State-of-the-art of e^+e^- colliders

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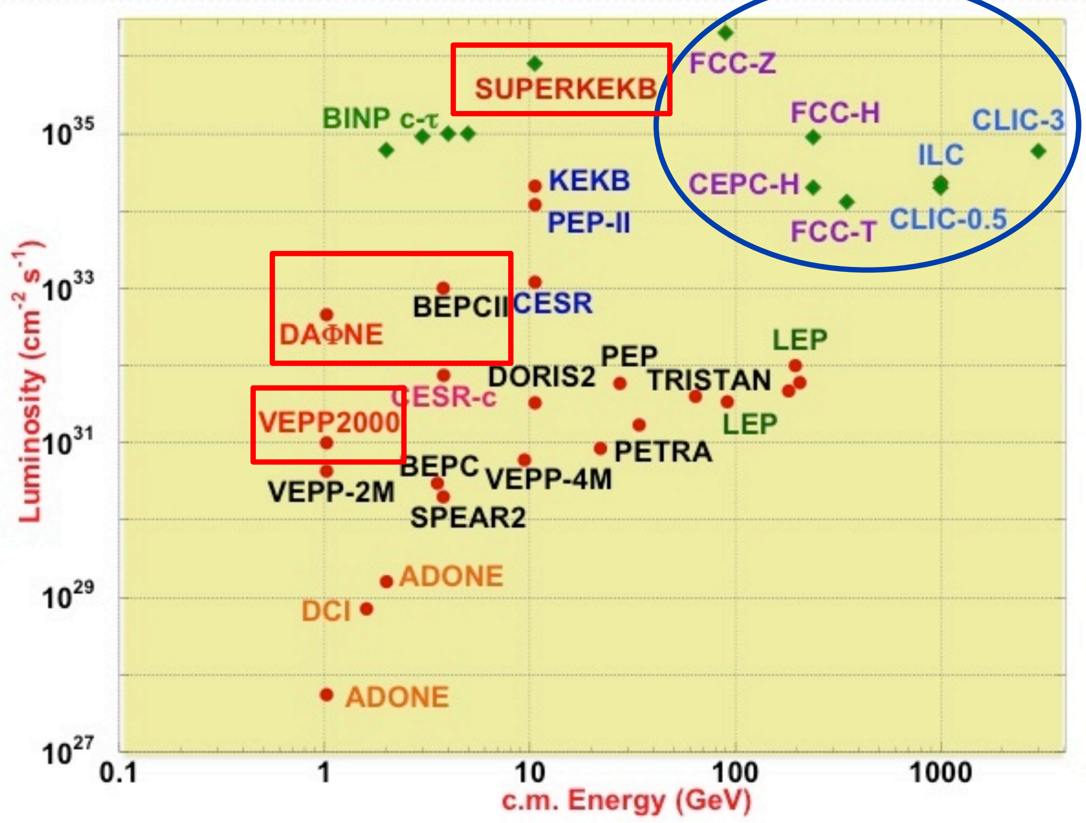
Aknowlegments

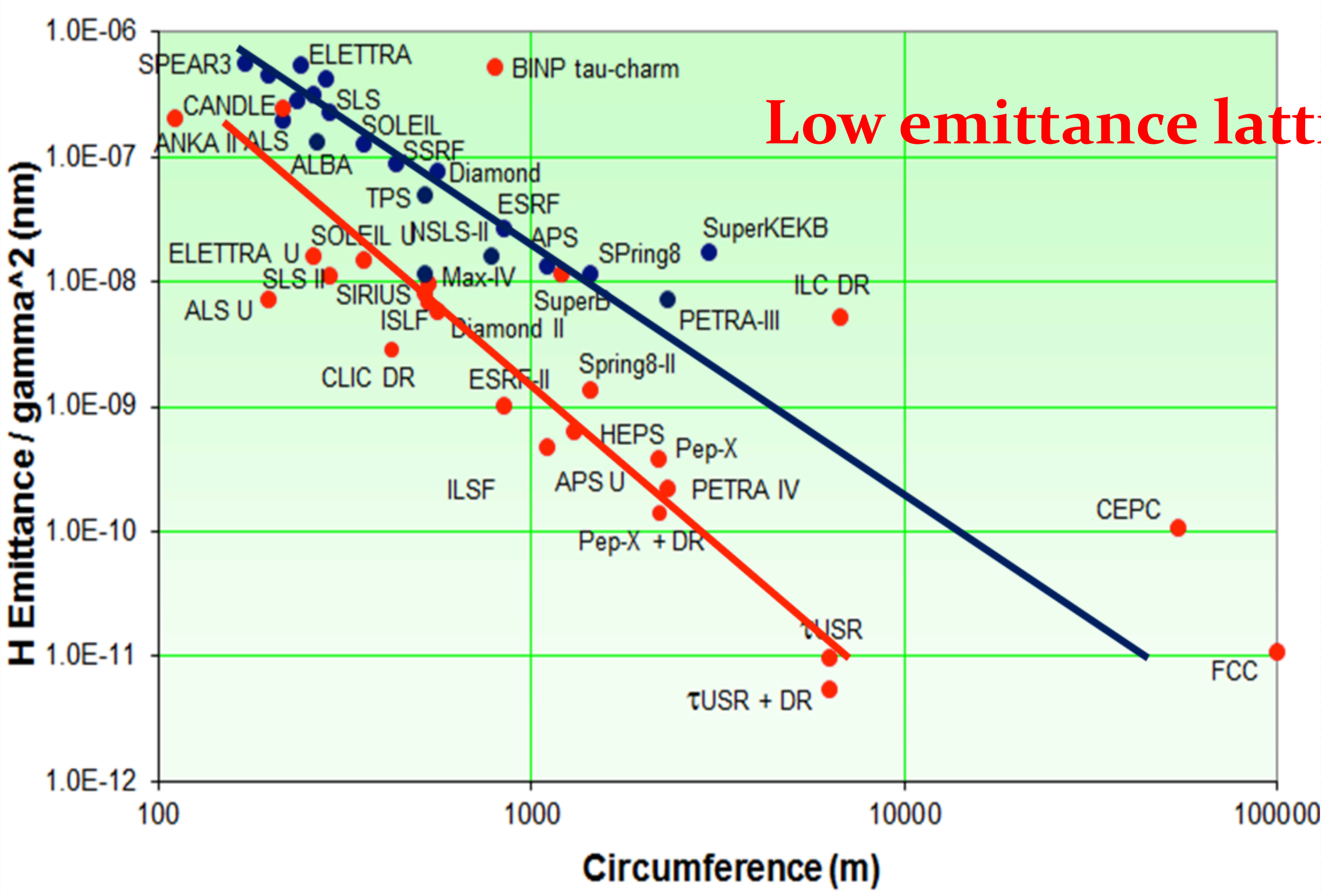
- Material for this talk by:
  - P. Bambade (LAL-IN2P3)
  - M. Boscolo (INFN-LNF)
  - P. Burrows (IAI)
  - Y. Chi (IHEP)
  - W. Chou (IHEP)
  - S. Fukuda (KEK)
  - Y. Funakoshi (KEK)
  - J. Gao (IHEP)
  - M. Koratzinos (Un. Geneva)
  - K. Ohmi (KEK)
  - S. Prestemon (LBNL)
  - D. Shatilov (BINP)
  - M. Sullivan (SLAC)
  - P. Vobly (BINP)
  - A. Yamamoto (KEK)
  - K. Yokoya (KEK)
  - D. Zhou (KEK)
  - F. Zimmermann (CERN)

Luminosity vs. centre-of-mass energy



past [orange, black, green centre-right], **present** (2016) [red] and **future** lepton colliders [blue, purple, green top-left] around the world

Normalized emittance vs. circumference



Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). The ongoing generational change is indicated by the transition from the blue line to the red line. (**Courtesy R. Bartolini, LER-2014, updated 2016**)

Some lessons learnt

- High beam currents possible → control trapped HOMs, e-cloud
- Crab waist works → lattice to meet sextupoles requirements
- Top-up injection is needed → very reliable injection complex
- e-cloud mitigation → solenoids, low SEY pipe material, coating, clearing electrodes, grooves, NEG
- Bunch-by-bunch Feedbacks work very well → upgrade
- Backgrounds increase with I_{beam} and L → masking, shielding, beamstrahlung control
- Emittance tuning needed to achieve low values → machine errors minimization (girders), fast online procedures for *orbit/beta/dispersion/coupling* correction
- IP orbit control needed → IP feedback
- Nano-beams require vibrations control for FF quads

The present

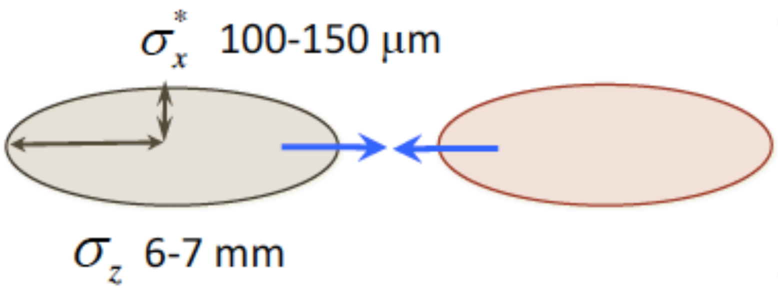
SuperKEKB

- SuperKEKEb, upgrade of the highly successful KEKB-Factory which holds peak and integrated luminosity world records, started its Phase I (no detector, no FF quads, no beams crossing) in February 2016 (for 5 months)
- This allowed for preparation of Phase II (detector but no vertex, detuned lattice, lower L) and Phase III (Vertex IN, low-beta, design L), facing quite a few problems
- SuperKEKB parameters are state-of-the-art with respect to KEKB and PEP-II, which twenty years ago were already pushing up their design Luminosity and beam currents with respect to previous colliders
- A boost in performances is expected by:
  - "*large Piwinsky angle and crab waist*" collision scheme invented by P. Raimondi (called here "Nano-beam", no crab waist sextupoles)
  - major upgrade of the technical systems
  - high charge/low emittance RF photo-injector for e^-
  - Damping Ring for e^+
  - very complicated FF layout (quads, solenoid, correcting coils)

Collision Scheme

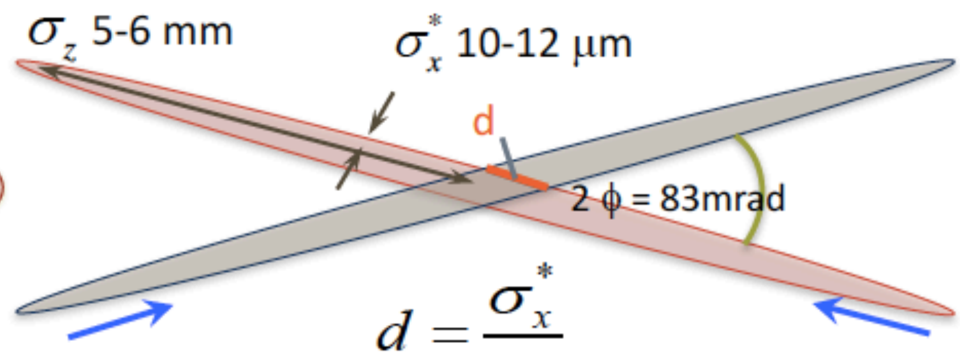
P. Raimondi

KEKB head-on (crab crossing)



interaction region = bunch length

Nano-Beam Scheme SuperKEKB



$$d = \frac{\sigma_x^*}{\phi}$$

$\phi_{pwinski} \sim 20$

Half crossing angle: ϕ

interaction region << bunch length

Hourglass requirement

$$\beta_y^* \geq \sigma_z \sim 6 \text{ mm}$$

$$\beta_y^* \geq \frac{\sigma_x^*}{\phi} \sim 300 \text{ μm}$$

Vertical beta function at IP can be squeezed to ~300μm.
Need small horizontal beam size at IP.
→ low emittance, small horizontal beta function at IP.

No crab waist scheme has been assumed at SuperKEKB

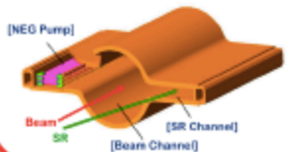
Major upgrades towards KEKB ×40

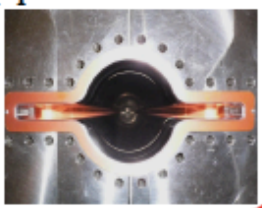
$$L = 8\times10^{35}\left[cm^{-2}s^{-1}\right] \propto \frac{I_{e\pm}\xi_{\pm y}}{\beta_y^*}.$$

Taking advantage of existing items

- **the KEKB tunnel,**
- **the KEKB components as much as possible!**

New beam pipe& bellows
TiN-coated beam pipe with antechambers

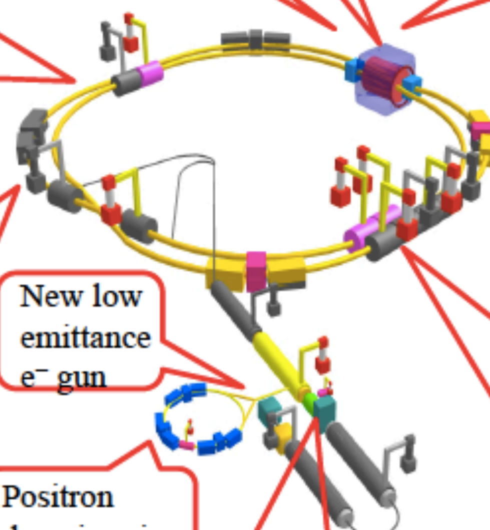




Belle detector is upgraded to Belle II

New design for IR

New QCS magnet for Nano-beam scheme
New superconducting final focusing quads

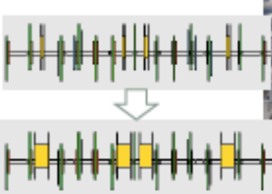


Add / modify RF systems for higher beam current

Main ring arc and straight section:
Redesign the lattices of both rings to reduce the emittance

KEKB

Super KEKB



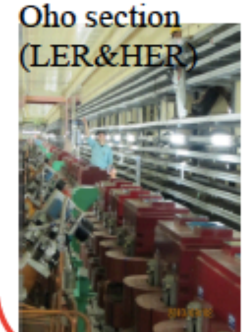
Main ring arc section:
LER: Replace all main dipoles
HER: Preserve the present cells

New low emittance e⁻ gun

Positron damping ring

New e^+ source

New and re-use wiggler magnets are mixed:
Oho section (LER&HER)
Nikko section (LER)



This might be a problem

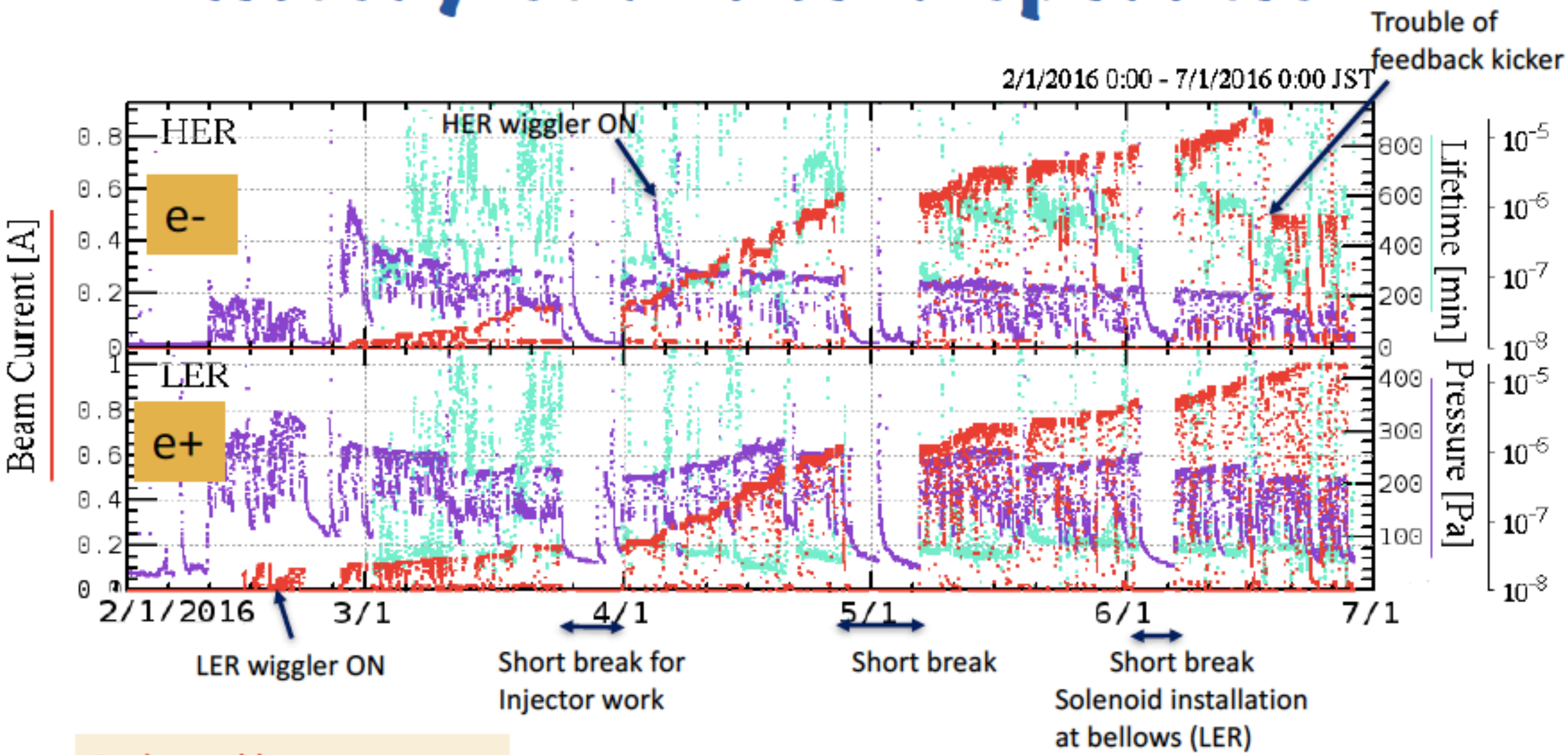
KEKB and SuperKEKB comparison

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

	KEKB Achieved		SuperKEKB Nano-beam		Factor
	LER	HER	LER	HER	
I_{beam} [A}	1.6	1.2	3.6	2.6	(>) 2
β_y* [mm]	5.9	5.9	0.27	0.30	(<) 20
ξ_y	0.09	0.12	0.088	0.081	~1
L [$cm^{-2}s^{-1}$]	2.1 x 10^{34}		8.0 x 10^{35}		(>) 40

SuperKEKB will be state-of-the-art in 2018

History of Phase 1 operation



Red: total beam current
Purple: vacuum pressure
Cyan: beam lifetime

HER:
870 mA, 5.7x10^{-8} Pa, ~200 min. (6/17)
LER:
1010mA, 4.7x10^{-7} Pa, ~60 min. (6/22)

Y. Funakoshi, KEK

SuperKEKB Phase-I issues with high current

Fixed during commissioning

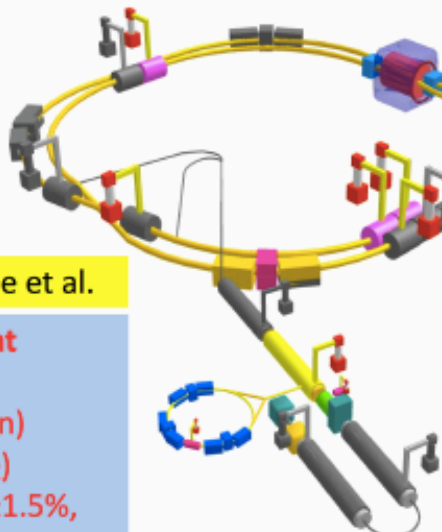
- Vertical beam size blowup as function of beam current (LER)
  - Due to electron clouds
  - Installation of permanent solenoids mitigated the situation.
- Frequent beam aborts associated with vacuum burst (LER)
  - Maybe due to dust particles, conditioning effect exits
- Longitudinal coupled bunch instability (LER)
  - Instability was first observed around 660mA. The mode number is ~-40. We needed the use of longitudinal feedback system to suppress it. At KEKB, we never needed the longitudinal feedback system. The source of the instability may be the 0 and π modes of the ARES cavities which were detuned for operational budget reduction.
- Longitudinal coupled bunch instability (HER)
  - Sometimes, detuned cavities induced the instability due to the fundamental mode. The -1 mode damper was set up to suppress the instability.
- Hardware troubles due to the high beam currents
  - Vacuum leakage by the direct hit by the beam at bellows near the abort kickers (HER)

As a test machine for FCC-ee/CEPC

SuperKEKB: extremely low β*

I_{e+}=3.6 A, I_{e-}=2.6 A
P_{SR} ~ 13 MW
C = 3 km

beam commissioning started this year

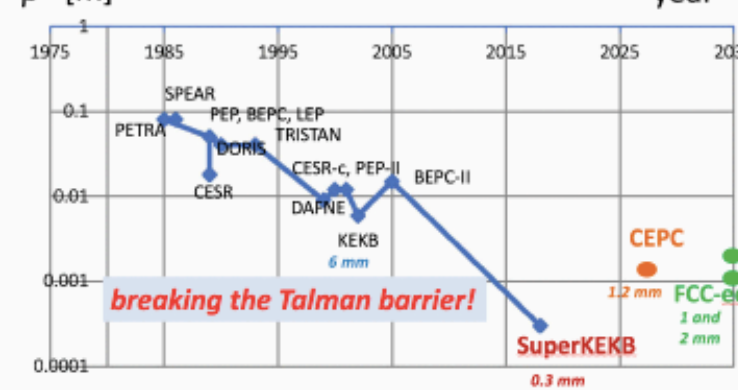


K. Oide et al.

top up injection at high current
β_y^* =300 μm (FCC-ee: 1 mm)
lifetime 5 min (FCC-ee: ≥20 min)
$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)
off momentum acceptance (±1.5%, similar to FCC-ee)
***e⁺* production rate** (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

SuperKEKB goes beyond *FCC-ee/CEPC*, testing all concept

β_y^* evolution over 40 years



entering a new regime for ring colliders –
SuperKEKB will pave the way towards β*≤2 mm

Frank Zimmermann
eeFACT2016, Daresbury, 24 October2016

The future

Future lepton colliders

Good for high E

Linear Colliders (energy extendable):

ILC (2 x 500 GeV) :

- SRF, longer pulse, higher E. effciency
- Klystron driven
- 1/10 scaled machine (EXFEL) realized

CLLIC (2 x 1,500 GeV) :

- NRF, HG →Compact
- Two beam driven

Good for high L

Circular Colliders (max. energy fixed):

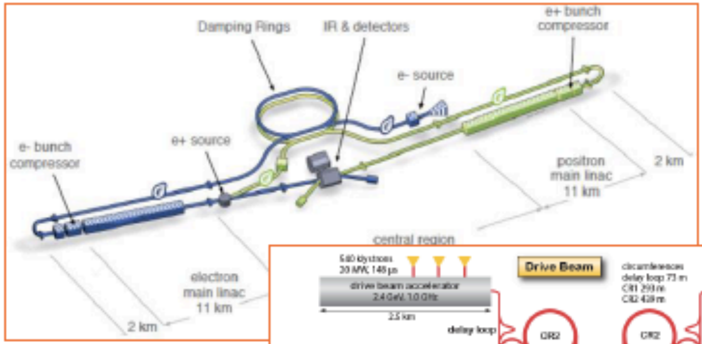
Based on Well-known technology

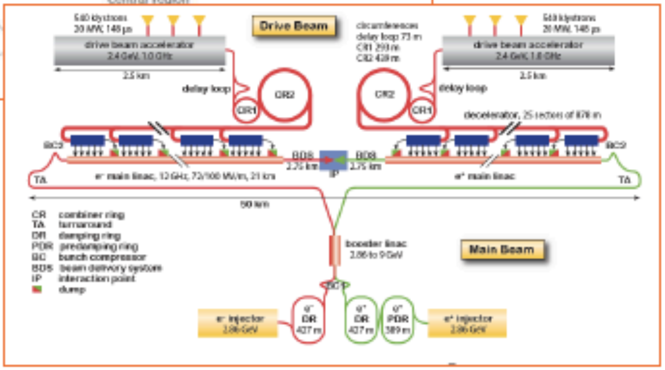
CEPC (2 x 120 GeV):

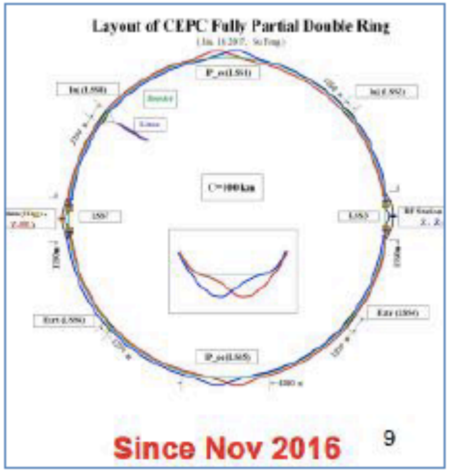
- SRF, higher L-eff., at ≤ 2x120 GeV,

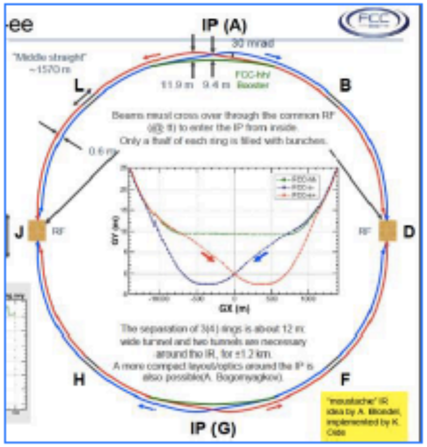
FCC-ee (2 x 175 GeV):

- SRF, higher L-eff. at ≤ 2 x 175 GeV,
- AC power limit/guideline to be mitigated









A. Yamamoto, IAS, HK, 2017

Parameters comparison

	Unit	ILC - TDR			CLIC – CDR+			CEPC	FCC-ee tt-bar
Technology		Linear SRF, Klystron driven			Linear NRF, 2-beam driven			Circular SRF	Circular SRF
Energy	GeV	250	**500**	1,000	380	500 – B/A	3,000	240	**350**
Acc. Length	km	~21	31	50	11	13	48	100	100
Lumin. / IP	10^{34} $cm^{-2}s^{-1}$	**0.82***	**1.8**	**3.6**	**1.5***	**2.3**	**5.9**	**3.3 / 5.4 ****	**1.9 ****
Acc. Gradient	MV/m	31.5	31.5	31.5/45	72	100/80	100	14	
Res. Frequency	GHz	1.3	1.3	1.3	12	12	12	0.65	0.65
IR, v. beam-size	nm	7.7	5.9	2.7	2.9	2.3	1	--	--
Beam Power	MW (2-beams)	2 x 2.9	2 x 5.2	2 x 13.6		2 x 4.7	2 x 14	--	--
SR loss	MW							30 / 50	100 (tbc)
AC Power	MW	**129**	**163**	**300**	**252**	**271**	**589**	**210 / 350 (tbc)**	**364**
L / AC	Relative	0.64	1.1	1.2	0.60	0.85	1.0	1.6 / 1.5	0.52**

A, Yamamoto, 17/01/26

* enable to be further optimized for staging

** effectively x N_{IR}

Recent changes/staging options

- ILC baseline now 250 GeV c.m.
- CLIC Phase 1 rescaled to 380 GeV, with an option to be fully klystron based
- CEPC now 2 rings, 100 km, FCCee-like
- FCCee injector now 6 GeV linac, CEPC-like
- Remarkably, the cost is now very similar

ILC (250 GeV)

	ILC	
CoM. Energy	250	500
Site Length	~21	31
Luminosity	0.82	1.8
AC Power	129	163
Value Cost in TDR	TBD	7.98

($5 - 6B)

CLIC (380 GeV)

380 GeV centre-of-mass energy.

	Value [MCHF of December 2010]
	1245
	974
	2038
	132
	2112
ure	216
	6690

CEPC (100 km)

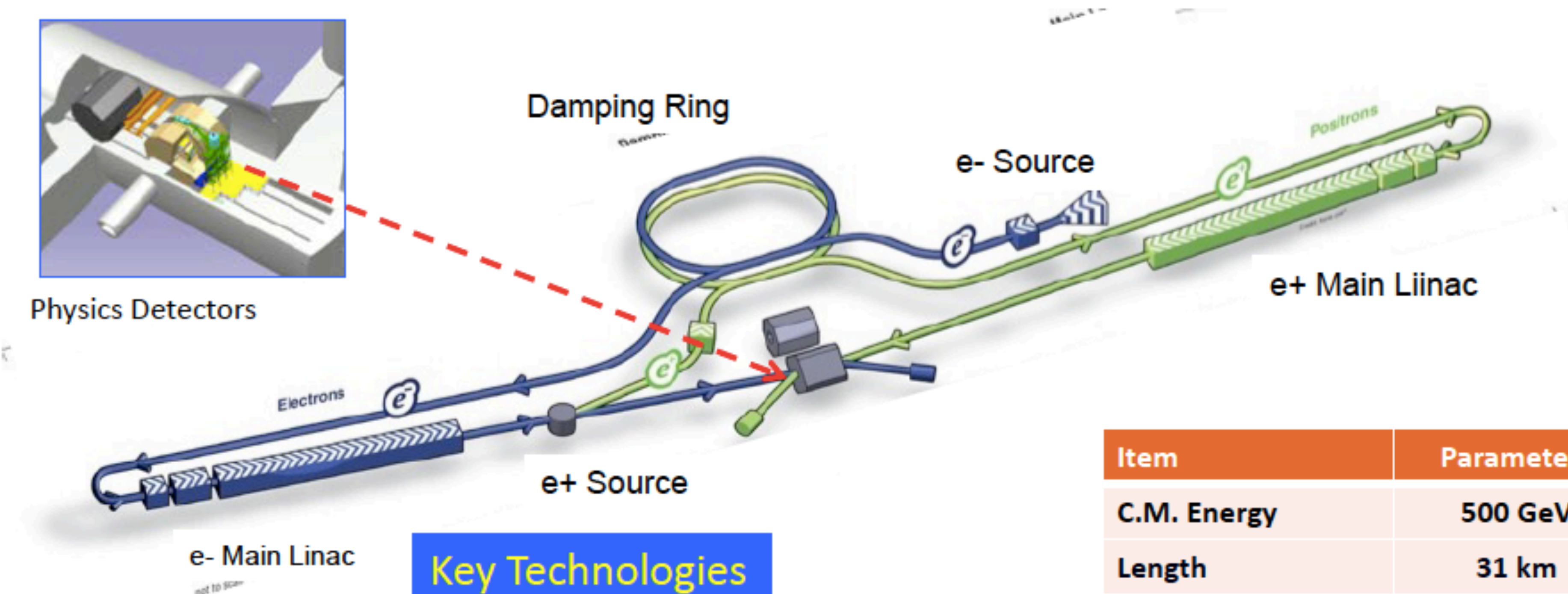
总价（万元）100公里
3606984.81
2323610.85
250227.56
32635.00
1000511.40

($5.3B)

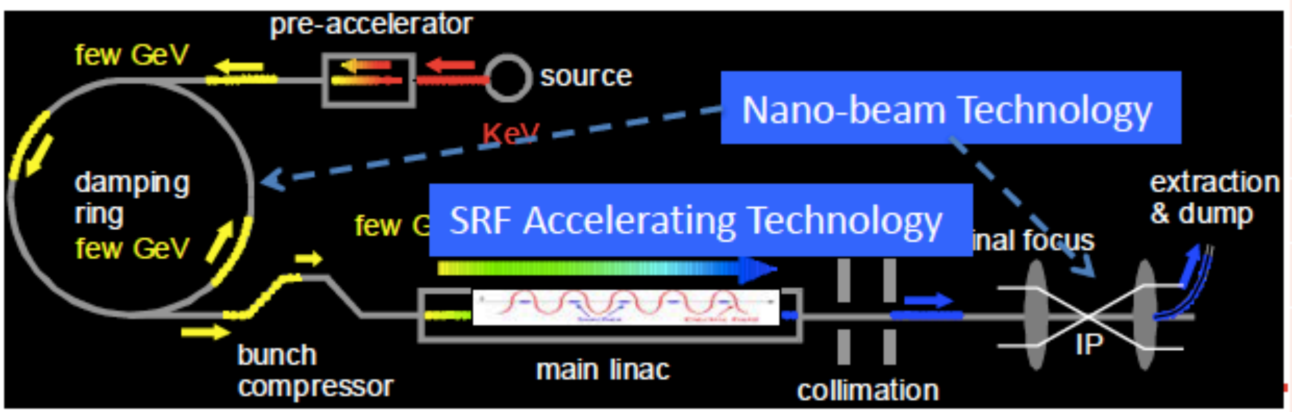
FCCee unknown

W. Chou, IAS, HK, 2017

ILC Acc. Design Overview (TDR)



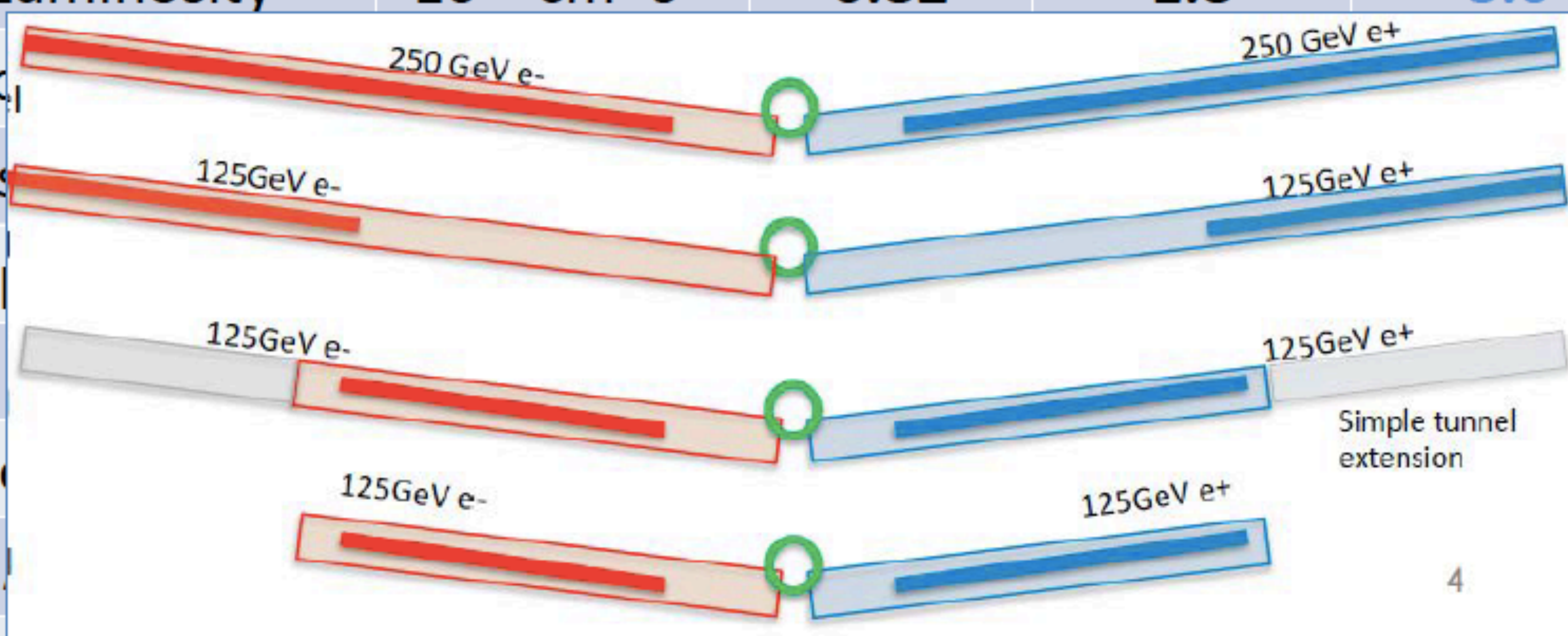
Key Technologies



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10^{10}

ILC Staging to be studied

	Unit	ILC		
CoM. Energy	GeV	**250**	**500**	1,000
Site Length	km	**~21**	**31**	50
Luminosity	10^{34} cm^{-2}s^{-1}	**0.82**	**1.8**	3.6
Ac				5
Res				
Re				
IR,				
B				6
Value Cost in TDR	BILC	**TBD**	**7.98**	TBD

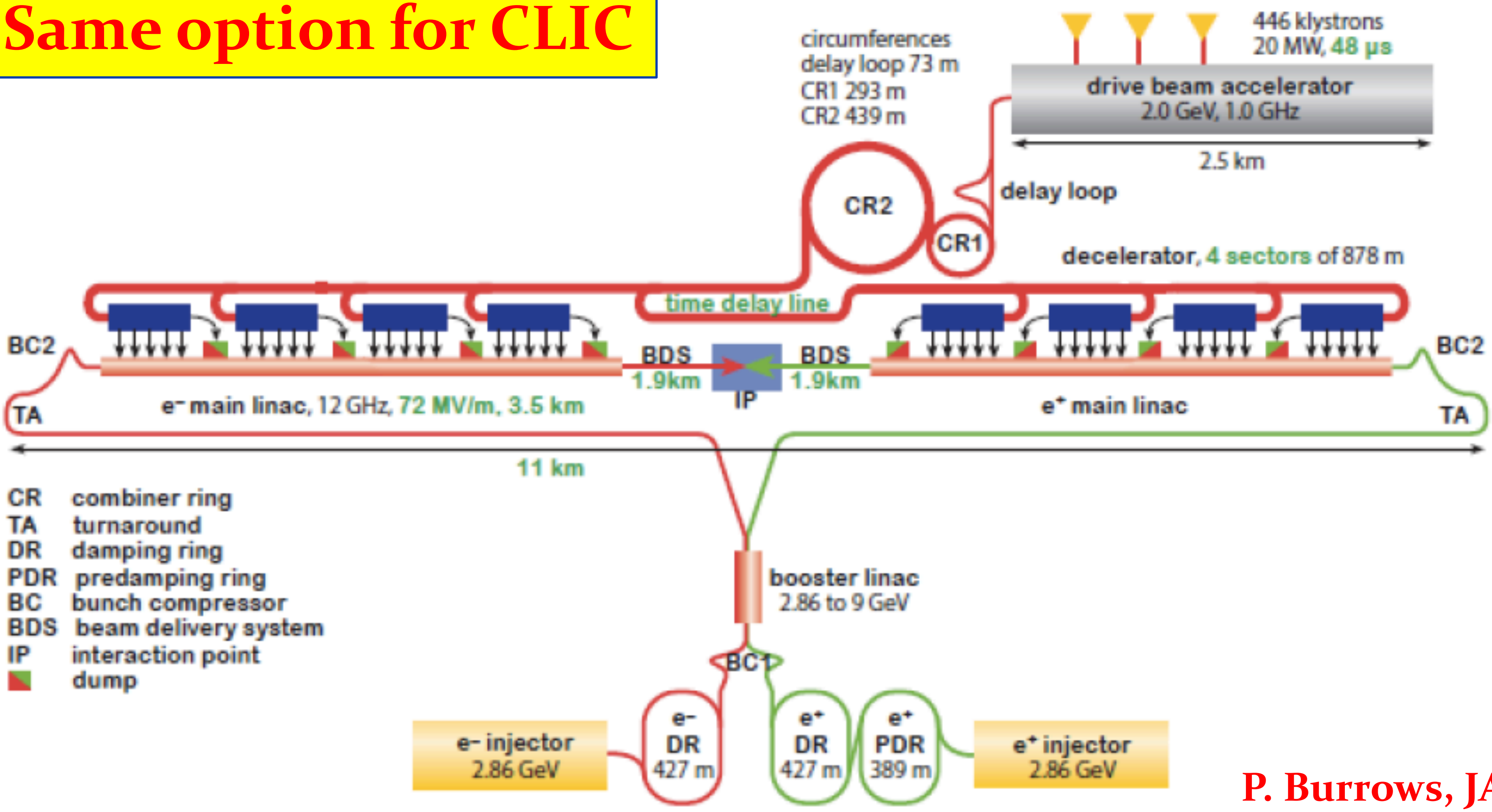


ILC staging

- Strong demand for cost reduction
- Improvement of Linac technology under study (however cost reduction 10-15% at most):
  - Higher gradient: 31 MV/m → 35 MV/m
  - Higher Q values: 10^{10} → 2×10^{10}
  - Nitrogen infusion developed at FNAL
- Staging is the option: start at 250 GeV c.m.
- Luminosity simply scaled at lower E is low (0.82×10^{34})→ needs a "real" 250 GeV design!
- Can be doubled by doubling Nbunch (1312 → 2625)
- Another factor of 2 for 10Hz collision (5 Hz for collision, 5Hz for e+ production)
- Positron source with undulator not suitable at low E → conventional? (but not polarized)
- Debating if 500 GeV or 250 GeV tunnel

New CLIC layout 380 GeV

Same option for CLIC



P. Burrows, JAS

CLIC staging

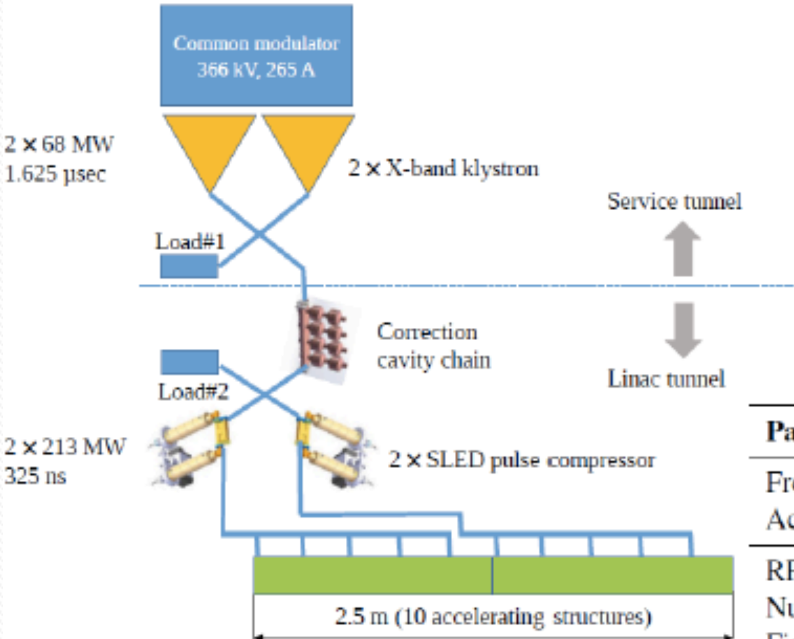
- Optimize cost and power consuption
- Produce optimized, staged design: 380 GeV (optimized for H and top) → 1.5 TeV → 3 TeV (exact choice depends on LHC findings)
- Support efforts to develop high-efficiency klystrons
- Consolidate high-gradient structure test results
- Choose new staged parameter sets, with corresponding upgrade path, considering the possibility to have a klystron-powered initial stage

Current rebaselined parameters

Table 8: Parameters for the CLIC energy stages. The power consumptions for the 1.5 and 3 TeV stages are from the CDR; depending on the details of the upgrade they can change at the percent level.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{pulse}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	µm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589

Klystron version (380 GeV)

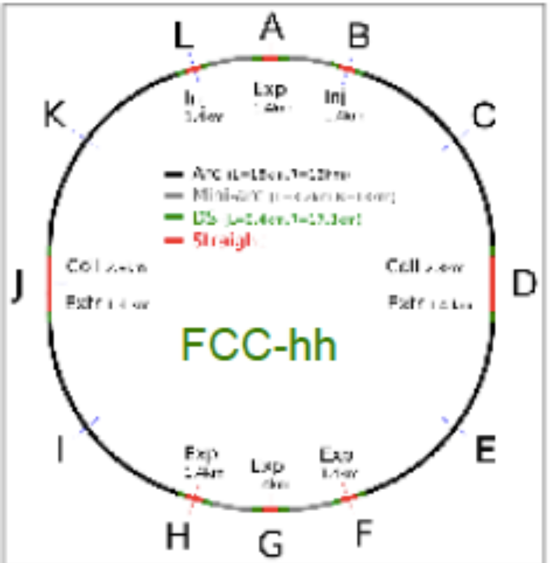


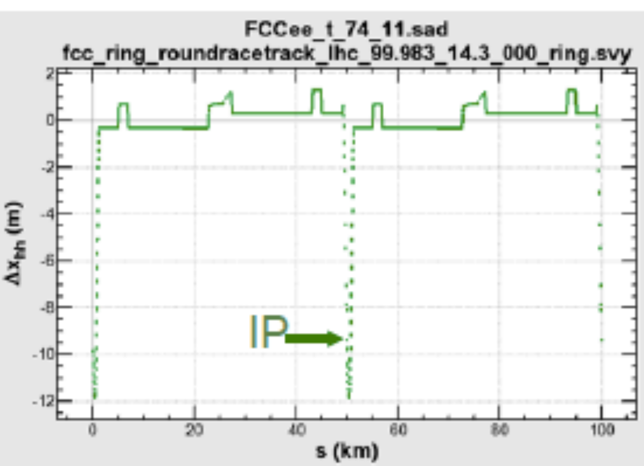
Costings relative to drive-beam version may be lower ~ 5%

Table 12: The parameters for the structure designs that are detailed in the text.

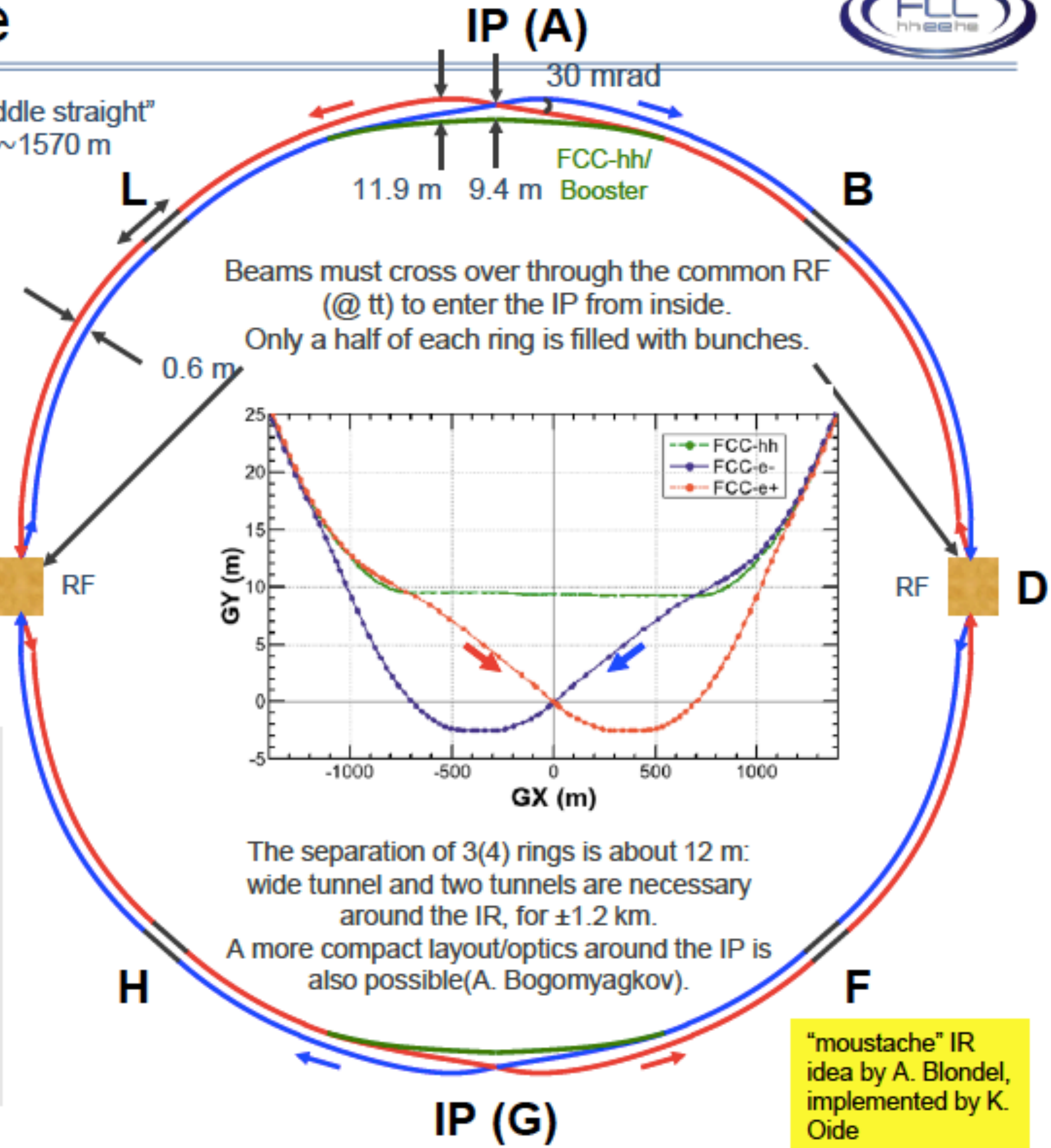
Parameter	Symbol	Unit	DB	K	DB244	K244
Frequency	f	GHz	12	12	12	12
Acceleration gradient	G	MV/m	72.5	75	72	79
RF phase advance per cell	$\Delta\phi$	°	120	120	120	120
Number of cells	N_c		36	28	33	26
First iris radius / RF wavelength	a_1/λ		0.1525	0.145	0.1625	0.15
Last iris radius / RF wavelength	a_2/λ		0.0875	0.09	0.104	0.1044
First iris thickness / cell length	d_1/L_c		0.297	0.25	0.303	0.28
Last iris thickness / cell length	d_2/L_c		0.11	0.134	0.172	0.17
Number of particles per bunch	N	10^9	3.98	3.87	5.2	4.88
Number of bunches per train	n_b		454	485	352	366
Pulse length	τ_{RF}	ns	321	325	244	244
Peak input power into the structure	P_{in}	MW	50.9	42.5	59.5	54.3
Cost difference (w. drive beam)	$\Delta C_{w.\,DB}$	MCHF	-50	(20)	0	(20)
Cost difference (w. klystrons)	$\Delta C_{w.\,K}$	MCHF	(120)	50	(330)	240

Layout of FCC-ee





Relative distance to FCC-hh



"moustache" IR idea by A. Blondel, implemented by K. Oide

Design constraints & assumptions (FCC-ee)

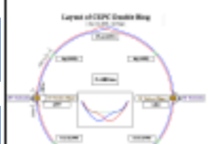
- C = 100 km, needs to fit to the FCC-hh tunnel and footprint as much as possible.
- 2 IPs / ring.
- 30 mrad crossing angle at the IP with crab waist.
- Common lattice for all energies (except for detector solenoid).
- $\varepsilon_x \leq$ 1.3 nm @ 175 GeV, scaling with energy at other points.
- $\pm$2% momentum acceptance at 175 GeV to mitigate beamstrahlung.
- Vertical emittance less than 2.5 pm at 175 GeV before collision.
- $\beta_{x,y}^*$ = (1 m, 2 mm) at 175 GeV, (0.5 m, 1 mm) at 45.6 GeV as the baseline.
- Critical energy of SR to the IP up to ~500 m upstream below 100 keV. No dipole magnets 100m upstream from the IP.
- "tapering" to cure the sawtooth at high energy.

K. Oide

lepton collider parameters

parameter	FCC-ee					(LEP2)
physics working point	Z		WW	ZH	tt_{bar}	
energy/beam [GeV]	45.6		80	120	175	105
bunches/beam	30180	91500	5260	780	81	4
bunch spacing [ns]	7.5	2.5	50	400	4000	22000
bunch population [10^{11}]	1.0	0.33	0.6	0.8	1.7	4.2
beam current [mA]	1450	1450	152	30	6.6	3
luminosity/IP x $10^{34}cm^{-2}s^{-1}$	210	90	19	5.1	1.3	0.0012
energy loss/turn [GeV]	0.03	0.03	0.33	1.67	7.55	3.34
synchrotron power [MW]	100					22
RF voltage [GV]	0.4	0.2	0.8	3.0	10	3.5
rms cm *E* spread SR [%]	0.03	0.03	0.05	0.07	0.10	0.11
rms cm *E* spread SR+BS [%]	0.15	0.06	0.07	0.08	0.12	0.11

CEPC option characteristics comparison

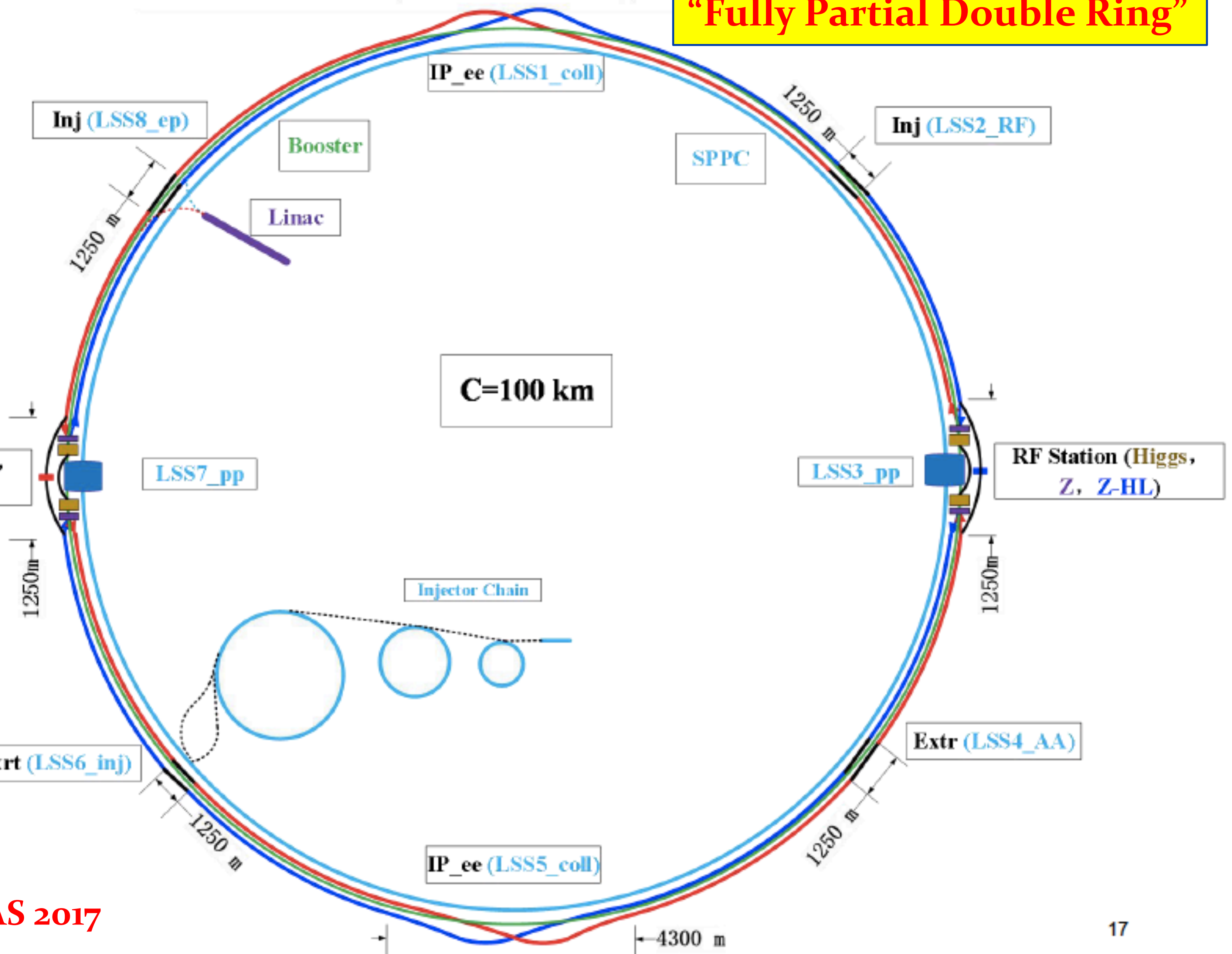
Option	Pretzel	Sawtooth effect	Beam loading	Dynamic Aperture	Orbit Correction	H luminosity	Z-pole luminosity	AC power	SRF syetem compatible for H and Z
 Single Ring (SR)	Yes ★	Very high ★	Low ★★★★★	Very small ★	Very hard ★	Low ★★★	Very low ★	High ★	Difficult ★★★
 Partial Double Ring（PDR）	No ★★★★★	High ★★	Very High ★	Medium ★★★	Hard ★★	Medium ★★★	Medium ★★★	Low ★★★★★	Difficult ★★★
 Advanced Partial Double Ring （APDR）	No ★★★★★	High ★★★	High ★★★	Medium ★★★	Medium ★★★	Medium ★★★	High ★★★★	Low ★★★★★	Difficult ★★★
 Full Parrtial Double Ring （FPDR）	No ★★★★★	Vey Low ★★★★★	Low ★★★★★	Large ★★★★★	Easy ★★★★★	High ★★★★★	Very High ★★★★★	Low ★★★★★	Very good ★★★★★

Different layout options considered

Layout of CEPC-SPPC

(Jan. 18, 2017, Su Feng)

"Fully Partial Double Ring"



J. Gao, IAS 2017

CEPC parameters for FDPR (2017)

	Pre-CDR	H-high lumi.	H-low power	W	Z	
Energy (GeV)	120	120	120	80	45.5	45.5
Circumference (km)	54	100	100	100	100	100
SR loss/turn (GeV)	3.1	1.67	1.67	0.33	0.034	0.034
N_e/bunch (10^{11})	3.79	1.12	1.12	1.05	0.46	0.46
Bunch number	50	555	333	1000	16666	65716
SR power /beam (MW)	51.7	50 !!	30	16.7	12.7	50
β_{IP} x/y (m)	0.8/0.0012	0.3/0.001	0.3/0.001	0.1 /0.001	0.12/0.001	0.12/0.001
Emittance x/y (nm)	6.12/0.018	1.01/0.0031	1.01/0.0031	2.68/0.008	0.93/0.0049	0.93/0.0049
ξ_x/ξ_y/IP	0.118/0.083	0.029	0.029	0.0082/0.055	0.0075/0.054	0.0075/0.054
RF Phase (degree)	153.0	0.083	0.083	149	160.8	160.8
V_{RF} (GV)	6.87	2.0	2.0	0.63	0.11	0.11
f_{RF} (MHz) (harmonic)	650	650	650	650 (217800)	650 (217800)	
Nature σ_z (mm)	2.14	**2.72**	**2.72**	**3.8**	**3.93**	**3.93**
Total σ_z (mm)	2.65	2.9	2.9	3.9	4.0	4.0
HOM power/cavity (kw)	3.6 (5cell)	0.75(2cell)	0.45(2cell)	1.0 (2cell)	1.6(1cell)	6.25(1cell)
Energy acceptance (%)	2	1.5	1.5			
Energy acceptance by RF (%)	6	1.8	1.8	1.5	1.1	1.1
Life time due to beamstrahlung_cal (minute)	47	52	52			
L_{max}/IP ($10^{34}cm^{-2}s^{-1}$)	2.04	5.42	3.25	4.08	18.0	70.97

Issues and challenges for future (Beam dynamics related)

- Dynamic aperture
- FF Non-Linearities
- Crab Waist sextupoles effect on DA
- Beam-beam with Space Charge, NL, CW
- Beam lifetime with BB, CW
- Backgrounds shielding (also technical!)
- e-cloud mitigation (also technical!)
- Saw-tooth orbit with energy
- Injection induced oscillations at IP
- ....

Issues and challenges for future (Technology related)

- Magnets (warm/cold SC, IR doublets, SC wires)
- Radiation damage on magnets
- HOMs in beam pipe
- SRF cavities
- Injectors (high reliability)
- Positron source (high number of e^+, polarization?)
- Beam pipe (material, vacuum, design,…)
- High efficiency klystrons
- High field accelerating sections (X-band, …)
- SRF cavities (single/multi-cells, cryogenics, 400/650/800 MHz)
- Energy saving options
- Civil Engineering
- Low field SC magnets for CEPC booster
- IP feedback and vibrations control
- …

FF Non-Linearities

- Kinematic terms and FF quads fringe fields introduce NL which affect beam dynamics
- Increase with low-β

K. Oide and H. Koiso, Phys. Rev. E47 (1993)
K. Ohmi and H. Koiso, IPAC'10 (2010)

$$J_y \leq \frac{\beta_y^{*2}}{(1+2|K|L^{*3}/3)L^*} A(\mu_y)$$

Ring	β_y^* (mm)	K1 (m^{-2})	L* (m)	J_y/A (mm)
SKEKB-HER	0,3	3,05	1,22	0,02
SKEKB-LER	0,27	5,1	0,76	0,03
CEPC	1,2	0,176	1,5	0,76
FCC-ee	1	0,336	2,2	0,22
KEKB	5,9	1,78	1,76	4,22
SuperB-HER	0,253	4,6	0,6	0,05
SuperB-LER	0,21	4,4	0,6	0,036

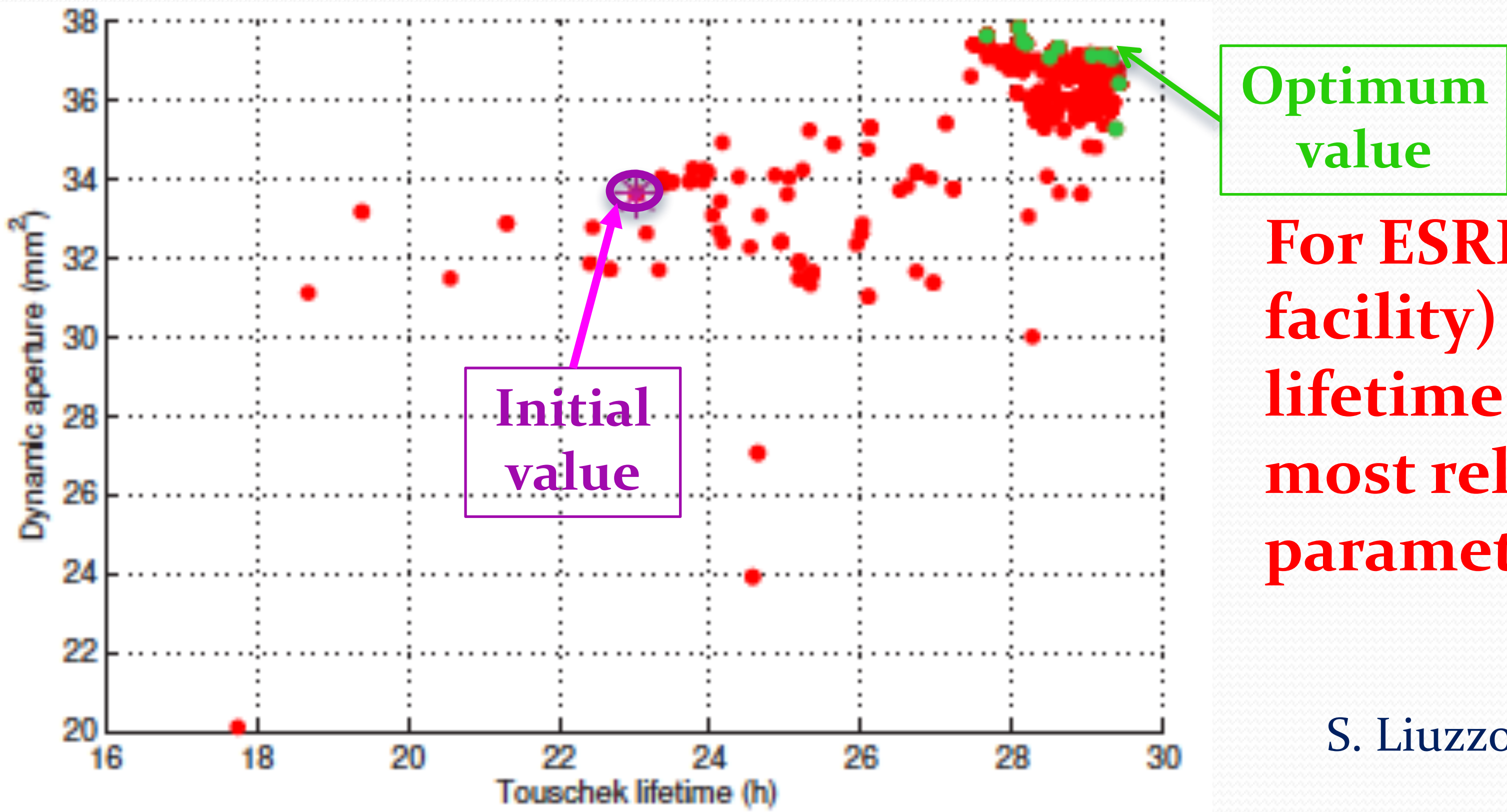
Should: increase β_y^*, decrease gradient and L*

Dynamic aperture

- Dynamic aperture is usually tight for low-emittance/high chromaticity rings
- Large "enough" DA and large energy acceptance are essential for lifetime, beam-beam, operational tune diagram
- FF nonlinearities reduce DA
- Beam-beam reduces DA
- Crab waist sextupoles are beneficial to bb BUT reduce DA
- Machine errors reduce DA
- New optimization methods seem to get good results:
  - Robust conjugate direction search method and particle swarm optimization method (Huang, SLAC)
  - Multi Objective Genetic Algorithm (used at NSLS-II, Yang, Li, et al.)
  - NSGA II (Non-dominated Sorted Genetic Algorithm 2, by Deb, Pratap, Agarwal, Meyarivan)

DA optimization @ ESRF

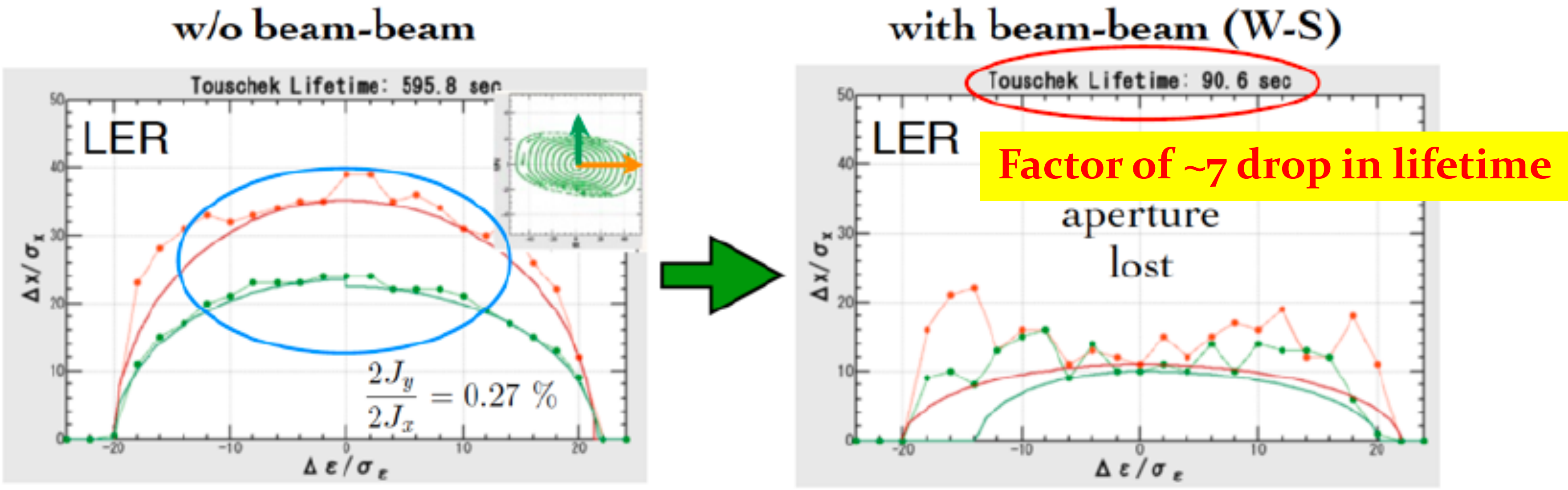
- Variables used for nonlinear optimization: chromaticities, sextupoles (six families) and octupoles (two families)
- Most relevant changes in linear optics include tunes and horizontal β function in the straight sections (IDs)



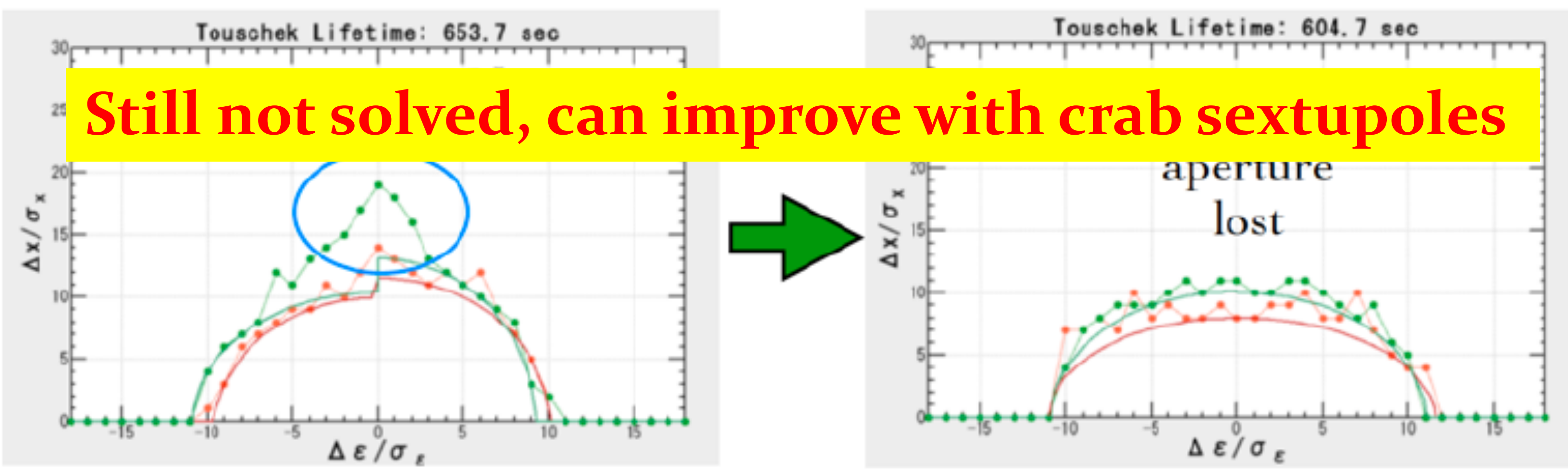
For ESRF (SL facility) Touschek lifetime is the most relevant parameter

S. Liuzzo, N. Carmignani

➤ DA and lifetime are sensitive to beam-beam interaction



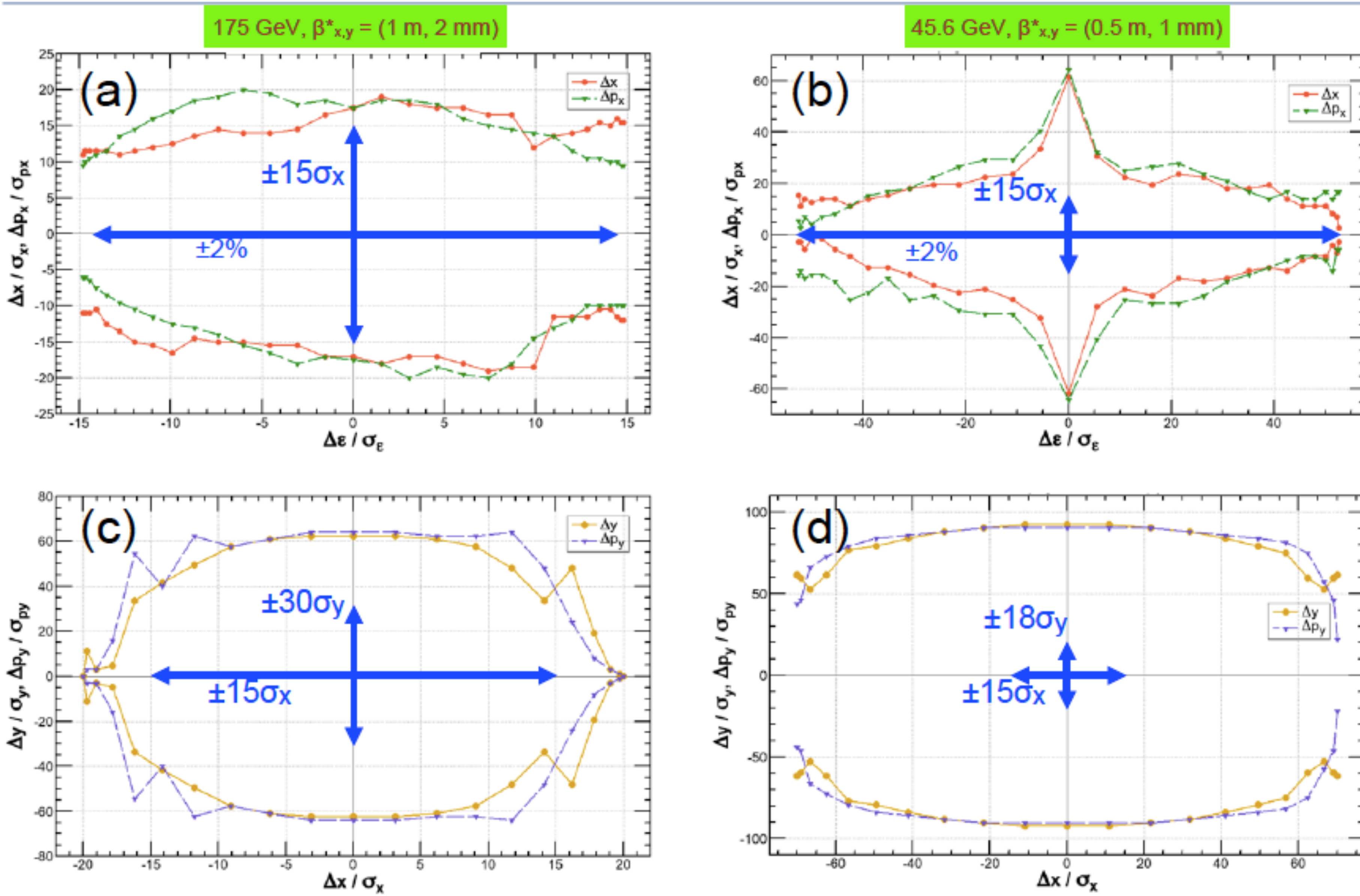
Transverse aperture is reduced significantly.



Effects included in the dynamic aperture study

Effects	Included?	Significance at $t\bar{t}$
Synchrotron motion	Yes	**Essential**
Radiation loss in dipoles	Yes	**Essential** – improves the aperture
Radiation loss in quadrupoles	Yes	**Essential** – reduces the aperture
Radiation fluctuation	Yes	**Essential**
Tapering	Yes	**Essential**
Crab waist	Yes	transverse aperture is reduced by $\sim 20\%$
Solenoids	Yes	minimal, if locally compensated
Maxwellian fringes	Yes	small
Kinematical terms	Yes	small
Beam-beam effects (strong-weak model)	Yes (D. Zhou)	affects the lifetime for $\beta_y^* = 1$ mm
Higher order fields/errors/misalignments	No	**Essential**, development of correction/tuning scheme is necessary

Dynamic Aperture satisfies the requirements



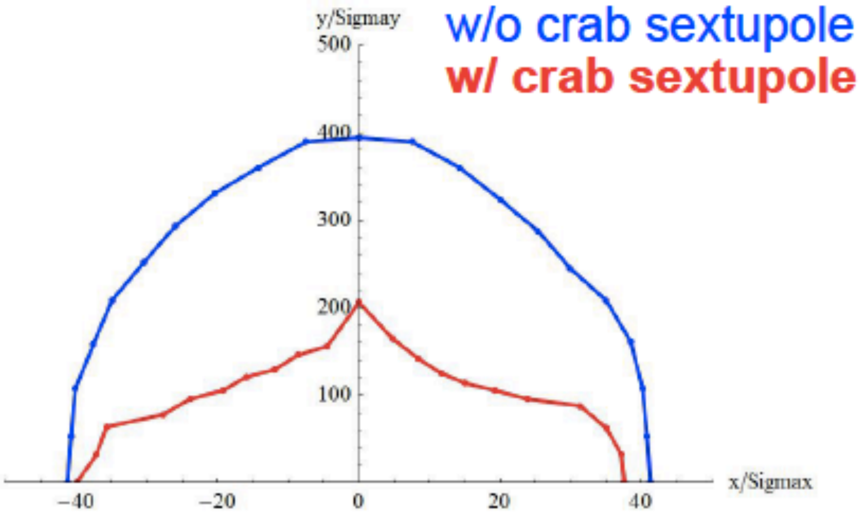
All effects in the previous slide are included except for radiation fluctuation and beam-beam, whose effects are found to be small.

CEPC

Dynamic aperture

Y. W. Wang

- Dynamic aperture study
  - Bare lattice
  - Synchrotron motion included
  - w/o damping
  - Tracking with around 1 times of damping time
  - Coupling factor κ=0.003 for εy
  - Working point (0.08, 0.22)
- Possible optimization for on-momentum DA
  - tune the beta functions @crab sextupoles to get a target DA shape $20\sigma x \times 40\sigma y$
- further work on DA study for double ring scheme is undergoing

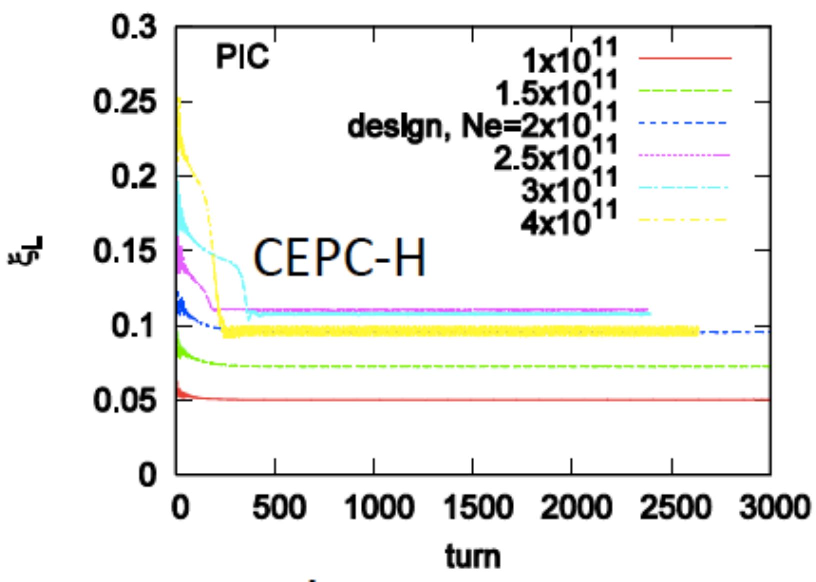


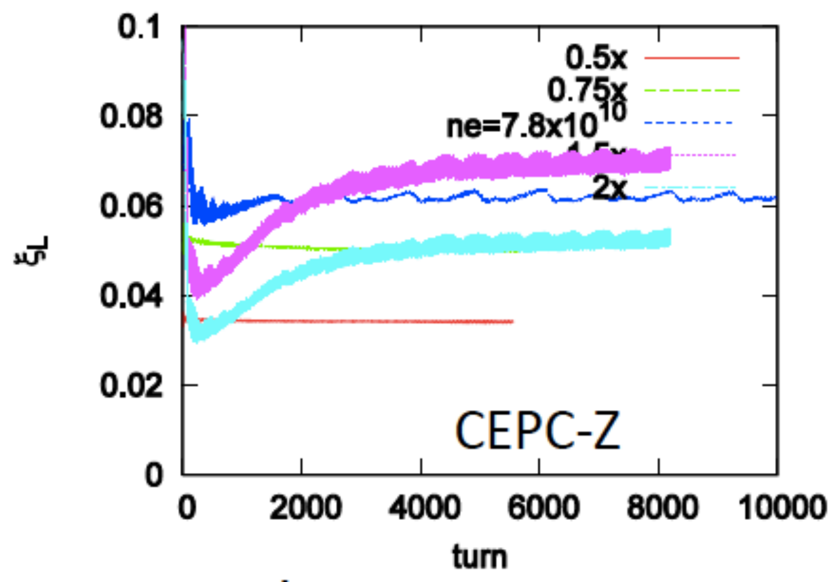
w/o crab sextupole
$40\ \sigma x \times 400\ \sigma y$
w/ crab sextupole (zero length)
$38\ \sigma x \times 180\ \sigma y$
On momentum DA is large enough to go ahead.

Beam-beam studies

Ohmi, Shatilov

- BB Strong-Strong simulations for FCCee and CEPC large angle collisions show a coherent bb instability with head-tail mode
- Will be experimentally studied at SuperKEKB
- Lower β_x^* in FCCee suppresses it: could need a revision of design parameters
- In CEPC: saturation of ξ_y, and Luminosity (slightly lower than design) fluctuates with high bunch current (critical for Z)





Space charge tune shift

- **Linear tune shift**
  - Same order for SC and BB
  - But have opposite signs

D. Zhou

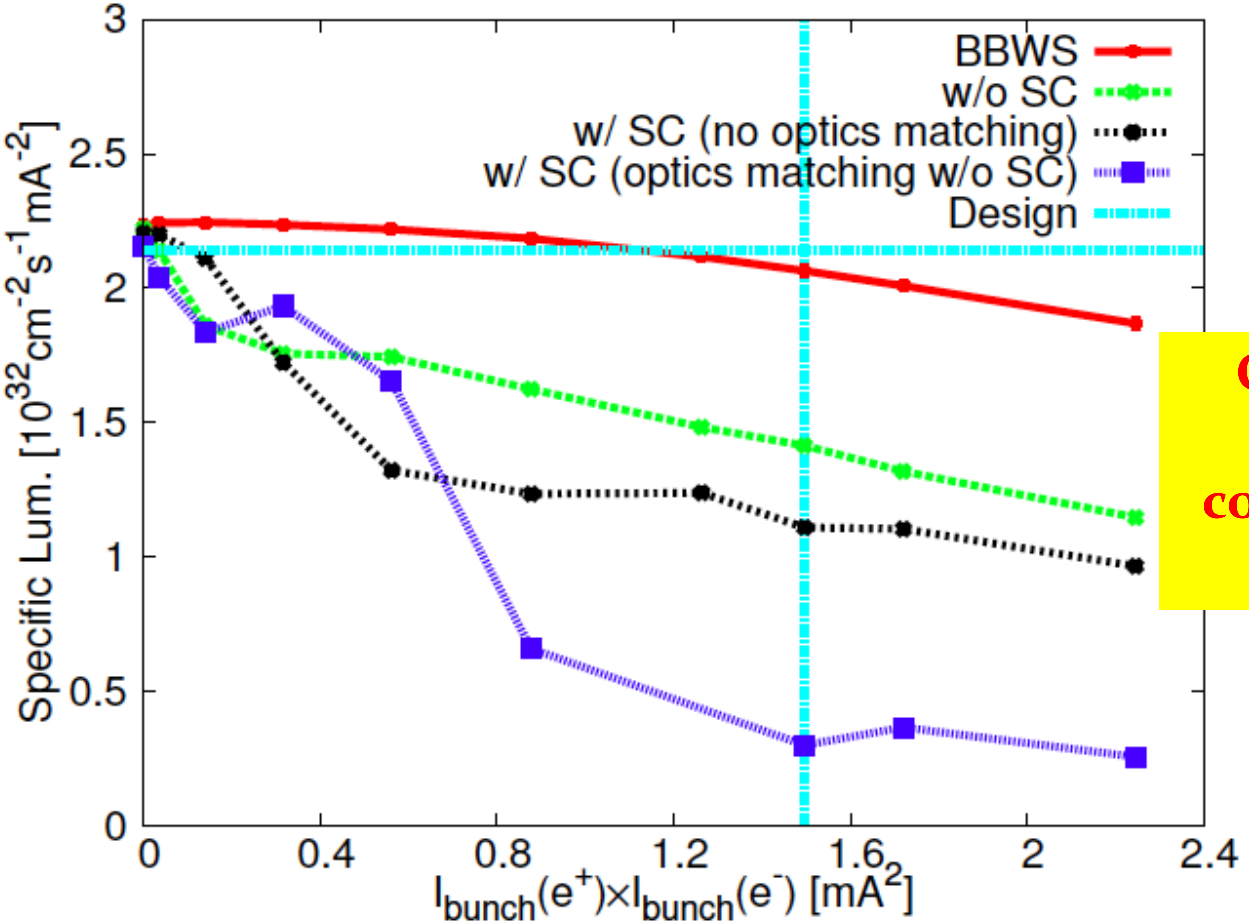
	SuperKEKB[1]		KEKB[4]	
	LER[2]	HER[3]	LER	HER
ε_x (nm)	3.2	4.6	18	24
ε_y (pm)	8.64	11.5	180	240
ξ_x	0.0028	0.0012	0.127	0.102
ξ_y	0.0881	0.0807	0.129	0.09
$\Delta\nu_x$	-0.0027	-0.0004	-0.0005	-3E-05
$\Delta\nu_y$	-0.0943	-0.0121	-0.0072	-0.0004

SuperKEKB LER luminosity with NL + SC + BB

D. Zhou

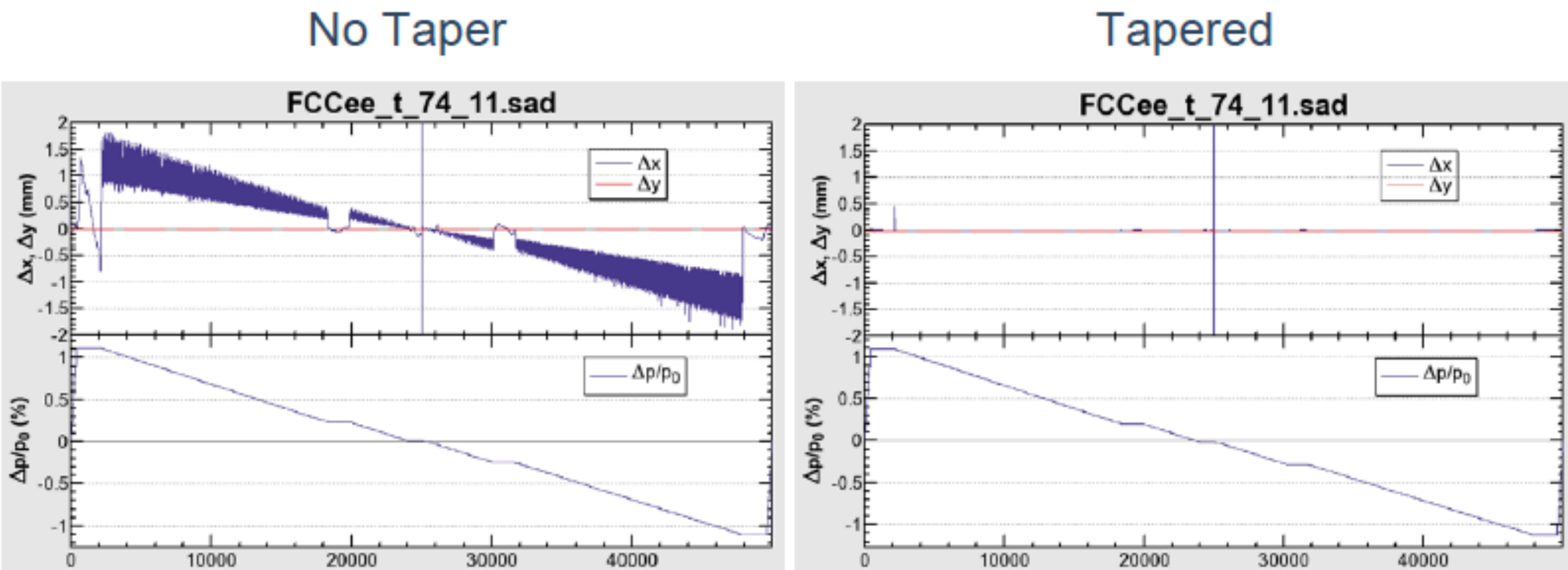
- **First try: optics matching w/o SC**
- **Compensate linear SC tune shift => Not successful**
- **Next try: optics matching w/ SC => Ongoing**

sler_1684



Chromatic XY coupling correction could help

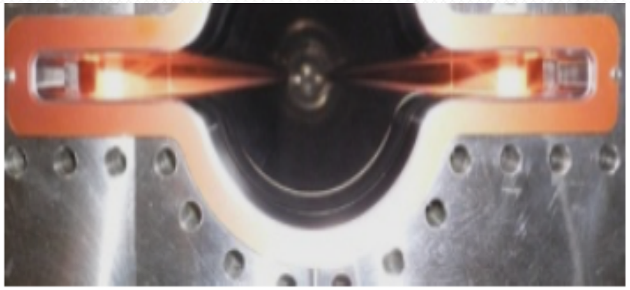
The Sawtooth & Tapering (FCC-ee @ 175 GeV)



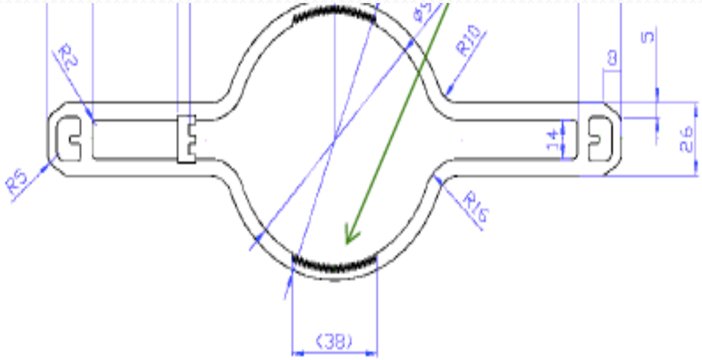
- The change of the orbit due to energy loss along the arc causes serious deformation on the optics, that results in loss of dynamic aperture.
- This can be cured by "tapering", i.e. scaling the strengths of magnets according to the local energy of the beam: this is an important advantage of a double-ring collider (F. Zimmermann).

E-cloud mitigation

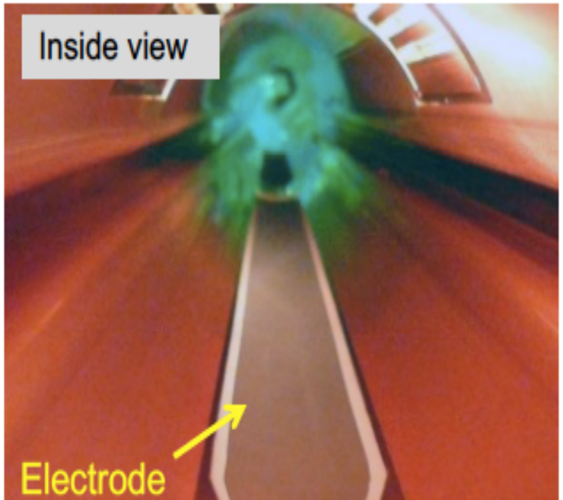
- To reduce Secondary Electron Yield (SEY): antechamber, solenoids, grooves, clearing electrodes, thin-films (e.g. titanium nitride, NEG-coating, amorphous carbon) or laser-ablated surface structures



Drift section: Antechamber + TiN coating



Arc Bend Cross Section



Drift section	Antechamber +Solenoid +TiN Coating
Q and Sx mag.	Antechamber +Solenoid +TiN Coating
Bend section	Antechamber +Groove+ TiN Coating
Wiggler section	Antechamber +Electrode (Cu)

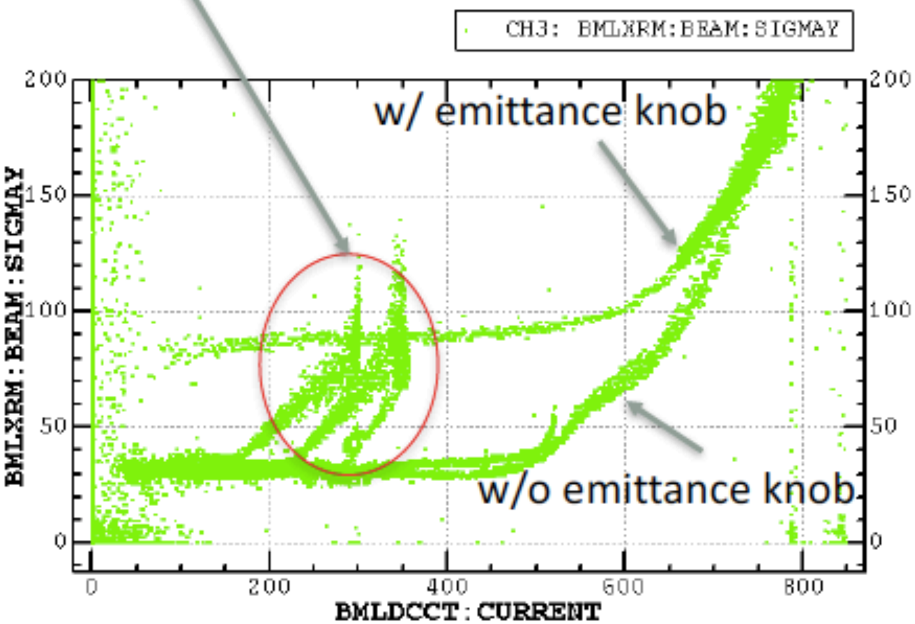
Wiggler section:

Antechamber + Clearing electrode

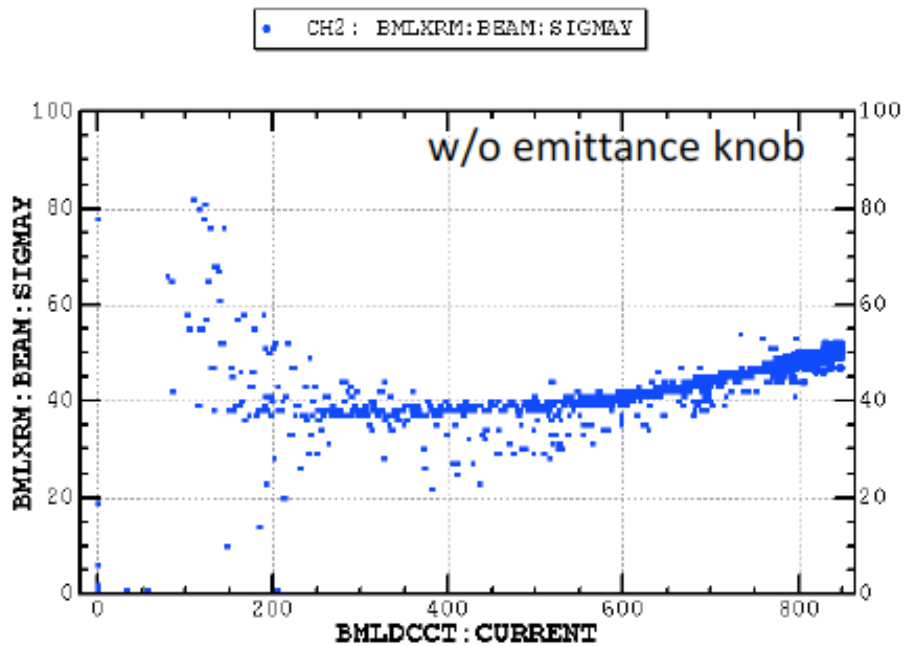
LER vertical beam size blowup

Measured at SuperKEKB Phase I

Blowup study with shorter bunch spacing



3.06 spacing (1576 bunches)



3.06 spacing (1576 bunches)

June 1st (before installation of solenoids at bellows chambers)

June 6th (after installation of solenoids at bellows chambers)

Before Phase 2, we will install solenoids at ante-chambers with TiN coating.

Beam lifetime at SuperKEKB

Radiative Bhabha	21.3h	9.0h	6.6h	4.5h	28min.	20min.
Beam-gas	45h[a)]	45h[a)]			24.5min.[b)]	46min.[b)]
Touschek	10h	-			10min.	10min.
Total	5.9h	7.4h	~133min.	~200min.	6min.	6min.
Beam current	2.6A	1.1A	1.6A	1.1A	3.6A	2.6A
Loss Rate	0.12mA/s	0.04mA/s	0.23mA/s	0.11mA/s	10mA/s	7.2mA/s

4nC@25Hz 2.9nC@25Hz

a) Bremsstrahlung

b) Coulomb scattering, sensitive to collimator setting

As for loss rate, beam loss accompanied with the beam injection should be added.

Top-up injection (continuous injection) is vital for SuperKEKB.

Injector should be upgraded to increase the bunch charges(e-/e+).

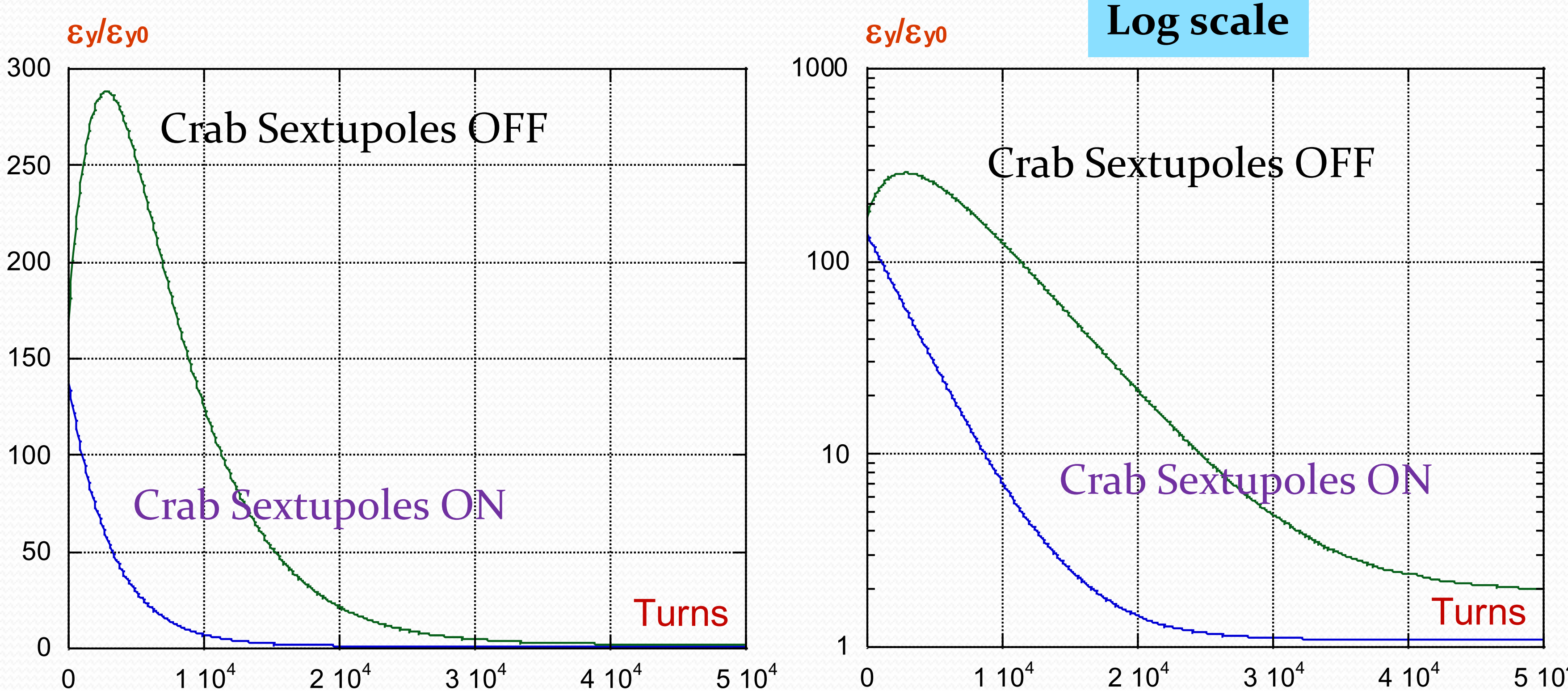
Injector complex issues

- Top-up requires high reliability and resistance to stresses (non stop operation)
- Photo-injector for low emittance/high charge electrons
- Damping Ring (electrons too?)
- High repetition rate
- Positron source (undulator, conventional, polarized)
- Control of injected beam oscillations at IP

Emittance evolution after injection, with and without crab sextupoles

Beneficial effect of crab sextupoles on vertical emittance during injection

Log scale



D.Shatilov

IR design and MDI

- One of the most difficult task
- Collaboration between detector and accelerator is crucial and trade off are mandatory:
  - L* (short for smaller quads aperture, large for detector and quads design,…)
  - Small crossing angle better but short space for quads on 2 beams
  - Luminosity monitor position and window
  - Masks design
  - Beam pipe design and material transitions
  - Trapped HOMs calculations

MDI issues (1)

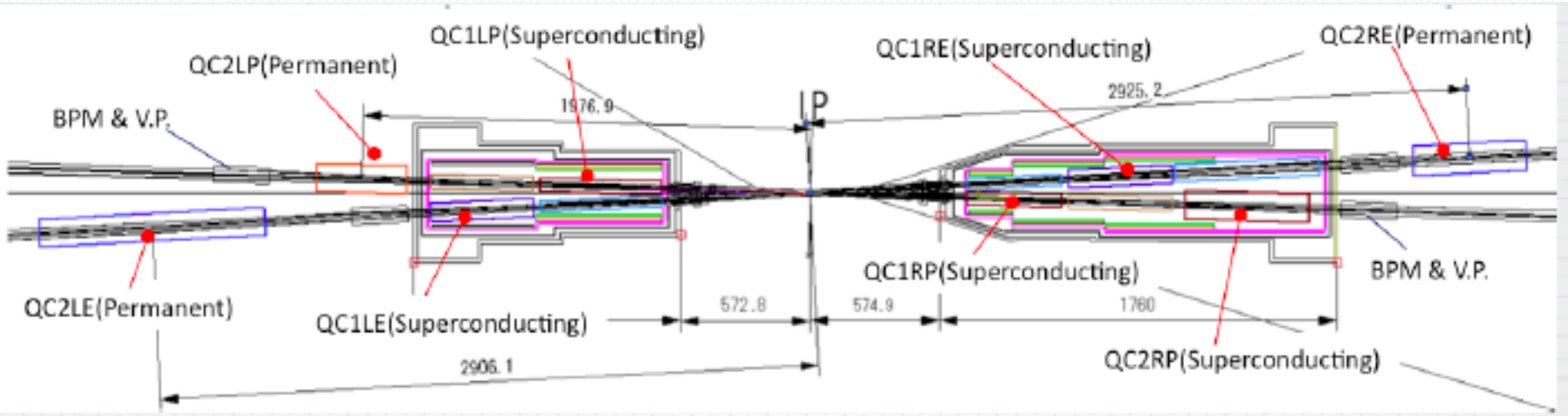
Recently addressed at
FCC-ee mini-workshop
CERN, 16-27 January 2017
(M. Boscolo et al)

- Lattice (betas, sextupole arrangements, quads non linearities)
- L* (distance IP-QD0)
- Beam pipe material (Be, Cu) (cold/warm) and thickness
- Beam pipe aperture and shape (round, elliptical)
- Shielding and masks (different sources of backgrounds, simulations with real layout)
- IR vacuum, water cooling, coating, HOM absorbers, (NEG, distributed pumping)
- IR trapped modes analysis (impedance budget)

MDI issues (2)

- Luminosity monitor design
- Solenoid compensation scheme
- Detector magnet layout and integration
- IR quadrupole design (single, split, pm, SC, modified Panofsky type, conventional *cosine-theta* design or *canted-cosine-theta* (CCT))
- IR collective effects, i.e. electron cloud, and mitigation (thin films or laser-ablated structures)
- Diagnostics (BPM, Beamstrahlung monitor, fast luminosity monitor)
- Beam stability (nano-beams, vibrations control)

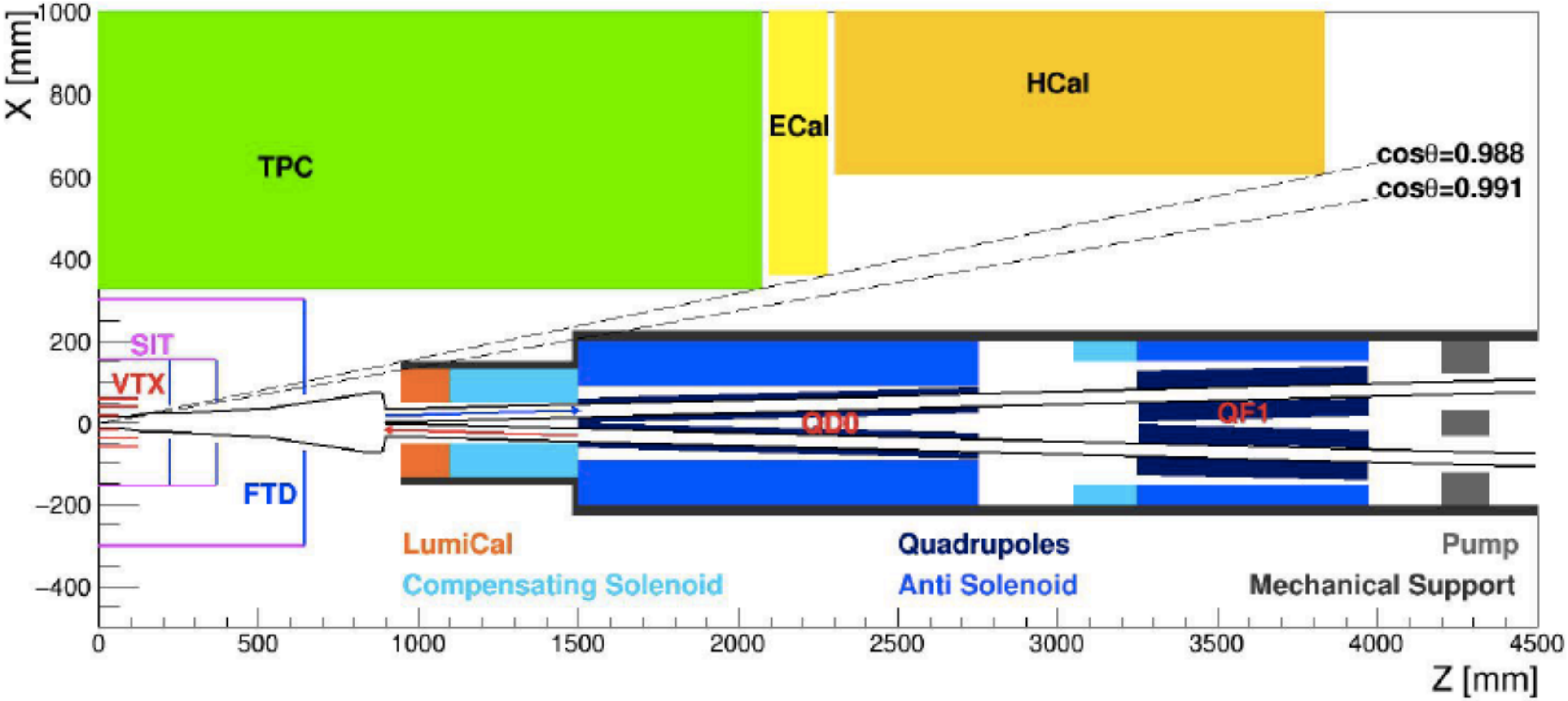
SuperKEKB Interaction Region scheme → real



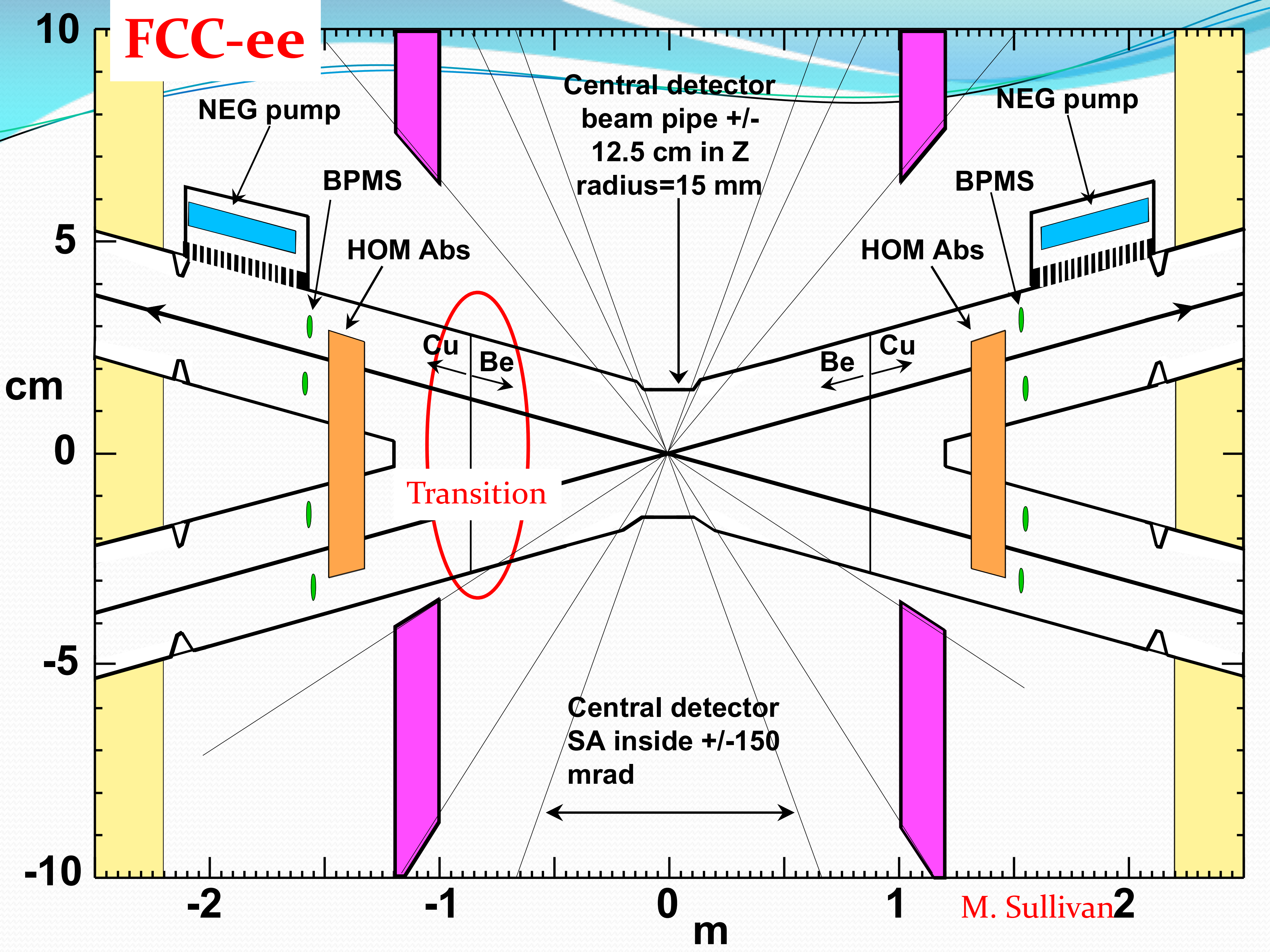
Very complicated

Preliminary Layout of CEPC IR

S. Bai



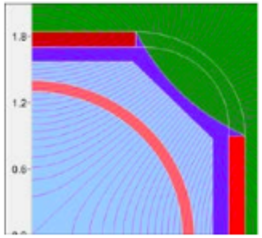
- $L^* = 1.5m$ @ $CEPC, (L^* \downarrow \rightarrow L \uparrow)$
- The crossing angle is 30 mrad in the double ring scheme
- Space are very tight for both the accelerator and the detector
  - Great challenge

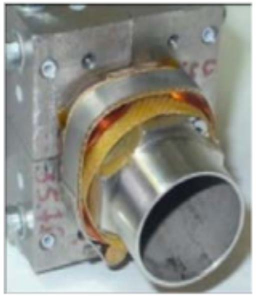

FCC-ee
10
5
0
-5
-10
cm
NEG pump
BPMS
HOM Abs
Central detector
beam pipe +/-
12.5 cm in Z
radius=15 mm
NEG pump
BPMS
HOM Abs
Cu
Be
Be
Cu
Transition
Central detector
SA inside +/-150
mrad
-2
-1
0
1
2
m
M. Sullivan

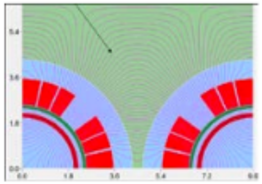
FF Quadrupoles

[H.Ten Kate, FCC-ee MDI, Jan. 2017]

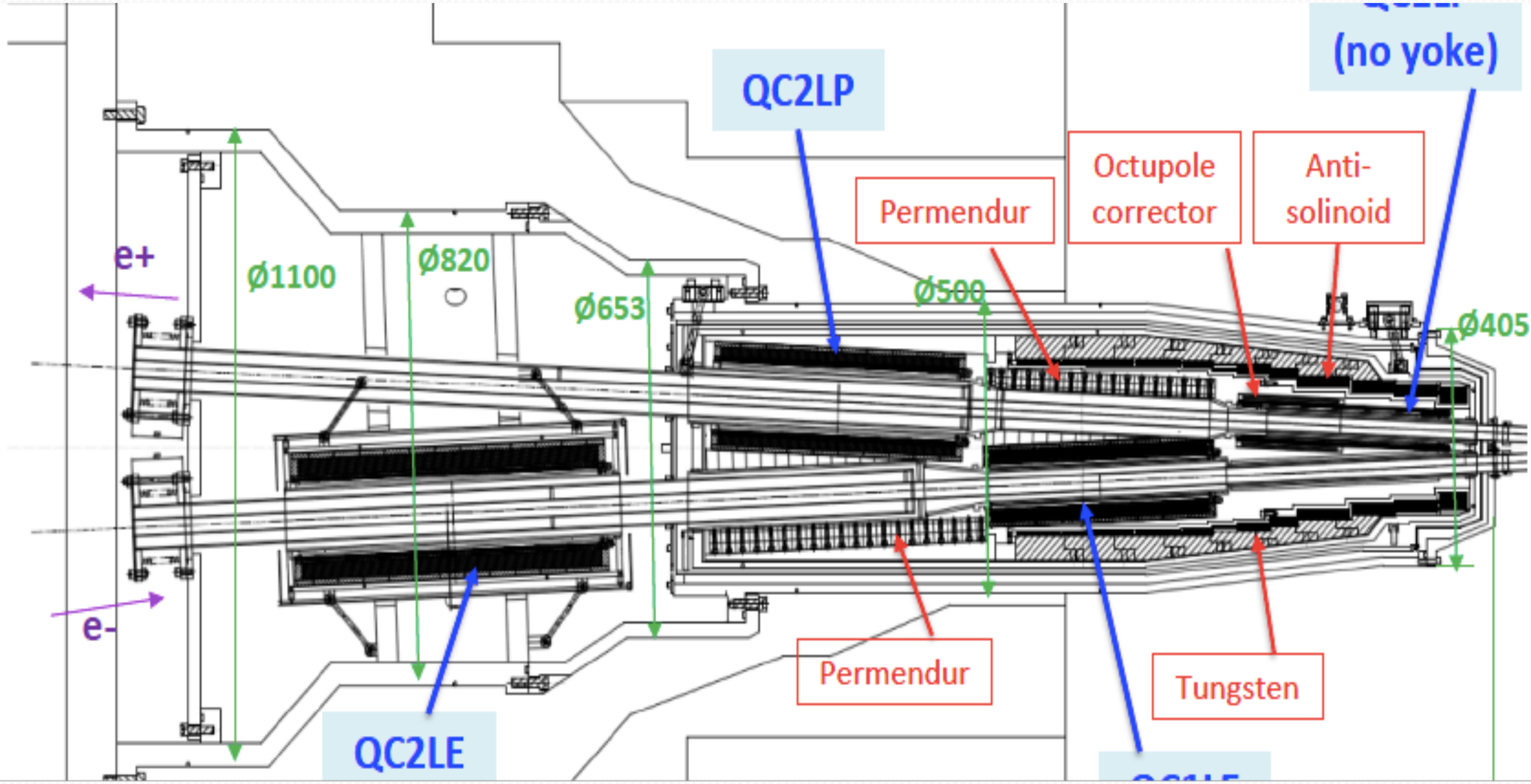
- Quads coil technology
  - We have seen BINP specific design with thin iron decoupling both quads, not requiring compensation. Gradient can be easily attained, and short demo coil produced. Looks simple and straightforward. A good baseline design to be approved.
  - Alternatively a no-yoke CCT design was proposed (M.K), yet to be demonstrated that dimensions can be equal or smaller and compensation for coupling can be implemented (to do).
  - For FF quads classical coils are proposed, not demonstrated for FCCee but reference is made to LHC standards.
  - Since from a coil point of view nothing is critical full size demonstration coils are not needed for the CDR (but short version recommended for CCT).





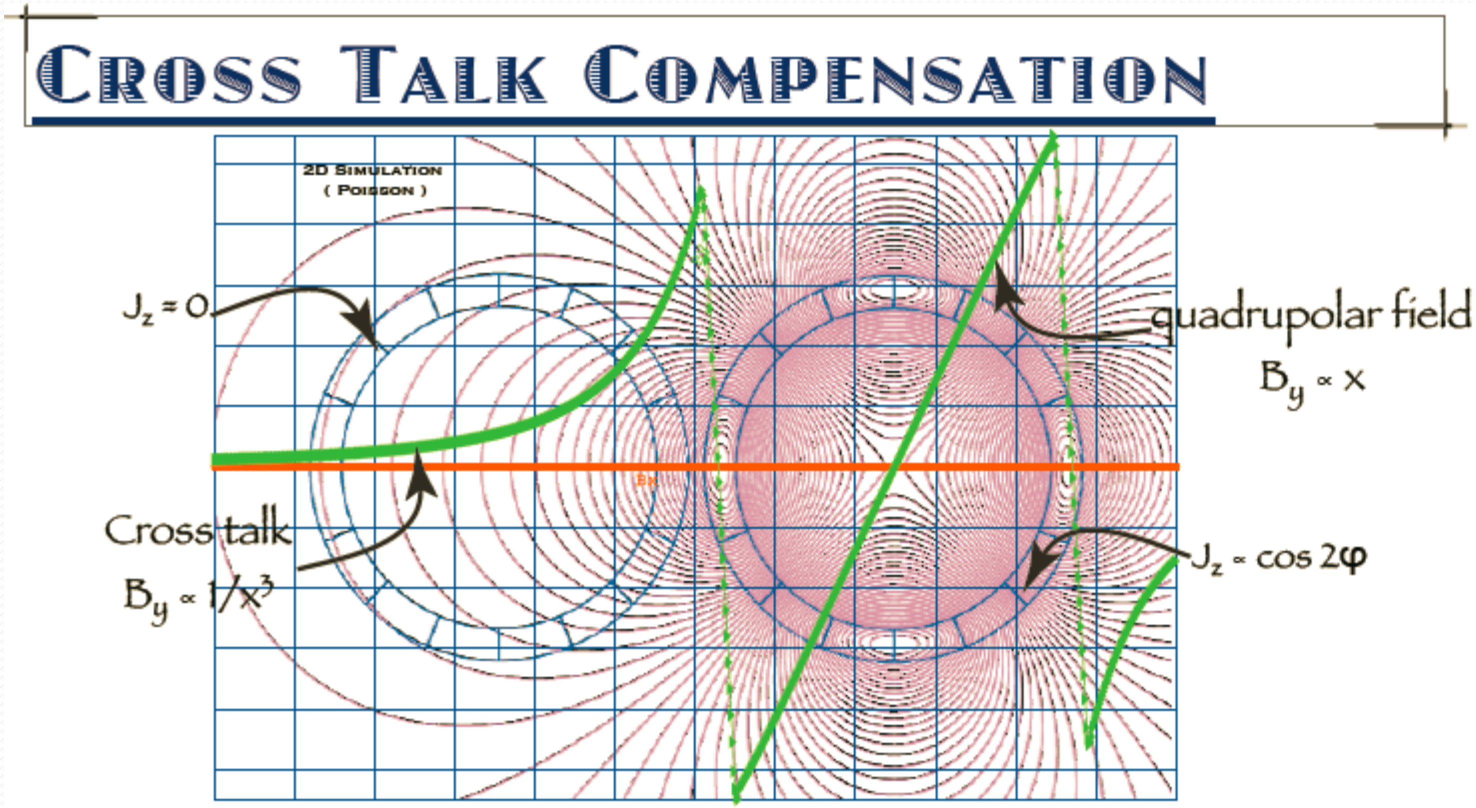


SuperKEKB QCS-L Magnets and Cryostat



SuperKEK

SuperB twin quads with helicoidal coils

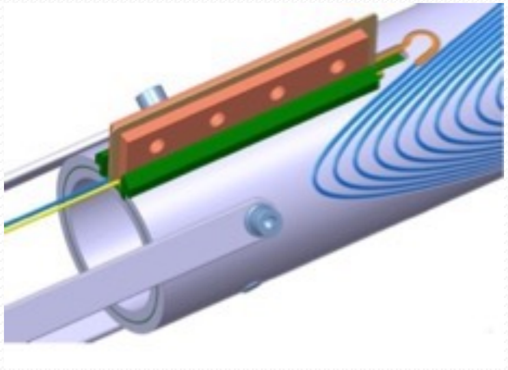
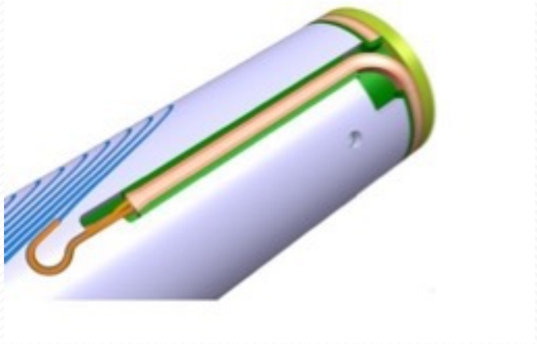
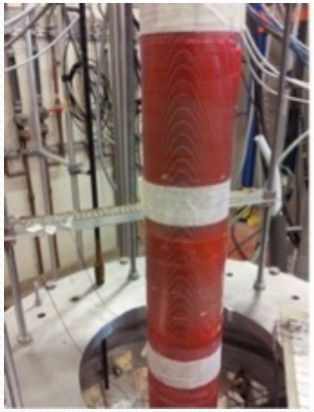


- Idea: exploit the superposition principle to design the coil shape in such a way that the integrated beam kick is a linear function of the displacement from the reference orbit

E.Paoloni, Univ. Pisa and INFN

SuperB

Construction of a model coil for addressing quench issues


Coil constructed at ASG Superconductors and successfully tested at 4.2 K at INFN-Ge and fed with a current of 2750 A
The limitation seems to be of mechanical nature (mechanical disturbances)
Further tests were planned but unfortunately the program was stopped when SuperB was not approved

P. Fabbricatore
INFN Genova

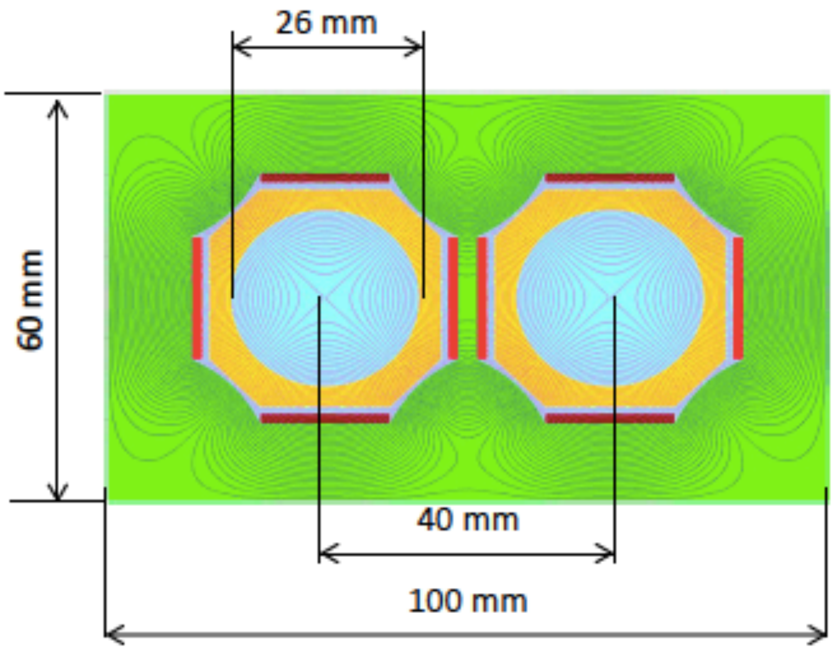
SuperB

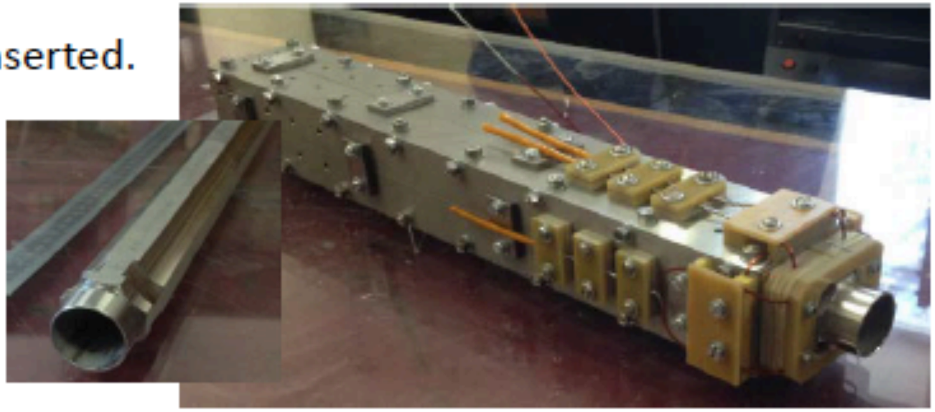
BINP Iron yoke twin-aperture quadrupole

Modified Panofsky type quadrupole was proposed originally by Pavel Vobly for the Super Charm Tau project in Novosibirsk.

Advantage – transversely very compact and can be placed close to the IP to intercept the beta growth; no influence to the adjacent quad; 100 T/m can be achieved in ∅26 mm; the field quality at R = 1 cm is ~10^{-4}.

Disadvantage – no correction coils can be inserted.





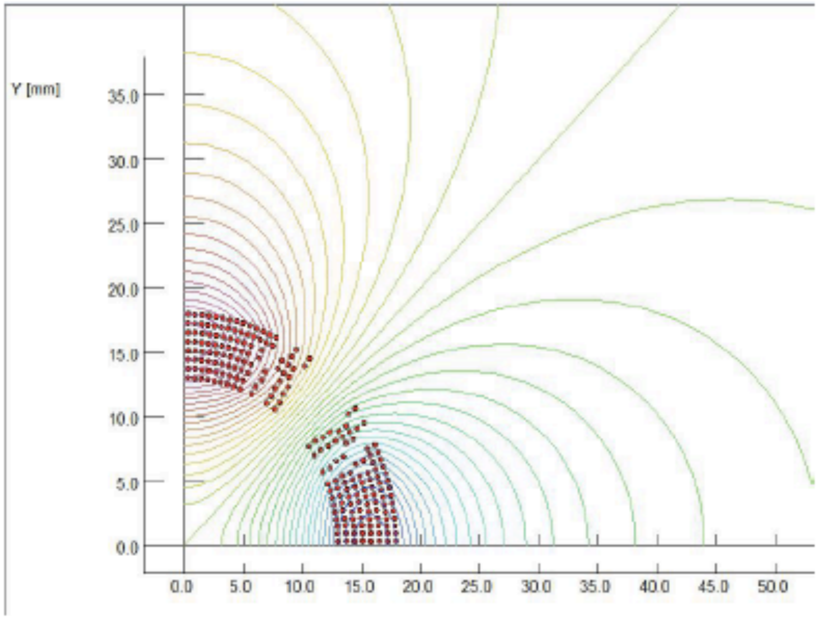
A 40-cm-prototype (+vacuum chamber) was built and cryo-tested at BINP. 1060 A was reached after 3 quenches.

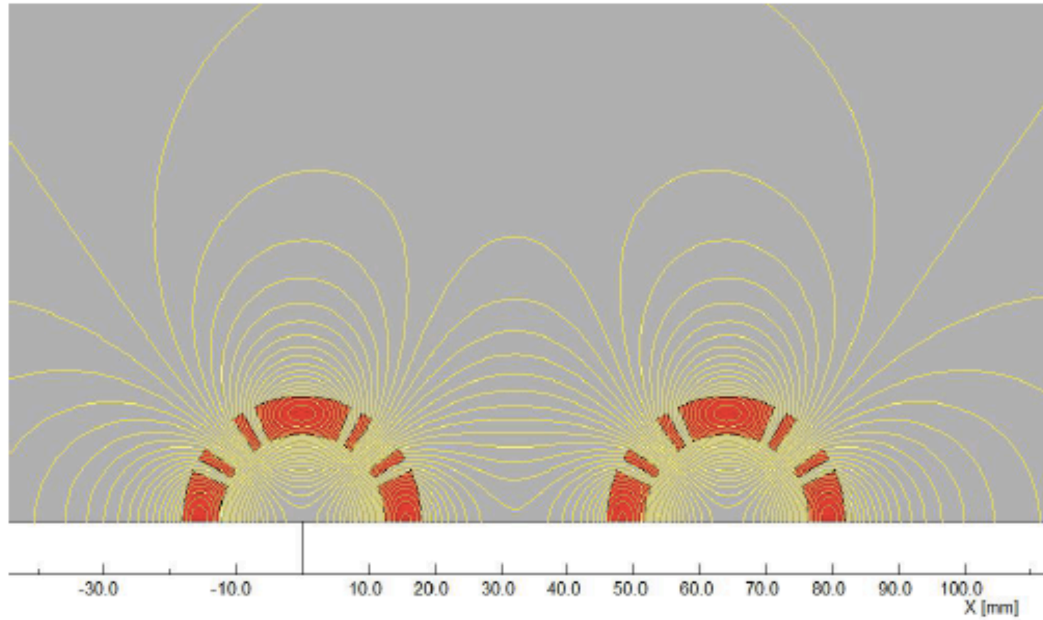
Main parameters:

Max.gradient 100 T/m	Max.current 1100 A
Length 40 cm	Aperture 2.6 cm
NbTi 1.8 x 1.4 mm^2	Saddle-type coils

Preliminary Design of QD0

By Yingshun Zhu





- The coils will be made of 0.5mm round NbTi-Cu conductor using direct winding technology.
- Eight Serpentine coil layers are used for the QD0 coil.
- The field in one aperture is affected due to the field generated by the coil in another aperture.
- Field cross talk of the two apertures is modelled and studied

CEPC

Technology:
reduce costs while improving performances

CEPC Accelerator Key technologies

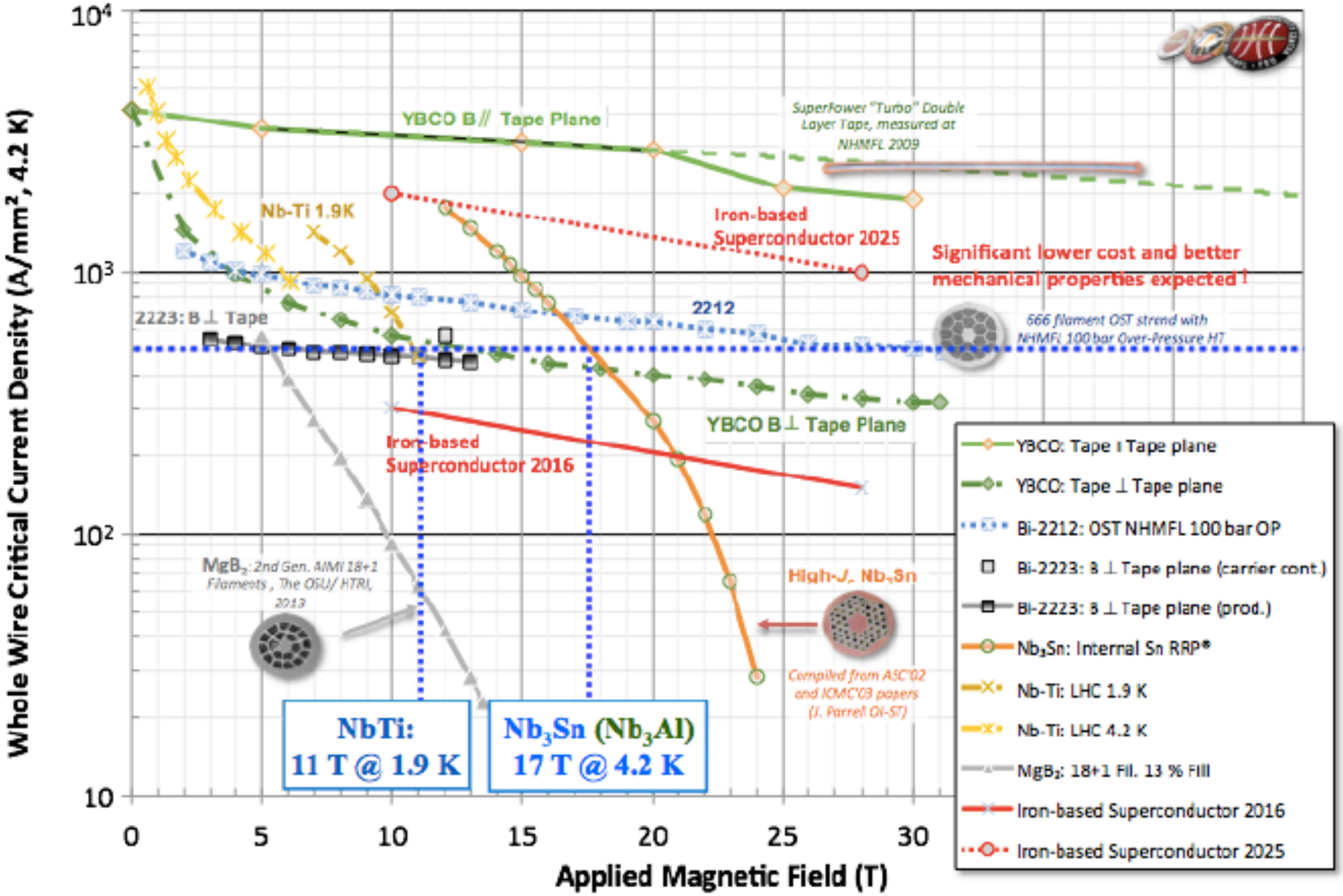
- Polarized electron gun
  - *Super-lattice GaAs photocathode DC-Gun*
- High current positron source
  - *bunch charge of ~3nC,*
  - *6Tesla Flux Concentrator peak magnetic field*
- High gradient accelerating tube
  - *30Mev/m for S-band structure*
  - *50Mev/m for C-band structure (option)*
- High Q SC Cavity and High power coupler
  - *Max operation Q0 = 2E10 @ 2 K*
  - *High power coupler: 300kW / 650MHz*
- High efficiency Klystron
  - *~ 80% goal for 650MHz klystron*
- Large Scale Cryogenics
  - *12 kW @4.5K refrigerator, Oversized, Custom-made, Site integration*

CEPC Accelerator Key technologies

- Low field dipole magnet
  - *Lmag=4m, Bmin=31Gs, Errors <5E-4*
- IR region QD0
  - *Field gradient 200T/m, magnetic length 1.46m*
  - *Central field 13T*
- Electro-static separator for deflect the e+ and e- bunches
  - *Maximum operating field strength: 20kV/cm*
  - *Maximum deflection: 145 urad*
- Vacuum system
  - *Dipole copper chamber*
  - *RF shielding bellows*
  - *NEG coating*

etc.

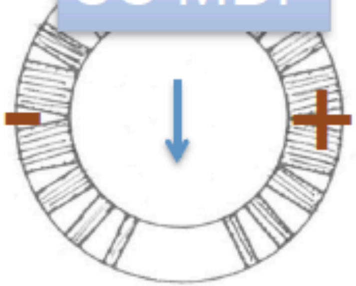
Superconductors (Q. Xu)



Challenge to the vendor: in 10-20 years, J_E x 10, cost ÷10

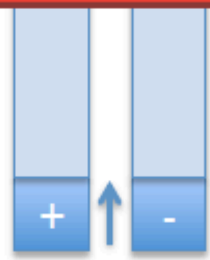
Efforts in US and China are complementary: focused on different structure concepts

US MDP



Cos(θ)
- Most common accelerator magnet concept
- Wedges used for field quality

China IHEP



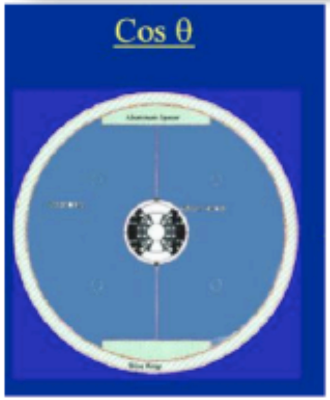
Common coil
- Starts with two racetracks=> simplicity
- “Naturally” provide two “beam pipes” for pp collider
- Field quality requires more complicated additional coils

CERN

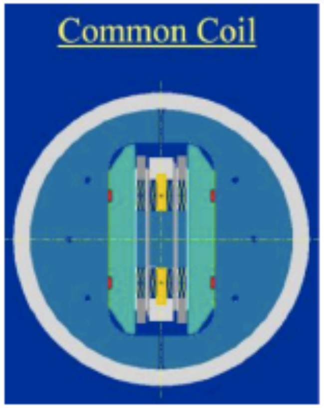
Block design
- Starts with two racetracks=> simplicity
- To get a beam through, need flared ends=>complications

US MDP

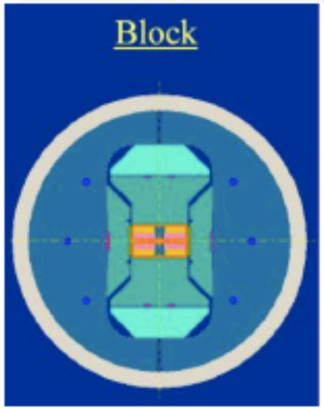
Canted Cos(θ)
- “Tilting” a solenoid winding results in Cos(θ) distribution, but need 2n layers to compensate the solenoid component
- Efficiency hit due to solenoidal compensation



D20
13.5T@1.9K



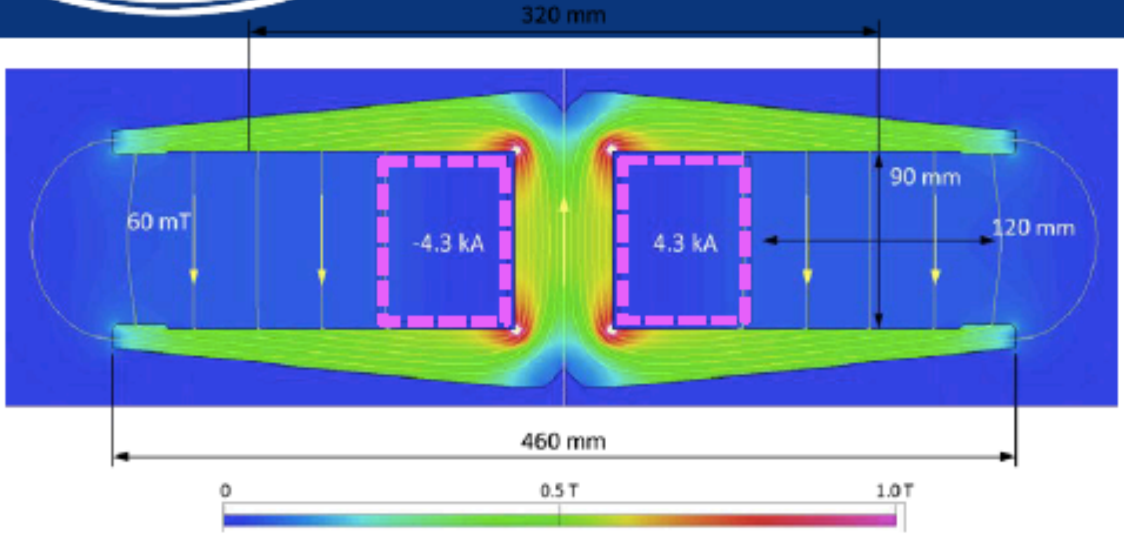
RD3B
14.7T@1.9K



HD1 (16T@4.2K; no bore)
HD2 (13.7T@4.2K; ~40mm bore)
HD3 (13.4T@4.4K; 43mm bore)

Record magnets in each configuration show no clear winner

arc magnets 2-in-1 design



dipole based on
twin aperture yoke
and single busbars as coils

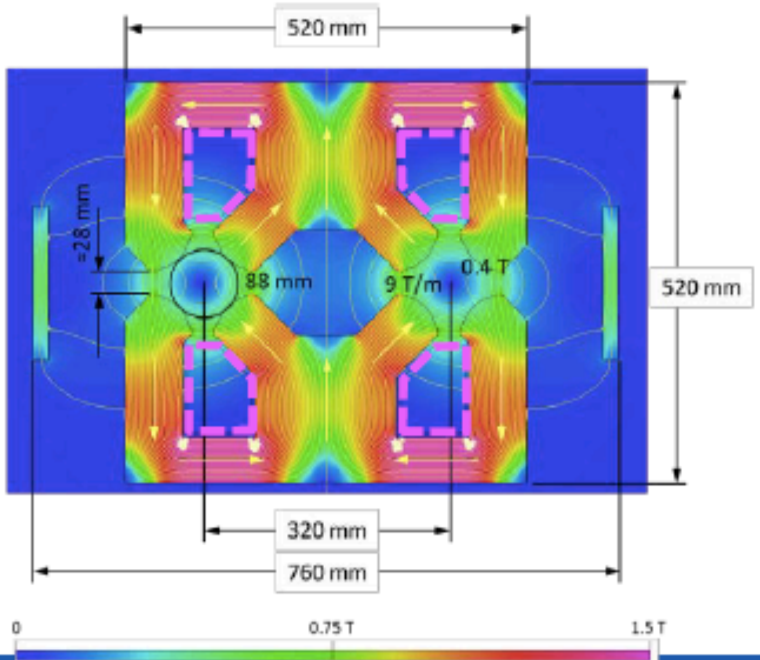
A. Milanese

conductor

twin 2-in-1 quadrupole

the novel arrangement of the magnetic circuit allows for considerable savings in Ampere-turns and power consumption, less units to manufacture, transport, install, align, remove,…

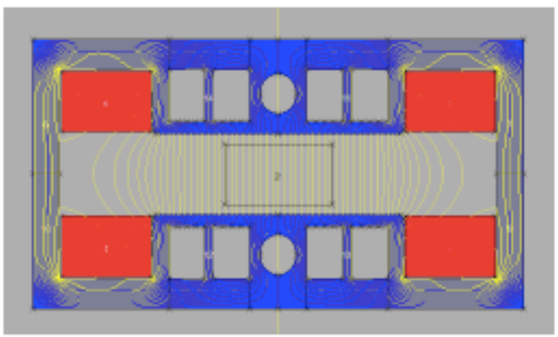
midplane shield
for stray field

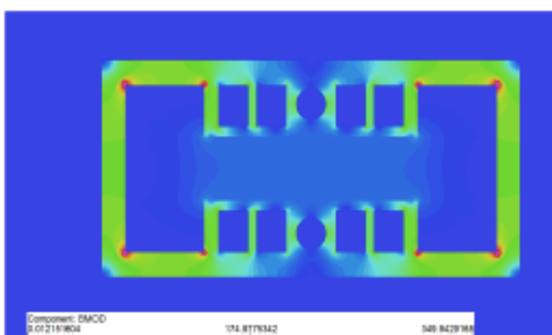


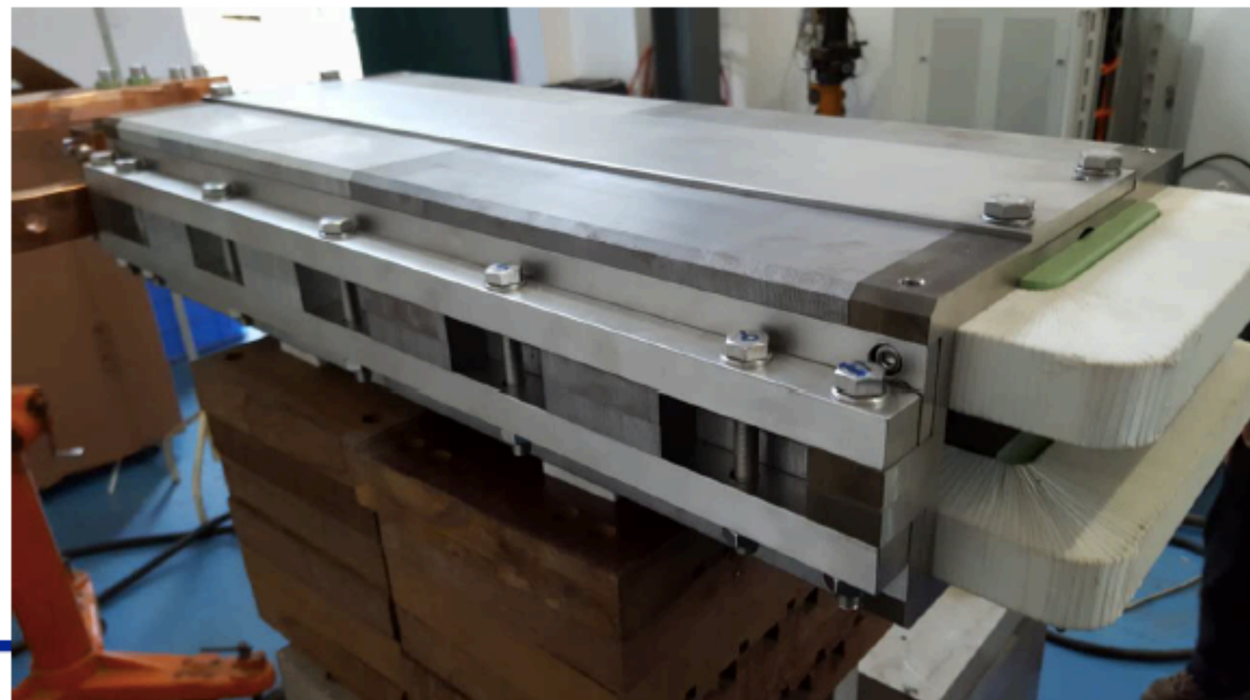
Low field dipole magnet R&D

- *Lmag=4m, Bmin=31Gs, Bmax=614Gs*
- To verify the magnet design and field simulation, a *1m* long prototype dipole magnet （booster） was developed and measured

  - Supported by IHEP workshop

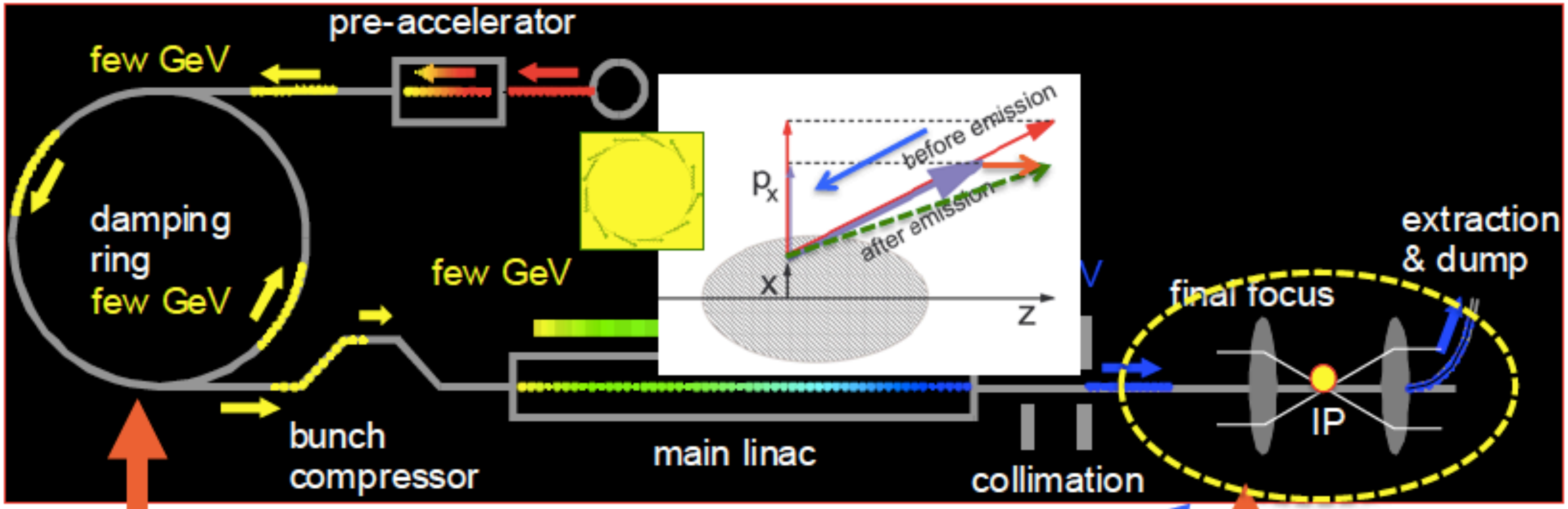






Institute of High Energy Physics

ILC 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)

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

Nano-beam technology advanced by ATF Collaboration, hosted at KEK.

Progress in FF Beam Size and Stability at ATF2

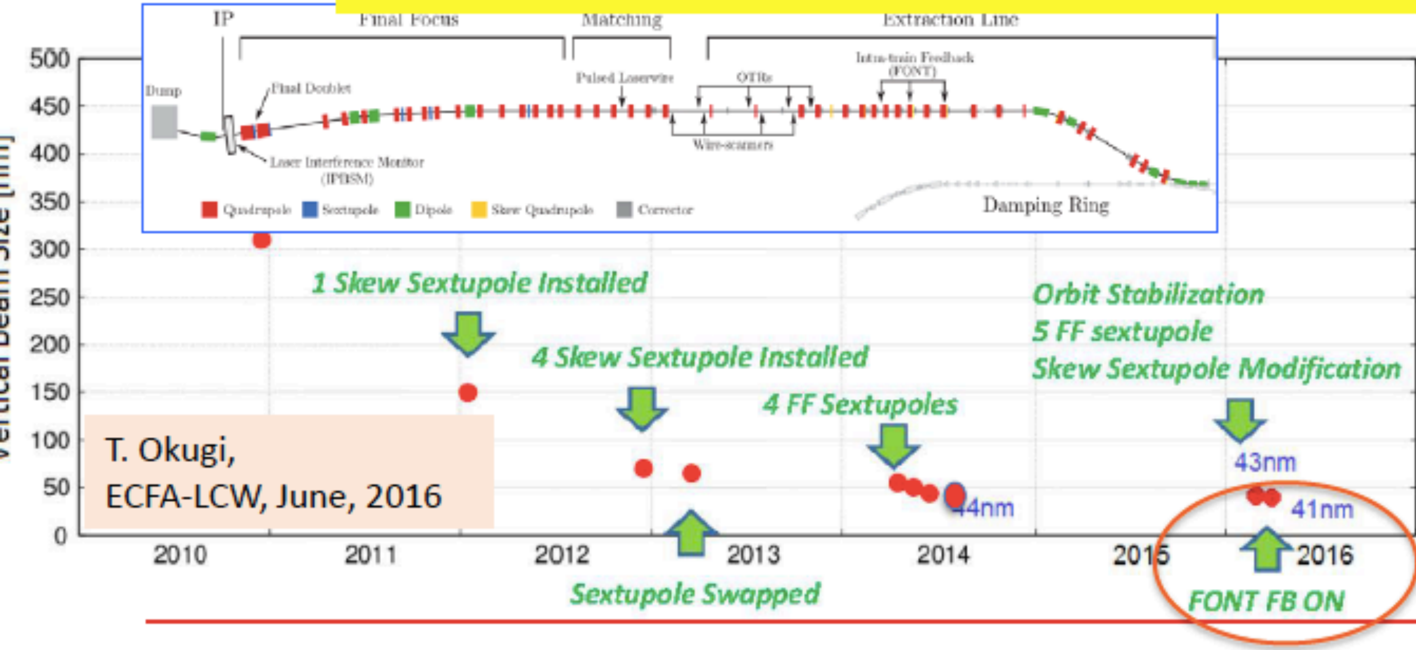
Goal 1:
Establish the ILC final focus method with same optics and comparable beamline tolerances

- ATF2 Goal : **37** nm → ILC **6** nm
    - Achieved **41** nm (2016)

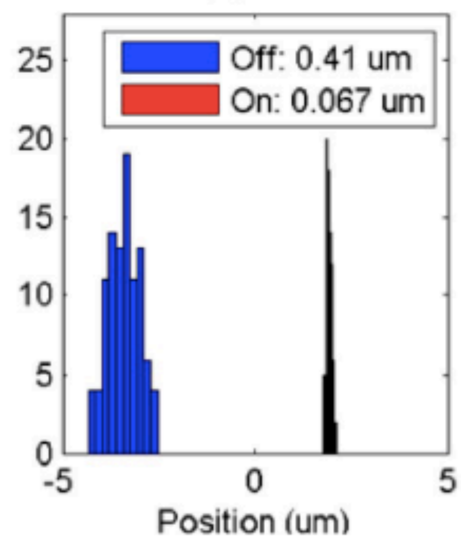
Goal 2:
Develop a few nm position stabilization for the ILC collision by feedback

- **FB latency 133 nsec achieved**
  (target: < 300 nsec)
- **positon jitter at IP: 410 → 67 nm (2015)**
  (limited by the BPM resolution)

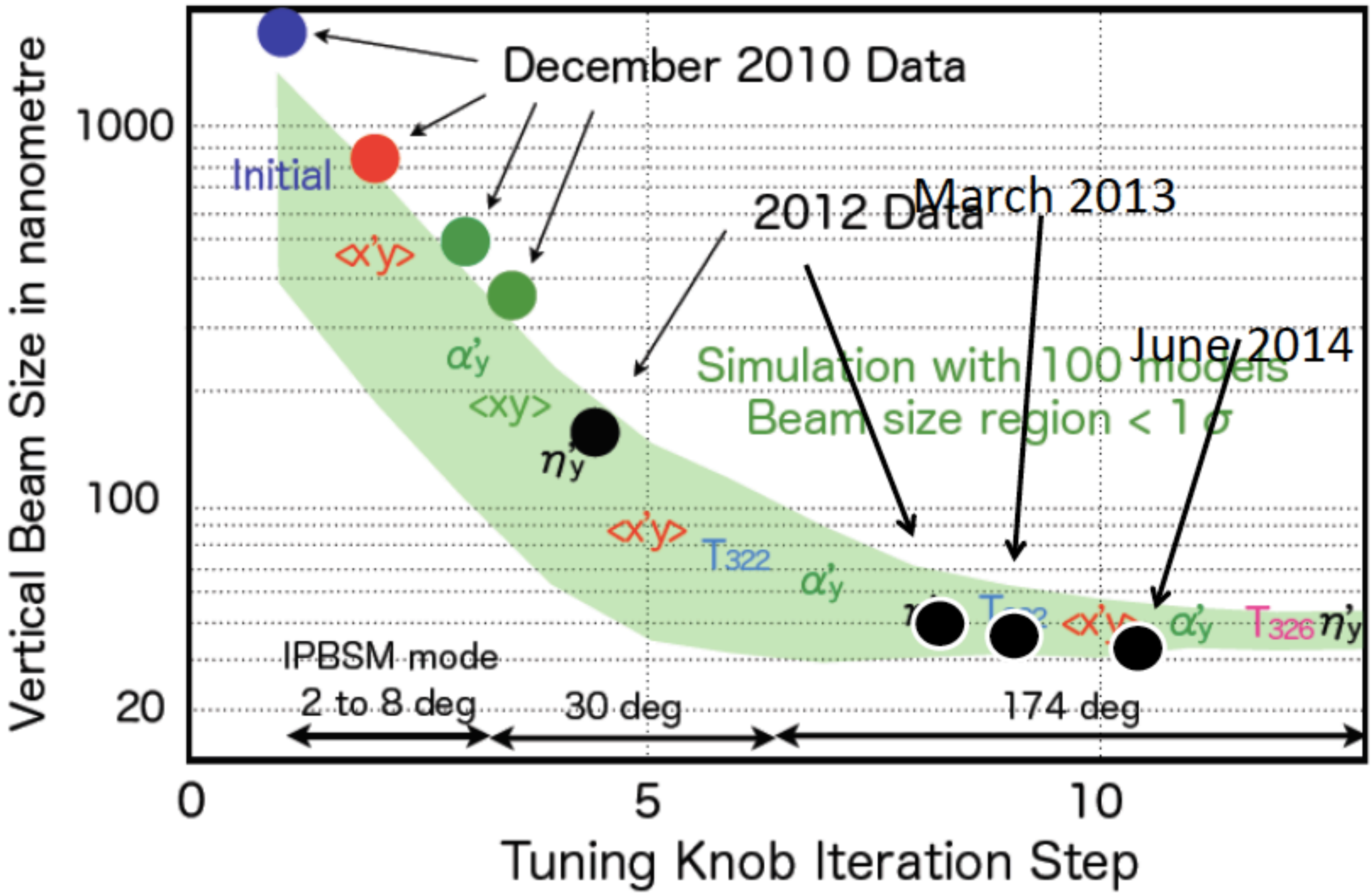
We continue efforts to achieve goal 1 and goal 2.



K. Kubo



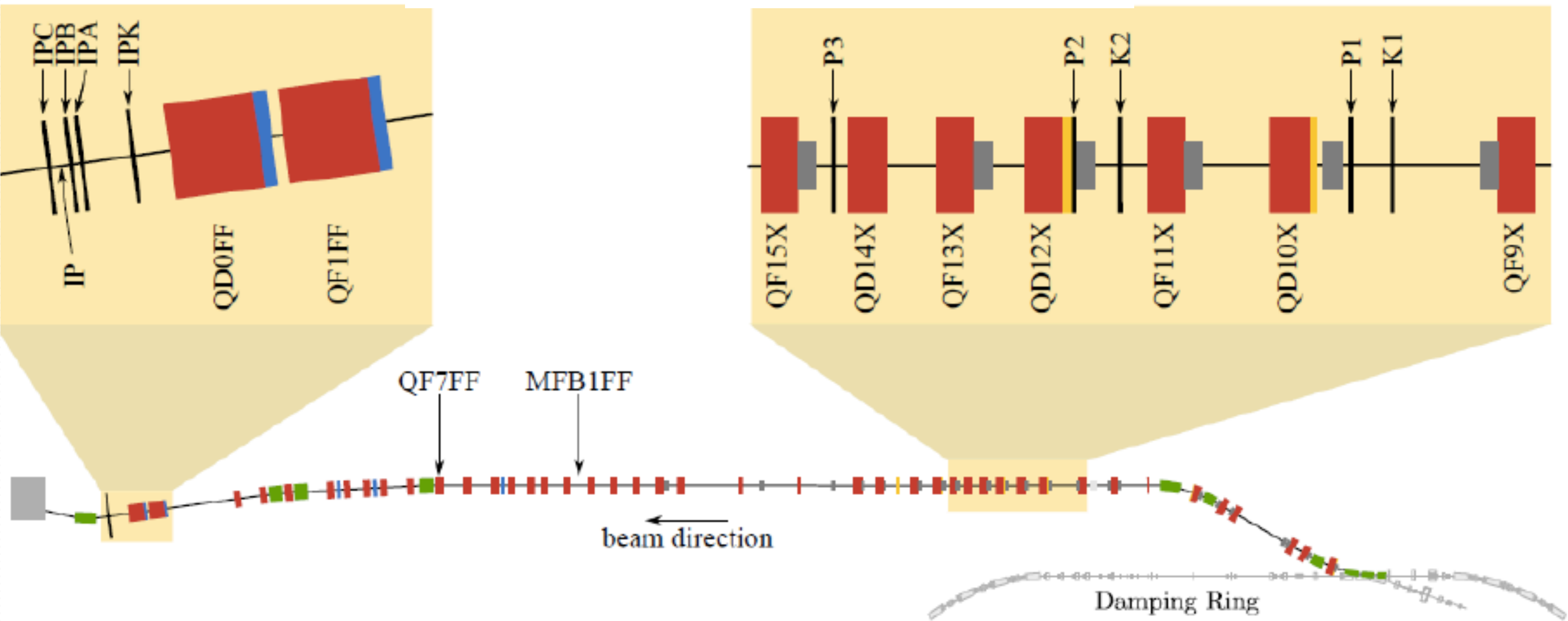
History of minimum beam size in ATF2



Experimental Validation of a Novel Compact Focusing Scheme for Future Energy-Frontier Linear Lepton Colliders, by G. White et al. (ATF2 Collaboration): Phys.Rev.Lett 112, 034802 (2014)

Stabilising beam near IP

CLIC+ATF2/FONT5



1. Upstream FB: monitor beam at IP
2. Feed-forward: from upstream BPMs → IP kicker
3. Local IP FB: using IPBPM signal and IP kicker

Predicted jitter reduction at IP

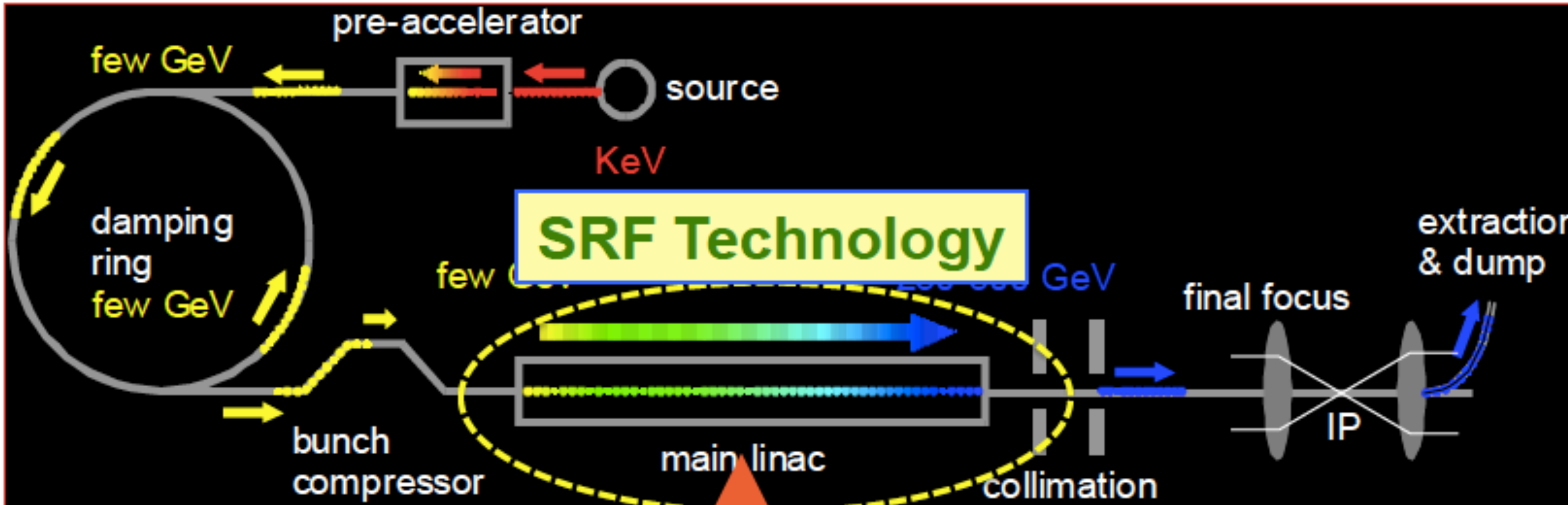
	Position y jitter (nm)		Angle y' jitter (urad)	
Bunch	Feedback off	Feedback on	Feedback off	Feedback on
1	9.5 ± 0.3	10.1 ± 0.3	89 ± 3	87 ± 3
2	9.4 ± 0.3	3.6 ± 0.1	87 ± 3	28 ± 1

Predict position stabilised at few nanometre level…

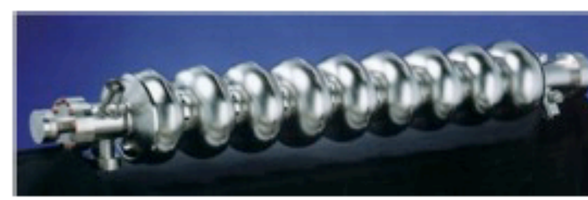
CLIC+ATF/FONT5

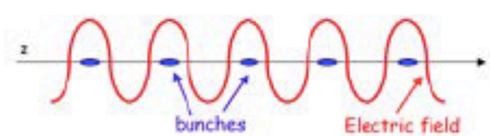
How to measure it?!

ILC SRF 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)





RF system R&D lines

400 MHz single-cell cavities preferred for hh and ee-Z (few MeV/m)

- Baseline Nb/Cu @4.5 K, development with synergies to HL-LHC, HE-LHC
- R&D: power coupling 1 MW/cell, HOM power handling (damper, cryomodule)

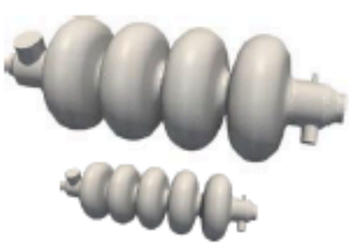
hh ≈ 32 single cell cavities per beam

Z ≈ 50 per beam single cell

W ≈ 120 cell per beam double cell

400 or 800 MHz multi-cell cavities preferred for ee-H, ee-tt and ee-W

- Baseline options 400 MHz Nb/Cu @4.5 K, ◄—► 800 MHz bulk Nb system @2K
- R&D: High Q_0 cavities, coating, long-term: Nb_3Sn material



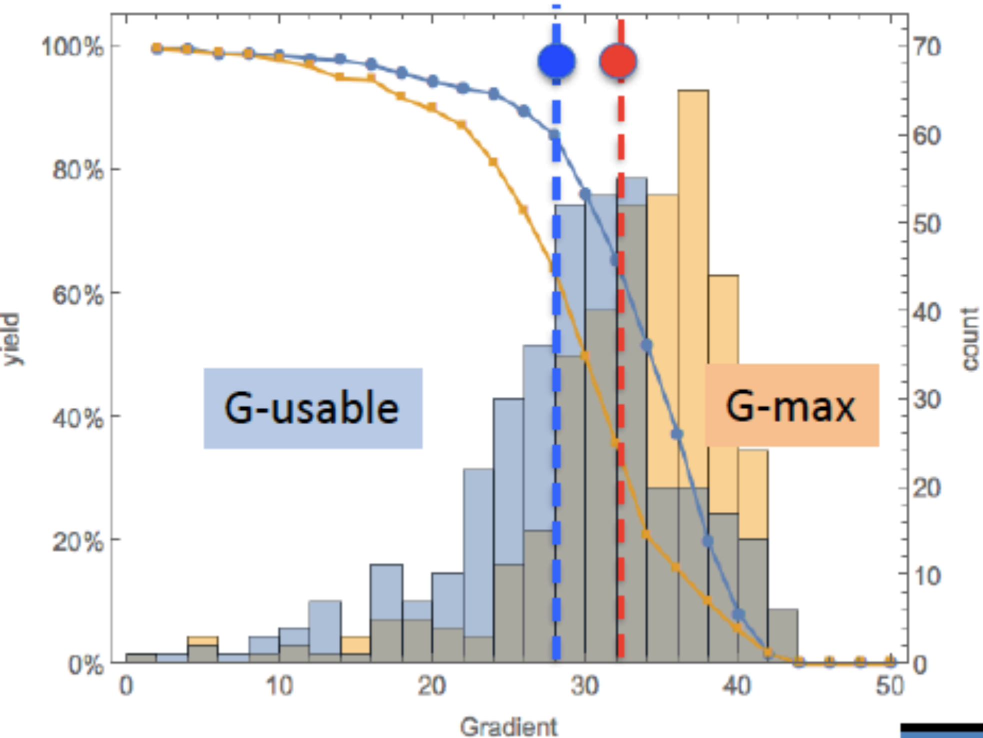
H ≈ 800 cells per beam 4 or 5 cell

t ≈ common 2600 cells for both beams

Booster ring:
Same RF system
(lower power)

O. Brunner, A. Butterworth, R. Calaga

E-XFEL: SRF Cavity Performance (as received)



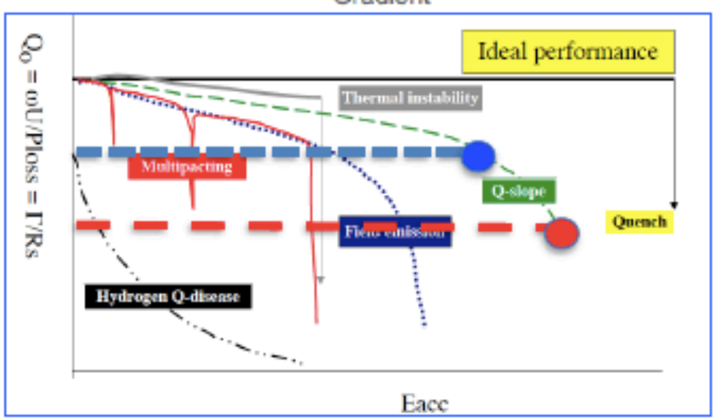
SRF cavity production/test ;

 # RI Cavities, 373 (as of Sept. 2015)

- Final process: 40 μm EP.
  - w/ same recipe to ILC-SRF's
- Tested at DESY-AMTF

Notes::

- "Ultra-pure water rinsing as the 2nd process improving the gradient performance (> ~10%) for lower-performed cavities (not shown here).



	G-usable ($Q_0 > 10^{10}$)	G-max	(ILC)
<G> MV/m	29.4	33	(35)
Yield at 28MV/m	66%	86%	(90%)

Electricity bill

W. Chou, IAS, HK, 2017

- Fermilab:
  - $ 440k per MW-year
  - **$ 20M a year** (~5% of lab budget)
  - *(5 US cents per kWh)*

- CERN:
  - 1,200 GWh /year
  - **CHF 65M a year** (~5% of lab budget)
  - *(5 Swiss cents per kWh)*

- BEPC II: (Qing Qin)
  - Annual machine operation: 100M yuan
  - Electricity: **40M yuan a year (US$ 6M)**
    (~3% of lab budget)

For a 500 MW collider in China:

To reach the required integrated luminosity, we need at least 4,400 hours for operation each year:

500 MW x 4,400 hours = 2.2 x 10^9 kW-hr

Annual electricity cost: **RMB 2.2B (US$ 320M)**

(RMB 1 yuan per kWh for industry, 3 times higher than in the US or France)

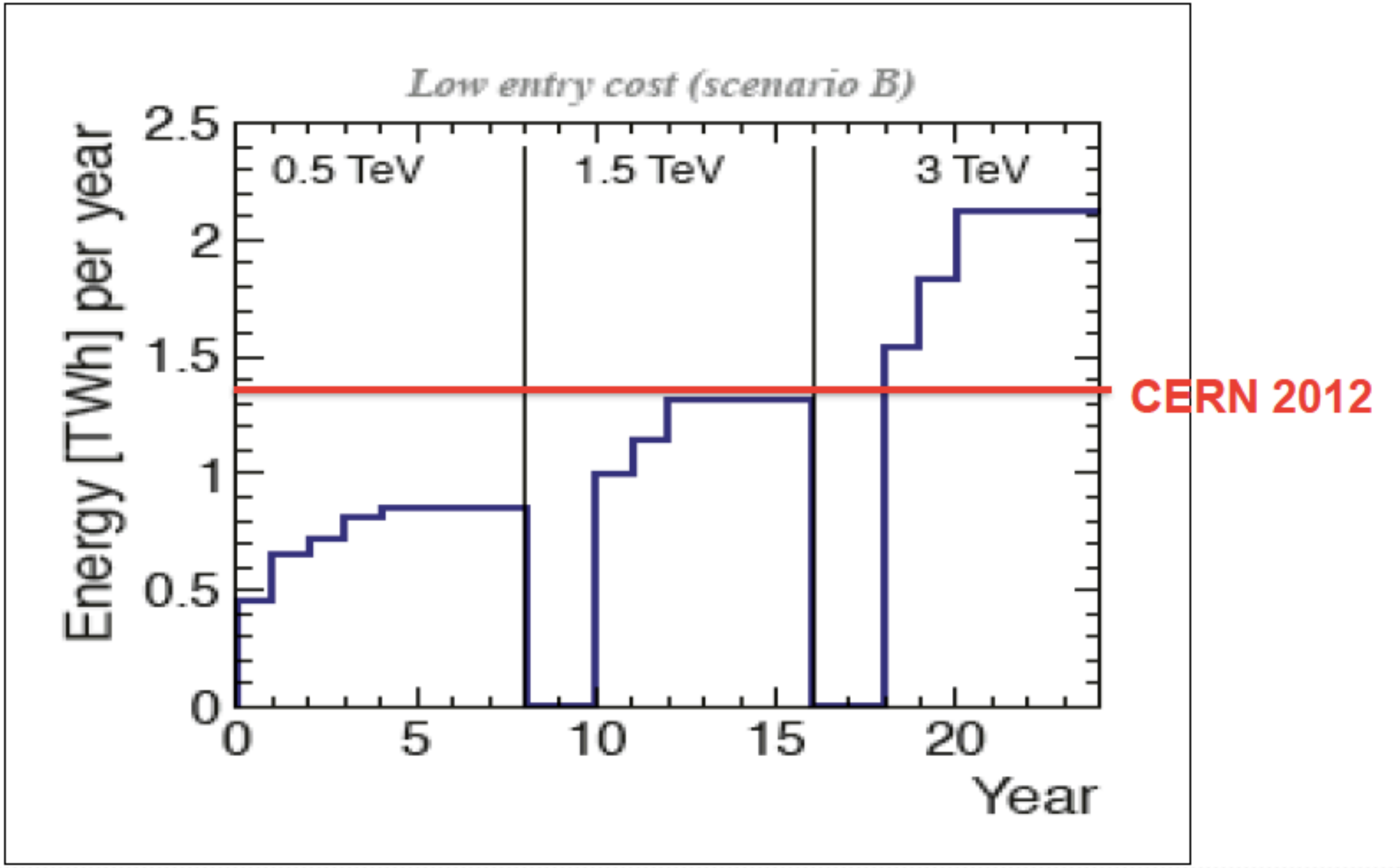
FCC-ee total power

subsystem	Z	W	ZH	$t\bar{t}$	LEP2 (av.2000*)
collider total RF power	163	163	145	145	42
collider cryogenics	2	5	23	39	18
collider magnets	3	10	23	50	16
booster RF + cryo	4	4	6	7	-
booster magnets	0	1	2	5	-
injector complex	10	10	10	10	<10
physics detectors (2)	10	10	10	10	9
cooling & ventilation**	47	49	52	62	16
general services	36	36	36	36	9
total	**275**	**288**	**308**	**364**	**120**

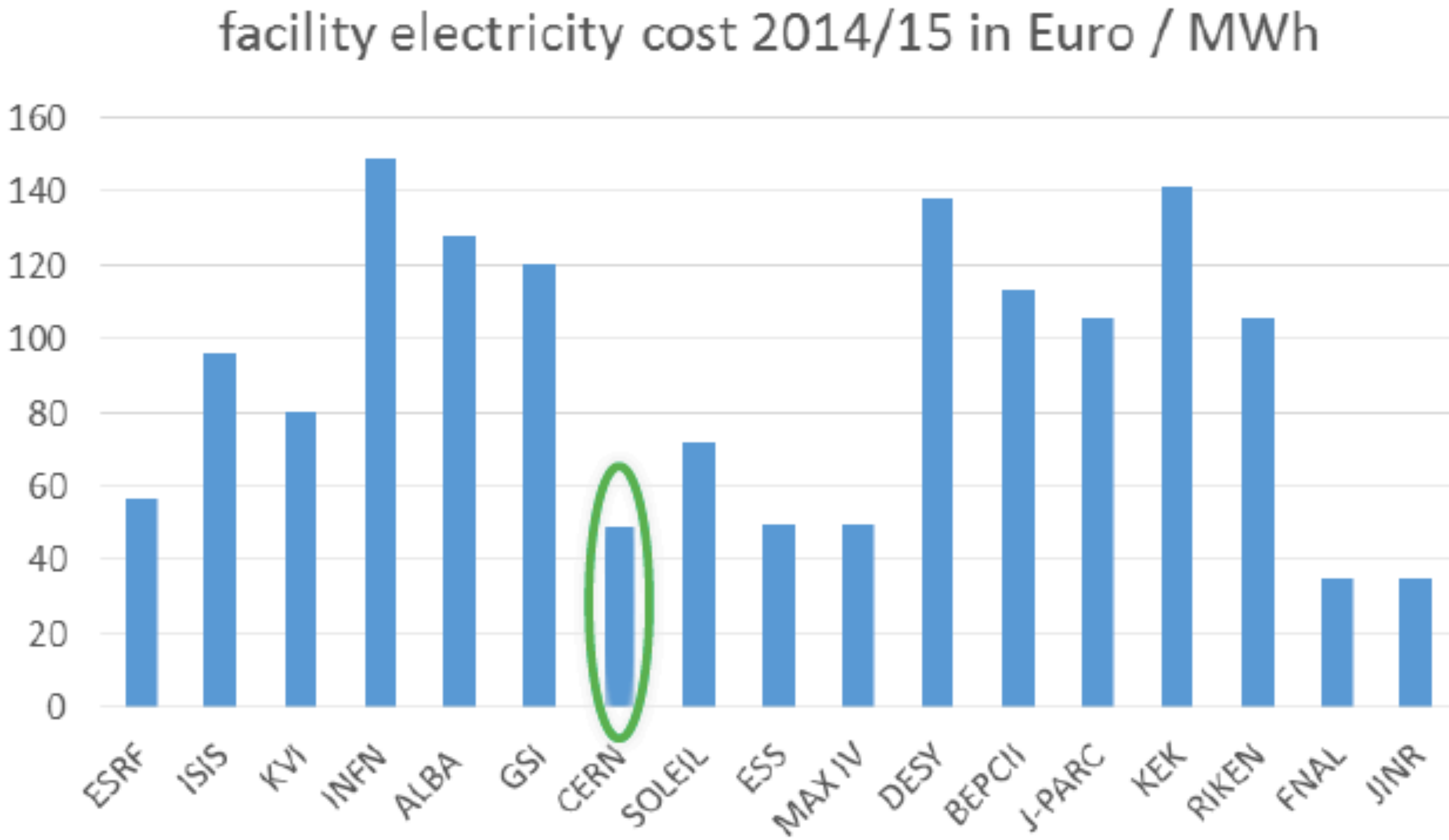
for comparison, total CERN complex in 1998 used up to 237 MW

** private discussions with M. Nonis

CLIC Energy consumption



electricity cost



Courtesy: M. Seidel, EuCARD-2, V. Shiltsev, K. Oide, Q. Qin, G. Trubnikov, and others

1400 GWh / yr → ~70 MEuro / yr

High efficiency klystrons

- Beams will require significant RF drive power (100 MW)
- An RF source with high efficiency is preferable to minimize the overall power required
- Klystrons with the current state of the art are operating at efficiencies of up to 70%
- Novel bunching methods, such as the Core Oscillation Method (COM), are being investigated
- Numerical simulation of klystrons featuring COM give efficiencies of up to 85% being predicted so far

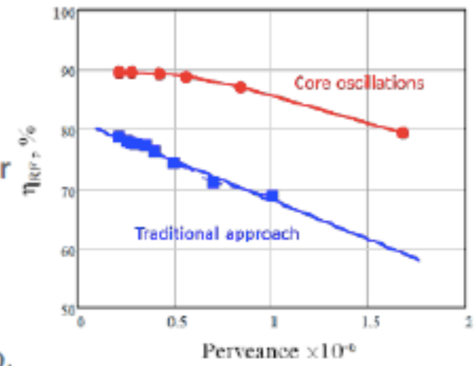
Constable

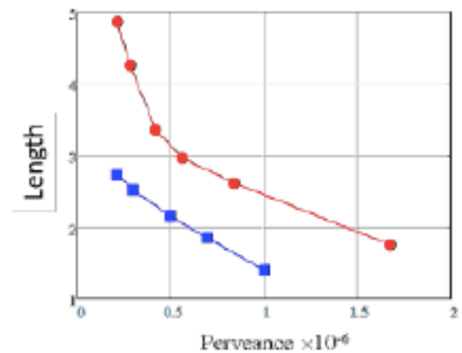
Core Oscillation Method (COM)

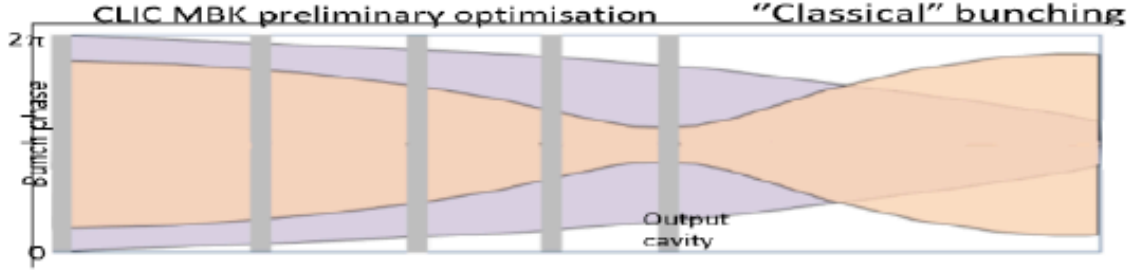
Lancaster University

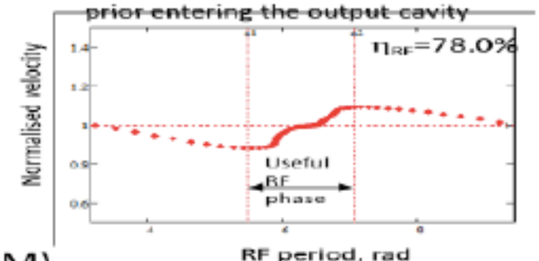
The Cockcroft Institute of Accelerator Science and Technology

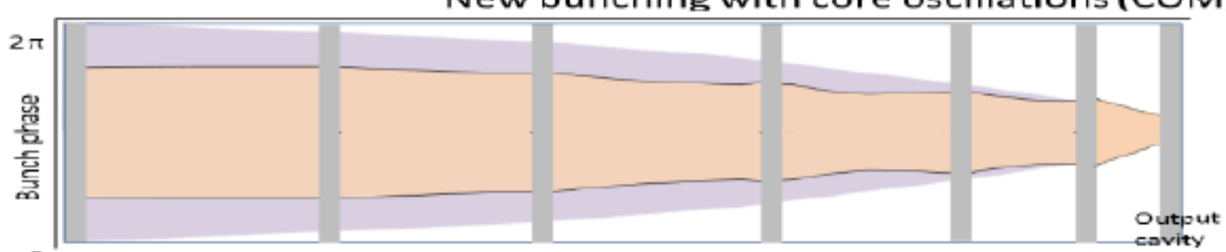
- Core oscillation method:
  - Centre of bunch allowed to bunch and de-bunch between cavities.
  - Core experiences larger space charge force.
  - Outsiders brought monotonically to bunch.
  - Outsiders experience larger phase shift due to smaller space charge forces.
- Tubes using core oscillations:
  - Longer in length.
  - Suitable for high frequency (X-band).
  - More electrons contained within bunch at output gap.
  - Therefore, higher maximum efficiency.

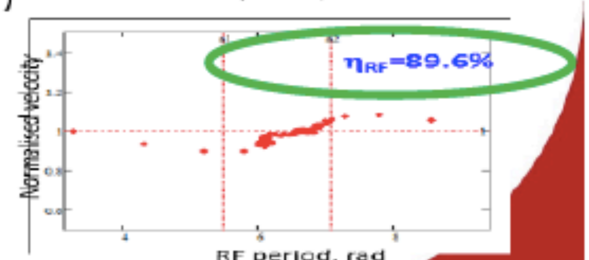












highly efficient RF power sources

2014 breakthrough in klystron theory:

–"**congregated bunch**" V.A. Kochetova, 1981]

- "**bunch core oscillations**" [A. Yu. Baikov, et al. 2014]

- "**BAC**" method [I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov 2013]

These three methods together promise a klystron efficiency ~90%

An international collaboration "HEIKA" (CERN, ESS, SLAC, CEA, MFUA, Lancaster U, Thales, L3, CPI, VDBT) is now designing, building and testing prototypes. **Simulations and first hardware tests extremely encouraging.**

work in progress

FCC klystron prototype - initial target parameters

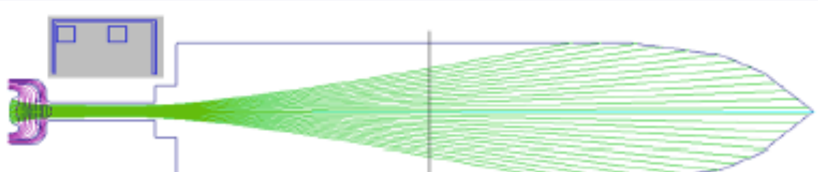
Operating frequency	800 MHz initially
Target RF Output power	1.5 MW (cw)
Voltage	40 kV
N-beams×Current	16 × 2.6 A = 42 A
Target Efficiency	**90%**
Perveance	16 × 0.33 μK = 5.25 μK
Number of cavities	8
Cathode loading	$< 2\ \mathrm{A\ mm^{-2}}$
Length	2.3 m

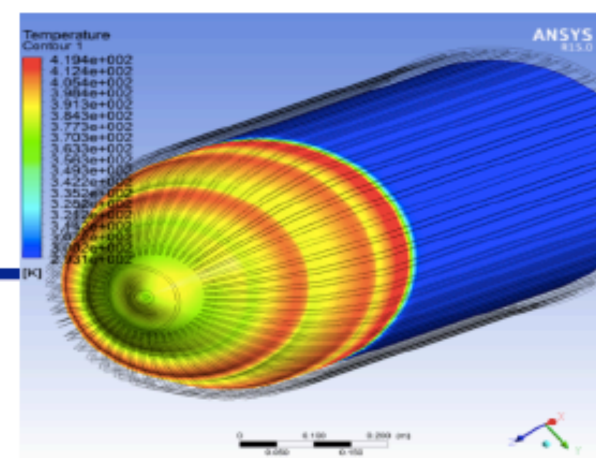
E. Jensen, I. Syratchev, C. Lingwood

650MHz *CW Klystron R&D*

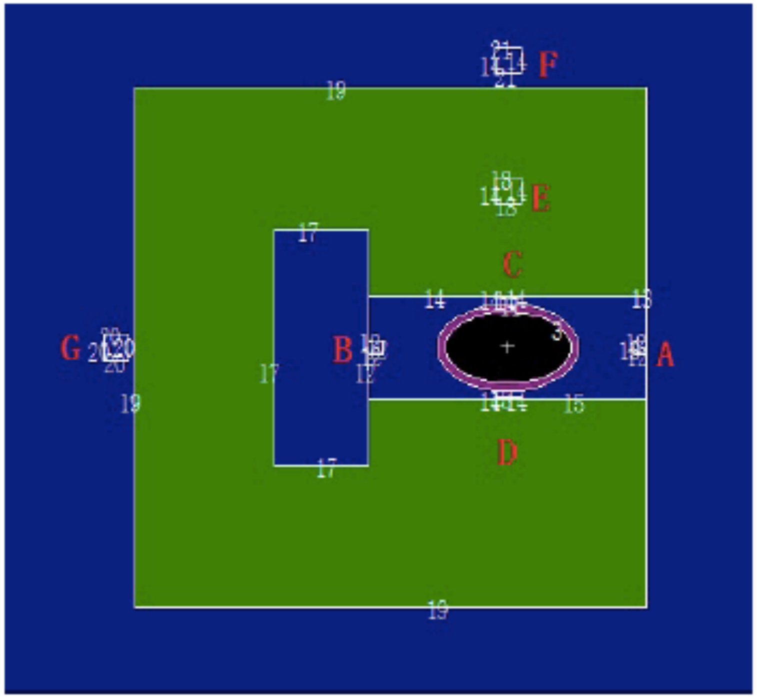
- CEPC Accelerator Physics and Key Technology R&D
  - *Supported by IHEP Science & Technology Innovation Program of IHEP (2015-2017)*

- Task 1： Research of High Q cavity (1.82 MCNY)
- Task 2： 650MH/ 300kW klystron development (3.71 MCNY)
  - ➢ *Design of high efficiency klystron (efficiency ~ 80%);*
  - ➢ *Beam tester for klystron development;*
  - ➢ *High power test for beam tester.*





CEPC Magnet Radiation Dose (Gy/A-hr, Yadong Ding)



At 120 GeV:

A: 6.94×10^5

B: 2.39×10^5

C: 3.59×10^5

D: 3.59×10^5

E: 2.87×10^4

F: 2.13×10^3

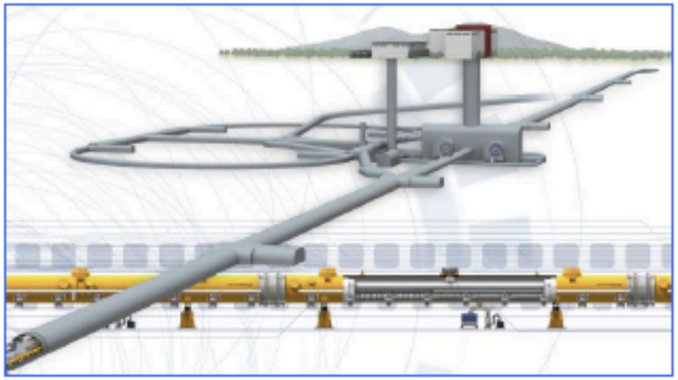
G: 5.74×10^3

Accelerator lifetime: radiation damage was found on LEP magnets when given to FNAL

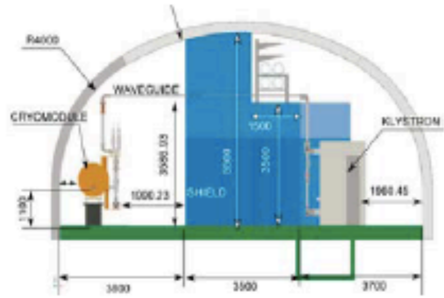
Unacceptable!

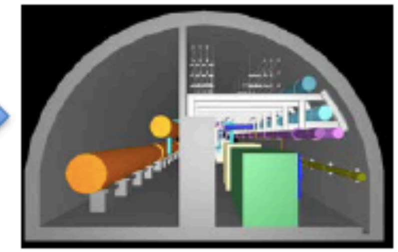
Insulation material	Upper dose limit (GY)	Radiation lifetime at 2 x 16.6 mA
Epoxy resin (coil)	2×10^7	2,500 hrs
Fiber glass (coil)	1×10^8	13,000 hrs
Semi-organic coating (lamination)	1×10^8	8,400 hrs

New Baselining of Civil-engineering,



Beam Line

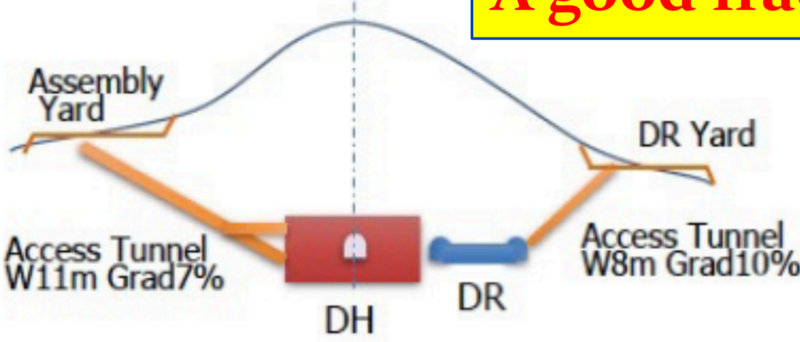


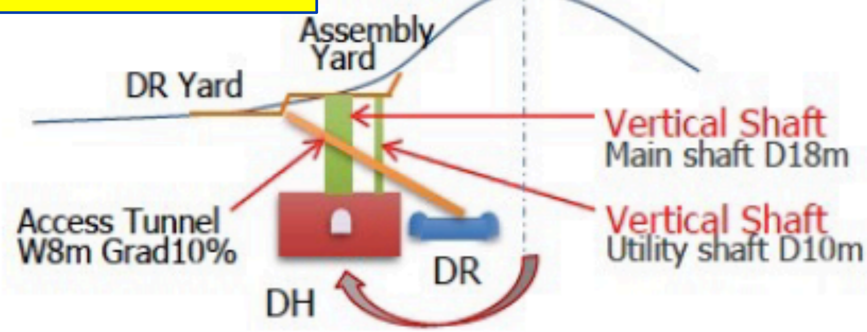


- Assembly Place: Surface Building/AH
- Access way to DHI underground
  - only Inclined Access Tunnel (AT)
  - Transport. by special long trailer

- Assembly Place: Underground/DH
- Access way to DH underground
  - mainly Vertical Shaft (VS)
  - Transport. by Gantry Crane

A good fraction of cost





Conclusions

- The future of lepton colliders, linear and circular, depends on solving both the pending technological issues and the beam dynamics ones
- Technology moves fast, and the worldwide collaboration which is already in place will help solving the most ”hot” issues in the next 20 years or so → time is a friend
- The success of the B-Factories was also due to the healthy competition between PEP-II and KEKB
- Two linear and two circular projects are being proposed and the synergy between the communities, as well as with the Synchrotron Light Sources one, will be crucial for the success of hopefully **at least** one of each

“No man is an island entire of itself; every man is a piece of the continent, a part of the main” (J. Donne, 1572-1631)