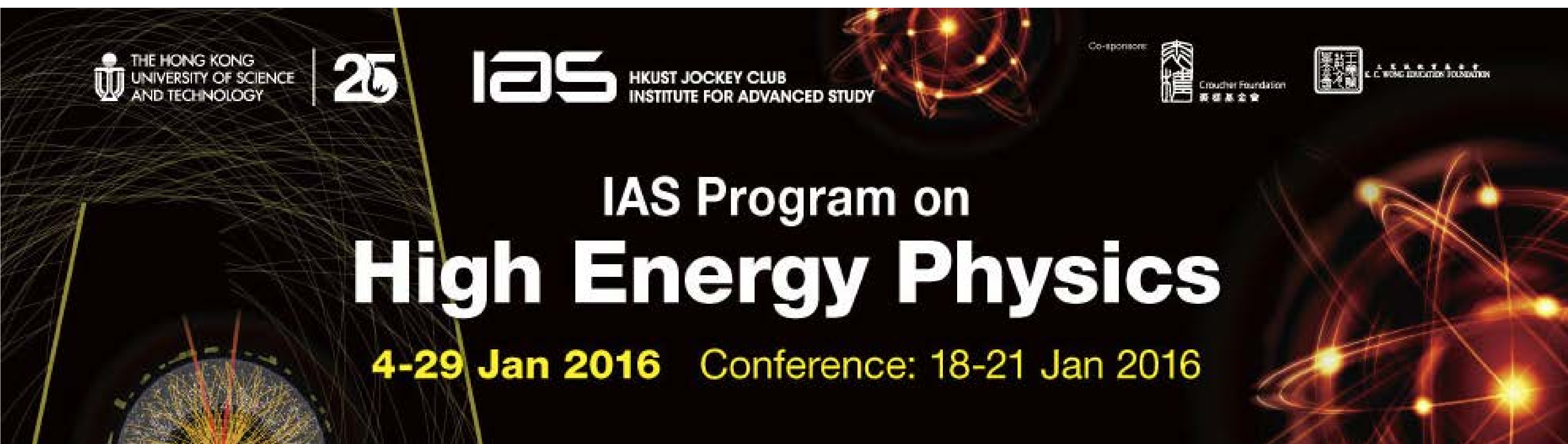
Summary of Accelerator Session

Qing Qin (秦庆), IHEP, CAS

2016-01-21



Acknowledgement

- All materials are from the speakers' slides at the IAS conference
- Henry, Yanjun, Tao, Prudence, et al…
- All participants of the IAS conference

Jan. 19 – 22, 2015, IAS'15 conference, we had:

	Monday, January 19	Tuesday	Wednesday	Thursday
8:00	**Registration**			
8:40	**Welcome (JCFP, local committee)**			
9:00	**Accelerator (Pedagogical)** (Vladimir Shiltsev, TBC)	**Preliminary Conceptual Design of CEPC-SPPC** (Weiren Chou)	**CEPC Accelerator** (TBD)	**Detectors at 100 TeV** (Ludovico Pontecorvo, TBC)
9:40		**How to Determine the Tunnel Circumference** (Richard M. Talman)	**TBD** (Haijun Yang)	**Detector optimization** (Bill Murray, TBC)
10:20	Coffee break	Coffee break	Coffee break	Coffee break
10:40	**Experiment (Pedagogical)** (Ashutosh Kotwal, TBC)	**Physics Motivation for future machines** (Serguei Ganjour, TBC)	**TBD** (Tao Liu)	**Neutrino** (Ernest Ma TBC)
11:20		**Physics at CLIC** (Frank Simon)	**Top-Higgs couplings measurements at the LHC and beyond** (Aurelio Juste)	**Testing Low Scale Sterile Neutrino signals** (Oliver Fischer)
12:00	Reception	**W and Z Boson Physics at HL-LHC and FCCee** (Roberto Techini)	**Higgs self coupling measurement at 100 Tev Collider** (Weimin Yao)	**Non-SUSY** (Jing Shu)
12:40		Self-arranged lunch	Self-arranged lunch	Self-arranged lunch
14:00	**Theory (Pedagogical)** (Chris Quigg)	**Higgs Prospects at HL-LHC** (Aleandro Nisati, TBC)	**Heavy Flavor Physics at Future Colliders** (Caidian Lv)	**Discussion panel (Accelerators)** Steve Gourley and Weiren Chou
14:40		**Higgs physics at Higgs Factory** (Jianmin Qian)	**TBD** (George Hou)	
15:20	Coffee break	Coffee break	Coffee break	Coffee break
15:40	**Distinguished Lecture** (Yifang Wang)	**Dark matter at 100 TeV pp collider** (Liantao Wang)	**Parallel talks:** Felix Yu, Hongbo Zhu, Kechen Wang, Rostislav Konoplich, Arely Cortes Gonzalez, Yunhai Cai, Huirong Qi, Haibo Li, Tao Hu, Jiaying Gu, Ying Li	**Discussion panel (Physics)** Ian Hinchliffe, Ashutosh Kotwal, TBD
16:20		**Dark matter** (Yuan-Hann Chang, TBC)		
17:00	(end of day)	**SUSY** (Albert De Roeck)		**Summary talk (Organization committee)** Nima Arkani-Hamed (TBC)
17:40	(end of day)			**Closing address** (Chair)

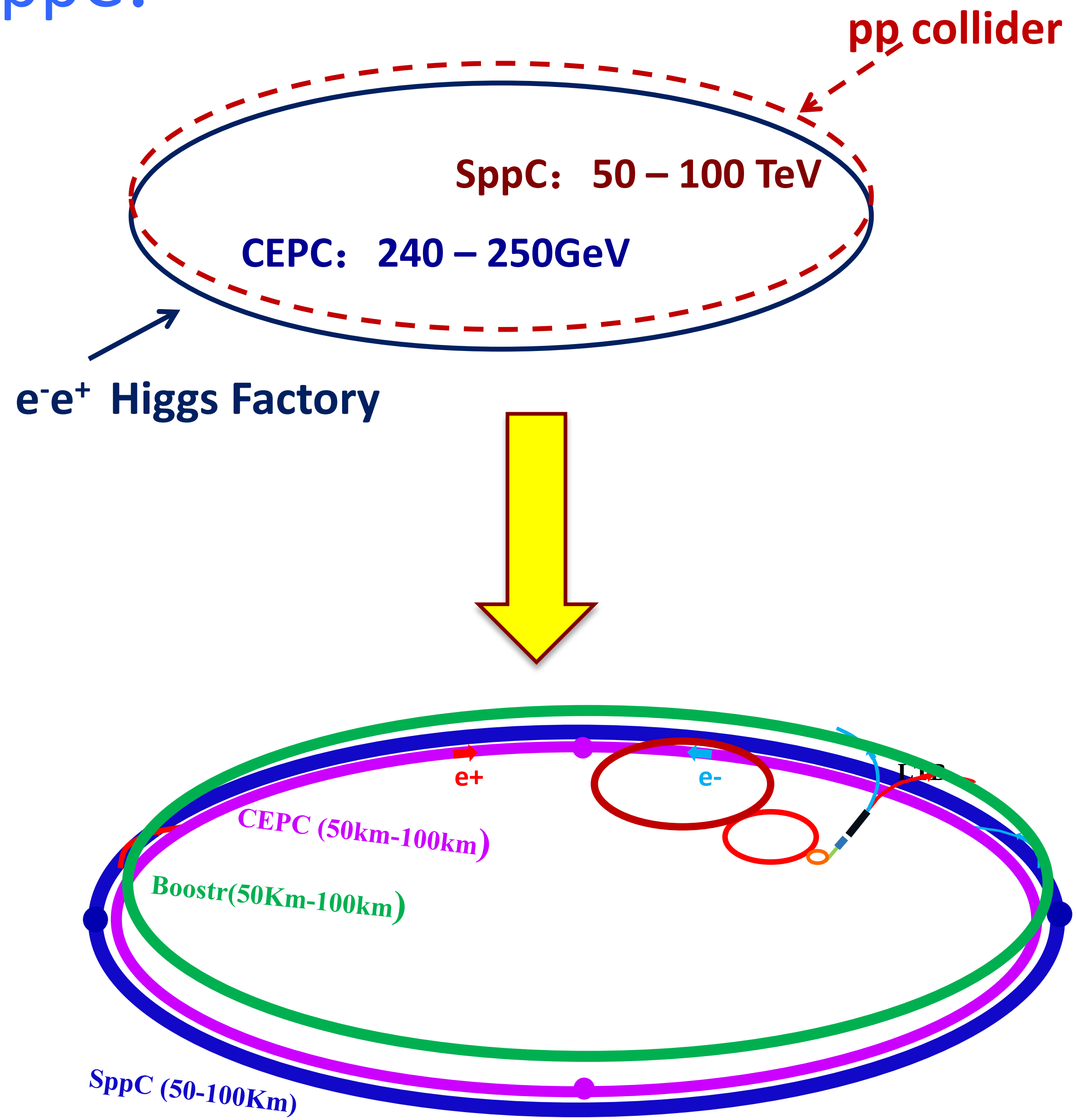
This year, we have:

	Monday		Tuesday		Wednesday		Thursday
	18-Jan		19-Jan		20-Jan		21-Jan
08:30- 08:50	Conference Registration						
08:50-09:00	Welcome Remarks						
	Session M1 Venue: IAS Lecture Theater (LT) [Chair: Michelangelo Mangano]		Session Tu 1 Venue: IAS Lecture Theater (LT) [Chair: JoAnne Hewett]		Session W1 Venue: IAS Lecture Theater (LT) [Chair: Christopher Tully]		Session Th 1 Venue: IAS Lecture Theater (LT) [Chair: Tao Liu]
9:00	Plenary #01 Scientific Overview (Chris Quigg)		Plenary #05, Precision Higgs physics at 100 TeV (Michelangelo Mangano)		Plenary #9 Detector Requirements for Precision Higgs Boson Physics (Jianming Qian)		LHC Resent Search Results (Serguei Ganjour)
9:40	Plenary #02 Physics at Higgs Factory (Matthew Reece)		Plenary #06 New Physics at 100 TeV (Matthew mcCullough)		Plenary #10 Status of the Studies for a FCC-hh Detector (Albert de Roeck)		Theory Summary (Shufang Su)
10:20	Chair's conclusion		Chair's conclusion		Chair's conclusion		Chair's conclusion
10:30	Coffee Break		Coffee Break		Coffee Break		Coffee Break
	Session M2 Venue: IAS Lecture Theater (LT) [Chair: Weiren Chou]		Session Tu 2 Venue: IAS Lecture Theater (LT) [Chair: Yunhai Cai]		Session W2 Venue: IAS Lecture Theater (LT) [Chair: Shan Jin]		Session Th 2 Venue: IAS Lecture Theater (LT) [Chair: Joao Guimaraes da Costa]
11:00	Plenary #03 A Brief History of Circular e+e- Colliders Emphasizing Future Applications (John Seeman)		Plenary #7 Challenges in pp and a Revisit to ee (Weiren Chou)		Plenary # 11 The International Linear Collider (ILC): Technical Status and Prospect (Akira Yamamoto)		Accelerator Summary (Qing Qin)
11:40	Plenary #04 CEPC Status and International Collaboration (Jie Gao)		Plenary #8 Status of the FCC Study (Katsunobu Oide)		Plenary #12, CEPC detector (Yuanning Gao)		Experiment/Detector Summary (John Hauptman)
12:20	Chair's conclusion		Chair's conclusion		Chair's conclusion		Chair's conclusion
12:30	Program Lunch for Registered Participants only		Self-arranged Lunch		Self-arranged Lunch		Self-arranged Lunch
	Parallel Sessions (Accelerator) Venue: IAS LT [Chair: Jie Gao]	Parallel Sessions (Experiment) Venue: IAS 2042 [Chair: Marcel Stanitzki]	Parallel Sessions (Detector) Venue: IAS LT [Chair: John Hauptman]	Parallel Sessions (Theory) Venue: IAS 2042 [Chair: Matthew Reece]	Parallel Sessions (Accelerator) Venue: IAS LT [Chair: Marica Biagini]	Parallel Sessions (Theory/Experiment) Venue: IAS2042 [Chair: Shufang Su]	Forum Session Venue: IAS Lecture Theater [Chair: Henry Tye]
14:00	Richard Talman (14:00 - 14:30)	Chris Tully (14:00 - 14:25)	Hongbo Zhu (14:00 - 14:25)	Michael Spannowsky (14:00 - 14:25)	Yongjun Li (14:00 - 14:30)	Christophe Grojean (14:00 - 14:25)	Forum Discussion Leader: Henry Tye Panel members: Jie Gao, I Hinchliffe, Michelangelo Mangano, John Seeman, Marcel Stanitzki, Liantao Wang, more... (14:00 - 15:30)
14:25		Guido Tonelli (14:25 - 14:50)	Massimo Caccia (14:25 - 14:50)	Maxim Perelstein (14:25 - 14:50)		Ian Low (14:25 - 14:50)	
14:30	Dou Wang (14:30 - 14:50)				Yuan Zhang (14:30 - 14:50)		
14:50	Anton Bogomyagkov (14:50 - 15:10)	Manqi Ruan (14:50 - 15:15)	Xiangming Sun (14:50 - 15:15)	Jan Hajer (14:50 - 15:15)	Huiping Geng (14:50 - 15:10)	Stefan Antusch (14:50 - 15:15)	
15:10	Catia Milardi (15:10 - 15:30)				Ivan Koop (15:10 - 15:30)		
15:15		Coffee Break (15:15 - 15:45)	Coffee Break (15:15 - 15:45)			Coffee Break (15:15 - 15:45)	
15:30	Coffee Break (15:30 - 16:00)				Coffee Break (15:30 - 16:00)		Coffee Break (15:30 - 16:00)
	Parallel Sessions (Accelerator) Venue: IAS LT [Chair: Eugene Levichev]	Parallel Sessions (Experiment) Venue: IAS 2042 [Chair: Marcel Stanitzki]	Parallel Sessions (Detector) Venue: IAS LT [Chair: John Hauptman]	Parallel Sessions (Theory) Venue: IAS 2042 [Chair: Maxim Perelstein]	Parallel Sessions (Accelerator) Venue: IAS LT [Chair: Weiren Chou]	Parallel Sessions (Theory/Experiment) Venue: IAS2042 [Chair: Tom Rizzo]	Closing Session Venue: IAS Lecture Theater [Chair: Henry Tye]
15:45		Aurelio Juste (15:45 - 16:10)	Marcel Stanitzki (15:45 - 16:10)	Zhen Liu (15:45 - 16:10)		Wei-shu Hou (15:45 - 16:10)	
16:00	Yunhai Cai (16:00 - 16:20)				Kaoru Yokoya (16:00 - 16:20)		Closing Talk No. 1 Han Tao (TBC) (16:00 - 16:45)
16:10		Shin-shan Yu (16:10 - 16:35)	Huirong Qi (16:10 - 16:35)	Cheng-wei Chiang (16:10 - 16:35)		Kingman Cheung (16:10 - 16:35)	
16:20	Michael Koratzinos (16:20 - 16:40)				Nikolay Muchnoi (16:20 - 16:40)		
16:35		Xin Chen (16:35 - 17:00)	Haijun Yang (16:35 - 17:00)	Qishu Yan (16:35 - 17:00)		Katz Andrey (16:35 - 17:00)	
16:40	Dmitry Shatilov (16:40 - 17:00)				Jingyu Tang (16:40 - 17:00)		Closing Remarks (16:45 - 17:00)
17:00	Kazuhito Ohmi (17:00 - 17:20)	Xuai Zhuang (17:00 - 17:25)	Sehwook Lee (17:00 - 17:25)	Oliver Fischer (17:00 - 17:25)	Feng Su (17:00 - 17:20)	Gang Li (17:00 - 17:25)	
17:10							
17:20	Eugene Levichev (17:20 - 17:40)				Telnov Valery (17:20 - 17:40)		
17:25			Michele Cascella (17:25 - 17:50)	Ning Chen (17:25 - 17:50)		Kai-feng Chen (17:25 - 17:50)	
17:30							
17:40	Stephen Gourlay (17:40 - 18:00)				Qingjin Xu (17:40 - 18:00)		
17:50			Short Break (17:50 - 18:00)				
18:00							

During the conference,we have:

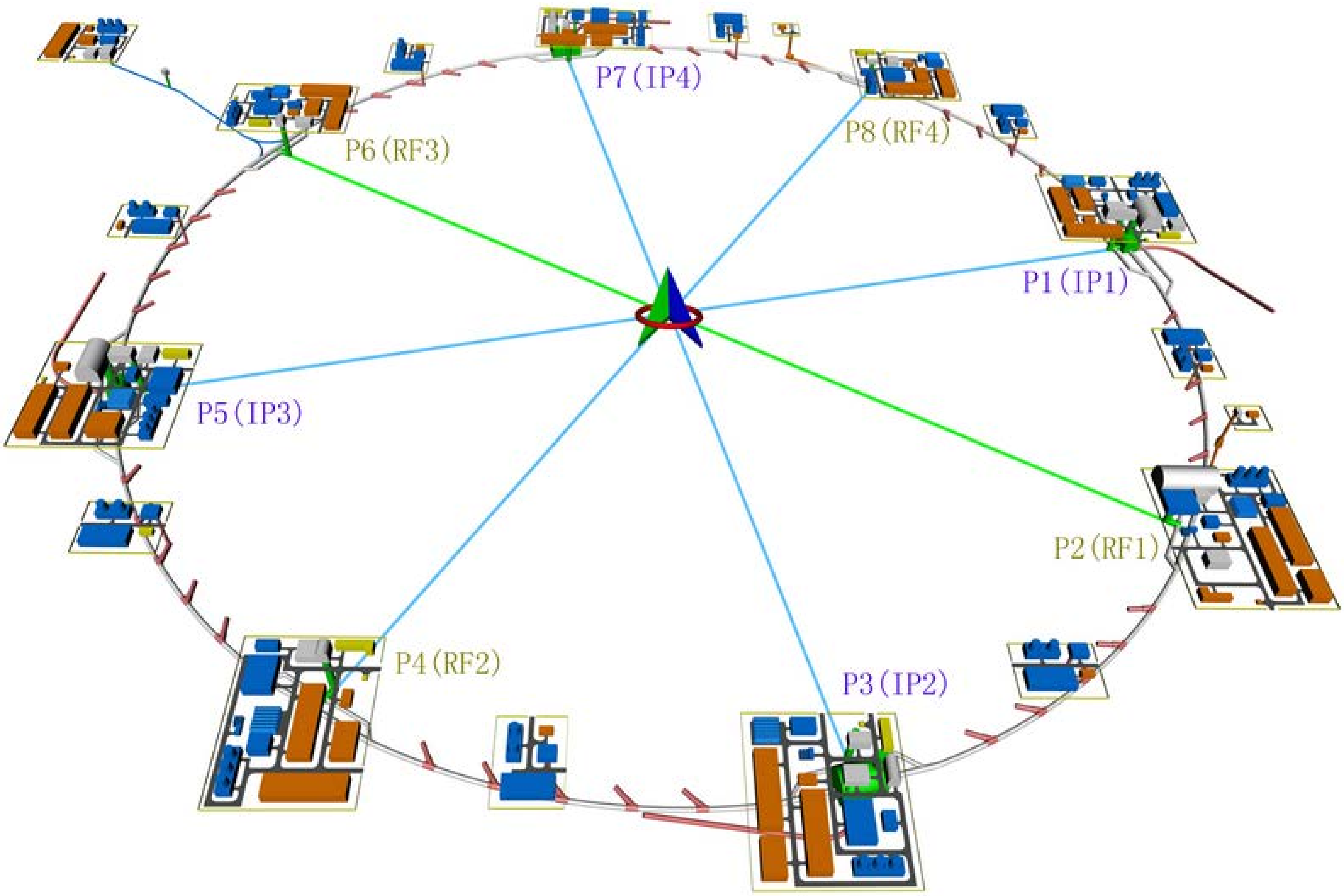
- 25 talks (5 plenary + 20 parallel)
  - 2 overview talks + 5 status talks
  - 16 AP talks + 2 Magnet talks
- Forum & Discussions on Accelerator
- Very informative & fruitful

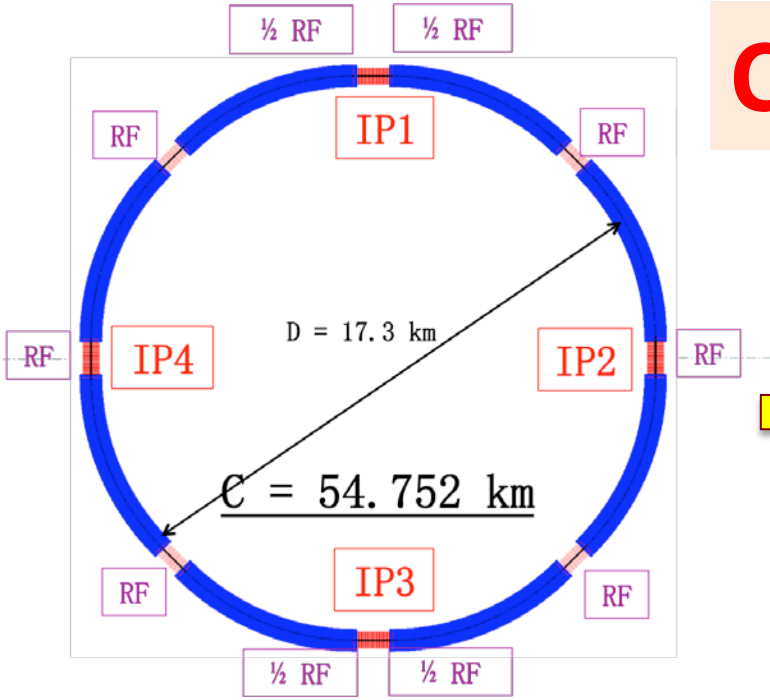
CEPC+SppC：



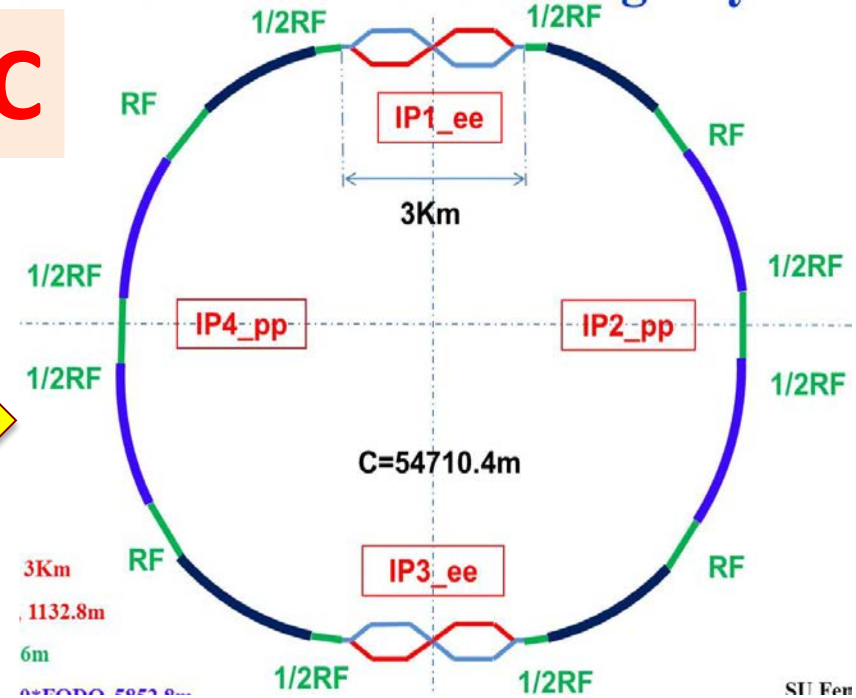
pp collider
SppC： 50 – 100 TeV
CEPC： 240 – 250GeV
e⁻e⁺ Higgs Factory
e+
e-
CEPC (50km-100km)
Boostr(50Km-100km)
SppC (50-100Km)

CEPC-SppC on Site





CEPC



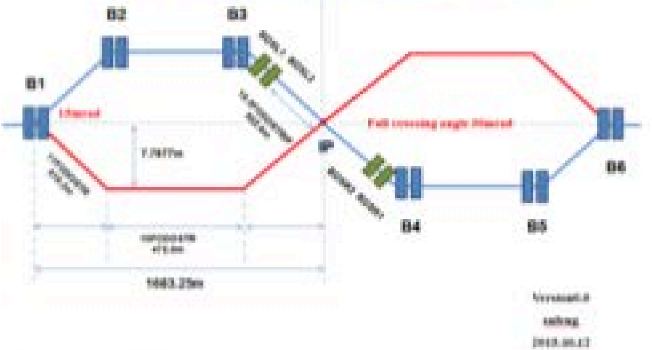
Main parameters for CEPC (Pre-CDR)

Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	Circumference [C]	m	54420
Number of IP[N_{IP}]		2	SR loss/turn [U_0]	GeV	3.11
Bunch number/beam[n_B]		50	Bunch population [Ne]		3.71E+11
SR power/beam [P]	MW	51.7	Beam current [I]	mA	16.6
Bending radius [r]	m	6094	momentum compaction factor [a_p]		3.39E-05
Revolution period [T_0]	s	1.82E-04	Revolution frequency [f_0]	Hz	5508.87
emittance (x/y)	nm	6.12/0.018	b_{IP}(x/y)	mm	800/1.2
Transverse size (x/y)	mm	69.97/0.15	$x_{x,y}$/IP		0.116/0.082
Beam length SR [$s_{s.SR}$]	mm	2.17	Beam length total [$s_{s.tot}$]	mm	2.53
Lifetime due to Beamstrahlung	min	80	lifetime due to radiative Bhabha scattering [t_L]	min	52
RF voltage [V_{rf}]	GV	6.87	RF frequency [f_{rf}]	MHz	650
Harmonic number [h]		117900	Synchrotron oscillation tune [n_s]		0.18
Energy acceptance RF [h]	%	5.98	Damping partition number [Je]		2
Energy spread SR [$s_{d.SR}$]	%	0.13	Energy spread BS [$s_{d.BS}$]	%	0.08
Energy spread total [$s_{d.tot}$]	%	0.16	n_g		0.23
Transverse damping time [n_x]	turns	78	Longitudinal damping time [n_e]	turns	39
Hourglass factor	Fh	0.692	Luminosity /IP[L]	$cm^{-2}s^{-1}$	2.01E+34

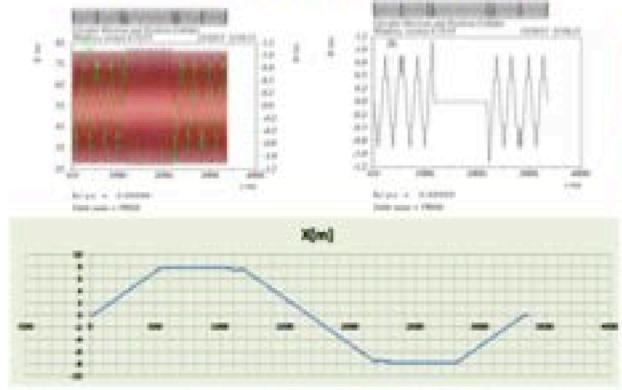
Primary parameter for CEPC local double ring (D. Wang et al)

	Pre-CDR	H-high lumi.		H-low power		Z
Number of IPs	2	2		2		2
Energy (GeV)	120	120		120		45.5
Circumference (km)	54	54		54		54
SR loss/turn (GeV)	3.1	2.96		2.96		0.062
Half crossing angle (mrad)	0	14.5	8.9	11.5	8.7	16.5
Piwinski angle	0	2	3.1	2	2	2.6
N_e/bunch (10^{11})	3.79	3.79	1.32	2.81	2.0	0.37
Bunch number	50	50	144	40	57	1100
Beam current (mA)	16.6	16.9	16.9	10.1	10.1	36.2
SR power /beam (MW)	51.7	50	50	30	30	2.2
Bending radius (km)	6.1	6.2	6.2	6.2	6.2	6.1
...entum compaction	3.4	3.0	2.3	2.6	2.5	5.4
[illegible] x/y (m)	0.8/0.0012	0.306/0.0012	0.058/0.0016	0.22/0.001	0.115/0.001	0.3/0.001
Emittance x/y (nm)	6.12/0.018	3.34/0.01	2.32/0.0058	2.67/0.008	2.56/0.0078	1.18/0.0069
Transverse [illegible]$_{IP}$ (um)	69.97/0.15	32/0.11	11.6/0.097	24.3/0.09	17.6/0.088	18.8/0.083
[illegible]$_x$/IP	0.118	0.04	0.01	0.04	0.028	0.02
[illegible]$_y$/IP	0.083	0.11	0.11	0.11	0.11	0.042
V_{RF} (GV)	6.87	3.7	3.6	3.6	3.7	0.28
f_{RF} (MHz)	650	650	650	650	650	650
Nature [illegible]$_z$ (mm)	2.14	**3.3**	**3.0**	**3.2**	**3.0**	**3.0**
Total [illegible]$_z$ (mm)	2.65	4.4	4.0	4.2	4.0	3.0
HOM power/cavity (kw)	3.6	3.3	1.0	1.5	0.95	0.73
Energy spread (%)	0.13	0.13	0.13	0.13	0.13	0.05
Energy acceptance (%)	2	2	2	2	2	
Energy acceptance by RF (%)	6	**2.2**	**2.2**	**2.2**	**2.4**	**2.0**
$n_{[illegible]}$	0.23	0.49	0.46	0.47	0.46	0.08
Life time due to beamstrahlung_cal (minute)	47	53	32	41	32	
F (hour glass)	0.68	0.73	0.89	0.69	0.7	0.83
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	2.97	2.75	2.03	2.07	1.25

CEPC Partial Double Ring Layout



Orbit (DR_RING_e1) Version0.0

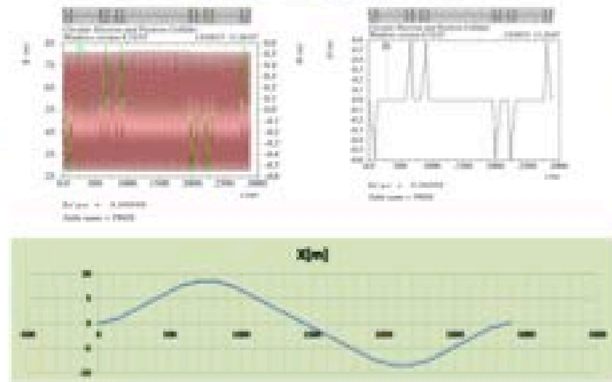


Dipole Strength Version0.0

	Angle(mrad)	L(m)	Rho(m)	Brho(E0/c) (T/m)	B(T)	Ec(KeV)	KeV/m
B0	3.506	19.6	5590.42	400	0.07155	685.173	34.9578
B1	-7.5	19.6	2613.33	400	0.15306	1465.71	74.7813
B2	7.5	19.6	2613.33	400	0.15306	1465.71	74.7813
B3	2.499894	19.6	7840.33	400	0.05102	488.551	24.9261
BDSL1	-19.865386	19.6	986.641	400	0.40542	3882.26	198.075
BDSL2	29.865598	19.6	656.273	400	0.60950	5836.59	297.785
BDSR2	-29.865598	19.6	656.273	400	0.60950	5836.59	297.785
BDSR1	19.865686	19.6	986.641	400	0.40542	3882.26	198.075
B4	-2.499894	19.6	7840.33	400	0.05102	488.551	24.9261
B5	-7.5	19.6	2613.33	400	0.15306	1465.71	74.7831
B6	7.5	19.6	2613.33	400	0.15306	1465.71	74.7831

CEPC Partial Double Ring Layout

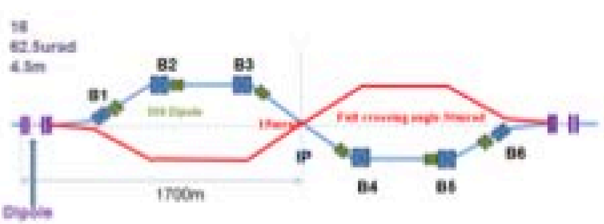
Orbit (DR_RING_e1) Version0.1



Dipole Strength Version0.1

	Angle(mrad)	L(m)	Rho(m)	Brho(E0/c) (T/m)	B(T)	Ec(KeV)	KeV/m
B0	3.506	19.6	5590.42	400	0.07155	685.173	34.9578
B1	-5.0	19.6	3920.0	400	0.10204	977.143	49.8542
B1DSL1	9.9336755	19.6	1973.09	400	0.20273	1941.32	99.0417
B1DSL2	-14.93323	19.6	1312.51	400	0.30476	2918.38	148.897
B2	5.0	19.6	3920.0	400	0.10204	977.143	49.8542
B2DSR1	-9.933058	19.6	1973.09	400	0.20273	1941.32	99.0417
B2DSR2	14.93292	19.6	1312.51	400	0.30476	2918.38	148.897
B3	5.0	19.6	3920.0	400	0.10204	977.143	49.8542
B3DSR1	-9.93336	19.6	1973.09	400	0.20273	1941.32	99.0417
B3DSR2	14.93323	19.6	1312.51	400	0.30476	2918.38	148.897

CEPC Partial Double Ring Layout

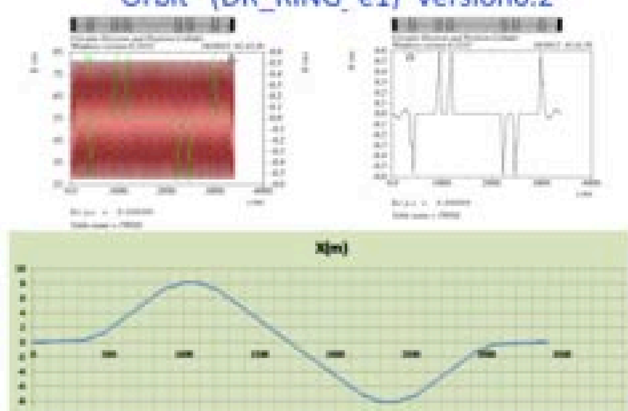


For CEPC 120GeV beam:

➢Max. deflection per separator is 66μrad.

Using Dipole after seperator to acquire 15 mrad

Orbit (DR_RING_e1) Version0.2



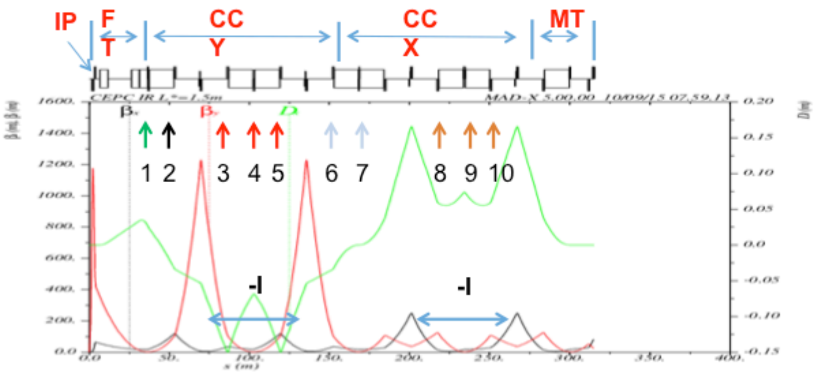
Dipole Strength Version 0.2

	Angle(mrad)	L(m)	Rho(m)	Brho(E0/c) (T/m)	B(T)	Ec(KeV)	KeV/m
B0	3.506	19.6	5590.42	400	0.07155	685.173	34.9578
Bsp	0.0625	4.9	78400	400	0.00510	48.8571	9.97
B1	-4.416	19.6	4438.41	400	0.09012	863.031	44.031
B1DSL1	9.021	19.6	2172.71	400	0.18410	1762.96	89.947
B1DSL2	-14.187	19.6	1381.55	400	0.28953	2772.55	141.456
B2	5.0	19.6	3920.0	400	0.10204	977.143	49.8542
B2DSR1	-9.933058	19.6	1973.09	400	0.20273	1941.32	99.0417
B2DSR2	14.93292	19.6	1312.51	400	0.30476	2918.38	148.897
B3	5.0	19.6	3920.0	400	0.10204	977.143	49.8542
B3DSR1	-9.93336	19.6	1973.09	400	0.20273	1941.32	99.0417
B3DSR2	14.93323	19.6	1312.51	400	0.30476	2918.38	148.897

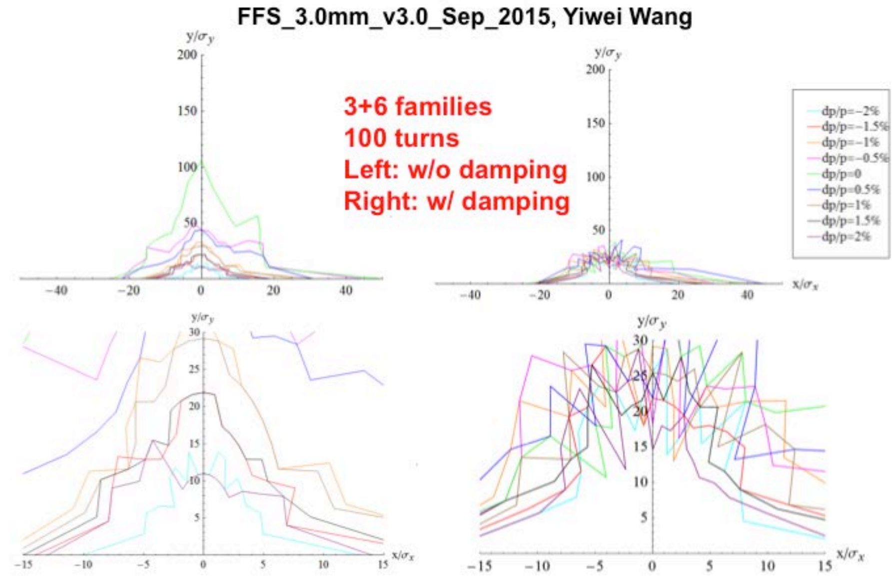
IR Design and sextupoles (Y.W. Wang et al)

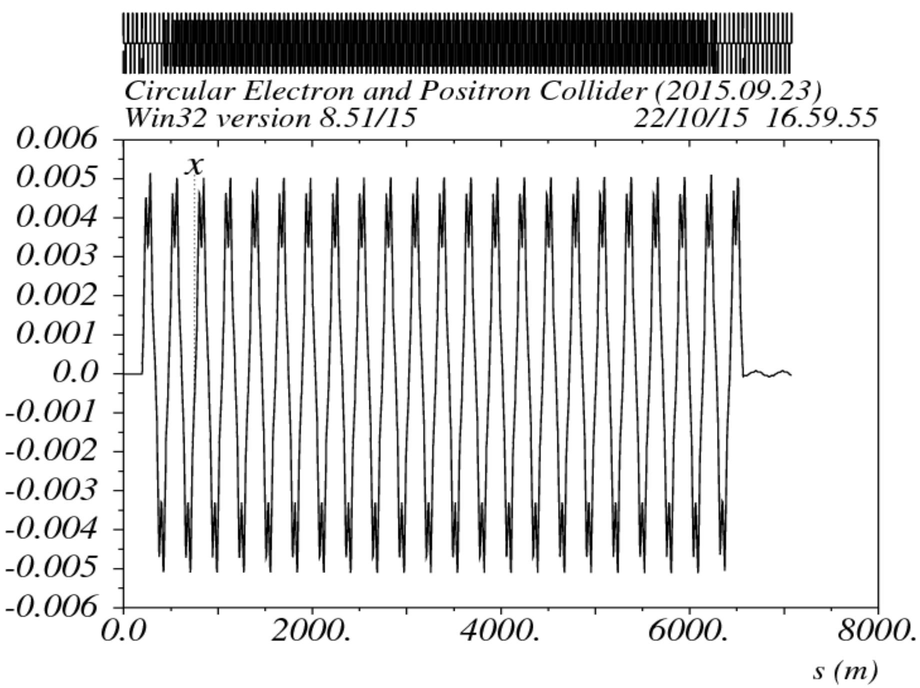
- Idea from Brinkmann
  - correct the high order chromaticity, break down of –I, second order dispersion

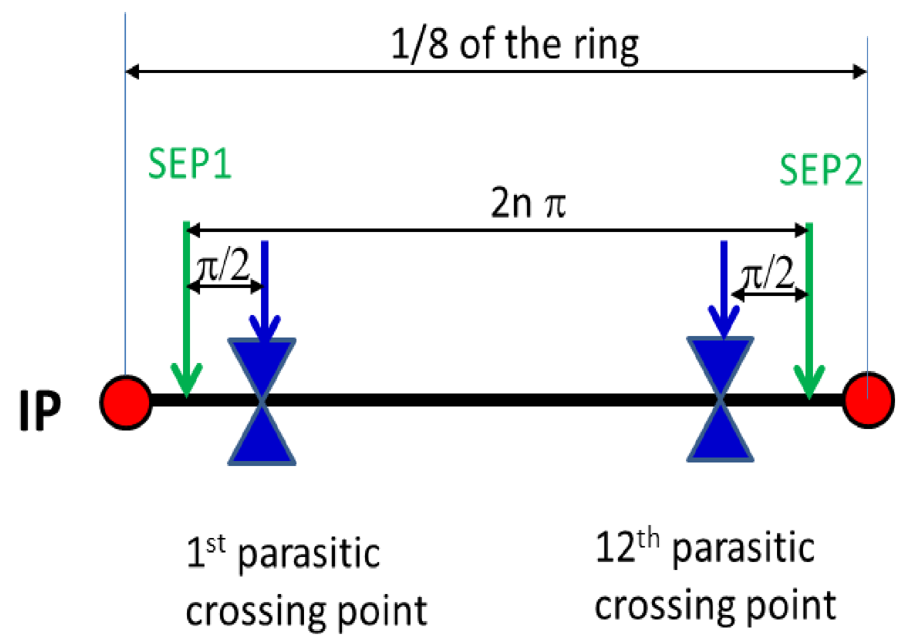
FFS_3.0mm_v3.0_Sep_2015, Yiwei Wang

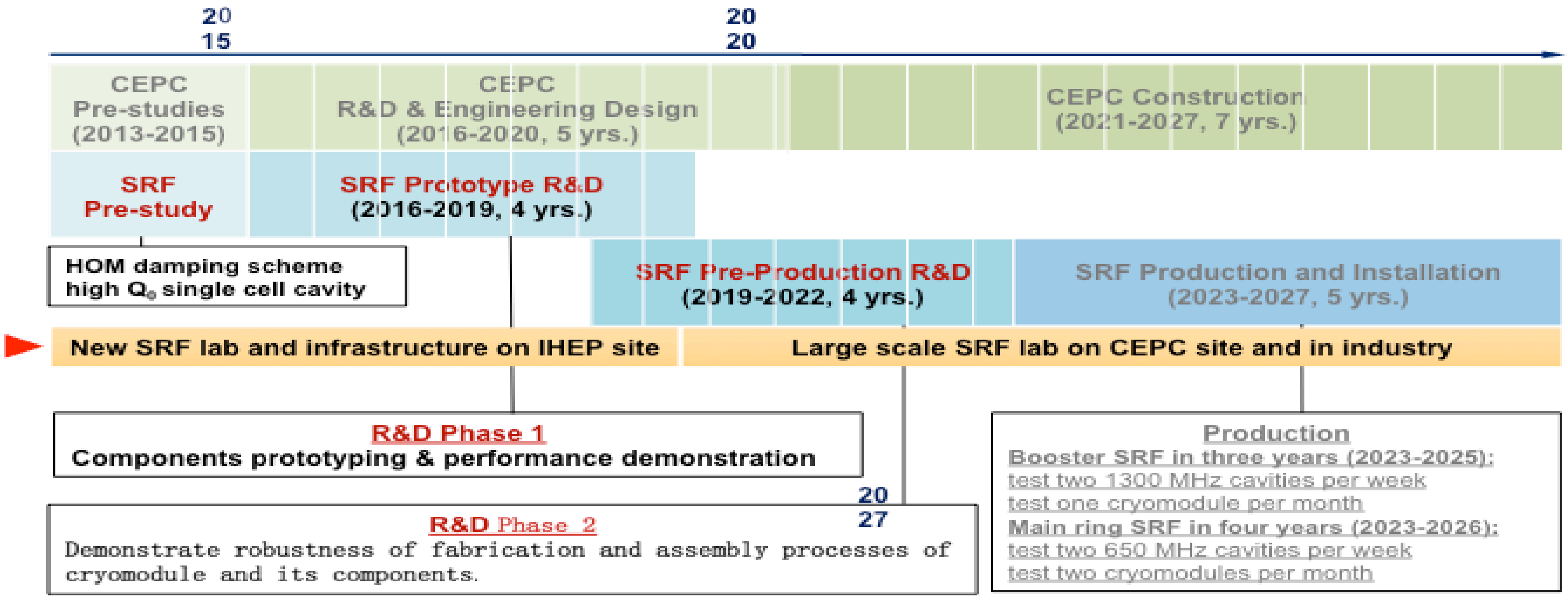


CEPC Single Ring DA Study (Y.W. Wang et al)







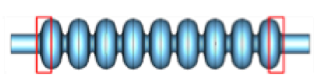


Parameters	CEPC-Collider	CEPC-Booster
Cavity Type	650 MHz 5-cell Nitrogen-doped Nb	1.3 GHz 9-cell Nitrogen-doped Nb
Operating E_{acc}	15.5 MV/m	19.3 MV/m
Operating Q_0	4E10 @ 2K	2E10 @ 2K
Cavity vertical test qualification	20 MV/m @ 4E10	23 MV/m @ 2E10
Input coupler power (CW)	320 kW	20 kW (DF 20%)
HOM damper power (CW)	10 kW ferrite + 1 kW hook	50 W (hook + ceramic)
Cavity number	384	256
Cryomodule number	96 (4 cav. / module)	32 (8 cav. / module)

CEPC Booster 1.3 GHz Cryomodule

Euro-XFEL/ILC/LCLS-II type

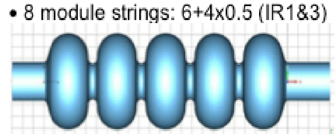
- 8 1.3 GHz 9-cell cavities per module
- 2 HOM couplers per cavity
- 1 beamline HOM absorber at 70 K
- module length: 12 m (no SCQ)
- 4 modules per module string connect without cryo & vac interval
- module string length: 48 m
- 8 module strings: 6+4x0.5 (IR1&3)

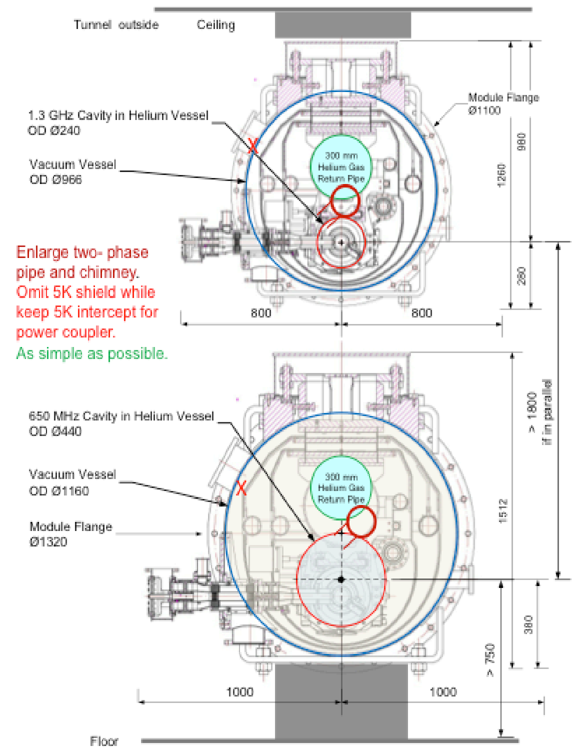


CEPC Collider 650 MHz Cryomodule

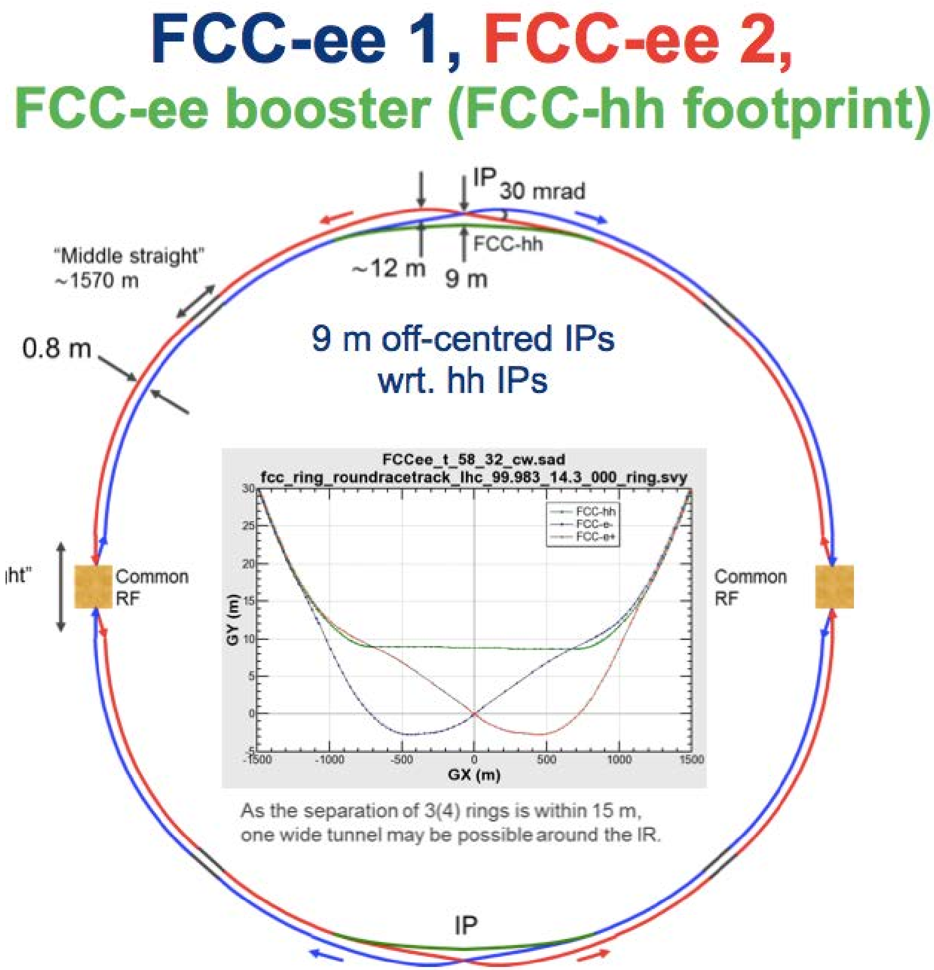
scaled from 1.3 GHz cryomodule

- 4 650 MHz 5-cell cavity per module
- 2 HOM couplers per cavity
- 2 beamline HOM absorbers at RT
- module length: 10 m
- 12 modules per module string
- module string length: 120 m
- 8 module strings: 6+4x0.5 (IR1&3)

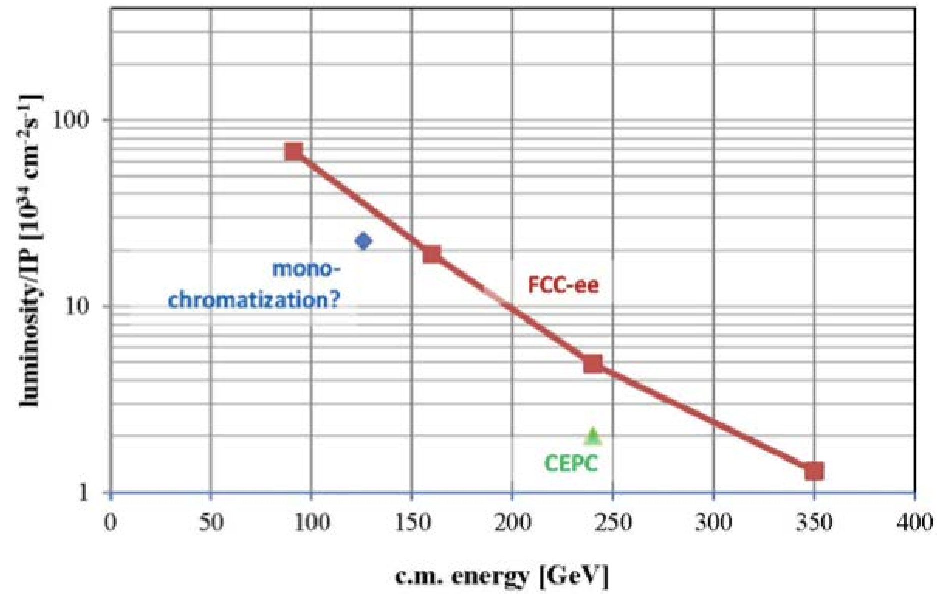




FCC-ee



As the separation of 3(4) rings is within 15 m, one wide tunnel may be possible around the IR.



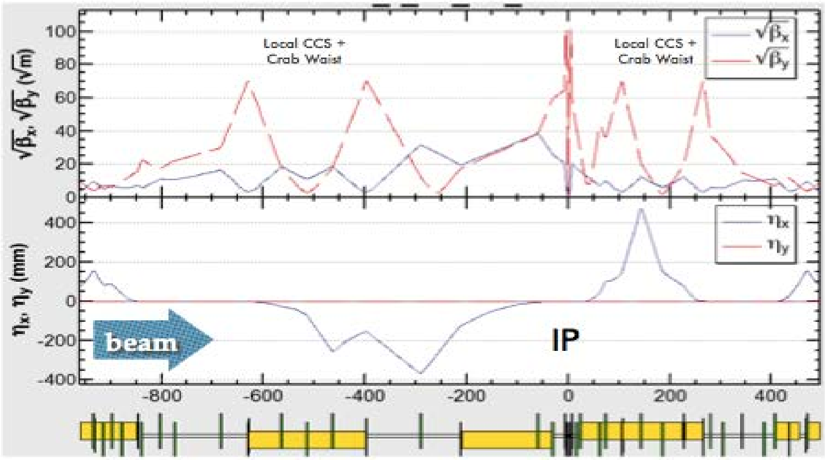
parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} cm^{-2}s^{-1}	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

FCC-ee: 2 separate rings & 2 IPs

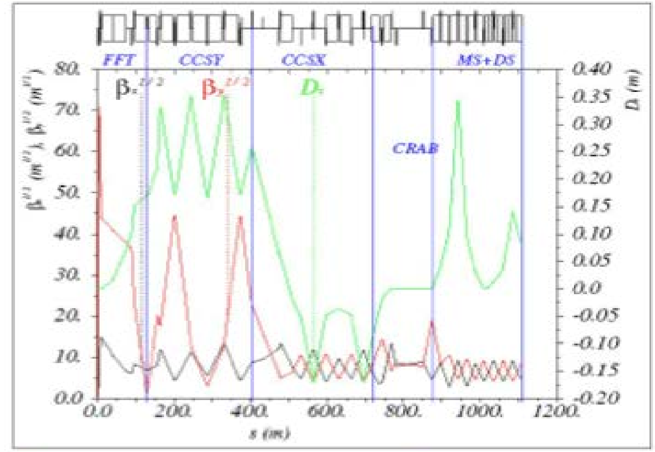
CEPC: single beam pipe version

Interaction Regions: KO 58_32

AB v. 8-1 ($\beta_x^* = 1$ m, $\beta_y^* = 2$ mm)



Synchroton radiation $E_{\gamma,c}$≤100 keV



Synchrotron radiation $E_{\gamma,c}$≤400 keV

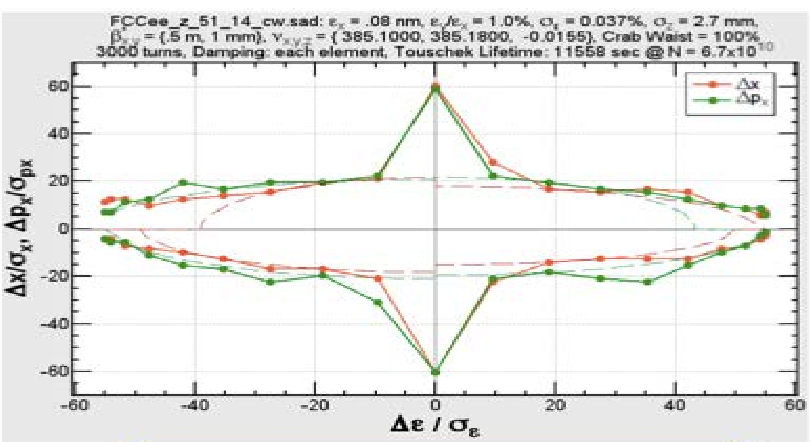
2 IPs		Z 45,5 GeV	W 80 GeV	ZH 120 GeV	tt 175 GeV
Luminosity	10^{34} cm^{-2}s^{-1}	~140	~42	~10	~4

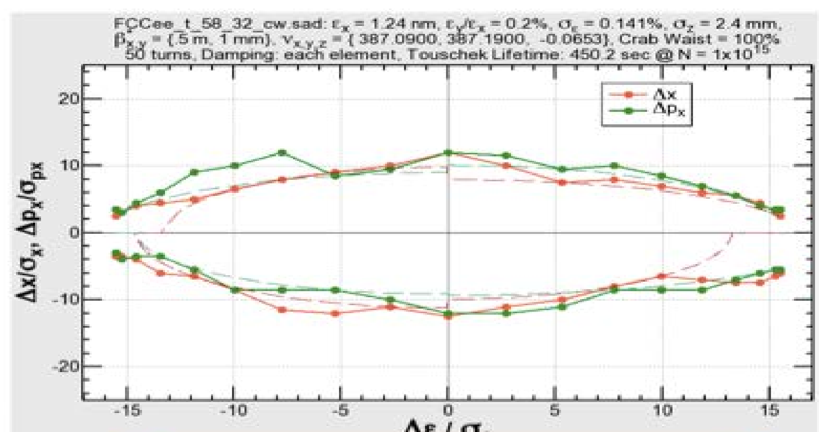
Dynamic Apertures (KO)

$\beta_{x,y}^* = (0.5\text{ m}, 1\text{ mm})$

$E_{\text{beam}} = 45.6$ GeV
3,000 turns

$E_{\text{beam}} = 175$ GeV
50 turns





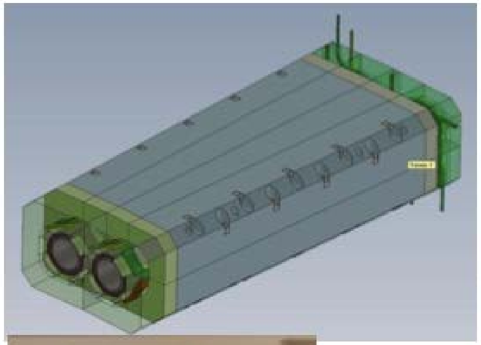
±2%

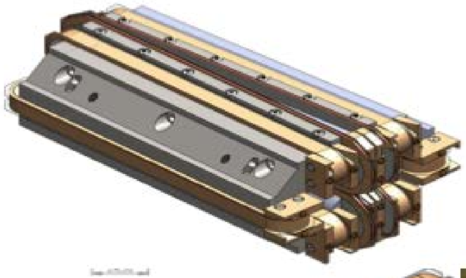
±2%

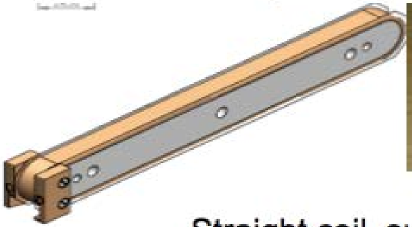
SC final focus quadrupole at BINP

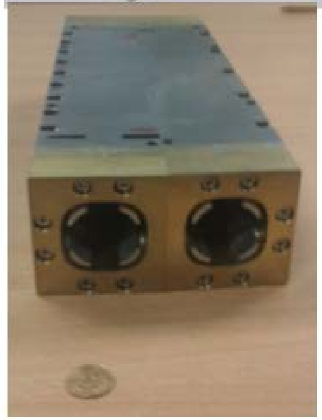
Main contributors are Ivan Okunev and Pavel Vobly

Two versions of the FF twin-aperture iron yoke quad prototype with 2 cm aperture and 100 T/m gradient are in production.









Saddle-shaped coils, complicated in production, the first coil failed. New winding device is in development.

Straight coil, successfully wound and tested (650 A instead of the nominal 400 A)

Also prototyping of CCT quadrupoles has started at CERN (M. Koratzinos, G. Kirby).

E. Levichev

Challenges in e+e- circular collider

- Luminosity – beamstrahlung dominated

$$\mathcal{L} = \frac{3}{8\pi} \ldots \xi_y \ldots \qquad \mathcal{L} = const \times \ldots \quad r_e^{2}\ P_{tot}\ \rho/E_0^{3}$$

The maximum luminosity is bound by the total power dissipated, the maximum achievable beam-beam parameter, the bending radius, the beam energy, the amount of vertical squeezing β_y^* , and the hourglass effect, a geometrical factor (which is a function of σ_z and β_y^*)

$$\mathcal{L} = 6.0\times10^{34} \left(\frac{P_{tot}}{50MW}\right)\left(\frac{\rho}{10km}\right)\left(\frac{120GeV}{E_0}\right)^{3}\left(\frac{\xi_y}{0.1}\right)\left(\frac{R_{hg}}{0.83}\right)\left(\frac{1mm}{\beta_y^*}\right) cm^{-2}\, s^{-1}$$

- Power consumption

For 100MW beam power:

	CEPC[1]	TLEP[2]
RF	250	180
Cryogenics	20	30
Power converters	90	20
Rest (cooling, ventilation, general services)	130	90
total	500MW	310MW

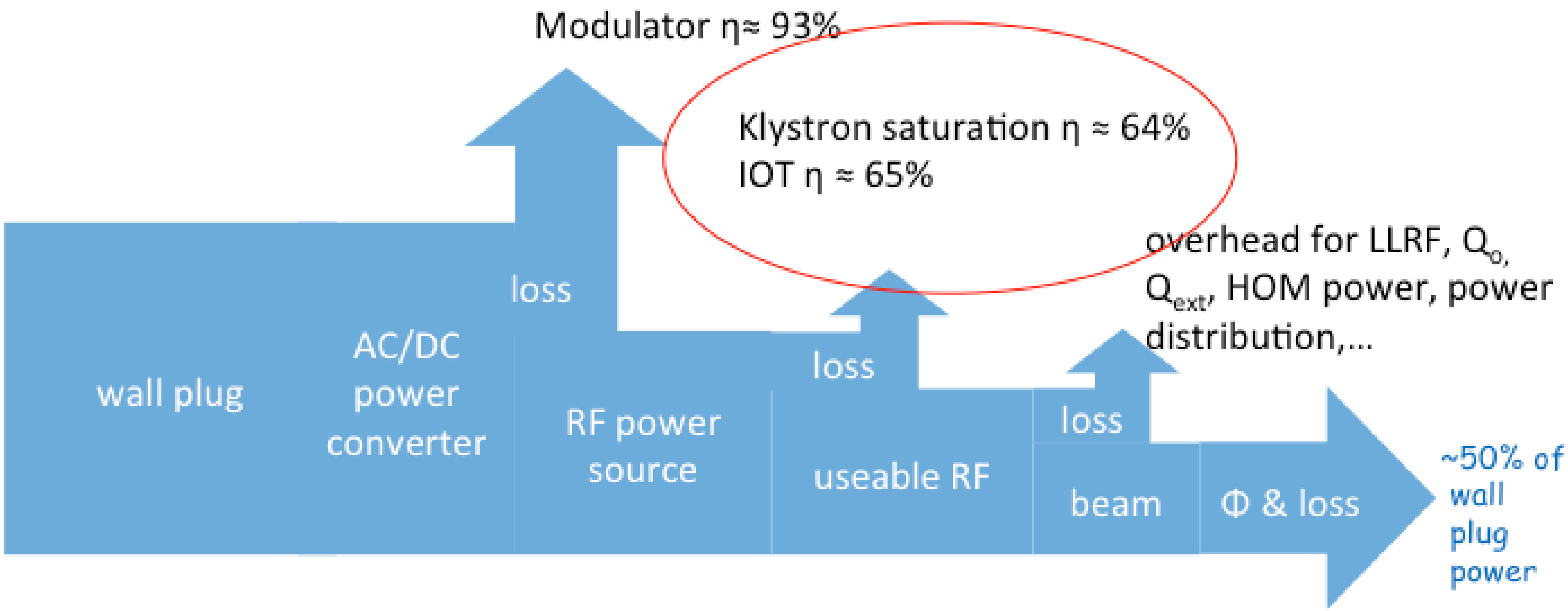
FCC-ee: no official value released yet

(1) W. Chou, Future Circular Colliders and R&D, EPS-HEP Conference July 22-29, 2015, Vienna, Austria

(2) TLEP power consumption in arXiv:1308.2629 [physics.acc-ph] and arXiv:1305.6498 [physics.acc-ph]

A big chunk is RF power consumption

RF power consumption

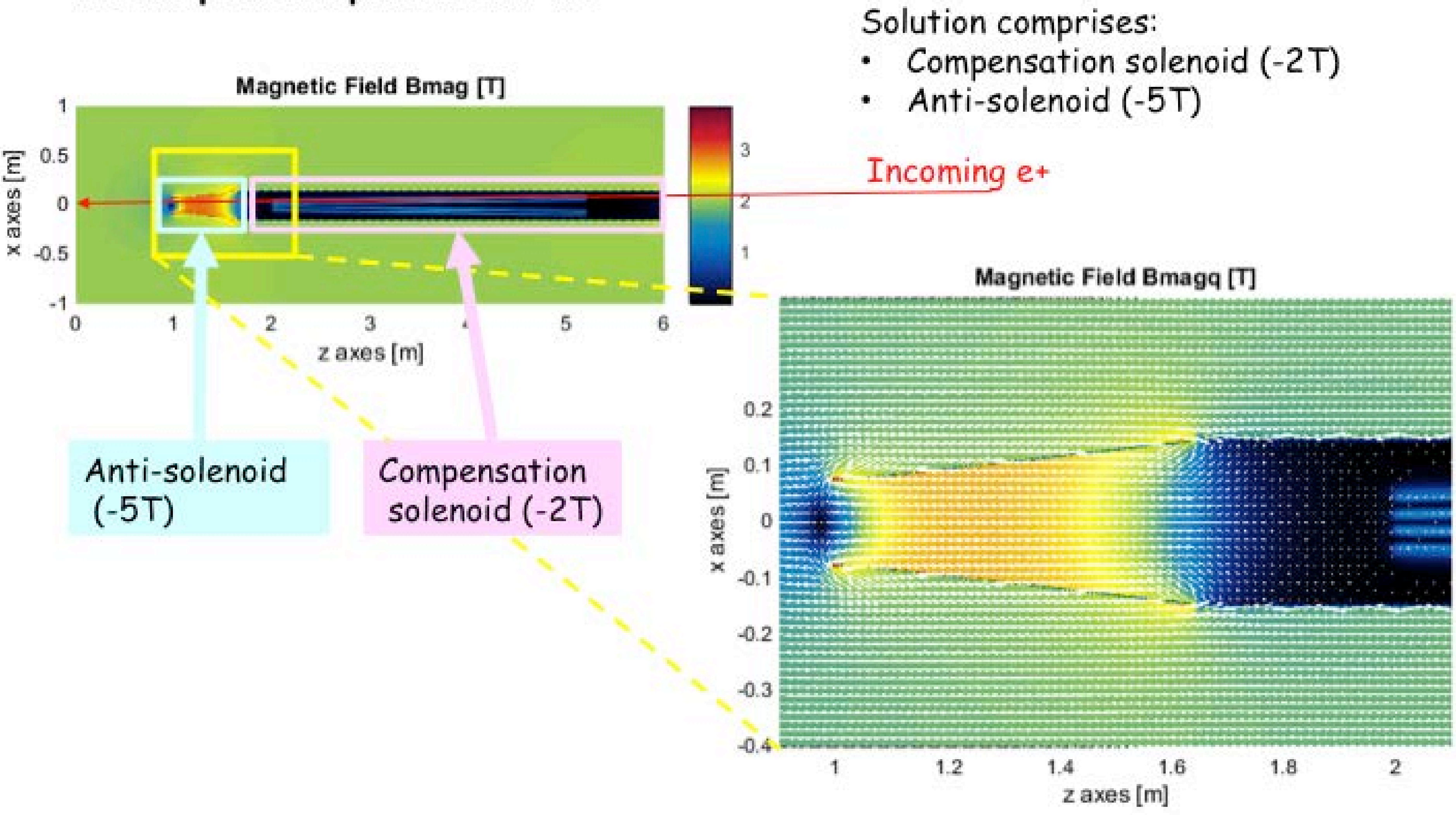


One single efficiency that, if improved, would have the largest impact: RF power source efficiency

- **Klystron efficiency currently ~65%, R&D to take this to ~90%**
- Other technologies: IOTs (inductive Output Tube), Solid state amplifiers

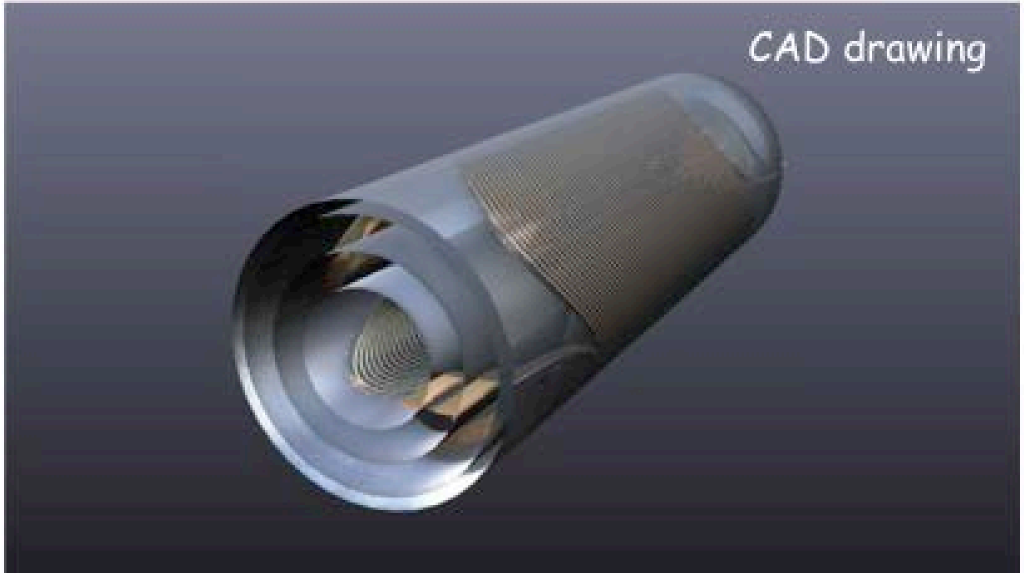
• IR design – a promising solution

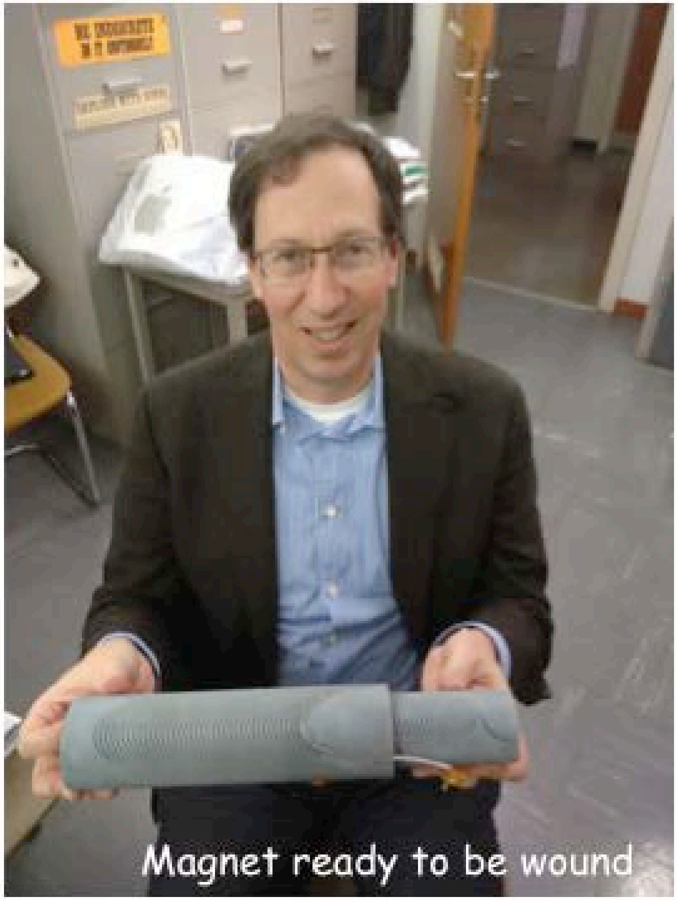
- Various layouts tried, the following gives best performance: **emittance blow up of 0.11pm for two IPs**



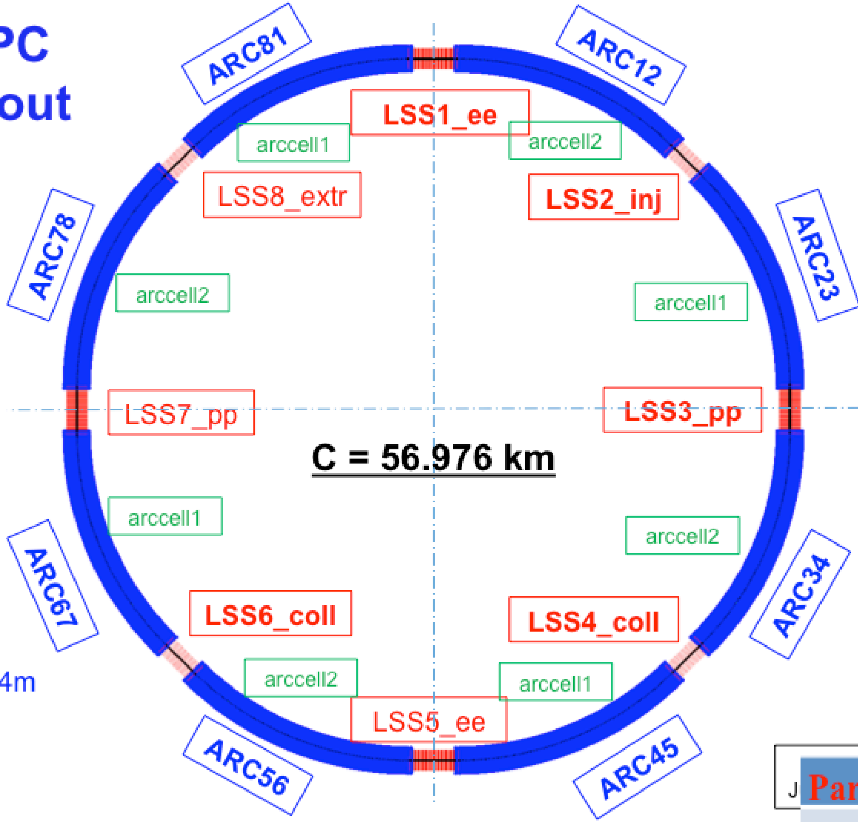
First piece of hardware of FCC-ee at CERN

- Prototype FCC-ee final focus magnet – 20cm length
- Will be wound with available NbTi cable (cross section $4mm^2$)
- Fast prototyping: 3D printed in 'bluestone'
- Real magnet will be ~3m long





SPPC Layout



LSS1/5

1107m

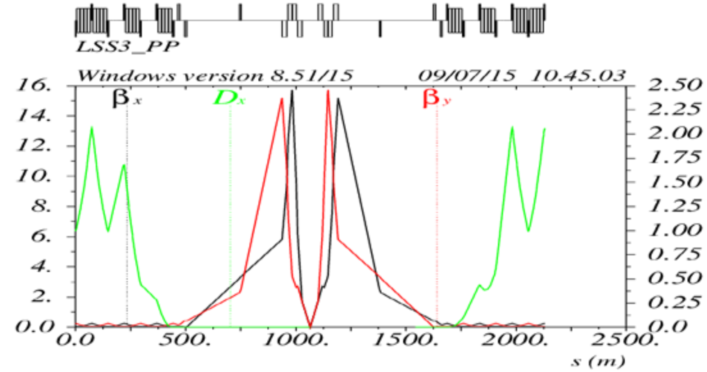
LSS2/4/6/8

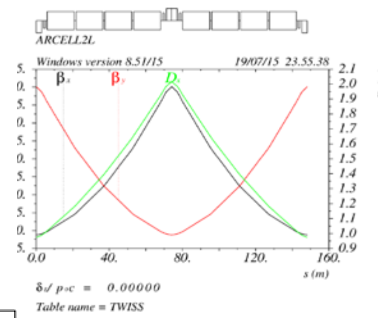
959.4m

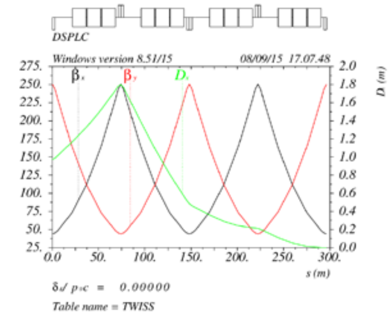
LSS3/7

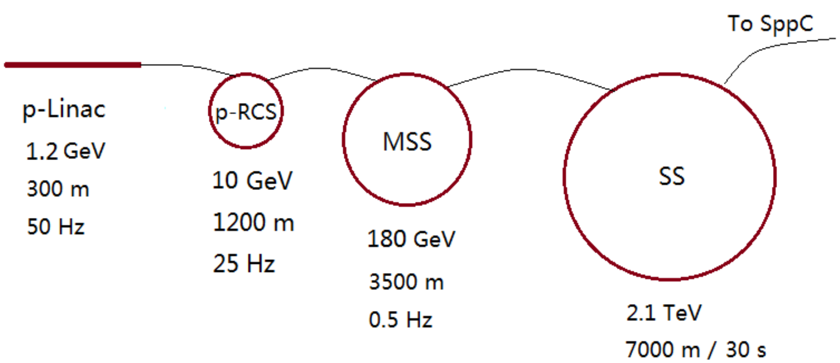
1244m

ARC 6077.84m







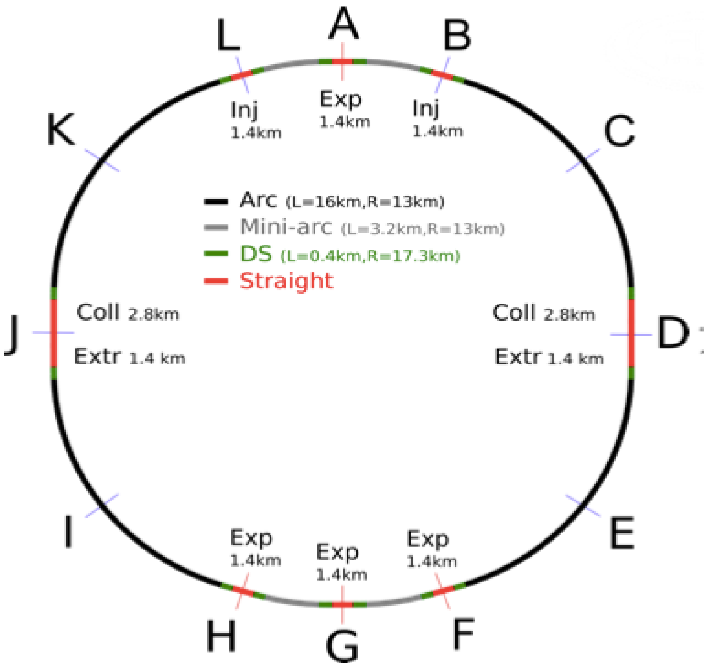


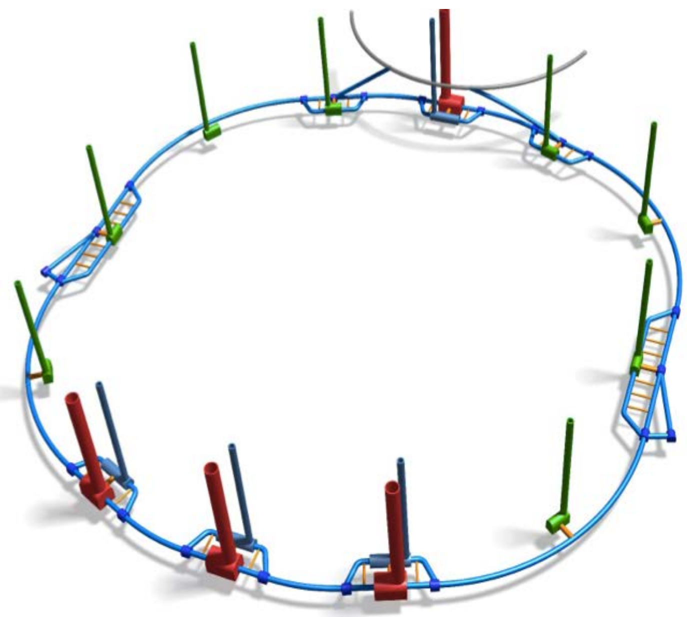
Parameter	Value	Unit
Circumference	54.36	km
C.M. energy	70.6	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.1E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Nominal beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56.9	W/m

Key technologies

- High-field SC magnets: 20 T dipoles
- Beam screen & vacuum: decrease SR heating
- Beam instrumentation & control
- Machine protection
- SC RF system
- Cryogenics

FCC-hh

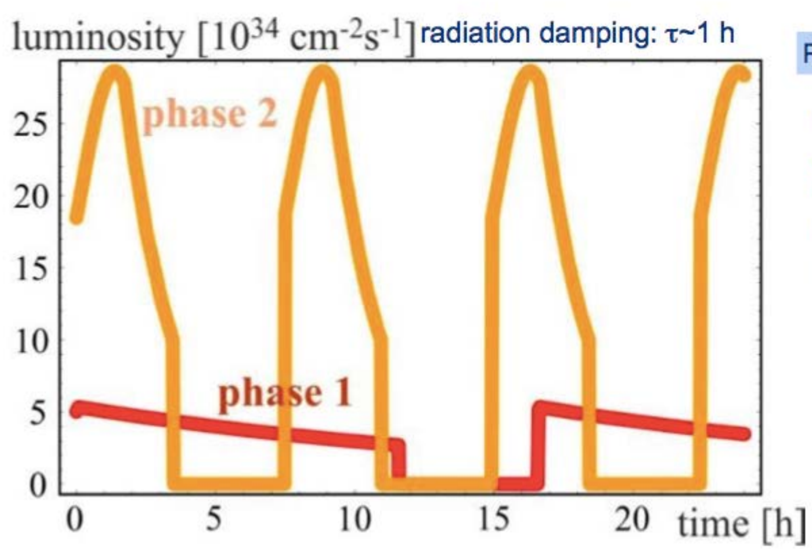




Parameter	FCC-hh		SPPC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main & 2		2	2 main & 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/Ip [10^{34} $cm^{-2}s^{-1}$]	5	~25	12	1	5
events/bunch crossing	170	~850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
synchrotron radiation [W/m/aperture]	30		58	0.2	0.35

phase 1: β^*=1.1 m, ΔQ_{tot}=0.01, t_{ta}=5 h, 250 fb^{-1} / year

phase 2: β^*=0.3 m, ΔQ_{tot}=0.03, t_{ta}=4 h, 1 ab^{-1} / year



PRST-AB 18, 101002 (2015)

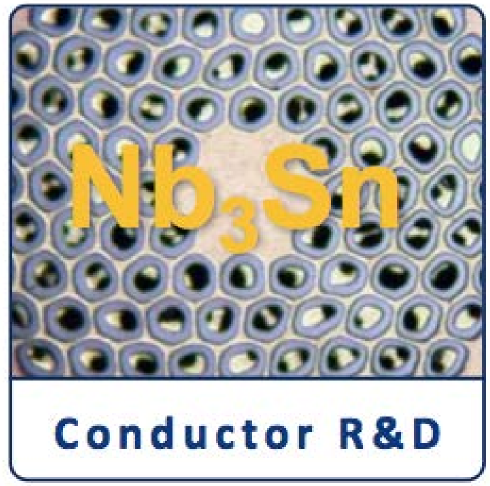
for both phases:

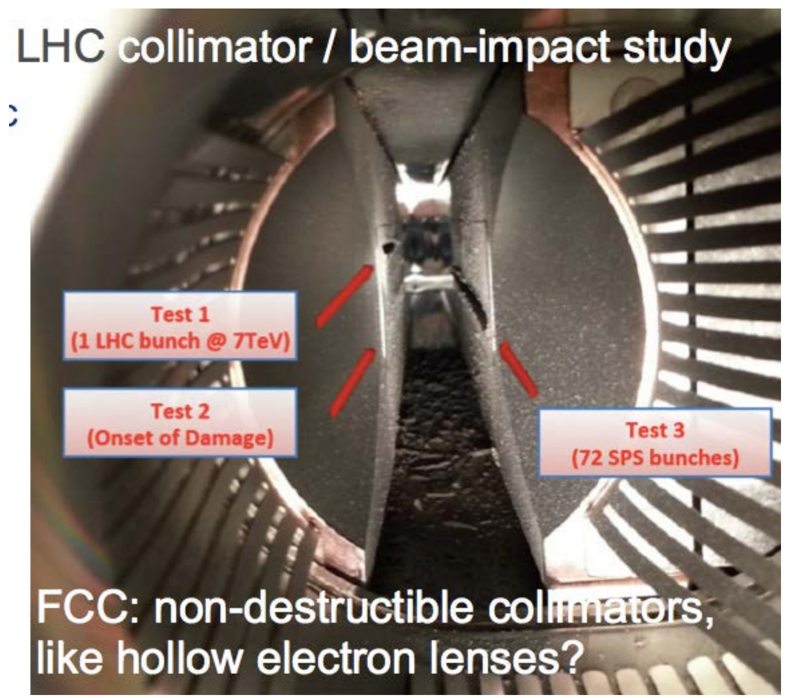
beam current 0.5 A

total synchrotron radiation power ~5 MW.

consistent with physics goal: 20 ab^{-1} in total

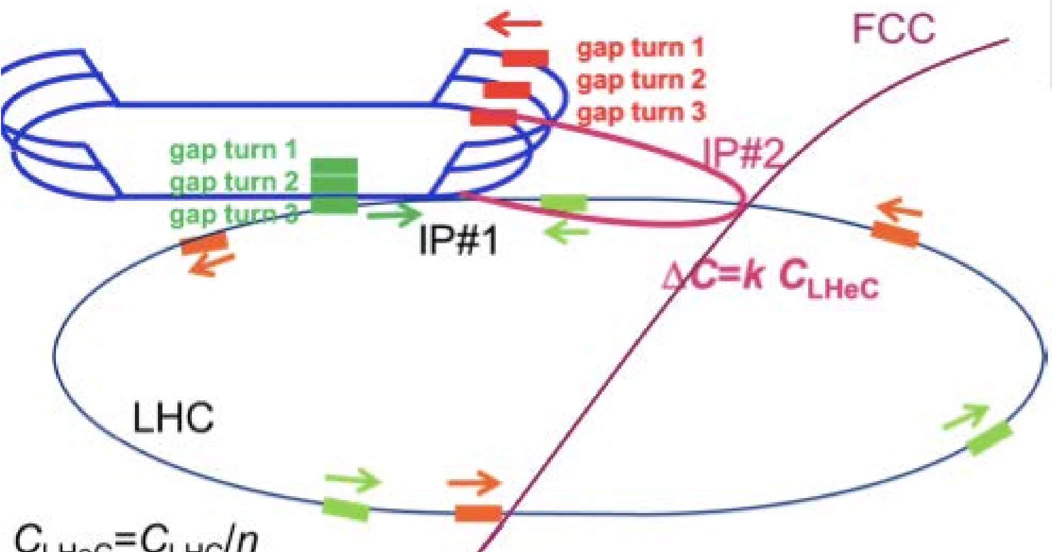
Key Technologies





FCC-he collider

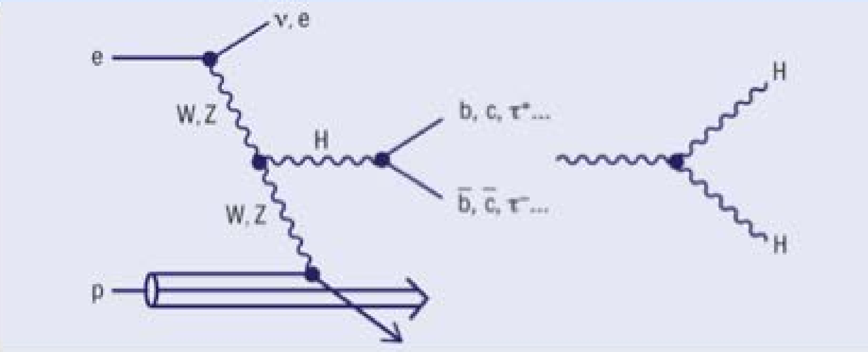
e⁻ from ERL, reusing the "LHeC";
LHeC CDR published in J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)



$C_{LHeC}=C_{LHC}/n$

future: $C_{LHeC}=pC_{FCC}/m$

m, *n* (=3 or 4), *k*: integer
p = 1 or 2



- ***h-e* Higgs-boson production and decay**
- ***H–bb* coupling** in ***WW–H* production**;
- **Higgs self-coupling *H–HH*** (<10% precision!? - under study), t
- **lepto-quarks up to ≈4 TeV**
- **Bjorken *x* as low as 10^{-7} - 10^{-8}** [of interest for ultra high energy ν scattering]

I_e~26 mA, $\sigma_{x,y}^*$~2 μm, luminosity/nucleon ~ 3×10^{34} $cm^{-2}s^{-1}$

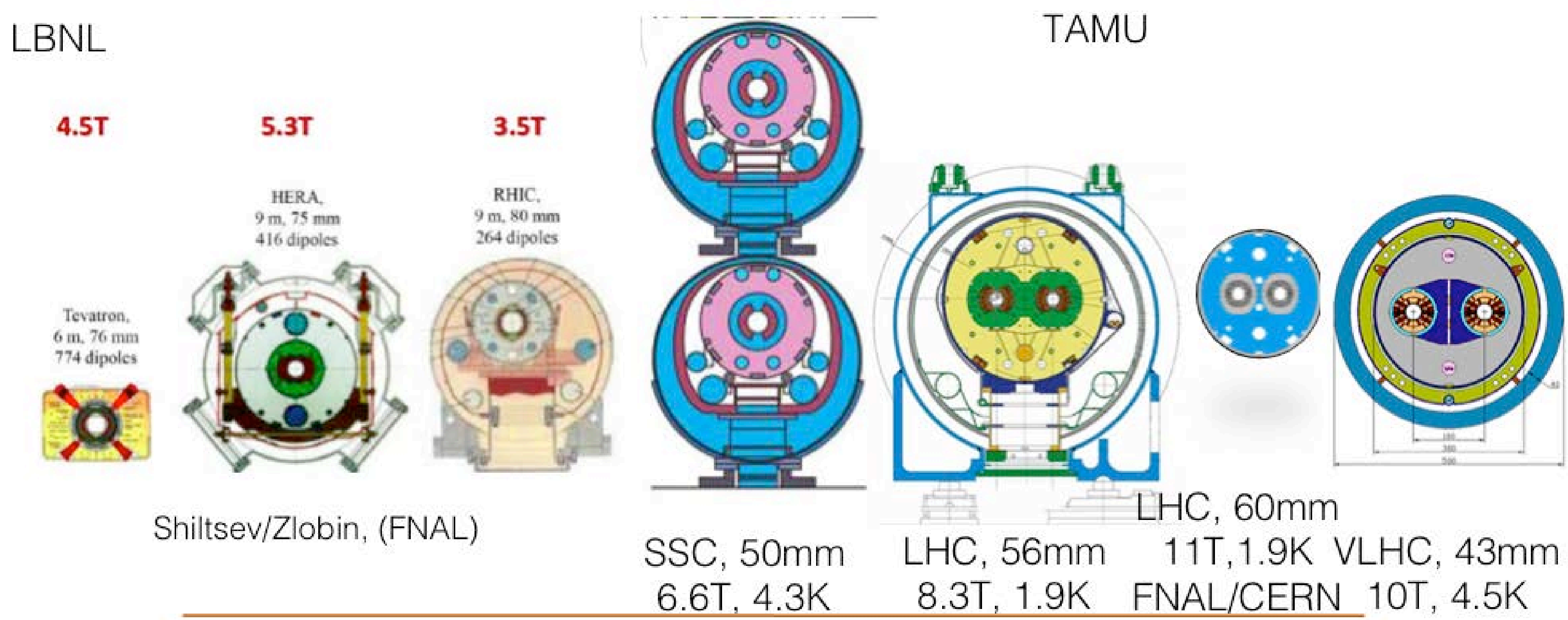
Challenges in pp collider

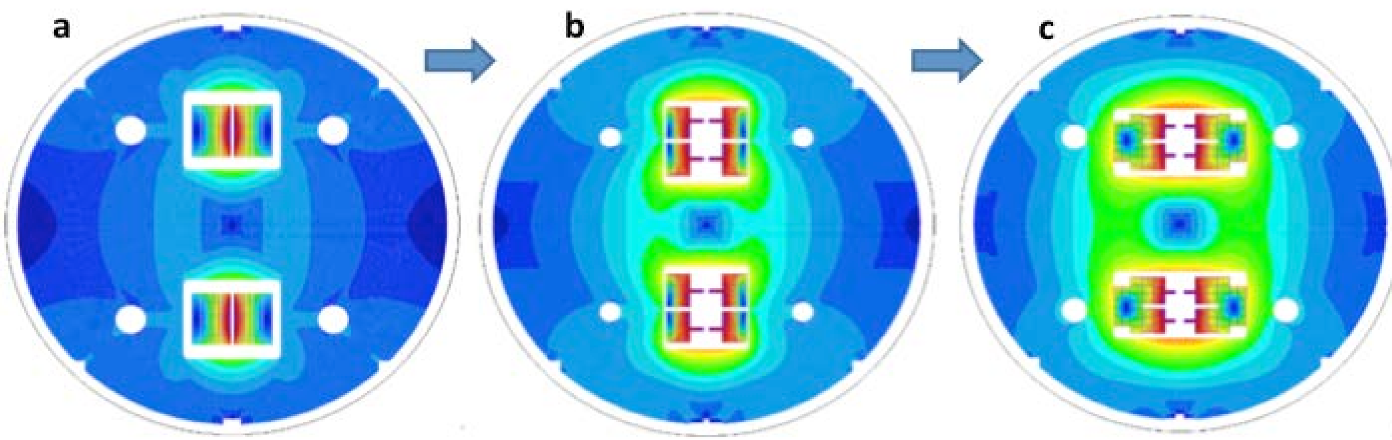
- Energy ($E \sim B\rho$) ⟶ **Money**
  - General agreement ~100 TeV
  - But we should look both above and below 100 TeV for new physics
  - The results from LHC and HL-LHC will inform the choices
  - A trade-off study of *B vs ρ* is going on at CERN, IHEP, and also at this workshop
- Luminosity ⟶ **Accelerator Physics**
  - There is no general agreement on the goal
  - Both FCC and SPPC aim at a reasonably achievable value close to HL-LHC (5e34 or 1.1 e35)
  - But should $L \sim E^2$ be a requirement? If so, what is the reference for this scaling?
  - W.r.t. HL-LHC (14 TeV, 5e34), this would require a 50-fold increase in L, or 2.5e36, corresponding to 7,000 events per crossing. (Scary!)
  - W.r.t. SSC (40 TeV, 1e33), 5e34 for a 100 TeV machine is more than enough.
- Cost:
  - Construction cost (< $xxB)
  - Operation cost (power consumption < 300 MW; as "green" as possible)

Main Technical Challenges

- Accelerator technology
  - SC magnet (increasing performance and decreasing costs)
  - Synchrotron radiation and beam screen (reducing power consumption)
  - Collimation (machine protection)
- Accelerator physics
  - IR design, low β_y^*, dynamic aperture
  - Synchrotron radiation, heat load and radiation damage lifetime
  - Beam-beam
  - e-cloud
  - Impedance and instabilities
  - Ground motion
  - MDI and background
  - Machine reliability
  - Cooling
- Non-technical:
  - Government strategic plan for S/T investment
  - Support from both HEP and non-HEP scientists

High-field SC magnet





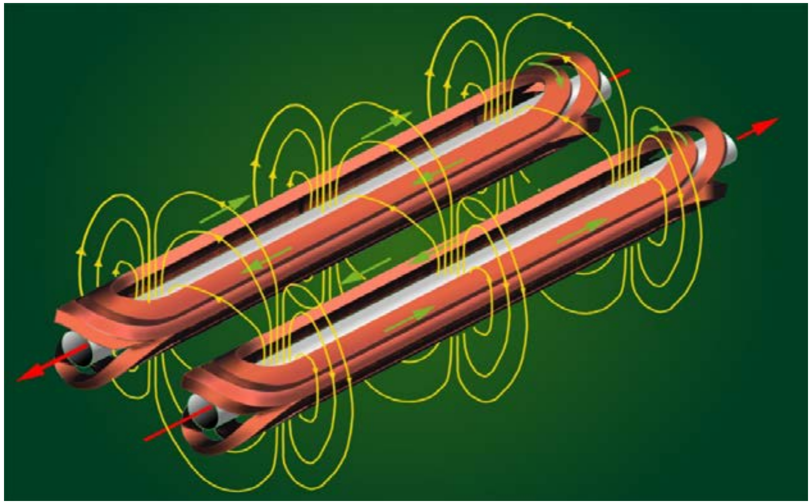
R&D Steps for SPPC Dipole Magnets

Comparison of different coil configurations

Efficiency, field quality, stress management, fabrication method…

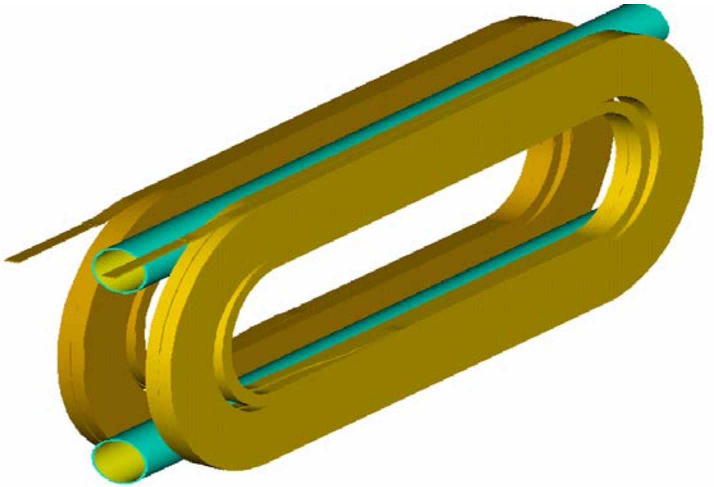
Cos-**th**eta dipole

Higher efficiency, complicated ends with hard-way bending



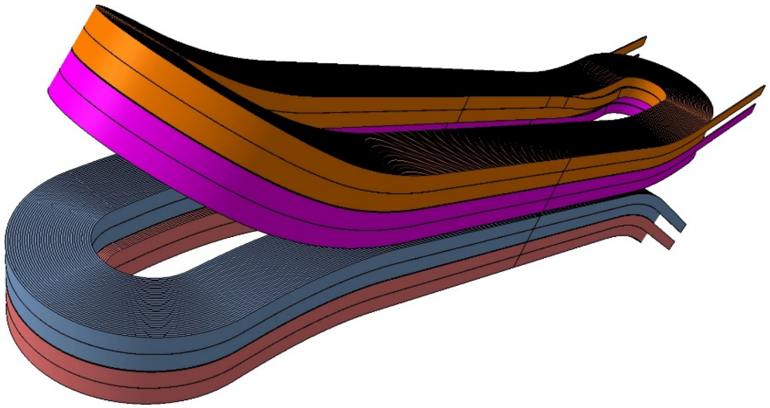
Common coil dipole

Simplest structure with large bending radius, lower efficiency



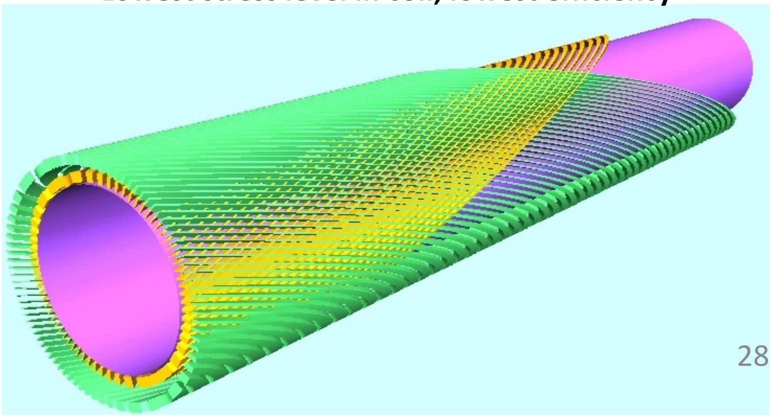
Block type dipole

Simpler structure with hard-way bending, lower efficiency



Canted cos-theta dipole

Lowest stress level in coil, lowest efficiency



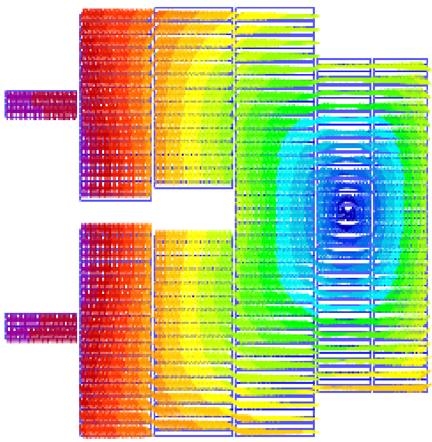
R&D Steps for SPPC Dipole Magnets

Comparison of different coil configurations

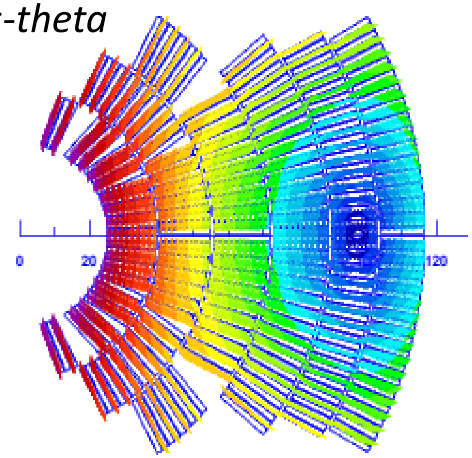
Common coil vs Cos-theta

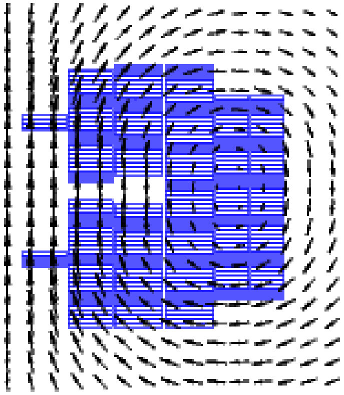
C. Wang et al.

Common coil



Cos-theta



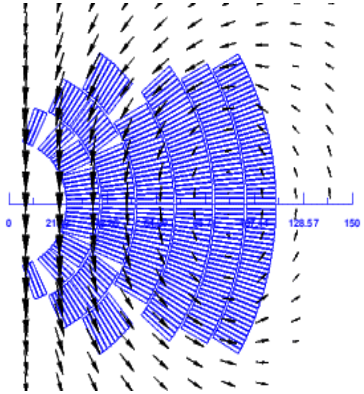


Common coil

Different coil configurations for 20-T dipole magnet

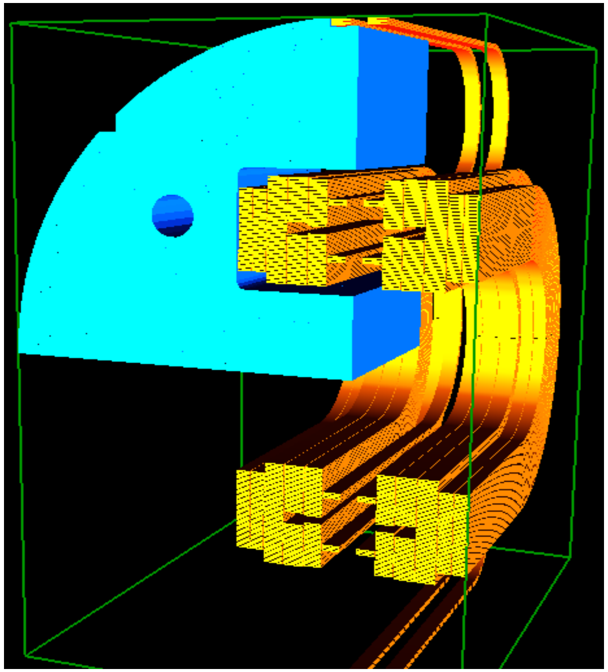
Left: Common coil

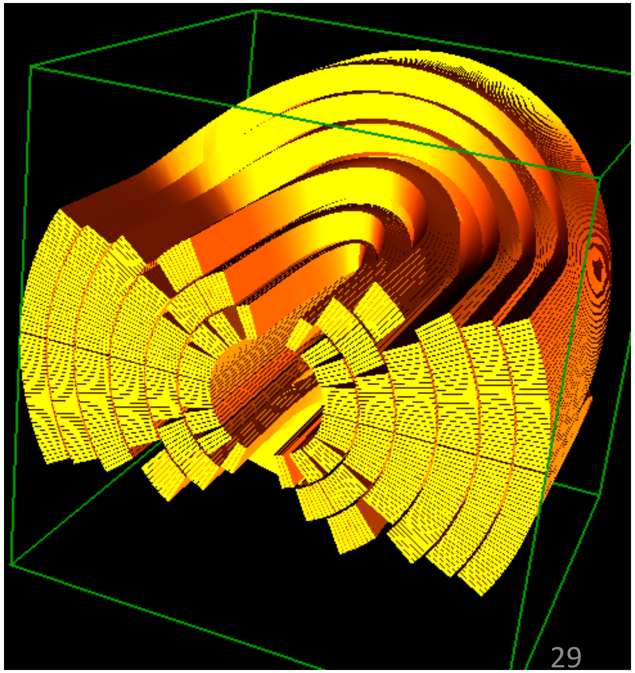
Right: Cos-theta



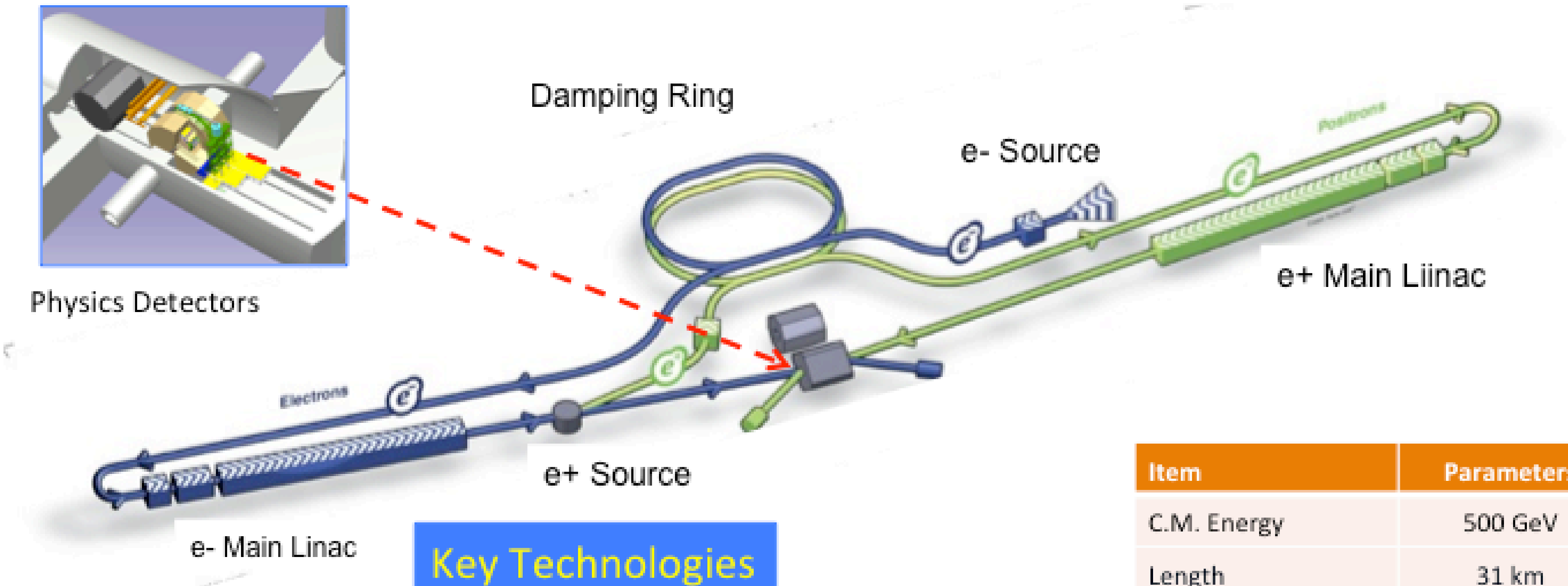
Cos-theta

Coil ends

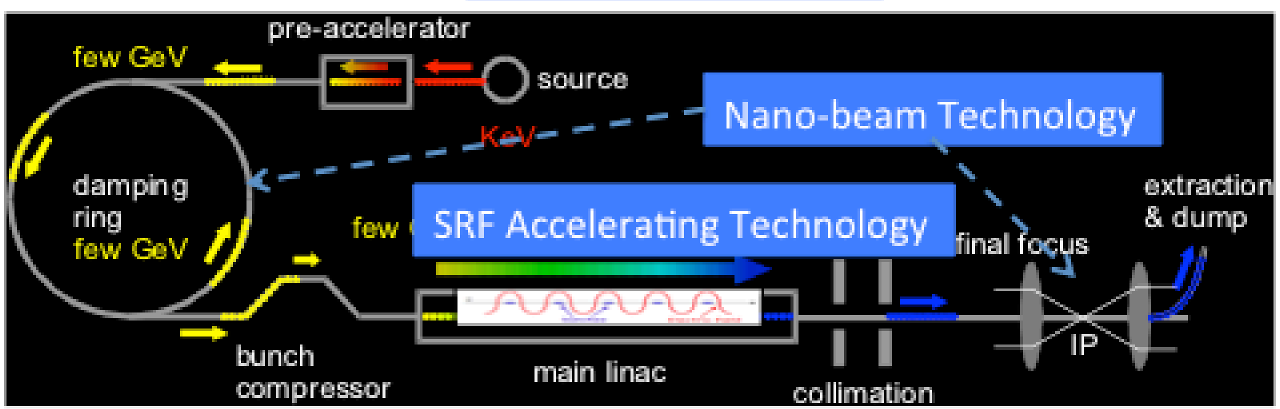




ILC/LCC



Key Technologies

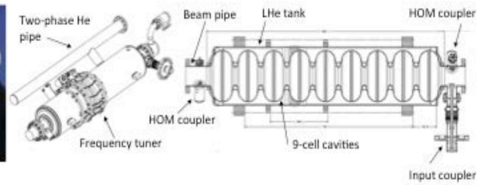


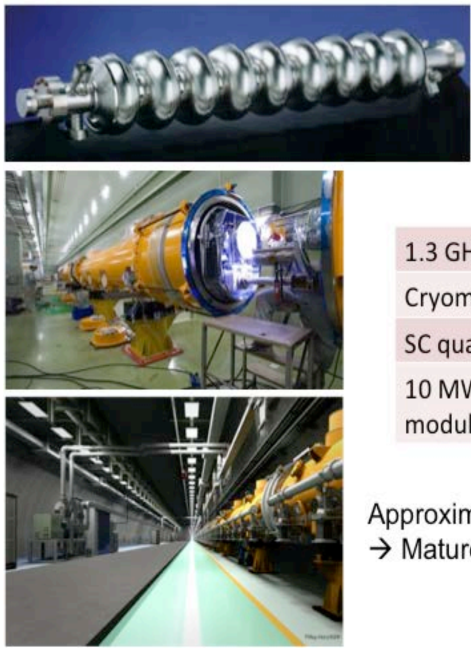
Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 $\times 10^{34}$ $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m $Q_0 = 1\times10^{10}$

Characteristics	Parameter	Unit	Demonstrated
SRF:			
Average accelerating gradient	31.5 (±20%)	MV/m	DESY, FNAL, JLab, Cornell, KEK,
Cavity Q_0	10^{10}		
(Cavity qualification gradient	35 (±20%)	MV/m)	
Beam current	5.8	mA	DESY-FLASH), KEK-STF
Number of bunches per pulse	1312		DESY
Charge per bunch	3.2	nC	
Bunch spacing	554	ns	
Beam pulse length	730	ms	DESY, KEK
RF pulse length (incl. fill time)	1.65	ms	DESY, KEK, FNAL
Efficiency (RF→beam)	0.44		
Pulse repetition rate	5	Hz	DESY, KEK
Nano-bam:			
ILC-FF beam size (y) KEK-ATF-FF equiv. beam size (y)	5.9 37 (44 reached)	nm nm	KEK-ATF

- **SRF** (→Report from H. Hayano)
  - **E-XFEL**: exceeded 90 % of 800 cavity production, and 65 % of 100 cryomodule assembly and testa, Excellent !! (→ Report from O. Napoli)
  - **Fermilab**-ASTA: reached the ILC specification gradient of ≥31.5 MV/m
  - **KEK**-STF2: CM1+2a (12 cavity string) under cold test, First 4 reaching> 35 MV/m
- **Nano-beam**
  - **ATF2 Collab.**: reached 44 nm at the FF, closing to the primary goal of 37 nm
- **CFS**
  - Geological Survey & boring at a candidate IP region in progress in Tohoku
  - Tunnel Optimization Tool (TOT) being developed by CERN/KEK-ARUP cooperation
- **Accelerator Design and Integration (ADI)**
  - Post-TDR design update (→ see The ILC Progress Report 2015)
    - **Common L*** for both detectors of ILD and SiD
    - **Vertical access** at Detector Hall at IR points
    - **Extension of ML tunnel length** for optimizing e+e- collision timing and redundancy of ML SRF

SCRF Linac



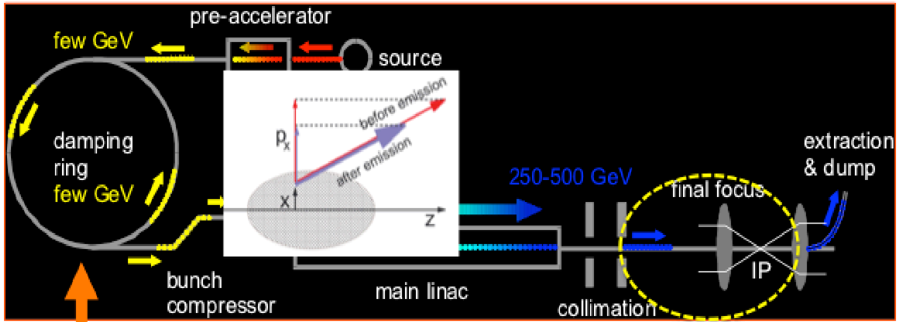


1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436 *

* site dependent

Approximately 20 years of R&D worldwide
→ Mature technology, overall design and cost

Nano-beam Technology

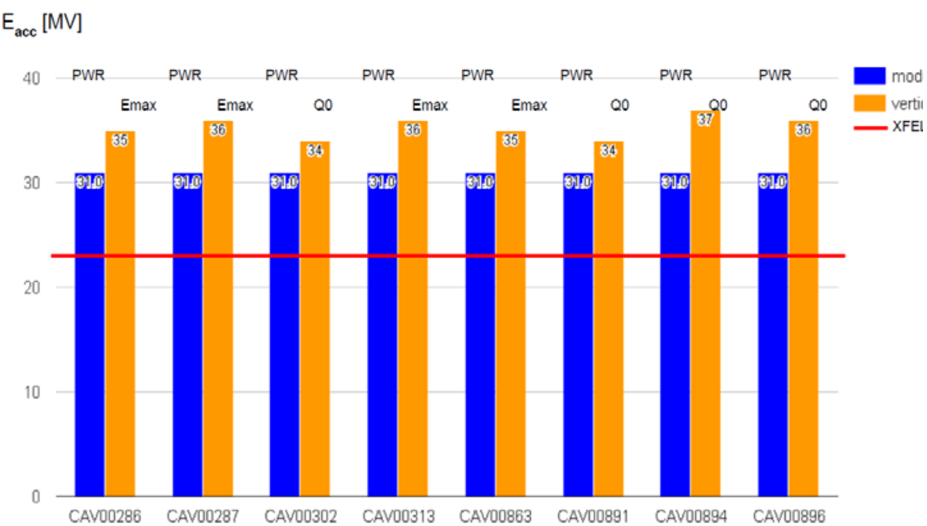


- Electron and Positron Sources (e-, e+) :
- Damping Ring (DR):
- Ring to ML beam transport (RTML) :
- Main Linac (ML) : SCRF Technology
- Beam Delivery System (BDS)

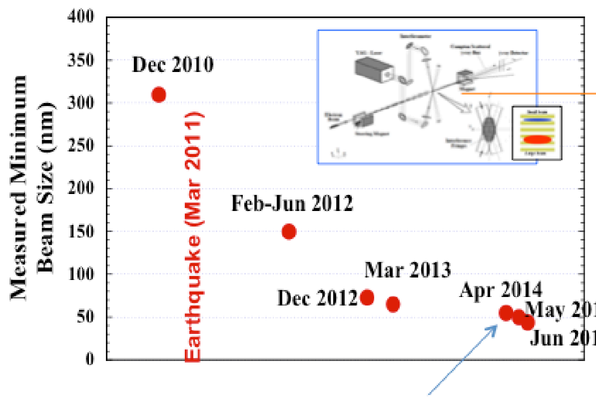
$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^*\sigma_y^*} \times H_D$$

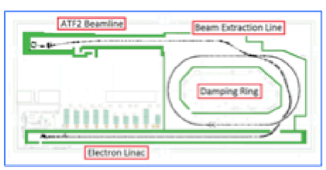
The nano-beam technology progressed with a global effort
Hosted at KEK (→ ATF Collaboration)

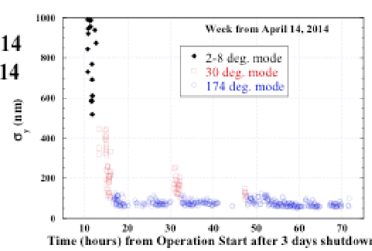
Cryomodule Operation



Progress in beam size at ATF2







Beam Size 44 nm observed,
(Goal : **37** nm
corresponding to **6** nm at ILC)

General Accelerator Physics issues for colliders (Seeman & Ohmi):

- **Lattices:**
  - x-y chromatic coupling in the IR is important: → skew sext.
  - Sextupole and skew quadrupole coupling corrections in IR
  - More studies of IR error tolerances needed.
- **Instabilities:**
  - e-cloud to allow more bunches.
- **Beam-Beam Calculations:**
  - Need mores studies of non-linear beam dynamics.
  - Parasitic crossing studies
- **Beam lifetimes:**
  - Short beam lifetimes (~10 min) with continuous top-off inj.
- **Tunes: half-integer for better collisions**
- **Crab cavities:**
  - Crab cavities tilt bunches as expected at IP.
  - Expected luminosity gains not, so far, fully achieved.
  - Must include dynamic β effect with respect to ring apertures.
  - Crab cavity trip rates need some additional study.

- **Large Piwinski Angle:**
  - Works in a collider.
  - Allows Θ_x >0.505
- **Crab waist:**
  - Crab waist can potentially improve the luminosity.
  - Effects of crab sextupoles on dynamic aperture needs work.
- **Round beams:**
  - Initial beam tests look promising.
  - Additional tolerance studies are needed.
- **Beamstrahlung**
  - Dominate the ring-based Higgs machine design
- **Polarized beam**

Key issues for future colliders (Seeman):

- IR design
  - 1 mm to 300 micron scale βy^*, large betas in IR quadrupoles, quadrupoles inside the detector, collision feedback, vacuum chamber design, magnet tolerances, alignment and jitter tolerances, crab cavities, crab waist
  - Test accelerators/facilities: SuperKEKB, CESR-TA, PETRA-3, vibration stabilization facility
  - Technologies:
    - 100+ Hz IP dither feedback on luminosity
    - Superconducting magnets
    - Permanent magnets
    - Power supply stability
    - Vibration control
    - Non-linear optics

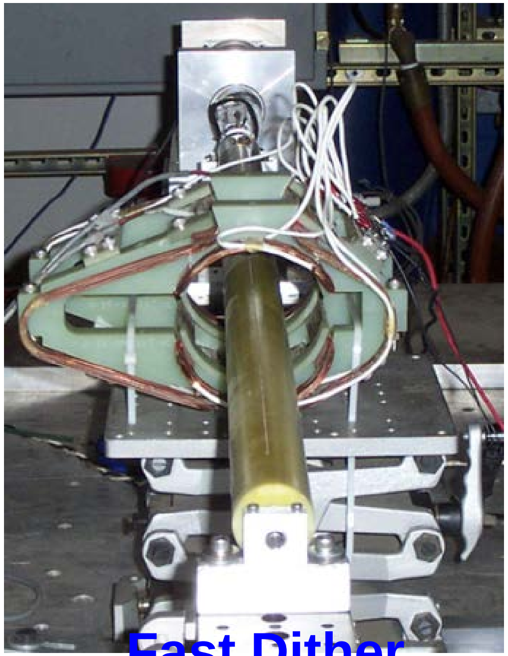
MDI

Key issue: Synchrotron radiation backgrounds, lost particle backgrounds, SR heating of vacuum chambers, radiation damage/lifetime of detectors, sensor occupancy, luminosity measurement.

Test accelerators/facilities: SuperKEKB, LHC, lab tests of high power vacuum chambers, lab tests of detector lifetime

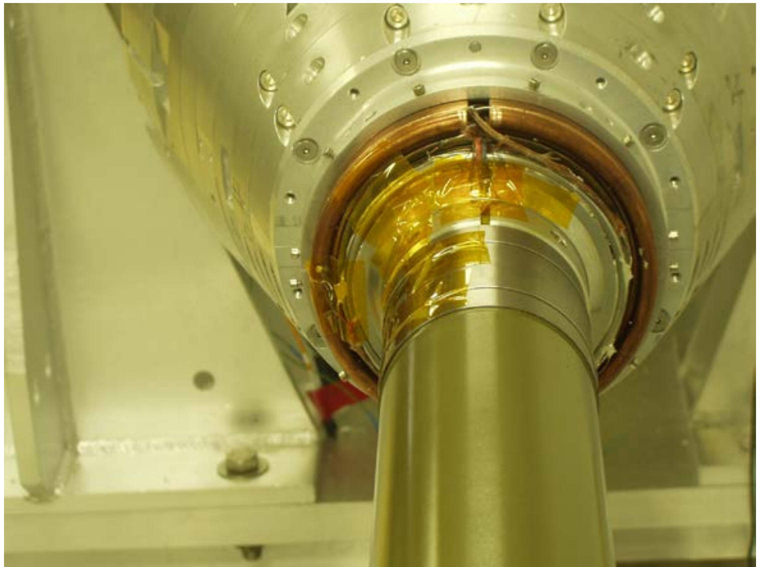
Technologies:

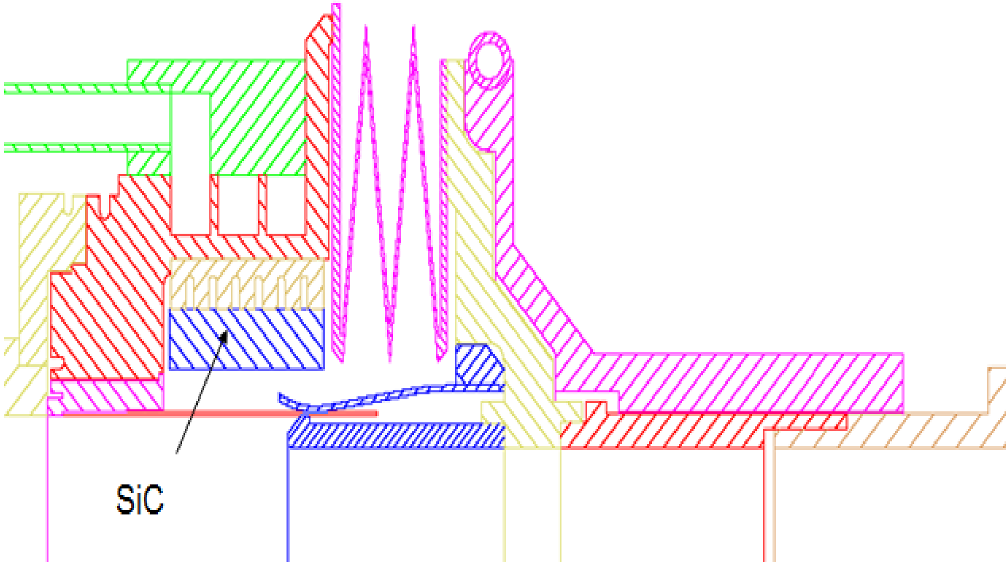
- IP vacuum pumping
- Advanced masking
- Rapid luminosity feedback
- Detector design



Fast Dither Feedback at SuperKEKB

IP Vertex Be Chamber Bellows Cooling at PEP-II





Low emittance

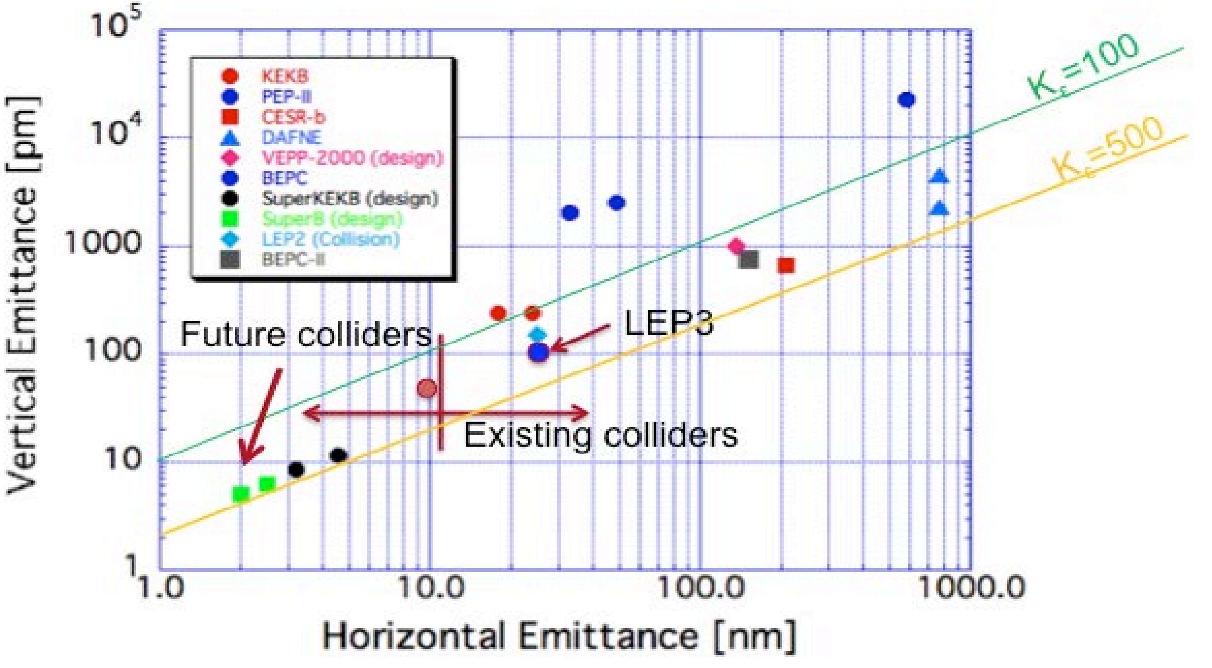
LEP2	3500
KEKB	940
SLC	500
FCC	*250*
CEPC	*150*
ATF2, FFTB	73 (35), 77
SuperKEKB	*50*
ILC	*5 – 8*
CLIC	*1 – 2*

Key issue: Component tolerances, vibration control, emittance measuring hardware, active feedbacks, field nonlinearities.

Test accelerators/facilities: SuperKEKB, PETRA-3, CESR-TA, NSLS-II, lab tests of x-ray size monitors

Technologies:

- 300 to1 emittance tuning techniques
- Coherent Synchrotron Radiation CSR simulations and measurements
- Fast Ion Instability FII simulations and measurements
- Intra-Beam Scattering IBS simulations and measurements
- Electron Cloud Instability ECI simulations and measurements
- Effects of spin rotators.
- Effects of beam-beam interaction on spin



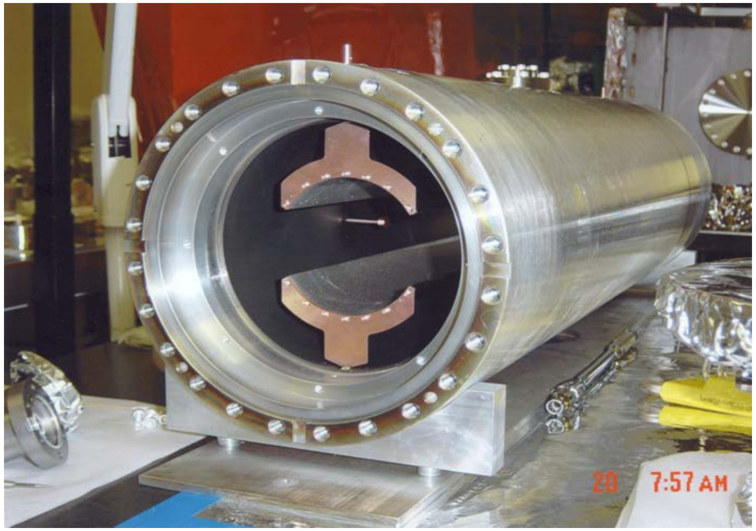
High current effects

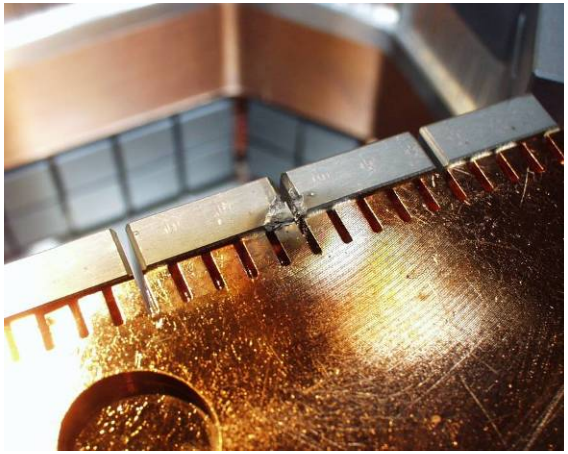
Key issues: Beam stability, high power RF, high power vacuum components, AC wall efficiency, injector capabilities, I> 1 A.

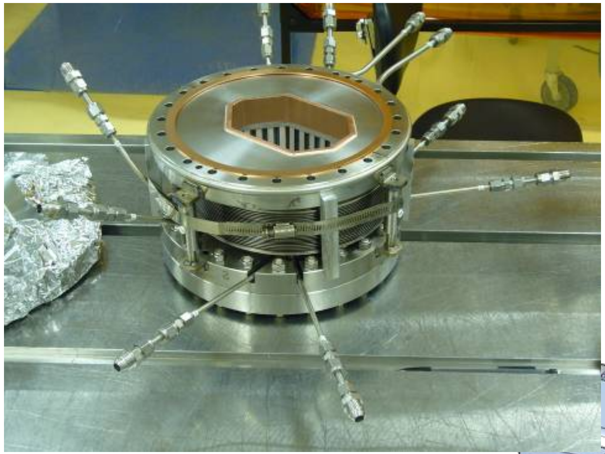
Test accelerators/facilities: SuperKEKB, CESR-TA

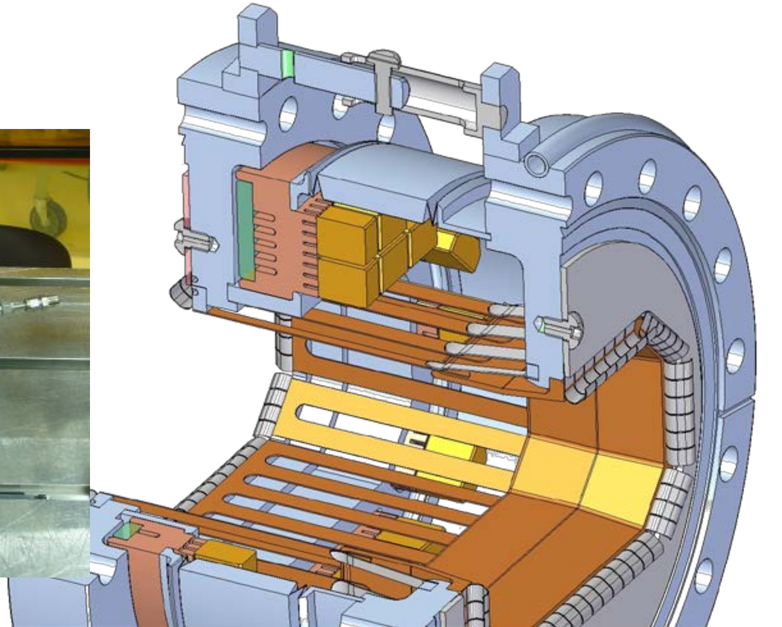
Technologies:

- Better bunch feedbacks
- Electron cloud instability control
- Intra-beam scattering mitigations
- Fast ion instability mitigations
- More efficient klystrons
- High power cavities
- Longitudinal beam feedback





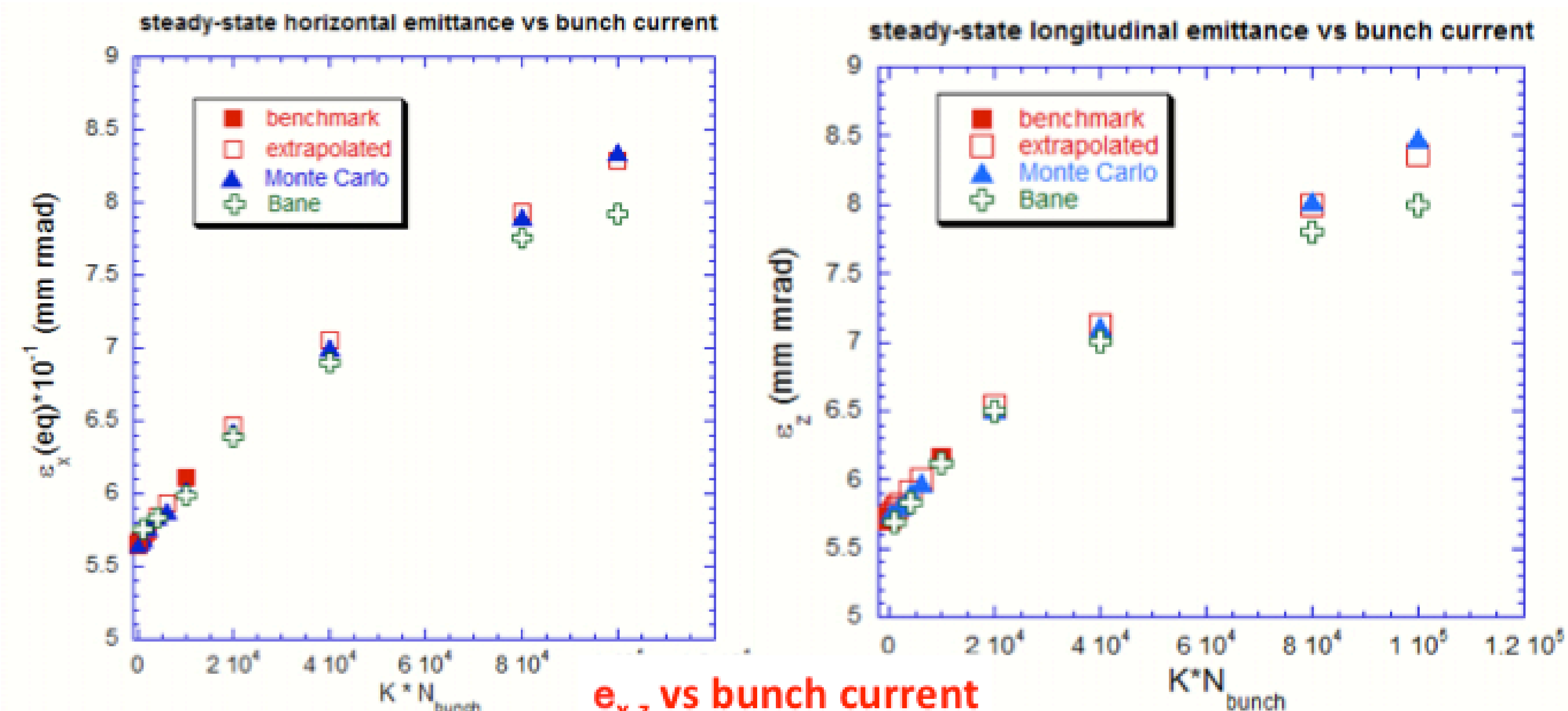




Intra-beam scattering

Three methods used, all in good agreement:

- Allows for emittance growth rates estimate and for emittance time evolution estimate
- 6D MonteCarlo → more accurate, all of above, will include non-gaussian tails



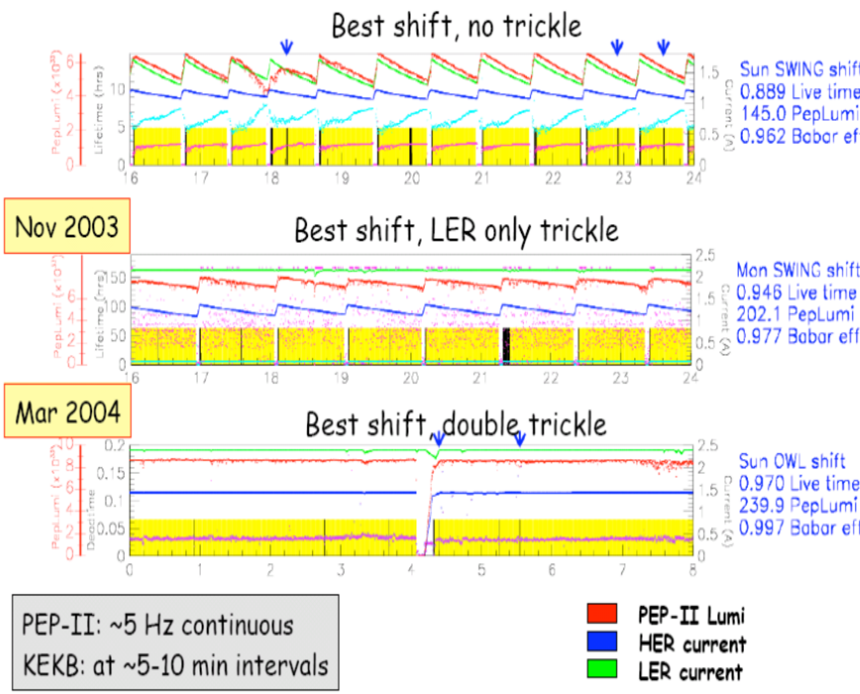
$e_{x,z}$ vs bunch current

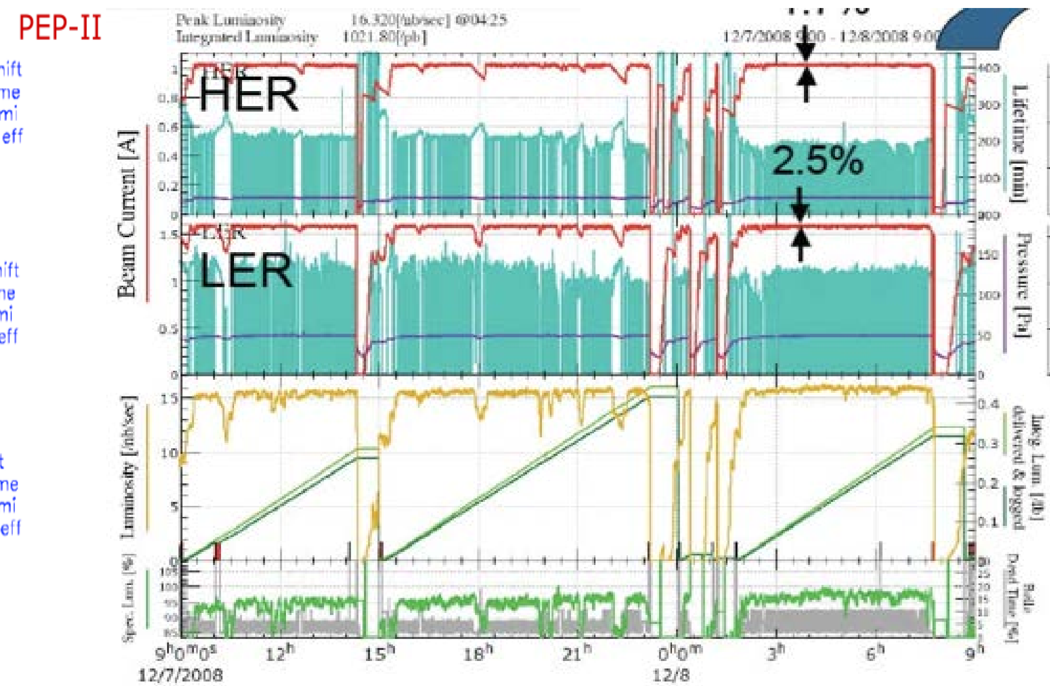
High Beam Power

- Higher currents and shorter bunches lead directly to much higher wake-field effects
  - HOM power and CSR
- Vacuum chamber impedances must be minimized
  - Causes bunch lengthening
  - Hard to do a lot better than present B-factories
- All components must be water-cooled
  - Again, difficult to do much better than present B-factories
- SR power levels increase with higher beam currents causing higher total beam losses
  - More RF power needed to restore the lost beam energy – more plug power

Beam lifetime

- Beam-beam, luminosity (Bhabha), beamstahlung, Touschek, vacuum, etc, determine the beam lifetime ~ 10 min or more.
- Full energy and top-off injection are required.

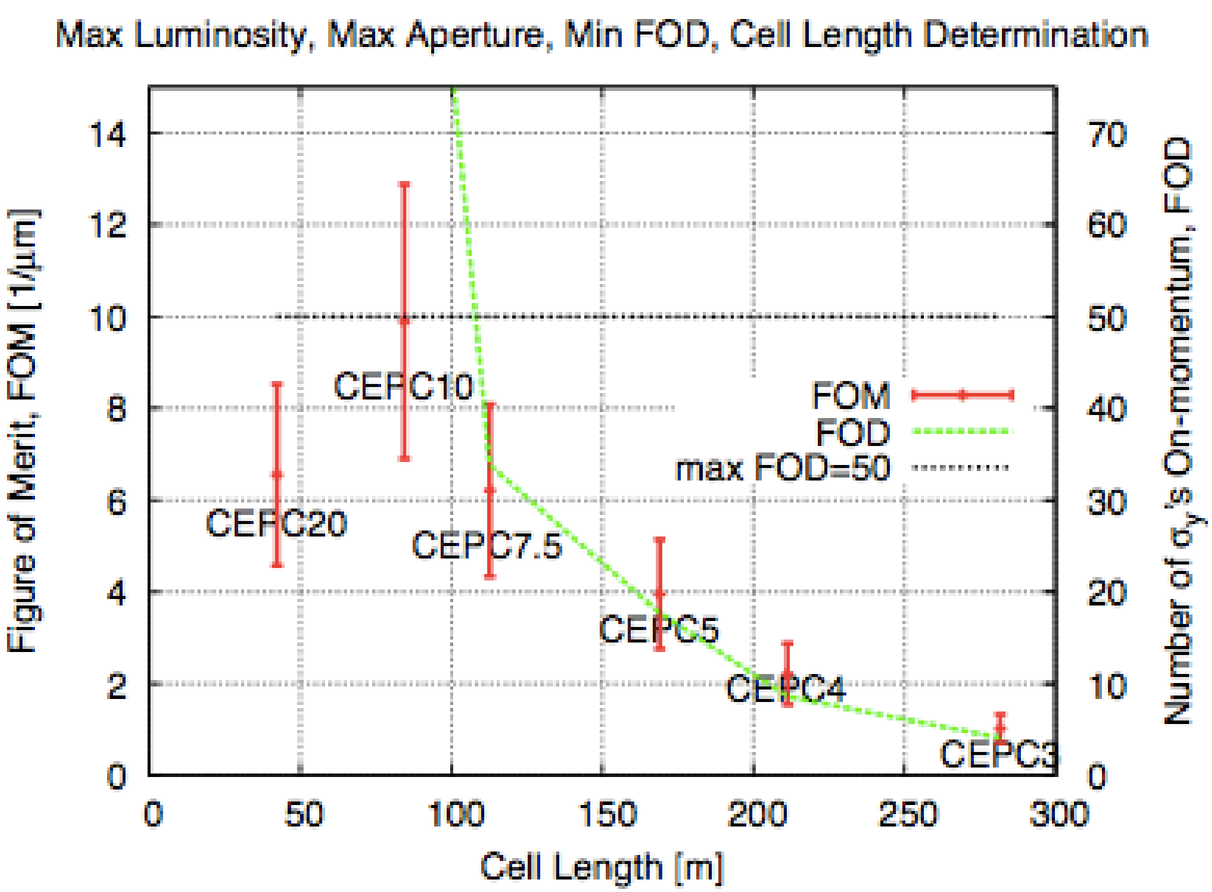




Beam injection & booster

AP studies to future lepton collider

- Lattice optimization
  - Cell length optimization



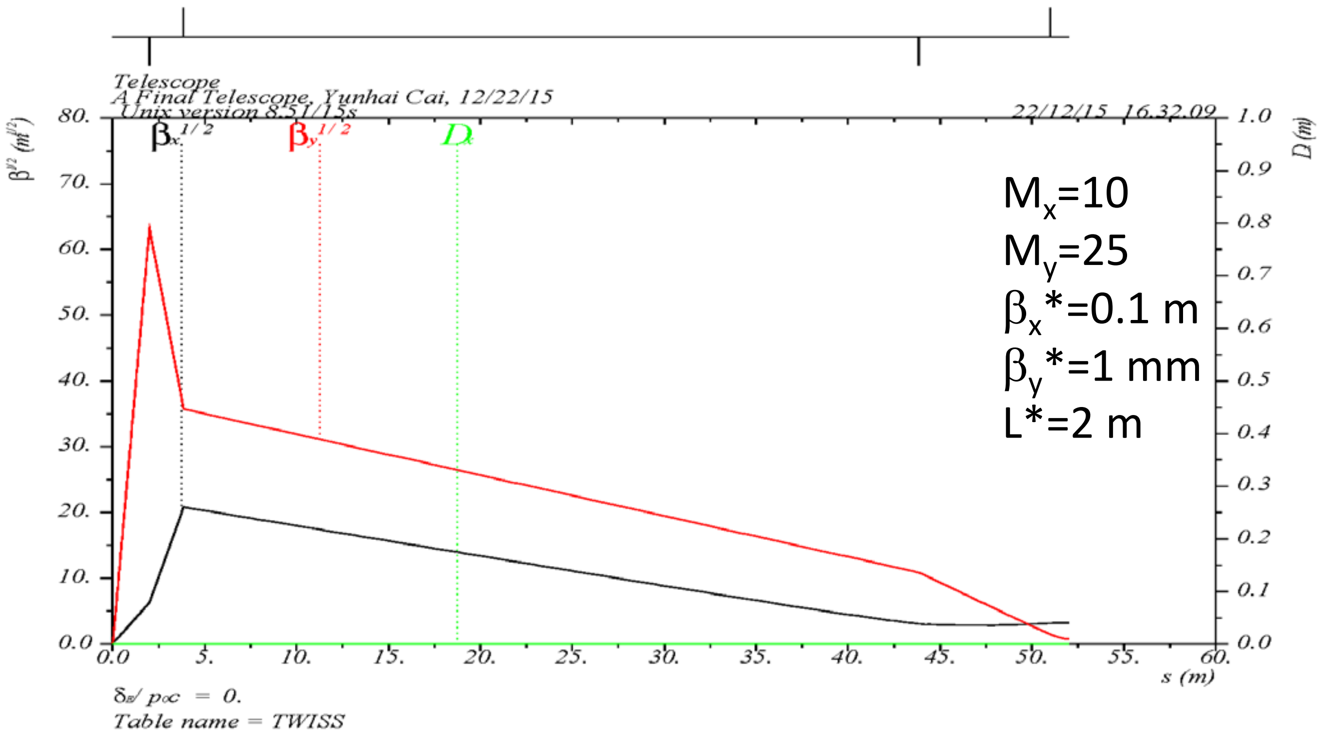
E GeV	β_y^* m	ξ_{sat}	$\mathcal{L}^{bb}$ $10^{34}cm^{-2}s^{-1}$	N_b	P_{RF} MW
120	0.0015	0.1	4.90	333	50.0
150	0.0015	0.11	2.51	164	50.0
175	0.0015	0.12	1.58	101	50.0
200	0.0015	0.12	1.06	66	50.0
225	0.0015	0.13	0.74	45	50.0
120	0.0020	0.1	3.68	134	50.0
150	0.0020	0.11	1.88	66	50.0
175	0.0020	0.12	1.19	41	50.0
200	0.0020	0.12	0.79	27	50.0
225	0.0020	0.13	0.56	18	50.0
120	0.0030	0.1	2.45	37	50.0
150	0.0030	0.11	1.26	18	50.0
175	0.0030	0.12	0.79	11	50.0
200	0.0030	0.12	0.53	7	50.0
225	0.0030	0.13	0.37	5	50.0

- Local chromaticity compensation is unnecessary (Talman), or not?
- Choice of vertical tune, momentum acceptance could be more than 3%.
- More IP free spaces brings large momentum accept.
- Finite dispersion and bends near the IP are also no needs, so synchrotron radiation incident on detector is dramatically reduced.
- For CEPC case, optimal cell length is 82 m, much longer than the current design.

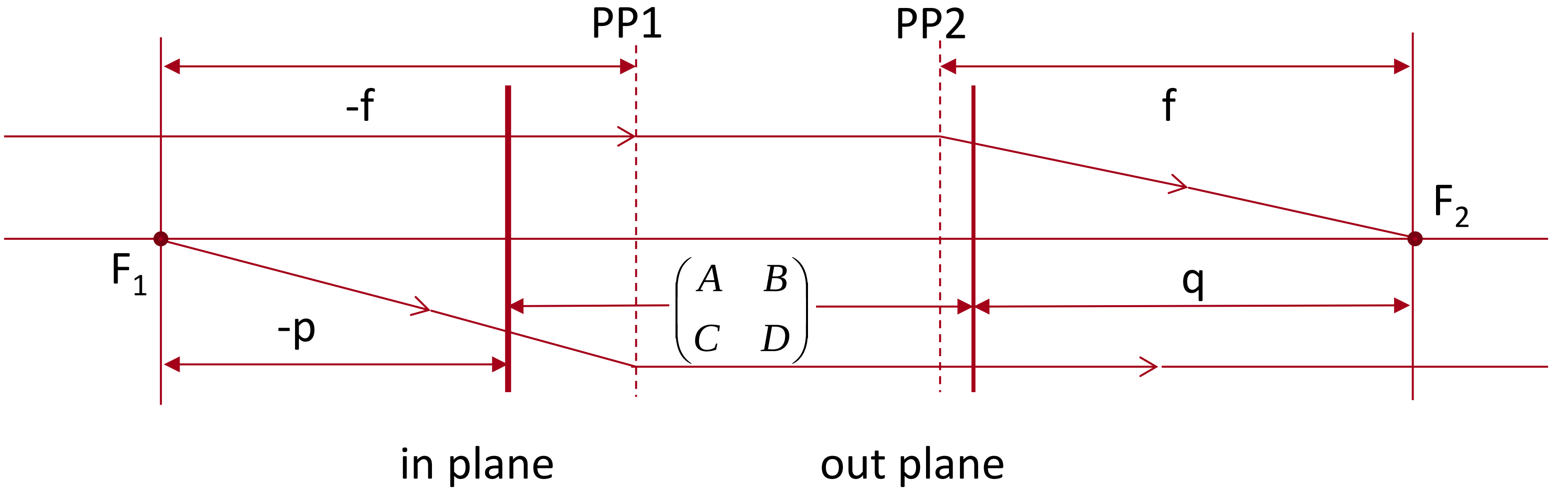
AP studies to future lepton collider

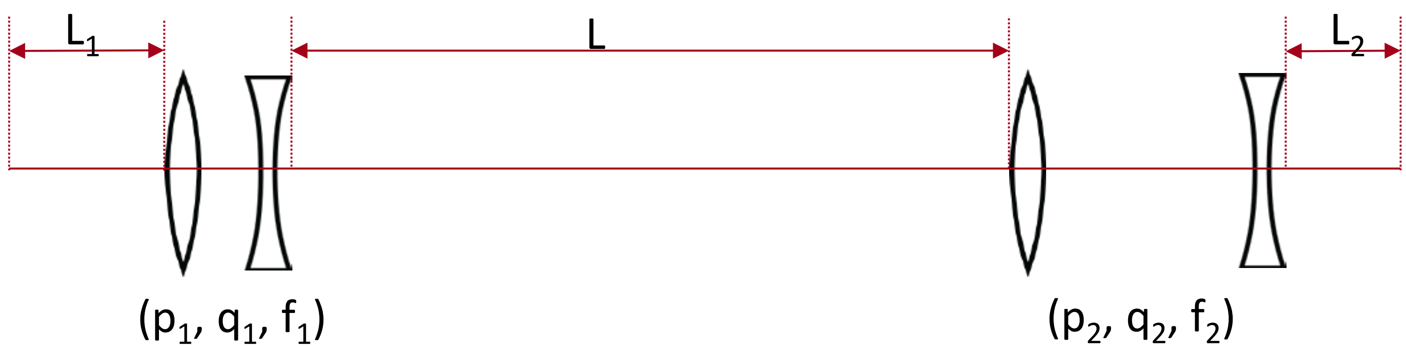
- Improvement on DA with a final telescope

IP



Parameters: L_1=2 m, d_1=1.85541 m, L=40 m, d_2=7.14276 m, L_2=1 m, f_1=1.36174 m, f_2=2.51748 m, f_3=15.11842 m, f_4= 17.01195 m





$$\begin{cases} p_2 = q_1 - L \\ q_2 = L_2 + M^2 (L_1 + p_1) \\ f_2 = M f_1 \end{cases}$$

p is the distance to the first focal point
q is for the second focal point
f is the effective focusing length
sign convention: >0 for right and <0 left
M is the magnification factor

The subsystems do not have to be doublets or thin lens. Moreover, these conditions are valid both in the horizontal and vertical planes.

Approximated Transfer Maps

A map up to the second order in the vertical plane:

$$\begin{cases} M_3 = -My + \dfrac{ML(L_1+p)}{f^2} y\delta + \dfrac{f^2(L_2+M^2L_1)+M^2L(L_1+p)^2}{Mf^2} p_y\delta \\ M_4 = -\dfrac{1}{M} p_y - \dfrac{L}{Mf^2} y\delta - \dfrac{L(L_1+p)}{Mf^2} p_y\delta \end{cases}$$

An approximated map:

$$\begin{cases} M_3 = -My + ML_1 p_y \delta \\ M_4 = -\dfrac{1}{M} p_y \end{cases}$$

$L_1+p=0$, implies that the first focus point of the final doublet is the interaction point. That is a very good approximation. Also assumed M>>1

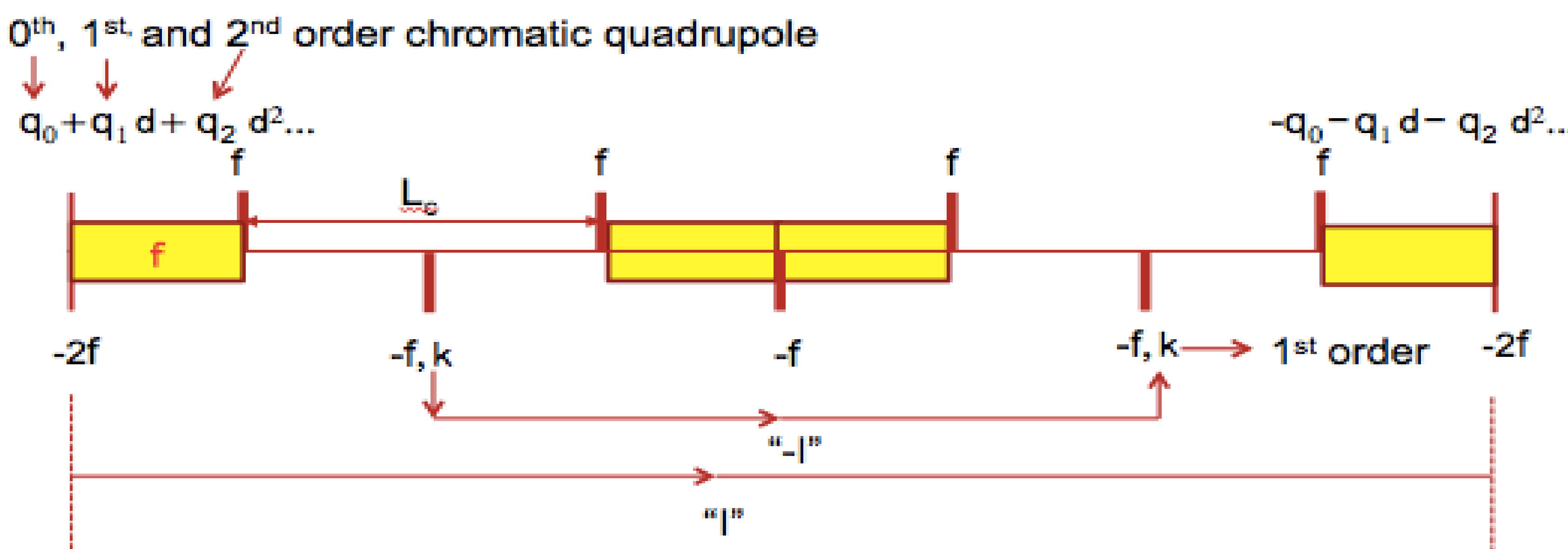
Chromatic Aberrations in Final Telescope

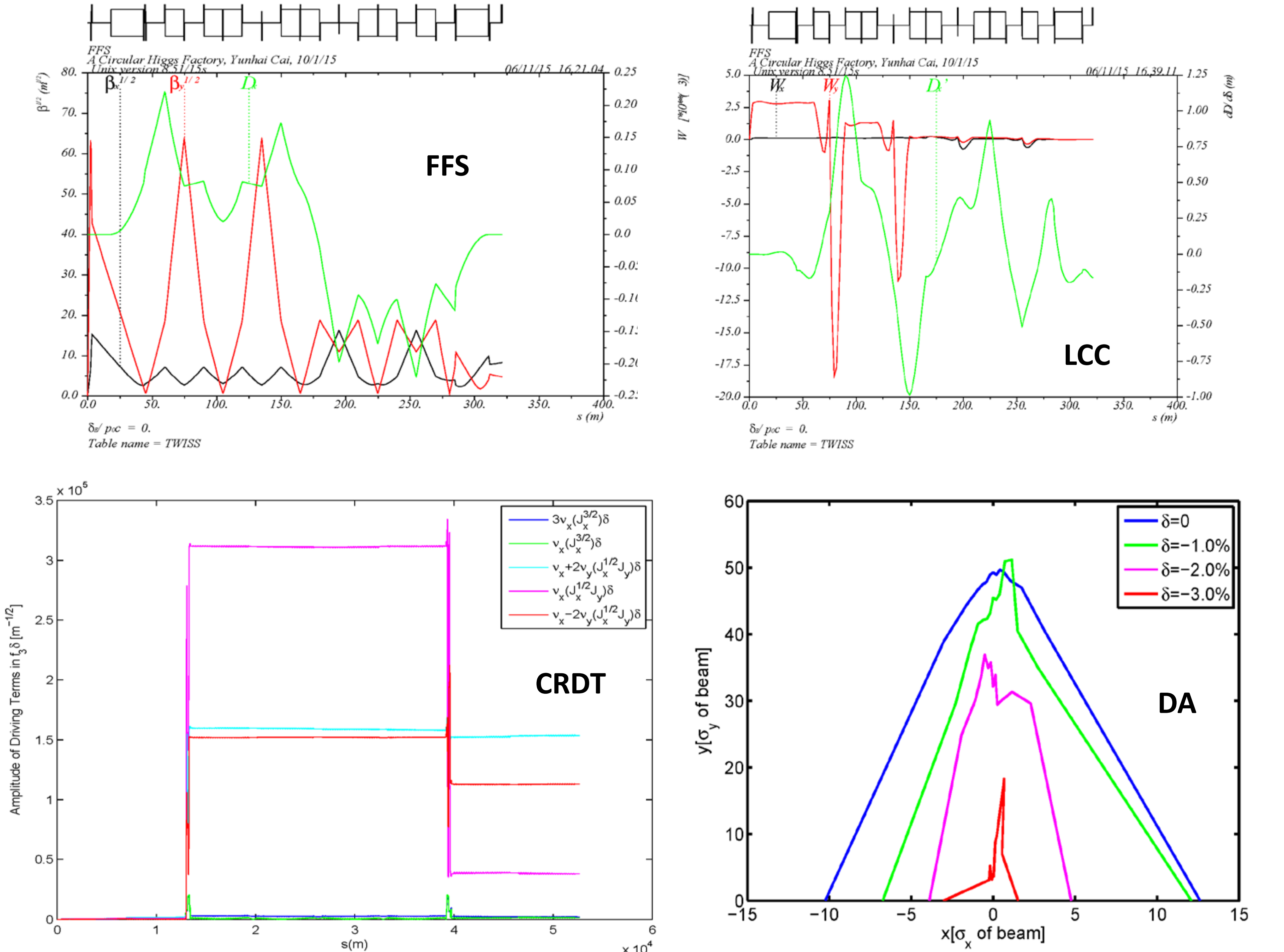
The simpler map leads to:

$$\begin{cases} \beta_y(\delta) = M^2 \beta_y^* [1 + (\dfrac{L^*}{\beta_y^*}\delta)^2] \\ \alpha_y(\delta) = \dfrac{L^*}{\beta_y^*}\delta \\ \psi_y(\delta) = \pi - \tan^{-1}(\dfrac{L^*}{\beta_y^*}\delta) \end{cases}$$

Back to the common notation, we use $L_1=L^*$. We have captured the most important chromatic aberrations in the final telescope. The first-order terms agree with the well-known results derived using the perturbation method in a periodical system. The large second-order term in the beta function was discussed extensively by Karl Brown. Here we show that the phase advance has to be corrected up to third order for a very small vertical beta function at the IP.

Chromatic Correction System in Vertical Plane




FFS
A Circular Higgs Factory, Yunhai Cai, 10/1/15
06/11/15 16.21.04
β^1/2 (m^1/2)
βx^1/2
βy^1/2
Dx
s (m)
δE/ p0c = 0.
Table name = TWISS
FFS
A Circular Higgs Factory, Yunhai Cai, 10/1/15
06/11/15 16.39.11
Wx
Wy
D'
dD/dδ (m)
s (m)
δE/ p0c = 0.
Table name = TWISS
LCC
Amplitude of Driving Terms in f3δ [m^−1/2]
x 10^5
s(m)
x 10^4
3νx(Jx^3/2)δ
νx(Jx^3/2)δ
νx+2νy(Jx^1/2Jy)δ
νx(Jx^1/2Jy)δ
νx−2νy(Jx^1/2Jy)δ
CRDT
y[σy of beam]
x[σx of beam]
δ=0
δ=−1.0%
δ=−2.0%
δ=−3.0%
DA

- Nonlinearity effect to DA (Levichev)

Source	Factors	Scheme
Low vertical beta at IP	- High FF chromaticity (Q and β) requires strong local correction sextupoles. - Kinematic effects - Large beta in FF quads emphasizes fringe field effects and field quality tolerance.	H-on*) NB CW
Large collision angle (>20 mr)**)	- Detector solenoid brings large betatron coupling. - Solenoid fringes generate nonlinear field components. - Low emittance needed for large luminosity limits the arc DA (similar to synchrotron light source)	NB CW
Full CW scheme	- Strong CW sextupoles.	CW
High energy	Radiation effects: - Strong damping improve DA. - Saw-tooth effect distorts COD like pretzel and can reduce DA.	Any

QD0 Fringe Fields

Quadrupole fringe field nonlinearity is defined by

$$H = -k_1'(s)x^2 y p_y / 2 + k_1'''\left(y^4 - 6x^2 y^2\right)/24$$

$$\alpha_{yy}^f = \frac{1}{16\pi} k_{10}\left(\beta_{y1}\beta_{y1}' - \beta_{y2}\beta_{y2}'\right)$$

$$\alpha_{yy}^f \approx -\frac{1}{4\pi} k_{10} \frac{L^{*3}}{\beta^{*2}} = -\frac{1}{4\pi} k_{10} L^* \xi^{*2}$$

Chromatic sextupoles

Vertical chromatic sextupole pair separated by –I transformer gives the following coordinate transformation in the first order*)

<u>Pair of sextupoles</u>

$$y = y_0$$
$$p_y = -p_{y0} - \frac{(K_2 L_s)^2 L_s}{6}\left(y_0^3 + x_0^2 y_0\right)$$

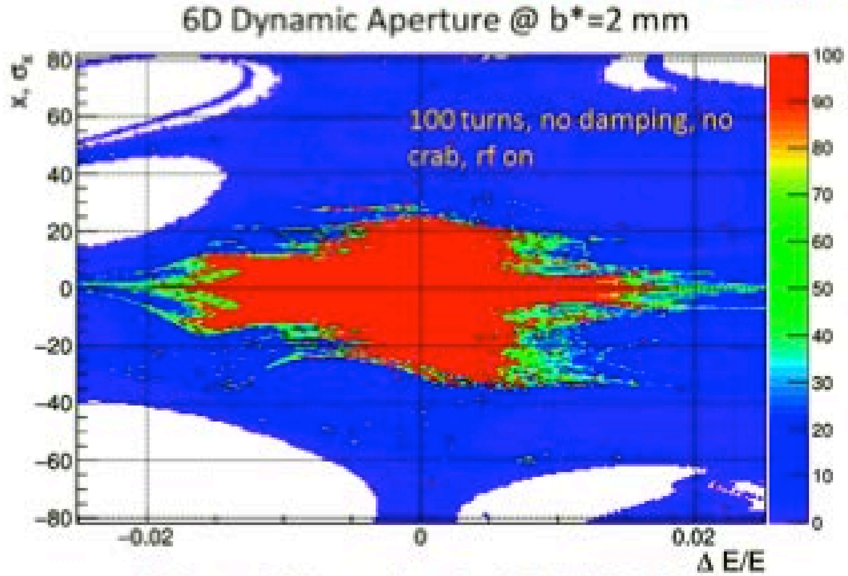
<u>Octupole</u>

$$y = y_0$$
$$p_y = p_{y0} - \frac{K_3 L}{6}\left(y_0^3 - 3x_0^2 y_0\right)$$

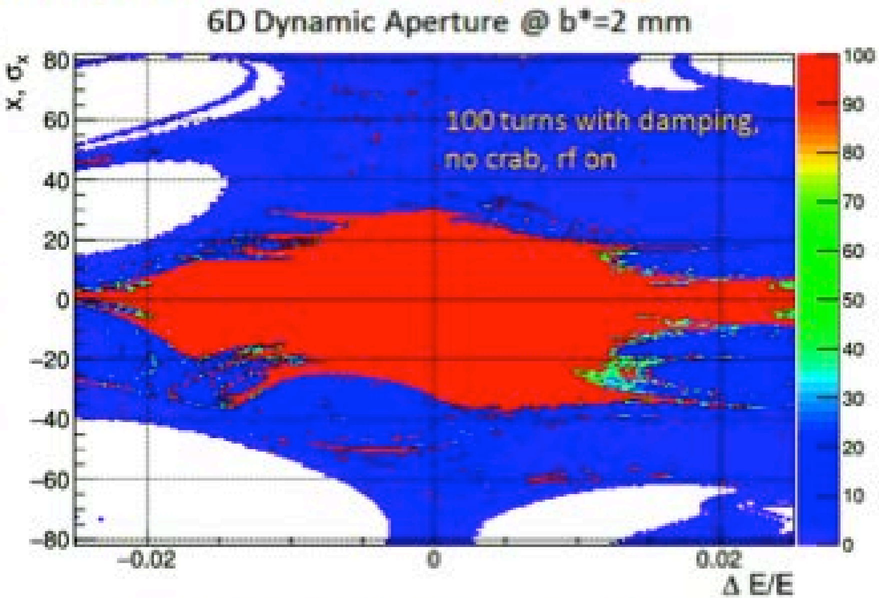
By analogy to the octupole and using the expression for the FF chromaticity we found for the vertical detuning (2 pairs)

$$\alpha_{yy}^{sp} = -\frac{1}{16\pi}(K_2 L_s)^2 L_s \beta_y^2 \approx -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\left(\frac{L^*}{\beta^*}\right)^2 = -\frac{1}{4\pi}\frac{L_s}{\eta_s^2}\xi^{*2}$$

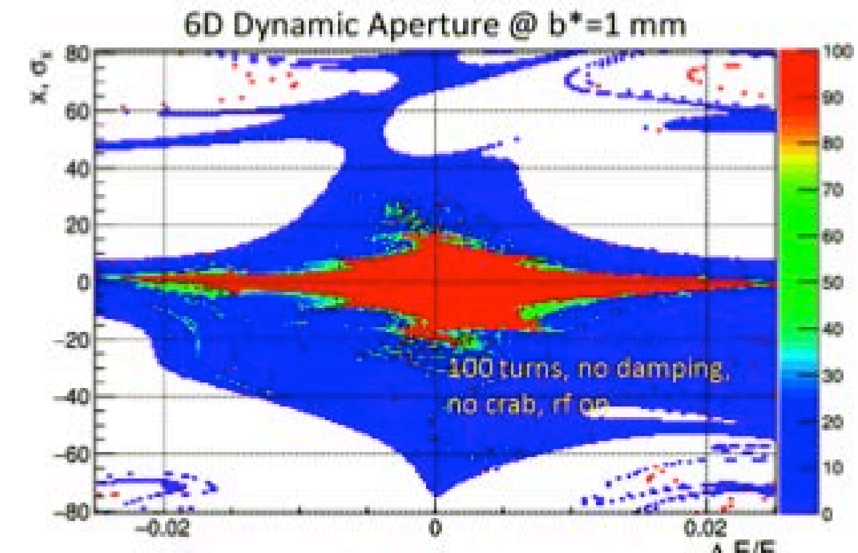
DA FCCee with/without damping



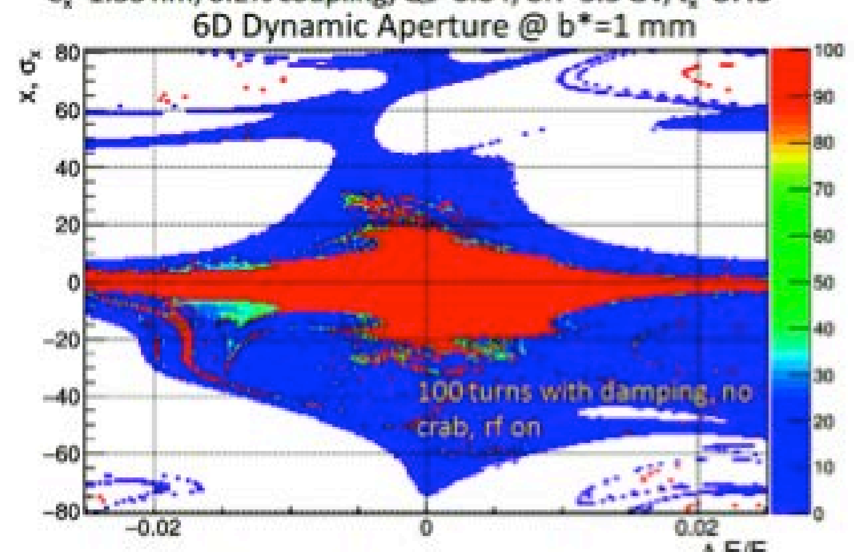
e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV



e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV, t_x=87.6



e_x=1.33 nm-rad, 0.2% coupling, Qs=0.04, Urf=5.5 GV

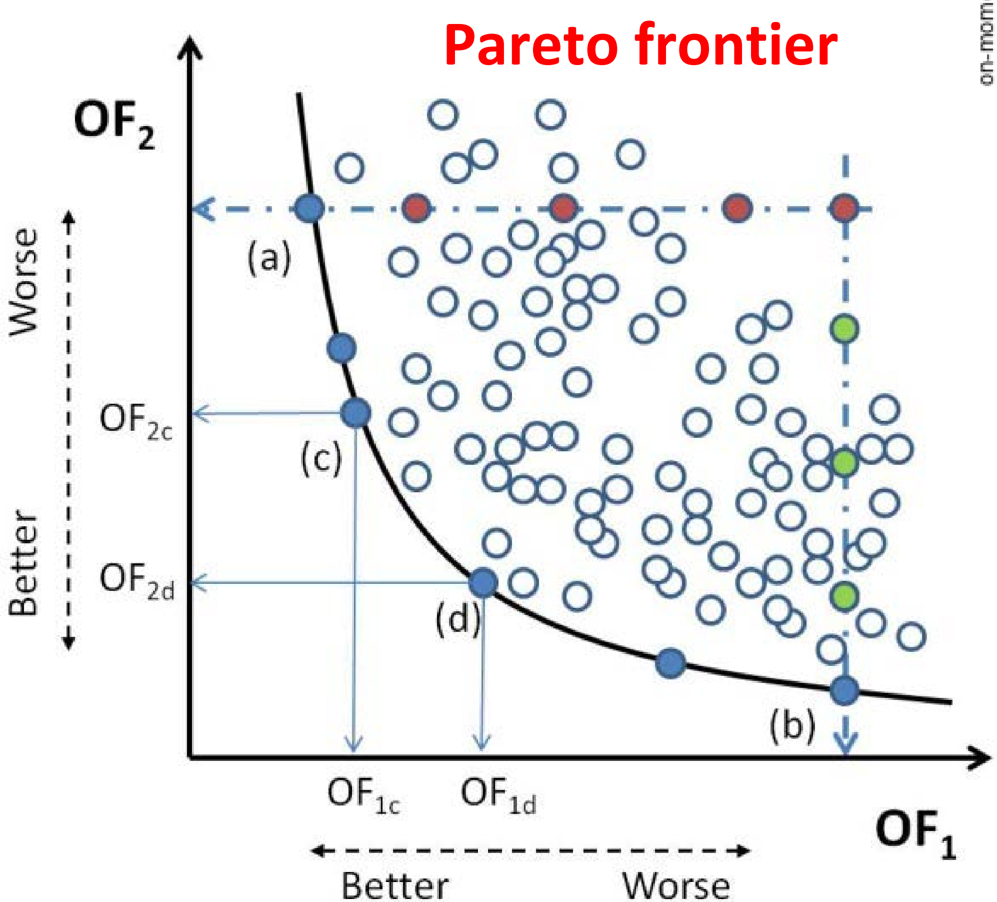


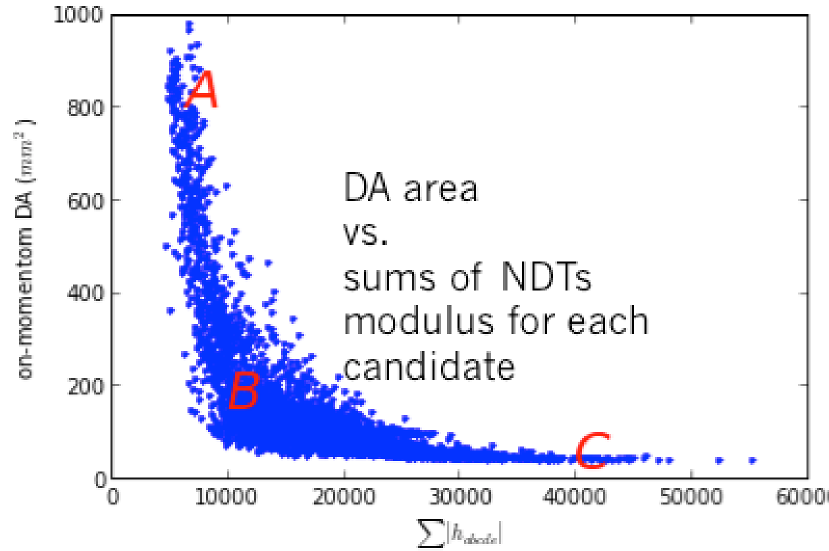
e_x=1.33 nm, 0.2% coupling, Qs=0.04, Urf=5.5 GV, t_x=87.6

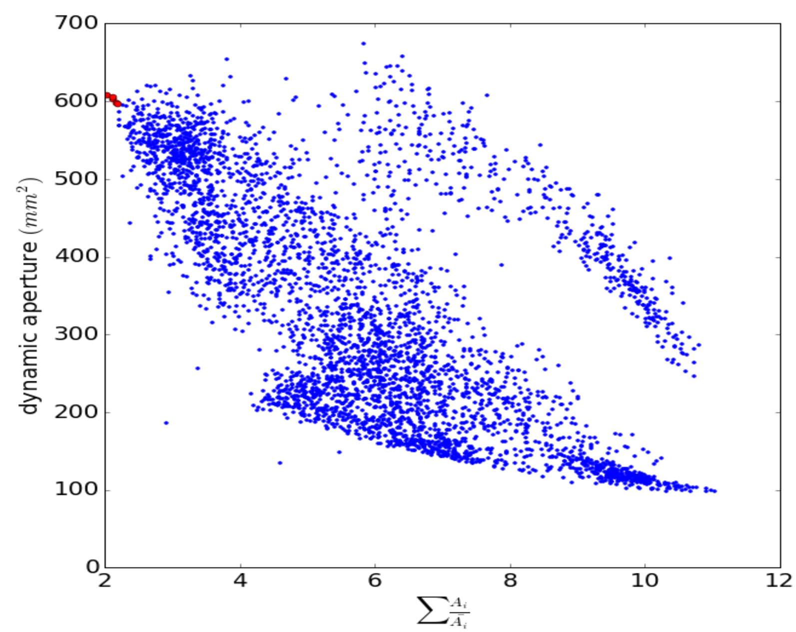
- DA limitation is a challenging problem. More efforts are needed to enlarge DA.
- Limiting factors: Vertical sextupole chromatic section at IR, FF quads fringes, and arc sext.
- Local + global compensation can give reasonable DA.
- Damping is important to increase the DA at high energy ring.
- A lot of problems are still remaining…

Other possible ways to improve DA

- MOGA







- Objective:
  - Chromaticity control
  - Longitudinal stability
  - DA & energy acceptance
- Need parallel computation
- Apply to big machine? Efficient? CPU time?

- Other AP issues:
  - Beam-beam simulation (Ohmi, Zhang,Shatilov)
  - Polarization (Koop, Yokoya)
  - Energy calibration (Muchnoi)
  - Crabbed waist (Milardi, Seeman)
  - Etc…

Collaborations

- CEPC:
  - IAC founded, 1st meeting held on Sept. 14-15, 2015
  - Established collaborations with KEK, BINP, SLAC, BNL, LBNL, INFN, LAL, HKUST, etc.
  - Collaborate with institutions and universities in China, mainly on accelerator technologies (SRF, SC magnet,
  - More collaborations are needed.
- FCC:

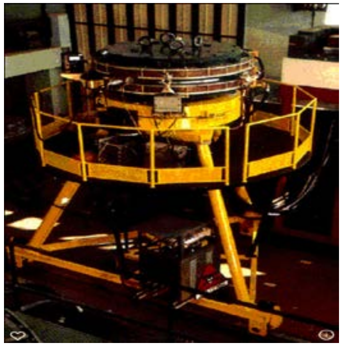
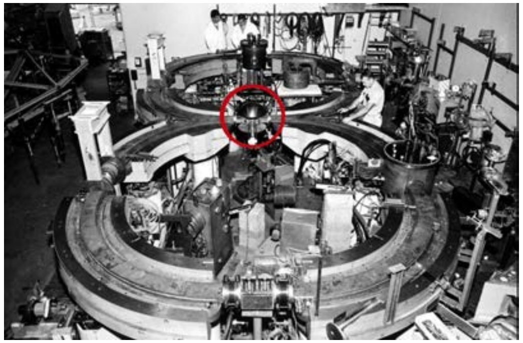
- ILC: SRF Facilities anticipated for Hub/Consortium

AMTF @DESY/E-XFEL, CEA,

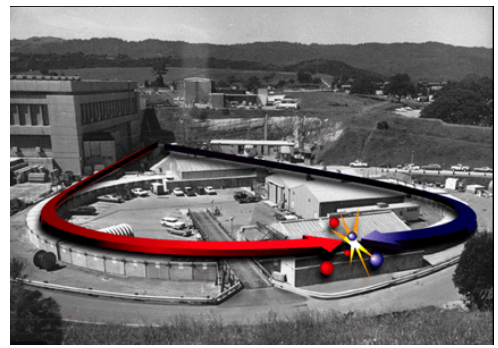
STF-CFF @ KEK

ASTA @ FNAL, TEDF @ JLab

The road to the future collider

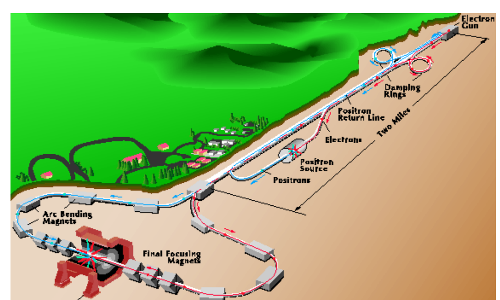


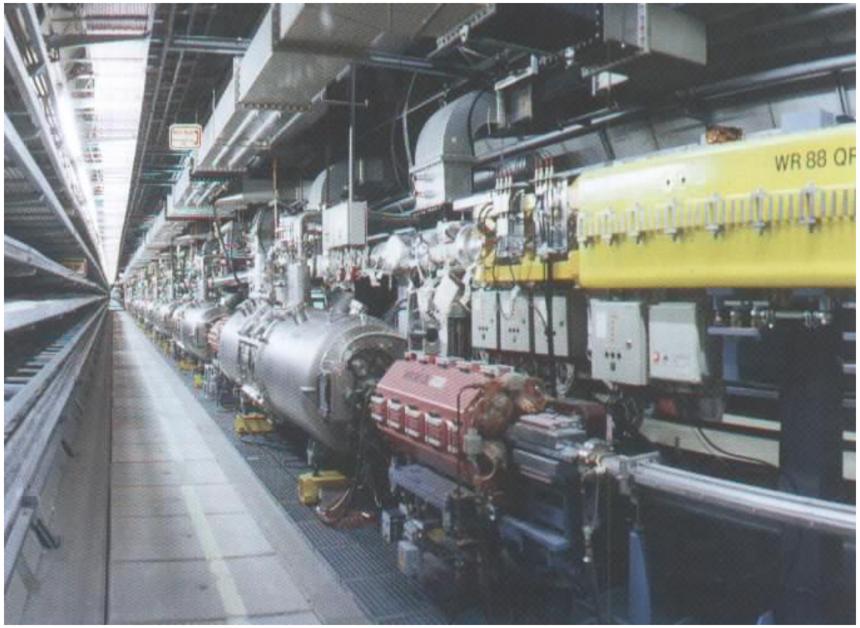




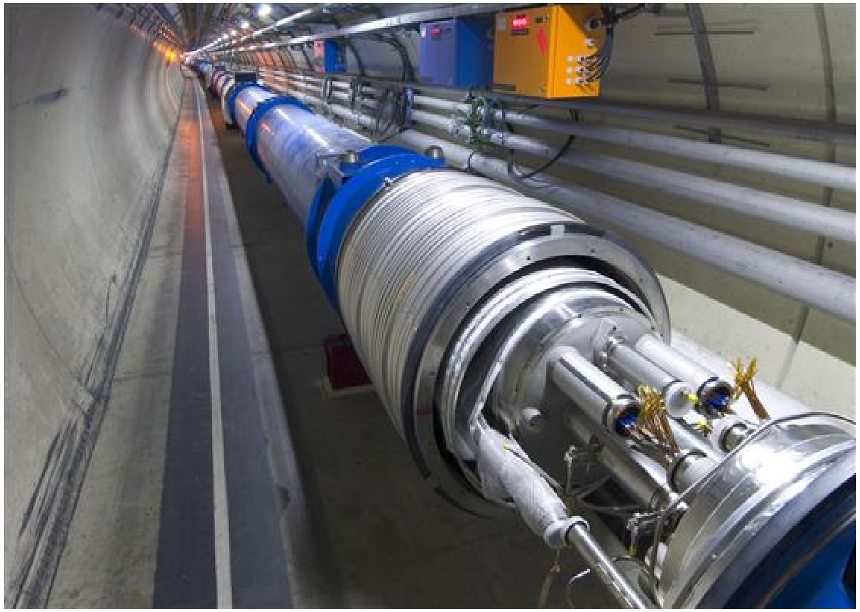


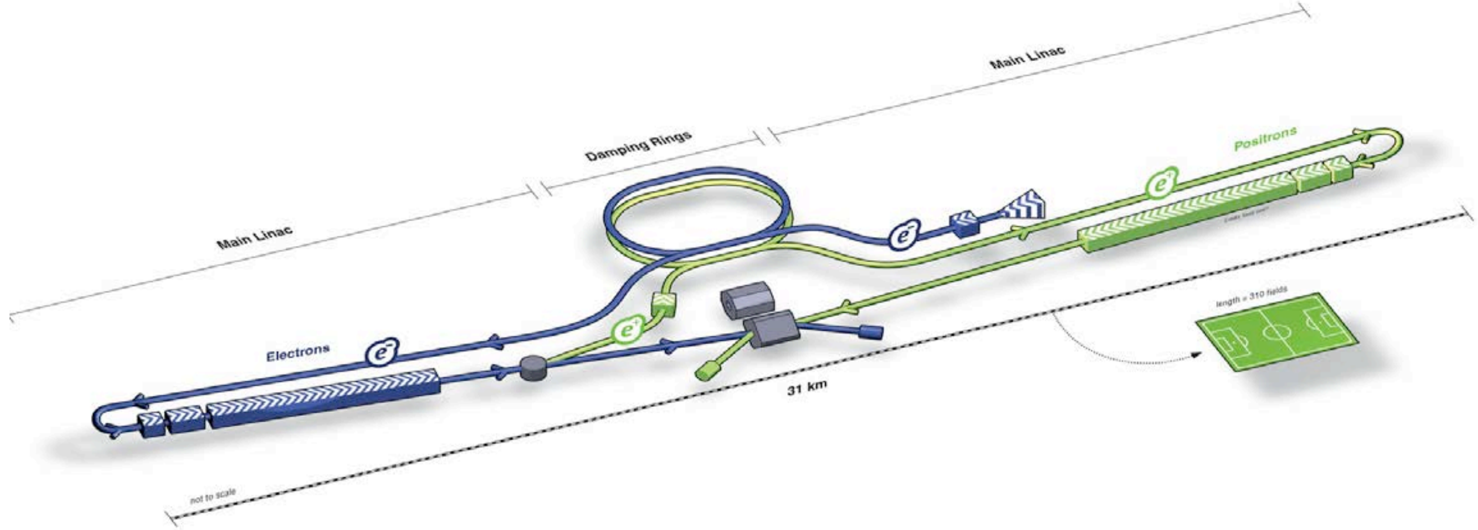

Electron Gun
Damping Rings
Positron Return Line
Electrons
Two Miles
Positron Source
Positrons
Arc Bending Magnets
Final Focusing Magnets
SLD Detector

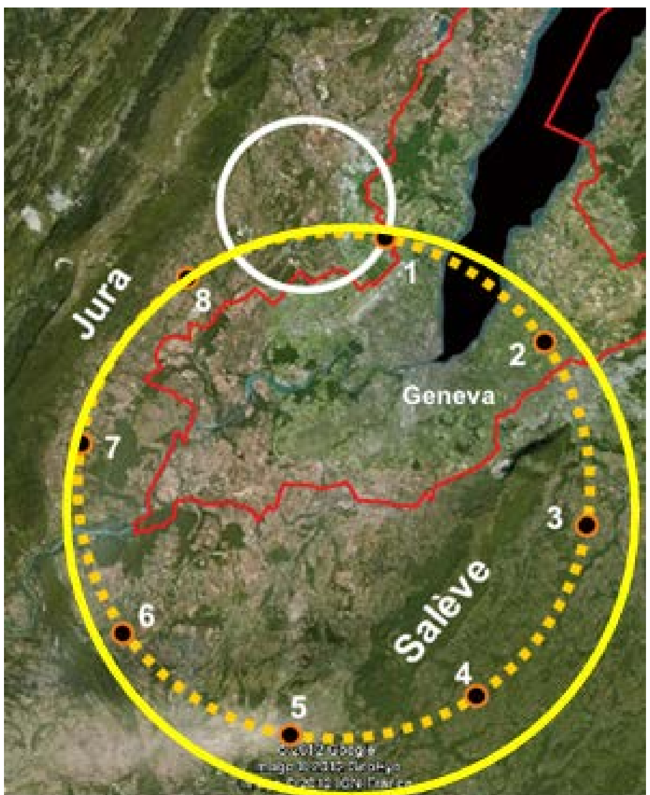
KEKB to SuperKEKB
To get x40 higher luminosity

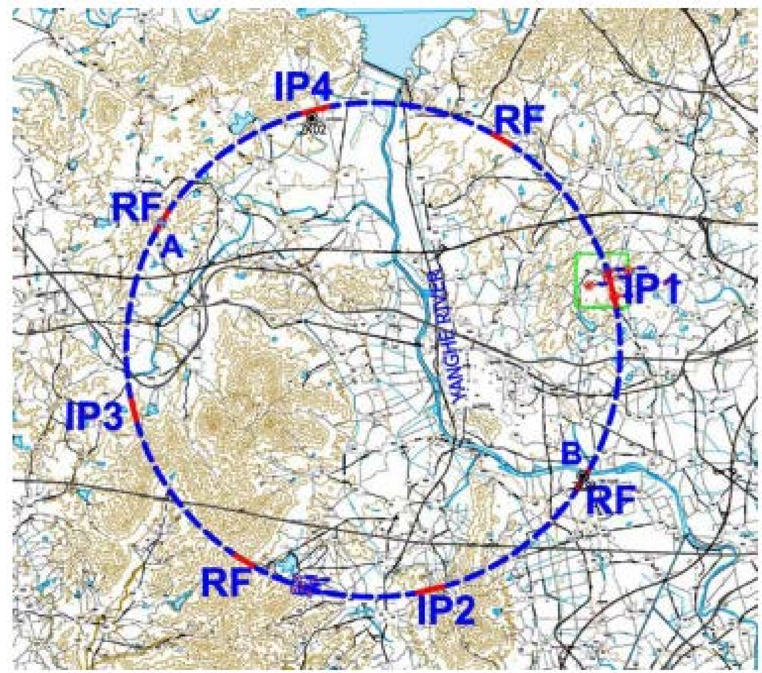

WR 88 QF


NORTHROP GRUMMAN

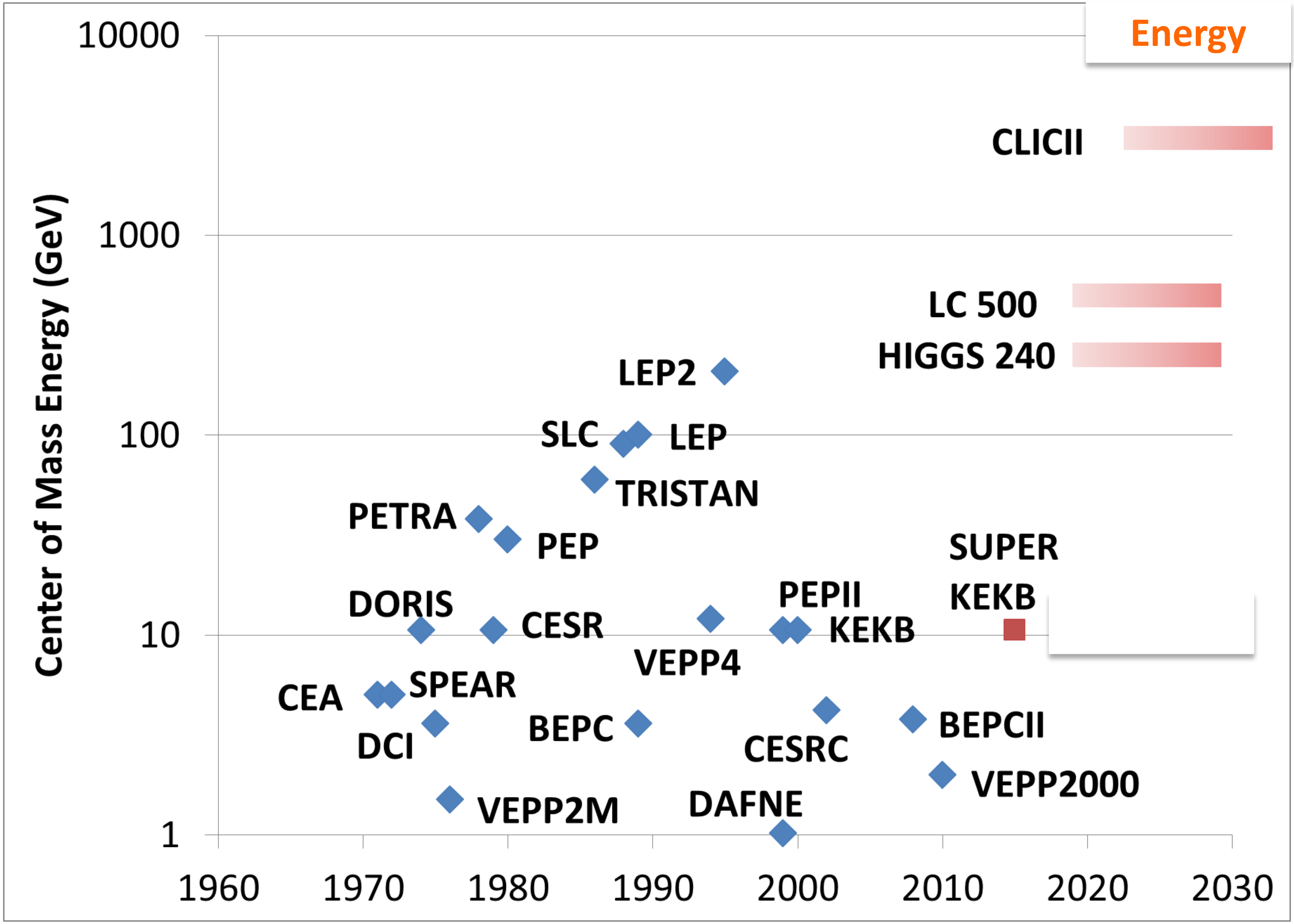




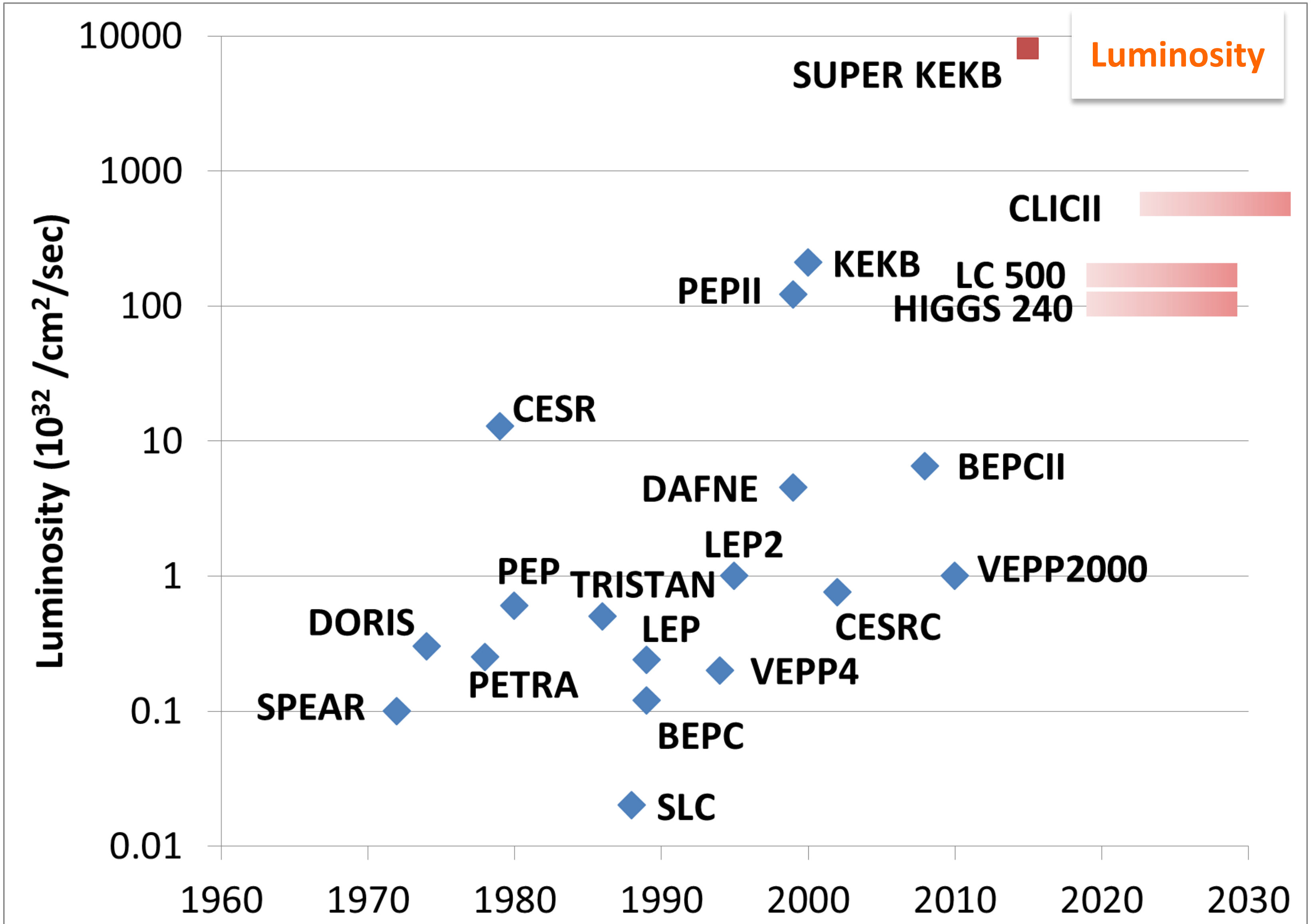




: A hypothetical location of the CEPC ring on the Qinghuangdao area



Energy
Center of Mass Energy (GeV)
10000
1000
100
10
1
1960
1970
1980
1990
2000
2010
2020
2030
CLICII
LC 500
HIGGS 240
LEP2
SLC
LEP
TRISTAN
PETRA
PEP
SUPER
KEKB
PEPII
DORIS
CESR
KEKB
VEPP4
CEA
SPEAR
BEPC
BEPCII
DCI
CESRC
VEPP2000
VEPP2M
DAFNE


Luminosity
Luminosity (10^{32} /cm^2/sec)
10000
1000
100
10
1
0.1
0.01
1960
1970
1980
1990
2000
2010
2020
2030
SUPER KEKB
CLICII
KEKB
PEPII
LC 500
HIGGS 240
CESR
BEPCII
DAFNE
LEP2
PEP
TRISTAN
VEPP2000
DORIS
LEP
CESRC
PETRA
VEPP4
SPEAR
BEPC
SLC

All workers on colliders unite!