## Future linear colliders, interaction regions and extraction lines

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Flectrons

amping Rings

Main Linac

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OSITTONS

SISTER

## Livingstone plot of accelerators





# LEP to a future LC

The end!



### ILC as N'th Generation e+e- Collider



### Physics at ILC

- Higgs
  - Detection + Decays
  - Coupling
  - Properties
- SUSY
  - Detection
  - Sparticle mass, spin
  - Parameters
  - SUSY dark matter
- Top quark
  - Mass, width, decay modes
- Signatures beyond SM
  - If there are some



### **Reference Design in a Nutshell**

- ECM = 500GeV max within a site footprint of ~31km.
- Main Linacs: operating superconducting (SCRF) cavities at Eacc = 31.5MV/m (16000 units of 9-cell cavities → 2 x ~12km)
- Injectors: Polarized (P~80%) e- source with 2 damping rings (e- and e
   +) around interaction region.
  - Undulator-based (150m @ 150GeV) e+ source within e- main linac
- Interaction region: Single IR with 14mrad beam crossing
- Lumi =  $2x10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>, f\_rep = 5Hz



Schematic Layout of the 500 GeV Machine

### ILC Cryostats and Cavities for Main linacs

1 cryomodule contains 8 cavities + 1 magnet or 9 cavities (E<sub>acc</sub> = 31.5MV/m on average, each having a length ~ 1m)



- Total ~1700 cryostats, ~16000 cavities.
- 3 cryostats to be driven by one 10MW L-band klystron
- Total 560 RF units in e+/e- main linacs



-IR design and extraction

## **ILC Beam Delivery subsystems**





### **The extraction line of a linear collider**

• It's now generally agreed that a future linear, electron-positron collider is the ideal partner machine for the LHC.

• The favoured designs, the ILC and CLIC, have strong beam-beam effects when the bunches collide, and the interaction and post-IP regions provide some interesting beam dynamics and design challenges.

• Will cover the extraction lines of the International Linear Collider (ILC), and the Compact Linear Collider (CLIC)

• Post-IP extraction beam line design is tied to the choice of beam crossing angle at the IP

- ILC has a choice of beam crossing angles (related to bunch structure)
  - 'large', 14 mrad
  - 'small', 2 mrad
  - 'zero', 0 mrad
- CLIC has less choice
  - 'large', 20 mrad

• We also need to worry about what happens at the very end, where the high power particle beams need to be dumped in a controlled way.



#### e<sup>+</sup>e<sup>-</sup> collision creates disrupted beam:

• Huge energy spread and large x,y divergence (emittance) in the outgoing electron beam.

• High power divergent beamstrahlung photon beam going in the same direction with electrons.

• Plus e+e- pair production. [(in)coherent]

#### **Issue:**

X (mm)

• Potential high beam loss in the extraction line due to over focusing of low energy electrons and divergence of the photon beam.

**Disrupted energy spread** 





Maximum IP angles for disrupted electrons and beamstrahlung photons

Option	No beam offset at IP				Large vertical offset at IP			
	electrons		photons		electrons		photons	
	X' (µrad)	Y' (µrad)	X' (µrad)	Y' (µrad)	X' (µrad)	Y' (µrad)	X' (µrad)	Y' (µrad)
Nominal, c11	529	253	369	212	474	685	366	537
Large Y, c13	956	492	768	396	716	668	573	586
Low P, c14	1104	580	668	344	1120	1190	684	918
High L, c15	1271	431	723	320	1280	1415	783	1232

### **General features of IR/XL**

There are many generic features of IR and post-IP designs

• The beam crossing angle is a key parameters, determining the interplay of the beam with the detector, the interaction of incoming and outgoing beam magnets and the possibility of post-IP diagnostics



### **Design considerations for the extraction line**

• **Beam channels**: to safely transport the outgoing electron and photon beams from IP to main dump(s).

• Large optical acceptance: to minimize beam loss from strong over-focusing and dispersion of low energy electrons. Requires careful optimization of energy dependent focusing and sufficient aperture.

• Large geometric acceptance: to minimize beam loss from the divergent beamstrahlung photons. Requires large aperture increasing with distance.

• Beam diagnostic system: to monitor luminosity, measure beam energy and polarization. Requires special downstream optics.

• Collimation system: to protect magnets and post-IP diagnostic devices from unavoidable beam loss and undesirable background.

• Main dump protection system: to avoid damage to dump window and prevent water boiling in the dump vessel from small undisrupted beam or under abnormal optical conditions (large errors, magnet failures). Requires enlargement of beam size at the dump window by optical means.

# **The ILC extraction lines**





# **ILC** machine parameters

Parameter	Symbol	Value	Unit	
Centre-of-mass energy	E	200-500	GeV	
RF frequency	f <sub>RF</sub>	1.3	GHz	
RF gradient	9 <sub>RF</sub>	31.5	MV/m	
Particle per bunch	N <sub>b</sub>	2.05	10 <sup>10</sup>	
Bunches / RF pulse	n <sub>b</sub>	2625		
Bunch spacing	t <sub>b</sub>	369	ns	
Repetition frequency	f <sub>rep</sub>	5	Hz	
Primary beam power	Р	10.8	MW	
Horizontal N. emittance	ε <sub>x</sub>	10	mm.mrad	
Vertical N. emittance	ε <sub>y</sub>	0.04	mm.mrad	
Horizontal beam size	$\sigma_x^*$	640	nm	
Vertical beam size	σ <sub>y</sub> *	5.7	nm –	
RMS bunch length	σ <sub>z</sub>	300	um	
Peak luminosity	L	2	10 <sup>34</sup> /cm <sup>2</sup> /s	

#### International Linear Collider

#### **Extraction designs for three** crossing angle options:

• 14 mrad (baseline), 2 mrad, and 0 mrad. **Beam line:** 

- 14 mrad: Independent straight line optics. One channel for e &  $\gamma$ .
- 0 and 2 mrad: Initial magnets shared with incoming beam, separate e and  $\gamma$ channels.

1.5

0.5

-0.5

FD



No time to cover this option

ILC2006e: Beam Delivery Systems

14 mrad

IP

n

Muon

Wall

### Crossing angle considerations

	0 mrad	2 mrad	14 mrad	
Beam separation	E-separators & bending Shared Final Doublet (FD)	Crossing angle & bending, shared FD	Crossing angle No shared magnets	
Detector	One detector beam hole: more background, calibration	e favorable hermeticity,	2 holes: less favorable hermeticity, background, calibration	
Luminosity	No luminosity loss Crab cavity (CC) not needed	~10% loss w/o CC CC ~0.5 km from IP	~70% loss w/o CC CC ~13 m from IP	
Solenoid & DID field	No orbit from solenoid DID & correctors not needed	Small orbit DID is not needed	Larger orbit Anti-DID required	
Push-pull	Beam trajectory not affected	Trajectory may change Correctors needed	Trajectory not affected	
Optics for diagnostics	Difficult, baseline diagnostics Alternate options are studied,	is not included but not yet a solution	Included: beam energy, polarization, GamCal	
Transport (e,γ)	Separate e,γ channels	Separate e, y channels	Shared e,γ channel	
Dumps (e,γ)	Intermediate and main dumps with holes	One shared or two sepa- rate dumps with a hole	One shared dump without holes	

# The ILC extraction line baseline



#### 14 mrad extraction beam optics

#### Large angle, so use different incoming and outgoing final doublets

• No shared FD: easier optics.

Quadrupoles: to focus at Compton IP, optimized for minimal loss.
Dipole chicanes: for diagnostics - beam energy, polarization and GamCal.

- Fast sweeping kickers: for dump protection.
- Collimators: for magnet and diagnostic protection.



### **Extraction diagnostics: 14 mrad**



### **Detector solenoid & anti-DID**

#### **Effects:**

• X-Y coupling due to  $B_z$  field causing IP beam size growth. It is corrected independent of crossing angle (anti-solenoid and/or skew quads).

Orbit due to B<sub>x</sub> field induced by crossing angle.
 Beams collide with angle, which causes beam-beam e<sup>+</sup>e<sup>-</sup> pairs to miss the beam exit hole thus increasing detector background. Can be corrected by Detector Integrated Dipole (DID).

• Anti-DID (~0.2 kG) is required to reduce detector background (reduces angular size of pairs and 'directs' down exit hole), but accept residual extraction orbit

•Corrector coils built on QDEX1, QFEX2A quads compensate the residual extraction orbit.

(0 mrad: No orbit. DID is not needed.
2 mrad: Orbit effect is small - DID is not needed.
Correctors outside of the detector can compensate residual extraction orbit.)



# **Smaller angle schemes**

Large crossing-angle :

1. Eases post-IP beam extraction & transport → diagnostics

2. But adds pre-IP constraints (crab-cavity control & tuning, non-axial solenoid + DID / anti-DID → pre / post-IP trajectory bumps)

Physics & detector advantaged by smaller crossing-angle IR : simpler forward geometries, better hermeticity, no (or less) DID / anti-DID

•2 mrad scheme : no crab-cavity (initially...), no electrostatic separators and order-of-magnitude smaller pre / post-IP trajectory bumps (for example, no need to worry about integration of anti-DID coils in IR region)

Latest design with simple concept aiming to be as short & economical as possible

It's sensible to have viable alternatives!

## "Minimal" extraction line concept

→ Explicit goals : short & economical, as few and feasible magnets as possible, more tolerant and flexible



window damage)

# Shared FD magnets + beamstrahlung tail = trouble



### 2mrad beam-pipe layout in IR region



## Beam power losses

#### 2 magnet masks

2 collimators to catch tail

	12						- '
Beam	QEX1C	QEX1	QEX2COLL	QEX2	BHEX1	COLL1	COLL2
	OLL	[kW]	[kW]	[kW]	[kW]	[kW]	[kW]
	[kW]						
Nominal	0	0	0	0	0	0.2	5.1
Nominal	0	0	0	0	0	0	2.9
(dy=200nm)							
Nominal	0	0	0	0	0	0.7	2.6
$(dx=1\sigma)$							
Low Power	2.8	0	1.3	0	0	65.3	50.0
Low Power	3.6	0	1.4	0	0	69.8	73.8
(dy=120nm)							
Low Power	1.4	0	0.7	0	0	34.5	19.3
$(dx=1\sigma)$							
High Lumi	12.3	0	4.4	0	0	202.1	131.9
High Lumi	14.8	0	4.5	0	0	200.0	195.8
(dy=120nm)							
High Lumi	8.3	0	2.8	0	0	101.9	49.1
$(dx=1\sigma)$							

Computed using GUINEA-PIG and DIMAD, for ILC parameter sets at machine energy of 500 GeV, with high statistics. Protection collimator jaws tuned to remove losses on magnets, and main collimator jaws tuned to loss specification of 200 kW and beam size on dump window.

# BHEX1 (C-dipole)

 The bend BHEX1, designed as a C-magnet to accommodate the beamstrahlung, outgoing beam and proximity of incoming beam, has been studied using the field solver POISSON/PRIAM



Extracted beam:  $B_v(x)=0.27036+0.0414362 x - 6.31707 x^2 + 8.24682 x^3 - 587.471 x^4$ 

## QEX1 modified "Panofsky"-style quad design

Design goal: G=7.5 T/m for extracted pocket, 200mmx85mm, with the incoming beam 150mm from centroid of the extracted beam, with no more than 10G of field



	(Bx	<pre>- iBy) = i[sum</pre>	n*(An + iBn)/r	* (z/r)**(n-1)]
tinole	n	n(An)/r	n(Bn)/r	Abs(n(Cn)/r)
	1	-1.8355E+00	0.0000E+00	1.8355E+00
ansion	2	-4.0798E+03	0.0000E+00	4.0798E+03
( N	3	-2.6446E+00	0.0000E+00	2.6446E+00
racted)	4	-6.4440E+01	0.0000E+00	6.4440E+01
	5	-1.1749E+00	0.0000E+00	1.1749E+00
	6	2.1582E+01	0.0000E+00	2.1582E+01
	7	-3.4437E-01	0.0000E+00	3.4437E-01
	8	-1.8381E+00	0.0000E+00	1.8381E+00
	9	-7.6307E-02	0.0000E+00	7.6307E-02
	10	-2.0240E+00	0.0000E+00	2.0240E+00

- Disrupted beam tracking (500 GeV) along the extraction line with multipoles:
  - Power loss increase of 1kW at 1 collimator

– Dump beam size increase of 5%

 Final focus? Quadrupole coefficient << BHEX1</li>

### IP background photons



## Vertex detector backscattered photon hits from extraction line losses

BDSIM model of extraction line constructed to assess photon hits in VXD from charged beam losses on the main extraction line collimators (with a Mokka model of the LDC detector, hit probability in detector ~2.2%)

	D [m]	X [cm]	P [kW]	#γ's/bx	VXD hits
QEX1COLL	45	20	0.2	1.3	0.02
QE2COLL	53	-	0	0	0
BHEX1COLL	76	41	0.1	0.2	0.004
COLL1	131	85	52.3	40	0.8
COLL2	183	115	207.5	82	1.8
COLL3	286	-	0	0	0

Conclusion: rate is negligible from this contribution compared to other sources e.g. beam-beam induced (incoherent pair) hits ~ 250/BX (Notes: γ's reach through LoS through BeamCal, radius 1.2 mm, Collimator as Cu) (Photons reach VXD through line-of-sight from collimator i.e. no reflections)

### Summary of pros & cons

#### **Advantages**

**14 mrad:** Independent flexible optics; larger magnet separation; downstream diagnostics; small to moderate beam loss; one beamline; one dump w/o holes; better compatible with  $\gamma\gamma$  and e<sup>-e-</sup> options.

**2 mrad:** DID not needed; less dependent on crab-cavity; favorable detector hermeticity, background and calibration; small to moderate beam loss.

#### **Disadvantages and R&D issues**

**14 mrad:** Crab-cavity, anti-DID & orbit correction required; less favorable detector background, hermeticity and calibration; SR in solenoid.

**2 mrad:** No downstream diagnostics; shared FD; beam in non-linear field of QF1/SF1 coil pocket; large aperture SC sextupole; large aperture NC magnets close to incoming beam; SR in FD  $\rightarrow$  photon backscattering; dump(s) with a hole; feedback BPM & kicker shared with disrupted beam.





## **CLIC** machine parameters

Parameter	Symbol	Value	Unit	
Centre-of-mass energy	E	3	TeV	
RF frequency	f <sub>RF</sub>	12	GHz	
RF gradient	9 <sub>RF</sub>	100	MV/m	
Particle per bunch	N <sub>b</sub>	3.72	10 <sup>9</sup>	
Bunches / RF pulse	n <sub>b</sub>	312		
Bunch spacing	t <sub>b</sub>	0.5	ns	•
Repetition frequency	f <sub>rep</sub>	50	Hz	
Primary beam power	Р	14	MW	
Horizontal N. emittance	ε <sub>x</sub>	660	nm.rad	
Vertical N. emittance	ε <sub>y</sub>	20	nm.rad	
Horizontal beam size	$\sigma_x^*$	40	nm	
Vertical beam size	$\sigma_y^*$	1	nm –	
RMS bunch length	σ <sub>z</sub>	45	um	
Peak luminosity	L	5.9	10 <sup>34</sup> /cm <sup>2</sup> /s	

# CLIC beam-beam

Few % for ILC



CLIC is 3 TeV, with  $\delta_{b}^{\star}$  = 29%. Hence

• The beamstrahlung tail of the beam is much longer than the ILC

• There are 2.2 photons/electron emitted per bunch crossing

• There are 5.10<sup>8</sup> pairs (coherent) per bunch crossing (10% of beam power)


## **CLIC** extraction concept

The design uses a large crossing angle and relies on the separation by dipole magnets of the disrupted beam, the beamstrahlung photons and the particles from e+e- pairs with the wrong-sign charge.



It is followed by a transport to the dump in dedicated lines:

- a short one for the wrong-sign charged particles of the coherent pairs, to prevent the transverse beam size from increasing too much.
- a much longer one for the disrupted beam and the beamstrahlung photons, to avoid a too small spot size for the undisrupted beam at the dump window.

## The separation dipoles

The first magnetic elements of the CLIC post-collision line are four dipoles, spaced by 1.5m, each with a field of 0.8 T and a length of 4m (bending angle: 0.64mrad at 1.5 TeV). Collimators are interspersed to tail catching



Magnet	Start [m]	Xpipe [cm]	Ypipe [cm]	G [cm]	H [cm]	nI [kA] turns
Dipole 1a	27.5	20.0	44.0	22.2	57.7	141.3
Dipole 1b	30.5	20.0	44.0	22.2	57.7	141.3
Dipole 2	38.0	27.0	70.2	29.6	83.9	188.4
Dipole 3	46.0	34.0	102.0	37.0	115.7	235.5
Dipole 4	54.0	41.0	139.4	44.4	153.1	282.6



### Beam transport



# Loss sources leading to IP background fluxes



This excludes direct beam-beam background e.g. pairs in solenoid field etc

### IP photon background from 1<sup>st</sup> mask



On-axis IP photon flux from 1<sup>st</sup> mask: **1.1E4 /cm<sup>2</sup> /s** 

To be compared to other sources and check VXD hit rate

# Summary

• A future linear collider is the ideal partner machine to the LHC

• This machine, be it the ILC, CLIC or something else, will suffer from intense beam-beam interactions at the IP, posing some interesting challenges for the post-IP beam line

• The ILC, with a large inter-bunch spacing, has a choice of beam crossing angles at the collision point

- 14 mad (large), the choice for the baseline
- 2 mrad (small), with some advantages
- 0 mrad (zero), an interesting alternative (no time to talk about this!)
- CLIC, with a small inter-bunch spacing, needs a large crossing angle. The intense beam-beam at this machine gives a new set of challenges
- Finally, the extraction line terminates with a water based dump, which provides some interesting dynamics

# **Backup slides**

# End of the road: Beam dumps



### Water beam dump for the ILC 18MW charged particle beam dump

**1966** SLAC installed two primary water beam dumps with 2.2MW power

capacity (Walz *et al*) Very successful, running at up to 800kW.



#### 1996

Walz et al. Design concept proposed for a 10MW beam dump based on 1966 design. 2005

**Walz et al.** Beam dump dissipating up to 18MW of average power is feasible with absorption medium being water, questions remain about radiation damage to window. **Schmitz et al.** Principally feasible, but inherent risks will make it difficult to "sell" it as reliable, safe and robust, transient pressure in water sited as a problem. -1.6bar to 3.7bar.

2007 Walz Vessel provides safety factor of 5 in terms of pressure;

#### **Energy deposition into water**



Contours of energy deposition Total energy deposited (By a bunch train) Deposited energy leads to transient shock waves (pressure wave) in the water medium of the dump

#### Pressure on internal surfaces of beam dump



Pressure on dump wall reaching 8 bar

Pressure at window reaching 4 bar due to reflecting pressure waves after the bunch train is deposited.

How big do pressure transients get around the dump?



#### Summary of predicted pressure transients

Conclusion: careful window design needed

#### **Comparison of transient window pressure for ILC and SLAC**



So, the transient pressure rise above the static water pressure in the region of the beam dump window is calculated to be 3 bar. This can be used to compute window stress, and understand what it means (paper under preparation)

### Superconducting magnets: 14 mrad

- Magnet design is well developed (BNL).
- Based on compact SC technology.
- Field shielding and correcting coils are built in.
- 38 cm QD0 prototype was tested in solenoid field and showed excellent field and quench performance.
- SC extraction quad parameters at 500 GeV CM:
- QDEX1: L=1.06-1.19 m, G=86-98 T/m, R=15-18 mm,
- QFEX2: L=1.1 m, G=31-36 T/m, R=30 mm.
- SC magnets require upgrade for 1 TeV CM.





**BROOKHAVEN** Layout Budget for a Self-Shielded ODO Superconducting Magnet Division Magnet Compatible with 14 mr X-ing. 14 mr @ L=3.5 m for 49 mm separation L\*=3.51 m QD0 Design for 14 mr X-ing Self-shielded coil design He-II for QDO allows the 30.0extracted beam to 20.0 10.0 pass very close to the coil windings without -10.0 experiencing significant -20.0 external field. Thus we 30.0 can consider trying to -50.0 accommodate smaller angles. -60.0 10.0 30.0 70.0 -10.0 50.0 Side-by-side would have too much cross talk this close in! 13

### **Optimised compact** final doublets

- Re-designed with acceptable losses and stay-clear for in / out charged & beamstrahlung beams  $\rightarrow$  JINST 1 P10005 (2006) (RBA and P. Bambade)
- Works for all proposed ILC beam parameter sets, including (new) "High ٠ Luminosity" at 1 TeV (GP++ large statistics at <a href="http://flc-mdi.lal.in2p3.fr/spip.php?rubrique17">http://flc-mdi.lal.in2p3.fr/spip.php?rubrique17</a>)
- Compact SC QD0,SD0 : NbTi LHC-like QD0 at 500 GeV, Nb<sub>3</sub>Sn SLHC-• like QD0 at 1 TeV, NbTi 60 mm radius SD0
- Standard warm QF1 & SF1, with 20 and 30 mm radius ٠
- Outgoing beam subject to non-linear pocket fields of QF1 and SF1

Table 1: The 500 GeV final doublet parameters.									
Parameter	QD0	SD0	QF1	SF1					
Length [m]	1.059	1.469	1.596	0.75					
Strength	$-0.270 \text{ m}^{-2}$	$2.969 \text{ m}^{-3}$	$0.0786 \text{ m}^{-2}$	$-2.044 \text{ m}^{-3}$					
radial aperture [mm]	28	60	20	30					
gradient $[T/m]$	225	-	65	-					

Table 1: The 5	500 GeV final	doublet parameters.

lable 4: The I lev final doublet paramet
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Parameter	QD0	SD0	QF1	SF1
Length [m]	1.352	2.5	3.192	1.5
Strength	$-0.210 \text{ m}^{-2}$	$1.502 \text{ m}^{-3}$	$0.0394 \text{ m}^{-2}$	$-0.943 \text{ m}^{-3}$
radial aperture [mm]	25	59	20	30
gradient [T/m]	350	-	66	-

Parameter set	QD0	SD0
High Luminosity CB [W] 500 GeV	<1	<1
High Luminosity RB [W] 500 GeV	0.46	0.2
High Luminosity CB [W] 1 TeV	<1	<1
High Luminosity RB [W] 1 TeV	0.82	0.04

~	$500~{\rm GeV}$	$1 { m TeV}$
l* [m]	4.5	4.5
QD0-SD0 [m]	0.8	0.8
SD0-QF1 [m]	3.03	2.05
QF1-SF1 [m]	0.5	0.5

### Beam power loss: 14 mrad

• Quad focusing optimized for minimal beam loss.

 5 collimators to protect magnets, diagnostics and dump: COLE – for low energy collimation, COLCD – for Cherenkov detector protection, COLW1, COLW2, COLW3 – for fast kicker and dump protection.

• Power loss is small at 500 GeV CM nominal parameters (c11), and acceptable at high disruption parameters (c14).

• No primary and photon loss on SC quads.

• Large y-offset and y-angle at IP increase load on collimators. These non-ideal conditions need to be efficiently corrected.



#### Beam power loss (kW) for optics with $L^* = 3.51$ m without solenoid

Option	<b>Primary electrons</b>							BS photons			
	Total on magnets	Diagnostic collimators		Dump collimators			Dump collimators				
	and pipe	COLE	COLCD	COLW1	COLW2	COLW3	COLW1	COLW2	COLW3		
c11	0	0	0	0	0	0.272	0	0	0		
c11, y-offset	0.001	0.001	0.0003	1.12	2.59	11.2	0.0001	0.025	0		
c13	0.007	0.001	0.0001	1.02	1.57	6.54	0.570	0.820	0		
c13, y-offset	0	0.0001	0	1.08	1.76	9.05	0.138	1.82	0		
c14	0.126	0.044	0.003	2.62	6.18	26.3	0.035	0.171	0		
c14, y-offset	0.581	0.549	0.161	85.9	43.7	82.1	10.9	20.1	0		

# Technical \_\_\_\_\_\_ TDP plans

Aim of future 2 mrad work is to bring the design to the level of a credible alternative to the 14mrad baseline design

- Optics and beam transport
  - variable I\* IR and extraction line layout (CI)
  - study of extraction line aberrations on final focus beam (CI, LAL)
  - Iteration of design and losses as magnet designs progress (LAL, CI)
  - integration of FD for 2 mrad in final focus optics design for the incoming beam (CI)
- Magnet design studies
  - design of large aperture final horizontal bends BB1 and BB2 (LAL, CI)
  - design of standard warm FD magnets QF1 and SF1 (LAL)
  - design of a modified Panofsky quadruple magnets (Kyoto) [Feasibility,Cost]
  - Engineering design of QD0 and SD0 (?) [Feasibility for compact size]
- Engineering, integration and cost-related work
  - Integration of final doublet into detector, including
    - cryostat design and FD support/services
    - anti-solenoid or skew-quadrupoles for coupling correction, with appropriate integration
  - design of beam pipe in shared area (LAL) [detailed drawings critical]
  - design of beampipe in extraction line (LAL) [detailed drawings critical]

There is real flexibility in this scheme, with margins and adjustable parameters

# BHEX1 (C-dipole)

 The bend BHEX1, designed as a C-magnet to accommodate the beamstrahlung, outgoing beam and proximity of incoming beam, has been studied using the field solver POISSON/PRIAM



•  $B_{y}(x)$  homogeneity < 4% (with shims) within outgoing beam envelope (checked and okay)

### **BHEX1** multipoles



Impact of non-linear fields on the extracted beam is minimal e.g. 1% - 2% power loss increase on the primary collimators

 $B_v(x)=0.27036+0.0414362 x - 6.31707 x^2 + 8.24682 x^3 - 587.471 x^4$ 

Quad component (Francois, Guy)

a1= 0.14249, which gives  $K_1$ =0.1708E-03 m<sup>-2</sup>, for 250 GeV beam, exposing the final focus.

Length of BHEX1 = 6m gives integrated strength  $\sim 0.001 \text{ m}^{-1}$  (!)

Included BHEX1 quadrupole component into 2 mrad FF optimised lattice (PAC'07) (later in talk)

Incoming beam:

### Variable I\* IR layout



Key: QD0 SD0 QF1 •IP

Optics design exist for I\*=4.5m. Variable I\* achieved by

- Fixed breakpoint located between SD0 and QF1
- Optics refitted by varying SD0-QF1 distance to obtain sufficient beam separation and minimum losses

• Some impact on beam power losses and beam separation

Keep physical size of FD magnet constant (change currents)

Variable I\* of detector gives varying downstream orbit. Correct using corrector dipoles

# Magnets and collimators in the rest of the line

Collimator	Position	Length	Power	X jaw	Material	Cooling
name	[m]		load	[mm]		
			[kW]			
QEX1COLL	38.75	1.0	15	104	Cu	Radiative
QEX2COLL	45.75	1.0	15	95	Cu	Radiative
COLL1	150	2.5	205	116	Al (balls)	Active
COLL2	200	2.5	205	204	Al (balls)	Active

Magnet	Length	Strength/angle	Radial	B [T]
			aperture	
			[mm]	
QEX1	3.0	0.011 /m	116	1.04
QEX2	3.0	0.0056 /m	138	0.63
BHEX1	8.0	2.0 mrad	-	0.21
BB1	8.0	2.0 mrad	-	0.21
BB2	8.0	2.0 mrad	-	0.21

- Designed proof-of-principle optics with reasonable QEX1,2, BHEX1 and BB1,2 apertures & strengths and acceptable losses on dedicated collimators at both 500 GeV and 1 TeV
- Can be adjusted depending on best choice of dump arrangement
- Flexibility : magnet + beam pipe designs  $\rightarrow$  final parameters

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# The International Linear Collider (ILC)



### **Collimation depths**



Best case GLD, worst case LDC, but the collimation depths are acceptable

# Luminosity loss without beam crab



### Beamstrahlung cones



Integrated power beyond half- opening angle

### Other magnets: 14 mrad

- Magnets share e & γ beams.
  Normal conducting bends and quadrupoles. Preliminary designs.
  Field can be doubled for 1 TeV
- upgrade. Polarimeter and GamCal bends do not change field for 1 TeV.
- Fast sweeping kickers assume TESLA design, but with larger aperture. Design feasible - to be done.

#### Bend field (T), length (m) and aperture (mm) at 250 GeV

Bends and kickers	Qty	L (m)	<b>B</b> (T)	Half-gap (mm)	Diagnostics
BVEX1E,2E,,8E	8	2.0	0.4170	85	Energy
BVEX1P,2P	2	2.0	0.4170	117	
BVEX3P	1	2.0	0.6254	117	Polarimeter
BVEX4P	1	2.0	0.6254	132	
BVEX1G,2G	2	2.0	0.4170	147	GAMCAL
XSWEEP	5	0.8	0.071	120	<b>K</b> ielsere
YSWEEP	5	0.8	0.071	120	RICKEIS

#### Quadrupole gradient (T/m), length (m) and aperture (mm) at 250 GeV

Quad	Otv	$L^* = 3.51 m$		L*=4.0 m			L*=4.5 m				
Quau	QUY	Grad	L	Aper	Grad	L	Aper	Grad	L	Aper	
QDEX1 (SC)	1	98.00	1.060	15	89.41	1.150	17	86.39	1.190	18	
QFEX2A (SC)	1	31.33	1.100	30	33.67	1.100	30	36.00	1.100	30	
QFEX2B,2C,2D	3	11.12	1.904	44	11.27	1.904	44	11.36	1.904	44	
QDEX3A,3B	2	11.39	2.083	44	11.37	2.083	44	11.36	2.083	44	
QDEX3C	1	11.39	2.083	44	11.37	2.083	44	11.36	2.083	44	
QDEX3D	1	9.82	2.083	51	9.81	2.083	51	9.80	2.083	51	
QDEX3E	1	8.21	2.083	61	8.20	2.083	61	8.19	2.083	61	
QFEX4A	1	7.05	1.955	71	7.04	1.955	71	7.04	1.955	71	
QFEX4B,4C,4D,4E	4	5.89	1.955	85	5.88	1.955	85	5.88	1.955	85	
	Quad QDEX1 (SC) QFEX2A (SC) QFEX2B,2C,2D QDEX3A,3B QDEX3C QDEX3C QDEX3D QDEX3E QFEX4A QFEX4B,4C,4D,4E	Quad         Qty           QDEX1 (SC)         1           QFEX2A (SC)         1           QFEX2B,2C,2D         3           QDEX3A,3B         2           QDEX3C         1           QDEX3B         1           QDEX3E         1           QFEX4B,4C,4D,4E         4	Quad         Qtr           QDEX1 (SC)         1         98.00           QFEX2A (SC)         1         31.33           QFEX2B,2C,2D         3         11.12           QDEX3A,3B         2         11.39           QDEX3C         1         98.20           QDEX3D         1         98.21           QDEX3E         1         9.82           QDEX3E         1         9.82           QDEX3E         1         9.82           QDEX4B,4C,4D,4E         4         5.89	L $+ = 3.51$ Quad $Crad$ LQDEX1 (SC)198.001.060QFEX2A (SC)131.331.100QFEX2B,2C,2D311.121.904QDEX3A,3B211.392.083QDEX3C111.392.083QDEX3D19.822.083QDEX3E18.212.083QFEX4A17.051.955QFEX4B,4C,4D,4E45.891.955	L*= $3.51$ mQuadGradLQDEX1 (SC)198.001.06015QFEX2A (SC)1 $31.33$ 1.10030QFEX2B,2C,2D311.121.90444QDEX3A,3B211.392.08344QDEX3C111.392.08351QDEX3D19.822.08351QDEX3E18.212.08361QFEX4A17.051.95571QFEX4B,4C,4D,4E45.891.95585	QuadL*=3.51 mLQuadQty $\mathbf{L}^*=3.51$ AperGradQDEX1 (SC)198.001.0601589.41QFEX2A (SC)131.331.1003033.67QFEX2B,2C,2D311.121.9044411.27QDEX3A,3B211.392.0834411.37QDEX3C19.822.083519.81QDEX3D19.822.083618.20QFEX4A17.051.955717.04QFEX4B,4C,4D,4E45.891.955855.88	QuadL*=3.51 mL*=4.0 mQuadQtyGradLAperGradLQDEX1 (SC)198.001.0601589.411.150QFEX2A (SC)131.331.1003033.671.100QFEX2B,2C,2D311.121.9044411.271.904QDEX3A,3B211.392.0834411.372.083QDEX3C19.822.083519.812.083QDEX3D18.212.083618.202.083QFEX4A17.051.955717.041.955QFEX4B,4C,4D,4E45.891.955855.881.955	L*=3.51 mL*=4.0 mQuadQtrGradLAperGradLAperQDEX1 (SC)198.001.0601589.411.15017QFEX2A (SC)131.331.1003033.671.10030QFEX2B,2C,2D311.121.90444411.271.90444QDEX3A,3B211.392.0834411.372.08344QDEX3C19.822.083519.812.08351QDEX3E18.212.083618.202.08361QFEX4A17.051.955717.041.95571QFEX4B,4C,4D,4E45.891.955855.881.95585	QuadL*= $3.51 \mathrm{m}$ L*= $4.0 \mathrm{m}$ LQDEX1 (SC)198.001.0601589.411.150AperGradQDEX1 (SC)131.331.1003033.671.1003036.00QFEX2A (SC)131.331.1003033.671.1003036.00QFEX2B,2C,2D311.121.9044411.271.9044411.36QDEX3A,3B211.392.0834411.372.0834411.36QDEX3C19.822.083519.812.083519.80QDEX3E18.212.083618.202.083618.19QFEX4A17.051.955717.041.955717.04QFEX4B,4C,4D,4E45.891.955855.881.955855.88	Quad $L = 3.51 m$ $L = 4.0 m$ $L = 4.0 m$ $L = 4.0 m$ QDEX1 (SC)198.001.0601589.411.1501786.391.190QFEX2A (SC)131.331.1003033.671.1003036.001.100QFEX2B,2C,2D311.121.9044411.271.9044411.361.904QDEX3A,3B211.392.0834411.372.0834411.362.083QDEX3C19.822.083519.812.083519.802.083QDEX3E18.212.083618.202.083618.192.083QFEX4A17.051.955717.041.955717.041.955QFEX4B,4C,4D,4E45.891.955855.881.955855.881.955	



### Superconducting magnets: 0 mrad

- Based on engineered LHC SC quadrupoles and sextupoles with R = 28 mm bore radius.
- Other option: FNAL design of SC quadrupole with 35 mm bore radius.
- NbTi coils to achieve 250 T/m (7 T) at 500 GeV CM.
- Nb3Sn coils to achieve 370 T/m (10.5 T) for 1 TeV CM upgrade preliminary R&D needed.

500 GeV	QD0	QF1	SD0	SF1
Length [m]	1.146	0.593	0.548	0.314
Gradient	250 T/m	250 T/m	3880 T/m2	3662 T/m2
Field @ bore	7 T	7 T	ЗТ	2.9 T

1 TeV	QD0	QF1	SD0	SF1
Length [m]	1.374	0.746	0.7	0.4
Gradient	373 T/m	370 T/m	5243 T/m2	4873 T/m2
Field @ bore	10.5 T	10.5 T	4.11 T	3.82 T

LHC





### Other magnets: 0 mrad

- Extracted e &  $\gamma$  beams are transported through the incoming magnets which must have large aperture.
- Initial 0.5 mrad deflection by 28 m E-separator overlapped with B-field.
- C-type B1 & B2 bends with large aperture. To be designed.
- Large aperture QD2A quad for 7 cm offset extracted e beam. To be designed.
- QF3 septum quadrupole based on PEP2 IR magnet. To be designed.
- Sweeping kickers need to be included.



### Optics for 500 GeV and 1 TeV



### Physical separation of the beams



- The wrong-sign charged particles of the e<sup>+</sup>e<sup>-</sup> pairs are separated from other outgoing beams 8.5 m downstream of the fourth magnet (D<sub>y</sub> = 6 cm).
- A 5 mm thick wall is inserted to physically separate the beams.
- Starting 2 m upstream of the first magnet, a collimator with a vertical half-aperture of 9 mm and a length of 1 m absorbs the beamstrahlung photons with |y'| ≥ 1 mrad in order to protect the separation wall.

### Alternative crossing: 0 mrad



### **Electrostatic separators: 0 mrad**



- Based on LEP experience and CESR separator design with split electrodes.
- Seven 4 m separators, enclosed in 8 mT dipole field for total 0.5 mrad kick.
- Sufficient 12 mm separation at beam parasitic crossing, 55 m from IP.
- 100 mm gap with 26.2 kV/cm field at 500 GeV CM.
- 4 generators to avoid chain sparking.
- Assumed sparking rate < 0.04 per hour.

#### Lots of R&D needed

#### Beam power loss: 0 mrad

- No loss on SC QD0, SD0. Up to 1 W loss on SC QF1, SF1 in low-P option.
- 1-2 kW loss on separators w/o splitting, acceptable loss with split electrodes.
- High power (650 kW) intermediate dump ~140 m from IP with two holes. Protects magnets from large angle photon and low energy electron loss. The dump model assumes AI & water 2.2 MW device at SLAC. Requires shielding protection. Backscattering to IP and E-separators needs to be checked.
- Set of collimators to remove photon tails and limit incoming magnet aperture.
- Main dump with a hole for incoming beam.



	OI Heado	II Beam LO	SSES (KVV),	SUD GEV CIV	
	_	charged beamstrahlur	Ig		
Loss Location	Nominal Parameters		Low Power Parameters		
	Headon	Vertical offset	Headon	Vertical offset	Radiative Bhabha's
QD0/SD0 (1)	0.	0.	0.	0.	1.5E-05
QF1/SF1 (1)	0.	0.	0.0010	2.0E-04	2.5E-05
Synch. Mask (2) (Z = 12 m)	0.	0.	0.0023	0.0011	5.5E-05
Sep. plates (3)	3.6E-04	2.4E-04	1.5	2.0	5.5E-04
Inter. dump (Z = 136 m)	75 140	90 240	415 215	539 416 (4)	-
Main dump	10,160 125	10,030 135	4,500 115	4,200 95	•

May 2007

Notes:

(1) 5.6 cm bore

(2) 2.0 cm full horizontal gap

(3) 10.0 cm full horizontal gap

(4) Exceeds the nominal 650 kW small beam limit for Al/water dumps – must check if OK for widely dispersed beam Extraction line generalities

## Beam-pipe in FD region



- Separating the incoming beam from the outgoing beam and beamstrahlung in the shared region from the FD to QEX1,2
- Separation of beamstrahlung after BHEX1

### Final focus optical considerations

- PAC07 lattice: integrated 2mrad FD into ILC2006e FFS
- Introduce BHEX1 quadrupole field
  - Observe linear optics shift at IP, plus higher order optics change
  - Attempt to refit the FFS optics
    - adjust FD to re-match the beam waist at IP ( $\alpha_x$  and  $\alpha_y$ )
    - all sextupoles optimised for chromatic correction
    - →luminosity drop ~20% at E0 (w.r.t. PAC07)
  - Reason is spoiling of sextupole geometric aberation cancellation
- Can do better: Look at general optimisation procedure:
  - Vary  $\alpha_x$  and  $\alpha_y$  at the exit of QF1 (But not this flexibility when we include BHEX1 as QD0 and QF1 re-adjusted to match beam waist at the IP)
  - "Pseudo –I" transform between SD0/SD4 (All  $R_{ii}$  = -1, R12 and R34 → tuning knobs)
  - "Pseudo +I" transform between SF1/SF6 (All  $R_{ii}$  = +1, R12 and R34  $\rightarrow$  tuning knobs)
  - H & V beam waists at QF7 (*This can be improved in 2 mrad FF w/o BHEX1*)
  - Vary B1,B2,B5 to obtain eta=0, eta' at IP and certain dispersion at SF5→ tuning knob

So look at linear optics between sextupole families.....
### Comparisons of R-matrices (SD0/SD4 & SF1/SF6)

ILC2	006e (SF1/SF6)			(SD0/SD4)		
	1.059 -19.58		-0.75	1.68		
	-0.00023 0.95		0.22	-1.81		
	0.75 -9.73			-0.95	0.52	
	0.0303 0.93			-0.116	-0.98	
2mrad (PAC07) (SF1/SF6)				(SD0/SD4)		
	1.059 -22.61		-0.67	0.84		

 -0.00023
 0.94

 0.66
 -12.70

 0.0303
 0.93

With BHEX1 (SF1/SF6)	(SD0/SD4)
0.985 -16.64 -0.001 1.04	-0.69 -1.03 0.134 -1.25
0.56 -17.93	-1.23 18.85
0.0289 0.85	-0.09 0.59

# Matching quadrupoles



# R-matrices (SD0/SD4 & SF1/SF6) matched by varying QD2A and QD2B

ILC2006e (SF1/SF6)	(SD0/SD4)
1.059 -19.58	-0.75 1.68
-0.00023 0.94	0.22 -1.81
0.75 -9.73	-0.95 0.52
0.0303 0.93	-0.116 -0.98

BHEX1 (SF1/SF6)	(SD0/SD4)
1.006 -18.83	-0.73 0.0
-0.001 1.015	0.13 -1.37
0.73 -10.94	-0.97 0.00
0.0303 0.91	-0.071 -1.03

# How the bandwidths compare



# IR magnets prototypes at BNL









#### Fast sweeping system

**14 mrad:** System of fast (1 kHz) X-Y kickers is included to sweep bunches of each train in one turn on 3 cm circle at the dump window. It enlarges the beam area to protect from window damage and water boiling caused by very small beam size in cases of undisrupted beam or under certain abnormal optics conditions (large errors, magnet failures).



## ILC Beam Dump

- parameters

#### Inputs

- material water (no gas contained in water)
- equation of state single phase shock
- domain size = 6m x 1.45m diameter
- boundary conditions = rigid tank walls
- duration of bunch = 30ns
- duration of interval between bunches = 330ns
- number of bunches in a bunch train = 2800bunches
- duration of a bunch train ~ 1ms
- energy deposited per bunch = ~1.19kJ
- energy deposited per bunch train = ~ 3.3MJ
- time averaged power deposition = 16.5MW
- number of electrons per bunch = 2e10
- beam energy = 500GeV
- beam rastoring radius = 30mm
- beam rastoring speed = 6280rad/s

#### ILC Beam Dump Peak Pressure



Refined mesh (2mmx2mm) around region of shower maximum indicates a peak pressure of ~13.5bar occuring after 0.01ms or about 28 bunches