Future τ/charm Factories

M. Biagini, LAL & INFN

French-Ukrainian Workshop on the instrumentation developments for high energy physics

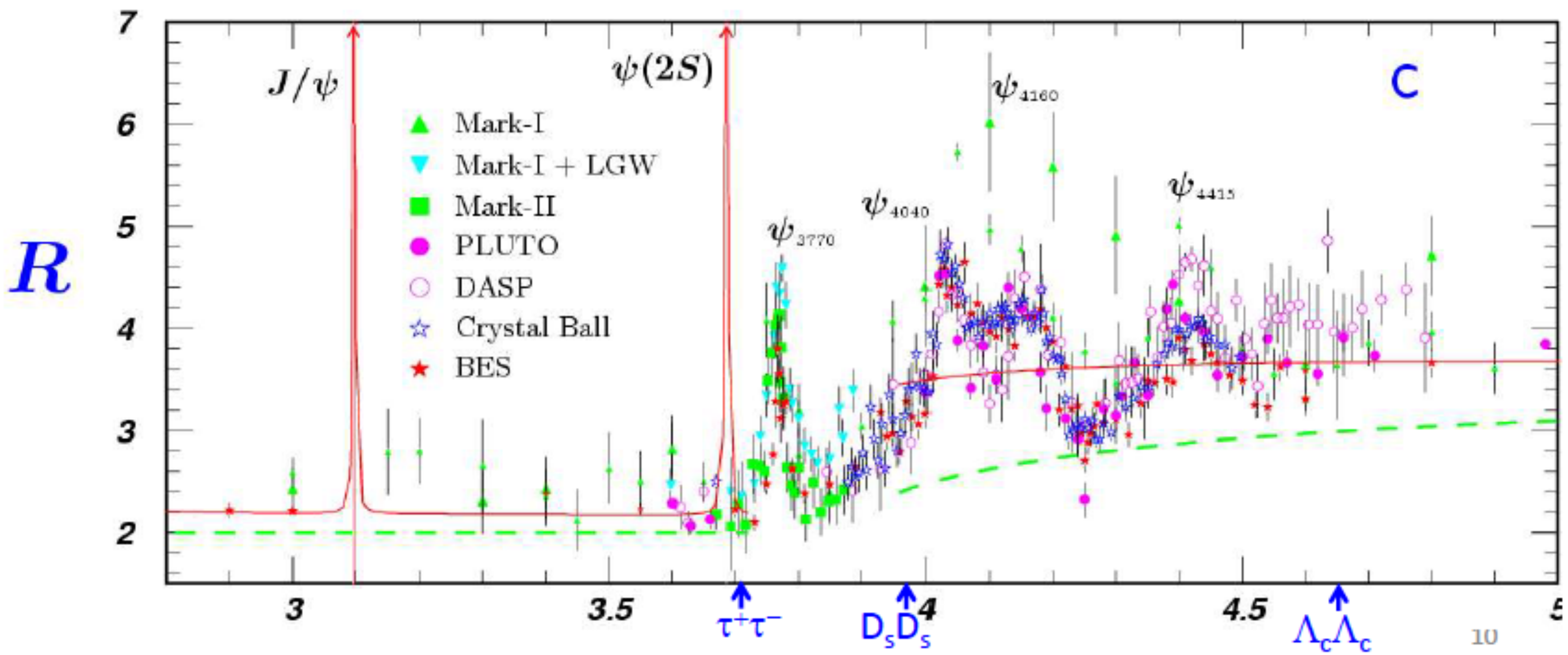
LAL, November 6-8 2017

Why a new τ/charm-Factory?

- Physics at rather low energy is still interesting (rare events decays)
- There is a physics community interested to
- The potential for discovery is still not negligible
- The cost is affordable by a medium size laboratory
- The time frame is much shorter than any future high energy project
- The machine can incorporate latest ideas and serve also as a test bench for accelerator R&D

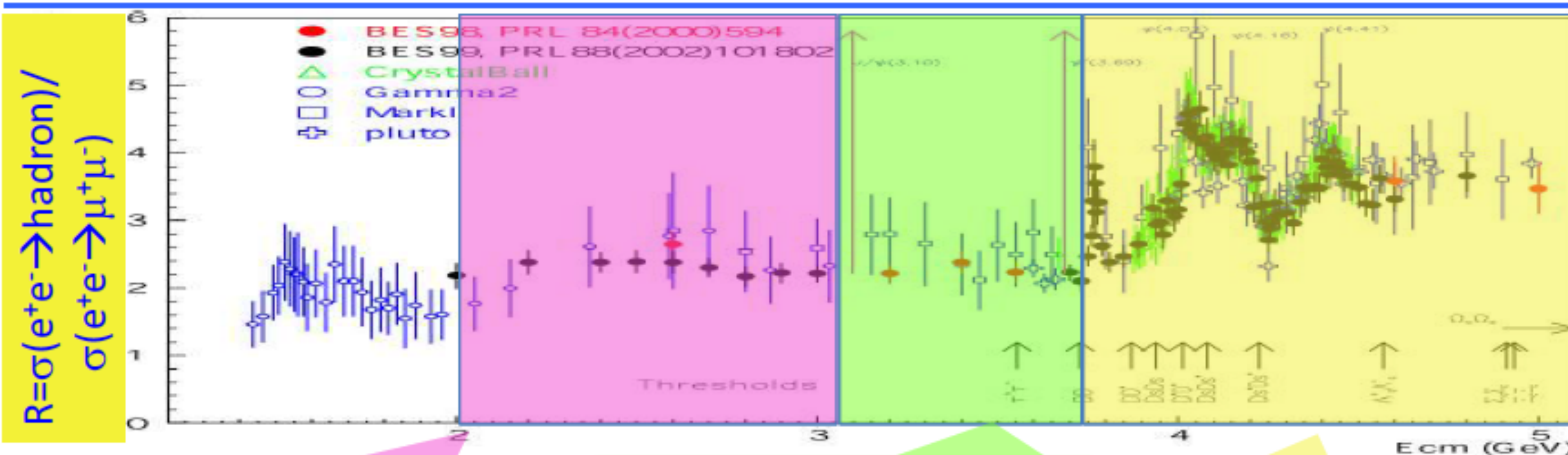
Features of the τ-c Energy Region

- Rich of resonances, charmonium and charmed mesons.
- Threshold characteristics (pairs of τ, D, D_s, charmed baryons…).
- Transition between smooth and resonances, perturbative and non-perturbative QCD.
- Mass location of the exotic hadrons, gluonic matter and hybrid.



W. Yan, From Phi-to-Psi, 2017

Physics at τ-c Energy Region



- Hadron form factors
- Y(2175) resonance
- Mutltiquark states with s quark, Zs
- MLLA/LPHD and QCD sum rule predictions

- Light hadron spectroscopy
- Gluonic and exotic states
- Process of LFV and CPV
- Rare and forbidden decays
- Physics with τ lepton

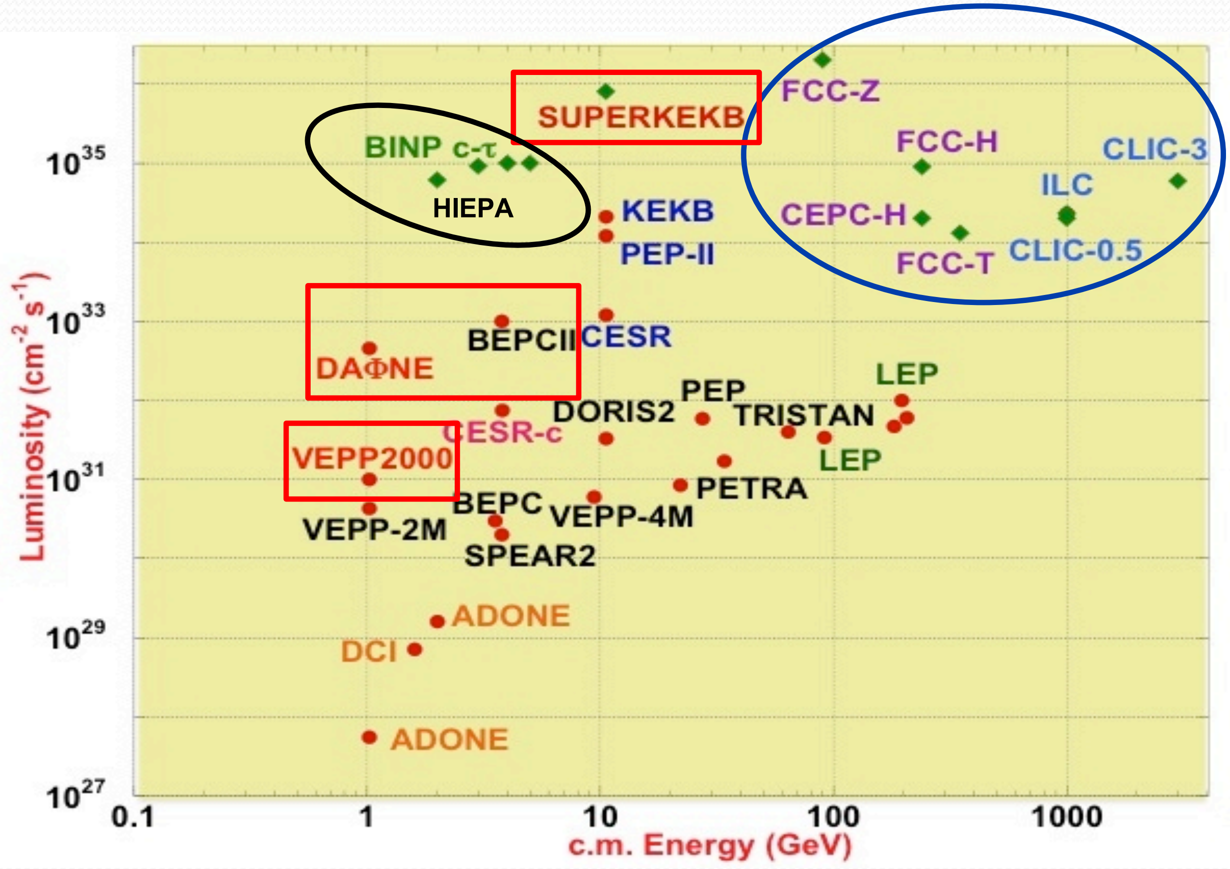
- XYZ particles
- Physics with D mesons
- f_D and f_{Ds}
- D_0-$\bar{D}_0$ mixing
- Charmed baryons

R scan

- **Precision $\Delta\alpha_{QED}$, a_μ, charm quark mass extraction.**
- **Hadron form factor(nucleon, Λ, π).**

W. Yan, From Phi-to-Psi, 2017

Luminosity versus center-of-mass energy

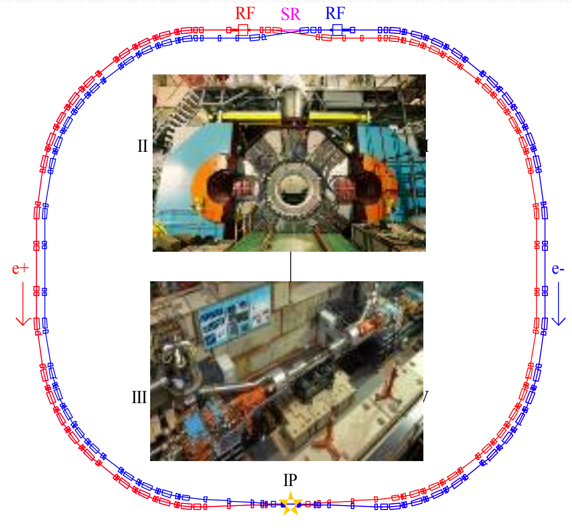


past [orange, black, green centre-right], **present** (2017) [red] and **future** lepton colliders [blue, purple, green top-left] around the world

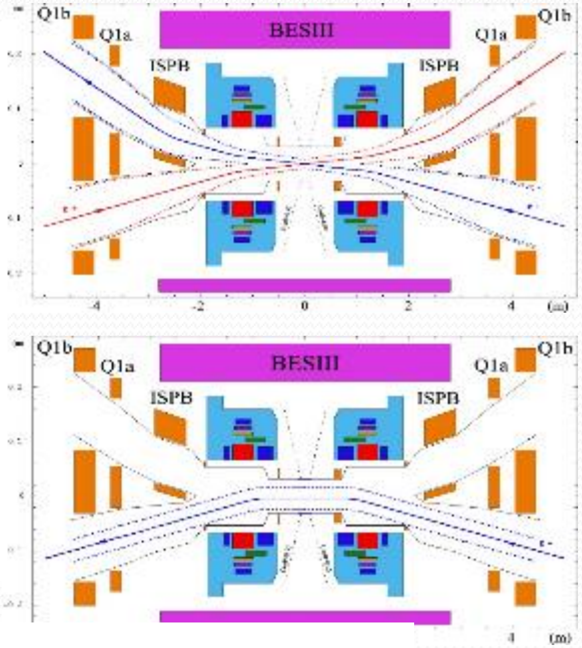
Present τ/charm-Factory

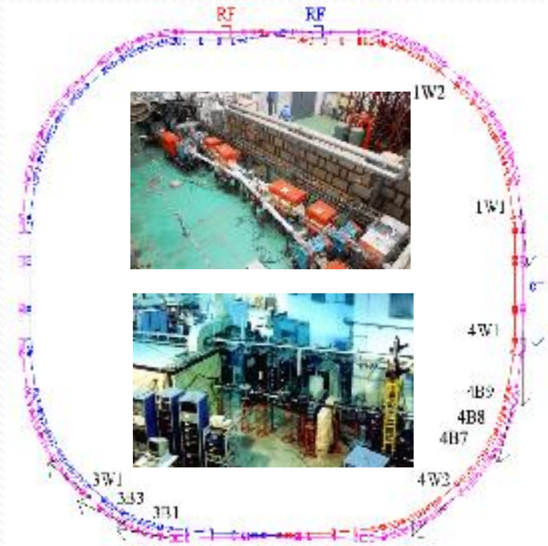
- BEPC-II is at present the only τ/charm-Factory, operating at IHEP Beijing (China)
- Upgrade of the BEPC collider, built with the possibility of a dedicated synchrotron light source (SR) operation mode
- Can operate between 2 and 4.6 GeV c.m. energy, with focus on the 1.89 GeV/beam
- Design luminosity of **10^{33} cm^{-2} s^{-1}** was reached in April 2016, after few years of optimization and hardware improvements, highest luminosity yet achieved for such an accelerator in this energy region
- Will be shutdown around 2024

BEPCII (IHEP, Beijing)



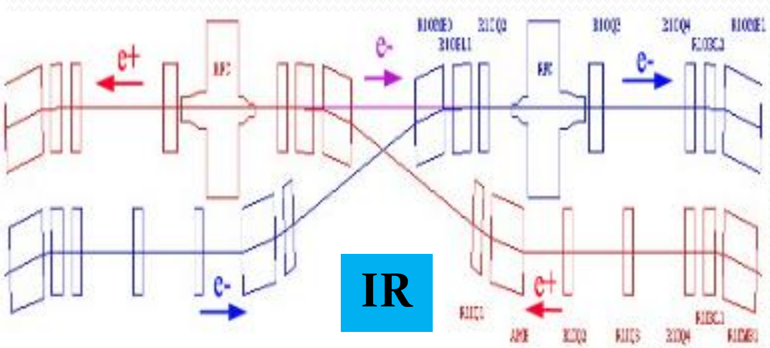
Collider





SR Facility

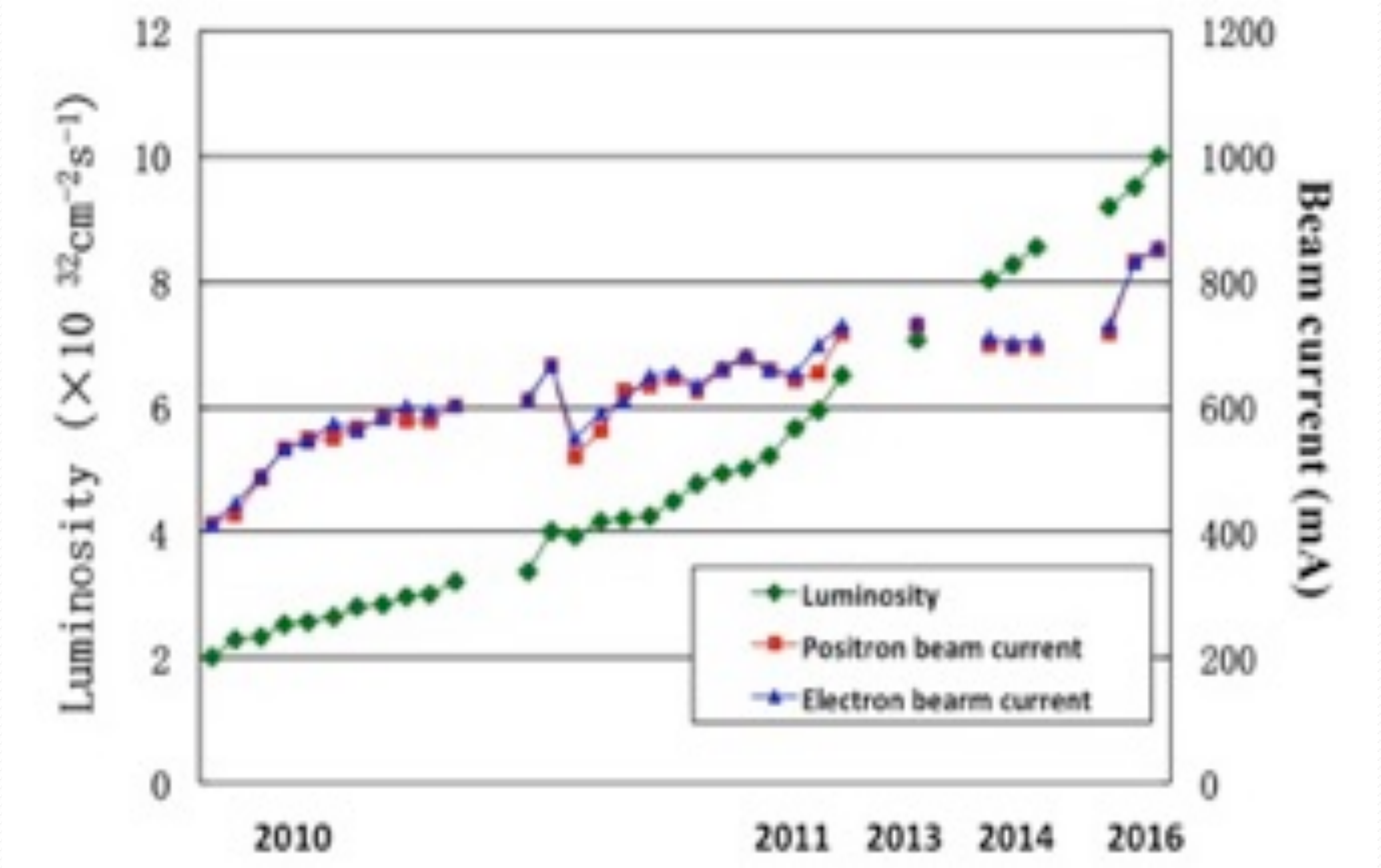
- Collision Mode
  - Beam energy range 1-2.1 GeV
  - Optimized beam energy 1.89 GeV
  - Luminosity 1×10^{33} $cm^{-2}s^{-1}$ **Design**
  - Full energy injection 1-1.89 GeV



- SR Mode
  - Beam energy 2.5 GeV
  - Beam current 250 mA

Q. Qin, Valencia 2017

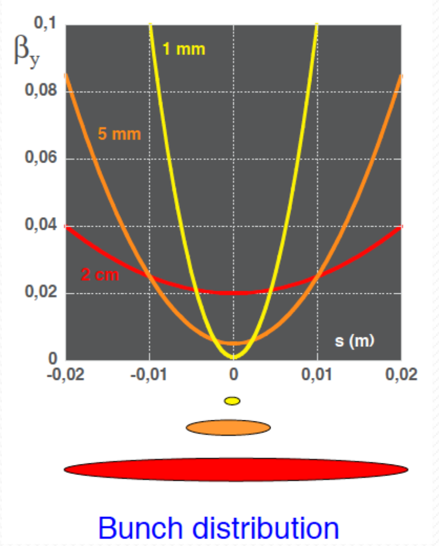
Evolution of luminosity and beam currents for BEPCII



Optimal performances need time!

“Standard” Collision Scheme Limitations

1. Hourglass effect limits minimum IP β_y: $\beta_y^* \leq \sigma_z$



2. Bunch length reduction not advisable:
   bunch lengthening, microwave instability,
   Coherent Synchrotron Radiation

3. Further multi-bunch current increase would result in:
   coupled bunch instabilities, HOM heating, higher wall-plug power

4. Higher emittances conflict with:
   beam stay-clear and dynamics aperture limitations

5. Tune shifts saturate, beam lifetime drops due to:
   beam-beam interactions

Changing the approach…

- 10 years ago the "brute force" (increasing currents) was still the only approach to higher luminosity
- P. Raimondi (LNF, now ESRF) designed a new collision scheme with larger crossing angle and lower IP beam sizes (*Large Piwinski Angle, LPA*) PLUS a couple of sextupoles to twist the IP waist and cure x-y and synchro-betatron resonances raising from the angle (*Crab Waist, CW*). Test at DAΦNE (LNF) was very successful
- Adopted by all collider projects after 2008

		Present KEKB LER/HER	High-current LER/HER	Nano-beam LER/HER	
Stored currents	I	1.8 / 1.4	9.4 / 4.1	$\sim 3/1.5$	A
Vert. beam-beam param.	ξ_y	$\lesssim 0.09$	~ 0.3	~ 0.1	
Vert. β at the IP	β_y^*	6	3 / 5	~ 0.2	mm
Hor. emittance	ε_x	~ 18	~ 18	~ 1	nm
Vert. beam size at the IP	σ_y^*	~ 1	~ 1	~ 0.05	μm
Crossing angle	θ_x	22	0 (crab)	~ 60	mrad
Luminosity	$\mathcal{L}$	1.8	~ 50	~ 80	10^{34} cm^{-2} s^{-1}

Oide, Progress of Theoretical Physics, Vol. 122, No. 1, July 2009

Large Piwinski angle and Crab Waist in 3 steps

1. Large Piwinski's angle $\Phi = tg(\theta)\ \sigma_z/\sigma_x$
2. Vertical beta comparable with overlap area $\beta_y \sim \sigma_x/\theta$
3. Crab waist transformation $y = xy'/(2\theta)$

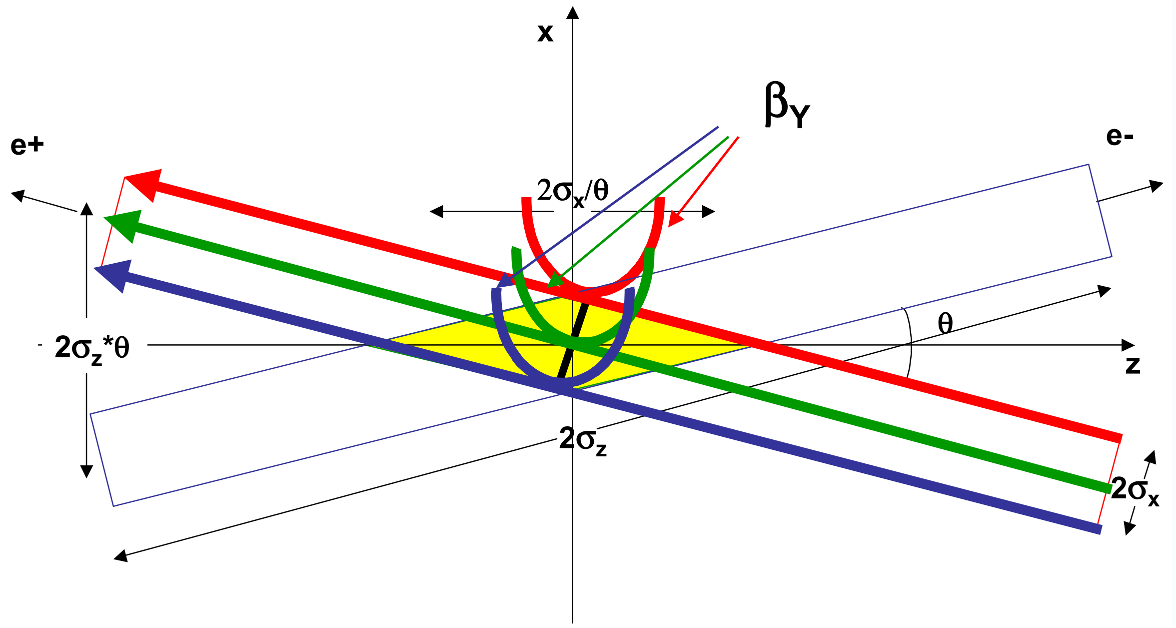
The LPA&CW scheme has two ingredients:

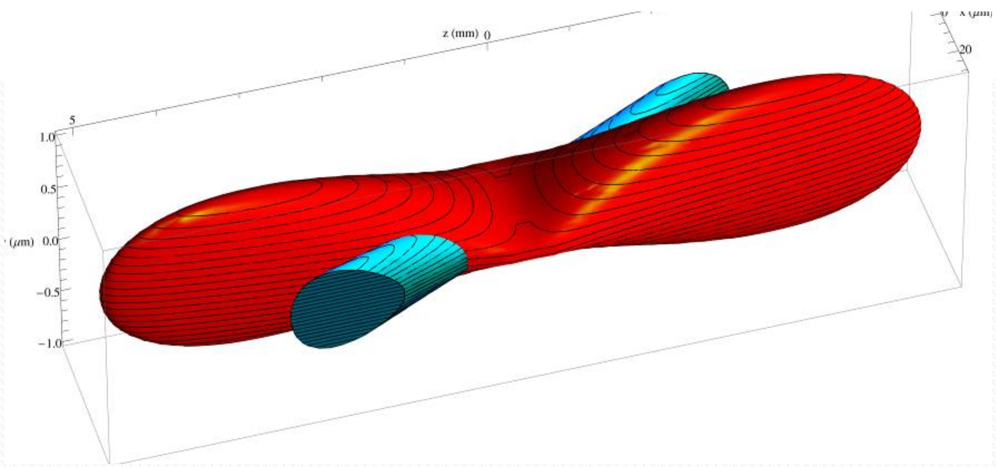
1) very small horizontal beam size and large crossing angle (this makes the Piwinski angle large)
2) a couple of sextupoles in phase with the IP in *X* and at $\pi/2$ in *Y* to twist the beams at the IP

The beams overlap area (yellow) is not related anymore to the bunch length, therefore β_y^*, which gives the actual luminosity gain, can be reduced as much as possible with the present magnet technologies

1. *P.Raimondi, 2° SuperB Workshop, March 2006*
2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033, 2007*

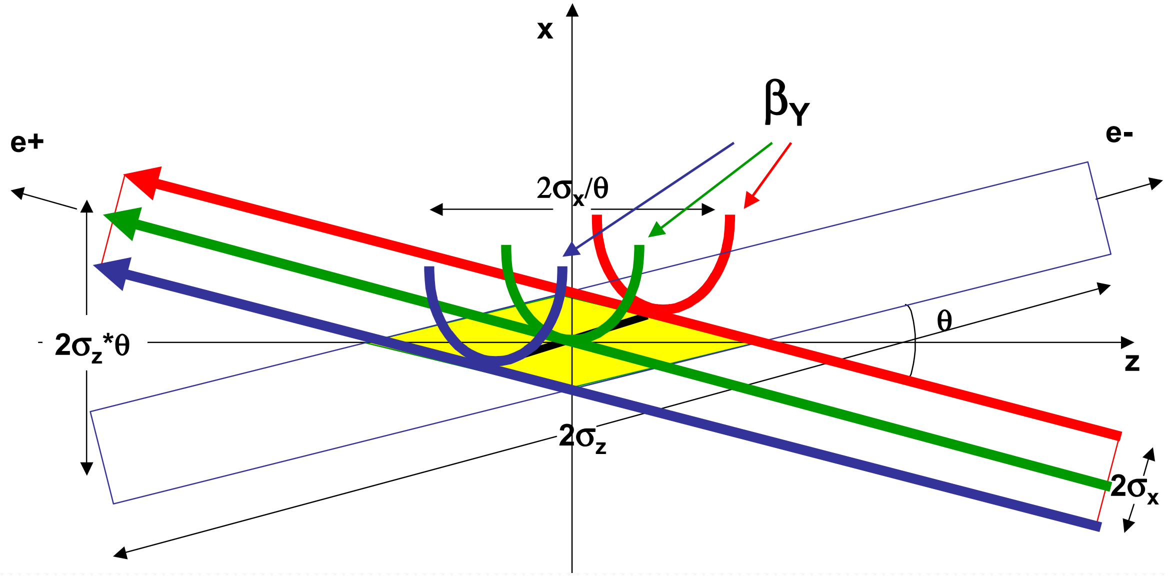
How the *crab waist sextupoles* work…

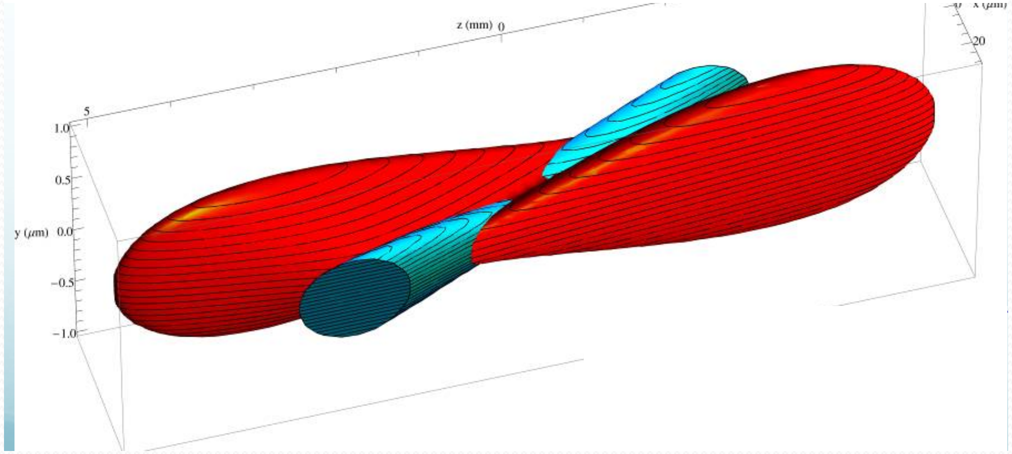




No crab waist sextupoles

With crab waist sextupoles





All particles in both beams collide at the minimum β_y^* spot (waist) with a net luminosity gain

Crab Waist Advantages

1. Large Piwinski's angle

$$\Phi = tg(\theta/2)\sigma_z/\sigma_x$$

- a) Luminosity gain with N
- b) Very low horizontal tune shift
- c) Vertical tune shift decreases with oscillation amplitude

2. Vertical beta comparable with overlap area

$$\beta_y \approx 2\,\sigma_x/\theta$$

- a) Geometric luminosity gain
- b) Lower vertical tune shift
- c) Suppression of vertical synchro-betatron resonances

3. Crab waist transformation

$$y = xy'/\theta$$

- a) Geometric luminosity gain
- b) Suppression of X-Y betatron and synchro-betatron resonances

….and besides…

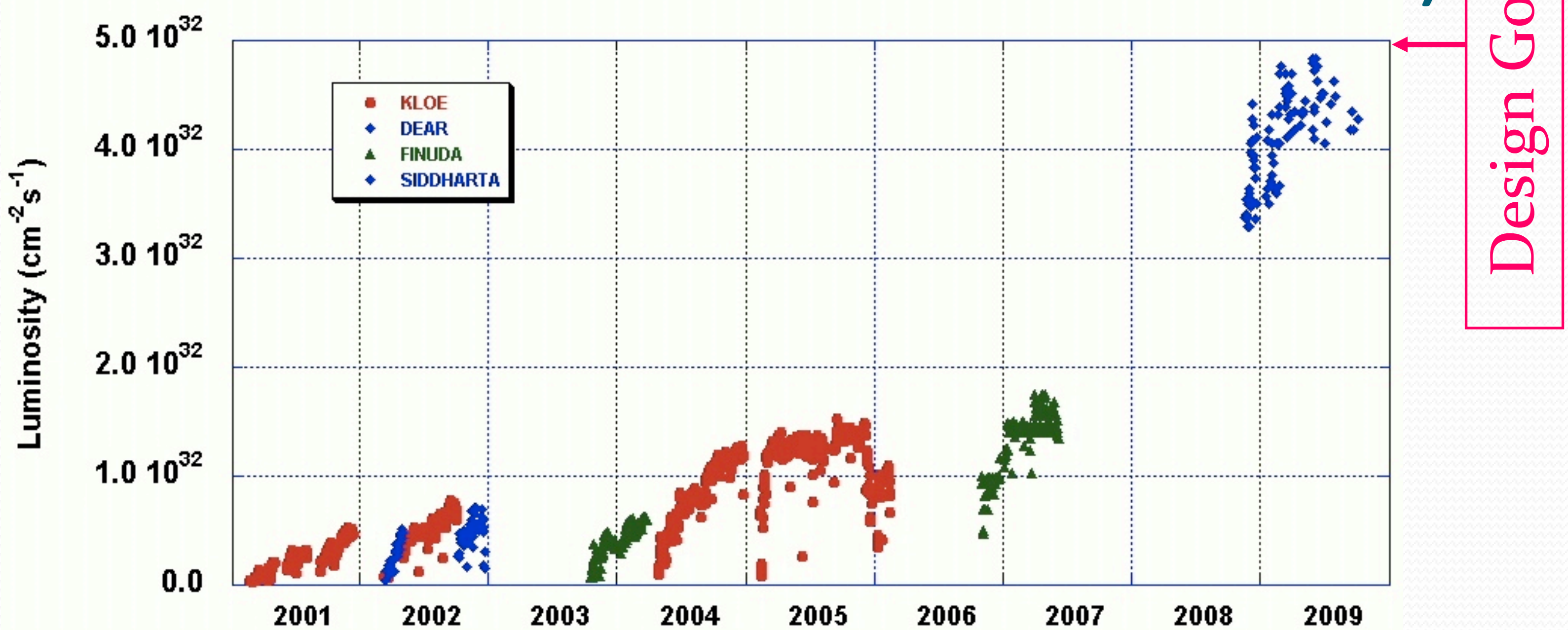
a) No need to increase excessively beam currents and to decrease the bunch length:

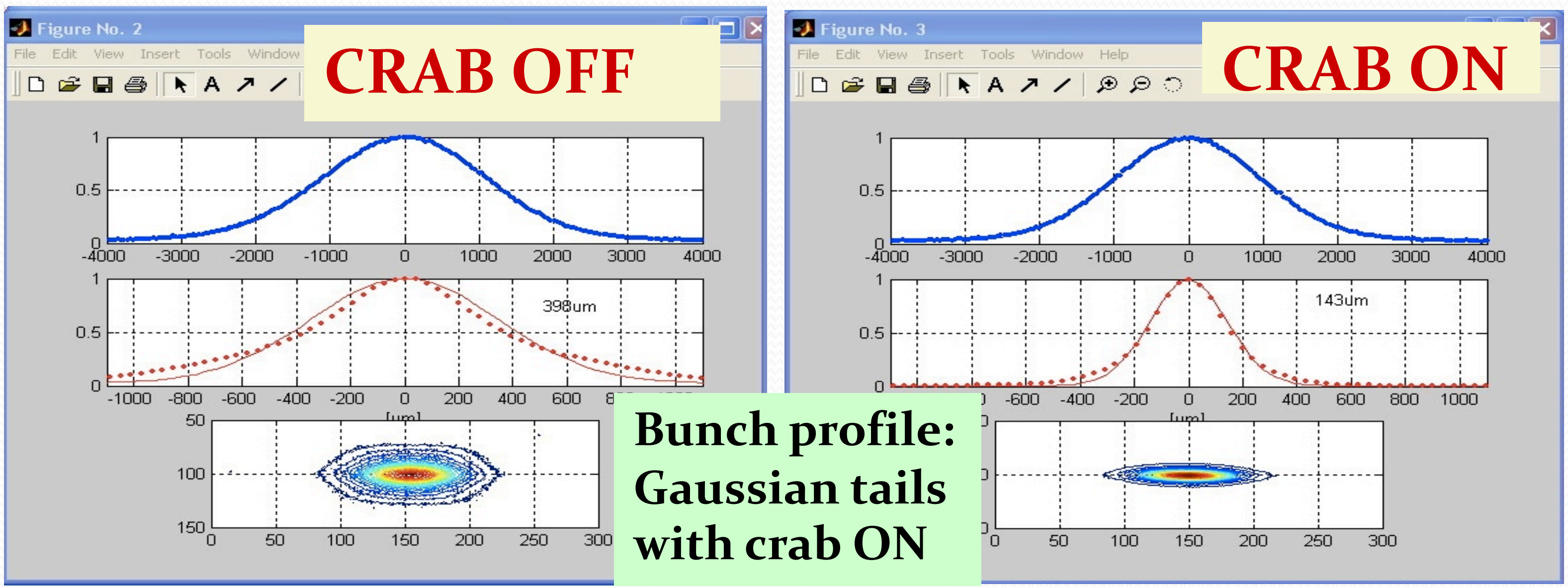
- ✓ Beam instabilities are less severe
- ✓ Manageable HOM heating
- ✓ No coherent synchrotron radiation of short bunches
- ✓ No excessive power consumption

b) Problem of parasitic collisions automatically solved due to higher crossing angle and smaller horizontal beam size

c) Less hourglass effect → β_y^* can be decreased "at will"

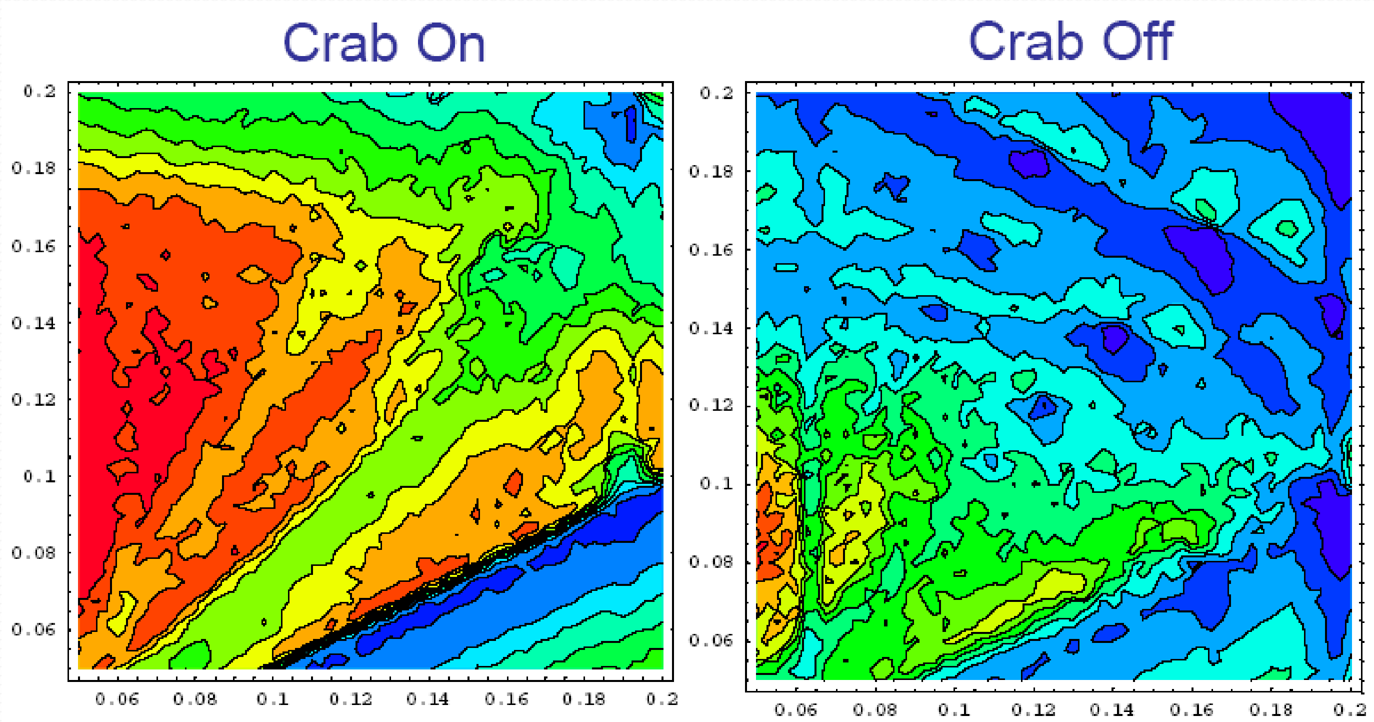
Crab waist scheme at DAΦNE(Frascati)





Bunch profile: Gaussian tails with crab ON

Beam-beam simulations for BINP τ/charm (similar parameters) in *CW* mode



Luminosity as a function of the working point of the betatron tunes (horizontal and vertical axes correspond to tune fractional part part) for crab sextupoles ON (left) and OFF (right).
The red and blue colors show large and small luminosity

τ/charm-Factory features (Frascati design)

- Designed after the Italian *SuperB* B-Factory project was cancelled
- Energy tunable in the range **E_{cm} = 2-4.8 GeV**
- **10^{35} cm^{-2} s^{-1}** peak luminosity at the τ/charm threshold and upper
- Symmetric beam energies
- Longitudinal polarization in the electron beam (60-70%)
- Beam parameters for reasonable lifetimes and beam currents
- Low power consumption → lower running costs
- Design features:
  - *LPA & CW sextupoles* collision scheme
  - Low H-emittance lattice
  - Small H-V coupling → ultra low V-emittance
  - Small IP β functions and beam sizes
  - Beam-beam tune shifts < 0.1
  - Low beam power for low running costs

Designed in 2013,
CDR published
https://arxiv.org/abs/1310.6944

Future projects

STCF τ/charm-Factory (BINP, Novosibrisk)

- BINP, as Orsay and Frascati, has a long lasting experience on building and operating low-medium energy colliders
- Since 2008 a Super τ/charm-Factory was studied
- Design and parameters inspired by Italian *SuperB* Factory project
- CDR appeared in 2011, the design has evolved since with more Machine-Detector-Interface studies, Dynamic Aperture optimization, high performance operation at all energies
- Proposal to be included in next 5-years Russian plan and hopefully funded

Specifications

- Beam energy from **1 to 2.5 GeV**
- Peak luminosity **~ 10^{35} cm^{-2} s^{-1} →**
- Longitudinal polarization of e$^-$ beam @ IP
- No energy asymmetry
- No energy monochromatization
- Energy calibration with medium accuracy sufficient (Compton Backscattering)

2 orders of magnitude w.r.t. presently achieved!

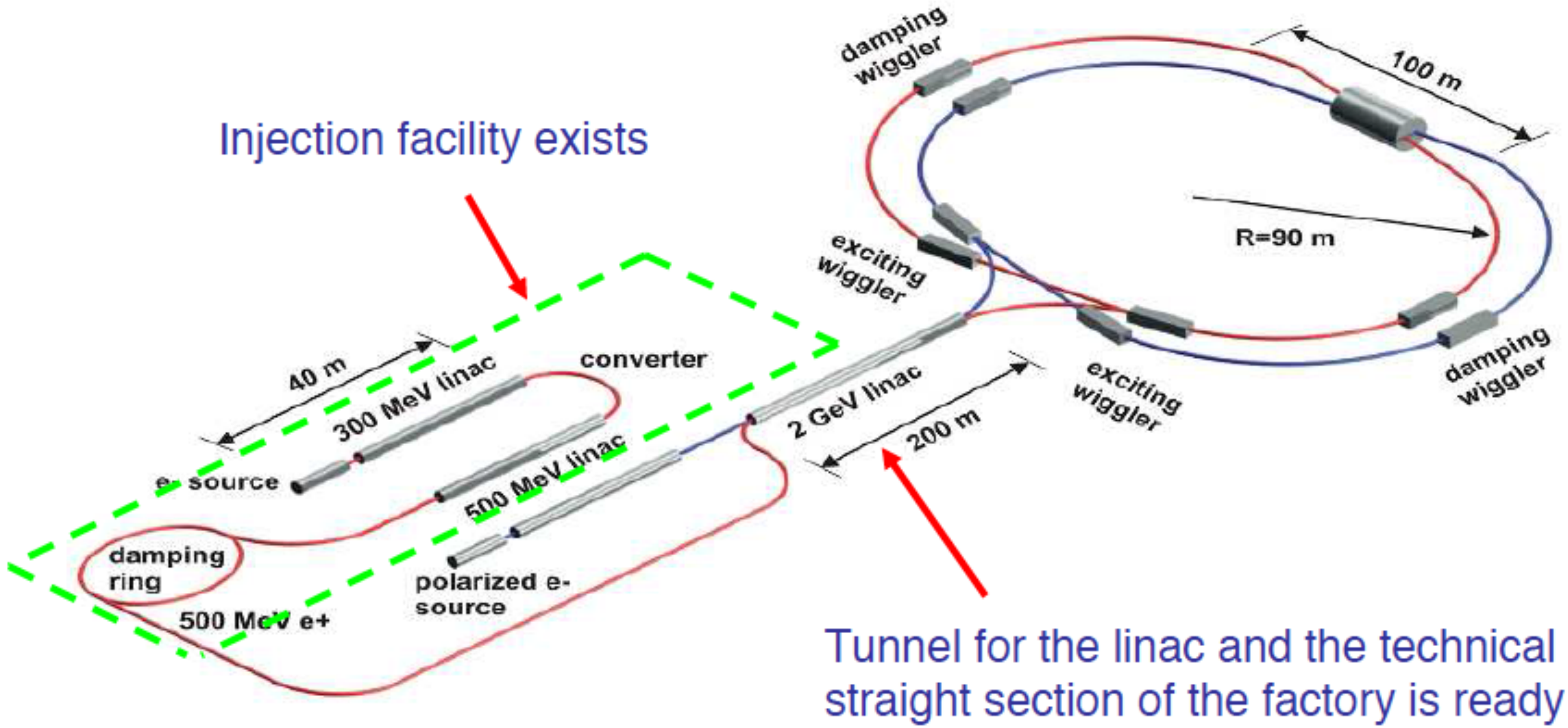
Key features

- Two rings
- LPA&CW collision scheme
- Small β-functions @ IP ($\beta_y \sim 800\ \mu$)
- Superconducting wigglers to keep same damping times and emittance in the whole energy range
- High beam currents
- 5 Siberian Snakes for spin gymnastics
- Electron polarized source (already produced by BINP for AmPS @ NIKHEF)
- Upgraded positron source → $2 \times 10^{11}\ e^+/\text{sec}$
- 2.5 GeV Linac

BINP STCF Parameters

Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	780 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	30/30/15 ms			
Bunch length	16 mm	11 mm	10 mm	10 mm
Energy spread	$10.1 \cdot 10^{-4}$	$9.96 \cdot 10^{-4}$	$8.44 \cdot 10^{-4}$	$7.38 \cdot 10^{-4}$
Momentum compaction	$1.00 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$	$1.06 \cdot 10^{-3}$
Synchrotron tune	0.007	0.010	0.009	0.008
RF frequency	508 MHz			
Harmonic number	1300			
Particles in bunch	$7 \cdot 10^{10}$			
Number of bunches	390 (10% gap)			
Bunch current	4.4 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.15	0.15	0.12	0.095
Luminosity	$0.63 \cdot 10^{35}$	$0.95 \cdot 10^{35}$	$1.00 \cdot 10^{35}$	$1.00 \cdot 10^{35}$

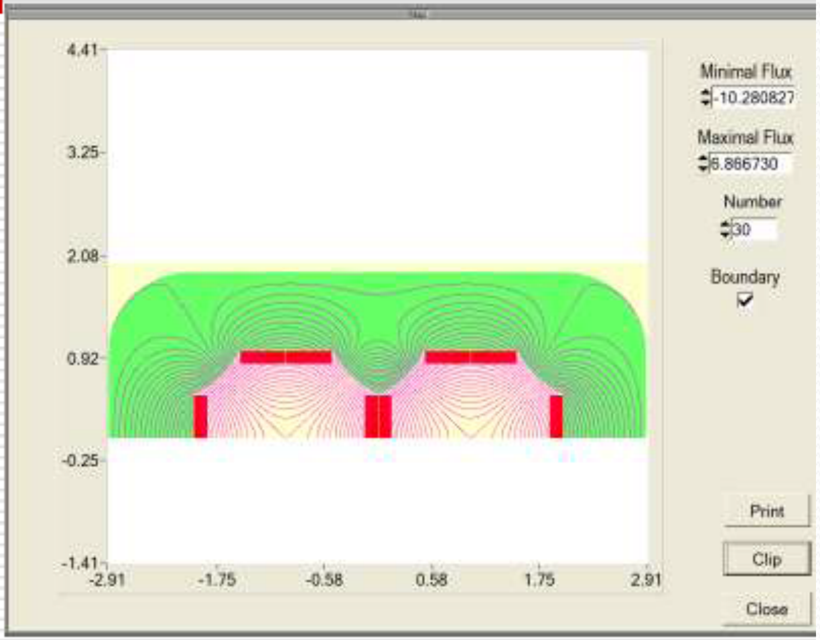
BINP STCF layout



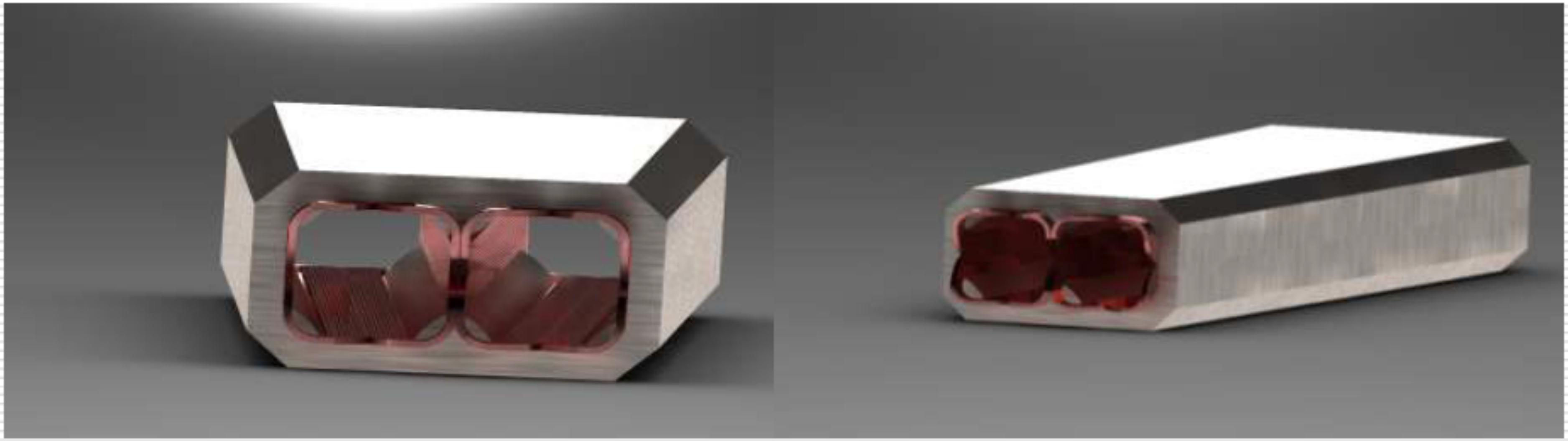
QD0 Lens

This hybrid design is proposed for FCCee too

SC iron yoke twin aperture magnet
Excitation current 1.15 kA
Aperture diam 2 cm
Gradient 10.7 kGs/cm
Length 20 cm

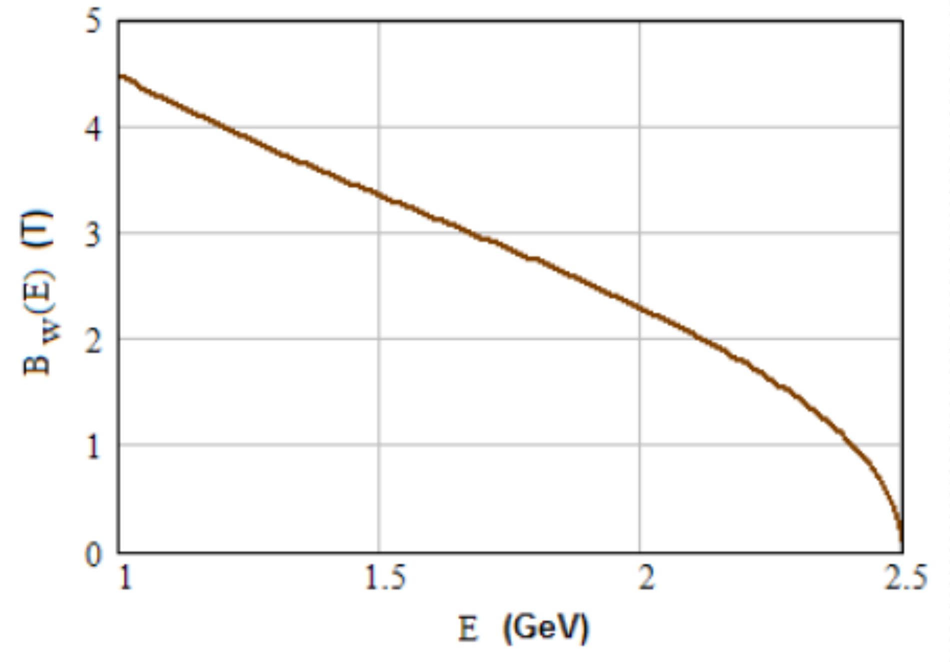


Prototype of QD0 now is constructed at BINP



Damping wigglers

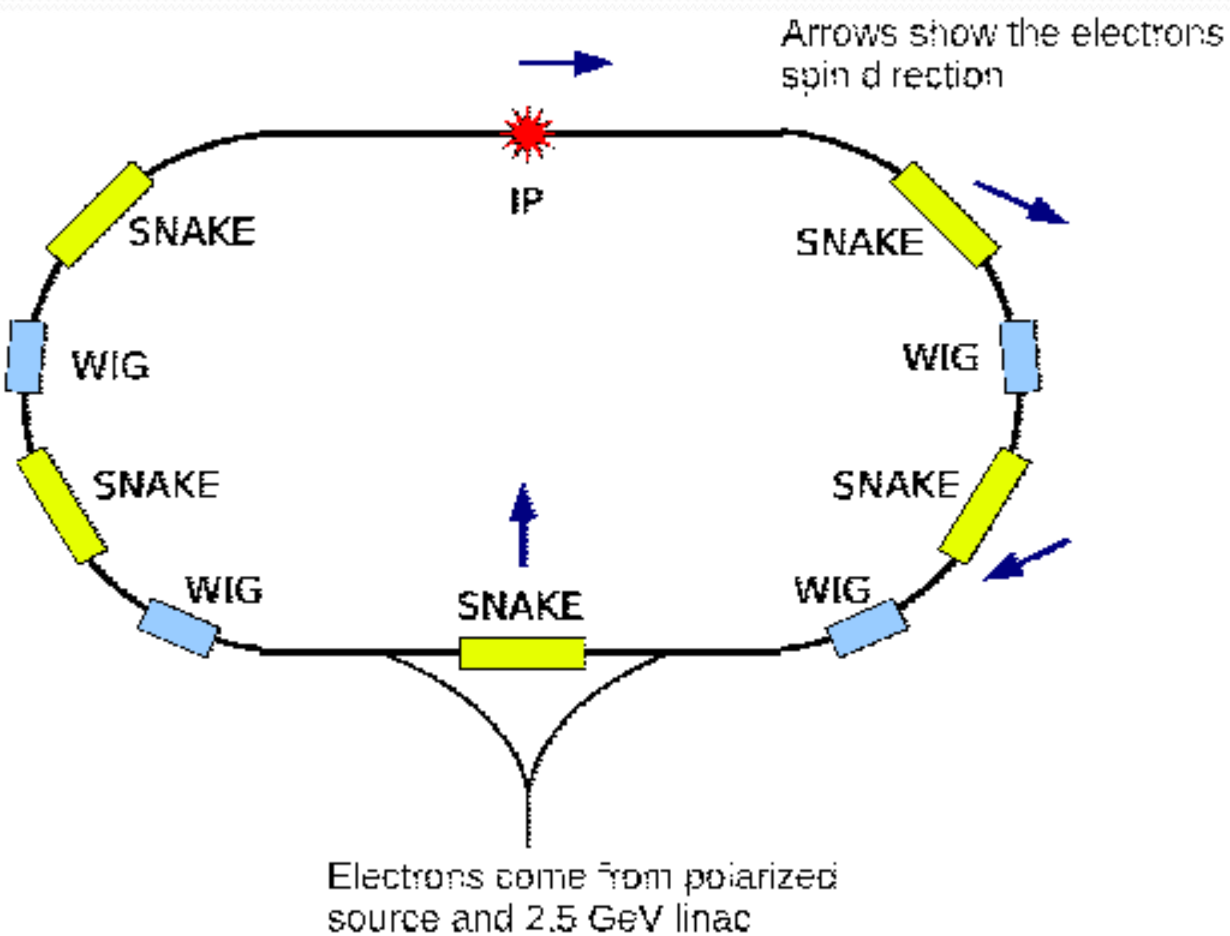
The damping wigglers keep the damping time τ_x =30 ms and the horizontal emittance (8 nm) in the energy range 1.0 – 2.5 GeV



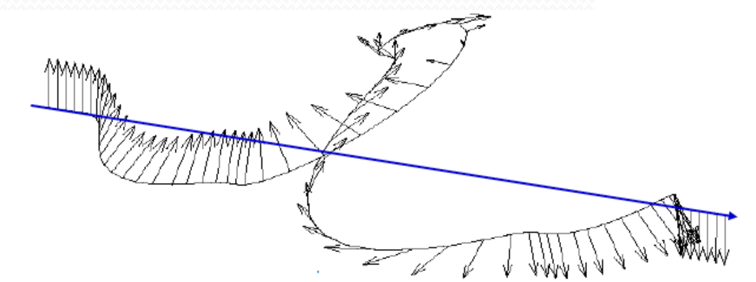
Wiggler with similar parameters produced by BINP

Electron polarization scheme in the ring

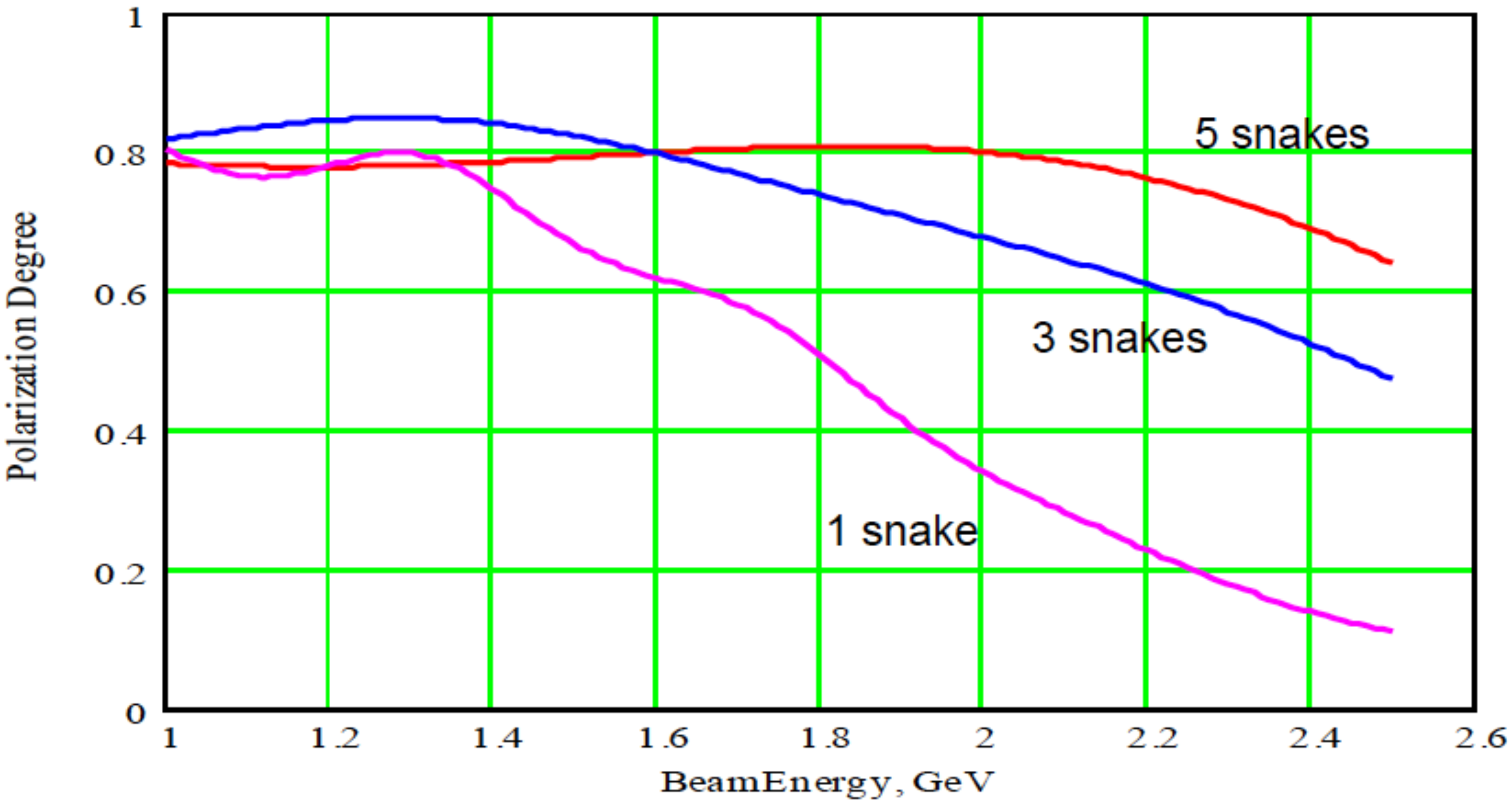
- 5 Siberian Snakes
- 4 damping wigglers in the arc middle



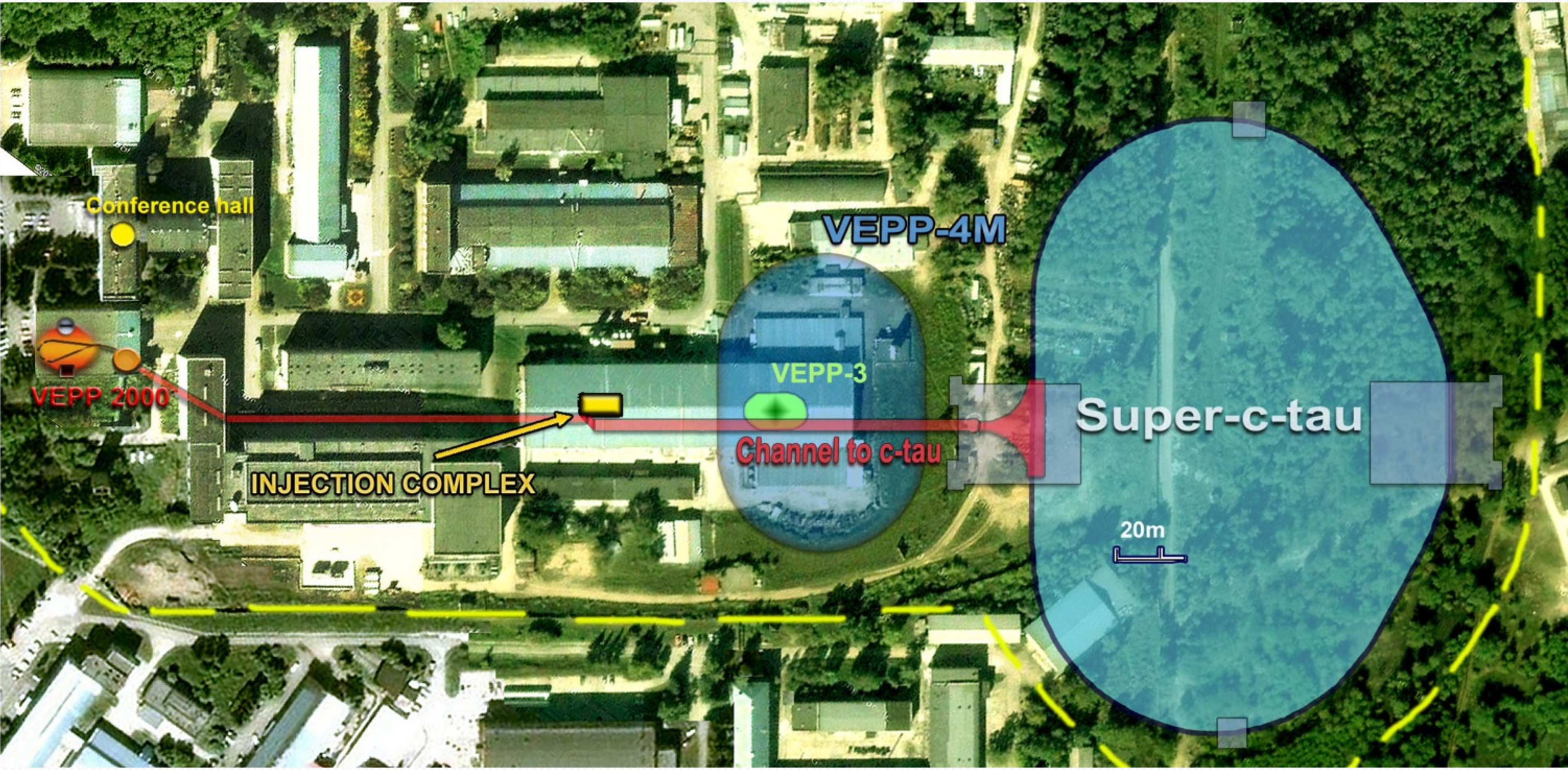
Siberian Snake: a group of dipole magnets with alternating horizontal and vertical field, rotate the spin direction by 180 deg



Polarization vs Energy



BINP STCF Site



- ◆ Construction: ~6 years, International review
- ◆ Total cost ~$400-440M€

HIEPA (High Intensity Electron Positron Accelerator, Hefei, China)

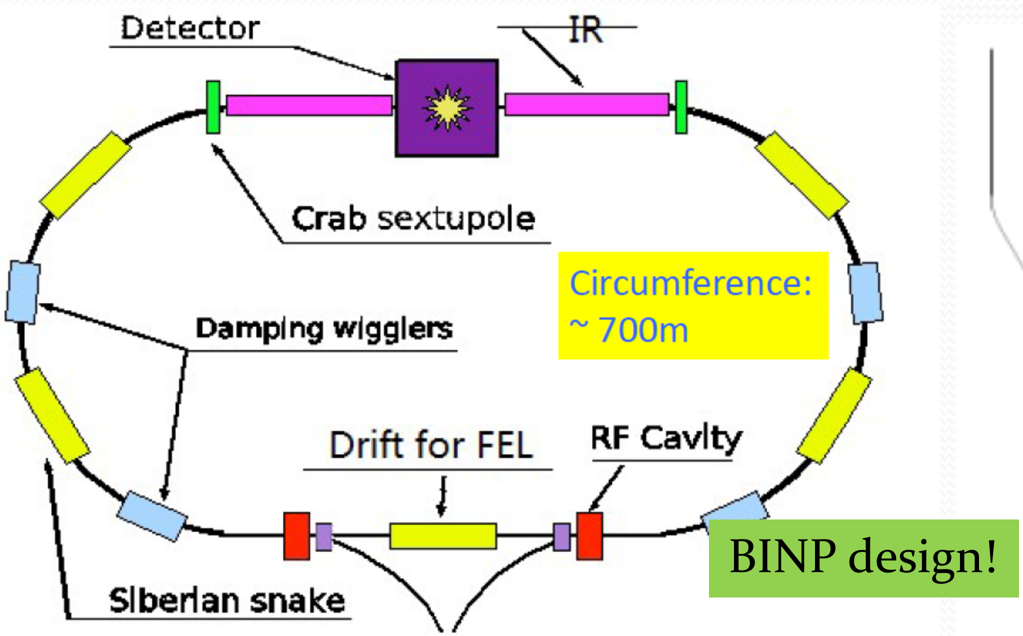
- Hefei Technical University has built and upgraded a Synchrotron Light Source since the ‘80
- e^+e^- collider with tunable energy range 2-7 GeV
- Luminosity @ 4GeV (c.m.) > 0.5 to 1 x 10^{35} cm^{-2} s^{-1}
- LPA & CW collision scheme
- Electron polarization available in Phase II through:
  - Polarized electron beam source
  - Siberian Snake in the ring
- Synchrotron Radiation Facility built-in
- Potential FEL facility from long Linac

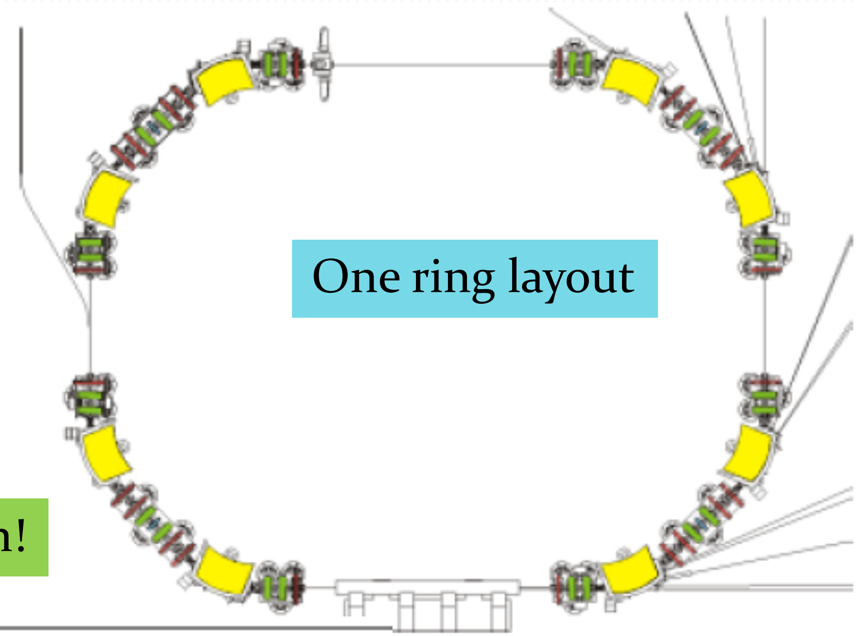
HIEPA beam parameters (very preliminary!)

Parameter	Phase I	Phase II
Circumference (m)	~600	~600
Beam Energy (GeV)	1-3.5 (2 for SR)	1-3.5 (2 for SR)
Peak Luminosity ($cm^{-2}s^{-1}$)	5×10^{34}	10^{35}
Source Brightness (Ph/s/$mm^2 mrad^2$)	$10^{17} \sim 10^{21}$	$10^{17} \sim 10^{21}$
Beam Current (A)	1.5	2
Beam Emittance $\varepsilon_x, \varepsilon_y$ (nm*rad)	5, 0.05	5, 0.05
IP Betatron functions β_x, β_y (mm)	100, 0.9	67, 0.6
Crossing Angle (mrad)	60	60
Hourglass factor	0.8	0.8
Beam-beam tune shift ξ_y	0.06	0.08

Accelerator design

- While the physics case and detector design are quite well developed, the accelerator design is still in a very immature state!





SC magnets needed

Type	Maximum Magnetic Field
Anti-solenoid	4.5 Tesla
Quadrupole	107Tesla/m
Damping wigglers	4.5 Tesla
Siberian snake solenoids	6 Tesla

Competitor Chinese project

- A 6 GeV diffraction-limited SLS (HEPS) is being designed at IHEP, Beijing
- This project is strongly supported by IHEP
- 50 M$ have been obtained for a test facility to test technologies of ultra-low-emittance design, such as small aperture magnets and vacuum systems

Parameters	Value	Unit
Energy	6	GeV
Beam current	200	mA
Circumference	1295.616	m
Natural emittance	59.4	pm.rad
Working point (H/V)	116.16/41.12	
Natural chromaticities (H/V)	-214/-133	
No. of superperiods	48	
ID section length	6	m
Beat functions at ID sect. (H/V)	9/3.2	m
Energy loss per turn	1.995	MeV
Rms energy spread	7.97×10^{-4}	
Momentum compactor	3.74×10^{-5}	

HEPS parameters

Colliders & Ultimate Light Sources together: my personal view

- The parasitic operation of a high luminosity Collider and an Ultimate Light Source can be problematic
- Both machine are using state-of-art technologies, pushing beam parameters to achieve their goals (Luminosity in colliders, lowest emittances for high flux and brilliance in ULS)
- Their performances can be affected when trying to design and operate an accelerator with both features at the same time
- Should be careful in considering all pros and cons, probably the best solution being to have a Phase I collider physics and a Phase II ULS

Conclusions

- Physics case at a τ/charm-Factory seems to be solid
- A τ/charm is presently taking data in Beijing and will continue to 2024
- Such low energy accelerator has contained costs and a size suitable for a medium size laboratory
- Several proposals worldwide (Frascati, BINP, Hefei, Turkey) but none funded up to now
- The BINP proposal, inspired by the Frascati design, is the most detailed and likely to be funded
- The Chinese project lacks of manpower and is less supported
- A dedicated workshop will be held at UCAS, Beijing, 19-21 March 2018
    - http://cicpi.ustc.edu.cn/hiepa2018/