Overview of Accelerator Programs in Korea and Their Potential Contributions to Neutrino/Muon Physics

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Large Accelerators in Korea

4GSR
(4th Generation Storage Ring)

PLS II
(Pohang Light Source)

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

RAON
(Rare isotope Accel. complex for ON-line experiments)

SGCC-HITS
(SNUH Gijang Cancer Center of Heavy Ion Therapy and Study)

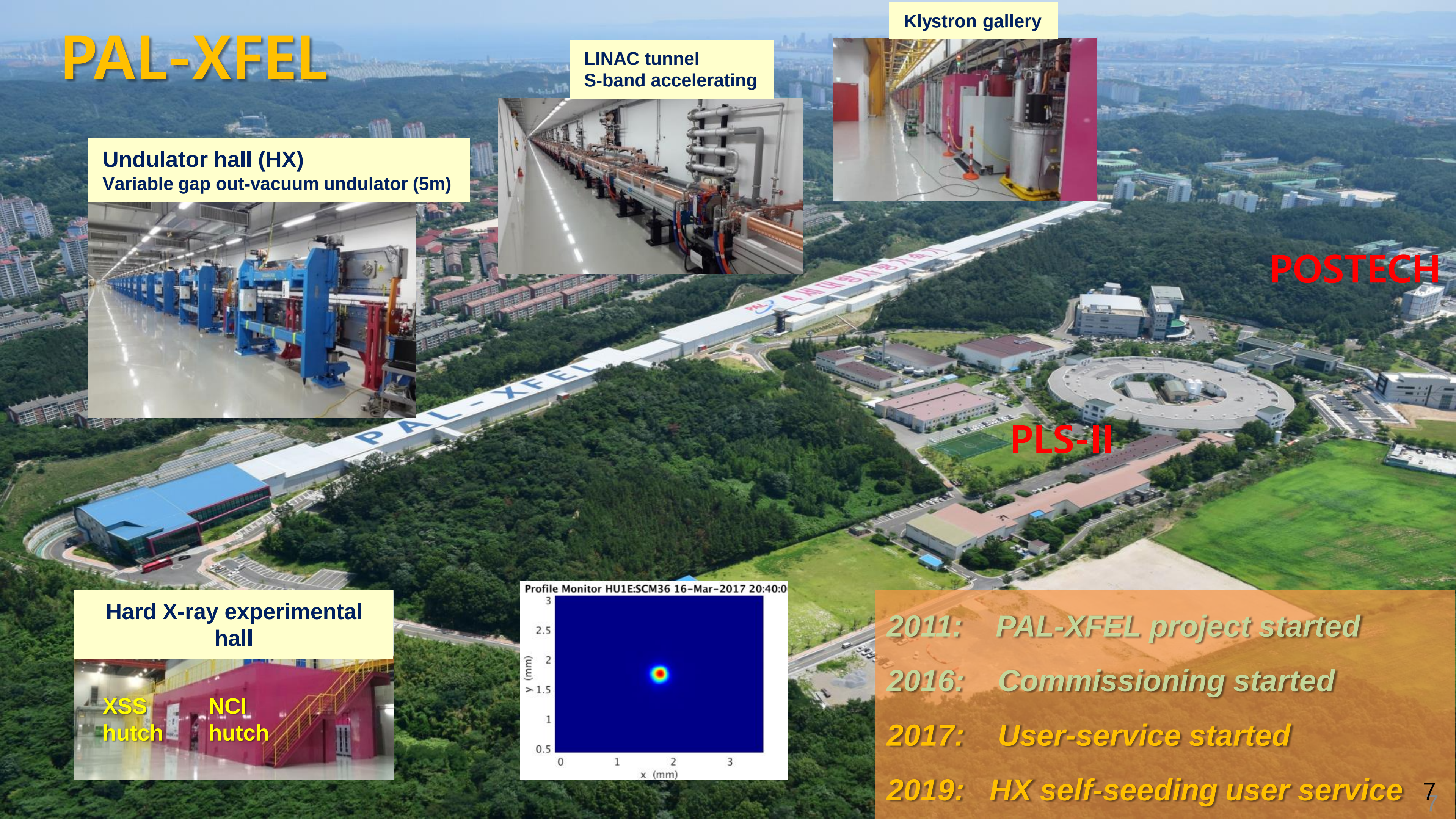
KOMAC
(Korea Multi-purpose Accelerator Complex)

Large Accelerators in Korea: 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^{79+}
Beam current	400 mA	20 mA (1.33 ms)	3 kA (0.2 nC/100 fs)	8 pμA U^{79+}
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 3GSR	~ front end of SNS/ORNL	~ LCLS/SLAC	~ FRIB/MSU

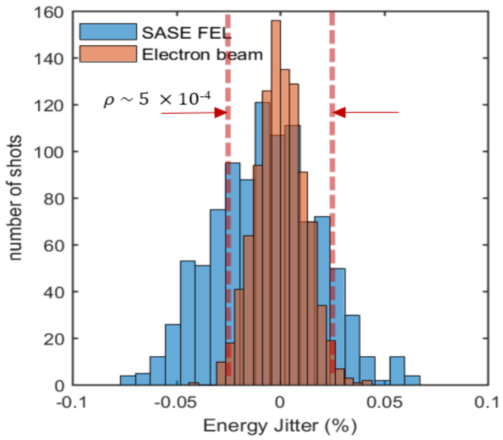
Electron Accelerator (PAL-XFEL)

[Courtesy of H. S. Kang]


PAL-XFEL
Klystron gallery
LINAC tunnel
S-band accelerating
Undulator hall (HX)
Variable gap out-vacuum undulator (5m)
POSTECH
PAL-XFEL
PLS-II
Hard X-ray experimental hall
XSS hutch
NCI hutch
Profile Monitor HU1E:SCM36 16-Mar-2017 20:40:0
y (mm)
x (mm)
2011: PAL-XFEL project started
2016: Commissioning started
2017: User-service started
2019: HX self-seeding user service

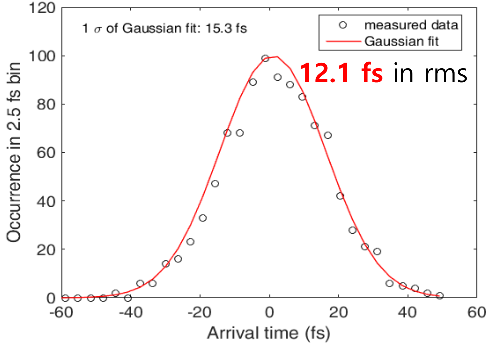
FEL beam performance of PAL-XFEL

- HX: 2.0 ~ 15.0 keV : mJ level intensity (> 1.5 mJ)
  15 ~ 20 keV : 0.4 ~ 1 mJ
- SX: 0.25 ~ 1.25 keV : 0.3 ~ 0.7 mJ
- FEL duration : 20 ~ 30 fs
- Beam availability : > 98%



- FEL intensity jitter < 5% RMS
- FEL position jitter < 10% of beam size
- FEL central wavelength jitter 0.024 % (1/5 of SASE BW)
- **Relative electron beam energy jitter** **1.2×10^{-4}**
- Electron beam arrival time jitter 12 fs
- **Timing jitter** **18 fs (rms)**
  between X-ray pulses and optical pulses

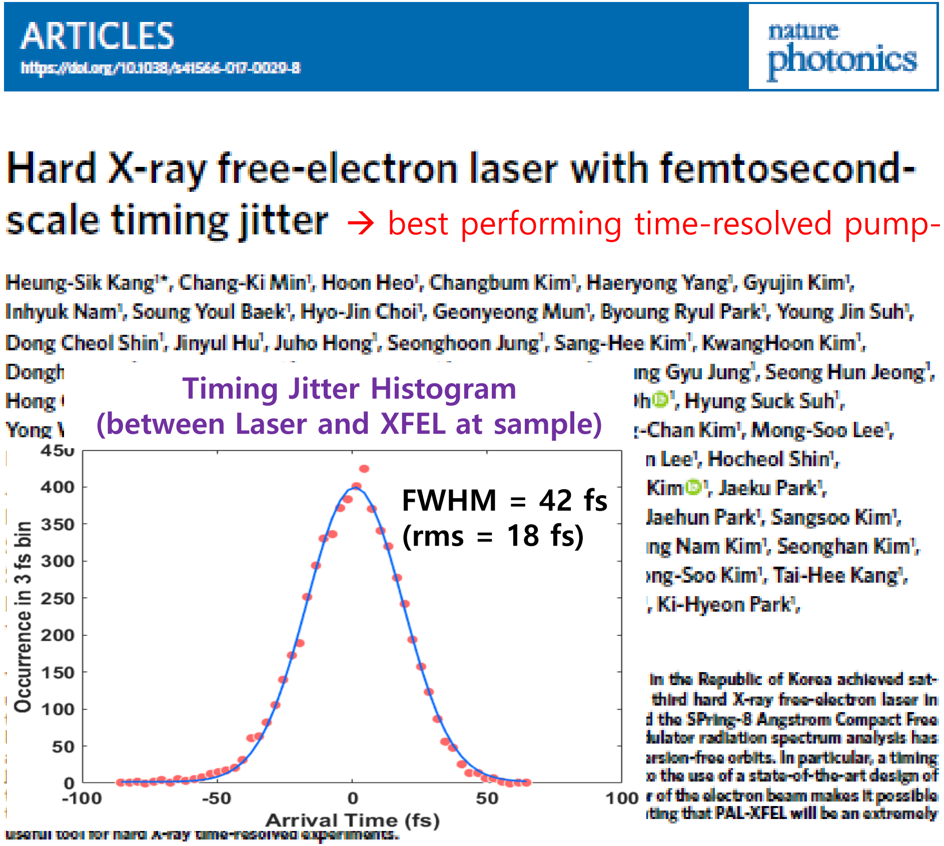
Electron beam arrival time jitter Histogram



- A reliable FEL beam with high timing stability is provided to users

PAL-XFEL: Femtosecond-scale timing jitter

Nature Photonics, **11**, 708–713 (2017)


ARTICLES
https://doi.org/10.1038/s41566-017-0029-8
nature photonics

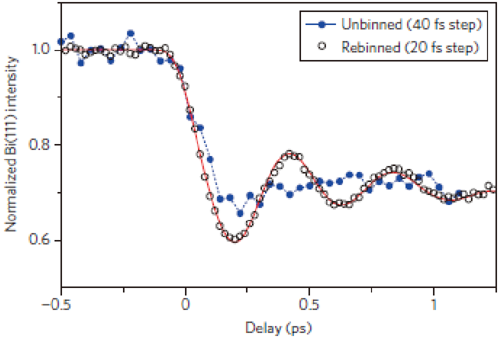
Hard X-ray free-electron laser with femtosecond-scale timing jitter

Heung-Sik Kang[1*], Chang-Ki Min[1], Hoon Heo[1], Changbum Kim[1], Haeryong Yang[1], Gyujin Kim[1], Inhyuk Nam[1], Soung Youl Baek[1], Hyo-Jin Choi[1], Geonyeong Mun[1], Byoung Ryul Park[1], Young Jin Suh[1], Dong Cheol Shin[1], Jinyul Hu[1], Juho Hong[1], Seonghoon Jung[1], Sang-Hee Kim[1], KwangHoon Kim[1], Dongh … ng Gyu Jung[1], Seong Hun Jeong[1], Hong … h[1], Hyung Suck Suh[1], Yong … -Chan Kim[1], Mong-Soo Lee[1], … n Lee[1], Hocheol Shin[1], … Kim[1], Jaeku Park[1], … Jaehun Park[1], Sangsoo Kim[1], … ng Nam Kim[1], Seonghan Kim[1], … ng-Soo Kim[1], Tai-Hee Kang[1], … , Ki-Hyeon Park[1],

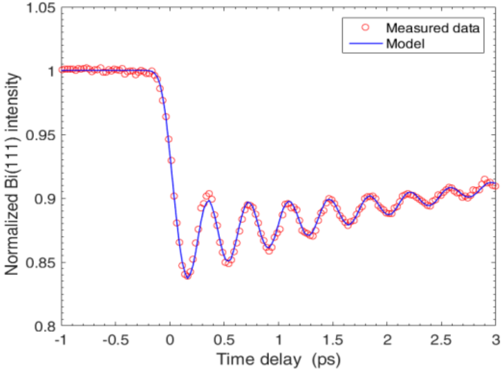
… in the Republic of Korea achieved sat- … third hard X-ray free-electron laser in … d the SPring-8 Angstrom Compact Free … dulator radiation spectrum analysis has … ersion-free orbits. In particular, a timing … o the use of a state-of-the-art design of … r of the electron beam makes it possible … ting that PAL-XFEL will be an extremely useful tool for hard X-ray time-resolved experiments.

→ best performing time-resolved pump-probe experiment

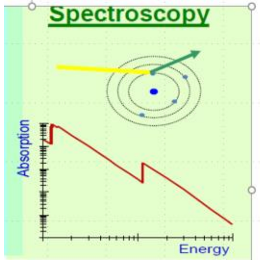
LCLS
Data binning (jitter correction) is necessary



PAL-XFEL
- No timing jitter correction
- Phonon oscillation is very clear



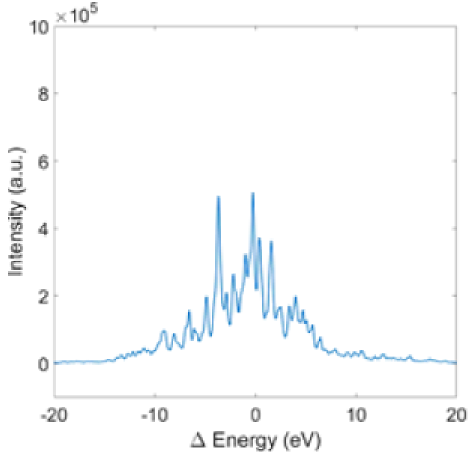
Narrow Bandwidth for Science Applications



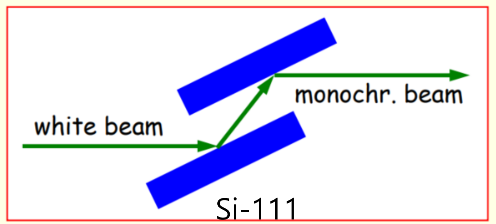
- X-ray Absorption Spectroscopy requires a high intensity, coherent X-ray beam which is tunable over a wide energy range → **Monochromator** is necessary

	SR	FEL: SASE	FEL: SS
Monochromator is necessary?	Yes	Yes	No (?)
Intensity	Very weak	weak	Very strong
Repetition rate	> 100 MHz	~100 Hz	~100 Hz
Time resolved	~ ps	~ fs	~ fs

SASE at 9.7 keV (1.5 mJ), PAL-XFEL

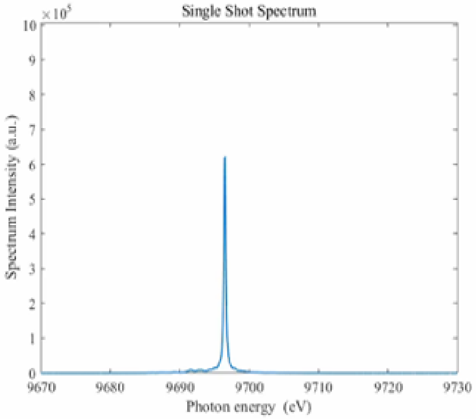


Double crystal monochromator



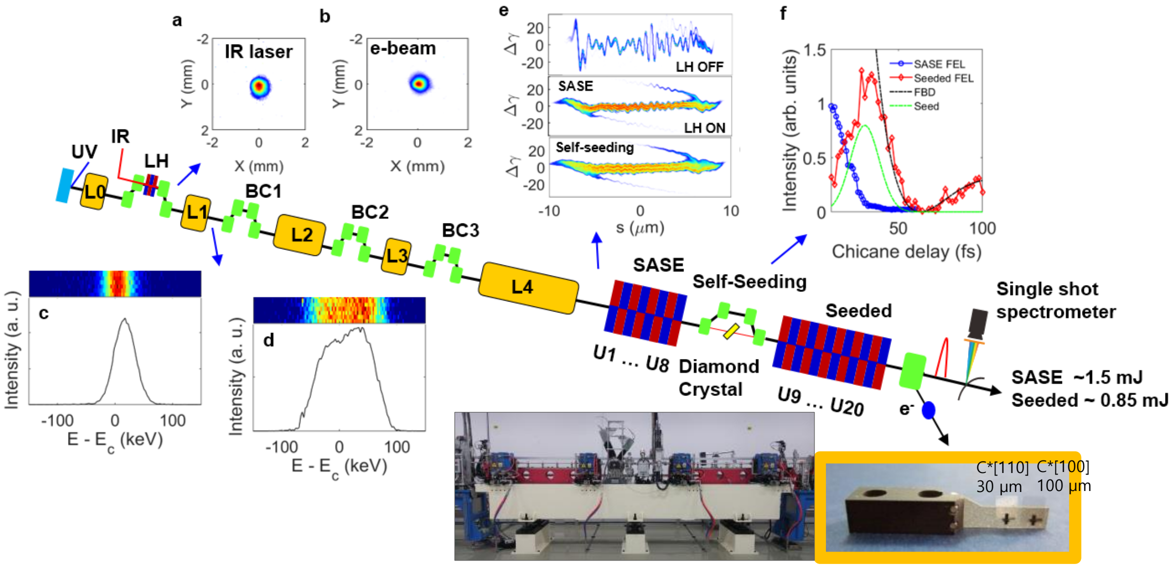
Si-111
Energy Resolution ~ 2x10-4

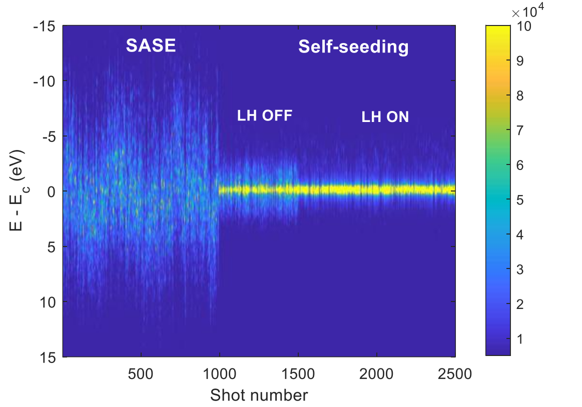
Self-seeding at 9.7 keV (850 μJ)

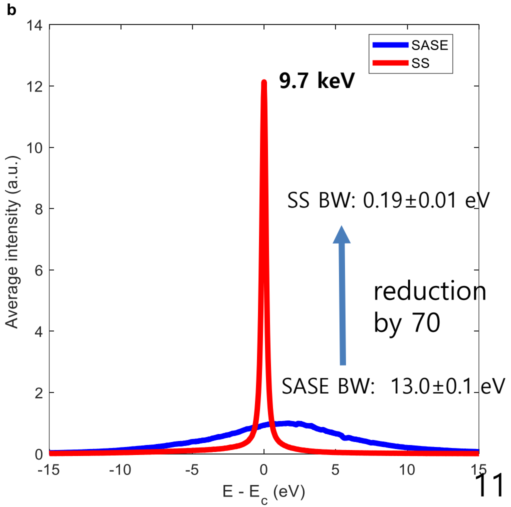


- Very spiky and broad spectrum
- Spectral bandwidth ~ 0.2 % of photon energy (~ a few tens of eV)
- Monochromator is used for narrow band (< a few eV)

PAL-XFEL Hard X-ray Self-seeding







1. Sideband effects are substantially suppressed by a laser heater (LH)
2. Close to Fourier-transform limited:

   Time-bandwidth product: (BW) x (FEL duration) = (0.19 eV) x (20fs) = 3.8 eV· fs ~ 2 X FTL
3. BW is reduced by 70 from SASE.
4. Spectral brightness of Self-seeding is 40 times the SASE

Inhyuk Nam *et al.* High-brightness self-seeded X-ray free-electron laser covering the 3.5 keV to 14.6 keV range. ***Nature Photonics*** **15**, 435-441 (2021)

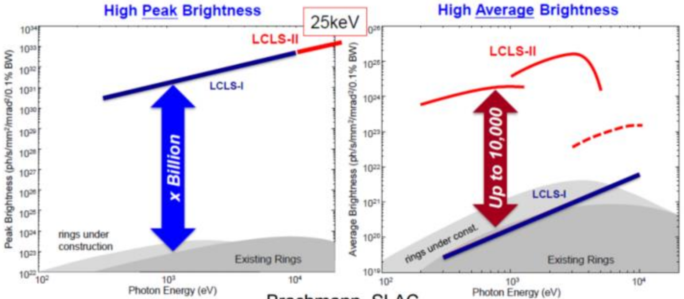
CW XFEL

❖ **CW SC RF electron Linac with electron beam pulse repetition rate of > 1 MHz**

- **LCLS-II:** 4-GeV SCRF (Superconducting RF) Linac, ~2022
- **LCLS-II-HE:** Add more cryomodules to LCLS-II to reach 8 GeV, ~2029
- **SHINE (**Shanghai HIgh repetition rate XFEL aNd Extreme light facility): 8 GeV SCRF Linac, 1.5B US$, ~2025

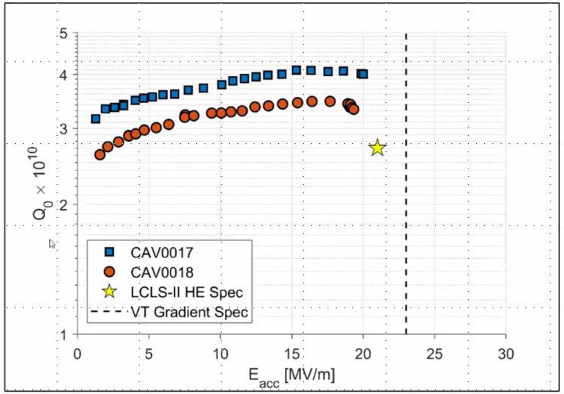
❖ Superconducting RF technology has improved substantially for the past 10 years (SLAC, Fermilab and Jefferson lab)

- N-doping & Mid-T baking method improve Q_o up to 3×10^{10}
  - → lower the cryogenic system cost
  - → lower the electricity consumption



Brachmann, SLAC

Fermilab and Jefferson Lab are developing high-Q (efficient) superconducting RF cavities for the LCLS-II-HE Project at SLAC



Courtesy of Fermilab

- Operating Temp: 2 °K
- $Q_0 = 2.7 \times 10^{10}$ at 21 MV/m

$$Q = \frac{\omega U}{P_{loss}} \qquad P_{loss} = I^2 R$$

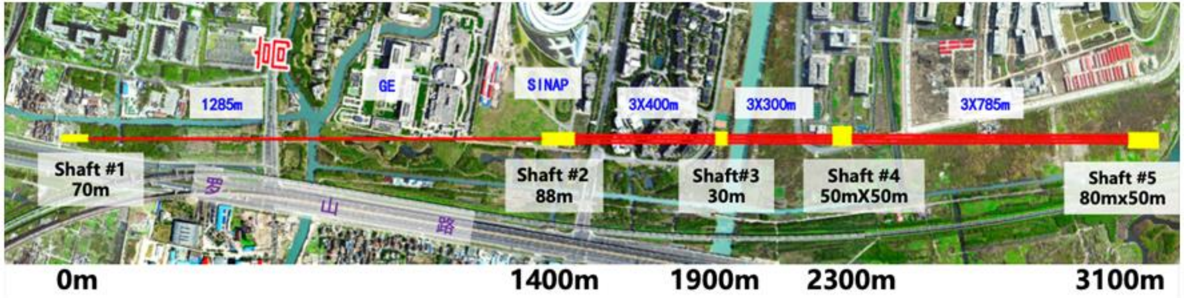
[From Nikolaos Vassilopoulos: New suggestions from China...]

SHINE: an introduction

Tsung-Dao Lee Institute

Only 4 km from TDLI!

- Located in Zhangjiang, Shanghai
- To be commissioned in 2026
- Electron accelerator:
  - 8 GeV energy
  - 1 MHz bunch frequency
  - 100 pC charge (6.25×10^8 electrons) per bunch



Courtesy of
Kim Siang Khaw

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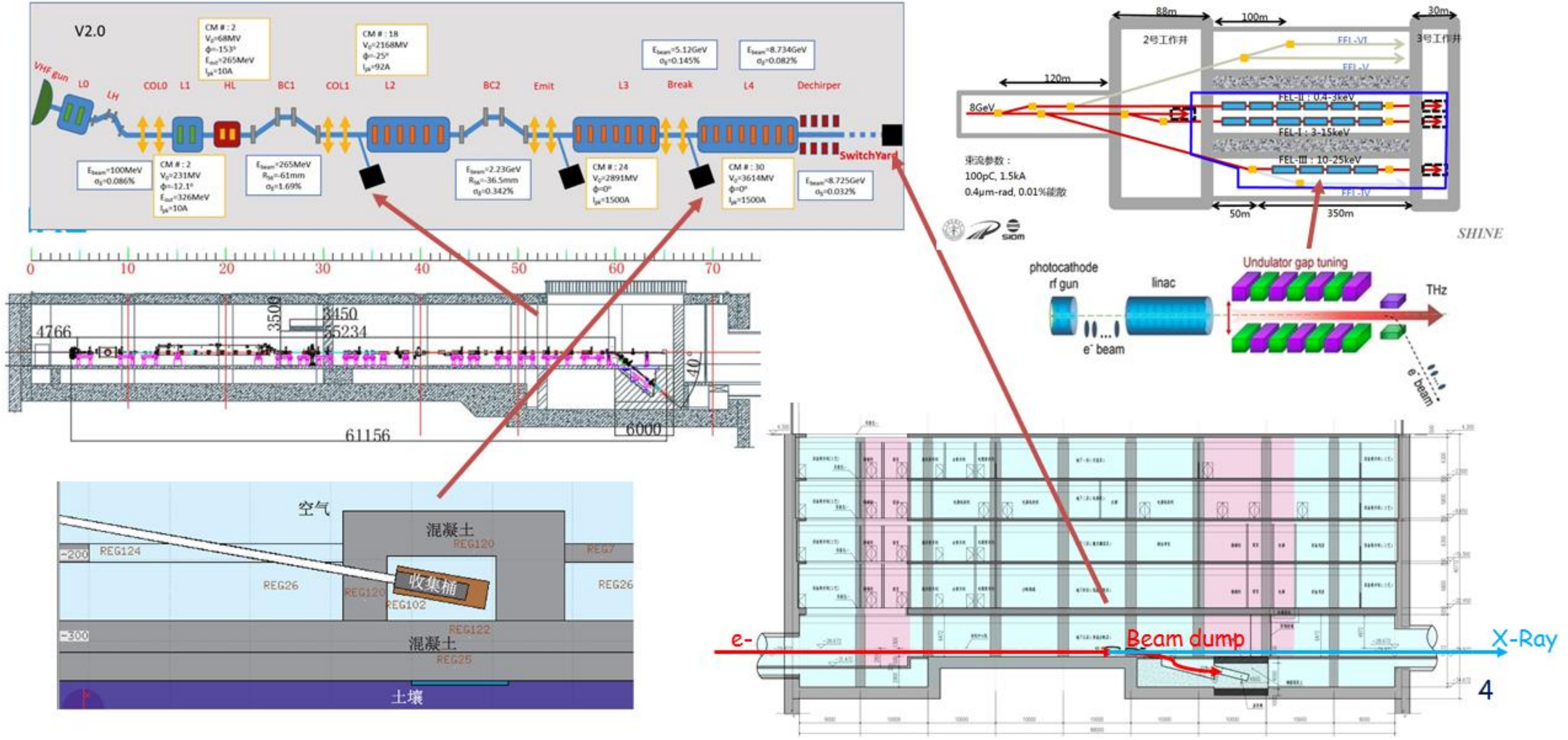
[From Nikolaos Vassilopoulos: New suggestions from China...]

Schematic of SHINE (Beam Dump)

李政道研究所 TSUNG-DAO LEE INSTITUTE



[From Nikolaos Vassilopoulos: New suggestions from China...]

Very rich physics SHINE-based program

李政道研究所
TSUNG-DAO LEE INSTITUTE

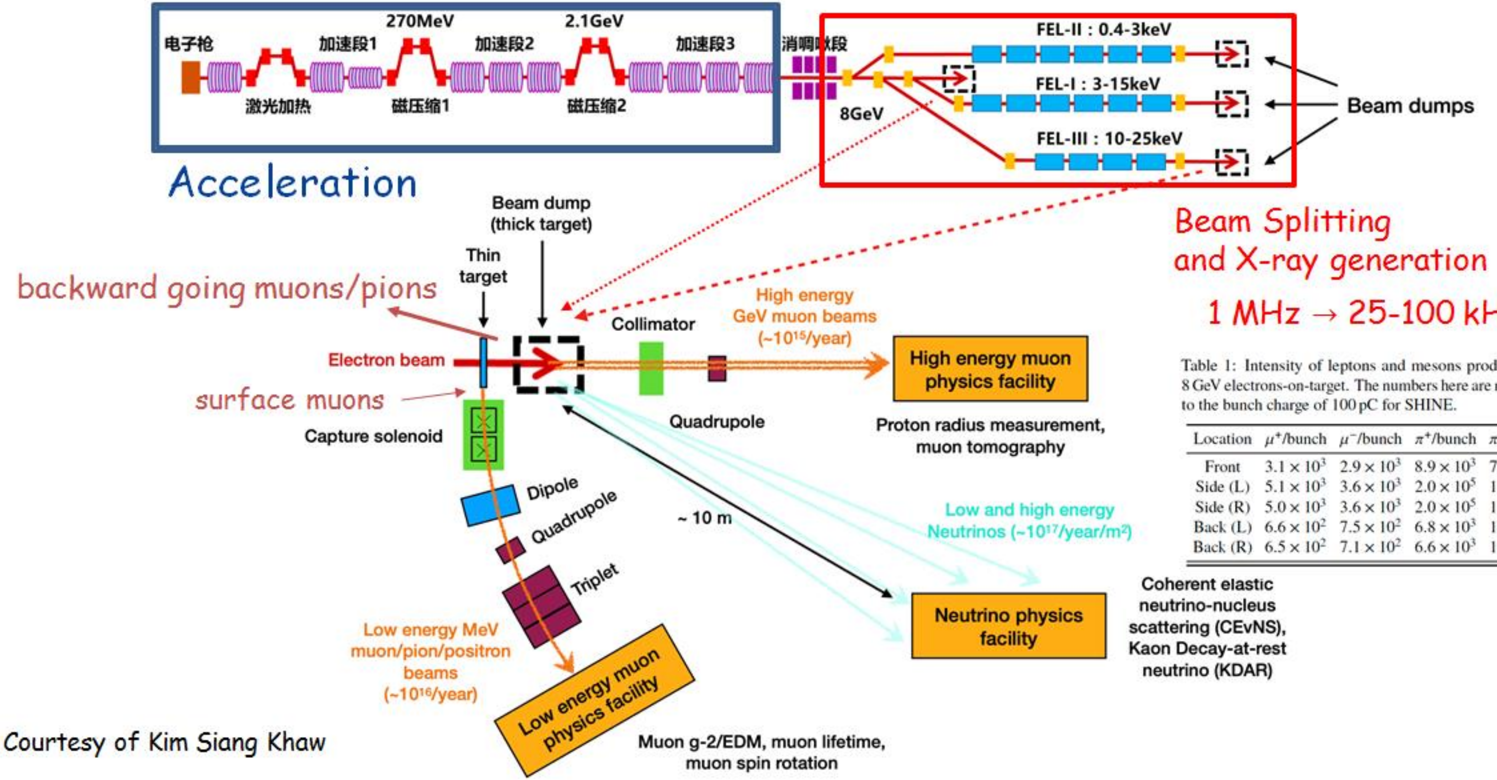


Table 1: Intensity of leptons and mesons produced from 8 GeV electrons-on-target. The numbers here are normalized to the bunch charge of 100 pC for SHINE.

Location	μ^+/bunch	μ^-/bunch	π^+/bunch	π^-/bunch
Front	3.1×10^3	2.9×10^3	8.9×10^3	7.6×10^3
Side (L)	5.1×10^3	3.6×10^3	2.0×10^5	1.9×10^5
Side (R)	5.0×10^3	3.6×10^3	2.0×10^5	1.9×10^5
Back (L)	6.6×10^2	7.5×10^2	6.8×10^3	1.0×10^4
Back (R)	6.5×10^2	7.1×10^2	6.6×10^3	1.0×10^4

Courtesy of Kim Siang Khaw

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Proton Accelerator (KOMAC)

[Courtesy of H. J. Kwon]

KOMAC (KOrea Multipurpose Accelerator Complex)

100 MeV Proton LINAC

History - Developed via Proton Engineering Frontier Project (2002.7~2012.12, 10.5 Year)
(Budget: ₩314B, Area: 180,000 m^2)

Spec - 100 MeV High Current Proton LINAC (max. peak current 20 mA)

Applications - Radiation Effects, RI, Bio, Basic Sciences, Neutron, etc

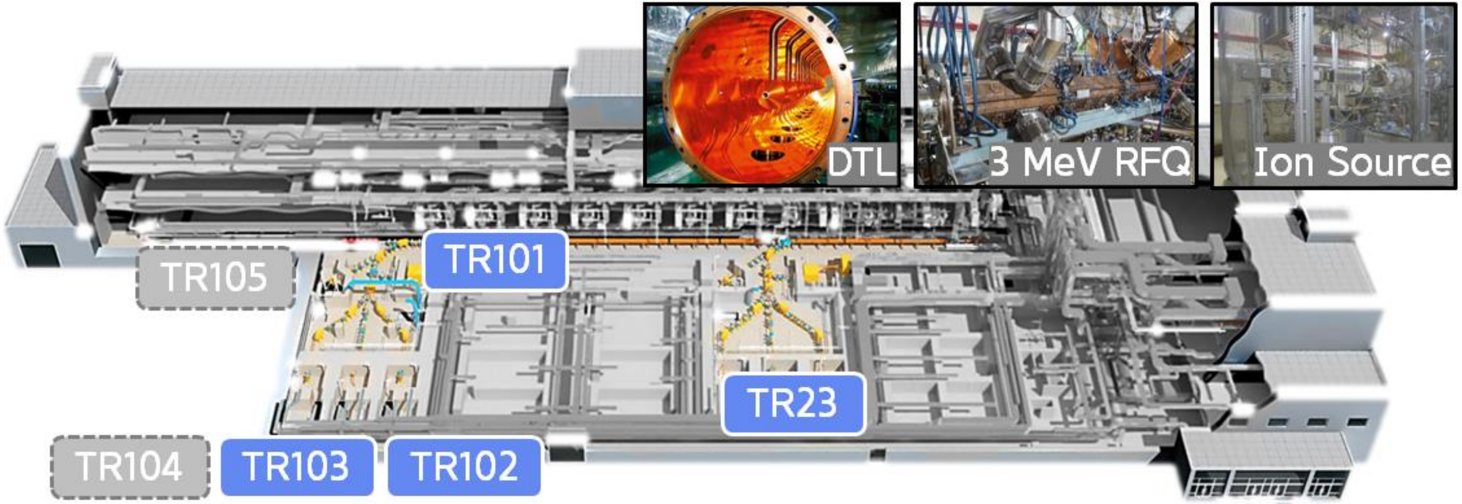
- In last 5 years, supported 459 research projects, 125 institutions, 1,489 users

100 MeV Proton LINAC

KOMAC Site

1
2
3
4
5
6
7
8
KOMAC
1 100 MeV LINAC
2 Ion Beam Facility
3 Power Station
4 Utility Building
5 Sewage Plant
6 Industry Support Center
7 Guest House
8 Main Office Bld.

LINAC Overview



- 50 keV Injector (Ion source + LEBT)
- 3 MeV RFQ (4-vane type)
- 20 & 100 MeV Drift Tube LINAC

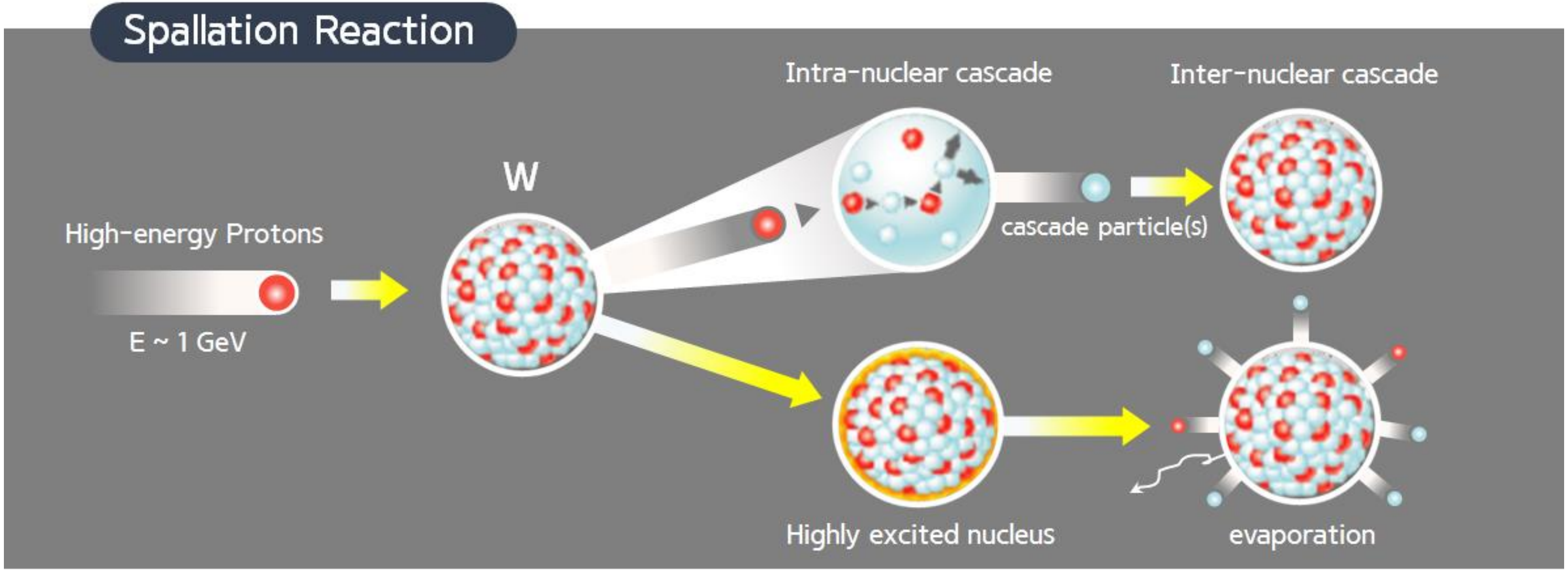
TR23	20 MeV General Purpose
TR101	RI Production
TR102	Low Flux
TR103	100 MeV General Purpose
TR104	(Internal Research)
TR105	(Internal Research)

Extraction Energy	100 MeV
Max. Peak Beam Current	20 mA
Max. Beam Duty	8%
Avg. Beam Current	(max) 1.6 mA
Pulse Length	0.1 - 1.33 ms
Max. Repetition Rate	60 Hz
Max. Average Beam Power	160 kW

Eventual Goal: Spallation Neutron Source

Accelerator-driven
Spallation Neutron Source

Accelerator-driven system that produces a number of neutrons via nuclear spallation induced by high-energy hadron beams on high-Z materials
(for example, 40 neutrons per proton at E_p=1 GeV on W)



Worldwide Proton Accelerators

Low performance compared to other accelerator facilities

Country, Name	LANSCE	SNS	ESS	ISIS	SINQ	J-PARC	CSNS	KOMAC
Institution	LANL	ORNL	ERIC	RAL	PSI	JAEA KEK	IHEP	KAERI
Accelerator Type	LINAC	LINAC	LINAC	Synchrotron	Cyclotron	RCS	RCS	LINAC
Established	1997	2006	2023	1985	1978	2008	2016	2012
Proton Beam Energy (GeV)	0.8	1.0 (1.3)	2.0	0.8	0.59	3.0	1.6	0.1
Average Beam Current (mA)	1.0	1.4 (2.2)	2.5	0.23	1.8	0.33	0.62 (0.31)	(1.6)
Average Beam Power (MW)	0.8	1.4 (2.8)	5.0	0.18	1.0	1.0	0.1 (0.5)	(0.16)
Spallation Neutron Source	O	O	O	O	O	O	O	X
Thermal Neutron Flux (n/sec)	$> 10^{15}$	$> 10^{17}$	$> 10^{18}$	$> 10^{16}$	$> 10^{14}$	$> 10^{17}$	$> 10^{16}$	-

- Most large-scale proton accelerator facilities have beam energy more than 800 MeV
- High-power accelerators are driving spallation neutron source for sciences

Future Plan: Staged Approach

Goal 1 Proton accelerator upgrade up-to 1 GeV

Goal 2 World-class proton and neutron science platform

① Proton sciences | ② Neutron sciences

Demand

Atmospheric/space radiation test for semiconductor devices in aerospace, automotive, data storage, and communications

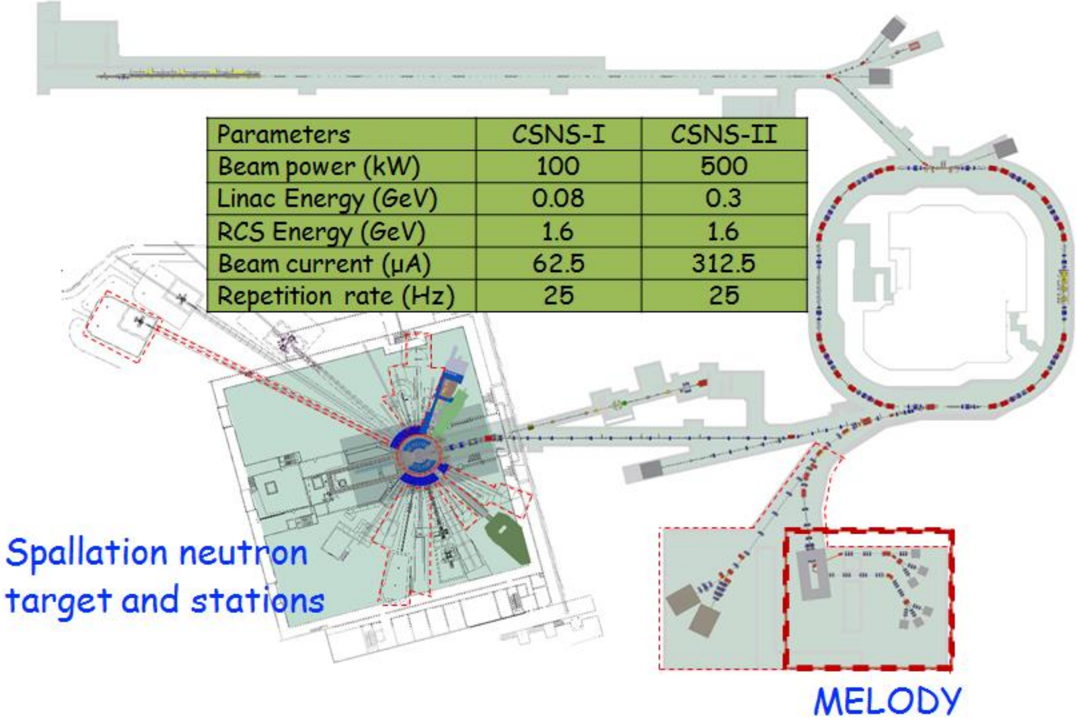
Neutron scattering techniques for most advanced science and technology

100 MeV LINAC (Present)	200 MeV LINAC (~29')	Spallation Neutron Source by 1 GeV Proton (30' ~)

[From Nikolaos Vassilopoulos: New suggestions from China…]

Muon station for sciEnce technoLOgy and inDustrY (MELODY) @ CSNS II

Parameters	CSNS-I	CSNS-II
Beam power (kW)	100	500
Linac Energy (GeV)	0.08	0.3
RCS Energy (GeV)	1.6	1.6
Beam current (μA)	62.5	312.5
Repetition rate (Hz)	25	25



Protons from RCS @ 20 kW, 1.6 GeV, 1 Hz

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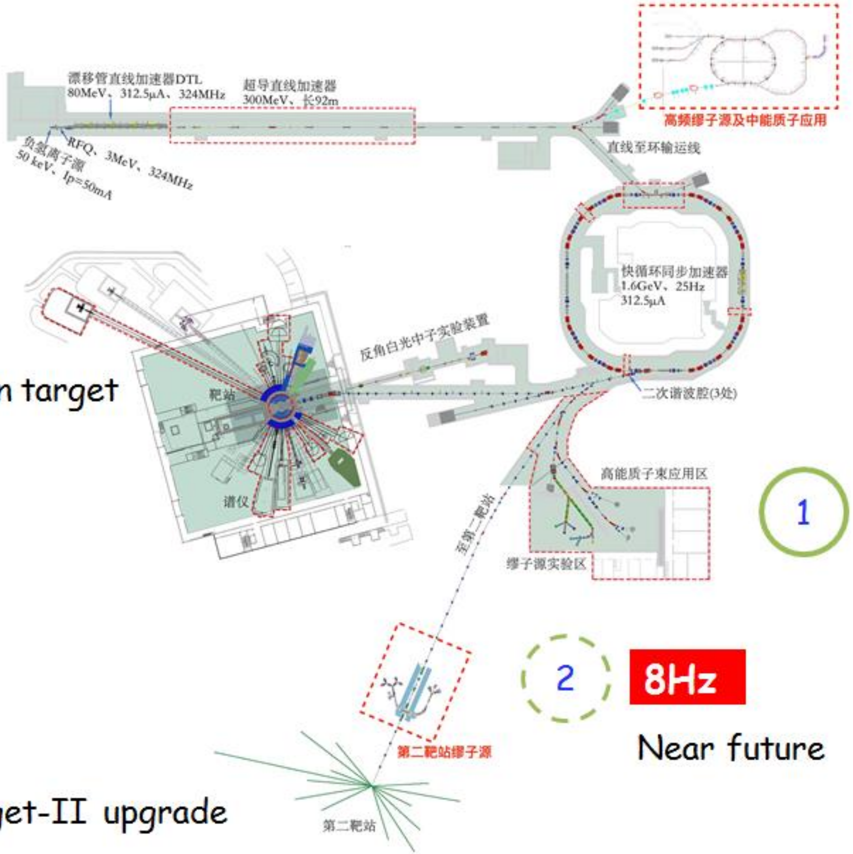
[From Nikolaos Vassilopoulos: New suggestions from China…]

Future muon beamlines



3 100~1000 Hz

Far future

Spallation target

1 1Hz, kick off

2 8Hz

Near future

Spallation target-II upgrade

Heavy Ion Accelerator (RAON)

[Courtesy of Y. S. Chung]

RAON: Rare isotope Accelerator complex for ON-line experiments

Goal	To build a heavy ion accelerator complex, RAON, for rare isotope science research
Period	1st Phase: 2011.12 - 2022.12 R&D for the 2nd Phase: 2022.12 - 2025.12
Budget	~$ 1.4 B (Facilities ~ $ 0.5 B; Land, Bldgs & Utilities ~ $ 0.9 B) * includes initial experimental apparatus

RAON

Accelerator complex

ISOL + In-Flight Fragmentation

Origin of Matter

- Nuclear Astrophysics
- Nuclear Matter
- Super Heavy Element Search
- High-precision Mass Measurement

Properties of Exotic Nuclei

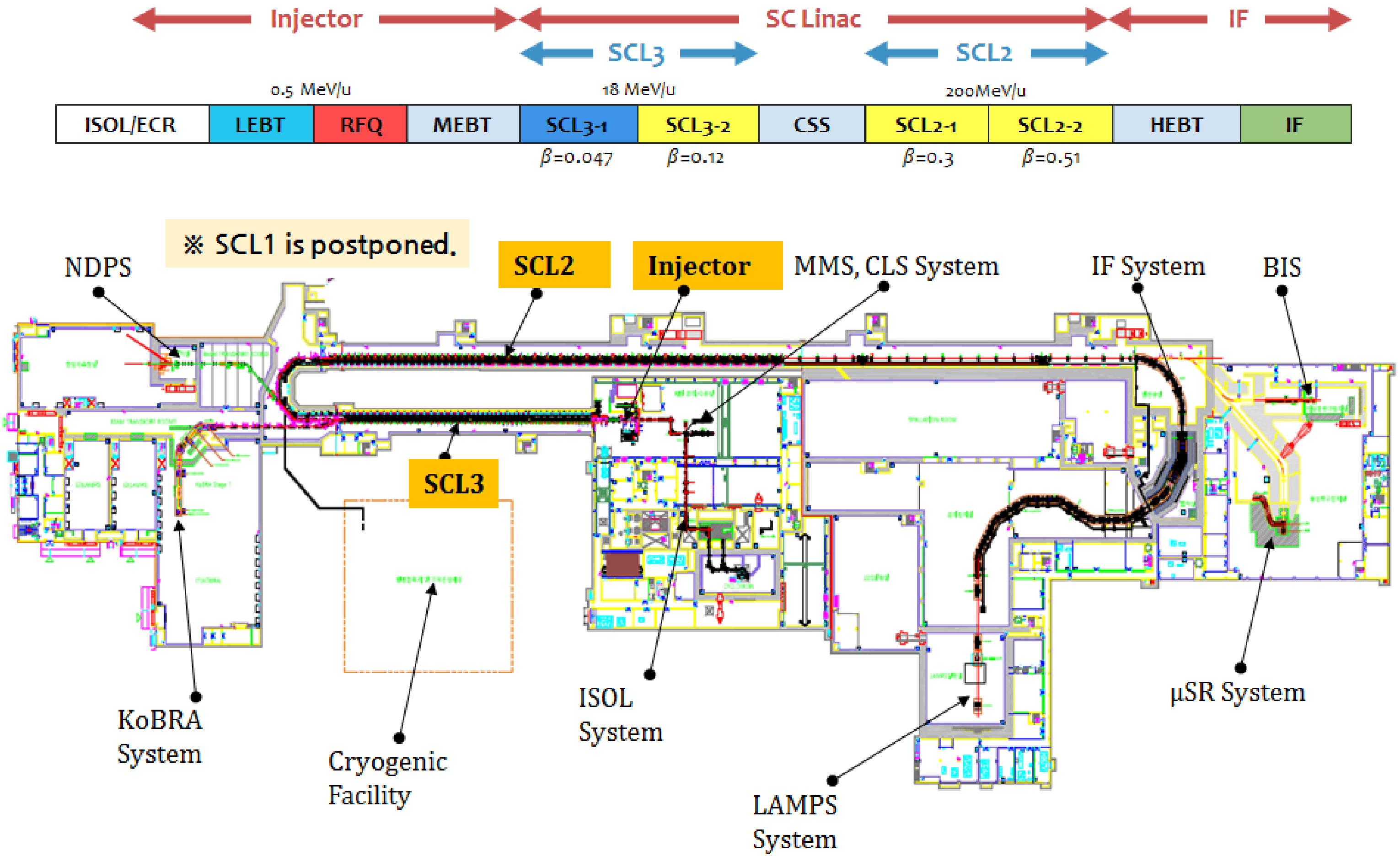
- Nuclear Structure
- Electric Dipole Moment and Symmetry
- Hyperfine Structure Study

Applied Science

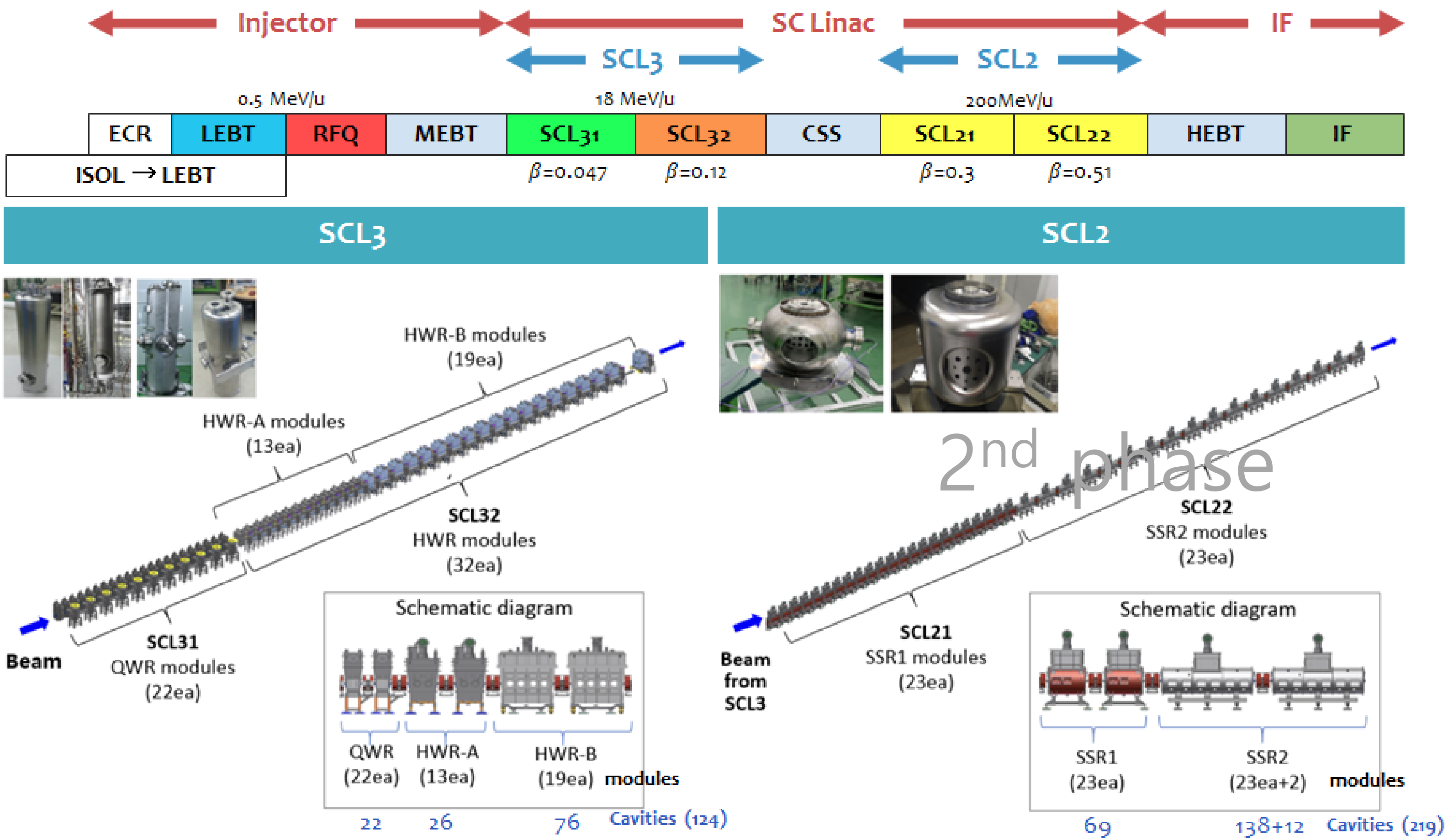
- Bio-Medical Sciences
- Material Sciences
- Neutron Science

Bird's-eye-view of RAON

Accelerator System



Accelerator System



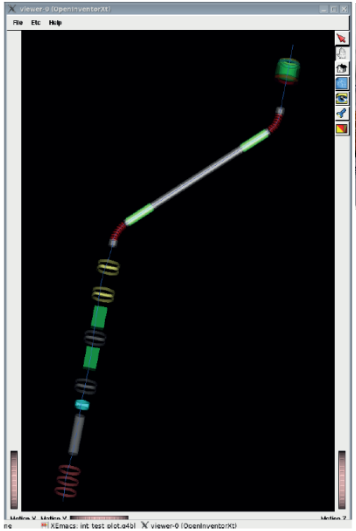
RAON μSR facility

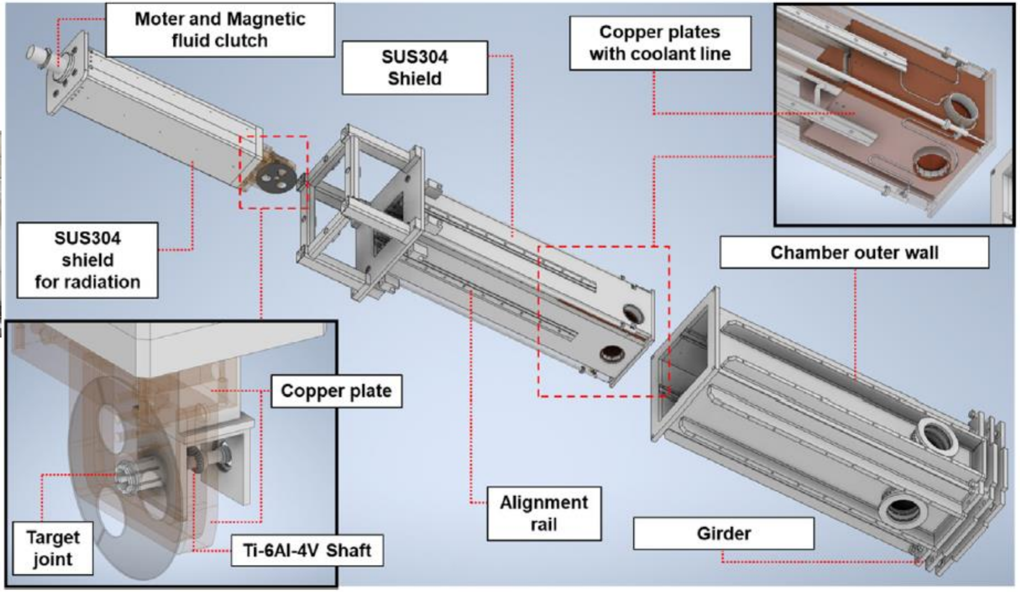
After the 2nd phase, the RAON will provide 600 MeV and 100 kW (one-fourth of the maximum power) proton beam:

Product	Bulk Density (g/cm^3)	Tensile Strength (MPa)	Compressive Strength (MPa)	Young's Modulus (GPa)	Coefficient of Thermal Expansion (10^{-6}/K)	Thermal Conductivity (W/(m·K))	Melting Point (°K)
Graphite (IG-430U)	1.84	56.8	99	10.8	5.2	140	3773
B_4C	2.3–2.55	261–569	2583–5687	362–472	3.2–9.4	17–42	2645–2780
BN	1.9–2.3	27–83.3	224–540	19.5–100	1–6	19–52	3150–3400

	Graphite	B_4C	BN
Surface muon yield (#/sec)	8.167×10^9	8.631×10^9	7.920×10^9
Standard deviation (#/sec)	9.037×10^4	9.290×10^4	8.900×10^4

muon beam transport system





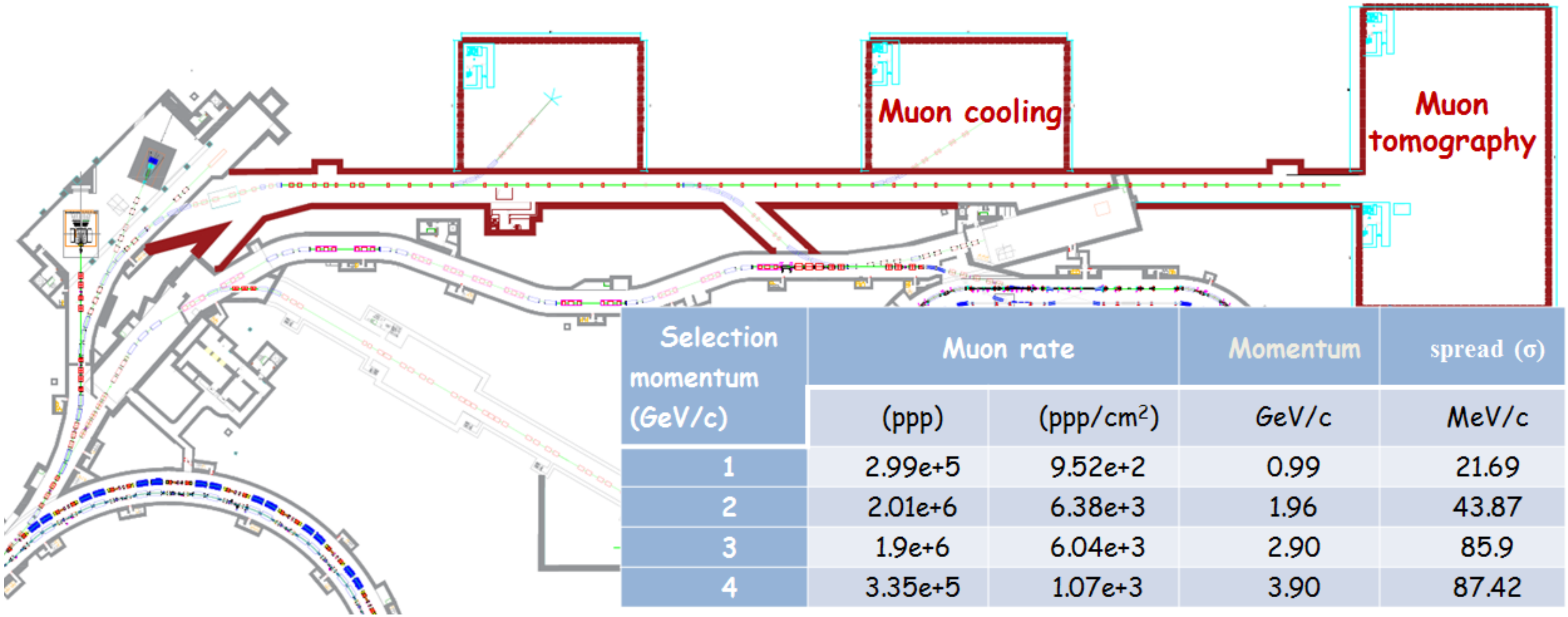
Composition of target system

[From Nikolaos Vassilopoulos: New suggestions from China…]

Muon Source plan at HIAF

Courtesy Zhao, He

4.26 GeV/u $^{36}Ar^{18+}$ + C(22.53g/cm^2)   Intensity: 1e+11 ppp



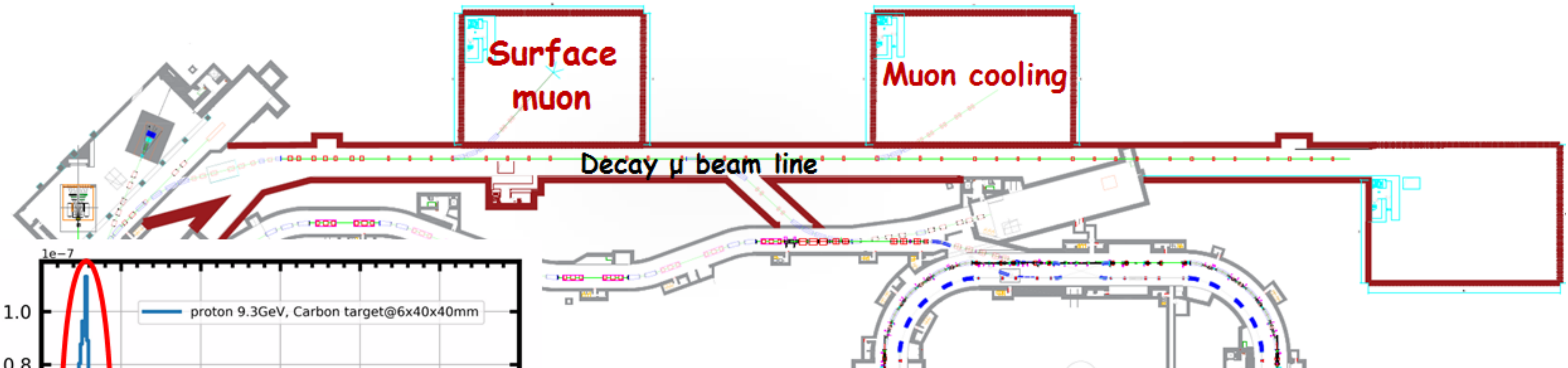
Selection momentum (GeV/c)	Muon rate (ppp)	Muon rate (ppp/cm^2)	Momentum GeV/c	spread (σ) MeV/c
1	2.99e+5	9.52e+2	0.99	21.69
2	2.01e+6	6.38e+3	1.96	43.87
3	1.9e+6	6.04e+3	2.90	85.9
4	3.35e+5	1.07e+3	3.90	87.42

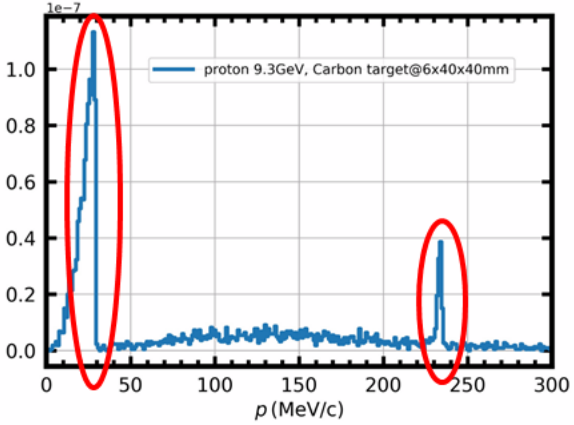
Courtesy Chen, Liangwen & Zhao, He

[From Nikolaos Vassilopoulos: New suggestions from China...]

Muon Source plan at HIAF

Proton 9300 MeV, 5×10^{13} ppp, 3 Hz





❑ HIAF surface muon beam:

- ~30 MeV/c surface muon (pion DAR), intensity of 1.7×10^7 μ+/s, pulse width of ~150 ns, 3 Hz.
- ~240 MeV/c surface muon (kaon DAR), pulse width of ~100 ns.

Courtesy Chen, Liangwen & Zhao, He

Accelerator-Based Neutrino/Muon Physics in Korea

Summary

- **Several large-scale accelerator projects are undergoing in Korea. Whereas these accelerators are not suitable for neutrino/muon physics yet, future upgrades may enable some physics programs.**

- **Ideas and inputs from the international and domestic user communities are crucial in developing future upgrade strategies. For example, China seems manage to incorporate some neutrino/muon physics programs in its accelerator projects.**