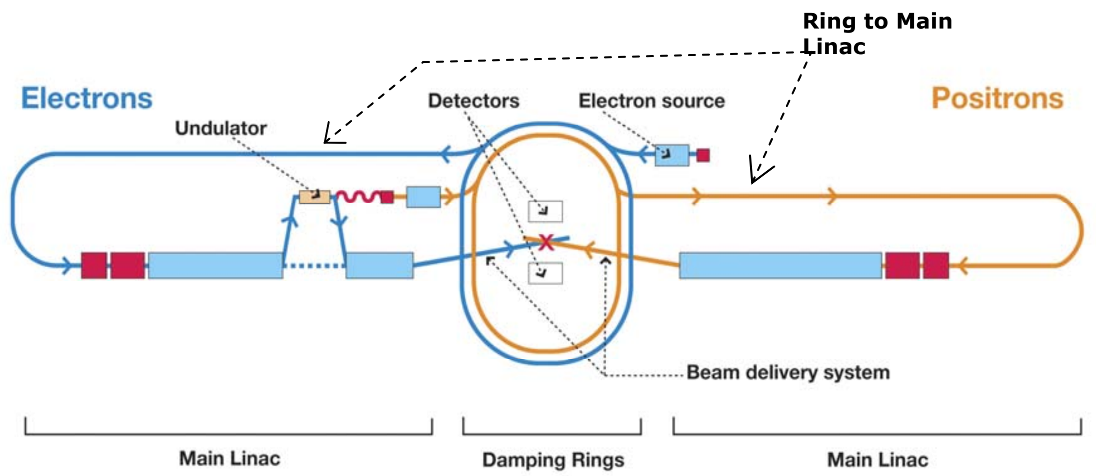
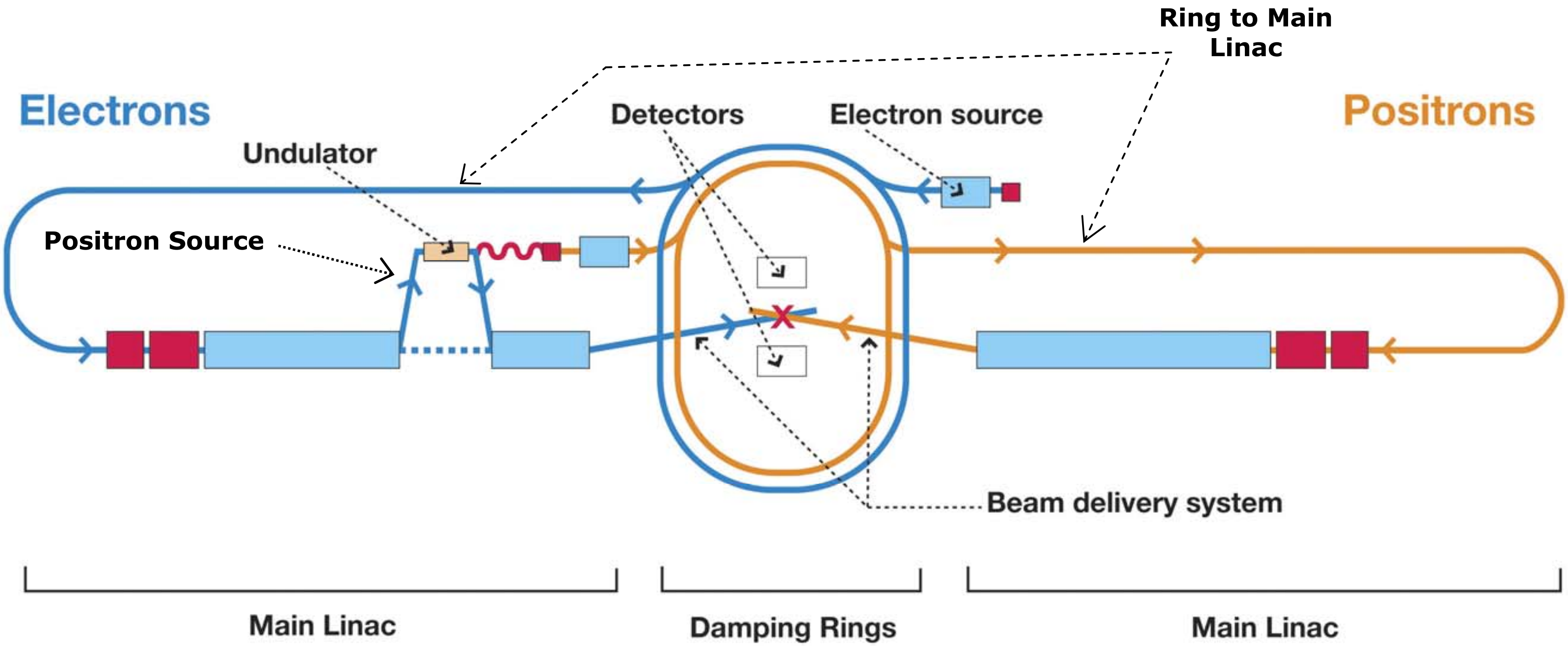
# Superconducting Magnets Needs for the ILC




J. Tompkins, Fermilab
For the ILC RDR Magnet Systems Group

# ILC RDR Layout




Machine configuration for RDR

# Overview

- The ILC Reference Design Report was released in February, 2007
  - Effort on RDR began in January 2006, following the release of the Baseline Conceptual Design in December of 2005
  - For the RDR, an international team of scientists, engineers, and designers was assembled
    - Area Systems – $e^-$ Source; $e^+$ Source; Damping Rings; Ring to Main Linac (RTML); Main Linac; and, Beam Delivery System
    - Technical Systems - Vacuum systems; Magnet systems; Cryomodule; Cavity Package; RF Power; Instrumentation; Dumps and Collimators; Accelerator Physics
    - Global Systems - Commissioning, Operations & Reliability; Control System; Cryogenics; Conventional Facilities and Siting; Installation
- This talk discusses the ILC superconducting magnet needs based on the RDR

# RDR Magnet Systems Group

- Leaders: R. Sugahara (Asia, KEK), J. Tompkins (Americas, FNAL), E. Bondarchuk (Europe, Efremov Inst.)
- The International Team:
  - Cherrill Spencer, SLAC
  - Vladimir Kashikhin, FNAL
  - Jin-Young Jung, LBNL
  - Ross Schlueter, LBNL
  - Brett Parker, BNL
  - Gianluca Sabbi, LBNL
  - Jim Clarke, Daresbury Lab
  - Mark Palmer, Cornell
  - Tom Mattison, UBC/SLAC
  - Paul Bellomo, SLAC
  - Mike Tartaglia, FNAL
  - David Warner, CSU
  - Nikolay Morozov, Dubna
  - Boris Kitaev, Efremov Inst.
  - Steve Marks, LBNL
  - Dave Plate, LBNL
- Task: determine the magnet requirements of each Area System and turn them into ‘designs’ with estimates of size, supports, current, cooling requirements, and costs

# Approach

## Developing magnet requirements/specifications

- Define 'standard' set of magnet input requirements; distribute to Area Systems Leaders; collect basic requirements data from Area Systems groups
  - Review input data from Area Systems
  - Iterate with Area Leaders: clarifications, magnet parameters, 'stringing' rules, etc.
- Reduce magnet lists to a manageable number of magnet styles
  - Iterate with Area Leaders on magnet styles decision
  - Coordinate – when possible – style development across Area Systems
- Develop conceptual designs for magnet styles
  - Focus on cost drivers – either large quantity or high complexity
- Develop associated requirements from conceptual design parameters
  - Power systems
  - Controls
  - Infrastructure – wall power, LCW, alcove space, cable trays, etc
- "Repeat as necessary" - Area Systems are evolving, major systems changes have taken place

# ILC Magnet Summary Table

## 250Gev X 250Gev - 14 December 2006

| Magnet Type | Grand Totals | | Sources | | | Damping Rings | | | 2 RTML | | 2 Linacs | | 2 BeamDel | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Styles | Quantity | Styles | e- Qty | e+ Qty | Styles | e- DR Qty | e+ DR Qty | Styles | Qty | Styles | Qty | Styles | Qty |
| Dipole | 22 | 1356 | 6 | 25 | 157 | 2 | 134 | 134 | 6 | 716 | 0 | 0 | 8 | 190 |
| Normal Cond Quad | 37 | 4182 | 13 | 93 | 871 | 4 | 823 | 823 | 5 | 1368 | 0 | 0 | 15 | 204 |
| Sextupole | 7 | 1050 | 2 | 0 | 32 | 2 | 504 | 504 | 0 | 0 | 0 | 0 | 3 | 10 |
| Normal Cond Solenoid | 3 | 50 | 3 | 12 | 38 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Normal Cond Corrector | 9 | 4047 | 1 | 0 | 871 | 3 | 540 | 540 | 4 | 2032 | 0 | 0 | 1 | 64 |
| Pulsed/Kickers/Septa | 11 | 227 | 0 | 0 | 19 | 5 | 46 | 46 | 1 | 52 | 0 | 0 | 5 | 64 |
| NC Octupole/Muon Spoilers | 3 | 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 8 |
| *Room Temp. Magnets* | *92* | *10920* | *25* | *130* | *1988* | *16* | *2047* | *2047* | *16* | *4168* | *0* | *0* | *35* | *540* |
| Supercond Quad | 16 | 715 | 3 | 16 | 51 | 0 | 0 | 0 | 0 | 56 | 3 | 560 | 10 | 32 |
| Supercond Sextupole | 4 | 12 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 12 |
| Supercond Octupole | 3 | 14 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 14 |
| Supercond Corrector | 14 | 1374 | 0 | 32 | 102 | 0 | 0 | 0 | 0 | 84 | 2 | 1120 | 12 | 36 |
| Supercond Solenoid | 4 | 16 | 1 | 2 | 2 | 0 | 0 | 0 | 1 | 8 | 0 | 0 | 2 | 4 |
| Supercond Wiggler | 1 | 160 | 0 | 0 | 0 | 1 | 80 | 80 | 0 | 0 | 0 | 0 | 0 | 0 |
| Supercond Undulator | 1 | 42 | 1 | 0 | 42 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| *Superconducting Magnets* | *43* | *2333* | *5* | *50* | *197* | *1* | *80* | *80* | *1* | *148* | *5* | *1680* | *31* | *98* |
| **Overall Totals** | **135** | **13253** | **30** | **180** | **2185** | **17** | **2127** | **2127** | **17** | **4316** | **5** | **1680** | **66** | **638** |

## Overall Magnet Totals

*250Gev X 250Gev - 14 December 2006*

| *Category* | *Styles* | *Totals* |
|---|---|---|
| Total Normal cond | 92 | 10920 |
| Total Superconducting | 43 | 2333 |

Note: this is table is Cherrill Spencer's magnet summary - ILCMagnet Count14Dec06NC_SC.xls - modified slightly for this talk

# General Issues for All Magnets

- Alignment with respect to beam path
  - Preserve beam properties
  - Offset of quadrupoles from beam axis must be adjusted by moving beam (dipole correctors), or magnet
  - Sub- μ accuracy achieved w/ mechanical movers in BDS
- Stability
  - Geometric – if magnet core is not mechanically stable its magnetic center will wander
  - Field stability/reproducibility
    - Over time (& thermal cycles for sc magnets)
    - With respect to changes in current/field – hysteresis, magnetization currents, etc.
- Reliability
  - MTBF for magnets $\geq 10^7$ hrs
  - Meeting reliability requirements must be a key component of design approach
  - R&D program/'lifetime' studies
- Stray Field
  - Magnetic elements near SCRF cavities must meet stray field limits at cavity of ≤1 μT (warm) and ≤10 μT (cold)
- Cost
  - Design must be cost efficient while meeting lattice and reliability requirements

# Overview of Superconducting Magnets

- There are 2333 superconducting magnets required for the ILC in the Reference Design
  - Roughly 60% are correction coils wound in the same cold mass as the main coils, or immediately adjacent to it
- Main Linac
  - Most of the SC magnets (~1680) are located in the RF cryomodules.
  - A package containing a focusing quadrupole (quad), steering dipole corrector(s) and a BPM in every third main linac cryomodule
- Damping Rings
  - Superconducting wigglers provide beam damping in the Damping Rings
  - *See paper 3108 - THPMS011 "Design Considerations and Modeling Results for ILC Damping Ring Wigglers Based on the CESR-c Superconducting Wiggler", J. A. Crittenden, et al.*

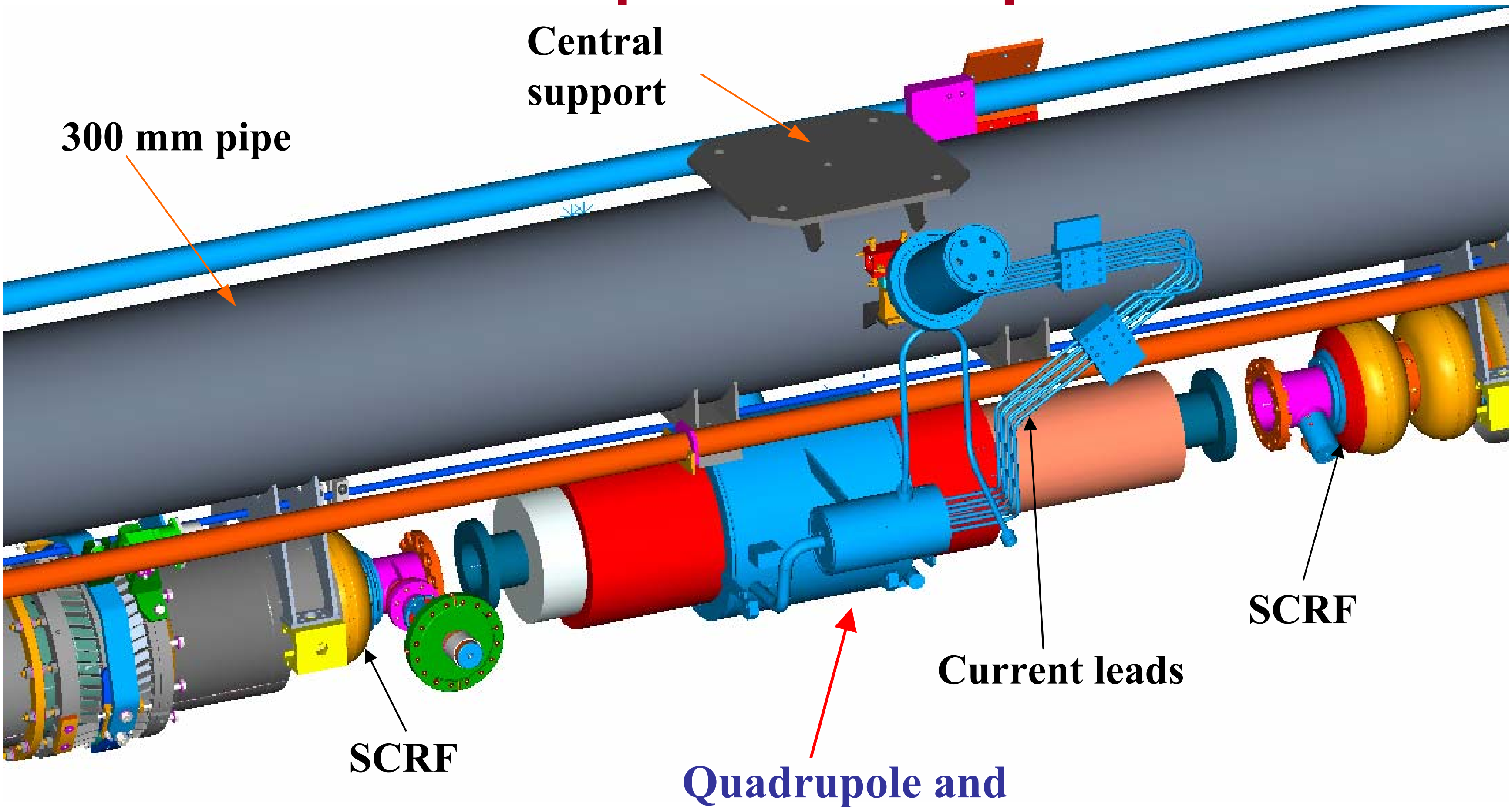
# ILC Superconducting Magnets, cont.

- Positron Source
  - Superconducting undulators in the $e^-$ linac provide the photons needed to create positrons in the positron source
  - *See papers: 1614 - THPMN070 "Development of a Full Scale Superconducting Undulator Module for the ILC Positron SourcePresenter", James Rochford, et al,; 1619 - THPMN071 "Status of R&D on a Superconducting Helical Undulator for the ILC Positron Source", J. Rochford et al*
- Beam Delivery System
  - Perhaps the most challenging superconducting magnets are those just before the interaction point. They have strong gradient fields with layers of correcting coils, and must fit into as small a radius possible to not interfere with the detector.
  - *See paper: 1910 - THPMS091 "The Superconducting Magnets of the ILC Beam Delivery System", B. Parker, et al.*
- Supercounducting Solenoids
  - In the ILC sources, there are superconducting solenoids for spin rotation and a few large aperture magnets that may be either conventional or superconducting, depending on detailed optimization of operating versus capital cost.

# Main Linac Quadrupole & Correctors

- Overview
  - Located at the center of a cryomodule
    - Operated at 2K
    - Quadrupole, dipole correctors, and BPM in one assembly
  - Maximum integrated strength ~36 T
    - ~54 T/m maximum gradient
  - Beam based alignment
    - Decrease gradient by ~20%, measure beam position in adjacent BPM while increasing field in steps
    - Critical requirement: quadrupole center must be stable to ~1μ over current/field range
  - Challenges
    - Center stability, reproducibility with field strength
      - Mechanical
      - Hysteretic effects due to magnetization currents
    - Stray field at adjacent cavities
      - < 10 μT when cold, < 1 μT warm

# Main Linac Quadrupoles and Dipole Correctors



# Specifications for Main Linac Quadrupole & Correctors

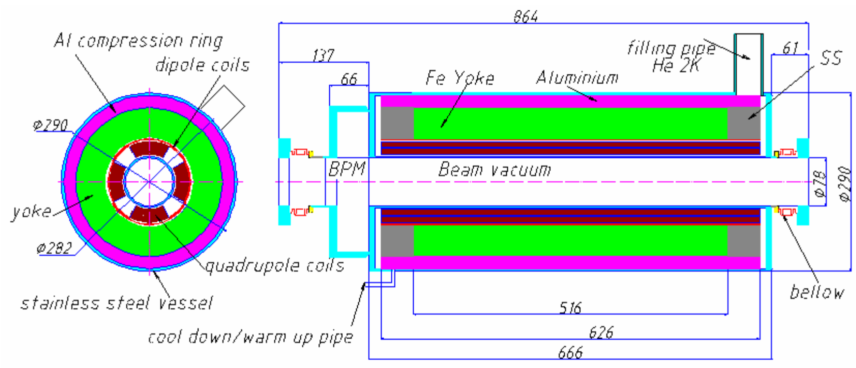
| | |
|---|---|
| Integrated gradient, T/m | 36 |
| Aperture, mm | 78 |
| Effective length, mm | 666 |
| Peak gradient, T/m | 54 |
| Field non-linearity at 5 mm radius, % | 0.05 |
| Dipole trim coils | Vertical+Horizontal |
| Trim coils integrated strength, T-m | 0.075 |
| Quadrupole strength adjustment for BBA, % | -20 |
| Magnetic center stability at BBA, um | 5 |
| Liquid Helium temperature, K | 2 |
| Quantity required | 560 |

# Quadrupole Programs

- DESY - Tesla & XFEL
  - CIEMAT (Spain) built prototype for TTF
    - Tested at DESY
  - CIEMAT also design and building a new version for XFEL
- ILC - SLAC
  - Will study magnetic center stability of CIEMAT TTF quadrupole
- ILC - Fermilab
  - R&D Program to build superferric models
    - Study magnetization effects & stability
    - First model under way – test end of summer (?)
- ILC - KEK
  - Beginning program to build quadrupole with nested correctors
    - KEKB experience

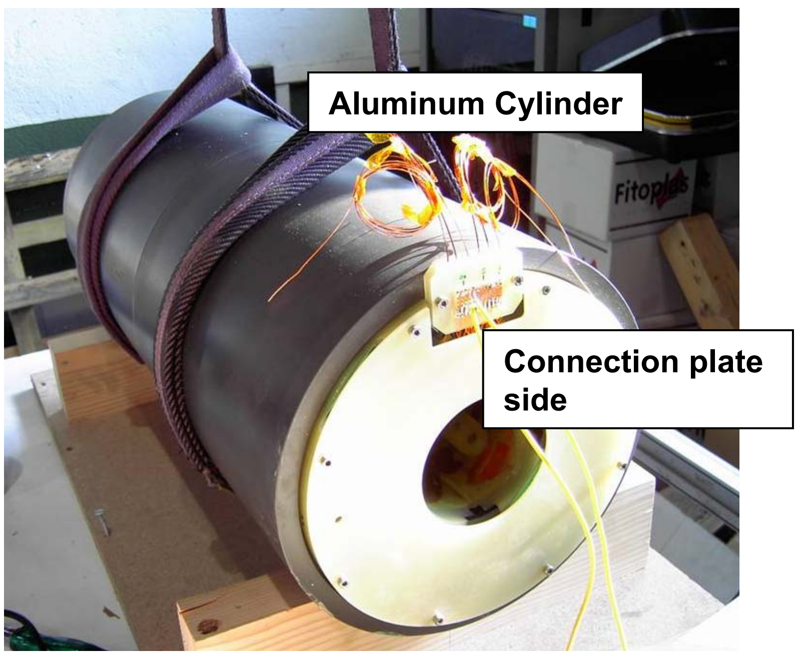
# CIEMAT Quadrupole w/ Dipole Windings

- CIEMAT (Spain) quadrupole prototype for Tesla/XFEL
- Tests at DESY revealed gradient dependence on corrector current




| | |
|---|---|
| quadrupole gradient | 63.5 T/m |
| quadrupole current | 100 A |
| dipole field | 0.11 T |
| dipole current | 40 A |
| max. field at conductor | 3.22 T |
| field length | 0.52 m |
| alignment error (angle) | 0.1 mrad rms |

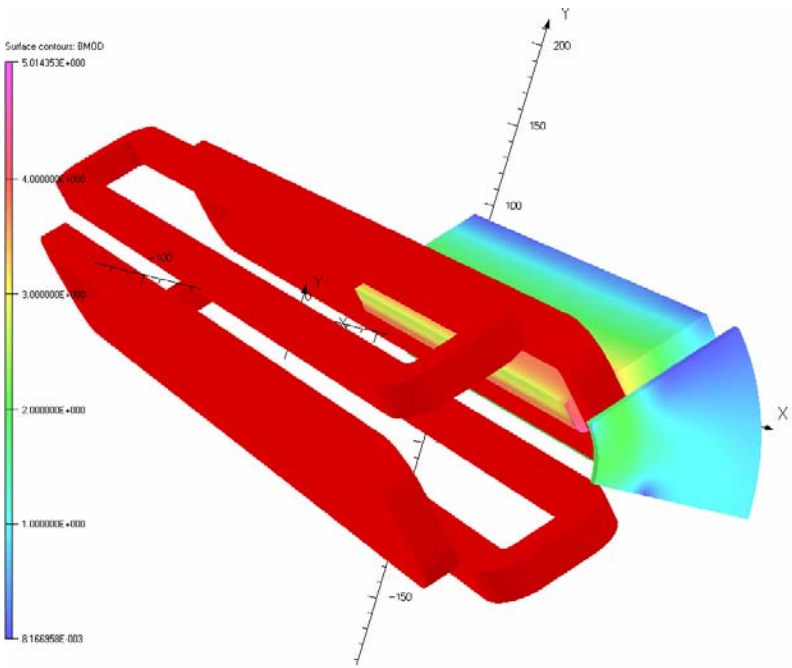
- Center stability study to be done at SLAC this summer

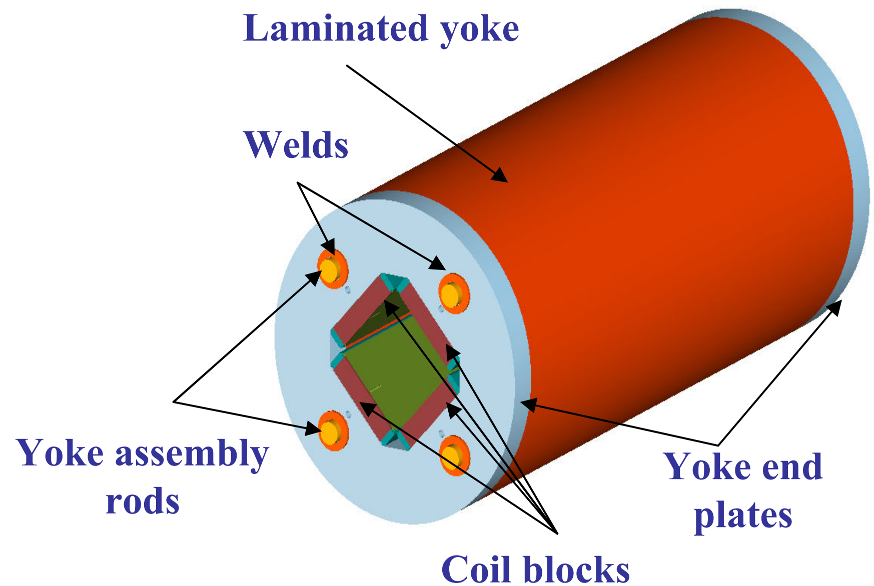


# Fermilab Approach

- Superferric quadrupole configuration
  - four racetrack coils, cold iron core
- Low peak current (100 A)
  - reduce heat load from current leads (each quadrupole is powered separately)
- NbTi wire with small filaments to reduce magnetization effects
- Racetrack coils and yoke configuration provide easy assemly/disassembly
  - Coils wound into a stainless steel channel: mechanical rigidity and robust coil manufacturing technology
  - Low carbon steel iron yoke is laminated to use stamping as more economic process - all four poles and flux return combined in one solid lamination
- Yoke has magnetic shields at both ends to reduce fringe fields
- Two dipole shell type trim coils mounted on beam pipe outer surface
  - Trim coils with beam pipe could be installed/removed

# Fermilab Design for a Superferric Quadrupole



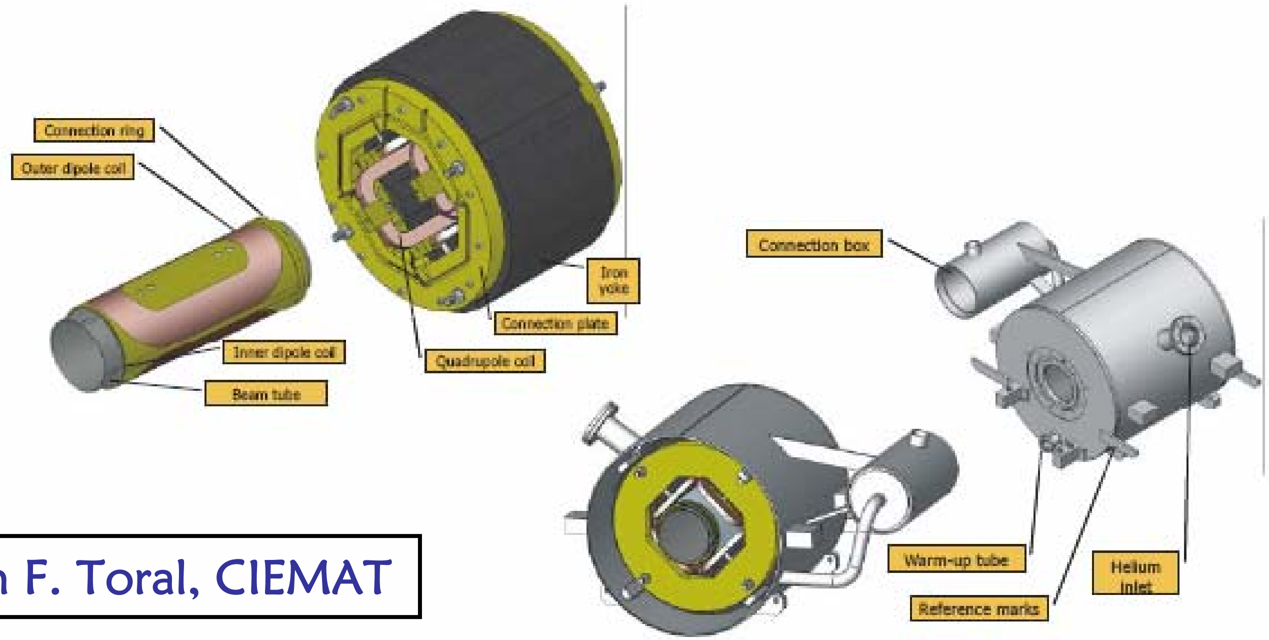

Cold mass: Length 680 mm
OD 280 mm

From Vl. Kashikhin, FNAL

# 2nd Generation CIEMAT Design

## XFEL contribution (II)

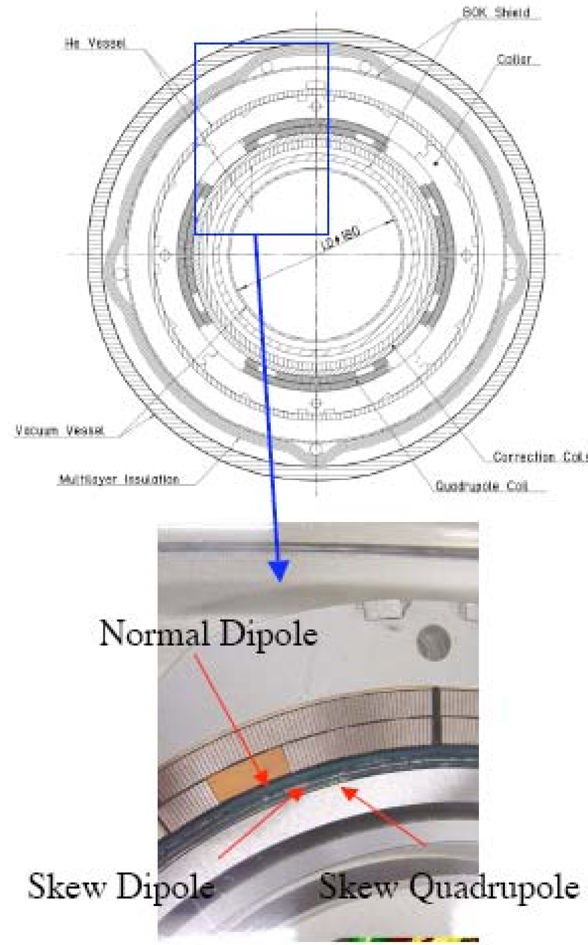
- Engineering design of a combined superferric magnet (2006).




From F. Toral, CIEMAT

# ILC-Quadrupole R&D plan at KEK

- KEK will study the nested quadrupole with corrector coils for the ILC quadrupole.
  - KEK has the experience of the nested magnet for the final focus quadrupole in KEKB.
  - KEK plans to make the magnetic field measurement system for studying the effect of the coupled fields in the magnet.
- The cross section of the magnet is now being studied.
  - For designing the magnet, the magnet current will be less than 300 A.
  - For transporting the current to the magnet, HTC current leads will be used, and the ceramic feed-through at low temperature is the R&D component.




From N. Ohuchi, KEK

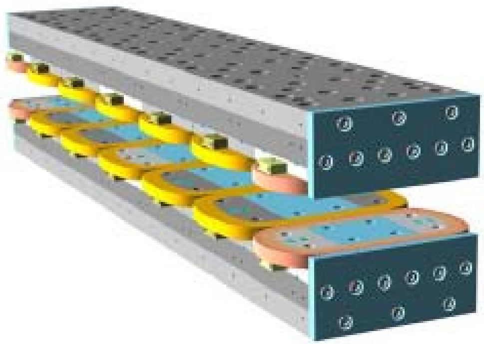
# Damping Ring Wigglers

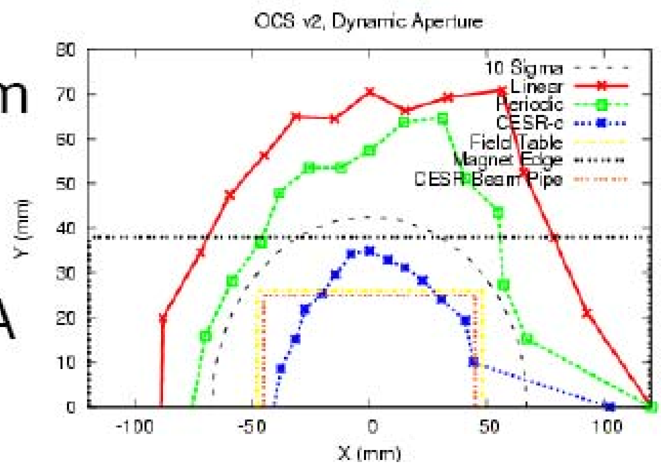
- The Damping Rings play a crucial role
  - they must accept the large emittances of the incoming e- and e+ beams and damp them to required levels within the 200 ms interval between machine pulses
- To achieve the short damping times required, 160 sc wigglers are required for the two rings.
- RDR design is based on Cornell CESR-c wiggler design
  - CESR-c: 1.3 meters
  - ILC RDR: 2.5 meters
  - Other parameters essentially the same
- Larger gap is considered
  - Simplify assembly
  - More space to handle ~10x increase in synchrotron radiation load
  - Field quality remains acceptable

# DR Wiggler Design Overview

## Modified CESR-c Wiggler

- $B_{peak}$ = 1.67 T
- $\lambda$ = 40 cm
- 5 periods + end poles
- Pole Width = 238 mm
- Pole Gap = 76 mm
- Beam Stay Clear = 50 mm
- Performed well in all BCD option DRs...too well?
- OCS v2: $DA_{linear\ wiggler}$ > PA > wiggler map



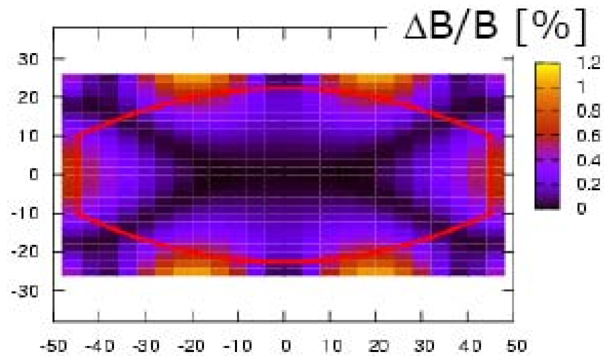



From: J. Urban, M. Palmer - Cornell

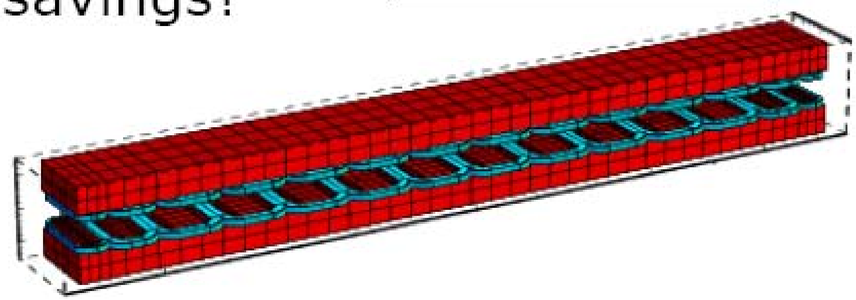
# DR Wiggler Design, cont.

## Physics Design Optimization

- CESR-c wiggler optimized specifically for CESR-c conditions
  - gap, width, coil shape, pole cutout/shim
- Field quality greater than necessary for ILCDR
- Potential for cost savings?
  - Field quality
  - Total number




Wiggler models in Opera & Radia

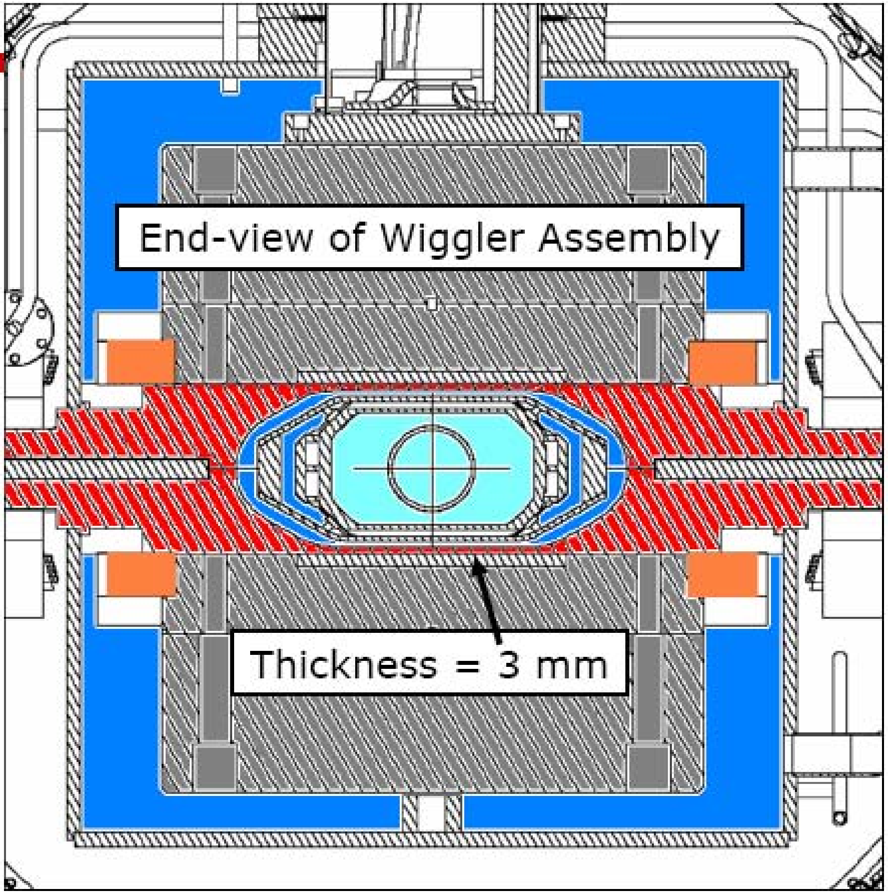


From: J. Urban, M. Palmer - Cornell

# DR Wiggler Design, cont.

## Gap Height

- Simplify construction & add flexibility
  - Larger gap
    - Simplifies support plate construction
    - Cost savings
  - Larger gap possible
    - 76 → >98 mm @ 1.67 T



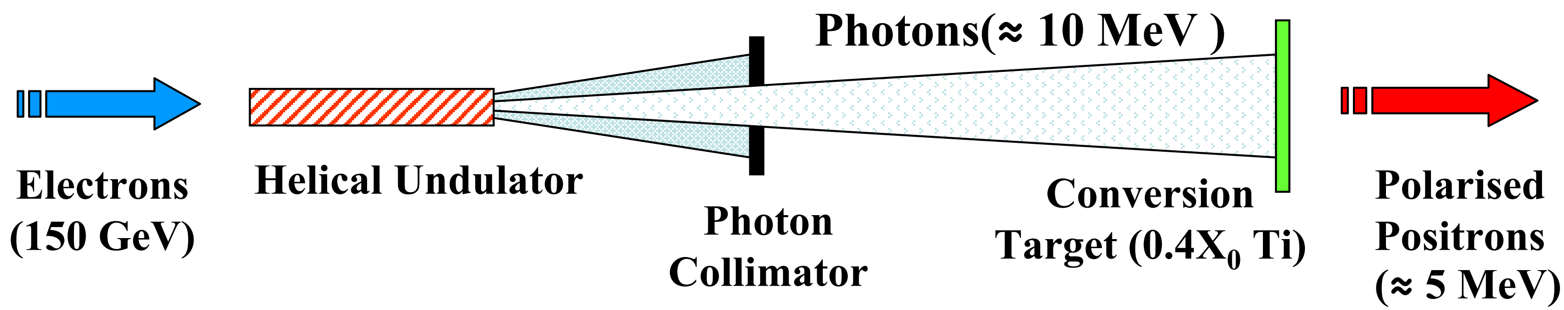

From: J. Urban, M. Palmer - Cornell

# Wigglers: Beyond the RDR

- Optimized and engineered design for ILC
  - 12 poles
  - Period: λ 40cm ⇨ 32cm
  - Field: B 1.67T ⇨1.95T
  - Gap: 76mm ⇨ 86mm
  - Wiggler/cryostat engineering design
    - Vacuum chamber/cold bore interface
    - Simplify design and fabrication
  - Cost reduction

# Undulators for the $e^+$ Source

- Positrons are created by the $e^-$ beam (at the 150 GeV point in the linac) passing through a helical wiggler generating synchrotron radiation (~10 MeV) which hits a conversion target
  - 2x synchrotron radiation power per period than that of a planar undulator



# e$^+$ Source Layout

## (Stolen from V. Bharadwaj, Hamburg ILC/LCWS 2007)

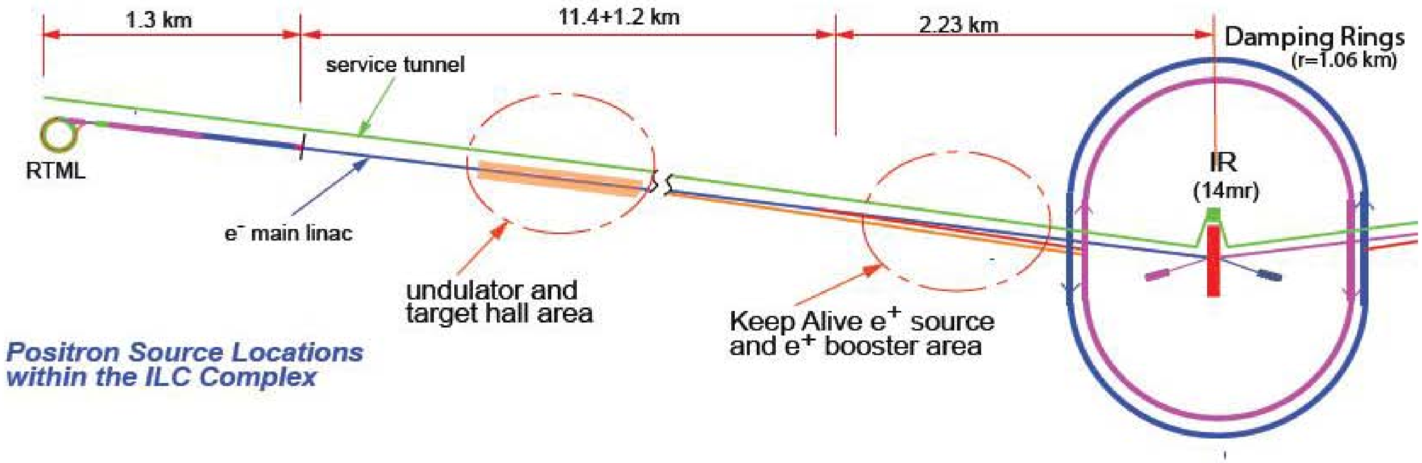



FIGURE 2.3-1. Layout of the Positron Source in the ILC

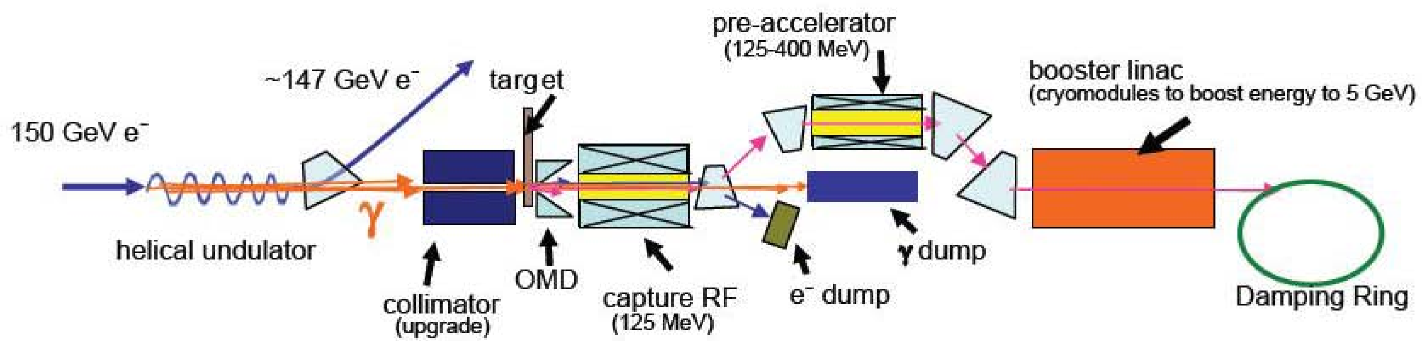



FIGURE 2.3-2. Overall Layout of the Positron Source

# Undulator Challenges
## (from J. Clarke)

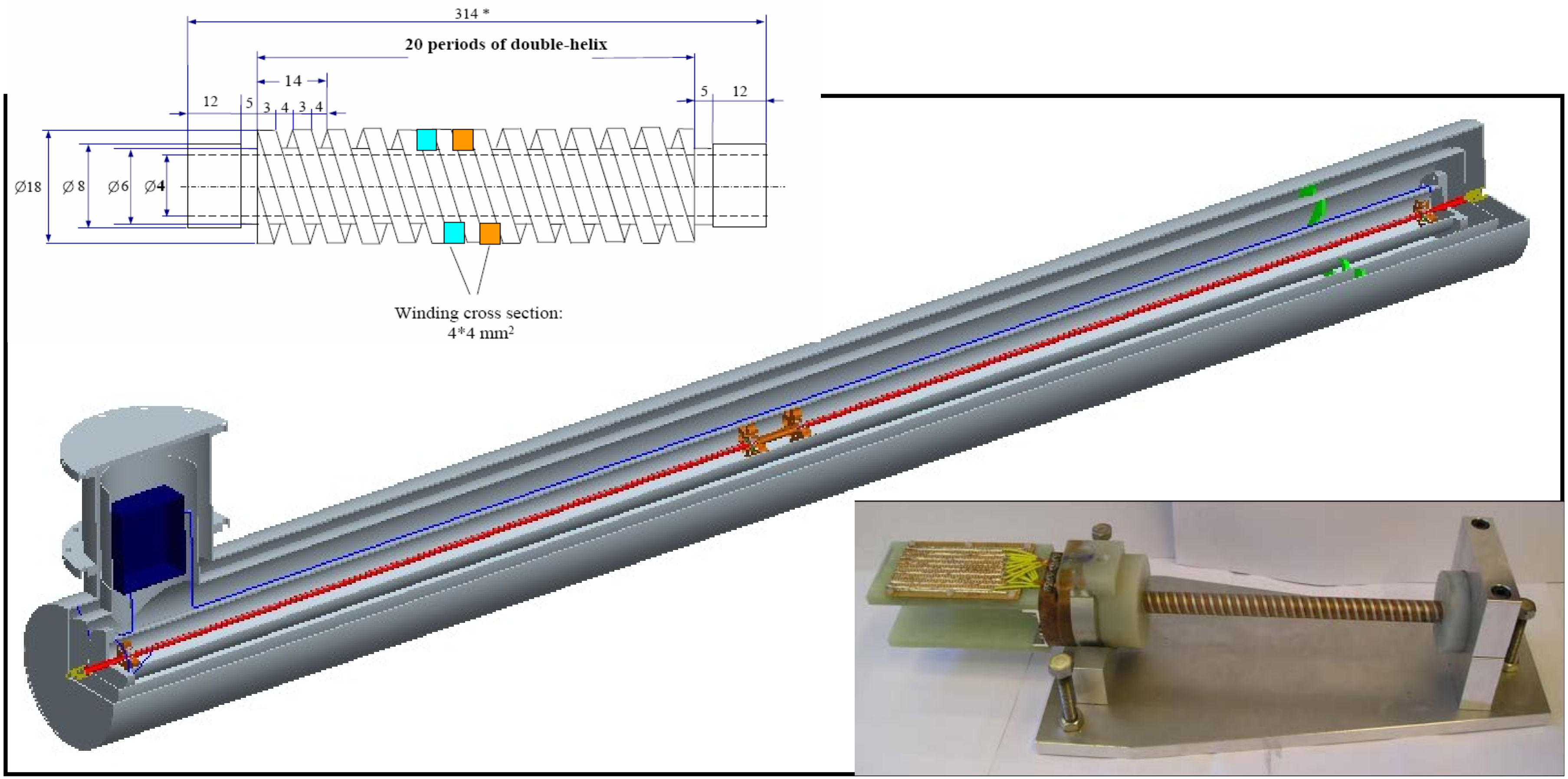
- High fields
  - Pushing the limits of technology
- Short Periods
  - Shorter periods imply higher fields
- Narrow apertures
  - Very tight tolerances - Alignment critical
- Cold bore (4K surface)
  - Cannot tolerate more than few W of heating per module
- Minimizing impact on electron beam
  - Must not degrade electron beam properties but have to remove energy from electrons
- Creating a vacuum
  - Impossible to use conventional pumps, need other solutions

# Baseline Undulator Design

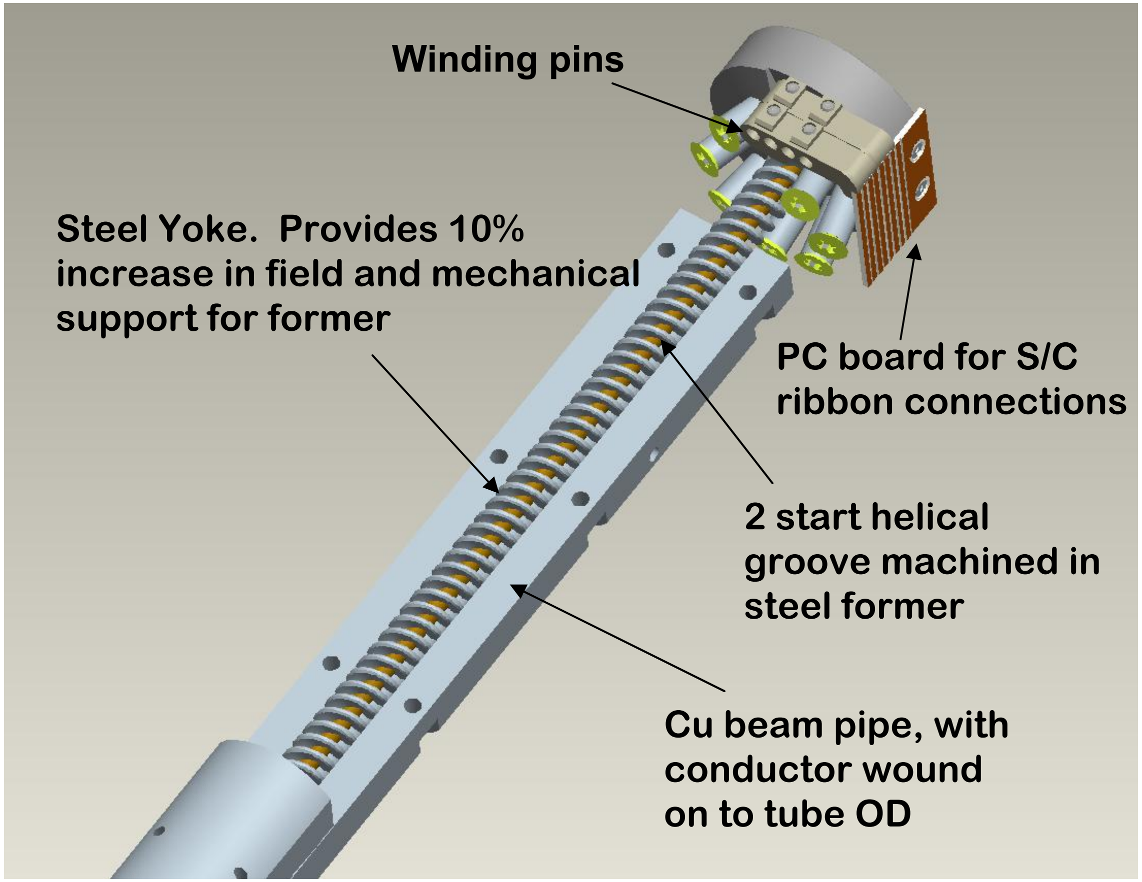
## HeLiCal Collaboration

- HeLiCal collaboration
  - University of Liverpool, CCLRC, University of Durham, DESY, ASTeC
    - CCLRC (Council for the Central Laboratory of the Research Councils ) ⇨Science and Technology Facilities Council (2007)
    - Rutherford Appelton Laboratory
    - Daresbury Laboratory
    - ASTeC - Accelerator Science and Technology

# Undulators for the $e^+$ Source

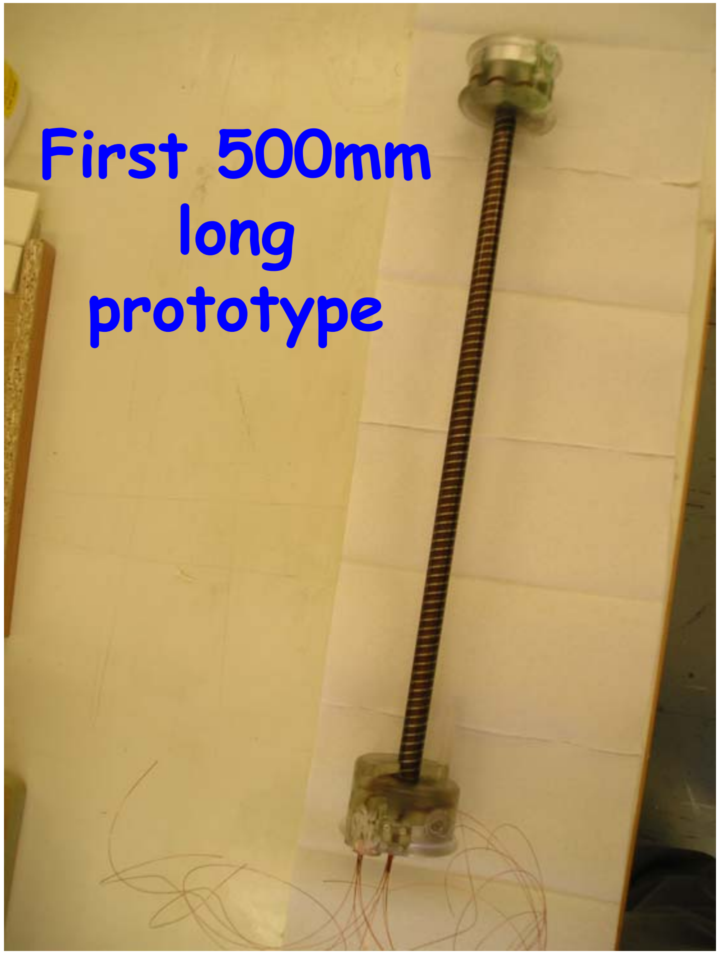


# Undulator - Magnet Design Concept



# Prototype 5

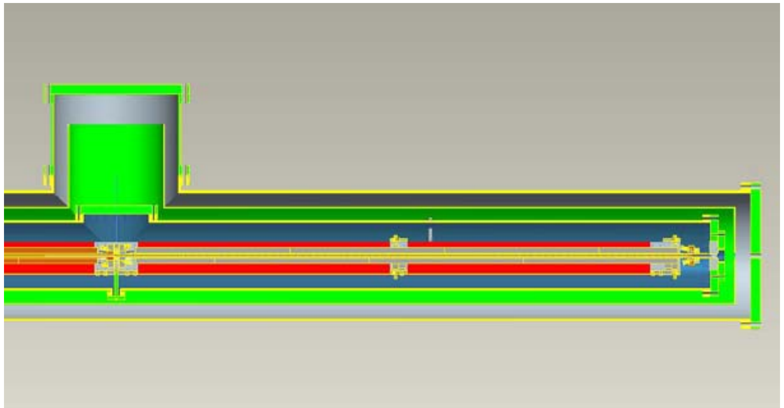
- Same parameters as RDR Baseline undulator
- 11.5 mm period
- 6.35 mm winding diameter
- Peak on-axis field spec of 0.86T (10 MeV photons)
- Winding directly onto copper tube with iron pole and yoke
- New wire with more aggressive Cu:SC ratio of 0.9:1.0



# Plans for a 4m Undulator Module

| | |
|---|---|
| On axis field | 0.86 T |
| Peak to peak variation | <1% |
| Period | 11.5 mm |
| Nominal Current | ~250 A (80% of short sample) |
| SC wire | NbTi 0.4mm dia., SC:Cu ratio 0.9:1 |
| Winding Cross Section | 7 wires wide x 8 high |
| Number of magnets per module | 2 (powered separately for tests) |
| Length of magnetic field | 2 x 1.74 m |
| Number of modules req'd | 42 |

- Complete testing of Magnet 1 – August 2007
- Complete testing of Magnet 2 – September 2007
- Complete Magnet/Cryostat assembly – November 2007
- Complete Testing of 4m Module – December 2007



From J. Clarke, Alison Birch/Steve Carr

# Undulator Status

- One 11.5mm period SC undulator (prototype 5) built and tested
  - Period further reduced to RDR value of 11.5mm
  - New SC wire used (Cu:SC - 0.9:1)
  - Field strength measured greater than expected, possibly due to increase in SC content of wire
  - Best ever field quality results (well within spec)
  - Full length prototype will use these parameters
- Full length prototype construction started
  - 4m prototype design complete
  - Fabrication has commenced

# Cornell Alternative Design

## (Mikhailichenko & Tigner)

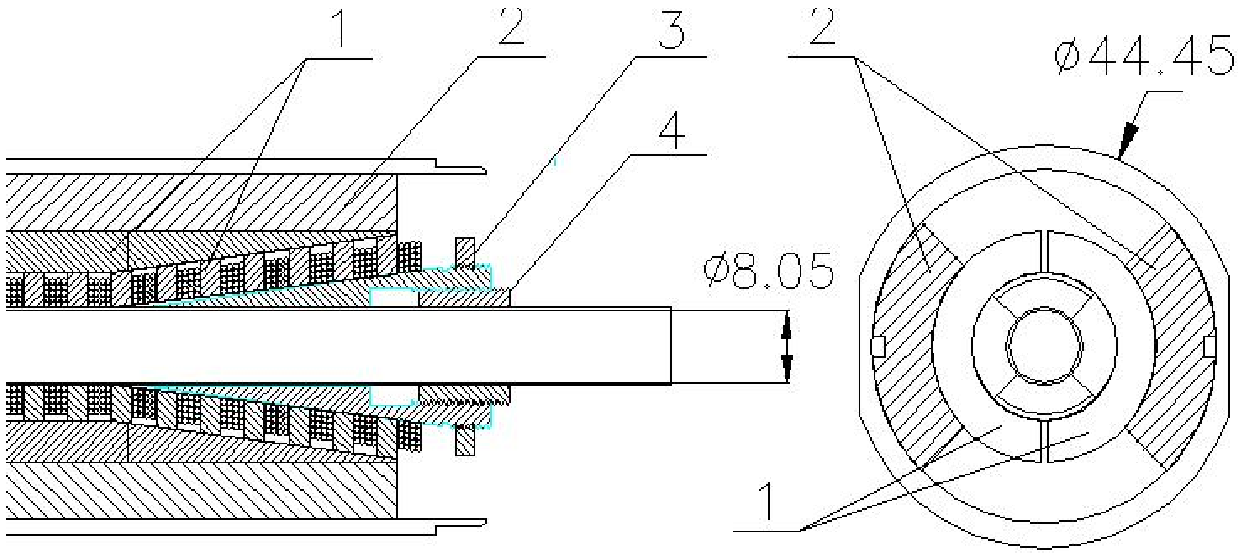



Fig.2:Details of design. 1–Iron yoke, 2–Copper collar, 3, 4–trimming Iron nuts. Inner diameter of Copper vacuum chamber is 8mm clear.



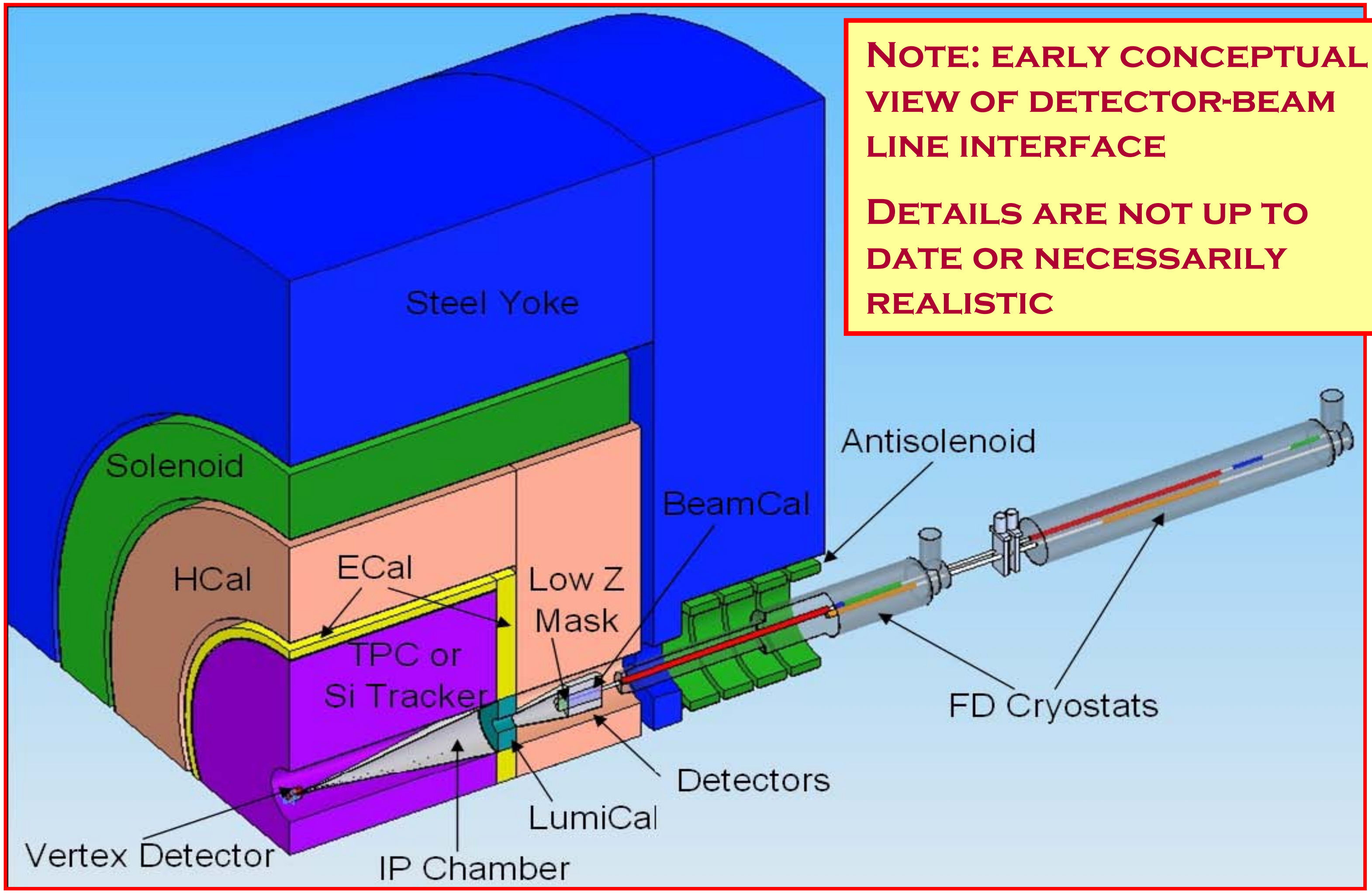
# Beam Delivery System Final Focus Magnets

- The final focus region is quite complicated
  - Incoming and outgoing beams are in very close proximity
  - There is a massive detector in the way
  - The last elements of the beamline are captured with the detector and must move with it
    - 'Push-pull' for the 2 detector scenario
  - Beam stability critical for collisions to occur
    - Mechanical and magnetic stability of the final focus elements
  - Significant radiation loads from interactions and the disrupted beams

# Final Focus Overview

- Brett Parker and colleagues (BNL) – have been working with the BDS group on final focus magnet designs and on integration issues with the detector groups (Brett actually began this work during NLC days…)
  - Compact magnet designs required due to very tight transverse space limitations caused by incoming and disrupted beam separation
  - Magnets must be shielded from the detector field
  - Adjacent beam lines must be shielded from each other
  - Higher order correction elements required

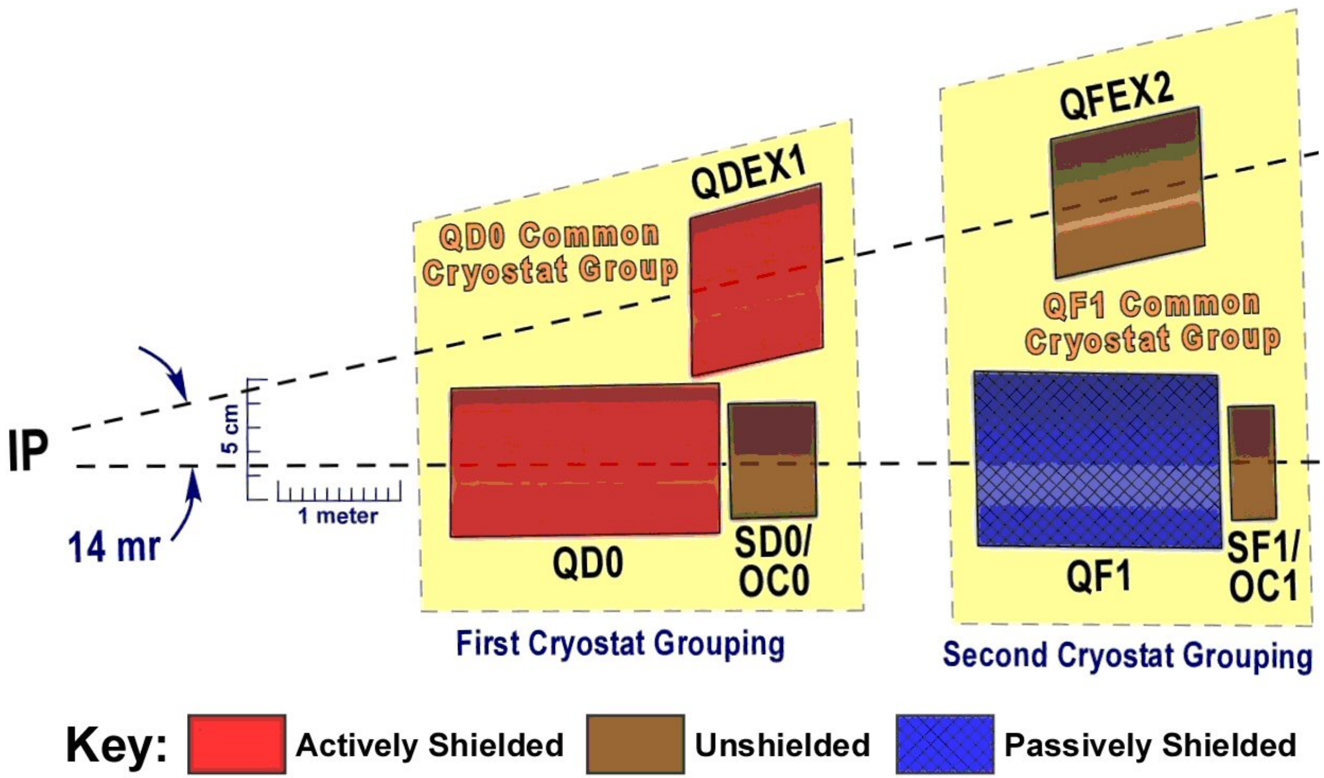
# BSD Superconducting Magnets




NOTE: EARLY CONCEPTUAL VIEW OF DETECTOR-BEAM LINE INTERFACE

DETAILS ARE NOT UP TO DATE OR NECESSARILY REALISTIC

# BDS – BNL Layout for Final Focus Magnets



## Individual magnetic elements in each of the coil groups in a cryostat from the RDR design

## QD0 Group moves with detector

## QF1 Group is fixed in beam line

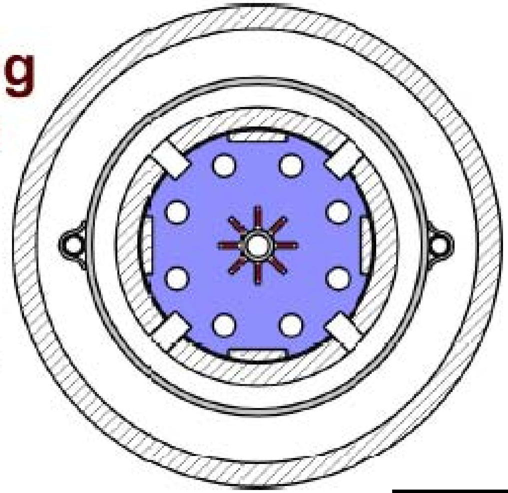
| | QD0 Group | QF1 Group 2 |
|---|---|---|
| Incoming Beam | QD0 | QF1 |
| | Main Quadrupole | Quadrupole |
| | Dipole | Dipole |
| | Skew Dipole | Skew Dipole |
| | Skew Quadrupole | Skew Quadrupole |
| | Shield Quadrupole | |
| | SD0 | SF1 |
| | Octupole | Octupole |
| | Sextupole | Sextupole |
| | Skew Sextupole | Skew Sextupole |
| | Dipole | Dipole |
| | Skew Dipole | Skew Dipole |
| Disrupted Beam | QDEX1 | QFEX2A |
| | Main Quadrupole | Quadrupole |
| | Dipole | Dipole |
| | Skew Dipole | Skew Dipole |
| | Skew Quadrupole | Skew Quadrupole |
| | Shield Quadrupole | |

# Other BDS Superconducting Magnets

- Detector Integrated Dipole
  - Compensate for beam at an angle to solenoid axis (not 'formally' a BDS magnet, part of detector)
- Compact Tail Folding Octupoles

Tail-Folding Octupole

Both IRs



Uses '6 around 1' cable, with strands run in series

75A max operating current

Reduces lead heating

Allows for conducting cooling (cryocoolers)

From Brett Parker, BNL

# Other Superconducting Magnets

- Superconducting Solenoids
  - Large aperture, high field strength solenoids are needed in several Areas:
    - $e^+$, $e^-$ Sources, RTML, BDS
    - Roughly 16 solenoids of 4 different "styles"
  - Some of the solenoids may have either conventional or superconducting technology solutions to be resolved by
    - Understanding of heat loads
    - Length vs. field tradeoffs
    - Operational cost (kwh & cooling) vs. capital cost & cryogenic operation
  - More work to be done
    - More detailed designs
    - Heat loads, backgrounds, etc.
    - Magnet engineers, designer/drafters…

# Summary

- ILC magnets are mostly lower field conventional magnets, but there are a significant number of superconducting magnets required
- The largest number of superconducting magnets in the Main Linac: there is an sc quadrupole plus dipole correctors in every third cryomodule
  - Plus quads & correctors associated with SCRF accelerating sections in other areas
- Superconducting magnets play important roles in the ILC
  - Positron Source – sc undulators provide $\gamma$'s which create positrons
  - Damping Rings– sc wigglers damp the beams within required 200 msec
  - BDS – compact, nested sc magnets provide the final beam focusing
- Much has already been accomplished in these sc magnet systems
  - R&D is under way - undulators, Final Focus components, wigglers
  - Successful prototypes have been built and tested
  - Designs are maturing and adapting to changing requirements