Magnets for Linacs WAMSDO'08

more exactly:

A Survey of Interesting Superconducting Magnets for Linacs

The Technical, R&D Challenges they pose

Linear Colliders

Low Energy Linacs

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Fermilab

Introduction

There are *MANY* LINACS around the world

Too many to cover comprehensively in a short talk

(also beyond my level of breadth and depth)

[see refs: LINAC96,…,04,06,(08)]

Superconducting Magnets used only if needed

In general, they are *NOT,* even in ScRF LINACS (e.g., SNS)

‘Usual’ Magnet Parameters (strength, field quality)

are not exceptionally challenging

Focus on recent areas, where I have had some involvement

The International Linear Collider

Requires a broad spectrum of Sc Magnet Types
across six diverse accelerator systems

- Examples which may be found in other LINAC systems

Challenges are representative of those faced elsewhere

Introduction

Low Energy LINACs

- High Intensity sources
  - leveraged by / pushing ScRF developments
  - new / upgrades to facilities
- Sc Solenoid Focusing offers a compact alternative to use of conventional Quads in Front End

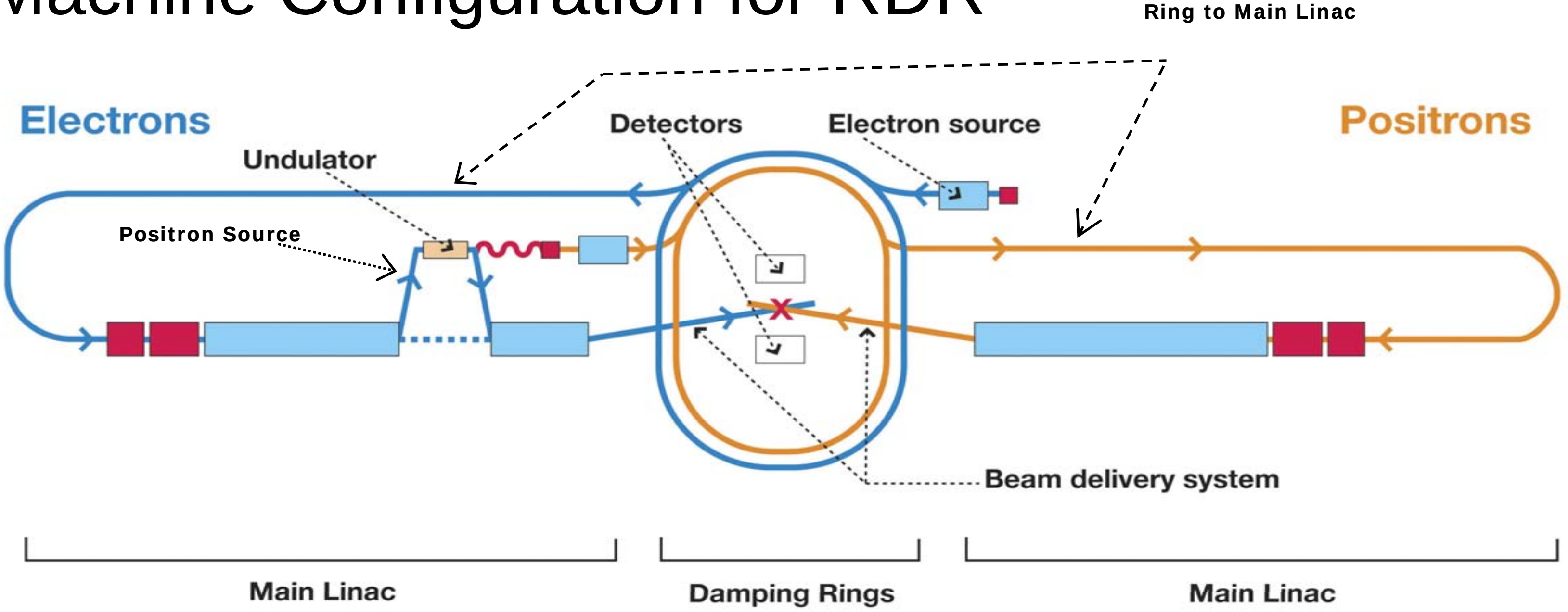
International Linear Collider

Machine Overview

- Baseline Conceptual Design (Dec. 2005)
- Reference Design (Feb. 2007)
  Report (RDR) and Cost Estimate for 250 GeV e- x 250 GeV e+
- International Team (Scientists/Engineers/Designers/Support Staff)
  - *Leadership in each geographic region* (Americas, Europe, Asia)
  - Area Systems (e+ / e- sources, DR, RTML, Main Linac, BDS)
  - Global Systems (Commissioning, Operations & Reliability, Controls, Cryogenics, Conventional Facilities & Siting, Installation)
  - Technical Systems [R.I.P.] (Vacuum, Magnets, Cryomodule, Cavity, RF Power, Instrumentation, Dumps/Collimators, Accelerator Physics)

This is a challenging machine: *A long train of small, intense, closely spaced bunches are created, quickly damped to very small cross sections, transported long distances during acceleration, then focused to nanometer size and brought into collisions at small crossing angle.*

Machine Configuration for RDR



- ❑ Magnet Requirements derived from standard set of Area Specifications
- ❑ Develop Conceptual Magnet Styles, associated parameters (power, cabling, controls, infrastructure); estimate costs and drivers;
- ❑ Iterate to reduce number of styles, costs (+some evolution of machine design)

General Issues for All Magnets

Alignment with respect to beam path

Focusing elements must preserve beam size (esp. after Damping Rings)

Offsets from beam axis must be adjusted by correction (steering)

Sub- μm accuracy achieved w/ mechanical movers in BDS

Stability

Geometry – stable mechanical core for stable magnetic center

Field stability/reproducibility

Over time (& thermal cycles for sc magnets)

With respect to changes in current/field

Reliability

MTBF for magnets $\geq 10^7$ hrs !

Meeting reliability requirements must be a key component of design approach

R&D program/'lifetime' studies required

Stray Field

Magnetic elements near ScRF cavities must meet stray field limits at cavity

$<1\ \mu T$ (warm) and $<10\ \mu T$ (cold)

Cost

Design must be cost efficient while meeting lattice and reliability requirements

FIELD QUALITY is not a driver in most areas (exc: DR, BDS) [single pass collider]

ILC Sc Magnets

Superconducting Magnet Overview

- ❑ Approx. 13000 Magnets (135 styles) Total in ILC Reference Design
- ❑ 2318 Superconducting Magnets
  - ➢ About 60% are Corrector Coils packaged with/near main coil
- ❑ 1680 in the Main Linac
  - ➢ Quad, Steering Dipoles BPM
  - ➢ Centered in every 3rd ScRF Cryomodule
- ❑ Damping Rings
  - ➢ Superconducting Wigglers damp e^-,e^+ by synch radiation
- ❑ Positron Source
  - ➢ Superconducting Undulators in e^- linac create energetic photons

ILC Sc Magnets

Superconducting Magnet Overview

- Superconducting Solenoids
  - For positron capture
  - For spin rotation in the RTML
  - Some large aperture magnets
    - Could be conventional: Optimize Capital vs Operating Cost
- Beam Delivery System
  - Some of the most challenging Sc Magnets at IR Final Focus
    - Strong Gradients with Corrector Coils
    - Tight space, field quality constraints
    - Detector Interface issues
    - Radiation and Disrupted Beam

ILC Main Linac

Main Linac Quadrupole Package (MQ,VD,HD,BPM)

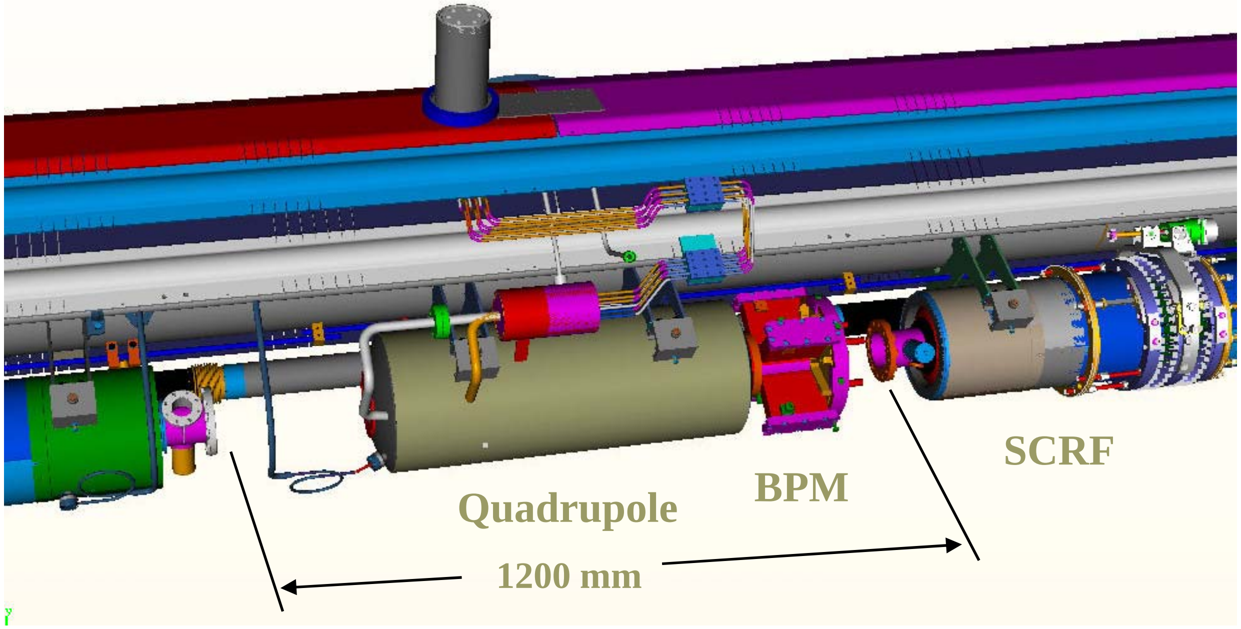
- Location: center of every 3rd Cryomodule (~6m length)
  - super-clean beam tube for super-c rf
  - quad + BPM center alignment (<.3 mm, warm -> cold)
- Separate cryostat considered as alt. design (easier for magnets)
- **2K operation:**

  small Heat Load

Beam Size in ML:

$\sigma x \sim 9\ \mu m$

$\sigma y \sim 20\ nm$



ILC Main Linac

Main Linac Quadrupole Package

- ❑ Specifications

	RDR ILC	Tesla500
Integrated gradient, T/m	36	35
Aperture, mm	78	90
Effective length, mm	666	588
Peak gradient, T/m	54	60
Field non-linearity at 5 mm radius, %	0.05	.4 (30mm)
Dipole trim coils	Vertical+Horizontal	V+H
Trim coils integrated strength, T-m	0.075	.085
Quadrupole strength adjustment for BBA, %	-20	
Magnetic center stability at BBA, µm	5	
Liquid Helium temperature, K	2	2
Quantity required	560	

- ❑ Small Beams, Large Aperture: Field quality is not an issue, but need to be on axis

ILC Main Linac

Main Linac Quadrupole Package

- ❑ Challenges
  - ➢ Quad Center stability, reproducibility to <~ 5μm

    Hysteresis, magnetization current effects
    - ▪ Beam–Based Alignment (Δgrad ~20% in slow steps)
    - ▪ versus (nested) corr. dipole currents
    - ▪ over field range (15-250 GeV)
  - ➢ Stray Field limits at adjacent ScRF cavities
    - ▪ <10 μT cold, <1 μT warm
- ❑R&D– Prototypes under study [Cos2θ, Superferric/racetrack]
  - ❑CIEMAT (TESLA500, TTF, XFEL) [F. Toral, et al., ASC'06, EPAC'06]
  - ❑FNAL (ILC) [Vl.Kashikhin, et al., PAC'07]

ILC Main Linac

Main Linac Quadrupole Prototypes

- CIEMAT Cos2θ model (2005): **meas’g center stability @SLAC *now***
- Superferric design: (250Gev Linac OK; Front End @ 500GeV)
  - Simpler racetrack coils should yield lower cost
  - Many turns of fine NbTi strand (low current, low PL heating)
    - need high packing factor: strand stress, potential shorts;
    - high inductance; iron saturation
  - Magnetic Measurements show
    - Quad Field quality is OK, but TF varied with Dipole currents
    - Quad, Dipole TF affected by hysteresis at low current
- Option: separate Quad and Corrector Dipoles
  - Eliminate some hysteresis effects due to persistent currents

ILC Main Linac

Main Linac Quadrupole Prototypes

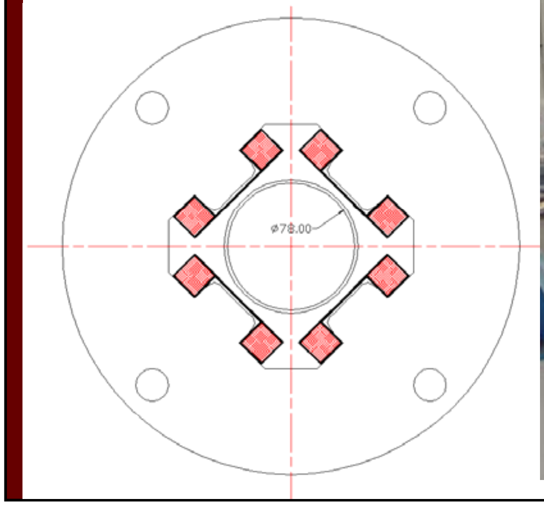
- Fermilab Design is similar
  - 1st model is complete, preparing to start test early June 2008
  - TQ model tests: can measure Quad center to <1µm (<90sec)

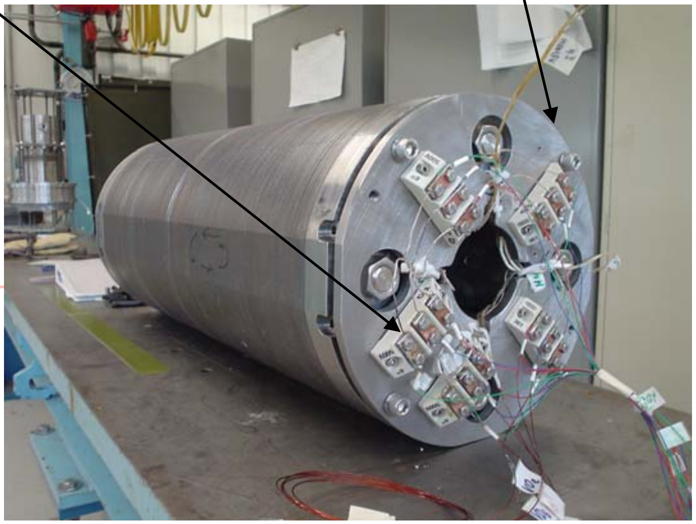
Coil connection blocks:

Racetracks include turns for quad and dipoles

Soft Iron End shields

capture stray field



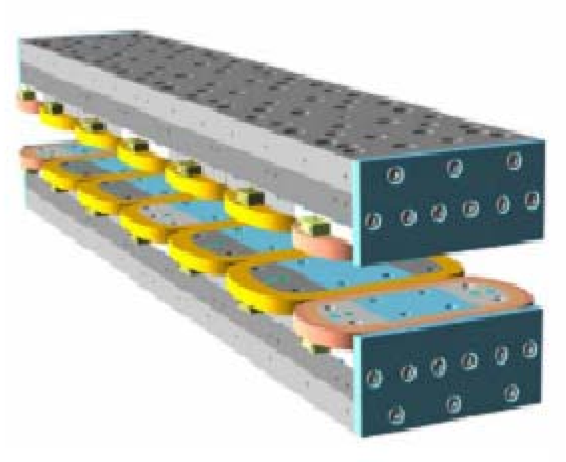


ILC Damping Rings

Superconducting Wigglers

- Fast Damping of the beams to small emittances
  - Positron emittance reduction by 10^5 in 200ms
  - Need 200 m of high field, short period wigglers per DR
- Based on CESR-c Wiggler, but longer

Peak Field	1.95 T
Number of Poles	12
Length	1.68 m
Period	0.32 m
Pole Width	23.8 cm
Gap Height	8.6 cm
dB/B0 at x=10mm	6.0 x 10-4
Coil Current	141 A
Conductor	NbTi
Temperature	4.5 K

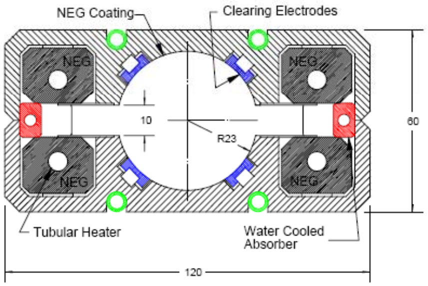


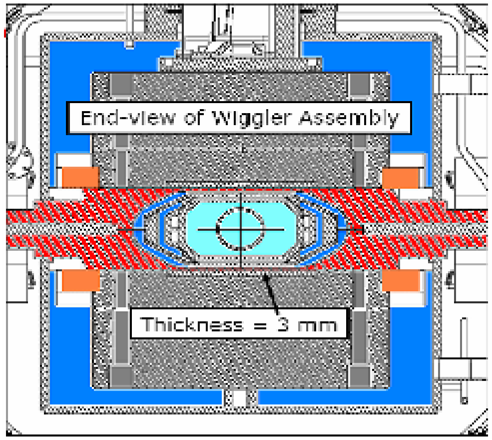
Superferric modular, shimmed racetrack pole pieces

ILC Damping Rings

Superconducting Wigglers

- Approx. 10 times the synch. Radiation load of CESR-c
  - **26 kW per wiggler radiation load** (2 W/m static load)
  - Vacuum chamber design as warm bore insert with integral absorber and cooling system (water)





- Larger Gap than CESR-c
  - simplifies support plate structure, reduces cost, heat load
  - Field Quality remains acceptable (e+ dynamic aperture)

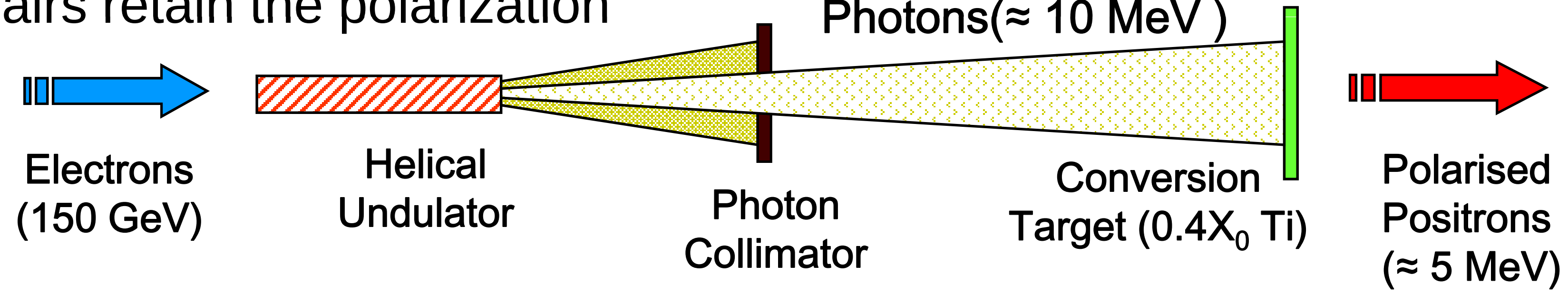
ILC Positron Source

Superconducting Undulators

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

If circularly polarized photons are selected (collimation), the $e^+ e^-$ pairs retain the polarization



Several groups have developed similar designs and tested prototypes

[HeLiCal collab., J.Clarke, et al, Darsbury,UK; PAC07]

[A.Mikhailichenko, M.Tigner, EPAC06]

ILC Positron Source

Parameters for 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 (16mm^2)
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

Undulator Period and required strength need superconducting solution

ILC Positron Source

Cold Copper Bore

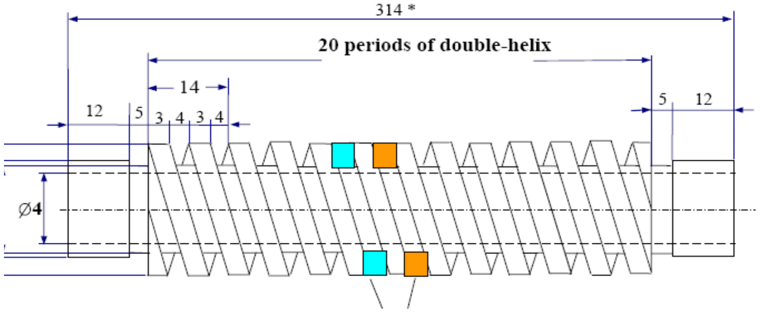
Inner diameter 5.85 mm

Cryopumped vacuum

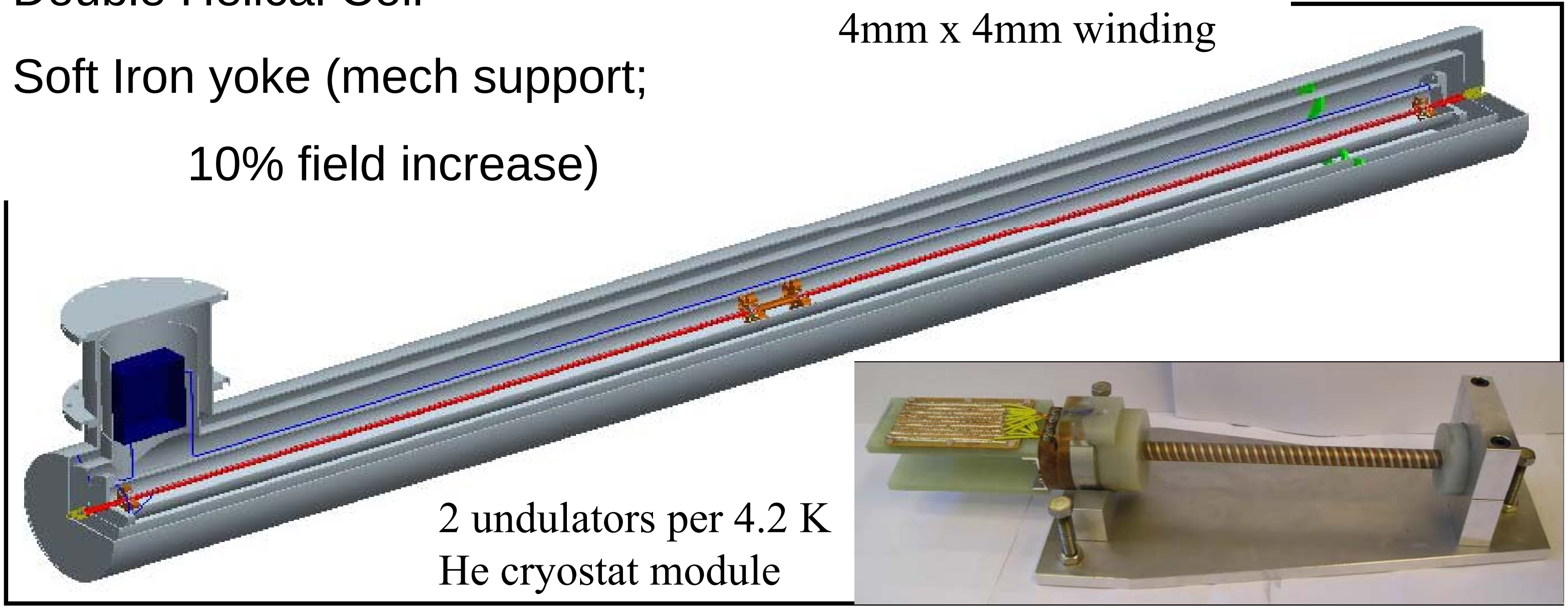
Double Helical Coil

Soft Iron yoke (mech support;

10% field increase)



4mm x 4mm winding



2 undulators per 4.2 K He cryostat module

500mm long prototype (~1/3 length) completed; expect additional test results soon

ILC Beam Delivery System

Sc BDS Magnets

BDS Beamlines must (be capable of 1 Tev, w/add’l magnets)

measure and correct ML beams (emittance, skew; polarization)

✓ collimate and reduce (γ,e,μ) halos

✓ demagnify beams to required size (*14x, *3.5y)

✓ extract disrupted beams w/big angle-,energy- spread to a dump

✓ compensate for the detector magnet

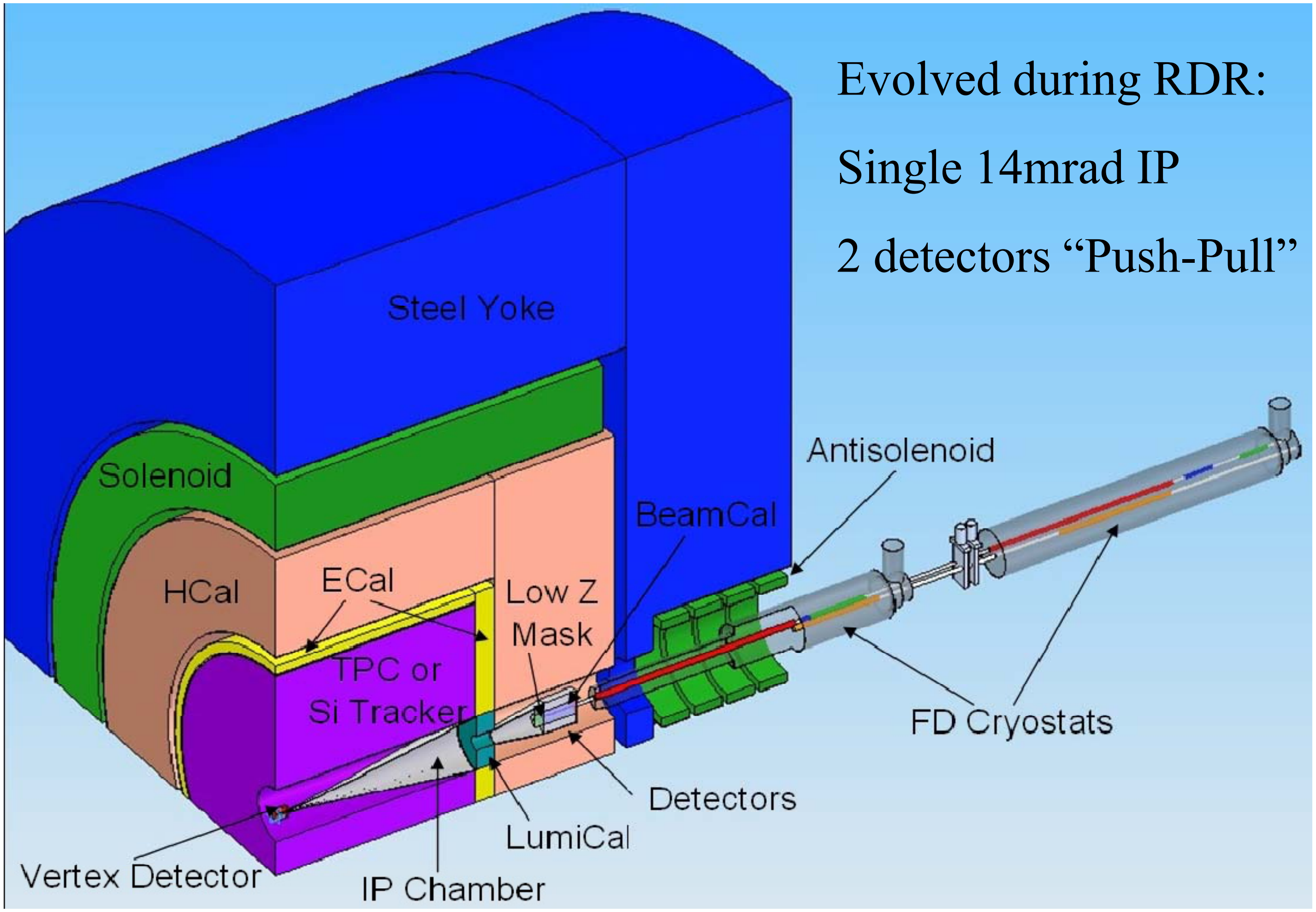
3TeV CLIC:

(*15x,*5y)

- ☐ Baseline 14mrad crossing angle BDS design & Sc Magnet solutions
  - [A.Seryi, et al., PAC07; B.Parker, et al., PAC07)
- ☐ Alt. head-on schemes under study [O.Napoly, et al. PAC’07]
  - Detector hermeticity, no crab cavity beam rotation
  - Incoming/Outgoing beams share innermost magnets

ILC Beam Delivery System

Final Focus IR Magnets



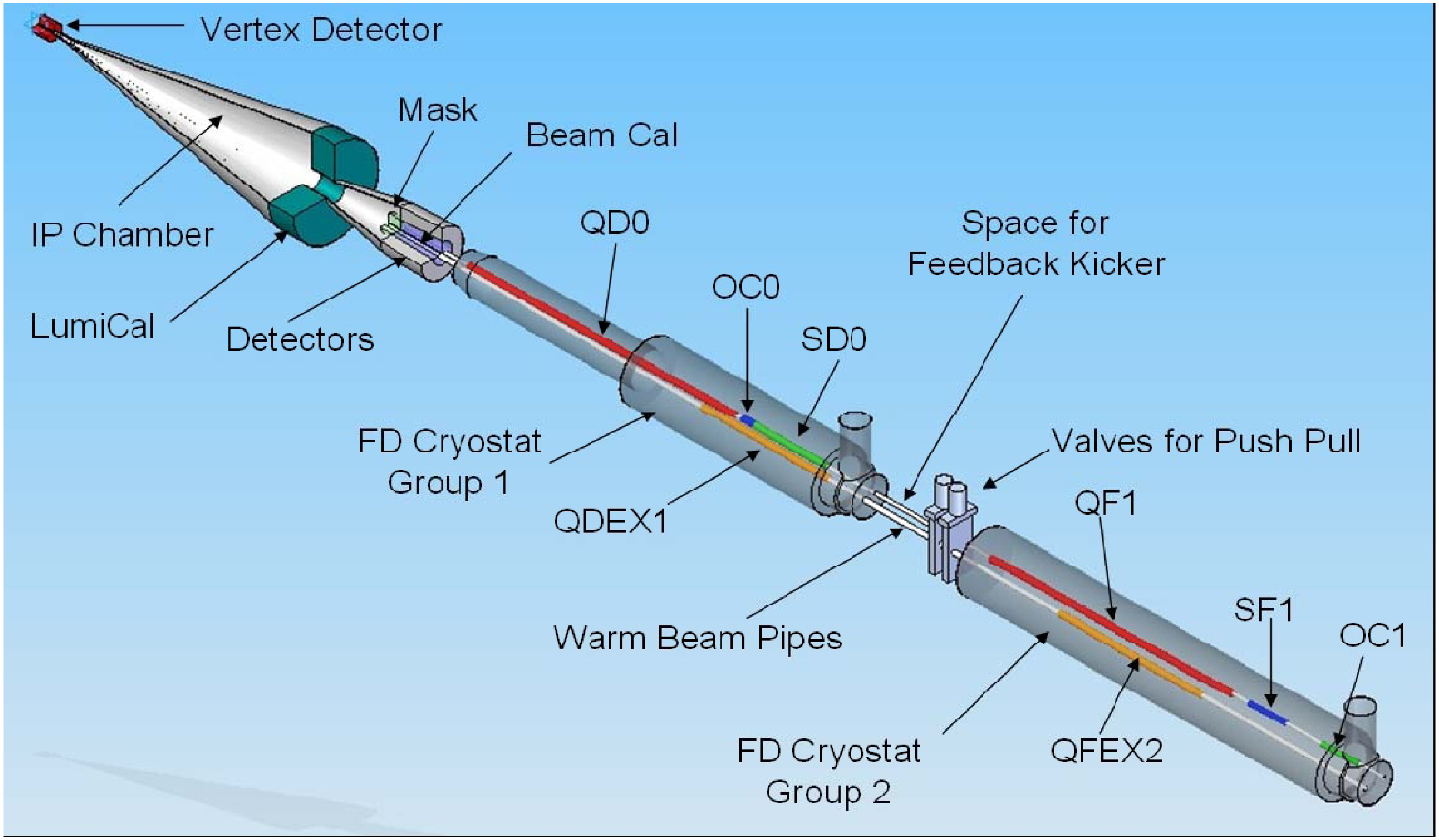
Evolved during RDR:

Single 14mrad IP

2 detectors “Push-Pull”

ILC Beam Delivery System

Final Focus IR Magnets



ILC Beam Delivery System

Final Focus IR Magnets

BNL Direct-Wind technology

QD0 inner/outer

Anti-solenoid coils in QD0

Cryostat

Operate at 2K

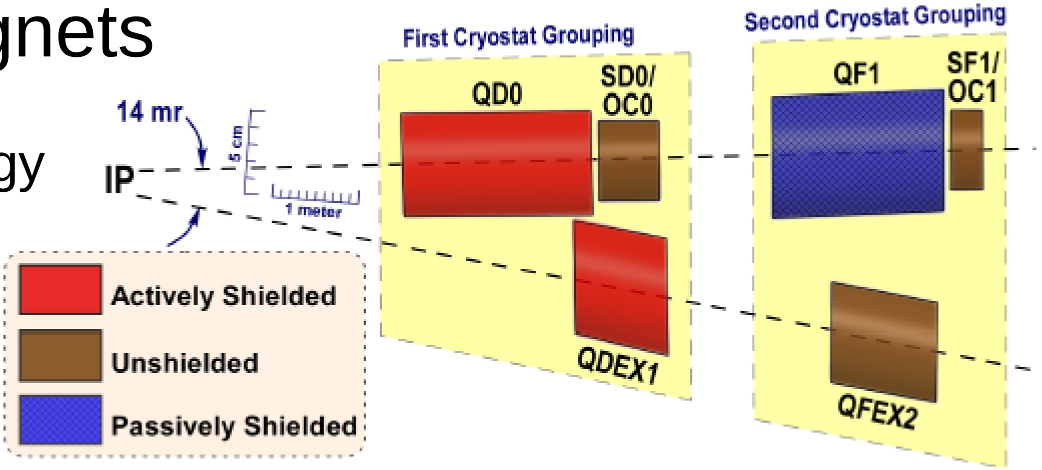
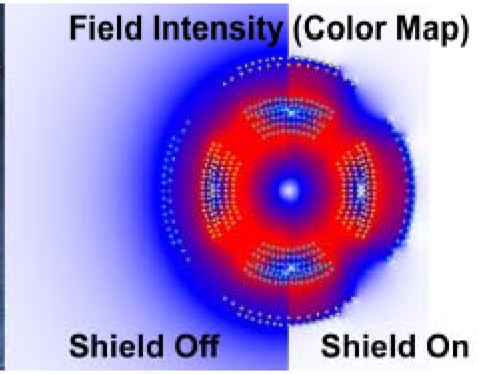


FIGURE 2.7-5. Schematic layout of magnets in the IR.



Detector Integrated Dipole

Windings at outer radius of detector solenoid compensate for vertical deflection of beam passing through solenoid at 14mrad

ILC Beam Delivery System

Final Focus IR Magnets

- Strong Focusing Doublet (BDS design for up to 1 TeV)
  - Intrudes into detector; “push-pull” complication
    - IP size (x=640, y=6) nm needs extraordinary stability
  - Cancellation of stray field nearby (can’t affect disrupted beam)
  - detector solenoid cancellation coils (force neutral)
  - steering and sextupole (local chromatic) correctors needed

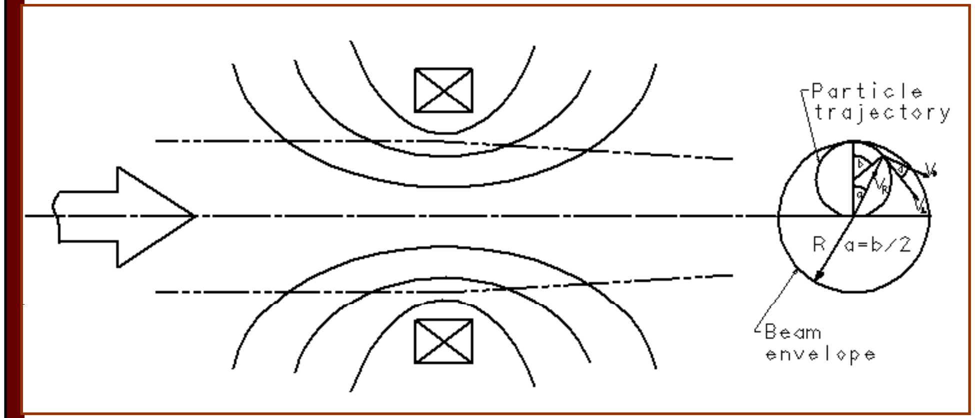
CLIC:(43,1)nm
450T/m

- “Tail-Folding” Doublets of Superferric octupoles upstream of FF nonlin. Optics to clear halo but not affect core beam
  - design for high gradient, but avoid pole saturation
  - implementation with a clever winding scheme, low cost
  - use cryocooler

Low Energy Linacs

Focusing by Solenoids

Motivation: lower rate of emittance growth in transport channels in comparison with quadrupoles



Radial component of a fringe field combined with asymmetric particle rotation (Bush theorem) provides radial component of the particle velocity; hence the focusing effect in **short lenses**

2. Rotation in the longitudinal field results in different azimuthal position of the particles after the lens.

Focusing length: $f = R \cdot \frac{\beta c}{v_R} = 4 \frac{m^2}{q^2} \beta^2 c^2 \cdot \frac{1}{B_c^2 L_{eff}} = \frac{8 \cdot \frac{m}{q} \cdot T(eV)}{B_c^2 L_{eff}}$

Limitation: low energy

[Ref: I. Terechkine]

Low Energy Linacs

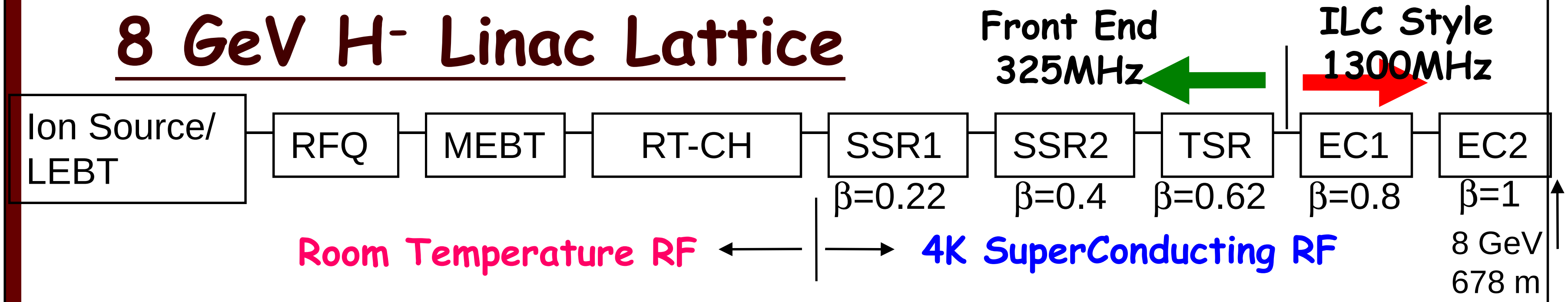
Superconducting Magnets for Front End Linacs

- ❑ At Fermilab
  - ➢HINS (High Intensity Neutrino Source) R&D project
    - H^- acceleration to 60 MeV at 27mA (1ms @ 10Hz)
    - Multiple ScRF cavities driven by single RF source
    - High Speed (ns) Beam Chopping @2.5MeV
    - Beam Tests in FY2011

- ❑ Similar Efforts Elsewhere (RIB facilities)
  - ➢ISAC-II TRIUMF RIB [M.Marchetto, et al., PAC07]
    - Operating
  - ➢RIA/FRIB [M.Johnson, et al., PAC05]
    - R&D Sc Solenoid and Quad in ScRF cryomodule

Low Energy Linacs - HINS/ProjX

8 GeV H^- Linac Lattice



	Ion Source	RFQ	MEBT	RT-CHSR	SSR1	SSR2	TSR
Eout	50 keV	2.5 MeV	2.5 MeV	10 MeV	30 MeV	120 MeV	~600 MeV
Zout	0.7 m	3.7 m	5.7 m	15.8 m	31 m	61 m	188m
Cavities			2 buncher cavities and fast beam chopper	16 copper CH-spoke cavities	18 single-spoke SC β=0.2 cavities	33 single-spoke SC β=0.4 cavities	66 triple-spoke SC β=0.6 cavities
Gradient					10 MV/m	10 MV/m	10 MV/m
Focusing			3 SC solenoids	16 SC solenoids	18 SC solenoids	18 SC solenoids	66 SC quads
Cryomodules					2	3	11

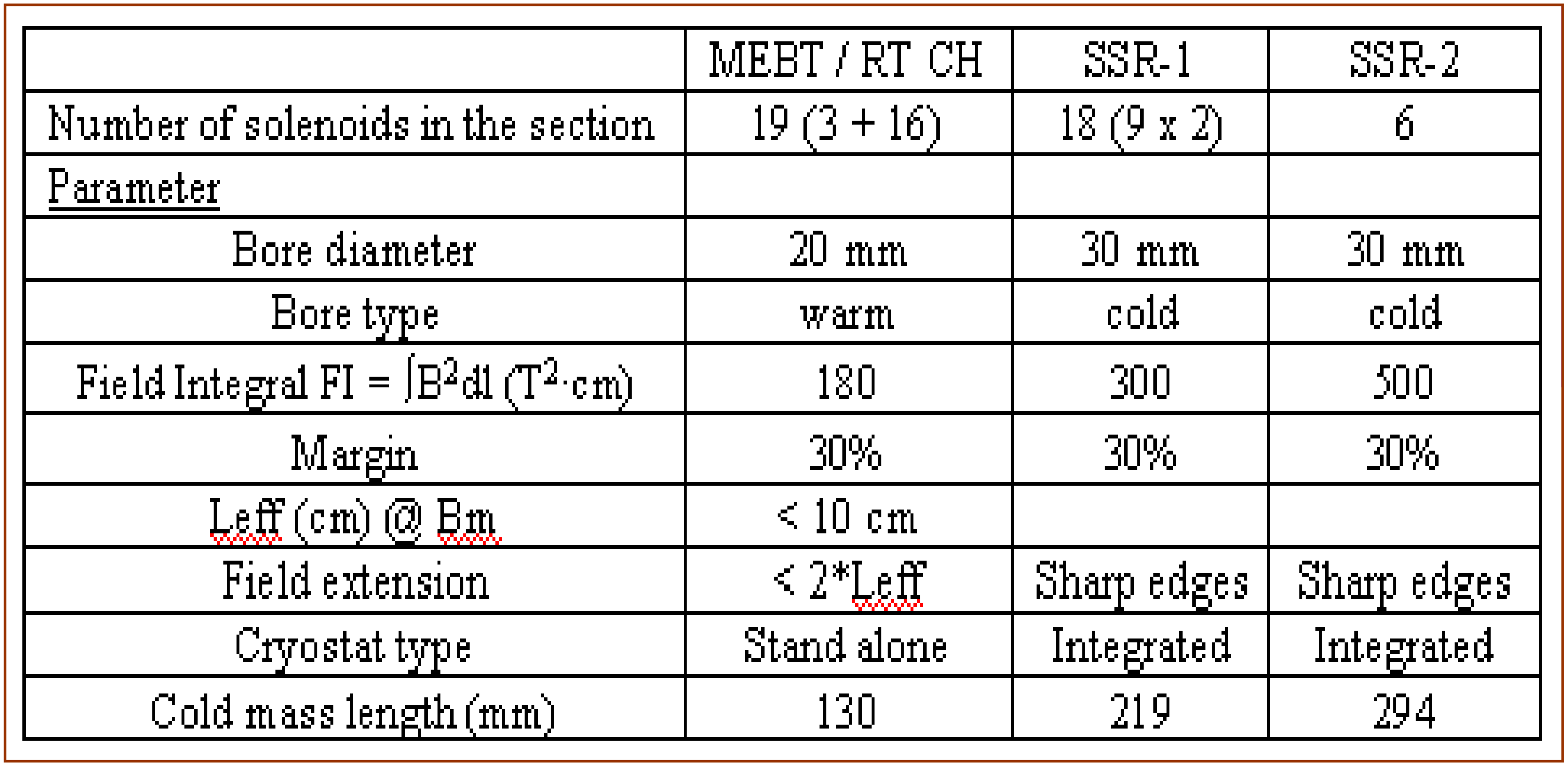
HINS R&D Program: RT Section + 3 Cryomodules

Low Energy Linacs - HINS

HINS Sc Solenoid Requirements

NbTi Sc Solenoids for focusing below, Sc Quads above 120MeV

Quad Design: ~Short version of ILC ML Quad

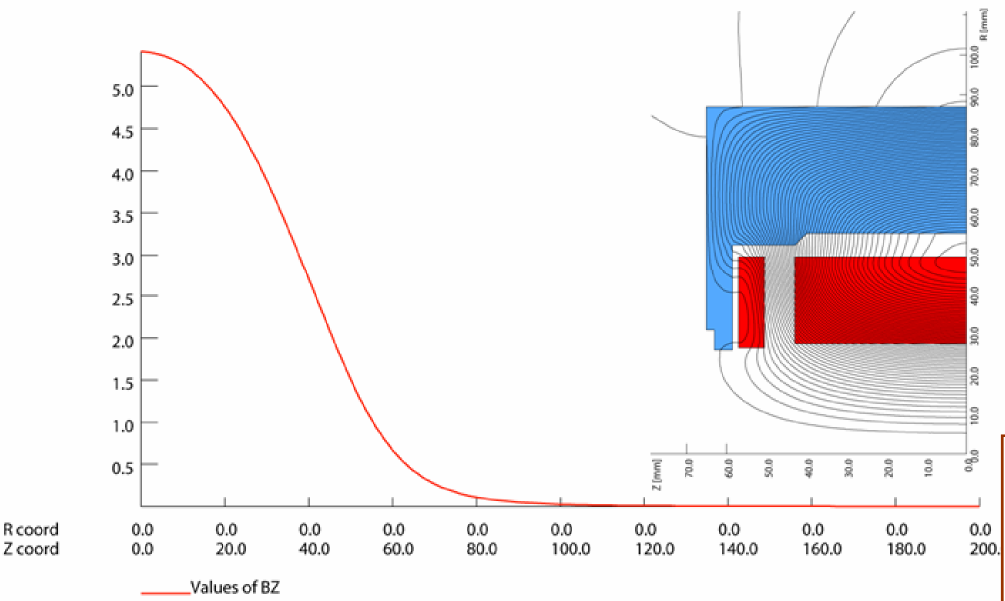


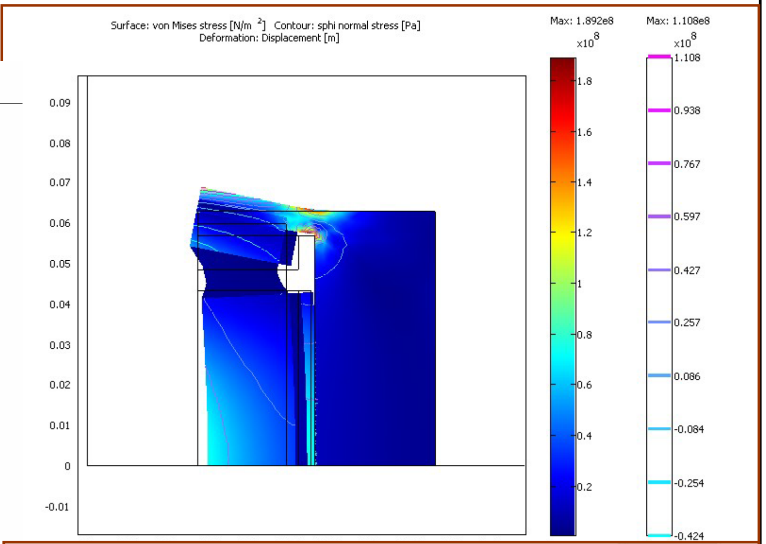
	MEBT / RT CH	SSR-1	SSR-2
Number of solenoids in the section	19 (3 + 16)	18 (9 x 2)	6
Parameter			
Bore diameter	20 mm	30 mm	30 mm
Bore type	warm	cold	cold
Field Integral FI = $\int B^2 dl$ ($T^2 \cdot cm$)	180	300	500
Margin	30%	30%	30%
Leff (cm) @ Bm	< 10 cm		
Field extension	< 2*Leff	Sharp edges	Sharp edges
Cryostat type	Stand alone	Integrated	Integrated
Cold mass length (mm)	130	219	294

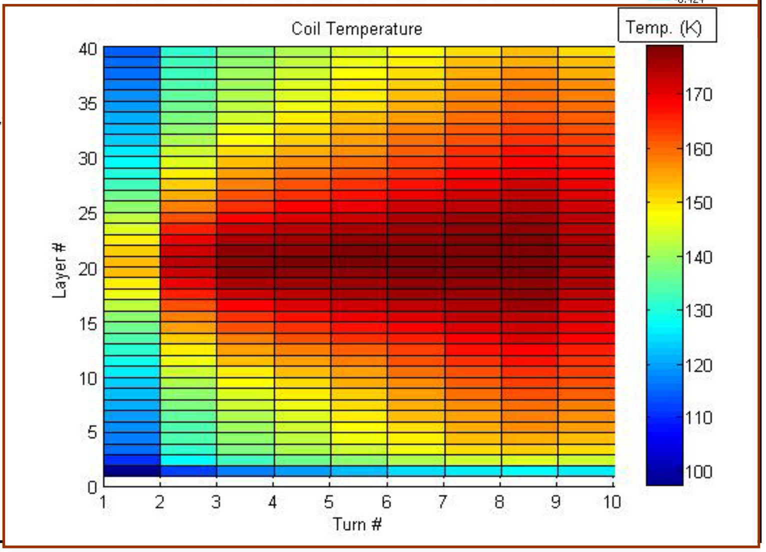
Variations: MC length, BC and Corr.Dipole strand,width, radii

Low Energy Linacs - HINS

HINS Sc Solenoid Design







{Magnetic, Stress, Mechanical, Strand, Quench Protection}

Low Energy Linacs - HINS

HINS Sc Magnet R&D

Solenoid Challenges:

- Limited Slot length in lattice: must be strong, compact lenses
  - 0.8mm NbTi strand; high packing factor
  - approx. 8T peak field at quench current
- Intense Source: Magnets need operating margin (design ~30%)
- Stray field requirements: Bucking Coils cancel axial field at ends
  - narrow w/ <0.6mm strand; internal stress issues
  - soft iron yoke to capture stray flux
  - magnetic shielding to <10mT at adjacent ScRF cavities
- Nested steering corrector dipoles: increase solenoid radius
  - good field quality (10%) needed at large R x single layer coil
- Tight installation alignment tolerances in SSR sections:
  - 9 solenoids and cavities in cryomodule (clean, no bore)
  - center position correct to ~ 0.1mm (300K… 4K)
- Quench Protection: BC temperature and voltage development
  - CH have proven to be robust, self-protecting
  - SSR-2 section is strongest lens; most difficult

Low Energy Linacs - HINS

HINS Sc Solenoid Status

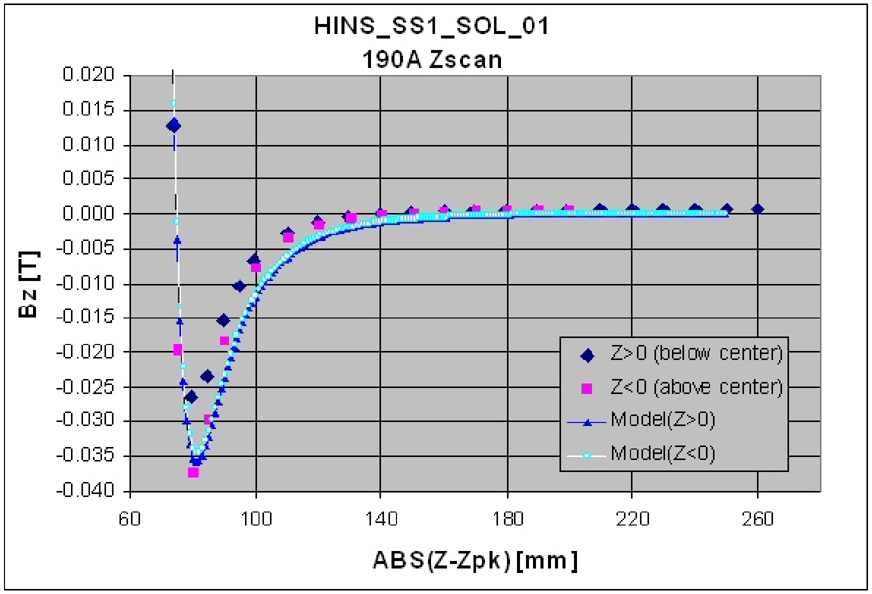
RT-CH solenoid R&D complete (6 models);

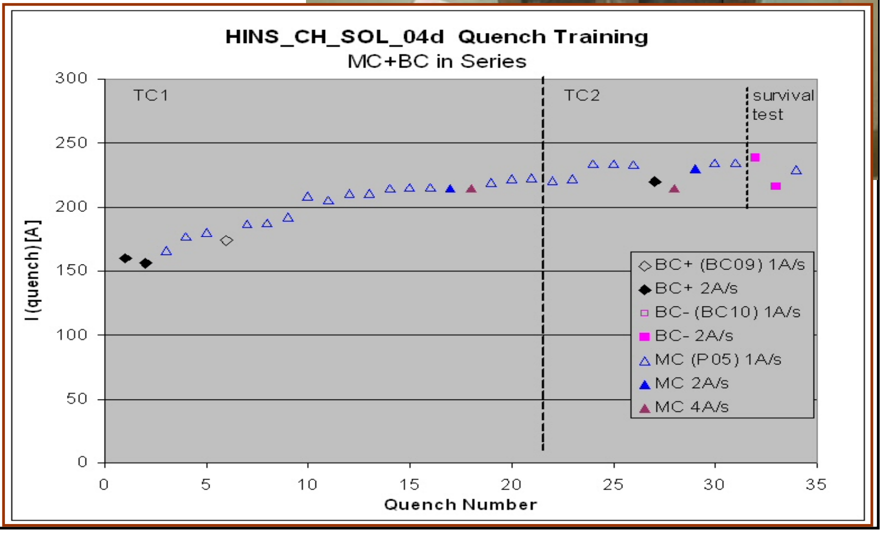
1st SSR-1 prototype tested

Excellent agreement with

performance predictions (Iq,B)

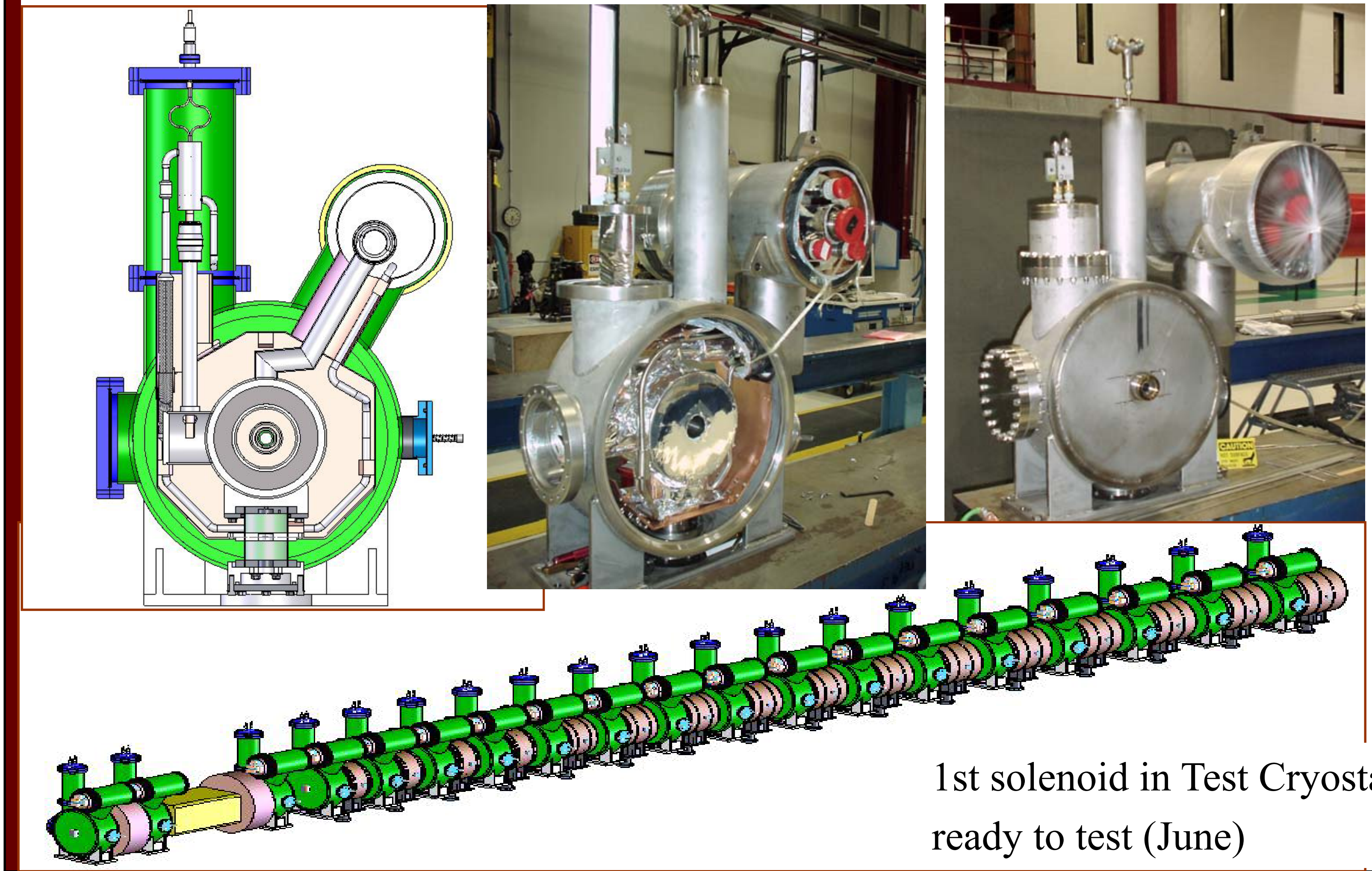
Industrial Production begun, testing soon





Low Energy Linacs - HINS

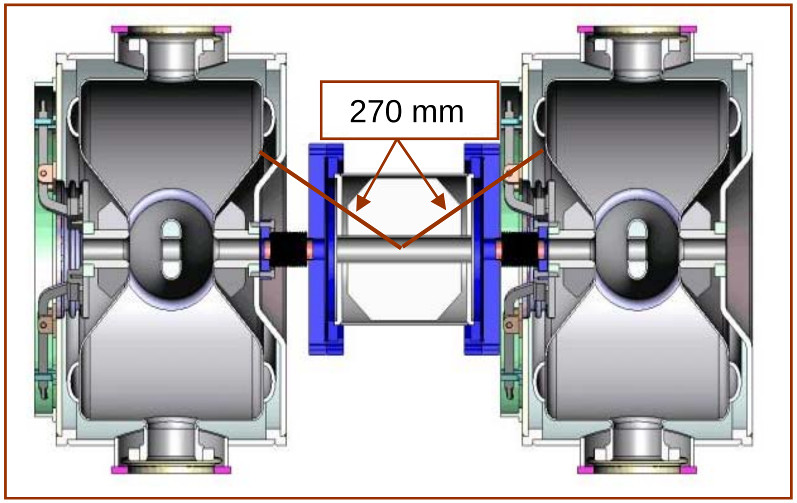
HINS CH Linac Section, Cryostatted Solenoids



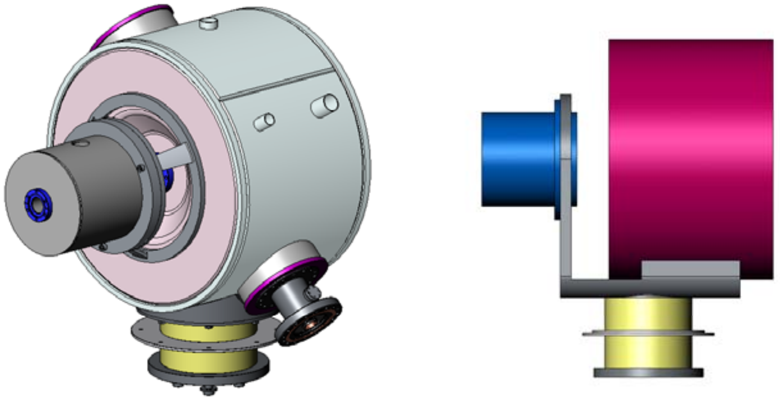
1st solenoid in Test Cryostat,
ready to test (June)

Low Energy Linacs - HINS

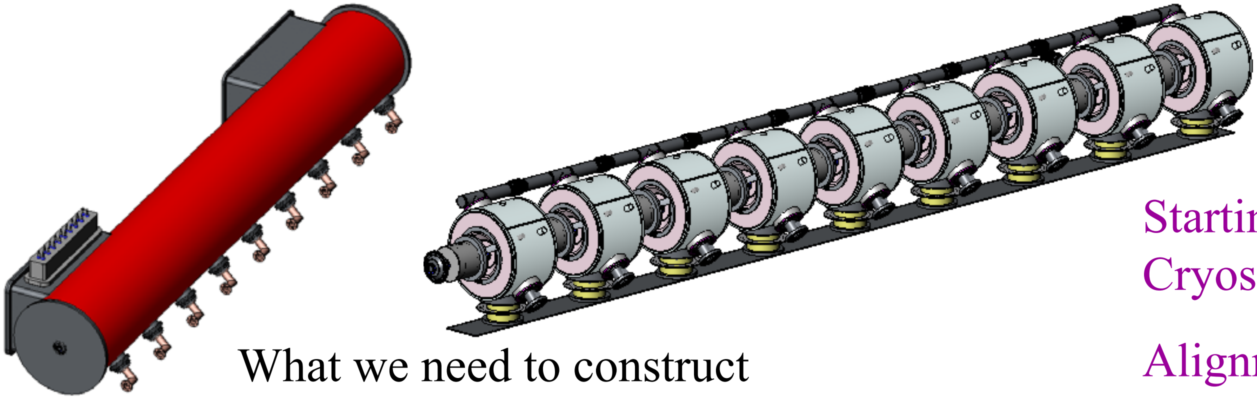
HINS SS-1 Linac Section, Solenoids Cryostatted w/ Cavities



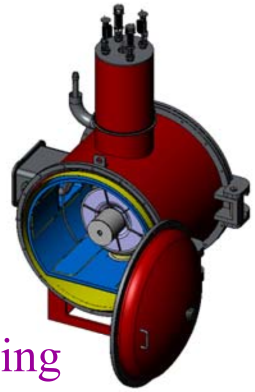
Solenoid with shield between SS cavities



Early conceptual support concepts; cavity position tolerances more relaxed (.5mm vs .1mm) – moving to separate supports



What we need to construct



Starting with Test Cryostat to study

Alignment, shielding

Magnets for LINACS

Summary

Sc Magnets are necessary for satisfying the requirements in many areas of the High Energy, High Intensity International Linear Collider.

They also provide flexibility in solving some interesting challenges that arise in response to particular machine demands.

Technical challenges span the gamut of areas in magnet design:

Strength, Field Quality, Operating Margin, Alignment, Mechanical and Magnetic Axis Stability, Stray Field Limits, Reliability, Cost, Machine-Detector Interfaces.

Innovative solutions have been devised (and continue to evolve) and prototype model development/testing is advanced.

Much work remains to complete integrated system designs