Progress and Perspective on Lepton Collider

Qing Qin (秦庆),

IHEP, CAS

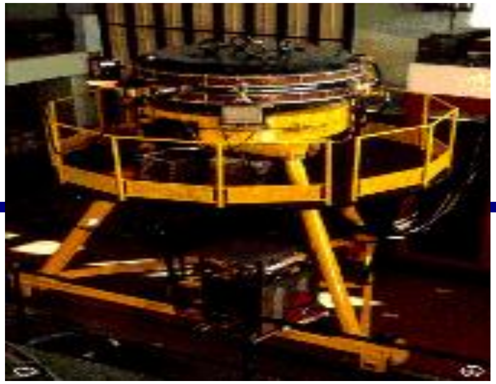
Oct. 25, 2019

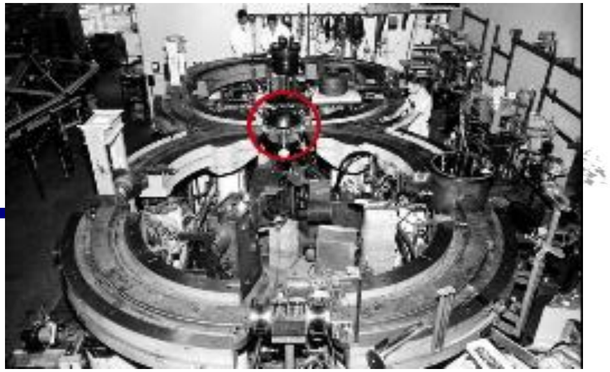
中国科学院高能物理研究所
Institute of High Energy Physics

Acknowledgement

- Weiren Chou, FNAL
- Catia Milardi, INFN-LNF
- Juhao Wu, SLAC
- Korao Yokoya, KEK
- Chenghui Yu, Chuang Zhang, Yuan Zhang, IHEP
- John Jowett, Frank Zimmermann, CERN

Lepton colliders







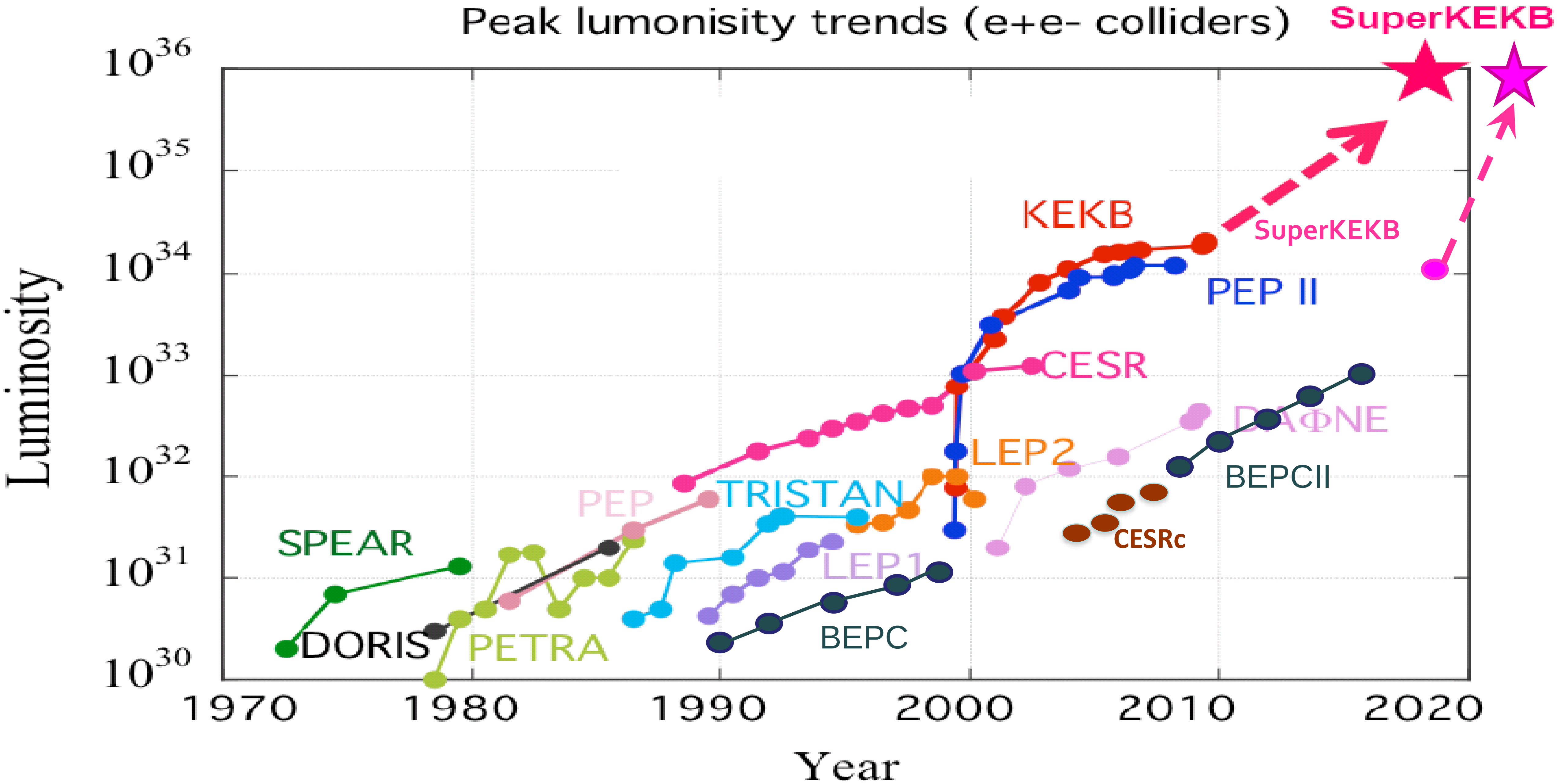




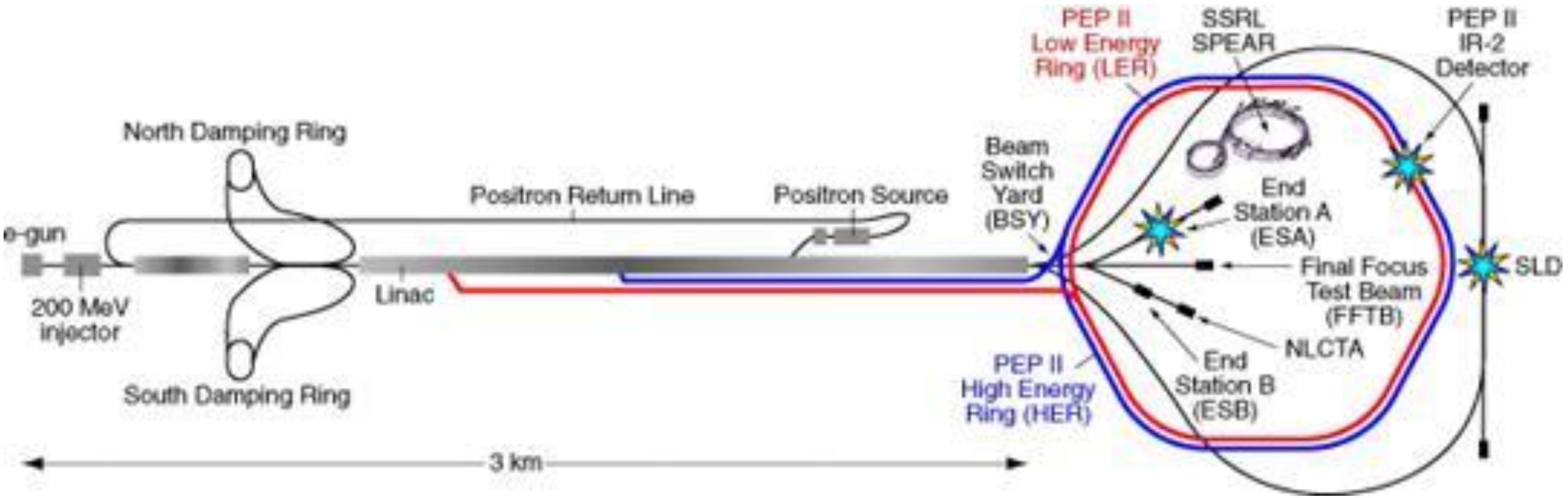




e⁺e⁻ Colliders

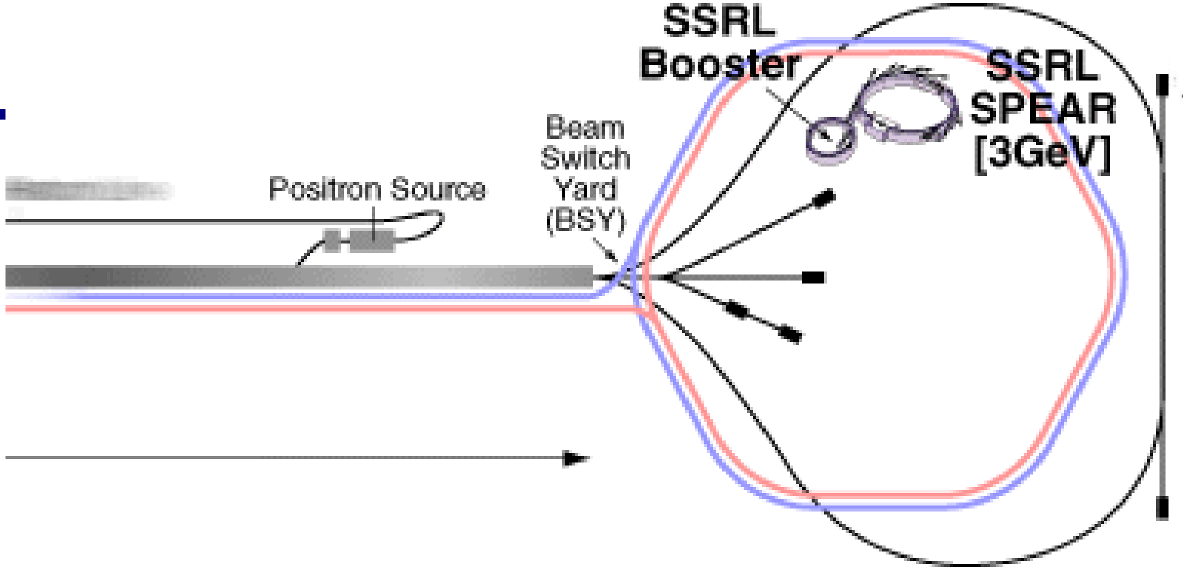


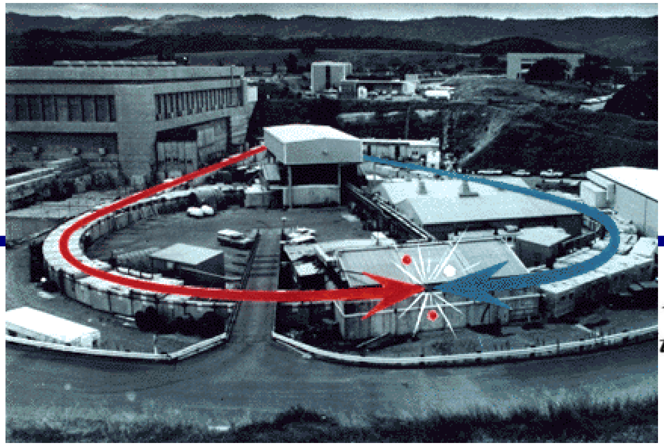
Colliders at SLAC – SPEAR, PEP/PEP-II, SLC

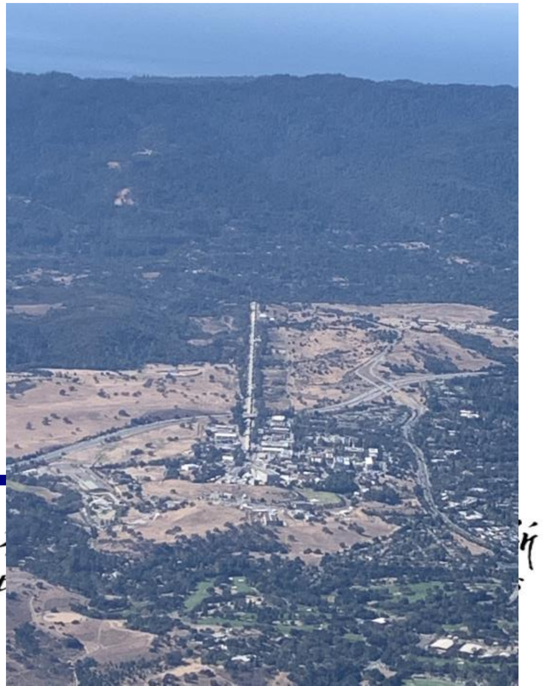


SPEAR/SPEAR II

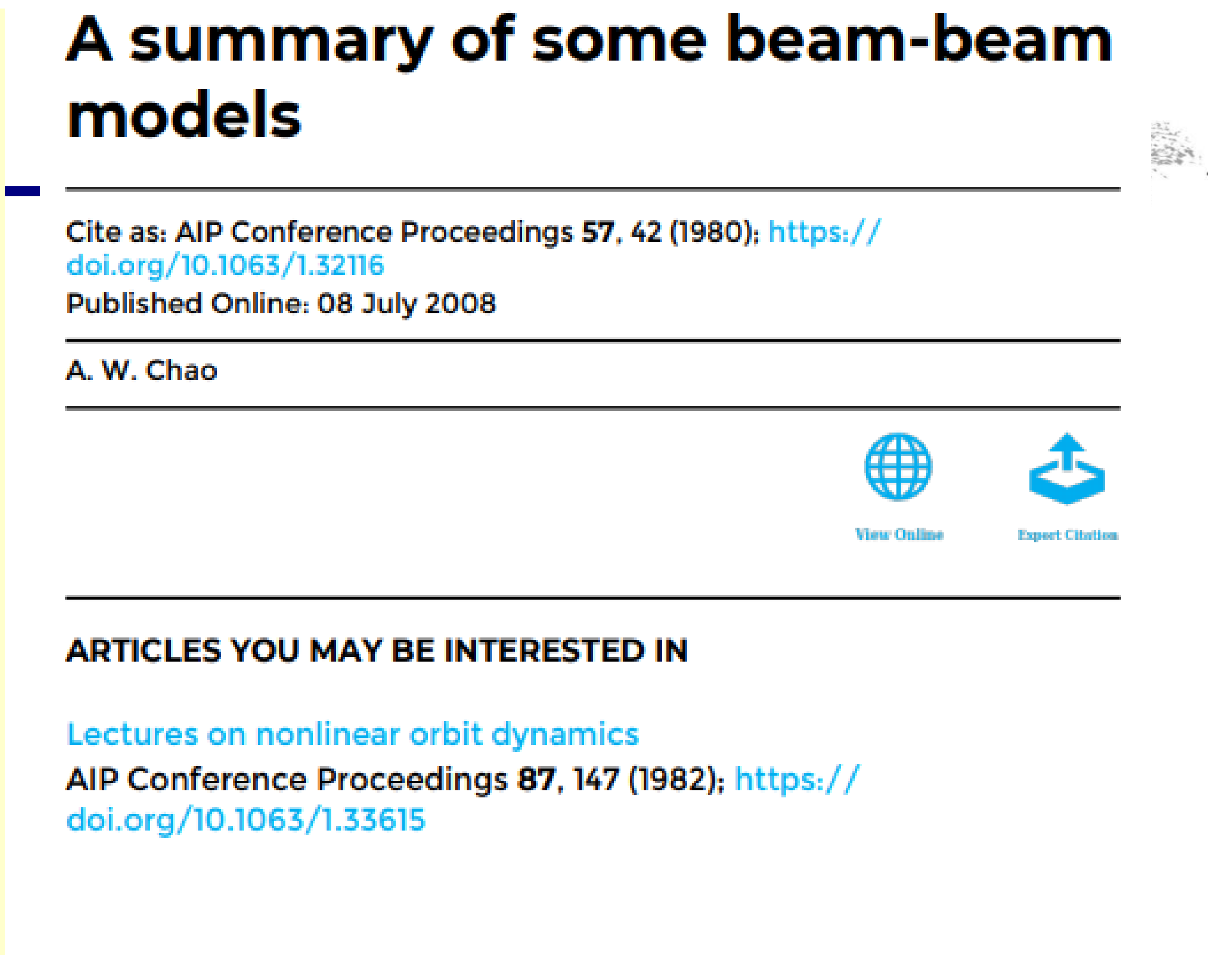
- 2-4 GeV e-e+ collider
- J/ψ & Charm-τ physics
- L_{peak} = 1E31/cm^2/s
- A lot of machine study on beam dynamics (beam-beam effect, wake field & impedance, resonance, etc)







- A. Chao, *Accelerator considerations of large circular colliders*, Mod. Phys Lett. A **31**(24), 1630022 (2016)
- Y.H. Chin, A.W. Chao, and M.M. Blaskiewicz, *Two particle model for studying the effects of space-charge force on strong head-tail instabilities*, Phys. Rev. Accel. Beams 19(1), 014201 (2016)
- J. Wu, T.O. Raubenheimer, A.W. Chao, *et al.*, *Luminosity loss due to beam distortion and the beam-beam instability*, Proc. PAC05, pp. 318 (2005)
- K. Ohmi and A.W. Chao, *Combined phenomena of beam-beam and beam-electron cloud interactions in circular e(+)e(-) colliders*, Phys. Rev. ST Accel. Beams **5**(10), 101001 (2002)
- Y. Cai, A.W. Chao, S.I. Tzenov, *et al.*, *Simulation of the beam-beam effects in e+e- storage rings with a method of reduced region of mesh*, Phys. Rev. ST Accel. Beams **4**(1), 01101 (2001)
- A.W. Chao, *Beam-Beam Instability*, AIP Conf. Proc. **127**, 201 (1985)
- A.W. Chao, R.D. Ruth, *Coherent beam-beam instability in colliding-beam storage rings*, Part. Accel. **16**(4), 201 (1985)



A summary of some beam-beam models

Cite as: AIP Conference Proceedings **57**, 42 (1980); https://doi.org/10.1063/1.32116

Published Online: 08 July 2008

A. W. Chao

ARTICLES YOU MAY BE INTERESTED IN

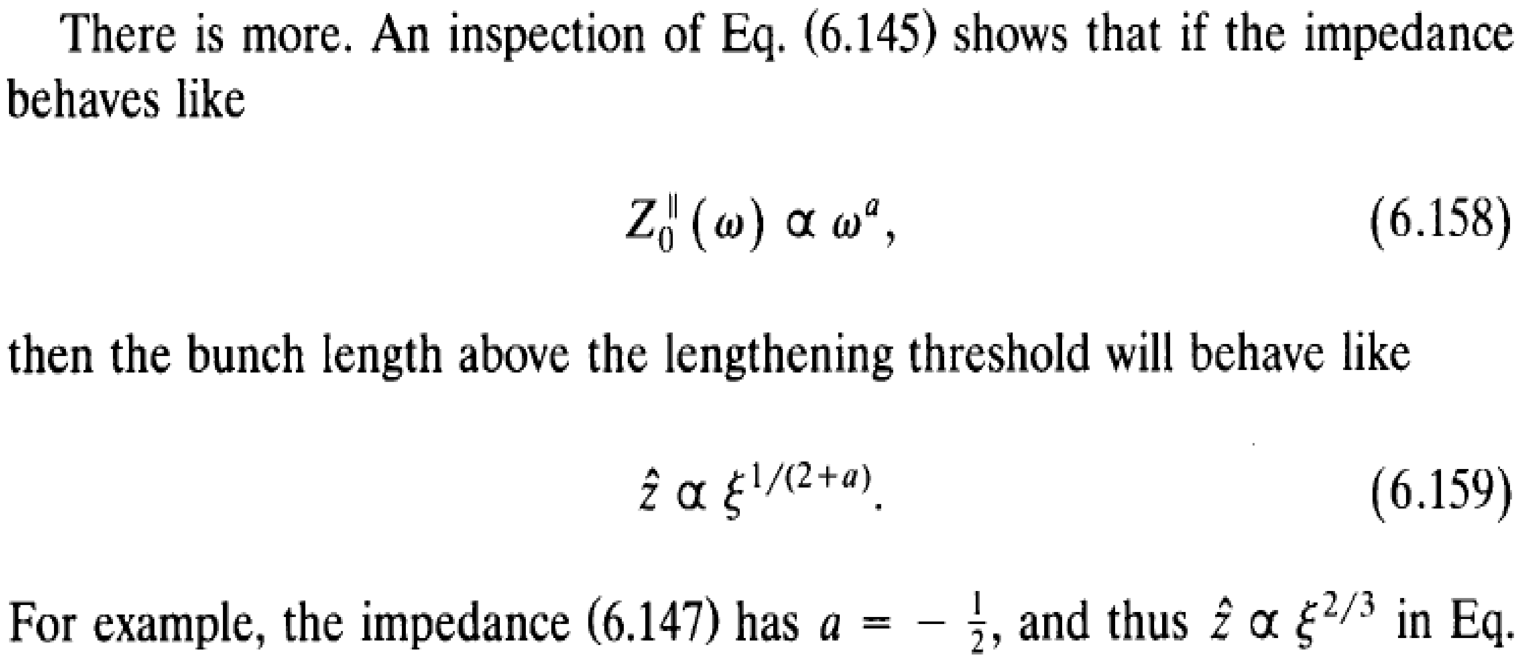
Lectures on nonlinear orbit dynamics

AIP Conference Proceedings **87**, 147 (1982); https://doi.org/10.1063/1.33615

A series of papers led the research avenue of coherent beam-beam effects. This view of the beam-beam effect (that limits the performance of storage ring colliders) was revolutionary at the time but has now become a standard vocabulary.

• SPEAR Scaling law

p. 330, A.W. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, Wiley, (1993).



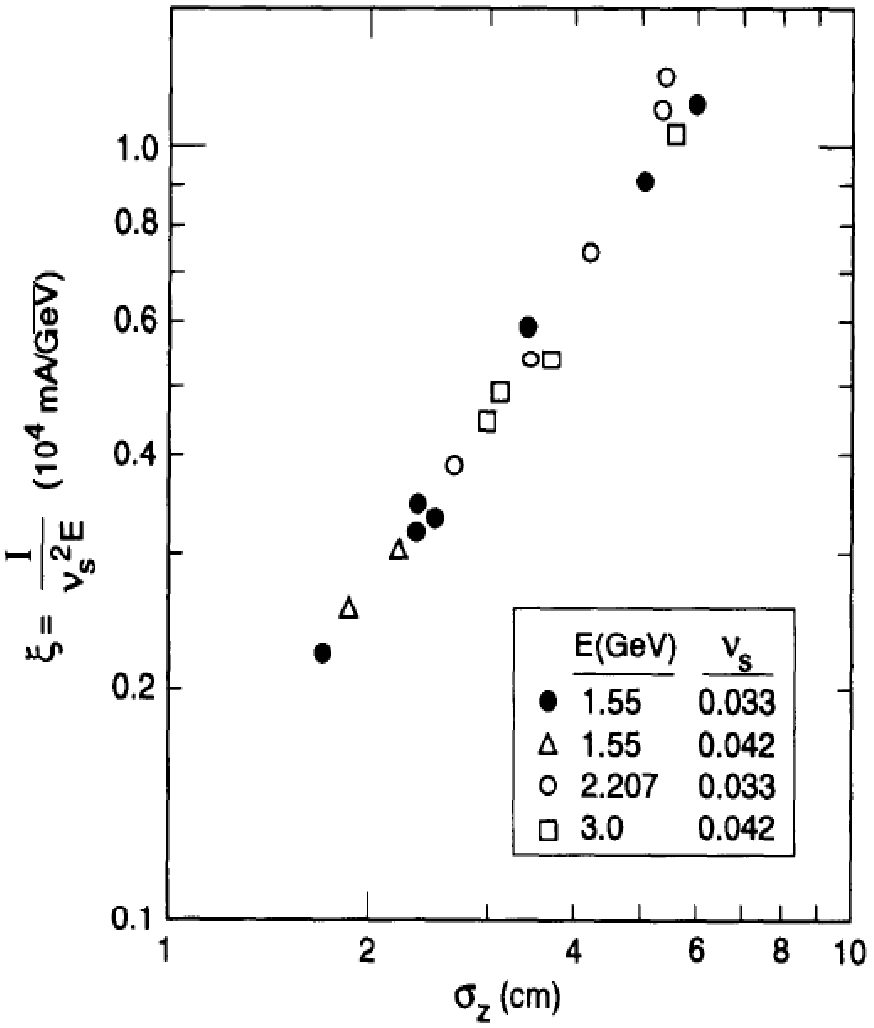
There is more. An inspection of Eq. (6.145) shows that if the impedance behaves like

$$Z_0^{\|}(\omega) \propto \omega^a, \qquad (6.158)$$

then the bunch length above the lengthening threshold will behave like

$$\hat{z} \propto \xi^{1/(2+a)}. \qquad (6.159)$$

For example, the impedance (6.147) has $a = -\frac{1}{2}$, and thus $\hat{z} \propto \xi^{2/3}$ in Eq.

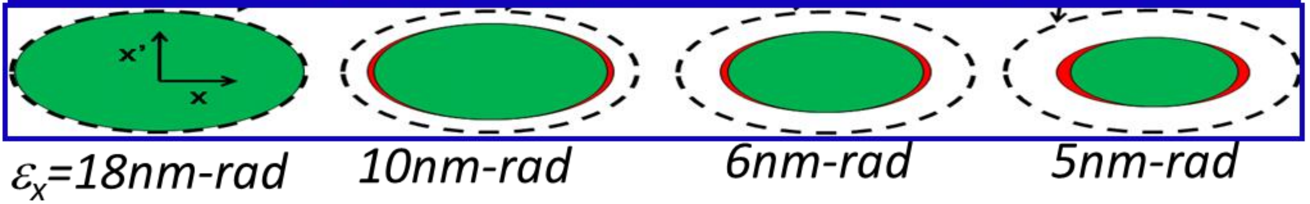


- **The Chao-Gareyte Scaling clarified the physical process of the anomalous bunch lengthening effect observed in electron storage rings.**
- **1st impedance model**

中國科學院高能物理研究所
Institute of High Energy Physics

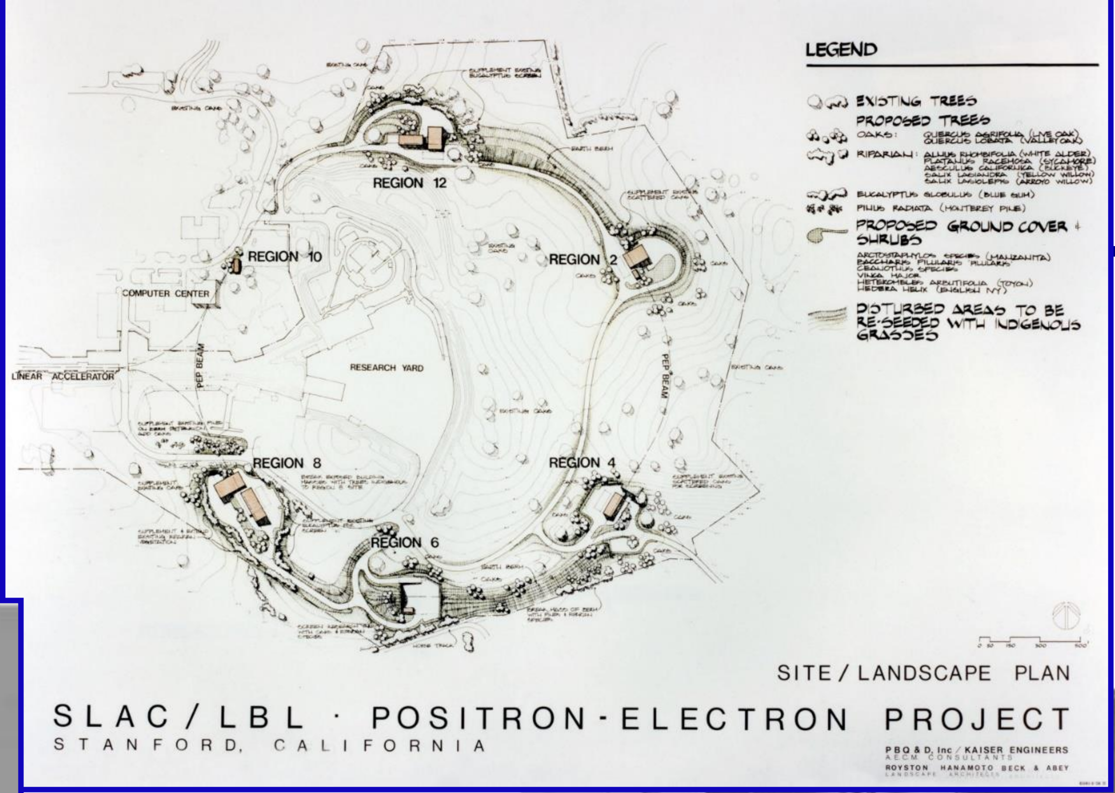
PEP technology developed from SPEAR upgrade

- SPEAR-NOTE-181. Chao, Lee. SPEAR II Touschek Lifetime. October 1974.
- SPEAR-NOTE-182 and PEP-105. Chao, Morton. Physical Picture of the Electromagnetic fields Between Two Infinite Conducting Plates Produced by a Point Charge Moving at the Speed of Light. February 1975.
- SPEAR-NOTE-183. Chao. Calculation of Single Resonance Effects. February 1975.
- SPEAR-NOTE-187. Chao, Keil, King, Morton, Lee, Paterson. Betatron-Synchrotron Resonances in SPEARII and a Possible Explanation. August 1975.

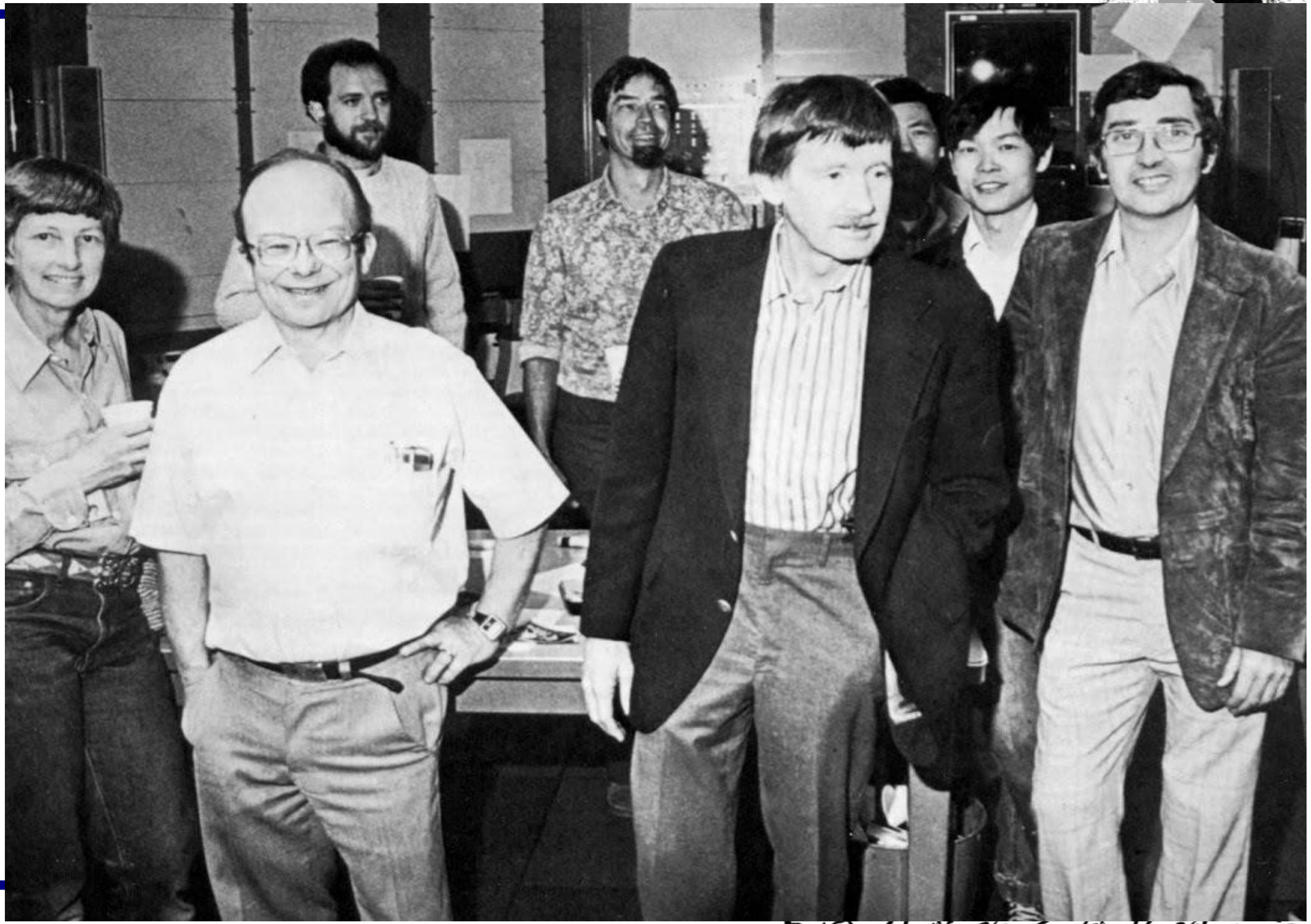


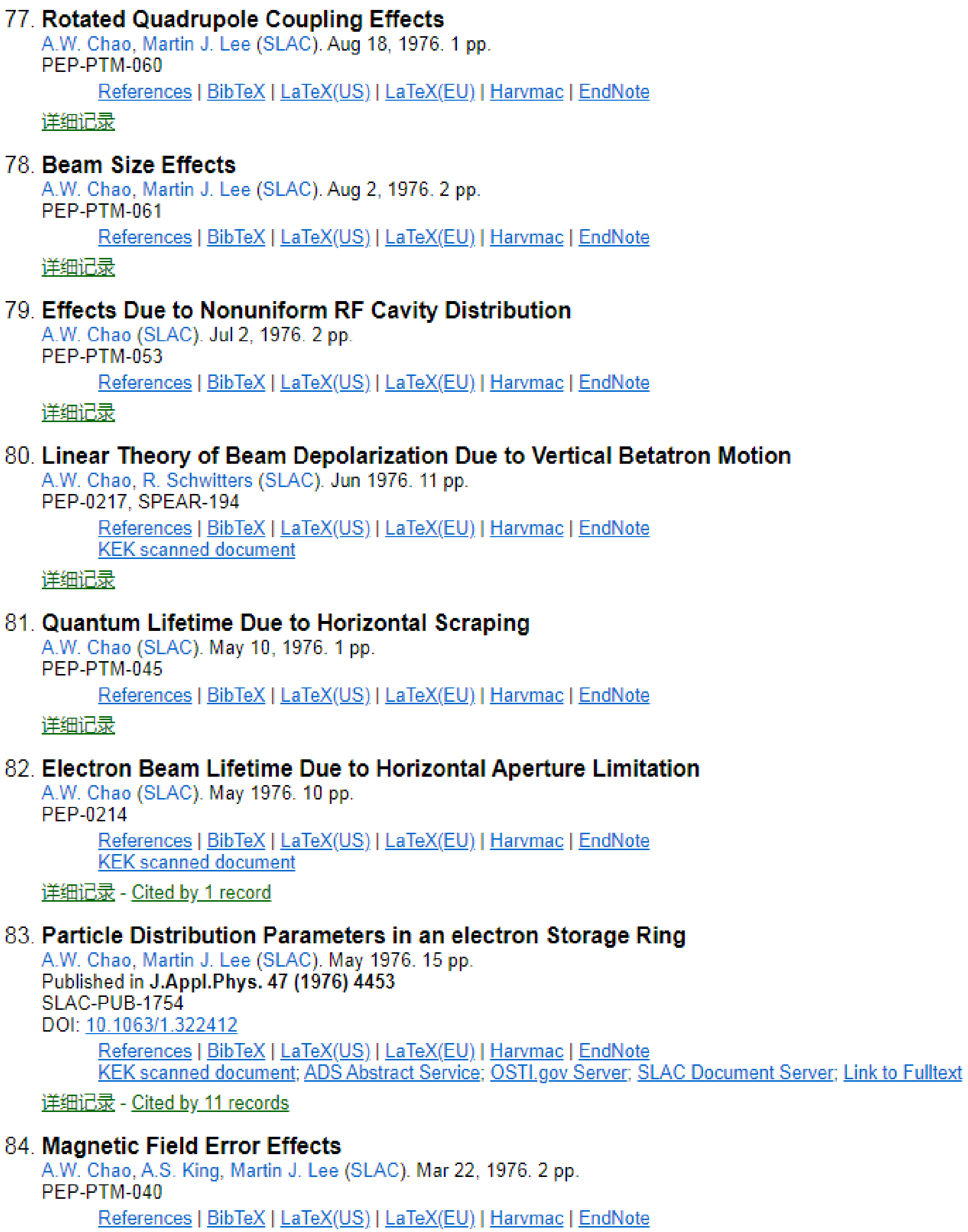
PEP/PEP-II

- **PEP: 15x15 GeV**
- **L = $1E32/cm^2/s$**



- **Celebrating first beam stored in PEP**





77. **Rotated Quadrupole Coupling Effects**
A.W. Chao, Martin J. Lee (SLAC). Aug 18, 1976. 1 pp.
PEP-PTM-060
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

78. **Beam Size Effects**
A.W. Chao, Martin J. Lee (SLAC). Aug 2, 1976. 2 pp.
PEP-PTM-061
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

79. **Effects Due to Nonuniform RF Cavity Distribution**
A.W. Chao (SLAC). Jul 2, 1976. 2 pp.
PEP-PTM-053
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

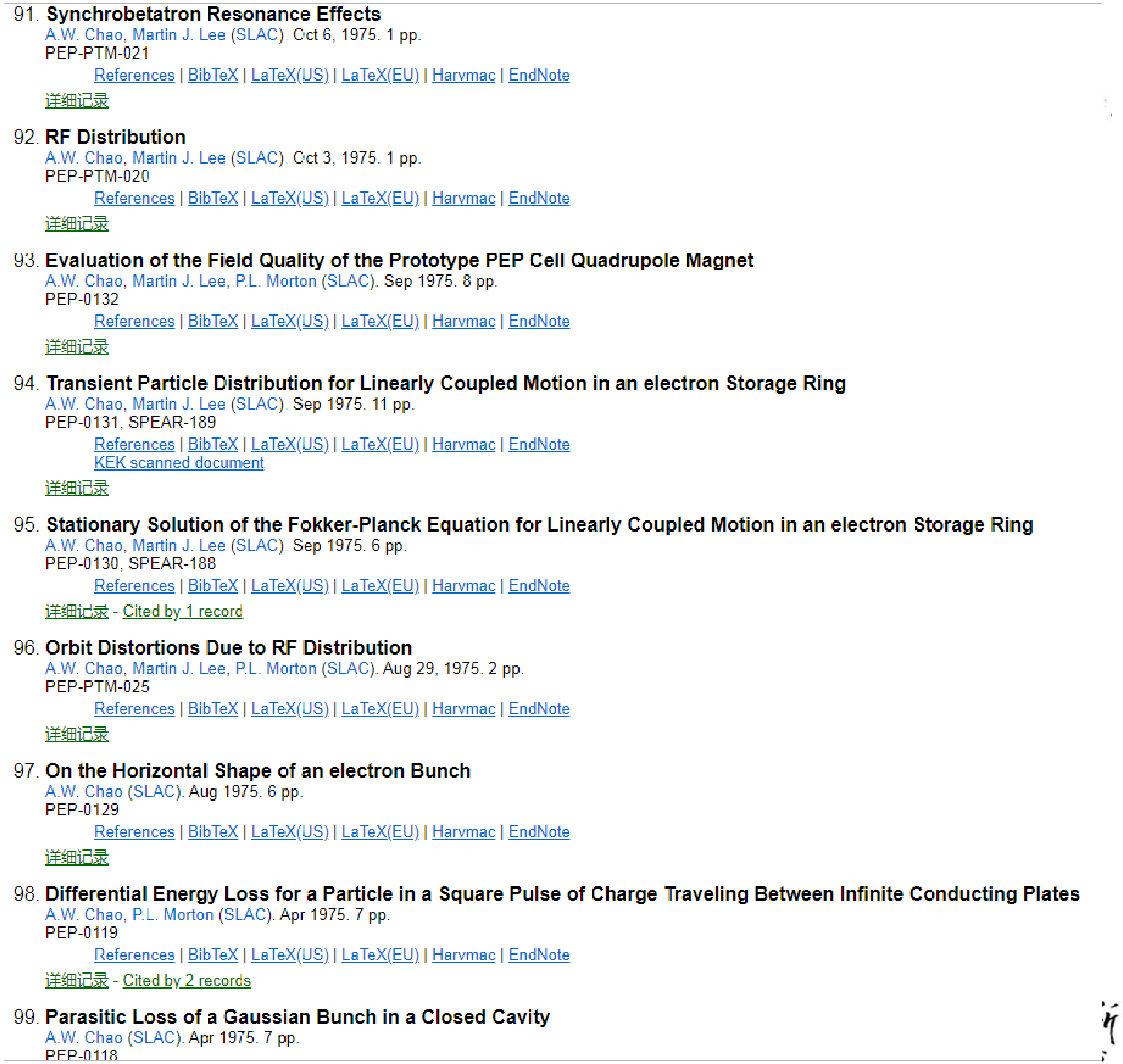
80. **Linear Theory of Beam Depolarization Due to Vertical Betatron Motion**
A.W. Chao, R. Schwitters (SLAC). Jun 1976. 11 pp.
PEP-0217, SPEAR-194
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document
详细记录

81. **Quantum Lifetime Due to Horizontal Scraping**
A.W. Chao (SLAC). May 10, 1976. 1 pp.
PEP-PTM-045
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

82. **Electron Beam Lifetime Due to Horizontal Aperture Limitation**
A.W. Chao (SLAC). May 1976. 10 pp.
PEP-0214
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document
详细记录 - Cited by 1 record

83. **Particle Distribution Parameters in an electron Storage Ring**
A.W. Chao, Martin J. Lee (SLAC). May 1976. 15 pp.
Published in **J.Appl.Phys. 47 (1976) 4453**
SLAC-PUB-1754
DOI: 10.1063/1.322412
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document; ADS Abstract Service; OSTI.gov Server; SLAC Document Server; Link to Fulltext
详细记录 - Cited by 11 records

84. **Magnetic Field Error Effects**
A.W. Chao, A.S. King, Martin J. Lee (SLAC). Mar 22, 1976. 2 pp.
PEP-PTM-040
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote



91. **Synchrobetatron Resonance Effects**
A.W. Chao, Martin J. Lee (SLAC). Oct 6, 1975. 1 pp.
PEP-PTM-021
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

92. **RF Distribution**
A.W. Chao, Martin J. Lee (SLAC). Oct 3, 1975. 1 pp.
PEP-PTM-020
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

93. **Evaluation of the Field Quality of the Prototype PEP Cell Quadrupole Magnet**
A.W. Chao, Martin J. Lee, P.L. Morton (SLAC). Sep 1975. 8 pp.
PEP-0132
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

94. **Transient Particle Distribution for Linearly Coupled Motion in an electron Storage Ring**
A.W. Chao, Martin J. Lee (SLAC). Sep 1975. 11 pp.
PEP-0131, SPEAR-189
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
KEK scanned document
详细记录

95. **Stationary Solution of the Fokker-Planck Equation for Linearly Coupled Motion in an electron Storage Ring**
A.W. Chao, Martin J. Lee (SLAC). Sep 1975. 6 pp.
PEP-0130, SPEAR-188
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录 - Cited by 1 record

96. **Orbit Distortions Due to RF Distribution**
A.W. Chao, Martin J. Lee, P.L. Morton (SLAC). Aug 29, 1975. 2 pp.
PEP-PTM-025
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

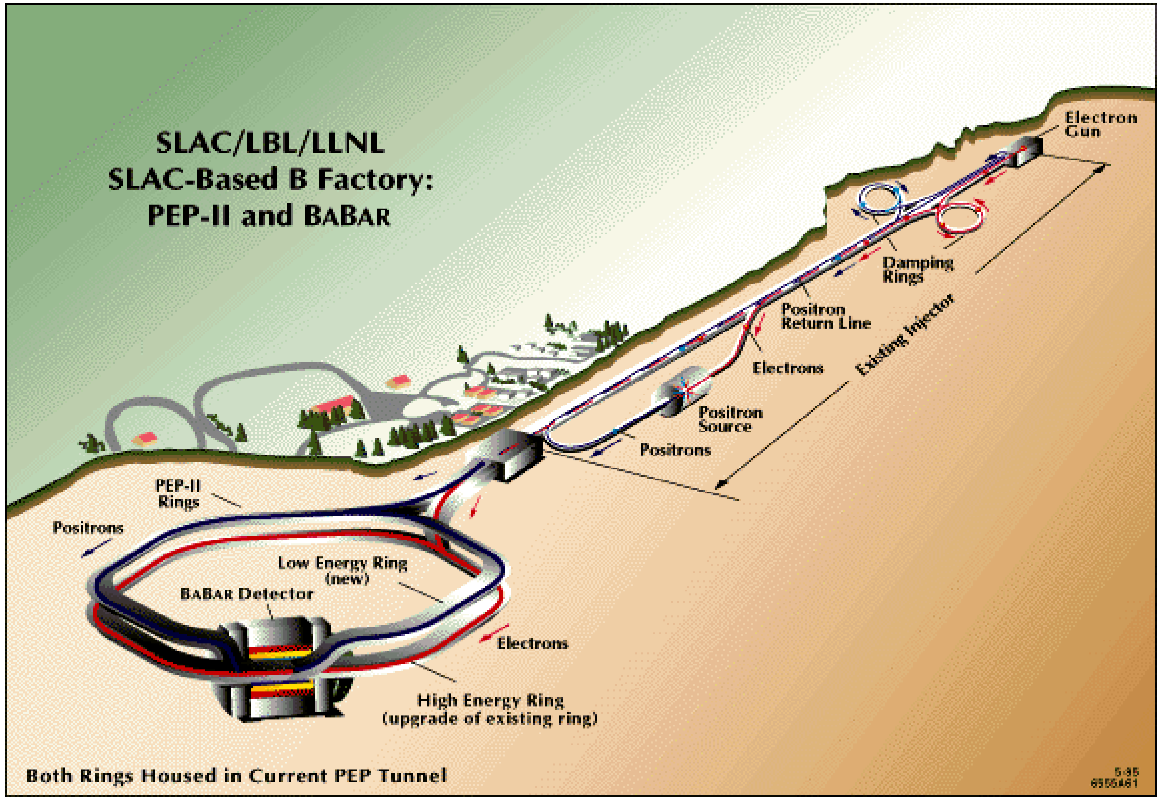
97. **On the Horizontal Shape of an electron Bunch**
A.W. Chao (SLAC). Aug 1975. 6 pp.
PEP-0129
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录

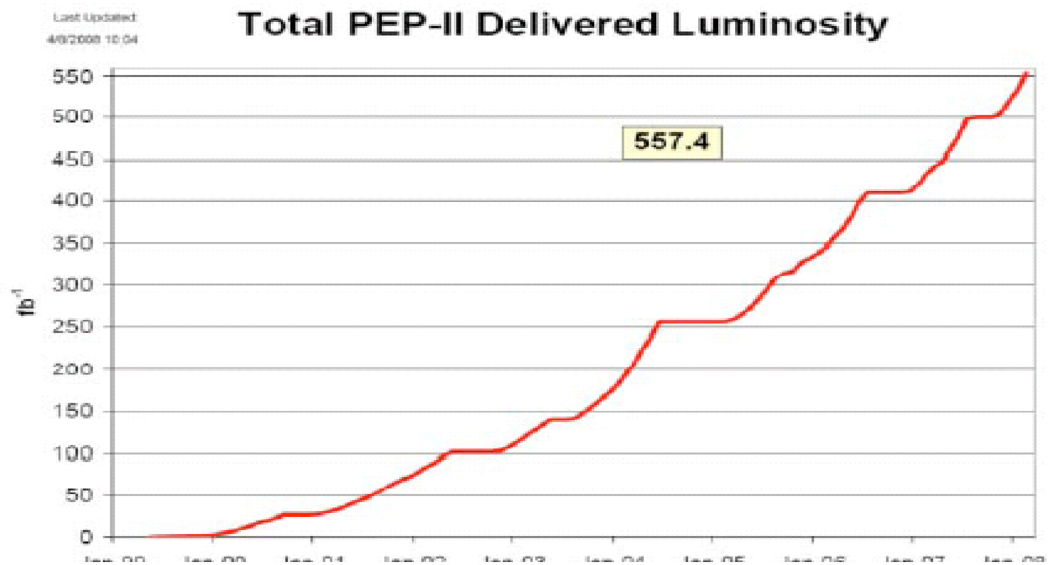
98. **Differential Energy Loss for a Particle in a Square Pulse of Charge Traveling Between Infinite Conducting Plates**
A.W. Chao, P.L. Morton (SLAC). Apr 1975. 7 pp.
PEP-0119
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
详细记录 - Cited by 2 records

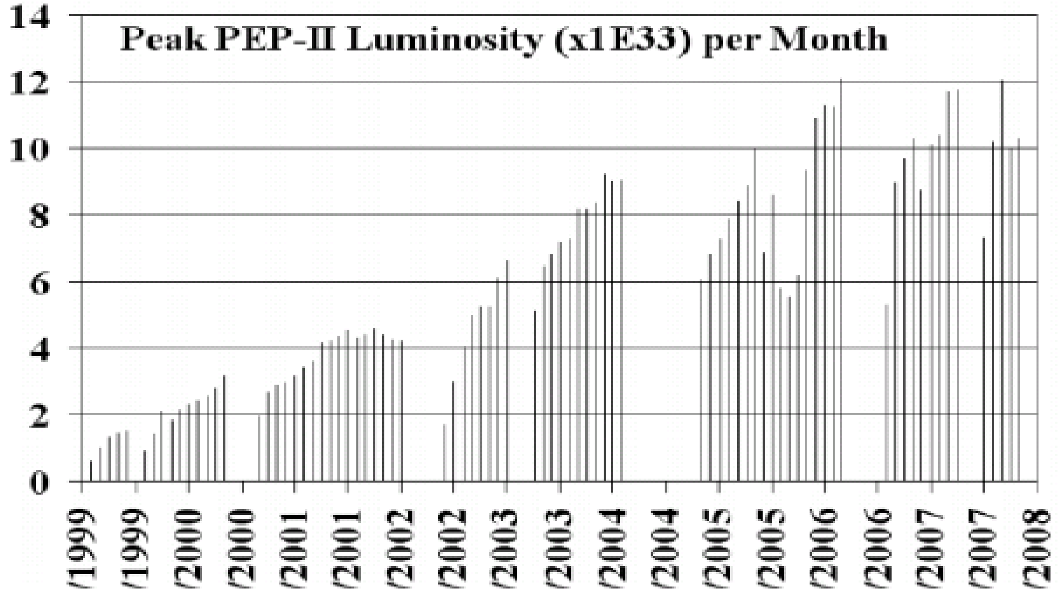
99. **Parasitic Loss of a Gaussian Bunch in a Closed Cavity**
A.W. Chao (SLAC). Apr 1975. 7 pp.
PEP-0118

PEP-II

- **A B-factory with asymmetric beam energy**

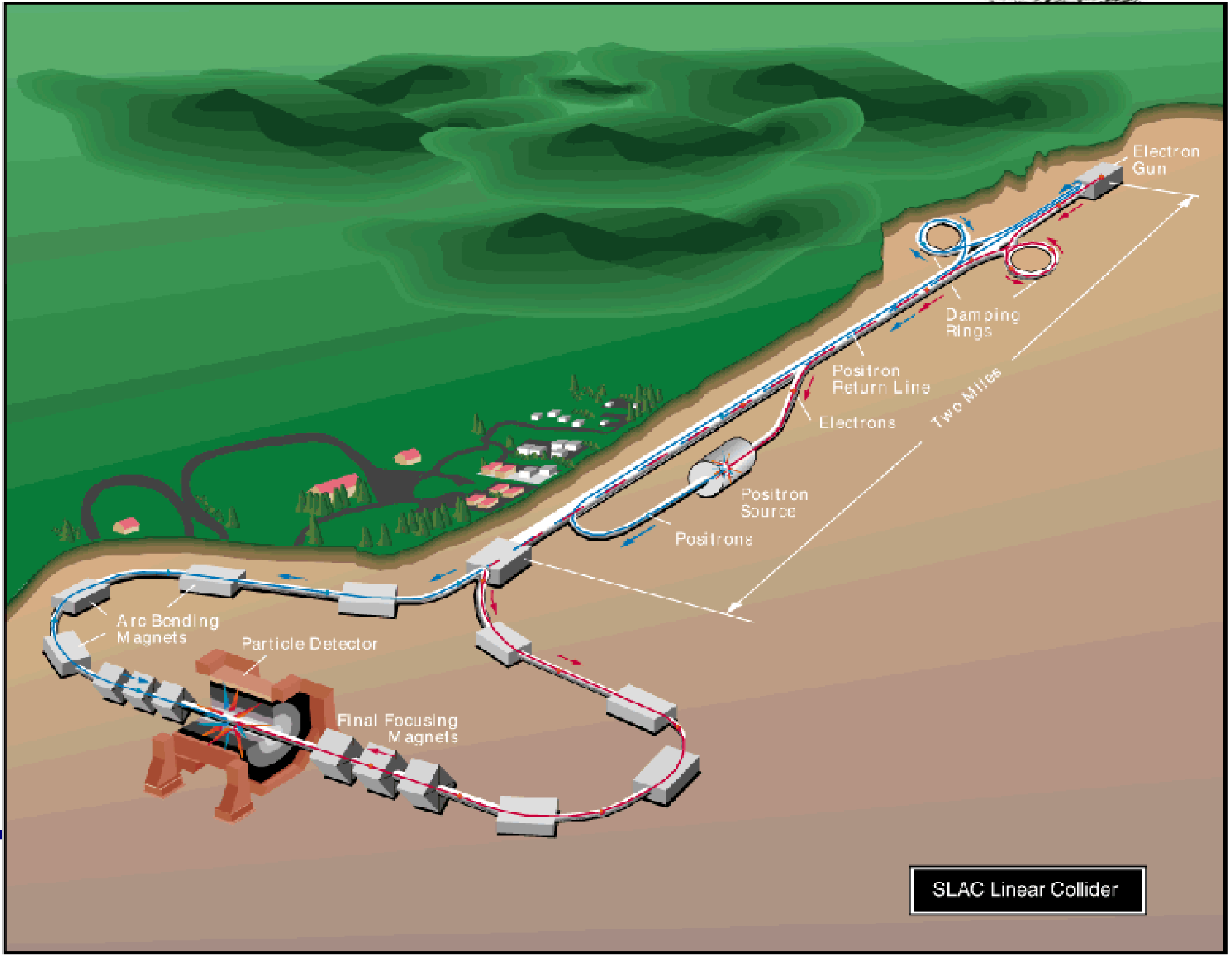


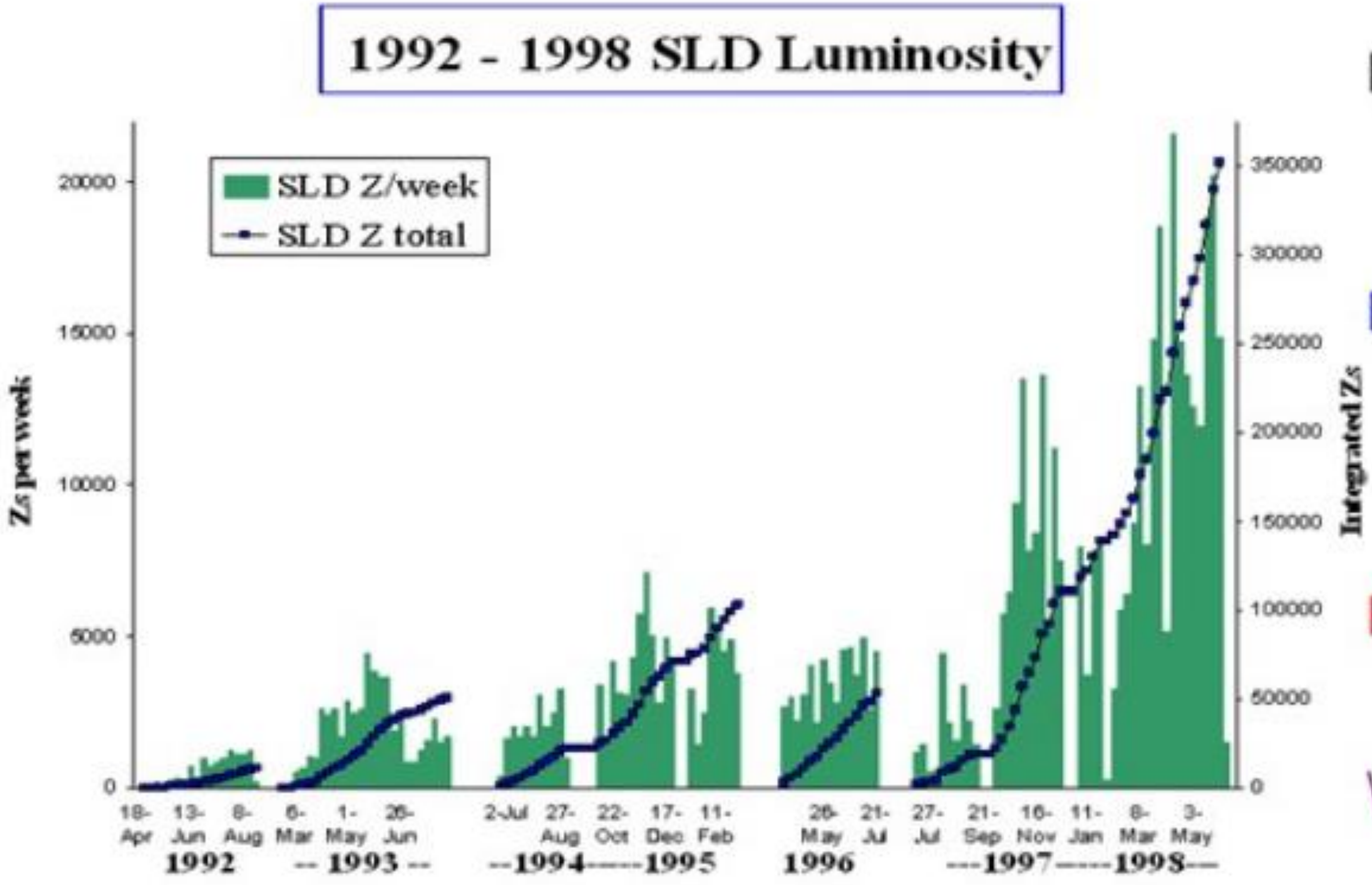




SLAC Linear Collider

- Study the Z_0 (E=92GeV)
- Demon of a linear collider and show its feasibility
- e- & e+ share the same linac
- More than a 10% prototype, L = 3E30





Flexible design to allow parameter optimization

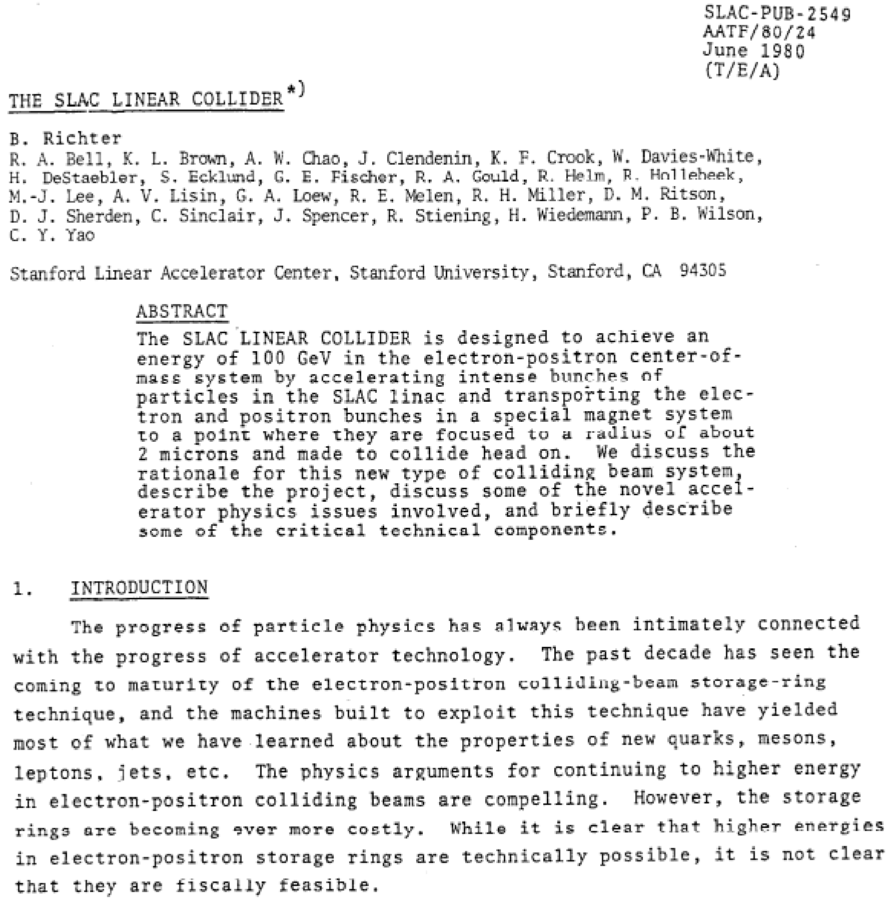
Extensive diagnostics for troubleshooting and tuning

Reliable and stable operation

Well designed collimation to limit backgrounds

→ Provides the basis for the next generation LC

Courtesy T. Raubenheimer



SLAC-PUB-2549
AATF/80/24
June 1980
(T/E/A)

THE SLAC LINEAR COLLIDER*)

B. Richter
R. A. Bell, K. L. Brown, A. W. Chao, J. Clendenin, K. F. Crook, W. Davies-White,
H. DeStaebler, S. Ecklund, G. E. Fischer, R. A. Gould, R. Helm, R. Hollebeek,
M.-J. Lee, A. V. Lisin, G. A. Loew, R. E. Melen, R. H. Miller, D. M. Ritson,
D. J. Sherden, C. Sinclair, J. Spencer, R. Stiening, H. Wiedemann, P. B. Wilson,
C. Y. Yao

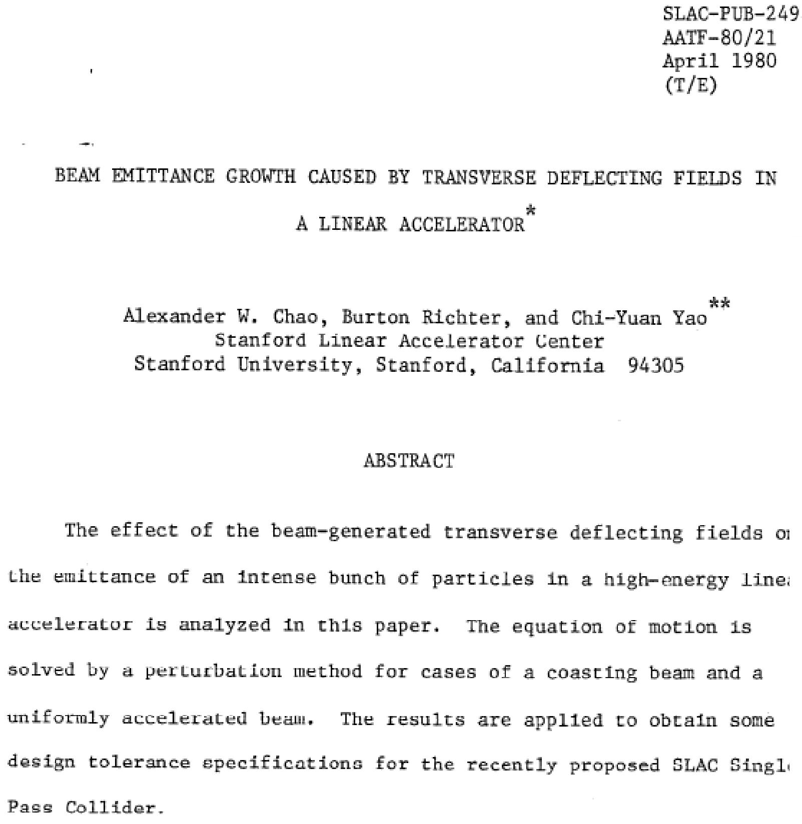
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94305

ABSTRACT

The SLAC LINEAR COLLIDER is designed to achieve an energy of 100 GeV in the electron-positron center-of-mass system by accelerating intense bunches of particles in the SLAC linac and transporting the electron and positron bunches in a special magnet system to a point where they are focused to a radius of about 2 microns and made to collide head on. We discuss the rationale for this new type of colliding beam system, describe the project, discuss some of the novel accelerator physics issues involved, and briefly describe some of the critical technical components.

1. INTRODUCTION

The progress of particle physics has always been intimately connected with the progress of accelerator technology. The past decade has seen the coming to maturity of the electron-positron colliding-beam storage-ring technique, and the machines built to exploit this technique have yielded most of what we have learned about the properties of new quarks, mesons, leptons, jets, etc. The physics arguments for continuing to higher energy in electron-positron colliding beams are compelling. However, the storage rings are becoming ever more costly. While it is clear that higher energies in electron-positron storage rings are technically possible, it is not clear that they are fiscally feasible.



SLAC-PUB-2498
AATF-80/21
April 1980
(T/E)

BEAM EMITTANCE GROWTH CAUSED BY TRANSVERSE DEFLECTING FIELDS IN A LINEAR ACCELERATOR*

Alexander W. Chao, Burton Richter, and Chi-Yuan Yao**
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

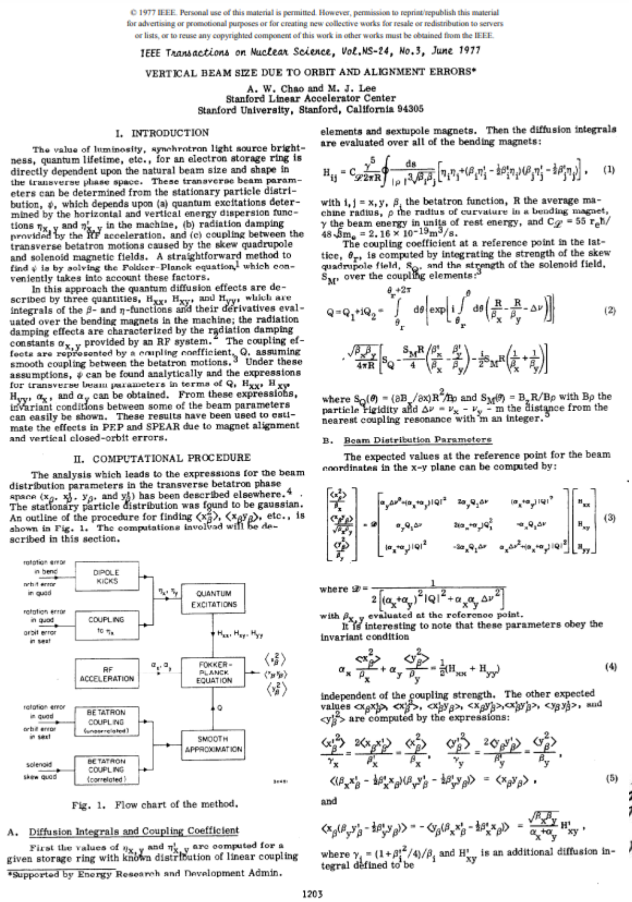
ABSTRACT

The effect of the beam-generated transverse deflecting fields o

the emittance of an intense bunch of particles in a high-energy line

accelerator is analyzed in this paper. The equation of motion is solved by a perturbation method for cases of a coasting beam and a uniformly accelerated beam. The results are applied to obtain some design tolerance specifications for the recently proposed SLAC Singl

Pass Collider.



IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

VERTICAL BEAM SIZE DUE TO ORBIT AND ALIGNMENT ERRORS*

A. W. Chao and M. J. Lee
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

I. INTRODUCTION

The value of luminosity, synchrotron light source brightness, quantum lifetime, etc., for an electron storage ring is directly dependent upon the natural beam size and shape in the transverse phase space. These transverse beam parameters can be determined from the stationary particle distribution, ψ, which depends upon (a) quantum excitations determined by the horizontal and vertical energy dispersion functions $\eta_{x,y}$ and $\eta'_{x,y}$ in the machine, (b) radiation damping provided by the RF acceleration, and (c) coupling between the transverse betatron motions caused by the skew quadrupole and solenoid magnetic fields. A straightforward method to find ψ is by solving the Fokker-Planck equation,[1] which conveniently takes into account these factors.

In this approach the quantum diffusion effects are described by three quantities, H_{xx}, H_{xy}, and H_{yy}, which are integrals of the β- and η-functions and their derivatives evaluated over the bending magnets in the machine; the radiation damping effects are characterized by the radiation damping constants $\alpha_{x,y}$ provided by an RF system.[2] The coupling effects are represented by a coupling coefficient, Q, assuming smooth coupling between the betatron motions.[3] Under these assumptions, ψ can be found analytically and the expressions for transverse beam parameters in terms of Q, H_{xx}, H_{xy}, H_{yy}, α_x, and α_y can be obtained. From these expressions, invariant conditions between some of the beam parameters can easily be shown. These results have been used to estimate the effects in PEP and SPEAR due to magnet alignment and vertical closed-orbit errors.

II. COMPUTATIONAL PROCEDURE

The analysis which leads to the expressions for the beam distribution parameters in the transverse betatron phase space (x_β, x'_β, y_β, and y'_β) has been described elsewhere.[4] The stationary particle distribution was found to be gaussian. An outline of the procedure for finding $\langle x_\beta^2\rangle$, $\langle x_\beta y_\beta\rangle$, etc., is shown in Fig. 1. The computations involved will be described in this section.

Fig. 1. Flow chart of the method.

A. Diffusion Integrals and Coupling Coefficient

First the values of $\eta_{x,y}$ and $\eta'_{x,y}$ are computed for a given storage ring with known distribution of linear coupling elements and sextupole magnets. Then the diffusion integrals are evaluated over all of the bending magnets:

$$H_{ij} = C_{\mathscr{L}}\frac{\gamma^5}{2\pi R}\oint\frac{ds}{|\rho|^3\sqrt{\beta_i\beta_j}}\left[\eta_i\eta_j+(\beta_i\eta'_i-\tfrac{1}{2}\beta'_i\eta_i)(\beta_j\eta'_j-\tfrac{1}{2}\beta'_j\eta_j)\right], \quad (1)$$

with $i, j = x, y$, β_i the betatron function, R the average machine radius, ρ the radius of curvature in a bending magnet, γ the beam energy in units of rest energy, and $C_{\mathscr{L}} = 55\, r_e\hbar/48\sqrt{3}m_e = 2.16\times10^{-19}m^3/s$.

The coupling coefficient at a reference point in the lattice, θ_r, is computed by integrating the strength of the skew quadrupole field, S_Q, and the strength of the solenoid field, S_M, over the coupling elements:[3]

$$Q = Q_1 + iQ_2 = \int_{\theta_r}^{\theta_r+2\pi} d\theta\left\{\exp\left[i\int_{\theta_r}^{\theta} d\theta\left(\frac{R}{\beta_x}-\frac{R}{\beta_y}-\Delta\nu\right)\right]\right\} \quad (2)$$

$$\cdot\frac{\sqrt{\beta_x\beta_y}}{4\pi R}\left[S_Q-\frac{S_M R}{4}\left(\frac{\beta'_x}{\beta_x}-\frac{\beta'_y}{\beta_y}\right)-\frac{i}{2}S_M R\left(\frac{1}{\beta_x}+\frac{1}{\beta_y}\right)\right]$$

where $S_Q(\theta) = (\partial B_x/\partial x)R^2/B\rho$ and $S_M(\theta) = B_z R/B\rho$ with $B\rho$ the particle rigidity and $\Delta\nu = \nu_x - \nu_y - m$ the distance from the nearest coupling resonance with m an integer.[5]

B. Beam Distribution Parameters

The expected values at the reference point for the beam coordinates in the x-y plane can be computed by:

$$\begin{bmatrix}\frac{\langle x_\beta^2\rangle}{\beta_x}\\ \frac{\langle x_\beta y_\beta\rangle}{\sqrt{\beta_x\beta_y}}\\ \frac{\langle y_\beta^2\rangle}{\beta_y}\end{bmatrix} = \mathscr{D}\begin{bmatrix}\alpha_y\Delta\nu^2+(\alpha_x+\alpha_y)|Q|^2 & 2\alpha_y Q_2\Delta\nu & (\alpha_x+\alpha_y)|Q|^2\\ \alpha_y Q_1\Delta\nu & 2(\alpha_x+\alpha_y)Q_1^2 & -\alpha_x Q_1\Delta\nu\\ (\alpha_x+\alpha_y)|Q|^2 & -2\alpha_x Q_1\Delta\nu & \alpha_x\Delta\nu^2+(\alpha_x+\alpha_y)|Q|^2\end{bmatrix}\begin{bmatrix}H_{xx}\\ H_{xy}\\ H_{yy}\end{bmatrix} \quad (3)$$

$$\text{where } \mathscr{D} = \frac{1}{2\left[(\alpha_x+\alpha_y)^2|Q|^2+\alpha_x\alpha_y\Delta\nu^2\right]}$$

with $\beta_{x,y}$ evaluated at the reference point.

It is interesting to note that these parameters obey the invariant condition

$$\alpha_x\frac{\langle x_\beta^2\rangle}{\beta_x}+\alpha_y\frac{\langle y_\beta^2\rangle}{\beta_y} = \frac{1}{2}(H_{xx}+H_{yy}) \quad (4)$$

independent of the coupling strength. The other expected values $\langle x_\beta x'_\beta\rangle$, $\langle x'^2_\beta\rangle$, $\langle x'_\beta y_\beta\rangle$, $\langle x_\beta y'_\beta\rangle$, $\langle x'_\beta y'_\beta\rangle$, $\langle y_\beta y'_\beta\rangle$, and $\langle y'^2_\beta\rangle$ are computed by the expressions:

$$\frac{\langle x'^2_\beta\rangle}{\gamma_x} = \frac{2\langle x_\beta x'_\beta\rangle}{\beta'_x} = \frac{\langle x_\beta^2\rangle}{\beta_x}, \quad \frac{\langle y'^2_\beta\rangle}{\gamma_y} = \frac{2\langle y_\beta y'_\beta\rangle}{\beta'_y} = \frac{\langle y_\beta^2\rangle}{\beta_y},$$

$$\langle(\beta_x x'_\beta-\tfrac{1}{2}\beta'_x x_\beta)(\beta_y y'_\beta-\tfrac{1}{2}\beta'_y y_\beta)\rangle = \langle x_\beta y_\beta\rangle, \quad (5)$$

and

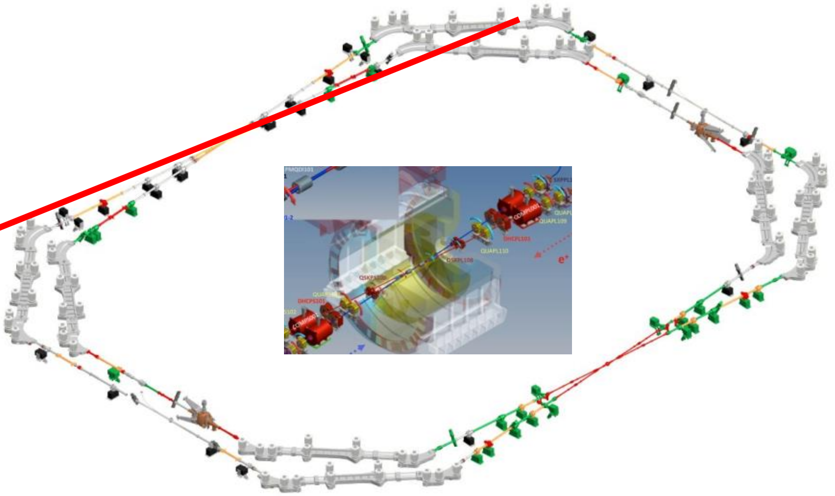
$$\langle x_\beta(\beta_y y'_\beta-\tfrac{1}{2}\beta'_y y_\beta)\rangle = -\langle y_\beta(\beta_x x'_\beta-\tfrac{1}{2}\beta'_x x_\beta)\rangle = \frac{\sqrt{\beta_x\beta_y}}{\alpha_x+\alpha_y}H'_{xy},$$

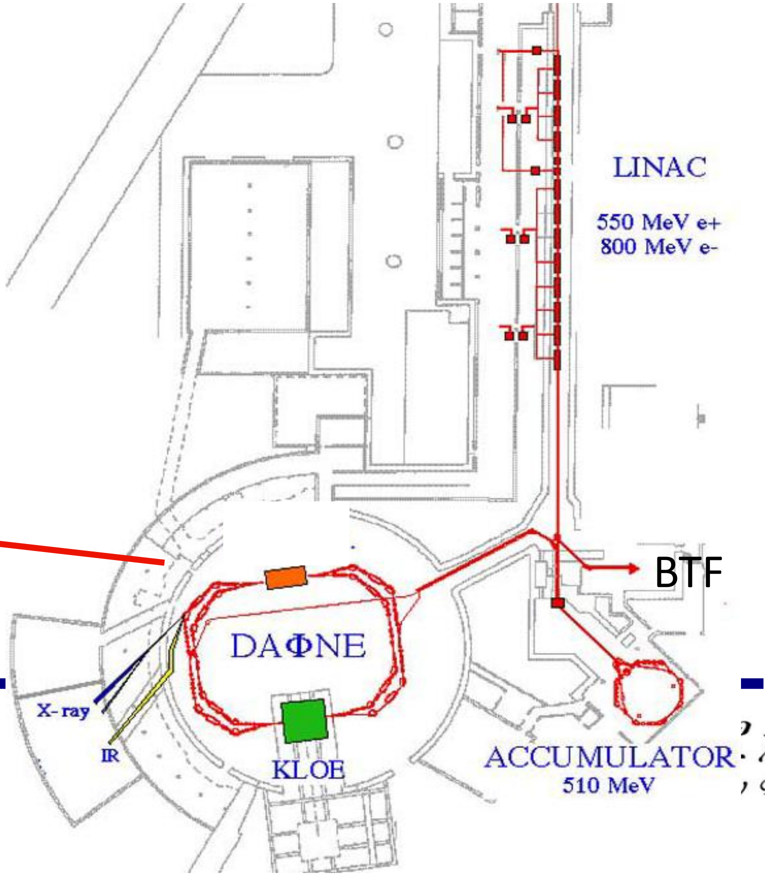
where $\gamma_i = (1+\beta'^2_i/4)/\beta_i$ and H'_{xy} is an additional diffusion integral defined to be

---

*Supported by Energy Research and Development Admin.

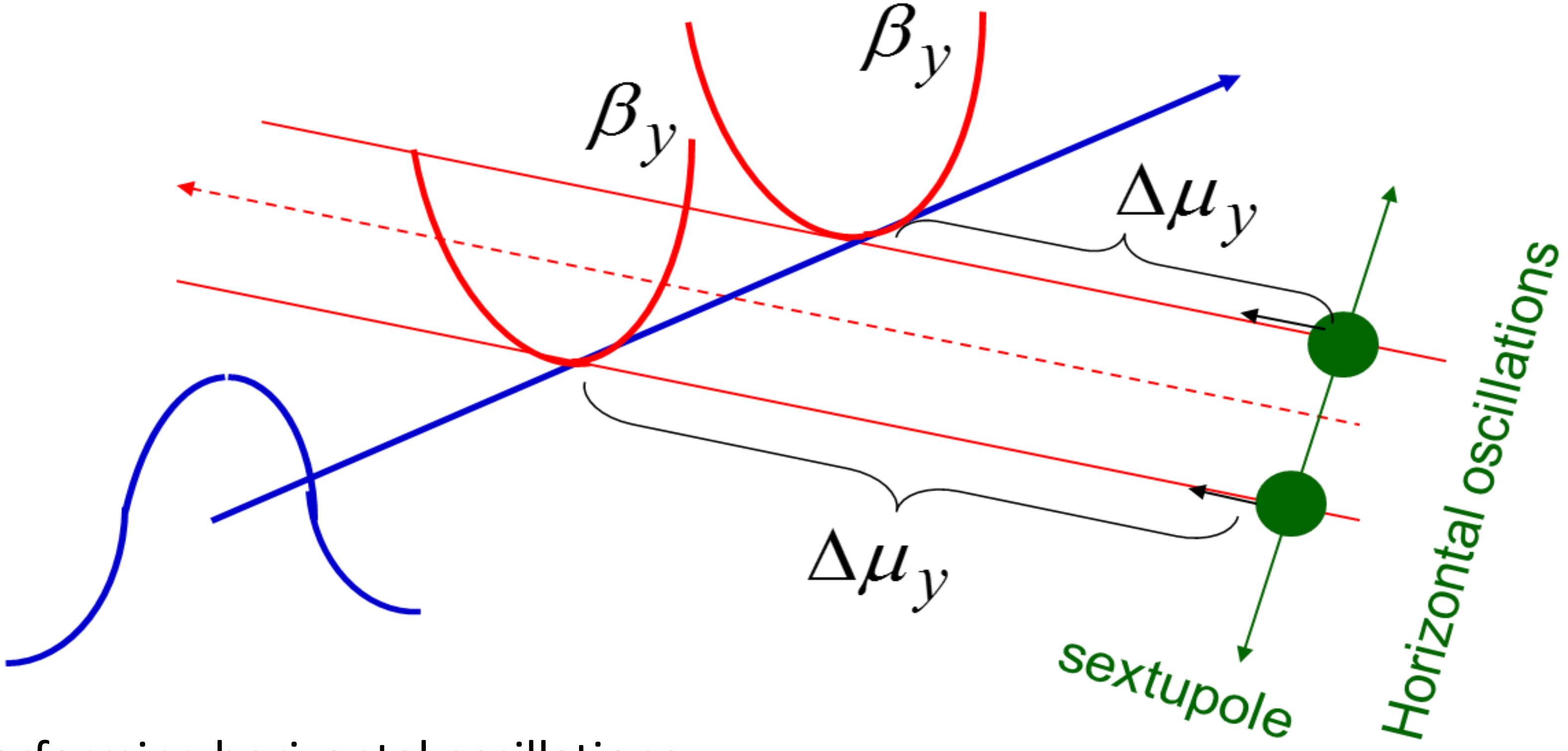
DAΦNE

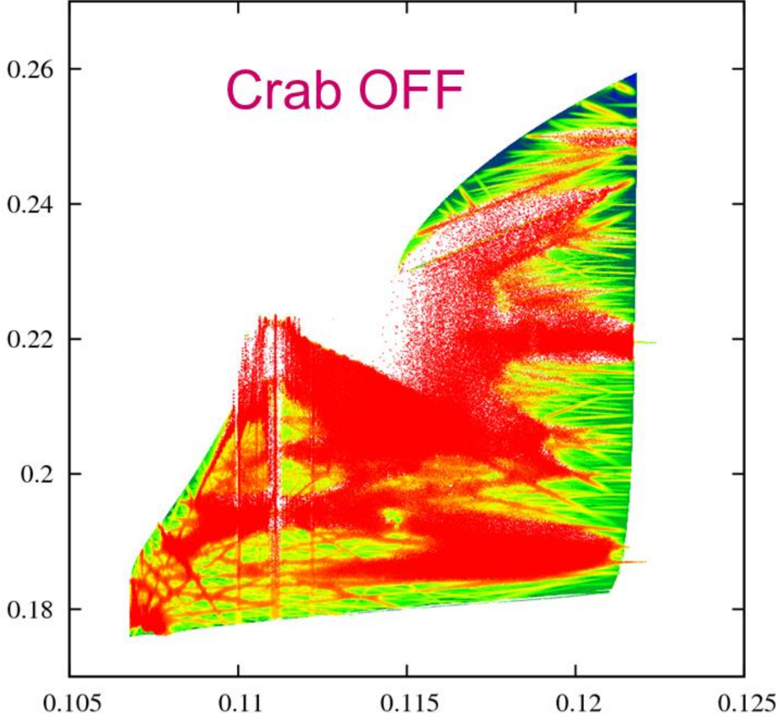


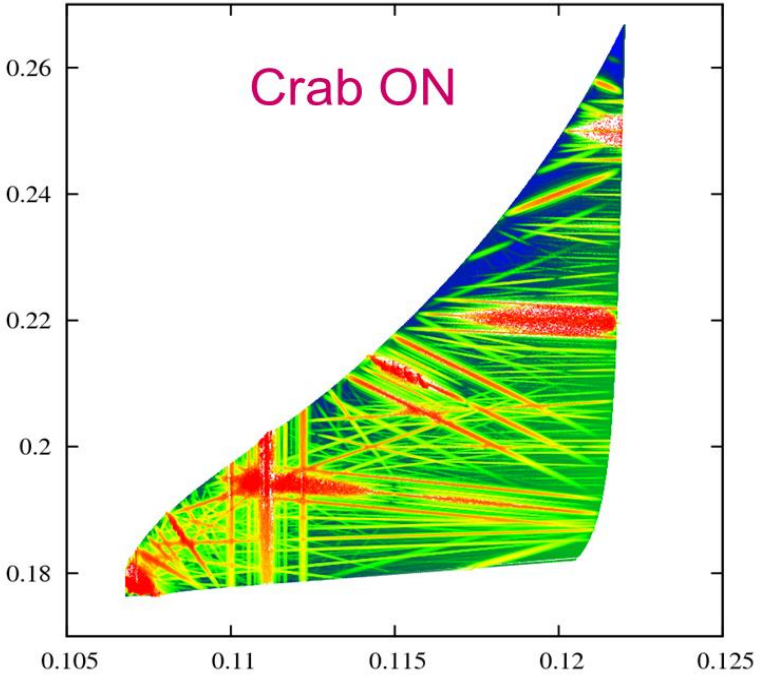


Energy per beam	510 [MeV]
Machine length	97 [m]
Max. beam current (KLOE run)	2.5(e-) 1.4(e+) [A]
N of colliding bunches	100-111
RF frequency	368.67 [MHz]
RF voltage	100-250 [kV]
Harmonic number	120
Bunch spacing	2.7 [ns]
Max ach. Luminosity (SIDDHARTA run)	4.5 10^{32} [$cm^{-2}s^{-1}$]

- **Crab waist to suppress the x-y resonances**



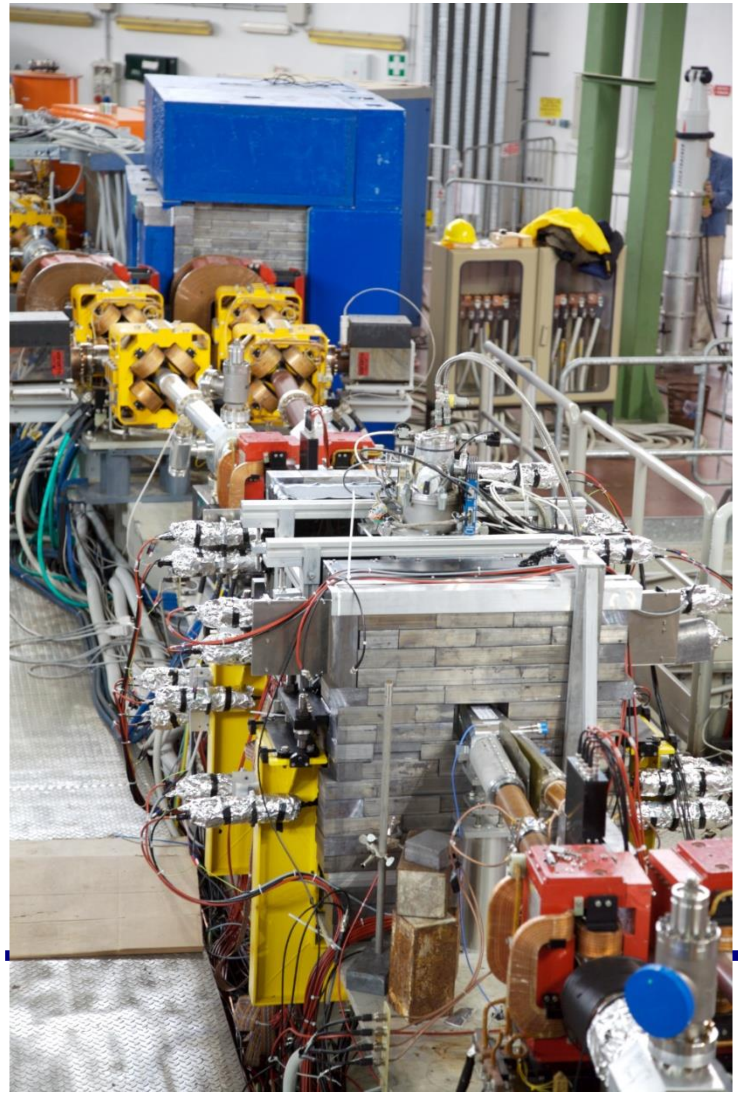




Performing horizontal oscillations:

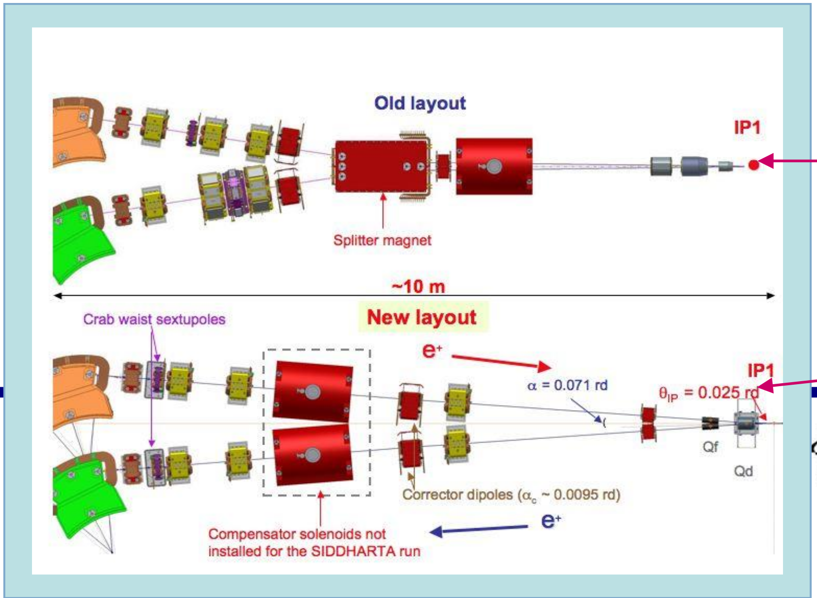
1. Particles see the same density and the same (minimum) vertical beta function
2. The vertical phase advance between the sextupole and the collision point remains the same ($\pi/2$)

New Interaction Region



DAΦNE IP Parameters

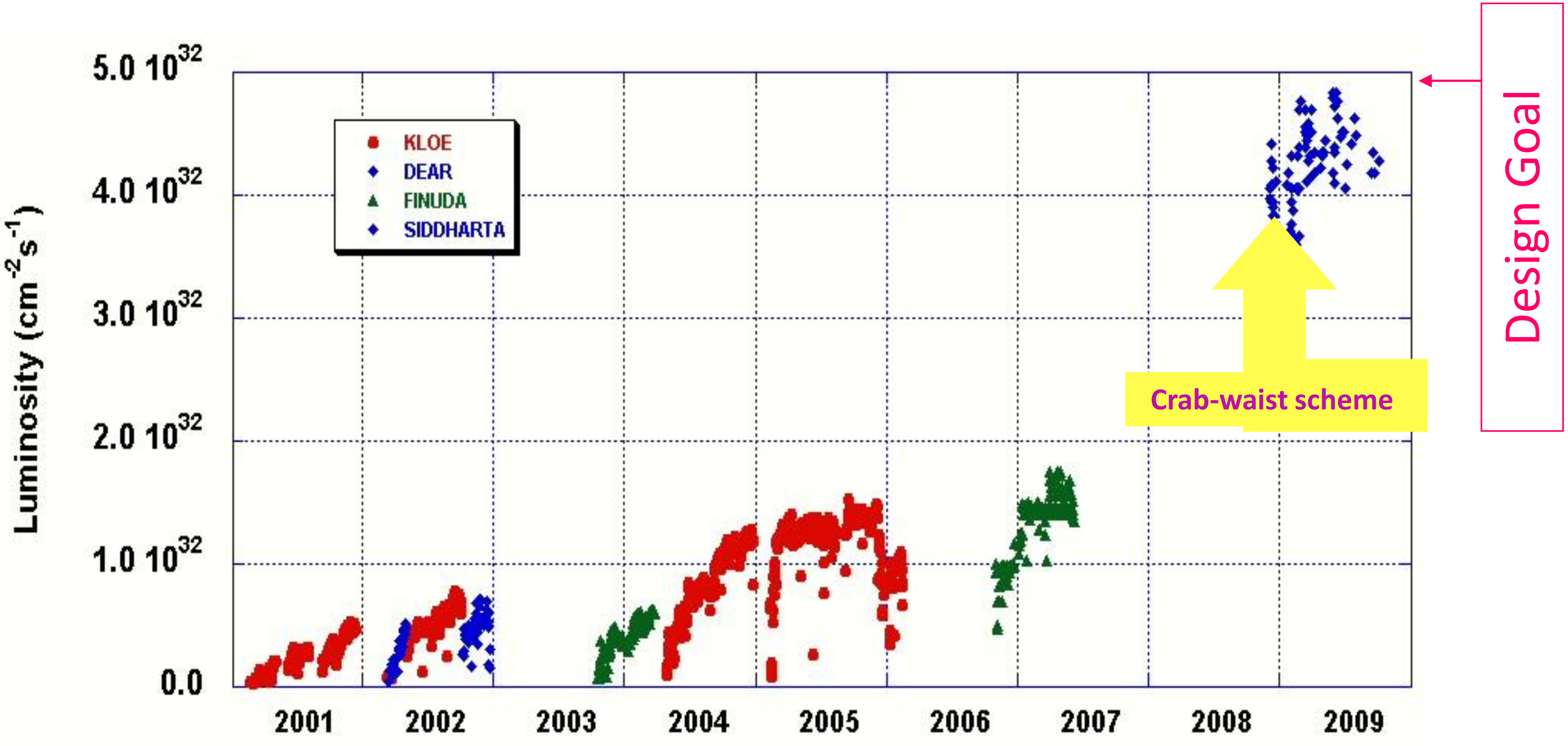
Parameter	***KLOE***	***FINUDA***	***SIDDHARTA***
Date	Sept. 2005	Apr. 2007	June 2009
ε_x, mm mrad	0.34	0.34	0.25
β_x, m	1.5	2.0	0.25
σ_x, mm	0.71	0.82	0.25
θ, mrad	25	25	50
σ_z, cm	2.5	2.2	1.7
Φ	0.44	0.34	1.70
β_y, cm	1.8	1.9	0.93



OLD

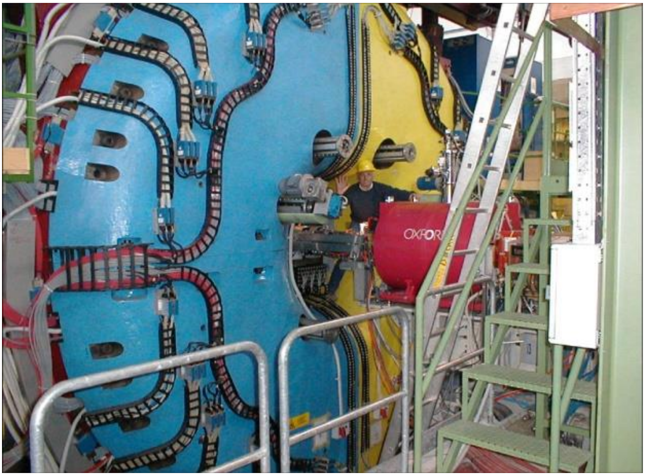
NEW

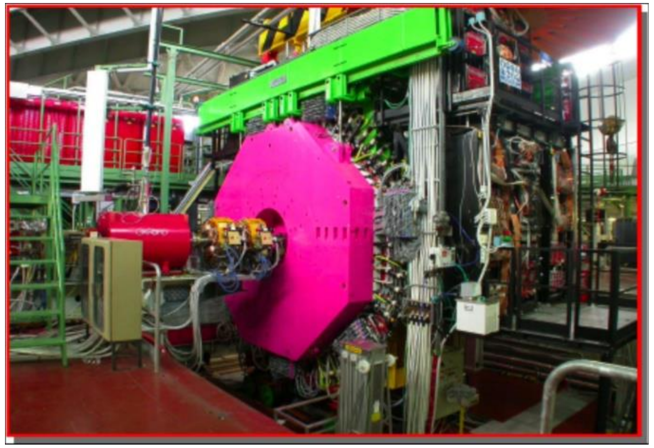
DAFNE Peak Luminosity

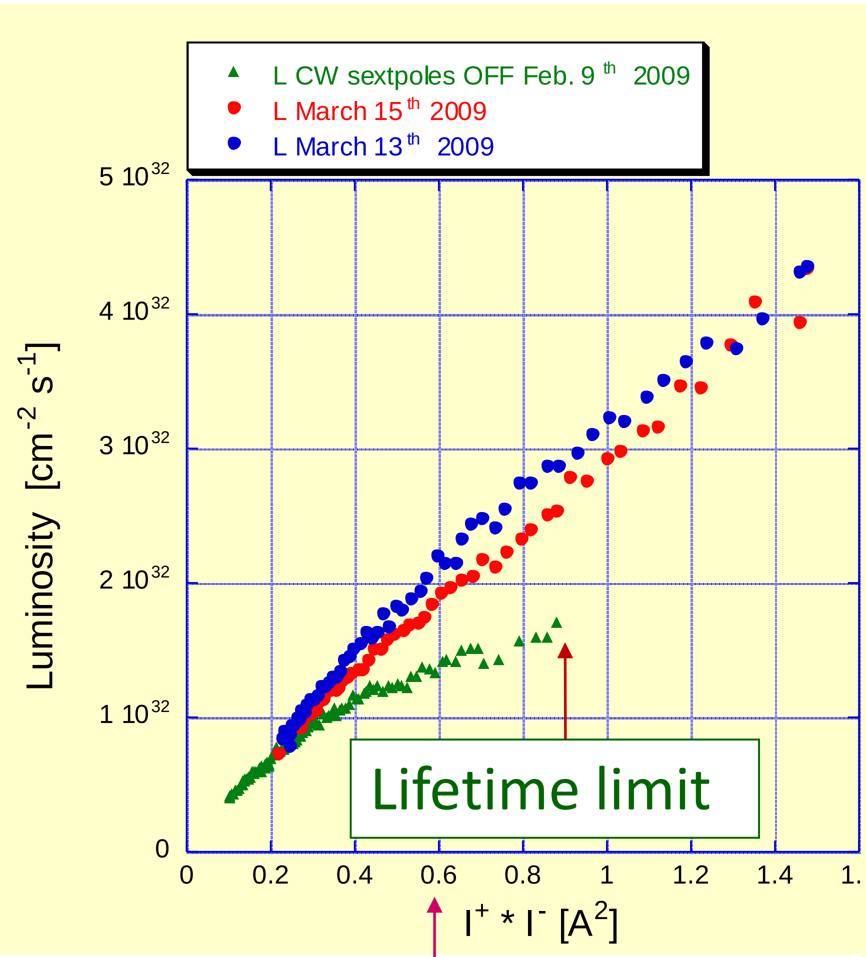


Crab-waist scheme

Design Goal



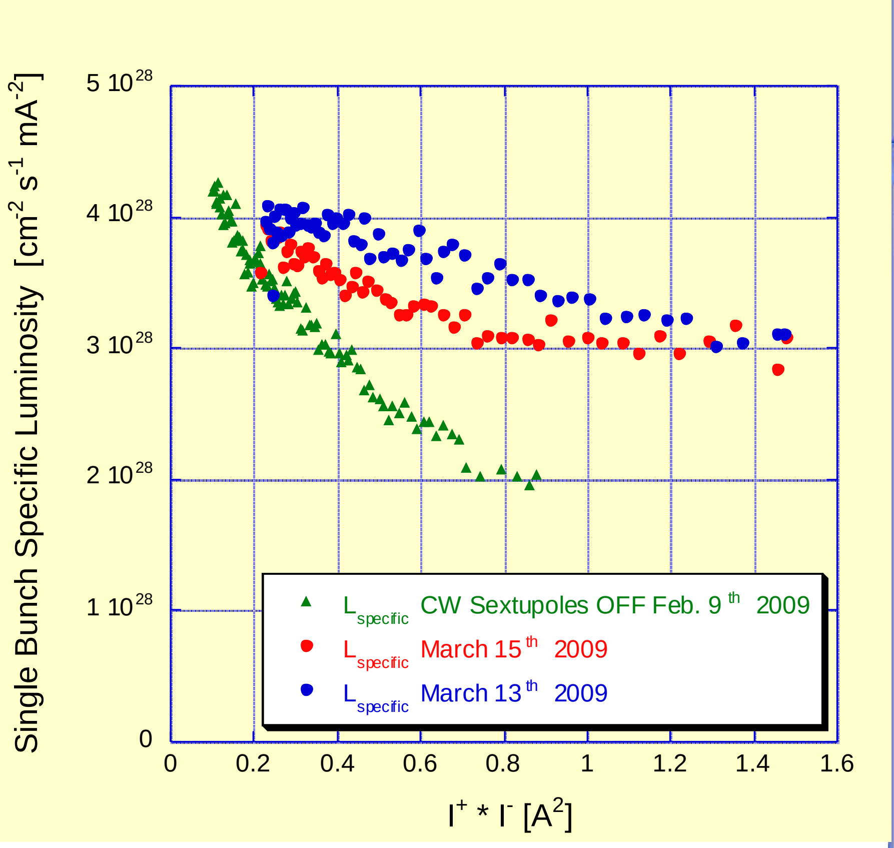


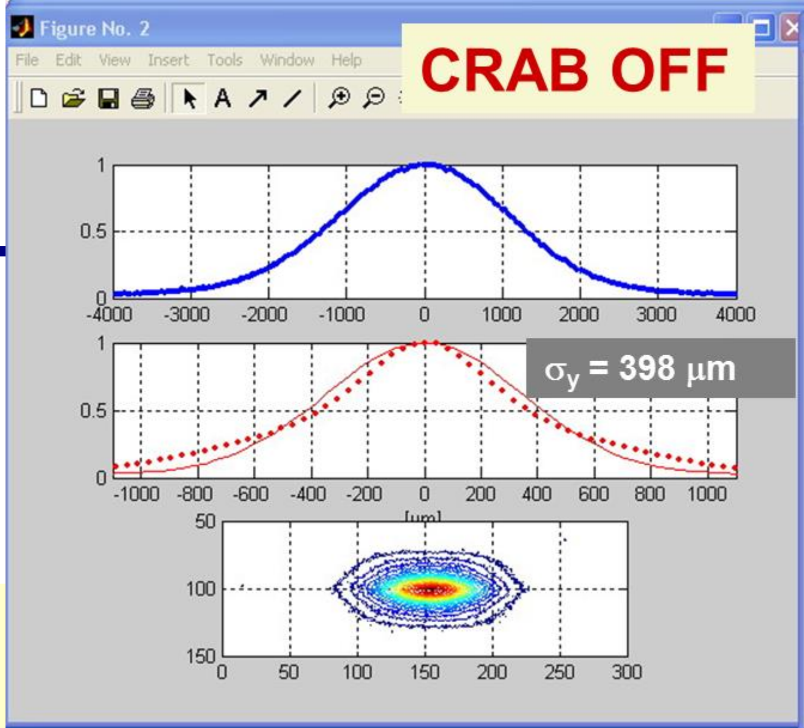


Lifetime limit

Crab on/off Luminosity vs Current Product

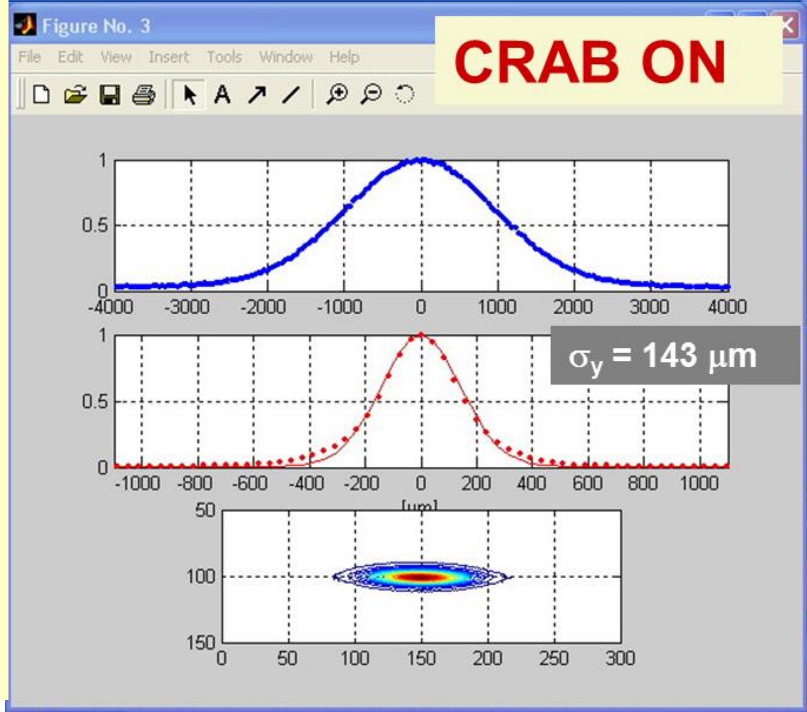
Crab on/off Specific Luminosity vs Current Product





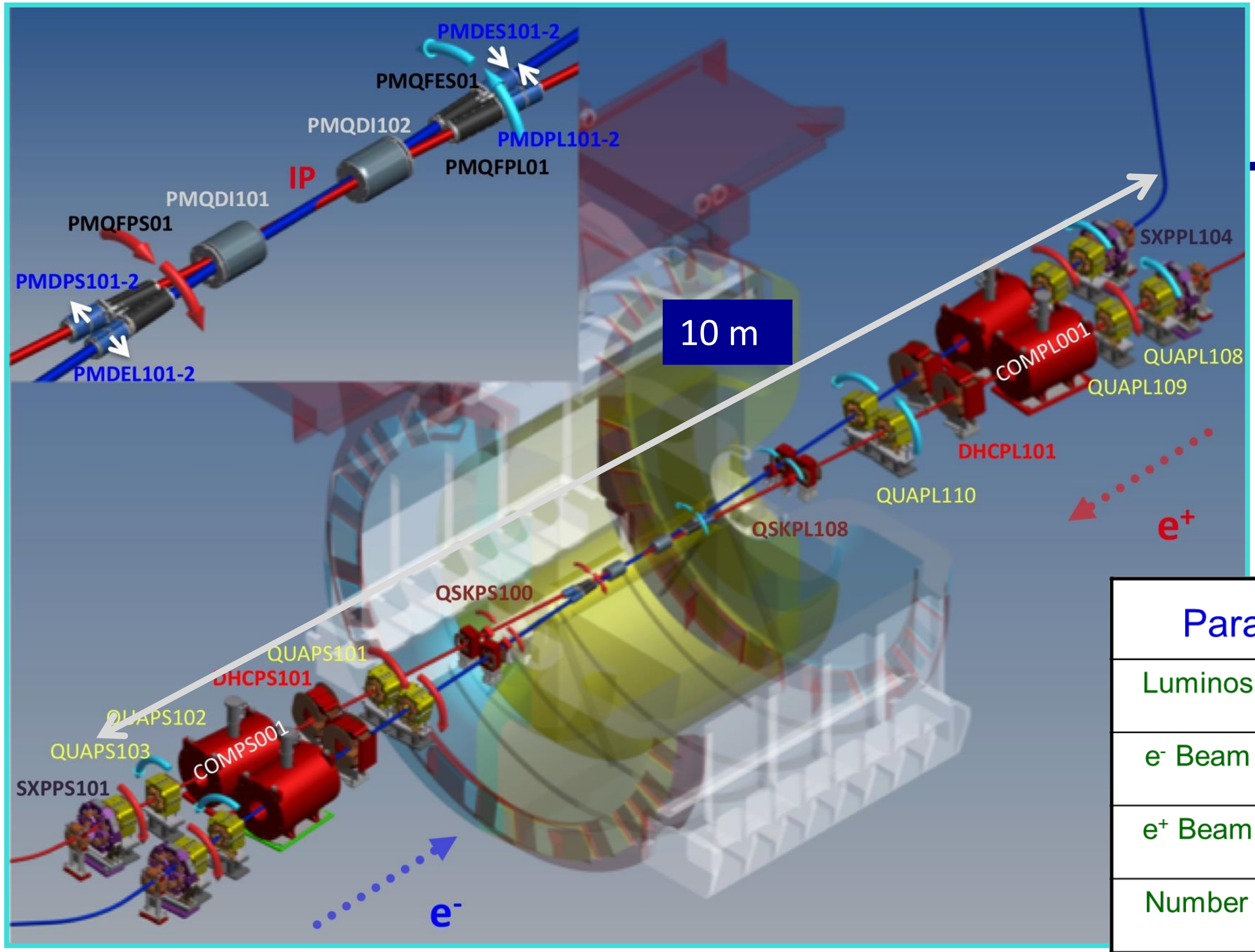
CRAB OFF

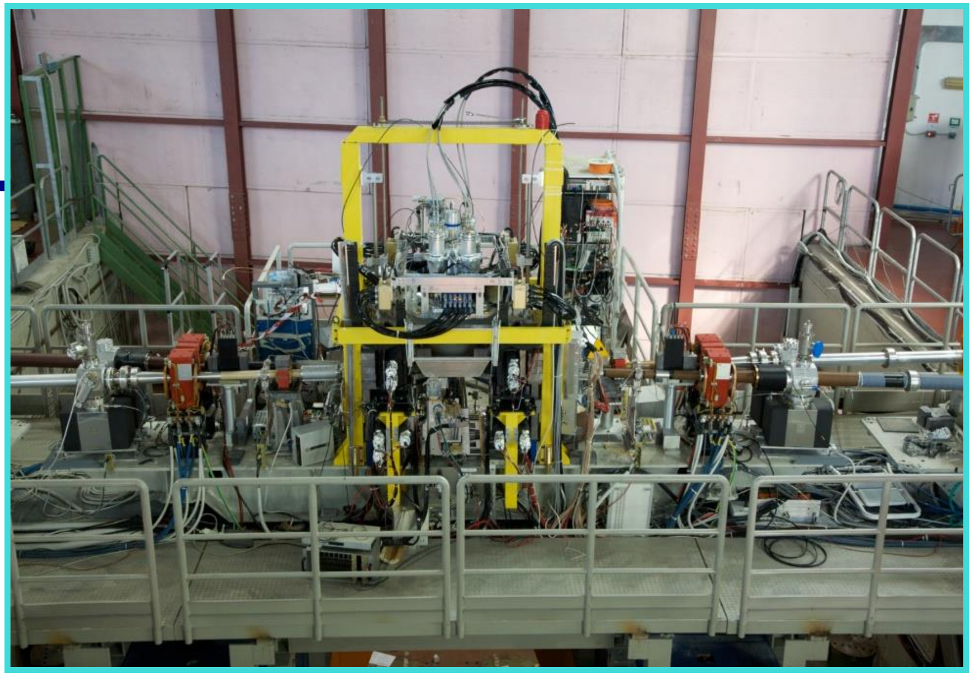
σ_y = 398 μm



CRAB ON

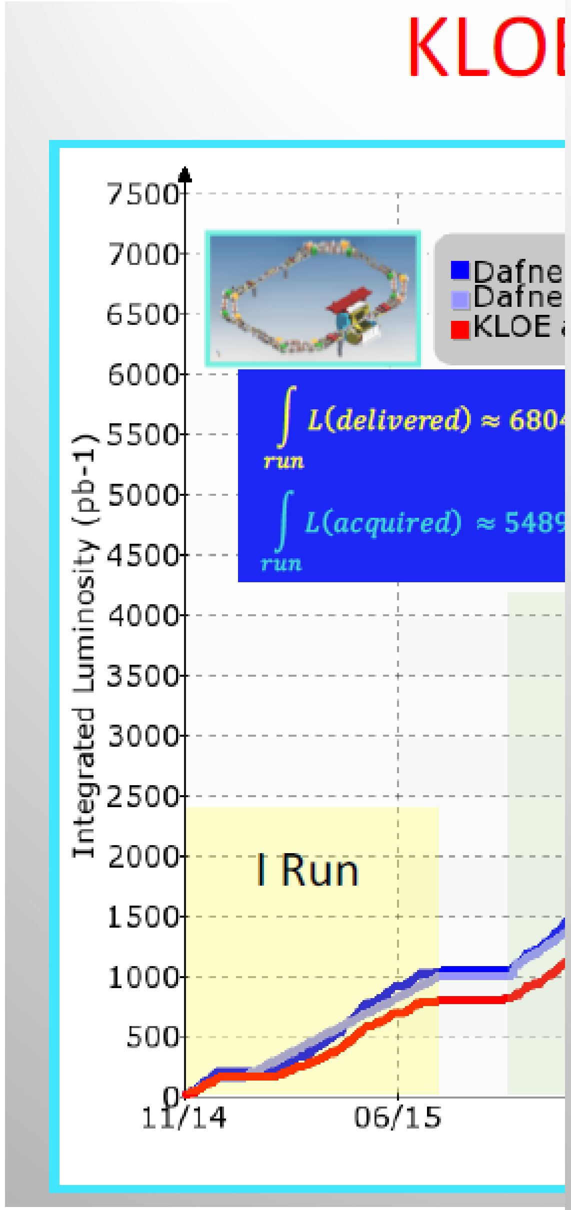
σ_y = 143 μm





Parameter	SIDDHARTA	KLOE-2
Luminosity [$cm^{-2}s^{-1}$]	4.53×10^{32}	2.13×10^{32}
e^- Beam Current [A]	1.52	1.13
e^+ Beam Current [A]	1.00	0.88
Number of Bunches	105	105
Specific Luminosity [$cm^{-2}s^{-1}mA^{-2}$/bunch]	3.13	2.25
Integrated Luminosity [pb^{-1}/day]	14.98	14.03

DAΦNE Timeline



March 31st 2018

end of the KLOE-2 Run

April ÷ July

KLOE-2 roll-out (completed on May 28th)

January 2019

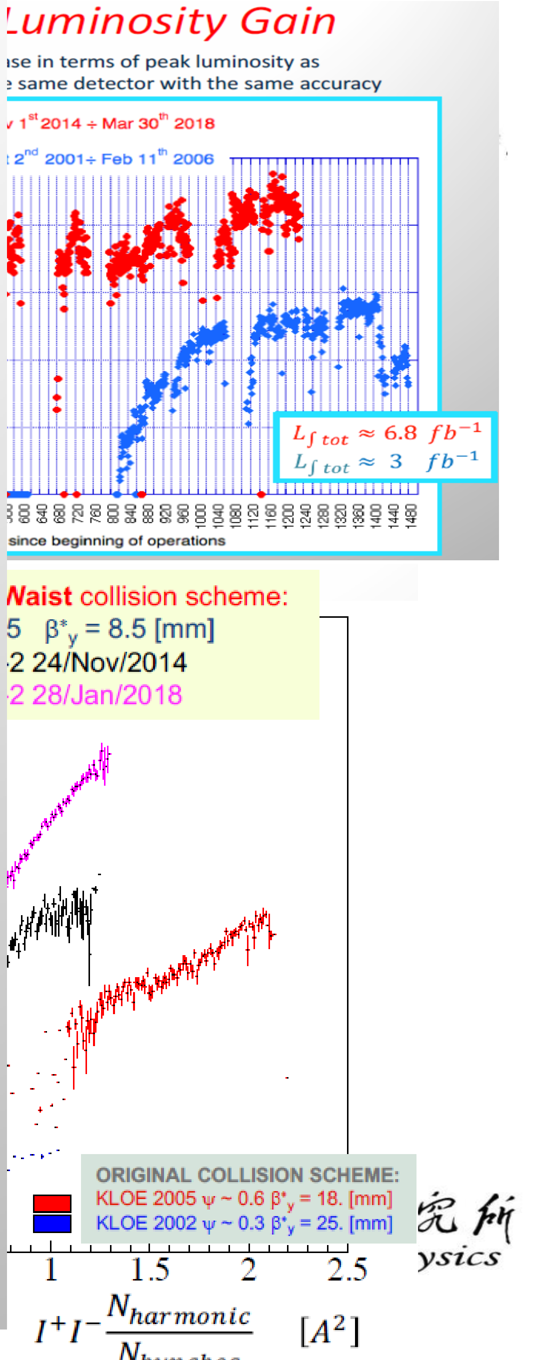
SIDDHARTA-2 IR installation

In year 2019

SIDDHARTA-2 data taking

Starting from 2020 DAΦNE might be transformed in a test facility:

DAΦNE-TF

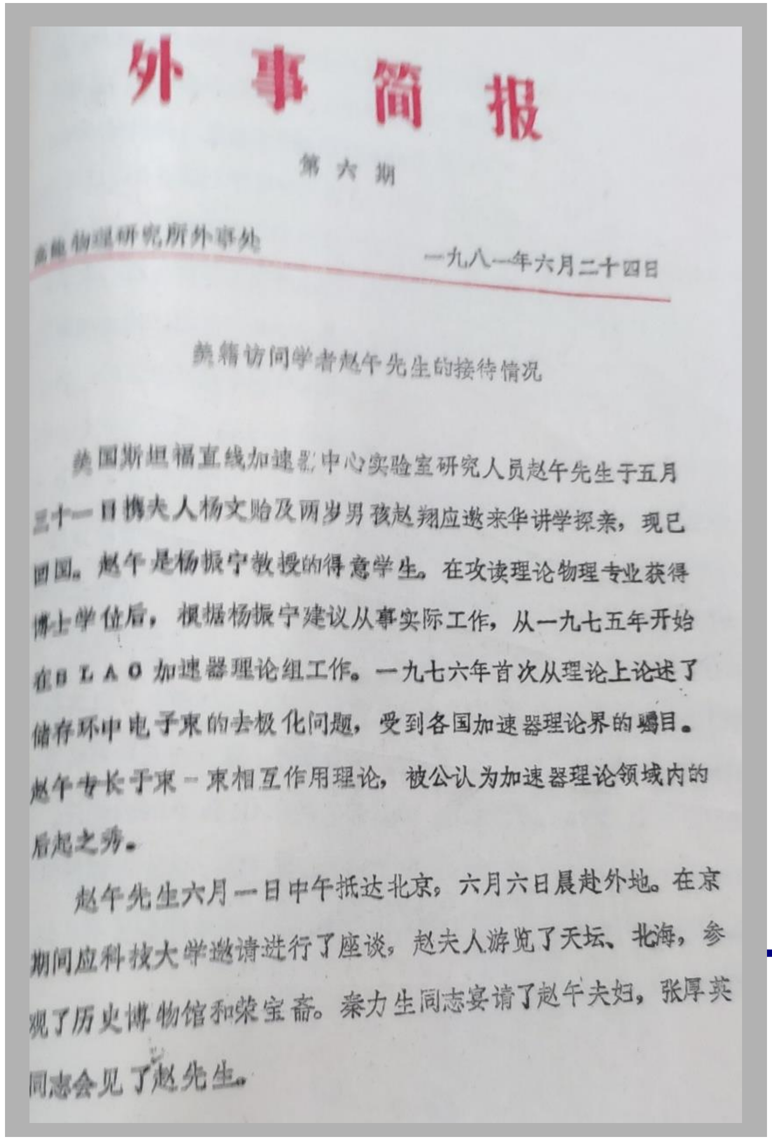


BEPC

- **BEPC (1988 – 2005) --- China's first large science facility (collider & 1st generation synchrotron radiation light source**

Visited IHEP in 1981

Joined commissioning in 1989



外事简报

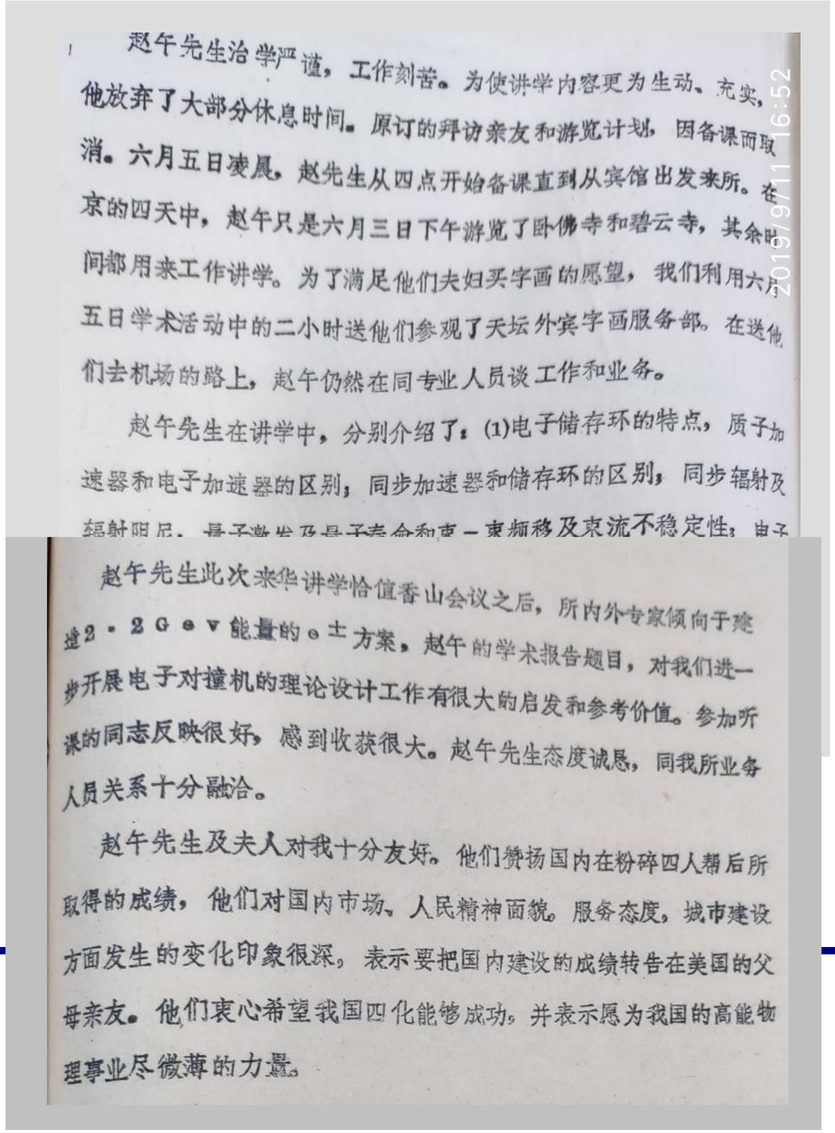
第六期

高能物理研究所外事处　　一九八一年六月二十四日

美籍访问学者赵午先生的接待情况

美国斯坦福直线加速器中心实验室研究人员赵午先生于五月三十一日携夫人杨文贻及两岁男孩赵翔应邀来华讲学探亲，现已回国。赵午是杨振宁教授的得意学生。在攻读理论物理专业获得博士学位后，根据杨振宁建议从事实际工作，从一九七五年开始在SLAC加速器理论组工作。一九七六年首次从理论上论述了储存环中电子束的去极化问题，受到各国加速器理论界的瞩目。赵午专长于束－束相互作用理论，被公认为加速器理论领域内的后起之秀。

赵午先生六月一日中午抵达北京，六月六日晨赴外地。在京期间应科技大学邀请进行了座谈，赵夫人游览了天坛、北海，参观了历史博物馆和荣宝斋。秦力生同志宴请了赵午夫妇，张厚英同志会见了赵先生。

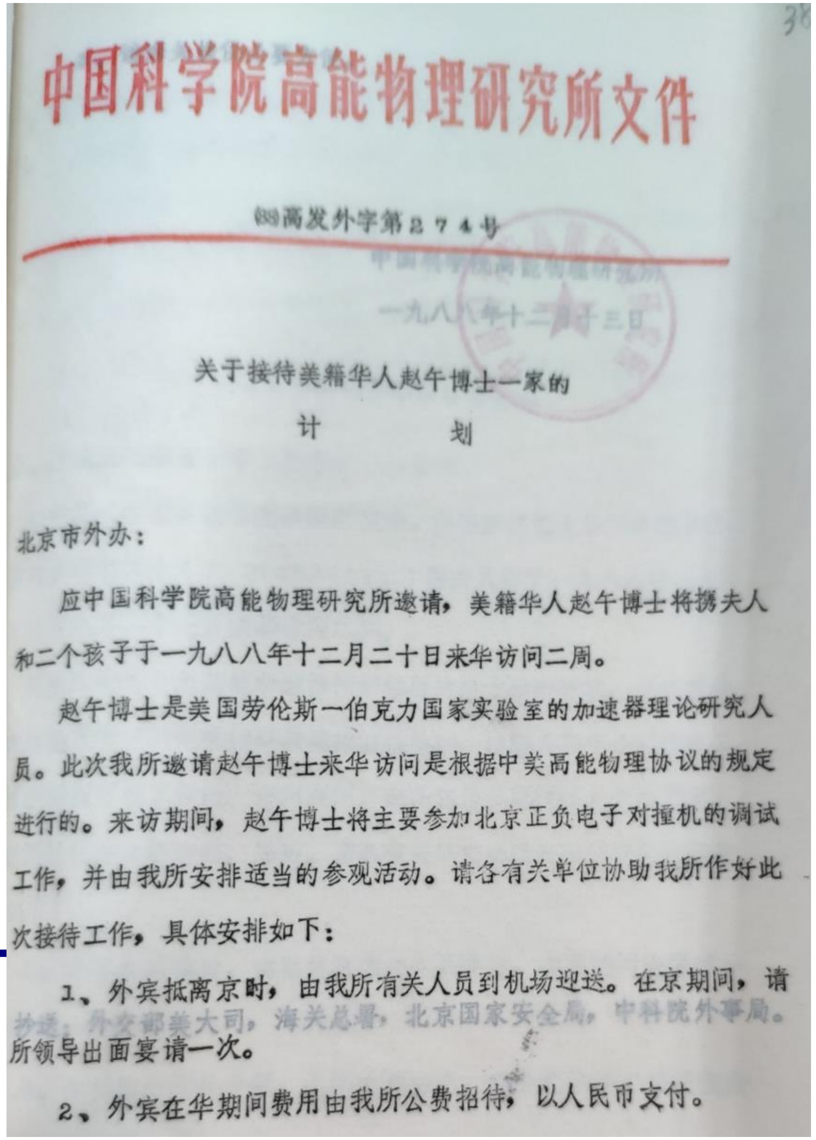


赵午先生治学严谨，工作刻苦。为使讲学内容更为生动、充实，他放弃了大部分休息时间。原订的拜访亲友和游览计划，因备课而取消。六月五日凌晨，赵先生从四点开始备课直到从宾馆出发来所。在京的四天中，赵午只是六月三日下午游览了卧佛寺和碧云寺，其余时间都用来工作讲学。为了满足他们夫妇买字画的愿望，我们利用六月五日学术活动中的二小时送他们参观了天坛外宾字画服务部。在送他们去机场的路上，赵午仍然在同专业人员谈工作和业务。

赵午先生在讲学中，分别介绍了：(1)电子储存环的特点，质子加速器和电子加速器的区别，同步加速器和储存环的区别，同步辐射及辐射阻尼、量子激发及量子寿命和束－束频移及束流不稳定性；电子

赵午先生此次来华讲学恰值香山会议之后，所内外专家倾向于建造2・2Gev能量的e±方案，赵午的学术报告题目，对我们进一步开展电子对撞机的理论设计工作有很大的启发和参考价值。参加听课的同志反映很好，感到收获很大。赵午先生态度诚恳，同我所业务人员关系十分融洽。

赵午先生及夫人对我十分友好。他们赞扬国内在粉碎四人帮后所取得的成绩，他们对国内市场、人民精神面貌、服务态度、城市建设方面发生的变化印象很深，表示要把国内建设的成绩转告在美国的父母亲友。他们衷心希望我国四化能够成功，并表示愿为我国的高能物理事业尽微薄的力量。



38

中国科学院高能物理研究所文件

(88)高发外字第274号

中国科学院高能物理研究所
一九八八年十二月十三日

关于接待美籍华人赵午博士一家的计划

北京市外办：

应中国科学院高能物理研究所邀请，美籍华人赵午博士将携夫人和二个孩子于一九八八年十二月二十日来华访问二周。

赵午博士是美国劳伦斯一伯克力国家实验室的加速器理论研究人员。此次我所邀请赵午博士来华访问是根据中美高能物理协议的规定进行的。来访期间，赵午博士将主要参加北京正负电子对撞机的调试工作，并由我所安排适当的参观活动。请各有关单位协助我所作好此次接待工作，具体安排如下：

1、外宾抵离京时，由我所有关人员到机场迎送。在京期间，请所领导出面宴请一次。

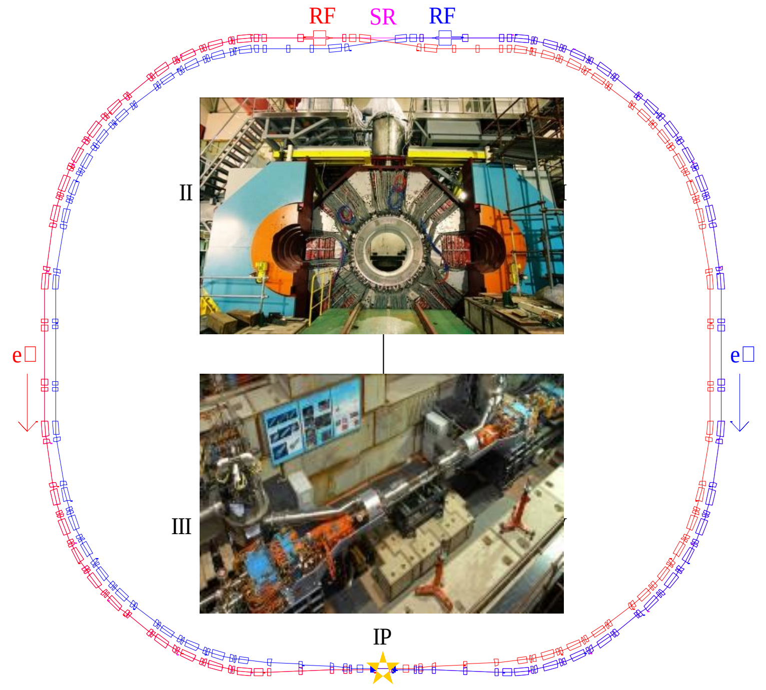
抄送：外交部美大司，海关总署，北京国家安全局，中科院外事局。

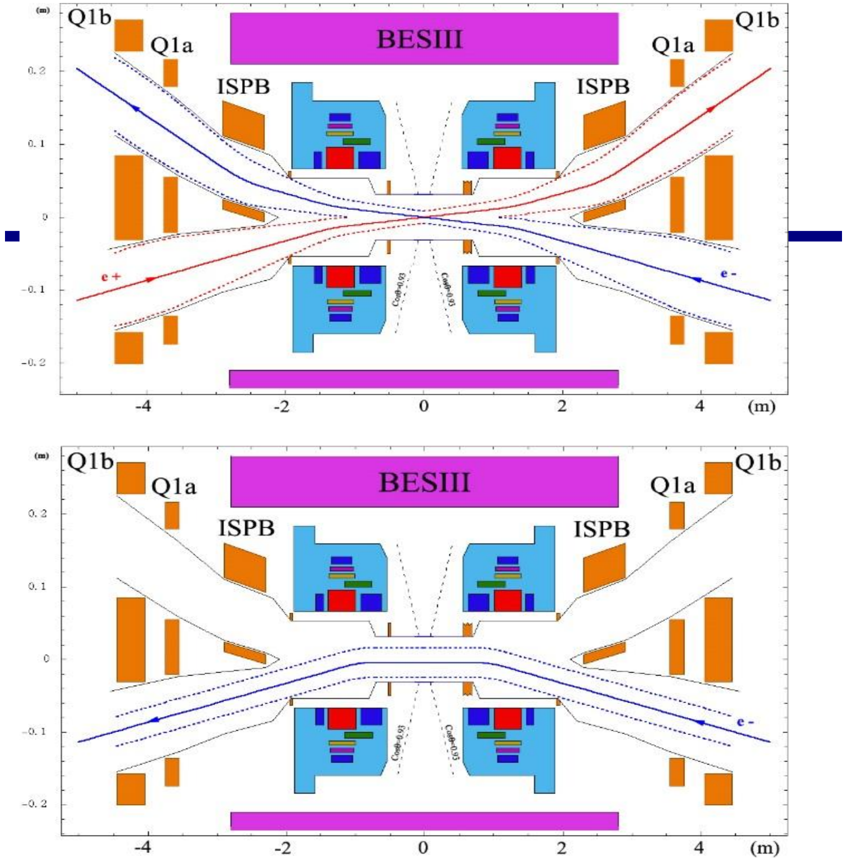
2、外宾在华期间费用由我所公费招待，以人民币支付。

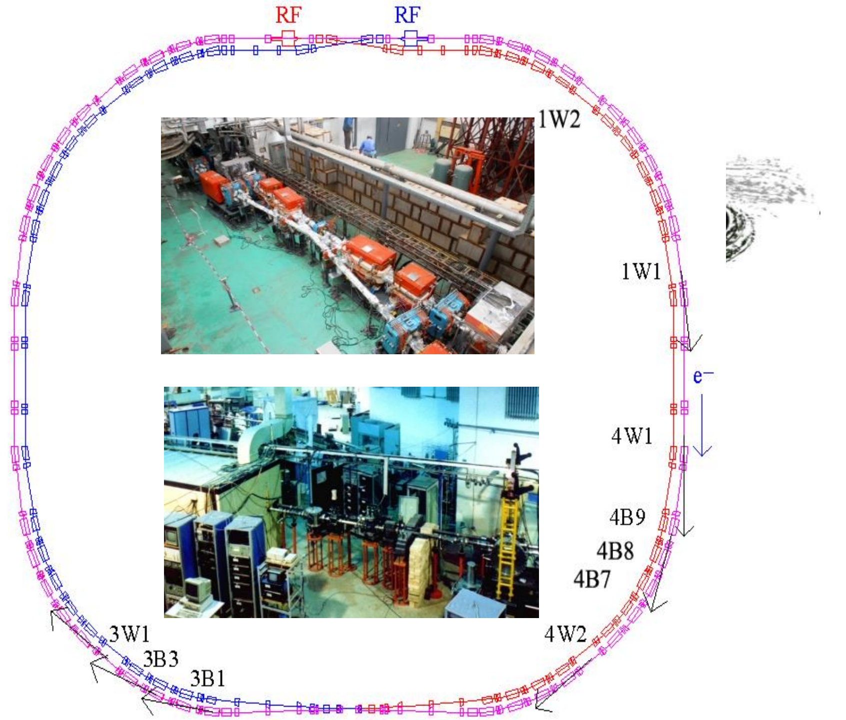
BEPCII

- BEPC (1988 – 2005) ➔ upgrade to BEPCII

BEPCII (2006 – now)
A double-ring factory-like machine
Deliver beams to both HEP & SR







Collider

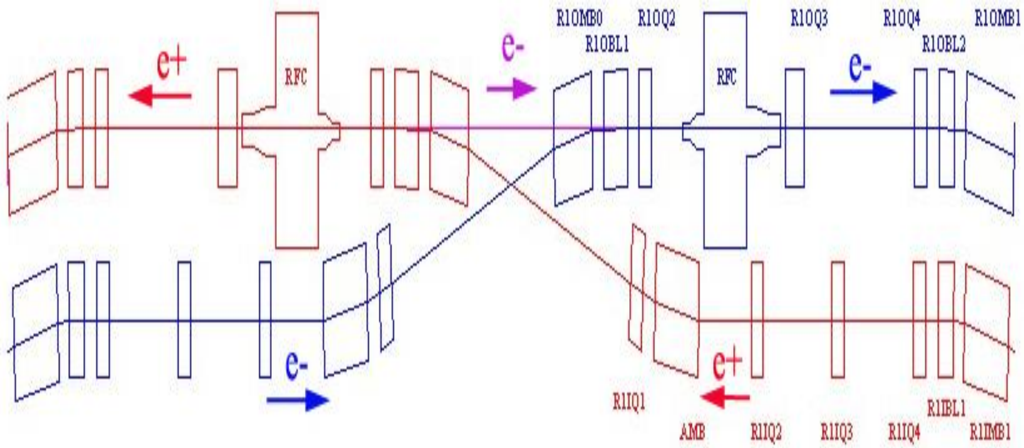
SR Facility

☐ Collision Mode

Beam energy range	1-2.1 GeV
Optimized beam energy	1.89 GeV
Luminosity	1×10^{33} cm^{-2}s^{-1}
Full energy injection	1-1.89 GeV

☐ SR Mode

Beam energy	2.5 GeV
Beam current	250 mA

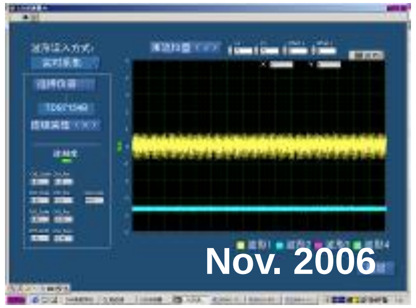


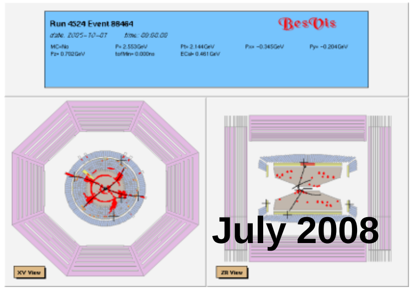
- **BEPCII design**


BEPCII Review@SLAC, May 13-15, 2002

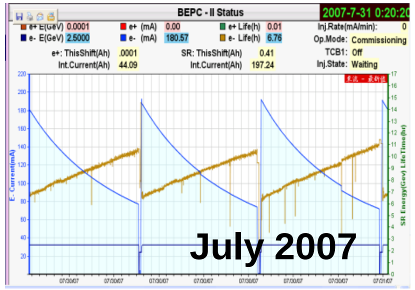

Mini-workshop on BEPC-II Optics
November 4-8, 2002

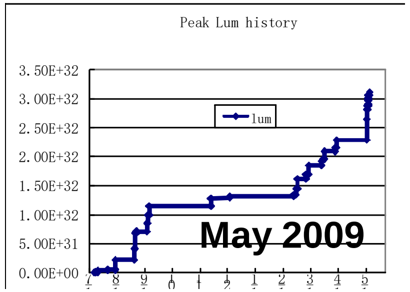
Milestones of BEPCII construction & operation

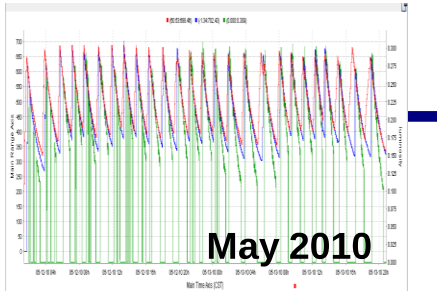


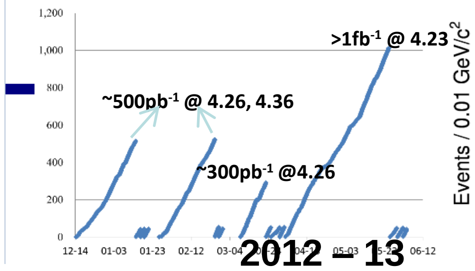


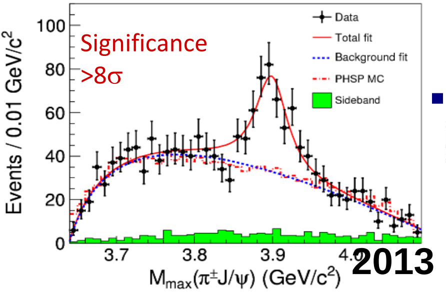
Jan. 2004	Construction started
May. 4, 2004	Dismount of 8 linac sections
Dec. 1, 2004	Linac delivered e^- beams to BEPC
July 4, 2005	BEPC ring dismount started
Mar. 2, 2006	BEPCII ring installation started
Aug. 3, 2007	Shutdown for IR-SCQ installation
Mar. 28, 2008	Shutdown for BESIII installation
July 19, 2008	First hadron event observed
May 19, 2009	Luminosity reached $3.3\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
July 17, 2009	Pass the National test & check
April 8, 2011	Luminosity reached $6.5\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
April 2013	Zc(3900) found & confirmed
Nov. 20, 2014	Luminosity reached $8.53\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
April 5, 2016	Luminosity reached $10.0\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

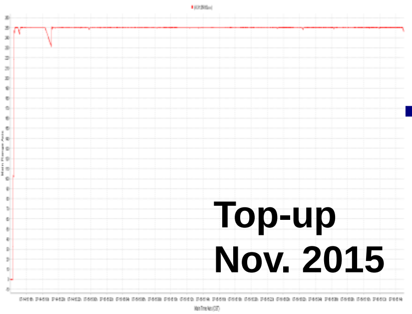








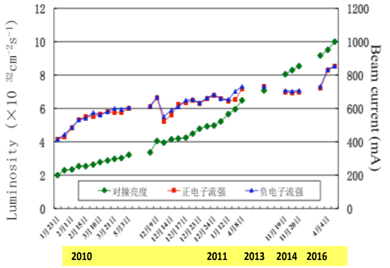




2016/04/05 22:29:47

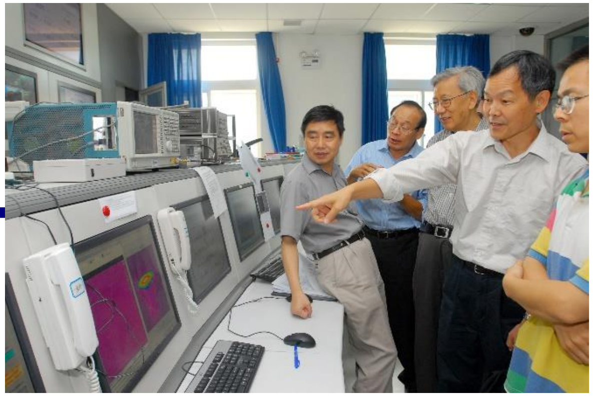
Luminosity 10.00 E32/cm^2/s

	e+	e−
Energy [GeV]	1.8831	1.8831
Current [mA]	849.18	852.31
Lifetime [hr]	1.53	2.30
Inj.Rate [mA/min]	0.00	0.00



International Machine Advisory Committee (IMAC) For the BEPC-II Project

Alex Chao (Chair)	Shin-Ichi Kurokawa
Jiaer Chen	Dave Rice
Senyu Chen	John Seeman
Paul Collier	Bill Weng
Shouxian Fang	Ferdi Willeke
Bob Hettel	Zhentang Zhao
Kenji Hosoyama	



Activity Report of

International Machine Advisory Committee (IMAC) For the BEPC-II Project

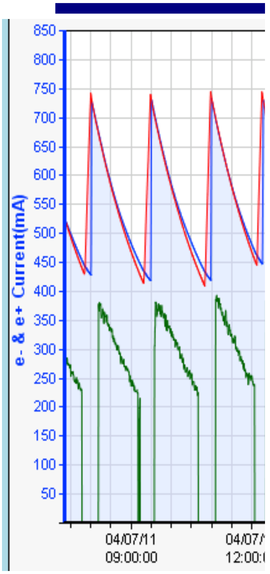
Alex Chao
On behave of the BEPC-II IMAC

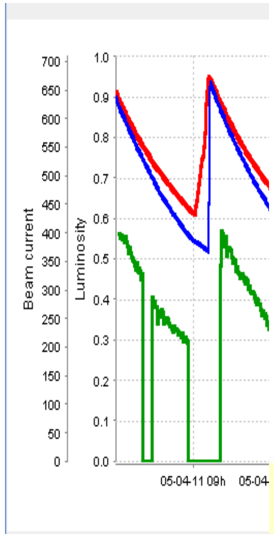
November 3, 2008
IHEP, Beijing

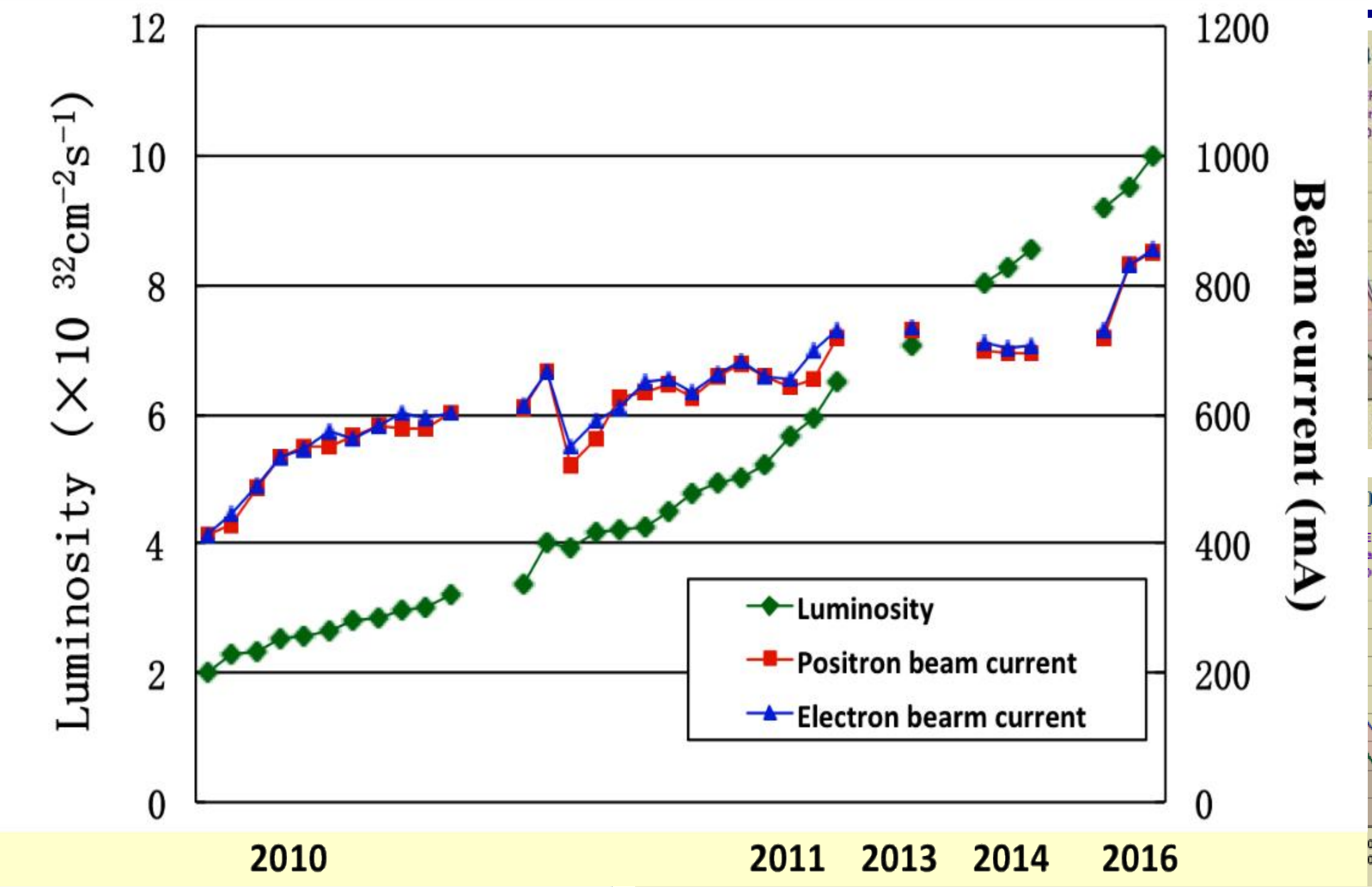
Main design parameters of three rings of BEPCII

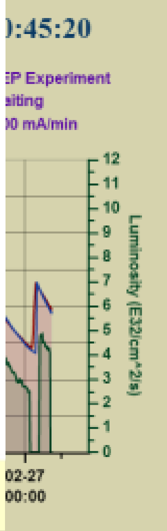
Parameters	BER/BPR	BSR
Beam energy (GeV)	1.89	2.5
Circumference (m)	237.53	241.13
Beam current (A)	0.91	0.25
Bunch current (mA) / No.	9.8 / 93	~1 / 160 - 300
Natural bunch length (mm)	13.6	12.0
RF frequency (MHz)	499.8	499.8
Harmonic number	396	402
Emittance (x/y) (nm·rad)	144/2.2	140
β function at IP (x/y) (m)	1.0/0.015	10.0/10.0
Crossing angle (mrad)	±11	0
Tune (x/y/s)	6.54/5.59/0.034	7.28/5.18/0.036
Momentum compaction	0.024	0.016
Energy spread	5.16×10^{-4}	6.67×10^{-4}
Natural chromaticity (x/y)	-10.8/-20.8	-9.0/-8.9
Luminosity ($cm^{-2}s^{-1}$)	1×10^{33}	—

Beam & luminosity performances









研究所
Physics

Future upgrade of BEPCII

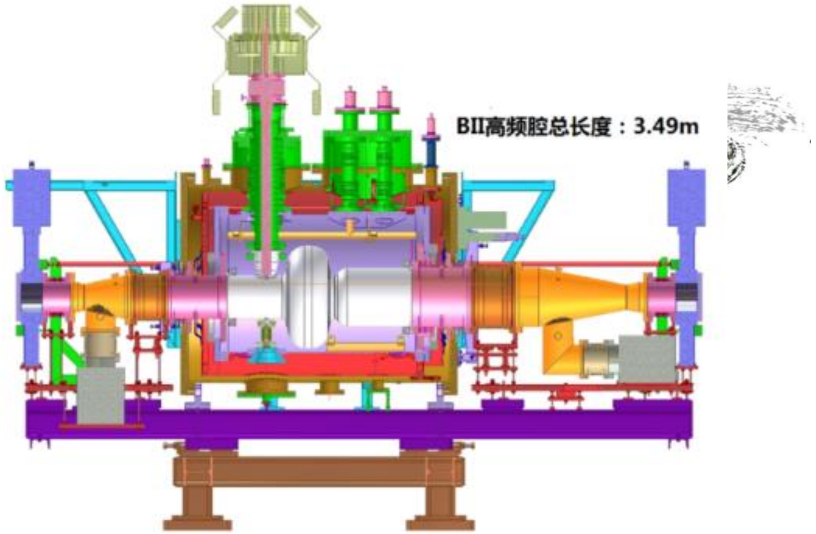
- **High luminosity & high beam energy**

$$L(\mathrm{cm}^{-2}\mathrm{s}^{-1}) = 2.17\times10^{34}(1+R)\xi_y \frac{E(\mathrm{GeV})\boxed{k_b I_b}(\mathrm{A})}{\boxed{\beta_y^*}(\mathrm{cm})}$$

Vertical β @IP ,
Limited by hourglass effect

Beam current,
Limited by multi-bunch instability and power

- **125kW -> 250kW**,
  - Beam Current：1100mA. BEPCII ~ 600mA。 (Feedback+RF)
  - Bunch Number： 120. BEPCII ~ 80。 (Feedback+RF)
  - Bunch Current： 9mA. BEPCII ~ 7mA。 (Feedback+RF)
  - Beam-Beam ： 0.04。BEPCII ~ 0.036。(RF，hourglass effect)



- **RF Voltage ~2.5MV，Power ~ 250kW**

Feedback system

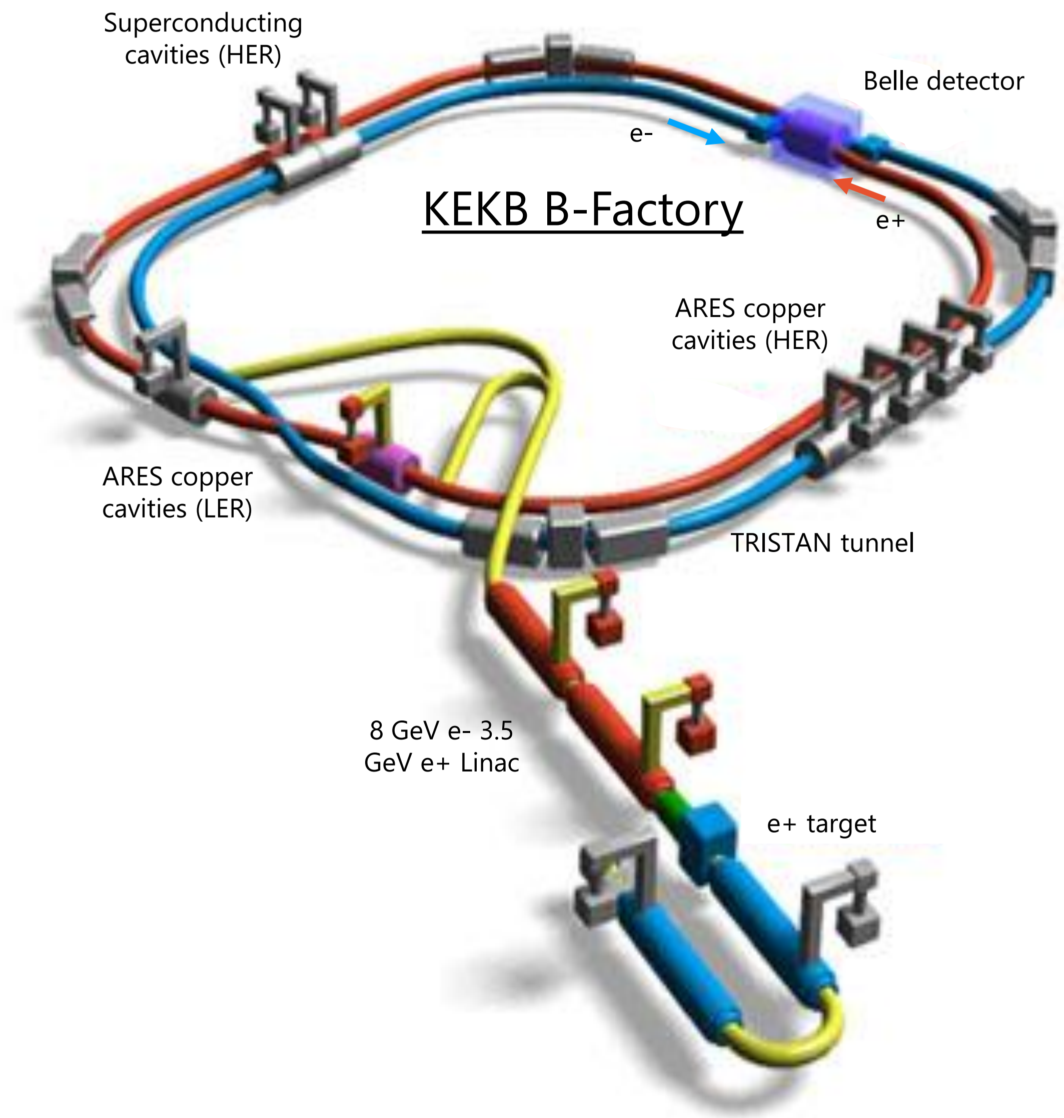
BEPCII Record: 910mA , 119 bunches

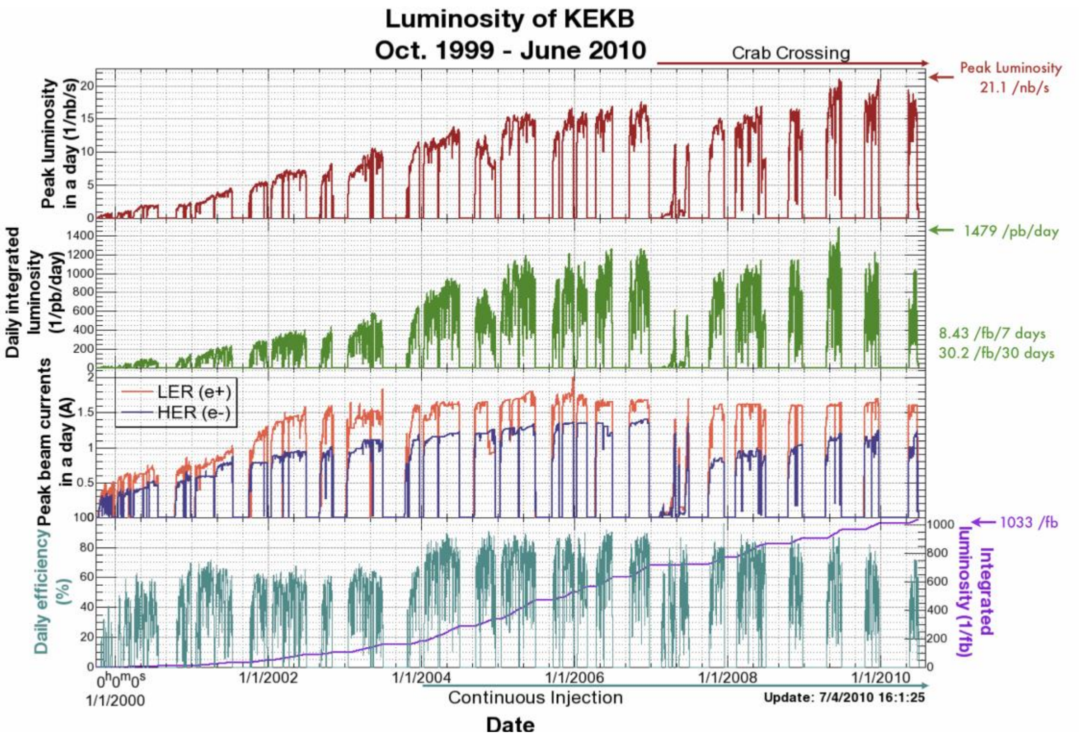
(700mA, 80 Bunches in daily operation)

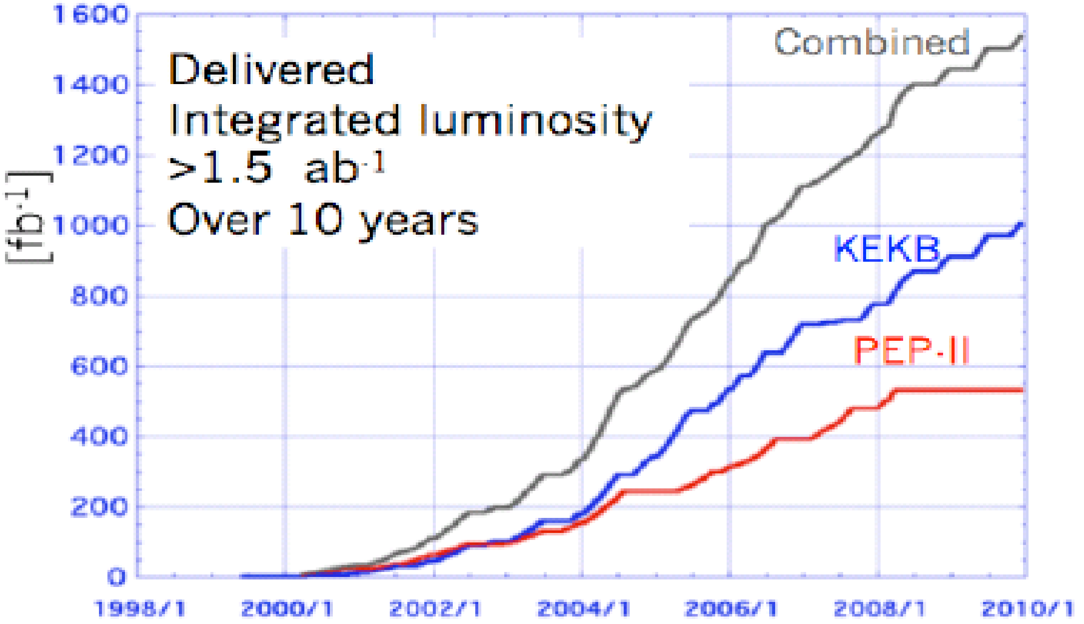
In order to increase the safe margin(more stable)

- Transverse
  - Bandwidth: 125 MHz -> 250 MHz
  - Amplifier Power: 75 W -> 250 W
- Longitudinal
  - New cavity-like kicker with shunt impedance: 160 -> 400 Ohm
  - Amplifier Power: 100 W -> 200 W

KEKB & SuperKEKB

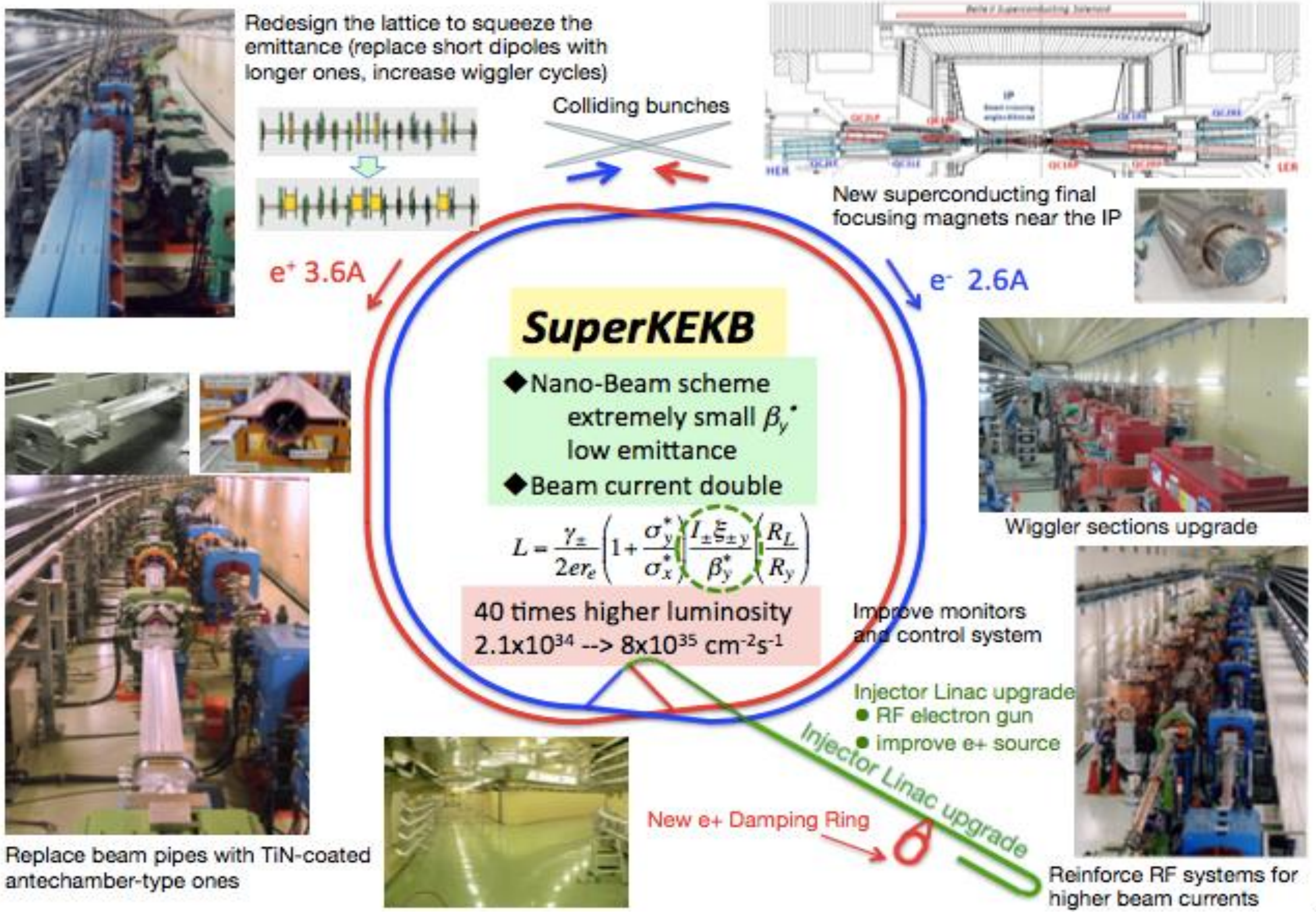






Super KEKB

- Upgrade project from KEKB
- e- - e+ 2-ring collider with
  - Linac: L ~600m
  - Damping ring: C ~100m
  - Main ring: C ~3016m
    HER: 7GeV, Ie- = 2.6A
    LER: 4GeV, Ie+ = 3.6A
  - Belle-II detector
- Design Luminosity
  - 80 x 10^{34} $cm^{-2}s^{-1}$
    (~40 times of KEKB)



Redesign the lattice to squeeze the emittance (replace short dipoles with longer ones, increase wiggler cycles)

Colliding bunches

New superconducting final focusing magnets near the IP

e^+ 3.6A

e^- 2.6A

SuperKEKB

◆Nano-Beam scheme
extremely small β_y^*
low emittance
◆Beam current double

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

40 times higher luminosity
2.1×10^{34} --> 8×10^{35} $cm^{-2}s^{-1}$

Wiggler sections upgrade

Improve monitors and control system

Injector Linac upgrade
- RF electron gun
- improve e+ source

Injector Linac upgrade

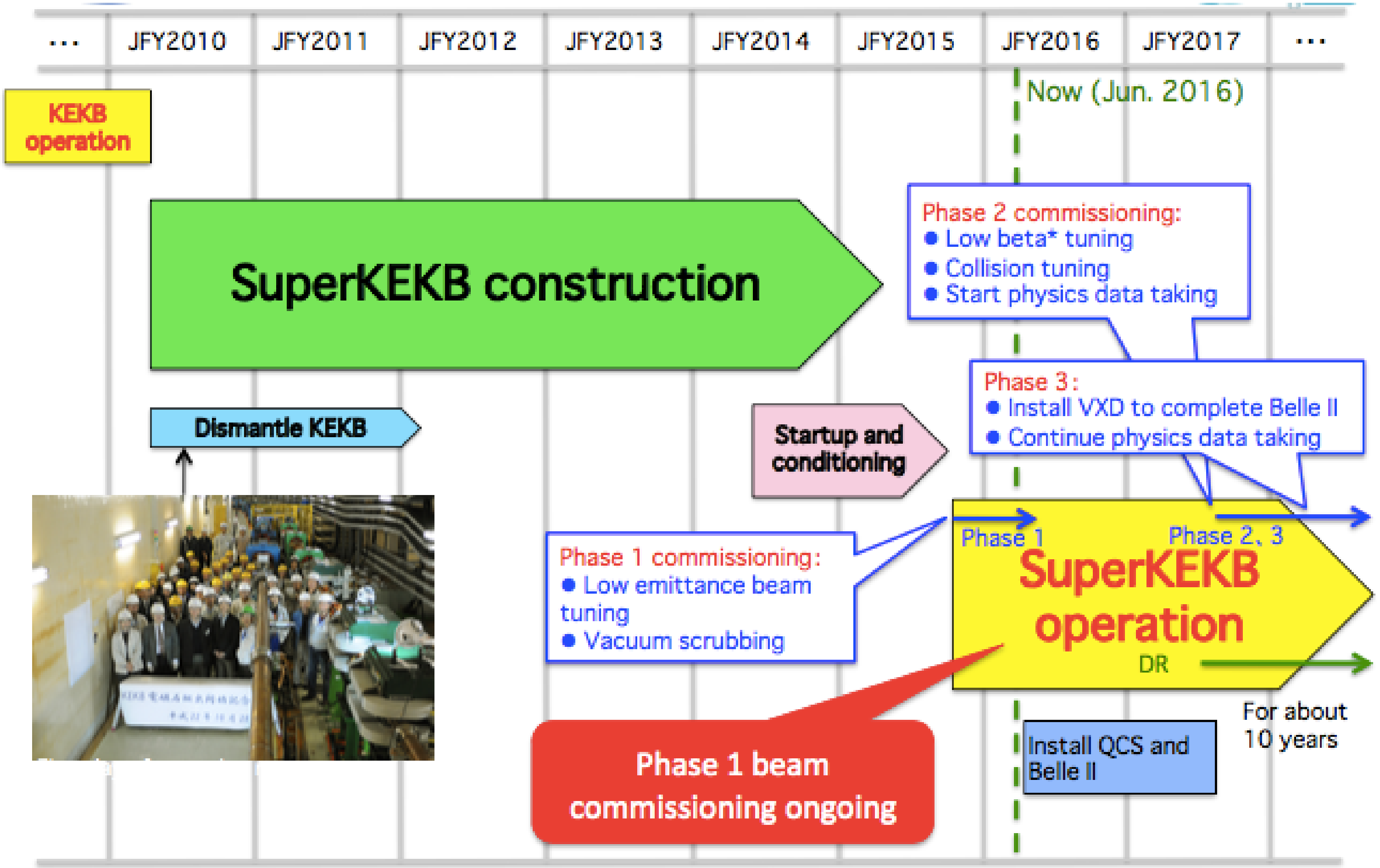
New e+ Damping Ring

Replace beam pipes with TiN-coated antechamber-type ones

Reinforce RF systems for higher beam currents

Courtesy K. Akai

Schedule and main parameters of SuperKEKB



… JFY2010 JFY2011 JFY2012 JFY2013 JFY2014 JFY2015 JFY2016 JFY2017 …

KEKB operation

SuperKEKB construction

Dismantle KEKB

Startup and conditioning

Now (Jun. 2016)

Phase 2 commissioning:
- Low beta* tuning
- Collision tuning
- Start physics data taking

Phase 3:
- Install VXD to complete Belle II
- Continue physics data taking

Phase 1 commissioning:
- Low emittance beam tuning
- Vacuum scrubbing

Phase 1

Phase 2, 3

SuperKEKB operation

DR

Phase 1 beam commissioning ongoing

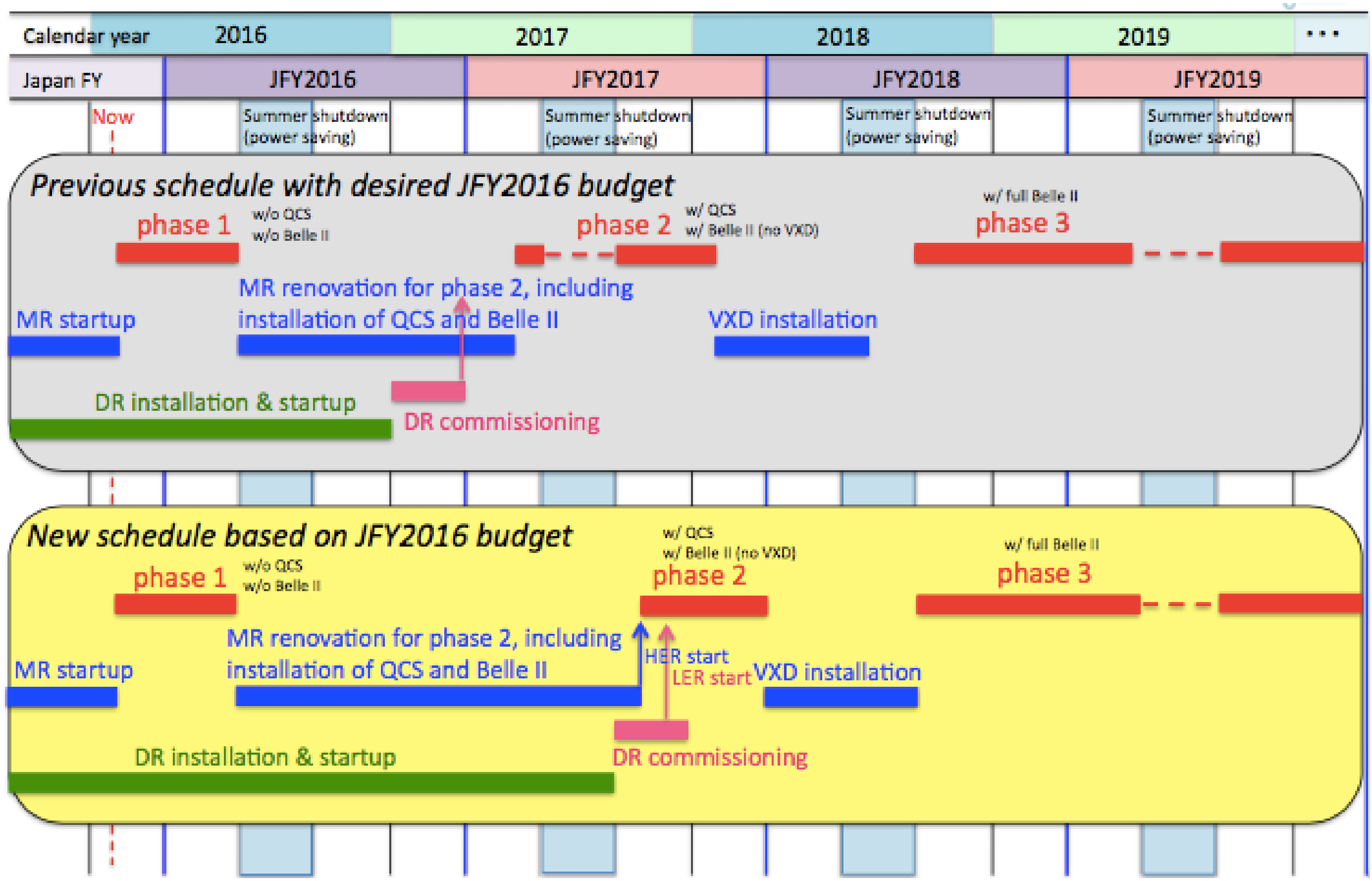
Install QCS and Belle II

For about 10 years

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.007
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/4.6
$\varepsilon_y/\varepsilon_x$ (%)	1	0.85/0.64	0.27/0.25
σ_y^* (nm)	1900	940	48/62
ξ_y	0.052	0.129/0.090	0.088/0.081
σ_z (mm)	4	6 - 7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	80

Courtesy K. Akai

Commissioning



Calendar year 2016 2017 2018 2019 ···

Japan FY JFY2016 JFY2017 JFY2018 JFY2019

Now

Summer shutdown (power saving)

Previous schedule with desired JFY2016 budget

phase 1 w/o QCS w/o Belle II

phase 2 w/ QCS w/ Belle II (no VXD)

phase 3 w/ full Belle II

MR startup

MR renovation for phase 2, including installation of QCS and Belle II

VXD installation

DR installation & startup

DR commissioning

New schedule based on JFY2016 budget

phase 1 w/o QCS w/o Belle II

phase 2 w/ QCS w/ Belle II (no VXD)

phase 3 w/ full Belle II

MR startup

MR renovation for phase 2, including installation of QCS and Belle II

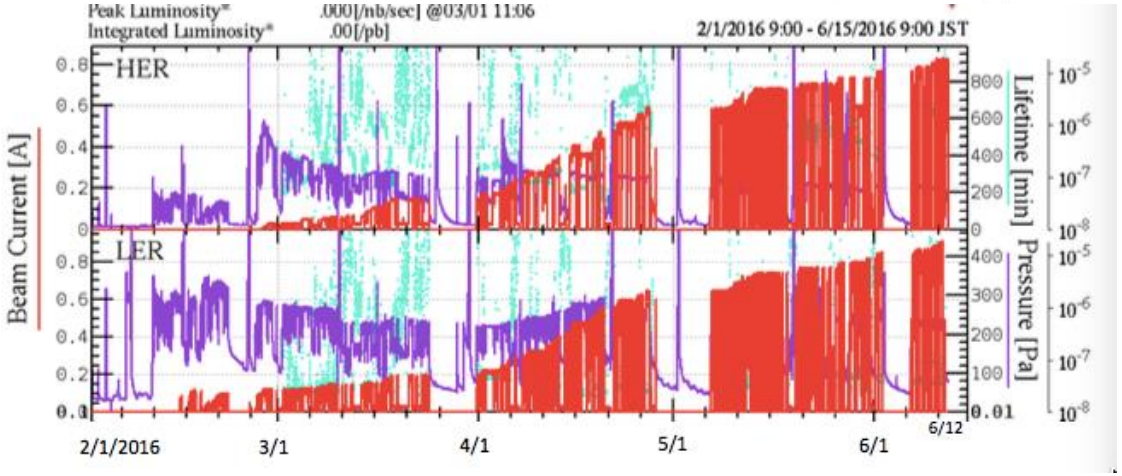
HER start

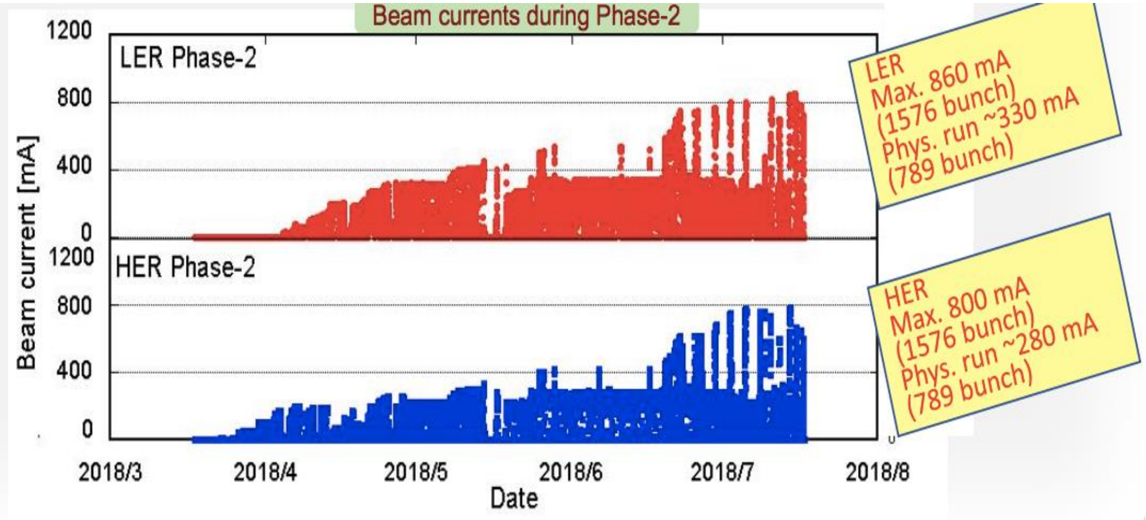
LER start

VXD installation

DR installation & startup

DR commissioning





LER Max. 860 mA (1576 bunch) Phys. run ~330 mA (789 bunch)

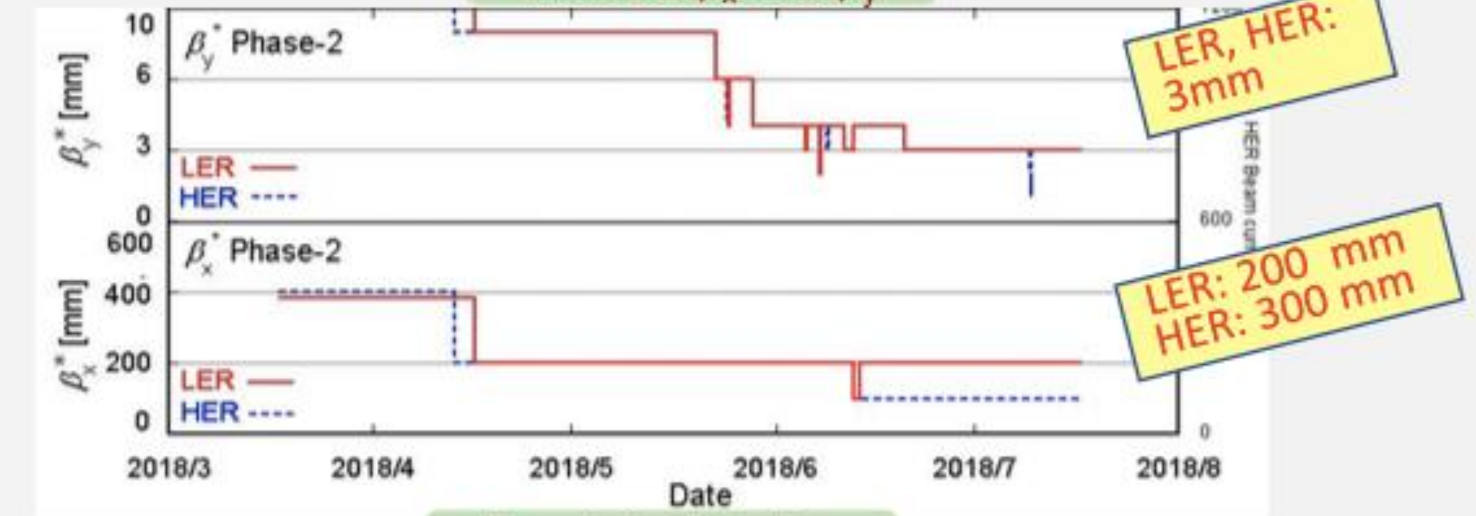
HER Max. 800 mA (1576 bunch) Phys. run ~280 mA (789 bunch)

Courtesy K. Akai & Y. Suetsugu

中国科学院高能物理研究所 Institute of High Energy Physics

- The collision tuning in MR proceeded squeezing β_y/β_x @IP gradually
- The first physics event observed on April 26, 2018

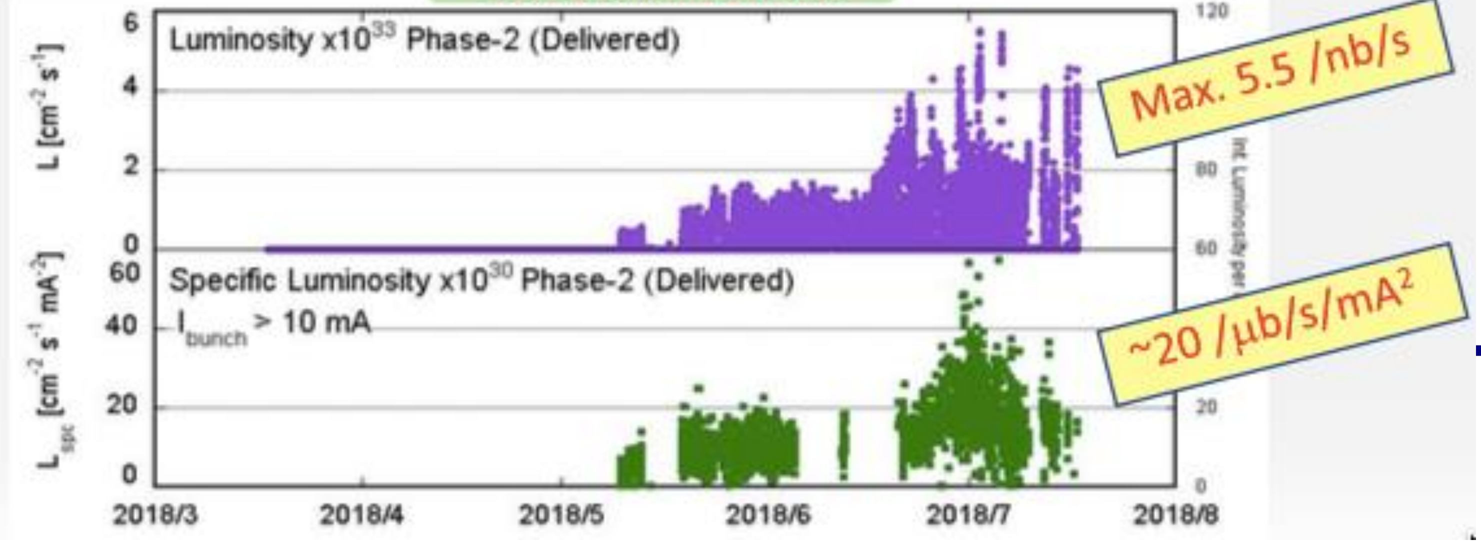
Trends of β_x^* and β_y^*



LER, HER: 3mm

LER: 200 mm
HER: 300 mm

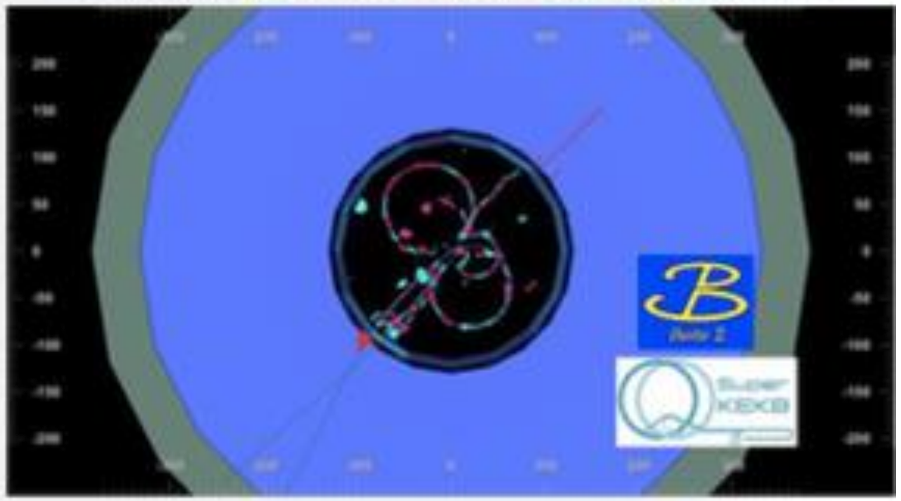
Trends luminosities



Max. 5.5 /nb/s

~20 /μb/s/mA^2

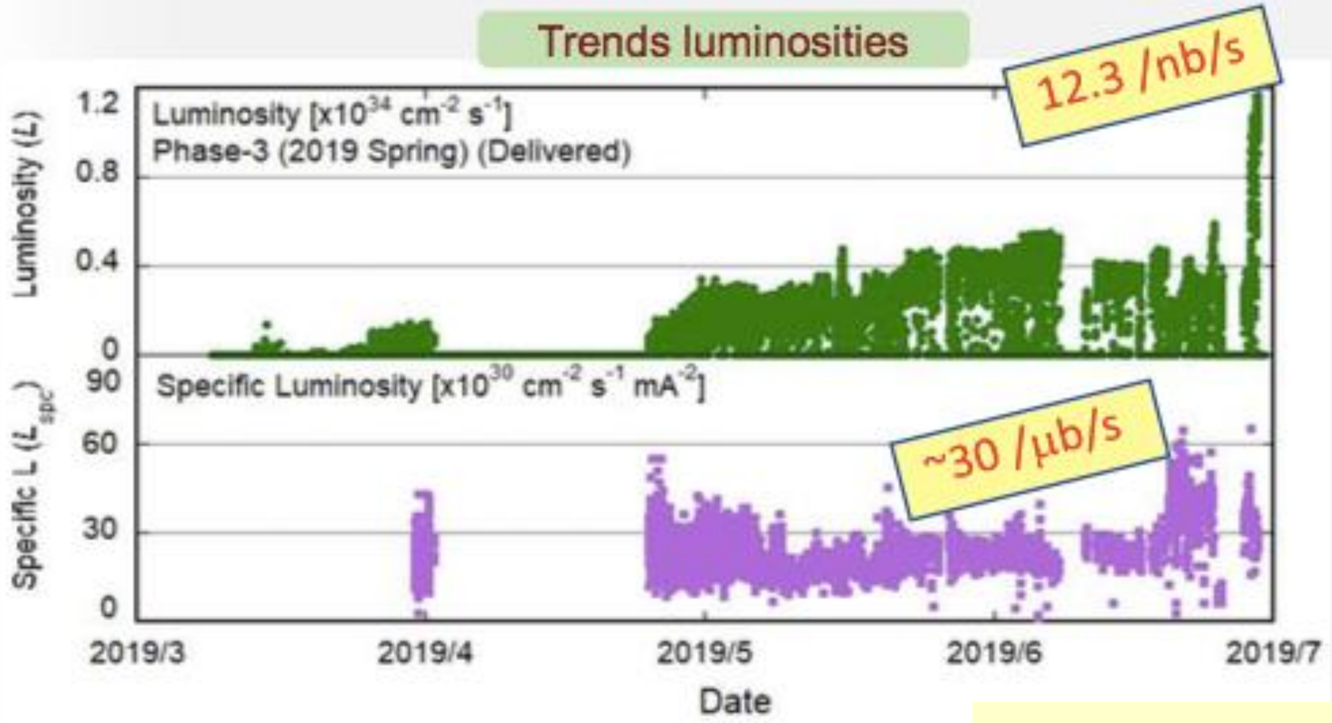
The first event on 26th, April 2018.

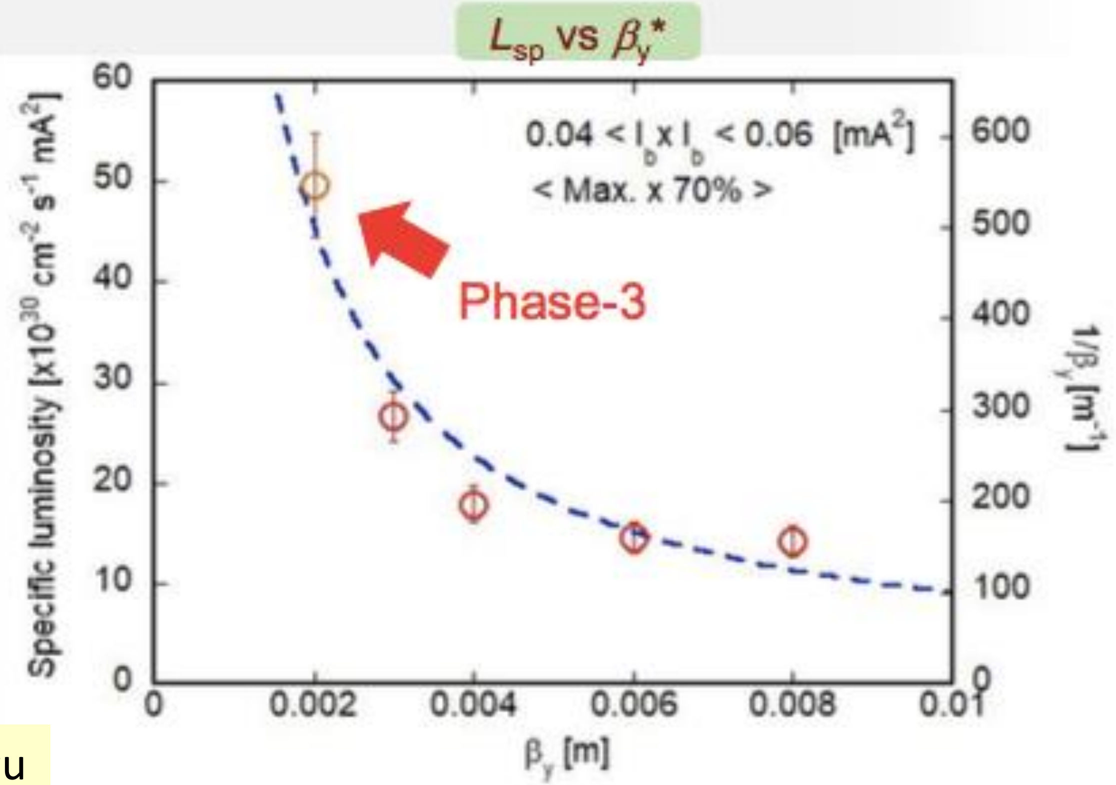


Courtesy Y. Suetsugu

Commissioning in Phase-3, 2019 spring

- β_x^*/β_y^* were squeezed to 80/2mm on June 21, 2019
- The max. lum. of $1.23\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ reached at 820/830mA, although the Belle-II HV was off due to high background
- Specified lum. increased in proportional to $1/\beta_y^*$, satisfied even at $\beta_y^* = 2\mathrm{mm}$.

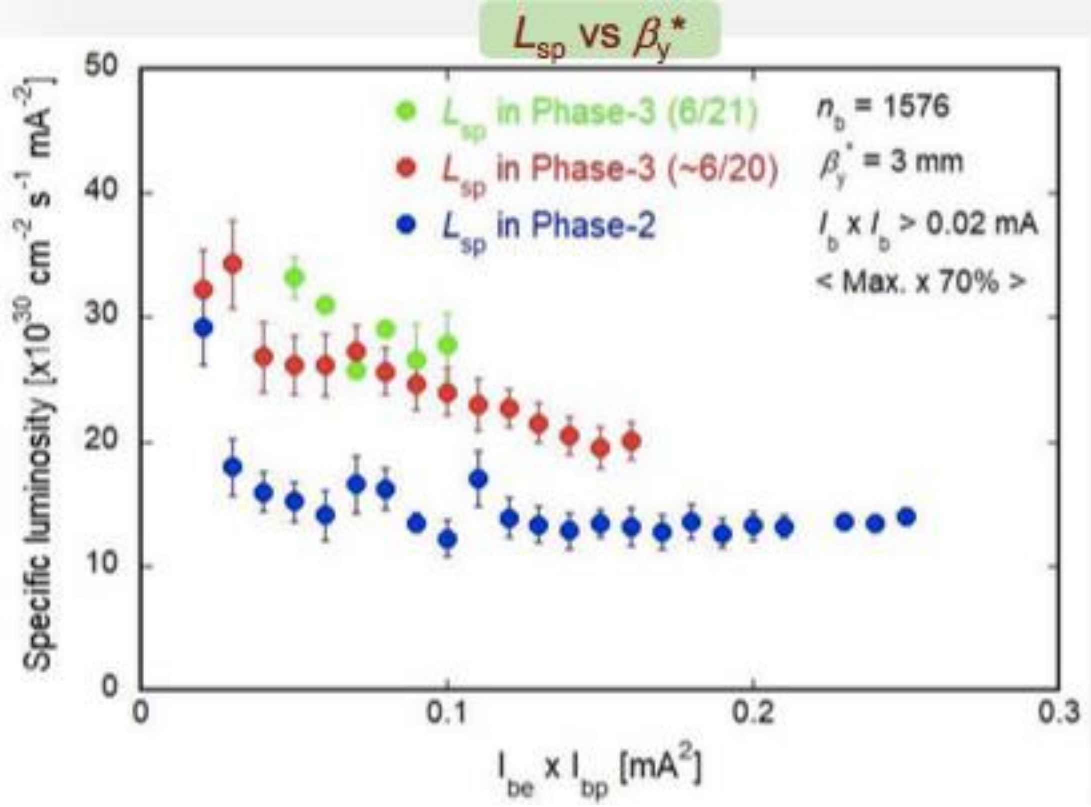


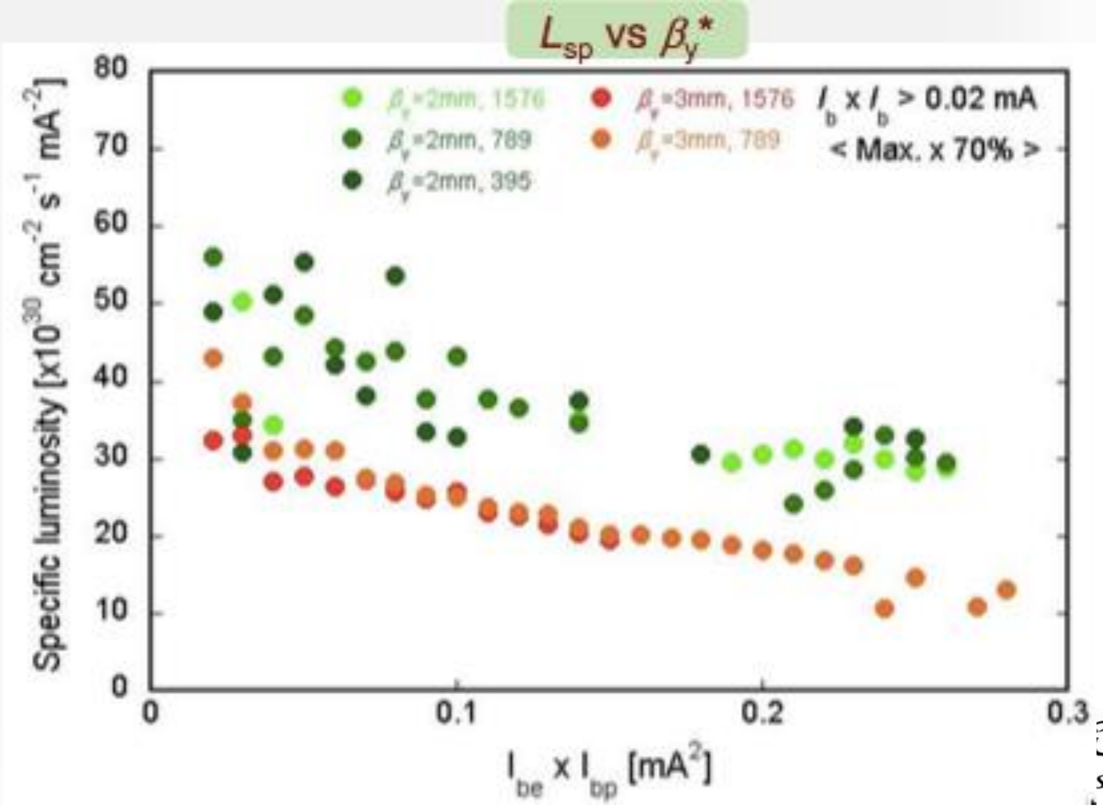


Courtesy Y. Suetsugu

Key challenges for high luminosity

- **Decrease in Lsp with bunch current product**
  - caused by the beam-size blowup due to beam-beam effect, although the mechanism has not been well understood yet.





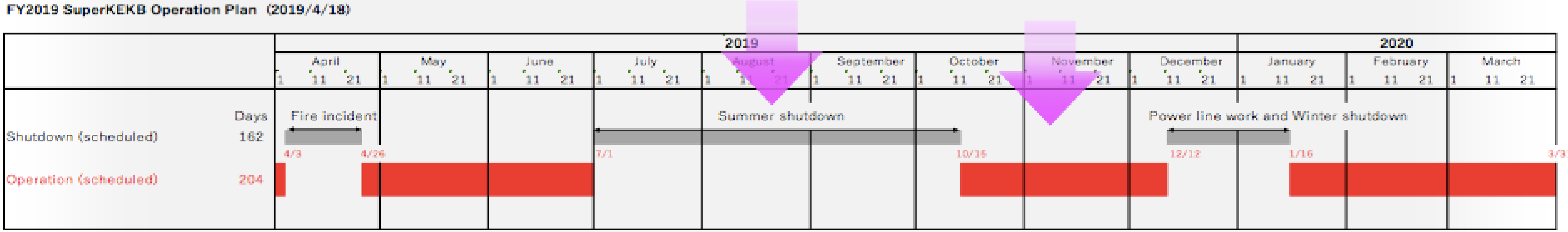
Courtesy K. Ohmi & Y. Ohnishi

- High background (BG)
  - Main BG source in LER was found to be the beam-gas Coulomb scattering
  - Bursts from stored beam, possible induced CDC trips and/or beam abort. Dust?
  - Bursts from injection beams. Changes in energy or orbit at the Linac?
  - Slow change in injection condition. BG degraded gradually, as well as injection efficiency, even in one shift (8 hours) and difficult to keep good injection condition. Temperature dependence?
- QCS quench and beam aborts
  - Frequency of QCS quenches in Phase-3 decreased, compared to that in Phase-2
  - 7 quenches (two types) happened.

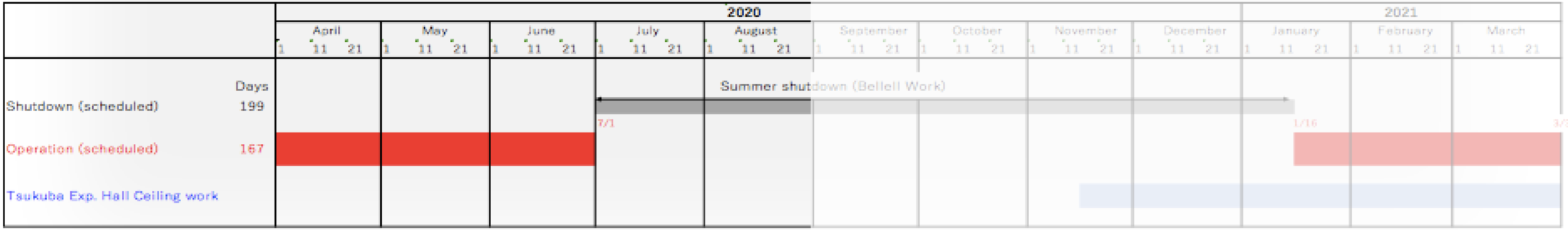
Commissioning plan

- Autumn run (2019/10/15 – 2019/12/12) – continue physics run and machine tuning
- Winter shutdown (- 2020/01/16) – 150kV power line work, collimator installed in LER
- 2020 Spring run (- 2020/06/30) – under discussion, but continue physics run.

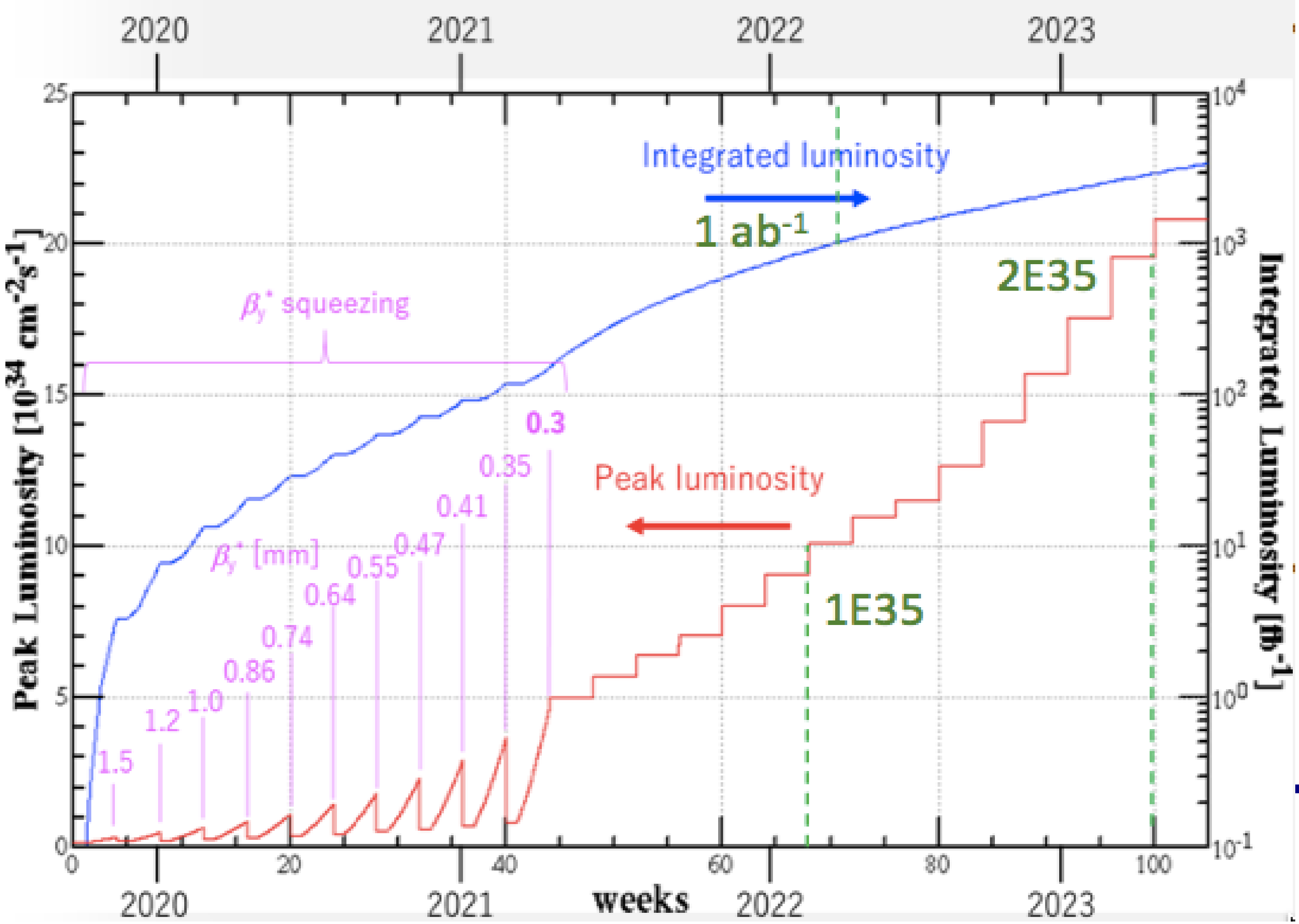
FY2019 SuperKEKB Operation Plan (2019/4/18)



FY2020 SuperKEKB Operation Plan (Not fixed)



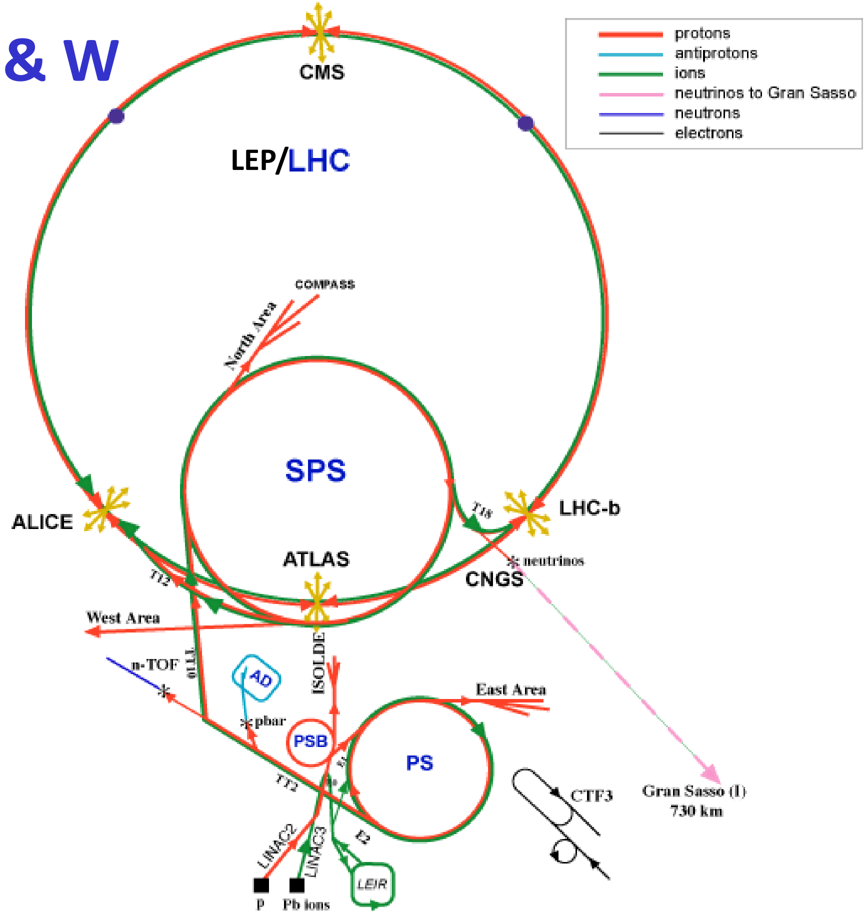
Commissioning plan



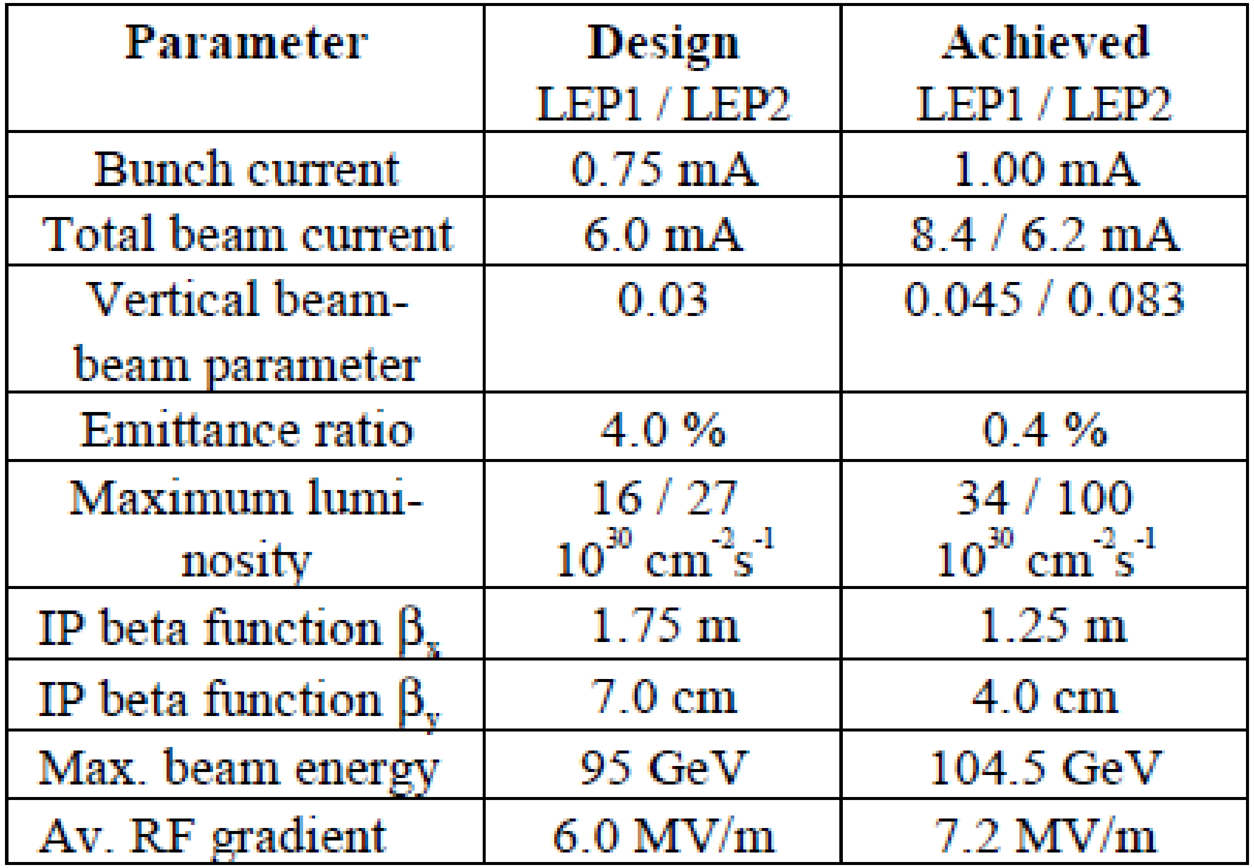
中国科学院高能物理研究所
Institute of High Energy Physics

Large Electron Positron Collider (LEP)

- Largest e^- -e^+ collider, Z & W
- E_{cm}=91 – 209 GeV
- Realized pretzel orbit
- N_b=4, $I_{beam, max}$=6.2mA
- Max. ξ_y=0.083
- L_{peak} = $2\times10^{32}cm^{-2}s^{-1}$
- 4 detectors
- Physics running started at 1989, and stopped at 2000.

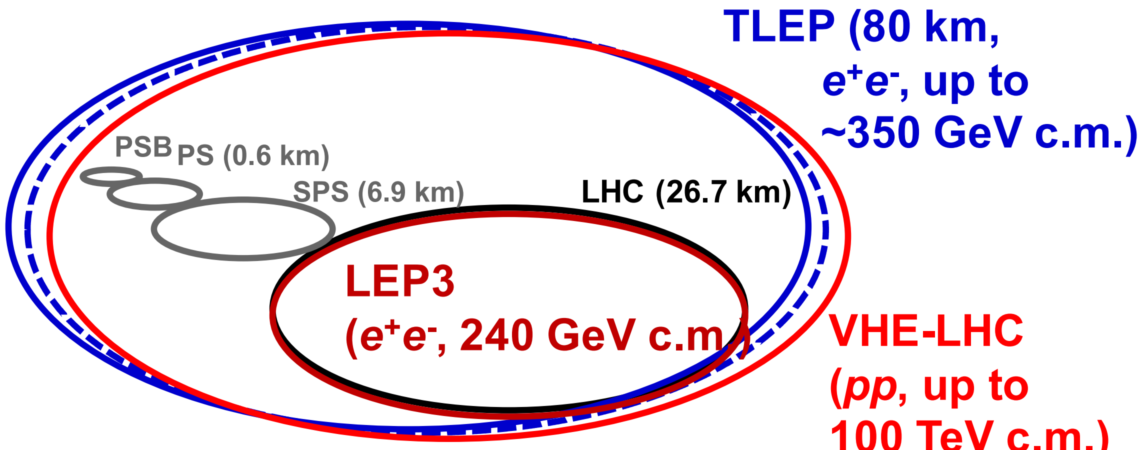


LEP technology worked well



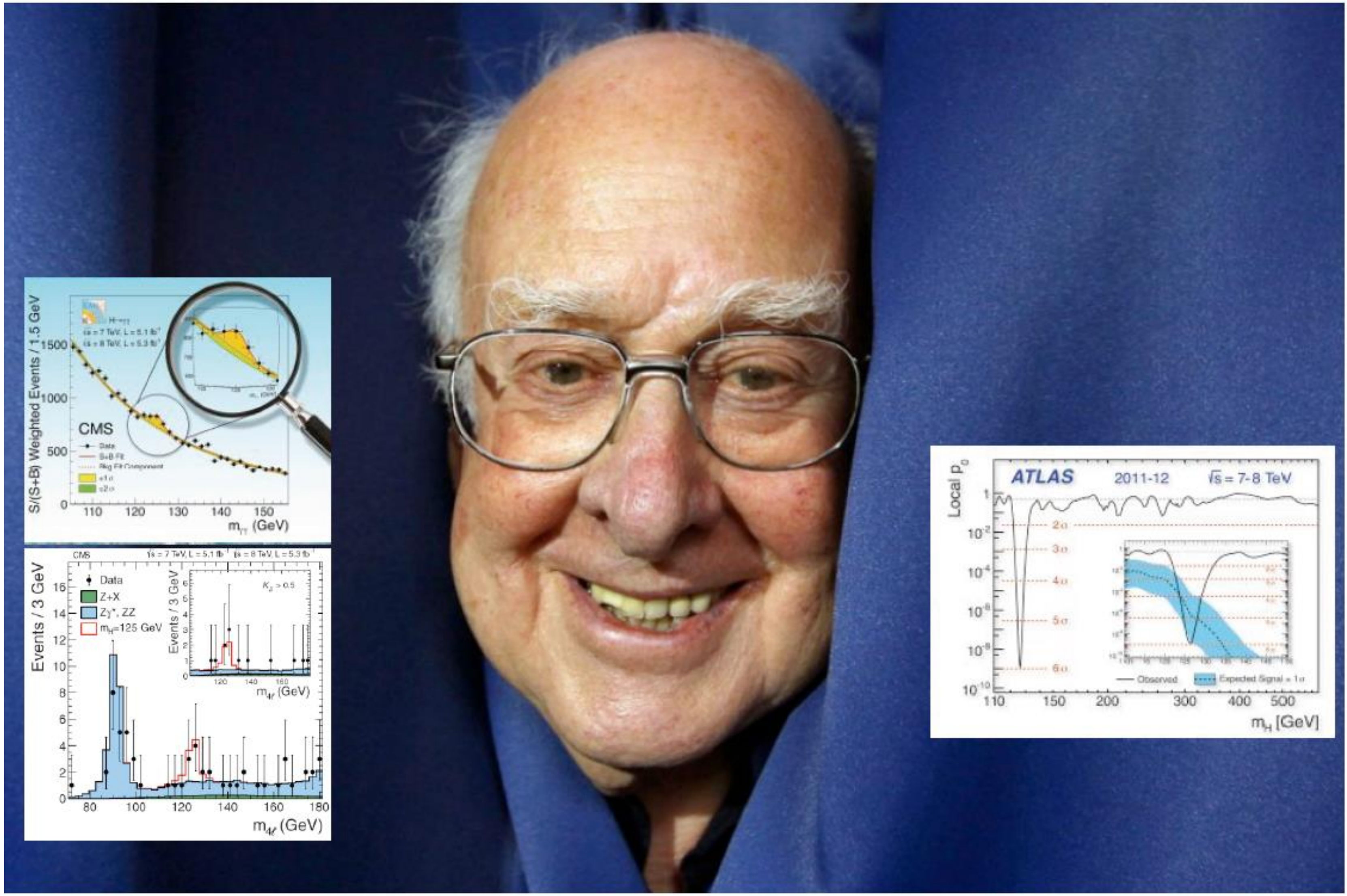
Parameter	Design LEP1 / LEP2	Achieved LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 6.2 mA
Vertical beam-beam parameter	0.03	0.045 / 0.083
Emittance ratio	4.0 %	0.4 %
Maximum luminosity	16 / 27 10^{30} cm^{-2}s^{-1}	34 / 100 10^{30} cm^{-2}s^{-1}
IP beta function β_x	1.75 m	1.25 m
IP beta function β_y	7.0 cm	4.0 cm
Max. beam energy	95 GeV	104.5 GeV
Av. RF gradient	6.0 MV/m	7.2 MV/m

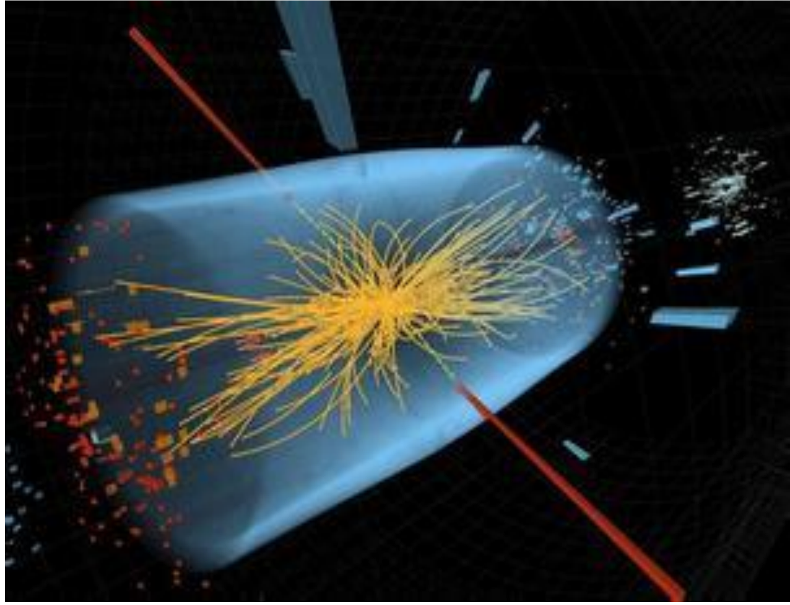
- **Future lepton collider**
  - **LEP3?**
  - **TLEP?**



also: ***e***$^{\pm}$ **(200 GeV) – *p* (7 & 50 TeV)** collisions

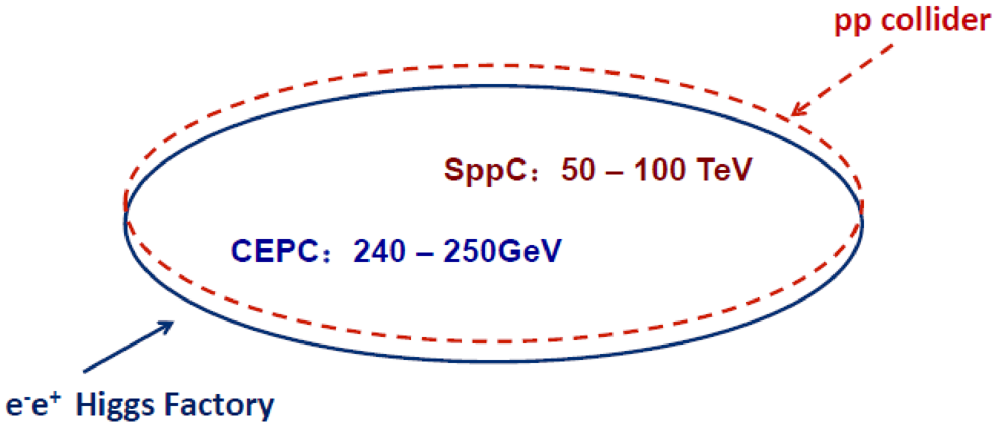
Higgs discovery





HF2012

- A CEPC (phase I) + SppC (phase II) was proposed in IHEP, Sept. 2012



pp collider

SppC：50 – 100 TeV

CEPC：240 – 250GeV

e^-e^+ Higgs Factory

FERMILAB-CONF-13-037-APC
IHEP-AC-2013-001
SLAC-PUB-15370
CERN-ATS-2013-032
arXiv: 1302.3318 [physics.acc-ph]

Report of the ICFA Beam Dynamics Workshop

"Accelerators for a Higgs Factory: Linear vs. Circular"

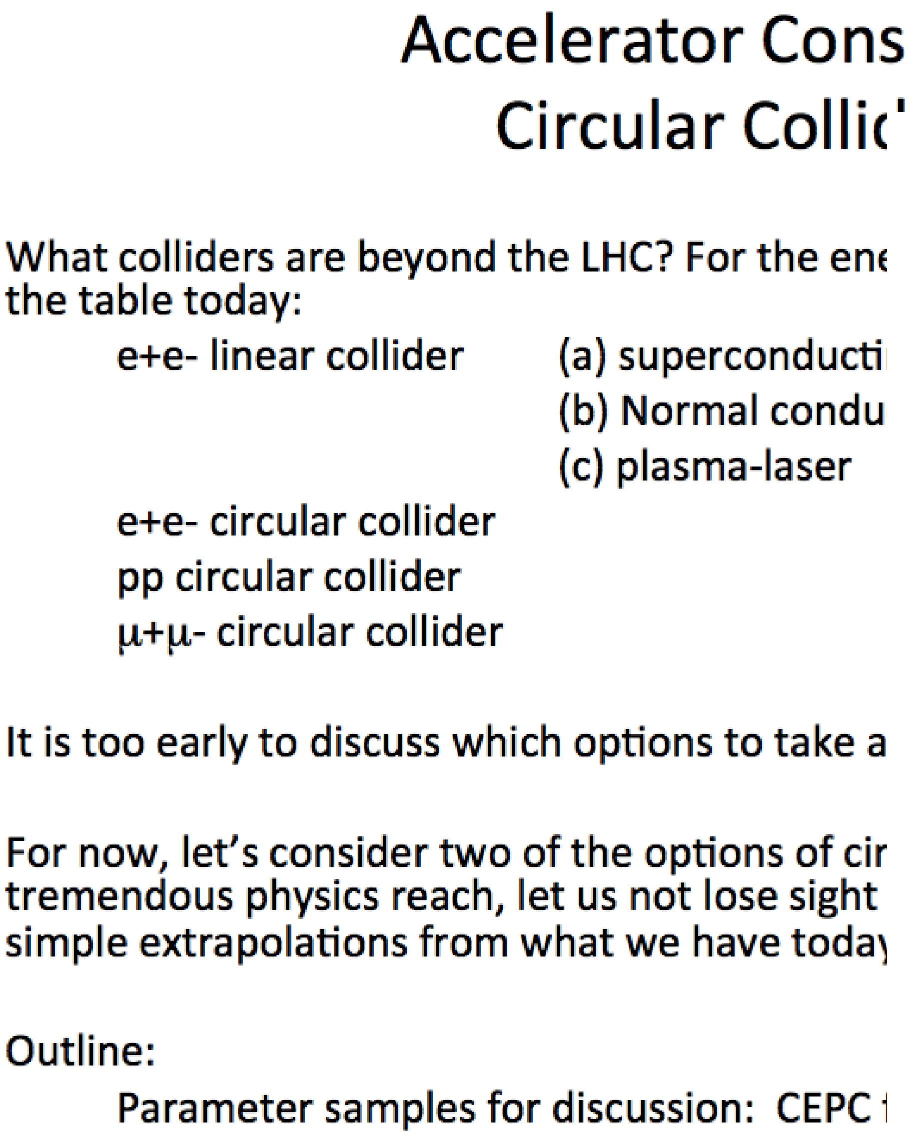
(HF2012)

Alain Blondel[1], Alex Chao[2], Weiren Chou[3], Jie Gao[4], Daniel Schulte[5] and Kaoru Yokoya[6]

[1] U. of Geneva, Geneva, Switzerland
[2] SLAC, Menlo Park, California, USA
[3] Fermilab, Batavia, Illinois, USA
[4] IHEP, Beijing, China
[5] CERN, Geneva, Switzerland
[6] KEK, Tsukuba, Japan

February 15, 2013

Discussion on large circular collider



Accelerator Considerations of Large Circular Colli

What colliders are beyond the LHC? For the ene
the table today:

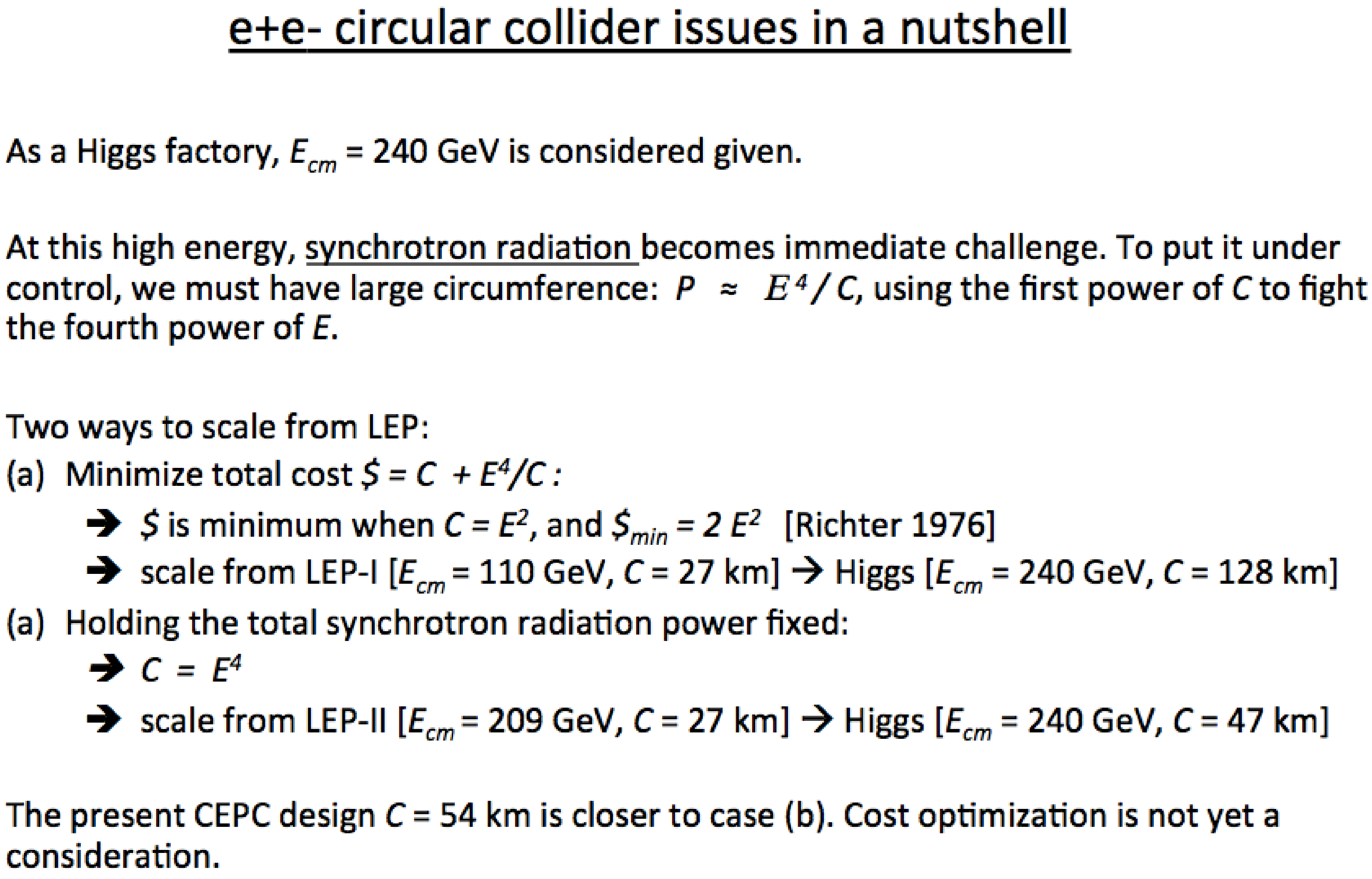
- e+e- linear collider (a) superconducti
  - (b) Normal condu
  - (c) plasma-laser
- e+e- circular collider
- pp circular collider
- $\mu+\mu$- circular collider

It is too early to discuss which options to take a

For now, let's consider two of the options of cir
tremendous physics reach, let us not lose sight
simple extrapolations from what we have toda

Outline:

Parameter samples for discussion: CEPC



e+e- circular collider issues in a nutshell

As a Higgs factory, E_{cm} = 240 GeV is considered given.

At this high energy, synchrotron radiation becomes immediate challenge. To put it under control, we must have large circumference: $P \approx E^4/C$, using the first power of C to fight the fourth power of E.

Two ways to scale from LEP:

(a) Minimize total cost $\$ = C + E^4/C$:

- ➔ $\$$ is minimum when $C = E^2$, and $\$_{min} = 2E^2$ [Richter 1976]
- ➔ scale from LEP-I [E_{cm} = 110 GeV, C = 27 km] → Higgs [E_{cm} = 240 GeV, C = 128 km]

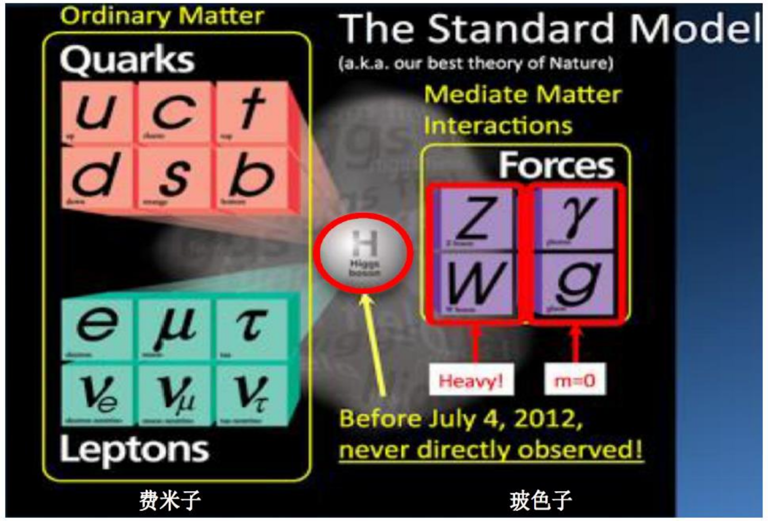
(a) Holding the total synchrotron radiation power fixed:

- ➔ $C = E^4$
- ➔ scale from LEP-II [E_{cm} = 209 GeV, C = 27 km] → Higgs [E_{cm} = 240 GeV, C = 47 km]

The present CEPC design C = 54 km is closer to case (b). Cost optimization is not yet a consideration.

CEPC – The Physics Case

The discovery of H(126) ⇒ golden opportunity

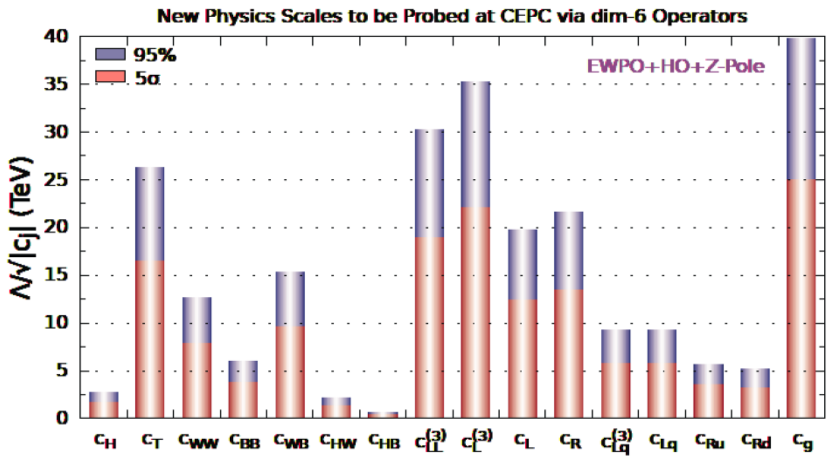


Higgs: it interacts with all fermions and W/Z

Is it connected to DM, DE?

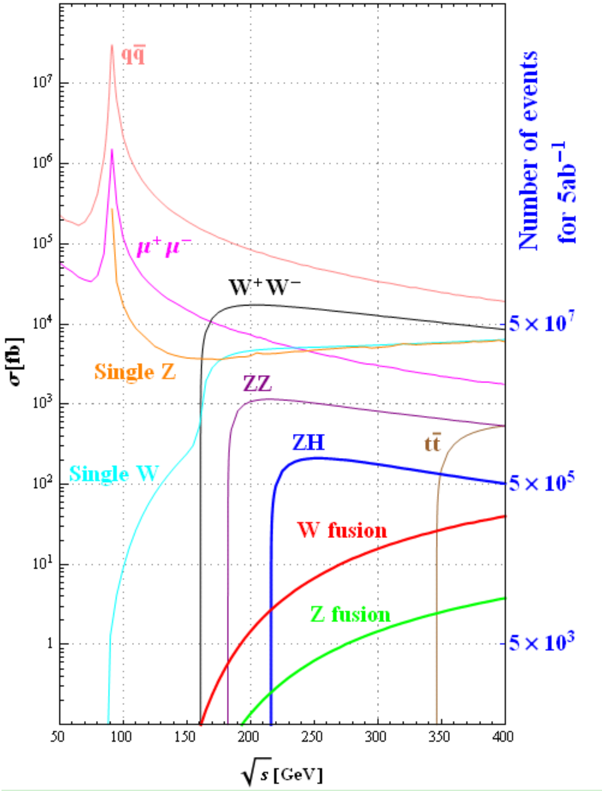
Experiment with the H: portal to the new world?

BSM new physics searches



S. Ge, H. He, R. Xiao, 1603.03385

Pre-CDR



CEPC directly / indirectly: probes new physics ~10s TeV scale

CEPC timeline

Pre-studies
(2013-2015)

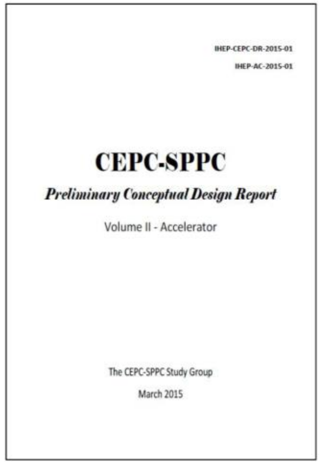
R&D
Engineering Design
(2016-2022)

Construction
(2022-2030)

Data taking
(2030-2040)

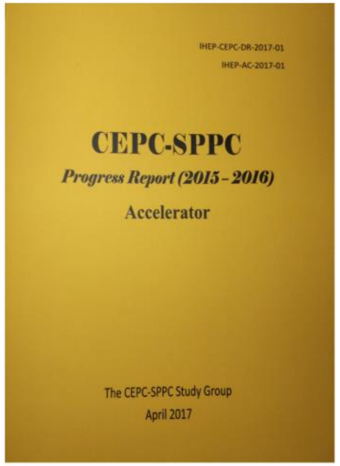
1st Milestone: Pre-CDR (by the end of 2014) ;
2nd Milestone: R&D funding from MOST (in Mid 2016);
3rd Milestone: CEPC CDR progress Report (by the end of 2016);
4th Milestone: CEPC CDR Report (by the end of Aug 2018);
5th Milestone: CEPC TDR Report and Proto R&D (by the end of 2022);
6th Milestone: CEPC construction start (2022);

http://cepc.ihep.ac.cn


IHEP-CEPC-DR-2015-01
IHEP-AC-2015-01

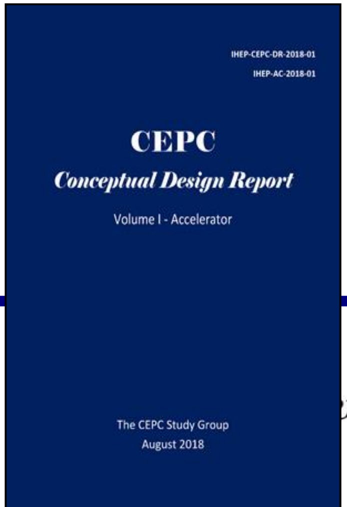
CEPC-SPPC
Preliminary Conceptual Design Report
Volume II - Accelerator

The CEPC-SPPC Study Group
March 2015


IHEP-CEPC-DR-2017-01
IHEP-AC-2017-01

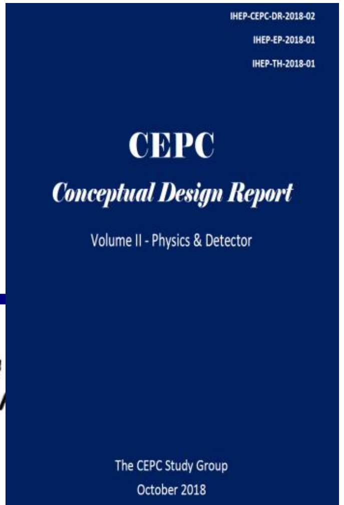
CEPC-SPPC
Progress Report (2015 – 2016)
Accelerator

The CEPC-SPPC Study Group
April 2017


IHEP-CEPC-DR-2018-01
IHEP-AC-2018-01

CEPC
Conceptual Design Report
Volume I - Accelerator

The CEPC Study Group
August 2018


IHEP-CEPC-DR-2018-02
IHEP-EP-2018-01
IHEP-TH-2018-01

CEPC
Conceptual Design Report
Volume II - Physics & Detector

The CEPC Study Group
October 2018

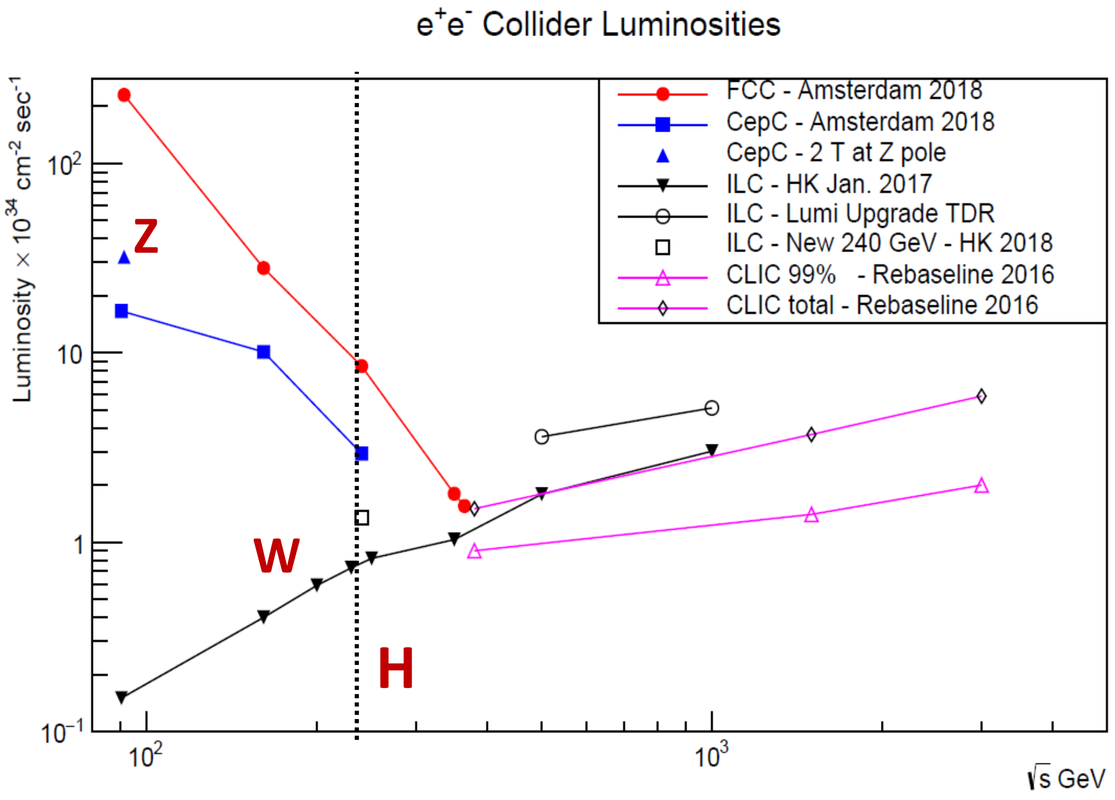
Public release of printed CDR volumes in IHEP on 14th Nov., 2018

Luminosity vs. CM energy

Circular:

offers higher lumi. @ LE
⇒unprecedented Z,W,+H program
mature technology
very long term: pp upgrade path

Linear:
very impressive Higgs precision
best Lumi. at higher energies, or only option for VHE

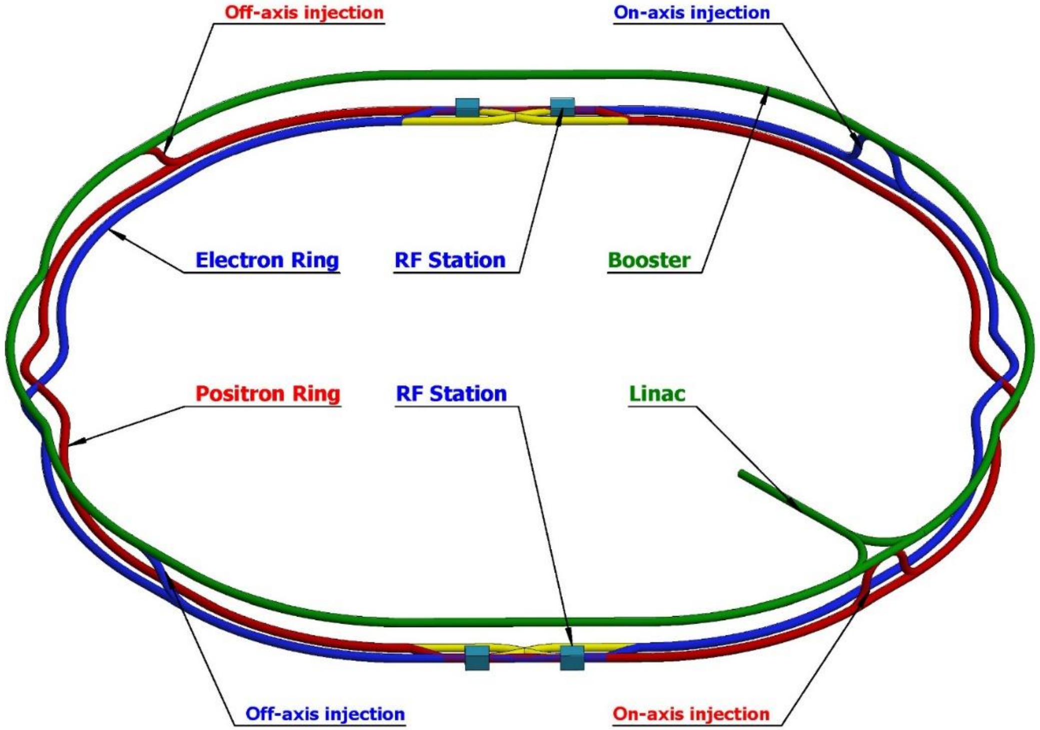


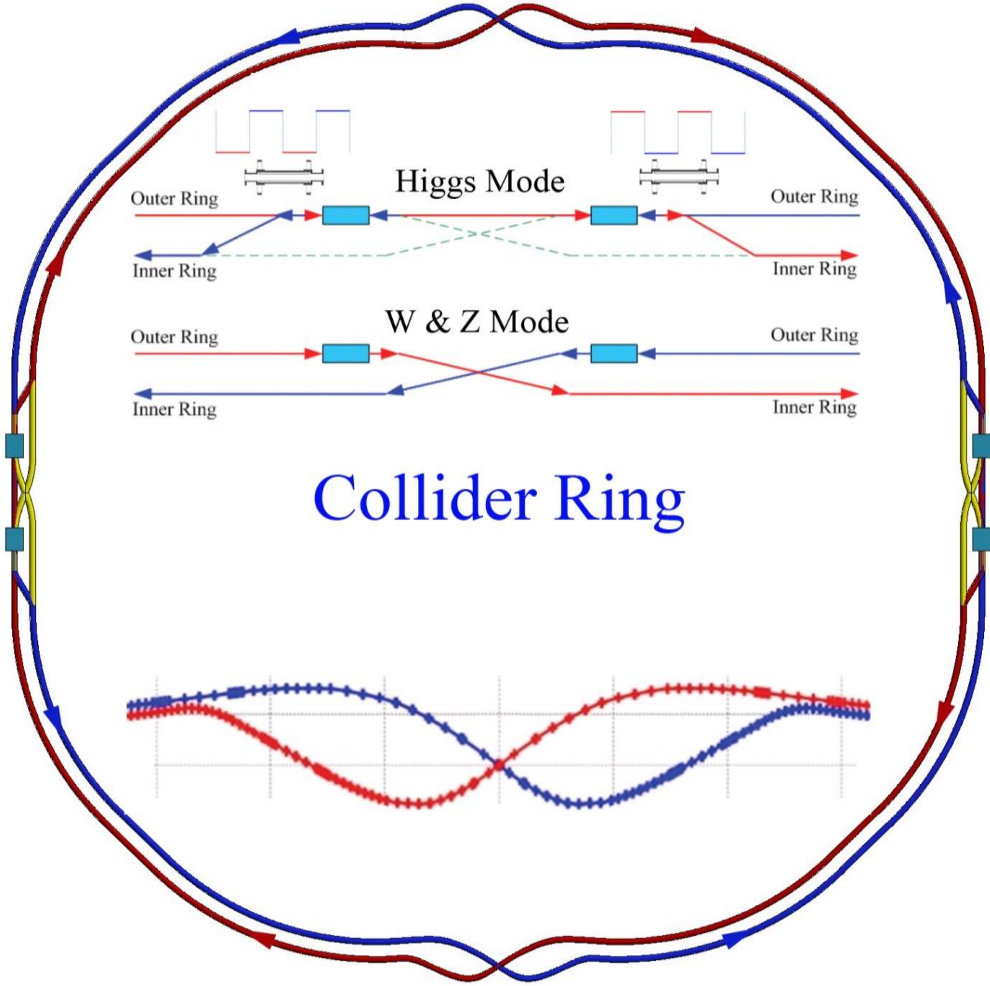
F. Bedeschi, INFN-Pisa

circular & linear colliders are ideally complementary to each other

- Double ring baseline design (30MW/beam
- Switchable between H and Z/W w/o hardware change (magnet switch)
- Use half SRF for Z and W
- Could be optimized for Z with 2T detector

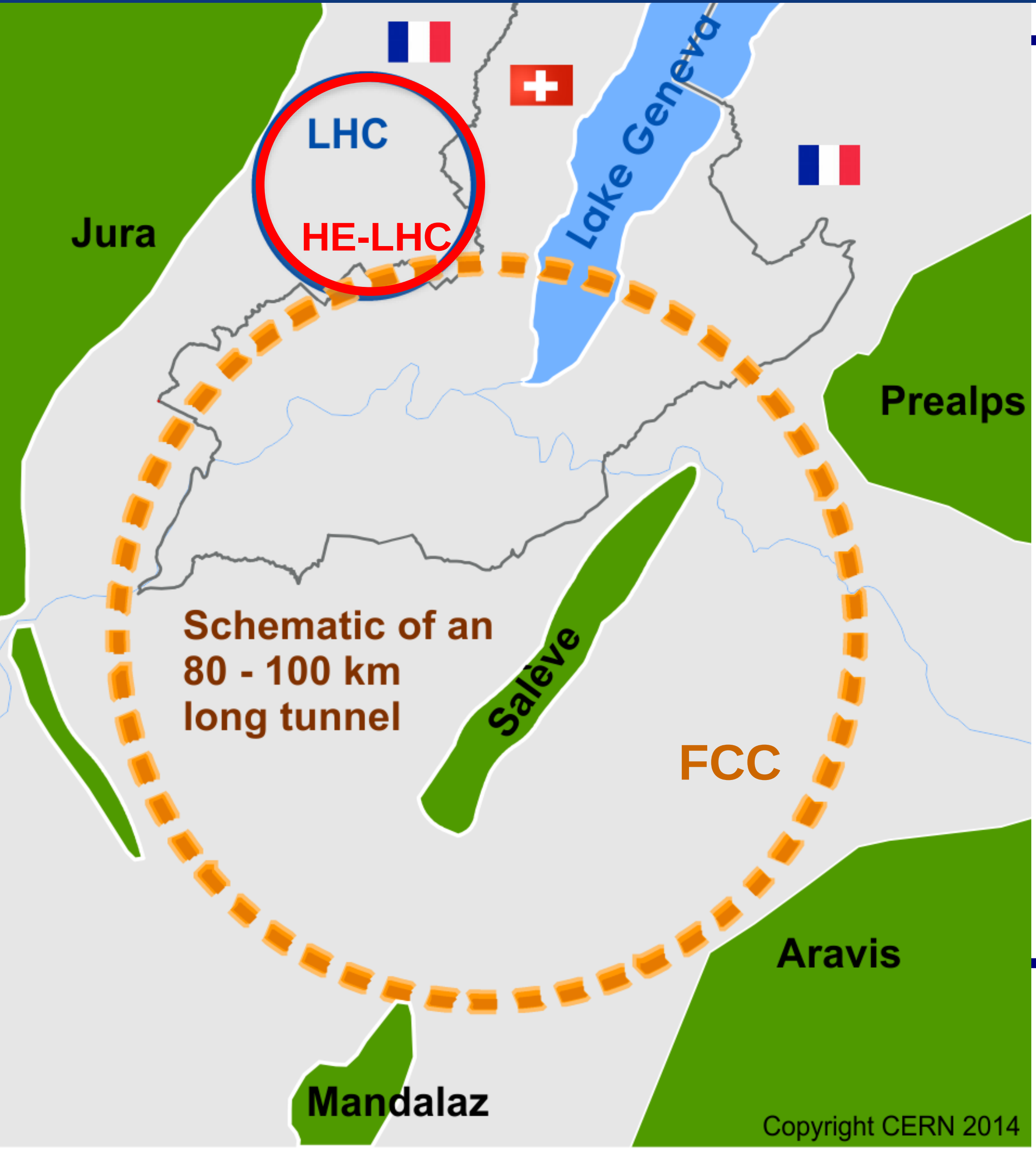
Lumi.	Higgs	W	Z	Z(2T)
$\times 10^{34}$	2.93	11.5	16.6	32.1





- Double ring collider with 2 IPs
- Compatible with the geometry of SPPC

Future Circular Collider Study - Scope



Copyright CERN 2014

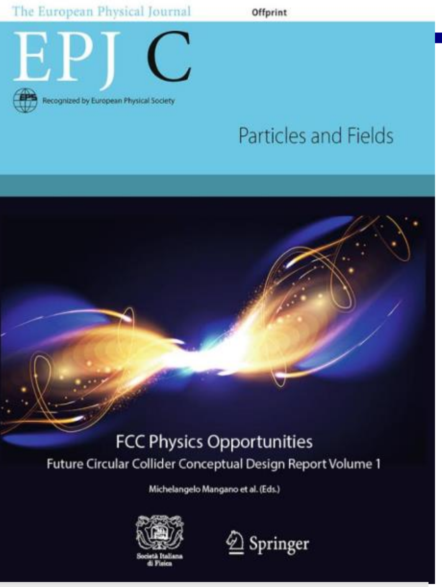
International FCC collaboration with CERN as host laboratory to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e^+e^-* collider (*FCC-ee*),** → potential first step
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements
- **HE-LHC** with *FCC-hh* technology
- **Ions** and **lepton-hadron** options with hadron colliders

~16 T ⇒ 100 TeV *pp* in 100 km

中国科学院高能物理研究所
Institute of High Energy Physics

FCC Conceptual Design Report


The European Physical Journal Offprint

EPJ C

Recognized by European Physical Society

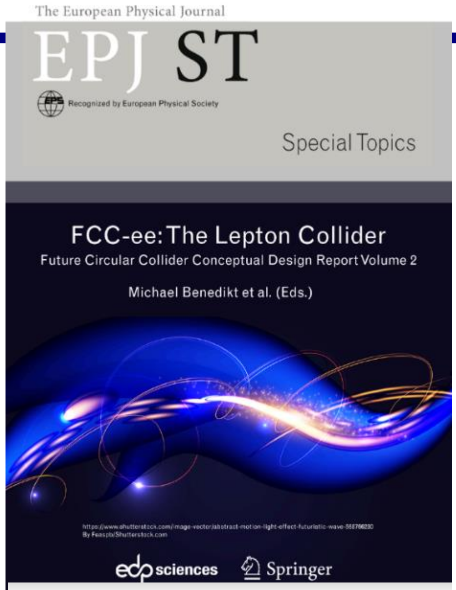
Particles and Fields

FCC Physics Opportunities

Future Circular Collider Conceptual Design Report Volume 1

Michelangelo Mangano et al. (Eds.)

Springer


The European Physical Journal

EPJ ST

Recognized by European Physical Society

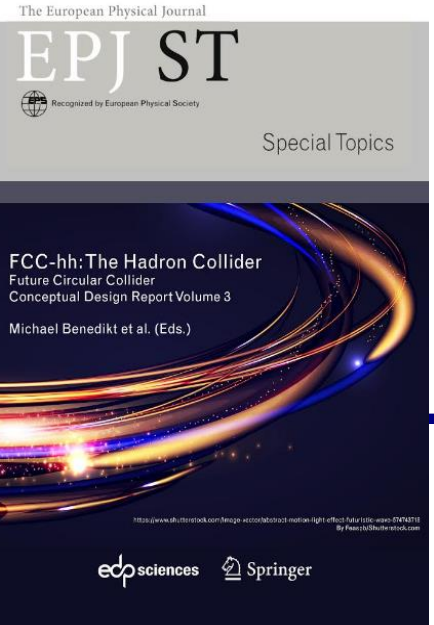
Special Topics

FCC-ee: The Lepton Collider

Future Circular Collider Conceptual Design Report Volume 2

Michael Benedikt et al. (Eds.)

edp sciences Springer


The European Physical Journal

EPJ ST

Recognized by European Physical Society

Special Topics

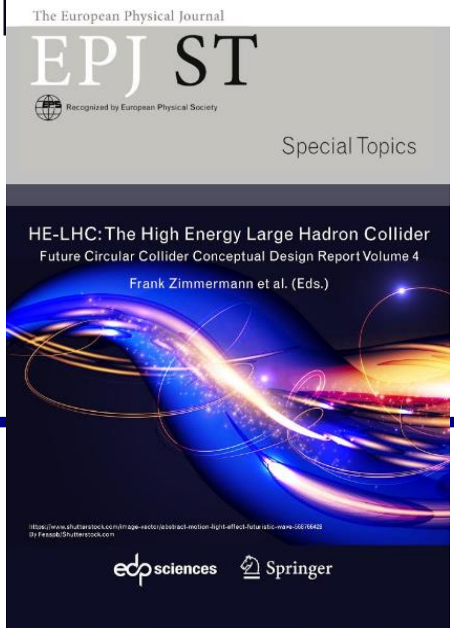
FCC-hh: The Hadron Collider

Future Circular Collider

Conceptual Design Report Volume 3

Michael Benedikt et al. (Eds.)

edp sciences Springer


The European Physical Journal

EPJ ST

Recognized by European Physical Society

Special Topics

HE-LHC: The High Energy Large Hadron Collider

Future Circular Collider Conceptual Design Report Volume 4

Frank Zimmermann et al. (Eds.)

edp sciences Springer

4 CDR volumes published in EPJ C and EPJ ST:

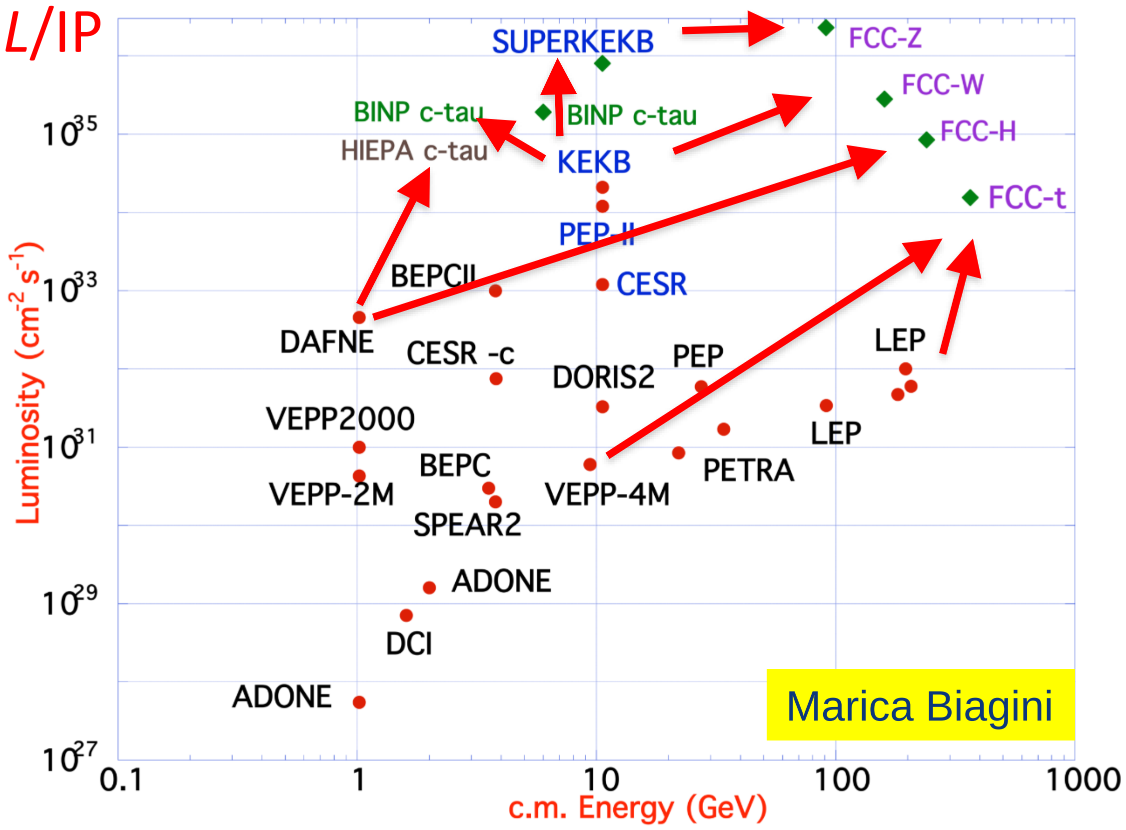
https://link.springer.com/article/10.1140/epjc/s10052-019-6904-3
https://link.springer.com/article/10.1140/epjst/e2019-900045-4
https://link.springer.com/article/10.1140/epjst/e2019-900087-0
https://link.springer.com/article/10.1140/epjst/e2019-900088-6

preprints available since 15 January 2019
http://fcc-cdr.web.cern.ch/

- FCC Physics Opportunities, FCC-ee, FCC-hh,HE-LHC

working point	assumed typical luminosity/IP [10^{34} $cm^{-2}s^{-1}$] = design minus 15%	total luminosity (2 IPs)/ yr; half of typical luminosity in 1st two years (Z) & 1st year ($t\bar{t}$)	physics goal	run time [yr]
Z 1st 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	1-2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearranging: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

- **FCC-ee reaches highest luminosities & energies by combining ingredients and well-proven concepts of several recent colliders**



Marica Biagini

B-factories: **KEKB & PEP-II:**
double-ring lepton colliders,
high beam currents,
top-up injection

DAFNE: crab waist, double ring

Super B-fact.,* S-KEKB: low β_y

LEP high energy, SR effects

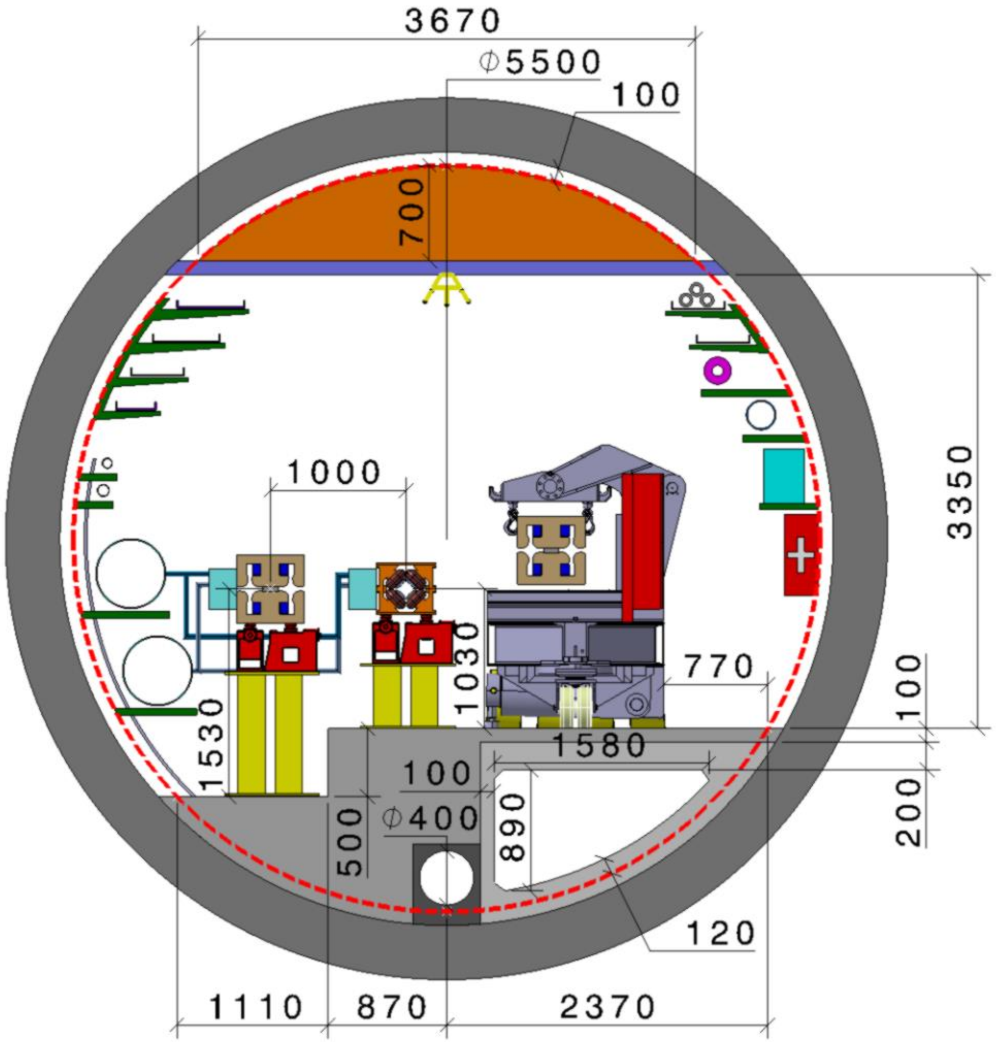
VEPP-4M, LEP: precision E calibration

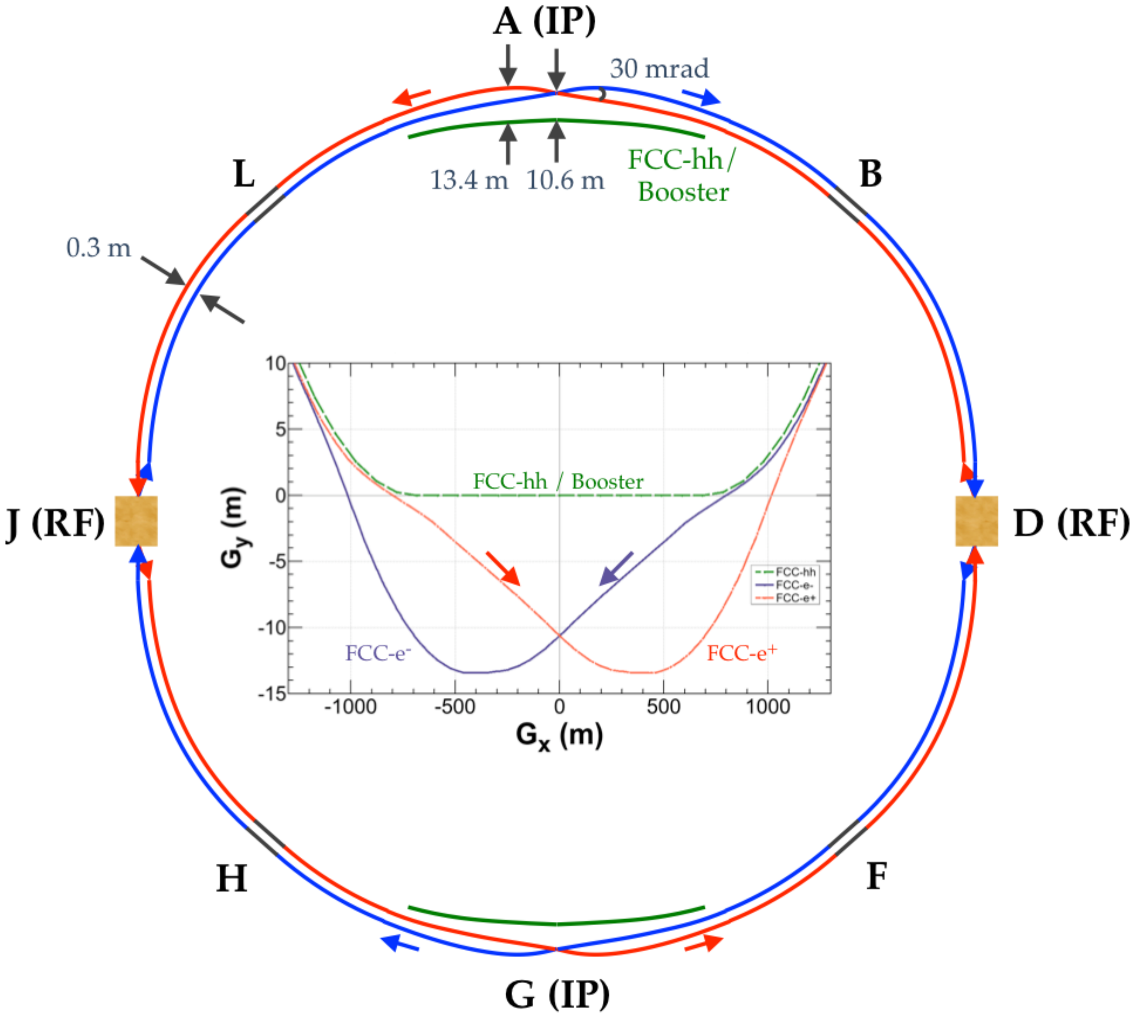
KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

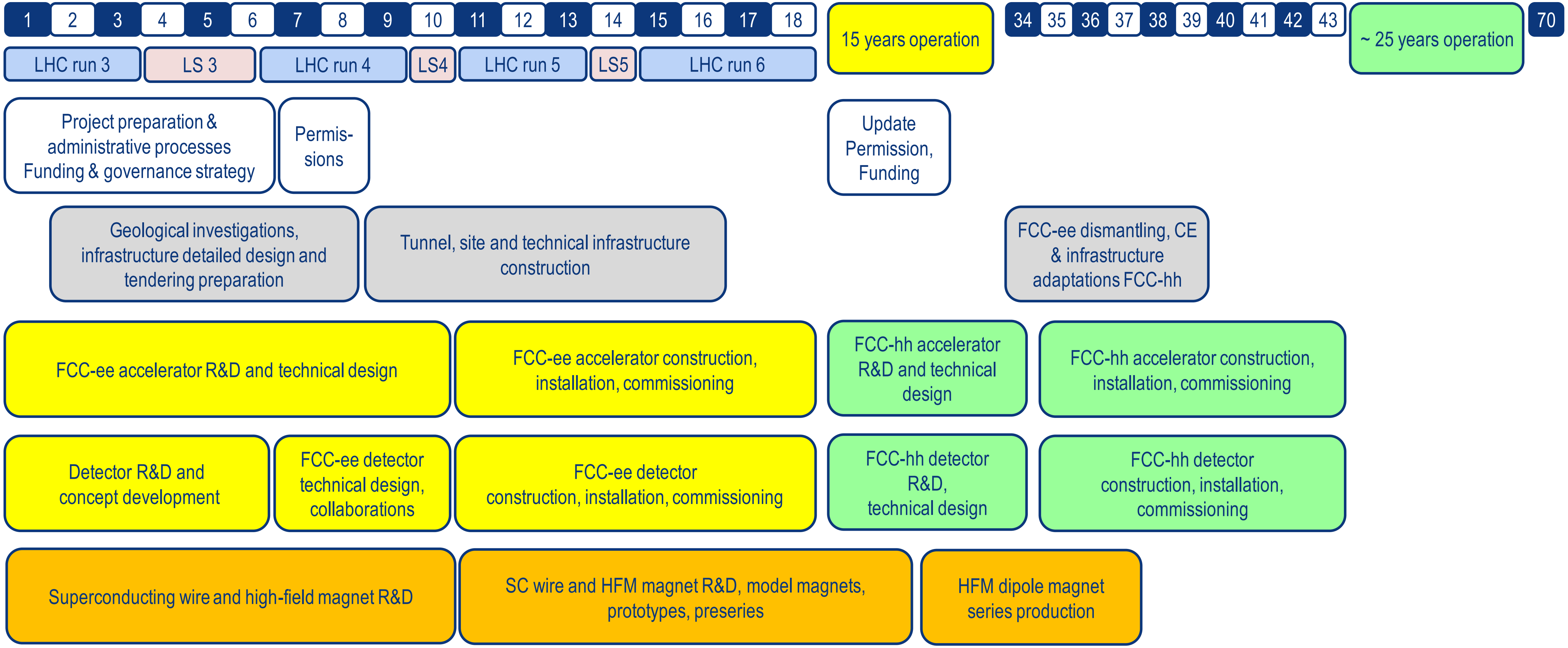
研究所
y Physics

- **Two main IPs in A, G for both machines.**
- **Common footprint except around IPs.**
- **FCC-ee asymmetric IR layout to limit synchrotron radiation**





- **FCC integrated project plan is fully integrated with HL-LHC exploitation provides for seamless further continuation of HEP in Europe.**



1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

15 years operation

34 35 36 37 38 39 40 41 42 43

~ 25 years operation

70

LHC run 3

LS 3

LHC run 4

LS4

LHC run 5

LS5

LHC run 6

Project preparation & administrative processes Funding & governance strategy

Permis-sions

Update Permission, Funding

Geological investigations, infrastructure detailed design and tendering preparation

Tunnel, site and technical infrastructure construction

FCC-ee dismantling, CE & infrastructure adaptations FCC-hh

FCC-ee accelerator R&D and technical design

FCC-ee accelerator construction, installation, commissioning

FCC-hh accelerator R&D and technical design

FCC-hh accelerator construction, installation, commissioning

Detector R&D and concept development

FCC-ee detector technical design, collaborations

FCC-ee detector construction, installation, commissioning

FCC-hh detector R&D, technical design

FCC-hh detector construction, installation, commissioning

Superconducting wire and high-field magnet R&D

SC wire and HFM magnet R&D, model magnets, prototypes, preseries

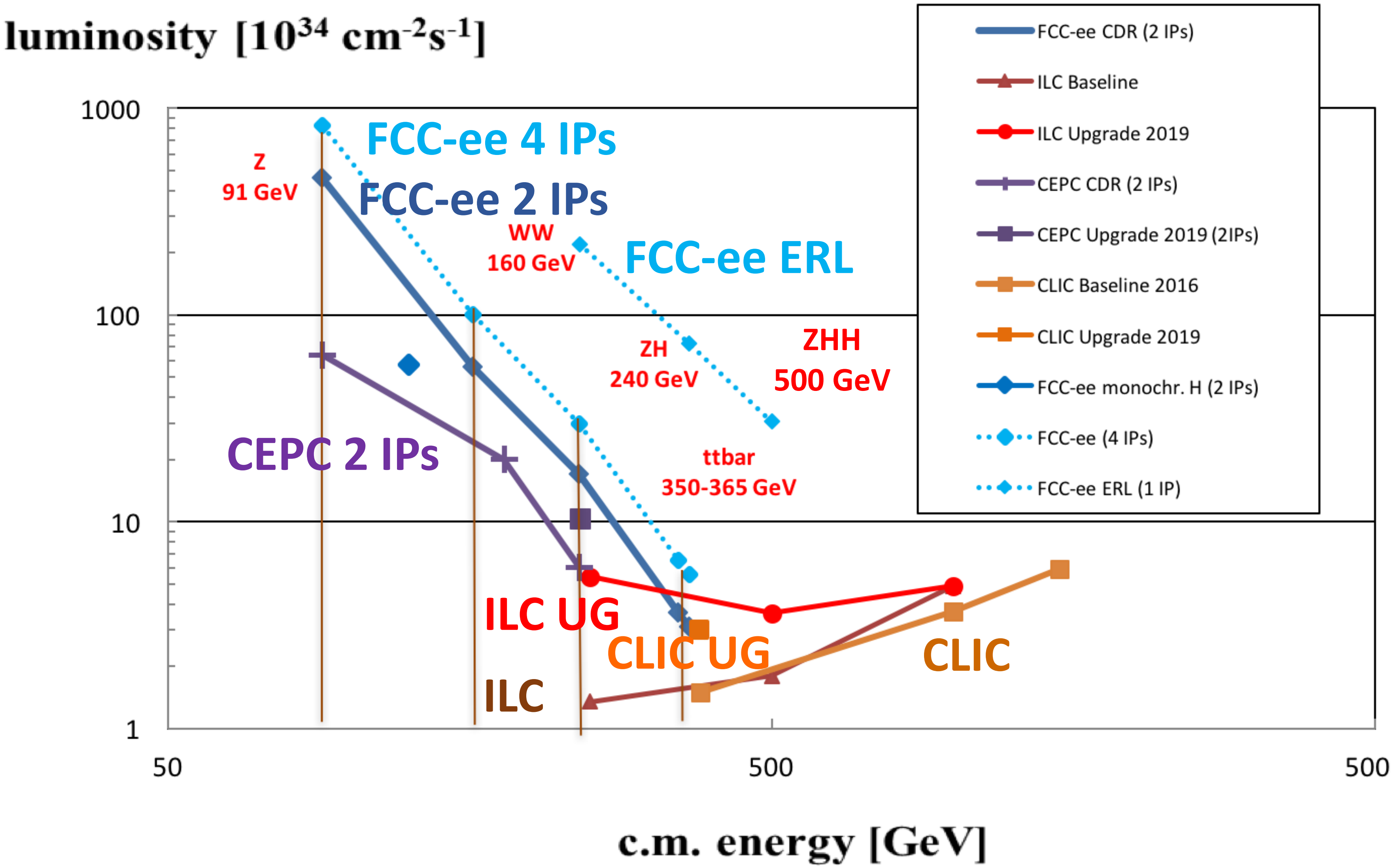
HFM dipole magnet series production

FCC - Next steps

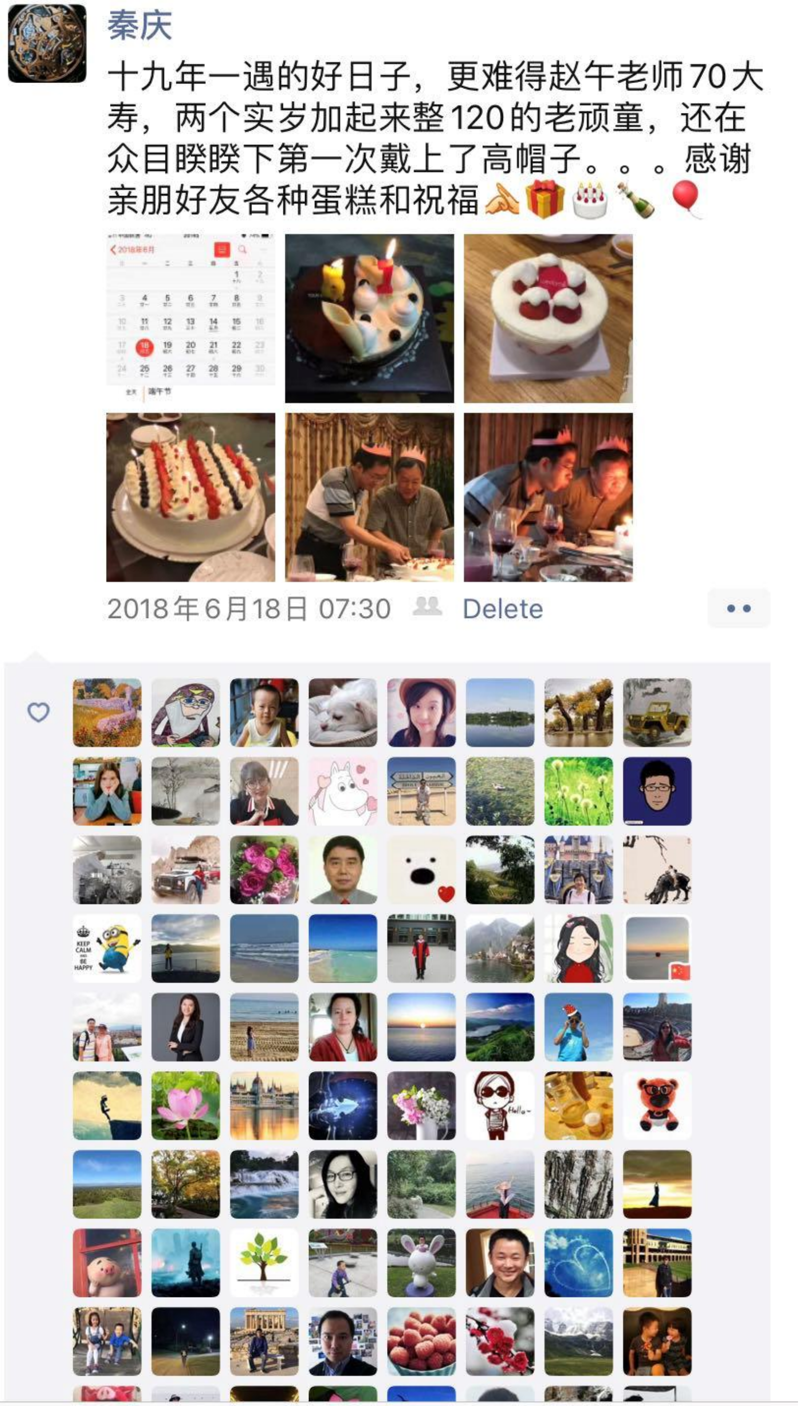
2019-2020:

- Layout **optimisation** and work on **implementation with host states.**
- Near-term focus on **FCC-ee as potential first step** (awaiting strategy recommendation).
- Preparation of **EU H2020 DS project** (INFRADEV call November 2019), focused on infrastructure implementation.

2020/21 – 2025/26: project preparation phase (if supported by EPPSU and CERN Council)



Benno List, Daniel Schulte, Dmitry Shatilov, Cheng Hui Yu, Vladimir Litvinenko, Thomas Roser



秦庆

十九年一遇的好日子，更难得赵午老师70大寿，两个实岁加起来整120的老顽童，还在众目睽睽下第一次戴上了高帽子。。。感谢亲朋好友各种蛋糕和祝福🙏🎁🎂🍾🎈

2018年6月18日 07:30 Delete

Thanks for your attentions!