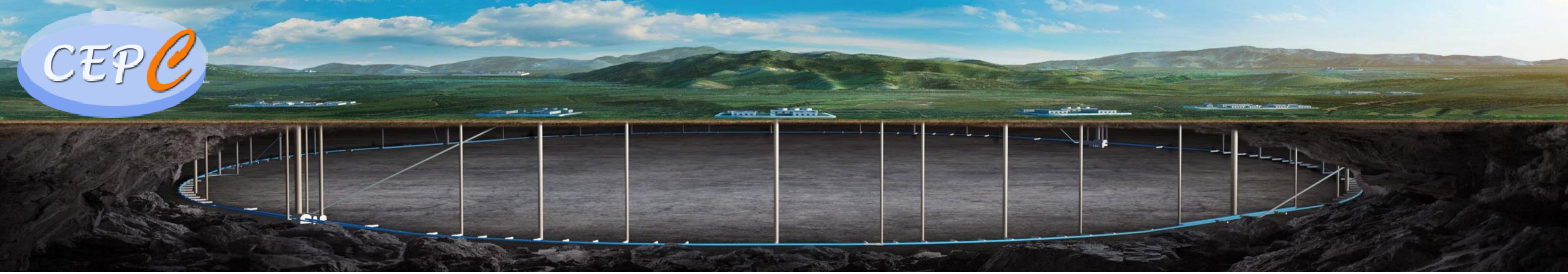


# CEPC Linac Injector Development in EDR

High Energy Physics 2024 (HEP2024)

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2024.01.24

On behalf of linac group, Institute of High Energy Physics, CAS

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- Introduction
- Physical design of Linac
- Source &RF system of Linac
- R&D of 5 cell normal conducting cavity of DR
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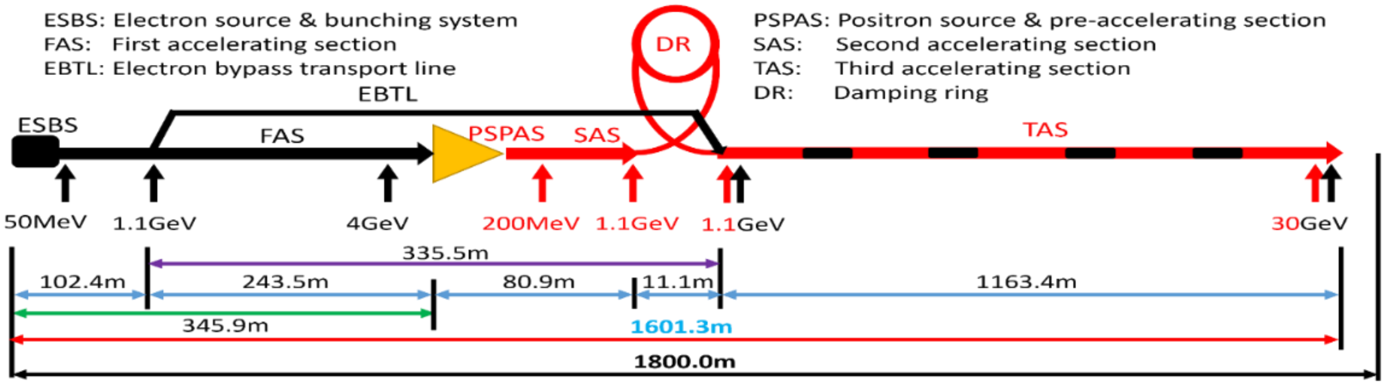
# Introduction

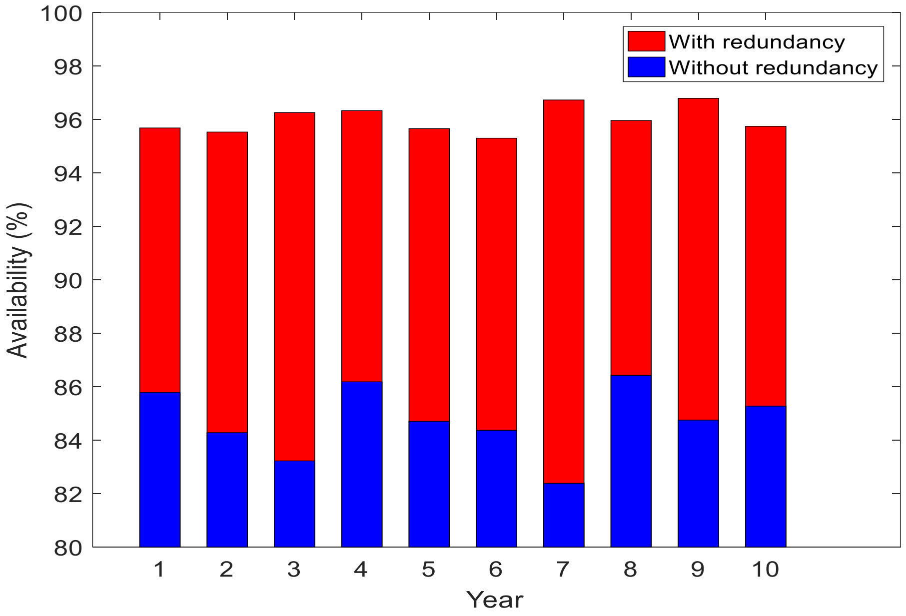
- The 30 GeV linac provides electron and positron beams for the booster, with 1.1GeV damping ring for the positron beam
  - Electron gun: thermal cathode
  - Positron source: Conventional scheme (fixed target)
  - 30 GeV normal conducting accelerating structures including bunching system
    - S-band Linac: FAS: 4GeV + PSPAS: 200MeV + SAS: 1.1GeV
    - C-band Linac: TAS： 1.1GeV→30GeV
  - 1.1GeV damping ring with two 5 cell normal conducting cavities
- The length of the linac tunnel 1.8km
  - Linac is about 1.6 km
  - 200 m as reserved space

| Parameter | Symbol | Unit | Baseline |
|---|---|---|---|
| Energy | $E_{e-}/E_{e+}$ | GeV | **30** |
| Repetition rate | $f_{rep}$ | Hz | 100 |
| Bunch charge | | nC | 1.5 (3) |
| Energy spread | $\sigma_E$ | | $1.5\times10^{-3}$ |
| Emittance | $\varepsilon_r$ | nm | 6.5 |

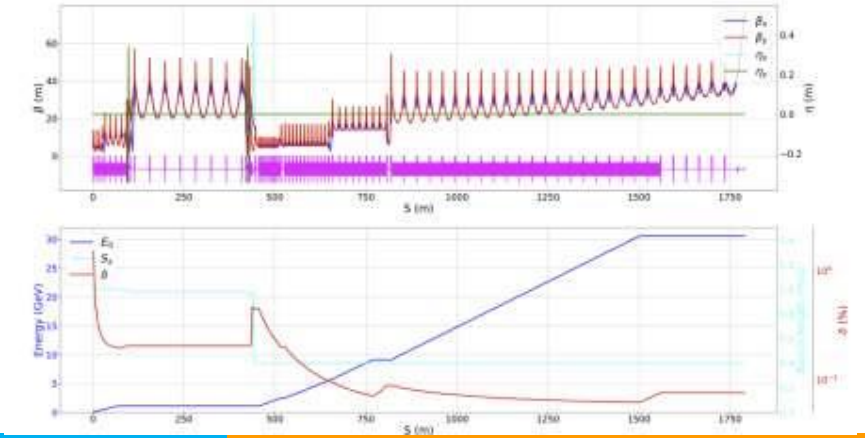


# Physical design of LINAC in EDR

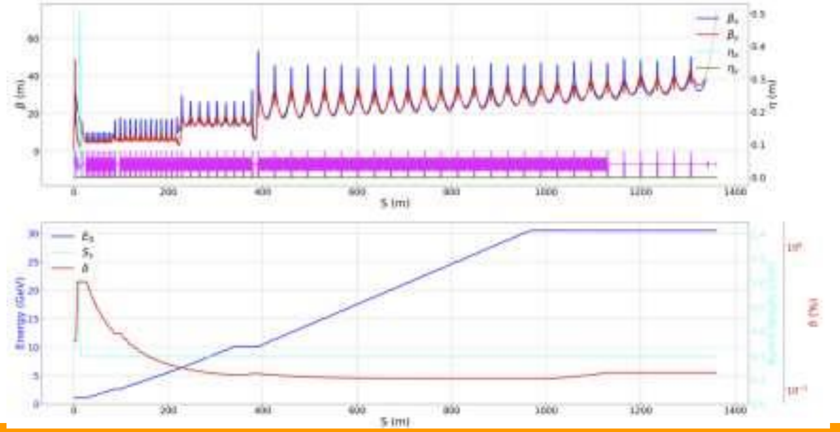
- TDR finished: Start to end simulations with errors have been conducted for both electron and positron beams with qualities satisfying design requirements
- In EDR:
  - Optimization of the physics design, especially double-bunch acceleration simulation will be done
  - Availability analysis of the Linac
    - During the CDR phase, there is a preliminary analysis, which will be further analyzed




e- in linac



e+ in linac



# Double-bunch-per-pulse experiment in EDR

- This is the proposed operation modes of CEPC, the pulse repetition rate of the linac is 100Hz. For Z mode, **double bunch per pulse** is needed

| | tt(180GeV) | Higs(120GeV) | W(80GeV) | Z(45.5GeV) |
|---|---|---|---|---|
| Pulse repetition rate(Hz) | 100 | 100 | 100 | 100 |
| Bunch number per pulse | 1 | 1 | 1 | 2 |

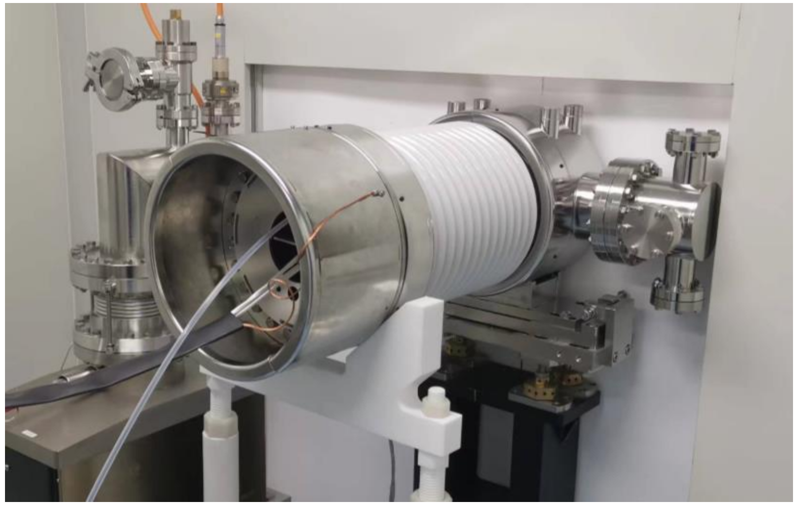
- double-bunch acceleration
  - The accelerators that achieve double-bunch acceleration are KEKB (high bunch charge) and the Swiss FEL (low bunch charge)
  - SuperKEKB is currently reattempting double-bunch acceleration operation mode. There are **still significant challenges**, especially with high bunch charge

# Double-bunch-per-pulse experiment on HEPS Linac

- The HEPS linac is a 500-MeV S-band normal conducting linear accelerator
- A maximum bunch charge of 8 nC at the exit of the Linac can be routinely achieved
- There is still time for Linac based machine studies before commissioning the HEPS storage ring
- With minor modification, the HEPS Linac could be used for double-bunch-per-pulse experiments

# Double-bunch-per-pulse experiment on HEPS Linac

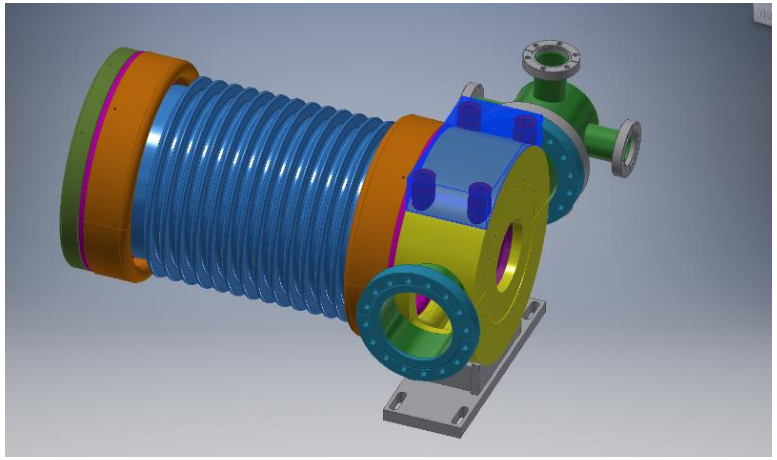
Modification and upgrade for the Double-bunch-per-pulse experiment



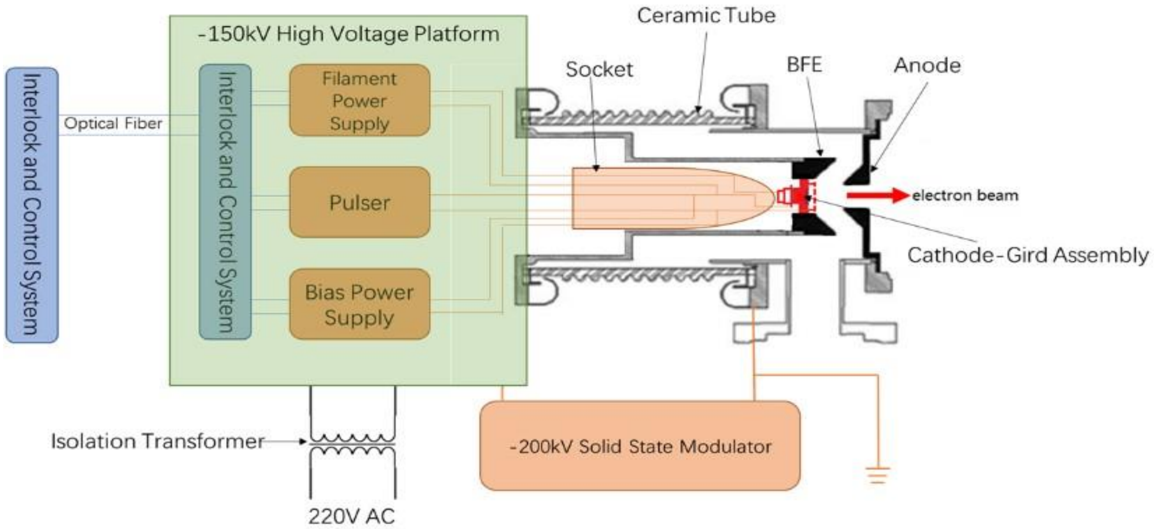
- The e-Gun
  - Only one pulser are currently installed
  - Additional pulser is needed for the double-bunch experiment
- Timing upgrade
  - One additional high precision timing module is needed for the second pulser
- Beam diagnostics
  - Current beam diagnostics can only be used for single-pass long separation pulses
  - A new system need to be developed for pulses with separation about 100 ns

# Sources-TDR finished

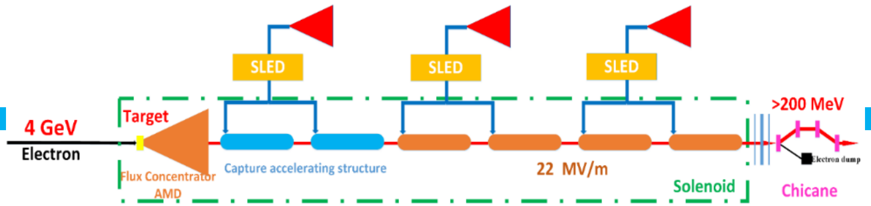
- Electron source
  - Traditional thermionic triode gun
  - Mature technology
- Design parameters of the TDR
  - 1.5 nC bunch charge for electron injection
  - 10 nC bunch charge for positron production
- The HEPS and BEPCII design can meet our requirement



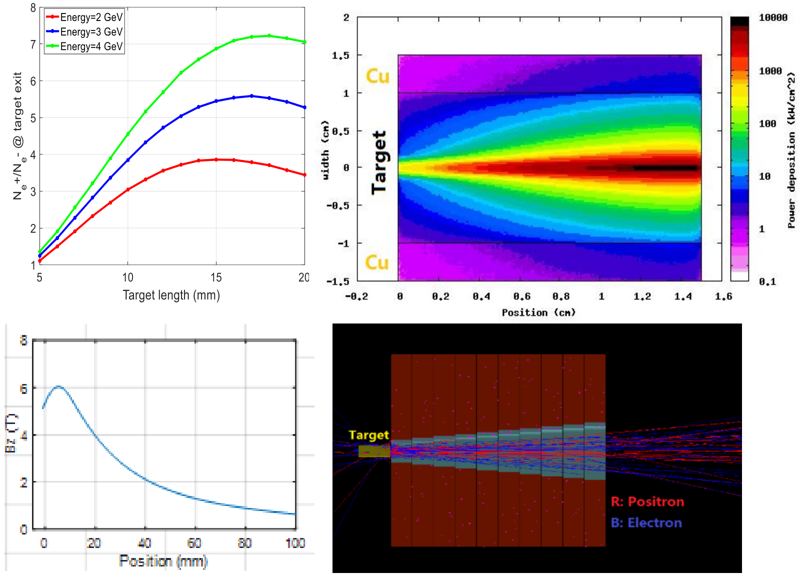
| Parameter | Unit | Value |
|---|---|---|
| Type | - | Thermionic Triode Gun |
| Cathode | - | Dispenser cathode |
| Beam current | A | > 10 |
| High voltage of anode | kV | 150 |
| Bunch charge 1 | nC | 3.3 ($e^-$ injection) |
| Bunch charge 2 | nC | 11 ($e^+$ production) |
| Repetition rate | Hz | 100 |
| Pulse duration | ns | 1 |

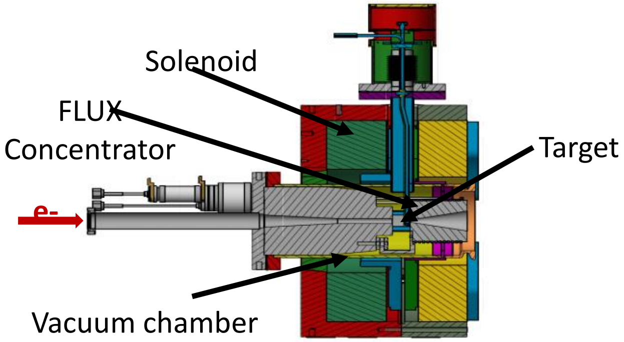


# Sources-TDR finished




- Positron source
  - Incident electron beam:4GeV/10nC/100Hz, Beam power 4kW
  - Fixed Target (tungsten,15mm thickness , Beam size: 0.5 mm)
  - Energy deposition: 0.784 GeV/e- @ FLUKA, 784 W → water cooling
  - We have made a prototype of the flux concentrator and it's power supply and successfully high power tested
- For the beam energy is high, under normal circumstances, there is no problem. We will research on the protection method of positron conversion target under extreme conditions

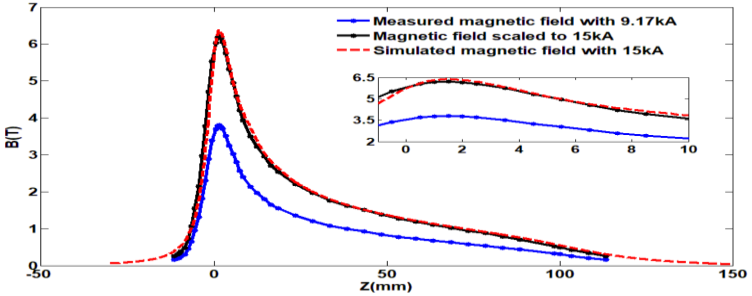



Design of positron converter device

The FLUX conentrator

The 15kA solid-state modulator

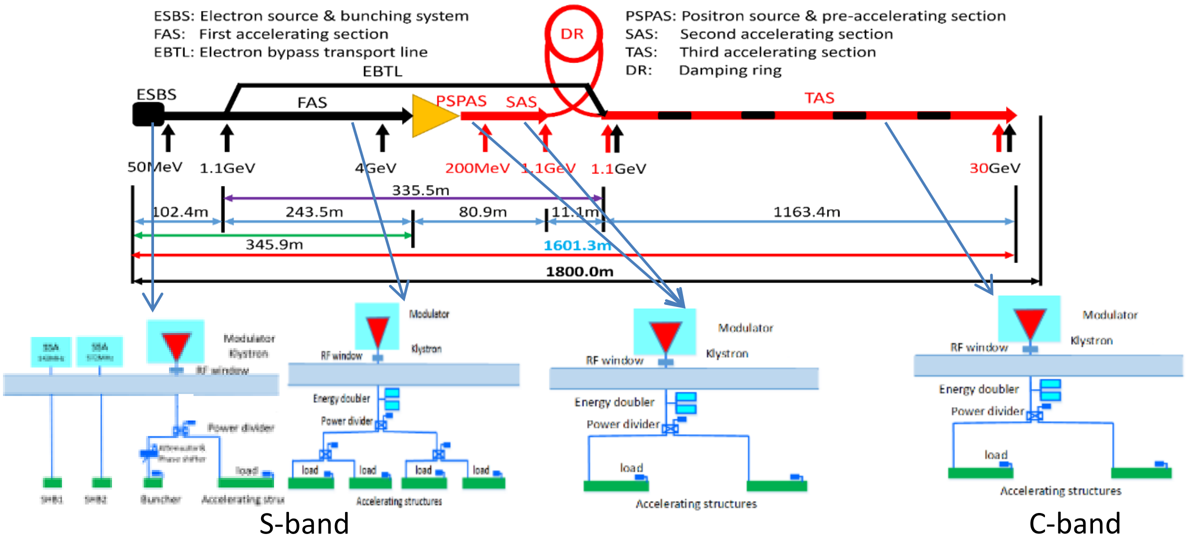



Test of the peak pulse magnetic field

# RF system

- RF distribution of the 30 GeV linac
  - S-band, 80 MW klystron, the number of S-band Acc. Structure is 93, big hole s-band structure after the positron source is 16. the number of pulse compressor is 33
    - 1-1(ESBS), 1 accelerating structure, 22MV/m
    - 1-4 (FAS), 21 sets, 84 standard accelerating structures, with pulse compressor, 22MV/m
    - 1-2(PSPAS), 8 sets, 16 big hole accelerating structures, 22MV/m, with pulse compressor
    - 1-2(SAS), 4 sets, 8 accelerating structures, 27MV/m , with pulse compressor
  - C-band, 50 MW klystron, C-band  structures: 470, with 235 pulse compressors
    - 1.1GeV-30GeV, 1-2(TAS), 235 sets, 470 accelerating structures, ~40MV/m,

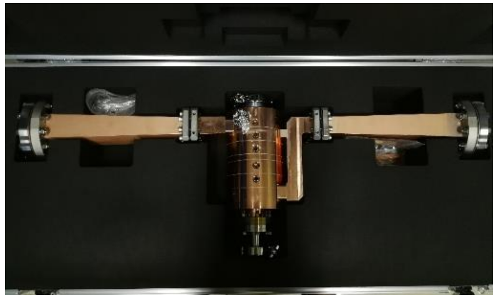
| Parameter | Unit | S-band | | C-band |
|---|---|---|---|---|
| Frequency | MHz | 2860 | | 5720 |
| Length | m | 3.1 | 2.0 | 1.8 |
| Cavity mode | | 2π/3 | | 3π/4 |
| Aperture | mm | 19~26 | 25 | 12~16 |
| Gradient | MV/m | 22/27 | 22 | 40~45 |
| Cells (include coupler cells) | | 86 | 55 | 89 |
| Number of Acc. Stru. | | 93 | 16 | 470 |
| Number of Klystron | | 33 | | 236 |
| Klystron Power | MW | 80 | | 50 |



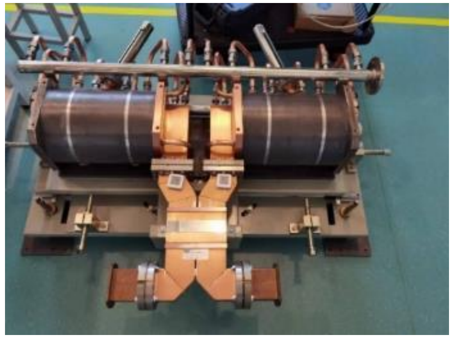
# Bunching cavities and S-band RF system-TDR finished

- The SHBs & buncher
  - Traditional cavity structure
    - Re-entrant SW for SHBs
    - TW/CI for buncher
- The same as HEPS only the frequency is a little deference
- S-band RF system
  - The prototype for CEPC was tested and the average gradient has reached 33 MV/m at high power test (with SLED)
- The S-band RF system successfully used in HEPS project and the gradient with beam reached 26MV/m

SHBs for HEPS



Buncher for HEPS



HEPS pulse compressor

For bunching cavities and S-band RF system, the technology is mature now for us.

# C-band RF system-TDR finished

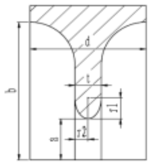
- The situation of other labs
  - The maximum average gradient with beam is about 40MV/m

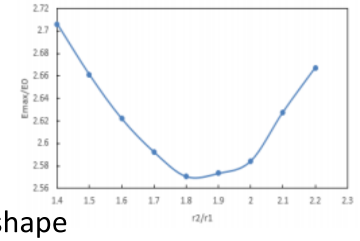
| | IHEP | SARI | RIKEN | INFN | PSI |
|---|---|---|---|---|---|
| Frequency(MHz) | 5712 | 5712 | 5712 | 5712 | 5712 |
| Mode | $3\pi/4$ | $4\pi/5$ | $2\pi/3$ | $2\pi/3$ | $2\pi/3$ |
| Length (m) | 1.8 | 1.8 | 2 | 1.4 | 2 |
| Gradient at high power test bench(MV/m) | - | 50[1] | 50.1[2] | 36[3] | 52[4] |
| Operating gradient with beam (MV/m) | - | 41.7(maximum, private talk) | 41.4 | 36 | 28 |

1. W. Fang, et al. THE C-BAND TRAVELING-WAVE ACCELERATING STRUCTURE FOR COMPACT XFEL AT SINAP . NIMA 2016
2. T. Sakurai, et al. C-band disk-loaded-type accelerating structure for a high acceleration gradient and high-repetition-rate operation. PHYSICAL REVIEW ACCELERATORS AND BEAMS 20, 042003 (2017)
3. D. Alesini, et al. HIGH POWER TEST RESULTS OF THE SPARC C-BAND ACCELERATING STRUCTURES. IPAC 2014
4. F. Loehl, et al. STATUS OF THE SWISSFEL C-BAND LINEAR ACCELERATOR. FEL 2013

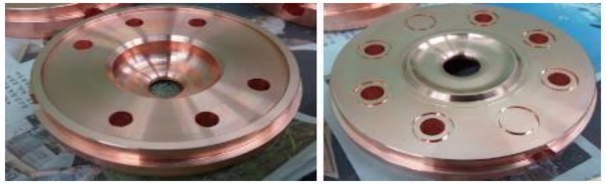
# C-band accelerating structure

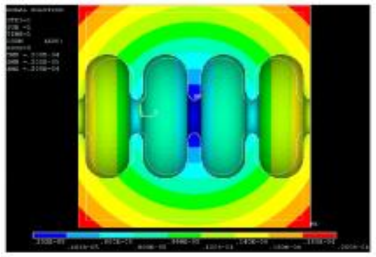
- The R&D of C-band accelerating structure at IHEP
  - The beam dynamics of linac based on this design
  - Constant gradient, 3π/4 mode, 1.8 meters long (Including mechanical length, Effective length is about 1.7m)
    - Round cavity shape
    - Racetrack symmetrical magnetic coupling
- **No high power test and beam testing**



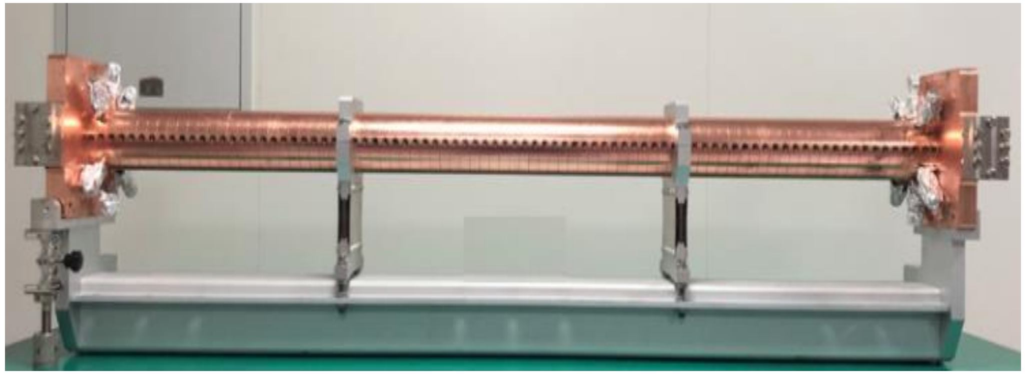


Cavity shape





The deformation caused by temperature variation



# C-band accelerating structure

- The design parameters between different lab
  - Mode :3π/4, 2π/3, 4π/5
  - Length
  - Disc thickness
- Though the phase advance is deferent, the other key parameters is similar

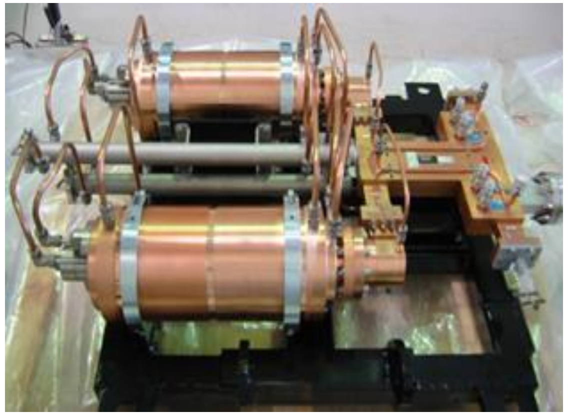
| | IHEP | Spring8 | SINAP[1] |
|---|---|---|---|
| Frequency: f（MHz） | 5712 | 5712 | 5712 |
| No. of Cells | 87+2 | 100 regular cells +2 coupler | 89+2 |
| Phase advance | 3π/4 | 2π/3 | 4π/5 |
| Total length(m) | 1.8 | 2 | 1.784 |
| Length of cell : d (mm) | 19.675 | 17.495 | 20.994 |
| Disk thickness: t (mm) | 4.5 | 4 | 5 |
| Average aperture: 2a (mm) | 14.04 | 15.938~12.107 | 15 |
| Average diameter : 2b (mm) | 45.6 | 43.196~41.869 | - |
| Shunt impedance(average) : Rs (MΩ/m) | 66.05 | 66 | 62 |
| Quality factor : Q | 11358~11186 | 9300/8900(measured) | 10470 |
| Group velocity: Vg/c (%) | 2.8% ~ 0.96% | 2.3%(average) | 1.7%(average) |
| Filling time : $t_f$ (ns) | 350 | 290 | 330 |
| Attenuation factor : τ | 0.56 | 0.59 | 0.585 |
| Epeak/E0 | 2.57 | 2.6 | 2.6 |

1. W. Fang, et al. THE C-BAND TRAVELING-WAVE ACCELERATING STRUCTURE FOR COMPACT XFEL AT SINAP

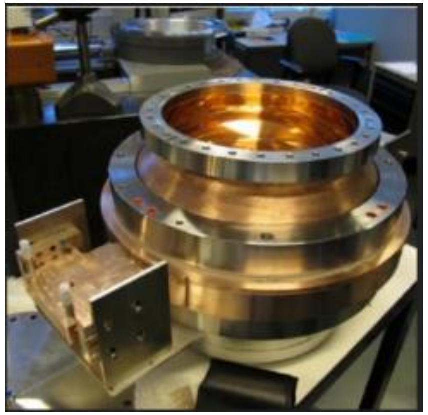
# C-band RF system-what EDR can do

- The model selection of the pulse compressor(PC)
  - SLAC type (Two cavities)
  - BOC type
  - Spherical type

Two cavities PC



SACLA C-band PC



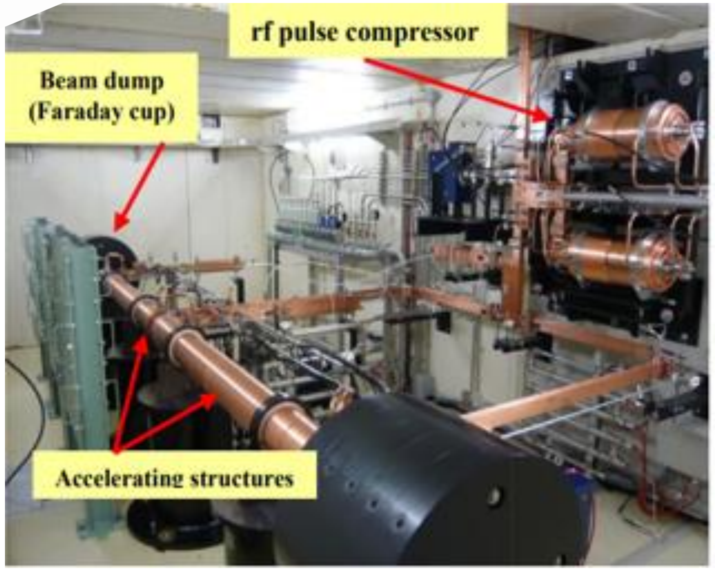
PSI BOC type PC

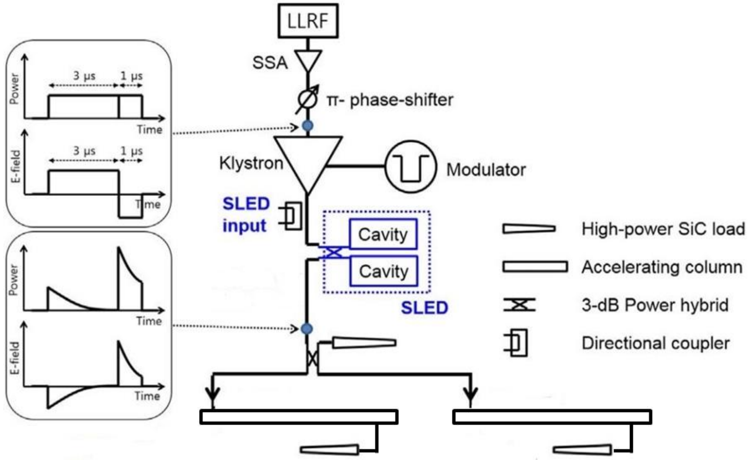
Spherical PC（Xband of SLAC）

- **No direct experience for us**

# C-band RF system-what EDR can do

- This is a high power test bench of Spring-8 before their mass-production
- We hope we can establish the C-band test bench and test the components. With pulsed compressor, waveguides, directional couplers, loads, bend and straight waveguides, etc.
- It is a complete unit and should cooperation with C-band power source

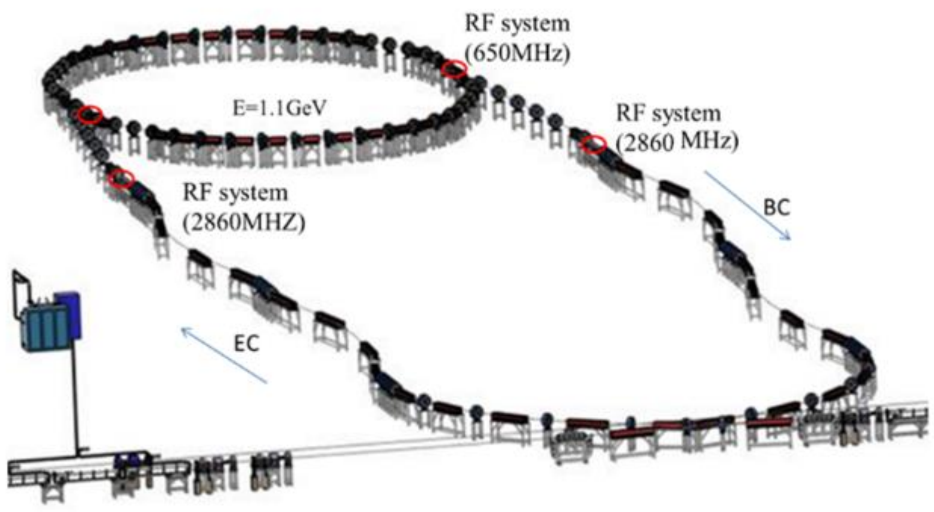



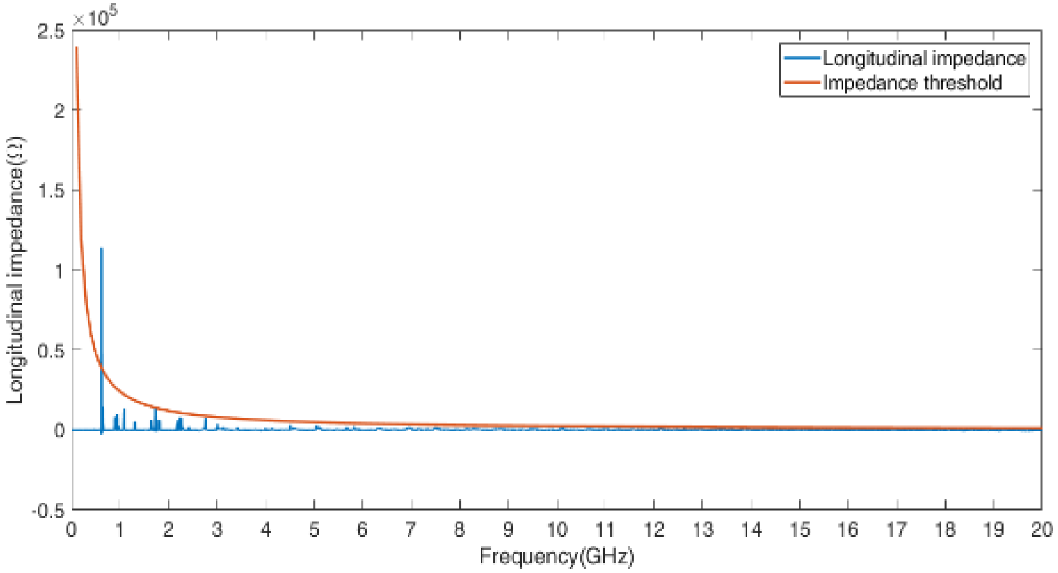



# Damping Ring RF cavity-TDR completed

D. Wang, Y.D. Liu, X.H. Cui

- The total cavity voltage requirement is 2.5MV
- 5 cell cavity aperture is decided by impedance、HOM and instability threshold
  - Taking into account the simulation results for impedance threshold and HOM power, the 5-cell cavity with a 90 mm aperture is considered the best choice

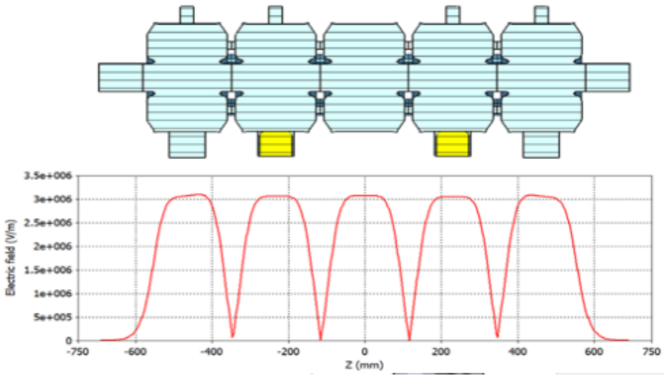


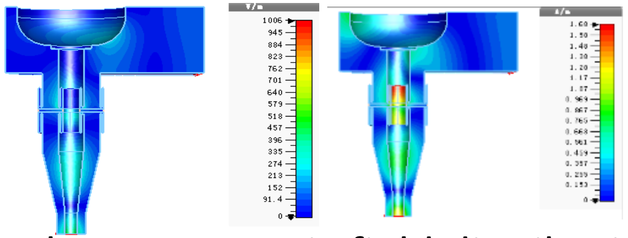



# Damping Ring RF cavity-TDR completed

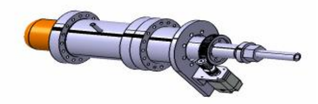
- The design of the 650MHz 5 cell cavity finished
  - RF cavity design
  - Input coupler and doorknob design
  - Vacuum design
  - Mechanical design

| | Unit | Value |
|---|---|---|
| **Beam tube aperture** | mm | 90 |
| **Cell length** | mm | 5*230.61 |
| **$\pi$-mode frequency** | MHz | 650.0 |
| **Q0** | | 31633 |
| **Shunt impedance** | MΩ | 32.4 |
| **R/Q** | Ω | 1023 |
| **Accelerating voltage per cavity** | MV | 1.25 |
| **Accelerating gradient E0** | MV/m | 1.08 |
| **Esmax/E0** | - | 4.62 |
| **Dissipated cavity power (20% margin)** | kW | 58 (84*) |

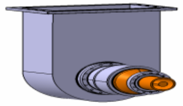


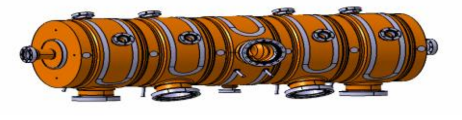
Electromagnetic field distribution



Tunner

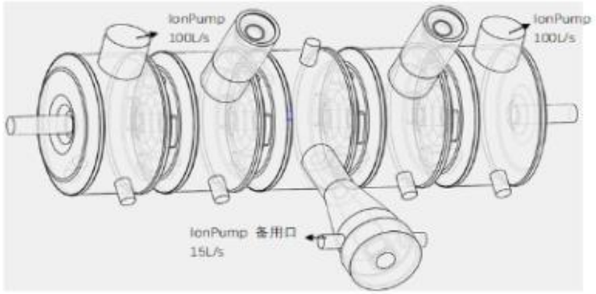


Coupler



Cavity

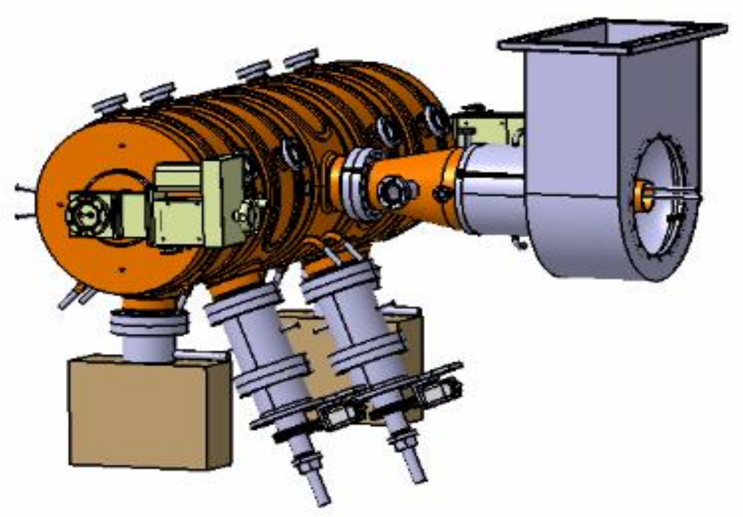
Mechanical design



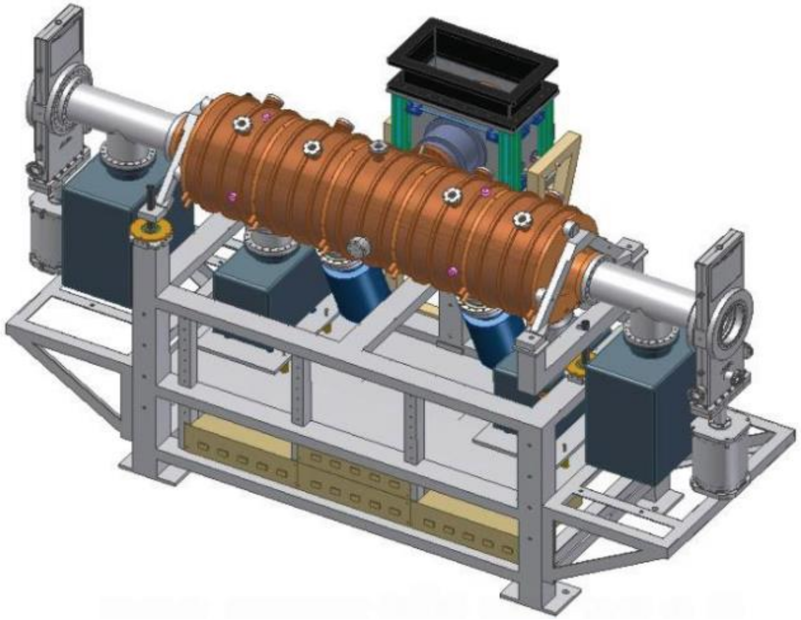

Ion pump distribution

# Damping Ring RF cavity-what EDR can do

- Further optimize the 5 cell cavity design
- If possible, we hope have fund to process the DR normal conducting 5 cell cavity. And finished the cold test of the cavity
- After the machining of the cavity completed, use PAPS (a test bench of IHEP at Huairou) test bench to do the high-power test of the DR normal conducting 5 cell cavity

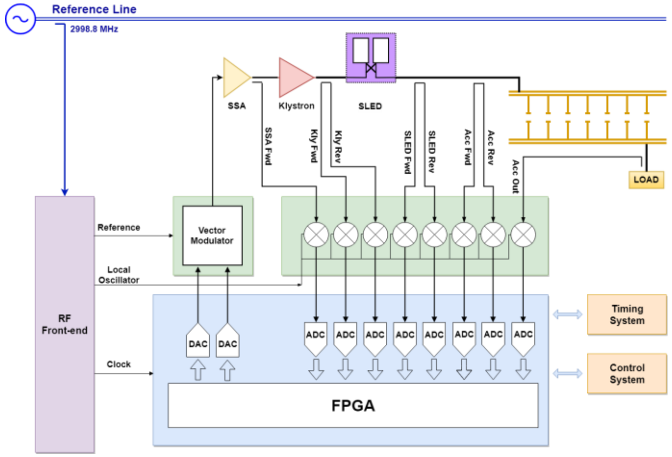


Mechanical design



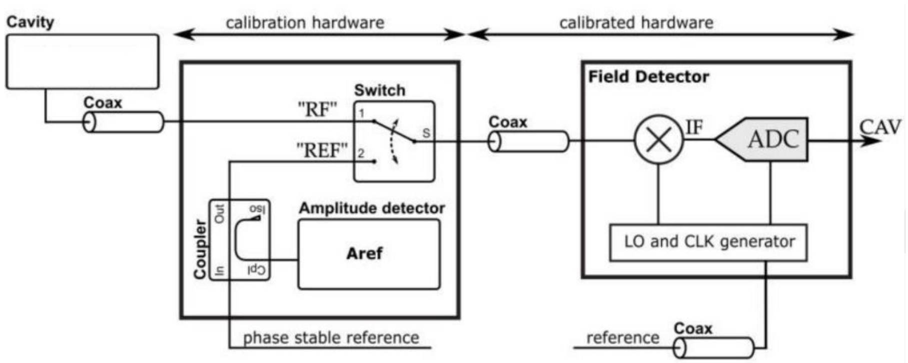
# Low Level RF for linac

- The MTCA LLRF system with a down-conversion architecture covering a frequency range of 500MHz to 6GHz has been successfully developed and applied to HEPS LINAC and BEPCII LINAC
- Further research is required to enhance control precision of the S-band and C-band LLRF system
  - Develop the low noise frequency synthesizer covering the S-band and C-band. The module is designed to be integrated into the MTCA chassis, make system more compact, improves reliability
  - Develop a phase drift compensation system to deal with the component temperature related phase drift of RF signals, technologies such as time-division multiplexing and pilot tone will be used




S-band LLRF System

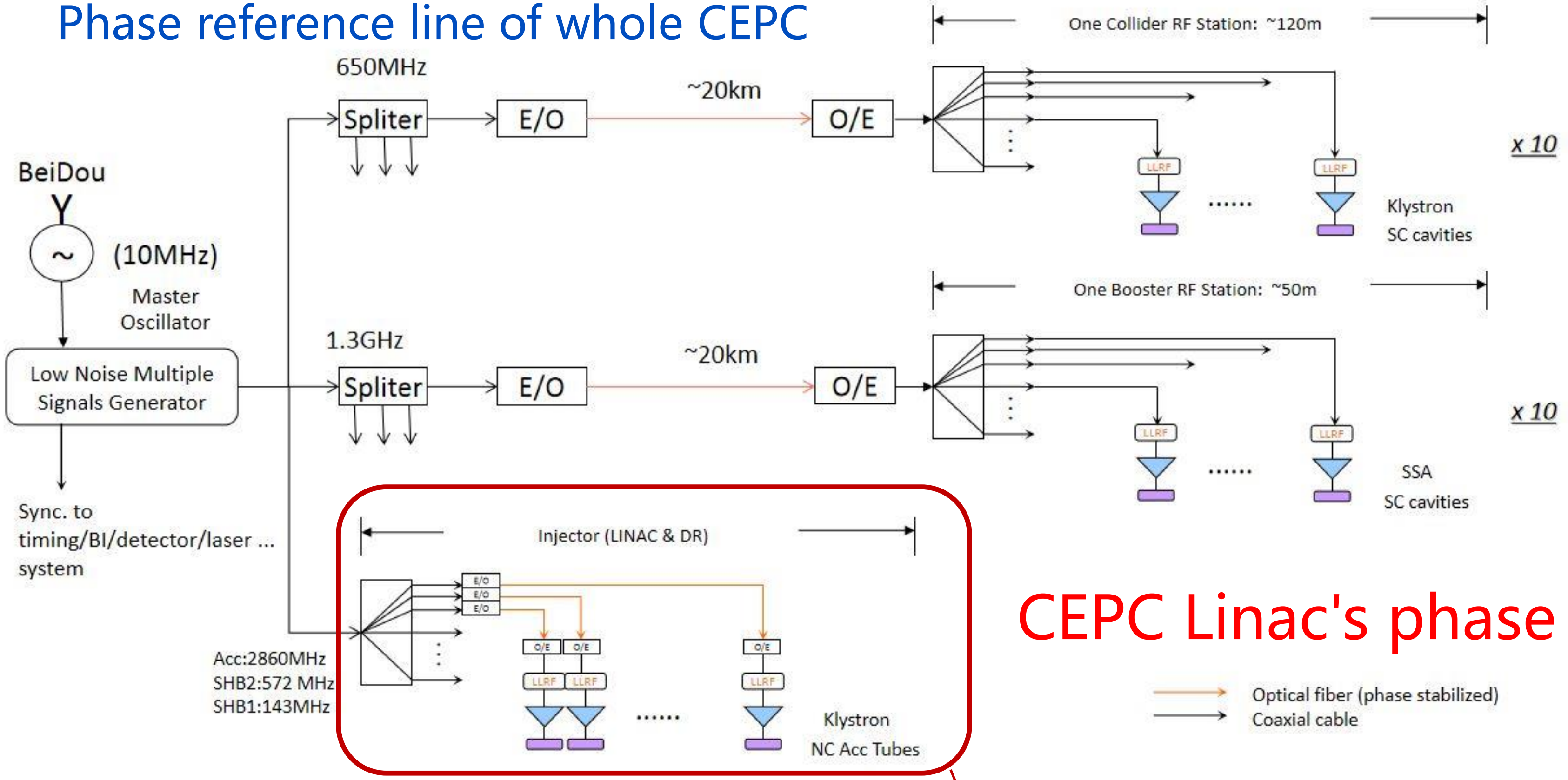
LO&Clock Generator




Phase drift compensation system

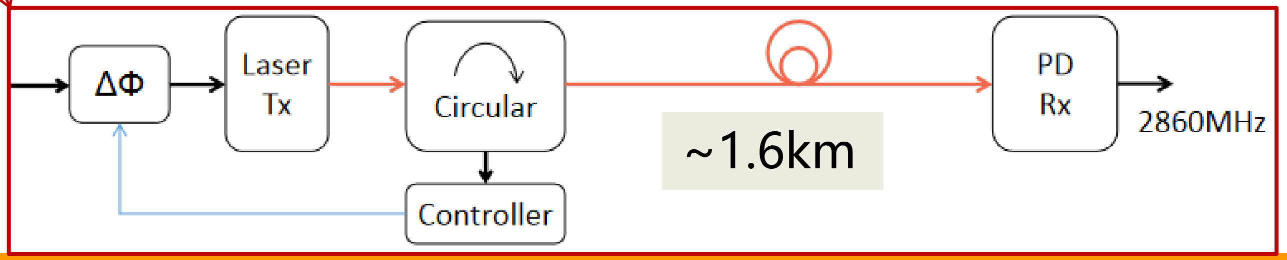
# Phase reference line for CEPC Linac

Phase reference line of whole CEPC




CEPC Linac's phase reference line;

Master oscillator will located at Linac to reduce cable length;

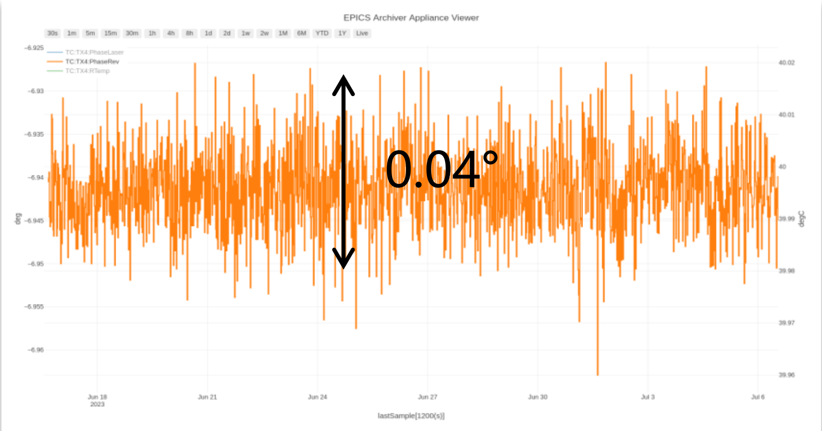


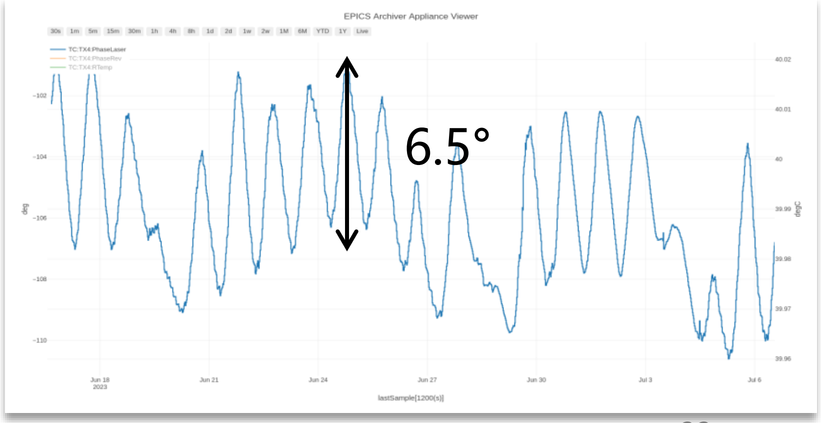
# Phase reference line for CEPC Linac

- Success example of RF phase reference on HEPS
  - 420m phase-stabilized optical fiber was used transfering MO 499.8MHz to Linac and booster RF
  - Stable Running >7 month ±0.02°(±110fs)  phase drift was measured
- New 2856MHz phase reference line planned:
  - New S-band(covering 2860MHz) Tx-Rx module under developed with  modifications of HEPS 499.8MHz version
  - This 2856MHz version will be used for PWFA accelerator based on BEPCII Linac as a CEPC new acceleration principle demo facility
- The corresponding internal design needs to be done for the newly 2860M frequency and consideration rematch circuit

(close loop and open loop stability, 21days，image: 2023.6.17-7.7)

HEPS operation



# Summary

- The physical design of linac need more optimization especially its availability analysis
- The technology of electron source, SHBs, buncher and S-band RF system is relatively mature
- The positron source needs to be consider the protection of positron conversion target under extreme conditions
- The C-band RF system needs to establish high power test bench and verify high-power performance
- The 5 cell cavity in damping ring needs to be machining and high power test
- Further research is required to enhance control precision of the S&C-band LLRF and reference line

**Thank you for your attention!**