Hard X-ray FEL project at Shanghai

Accelerator System

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For the SCLF Accelerator Team

February 2nd , 2018, ESS, Lund

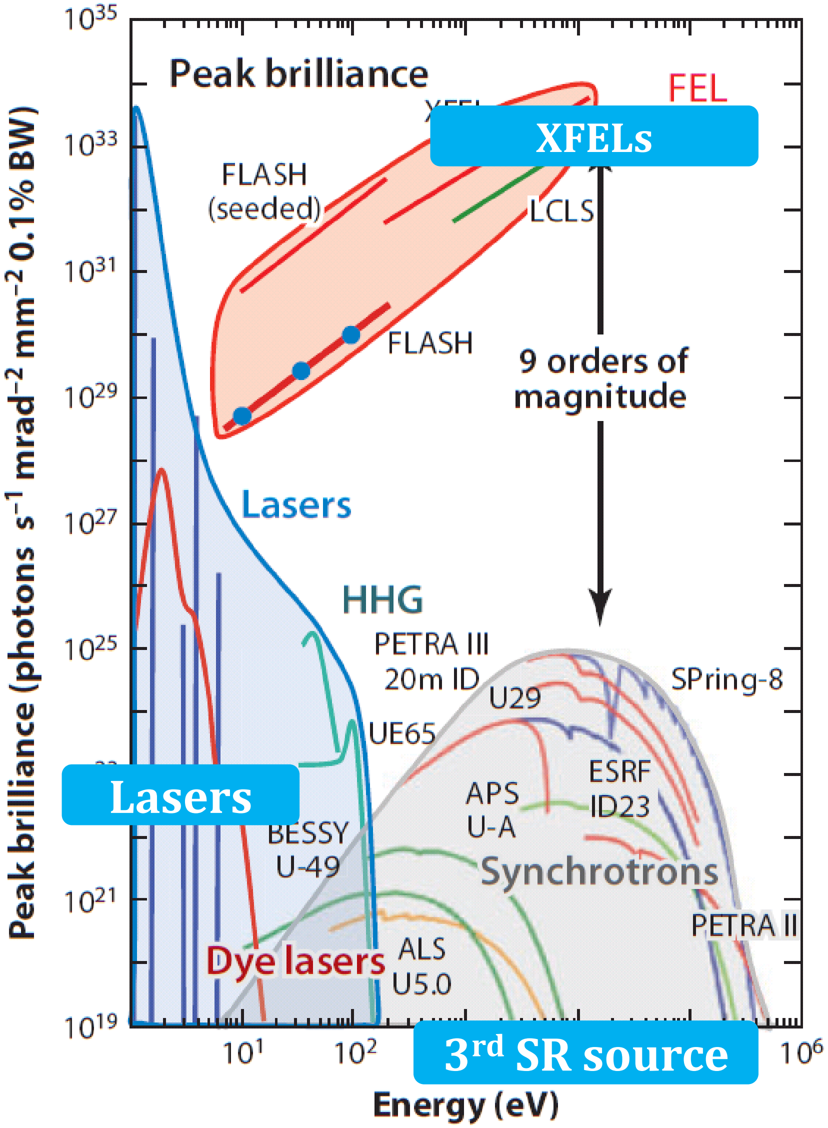
SCLF

Outline

- Introductions
- General layout and parameters
- Linac
- FEL&Undulator
- Summary

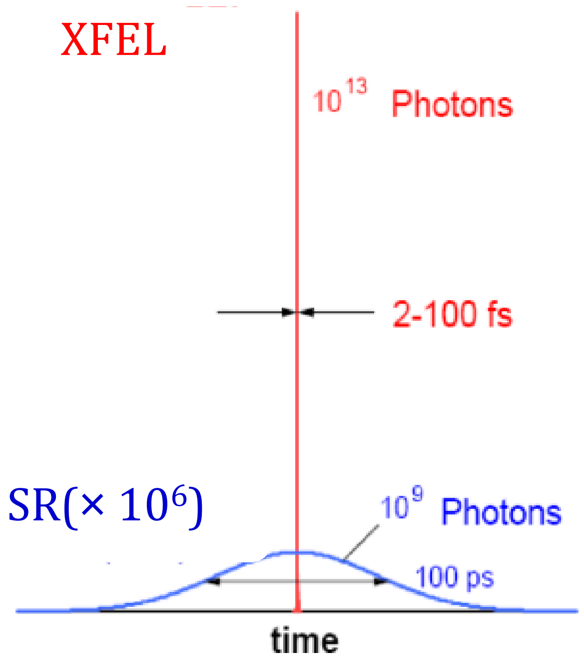
SINAP Zhangjiang Campus, Shanghai

XFEL: new generation



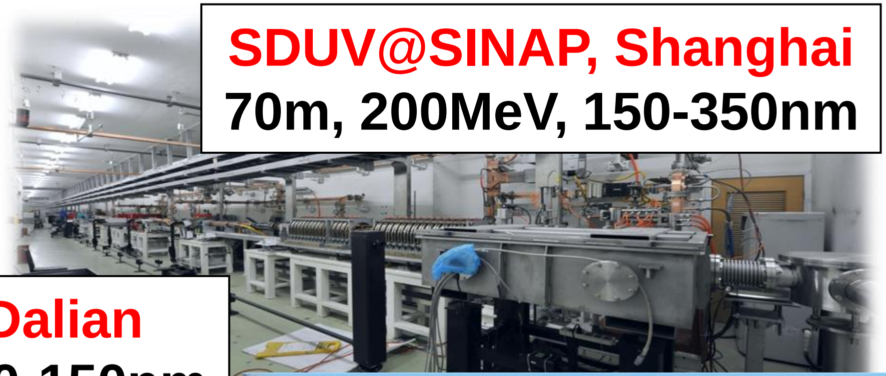
XFEL

- Coherent
- <10 fs ultra fast
- ~10^{12} photons/pulse ultra right



Lots of XFEL are being built/ designed including one in Lund

Existing High-gain FELs in China



SDUV@SINAP, Shanghai
70m, 200MeV, 150-350nm

150M Euro
Total investment

DCLS@DICP, Dalian
150m, 300MeV, 50-150nm

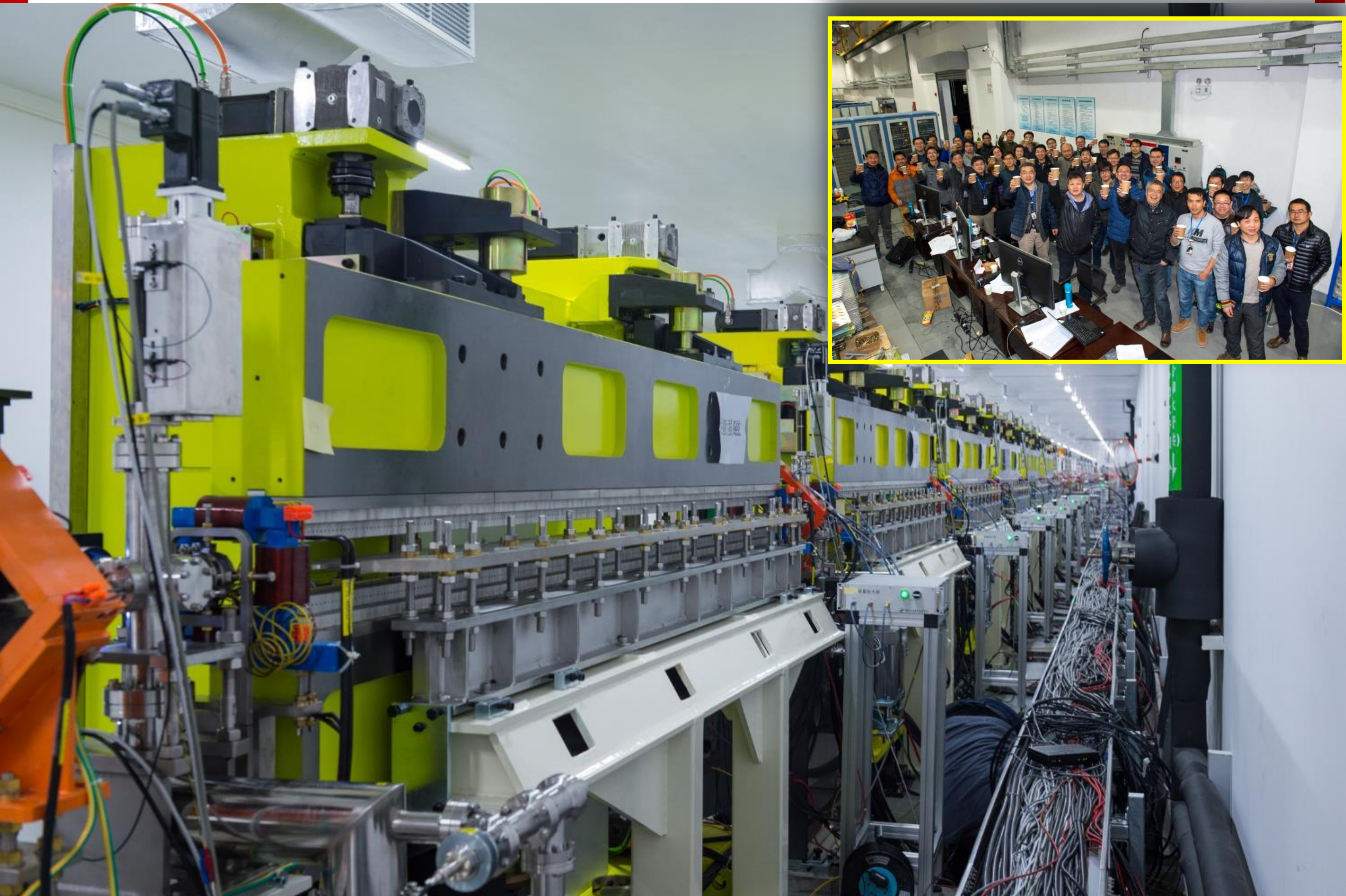
SXFEL@SINAP, Shanghai
300m, 840MeV, 9-40nm

SXFEL-user@SINAP, Shanghai
532m,1.5GeV, 2-20nm

XFEL Test Facility (2015-2018)

X-ray FEL Test Facility：0.84GeV warm linac

XFEL Test Facility

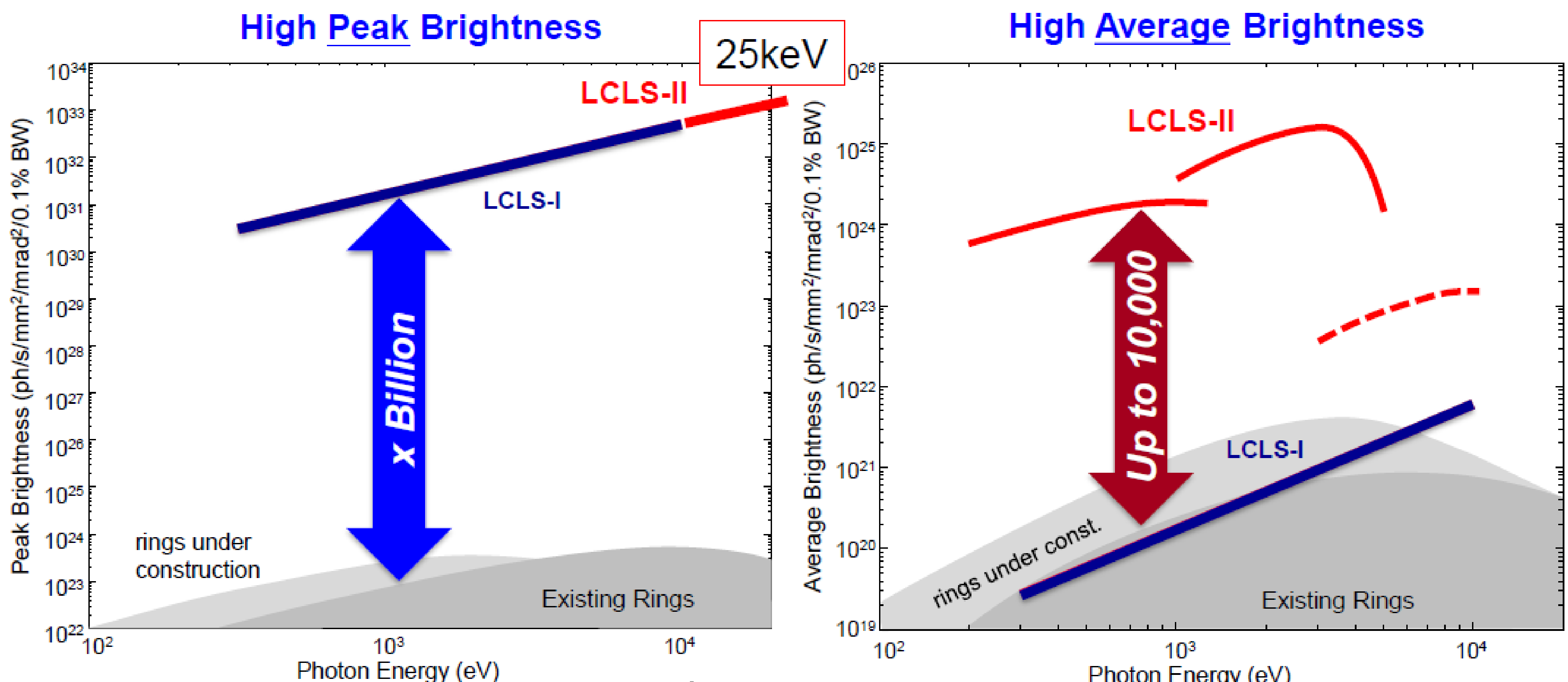



SSRF
3.5GeV Light Source
Hard XFEL
8 GeV SC, 3.1km
3 FEL lines, 10 stations
Soft XFEL User Facility
1.5GeV e- / ~1keV x-ray
532m, 2 FEL lines/5 stations
Photon science complex at Shanghai

Why scRF-based XFELs?

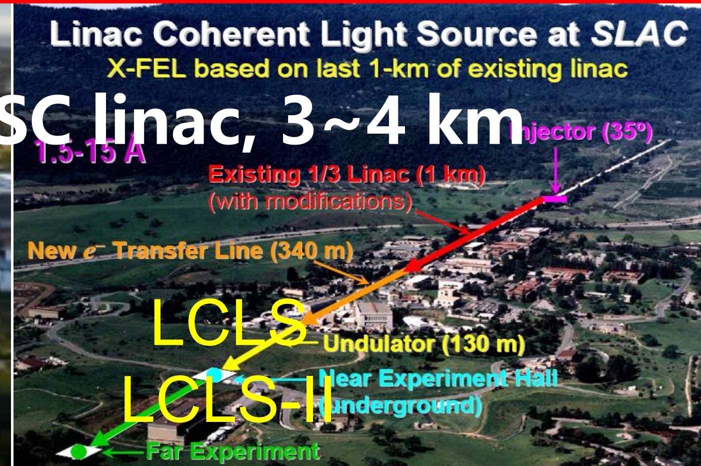
LCLS-II provides a factor >10^3 in average brightness (to 5 keV), and extends the reach of the Cu linac to 25 keV

SLAC

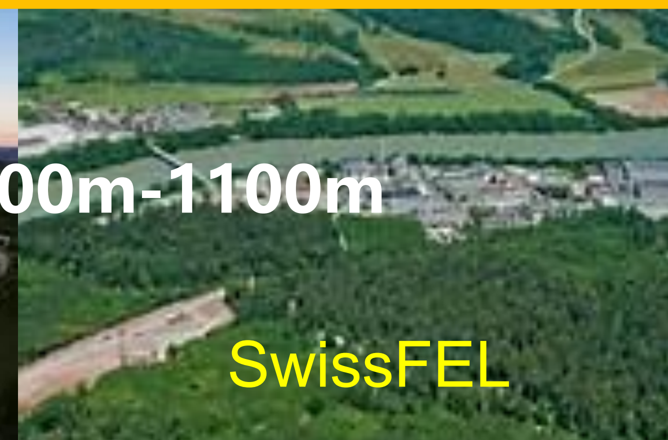


Bachmann, SLAC

Hard X-ray FELs, SC linac, 3~4 km



Hard X-ray FEL, warm linac, 700m-1100m



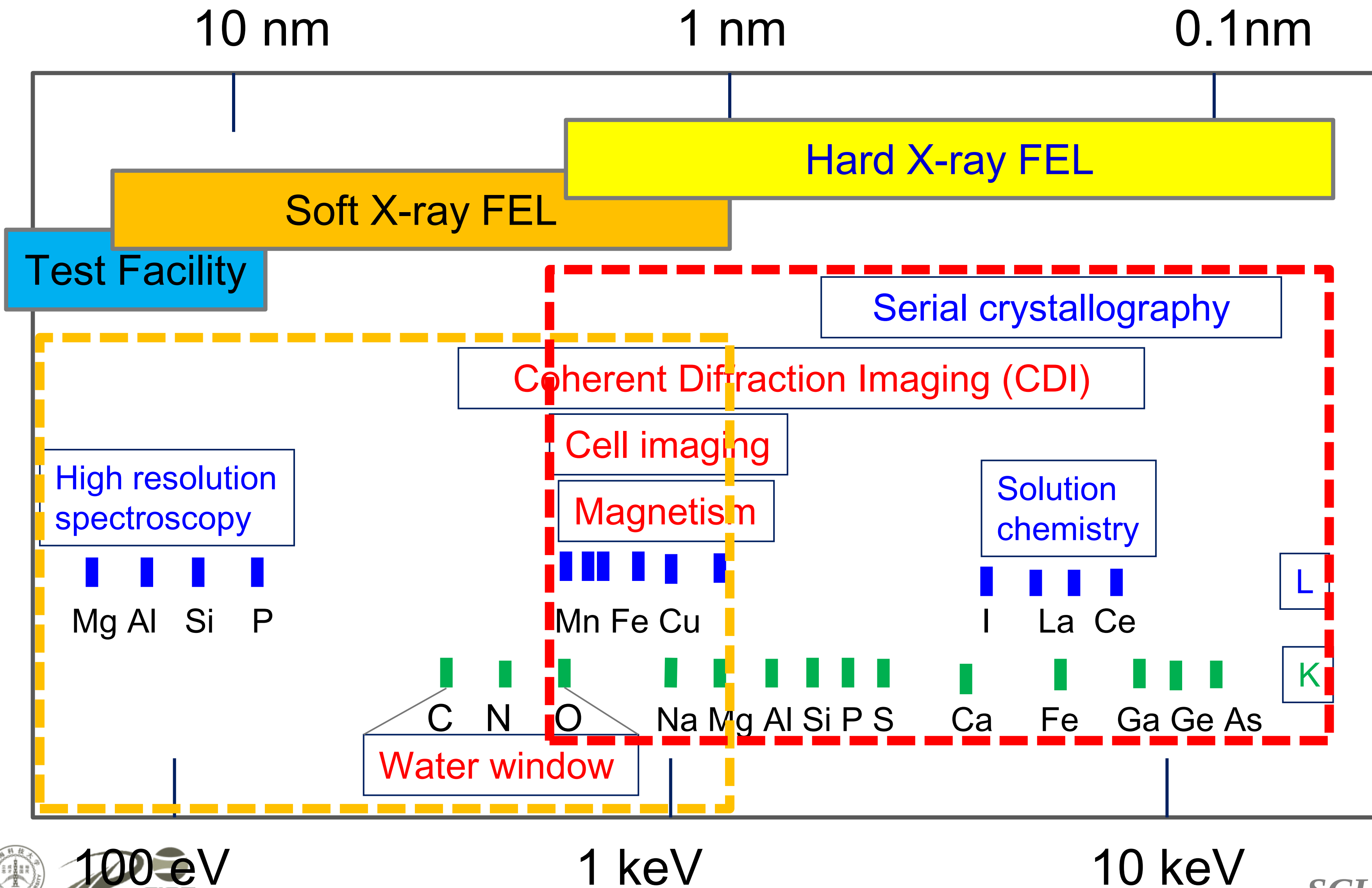
Soft X-ray FEL, warm linac, 400m-500m

Decision making on next XFEL project

- Initial plan: **low rep-rate XFEL with warm linac,**
  - PROS: low cost/compact/early operation
  - CONS: quite limited performance
- CW option: **high rep-rate XFEL with cw scRF linac**
  - PROS: high performance, much more potentials
  - CONS: expensive/late operation/technical challenge

Finally, with strong support by local government (75% of total cost and 100% R&D funding), **cw option** was chosen.
Approval by national/local funding agency: April 28, 2017

Scientific needs for XFELs at SINAP



Scope of Hard X-ray FEL at Shanghai

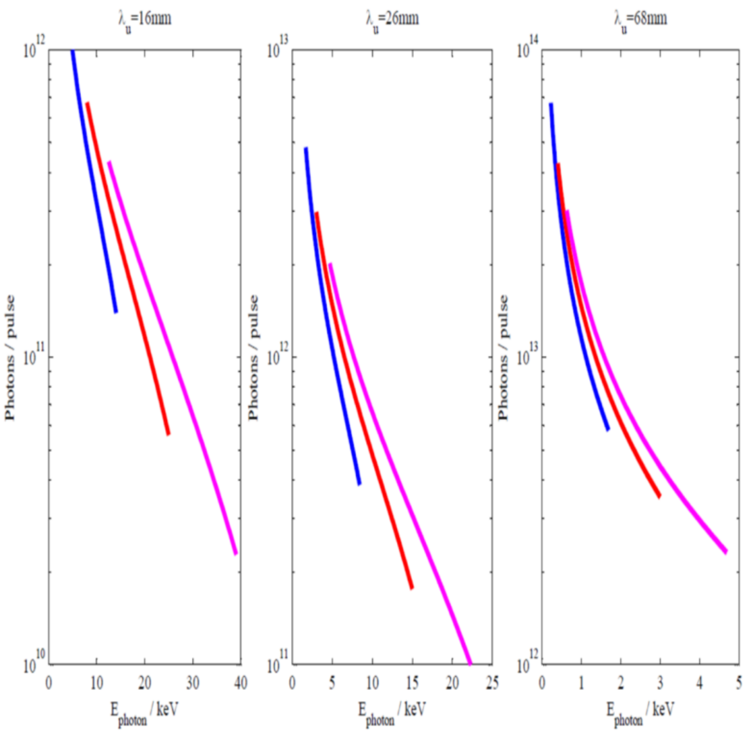
- ~3km long, 8GeV cw linac, 1MHz rep-rate, 3 FEL lines
- 3 beamlines, 0.4-25keV, ~10 stations, multi-PWs laser
- Cost: ~1.2 B Euros
- Schedule: 7 years(2018-25)
- R&D: 0.1B Euros, most for scRF tech./ infrastructures
- Potentials: 6 undulator/beamline, ~30 stations, 100PW laser vs. XFEL collisions, gamma ray physics, etc.

Main Parameters

Parameters	Design Goal
Electron Energy (GeV)	8
Slice Energy Spread (rms)	≤0.01%
Slice Emittance (mm·mrad , rms)	≤0.4 (0.2-0.7)
Bunch Charge (pC)	100(20-200)
Peak Current (A)	~1500 (500-3000)
Max. Rep. Rate (kHz)	1000
Photon Energy Range (keV)	0.4 - 25
Pulse Length (fs)	fs ~ 100 fs
Arrival Jitter (fs)	<30
Stability	<10%
Coherence	Transverse and temporal
Peak Power (GW)	>10 @12keV>20 @1keV

Overall Parameters Choice

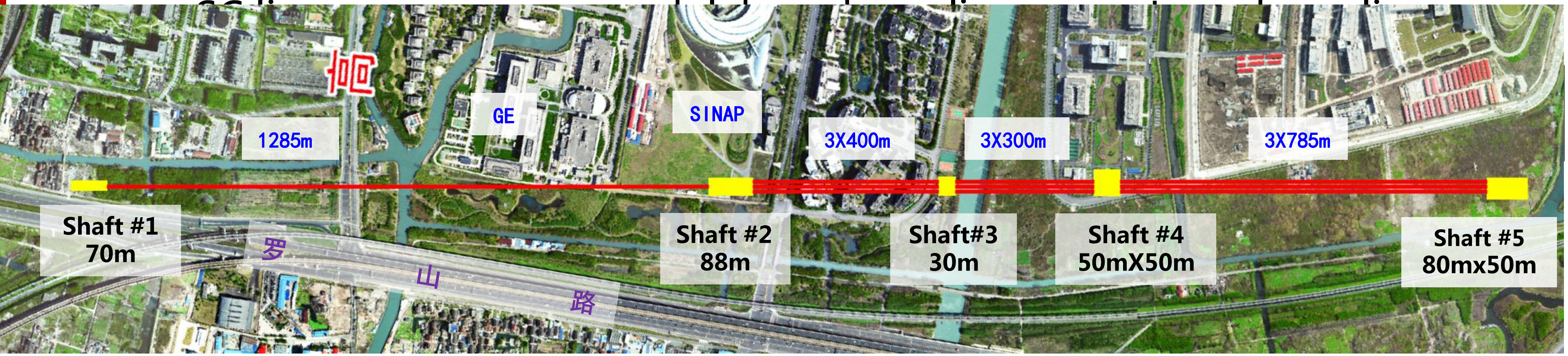
8 GeV linac, 3 FELs, 10 exp. stations

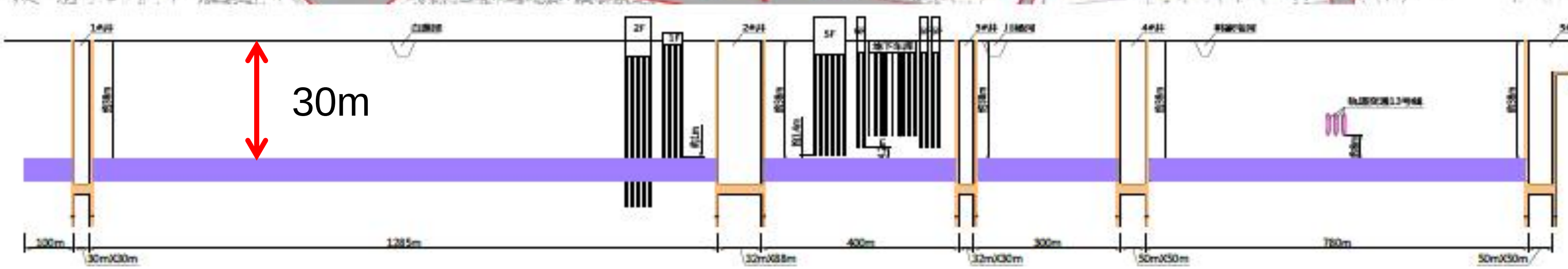


Flux vs. Beam energy and Undulator period
Blue： 6GeV， Red： **8GeV，** Purple： 10GeV

	FEL-I	FEL-II	FEL-III
Undulator type	flat	flat+EPU	sc
Period	26mm	68mm	16mm
Length	5m	4m	4m
FEL modes	SASE HXSS	SASE SXSS EEHG	SASE HXSS
Photon Energy	3.0-15keV	0.4-3.0keV	10.0-25keV
Peak power	5-25GW	30-55GW	4-18GW
Pulse energy	25-1100μJ	130-2400μJ	20-800μJ
Bandwidth （RMS）	0.06%	0.1%	0.027%
Spot size（RMS）	50μm	60μm	40μm
Divergence（RMS）	5μrad	7μrad	3μrad

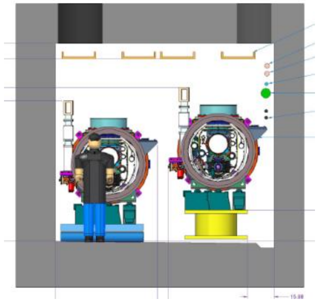
Shanghai Hard XFEL layout



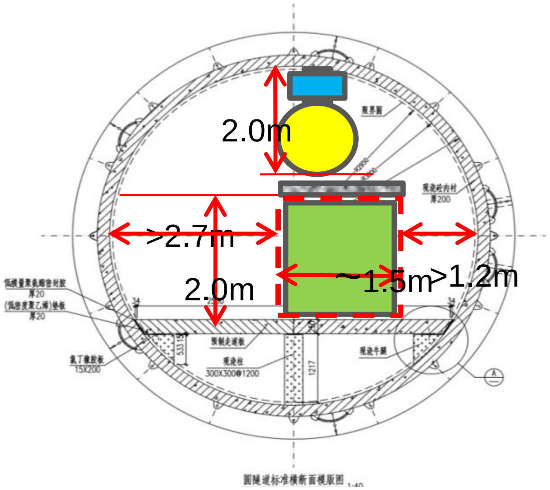


EXFEL，LCLS-II and Shanghai XFEL

European XFEL



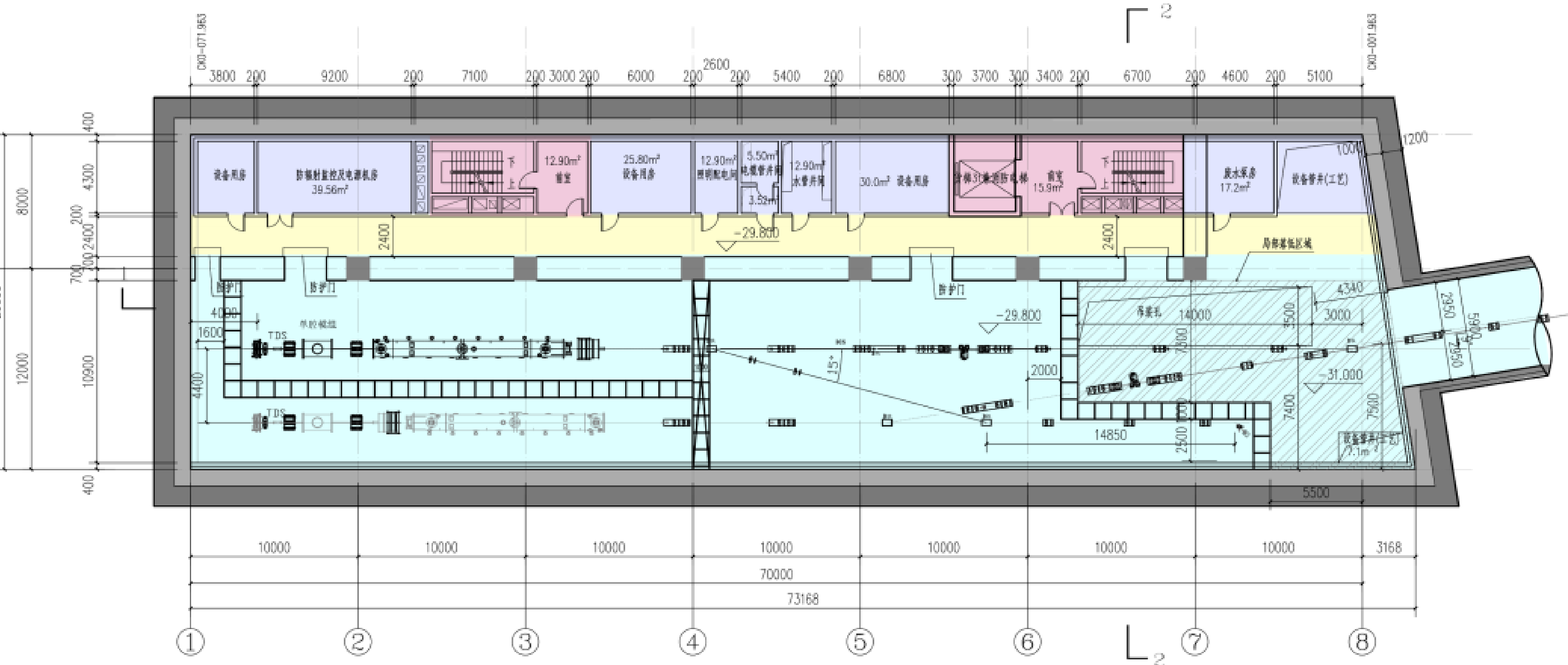
LCLS-II



	EuropeanXFEL	LCLS-II（HE）	Shanghai XFEL
RF mode	Pulsed	CW	CW
Power source	Klystron	SSA	SSA
Install	Same Tunnel	Tunnel + Gallery	Same Tunnel
2K heat load/CM	~20w/CM	80~110w/CM	80~110w/CM
Tunnel slope	~	0.5%	~
N of modules	~100	~35（+19）	~75
2K capability	~3kW	~ 2 x 4kw	~ 3 x 4kw

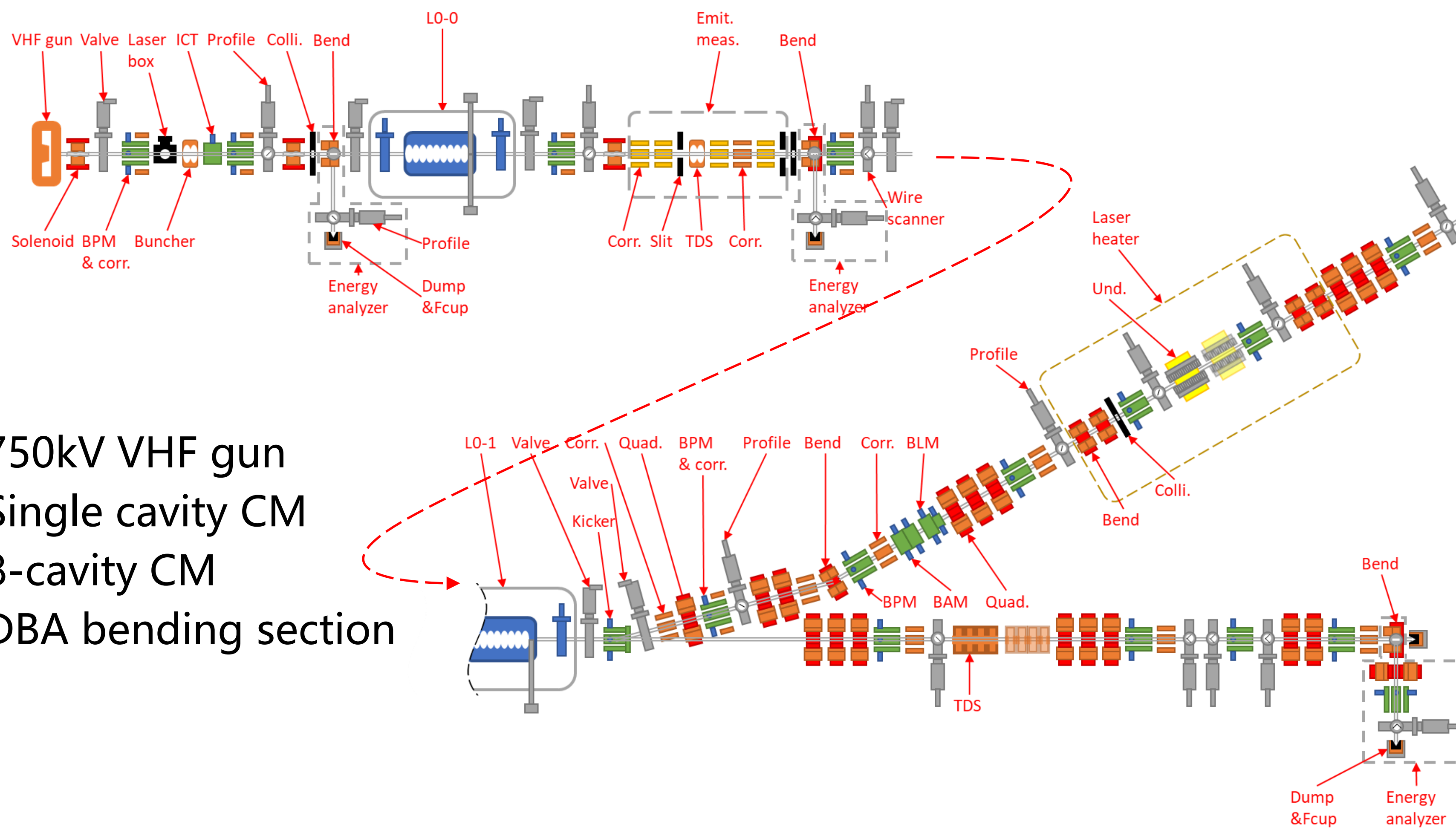
N
Shanghai Hard X-ray FEL
Injector
Linac
Switchyard
SINAP
S
STU
Far Hall
SARI
Near Hall
Beam Dump
Undulator

Shaft #1: Injector



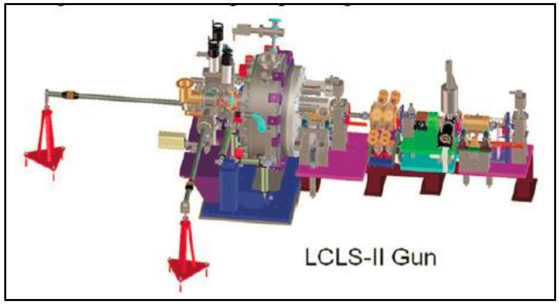
- ☐ 2 injectors in parallel possible
- ☐ allow independent commissioing

Injector layout designs



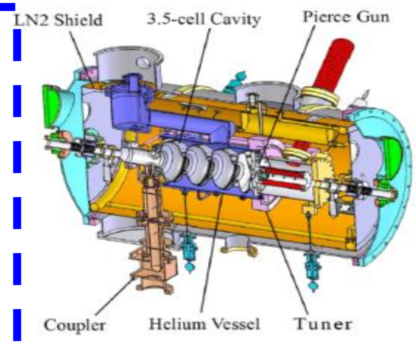
- 750kV VHF gun
- Single cavity CM
- 8-cavity CM
- DBA bending section

High rep-rate gun：VHF as baseline

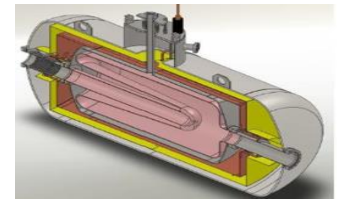


APEX-VHF

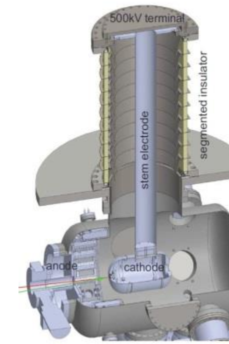
SINAP-VHF



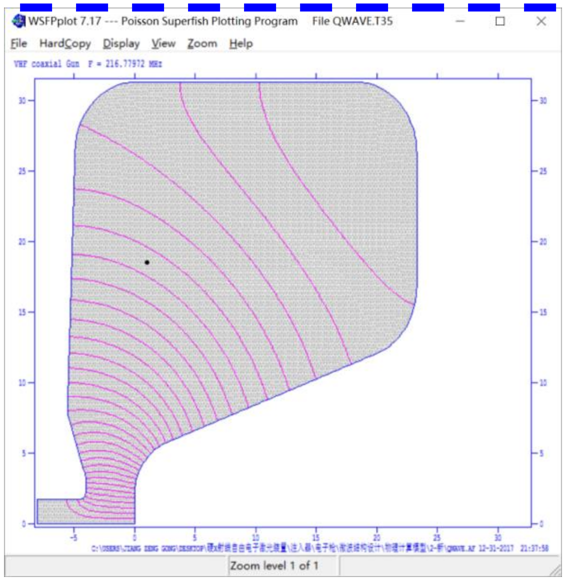
PKU-SC-DC



WU-BNL-SC



CU-DC

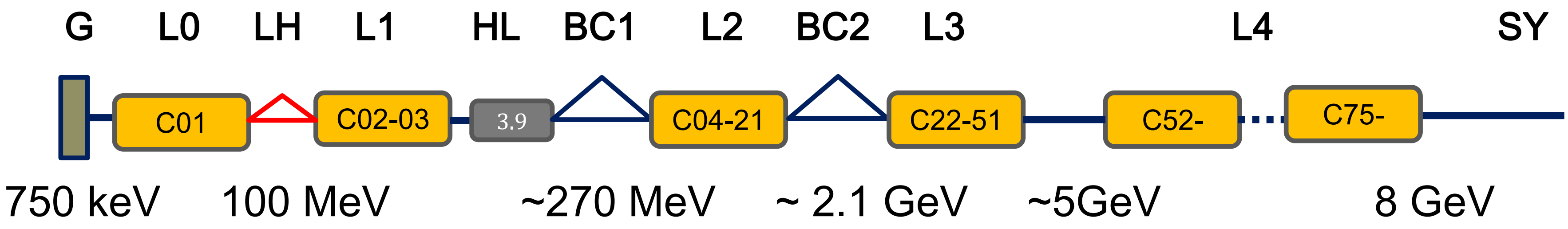


Field calculations

Frequency	216 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19.6 MV/m
Q_0 (ideal copper)	29439
Shunt impedance	5.76 MΩ
RF Power @ Q_0	100 kW
Stored energy	2.16 J
Peak wall power density	30.9 W/cm^2
Accelerating gap	4 cm

Main parameters

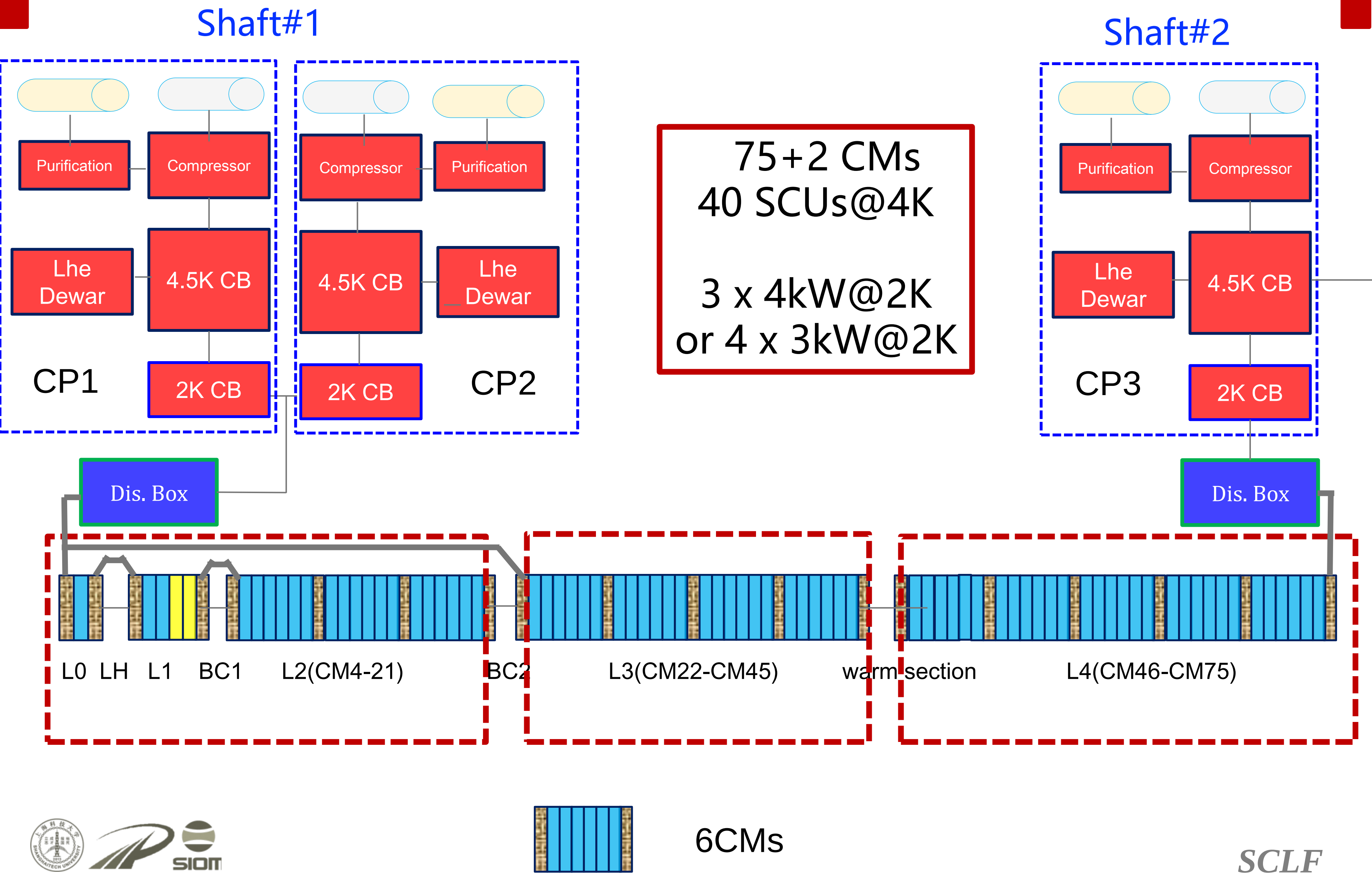
8GeV Linac



	CMs	Cavities	Powered*	Gradient (MV/m)	Energy(MeV)	σ_z (mm)	σ_δ (%)	ϕrf	R56 (mm)
L0	1	8	7	16.3	100	1	0.04	0	-
L1	2	16	15	14.8	326	1	0.383	-12.7	-
HL	2	16	15	12.5	269	1	1.433	-150	-
BC1	-	-	-	-	269	0.14	1.433	-	-61
L2	18	144	135	15.5	2148	0.14	0.365	-30	-
BC2	-	-	-	-	2148	0.007	0.365	-	-36.5
L3	24	192	180	15.5	5235	0.007	0.085	0	-
L4	30	240	224	15.5	8653	0.007	0.085	0	-

* 6% spare

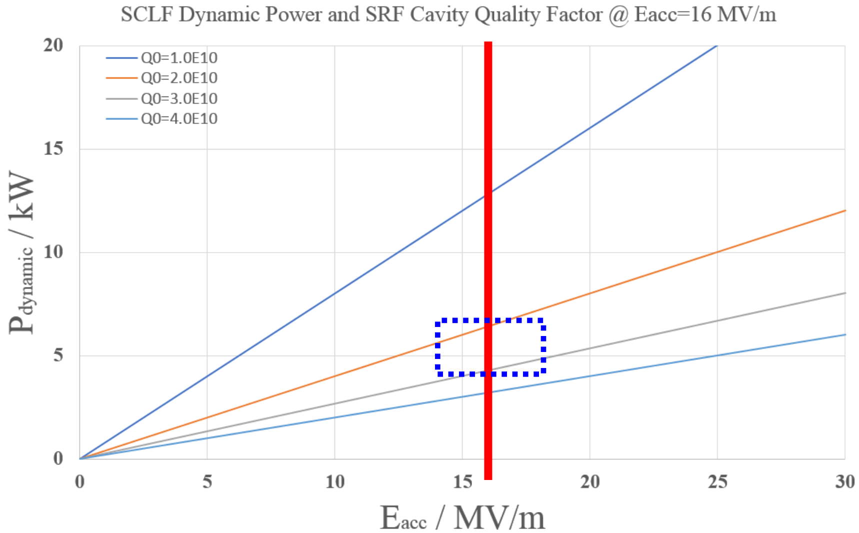
CMs and cryogenic system



75+2 CMs
40 SCUs@4K

3 x 4kW@2K
or 4 x 3kW@2K

Cryogenic plant: ~12kW@2K total

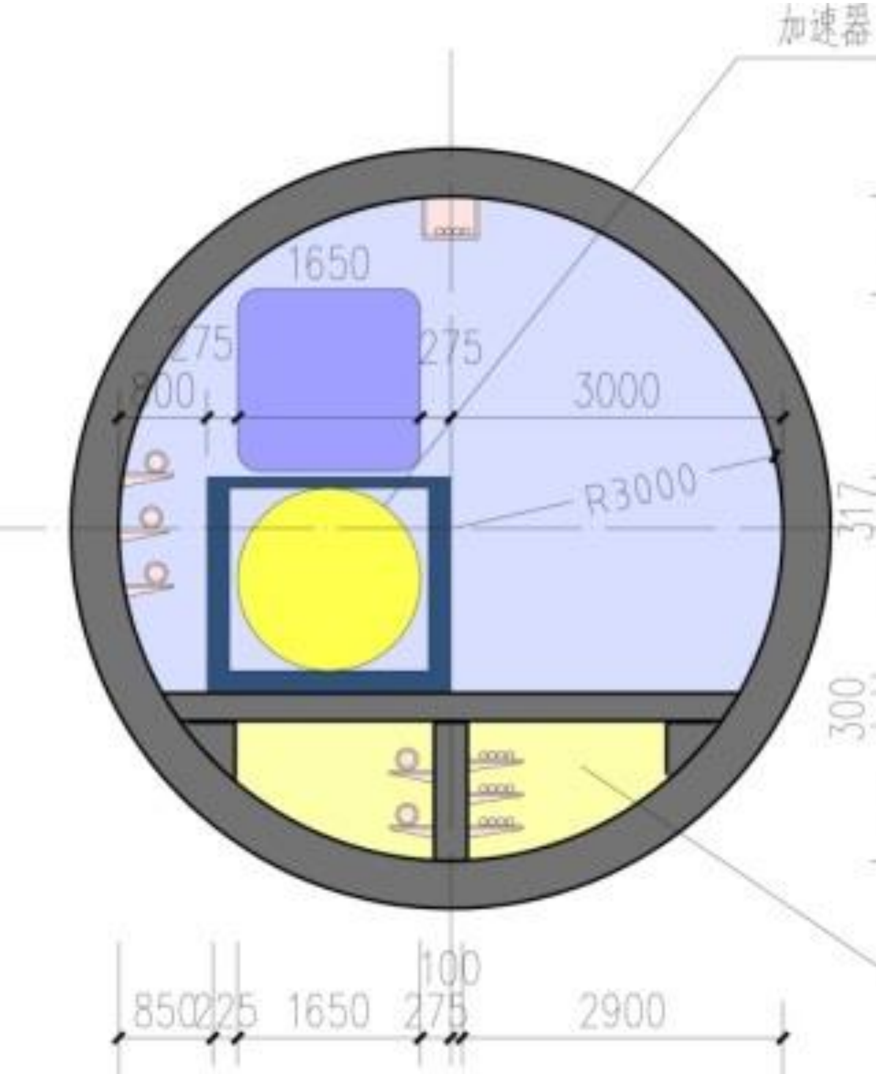


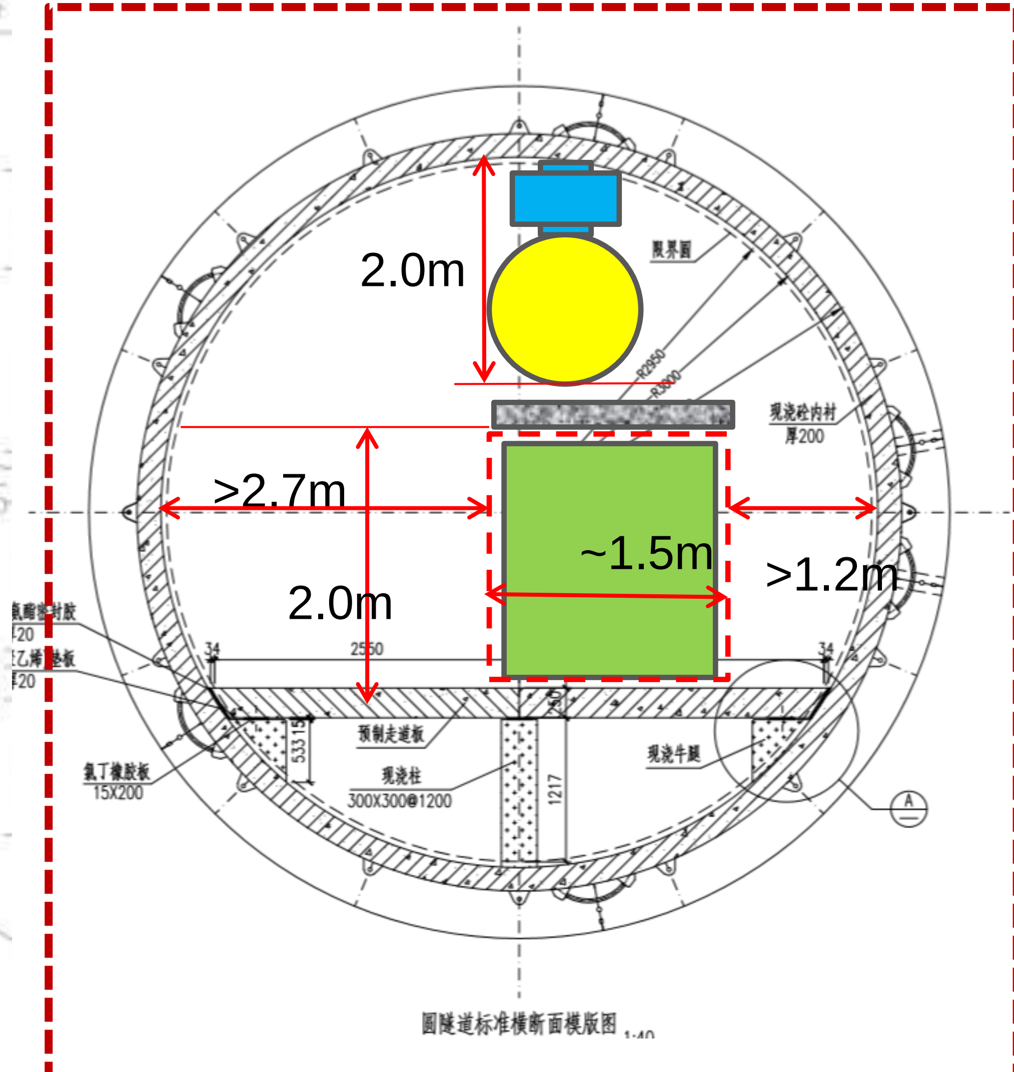
Gradient: 14~18MV/m
Qo: 2.0~3.0E10
Load_d: 4~8kW@2K

Plant: ~12 kW@2 K

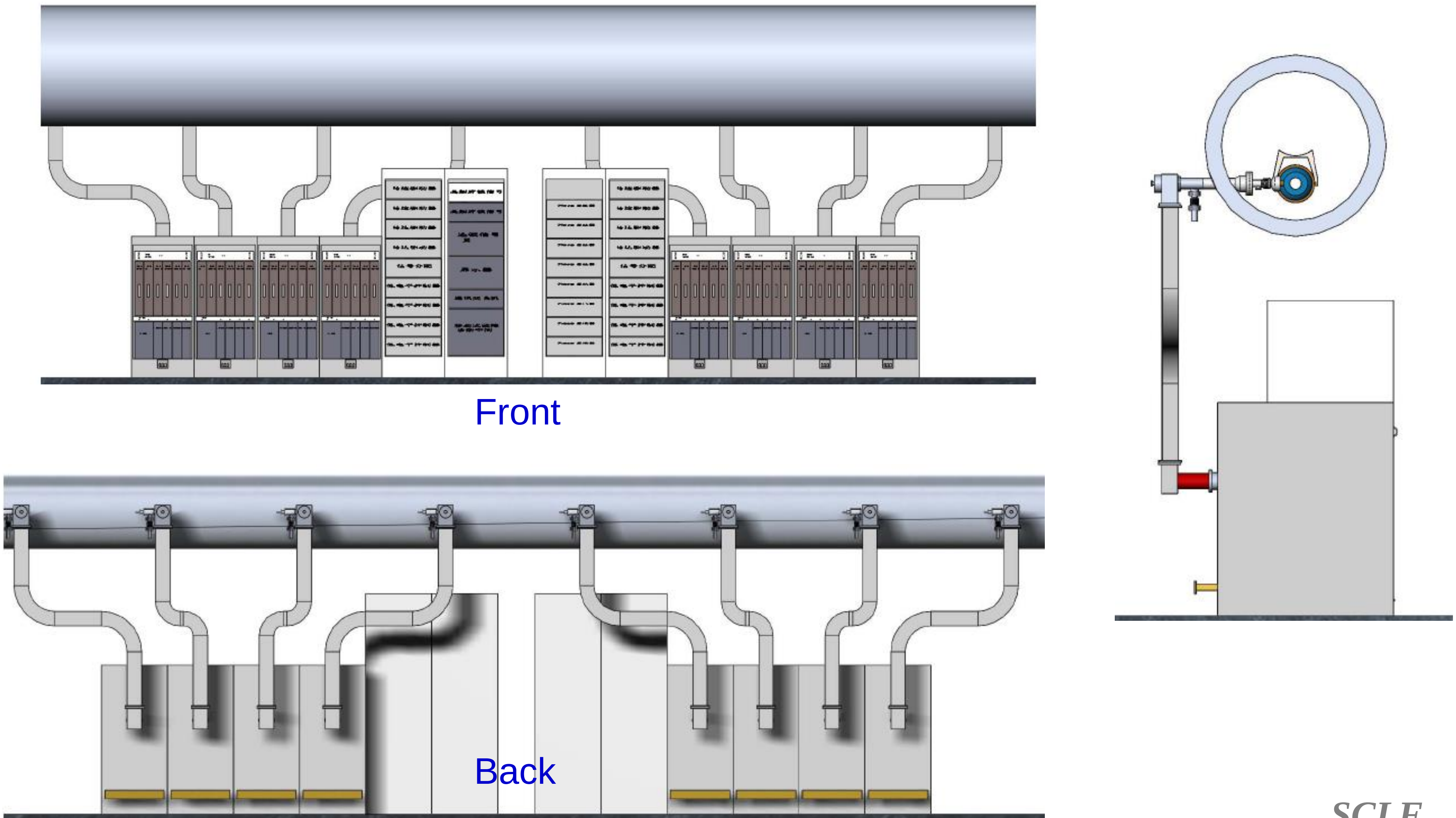
Components		2K load（kW）	4.5K load（kW）
SCRF 16MV/m, 2.7E10	Static	0.75	1.575
	Dynamic	6.075	0.375
	Total	6.825	1.95
SCU	Static		0.4
	Dynamic		4
Distribution		1.0	1.0
	Pipes	1.5	1.5
Total		9.325	8.85

Linac tunnel: 5.9 m diameter



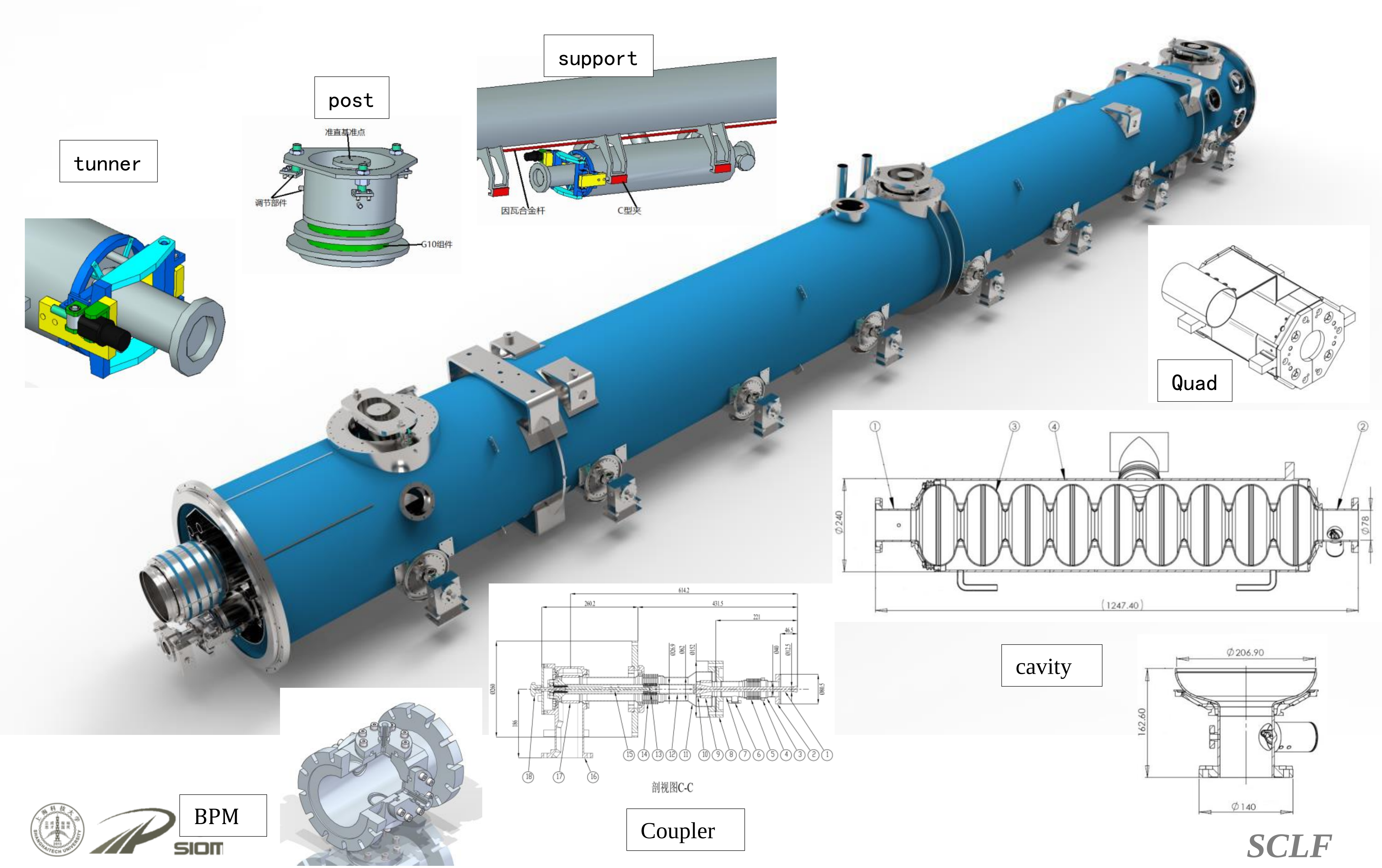


Cavities are powered by SSAs



SCLF

Cryomodule
based on EXFEL&LCLS-II type



SCLF

Design issues

- Based on rapid progress on cw scRF technologies, especially on cavity performance and cryomodule technologies in past years, boosted by EuXFEL and LCLS-II in particular.
- The community is optimistic on further improvements. We are going to take this huge opportunity to contribute to the advancements of scRF field
  - Cavity performance improvement through various techniques
  - New cryomodule design and prototype modules
  - cw linac in underground tunnel

1.3GHz TESLA-type cavities

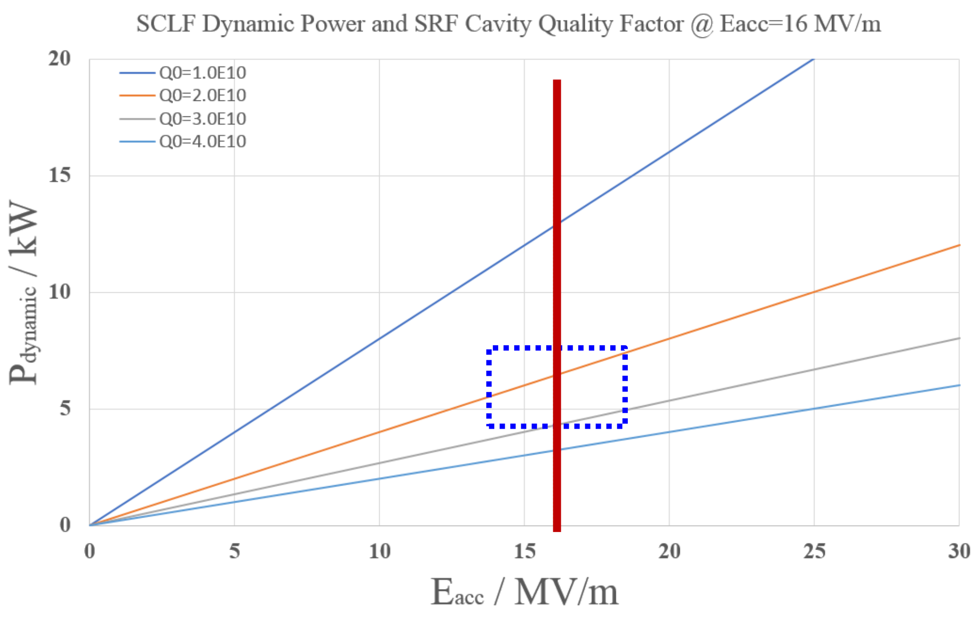
- Parameters

SCLF is operating at cw mode, high Q0 can lower cryogenic load hence the costs

  - Q0 ≥2E10 @ 16 MV/m
  - Surface treatment : N-doping, infusion
  - Large grain materials
  - 2.0 K→1.8K operating

Lots prototyping ahead

TESLA 9-cell 1.3GHz cavity

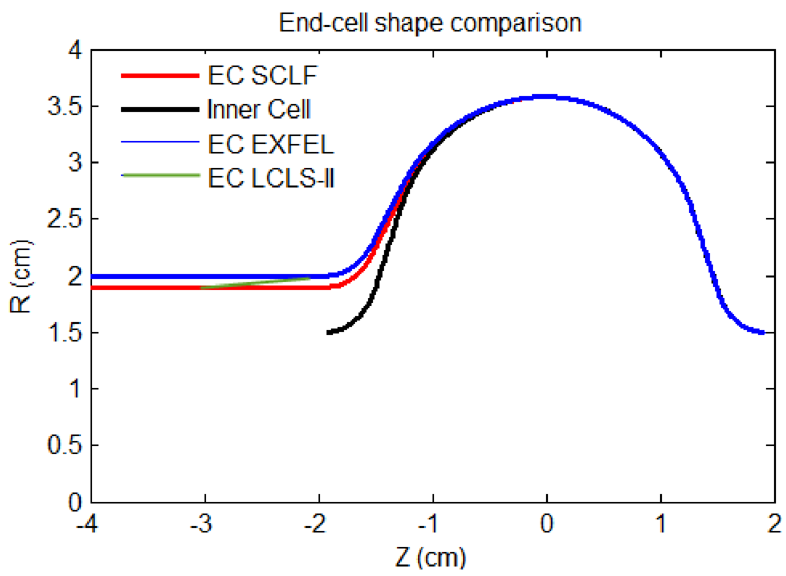


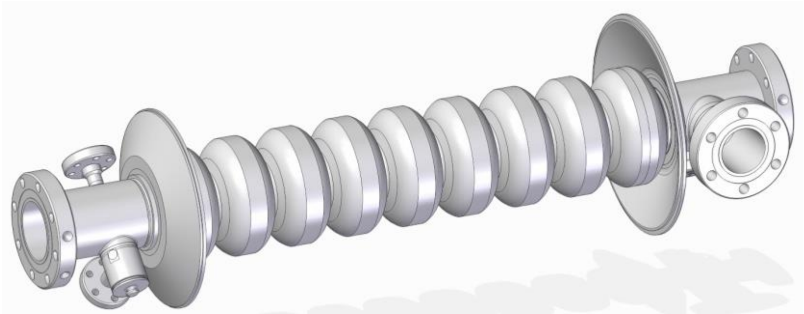
SCLF

3.9 GHz cavity optimization

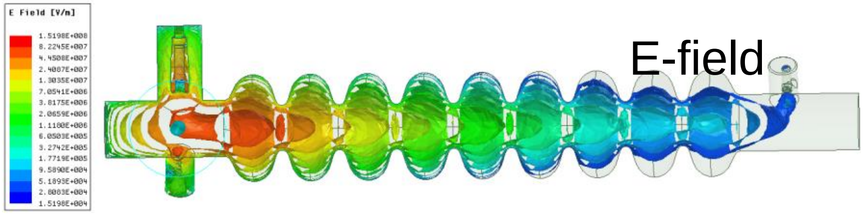
- End group redesigned

Courtesy: J. F. Chen





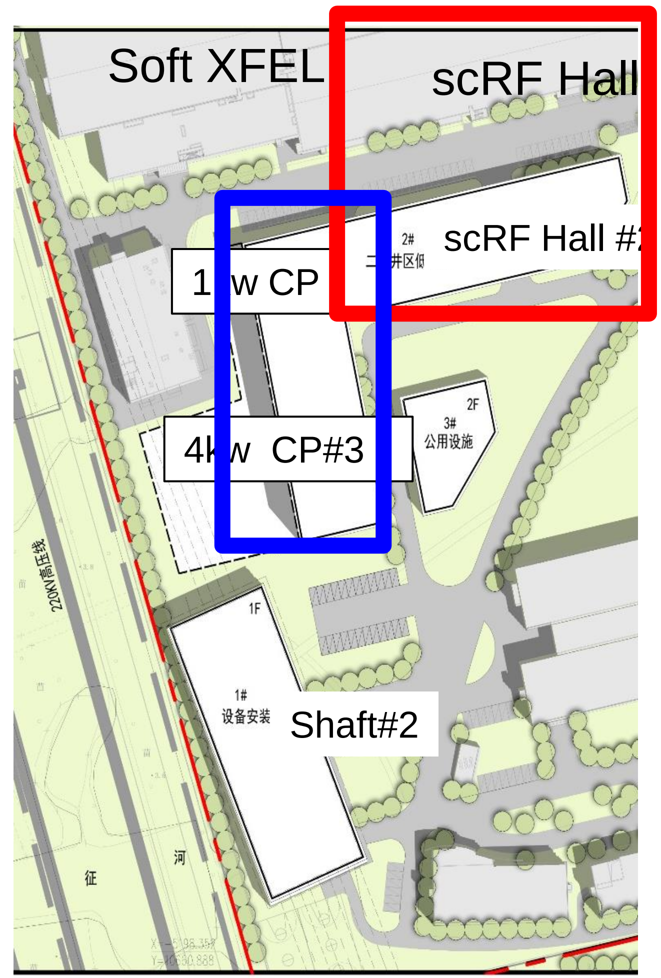
SCLF 3.9GHz cavity



Lowest dipole	Frequency (MHz)	Distance to π-mode (MHz)
EXFEL	3992	92
LCLS-II	4092	192
SCLF	4170	270

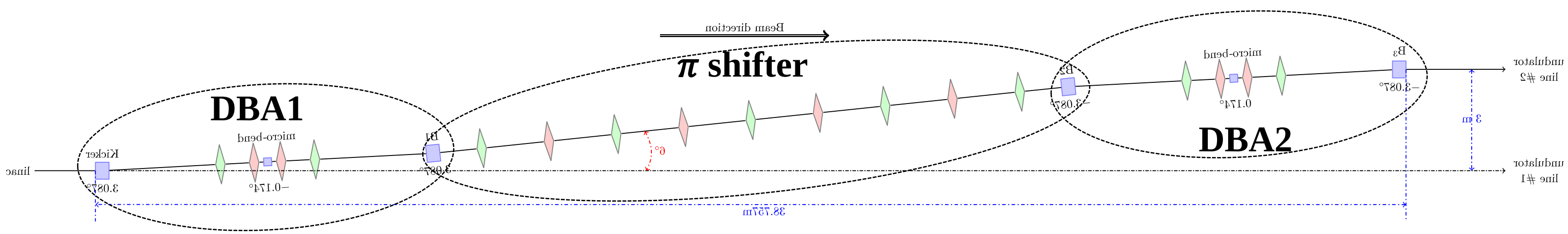
◆ to shift away the potentially troublesome lowest dipole mode

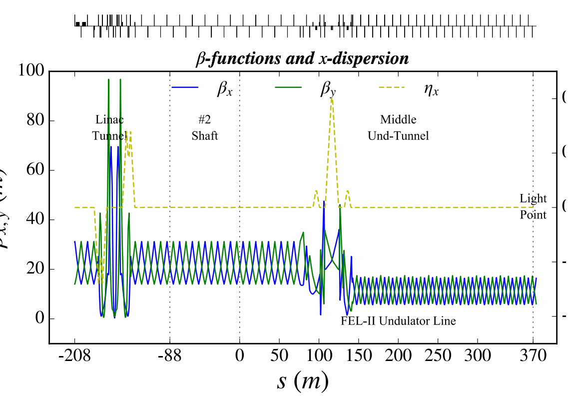
Shaft #2 (at SINAP): switchyard

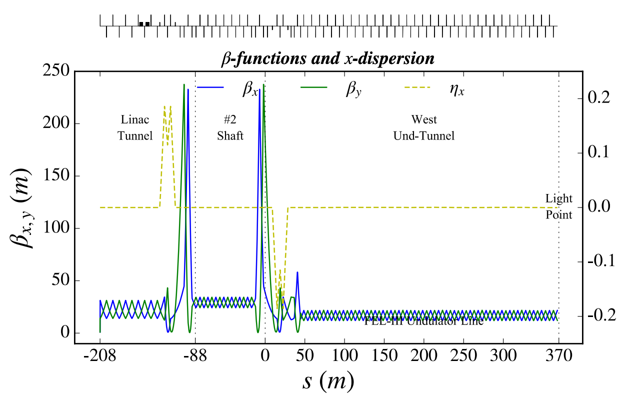


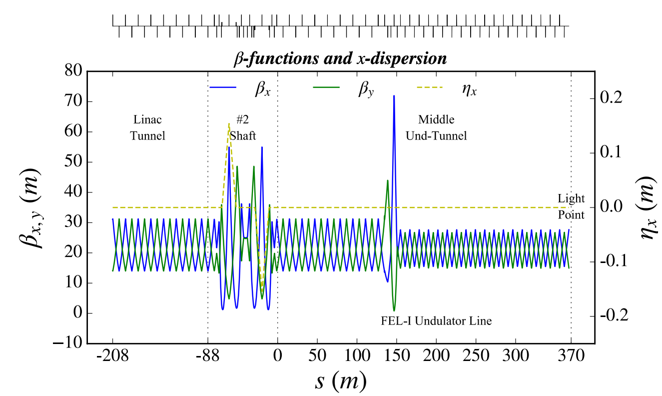
Beam distributions

- Design considerations：dog-leg with duel-DBA
  - ✓ $\eta_x=\eta_y=0$，$\eta'_x=\eta'_y=0$
  - ✓ CSR suppression
    - Small bending angle
    - Optics compensation
  - ✓ micro-bunching： adjustable R_{56}



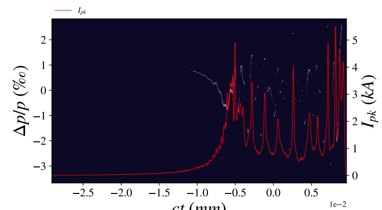




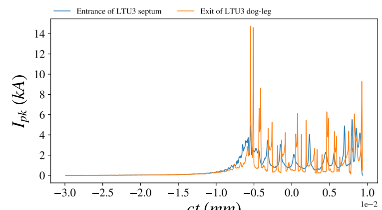


Simulations of microbunching

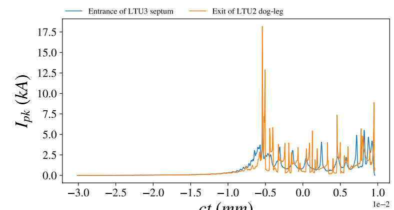
- R_{56} effects :
  - ~ a few hundred μm R_{56} ;



End of Linac

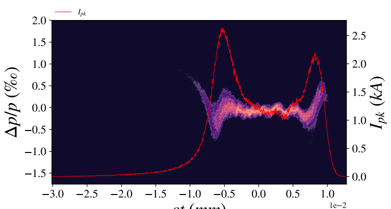


Exit of LTU3 dog-leg

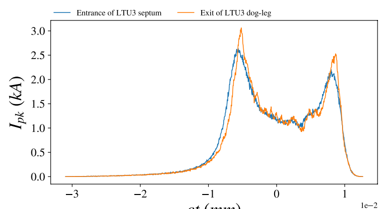


Exit of LTU2 dog-leg

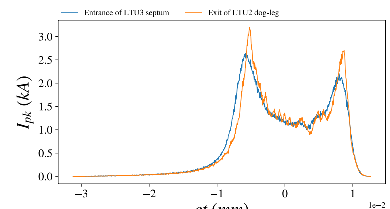
No Laser-heater



End of Linac



Exit of LTU3 dog-leg

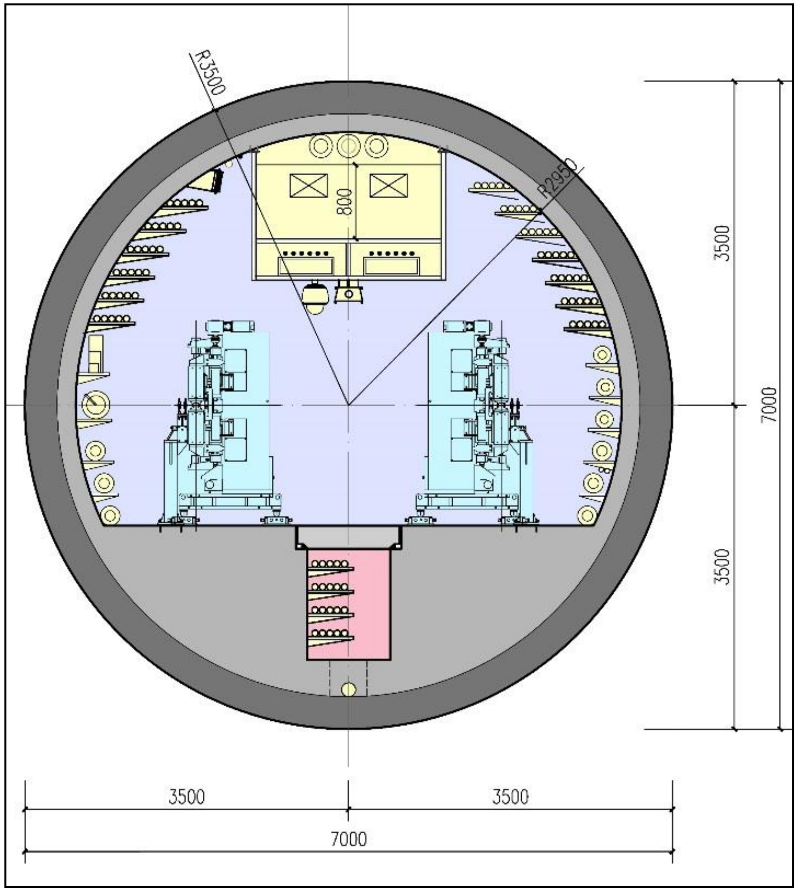


Exit of LTU2 dog-leg

Laser-heater

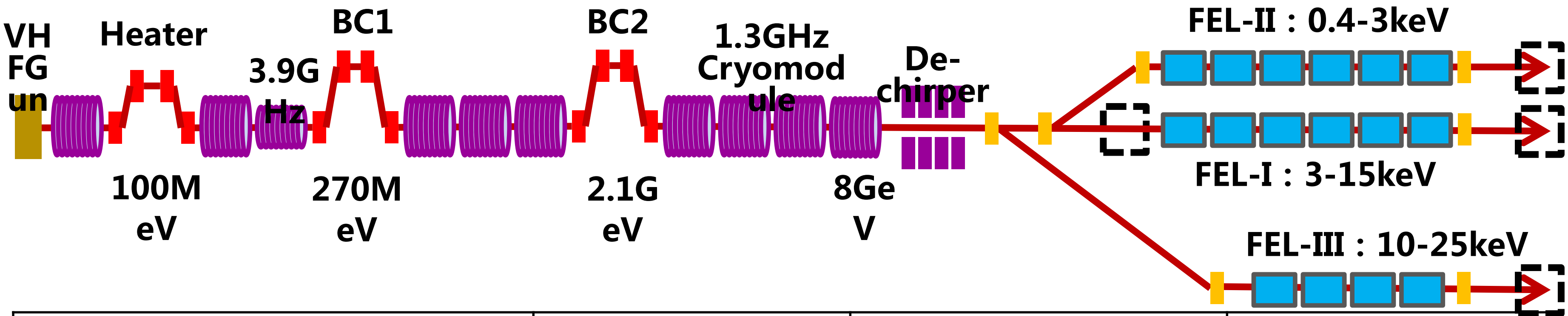
- Laser-heater needed

FEL Undulator Lines



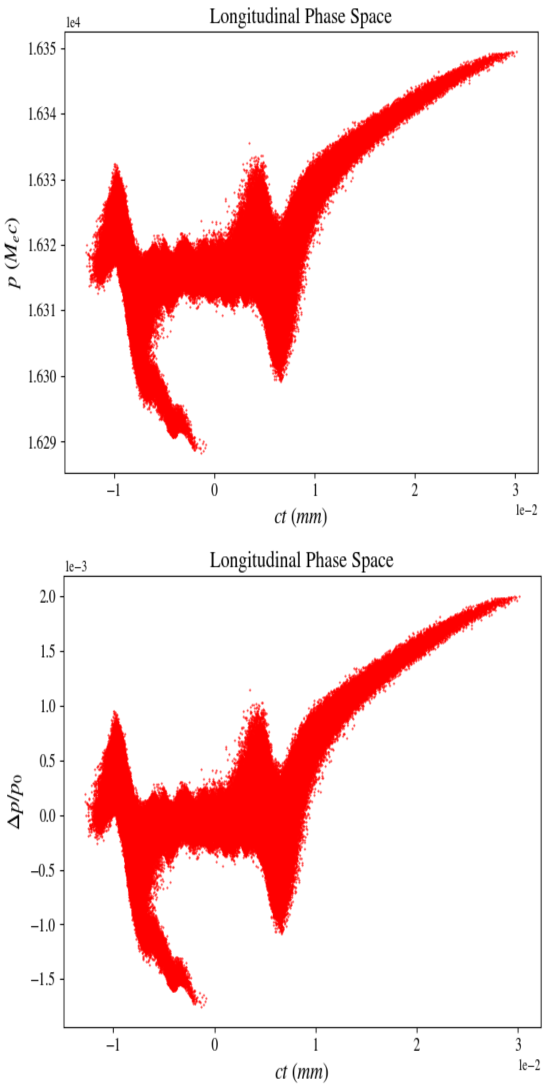
- Left：EXFEL, single FEL line per 4.5m tunnel
- Right：SCLF, two FEL lines per 5.9m tunnel

FEL parameters

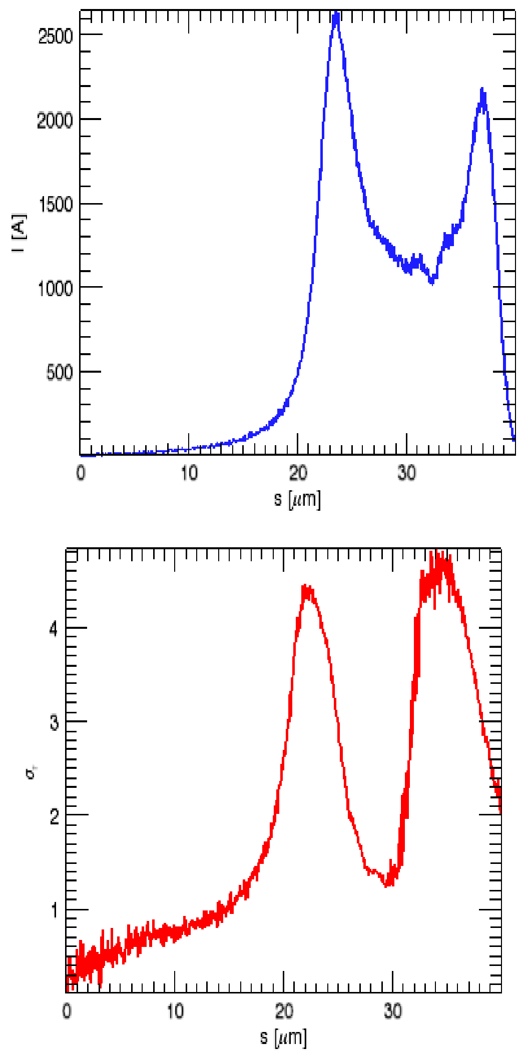


	FEL-I	FEL-II	FEL-III
Undulator type	planar	Planar + EPU	SCU
Period length	26mm	68mm	16mm
Section length	5m	4m	4m
FEL modes	HXSS/SASE	SXSS/EEHG/SASE	HXSS/SASE
FEL photon energy	3.0-15keV	0.4-3.0keV	10-25keV
FEL peak power	5-25GW	30-55GW	4-18GW
FEL pulse energy*	25-1100μJ	130-2400μJ	20-800μJ
FEL BW (RMS)	0.06%	0.1%	0.027%
FEL spot (RMS)	50μm	60μm	40μm
FEL diverge. (RMS)	3μrad	10μrad	2μrad

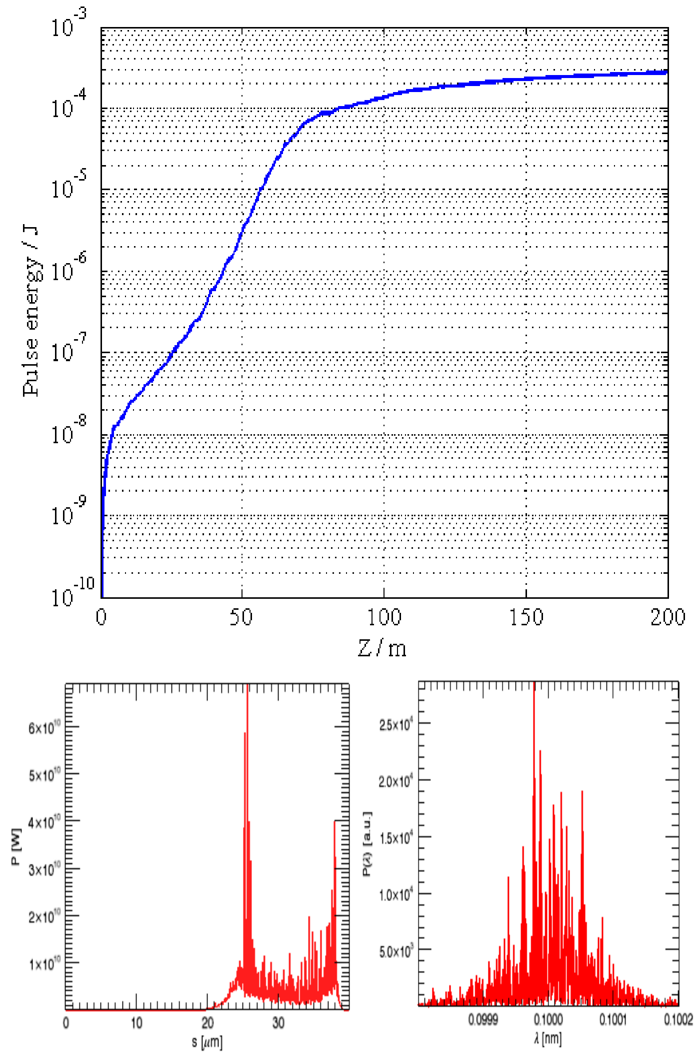
FEL S2E Simulations



Electron beam profiles

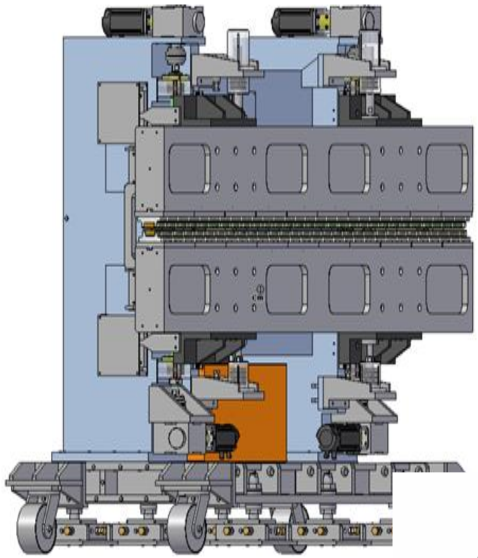


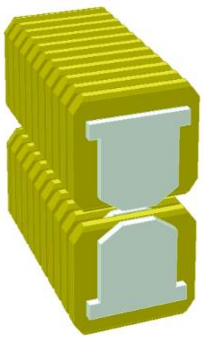
Peak current
Energy spread

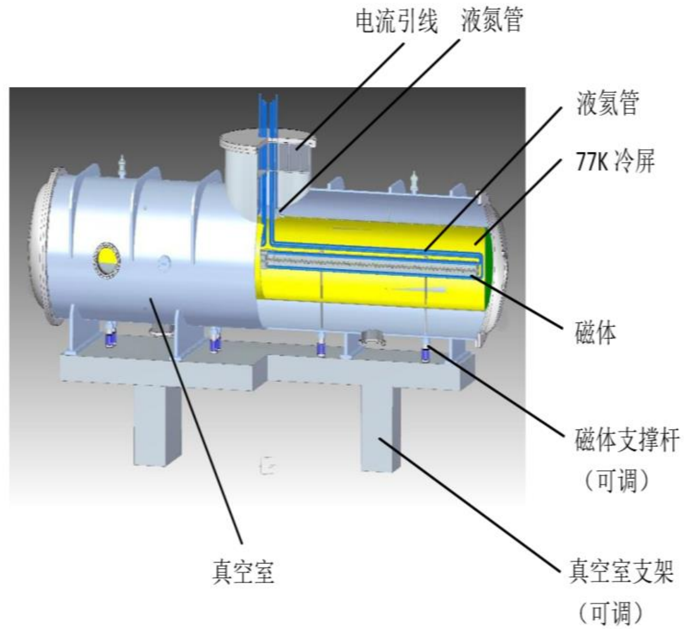


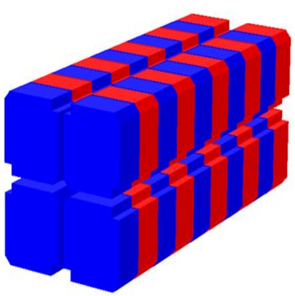
FEL-I performance
(12.4keV , 300μJ)
Gain/temporal

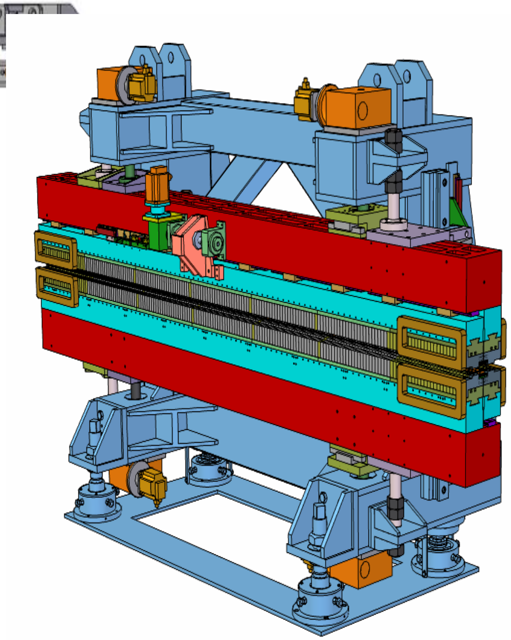
Undulators

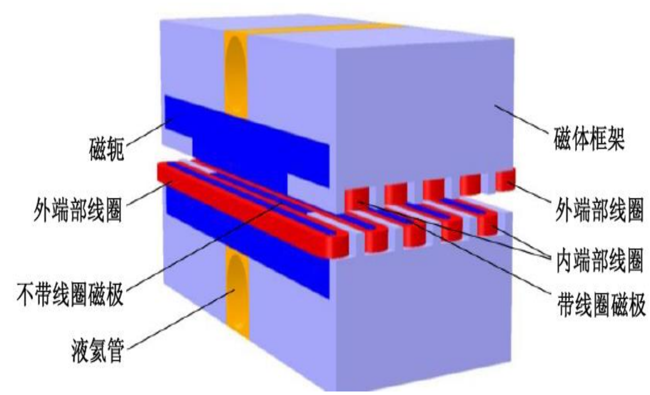





电流引线
液氮管
液氦管
77K 冷屏
磁体
磁体支撑杆
(可调)
真空室
真空室支架
(可调)






磁轭
外端部线圈
不带线圈磁极
液氦管
磁体框架
外端部线圈
内端部线圈
带线圈磁极

Home-made undulators


上海光源椭圆极化波荡器


上海光源低温永磁波荡器

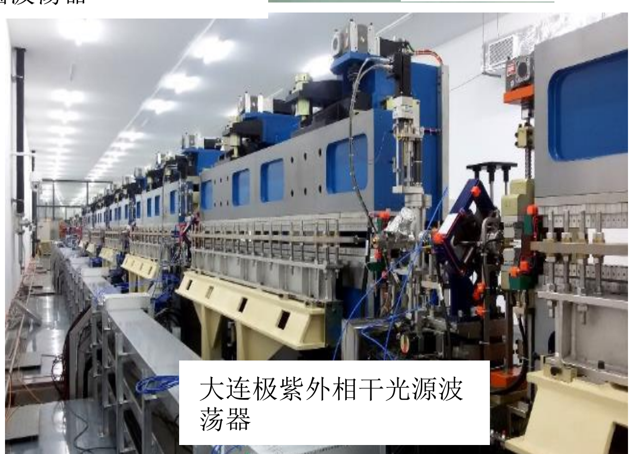

上海光源真空内波荡器


上海光源超导波荡器样机


上海光源“梦之线”双椭圆波荡器


合肥光源椭圆极化波荡器

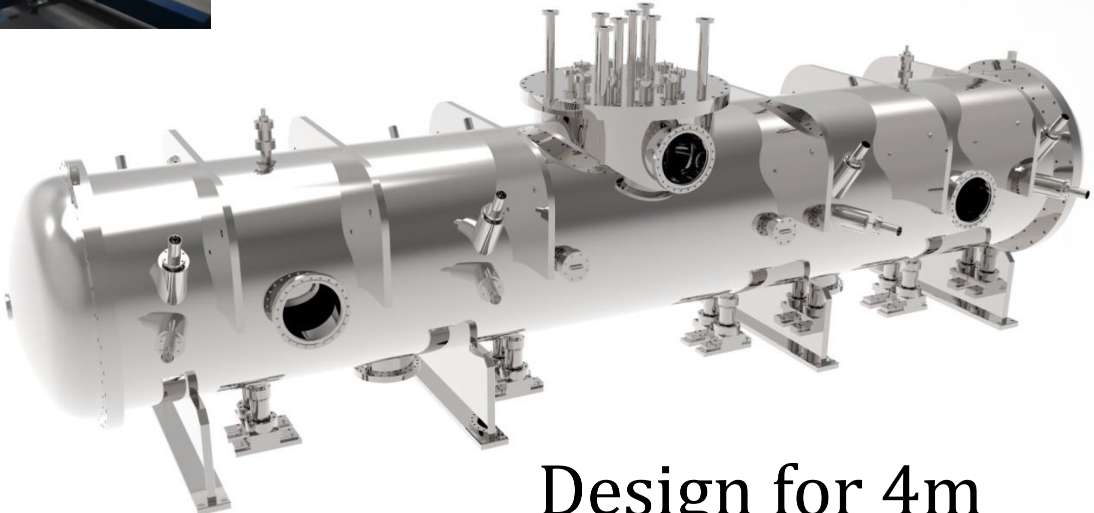

韩国浦项光源真空内波荡器


大连极紫外相干光源波荡器


上海软X自由电子激光波荡器

SC undulator

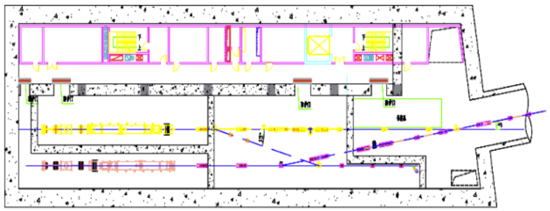
- SC undulator protype
- 0.8m length
- in test



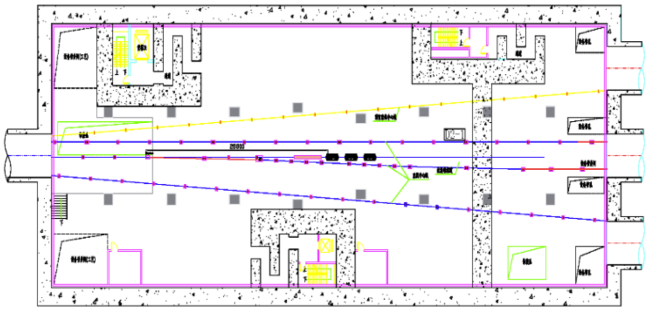
Design for 4m

Radiation and beam dumps

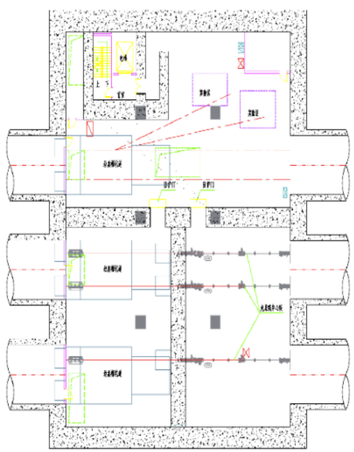
一号井

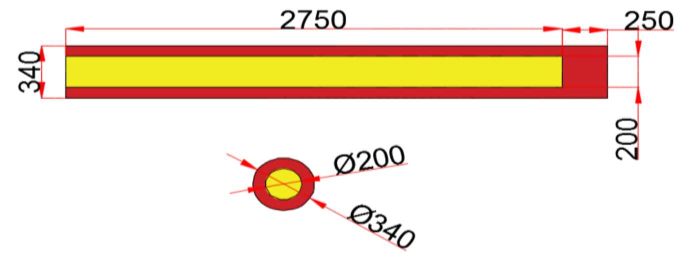


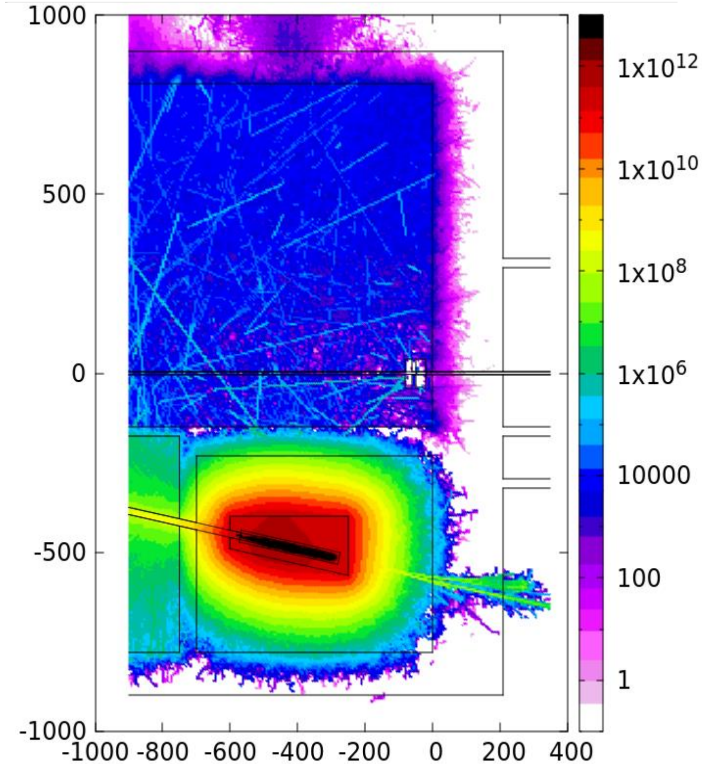
二号井



三号井



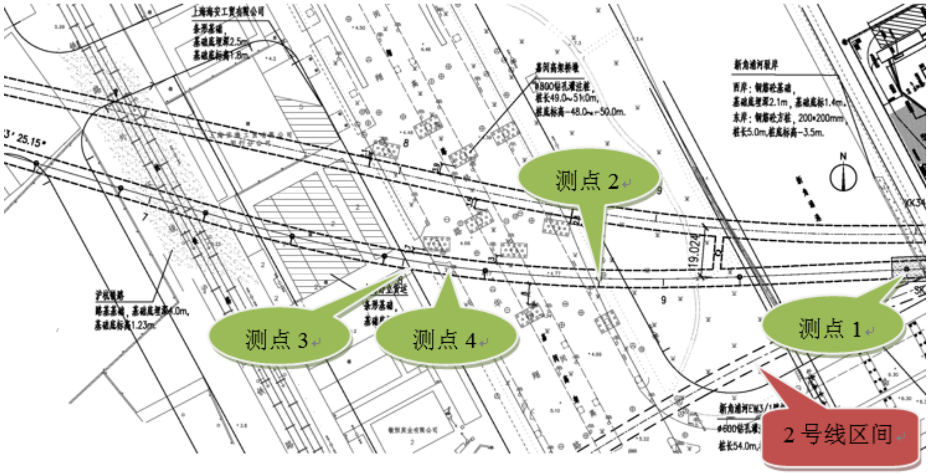


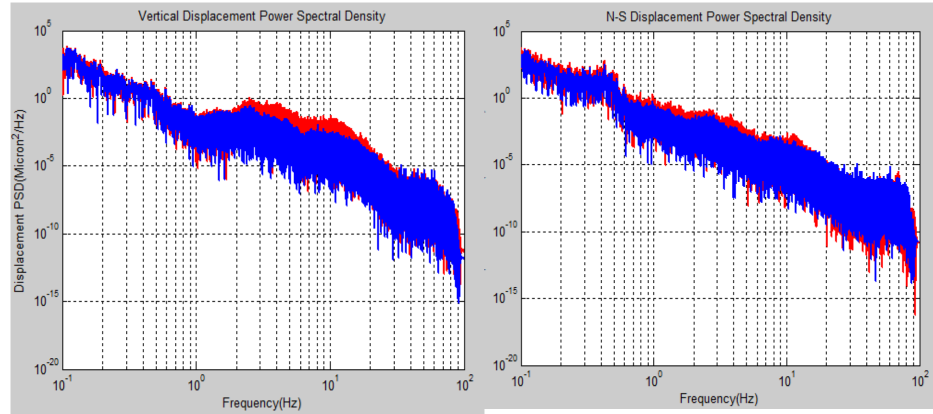


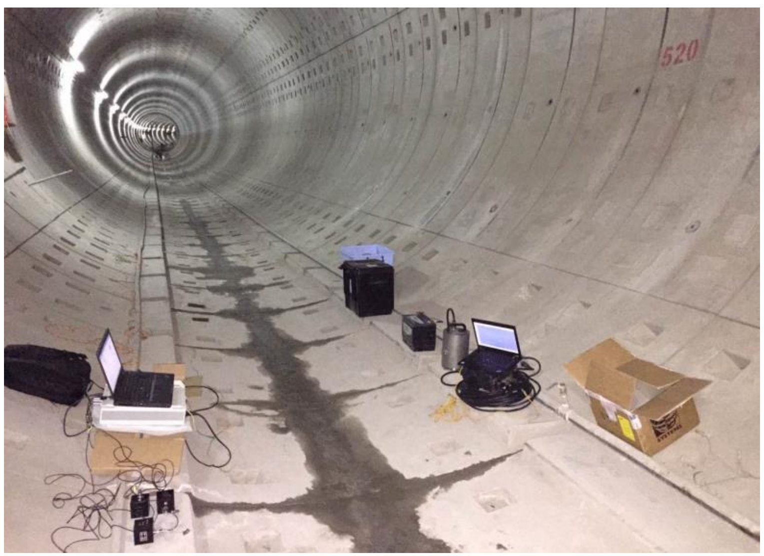
Simulations on beam dumps

Tunnel vibration measurements

R. Deng, J. Wang, et al







20170122				1-100Hz rms movements		
Pts	Position	Depth	Time	Vert.	N-S	W-E
3	Ground		13:40-13:50	0.4111	0.2338	0.2407
4	Tunnel	24.3m		0.1962	0.1549	0.1404
4	Tunnel	24.3m	03:00-03:10	0.0629	0.0927	0.0649

Measurements of vibrations in similar tunnels

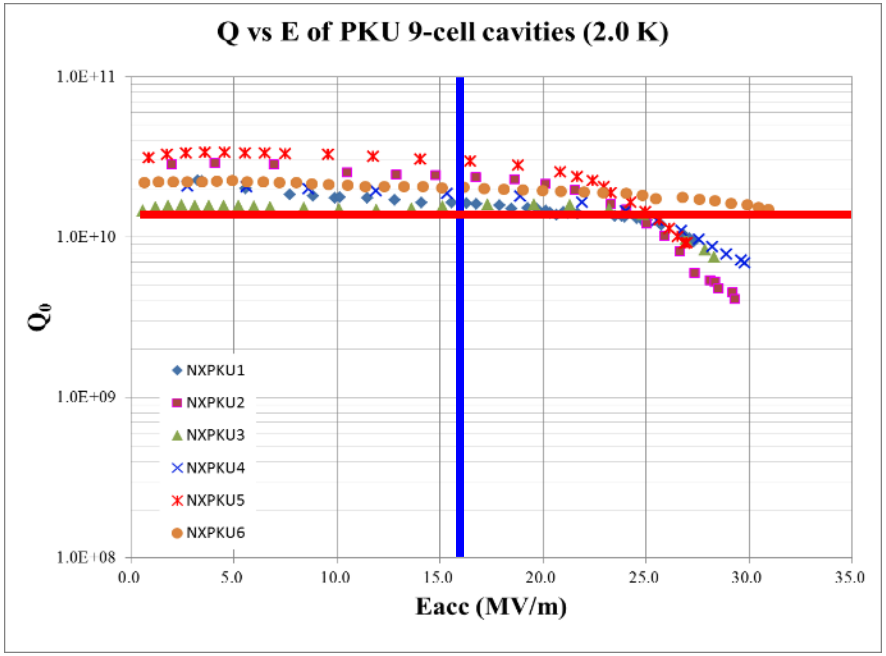
SCLF

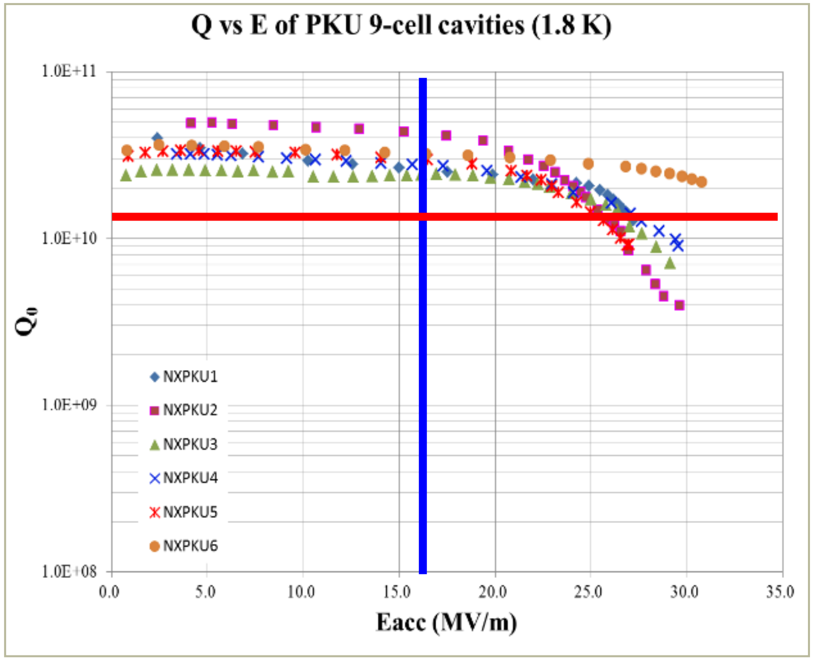
SXFEL project includes sc cavity R&D

6 Large Grain 1.3GHz cavities made in OTIC

Large grain cavities: VT results by PKU

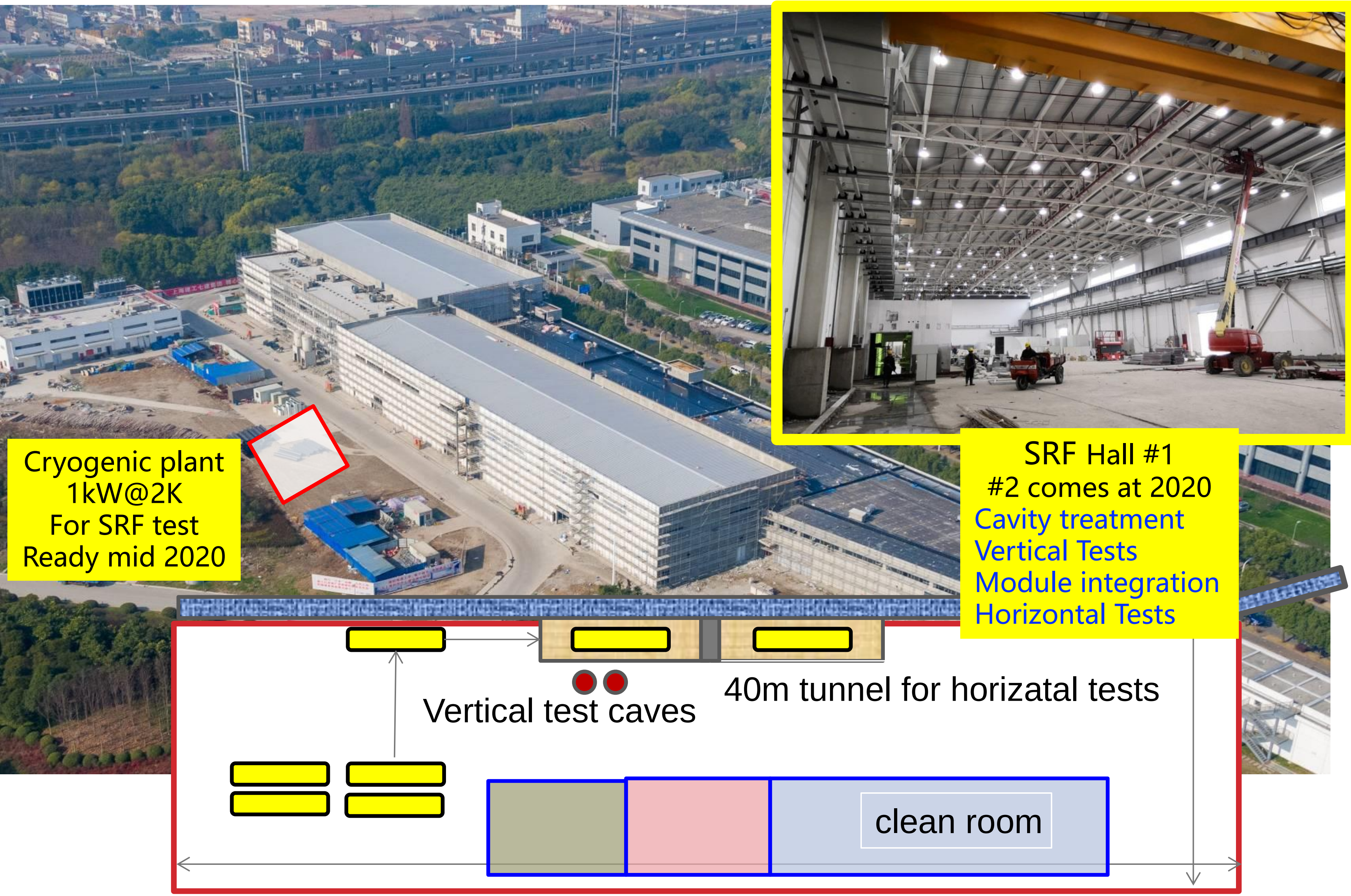
- E_{acc} >25 MV/m (SCLF baseline : 16MV/m , blue)
- Q_0 ~ 1.6-2.4E10 @ 2K , at 16 MV/m, ~3.5E10 @1.8K





- $Q_0(1.8K)/Q_0(2.K)$ = 1.50-1.79 (@~16 MV/m)
- Operation @1.8 K could be an option

SRF R&D Halls and cryogenic plant



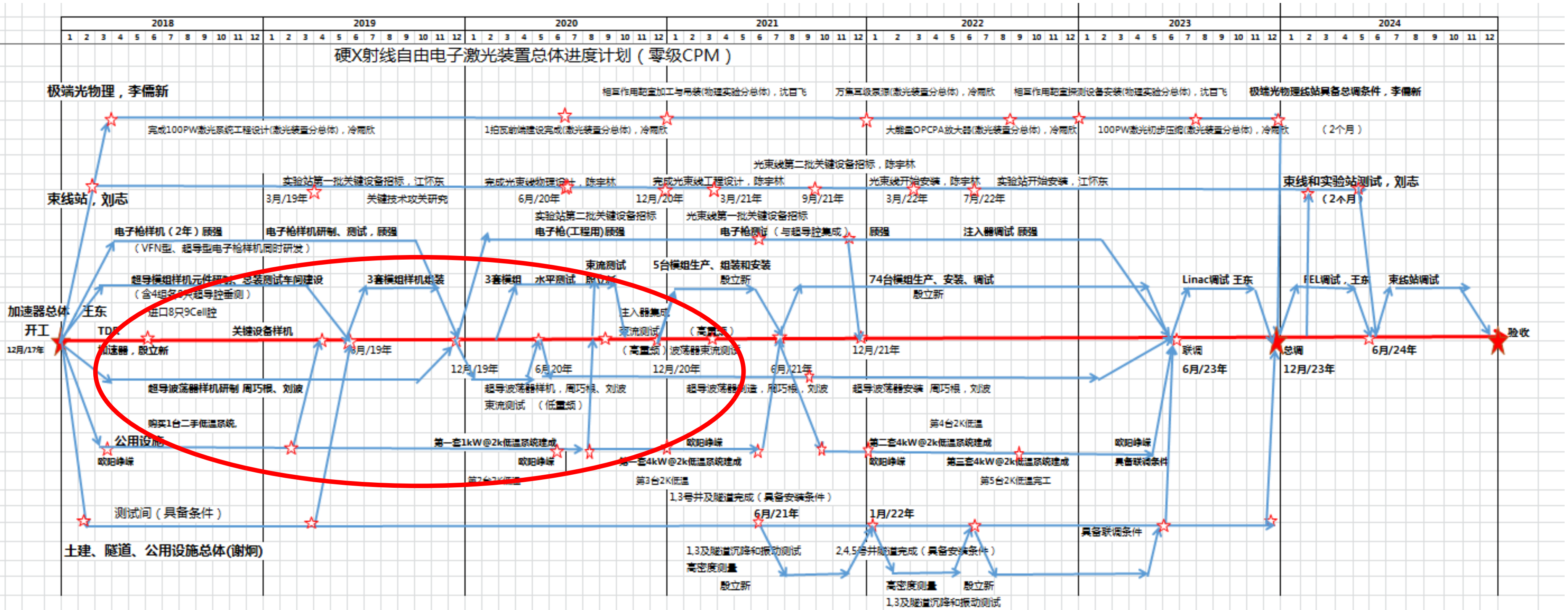
Domestic collaborations IHEP, PKU, IMP, industries, etc.

- "Platform of Advanced Photon Source Technology R&D", to provide infrastructure for construction of future project.
- Budget: 500M CNY funded by Beijing Gov.
- Construction: 2017.5-2020.6
- Consist of 7 systems:
  - RF system
  - Cryogenic system
  - Magnet technology
  - Beam test
  - X-ray optics
  - X-ray detection
  - X-ray application

F. He, IHEP

Schedule

Duration: 7 years (likely 2018-2025)
Prototyping: starting 2017(separate funding)



Cryo-module design/fabrications and cryo-plant are critical.

Summary

- Next major facility will be hard X-ray FEL based on scRF technologies despite of huge technical challenges.
- The main parameters and general layout have been preliminarily explored to meet the requirements by the XFEL performance.
- We are determined to greatly strengthen our scRF related capabilities through the intense R&D programs and actively seek the co-operations domestically and internationally to accomplish the project and eventually contribute to the community.


Thank you !