深圳综合粒子设施研究院
Institute of Advanced Science Facilities,Shenzhen,China

The 2024 MicroTCA/ATCA for Large Scientific Facility Control Workshop

Preliminary Deployment of MTCA.4 Based LLRF System for the S³FEL LINAC

Jinfu Zhu, on behalf of the S³FEL LLRF group

Hongli Ding, Jinfu Zhu, Wei Li, Weixin Qiu, Jiawei Han, Qiaoye Ran, Zhiyuan Zhang, Xiwen Dai, Yue Li, Long Ma, Jianfu Zheng

Institute of Advanced Science Facilities, Shenzhen

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Motivation

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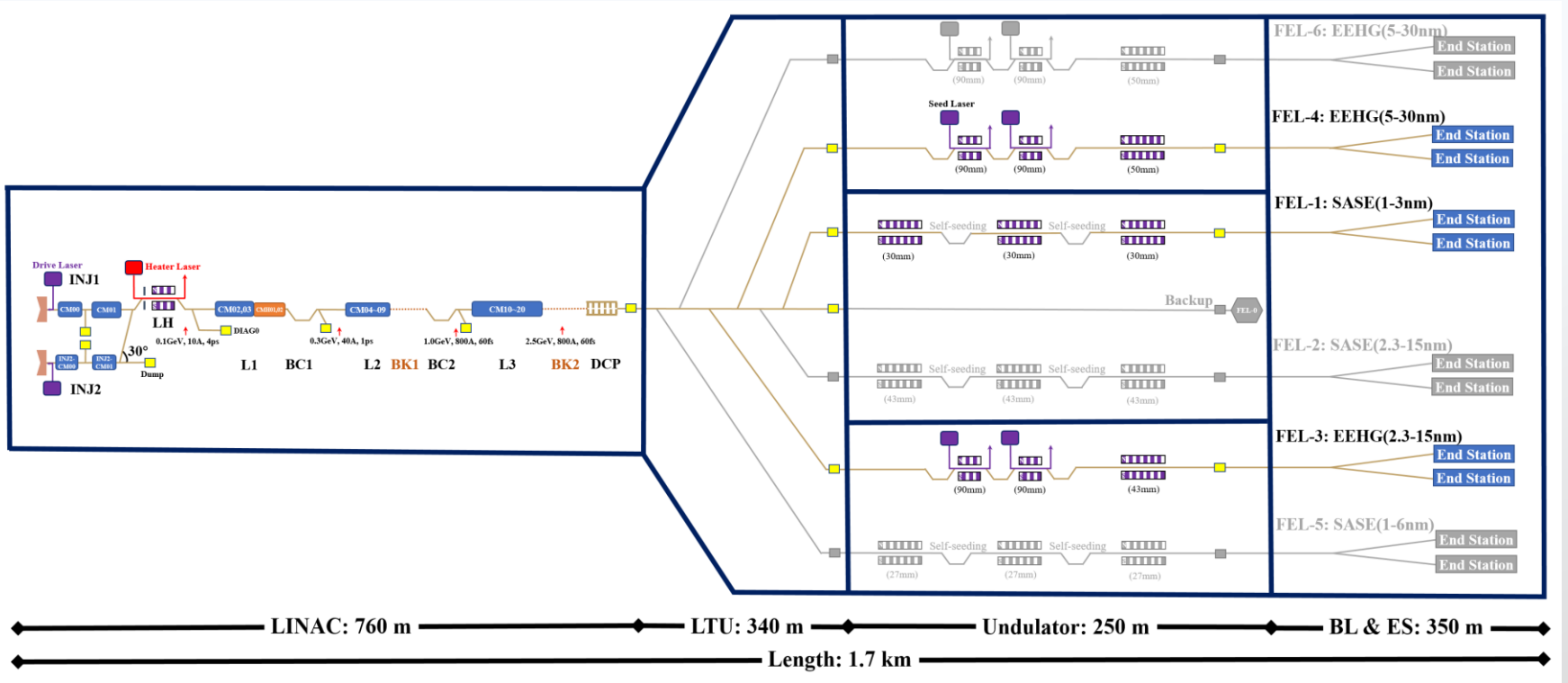
S³FEL facility

FEL facility	Length / m	Electron beam energy / GeV	Wavelength range / nm	Repetition rate / Hz	Completion year
Shenzhen Superconducting Soft x-ray Free Electron Laser, S³FEL	1700	2.0-2.5	1-30	1,000,000	Expected ~2030



Motivation

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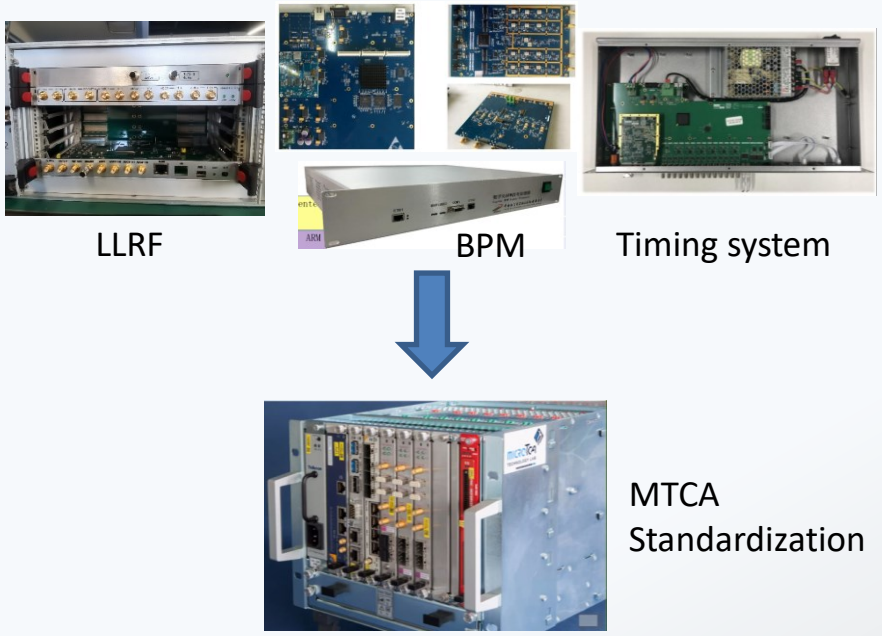
Motivation 1: MTCA.4 Based Hardware Deployment for the S³FEL

System type	Name	Equipment functions	Main indicators	Quantity/set S³FEL (Preliminary)
Accelerator class	Microwave Low-Level RF controller (LLRF)	Microwave signal acquisition and control	Amplitude and phase stability<0.02%/0.02 ° (RMS);	~200
	Superconducting Cavity Tuning (SCT)	Tuning control of superconducting cavities	Misalignment (RMS)<0.2Hz	~200
	Stripe beam position monitoring (SBPM)	Beam position monitoring	Position accuracy (RMS)<4um	~300
	Cavity beam position monitoring (CBPM)	Beam position monitoring	Position accuracy (RMS)<1um	~240
	Beam Charge Monitoring (ICT)	Beam charge monitoring	Charge accuracy (RMS)<2% @ 100pC	~30
	Beam Loss Monitoring (BLM)	Beam loss position monitoring	Position resolution (RMS)<0.5m	~20
	Event Generation and Reception System (EVO)	Generate and receive timestamps	Adjustable delay, timing jitter (RMS)<10ps	~4
	Event triggered system (EVE)	Receive trigger and output electrical signal	Output jitter (RMS)<10ps	~20
	Accelerator driven laser system (DL)	Laser energy stability control	Energy jitter (RMS)<1%	~6
Beamline class	Gas detector (GMD)	Online light intensity and position monitoring	0.1~1700uj, measurement accuracy (RMS)<1%	~20
	Microchannel Panel (MCP)	Relative light intensity measurement	100pj~1uj, measurement accuracy (RMS)<1%	~100
	Interception type light intensity detection (PD)	Absolute light intensity measurement	0.1~1700uj, measurement accuracy (RMS)<2%	~80
	Multiple Event Relative Time Measurement (ET)	Accurate time measurement	Time Resolution (RMS)<80ps	~20
	Ring down cavity signal measurement (CRDS)	Absolute measurement	Measurement jitter (RMS)<0.1%	~30
	Precision Temperature Controller (TC)	Temperature stability control	-55~150 ℃, measurement resolution 0.001 ℃	~40
	Laser driver (LD)	Current source drives laser operation	0-500mA, noise (RMS)<3 μA. Modulation bandwidth DC-20MHz	~30



- MTCA.4 Based Hardware will be deployed in both the accelerator and beamline of the S³FEL.
- There are hardware, firmware, software development, and maintenance advantages.

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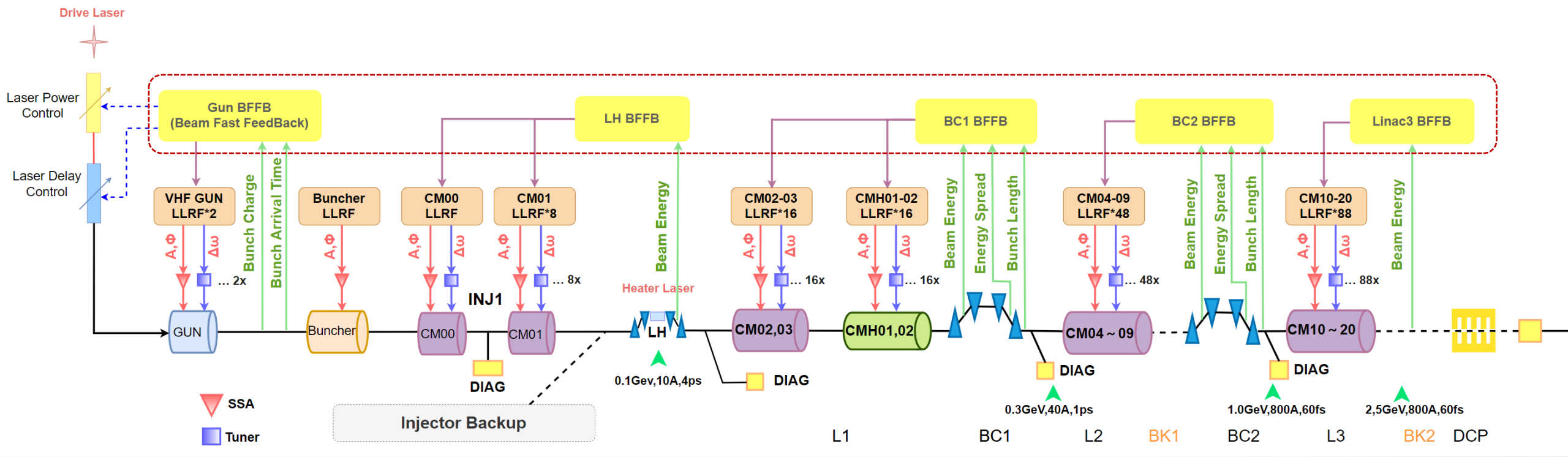
Motivation 2: Longitudinal RF Feedback for Beam Stabilization



- Five longitudinal feedback loops are preliminarily designed for the S^{3}FEL LINAC.

Gun, LH, BC1,BC2, Linac3

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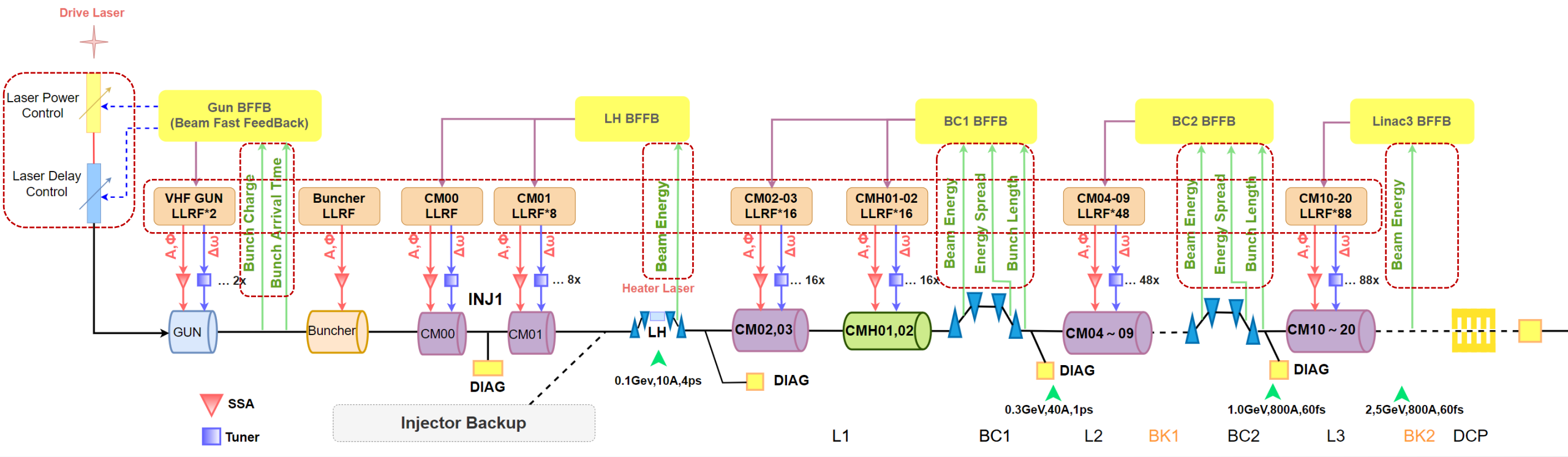
Motivation 2: Longitudinal RF Feedback for Beam Stabilization



- Laser control, LLRF, Beam monitor systems will be deployed.

Laser Control: Refer to Zhang, B., Li, X., Liu, Q., Zhu, Z., Zhang, W., He, Z., ... & Yang, X. (2023). High repetition-rate photoinjector laser system for S3FEL. Frontiers in Physics, 11, 1181862.

Beam monitor systems: Refer to Lei Shi's talk

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Deployment of LLRF Systems

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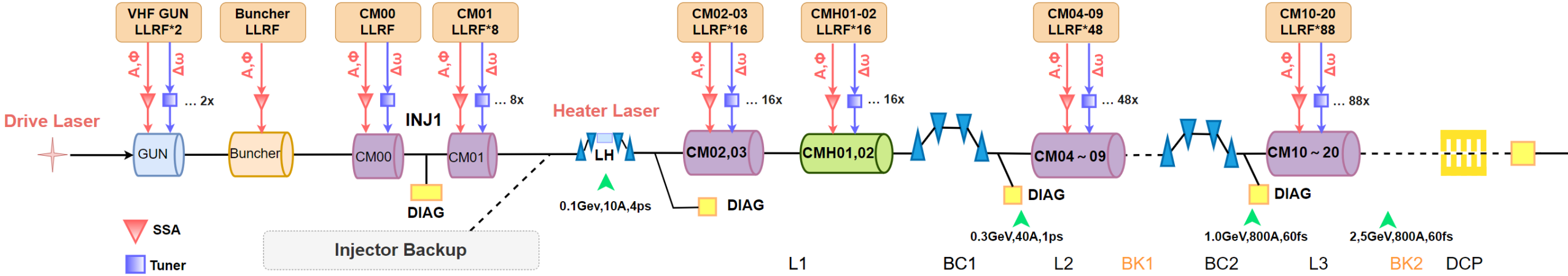
Preliminary arrangement



Part	Module No.	Quantity	Temperature	Function & Cavity	RF	No. of Amplifier/LLRF
INJ / INJ(Backup)	GUN	2	NC	**Photocathode GUN**	VHF-band, 216 MHz	4
	Buncher	2	NC	**Buncher, 1*2-cell**	L-band, 1.3 GHz	2
	CM00	2	SC	**Pre-accelerator, TESLA, 1*9-cell**	L-band, 1.3 GHz	2
	CM01	2	SC	**Main accelerators, TESLA, 8*9-cell**	L-band, 1.3 GHz	16
L1	CM02, 03	2	SC	Main accelerators, TESLA, 8*9-cell	L-band, 1.3 GHz	16
	CMH01, 02	2	SC	**Harmonic, TESLA, 8*9-cell**	S-band, 3.9 GHz	16
L2	CM04 ~ 09	6	SC	Main accelerators, TESLA, 8*10-cell	L-band, 1.3 GHz	48
L3	CM10 ~ 20	11	SC	Main accelerators, TESLA, 8*10-cell	L-band, 1.3 GHz	88
Diagnostic part	Before L2	4	NC	**S-band Deflector**	S-band, 2997 MHz	4
	After L2	7	NC	**X-band Deflector**	X-band, 11989 MHz	7

- Seven kinds of LLRF systems for the S^{3}FEL LINAC will be arranged.
- Same AMC and different RTMs for different LLRF systems.

E.g. RF direct-sampling for VHF GUN, Frequency multiplication for 3.9G and X-band system.

∑ 168, >80% of the total

Deployment of LLRF Systems

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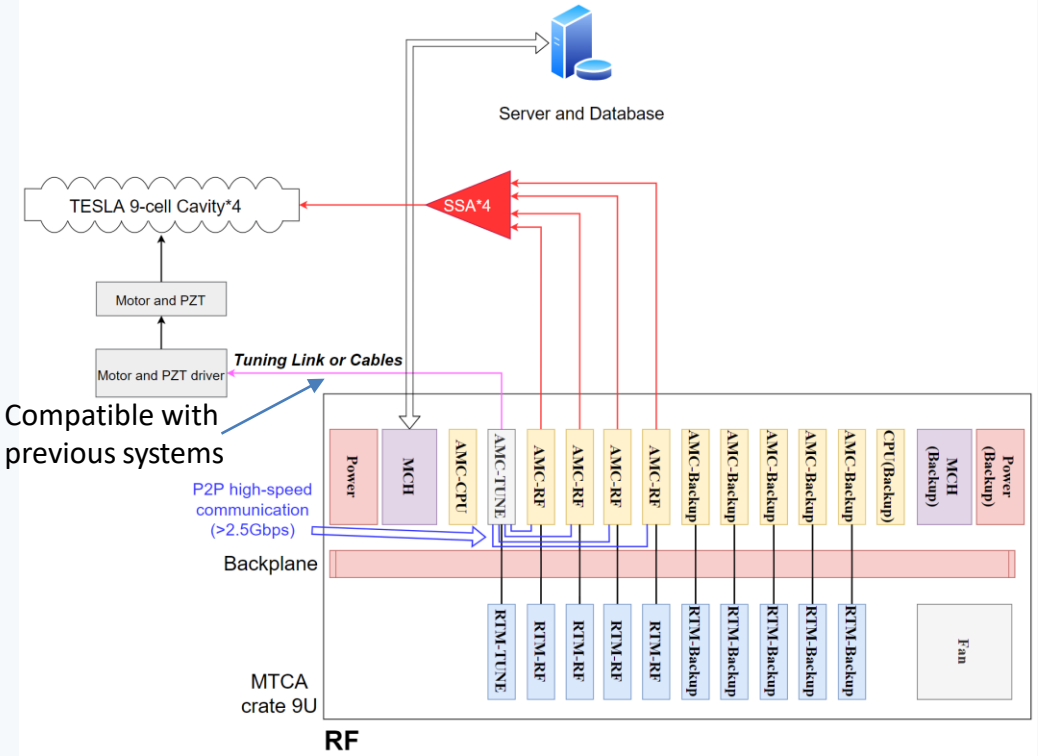
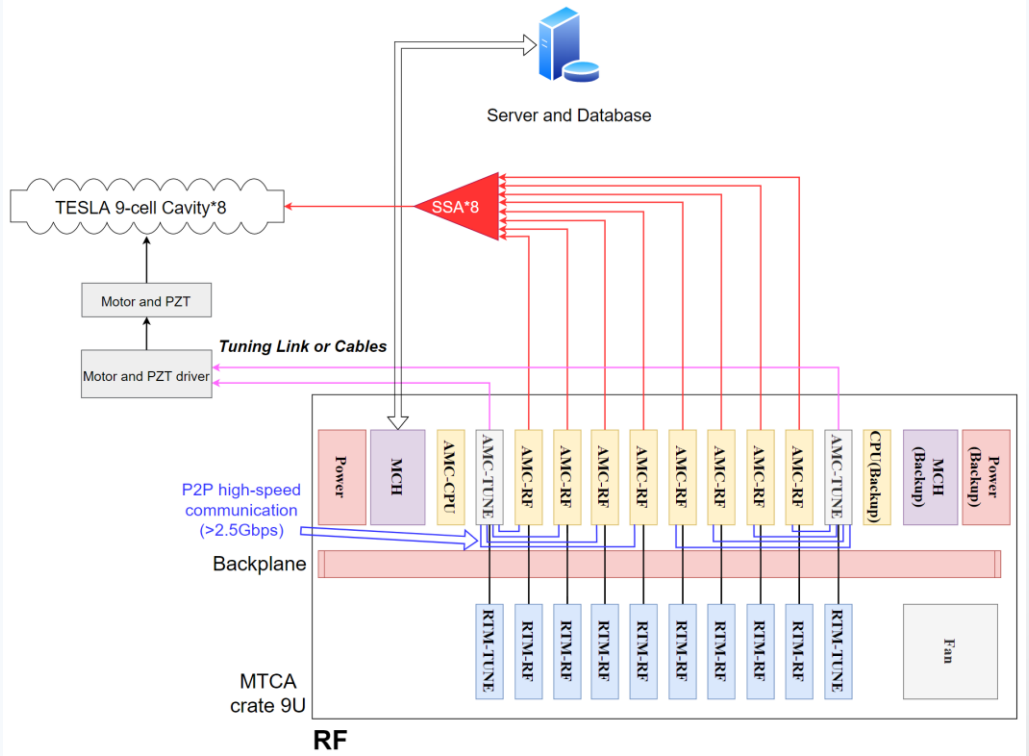
Layout plan of LLRF systems for main accelerators

Plan A: Two crates for one CM (superconducting module)



Plan B: One crate for one CM



- There are eight superconducting cavities(9-cell TESLA) in one CM.
- We will develop two kinds of AMC boards and their RTMs: AMC-RF and AMC-TUNE.
- Four AMC-RF boards are connected to AMC-TUNE via P2P high-speed lines to transmit tuning quantities (Δω).
- AMC Backup: AMC-SAM (Strike Arc Monitor), AMC-HOM (High-order mode signal) ...

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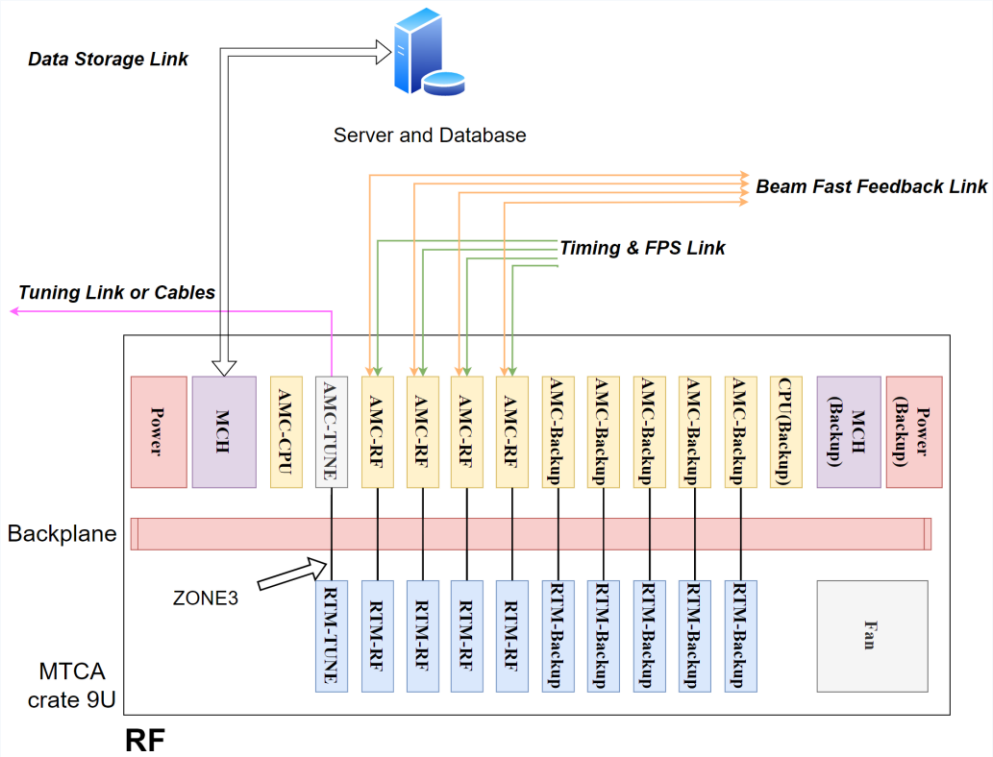
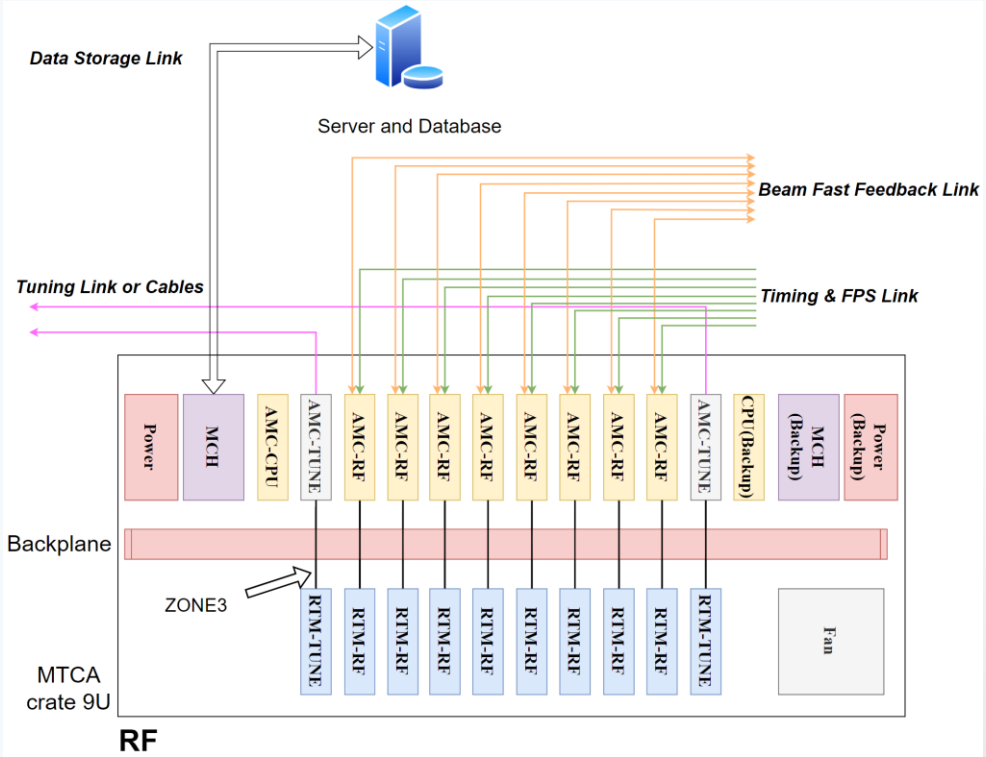
External interfaces

Plan A: Two crates for one CM (superconducting module)



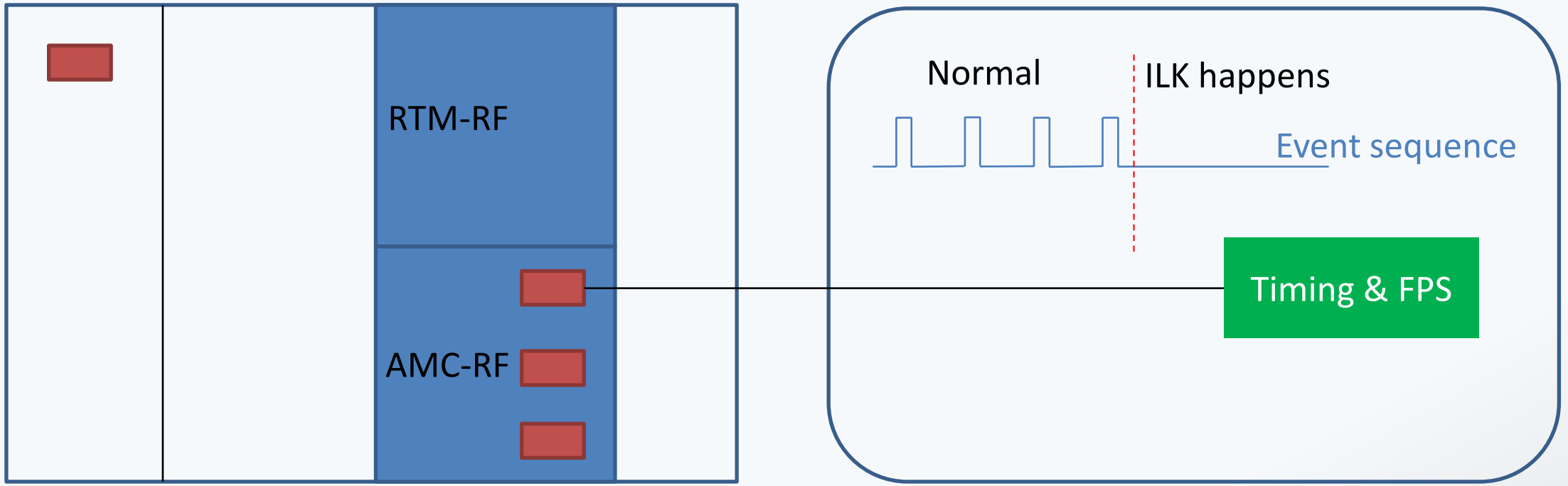
Plan B: One crate for one CM



- To achieve functions such as beam feedback, we have designed four external fiber optic interfaces: Data Storage Link (Data storage, diagnostic analysis), Tuning Link (Tuning control), Beam Fast Feedback Link, Timing & FPS Link (Timing and Fast Protection).

Deployment of LLRF Systems

External interfaces - Timing & FPS Link for LLRF systems



- When an ILK happens, the timing system stops sending the event sequence.

Deployment of LLRF Systems

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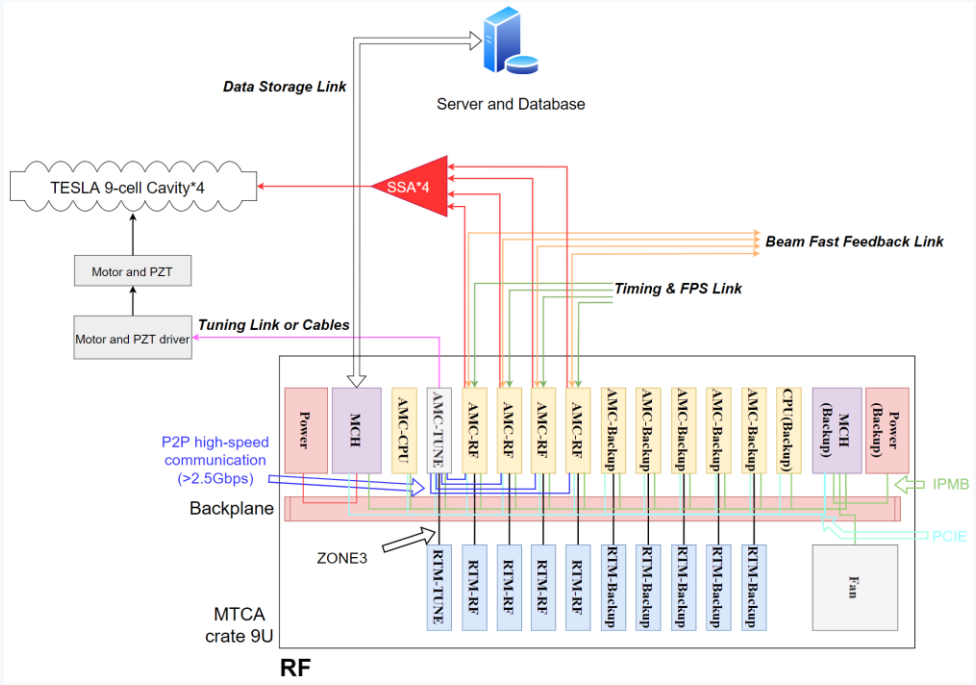
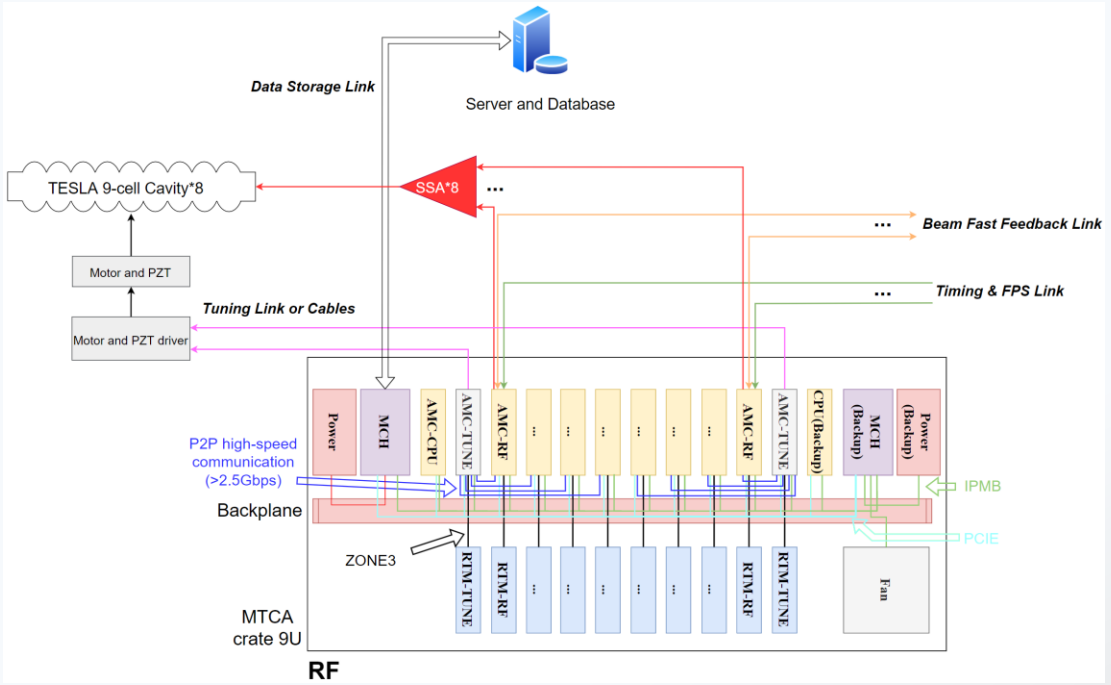
Overall layout plan

Plan A: Two crates for one CM (superconducting module)



Plan B: One crate for one CM



- The final choice between Plan A and Plan B is still under discussion.
- Plan A is more flexible and reliable for backup while Plan B is more compact.

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Hardware R&D of LLRF Systems

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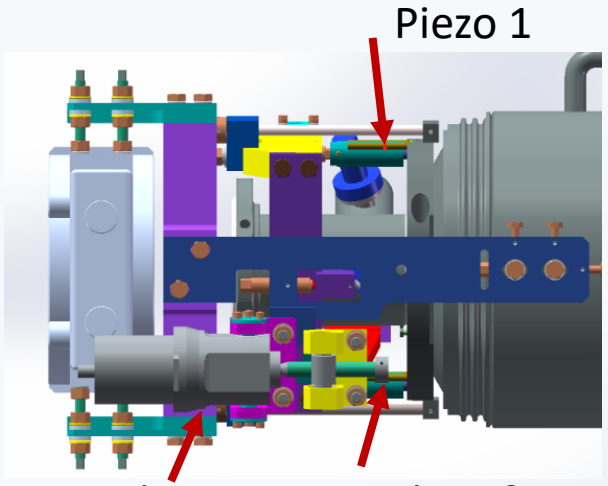
Requirement analysis

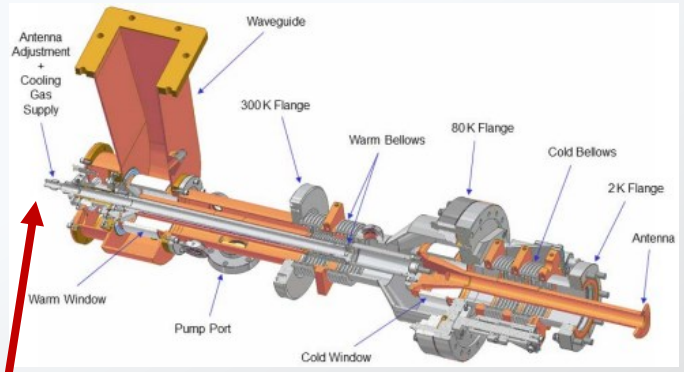
The basic requirement for one CM：

- RF acquisition * 64: *Pt, Pr, Pf, REF, VM, SSA_{in}, SSA_{out}, and one backup per cavity.*
- SSA excitation * 8: *One excitation per cavity.*
- Tuning motor control * 8: *One tuning motor control per cavity.*
- Tuning piezo control * 16: *Two tuning piezo controls per cavity.*
- Coupler motor control * 8: *One coupler motor controls per cavity.*
- External fiber optic interfaces * 24, *Two fiber optic interfaces and one backup per cavity.*

Eight AMC-RF and RTM-RF boards and **two AMC-TUNE and RTM-TUNE boards** are required for **one CM.**

Eight 9-cell TESLA in one CM





Coupler motor
for high-power coupler adjustment

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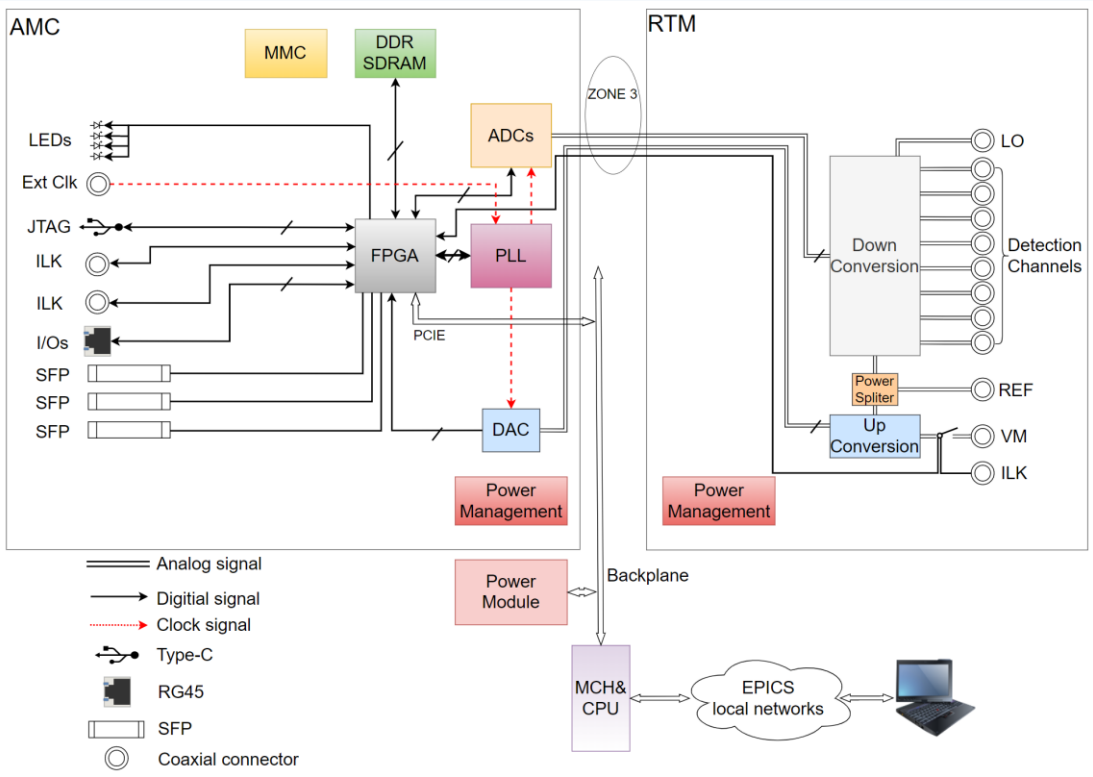
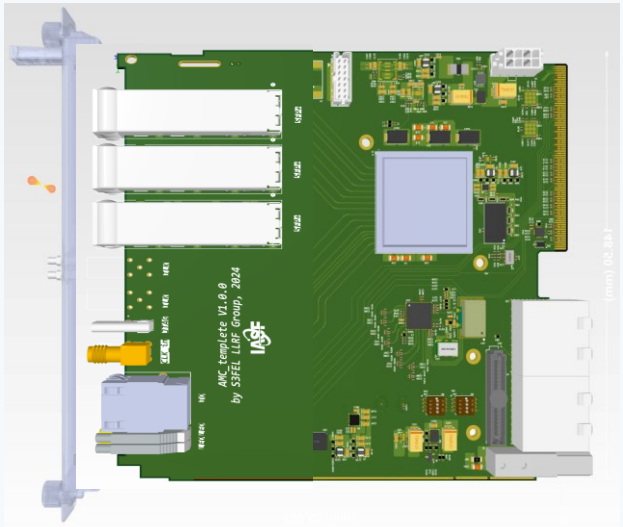
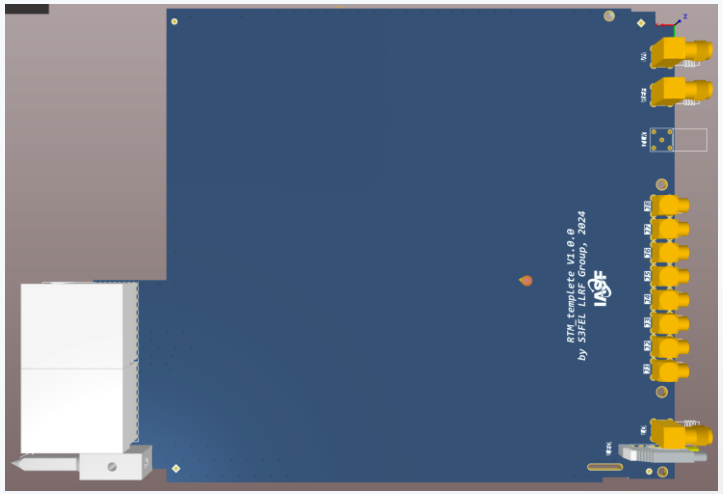
AMC-RF and RTM-RF



AMC-RF & RTM-RF, ZONE3 A1.0





Under designed

Hardware R&D of LLRF Systems

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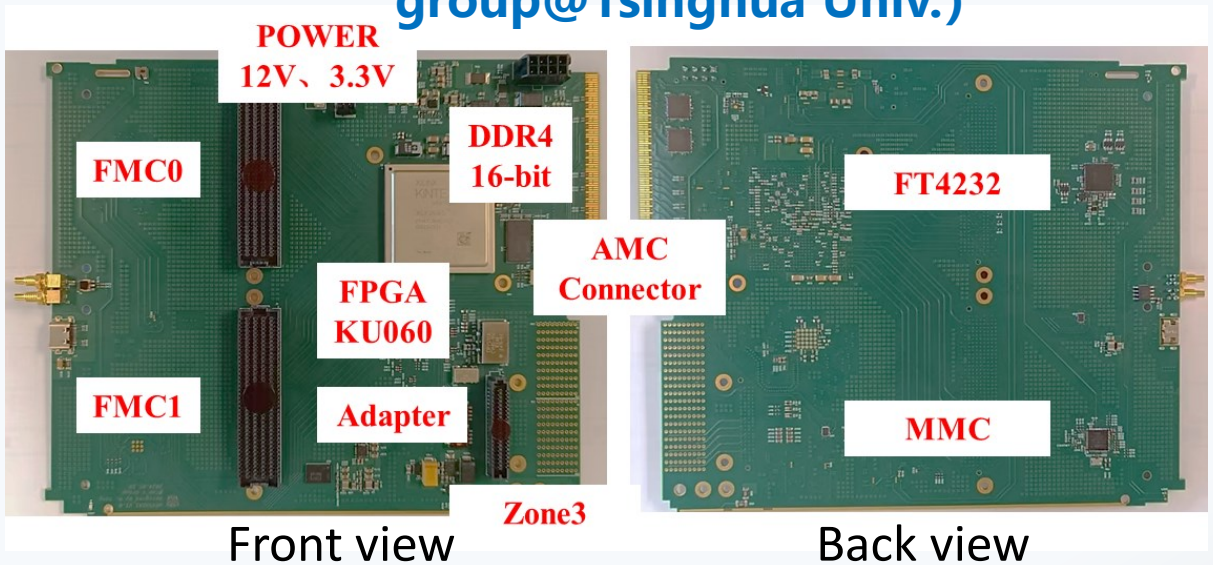
AMC prototype design for RF performance test

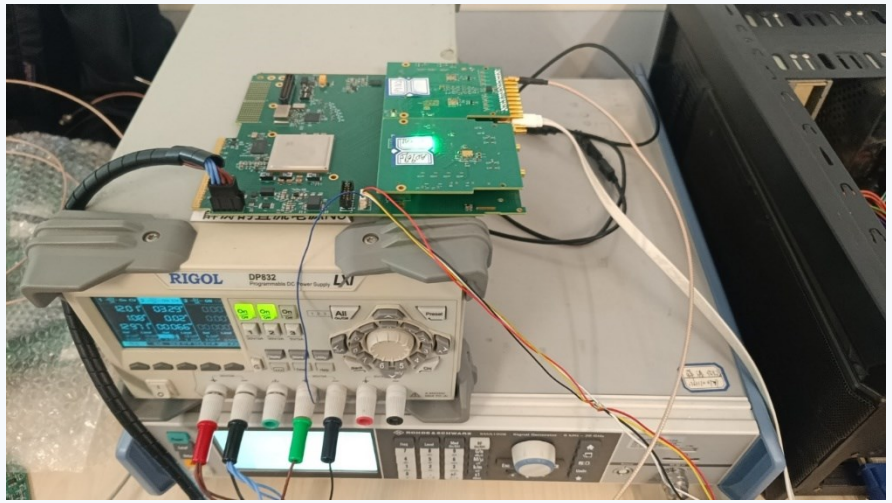
(Collaborated with Tao Xue's group@Tsinghua Univ.)

The AMC board (WRX502A1):

- Core chip: Xilinx Kintex Ultrascale KU060
- Memory: 1Gb DDR4 SDRAM
- GTH links: Up to 28 x 16 Gbps
- Highlights: Flexible and Expandable. Dual FMC connectors, Zone3 – Adapter architecture, FT4232 Type-C JTAG connector

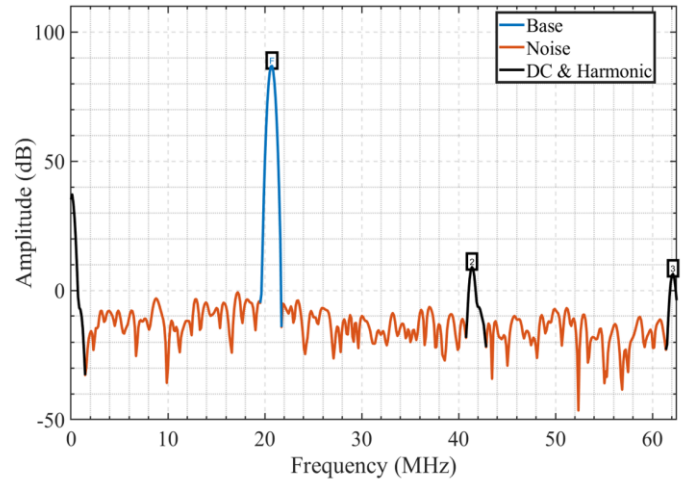


Front view Back view



125MSPS ADC performance test @20.7MHz

	ENOB	SNR	SFDR	Isolation
ch0	12. 4372	76. 33	77. 71	87.23
ch1	12. 5407	76. 96	77. 76	87.17
ch2	12. 5099	76. 77	78. 53	87.55
ch3	12. 4069	76. 15	78. 53	87.58
ch4	12. 4666	76. 51	78. 40	86.97
ch5	12. 3585	75. 86	78. 03	87.28
ch6	12. 5260	76. 87	78. 66	87.23
ch7	12. 3225	75. 64	77. 74	86.79



Hardware R&D of LLRF Systems

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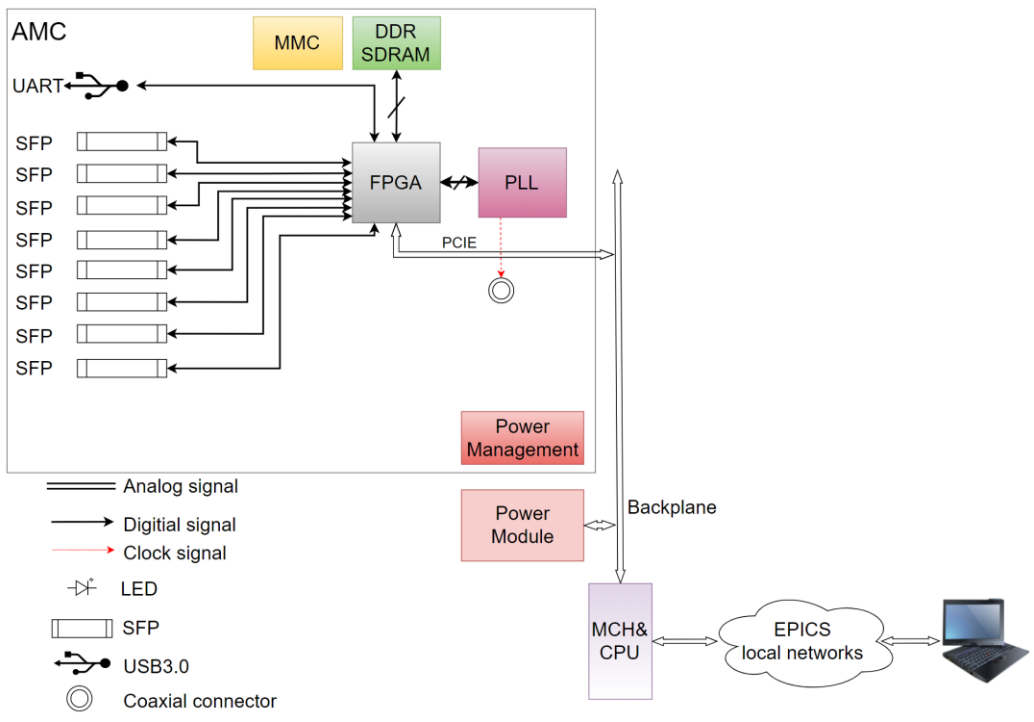
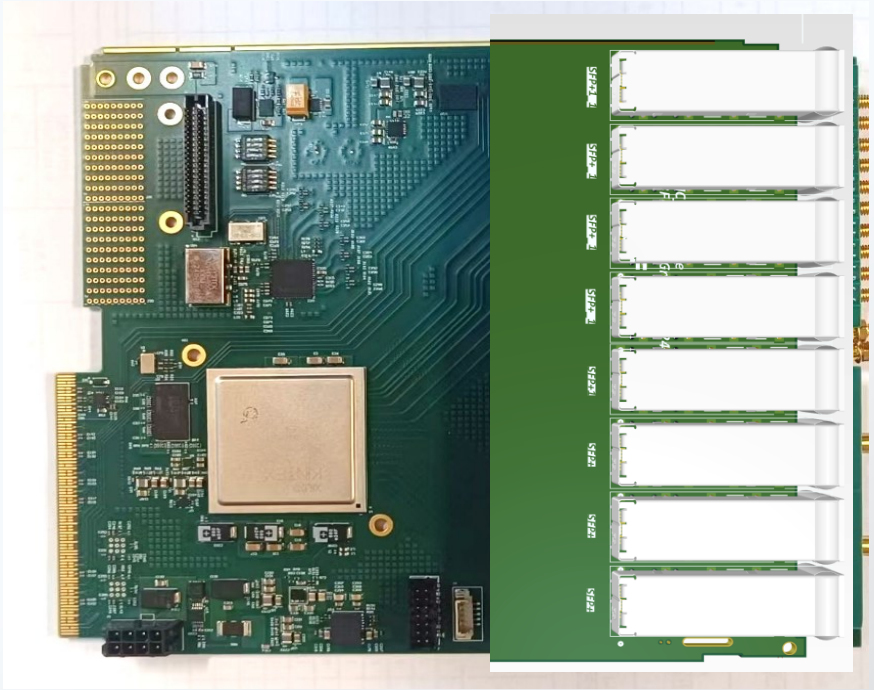
AMC prototype design for AMC-LBFF (Longitudinal Beam Fast Feedback)

(Collaborated with Tao Xue's group@Tsinghua Univ.)

The AMC board (WRX502A1):

- Core chip: Xilinx Kintex Ultrascale KU060
- Memory: 1Gb DDR4 SDRAM
- GTH links: Up to 28 x 16 Gbps
- Highlights: Flexible and Expandable. Dual FMC connectors





Hardware R&D of LLRF Systems

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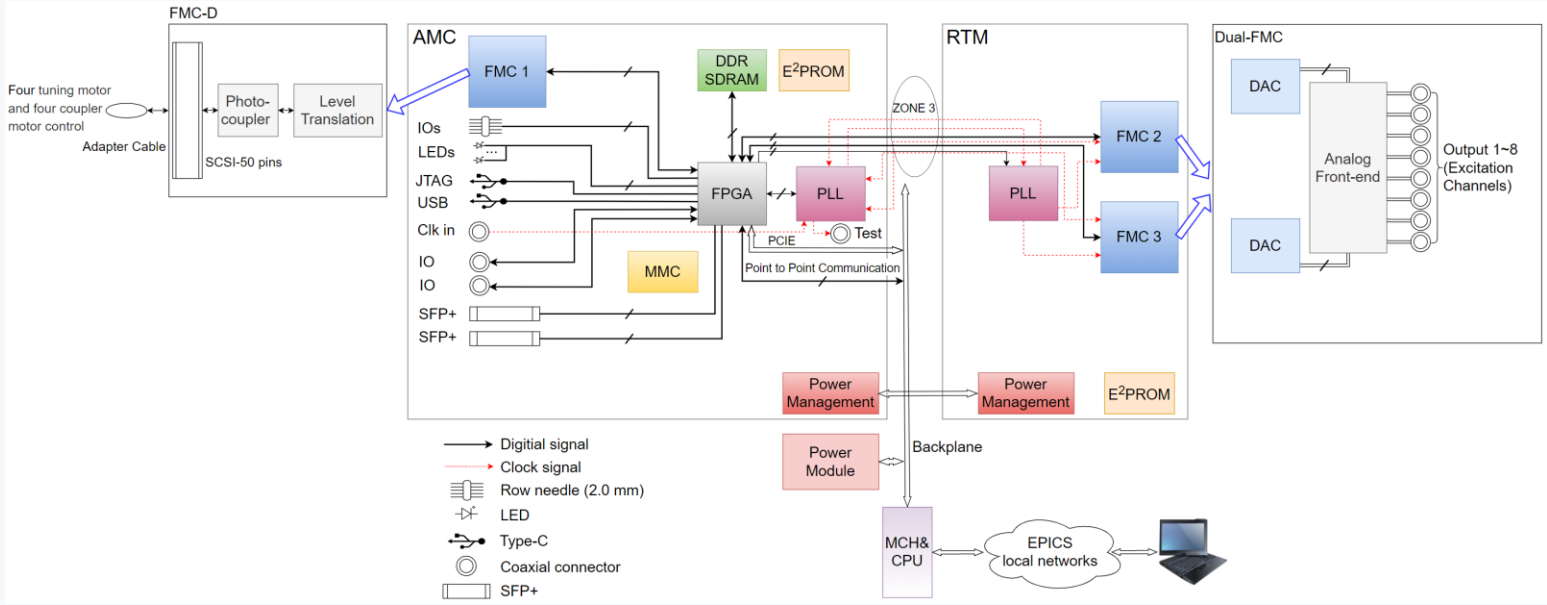
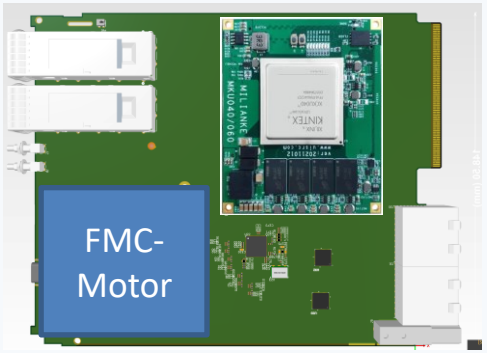
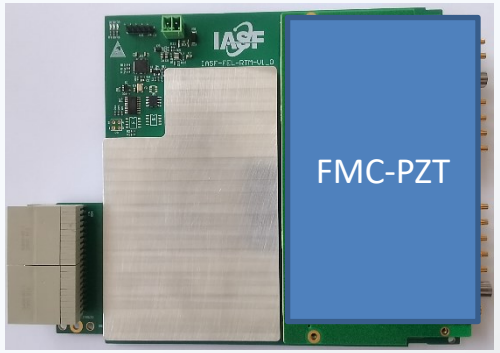
AMC-TUNE and RTM-TUNE



AMC-TUNE & RTM-RF, ZONE3 D1.0





FMC boards are under designed.

Hardware R&D of LLRF Systems

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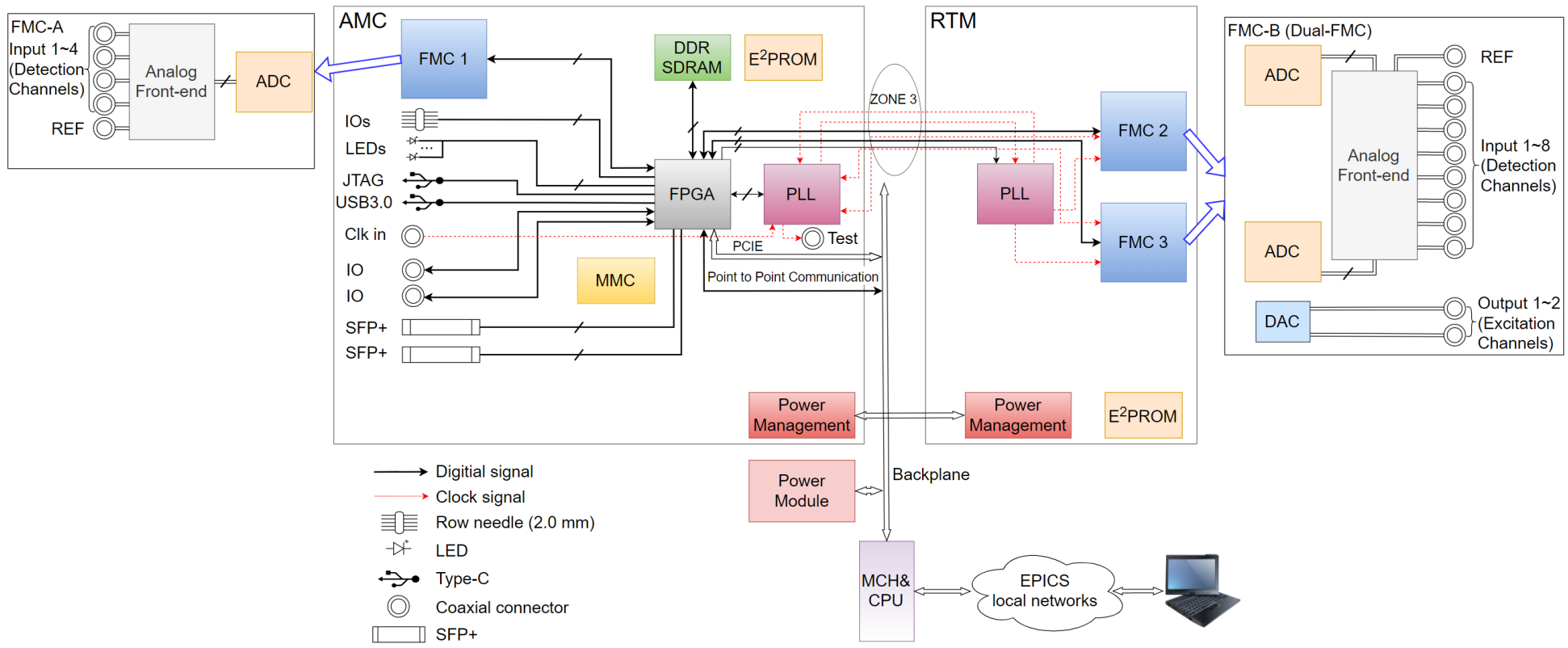
AMC and RTM for other applications



GMDs, ICTs, BPMs, Klystron high-voltage or Magnetic power monitors, etc.

Refer to: *Zhu, J., Ding, H., Li, H., Ran, Q., Dai, X., Li, W., ... & Zhang, W. (2024). Preliminary Design of a General Electronics Platform for Accelerator Facilities. arXiv preprint arXiv:2406.15407.*

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Summary and Next work

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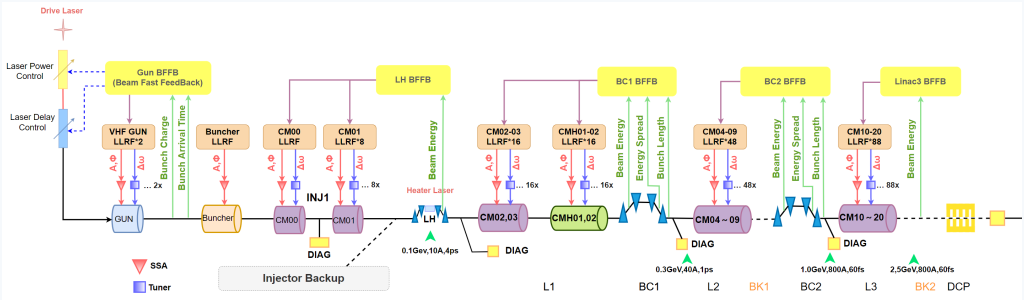
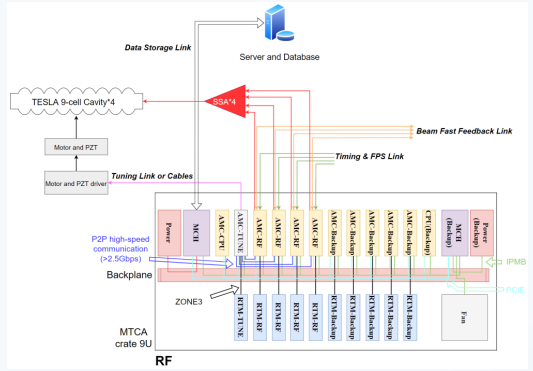
Summary

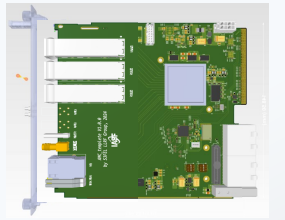
- We have deployed the LLRF system of S3FEL LINAC based on the overall MTCA.4 based hardware standardization of S3FEL.

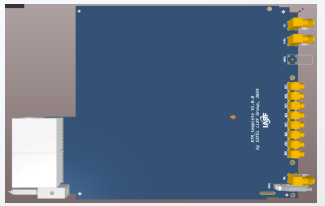


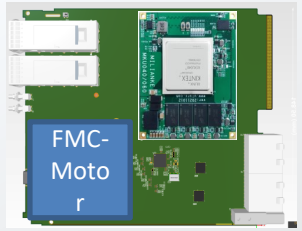
- We designed an LLRF system scheme based on fiber optic interconnection to meet the requirements of longitudinal beam feedback.



- We also carry out hardware design of LLRF boards, such as AMC-RF, RTM-RF, AMC-TUNE, RTM-TUNE, and AMC-LBBF.







Summary and Next work

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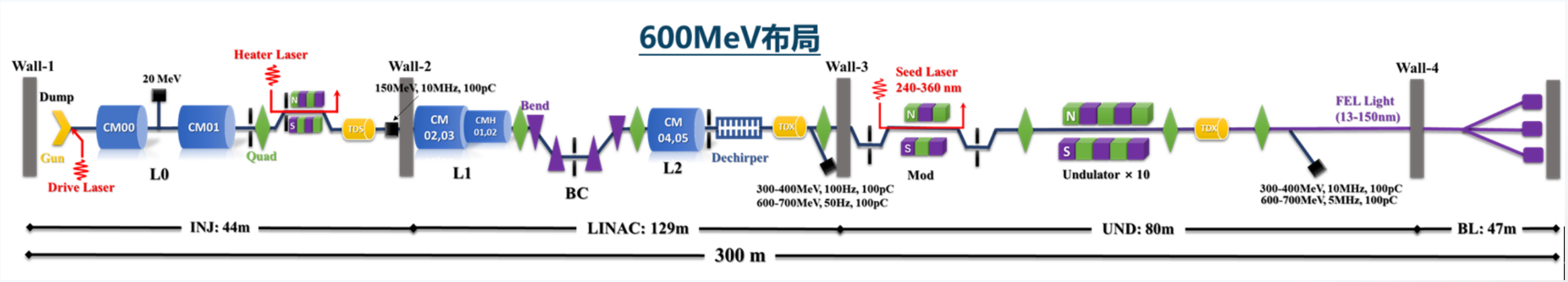
Next work

- Next, we will validate the scheme and critical technology based on the Shenzhen beam testing platform.



LINAC		Freq./MHz	Module No.	Cavity
SC	CM00	1300	1	1*9cell
SC	CM01-CM05	1300	5	8*9cell
SC	CMH01,02	3900	2	8*9cell

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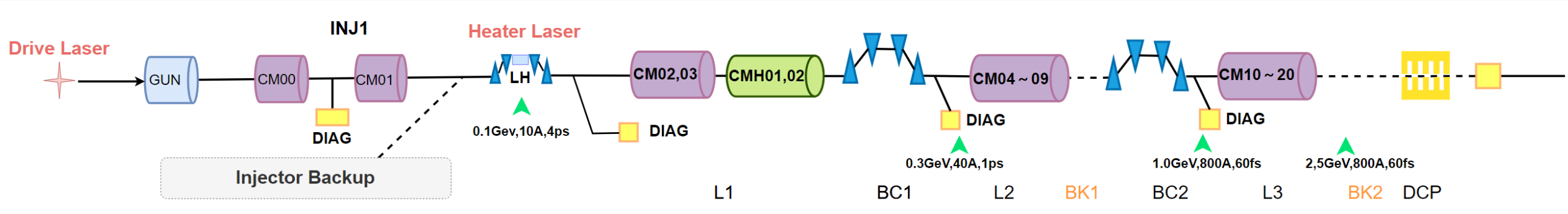
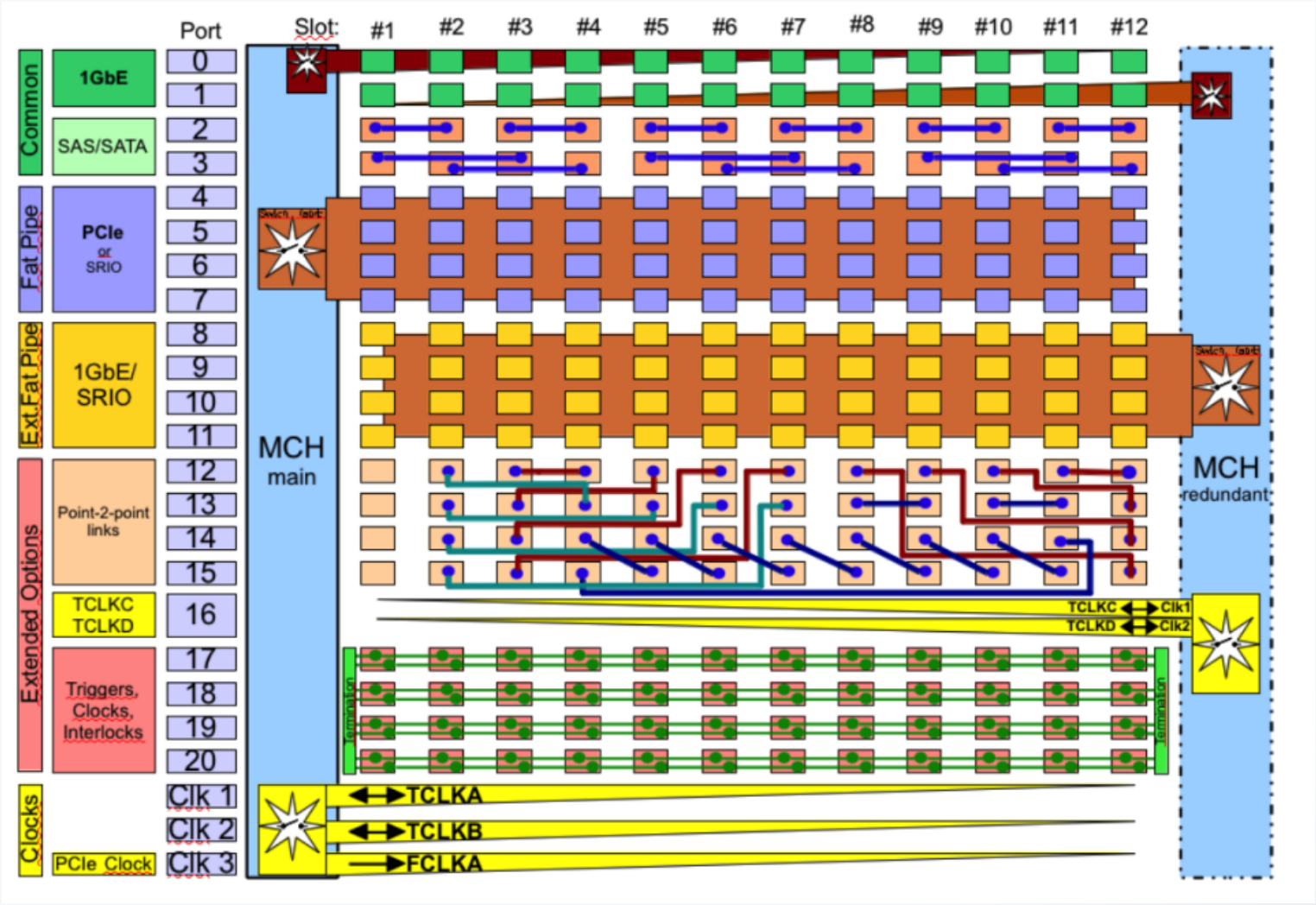
Thanks for your attention

Our group would like to thank DESY and demotic institutions SHINE, IHEP, IMP, USTC, Peking, and Tsinghua Univ., etc. for their support over the years.



FEL facility	Microwave	Temperature	Function & Cavity	RF	No. of Amplifier/LLRF
S^3FEL LINAC	Continuous Wave (CW)	SC	Main accelerators, TESLA, 8*9-cell	L-band, 1.3 GHz	168
		SC	Harmonic, TESLA, 8*9-cell	S-band, 3.9 GHz	16
		SC	Pre-accelerator, TESLA, 1*9-cell	L-band, 1.3 GHz	2
		NC	Photocathode GUN	VHF-band, 216 MHz	4
		NC	Buncher, 2-cell	L-band, 1.3 GHz	2
	Pulsed	NC	Deflector	S-band, 2997 MHz	4
		NC	Deflector	X-band, 11989 MHz	7


Port
Slot:
#1
#2
#3
#4
#5
#6
#7
#8
#9
#10
#11
#12
Common
1GbE
SAS/SATA
Fat Pipe
PCIe
or
SRIO
Ext.Fat Pipe
1GbE/
SRIO
Extended Options
Point-2-point
links
TCLKC
TCLKD
Triggers,
Clocks,
Interlocks
Clocks
PCIe Clock
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
Clk 1
Clk 2
Clk 3
MCH
main
MCH
redundant
TCLKC
Clk1
TCLKD
Clk2
TCLKA
TCLKB
FCLKA