Damping Rings
Lesson 8 – $e^+ e^-$ Circular Colliders

S. Guiducci, INFN-LNF

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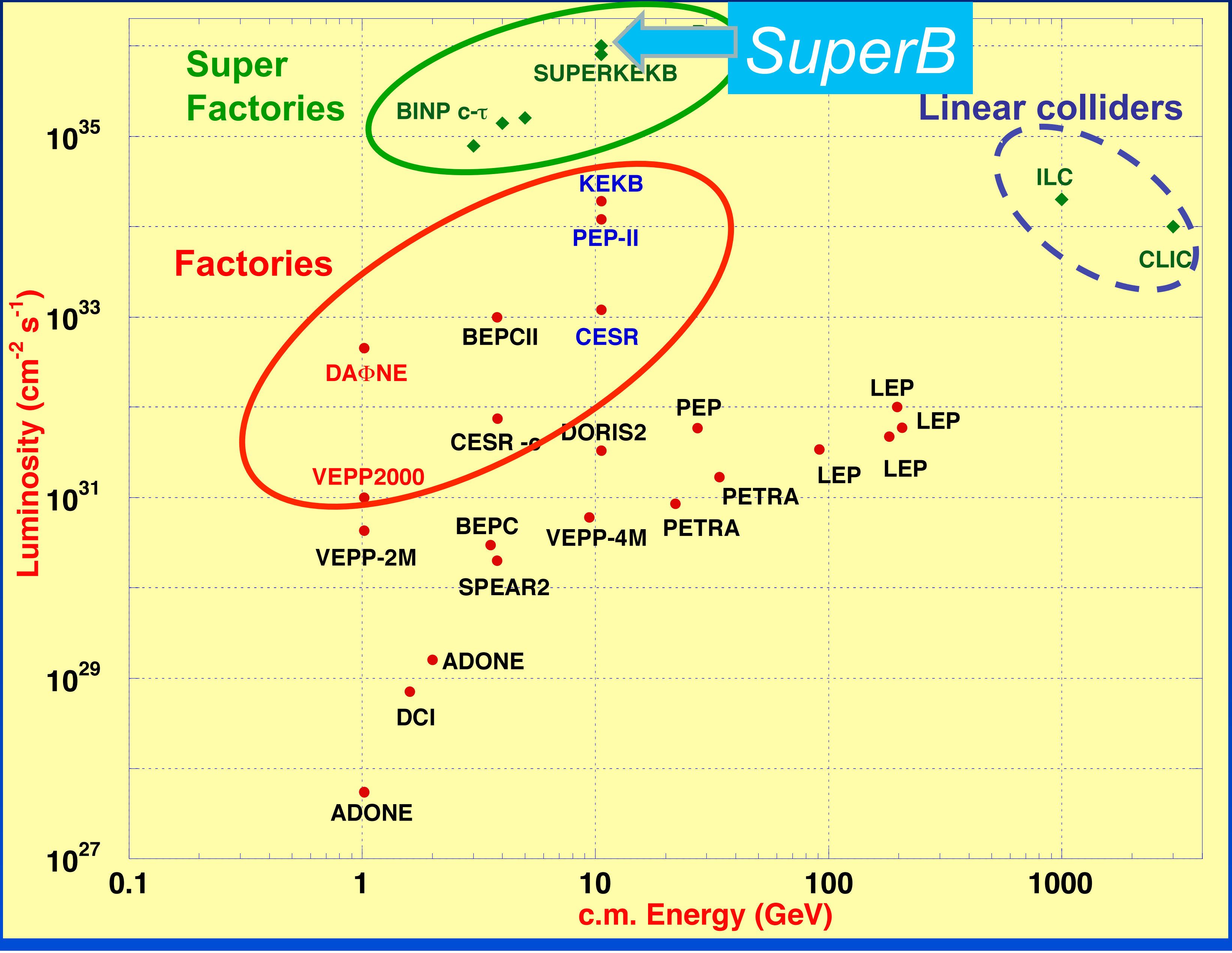
Outline

- Basics concepts of circular colliders:
  - luminosity
  - tune shifts
- Main design criteria and challenges of the **high luminosity** and **high energy** colliders including:
  - different collision schemes
  - luminosity optimization
  - beam lifetimes
  - examples of colliders achievements and design choices for future colliders

World e^+e^- colliders luminosity



World e^+e^- colliders luminosity plot

- Two regions:
  - High luminosity frontier
    - Factories, high precision physics measurements
  - High energy frontier
    - Discovery measurements
    - Before Higgs
      - LEP2 latest circular collider
      - Next is a linear collider ILC or CLIC
    - After LHC Higgs discovery at E = 126 GeV
      - Many proposals for a "Higgs Factory" circular collider (still at "brainstorming" level)

A Circle?

- At Snowmass 2001, all options for after-the-LHC were on the table:
    - Linear e+e-
    - Circular e+e-
    - VLHC
    - Muon collider
    - High intensity proton source (aka Proton Driver)
- In the following years, ICFA played a leading role in making the choice:
    - The next one would be an **e+e- collider**
    - It would be a **linear e+e- collider**
    - It would be a **cold linear e+e- collider**
- And the world HEP community followed faithfully
- However, the debate seemed to come back again after July 4, 2012:
    - The discovery of a Higgs boson may justify a dedicated Higgs Factory
    - The low Higgs mass (126 GeV) makes a circular Higgs Factory possible
    - Even a warm Higgs factory is not bad

Comparison Table – Circular Higgs Factories

Top Level Parameters								
		Circular e+e- collider						
		LEP3	**TLEP**	**Super-TRISTAN**	**Fermilab Site-filler**	**IHEP Ring**		**SLAC/LBNL Ring**
						IHEP-50km	**IHEP-80km**	
Energy (center of mass)	GeV	240	240 (375)	240	240	240	240	240
Luminosity (per IP)	$10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	1	5	1	0.52	2.5	3.85	1
No. of IP		2 (4)	2 (4)	1	1	2	1	1
No. of Higgs per year (per IP)		20k	100k		13k	100k	200k	
Size (length or circumference)	km	26.7	81	40	16	49.78	69.88	26.7
P(wall)	MW	200	200	100	200	300	300	200
Polarization								
e-		0	0		0			
e+		0	0		0			
μ+, μ-								
γ								
Energy upgrade limit		240	100 TeV (pp)		240	250	250	240
Technical readiness (no. of years from now)		3	5	> 2	0	unknown	unknown	
Specific issues requiring further R&D		IR	Tunnel		RF	unknown	unknown	
		SR shielding	IR		Vacuum			
		RF coupler	SR shielding		(not extensive)			
			RF coupler					

Luminosity

- The Luminosity L is a measure of the probability of particle encounters per unit area per second in a collision process
- Given the cross section of a physics process σ_{phys} the counting rate of a physics event is

$$\mathbf{R}\ [s^{-1}] = \sigma_{\mathbf{phys}}\ [cm^{-2}]\ \mathbf{L}\ [cm^{-2}s^{-1}]$$

Luminosity

- For head-on collisions, bunched beams of opposite charge, Gaussian charge distributions, L can be written as:

$$\boxed{L = \frac{f_{coll}}{4\pi}\frac{N^{+}N^{-}}{\sigma_x^{*}\sigma_y^{*}}}$$

f_{coll} = $n_b f_0$ = collision frequency

n_b= number of bunches, f_0=revolution frequency

N^+, **N^-** number of particles/bunch

σ^*_x, σ^*_y transverse beam sizes at Interaction Point (IP)

$4\pi\sigma^*_x\sigma^*_y$ area of colliding beams

- To get high luminosity:
  - Increase the collision frequency
  - Increase the bunch density

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  - Increase the collision frequency
  - Increase the bunch density ➔ but

Beam-beam effects pose a limitation on the maximum achievable bunch density

Beam-beam effects

Beam-beam effects pose a limitation on the maximum achievable bunch density

- Particles in a bunch are strongly affected by the nonlinear field of the counter rotating bunches
- Increasing the bunch density produces beam blow-up and particle losses
- A measure of the strength of the beam-beam interaction is given by the **linear beam-beam tune shift ξ_x, ξ_y**
- It exists an empirical upper bound on ξ_x, ξ_y

Achieved beam-beam tune shifts

From ICFA Lepton Colliders Database v8 2005 (M. Biagini)

LEPTON COLLIDERS (e+/e-)		Units	DAFNE	BEPC	CESR	PEP-II	KEK-B	LEP I	LEP II
			KLOE			BaBar	Belle		
Energy/ring (e+/e-)	E	GeV	0.51	1.89/1.89	5.3	3.1/8.99	3.5/8.0	44 - 47.5	80.5 - 104.5
Circumference	C	m	97.69	240.4	768	2199	3016	26658.9	26658.9
Number of rings			2	1	1	2	2	1	1
Half crossing angle	$\phi/2$	mrad	12.5	0	2.3	0	11	0	0
Number of Bunches	N_b		49	1	45	1034	1284	8	4
Peak Luminosity (10^{32})	L_{peak}	$cm^{-2}\ sec^{-1}$	0.8	0.112	13	65.82	105.67	2.05E-01	1
Beam current (e+/e-)	I	A	1.14/.756	0.045	.356/.329	1.55/1.175	1.376/1.049	1.70E-03	2.88E-03
Collision frequency	F_{coll}	MHz	185	1.25	71	159	125	0.090	0.045
Particles/bunch (e+/e-)	N_{part}	10^{+10}	4.7/3.1	23	12.7/11.7	9.3/5.	7./5.2	11.8	40
Transverse emittances @	H	nm	770	140	180	18/18			
	V	nm	1.54/2.31	2.1	1	0.36/0.36			
β function @ IP (e+/e-)	H	m	2.7	1	0.7	0.3/0.3			
	V	cm	2.7	1.5	1.1	1.0/1.0			
Beam size @ IP (e+/e-)	H	μm	1440	370	400	74			
	V	μm	7.9	5.61	6	1.9			
Σ in collision	H	μm		869	470	140	159	197	178
	V	μm	6	52	3.6	6.8	4	3.4	3.3
Coupling factor (e+/e-)	$\kappa=\varepsilon_y/\varepsilon_x$	%	0.2/0.3	1.5	1.3	2			
Betatron coup. fact. (e+/e	$\kappa_\beta=\beta_y/\beta_x$	%	1	1.5	1.6	3.3			
B-B tune shift/IP (e+/e-)	ξ_x		0.028	0.041	0.025	0.075/0.065	0.097/0.067	0.03	0.043
	ξ_y		0.02	0.029	0.06	0.06/0.048	0.066/0.05	0.033	0.079

KEKB has achieved $\xi_x = 0.127/0.122$, $\xi_y = 0.129/0.090$ and $L = 210.8\ 10^{32}\ cm^{-2}/s$

Achieved peak luminosities

Factories		Achieved Luminosity
KEKB	B-Factory KEK, Japan	2.1 x 10^{34}
PEP-II	B-Factory SLAC, USA	1.2 x 10^{34}
DAΦNE phase I	Φ-Factory Frascati, Italy	1.6 x 10^{32}
DAΦNE upgrade	Φ-Factory Frascati, Italy	4.5 x 10^{32}
BEPCII	C-Tau-Factory Beijing, China	0.8 x 10^{33}

The previous table is not up to date but is useful since it lists many useful parameters

Here are the updated numbers for the peak luminosities

M. Zobov, IPAC10

Beam-beam tune shift – Bassetti - Erskine formula

- The electric field of a gaussian bunch with N particles seen by a test particle in collision can be expressed in terms of the complex error function:

$$E_x - iE_y = i\frac{Ne}{2\varepsilon_0\sqrt{2(\sigma_x^2-\sigma_y^2)}}\left[w(a+ib) - w(ar+i\frac{b}{r})e^{[-(a+ib)^2+(ar+ib/r)^2]}\right]$$

$$r=\sigma_y/\sigma_x;\quad a=\frac{x}{\sqrt{2(\sigma_x^2-\sigma_y^2)}};\quad b=\frac{y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\qquad w(z)=e^{-z^2}[1+\frac{2i}{\sqrt{\pi}}\int_0^z e^{\zeta^2}d\zeta];\quad \zeta=at+ib/t;\quad (r\le t\le 1)$$

- For relativistic particles the electric and magnetic field are equal
- These expressions of the fields can be used in simulation programs to evaluate the beam-beam effects with realistic beam distributions
- The beam-beam interaction at large amplitudes is highly nonlinear
- For small amplitude particles it is characterized by a quadrupole-like force with focal length:

$$\frac{1}{f_x}=K_x=\frac{2r_eN}{\gamma\sigma_x^*(\sigma_x^*+\sigma_y^*)}\quad;\quad\frac{1}{f_y}=K_y=\frac{2r_eN}{\gamma\sigma_y^*(\sigma_x^*+\sigma_y^*)}$$

- The beam-beam tune shift is the first order approximation to the betatron tune change given by: $\xi_{x,y} = \beta^*_{x,y} K_{x,y}/(4\pi)$

M. Bassetti, G. A. Erskine
CERN-ISR-TH/80-06

Beam-beam tune shift

- The beam-beam tune shift is given by:

$$\xi_{x,y} = \frac{N r_e}{2\pi\gamma} \frac{\beta^*_{x,y}}{\sigma^*_{x,y}(\sigma^*_x + \sigma^*_y)}$$

- Inserting in the luminosity formula we get

$$L = f_{coll} \frac{\pi\gamma^2}{r_e^2} \frac{\xi_x \xi_y \varepsilon_x}{\beta_y} (1 + \frac{\sigma_x}{\sigma_y})$$

- For flat beams $\varepsilon_y / \varepsilon_x = \kappa << 1$ and $\kappa_\beta = \beta_y / \beta_x$

$$\xi_x \approx \frac{r_e}{2\pi\gamma} \frac{N}{\varepsilon_x} \qquad \xi_y \approx \frac{r_e}{2\pi\gamma} \frac{N}{\varepsilon_x} \sqrt{\frac{\kappa_\beta}{\kappa}} \qquad L \approx f_{coll} \gamma N \frac{\xi_y}{\beta_y}$$

Beam-beam tune shift

Assume both tune shifts equal to the limit value i.e. $\kappa_b=\kappa$

$$\xi_x \approx \xi_y \approx \frac{r_e}{2\pi\gamma}\frac{N}{\varepsilon_x} \qquad L \approx f_{coll}\gamma N\frac{\xi_y}{\beta_y} = \gamma\frac{I}{e}\frac{\xi_y}{\beta_y^*}$$

At the b-b limit to further increase luminosity we can:

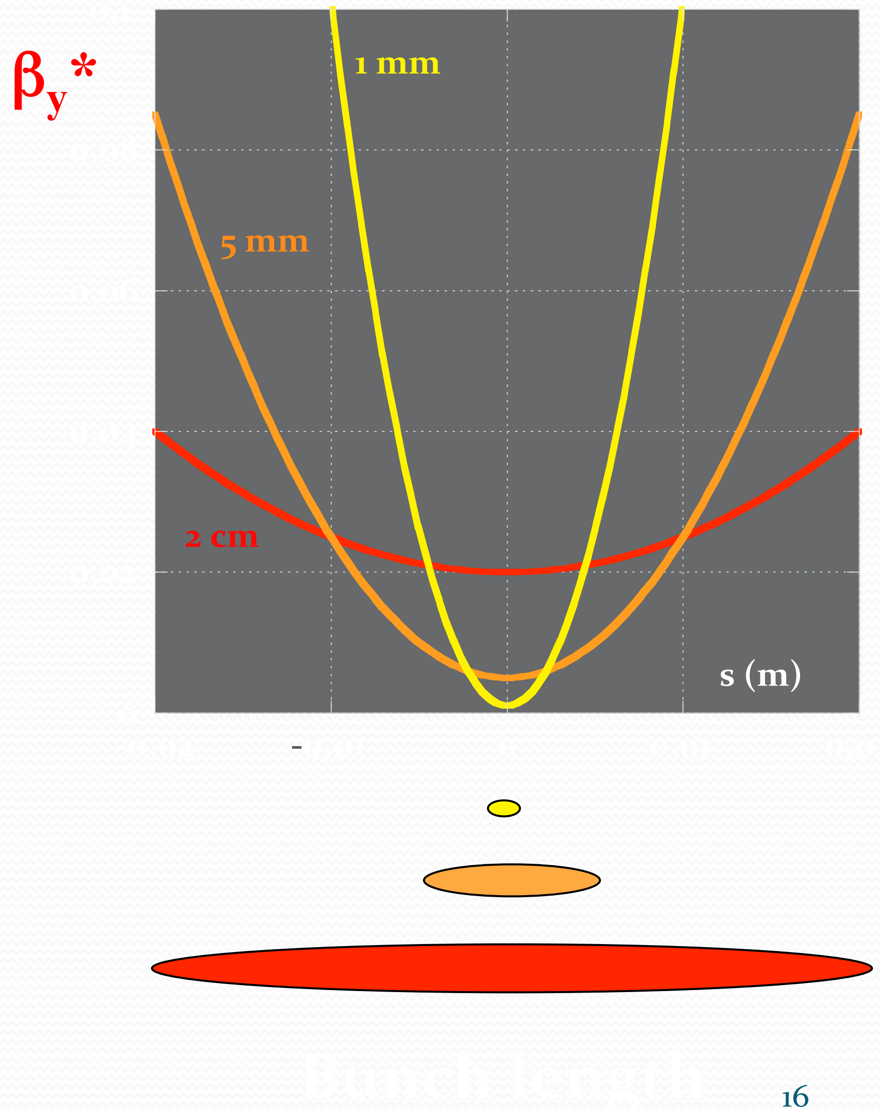
- **Increase the current** and the emittance keeping the tune shift constant
  - Current is limited by the RF power available, vacuum system limits and beam instabilities
  - Emittance is limited by vacuum chamber aperture and dynamic aperture
- **Reduce β_y** with challenges on the IR design and dynamic aperture
- Minimum β_y is limited by the hourglass effect

Hourglass effect: why short bunches?

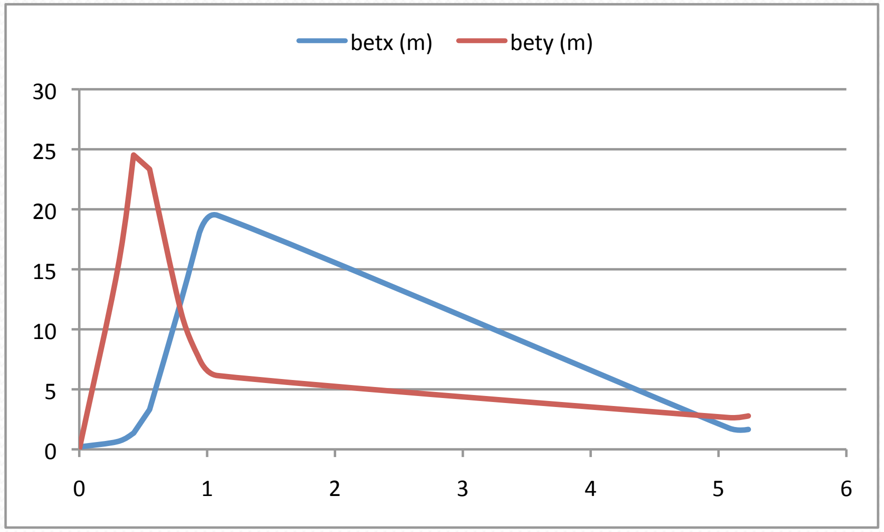
- In the drift near the IP:

  $$\beta_y(s) = \beta_y^* + s^2/\beta_y^*$$

- To squeeze the vertical beam size, and increase Luminosity, β_y^* at IP must be decreased
- This is efficient only if at the same time the bunch length is shortened to $\sigma_z \approx \beta_y$ otherwise particles in the head and tail of the bunches will collide at a larger β_y



Low β_y insertion



DAΦNE - Siddharta IR

L* is the length of the drift between the IP and the first QD quadrupole focusing in the vertical plane

$\beta(s) = \beta^* + s^2/\beta^* \Rightarrow \beta_{max} \approx L^{*2}/\beta^*$

DAΦNE

$L^*=0.3$ m $\beta^*= 6$ mm $\beta_{max} \approx 15$ m

QD quadrupole

gradient = 26 T/m length = 0.25 m

Permanent Magnet

SuperB

$L^*=0.52$ m $\beta^*= 0.21$ mm $\beta_{max} \approx 1700$ m

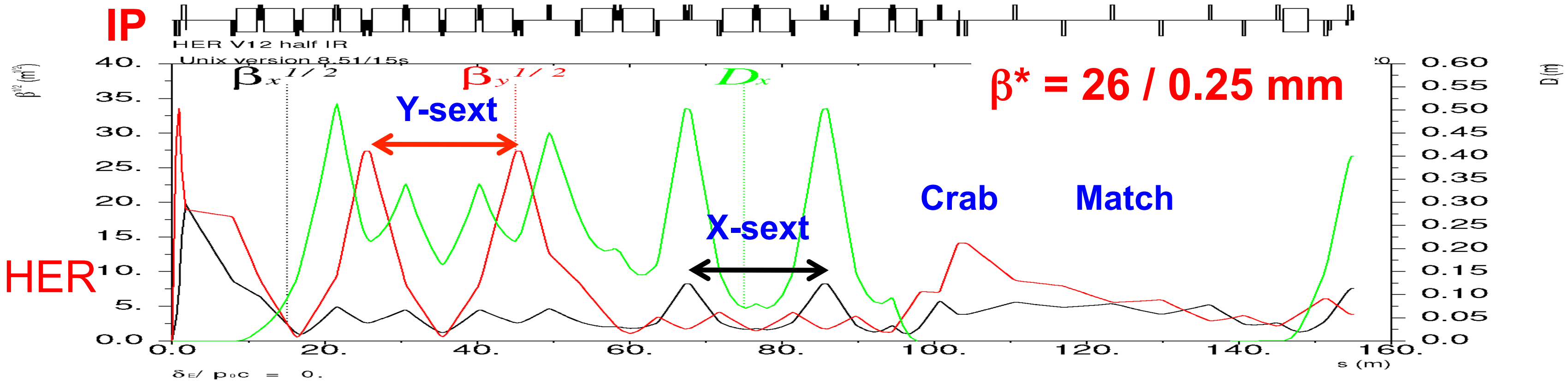
QD quadrupole

gradient = 100 T/m length = 0.3 m

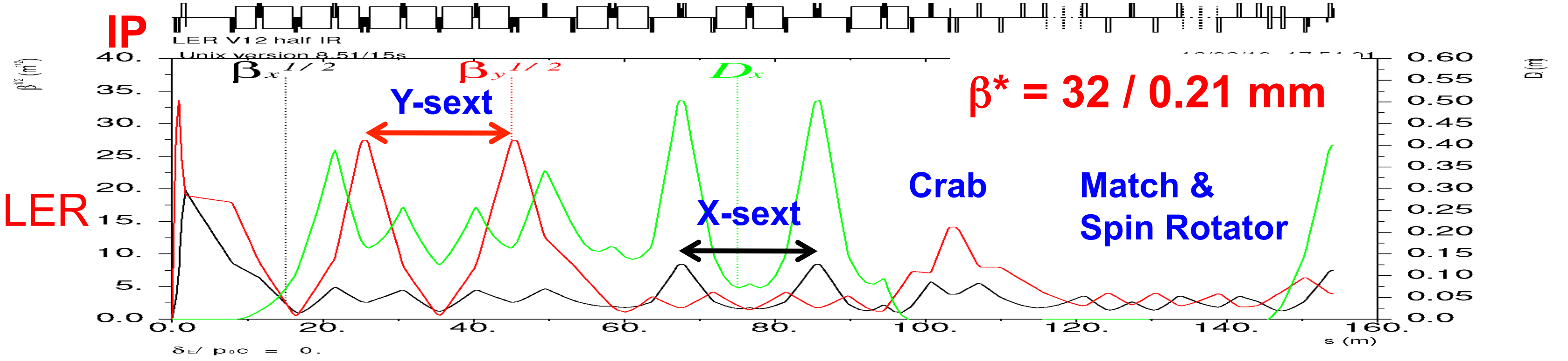
Superconducting

SuperB Final Focus sections

“Spin rotator” optics is replaced with a simpler matching section



Matching section is shorter than HER to provide space for SR optics



P. Raimondi
L. Malisheva

Different collision schemes

- Single ring, few bunches, few IPs, head-on collisions (Aco, Adone, VEPPII, Spear, Petra, PEP, LEP, BEPC…?)
- Exotic schemes (DCI (4 beams), Doris (first attempt with a vertical crossing angle), VEPP2000 (round beams), CESR (pretzel orbit))
- Double rings, multibunch, 1 IP, crossing angle
  - Small Piwinski angle (Factories: PEPII, KEKB, DAΦNE, BEPCII)
  - Large Piwinski angle and crab waist (present DAΦNE, SuperB, SuperKEKB, BINP τ/charm proposal)

Single ring - head-on collision

- The number of IPs is $2n_{b,}$ twice the number of bunches
- Beam-beam sets a limit on the maximum tune shift in the ring: more IPs ⇒ less luminosity per IP
- Therefore the number of bunches is small, ~1÷8, and the collision frequency is of the order of the revolution frequency
- Below beam-beam limit luminosity is proportional to the square of the particles per bunch N^2/β_y
- Above beam-beam limit, luminosity increases linearly with N/β_y
- Due to hourglass effect $\sigma_z \approx \beta_y$
- Bunch peak current is pushed to the maximum

Single ring - head-on collision

- At low energy main limitations are
  - single bunch instabilities due to the interaction of the bunch e.m. fields with the vacuum chamber (HOM heating, bunch lenghtening, …)
  - Large beam emittances requiring large magnetic apertures and large dynamic apertures
- At high energy main limitations come from
  - RF power available and issues related to high synchrotron radiation power
  - HOM heating and stability issues related to high bunch charge and short bunches

Double rings – crossing angle

- The bunches are stored in 2 separate rings crossing at 1 IP with a crossing angle
- They travel in the same vacuum chamber in a short region near the IP
- In this region the bunches see each other with an offset at a number of parasitic points, at distances from the IP equal to half the bunch distance
- The tune shift due to the parasitic crossings is inversely proportional to the square of the bunch separation

Double rings – crossing angle

- Luminosity is proportional to the number of bunches $L \propto n_b$
- Below bb limit $L \propto N^2$
- Above bb limit $L \propto N$
- Therefore it is convenient to increase number of bunches instead of the particles per bunch N, i.e. increase the average current $I = en_b N/T_0$ at constant bunch peak current $I_{peak} = eN/\sqrt{(2\pi\sigma_l)}$ decreasing the impact of single bunch instabilities
- The limit on maximum n_b is the tune shift due to the parasitic crossings
- The limit to the maximum ring current is again RF power, and issues related to high synchrotron radiation
- At Factories very large currents have been stored with collision frequencies of the order 100 ÷ 350 MHz

Beam Current Records at Factories

Parameters	PEP-II		KEKB		DAΦNE	
	LER	HER	LER	HER	e+	e-
Circumference, m	2200	2200	3016	3016	97.69	97.69
Energy, GeV	3.1	9.0	3.5	8.0	0.51	0.51
Damping time, turns	8.000	5.000	4.000	4.000	110.000	110.000
Beam Currents, A	3.21	2.07	1.70*	1.25*	1.40	2.45

Maximum positron beam current

Maximum currents with SC cavities

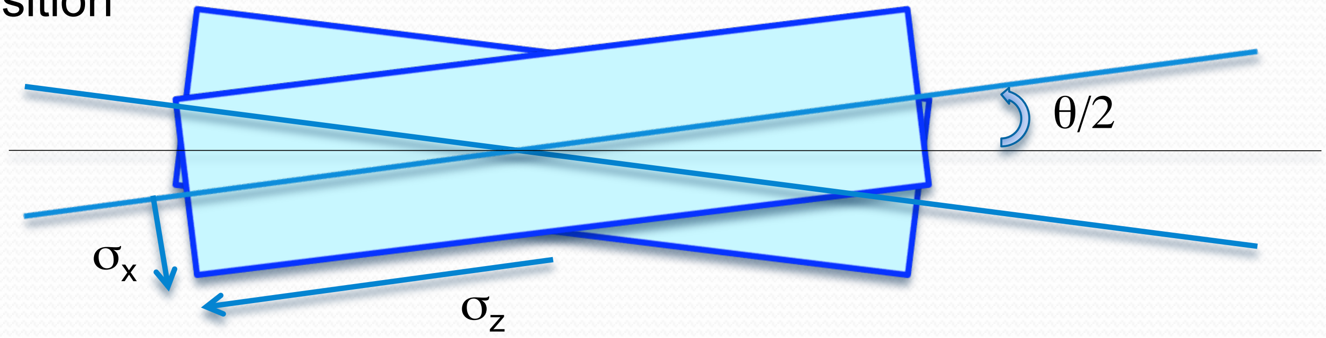
* 2.00 A and 1.40 A without crab cavities

Maximum electron beam current

M. Zobov, IPAC10

Crossing angle and Piwinski angle

Crossing angle induces a coupling between the synchrotron and betatron motion since the kick experienced by a particle depends on its longitudinal position



Small Piwinski angle to reduce strength of synchro-betatron resonances

$$\Phi = \sigma_z tg(\theta/2)/\sigma_x < 1$$

Since generally $\sigma_x \ll \sigma_z$ small Piwinski angle implies small crossing angle $\theta \ll 1$

Luminosity strategy with double rings

- Small beta function at the IP β_y^*
- Higher number of particles per bunch N
- More colliding bunches n_b
- Large beam emittance ε_x
- Higher tune shift parameters $\xi_{x,y}$
- Crossing angle θ
- \- Small Piwinski angle $\Phi = \sigma_z tg(\theta/2)/\sigma_x < 1$

→ *small crossing angle* $\theta < \sigma_x/\sigma_z$

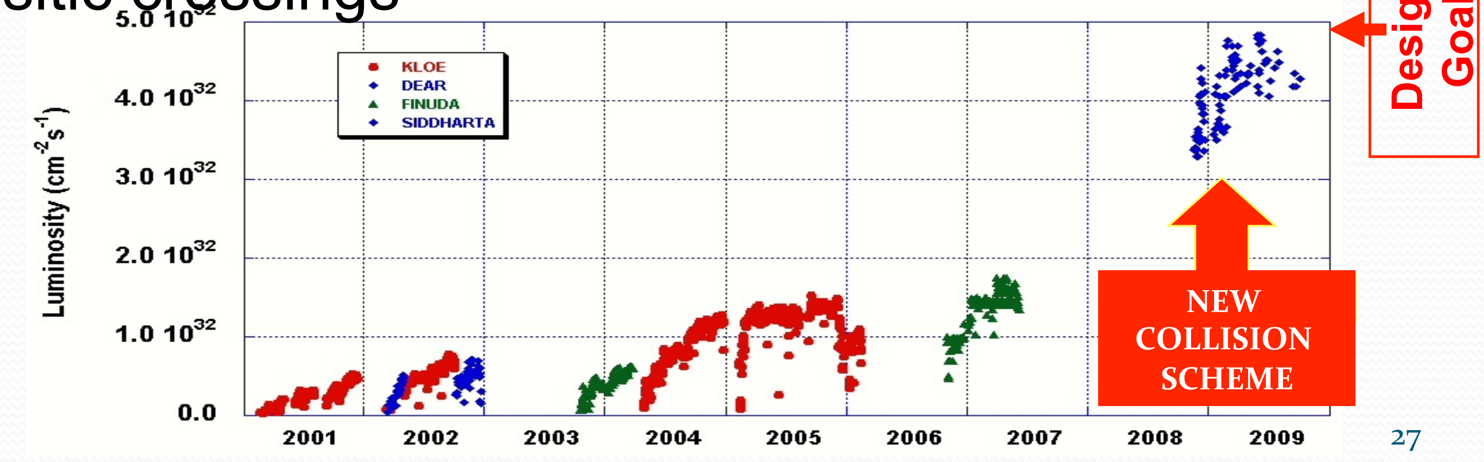
To avoid parasitic crossings

To reduce strength of synchro-betatron resonances

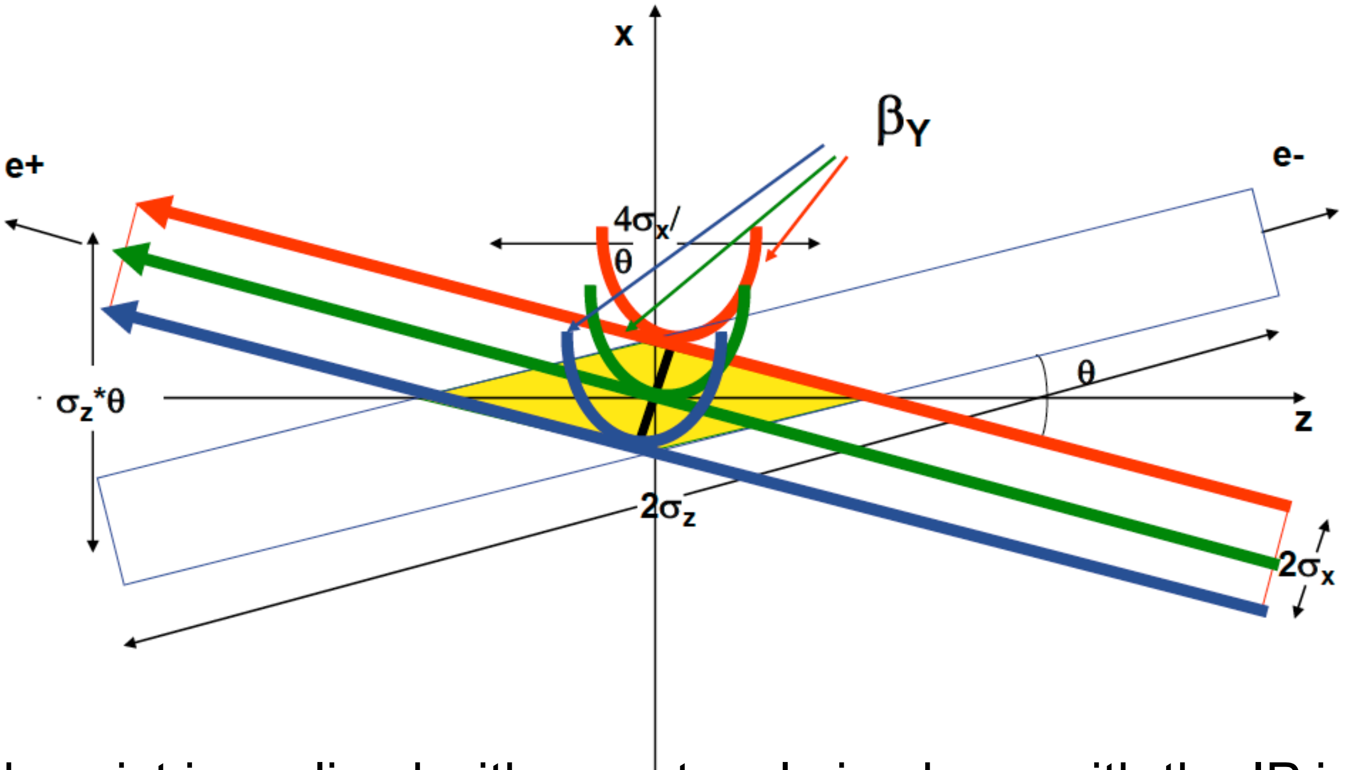
Large Piwinski Angle & Crab Waist scheme

- To break B-Factories record in peak luminosity a new collision scheme is needed
- The «Large Piwinski Angle» and «crab-waist sextupoles» *(LPA&CW)* option was first developed by P. Raimondi and tested at DAΦNE (LNF)
- Large crossing angle and very small beam sizes:
  - collision area is shorter
  - IP β functions can be smaller
  - less parasitic crossings

$$\Phi_{Piwinski} = tg(\theta)\sigma_z/\sigma_x$$

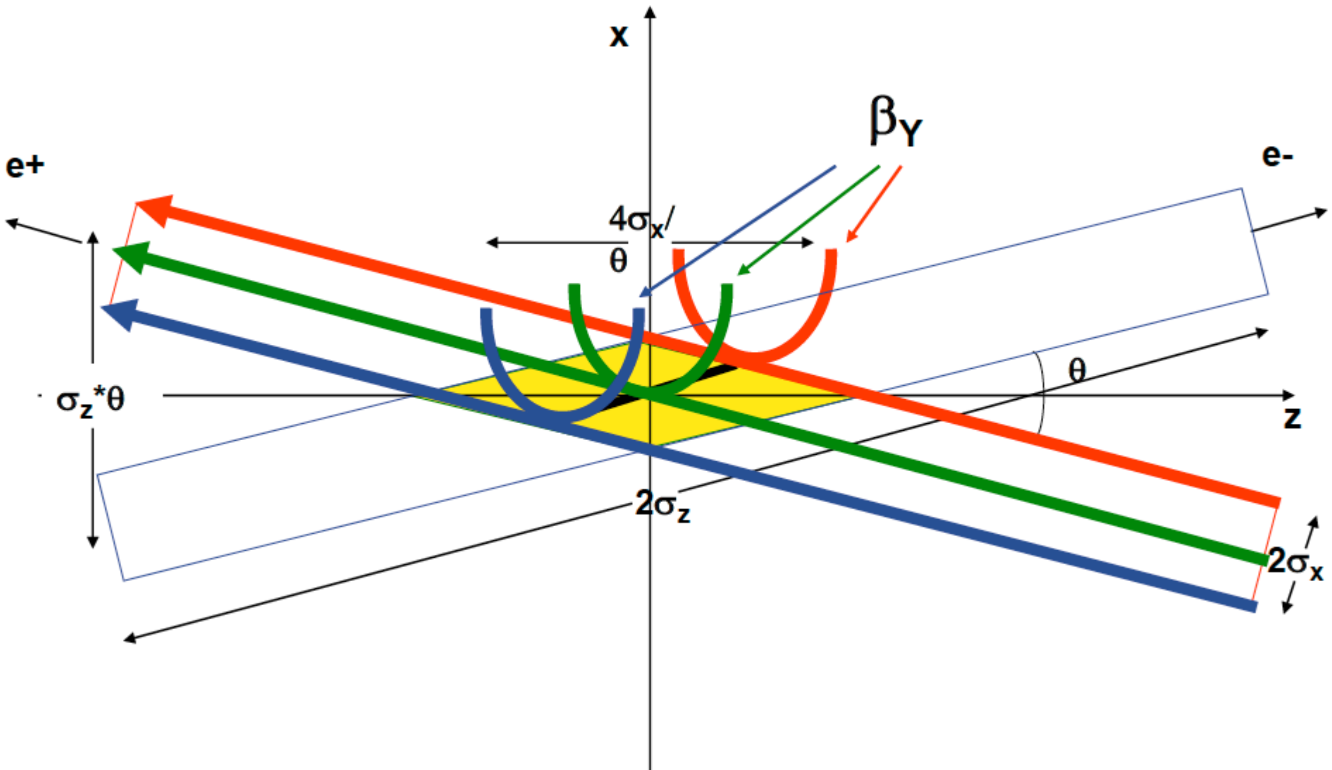


Crab sextupoles off



Crab waist is realized with a sextupole in phase with the IP in x and at $\pi/2$ in y

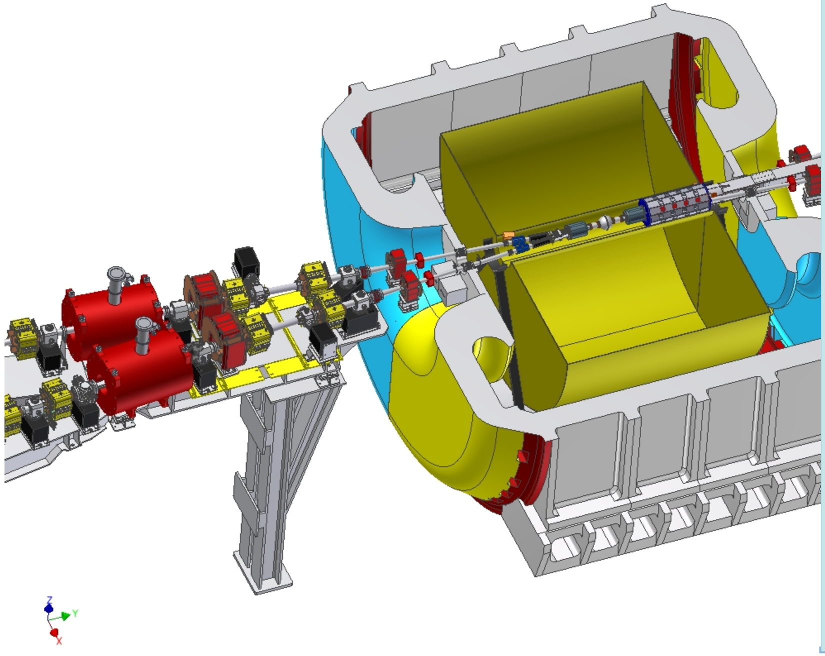
Crab sextupoles on

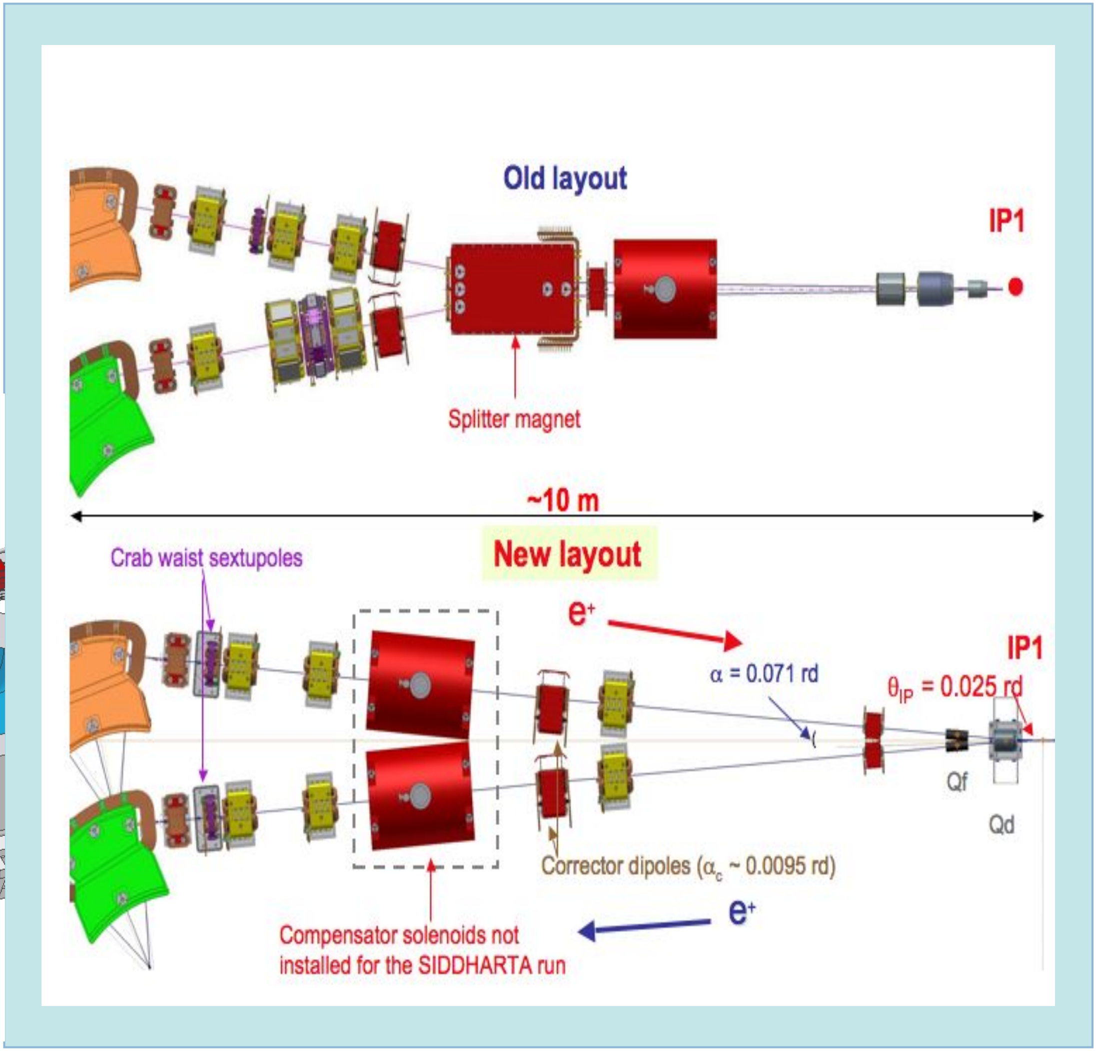


Crab waist is realized with a sextupole in phase with the IP in x and at $\pi/2$ in y

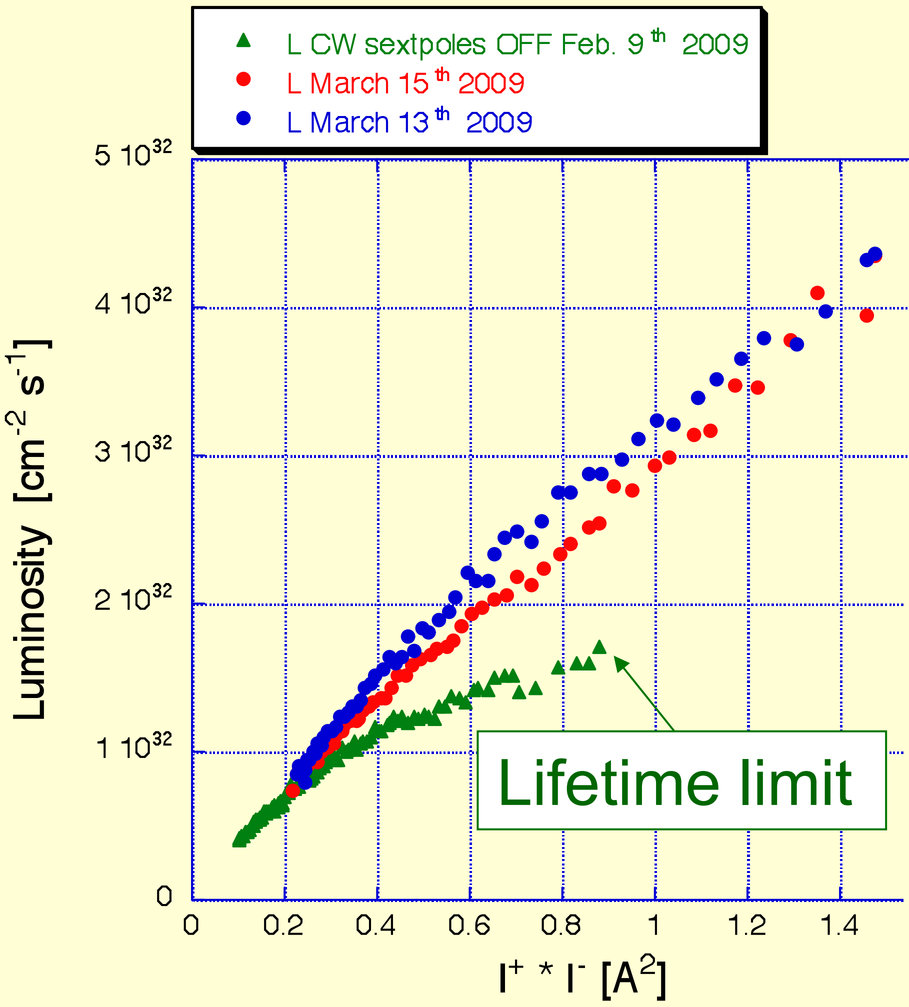
New DAΦNE Experimental Interaction Region

KLOE IR



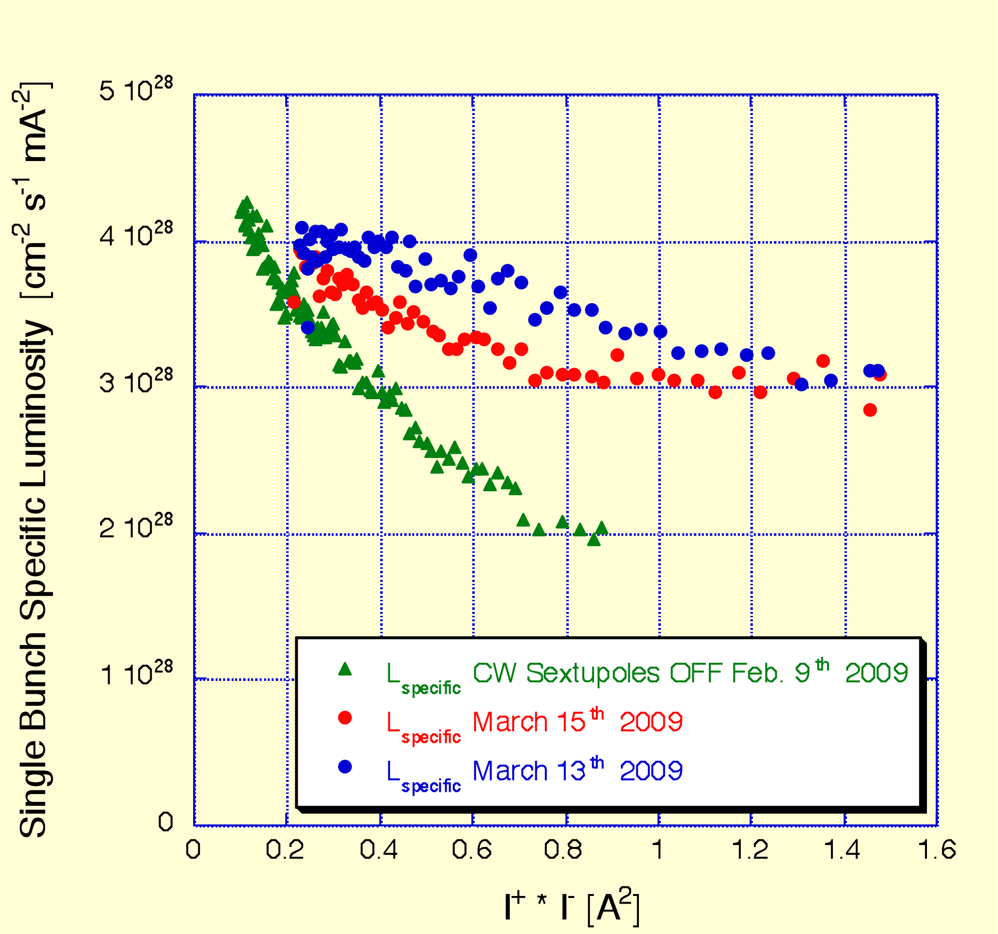


P. Raimondi, April 22-2010



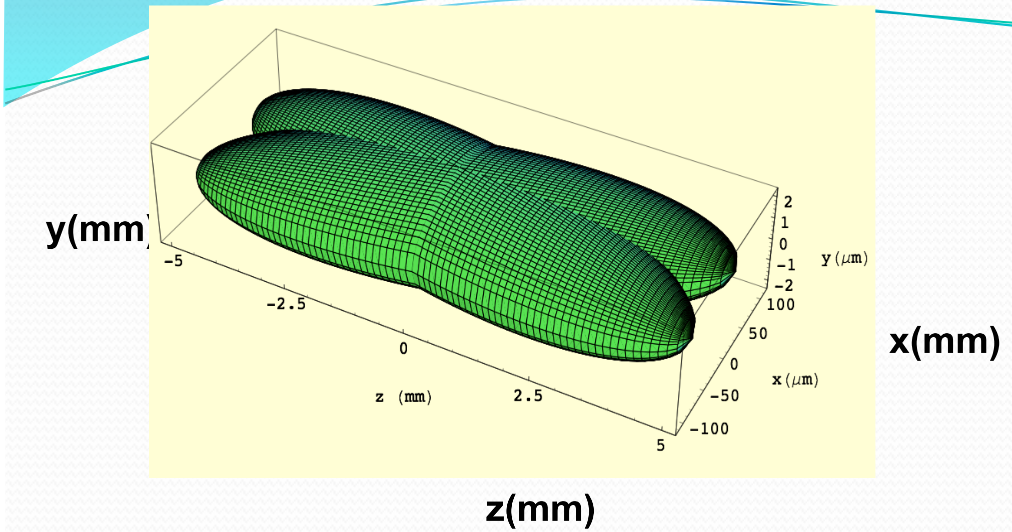
Crab on/off Luminosity vs Current Product

Crab on/off Specific Luminosity vs Current Product



P. Raimondi, Fermilab, April 22-2010

IP beam distributions for KEKB

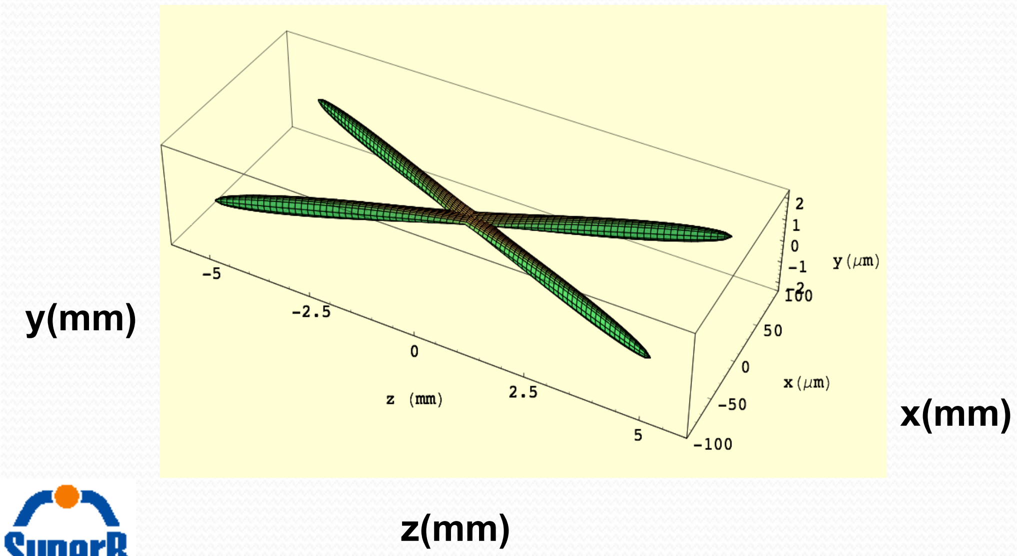


SuperB beams are focused in the y-plane 100 times more than in the present factories, thanks to:

- small emittances
- small beta functions
- larger crossing angle

Tune shifts and longitudinal overlap are greatly reduced

IP beam distributions for SuperB

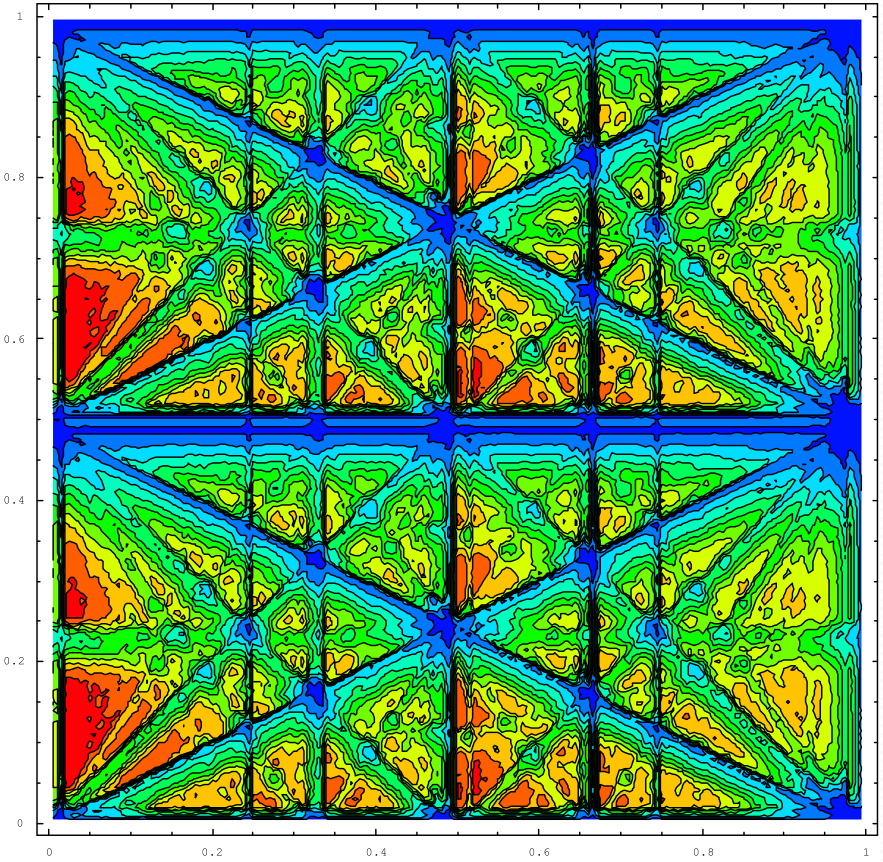


	KEKB	SuperB
I (A)	1.7	2.
β_y^* (mm)	6	0.22/0.39
β_x^* (mm)	300	22/39
σ_y^* (μm)	3	0.039
σ_x^* (μm)	80	10/6
σ_z (mm)	6	5
L ($cm^{-2}s^{-1}$)	1.7×10^{34}	$1. \times 10^{36}$

Example of x-y resonance suppression

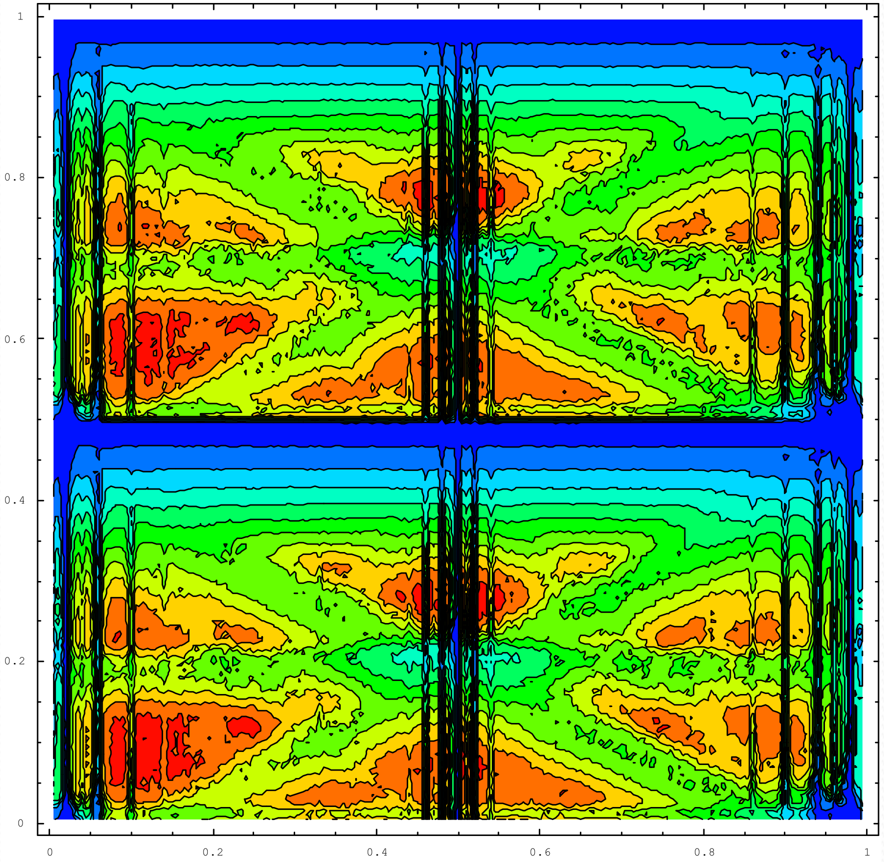
D.Shatilov's (BINP), ICFA08 Workshop

Much higher luminosity



Typical case (KEKB, DAFNE):

1. low Piwinski angle $\Phi < 1$
2. β_y comparable with σ_z



Crab Waist On:

1. large Piwinski angle $\Phi >> 1$
2. β_y comparable with σ_x/θ

Crossing angle schemes

Requirements

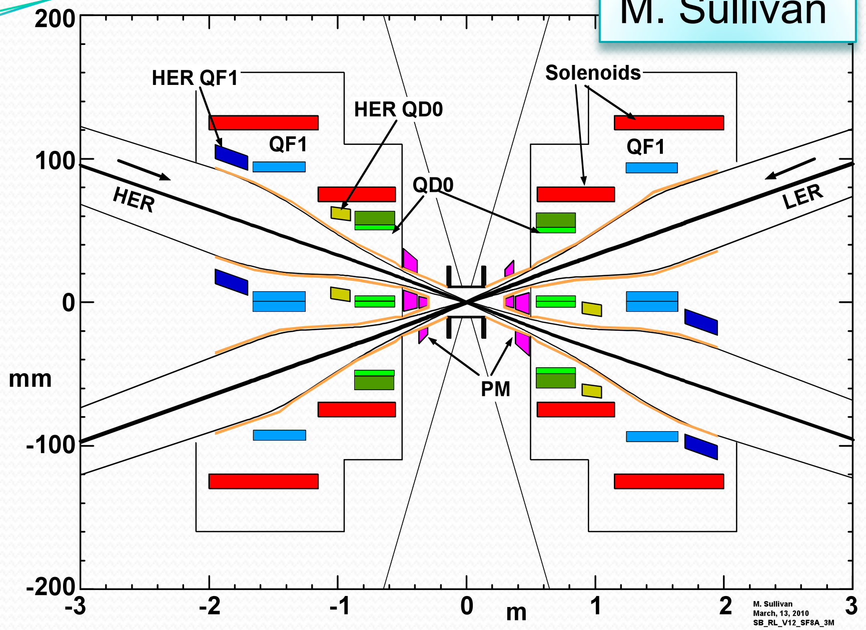
- Small Piwinski angle:
  - High current, very short bunches
- LPA&CW :
  - Low emittance, very small β_y

Challenges

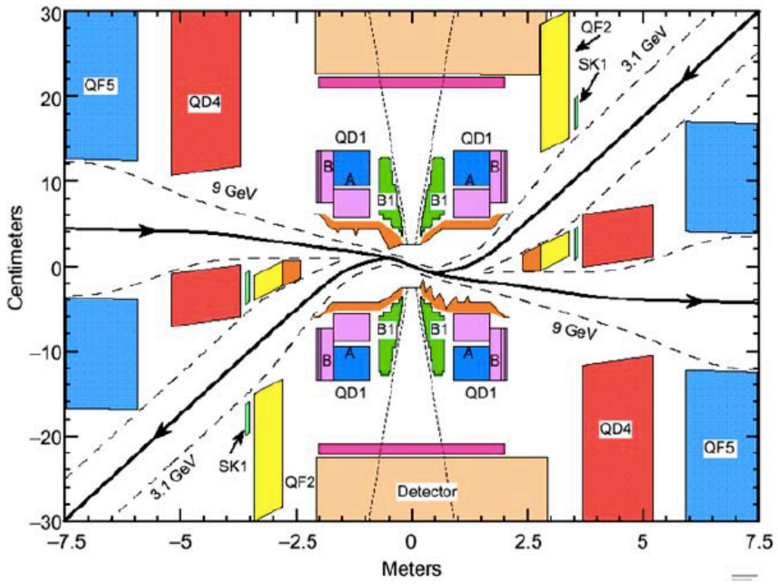
- Small Piwinski angle:
  - Wall plug power, RF and vacuum systems, vacuum chamber heating, instabilities
- LPA&CW:
  - Dynamic aperture, IR design

IR design: PEPII and SuperB

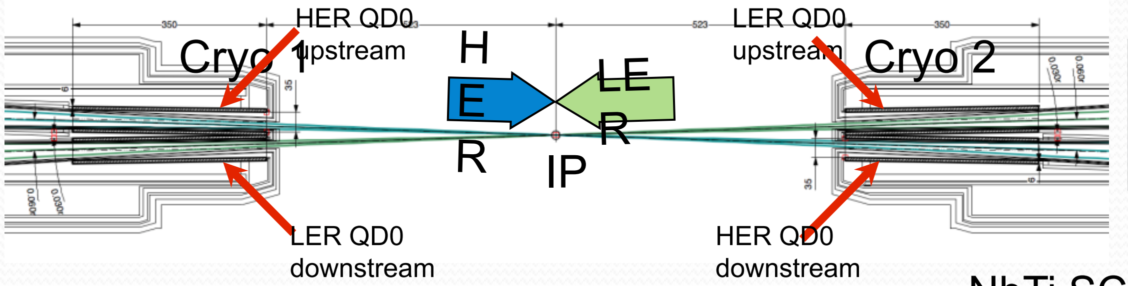
M. Sullivan



SuperB IR with large crossing angle θ = 60 mrad



PEPII IR with head-on collisions



P. Fabbricatore

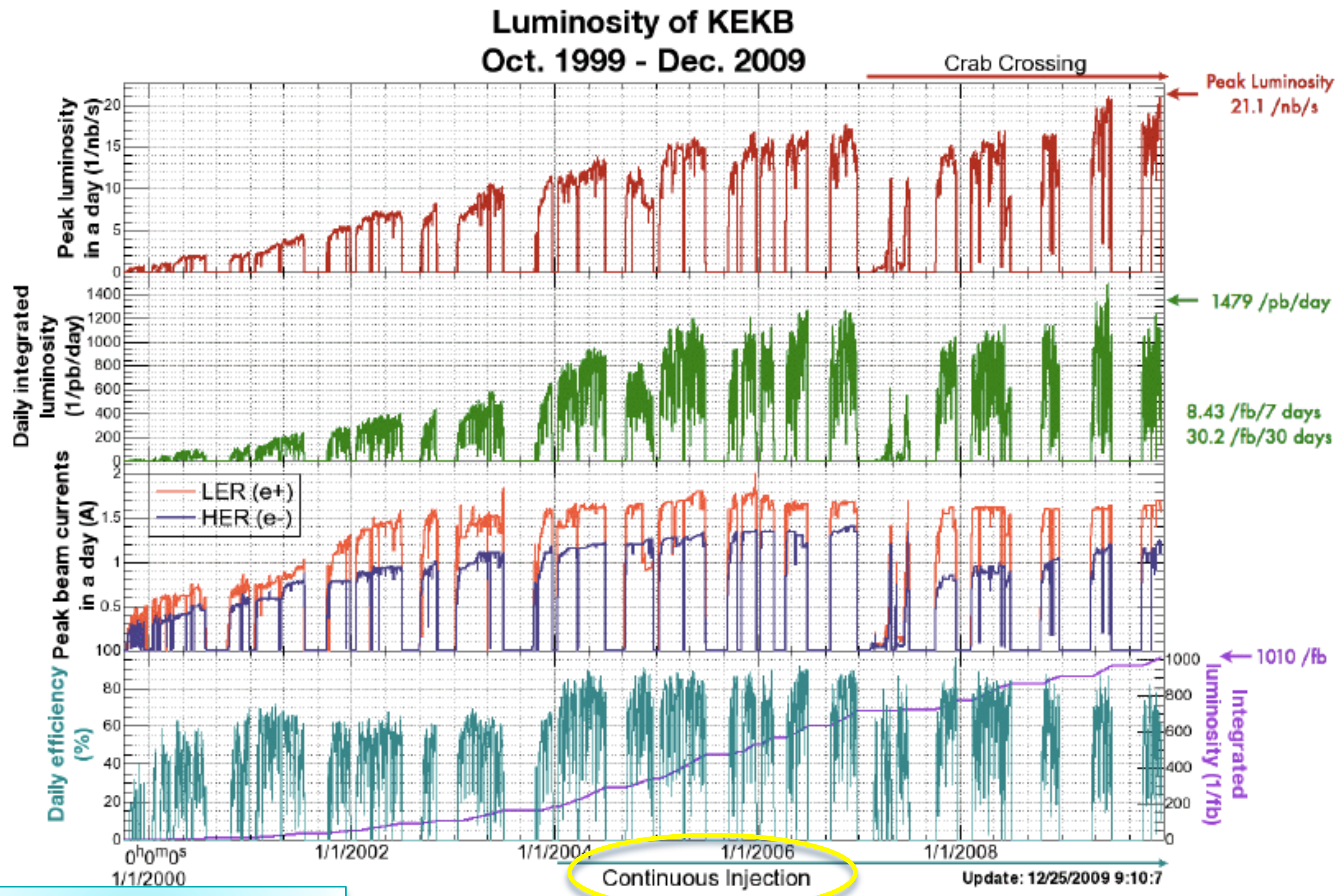
QD0 prototype early building stage

NbTi SC wire for a nominal current of 2650 A
Successfully tested up to 2750 A

Integrated luminosity

- The main goal of a high energy physics detector is to collect a large number of events during an experimental run of a few years
- The measure of the machine performance is not peak luminosity but the luminosity integrated over time: day, month, year
- To increase integrated luminosity
  - Increase $L_{average}/L_{peak}$
    - Beam lifetime, luminosity lifetime, continuos injection
  - Increase machine availability
    - Maintenance, spares

KEKB history: peak and integrated luminosity



Y. Funakoshi, IPAC10

Beam lifetime

- Processes that lead to particle losses:
  - Single beam
    - Quantum lifetime
    - Touschek scattering
    - Gas scattering
  - Colliding beams
    - Bhabha interactions:
      - elastic Bhabha $e^+e^- \rightarrow e^+e^-$
      - radiative Bhabha $e^+e^- \rightarrow e^+e^-\gamma$
    - Beamsstrahlung

Beam lifetime

- The beam lifetime τ of the ring is defined as:

$$\tau \equiv N(t) \Big/ \frac{dN}{dt}$$

- Assuming $\tau = \tau(t_0)$ constant at the maximum current we make a conservative approximation since τ decreases with the current
- In this approximation the number of particles decreases with exponential behavior and the contribution to lifetime due to different processes can be easily combined

$$N(t) \approx N(t_0)(e^{-\frac{t}{\tau_1}} e^{-\frac{t}{\tau_2}} \ldots)$$

$$\frac{1}{\tau} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \ldots$$

Bhabha interactions lifetime

- Radiative and elastic Bhabha scattering occurring at the interaction point cause beam particle losses
- The loss rate depends on the luminosity *L* and on the "particle loss" cross section σ_B

$$\dot{N} = \frac{dN_{TOT}}{dt} = -\sigma_B L$$

where $N_{TOT} = n_b N$ is the total number of particles in the ring

- The beam lifetime τ of the ring at time t_0 is then

$$\tau \equiv N_{TOT} \Big/ \frac{dN_{TOT}}{dt} = \frac{N_{TOT}(t_0)}{\sigma_B L}$$

$e^+e^- \rightarrow e^+e^-\gamma$ radiative Bhabha

- The energy loss due to the photon emission can bring the radiating lepton outside the energy acceptance of the storage ring
- The cross section of this process is given with good approximation by:

$$\sigma \cong \frac{16\alpha r_e^2}{3}\left[\left(\frac{1}{2}-\ln\frac{s}{m_e^2}\right)\left(\frac{5}{8}+\log\Delta\varepsilon\right)+\frac{1}{2}(\ln\Delta\varepsilon)^2-\frac{3}{8}-\frac{\pi^2}{6}\right]$$

with:

$\Delta\varepsilon$ fractional energy acceptance of the ring

α fine structure constant

s square of total energy in the c.m.

$e^+e^- \rightarrow e^+e^-$ elastic Bhabha

- An electron and a positron can knock each other hard enough to be deflected outside the transverse ring acceptance
- The cross section can be evaluated by:

$$\sigma_{el} \approx \frac{8\pi(\hbar c\alpha)^2}{s}\frac{E_j}{E_i}\left(\frac{1}{\vec{\vartheta}_x^2}+\frac{1}{\vec{\vartheta}_y^2}\right)$$

- E_i is the energy of the beam, E_j is the energy of the opposite beam and θ_x (θ_y) are the horizontal (vertical) angular deflection beyond which scattered particles would be lost
- This process is less critical than the radiative Bhabha

Radiative Bhabha lifetime

	PEPII	KEKB	SuperB	SuperKEKB	LEP2	LEP3	DLEP
E cm	10.58	10.58	10.58	10.58	209	240	240
energy acceptance	0.01	0.01	0.01	0.01	0.01	0.01	0.01
cross section (mbarn)	170	170	170	170	215	215	215
L (cm-2 s-1)	1.20E+34	2.11E+34	1.00E+36	8.00E+35	5.00E+32	2.00E+34	2.80E+34
# bunches/beam N_b	1034	1284	978	2500	4	4	60
particles/bunch N	1.28E+11	8.03E+10	6.56E+10	9.05E+10	5.75E+11	1.00E+12	2.67E+11
particles/beam N_{TOT}	1.33E+14	1.03E+14	6.42E+13	2.26E+14	2.3E+12	4.00E+12	1.60E+13
tau (min)	1085	479	6.3	28	357	16	44

- Beam lifetimes calculated for 1% energy acceptance
- A few cases to show range of parameters
- The cross section is calculated by BBBREM code for SuperB and LEP2 and is in good agreement with LEP data, the formula gives a slightly larger value
- The cross section has a logarithmic dependence on the energy acceptance
- For SuperB and SuperKEKB is dominant process for beam lifetime and detector backgrounds

BBREM, R., Kleiss, H. Burkhard, CERN SL/94-03 (OP), January 1994

Beamstrahlung

- Emission of synchrotron radiation due to the electromagnetic field of the opposite beam
- Also in this case particles emitting a photon with an energy larger than the ring acceptance ηE_0 get lost
  - Lifetime limitation
  - Detector background
  - Important at high energies: Higgs Factories

See:

- V. I. Telnov, “Restriction on the energy and luminosity of e^+e^- storage rings due to beamstrahlung” arXiv:1203.6563
- D. Schulte et al., Beam-Beam Simulations with GUINEA-PIG, ICAP98, Monterey, CA, USA(1998), CERN/PS 99-014 (LP)

Beamstrahlung

Critical energy for synchrotron radiation

$$E_c = \hbar\omega_c = \hbar\frac{3\gamma^3 c}{2\rho}$$

The maximum effective field for flat Gaussian beams is

$B \approx 2eN/(\sigma_x\sigma_z)$

The bending radius $\rho = pc/eB \approx mc^2/eB = \gamma\sigma_x\sigma_z/2r_e$

Substituting we find: $$\frac{E_c}{E_0} = \frac{3\gamma r_e^2 N}{\alpha\sigma_x\sigma_z}$$

To achieve a beam lifetime $\tau > 30$ min it is needed

$E_c/E_0 < 0.1\eta$

This condition sets a limit on $N/(\sigma_x\sigma_z)$

From V. Telnov, arXiv:1203.6563

Beamstrahlung

$N/(\sigma_x\sigma_z) < 0.1\eta\alpha/(3\gamma r_e^2)$	Lifetime limitation
$L \propto f_{coll}\, N^2/(\sigma_x\sigma_y)$	Luminosity
$P \propto f_{coll}\, N\, \gamma^4/\rho_D$	Beam power

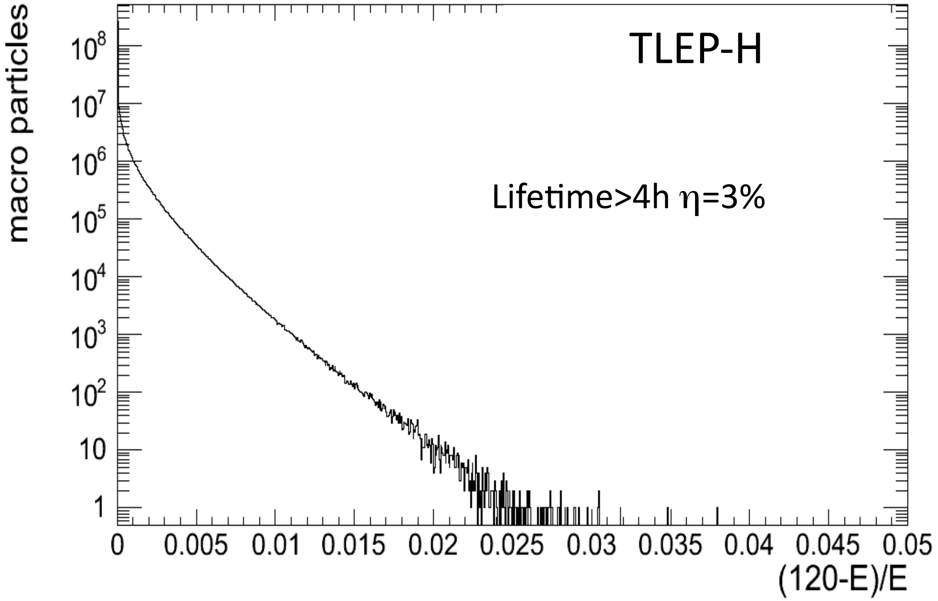
ρ_D= magnets bending radius

To increase beam lifetime:

- Reduce N and increase f_{coll} keeping P constant
  - Reduces L as well
- Increase σ_x and reduce σ_y keeping luminosity constant
  - Increases ξ_y (ok if you are below the tune shift limit)
- Increase the ring energy acceptance
  - High RF voltage
  - Large off energy dynamic aperture: a challange to achieve with the large chromaticity of the low β insertion

BS lifetime

- Simulate and track O(10^8) macroparticles and check the energy spread spectrum
- Lifetime computed from the fraction of particles beyond a given momentum acceptance (η)
- Exponential dependence on η



- BS lifetime for nominal parameters (assuming $\eta=0.04$):
  - LEP3: >~ 30 min
  - TLEP-H: ~day
    - >4h for $\eta=0.03$, ~4 min for $\eta=0.02$

M. Zanetti, HF2012

SuperB beam lifetime estimation

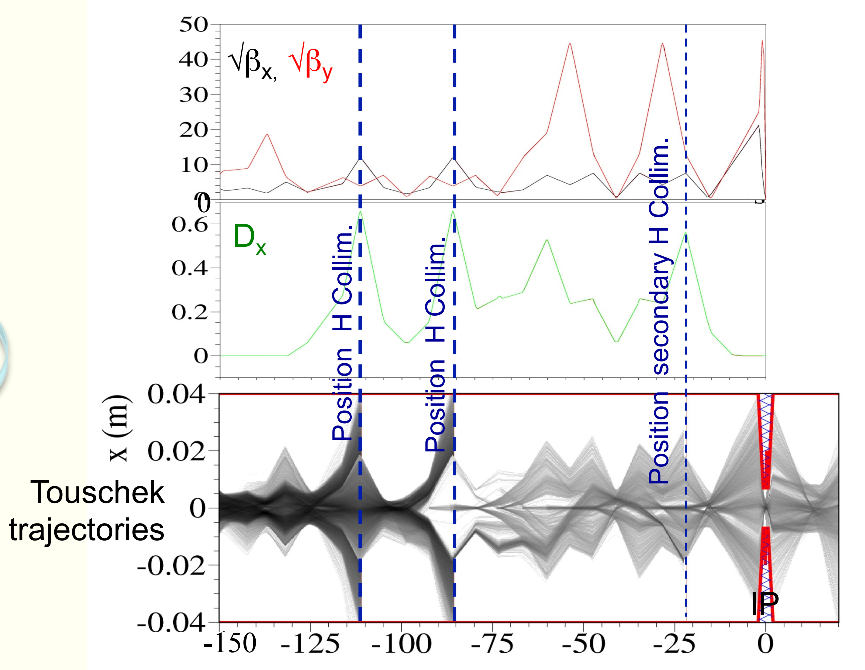
- Dominated by luminosity itself- all other contributions are much smaller but for the Touschek effect in the LER.
- Dynamic aperture and momentum acceptance are crucial for the Touschek lifetime
- dedicated Monte Carlo simulation (for all the effects contributing to particle losses) necessary for:
  - lifetime evaluation
  - careful study of backgrounds, horizontal/vertical collimation system design and shieldings

Lifetime (seconds)	**HER**	**LER**
Radiative Bhabha	290* / 280+	380* / 420+
Touschek	1320	420
Coulomb Beam-gas	3040	1420
Bremsstrahlung	72 hrs	77 hrs

with collimators inserted and IBS included
(momentum acceptance calculated with tracking)

* 1% momentum acceptance assumed
+ momentum acceptance calculated with tracking

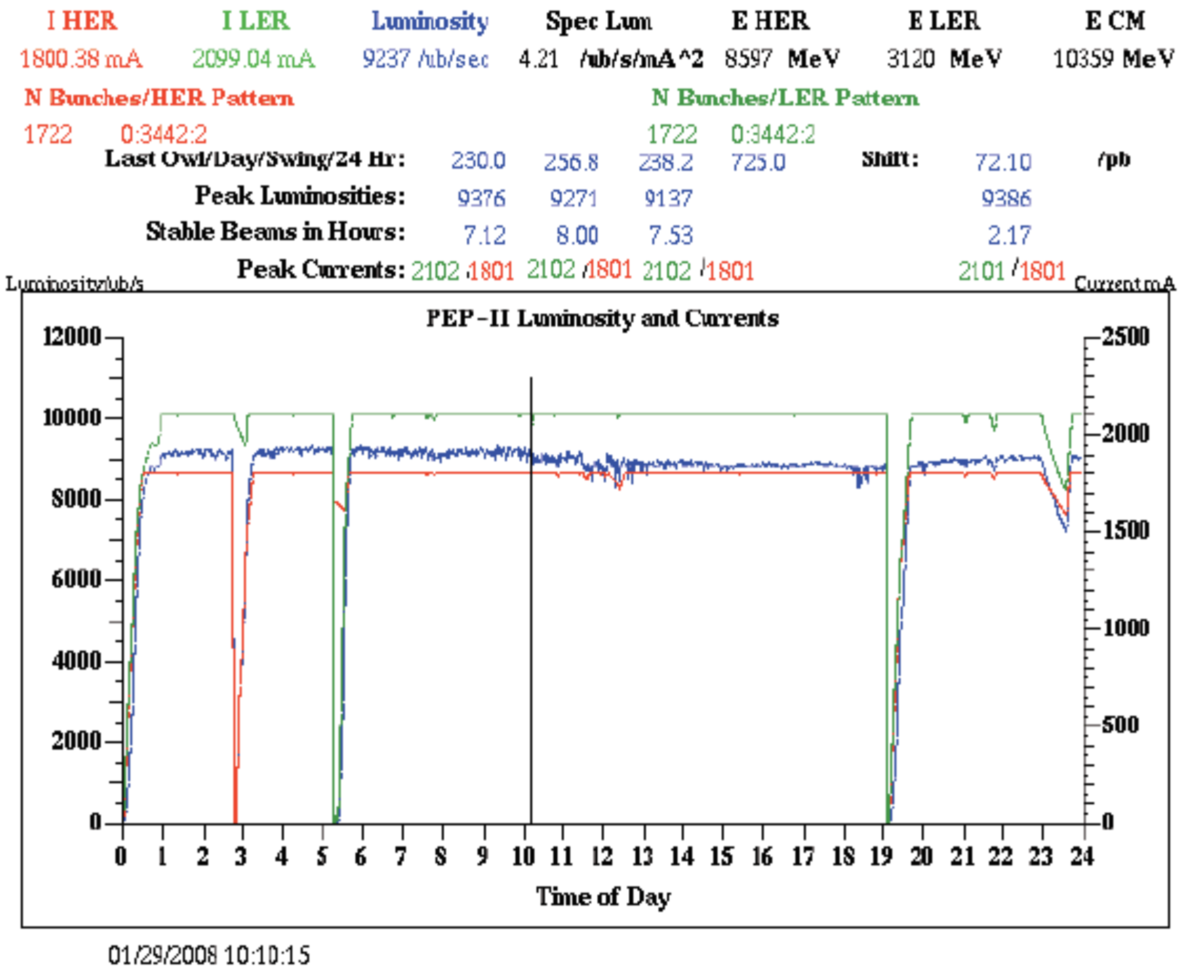
Total Lifetime	**220 s** (3.7 min)	**180 s** (3.0 min)



M. Boscolo

Continuous injection

- To keep the luminosity nearly constant continuous injection at high repetition rate is needed
- PEP-II had the most powerful injector!



I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1800.38 mA	2099.04 mA	9237 /ub/sec	4.21 /ub/s/mA^2	8597 MeV	3120 MeV	10359 MeV

N Bunches/HER Pattern	N Bunches/LER Pattern
1722 0:3442:2	1722 0:3442:2

Last Owl/Day/Swing/24 Hr:	230.0	256.8	238.2	725.0	Shift:	72.10	/pb
Peak Luminosities:	9376	9271	9137			9386	
Stable Beams in Hours:	7.12	8.00	7.53			2.17	
Peak Currents:	2102 /1801	2102 /1801	2102 /1801			2101 /1801	

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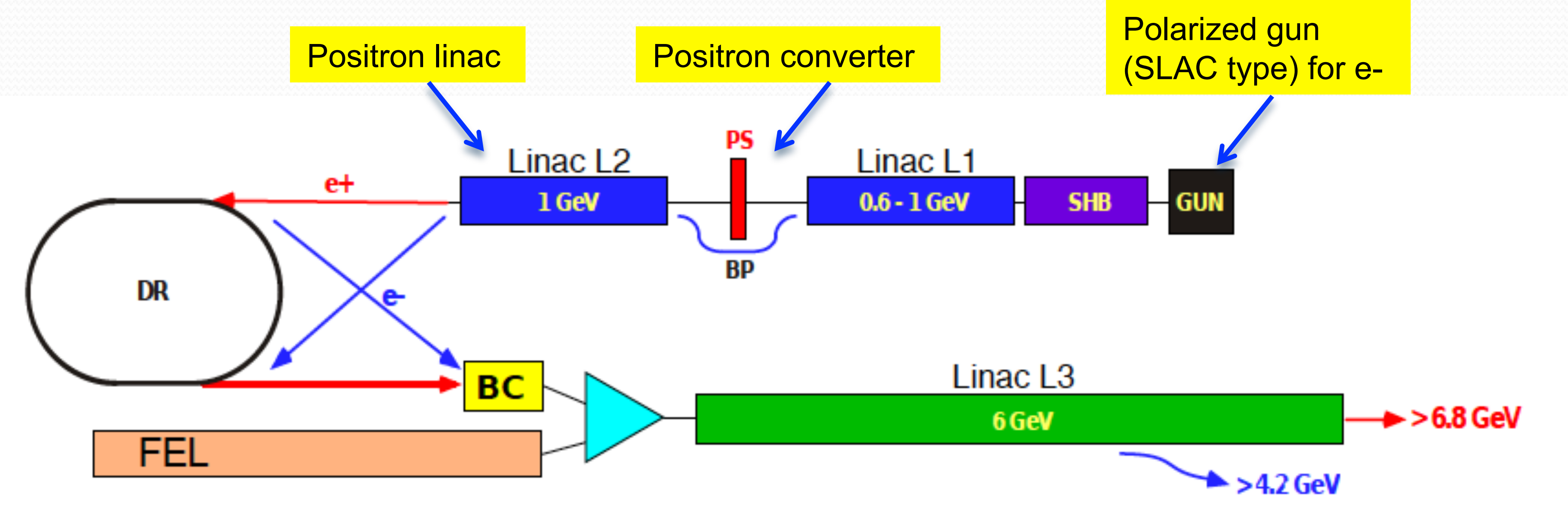
SuperB Injection system layout



At a luminosity of 10^{36} $cm^{-2}s^{-1}$ beam lifetime is limited by Bhabha scattering at IP to ~ 5 min

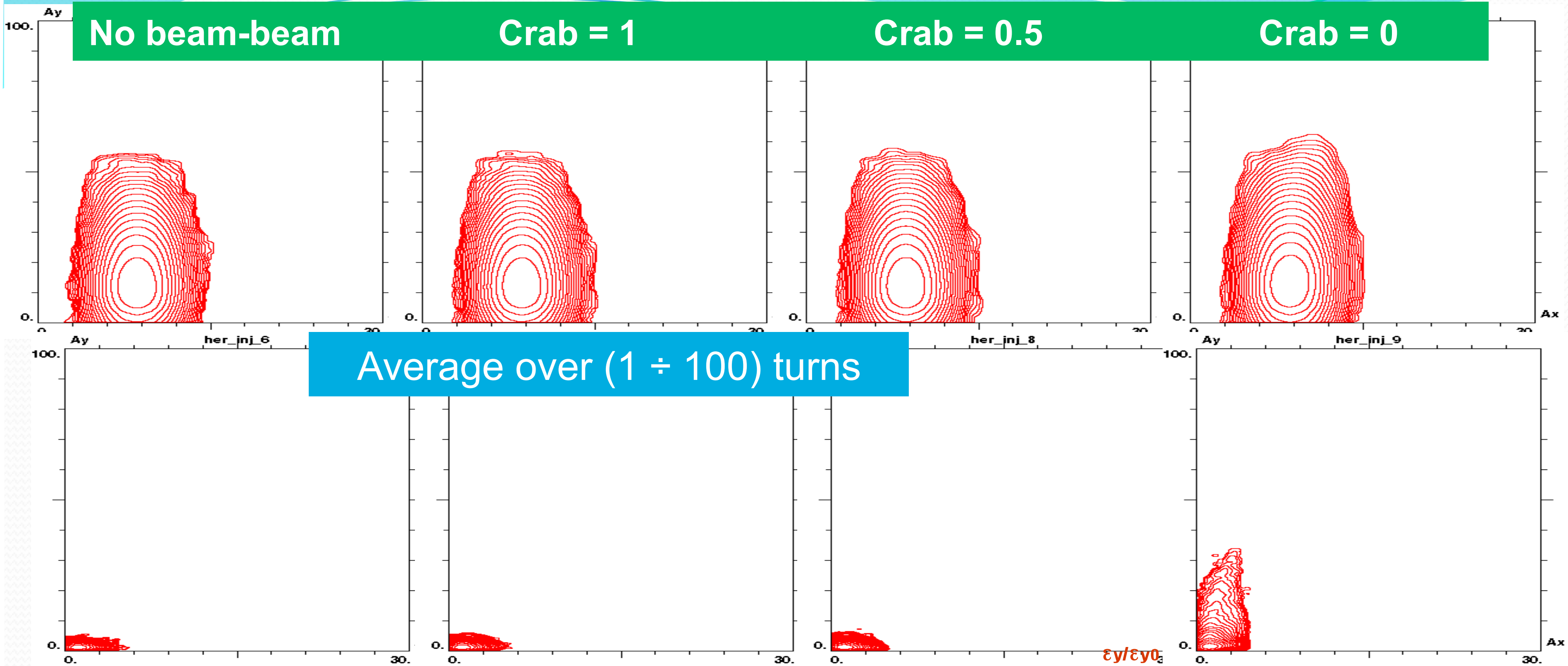
To keep nearly constant such a high luminosity continuous injection in the two rings of the collider, with high efficiency ~ 99%, is needed:

~ $3\ 10^{11}$ e^- and e^+ per second

Beams from the sources are alternatively stored in a damping ring (DR) reducing the emittances to the very low values required

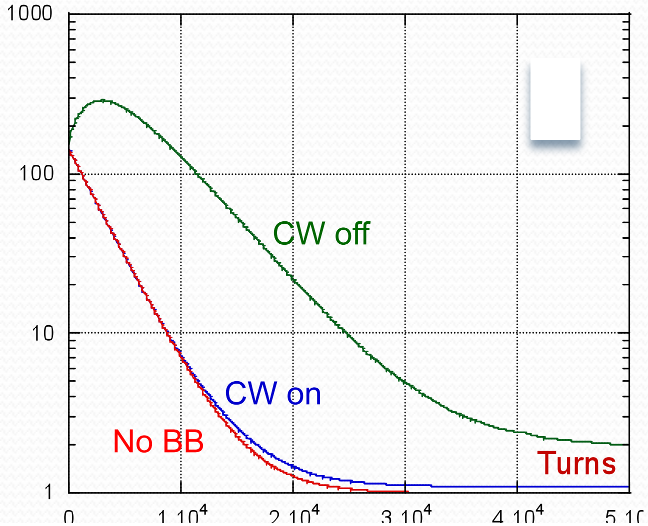
Injection tracking with beam-beam for SuperB

No beam-beam | Crab = 1 | Crab = 0.5 | Crab = 0



Average over (1 ÷ 100) turns

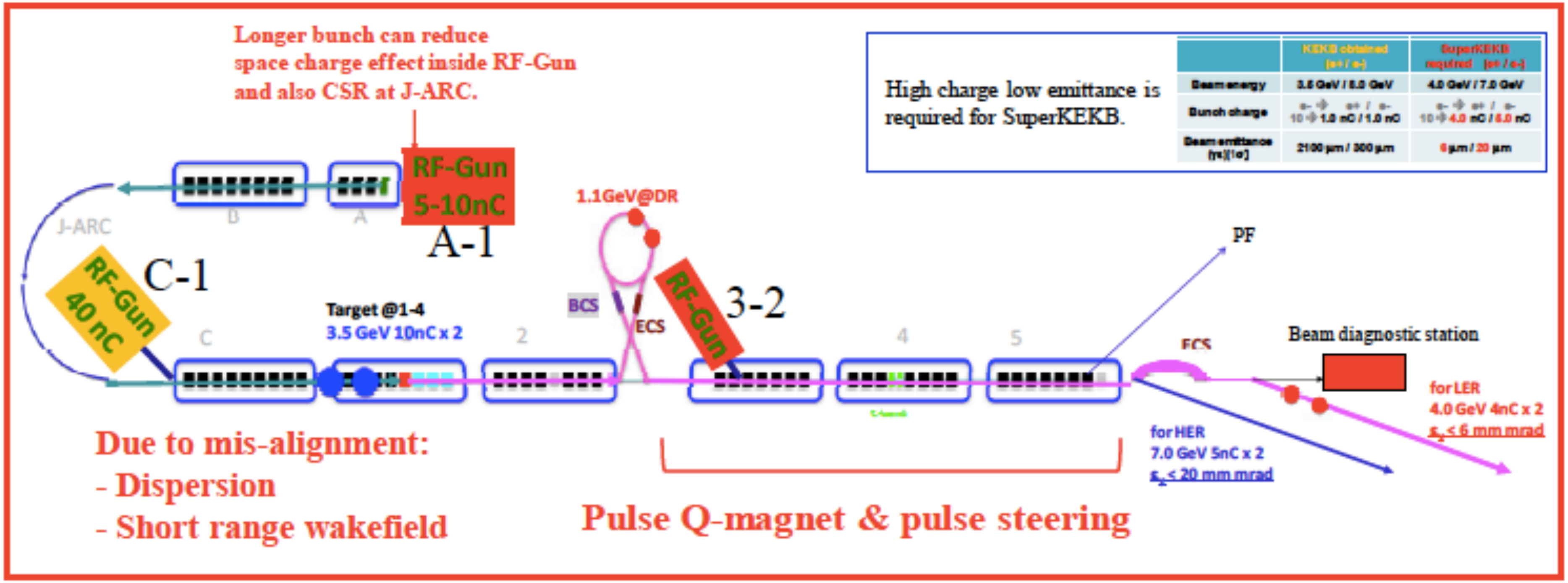
Average over (30001 ÷ 30100) turns (6 damping times)



Contour plots of the injected beam distribution in the plane of normalized betatron amplitudes. 10^5 particles were tracked, and their coordinates over 100 consecutive turns were collected to build the distribution.

D.Shatilov

SuperKEKB Injection system layout



Longer bunch can reduce space charge effect inside RF-Gun and also CSR at J-ARC.

High charge low emittance is required for SuperKEKB.

	KEKB obtained (e+ / e-)	SuperKEKB required (e+ / e-)
Beam energy	3.5 GeV / 8.0 GeV	4.0 GeV / 7.0 GeV
Bunch charge	e- → e+ / e- 10 → 1.0 nC / 1.0 nC	e- → e+ / e- 10 → 4.0 nC / 5.0 nC
Beam emittance (γε)(1σ)	2100 μm / 300 μm	6 μm / 20 μm

Due to mis-alignment:
- Dispersion
- Short range wakefield

Pulse Q-magnet & pulse steering

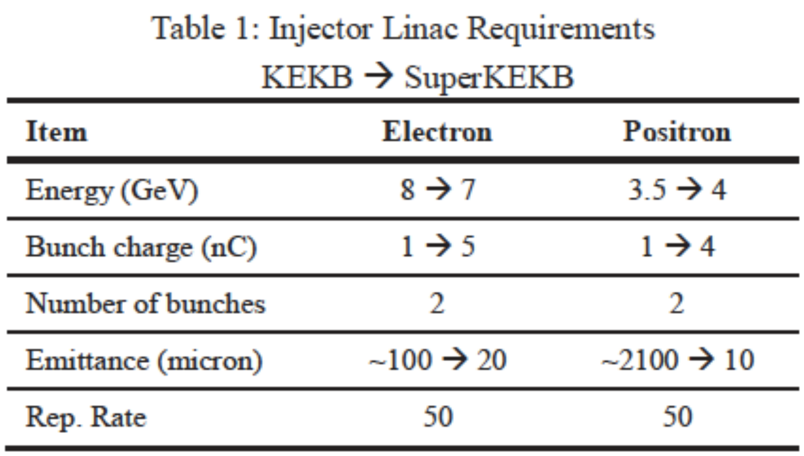


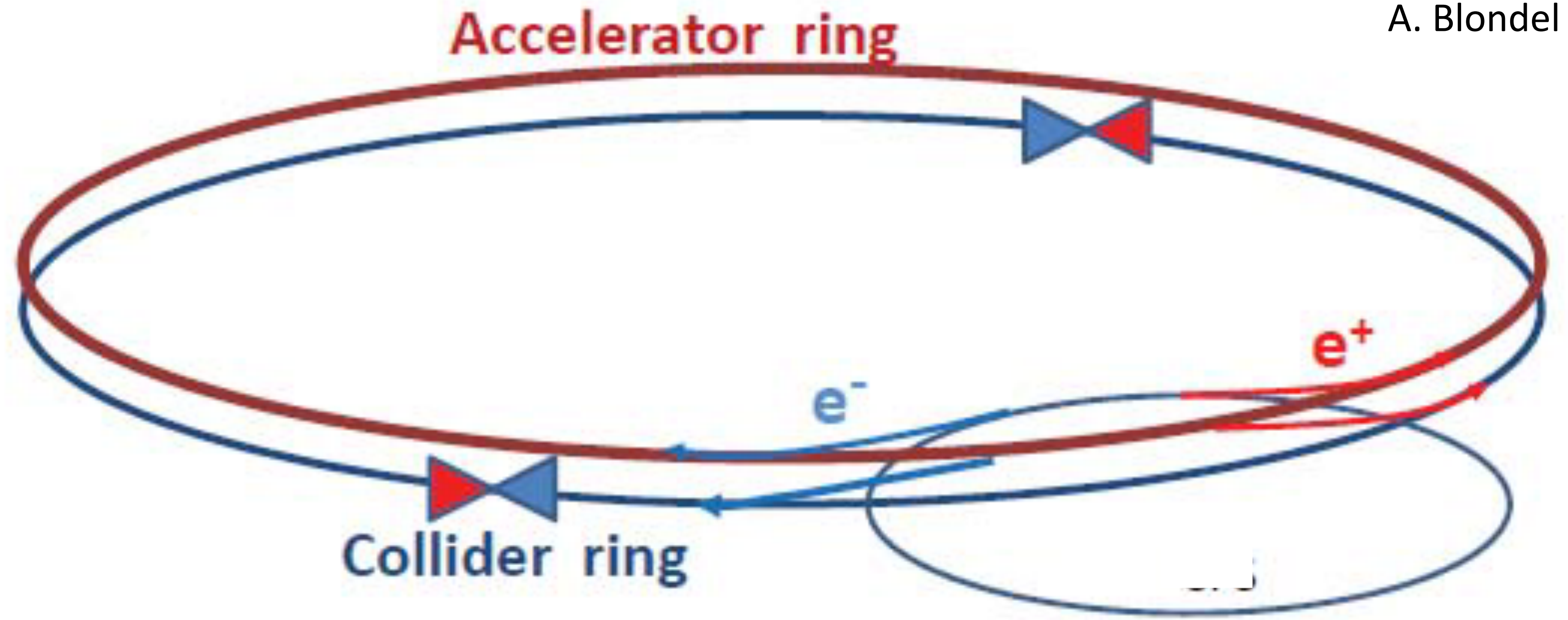
Table 1: Injector Linac Requirements
KEKB → SuperKEKB

Item	Electron	Positron
Energy (GeV)	8 → 7	3.5 → 4
Bunch charge (nC)	1 → 5	1 → 4
Number of bunches	2	2
Emittance (micron)	~100 → 20	~2100 → 10
Rep. Rate	50	50

M.Yoshida, T. Higo IPAC12

LEP3/TLEP: **double ring w. top-up injection** supports short lifetime & high luminosity

A. Blondel



a first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, which includes high luminosity ≥10^{34} cm^{-2} s^{-1} interaction points

F. Zimmermann HF2012

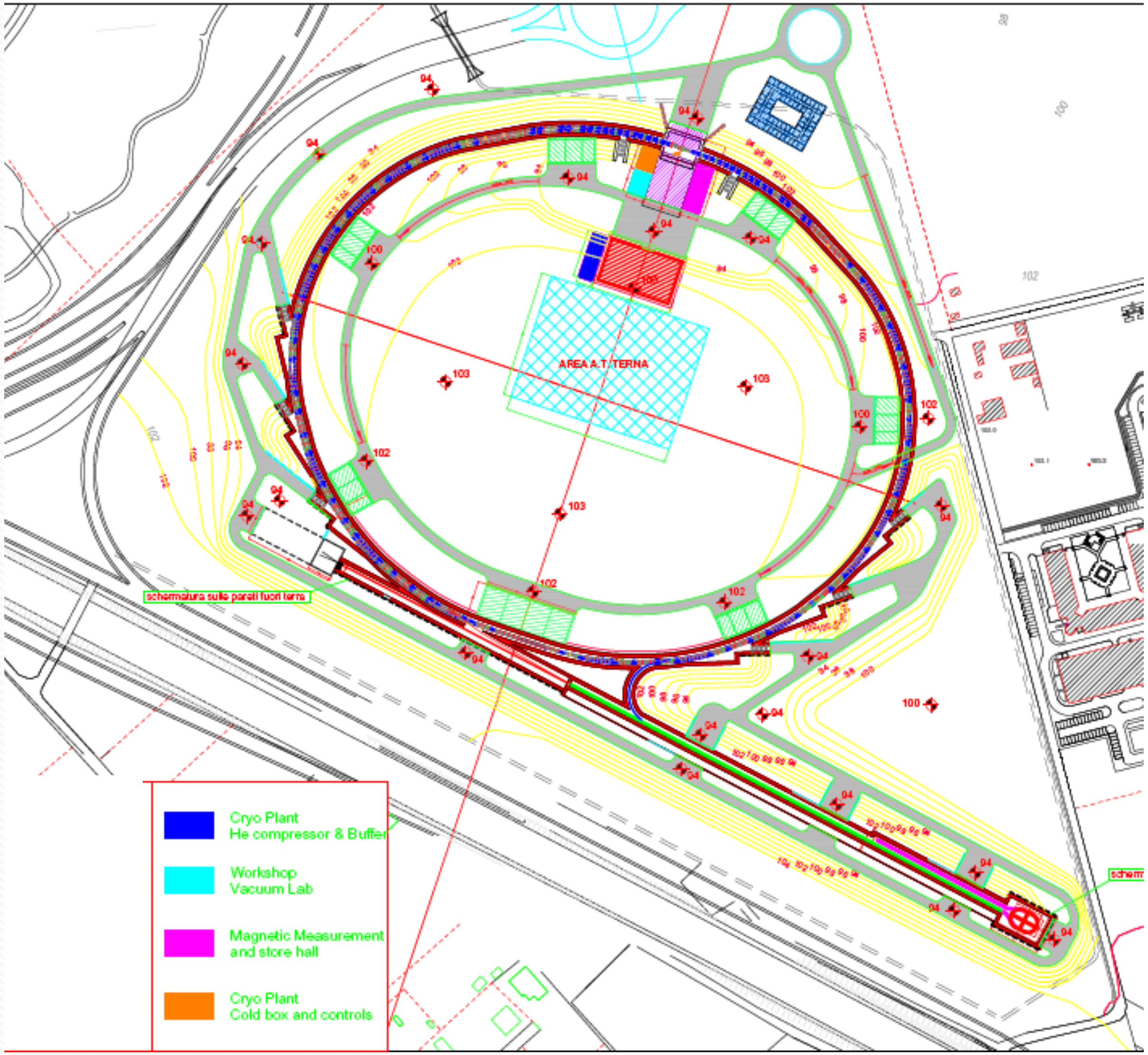
SuperB - ultra high luminosity

- SuperB is an asymmetric lepton collider aiming at a luminosity of 10^{36} cm^{-2} s^{-1} at the Y(4S) center of mass energy 10.6 GeV
- The target luminosity is ~ two orders of magnitude larger than that achieved by PEP-II (SLAC, USA) and KEKB (KEK, Japan)
- The leptons are stored in two rings (e^+@6.7 GeV, e^-@4.2 GeV) intersecting with a crossing angle at the interaction point
- Interaction region design is based on “crab waist scheme”

Layout @ Tor Vergata University campus

SuperB project has been approved by the Italian Government as part of the National Research Plan

Will be built by the Cabibbo Lab in the Tor Vergata University campus, just 5 Km away from the INFN Frascati National Laboratories.



SuperB-Factory design in a nutshell

- Low emittance, large Piwinski angle
- Longitudinal overlap area related to horizontal beam size not to bunch length, so it can be greatly reduced allowing a reduction of:
  - Vertical beta, beam size, hourglass and tune shift
  - Horizontal tune shift (1D beam-beam)
- «Crab-waist» sextupoles at a proper phase with respect to the IP:
  - suppress most of XY resonances
  - tunes area for operation is larger
- Same Luminosity with lower currents:
  - lower HOM heating
  - less power consumption

Design requirements & challenges (some!)

- Extremely small emittances, both H and V, comparable to those achieved in the last generation SR sources or planned for linear colliders Damping Rings
- Strong IP doublets:
  - SC quads in a restricted space
  - separated beams
  - control of background rates
  - physical aperture
- Coupling & chromaticity correction in the IR
- Dynamic aperture with crab sextupoles
- Control of vibrations at IP
- Sensitivity to magnets alignment errors → Low Emittance Tuning
- Touschek lifetime and IBS emittance growth

Super B-Factories main parameters

Parameter	SuperB		SuperKEKB	
	HER (e^+)	LER (e^-)	HER (e^-)	LER (e^+)
Luminosity ($cm^{-2}s^{-1}$)	10^{36}		$8x10^{35}$	
C (m)	1200		3016	
E (GeV)	6.7	4.18	7.007	4
Crossing angle (mrad)	60		83	
Piwinski angle	20.8	16.9	19.3	24.6
I (mA)	1900	2440	2600	3600
$\varepsilon_{x/y}$ (nm/pm) (with IBS)	2/5	2.5/6.2	4.6/11.5	3.2/8.6
IP $s_{x/y}$ (mm/nm)	7.2/36	8.9/36	10.7/62	10.1/48
σ_l (mm)	5	5	5	6
N. bunches	978		2500	
Part/bunch ($x10^{10}$)	5.1	6.6	6.5	9.04
σ_E/E ($x10^{-4}$)	6.4	7.3	6.5	8.14
bb tune shift (x/y)	0.0026/0.107	0.004/0.107	0.0012/0.081	0.0028/0.088
Beam losses (MeV)	2.1	0.86	2.4	1.9
Total beam lifetime (s)	254	269	332	346
Polarization (%)	0	80	0	0
RF (MHz)	476		508.9	

M. E. Biagini IPAC12

Acknowledgements

- In this lesson is described the work of many accelerator physicists since AdA; I'll try to give the references but it's impossible to reference all
- A useful source of information on circular colliders is the ICFA BD Newsletter 48
- Very interesting and updated material on the new "Higgs Factories" can be found at the workshop HF2012, Accelerators for a Higgs Factory, Fermilab, 14-16 November 2012
- Other data and references can be found in the proceedings of the IPAC (and PAC, EPAC, APAC) conferences
- Thanks to all the contributors and in particular to my colleagues Marica Biagini, Mikhail Zobov and Manuela Boscolo who borrowed me their slides and to Mario Bassetti who introduced me in the field

This presentation is based on the work of many physicists over many years and on fruitful discussions with many colleagues
Sorry for not mentioning everybody in the slides or in the references

Thanks to all