### **International Linear Collider**

Parameters	Value			e+ bunch	
C.M. Energy	500 GeV	Damping Rings	IR & detectors	compressor	
Peak luminosity	1.8 x10 <sup>34</sup> cm <sup>-2</sup> s <sup>-1</sup>		/		
Beam Rep. rate	noture				
Pulse duration	nature				
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	Japan delays dee	ision on whether to nos	a 0597 binon mea	accelerator but competing	
	proposals are als	so in development.			-
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### **Muon Collider**

#### Pros:

- Muon is a lepton
- 200 time heavier than electron → less synchrotron radiation
- Muon collider is compact relative to e+ecolliders

#### Cons:

- $\bullet$  The muon lifetime is 2.2  $\mu s$  at rest
- Muon production, manipulation, acceleration to high energy and into collision within muon lifetime
- Needs muon cooling by large factors



Accelerator physics issues:

- Ionization cooling
- RF cavity operation in strong magnetic fields





#### **Advanced Accelerators**

Driv	Medium Driver Dielectric				Plasma				
Laser Pulse Dielectric Laser Accelerator DLA		erator	Laser Wakefield Accelerator LWFA						
Par	Particle Bunch		Structure Wakefield Accelerator SWFA			elerator	Plasma Wakefield Accelerator PWFA		
			0 스	베너지 :프레드	D	WFA (미국 {	<u></u>		
	ANA	Energy C	Gain 4	ΔΕ/E %	Charge (pC)	Peak Gradient GeV/m	Efficiency <sup>1</sup> %	Ref.	<sup>1</sup> Quoted as bunch to bunch energy transfer efficiency.
	LWFA	4.2 Ge	4.2 GeV         3           42 GeV         100           1.6 GeV         0.7		6	47	-	2	<sup>2</sup> Leemans, Phys. Rev. Lett. 113, 245002 (2014)
	PWFA	42 Ge			-	53	-	3	<sup>4</sup> <sup>3</sup> Blumenfeld, Nature 445, 741-744 (15 February 2007)
		1.6 Ge			74	4.4	30	4	$^{5}$ O'Shea Nat Comm 7 12763 (2016)
	SWFA	SWFA30 MeVDLA24 keV		0.7	944	0.32	80	5 	<sup>6</sup> Wooton, Optics Letters 41(12), 2696 (2016)
	DLA			100	-	0.69	-	0	

- → Good parameters achieved individually, but not simultaneously
- → 한국도 LWFA 분야에서는 세계적인 Player (GIST, IBS, UNIST, KAERI, KERI, PAL 등)



#### **Advanced Accelerators**

#### nature

International weekly journal of science

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#### CURRENT ISSUE

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#### AWAKE successfully accelerates electrons

Proton beams from the SPS at CERN were used to generate plasma waves upon which the electrons "surfed"

29 AUGUST, 2018 | By Achintya Rao



AWAKE's electron beam line (Image: CERN)

#### Transformer ratio limit $\rightarrow$ Proton-driven $\rightarrow$ AWAKE (CERN)



### Comparison of Particle Colliders To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



**Advanced Accelerator** d= table top



## 밝은 빛 공장으로서의 가속기: Quality





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### Ultimate (4<sup>th</sup> Generation) Storage Ring



- Quantum excitation + Dispersion Coupling control
  - Chromatic aberration and Non-linearity due stronger focusing
  - Intra Beam Scattering (IBS)
  - Transverse and Longitudinal (cavity HOMs) beam instabilities
  - Injection



~ Radiation damping

### **X-ray Free Electron Laser**



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### 5<sup>th</sup> Generation Light Source ?



- High average brilliance
- Full spatial coherence
- fs to ps pulses
- Many experiments
- Ready tunability
- High flux
- Stability
- High-energy x-rays
- Flexible pulse characteristics
- 10<sup>9</sup> pulses/s
- Narrow energy spread
- Flexible machine parameters
- Drive XFELO, high rep-rate XFEL

#### ERL

XFFL

Storage Ring

### Energy recovered during deceleration is used to accelerate new bunches.

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[Joel D. Brock]



### **Advanced FEL's**

- A compact light source driven by a Laser Plasma Wakefield Accelerator:



Challenges: Repetition rate, Energy spread, Higher electron energy?



#### [표지로 읽는 과학]가속기 없이 만드는 강력한 방사광

2021.07.24 04:00



#### 중국과학원(CAS)

네이처는 이번 연구결과에 대해 "기존 가속기 장비에서 생성하는 X선 자유전자 레이저의 성능과 동일한 성능을 아직 낼 수는 없다"면서도 "X선 자유전자 레이저 수준의 방사광을 만들어내는 기 술의 안전성, 재현성, 효율성을 높이면 대학에서도 갖출 수 있는 소형 가속기로 구동되는 X선 자 유전자 레이저를 만들 길을 열었다"고 평가했다.



네이처 제공.

## 고강도 중성자원으로서의 가속기: Power



### **Intensity (Power) Frontier**





### **Spallation Neutron Source**

#### - 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  $\mu s$  ring revolution time
- Accumulator ring with ~1000 turn charge exchange injection
- A short-pulse neutron source (1.4 MW,700 ns pulse on target)
- Power upgrade by 2025 ( $\rightarrow$  2.8 MW)

#### - European Spallation Source (ESS)



- Space-charge resonances



#### **International Fusion Material Irradiation Facility**





### **Accelerator Driven System (ADS)**



#### Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

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

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<sup>6</sup>), high-resolution measurement of beam particle distributions



### Heavy Ion Fusion (HIF)

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

#### Accelerator physics issues:

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





## 국내 대형가속기 현황



#### **Accelerator Projects in Korea**



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#### **Beam Parameters**

Parameter	PLS-II	KOMAC	PAL-XFEL	RAON		
Species	Electron	Proton	Electron	Proton ~ Heavy ion		
Energy	3 GeV	100 MeV	10 GeV	200 MeV/u for U <sup>79+</sup>		
Beam current	400 mA	20 mA (1.33 ms)	3 kA (0.2 nC/100 fs)	8 ρμΑ U <sup>79+</sup>		
Rep. Rate	499.973 MHz (ring)	60 Hz	120 Hz	CW		
Accelerating Structure	NC S-band (linac) SCRF (ring)	Vane-type RFQ 350 MHz DTL	3 Bunch Compressor 2.856 GHz (S-band)	SCRF: QWR (81.25 MHz), HWR (162.5 MHz), SSR (325 MHz)		
Research Areas	Condensed matter, Surface/Cluster, Material science, Chemistry/Biology, Energy/Medicine	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		
~Typical     ~ front end of       3GSR     SNS/ORNL       53     Moses Chung   Accelerator Physics: Present and Future						

### Conclusions

- Over the decades, accelerator physics has grown into a unique and mature field of applied physics.
- Many exciting and challenging accelerator projects await young and talented accelerator physicists.





# 감사합니다.

