Preliminary concept of low energy small-size e+e- collider with crab waist collision

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CW idea

In 2006 Pantaleo Raimondi proposed a Crab Waist collision scheme.

Later the idea was confirmed by Raimondi, Zobov (LNF) and Shatilov (BINP).

The method allows luminosity increase in e+e- colliders by ~10-100 times compare to the head-on collision.

P.Raimondi, 2nd SuperB Workshop, LNF, Frascati, March 2006

P.Raimondi, D.Shatilov, M.Zobov, arXiv:physics/0702033, 2007

Head-on collision luminosity

$$L = f_0 \frac{N^2}{4\pi\sigma_x\sigma_y}$$

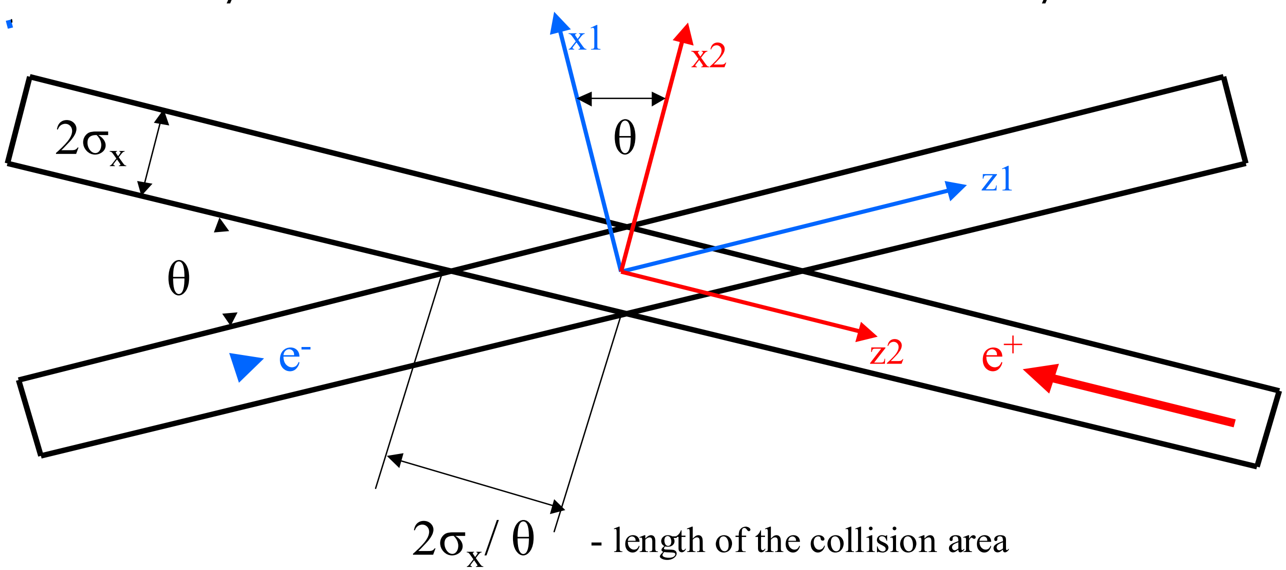
It seems one can increase luminosity by beam squeezing at the IP as much as possible.

Two effects counteract: (1) the beam size can not be less than the bunch length (hour glass) while the bunch length can not be reduced due to collective effects, (2) beam squeezing awakes dangerous beam-beam resonances caused by electromagnetic interaction of the beams.

Crab Waist (small beta)

Small size beams collide at large crossing angle (~30-60 mrad)

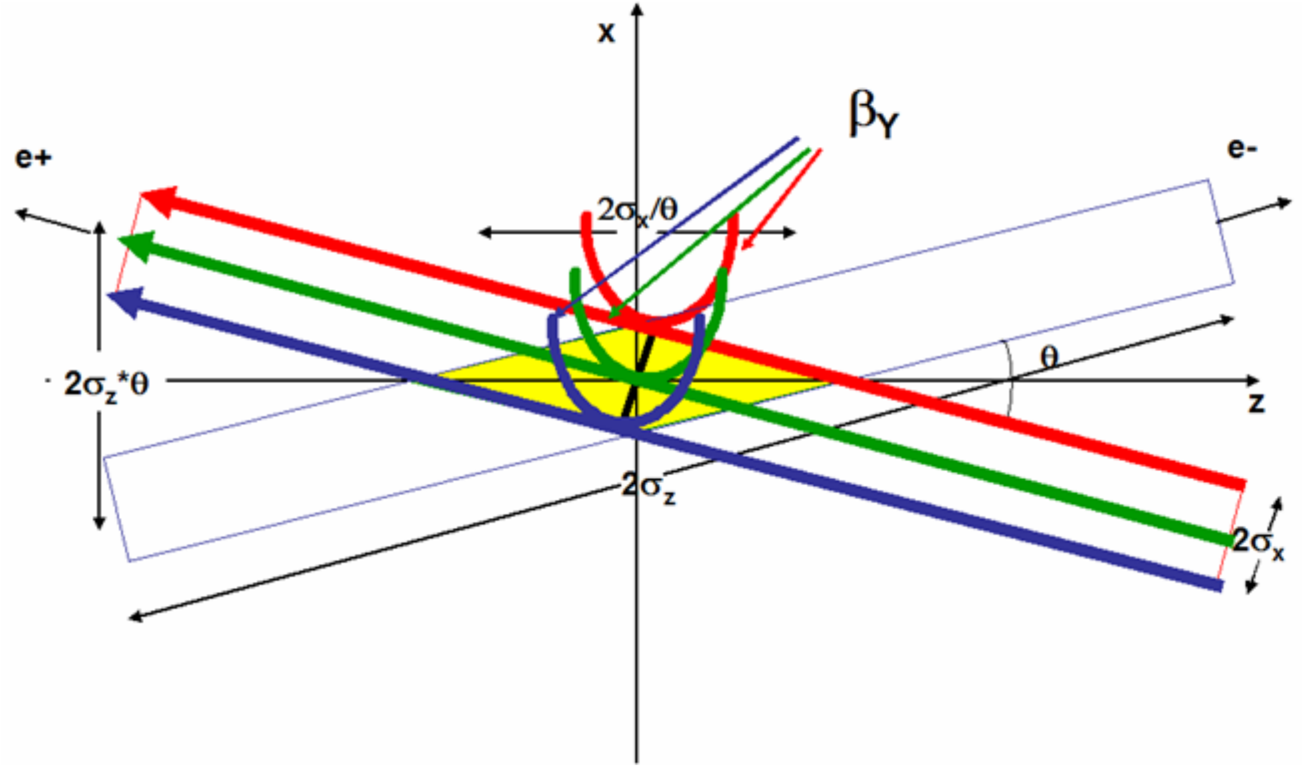
$\beta_y \approx \sigma_x/\theta \sim 0.2\text{-}1$ mm $L \sim 1/\beta_y$



Problem: collision at large crossing angle produces many dangerous coupling resonances which reduces luminosity

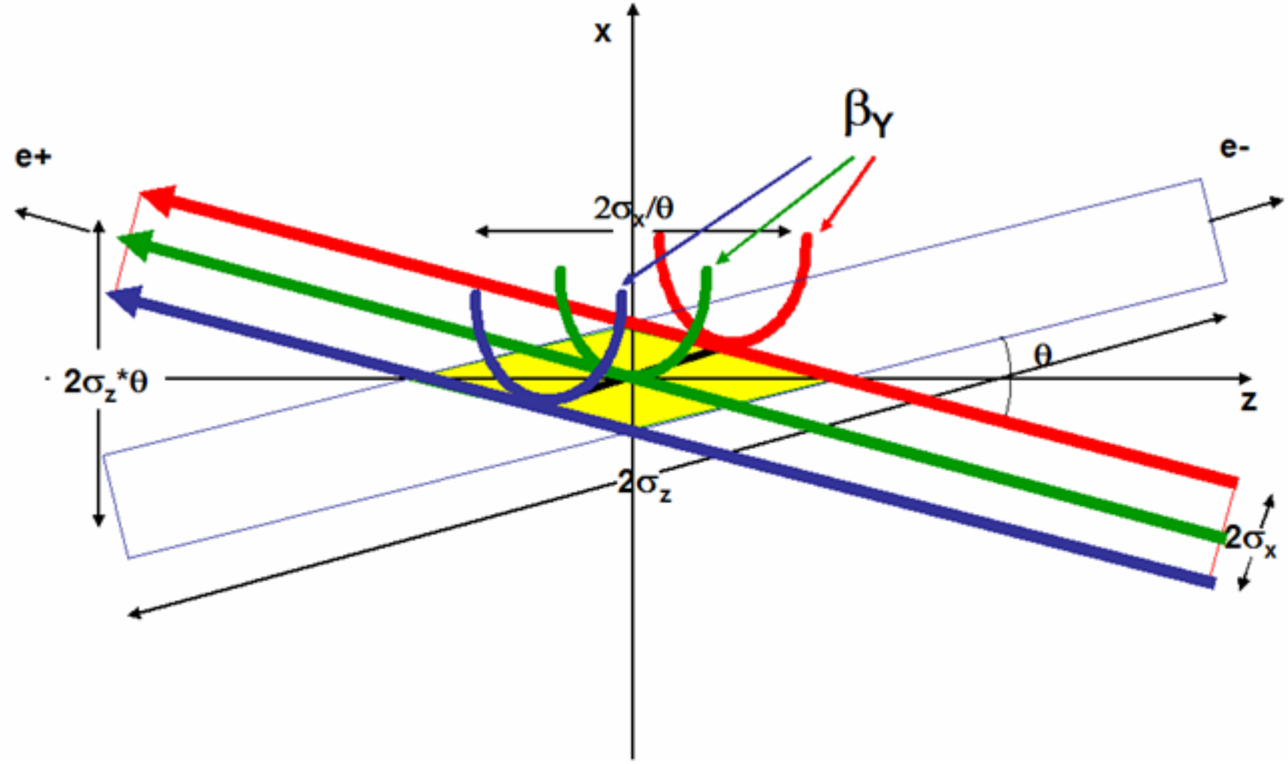
Crab Waist (waist rotation)

Local focusing of the beam by the sextupole pair rotates vertical beam waist at the interaction point along the axis of the opposite beam

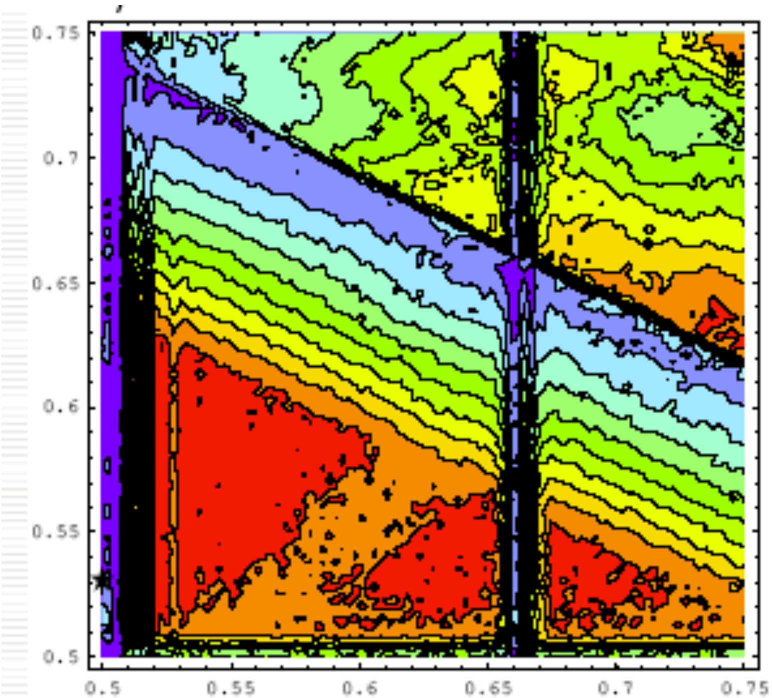


Crab Waist (waist rotation)

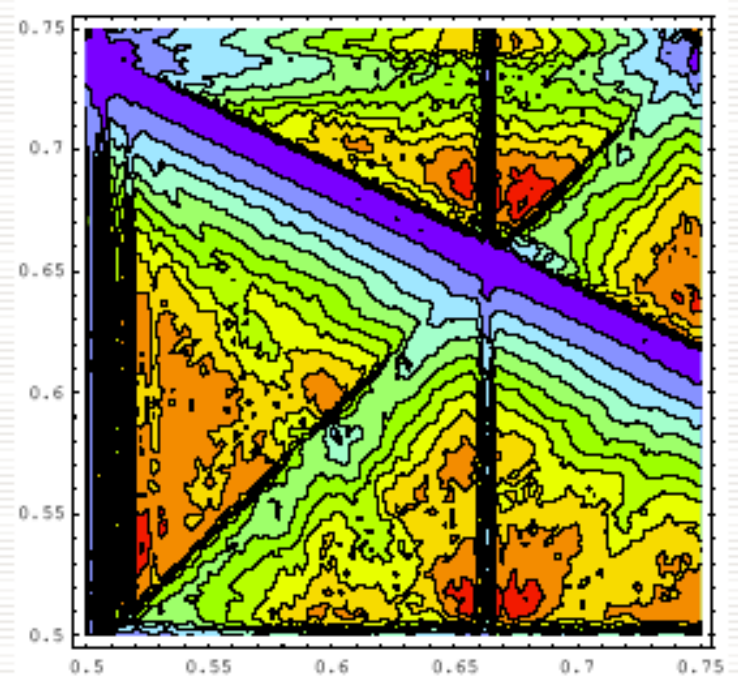
Betatron motion is decoupled, the resonances are suppressed and the luminosity increase is not spoiled by large crossing angle



Crab On/Off simulation



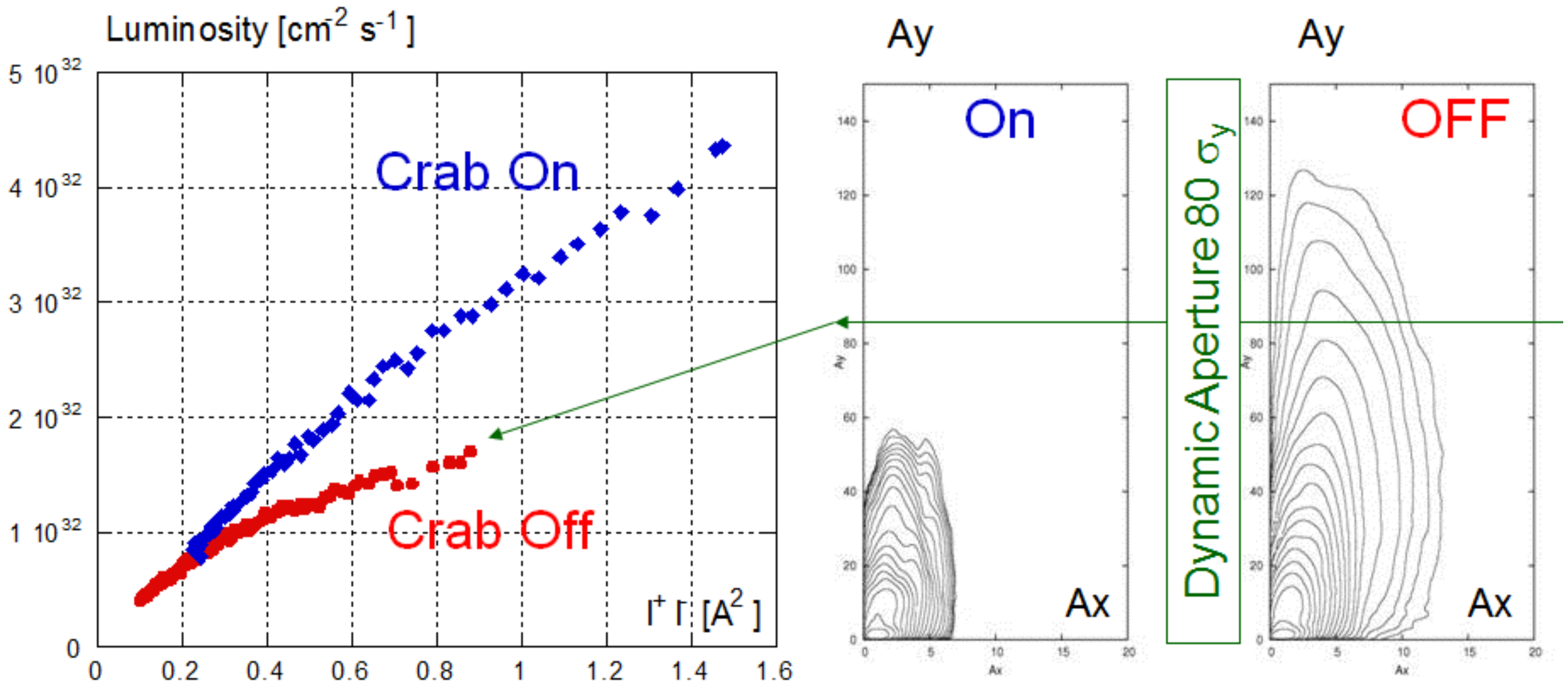
Crab ON: $\xi_y=0.13$



Crab OFF: $\xi_y=0.06$

LIFETRAC luminosity simulation: red color indicates large luminosity.

Crab Waist experiment at DAΦNE



LIFETRAC + ACCELERATICUM

M.Zobov et al. Phys.Rev.Lett.104, 30 April 2010

CW triumph

- FCC-ee Higgs factory CW option

100 km, 90-350 GeV c.m.

At Z CW increase the luminosity by ~10 (2×10^{36} $cm^{-2}s^{-1}$).

- SuperB (LNF-Italy; KEK-Japan):

~2 km, 11 GeV, ~10^{36} $cm^{-2}s^{-1}$

- SuperC (Novosibirsk, LNF, Hefei):

~1 km, ≤ 5 GeV c.m., ~10^{35} $cm^{-2}s^{-1}$

CW triumph

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- SuperC (Novosibirsk, LNF, Hefei):

~1 km, ≤ 5 GeV c.m., ~10^{35} $cm^{-2}s^{-1}$

- Super ϕ-ψ

≤ 0.1 km, ≤ 2÷3 GeV c.m., ~$10^{??}$ $cm^{-2}s^{-1}$

Main aims

Main aims of our study is to understand

(i) which luminosity can be achieved in a compact (<100 m), low-energy (from ϕ to ψ) e+e- collider with CW;

(ii) which factors limit the performance;

(iii) how to overcome the limitations.

Preliminary! Pre-feasibility study!

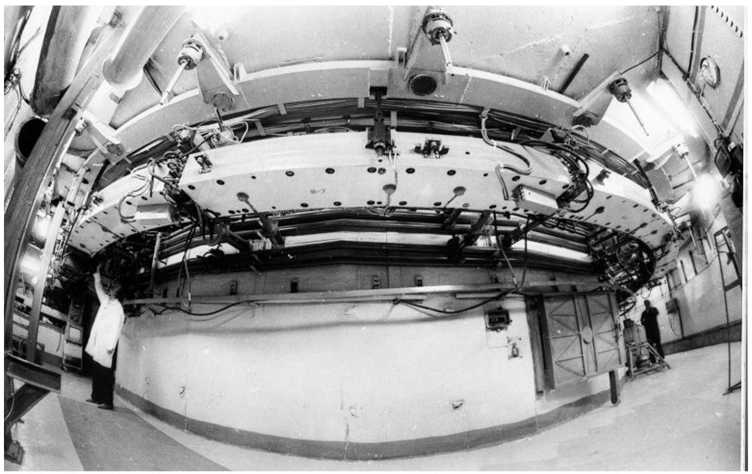
CW challenges

- Low emittance → large arc chromaticity → strong sextupoles → small dynamic aperture (small momentum acceptance)
- Low beta at the IP → large IP chromaticity, etc.
- Crab sextupoles → tricky IR, small DA and MA
- Low energy + large current + low emittance → strong IBS, low beam lifetime (large MA is needed)
- Large beam loss (lumi+IBS) → effective injection (large DA) is needed

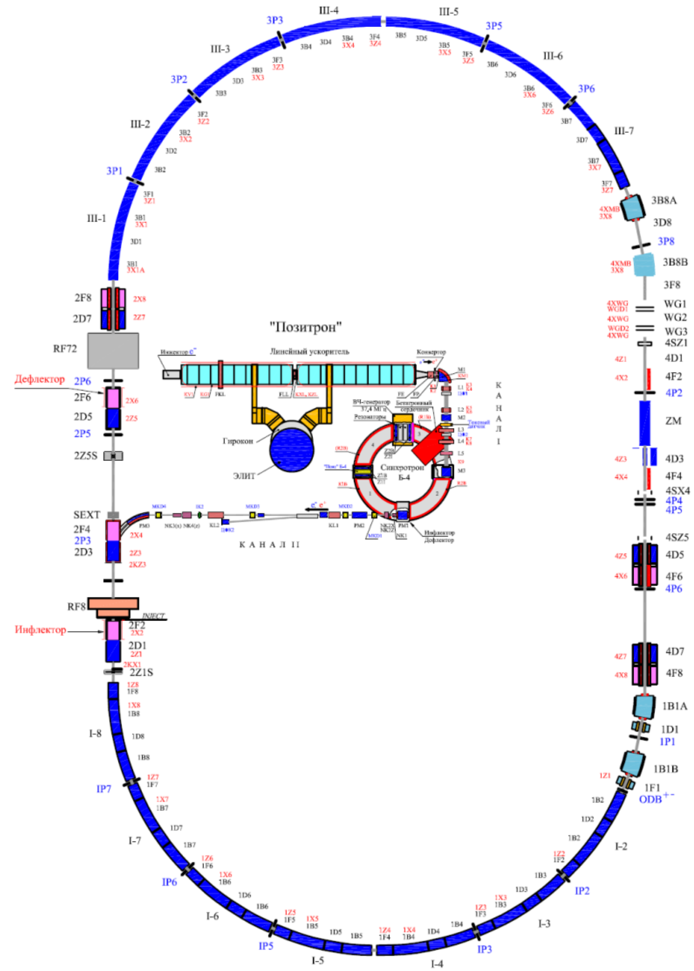
All required parameters were obtained before in colliders or SR sources, but never before in the same machine.

Size and shape constrains

To explore the limiting factors inspired by the ring size and form-factor we accommodate the new collider in the BINP VEPP-3 infrastructure



VEPP-3 is mounted up under the ceiling



2 GeV VEPP-3 storage ring has a race-track shape ≈75 m in circumference

Parameters selection

Approach: we optimize the maximum luminosity at 1 GeV/beam and then extrapolate it to ϕ (0.51 GeV) and ψ (1.55 GeV). The luminosity in practical units is

$$L \approx \frac{\gamma}{2er_e}\frac{I\cdot\xi_y}{\beta_y} = \frac{\gamma}{2r_e}\frac{N\cdot f_{RF}\cdot\xi_y}{\beta_y}$$

Current I_{max} = 2.3 A — by precedent at DAΦNE and PEP II — f_{RF} = 350 MHz, 80 bunches, N = 4.9x10^{10}e/bunch

$\xi_y \le 0.15$ — CW allows to have rather large ksi (up to 0.2 according to the beam-beam simulation). To be on a safe side we fix ksi ≤ 0.15

β_y = 4 mm — CW allows to have the beta ≤ 1 mm, but at such a compact collider we shall not cope with large FF chromaticity, so we have to limit the beta at 4 mm

Then the luminosity estimation is

$$L\left[cm^{-2}s^{-1}\right] = 1.9\cdot 10^{34}\,E\left[GeV\right]$$

Two questions are essential: (1) can we reach Ksi_y = 0.15 at 1 GeV/beam and (2) can we preserve this value at phi and psi?

Luminosity @ 1 GeV/beam

Ksi_y in practical units:

$$\xi_y = \frac{r_e N}{2\pi\gamma} \frac{\sqrt{\beta_y}}{\theta \cdot \sigma_z \sqrt{\kappa \cdot \varepsilon_x}}$$

Half crossing angle θ = 50 mrad — Limited by the two-aperture compact SC FF quadrupole design

Bunch length σ_z= 6÷10 mm — Factories (DAΦNE, PEP II, KEK B) experience. Limited by collective instabilities.

Emittance ε_x=10 nm with IBS
$\varepsilon_x \approx$ 5 nm without IBS — SR sources experience. Limited by IBS and Touschek lifetime.

Coupling factor k = 0.5 ÷1% — Storage rings experience. Limited by production and alignment tolerance and coupling correction algorithm.

Several sets of parameters:

k =1.0%, β_y=4 mm, ε_x=10 nm, σ_z=10 mm, N = 4.9x10^{10}e/bunch, I = 2.3 A, ξ_y= 0.14, L = 1.9x10^{34}cm^{-2}s^{-1}
k =0.5%, β_y=4 mm, ε_x=10 nm, σ_z=10 mm, N = 3.5x10^{10}e/bunch, I = 1.7 A, ξ_y= 0.14, L = 1.3x10^{34}cm^{-2}s^{-1}
k =1.0%, β_y=3 mm, ε_x=10 nm, σ_z= 8 mm, N = 3.7x10^{10}e/bunch, I = 2.1 A, ξ_y= 0.14, L = 2.2x10^{34}cm^{-2}s^{-1}

At different levels of optimism, the luminosity ~ 1÷2 x10^{34}cm^{-2}s^{-1} can be achieved.

For the further lattice design we have fixed the parameter line in blue.

Luminosity @ ϕ and ψ

$$L \approx \frac{\gamma}{2er_e}\frac{I\cdot\xi_y}{\beta_y} = \frac{\gamma}{2r_e}\frac{N\cdot f_{RF}\cdot\xi_y}{\beta_y}$$

$$\xi_y = \frac{r_e N}{2\pi\gamma}\frac{\sqrt{\beta_y}}{\theta\cdot\sigma_z\sqrt{\kappa\cdot\varepsilon_x}}$$

ϕ (0.511 GeV/beam)

ξ_y increases with energy decrease and the bb effects blow the beam up.

The IBS increases the emittance (also we can control the coupling and/or the bunch length), so we may hope to keep ξ_y constant with the energy reduction and the luminosity will go down proportionally to the energy

$L_\phi \approx 1\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

ψ (1.55 GeV/beam)

ξ_y decreases with energy increase while the emittance is almost constant due to the combined effect of IBS (↓) and radiation (↑). Therefore the luminosity should be almost the same as for 1 GeV

$L_\psi \approx 1.9\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

If we can reduce the coupling or the emittance (by damping wigglers) we can also increase ξ_y and the luminosity

$L_\psi \approx 2.5\div 4\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$

Storage ring target parameters

Parameter	DAΦNE KLOE	DAΦNE FINUDA	DAΦNE SIDDHAR	VEPP2M	VEPP 2000
E_{max} (GeV)	0.51	0.51	0.51	0.7	1
C (m)	97.7	97.7	97.7	18	24
I_{tot} (A)	e^-: 1.38 e^+: 1.18	e^-: 1.50 e^+: 1.10	e^-: 1.52 e^+: 1.00	0.1	0.15
Bunches/ring	111	106	105	1	1
β^*(cm) h/v	150/1.8	200/1.9	25/0.9	48/4	6/6
ε_x (nm)	340	340	340	400	250/250
σ_s (cm)	1.5÷2.0[1)]	1.5÷2.0[1)]	1.5÷2.0[1)]	3	4
Cross.angle (mr)	25	25	50	0	0
IP drift (m)	±0.3	±0.3	±0.3	±1.0	±1.0
L (10^{32} cm^{-2}c^{-1})	1.53	1.6	4.53	0.05	1.0

← Operated/operating colliders

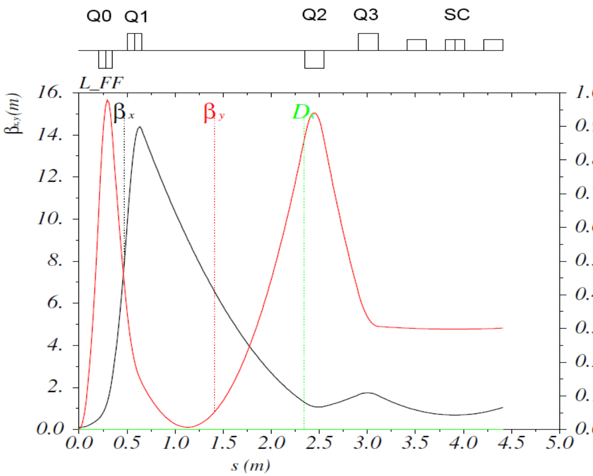
LECW = Low Energy Crab Waist Collider

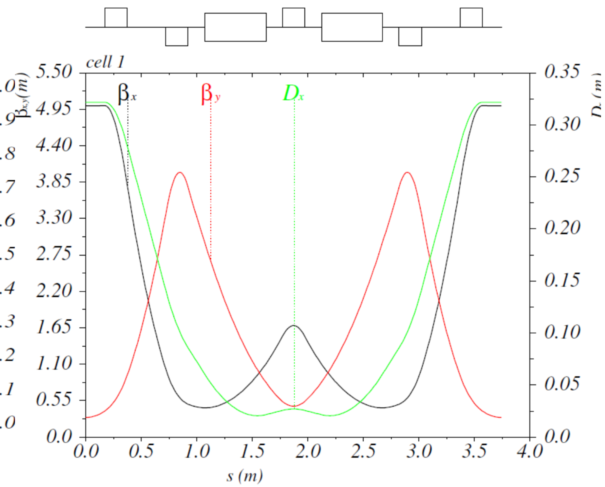
Projects →

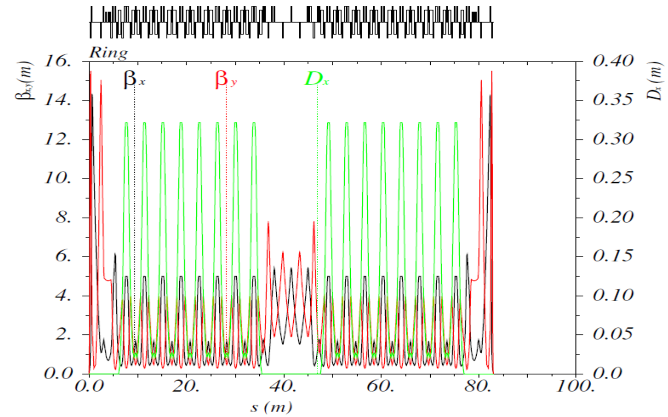
Parameter	ϕ-factory Novosib	DANAE @ϕ	DANAE 1.2 GeV	LECW @ϕ	LECW 1.0 GeV	LECW @ψ
E_{max} (GeV)	0.51	0.51	1.2	0.51	1.0	1.55
C (m)	47	96.34	96.34	~80	~80	~80
I_{tot} (A)	0.55	2.25	0.5	2.3	2.3	2.3
Bunches/ring	11	150	30	80	80	80
β^*(cm) h/v	1.0/1.0	100/0.8	100/1	10/0.4	10/0.4	10/0.4
ε_x (nm)	125/125	450	450	~30 (IBS)	~10 (IBS)	~10 (IBS)
σ_s (cm)	1	1	1.5	1	1	1
Cross.angle (mr)	0	30	30	100	100	100
IP drift (m)	±1.0	±0.3	±0.3	±0.2	±0.2	±0.2
L (10^{32} cm^{-2}c^{-1})	25	10	>1	~100	~190	~190

J.Beringer et al. (PDG), Phys. Rev. **D86**, 010001 (2012/13/14) .
R.M. Barnett et al. (PDG), Physical Review **D54**, 1 (1996).
M.Zobov et al. Phys.Rev.Lett.104, 30 April 2010.
P.Raimondi, D.Shatilov, M.Zobov, LNF-07/003 (IR), 29 January 2007, arXiv:physics/0702033.

Lattice design







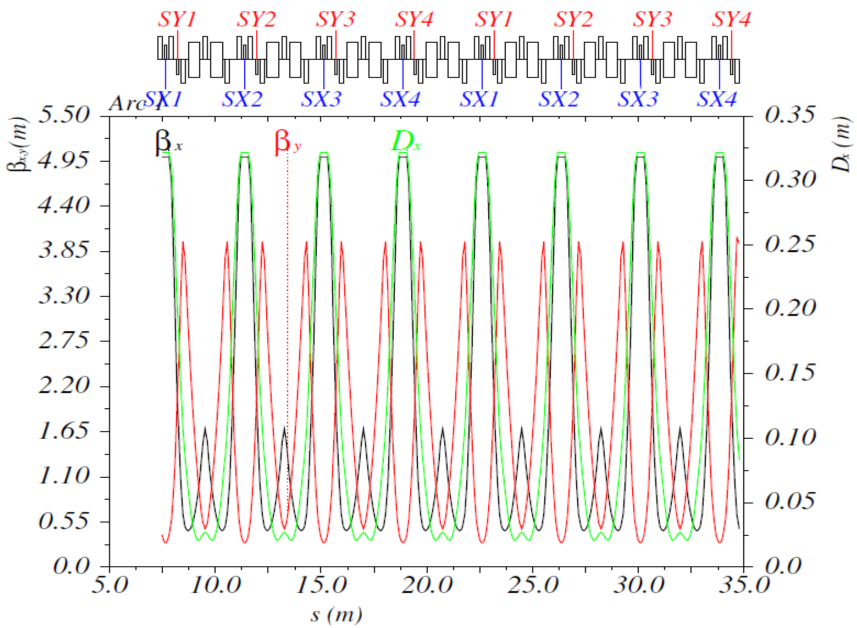
IR section. Very short. No room for chromatic section → at IP β_y=4 mm only. Crab sextupoles (SC) are inserted at proper position.

Low emittance flexible regular arc cell. Provides ε_x=4.3 nm @ 1 GeV. Allows to install 4 sextupole families in each plane to optimize both transverse and energy DA.

The whole ring lattice ~80 m in circumference. One long (~11 m) drift is for the detector accommodation, another one is for injection and RF section.

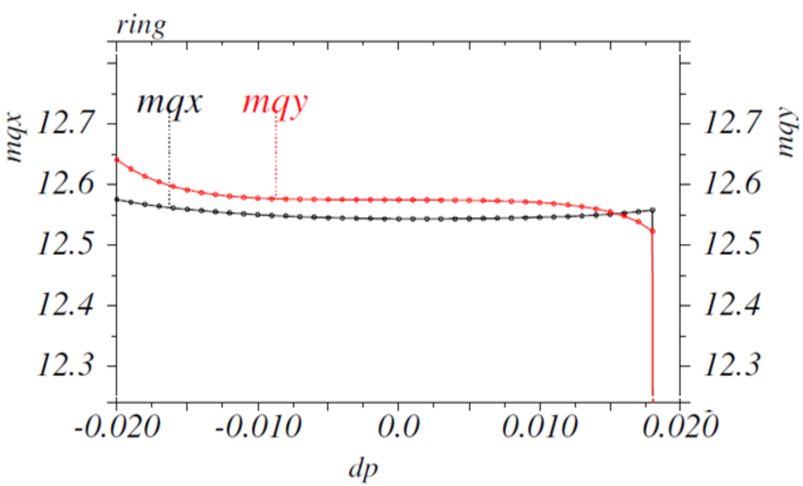
A.Bogomyagkov, E.Levichev, P.Piminov, Low emittance lattice cell with large dynamic aperture, arXiv:1405.7501, 2014.

Chromaticity correction



← 4X +4Y properly phased sextupole families in each arc allows to optimize the nonlinear chromaticity up to the 4th order (providing large momentum acceptance) and reasonable transverse dynamic aperture.

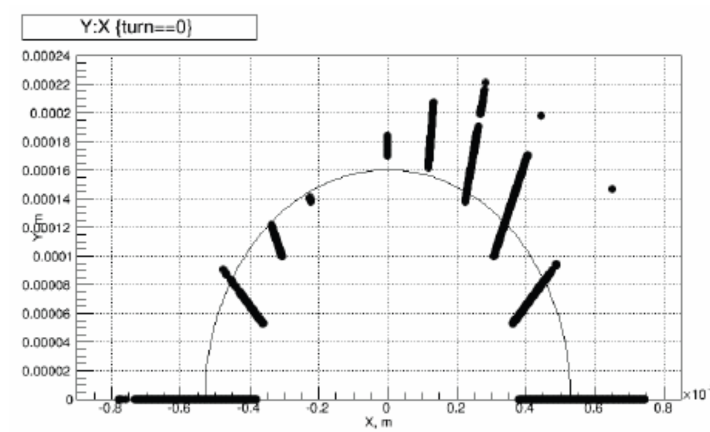
Further optimization is available.



Energy acceptance ≈±2%

$(16\sigma_x, 44\sigma_y)$ $E = 500$ МэВ ($\varepsilon_x \approx 30$ нм)

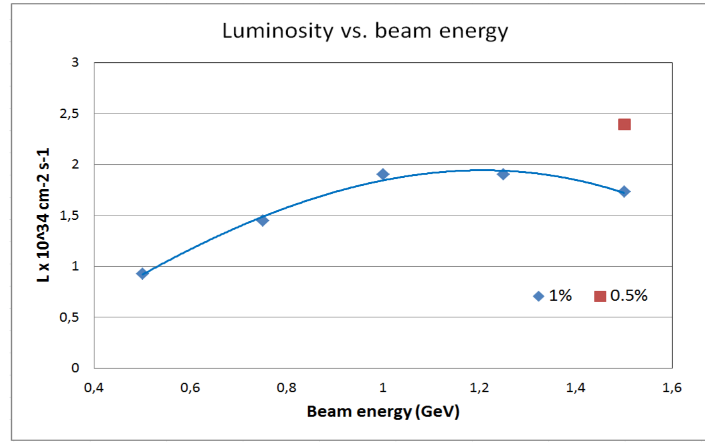
$(27\sigma_x, 75\sigma_y)$ $E = 1.0 \div 1.5$ ГэВ ($\varepsilon_x \approx 10$ нм)

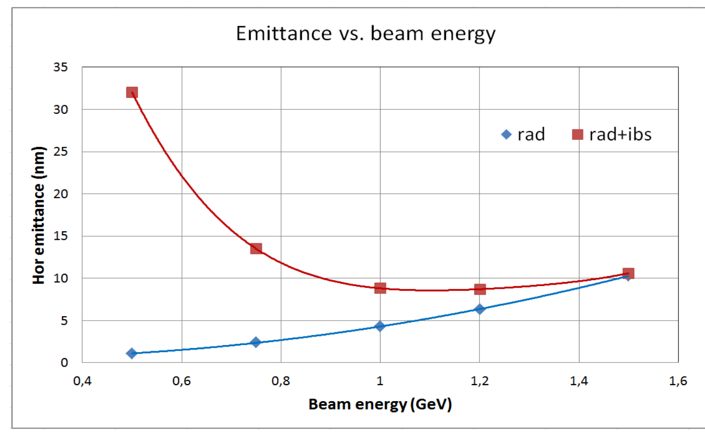


Transverse DA

IBS parameters

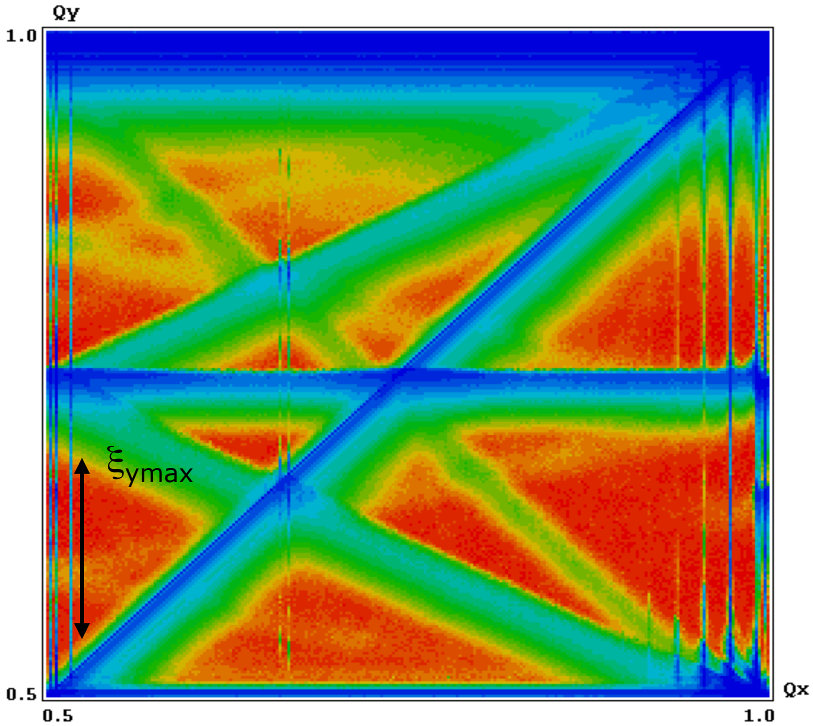
Energy	GeV	0.5	1	1.55	1.55*)
Compaction factor		2.27E-03			
Energy loss/turn	MeV	0.002	0.032	0.182	0.182
RF voltage	MV	0.584	0.213	0.468	0.468
Bunch length σ_s (SR)	mm	1.195	5.626	7.594	7.594
Energy acceptance	%	2.00	2.00	2.00	2.00
Bunch current	mA	28.816			
Particles/bunch		4.98E+10			
Bunch number		80			
Total current, A		2.305			
Horizontal emittance (SR)	nm*rad	1.07	4.28	10.27	10.32
Coupling coefficient	%	1.0			0.5
Energy spread (SR)	10E-3	0.255	0.510	0.791	0.791
Damping times	ms	141.71	17.714	4.7568	4.7568
Results with IBS					
Horizontal emittance	nm*rad	35.210	8.815	10.570	10.570
Vertical emittance	nm*rad	0.35	0.088	0.106	0.054
Energy spread	10E-3	2.134	0.908	0.813	0.823
Bunch length (SR+IBS)	mm	10.00	10.00	10.00	10.17
Lifetime (Touschek+IBS)	s	357	345	1064	788
σ^*_x	µm	59.4	29.7	32.5	32.5
σ^*_y	µm	1.18	0.593	0.650	0.464
Total crossing angle	mrad	100			
Piwinsky angle		8.480	16.945	15.463	15.512
ξ_x		0.009	0.004	0.003	0.003
ξ_y		0.153	0.153	0.090	0.125
Luminosity (no hour glass)	10+34	0.962	1.92	1.76	2.41
Luminosity (hour glass)	10+34	0.943	1.91	1.75	2.39



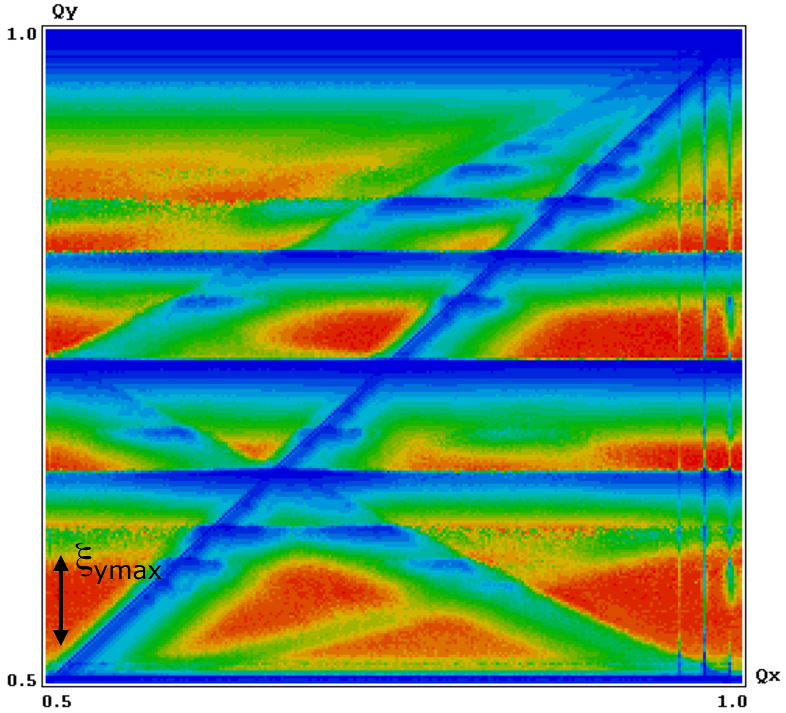


BB simulation

D.Shatilov, Lifetrac



$\beta_y \approx \sigma_x/\theta \approx 1$ mm



$\beta_y \approx 10\sigma_x/\theta \approx 10$ mm

Tune scan of the vertical beam blow up due to bb effects:
Red – no blow up (high luminosity) Blue – large blow up (low luminosity)

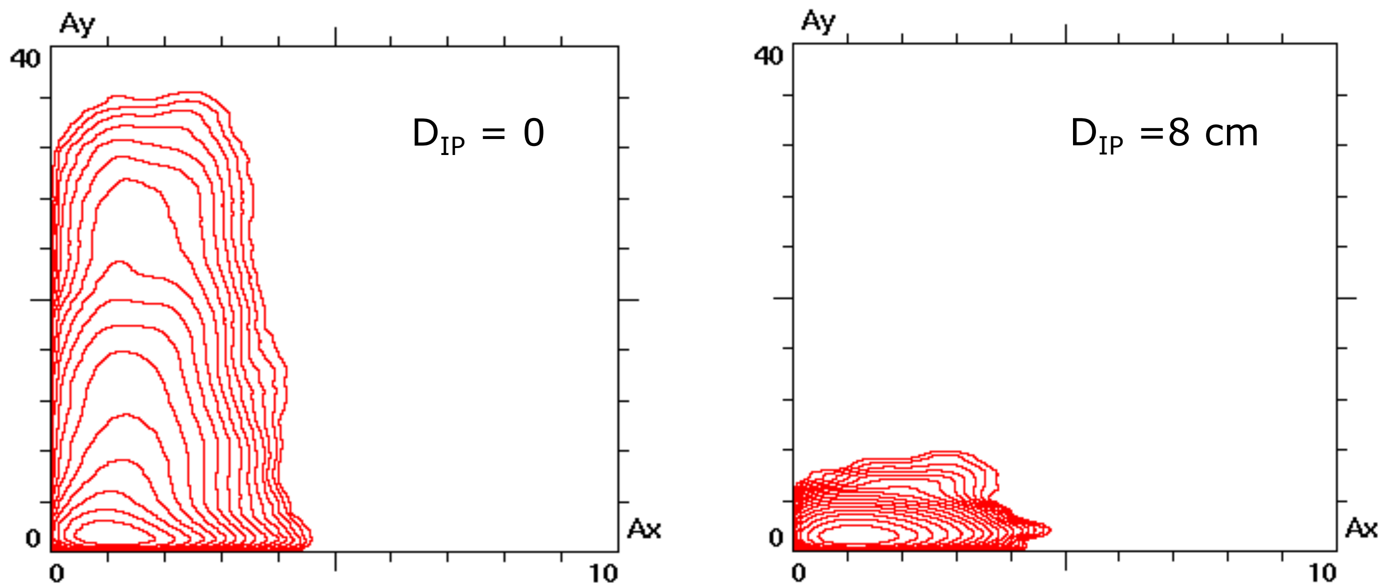
Large (compare to the bunch collision area) β_y induces strong vertical resonances limiting the luminosity.

D.Shatilov, Lifetrac

Large β_y compensation

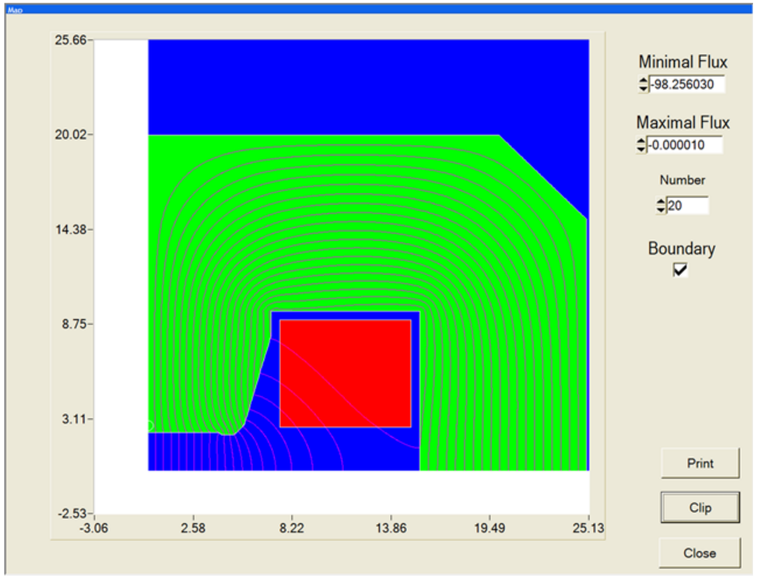
To compensate the vertical resonances generation it is enough to introduce small horizontal dispersion at the IP.

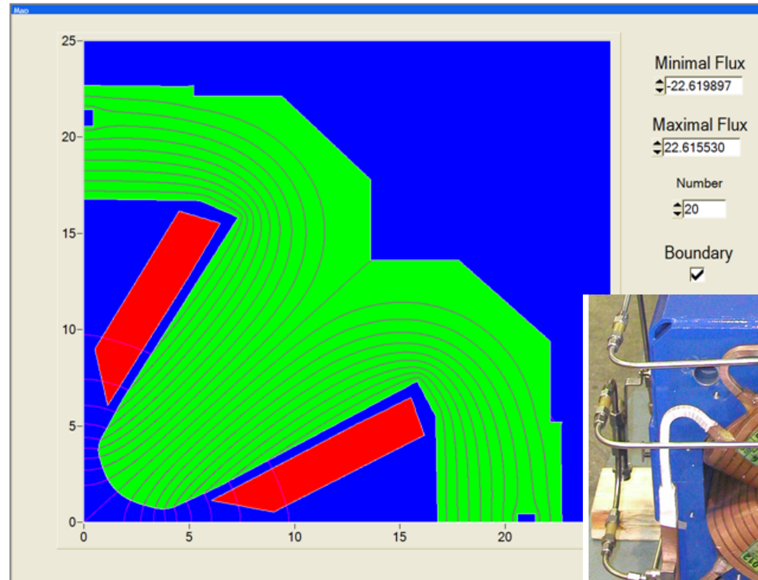
$\beta_y \approx 10\sigma_x/\theta \approx 10$ mm

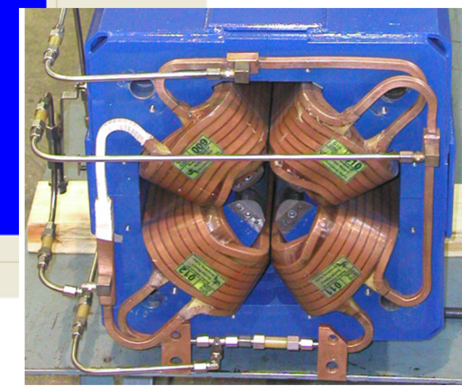


Dispersion at the IP suppresses the vertical beam blow up, decreases particles loss and increases the luminosity

Magnets





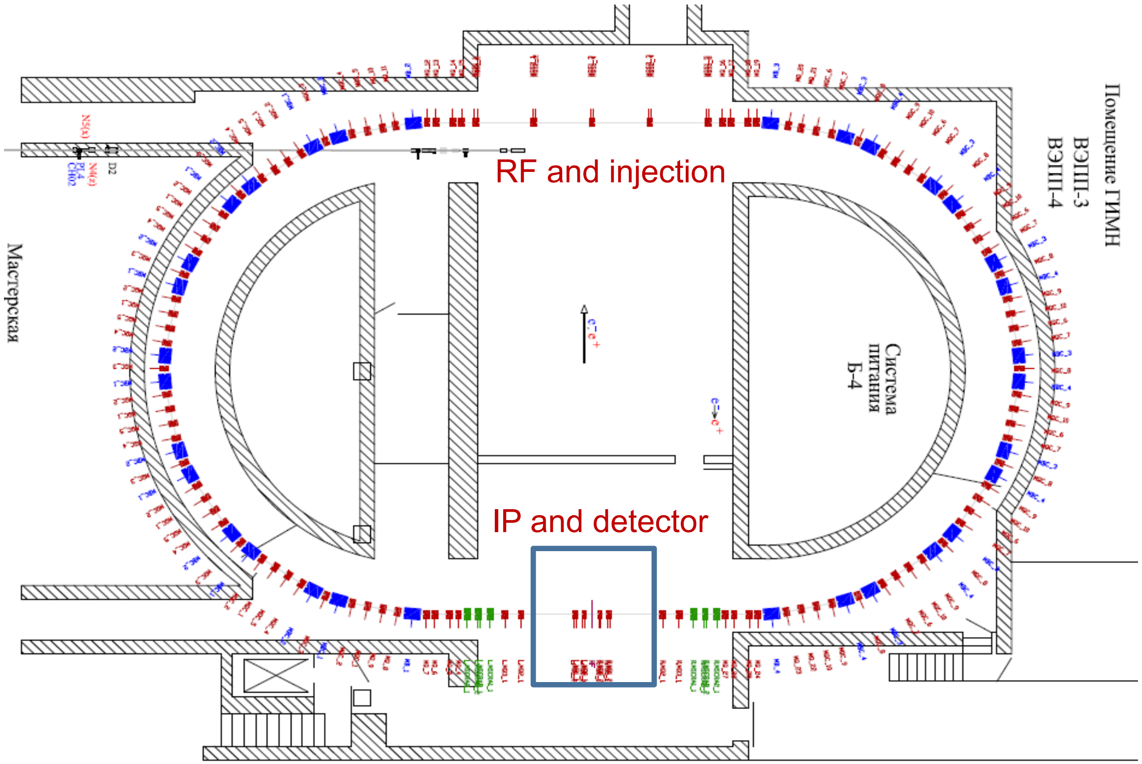


E = 1 GeV
Bmax = 1.4 T
Gap = 46 mm
$\Delta B/B = 10^{-4}$ @ $\Delta X = \pm 20$ mm

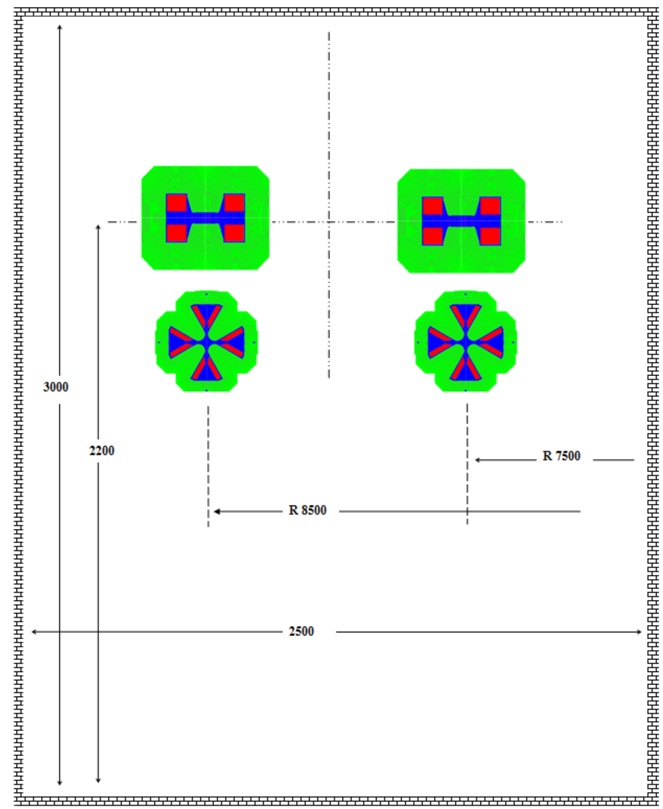
E = 1 GeV
Gmax = 40 T/m
Bore diam = 45 mm
$\Delta G/G = \pm 2\times10^{-3}$ @ $\Delta R = 21$ mm

Gran Sasso CERN beam line quad produced by BINP

Ring location in the VEPP3 infrastructure



Accommodation of the ring (only one) in the VEPP-3 tunnel



The tunnel cross-section and the magnets fixing under the ceiling for both collider rings

LECW collider at BINP

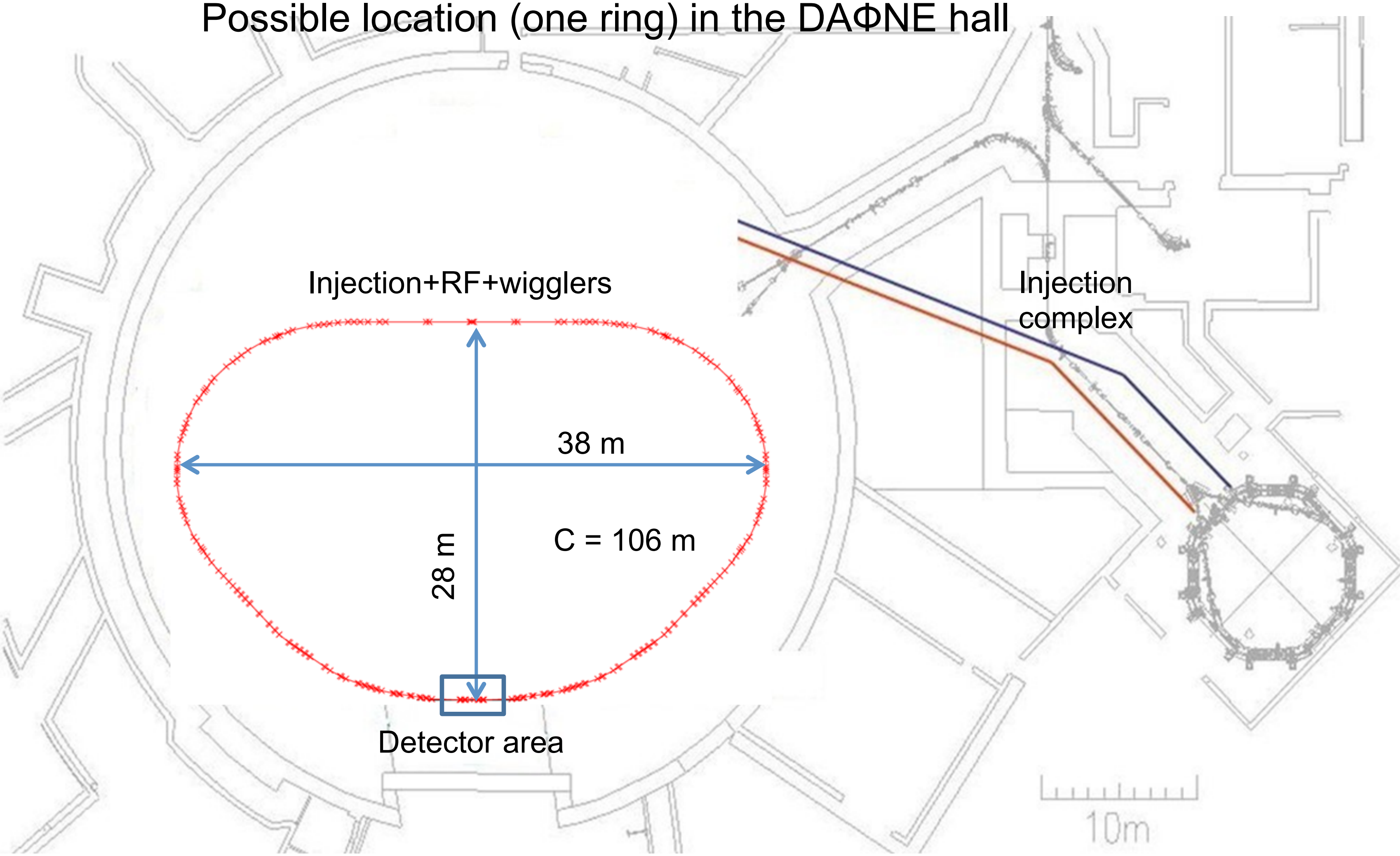
- Maximum energy only ≈ 1 GeV/beam. For higher energy the magnets can not be accommodated in the tunnel.
- At the IP $\beta_y = 4$ mm. The ring is too compact (~80 m) and there is no place for the chromatic correction sections.
- The luminosity is ≈ 10^{34} $cm^{-2}s^{-1}$ at ϕ and ≈ $2x10^{34}$ $cm^{-2}s^{-1}$ at 1 GeV
- The lattice provides the crab sextupoles installation, large momentum acceptance, reasonable dynamic aperture, enough beam lifetime, etc. seems OK as a first approximation.
- Problems which should be studied in details (and solved/optimized): collective effects, impedances, low momentum compaction, etc.

Size constrain relaxing

- No VEPP3 tunnel constrain.
- The orbit length is around 100 m.
- Vertical chromatic section arrangement.
- Beta_y reduction below 4 mm.
- Long straight section for damping wigglers accommodation.

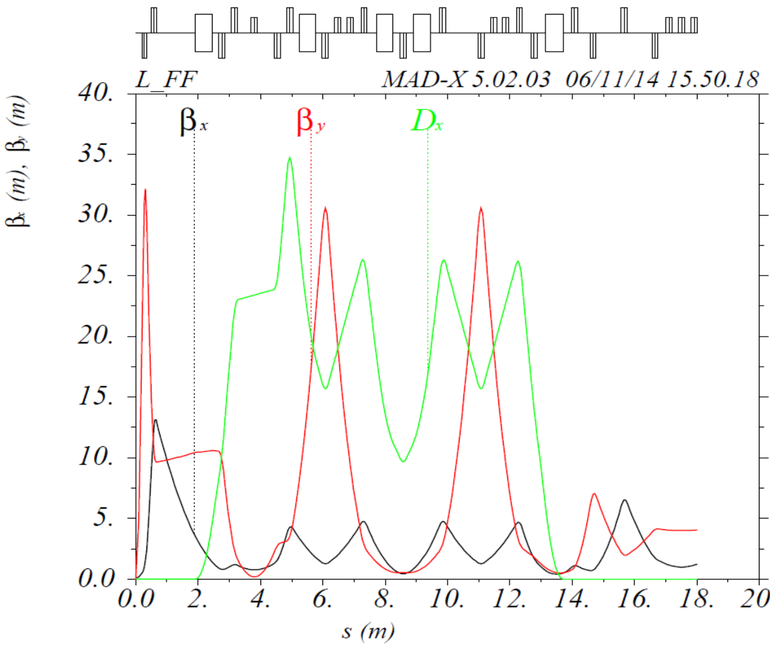
LECW collider at LNF (location)

Possible location (one ring) in the DAΦNE hall



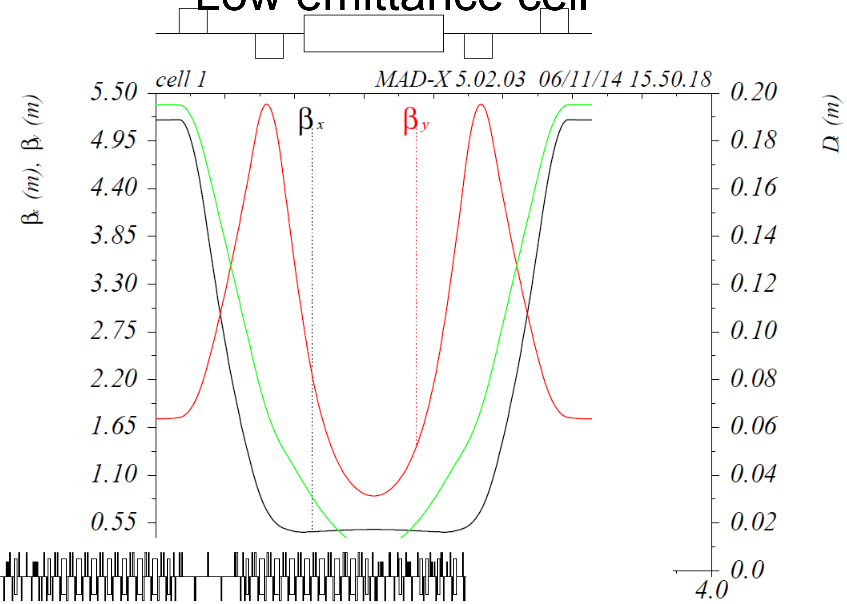
Very preliminary! Two-days-ago results!

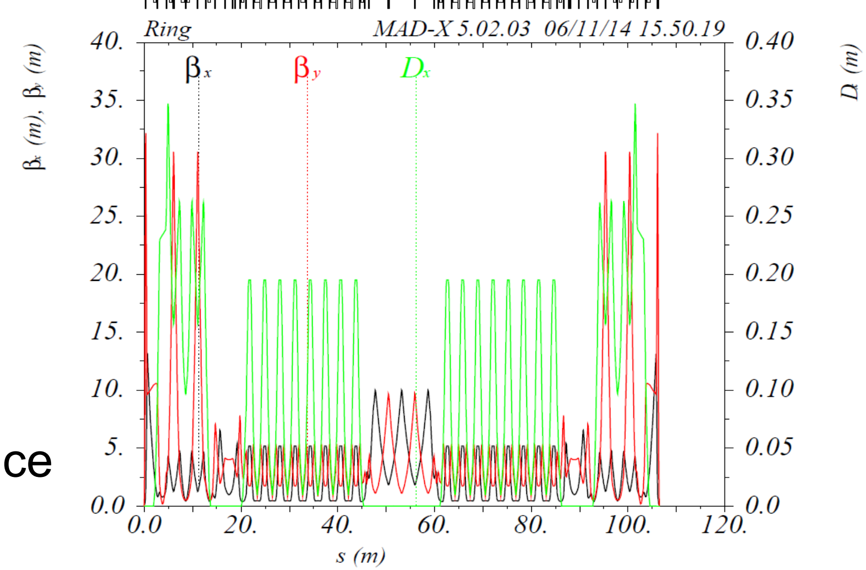
LECW collider at LNF (lattice)



IR with Y chromatic section and CW sextupoles. β_y=2 mm

Low emittance cell





The whole ring lattice

LECW collider at LNF (parameters)

IBS included

E, Mev	500.	1000.
θ	0.05	0.05
I,A	2.31616	2.31616
N	6.39×10^{10}	6.39×10^{10}
Nb	80.	80.
ϵx,m rad	3.5×10^{-8}	$9.\times10^{-9}$
ϵy,m rad	3.5×10^{-10}	$9.\times10^{-11}$
$\epsilon y/\epsilon x$	0.01	0.01
βx,m	0.1	0.1
βy,m	0.002	0.002
ηx, m	0.	0.
$\sigma\epsilon$	0.000255902	0.000511805
σs	0.00929271	0.00938806
$\tau\epsilon$, sec	0.089567	0.0111959
U0, keV/turn	1.97382	31.5811
N_{IP}	1.	1.
ξx	0.0133047	0.00660234
ξy	0.149356	0.146648
τ_L, sec	2064.55	1003.29
L, m	0.00146986	0.000749834
$\frac{L1}{L0}$	0.934783	0.979547
L1/IP, $cm^{-2}s^{-1}$	1.75226×10^{34}	3.60574×10^{34}

We have reduced β_y= 2 mm (compare to the BINP case of 4 mm) but with the increased circumference (80 m → 100 m), the luminosity is not doubled exactly.

However the larger circumference and smaller beta provide the following advantages:

- Vertical BB resonances reduction and larger area for high luminosity.
- Possibility to increase energy up to ψ.
- Possibility to install the damping wiggler for the luminosity increase at high energy.
- Magnets with larger aperture, impedance problem relaxing.

LECW collider at LNF (conclusion)

Positive:

- Wide hall, not the tunnel → larger magnets can be installed and higher energy hope to be achieved (ψ).

- Larger circumference (~100 m) → a chromatic correction section can be arranged providing $\beta_y = 2$ mm → additional luminosity increase and BB effects suppression.

- Larger circumference allows to install the damping wigglers in the drifts to control the emittance and to increase the luminosity at ψ.

- Larger circumference allows manipulation (spin rotators, Siberian snakes…) with e- spin.

Problems/challenges:

- New injector with higher energy and higher positron production is needed.
- High current effects with low emittance should be studied in more details.

Thumb-up cost estimation (for BINP experience):

- Cost and time estimation: 40 ME (2 rings collider with all systems), 4 years delivery time.