Accelerator design and R&D efforts for Super Tau-Charm Facility

Jingyu Tang

On behalf of the STCF accelerator team

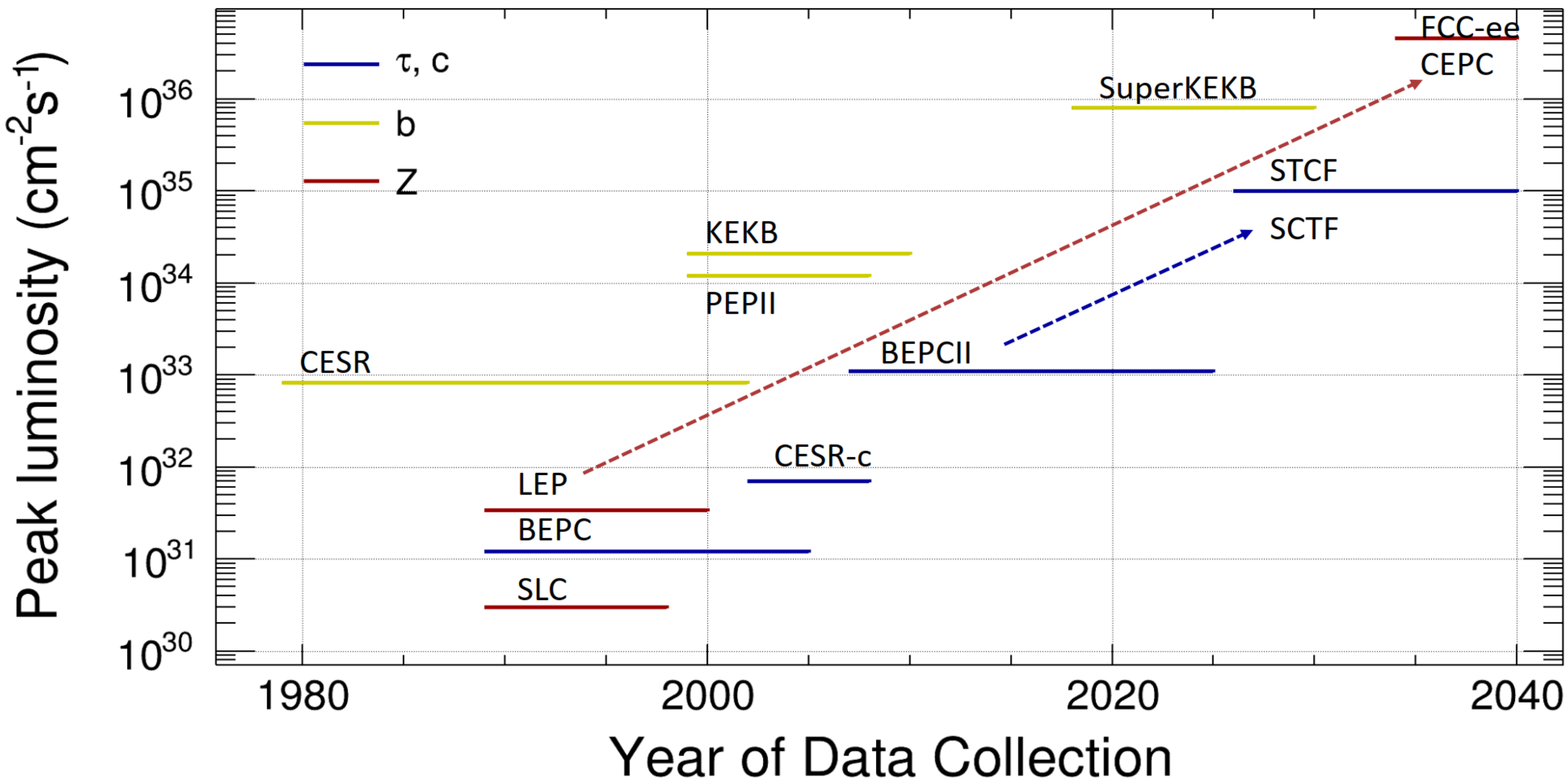
ICHEP 2024, July 17-24, 2024, Prague

Topics

- Design goals of STCF
- Current accelerator design scheme and key parameters
- Key challenges in accelerator physics and technologies
- Organization of the STCF accelerator study
- Summary

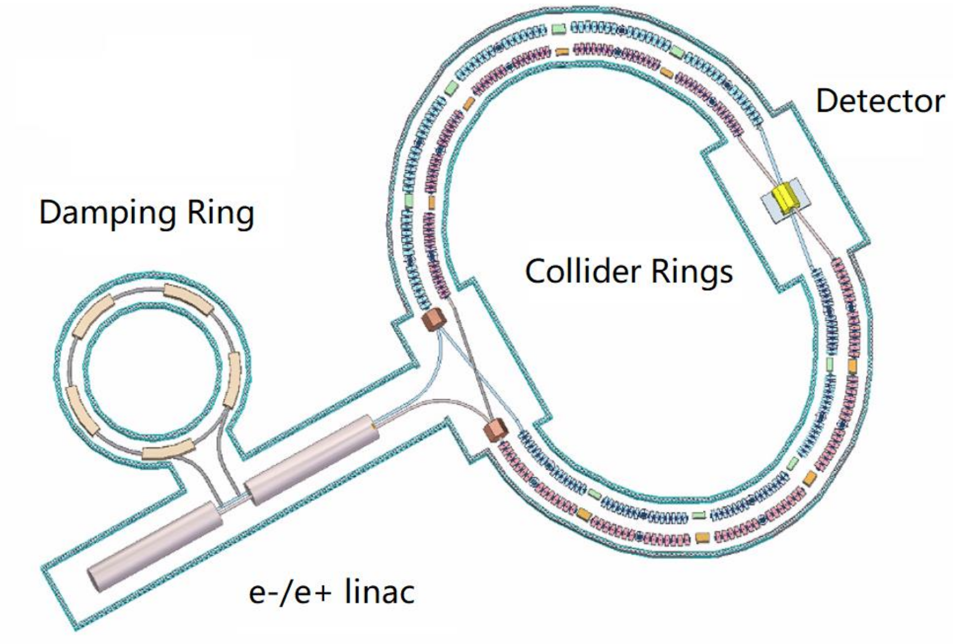
High-lumi e+/e- circular colliders

1st Generation	2nd Generation	3rd Generation
Single ring	Double-ring	Double-ring
	More bunches	Large Ib and crossing angle
	Low β_y@IP	Extremely low β_y@IP



STCF Design Goals

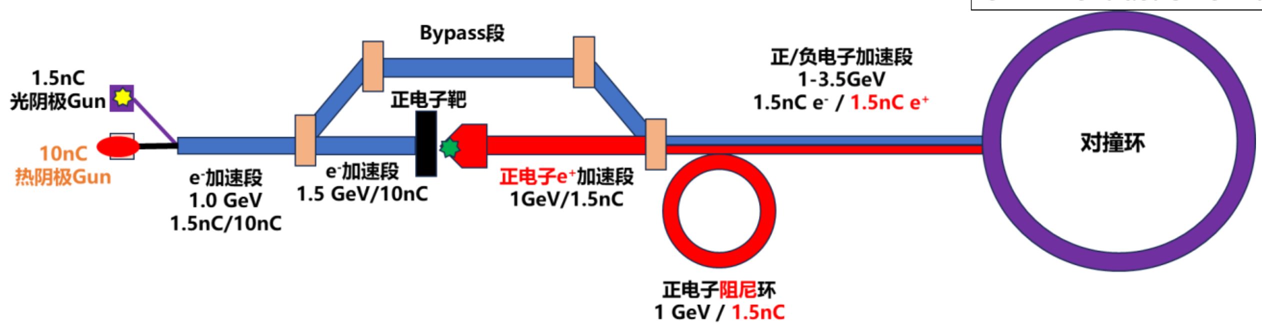
- Core design goal:
  - CoM energy: 2-7 GeV
  - Luminosity: >5×10^{34} $cm^{-2}s^{-1}$ @4GeV
  - Upgrading potential: polarized beam, higher luminosity
- Accelerator structure
  - Double-ring collider: low emittance, high current, large Piwinski angle
  - Injector: full-energy linac, e+ damping ring or accumulator, beam transport lines



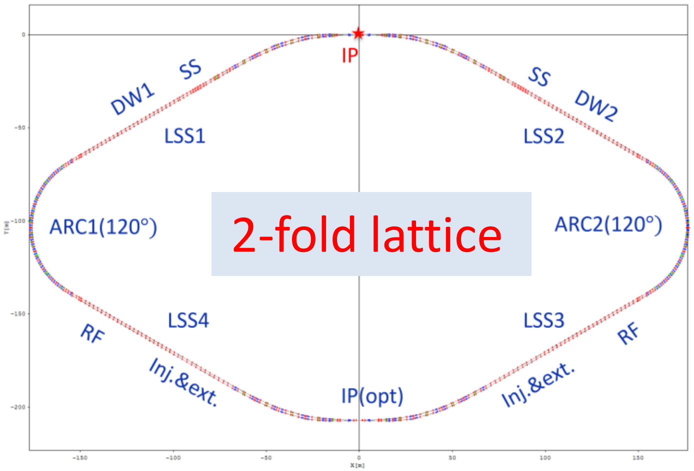
Current deign scheme and main parameters

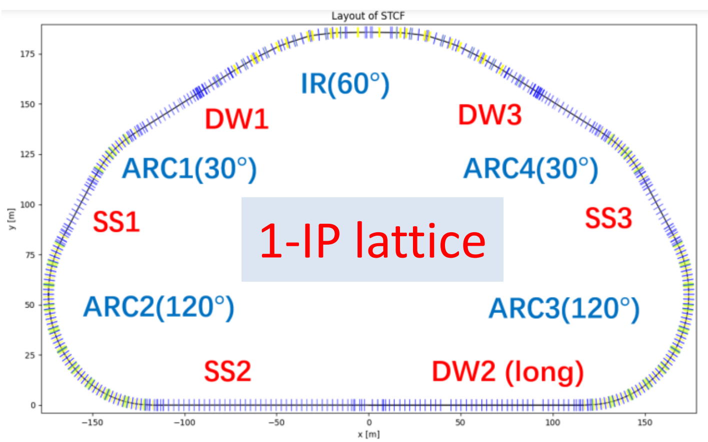
- Injector:
  - Variable energy: 1-3.5 GeV
  - High beam quality (emittance, energy spread)
  - Two different CR injection: off-axis and swap-out
  - Damping ring or accumulator ring for positrons @1 GeV
  - Total length: ~400 m (+100 m beam transp.)

Parameters	Value		Unit
E-gun type	Photo /Thermal	Thermal /Thermal	
Injection e- bunch charge	1.5	8.5	nC
Injection e+ bunch charge	1.5	8.5	
Injection energy	1.0-3.5	1.0-3.5	GeV
Optimal energy	2.0	2.0	GeV
MW frequency	2998.2	2998.2	MHz
Injection emittance (Geo, rms)	≤6	≤30	nm-rad
Injection energy spread (rms)	≤0.1	≤0.3	%
Injection bunch length (rms)	<7		mm
Injection frequency e-	30	30	Hz
Injection frequency e+	30	30	Hz
e+ DR injection emittance	≤1400	-	nm-rad
e+ DR extraction emittance	≤11	-	nm-rad
e+ DR RF frequency	499.7	-	MHz
e+ DR bunch numbers	5	-	
e+ AR injection charge	-	2.5	nC
e+ AR injection frequency	-	120	Hz
e+ AR injection emittance	-	≤1400	nm-rad
e+ AR extraction emittance	-	≤30	nm-rad



- Collider rings:
  - Injection energy: 1-3.5 GeV
  - Optimal energy: 2 GeV
  - Two injection schemes: off-axis, swap-out✓



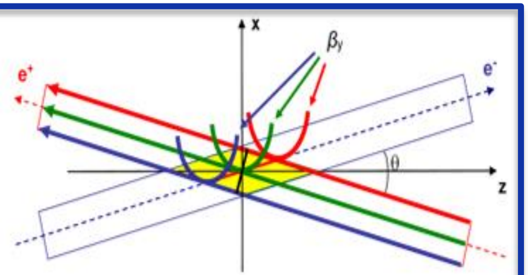


Parameters	Units	STCF
Optimal beam energy, E	GeV	2
Circumference, C	m	871.76
Crossing angle, 2θ	mrad	60
Revolution period, T	μs	2.908
Horizontal emittance, $\varepsilon_x/\varepsilon_y$	nm	6.857/0.034
Coupling, k		0.50%
Beta functions at IP, β_x/β_y	mm	40/0.6
Beam size at IP,σ_x/σ_y	μm	16.56/0.143
Betatron tune, ν_x /ν_y		32.55/29.57
Momentum compaction factor, α_p	10^{-4}	12.322
Energy spread, σ_e	10^{-4}	8.986
Beam current, I	A	2
Number of bunches, n_b		726
Particles per bunch, N_b	10^{10}	5.00
Single-bunch charge	nC	8.01
Energy loss per turn, U_0	keV	406.8
Damping time, $\tau_x/\ \tau_y/\ \tau_z$	ms	28.4/28.6/14.4
RF frequency, f_{RF}	MHz	499.333
Harmonic number, h		1452
RF voltage, V_{RF}	MV	1.8
Synchrotron tune, ν_z		0.0158
Bunch length, σ_z	mm	9.72
RF bucket height, δ_{RF}	%	1.47
Piwinski angle, ϕ_{pwi}	rad	17.61
Beam-beam parameter, ξ_x/ξ_y		0.0027/0.082
Hour-glass factor, F_h		0.87
Luminosity, L	$cm^{-2}s^{-1}$	1.0×10^{35}

Key challenges in accelerator physics and technologies

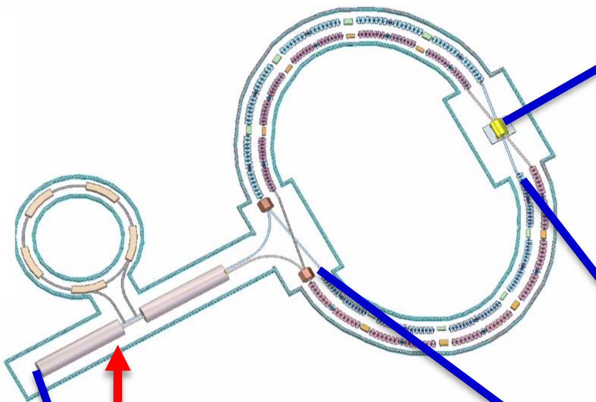
Key challenges on AP and technologies

- Design goal: Super-high lumi., high-quality (high-current, low emittance) e+/e- beams collision (extremely low β*), stable operation
- Great challenges: IR strong nonlinearity and collective effects; IR superconducting magnets



$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

Big Piwinski angle + Crab Waist



Collider Ring and IR AP design: IP beam size (Y) nm scale, Crab-Waist, nonlinear compensation extremely difficult

IR Technologies: SC magnets, MDI

Injection into CR (small DA): high I_b and low ε e+/e- sources

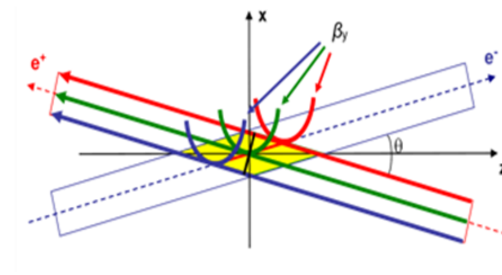
Other key technologies: Ring RF, beam instrum. and control, beam injection…

Key challenges on AP and technologies

No	Key design or tech	Prio.	Comments
1	Collider ring AP design	A+	Espec. IR, key to realize high-lumi
2	IR SC magnets	A+	Complex structure, high-field, tight space, less exp.
3	Collider ring RF	A+	High-power, deep-damped HOM, less exp.
4	Injector AP design	A	Prov. high-qual. beams to CR, 2 injection schemes
5	MDI	A	Very tight space and complex mech. (acc. and det.)
6	Collider beam instrum.	A	High-prec. and fast bunch meas., fast feedbacks
7	Collider ring injection	A	ns-scale kickers for bunch swap-out injection
8	Positron source	A	Low e- energy to generate e+ beam
9	Collider ring vacuum	A-	High-current circ. beams, ultra-high vacuum for IR
10	Electron source	A-	High-bunch charge photocathode e-gun
11	Linac microwave	A-	Large-aper. S-band acc. struct., less exp, LLRF
12	Linac power source	A-	High-power solid-state modulator

Key challenges (1) – CR AP design

- A new-generation e+/e- collider
  - How to attain two-order lumi. gain over the last-generation collider (BEPC-II)?
- IR physics design
  - The key and challenge for STCF accelerator
  - New collision scheme: beam param (I_b, ε_x ; nm spot at IP), crossing angle, correlation with the B-B effect [Luminosity need]
  - Special optics: Final Focus + Crab Waist (Telescope-Mini β, dispersion, phase advance) [Complexity]
  - Strong nonlinearity: Local CC for extreme-low β, fringe-field, crab sextupoles ➔ very small DA and MA [very short beam lifetime]
  - Complex MDI: SC magnets, vacuum, cryostat, beam monitors, interface with detector [Iterations]



$$L = \frac{\gamma n_b I_b}{2 e r_e \beta_y^*} \xi_y H$$

大Piwinski Angle + Crab Waist

➔Take advantage of a new machine, lessons from SuperKEKB ➔ better design

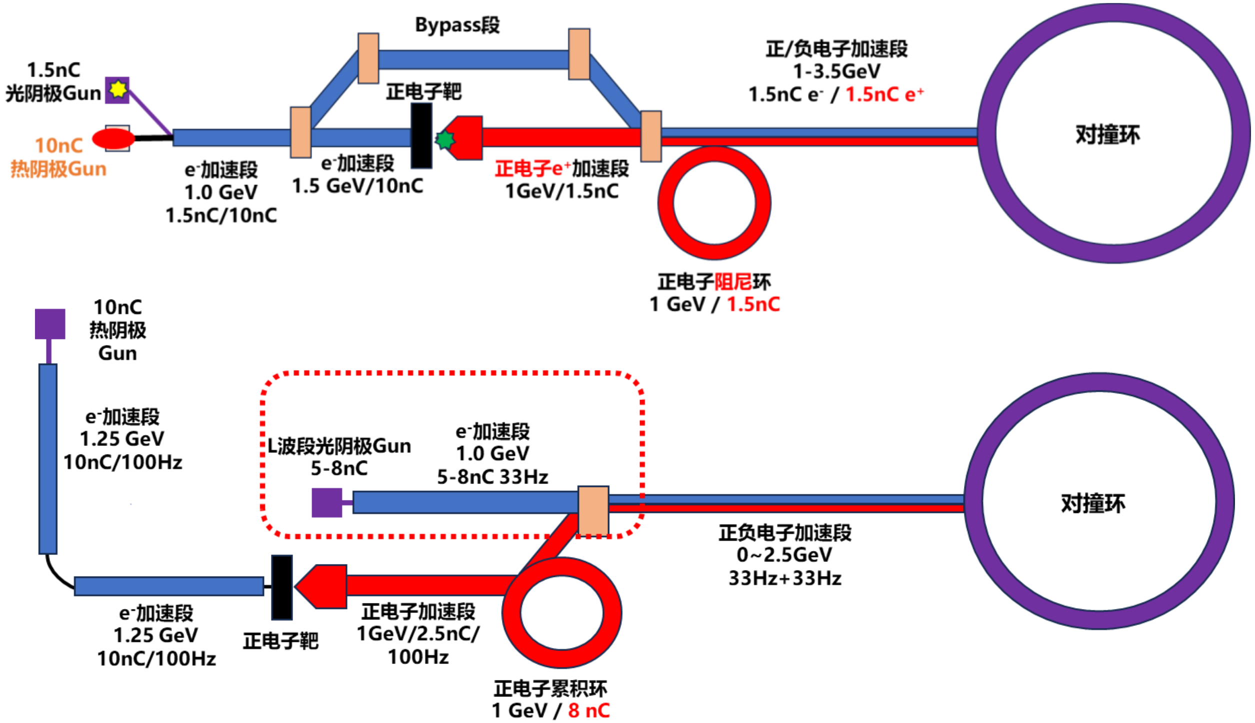
Other key problems in CR AP design

- Beam-Beam effects
  - 3rd-Gen colliders pushing ξ_y to 0.1 or higher (Limiting ξ_x)
  - Large Piwinski + Crab-Waist: strong correlation with transverse motion
  - Mutual influencing with frequent injections
- Collective effects
  - Factors: high current, low emittance, high impedance
  - Intra-beam scattering: transverse IBS, Touschek (very short lifetime)
  - Impedance: multiple strong collective instabilities, in particular the coupling bunch instability
- Beam injection
  - Touschek lifetime very short (<300 s), frequent injections
  - At different beam energies: damping time by damping wigglers
  - Injection schemes: off-axis injection easier, emittance blow-up and background; bunch swap-out injection ➔ more powerful injector
- Beam collimation
  - Very high beam loss rate: background and radiation protection
  - Collimation efficiency and impedance: more complex collimation design (e.g. nonlinear collimation)

Key challenges (2) – Injector AP design

- Injector providing e+/e- beams to CR
  - Quality: energy spread, bunch charge, emittance, stability
  - High frequency injections (~30 Hz)
  - Large energy range: 1-3.5 GeV, ε <20 nm
  - High current: 1.5 nC (off-axis); 8-10 nC (swap)

➔Better design:
A new machine, utilizing design and technology from FEL and 4G light source linacs.

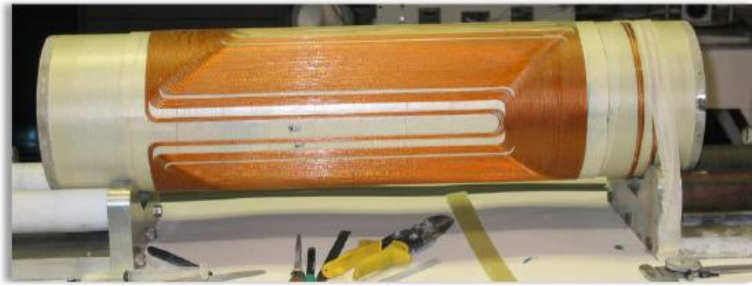


Off-axis injection

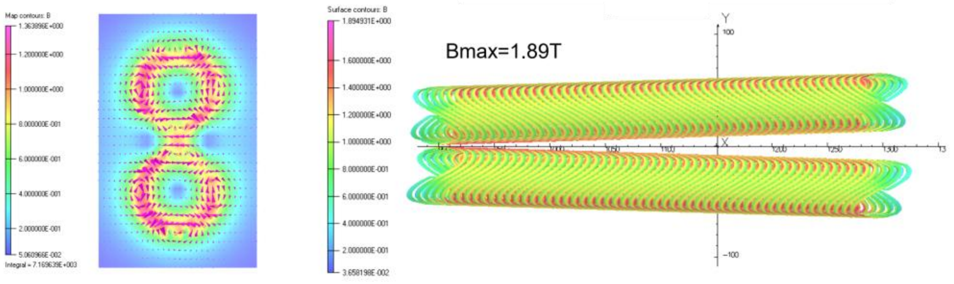
Swap-out injection

Key challenges (3) – IR SC magnets

- IR SC magnets
  - Technically very challenging, very few labs have experience
  - Very tight space, complex and combined coils
  - 3rd-Gen e+/e- colliders even more difficult: twin-aperture, higher field gradient (~50 T/m)
  - In China: IHEP built the first IR magnet for BEPC-II; some experience in other SC magnets
  - STCF R&D: developing prototypes by steps, different technologies under consider. (BEPCII serpentine, CCT✓, cos2θ/DCT)



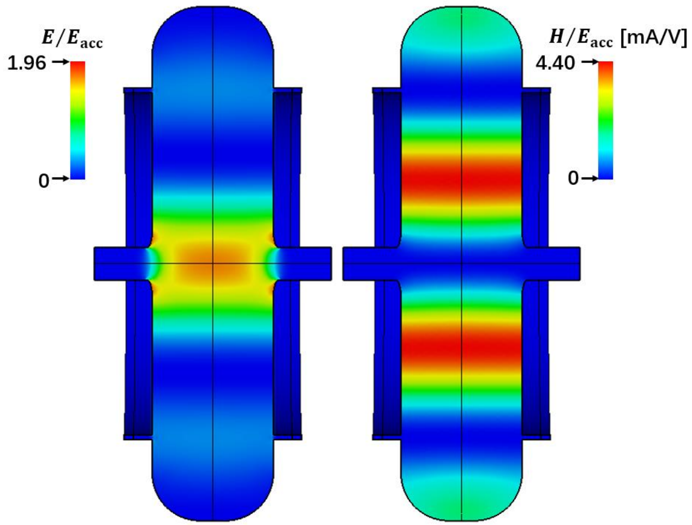
IHEP BEPCII-U (Serpentine)



A CCT type prototype just started
(60 mrad, 54 mm separation, 50 T/m)

Key challenges (4) – Ring RF

- RF for Collider rings
  - High synchrotron radiation (2 Amperes): RF power and couplers
  - HOM deep-damped: instabilities
  - Large energy range (1-3.5 GeV): high V_{RF}
  - Beam loading: at bunch swap-out injection
  - Stability: more powerful LLRF
  - Selected for R&D: TM020 RT cavity, 500 MHz; 200 kW coupler

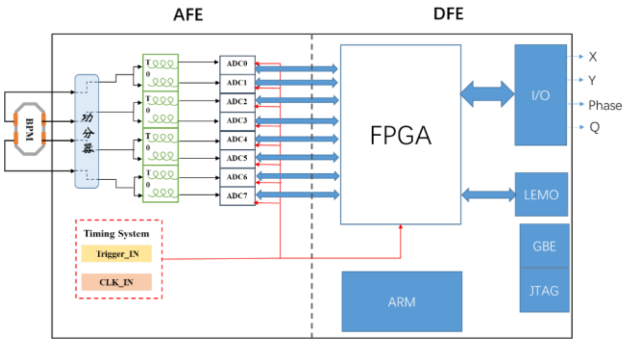


TM020 cavity in prototyping

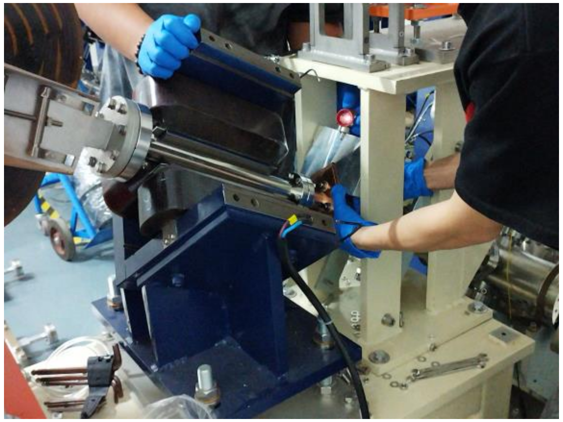
RF parameters	
Working mode	TM020
Frequency [MHz]	499.7
R/Q [Ω]	84.4
Unloaded quality factor	62828
E_p/E_{acc}	1.92
B_p/E_{acc} [mA/V]	2.64
Vcav (inpot: 100 kW) [kV]	728.2

Key challenges (5) – Beam instrumentation

- Requirements for beam instrum.
  - CR precise bunch meas.: bunch-by-bunch 3D meas., trans. position res. <5 μm, long. phase res.<0.2 ps
  - CR B-by-B fast feedback: coupled bunch inst.
  - IP: orbit feedback
  - Injector: bunch length and charge meas.
- R&D efforts
  - Bunch 3D meas.: probe, signal treat, electronics, S/N, integration
  - B-by-B fast feedback: raising bandwidth, avoiding interference to single bunch
  - Injector bunch length and charge meas.: cavity-based
  - Prototypes: beam tests in different machines



Integrated board for B-by-B 3D meas.

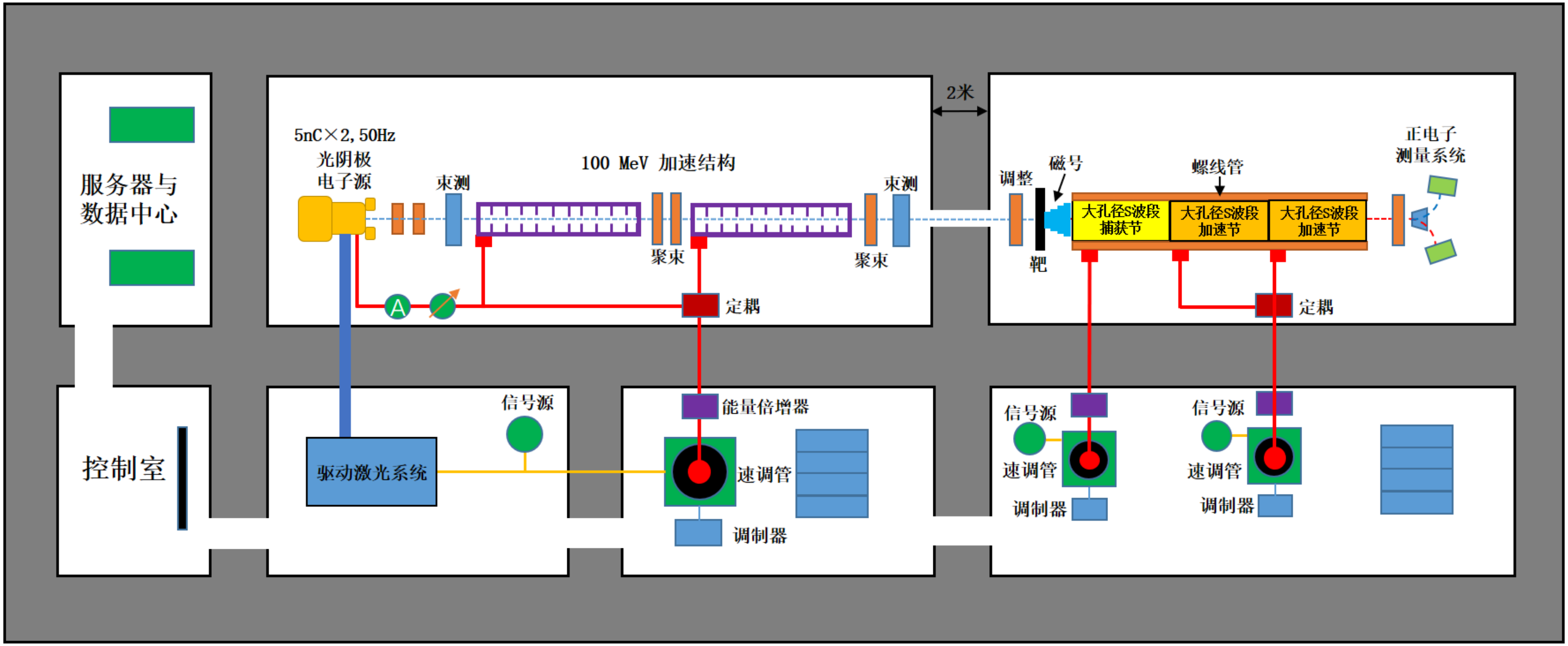


Cavity-based: bunch length, charge and profile meas.

Electron-positron beams test platform

- Test platform for supporting several injector R&Ds
  - Electron source: mainly photocathode (also thermal e-gun)
  - High-power solid-state modulator
  - Positron target
  - Magnetic horn
  - Large-aperture S-band acceleration tube
  - Beam diagnostic devices
- Basic requirements
  - Photocathode electron source
  - 100-MeV e- linac
  - Positron target and magnetic horn
  - 100-MeV e+ linac
  - Beam properties measurements, beam dumps

e- linac: 2* 6-m sections; e+ linac: 3 large-aper. accel. tubes



Located in the accelerator test hall of HALF (Hefei Advanced Light Facility under construction)

From prelim. study phase to R&D phase

- Preliminary study phase (from 2018 to mid 2023)
  - Very limited manpower (a dozen, mostly: small-portion part-time, students, retired consultants): preliminary conceptual design on the STCF accelerator
  - Lacking experience in colliders
  - Supporting the STCF study project
- Key R&D phase (since August 2023)
  - National Synchrotron Radiation Laboratory (NSRL) fully engaged in, as the co-supporter of the STCF project
  - NSRL is focusing on the constr. of HALF (a 4G synchrotron light source, 2023.5 to 2028.9), still limited manpower
  - Domestic collaborations: 8 institutions, contributing to half of current manpower
  - About 90 persons, half are students, majority without experience in colliders

SUMMARY

- STCF accelerator goal is very challenging
- Provincial and national financial resources to support the design and key technological R&Ds, aiming for construction in late 2020
- STCF is a national project, attracts domestic institutions in the study
- It is very important to collaborate with international labs, in particular, KEK and BINP

Thanks for attention!