Issues for Optimization of a Super-B Factory

John T. Seeman

SBF Workshop

SLAC

June 14, 2006

High Luminosity Topics

- Horizontal emittance
- Vertical emittance
- Bunch length and compression
- Maximum beam-beam parameter
- Crab cavities
- Crab waist
- Damping ring circumference
- IR design
- AC power vs synchrotron radiation power
- Beam-beam effects makes optimum “non-linear”

History

- **2003-2005: Both KEKB and PEP-II B-Factories have reached over 1 x 10^{34} /cm^2/s!**
- **2002-2005: Both KEK and SLAC pursued Super-B upgrades with significantly higher currents and lower β_y*.**
- **2004: Super-KEKB design is presented to the KEK Laboratory.**
- **March 2005: Emerged from the Super-B Workshop in Hawaii a concept of a single pass Linear Super-B Factory**
- **November 2005: Frascati workshop outlined a Super-B design with single pass collisions, bunch compression, and energy recovery linacs.**
- **March 2006: Frascati workshop outlines a Super-B Collider design that collides every turn but with bunch compression or large crossing angles. Crab waists help.**
- **May 2006: Beam-beam simulations with more slices show larger tune shifts.**

PEP-II

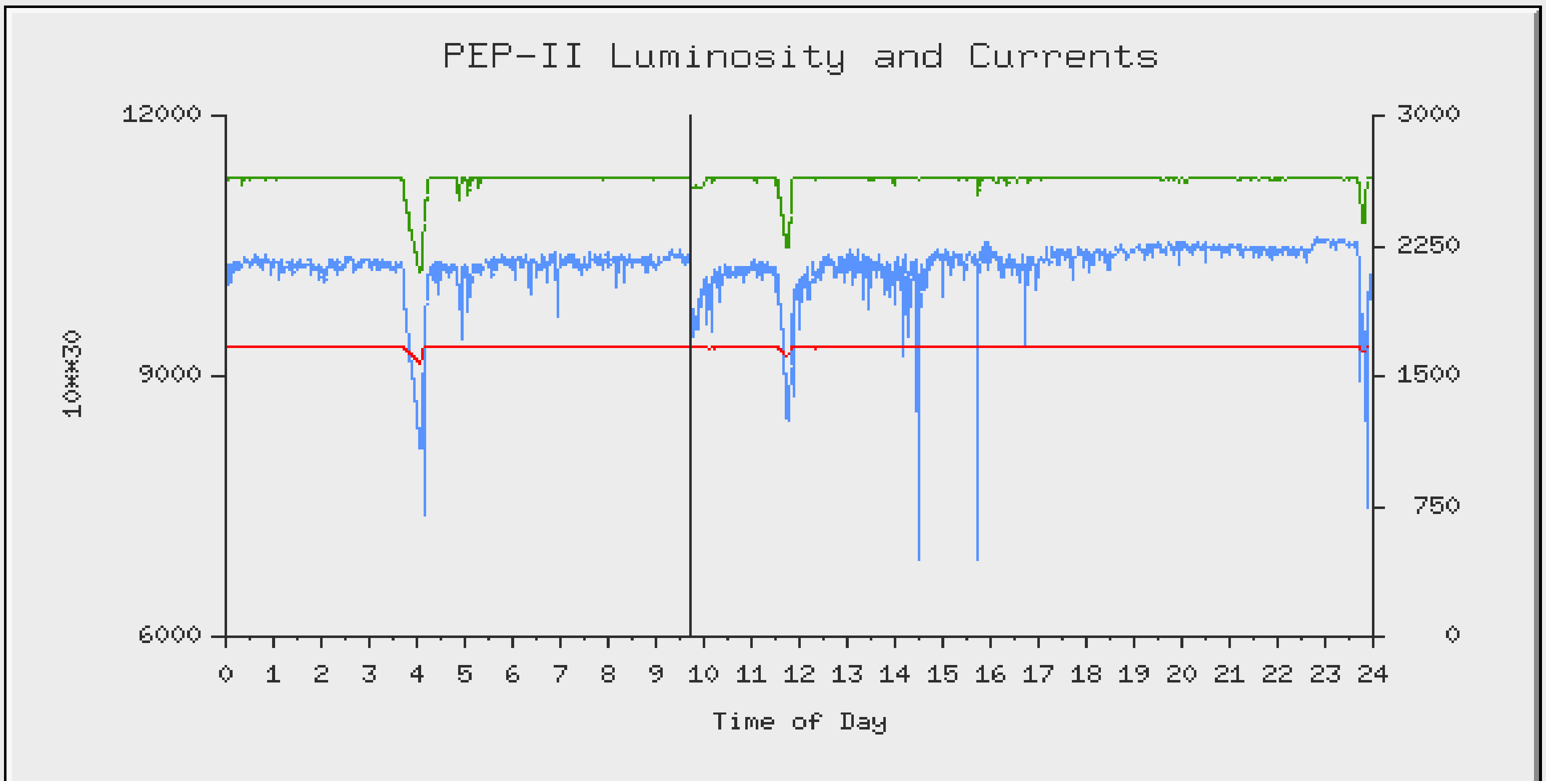
I HER	I LER	Luminosity	Spec Lum	E HER	E LER	E CM
1680.41	2649.57	10366	4.01	8917	3120	10549
mA	mA	10**30/Sec	N*10**30 / mA**2/Sec	MeV	MeV	MeV

HER N Buckets / Pattern LER N Buckets / Pattern

1722 0=1;3442=0.96;0:3442:2=· 1722 0:3442:2

Best shift and 24 hr

Last Owl/Day/Swing/24hr	293.9	290.4	299.4	883.7	Shift:	65.85 /pb
Peak Luminosities	10510	10587	10608			10515



06/12/2006 09:45:16

PEP-II Records

Last update: June 12, 2006

Peak Luminosity

10.877×10^{33} $cm^{-2}sec^{-1}$ May 25, 2006

1722 bunches 2700 mA LER 1775 mA HER

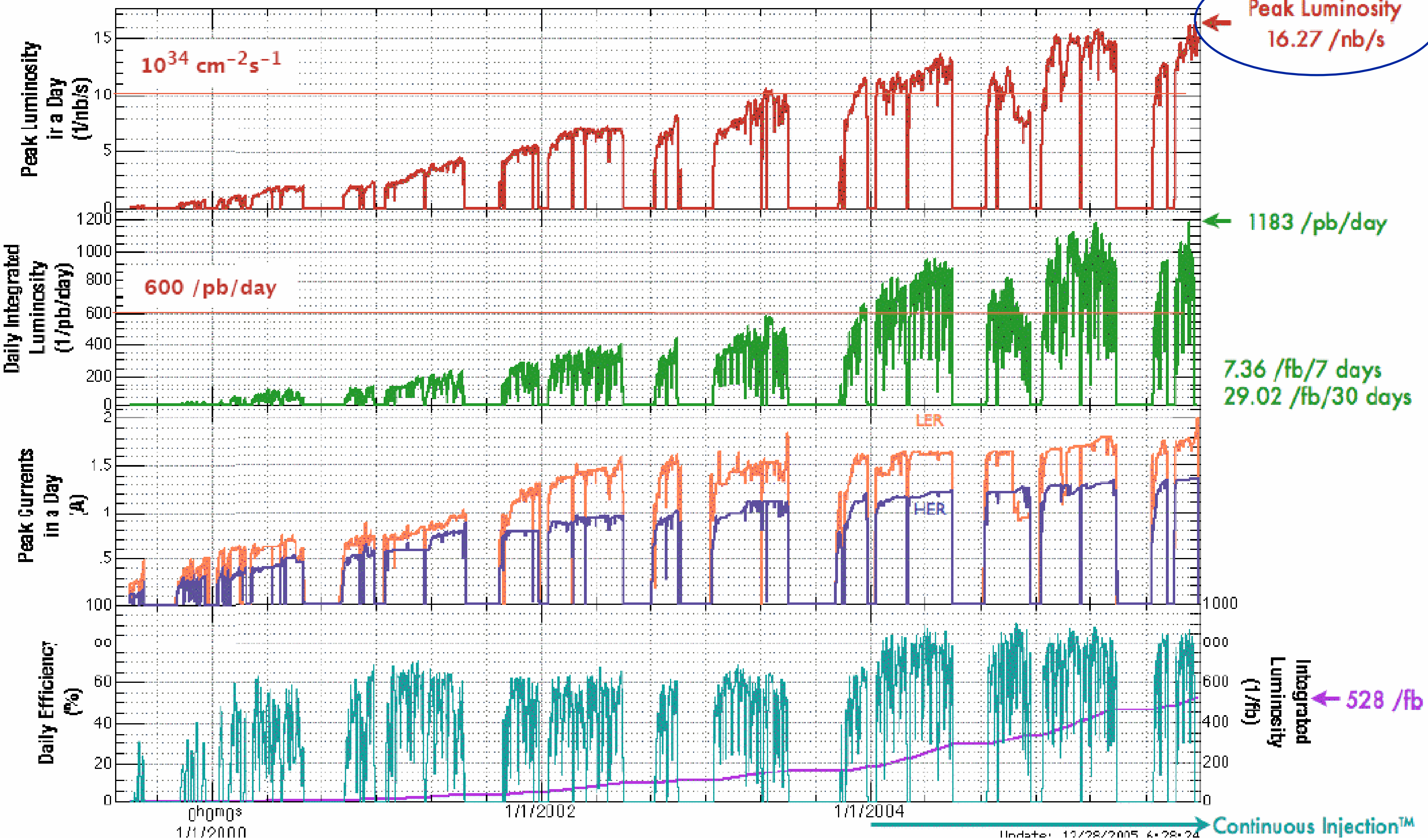
Integration records of delivered luminosity

Best shift (8 hrs, 0:00, 08:00, 16:00)	299.4 pb^{-1}	Jun 11, 2006
Best 3 shifts in a row	883.7 pb^{-1}	Jun 11-12, 2006
Best day	786.3 pb^{-1}	Jun 11, 2006
Best 7 days (0:00 to 0:00)	4.464 fb^{-1}	Jul 25-Jul 31, 2004
Best week (Sun 0:00 to Sat 24:00)	4.464 fb^{-1}	Jul 25-Jul 31, 2004
Peak HER current	1776 mA	May 31, 2006
Peak LER current	2995 mA	Oct 10, 2005
Best 30 days	16.720 fb^{-1}	Jul 2 – Jul 31, 2004
Best month	17.036 fb^{-1}	July 2004

Total delivered

371 fb^{-1}

Luminosity of KEKB
June 1999 - Dec. 2005



Super-B Basic concepts

- Higher currents and large number of bunches make more luminosity but needs higher RF power.
- Faster damping allows stronger collisions but needs higher RF power.
- Shorter bunches allow smaller vertical spot sizes but larger HOMs. Crab waists helps.
- Lower emittance makes for smaller spot sizes but leads to single ring enlargment issues.
- Need small energy spread ($\sim 10^{-3}$) in the collisions to match Y4S resonance shape.

Luminosity

- The luminosity for a linear collider is:

  $L = Hd\ Np\ P / 4\pi E\ \sigma_x \sigma_y$

  Hd : disruption enhancement

  P : average beam power

- For a storage ring is:

  $L = 2.17 \times 10^{34} (1+r)\ \xi_y\ EI / \beta_y$

  I : beam current

  ζ_y : vertical tune shift

  β_y : IP vertical beta function

Scaling laws to optimize the single pass IP parameters

- **Disruption:**

$$D \approx \frac{N\sigma_z}{\left(\sigma_x \sigma_y\right)}$$

Decrease σ_z + decrease N
Increase spotsize

- **Luminosity**

$$L \approx \frac{N^2}{\left(\sigma_x \sigma_y\right)}$$

Increase N
Decrease spotsize

Contradicting requests!

- **Energy spread:**

$$\delta_E \approx \frac{N^2}{\left(\sigma_x^2 \sigma_z\right)}$$

Increase σ_z + decrease N
Increase spotsize

P. Raimondi

More Detailed Luminosity Equation

$$L = 5x10^{35}\left[\frac{\xi_y}{0.1}\right]\left[\frac{N}{10^{11}}\right]\left[\frac{1mm}{\beta_y^*}\right]\left[\frac{1m}{s}\right]\left[\frac{E}{5GeV}\right]F$$

ξ_y* = beam-beam parameter = $D_y/4\pi$.

N = number of particles

β_y* = vertical beta function

s = bunch spacing

E = beam energy

F = Hourglass + parasitic collision factor (~<1.0)

Parameters of Super-B Designs

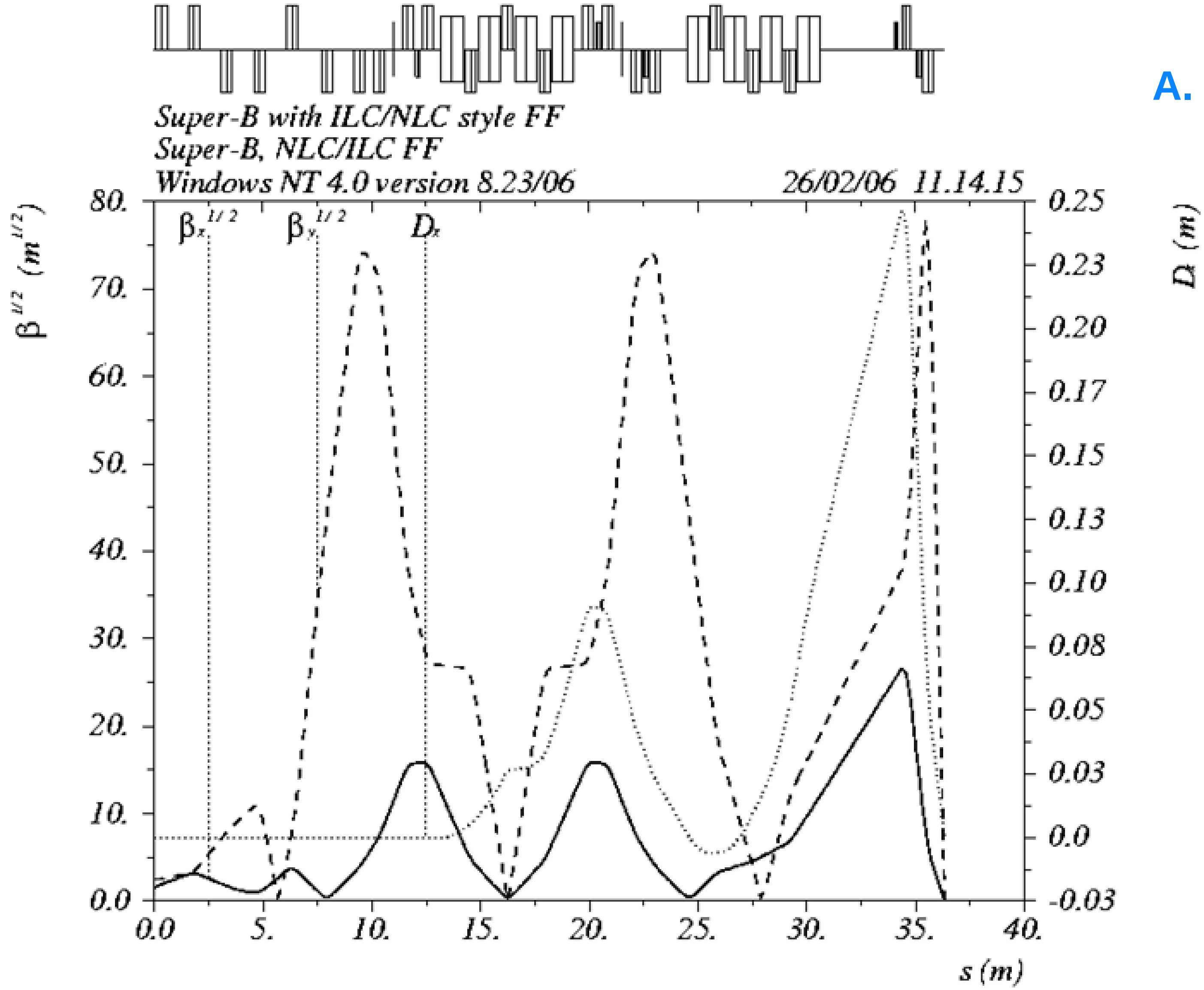
Collider		ξ_y	N	β_y*	s	E	F	Lumin
Units			10^{10}	mm	m	GeV	(~Hd)	10^{35}
PEP-II	Normal	0.07	8	10	1.26	3.1	0.84	0.11
KEKB	Normal	0.065	5.8	6	2.1	3.5	0.76	0.16
Super-PEP-II	High I low βy	0.12	10	1.7	0.32	3.5	0.81	7
Super-KEKB	High I low βy	0.28	12	3	0.59	3.5	0.85	8
Linear SuperB	Single pass	29.	10	0.5	250	4	1.07	10
SuperB	Bunch shorten	0.14	6	0.4	0.63	4	0.75	10
SuperB	X'ing angle	0.045	2	0.08	0.5	5	0.8	10

Final Focus

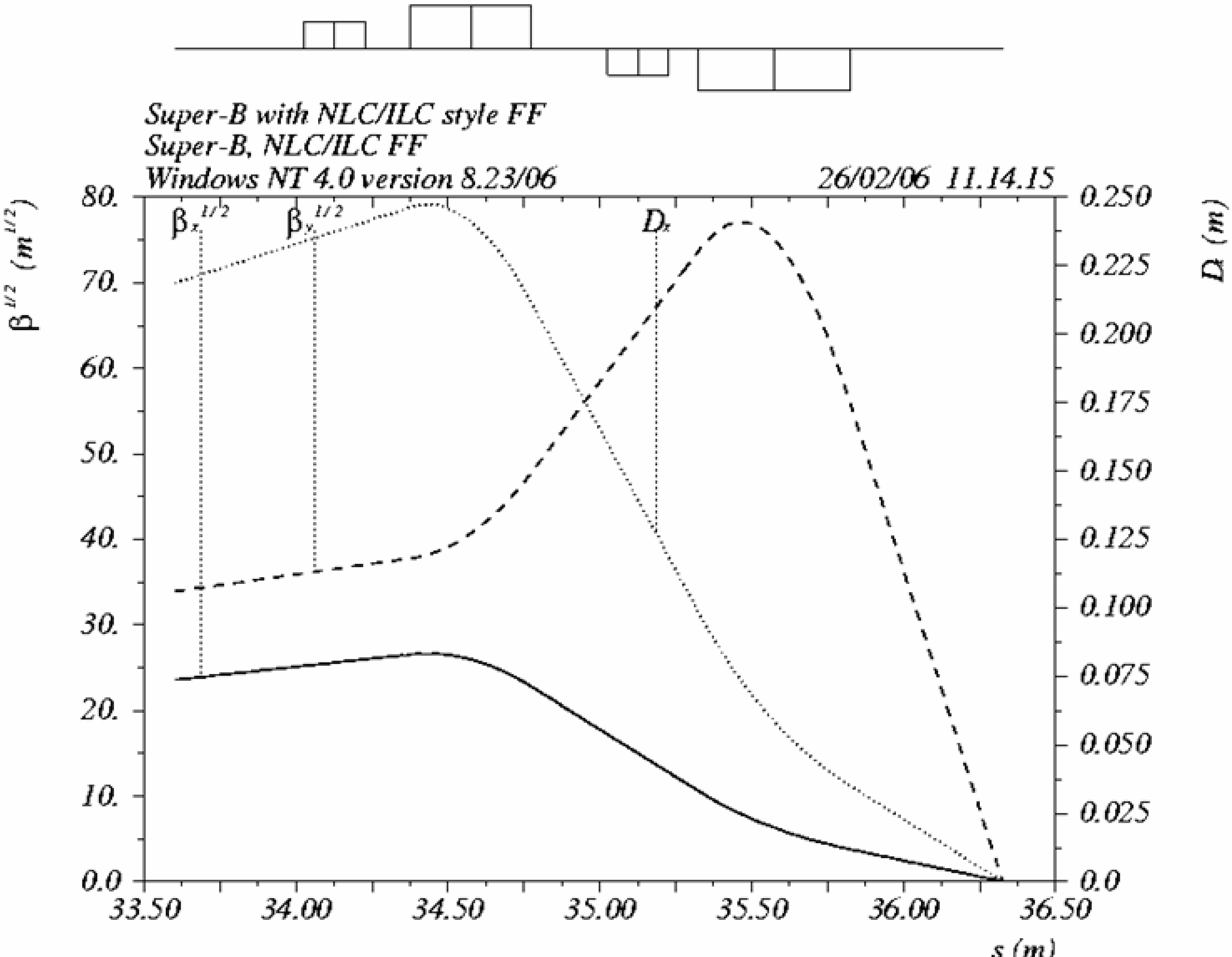
- Use ILC final focus concept
- Scale to B Factory energies
  - (4 x 7 GeV) (3.75x7.5 GeV) (3.5 x 8 GeV) (3.1 x 9 GeV).
- Use small superconducting quadrupoles for the final doublet.
- Chromatic corrections done in the IR with sextupoles.

Optics of FF

A. Seryi



Final doublet part

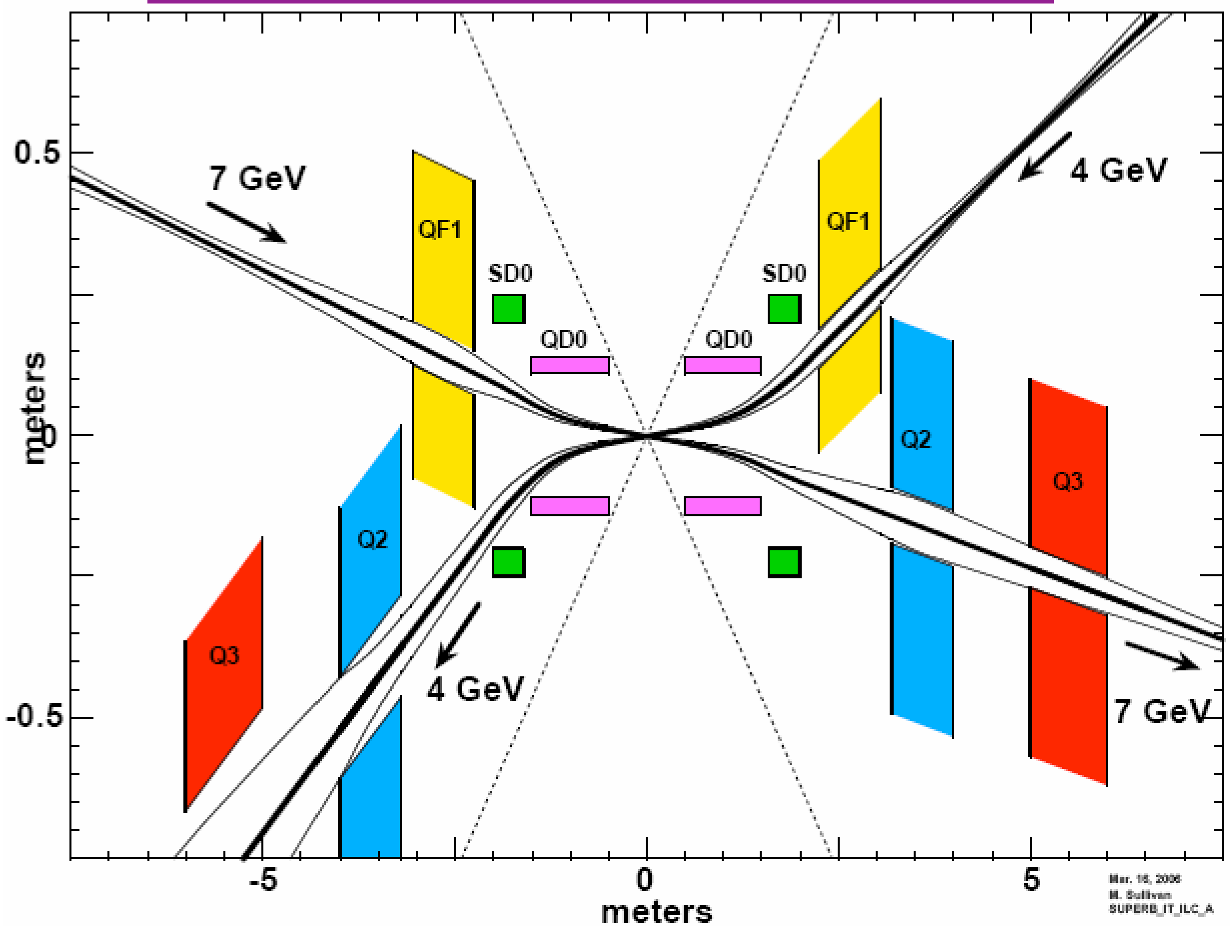


IR Design
M. Sullivan

Some IP Parameters

	HER	LER
Beta x (mm)	2.5	2.5
Beta y (mm)	0.08	0.08
Emittance x (nm-rad)	0.4	0.4
Emittance y (nm-rad)	0.002	0.002
Sigma x (μm)	2.67	2.67
Sigma y (μm)	0.0126	0.0126
Bunch spacing (m)	0.6	
Crossing angle (mrad)	±25	
Luminosity	0.8×10^{36}	

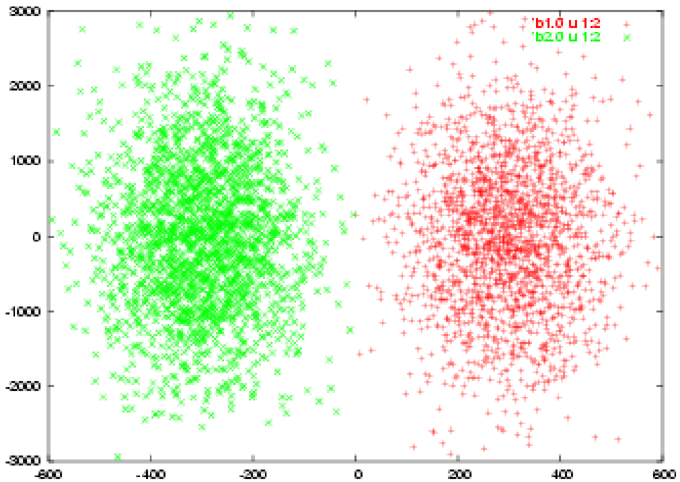
Layout of IR orbits for ILC version Super B Factory



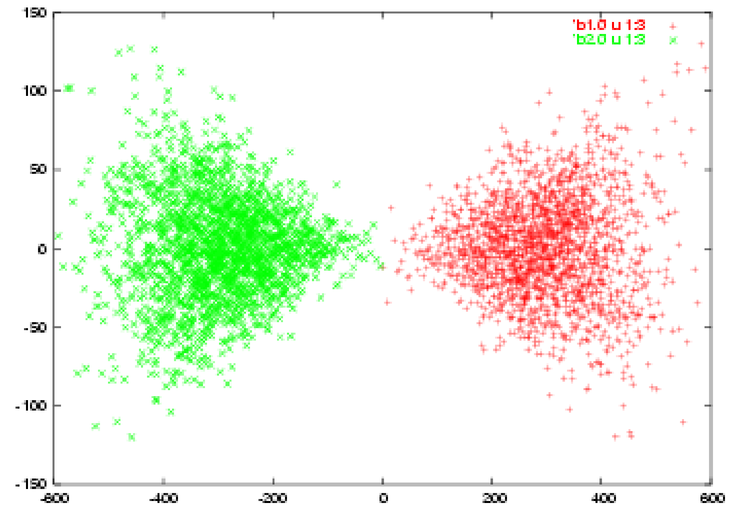
M. Sullivan

Beam-Beam Simulations

- Track macro-particles through the collision to see blow up effects. (Guinea Pig code from ILC + Ohmi beam-beam code + Cai beam-beam code)
- Compare single pass beam-beam effects with ring beam-beam effects.
- Couple single pass collisions with damping in a ring.



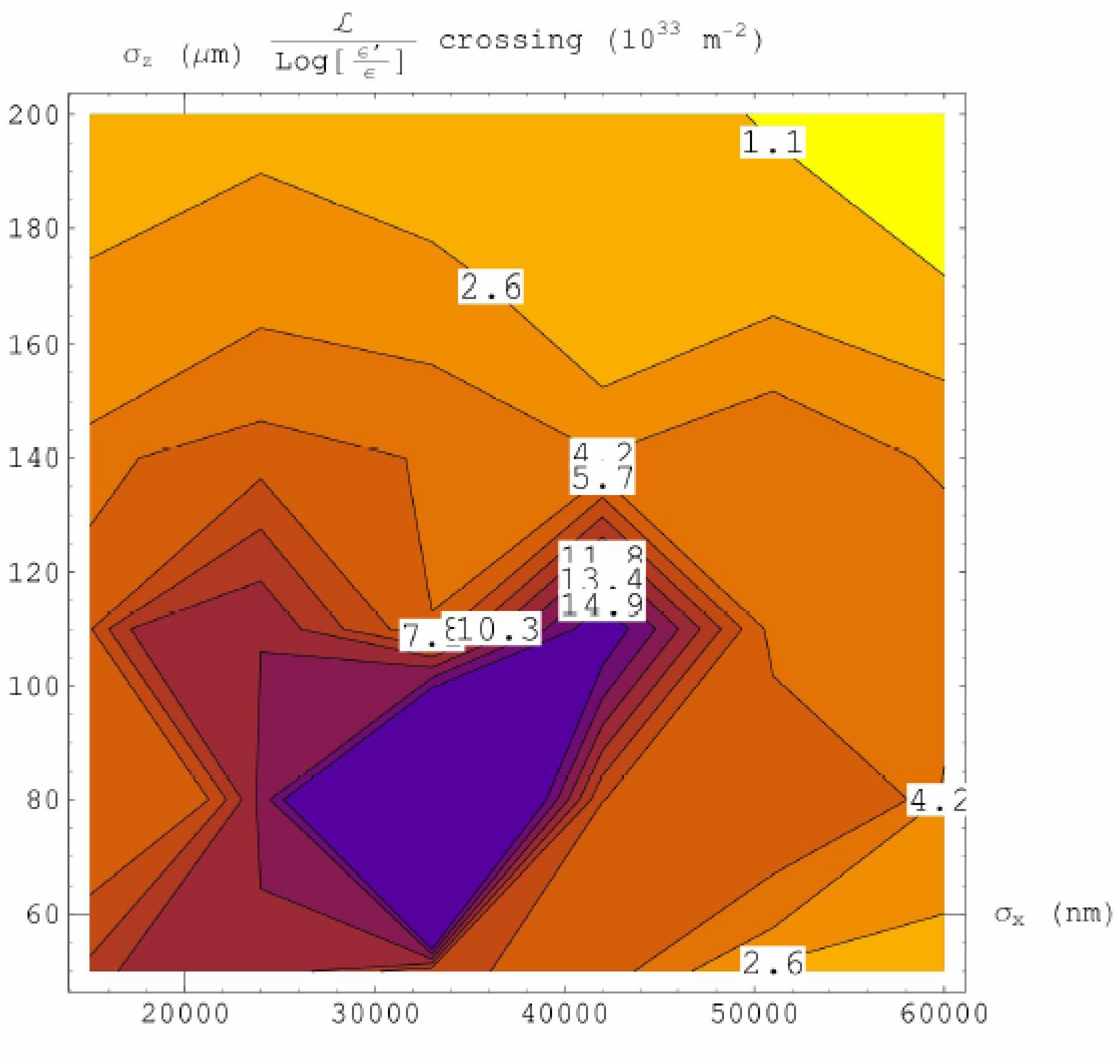
Horizontal Collision



Vertical collision

Effective horizontal size during collision about 10 times smaller, vertical size 10 times larger

Simulations by D.Schulte/Raimondi/Biagini


σz (μm) ℒ / Log[ε′/ε] crossing (10^33 m^-2)
200
180
160
140
120
100
80
60
20000
30000
40000
50000
60000
σx (nm)
1.1
2.6
4.2
5.7
11.8
13.4
14.9
10.3
4.2
2.6

New Parameter Set for 8×10^{35} -- by K. Ohmi

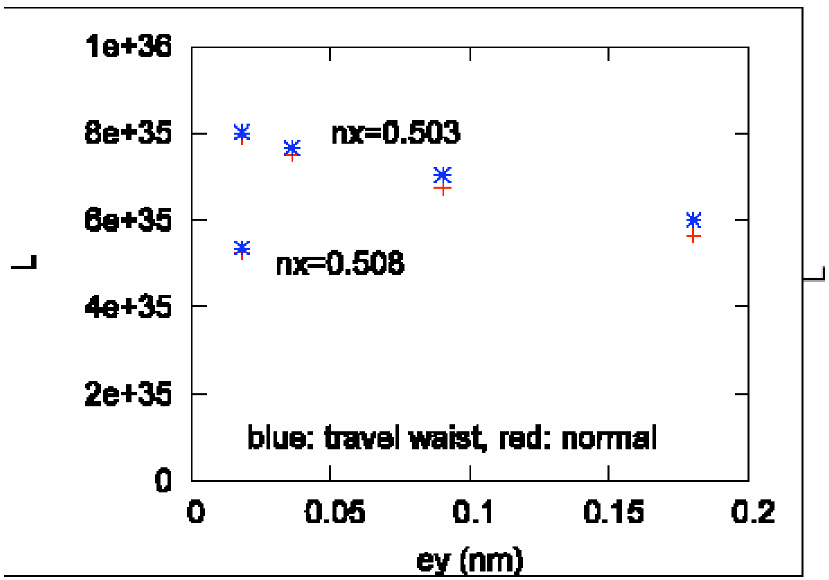
May 2006

	SuperKEKB	Crab waist			
εx	9.00E−09	6.00E−09	6.00E−09	6.00E−09	6.00E−09
εy	4.50E−11	6.00E−11	6.00E−11	6.00E−11	6.00E−11
βx (mm)	200	100	50	100	50
βy (mm)	3	1	0.5	1	0.5
σz (mm)	3	6	6	4	4
νs	0.025	0.01	0.01	0.01	0.01
ne	5.50E+10	5.50E+10	5.50E+10	3.50E+10	3.50E+10
np	1.26E+11	1.27E+11	1.27E+11	8.00E+10	8.00E+10
φ/2 (mrad)	0	15	15	15	15
ξx	0.397	0.0418	0.022	0.0547	0.0298
ξy	0.794→0.24	0.1985	0.179	0.178	0.154
Lum (W.S.)	8E+35	6.70E+35	1.00E+36	3.95E+35	4.80E+35
Lum (S.S.)	8E35	4.77E35	5.65E36	3.94E35	4.27E35

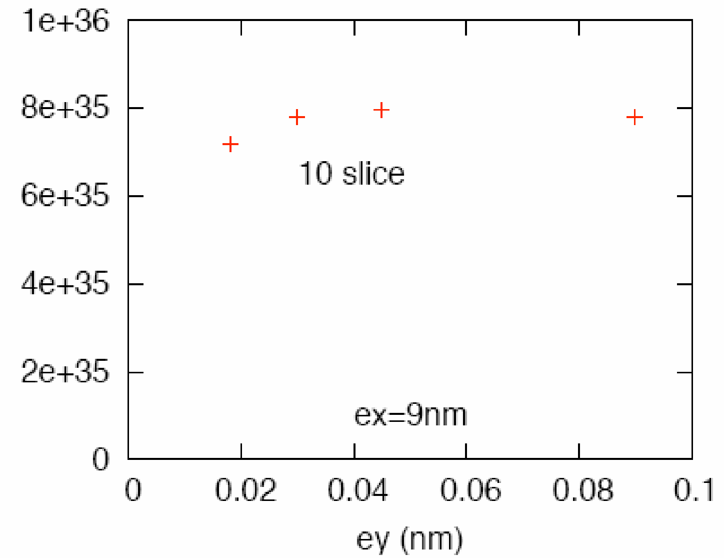
- Good parameters are not yet found with crab waist.

Smaller emittances

K. Ohmi



ex = 18 nm



ex = 9 nm

- For ex = 18 nm, smaller ey gives higher luminosity.
- For ex = 9 nm, luminosity is high up to ey/ex < 1%.

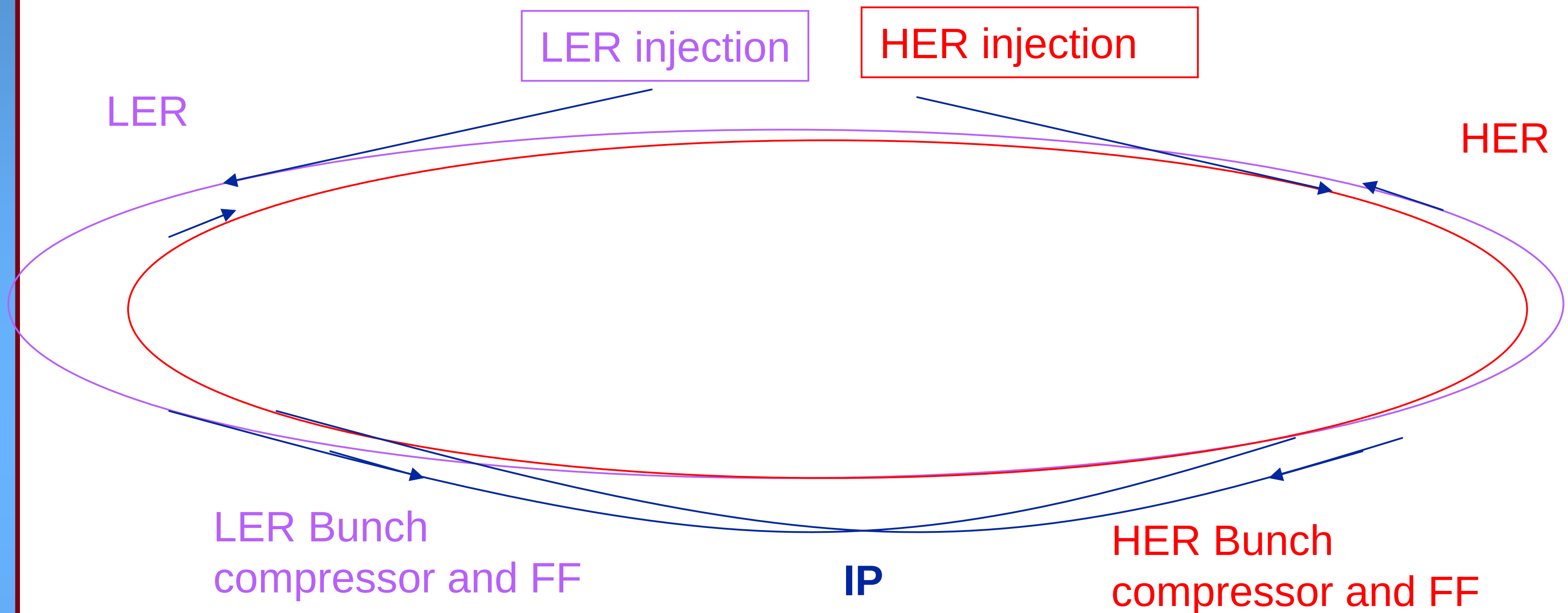
Why was higher luminosity made possible?

- 8×10^{35} cm^{-2}s^{-1} is achievable with same beam currents, beta, bunch length as 4×10^{35} cm^{-2}s^{-1}.
- The simulation was improved by more longitudinal slices to reduce the numerical noises and the instability, using a new supercomputer at KEK.
- A new choice of parameters with smaller emittance ratio or smaller horizontal emittance.
- Crab crossing is necessary.
- No crab waist, travel focus are needed for luminosity, but may help the lifetime.

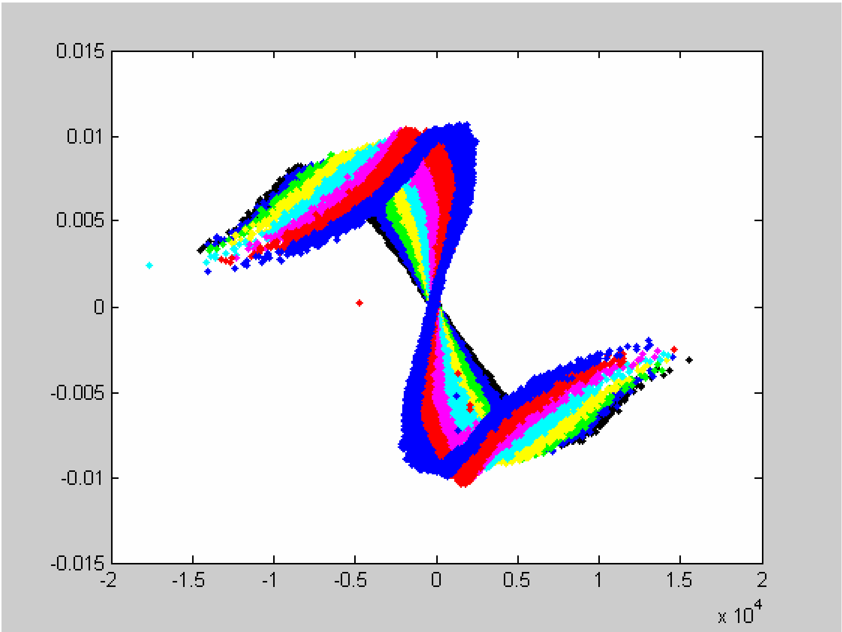
Single Pass Linear Super-B

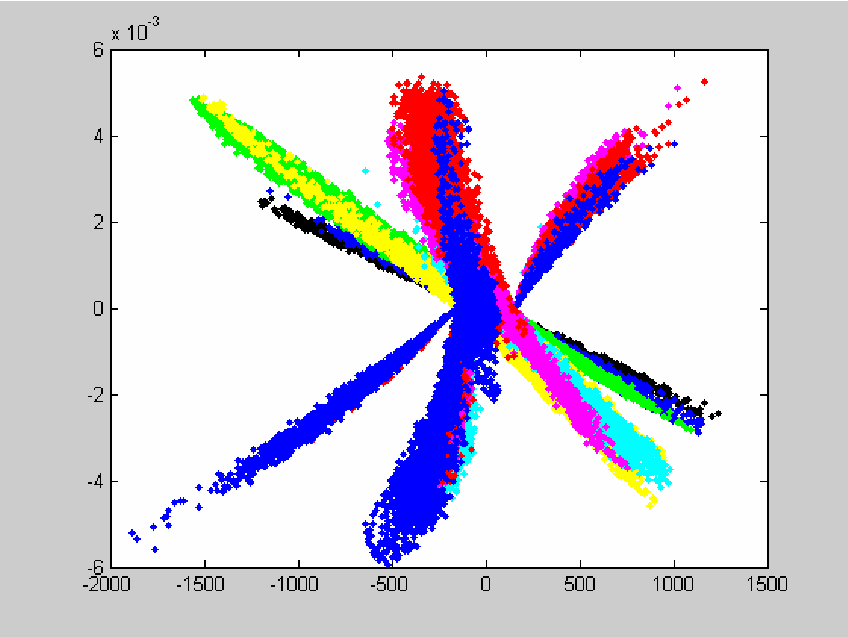
- Collide each bunch once very hard making a lot of luminosity.
- Use very small beta functions at the IP like ILC.
- Re-inject into the damping rings and damp for several damping times.
- Collide again after the disrupted emittances have damped.
- Simulations show vertical emittance blow up is about 300 times.
- Need about 6 damping times between collisions.
- Need very short damping times → high power.

Linear-B scheme



Overall ring length about 6Km,
Collision frequency about 120Hz*10000bunch_trains=1.200MHz
Bunch train stays in the rings for 8.3msec, then is extracted, compressed and focused. After the collision the bunch is reinjected in its ring





Horizontal phase after the collision

Vertical phase after the collision

IP Parameters set considered at the workshop caused large increase of the emittance due to the collision:

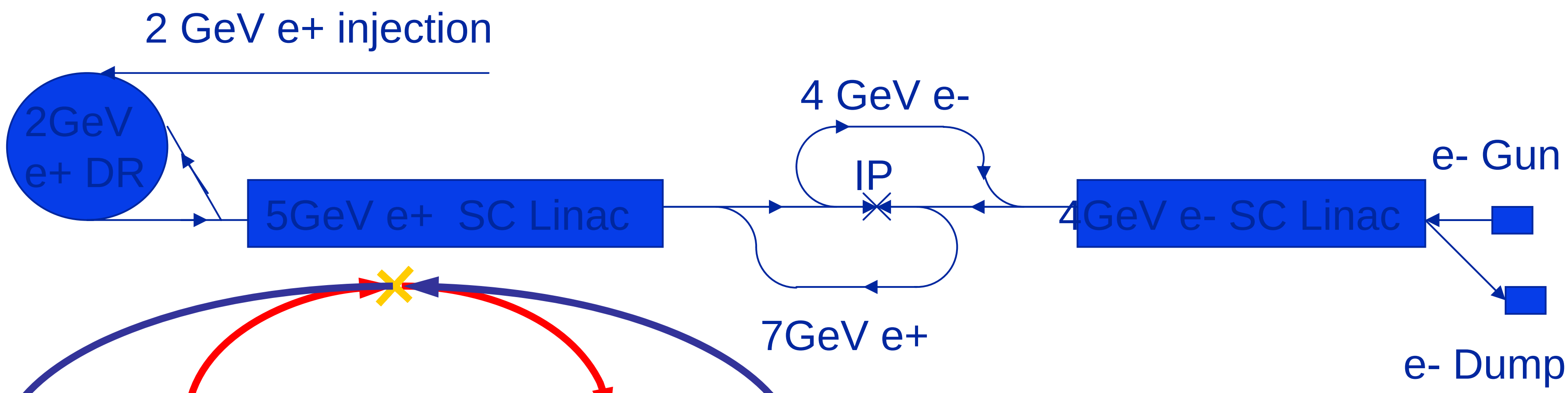
$\varepsilon_{x\_out}/\varepsilon_{x\_in}=12 \quad \varepsilon_{y\_out}/\varepsilon_{y\_in}=300$

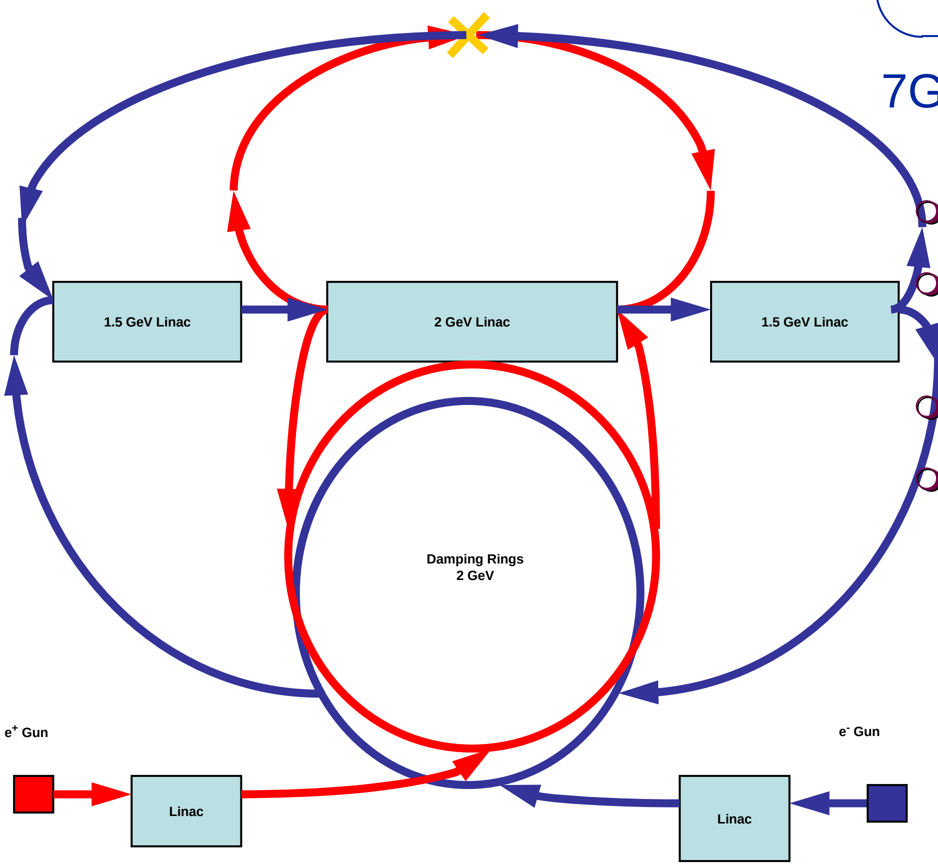
M. Biagini studies

Type 2 Energy Recover Linear Super-B

- Use single pass collider idea but use energy recovery linacs (ERLs) to accelerate, collide, then deccelerate the beams to the reduce damping ring energy and energy loss to synchrotron radiation.
- This technique saves energy lost in damping rings between $\sim E^2$ and $\sim E^4$.
- Acceleration also adiabatically damps emittance and energy spread making bunch compression easier.

Linear Super B schemes with acceleration and energy recovery, to reduce power





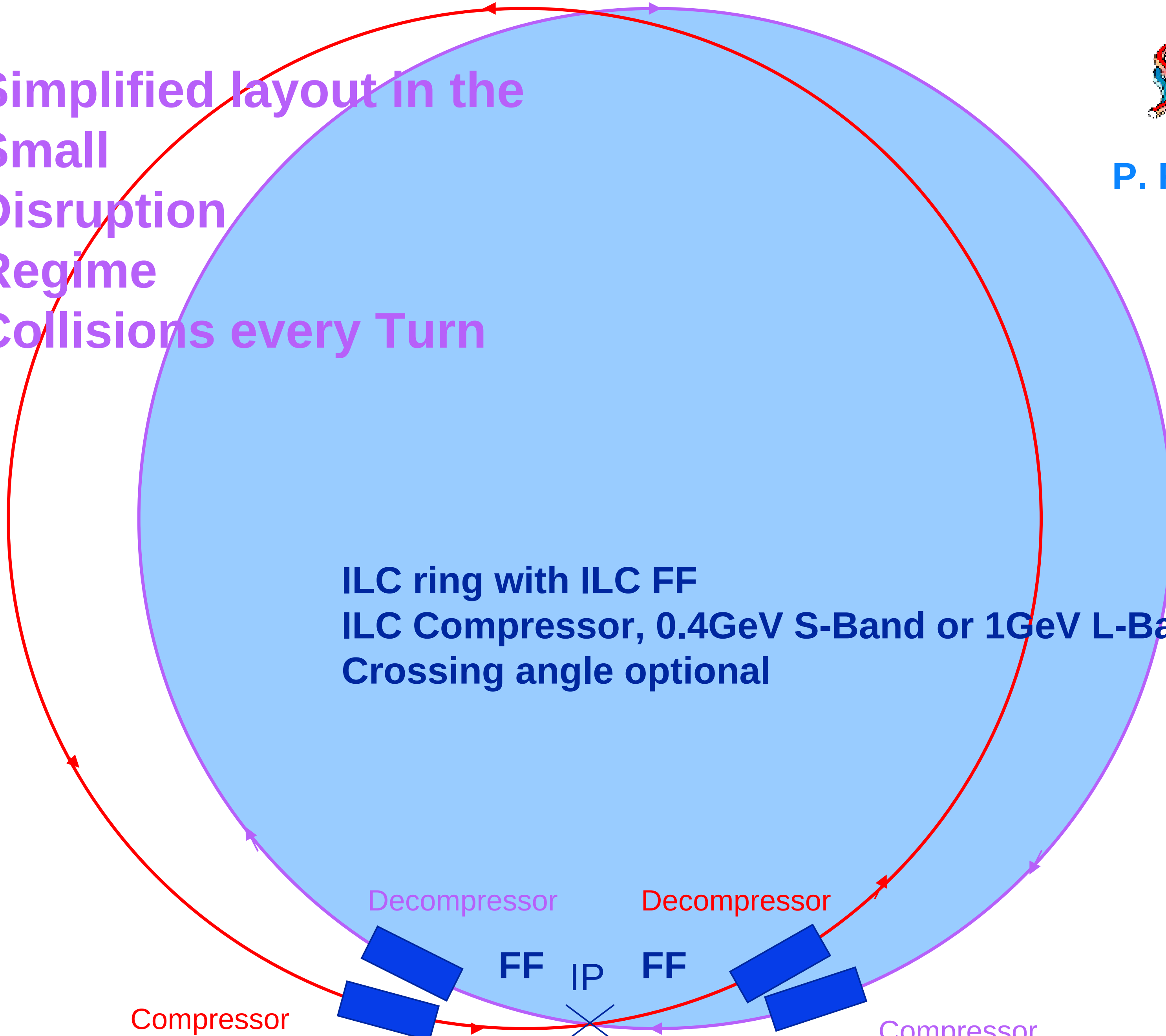
- **Use SC linacs to recover energy**
- **Use lower energy damping rings to reduce synchrotron radiation**
- **No electron damping ring**
- **Make electrons fresh every cycle**
  - Damping time means time to radiate all energy
  - Why not make a fresh beam if storage time is greater than 1 damping time

Type 3 Super-B with Bunch Compression

- Collide every turn in the damping ring.
- Install an ILC like final focus.
- Choose parameters to cause small emittance blow up.
- Use bunch compressor to shorten the bunches at the IP. Decompress after the IP.
- Use monochromator scheme at IP to compensate the energy spread to match the small Y4S resonance.

Simplified layout in the Small Disruption Regime Collisions every Turn

P. Raimondi



ILC ring with ILC FF
ILC Compressor, 0.4GeV S-Band or 1GeV L-Band
Crossing angle optional

ILCDR Nominal Parameters

Number of Bunches/train	2820
Bunch charge	$2\ 10^{10}$
Train repetition rate	5 Hz
Injected bunch separation	330 ns
Maximum injected norm. betatron amplitude (e+)	0.09 m-rad
Injected full width energy spread (e+)	1%
injected norm. emittance (e-)	45 μm
Injected full width energy spread (e-)	0.1%
Extracted norm. horizontal emittance	8 μm
Extracted norm. vertical emittance	20 nm
Extracted bunch length	6 mm
Extracted energy spread	$1.4\ 10^{-3}$

Approximate AC Power

- **PEP-II (2200 m) (1 ring LER and HER)**
  - RF AC Power LER at 3.1 GeV = 1 MeV/turn x 4 A x 2 = 8 MW
  - RF AC Power HER at 9.0 GeV = 3.6 MeV/turn x 2 A x 2 = 14.5 MW
  - Total RF AC power = 22.5 MW.
- **Super-B factory (4400 m) (2 rings LER and HER)**
  - RF AC Power LER at 4 GeV ~ 1.8 MeV/turn x 4 A x 2 x 2= 29 MW
  - RF AC Power HER at 7.0 GeV ~ 2.2 MeV/turn x 2.5 A x 2 x 2= 22 MW
  - Total RF AC power = 51 MW.

Type 4 Super-B with Large Crossing Angles

- Collide with a large crossing angle (2x25 mrad)
- Thus, only a small longitudinal part of each bunch collides with a small longitudinal part of the opposing bunch. (luminosity loss)
- However, the vertical beta function can be made very small while keep the overall bunch length long. (luminosity gain) (better for beam instabilities)
- Use ILC final focus.
- Do not need strong damping.

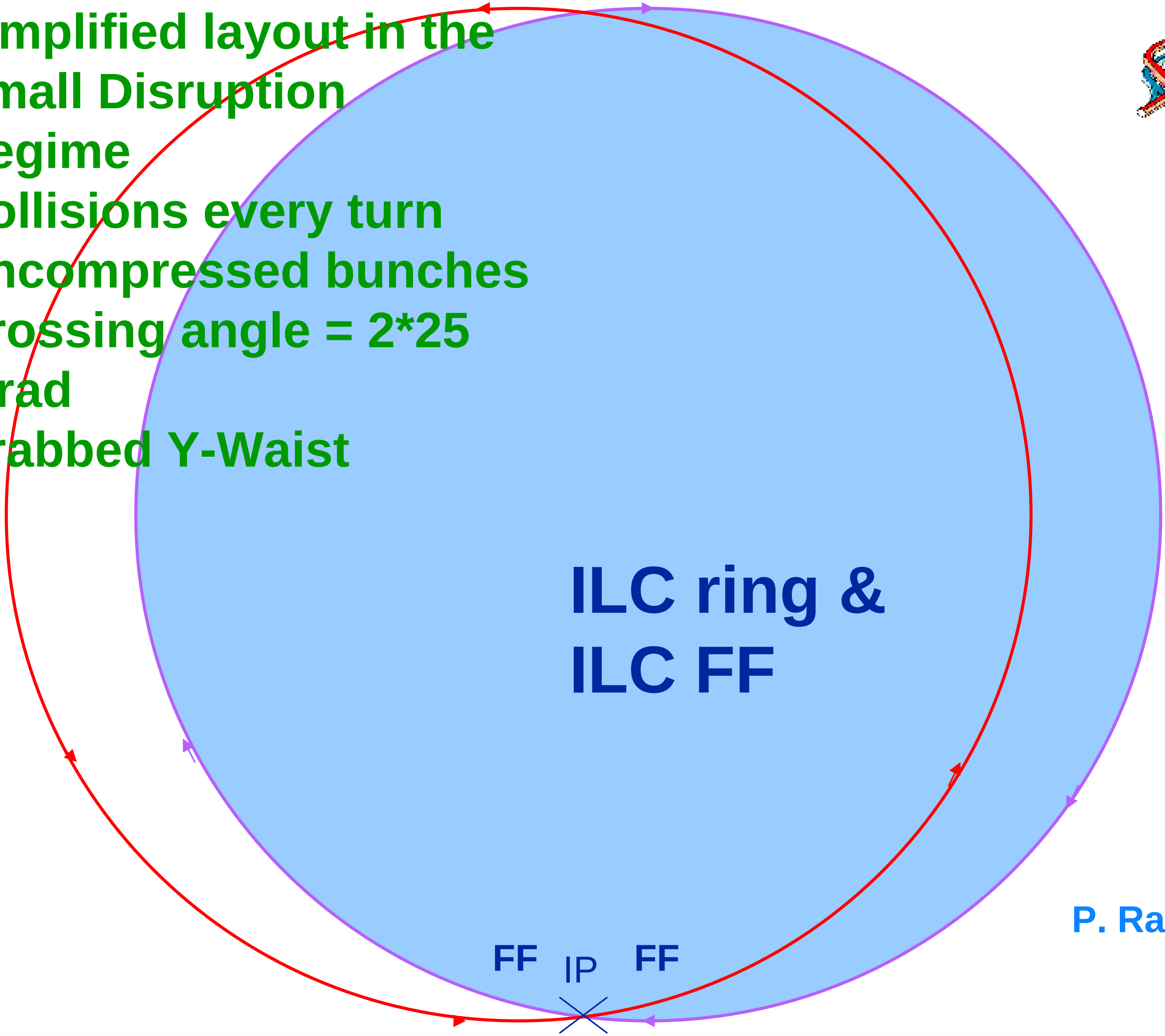
Simplified layout in the Small Disruption Regime

Collisions every turn

Uncompressed bunches

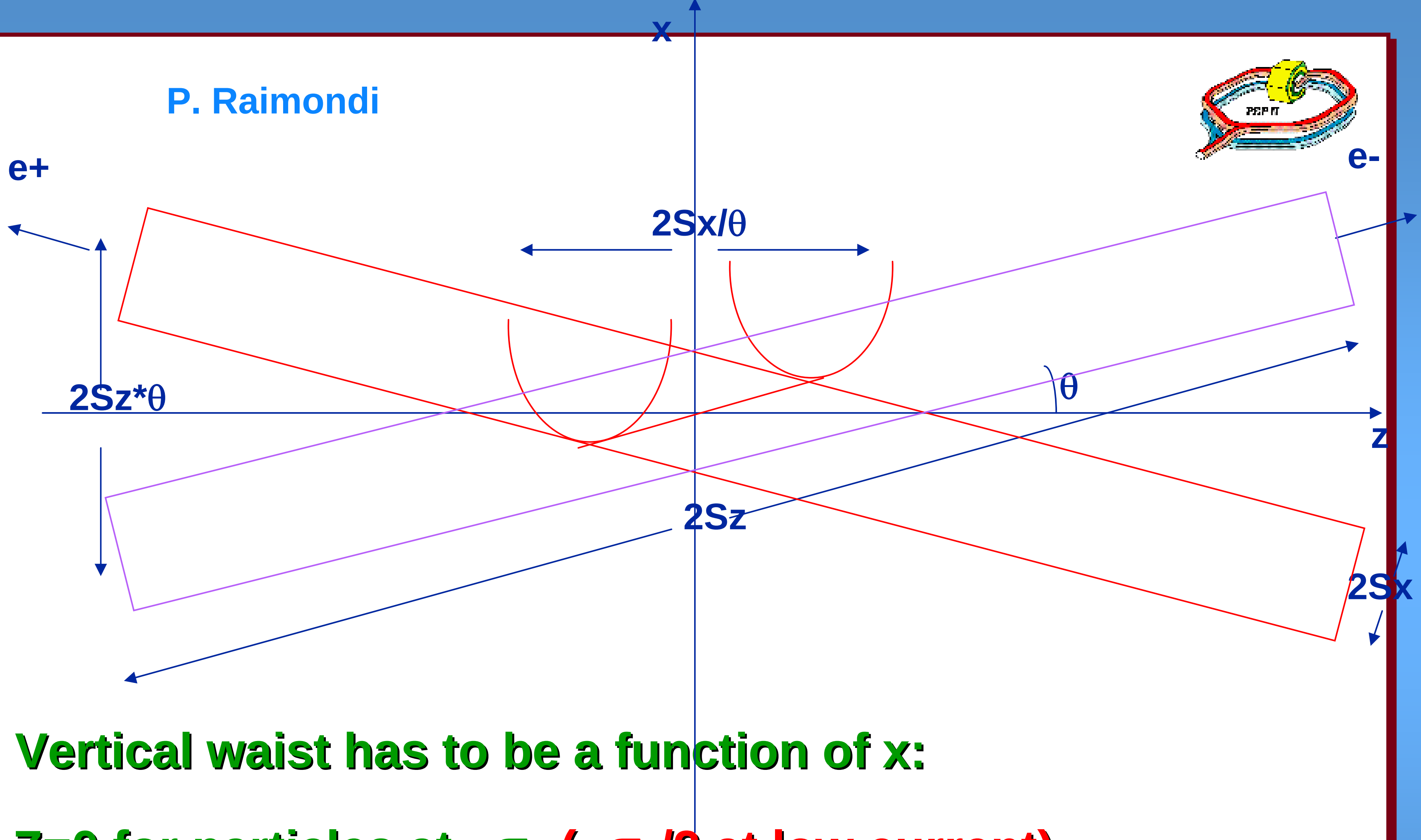
Crossing angle = 2*25 mrad

Crabbed Y-Waist



P. Raimondi

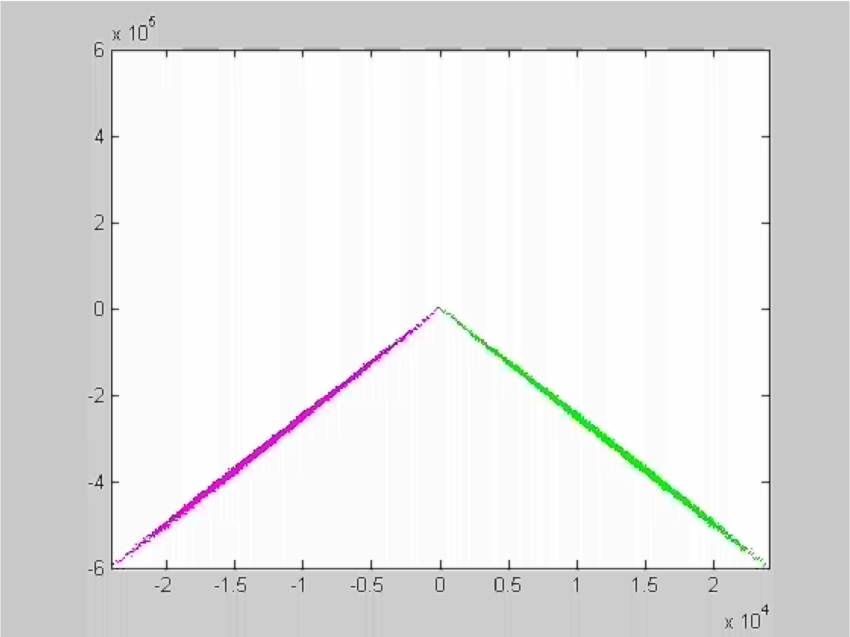
P. Raimondi



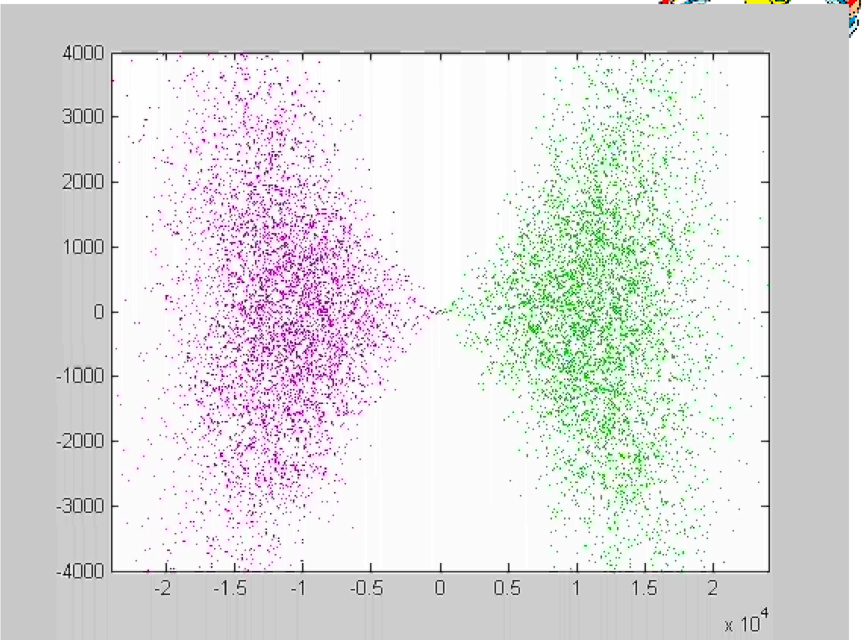
Vertical waist has to be a function of x:

Z=0 for particles at $-\sigma_x$ ($-\sigma_x/2$ at low current)

Z= σ_x/θ for particles at + σ_x ($\sigma_x/2$ at low current)



Horizontal Plane



Vertical Plane

Collisions with uncompressed beams

Crossing angle = 2*25mrad

Relative Emittance growth per collision about $1.5*10^{-3}$

$\varepsilon_{yout}/\varepsilon_{yin}=1.0015$

Raimondi

Parameters of Super-B Designs

Collider		ξ_y	N	β_y*	s	E	F	Lumin
Units			10^{10}	mm	m	GeV	(~Hd)	10^{35}
PEP-II	Normal	0.068	8	11	1.26	3.1	0.84	0.10
KEKB	Normal	0.065	5.8	6	2.1	3.5	0.76	0.16
Super-PEP-II	High I low βy	0.12	10	1.7	0.32	3.5	0.81	7
Super-KEKB	High I low βy	0.28	12	3	0.59	3.5	0.85	8
Linear SuperB	Single pass	29.	10	0.5	250	4	1.07	10
SuperB	Bunch shorten	0.14	6	0.4	0.63	4	0.75	10
SuperB	X'ing angle	0.045	2	0.08	0.5	5	0.8	10

	Round single pass	Flat single pass	Flat Ring with compressor	Flat Ring no compressor
Sigx* µm	0.9	30 (2 betatron)	18 (2 betatron)	2.67
Etax mm	0.0	+-1.5	+-5.0	0.0
Sigy nm	900	12.6	63.2	12.6
Betx mm	0.55	5.0	5.0	8.9
Bety mm	0.55	0.080	0.500	0.080
Sigz_IP mm	0.8	0.100	0.600	4.0
Sige_IP	1.0e-3	2.0e-2	3.5e-3	1.0e-3
Sige_Lum	0.7e-3	1.0e-3	1.0e-3	0.7e-3
Emix nm	1.5	0.8	0.8	0.8
Emiy nm	1.5	0.002	0.008	0.002
Emiz µm	0.8	2.0	2.0	4.0
Cross_angle mrad	Optional	Optional	>2*12	2*25
Sigz_DR mm	0.8	4.0	4.0	4.0
Sige_DR	1.0e-3	0.5e-3	0.5e-3	1.0e-3
Np 10e10	7.0	7.0	2.0	2.0
Nbunches	12000	12000	12000	12000
DR_length km	6.0	6.0	6.0	6.0
Damping_time msec	20	20	20	20
Nturns_betwe_coll	50	50	1	1
Collision freq MHz	12.0	12.0	600	600
$L_{singleturn}$ 1e36	1.5	1.5	1.7	1.3
$L_{multiturn}$ 1e36	1.1	1.1	0.9	0.9

P. Raimondi
March 2006

Conclusions

-There has been rapid progress in the optimization of the Super-B Collider parameters and layout

--Workable parameter set contains:

- ILC damping ring,
- ILC bunch compressor,
- ILC Final Focus

- The optimal collision rate seems to be every turn.

Conclusions (2) for large crossing angle collider

-Solution with a ILC DR + ILC FF seems very promising:

- Crossing angle of about 25mrad allows low vertical beta function with no bunch compression

- Thus: No compressor and no energy acceleration

- Uses all the work done for ILC
- Ring and FF layouts similar to ILC
- 6 km circumference rings
- Strong synergy with ILC
- Beam stay clear about 20 sigma assuming 1cm radius beam pipe
- Beam currents about 2 Amps
- Power around 70 MW, further optimization may be possible.
- Reuse PEP RF system, power supplies, vacuum pumps, etc.
- Standard injection system.