SPPC Study Progress

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for the SPPC team
IAS Program for High Energy Physics
January 22-25, 2018, HKUST

Outline

- Ongoing SPPC study
- Collider accelerator physics
- Technical issues
- Injector chain
- SPPC in CEPC CDR
- Domestic and international collaborations
- Summary

Ongoing SPPC Study

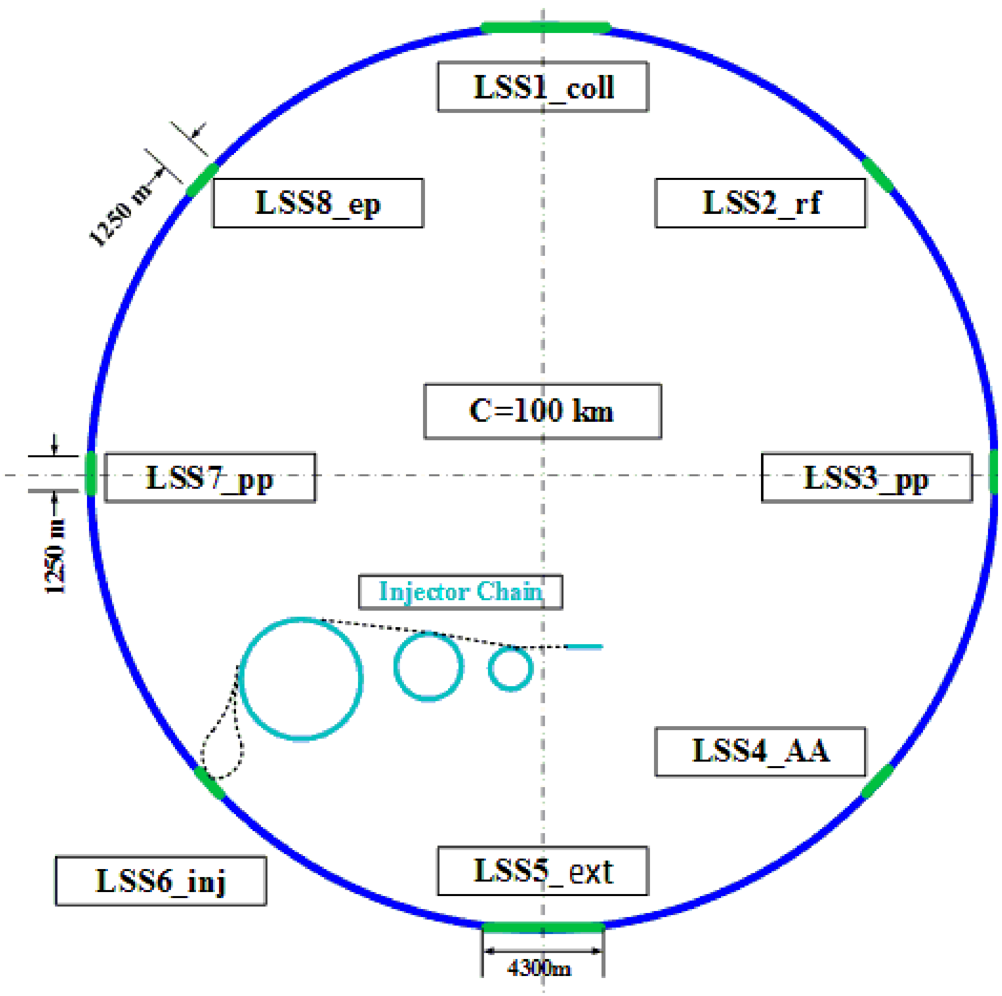
- Accelerator physics
  - Describing what a future proton-proton collider looks like, physics performance
  - Layout design with compatibility to CEPC
  - Key accelerator physics: lattice, collimation, beam-beam effects, longitudinal dynamics, injection/extraction, instabilities, machine protection strategy
- Technological developments
  - Identifying key technical challenges, for some of them needing long-term R&D efforts
  - Strong R&D program on high-field superconducting magnets
  - Beam screen issues
  - High-Q ferrite-loaded RF cavities
- Fewer people working on SPPC now, budget lacking

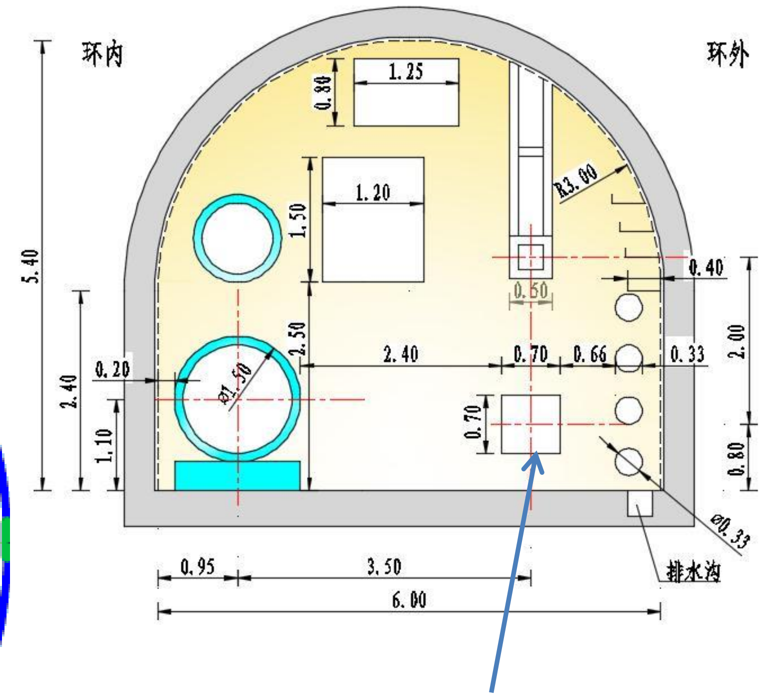
SPPC main parameters

Parameter	Unit	Value		
		PreCDR	CDR	Ultimate
Circumference	km	54.4	100	100
C.M. energy	TeV	70.6	75	125-150
Dipole field	T	20	12	20-24
Injection energy	TeV	2.1	2.1	4.2
Number of IPs		2	2	2
Nominal luminosity per IP	$cm^{-2}s^{-1}$	1.2e35	1.0e35	-
Beta function at collision	m	0.75	0.75	-
Circulating beam current	A	1.0	0.7	-
Bunch separation	ns	25	25	-
Bunch population		2.0e11	1.5e11	-
SR power per beam	MW	2.1	1.1	-
SR heat load per aperture @arc	W/m	45	13	-

Tunnel cross-section

SPPC Layout





More space required for CEPC double-ring scheme

Collider Accelerator Physics

- Lattice, layout, dynamics aperture: Yukai Chen, Dengjie Xiao
- Collimation: Jianquan Yang, Ye Zou, Jingyu Tang, LAL, LHC
- Beam-beam, Luminosity leveling: Lijiao Wang, KEK, FNAL, BNL
- Longitudinal dynamics: Linhao Zhang
- Instabilities: Yudong Liu
- Machine protection strategy: Zhiliang Ren, Hongliang Xu

Collider Accelerator Physics

-Parameter list updating

Parameter	Value	Unit
Main parameters		
Circumference	100	km
Beam energy	37.5	TeV
Lorentz gamma	39979	
Dipole field	12.00	T
Dipole curvature radius	10415.4	m
Arc filling factor	0.780	
Total dipole magnet length	65442.0	m
Arc length	83900	m
Total straight section length	16100	m
Energy gain factor in collider rings	17.86	
Injection energy	2.10	TeV
Number of IPs	2	
Revolution frequency	3.00	kHz
Revolution period	333.3	µs
Physics performance and beam parameters		
Nominal luminosity per IP	1.01E+35	$cm^{-2}s^{-1}$
Beta function at initial collision	0.75	m
Circulating beam current	0.73	A
Nominal beam-beam tune shift limit per	0.0075	
Bunch separation	25	ns
Bunch filling factor	0.756	
Number of bunches	10080	
Bunch population	1.5E+11	
Accumulated particles per beam	1.5E+15	
Normalized rms transverse emittance	2.4	µm
Beam life time due to burn-off	14.2	hour
Turnaround time	3.0	hour
Total cycle time	17.2	hour

Total / inelastic cross section	147	mbarn
Reduction factor in luminosity	0.85	
Full crossing angle	110	µrad
rms bunch length	75.5	mm
rms IP spot size	6.8	µm
Beta at the 1st parasitic encounter	19.5	m
rms spot size at the 1st parasitic encoun	34.5	µm
Stored energy per beam	9.1	GJ
SR power per ring	1.1	MW
SR heat load at arc per aperture	12.8	W/m
Critical photon energy	1.8	keV
Energy loss per turn	1.48	MeV
Damping partition number	1	
Damping partition number	1	
Damping partition number	2	
Transverse emittance damping time	2.35	hour
Longitudinal emittance damping time	1.17	hour

Considerations on layout

- Layout consideration
  - 8 arcs and long straight sections (accepted by CEPC)
  - Arcs will be traditional FODO based, 6-8 long SC dipoles per half cell, LHC-type dispersion suppressors mainly for compatibility with CEPC (next slide)
  - Long straight sections (LSS) are important for pp colliders: two IPs, injection, extraction, collimation and RF stations

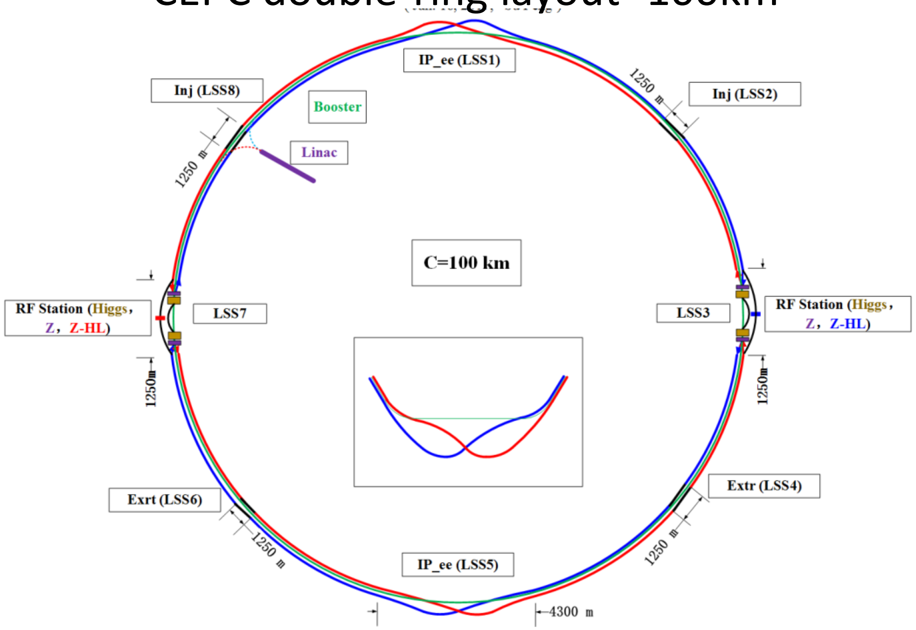
  [Two very long LSSs for collimation and extraction

  Perhaps one IP more for A-A and one for e-p]

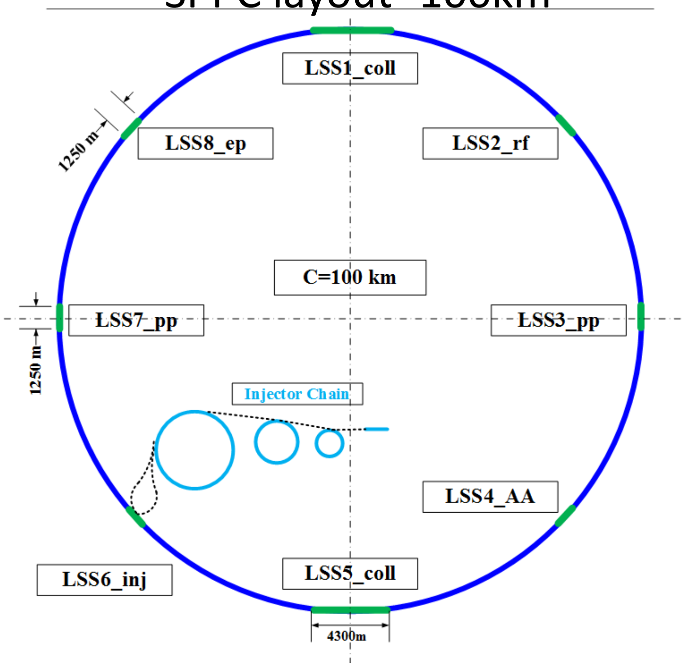
Compatibility between CEPC and SPPC

- CEPC first to be built, keeping potential to add SPPC later
- Three machines in one tunnel: e booster, ee double-ring collider, pp double-ring collider
- It is in discussion to allow ee/ep collisions when adding pp collider, crucial to detour different detectors (up to six) in the two colliders
- Several rounds of interactions between CEPC and SPPC design teams, but long way to go

CEPC double-ring layout- 100km



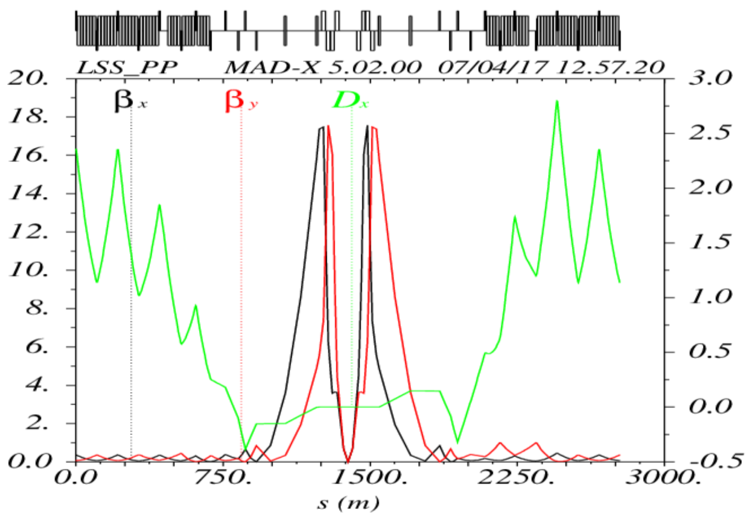
SPPC layout- 100km



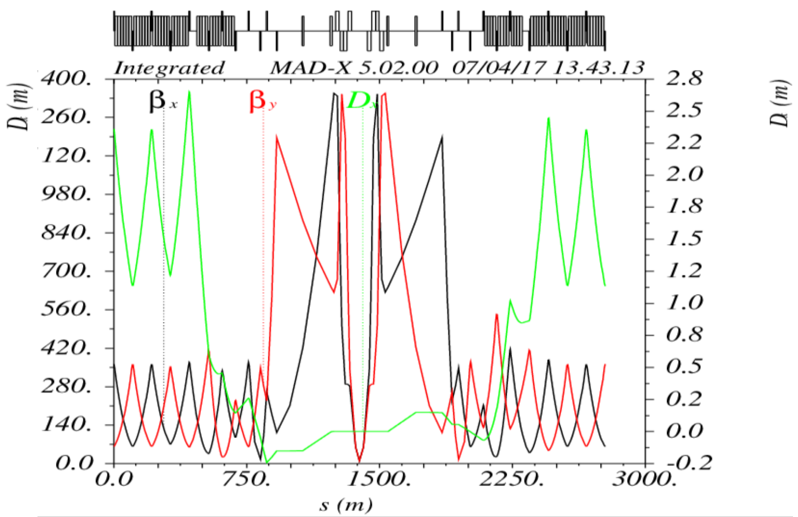
Lattice design

Yukai Chen,
Dengjie Xiao

- Different lattice designs
  - Different schemes (now on 75 TeV @100 km)
  - Lattice at injection and collision
  - Compatibility between CEPC and SPPC
  - Arc cells, dispersion suppressors, insertions
- For supporting other studies, e.g. magnets, collimation, dynamic aperture, …



IP: at collision



IP: at injection

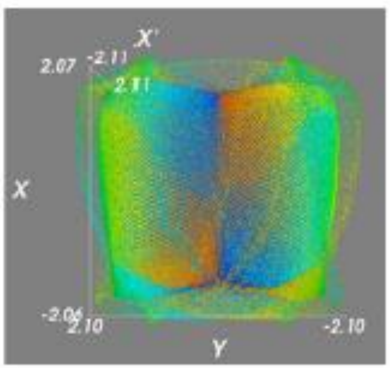
Dynamic aperture study

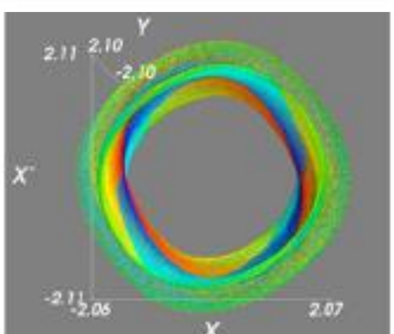
Yukai Chen,
collaborating with
F. Schmidt

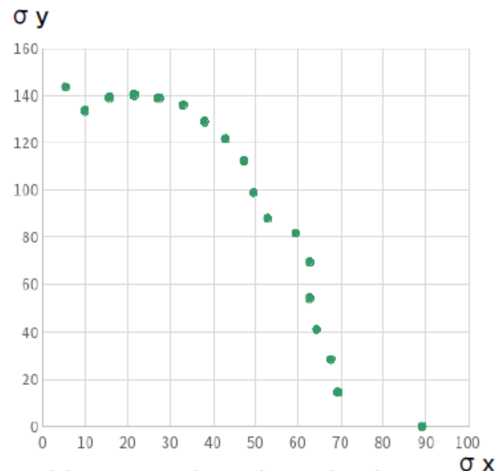
- At collision energy
- At injection energy

(Sixtrack code)

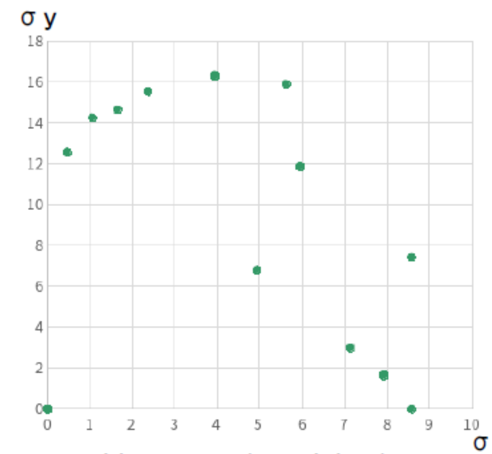
For the moment, it is ok, with iterations with magnet design



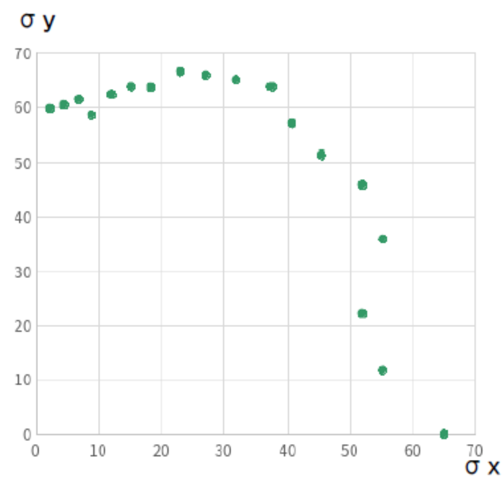




Adding sextuple without dipole error
(chromaticity corrected)



Adding sextuple and dipole error
(chromaticity corrected)



Adding sextuple without dipole error
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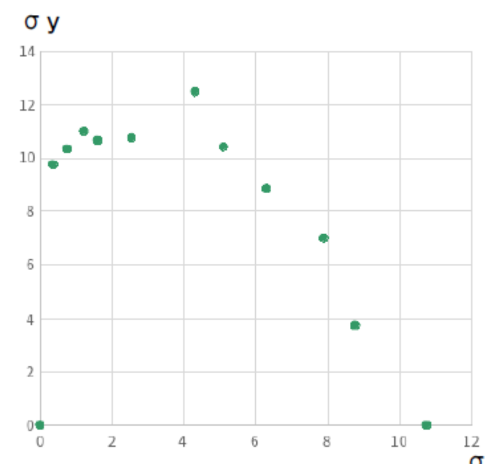


Adding sextuple and dipole error
(chromaticity corrected)

Collimation study

Jianquan Yang, Ye Zou, Jingyu Tang collaborating with LAL and LHC

- *Requirements*
  - SC magnet quench prevention:

Huge stored energy: 9.1 GJ/beam

$$\tilde{\eta}_c = \frac{\tau_{\min} \cdot R_q}{N_{tot}^q}$$

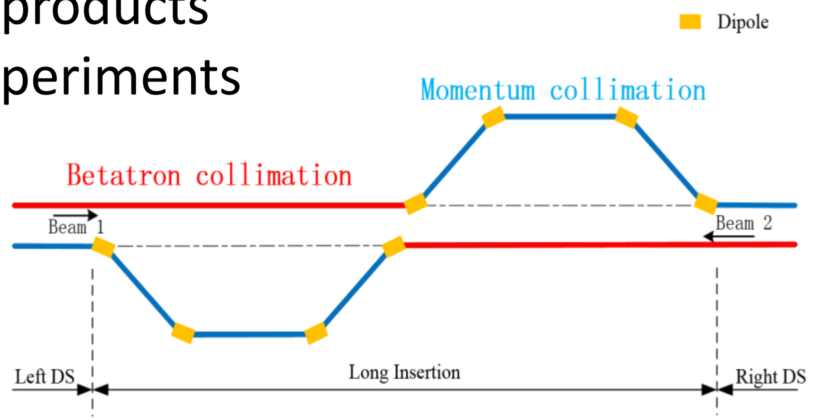
Rq: ~10^6 protons/m/s

N_{tot}^q : 1.5×10^{15}

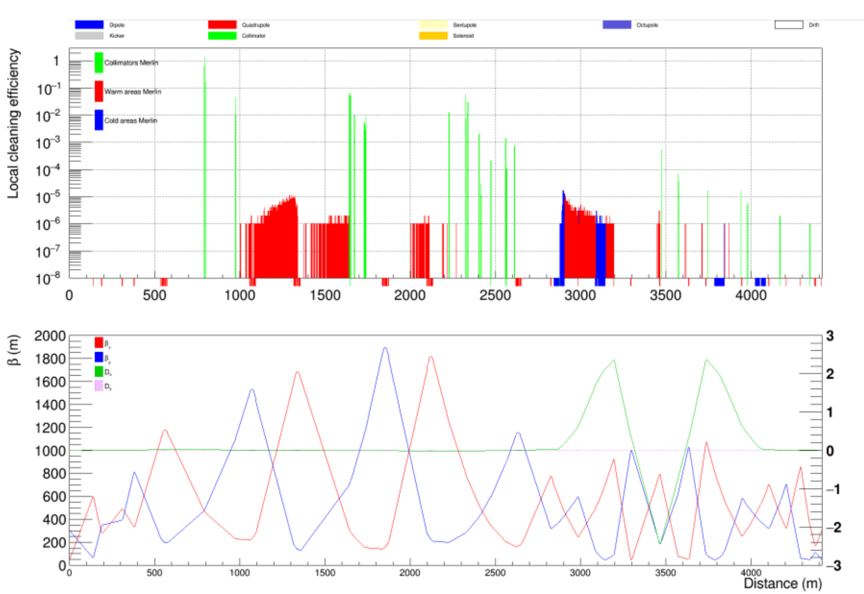
$\tau_{\min}$: 0.2 h /5 h

$$\tilde{\eta}_c < 4.5\times10^{-7}\ \text{m}^{-1}$$

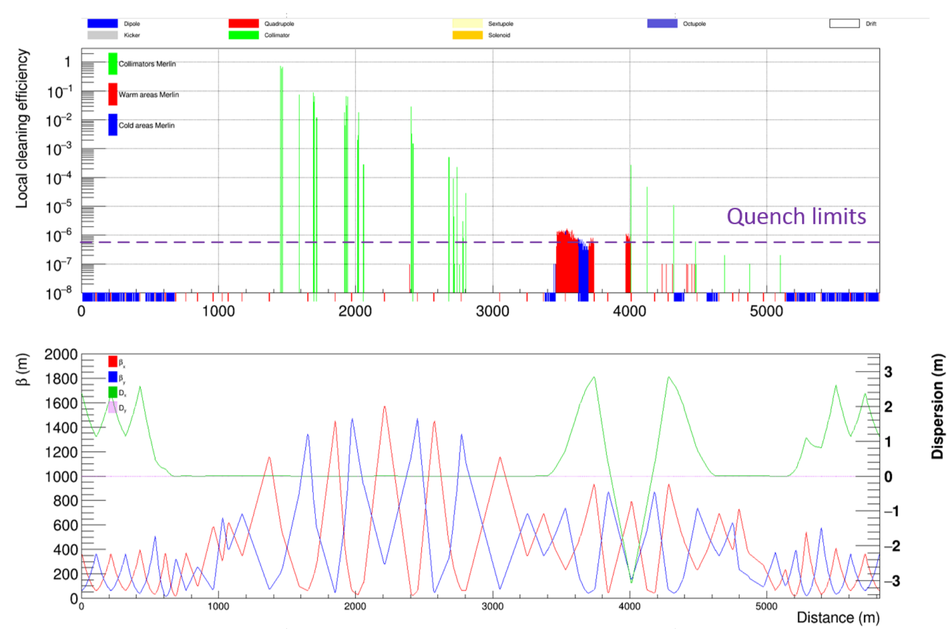
  - Halo particles cleaning
  - Machine protection: prevent damaging radiation-sensitive devices
  - Radiation losses concentration: hands-on maintenance
  - Cleaning physics debris: collision products
  - Optimizing background: in the experiments
- Further developing the concept of combining betatron and momentum collimations in a same long straight section (4.3km)



- Recently a new design for the transverse collimation section, by introducing protected large-aperture superconducting magnets and add an additional collimation stage
  - Simulations show good effect in collimation efficiency
  - Protection-aid low-field SC quadrupoles workable



With RT magnets in beta-collimation



With SC magnets in beta-collimation

Longitudinal dynamics

Linhao Zhang

- Starting point and goal:

  -- Based on the requirements for luminosity and its upgrade, it's critical to get a set of self-consistent bunch and RF parameters to achieve the goal of 7.55-cm bunch length or even shorter

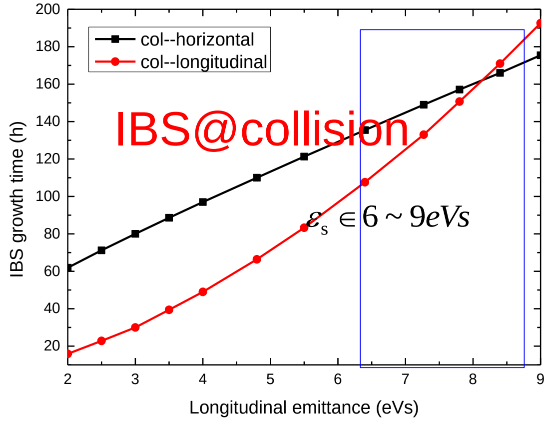
- Two main constraints:

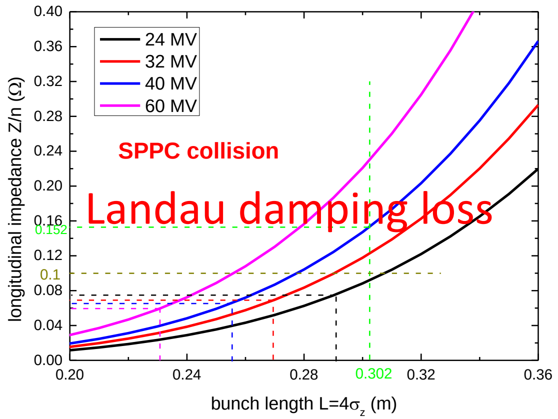
  --Intrabeam scatering (IBS);

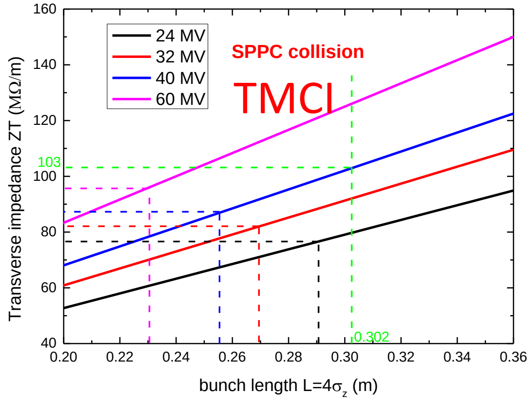
  --Beam instabilities (Loss of Landau damping and TMCI)

Longitudinal impedance: < 0.1Ω

Transverse impedance: < 100MΩ/m







- Higher RF frequency (800MHz) is considered helpful, and maybe together with 400 MHz (dual-harmonic RF system)

- Compared to 400MHz, both transverse and longitudinal impedance threshold have been improved, and the bunch length will be shorter at 800MHz, which is beneficial to luminosity

RF frequency (MHz)	**400**	**800**
RF voltage (MV)	40	52
Longitudinal emittance(eVs)	8.4	6.4
RMS bunch length(cm)	7.55	5.2
RMS momentum spread ($\times10^{-4}$)	0.71	0.78
Bucket area (eVs)	26.73	10.77
Energy acceptance ($\times10^{-4}$)	2.2	1.8
IBS growth time (h) --H -- V	166 171	168 118

The study suggests: injection capture using 400MHz, acceleration and physics collision using 800MHz.

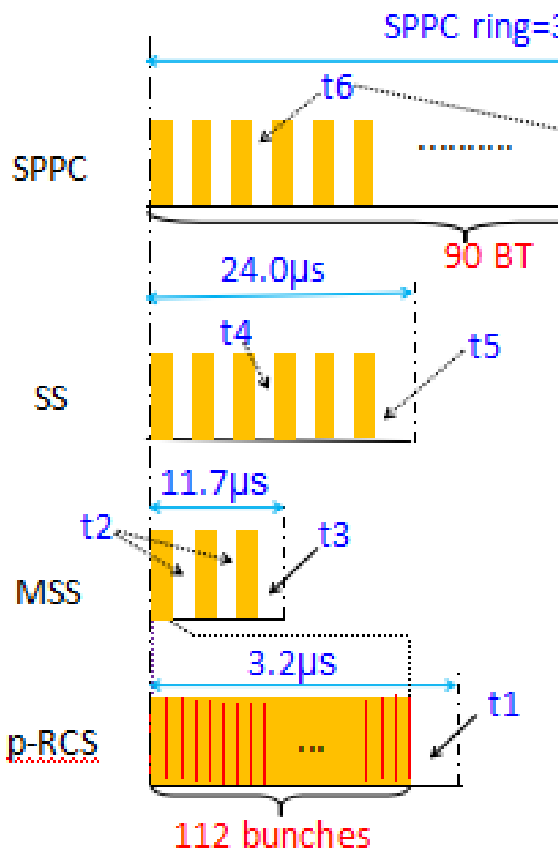
And the corresponding RF parameters of the injector chain have been accordingly followed this scheme.

Bunch filling schemes

Linhao Zhang

- 100 km - 75 TeV -25 ns (also for different SPPC designs)

Bunching filling factor: ~76%



10 times of SS, but each with 9 injections

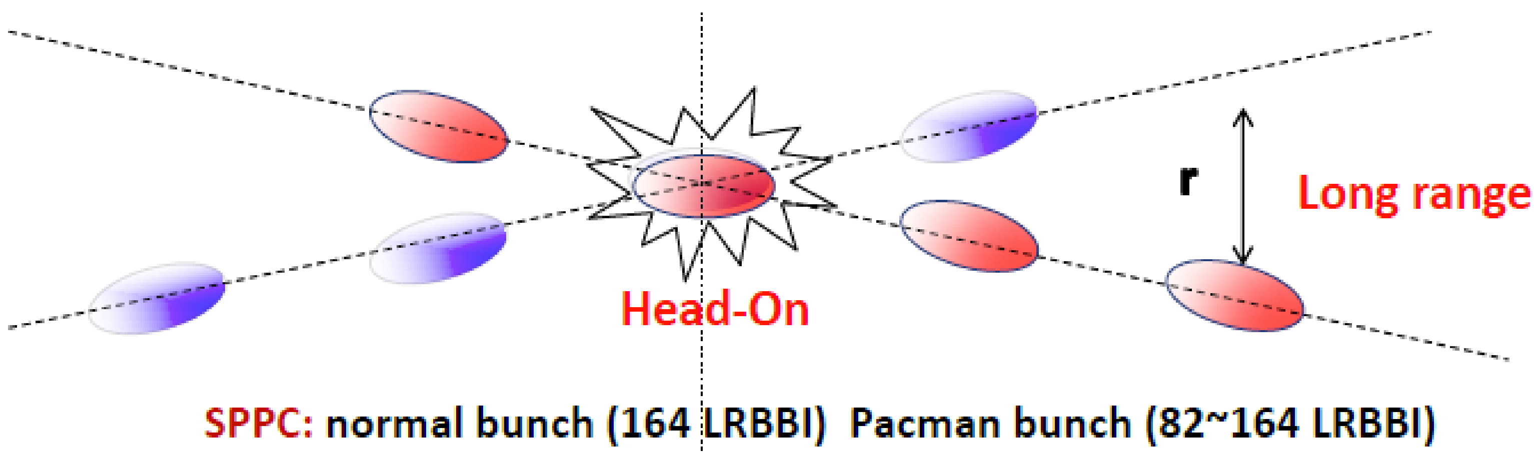
BT: a p-RCS batch with 112 bunches
111*25ns=2.775μs;
t1: p-RCS extraction kicker rise time 425ns;
t2: MSS injection kicker rise time 0.925μs;
t3: MSS extraction kicker rise time 1.525μs;
t4: SS injection kicker rise time 0.925μs;
t5: SS extraction kicker rise time 2.725μs;
t6: SPPC injection kicker rise time 0.90μs;
t7: SPPC beam dump kicker rise time 3.45μs

Beam-beam effects

Lijiao Wang,
collaborating with
K. Ohmi and T. Sen

- Beam-beam effect has direct impact to the luminosity
- Studying different effects (ongoing)
  - Head-on interaction
  - Long-range interaction
  - Pacman effects
  - Orbit effects
  - Coherent beam effects
  - BB compensation methods (Electron lens, Compensation wires)

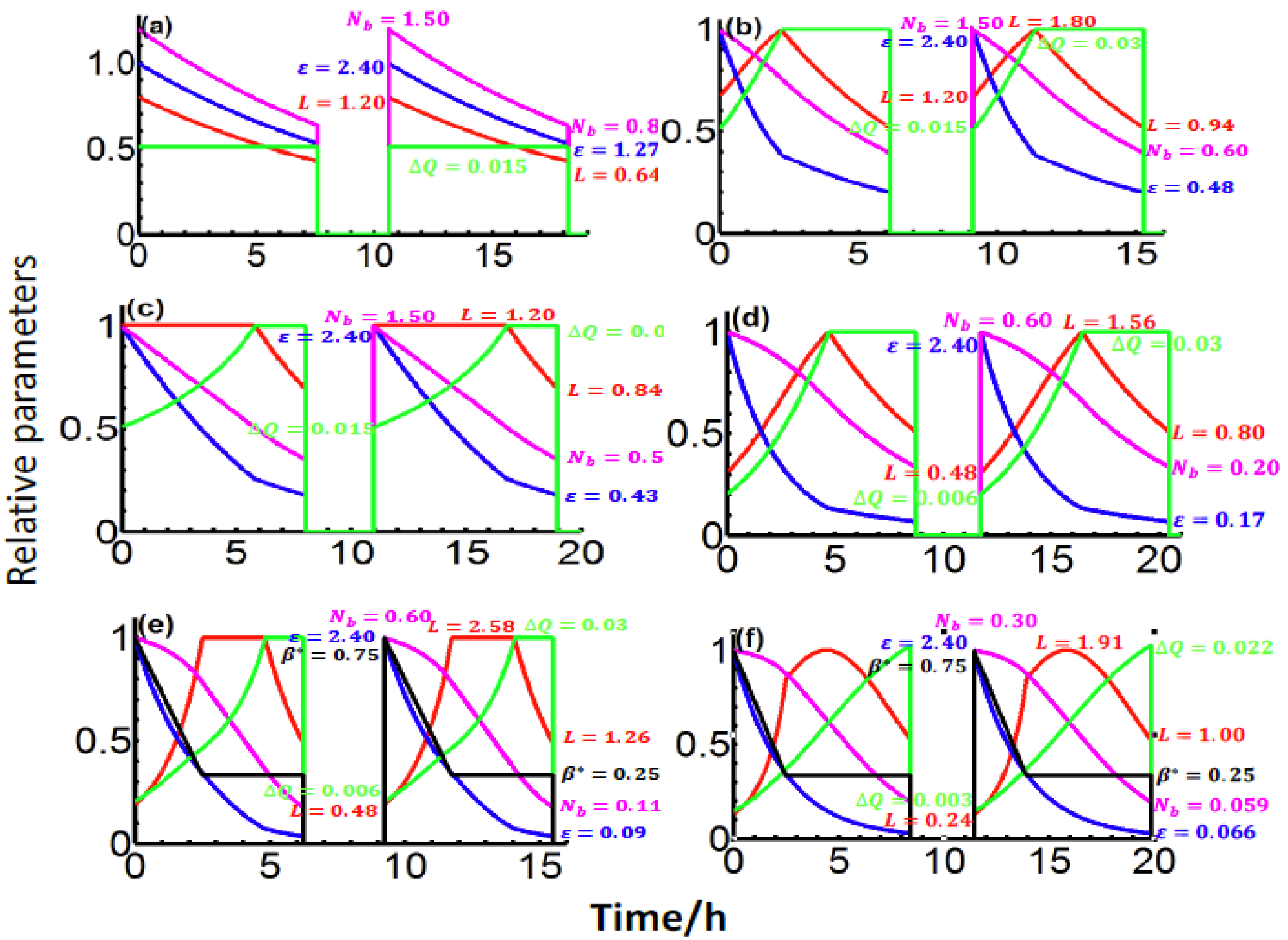
$$\mathcal{L} \propto \xi \frac{1}{\beta_y} N n_b f_r$$



Luminosity Leveling

Lijiao Wang,
R. Palmer

Increasing the average luminosity by programing the beam collision scenario (controlled emittance shrinking, turnaround time, beta*, B-B parameter, bunch spacing)

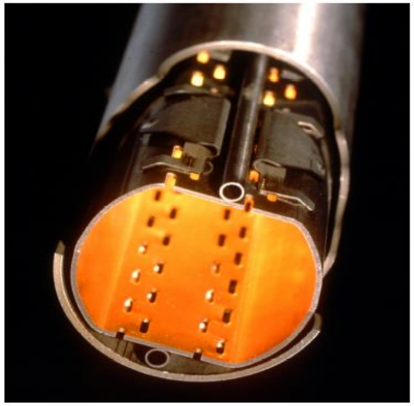


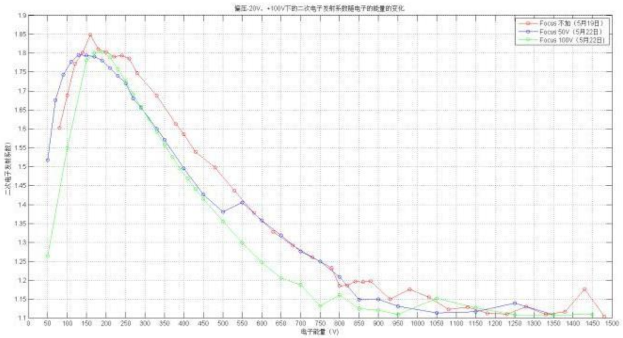
- Turnaround:
  0.8 hrs (min),
  2.4 hrs (ave)
- ΔQ: 0.03 (max)
- Spacing:
  25, 10, 5 ns
- Beta*:
  0.75 m
  0.75->0.25m

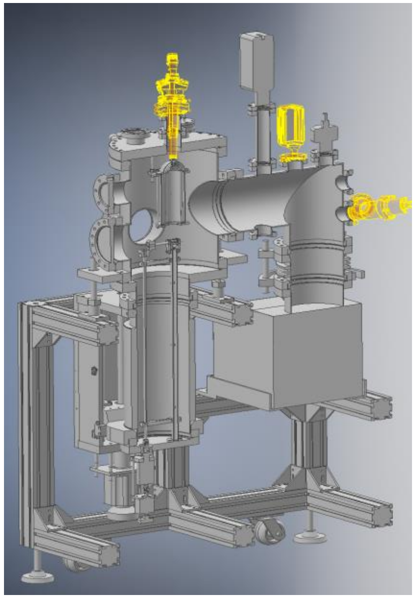
Impedance and Instabilities

Yudong Liu

- Analysis on key impedance contributions: beam screens and collimators
- Study on wall impedance for multilayer chamber: analytical and simulations
  - Beam screen: stainless steel (0.6mm) with coating copper (50μm), also HTS
  - Injection protection collimator: hBN (hexagonal boron nitride) coating with Ti (5 μm)
  - Others
- Electron cloud study in different sections; characteristics measurements (with a NSFC fund)



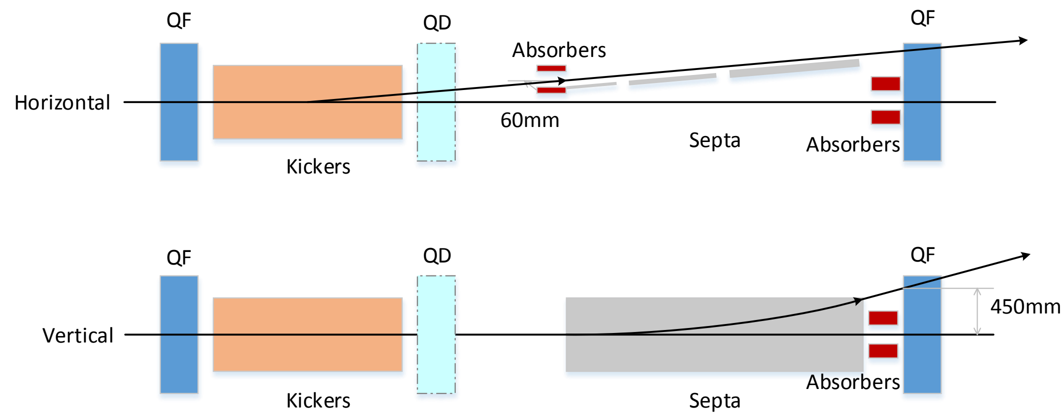


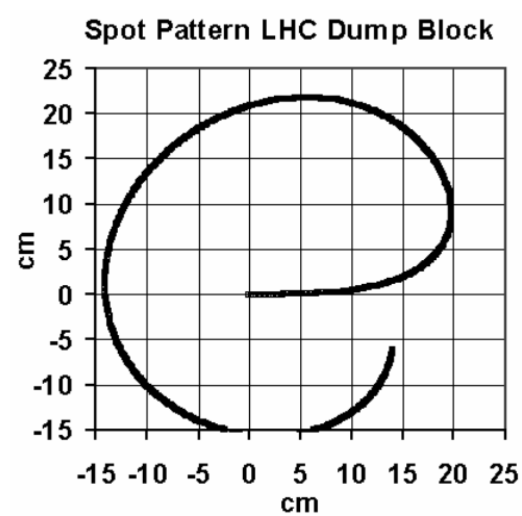


Injection and extraction

THU: Ye Yang, Guangrui Li

- Injection:
  - Beam transfer from SS to SPPC (two beams)
  - Multiple injections
  - Injection scenario
- Extraction/abort:
  - MPS safety concerns
  - Optics
  - Energy dilution methods
- Identifying technical challenges
  - SC septum magnets
  - Kicker risetimes
  - Dump materials





Machine Protection

USTC: Hongliang Xu, Zhiliang Ren

- Work on
  - Safety operation strategy of the machine
  - Analysis of different safety issues related to beams and magnets
  - Injection and extraction issues
  - Beam transfer from SS to SPPC
  - Safety issues in the high-power injector accelerators

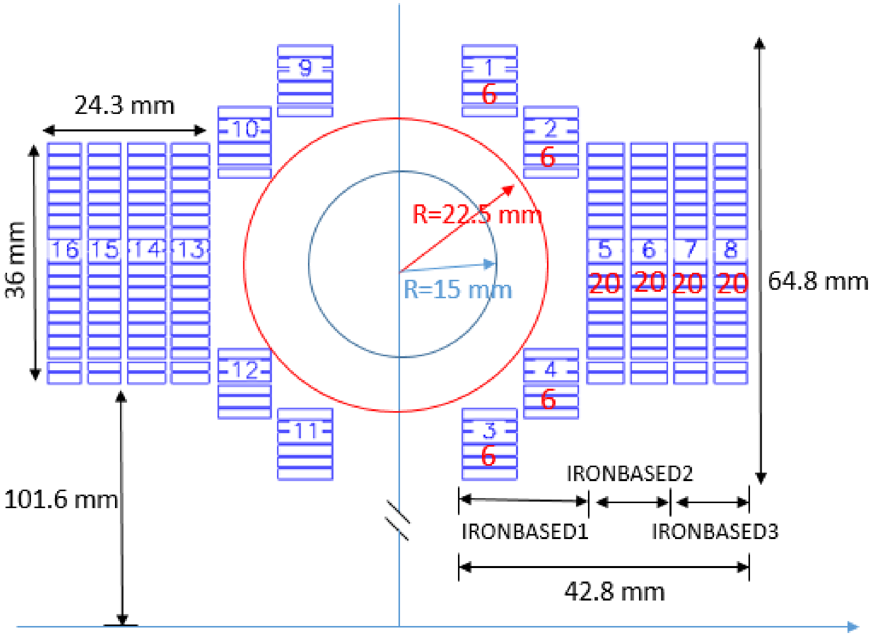
Technical challenges and R&D requirements
-High field SC magnets

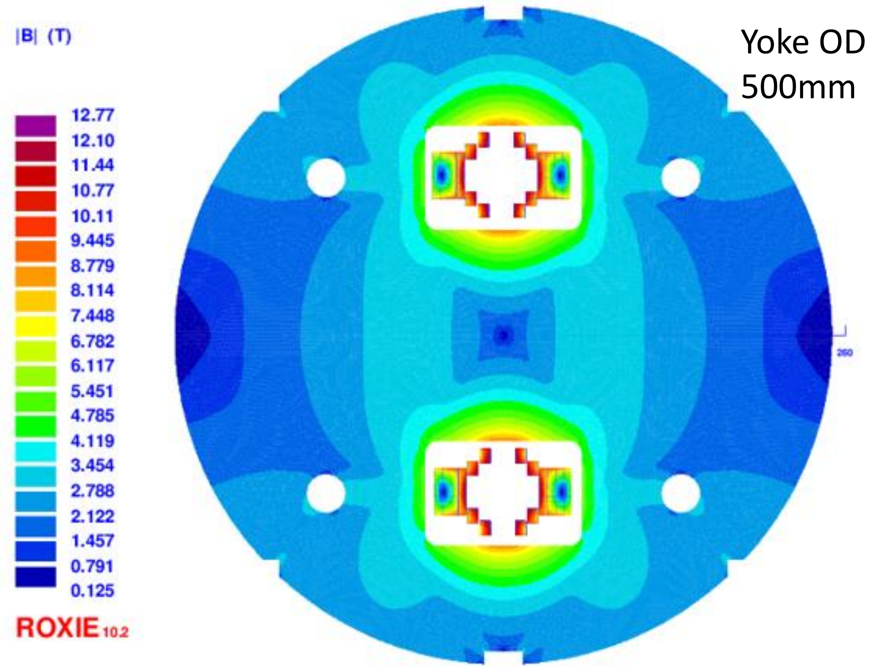
Mini-Workshop: Jan. 18-19
Report by Q.J. Xu

- SPPC design scope
  - Phase I: 12 T, all-HTS (preferable iron-based conductors)
  - Phase II: 20-24 T, all-HTS
- New magnet design for 12-T dipoles
- R&D effort in 2016-2018
  - Cables, infrastructure
  - Development of a 12-T Nb3Sn-based twin-aperture magnets (alone, with NbTi, with HTS)
- Collaboration
  - Domestic collaboration frame on HTS (material and applications) formed in October 2016: now regular meetings every three months
  - CERN-IHEP collaboration on HiLumi LHC magnets

Design of 12-T Fe-based Dipole Magnet

C. Wang, E. Kong (USTC), Q. Xu et al.





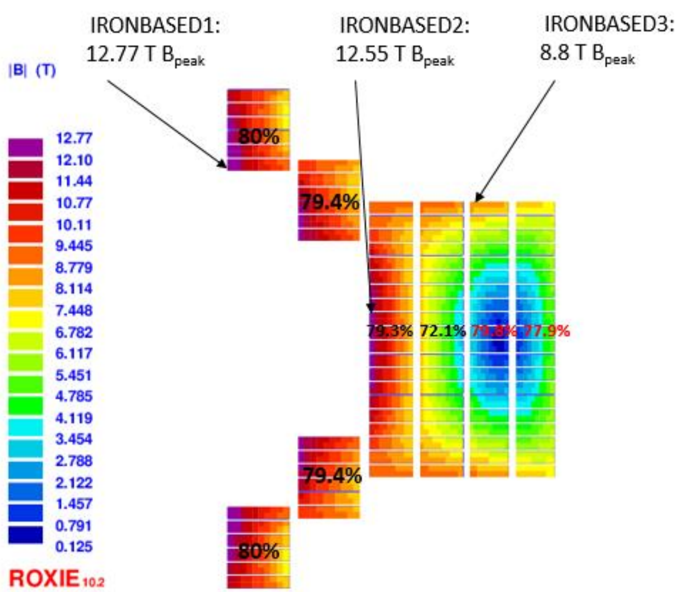


Table 1: Main parameters of the cables

Cable	Hight	Width-i	Width-o	Ns	Strand	Filament	Insulation
IRONBASED1	8	1.5	1.5	20	IRON-BASED	FE-BASED	0.15
IRONBASED2	5.6	1.5	1.5	14	IRON-BASED	FE-BASED	0.15
IRONBASED3	5	1.5	1.5	12	IRON-BASED	FE-BASED	0.15

Table 2: Main parameters of the strand

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IRON-BASED	0. 802	1	200	4. 2	10	4000	111

For per meter of such magnet, the required length of the iron-based strand: 6.08 Km

Domestic Collaboration on HTS

Applied HTS Collaboration established in Oct. 2016.

- **Goal：**

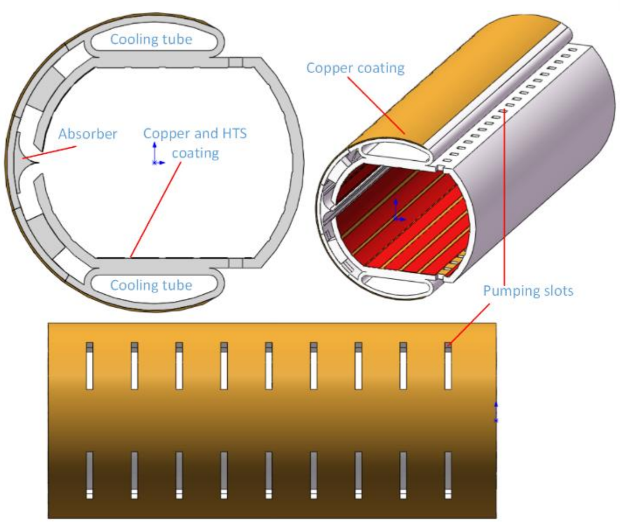
1) To increase J_c of **IBS** by 10 times, reduce the cost to **20 RMB/kAm @ 12T & 4.2K**; 2) To reduce cost of **ReBCO and Bi-2212** conductors to 20 RMB/kAm @ 12T & 4.2K; 3) Realization and Industrialization of iron-based magnet and SRF technology.

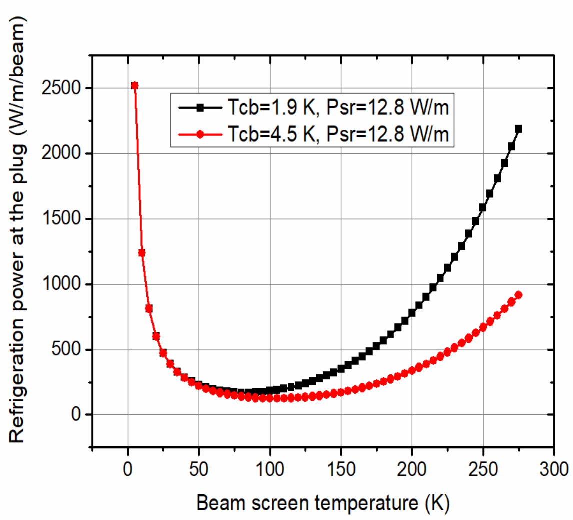
- **Working groups：** 1) **Fundamental science** investigation; 2) **IBS** conductor R&D; 3) **ReBCO** conductor R&D; 4) **Bi-2212** conductor R&D; 5) **performance** evaluation; 6) **Magnet and SRF** technology.
- **Collaboration meetings**: every 3 months, to report the progress and discuss plan for next months.

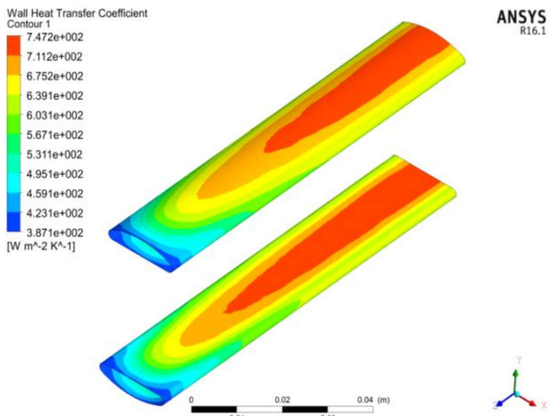
Beam screen study

PKU: Kun Zhu,
Pingping Gan

- With the new design scope, SR power decreases from 45 W/m to 12.8 W/m, but still very important, and beam screen still a critical issue
- Different effects combined: impedance, electron cloud, vacuum, magnet quenches, cooling etc.➔ a small working group
- Recent work focused on: structure, HTS coating, working temperature, impedance, cooling method







Cryogenic temperature for SPPC

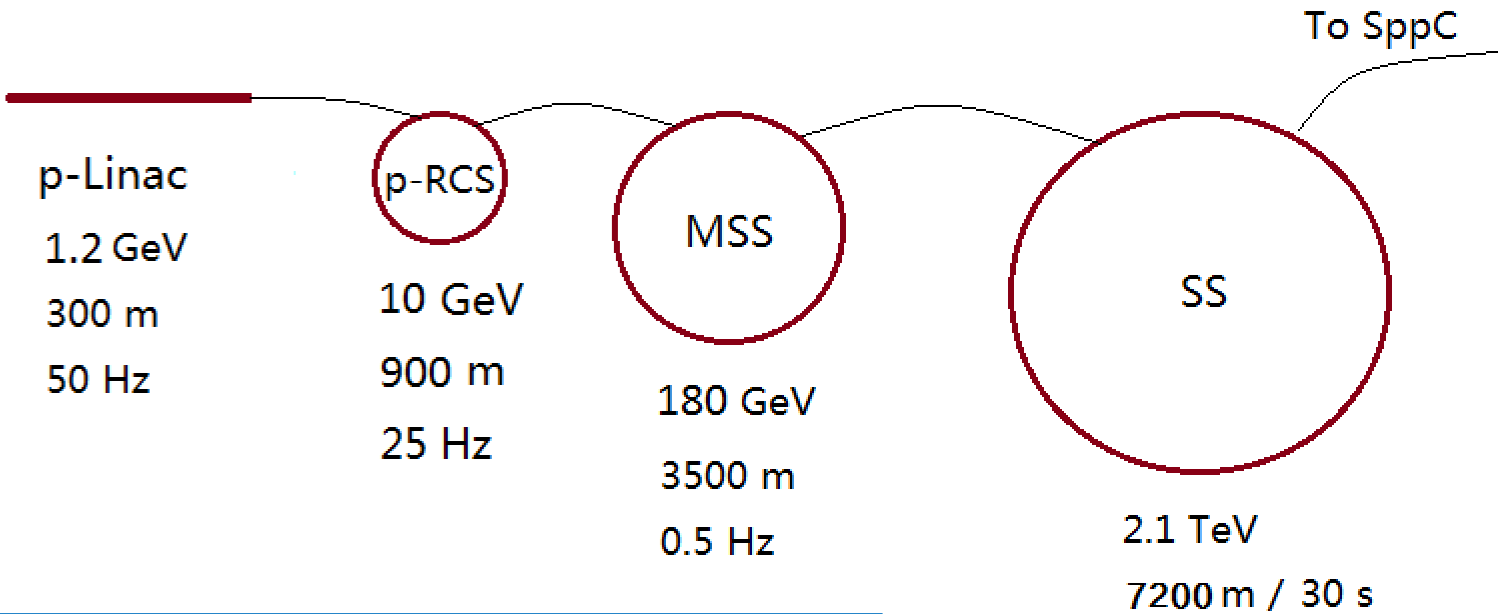
Led by A. Krasnov (BINP)

- SPPC uses HTS magnets, potentially higher temperature for cold bore
- Vacuum pumping is related to the cryogenic temperature
- Problems:
  - Role of surface and radiation
  - Cold beam pipe. Hydrogen accumulation. PSD
  - Equations for residual dynamic gas density prediction
  - CB and BS temperatures
  - NEG coating
  - Activation, surface impedance
- Different solutions under investigation:
  - Traditional BS solution with cold bore temperature <3.6 K;
  - Cryosorbers with independent choice of magnets temperature (4-8 K);
  - Separation of beam vacuum with magnet vacuum, use NEG coating

Other important technical challenges

- Collimation system: new materials to reduce impedance and tolerate more heat deposit
- Very large scale cryogenics system: SC magnets, SRF, beam screens
- Sophisticated beam feedback system: to control the emittance heat-up and suppress beam instabilities
- Machine protection system: fast detection of abnormal function, reliable beam abort (kickers and septa)
- There are also many technical challenges in building high-power injector chain: e.g. RF systems for p-RCS and MSS, fast ramping for SS

Injector chain
(for proton beam)



p-Linac: proton superconducting linac

p-RCS: proton rapid cycling synchrotron

MSS: Medium-Stage Synchrotron

SS: Super Synchrotron

Ion beams have dedicated linac (I-Linac) and RCS (I-RCS)

Preliminary design of the injector chain

- Accelerator schemes and parameter lists
- Preparation of the beam for injection into SPPC: energy, intensity, emittance, bunch pattern, turnaround time
- Maximize the performance with modest cost for each accelerator (different settings from service to SPPC)
- Pre-conceptual design on each stage:
  - p-Linac/i-Linac: Yuanrong Lu, Haifeng Li (RFQ, DTL, SC cavities)[PKU]
  - p-RCS/i-RCS: Linhao Zhang, Jingyu Tang (parameter design)
  - MSS: Yang Hong (parameter design, lattice)
  - SS: Xiangqi Wang, Tao Liu (parameters, lattice, injection/extraction, acceleration) [USTC]

Major parameters for the injector chain

	Value	Unit		Value	Unit
p-Linac			MSS		
Energy	1.2	GeV	Energy	180	GeV
Average current	1.4	mA	Average current	20	uA
Length	~300	m	Circumference	3500	m
RF frequency	325/650	MHz	RF frequency	40	MHz
Repetition rate	50	Hz	Repetition rate	0.5	Hz
Beam power	1.6	MW	Beam power	3.7	MW
p-RCS			SS		
Energy	10	GeV	Energy	2.1	TeV
Average current	0.34	mA	Accum. protons	1.0E14	
Circumference	970	m	Circumference	7200	m
RF frequency	36-40	MHz	RF frequency	200	MHz
Repetition rate	25	Hz	Repetition period	30	s
Beam power	3.4	MW	Protons per bunch	1.5E11	
			Dipole field	8.3	T

More about the Injector Chain

- Injector chain by itself is a very complicated and powerful accelerator system, large enough by a single stage
  - Totally new, different from LHC or Tevatron (building-up by steps)
  - No close reference accelerators (scaled up by large factors)
  - Should be built earlier than SPPC by a few years to allow relatively long-time commissioning stage by stage
- Rich physics programs for each stage, e.g.:
  - p-Linac: producing intense neutrons and muons and rare isotopes for wide research areas
  - p-RCS and MSS: producing very powerful neutrino beams for neutrino oscillation experiments
- Key technical challenges should be identified, so needed R&D program can be pursued (e.g. high-Q ferrite-loaded RF cavities)

Contents of SPPC Chapter in CEPC CDR

Ch.8 Upgrade to SPPC

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- 8.1.1 Science reach at the SPPC
- 8.1.2 The SPPC complex and design goals
- 8.1.3 Overview of the SPPC design
- 8.1.4 Other physics options

8.2 Key accelerator issues and design
- 8.2.1 Main parameters
- 8.2.2 Key accelerator physics issues
- 8.2.3 Preliminary lattice design
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- 8.2.7 Other technical challenges

8.3 High-field superconducting magnets

8.4 Injector chain
- 8.4.1 General considerations
- 8.4.2 Preliminary design concepts

Domestic Collaboration

- HTS technology: Applied High Temperature Superconductor Collaboration (AHTSC)
- Accelerators:
  - USTC: beam dynamics, instrumentation, magnets, vacuum, machine protection
  - THU: injection/extraction
  - PKU: linac, beam screen
  - SINAP: instrumentation

International Collaboration

- CERN: magnets, collimation, dynamic aperture
- LAL: collimation
- BNL: general accelerator physics, luminosity leveling; magnets
- JLAB: e-p collision
- KEK: beam-beam effects
- FNAL: beam-beam effects
- LBNL: magnets
- BINP: cryogenic vacuum
- EPFL: beam-beam effect, instabilities

Summary

- We have been making progress on SPPC study selectively and steadily.
- Strong domestic collaboration on HTS technology will support the SPPC magnet development.
- SPPC chapter in the CDR report ready.
- Much welcome international experts join SPPC study.

THANKS FOR ATTENTION!