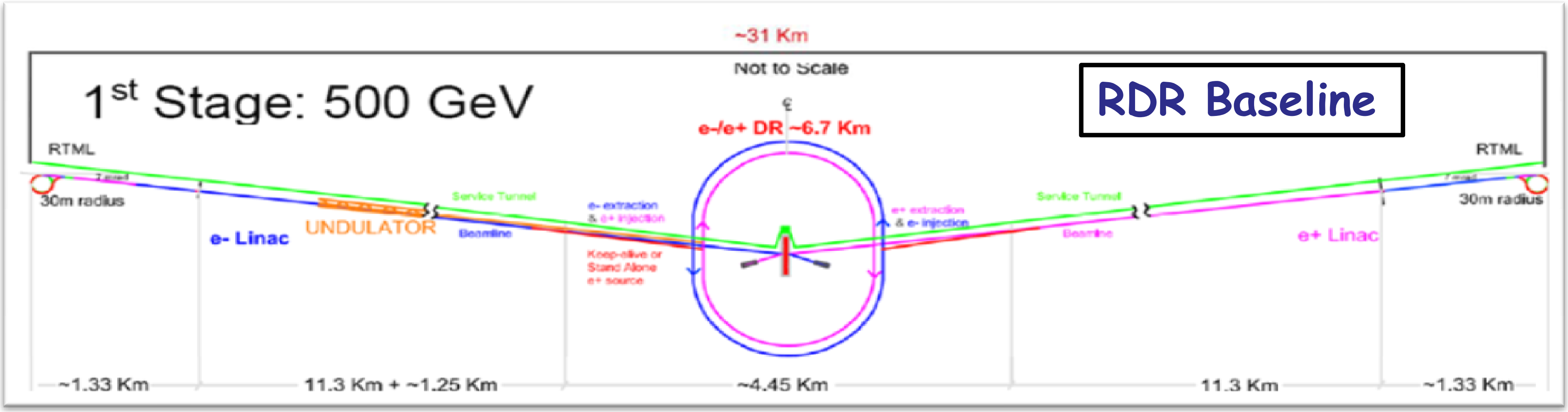
Main Linac SC Quad Requirements and Specifications

Nikolay Solyak

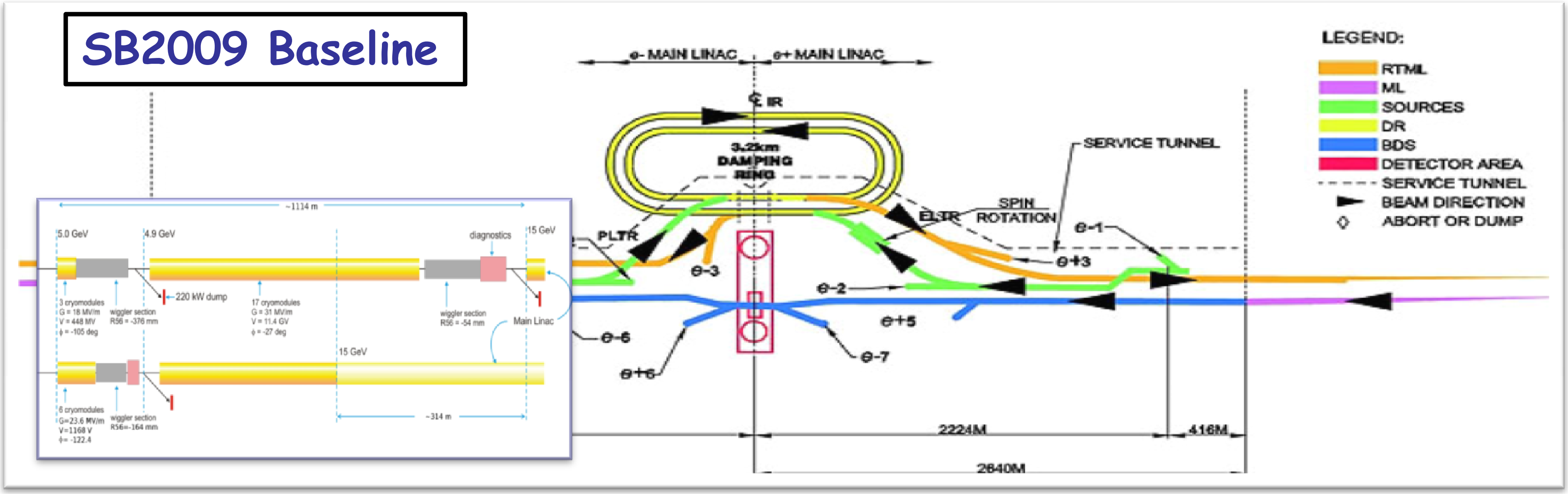
Fermilab

ART review, March 2, Fermilab

Schematic of the 500 GeV Machine



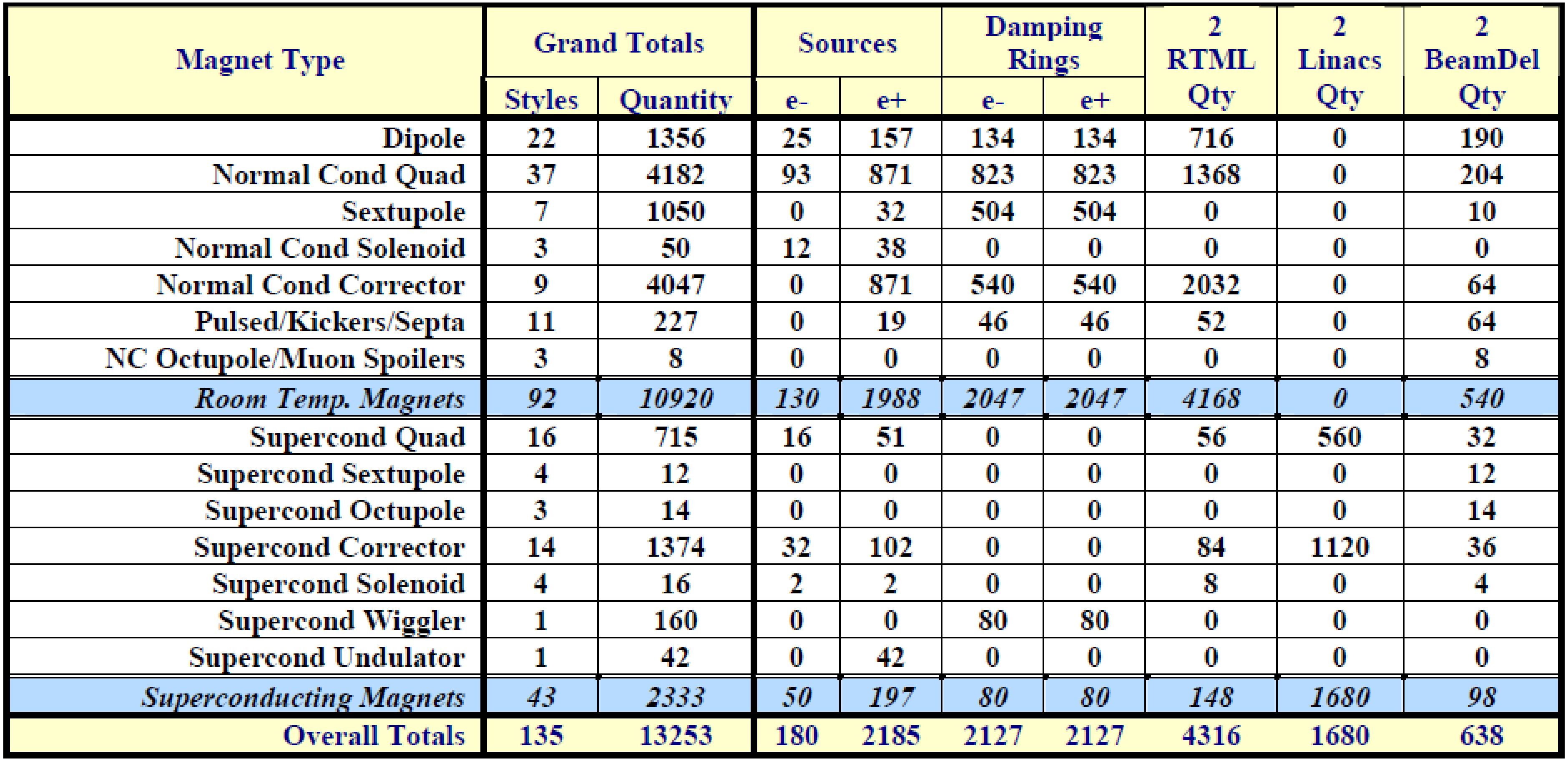
RDR Baseline



SB2009 Baseline

All ILC magnets

Table 1: ILC RDR Magnet Summary Table (250GeV X 250GeV – 14 December 2006)



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

SUPERCONDUCTING MAGNET NEEDS FOR THE ILC*, J. C. Tompkins, *Vl. Kashikhin et.all, PAC07*

Number of SC quads (RDR and SB2009)

RTML(5-15 GeV)	**# CM**	**# Quad**
e^-/e^+ Bunch compressor	45 / 45	17/17
Total	90	34

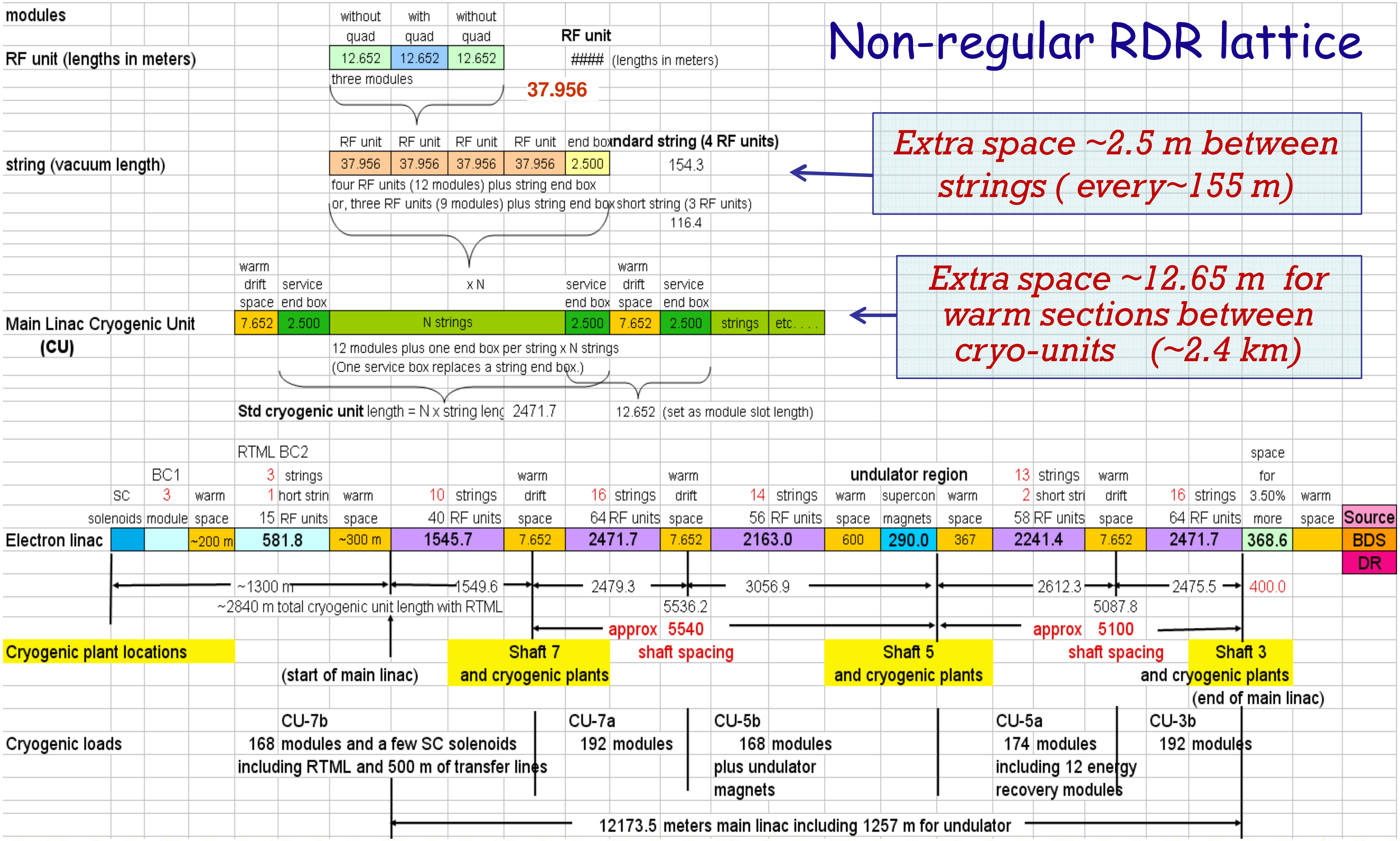
Main linac (15-250 GeV)	**# CM**	**# Quad**
Electron Linac*	846	282
Positron Linac	834	278
Overhead (3.5%)	30+30	10+10
Total	1680+60	560+20

* Incl. 12 CMs to recover 3.23 GeV energy losses in undulator

Note: each quad is combined with vertical corrector, every second quad has also horizontal corrector

- Proposed changes in SB2009 lattice:
    - Single stage compressor: 6 CM’s (quad in each)
    - Post-acceleration 5 ➔ 15 GeV is part of ML
    - Total number of CM’s is reduced by 3, but # quads increases +1

RDR Main Linac: 9-8-9 Configuration



Non-regular RDR lattice

Extra space ~2.5 m between strings (every~155 m)

Extra space ~12.65 m for warm sections between cryo-units (~2.4 km)

modules

	without quad	with quad	without quad	
RF unit (lengths in meters)	12.652	12.652	12.652	**RF unit** ##### (lengths in meters)

three modules

37.956

	RF unit	RF unit	RF unit	RF unit	end box	**ndard string (4 RF units)**
string (vacuum length)	37.956	37.956	37.956	37.956	2.500	154.3

four RF units (12 modules) plus string end box

or, three RF units (9 modules) plus string end box short string (3 RF units) 116.4

x N

	warm drift space	service end box		service end box	warm drift space	service end box		
Main Linac Cryogenic Unit (CU)	7.652	2.500	N strings	2.500	7.652	2.500	strings	etc. . . .

12 modules plus one end box per string x N strings

(One service box replaces a string end box.)

Std cryogenic unit length = N x string leng 2471.7

12.652 (set as module slot length)

	SC solenoids	BC1 3 module	warm space	RTML BC2 3 strings 1 hort strin 15 RF units	warm space	10 strings 40 RF units	warm drift space	16 strings 64 RF units	warm drift space	14 strings 56 RF units	undulator region warm space	supercon magnets	warm space	13 strings 2 short stri 58 RF units	warm drift space	16 strings 64 RF units	space for 3.50% more	warm space	Source
Electron linac			~200 m	581.8	~300 m	1545.7	7.652	2471.7	7.652	2163.0	600	290.0	367	2241.4	7.652	2471.7	368.6		BDS DR

~1300 m 1549.6 2479.3 3056.9 2612.3 2475.5 400.0

~2840 m total cryogenic unit length with RTML 5536.2 5087.8

approx 5540 shaft spacing approx 5100 shaft spacing

Cryogenic plant locations

(start of main linac)

Shaft 7
and cryogenic plants

Shaft 5
and cryogenic plants

Shaft 3
and cryogenic plants
(end of main linac)

Cryogenic loads

CU-7b
168 modules and a few SC solenoids
including RTML and 500 m of transfer lines

CU-7a
192 modules

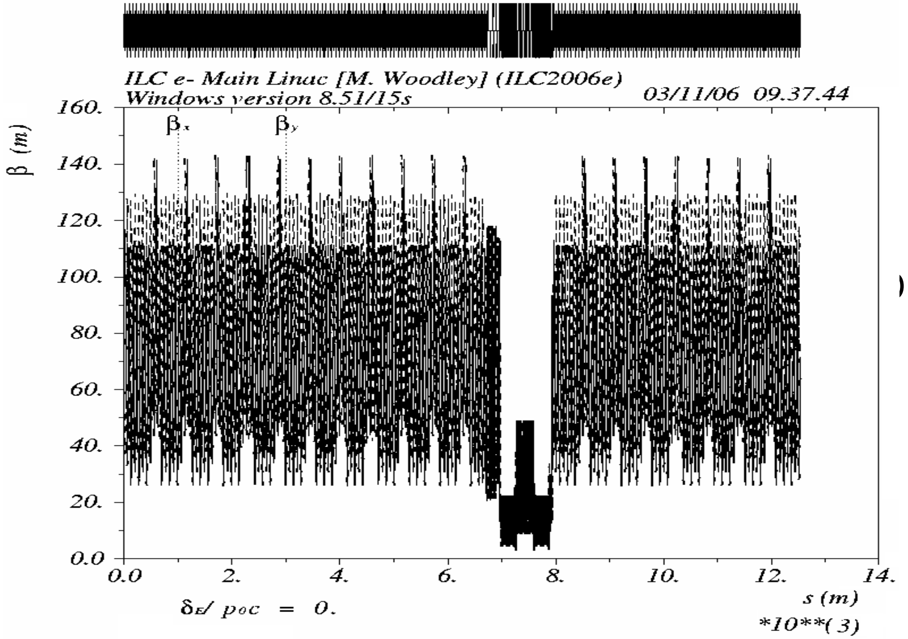
CU-5b
168 modules
plus undulator
magnets

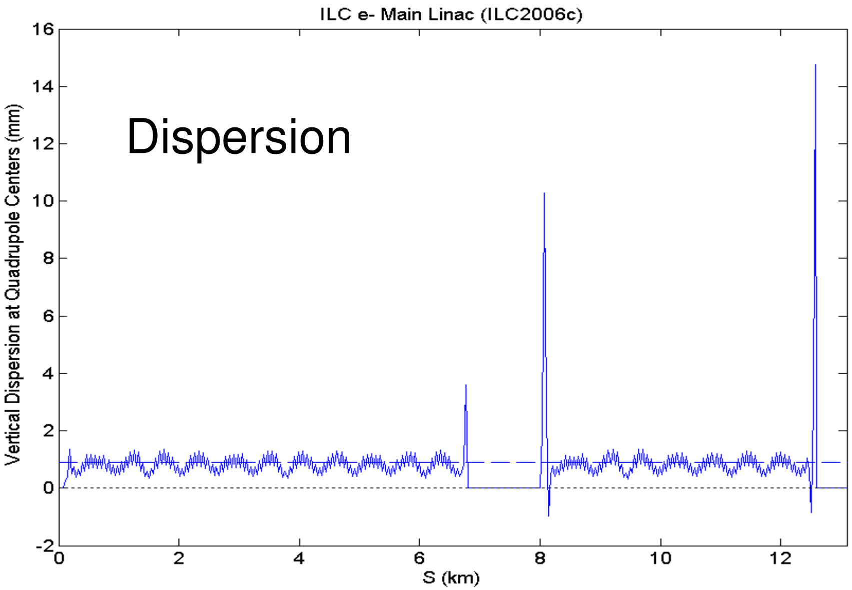
CU-5a
174 modules
including 12 energy
recovery modules

CU-3b
192 modules

12173.5 meters main linac including 1257 m for undulator

RDR Main Linac Lattice: Curved linac





Lattice in ML (5 - 250 GeV per linac)

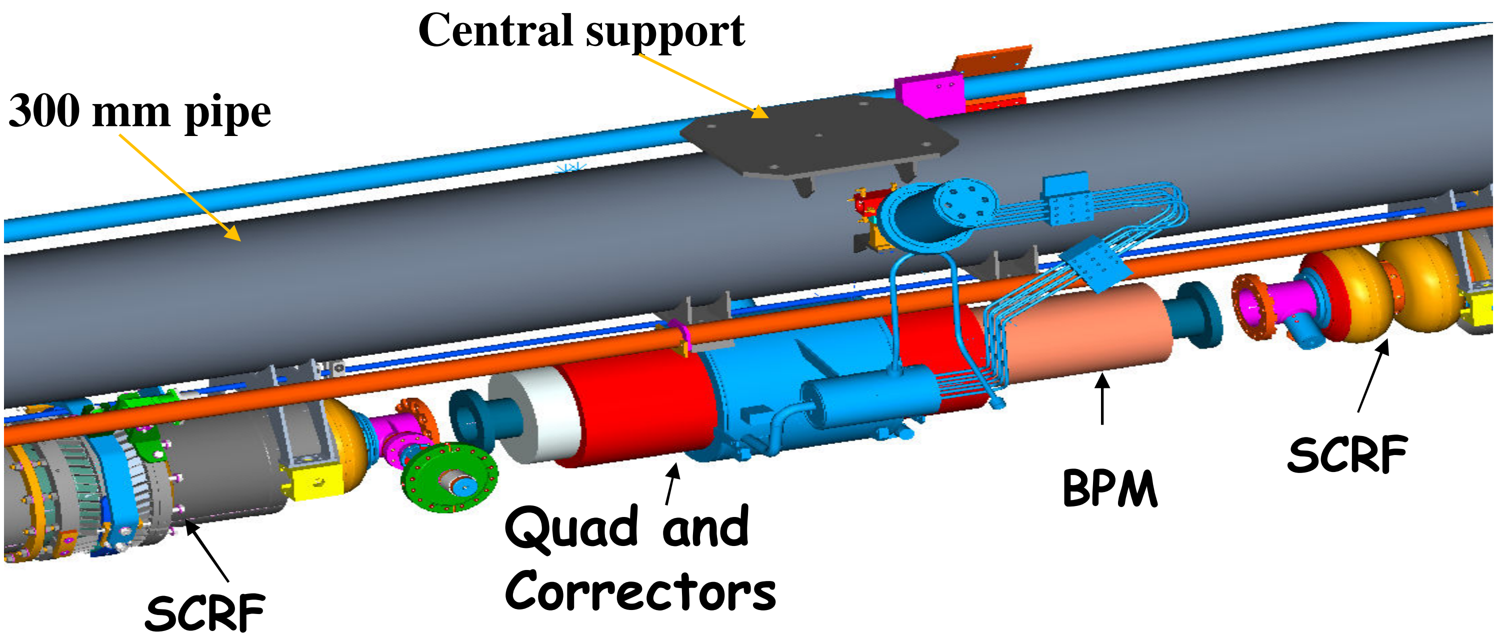
- 1Quad/3CM (9-8-9)
- Quad Spacing ~38m
- Curved linac
- Phase advance x/y = 75°/60°
- matching sections require ~10% higher quad strength

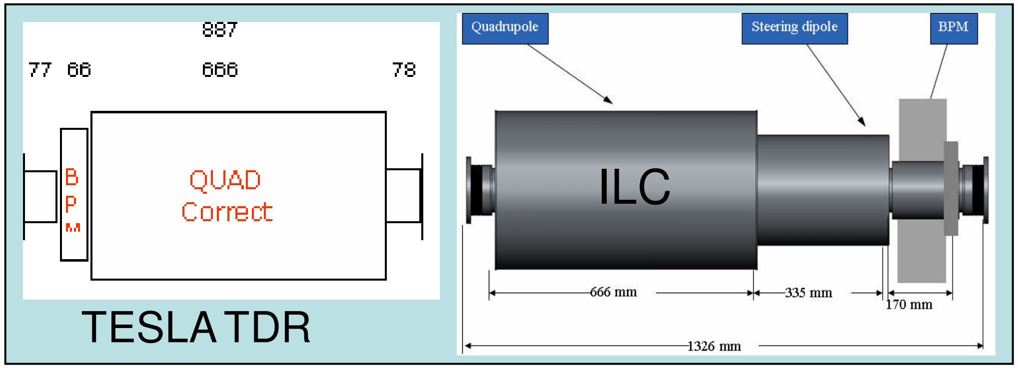
Energy upgrade scenario

(250 → 500 GeV per linac)

- Same layout 1Q / 3CM (FFODDO)
- Same Quad strength
- Half-phase advance: x/y = 37°/30° for upgraded HE linac
- Stronger correctors ~10% (for the same vertical curvature)

Main Linac Type-4 Cryomodule



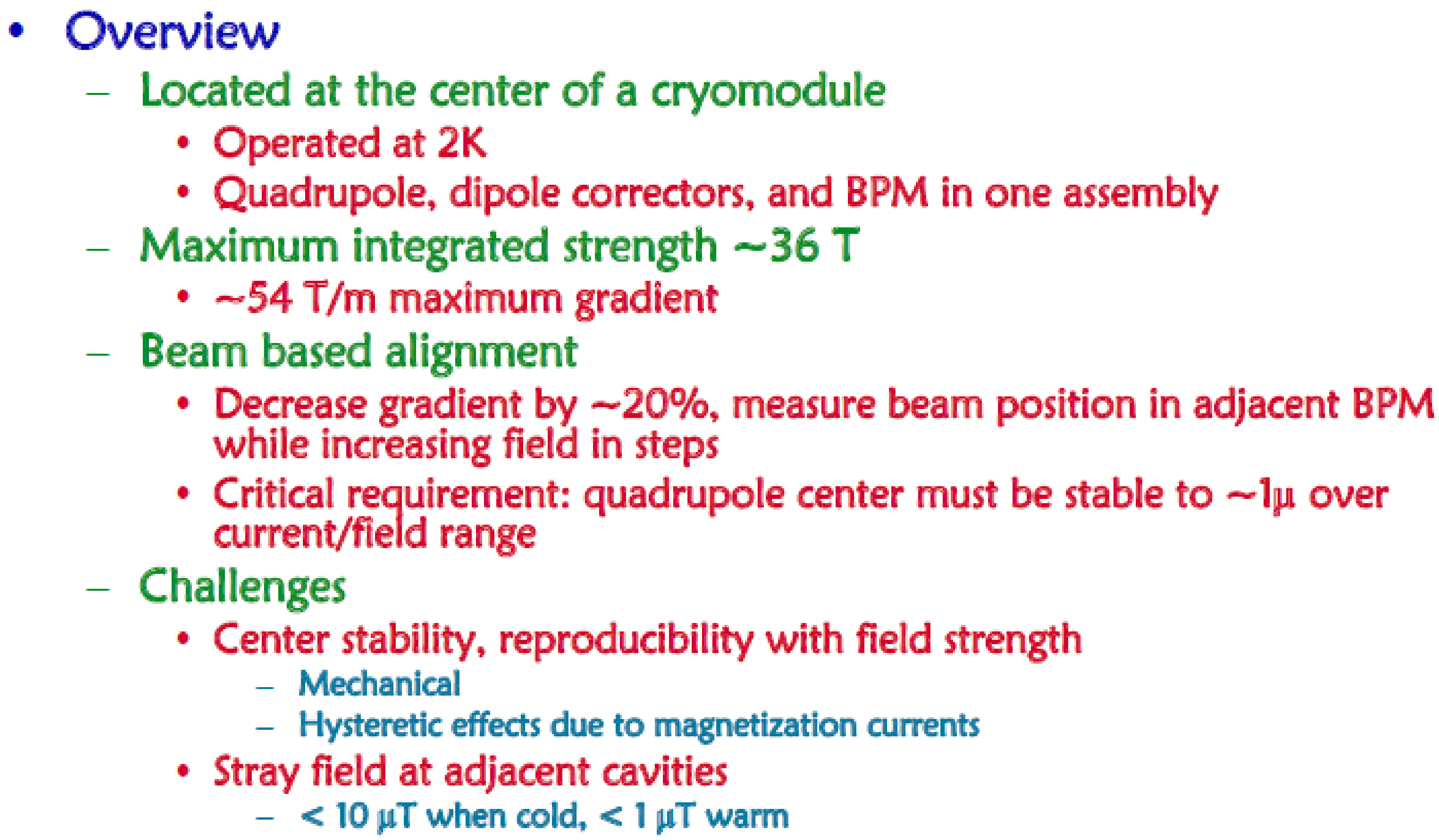


Space available for Quad

- Total package: ~1.3m, incl.
  - BPM: ~170 mm
  - Quad: ~ 660 mm
  - correctors: 335 mm

Combined or stand alone correctors (Quad center stability issues) ?

Main Linac Quadrupole & Correctors

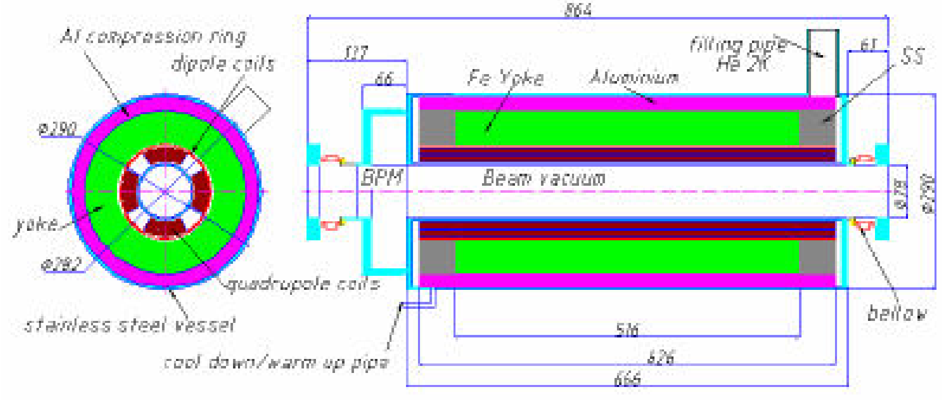


- Overview
  - Located at the center of a cryomodule
    - Operated at 2K
    - Quadrupole, dipole correctors, and BPM in one assembly
  - Maximum integrated strength ~36 T
    - ~54 T/m maximum gradient
  - Beam based alignment
    - Decrease gradient by ~20%, measure beam position in adjacent BPM while 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

J.Tompkins, PAC'07

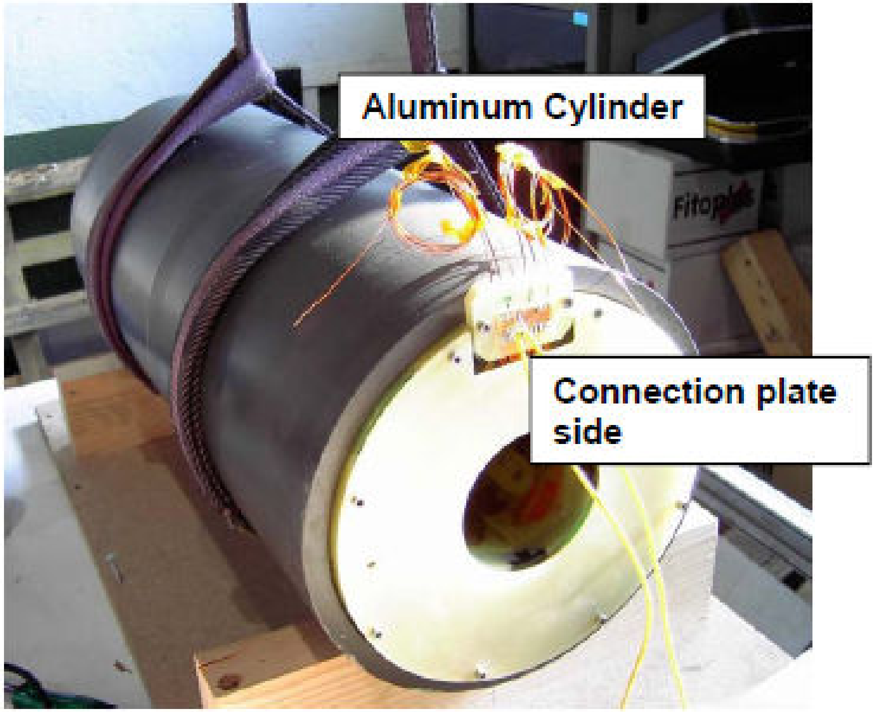
CIEMAT Quadrupole w/ Dipole Windings

- 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


Aluminum Cylinder

Connection plate side

Quad Strength

- Quad strength is defined by quad spacing, required phase advance (μ) and beam energy.

$$B' \cdot L = \frac{Energy}{e} \cdot \frac{2}{s} \cdot \sin(\frac{\mu}{2}) = \frac{Energy(GeV)}{0.3} \cdot \frac{2}{s} \cdot \sin(\frac{\mu}{2}) \quad [Tesla]$$

- For flexibility quad should provide optics with phase advance ***μ=90°*** up to final energy E=250 GeV (~20%)
- Extra strength will need for matching.
- Lattice with quad spacing ***s = 38 m*** (9+8+9 cavities in RF unit)
- L_{quad} (effective) = 0.626 m (in TESLA design)

$$B' \cdot L = \frac{250}{0.3} \cdot \frac{\sqrt{2}}{38} \approx 31 \ T$$

or

$$B' \left[\frac{T}{m}\right] \approx 50 \cdot \left[\frac{Energy}{250 GeV}\right]$$

Final choice for gradient: $B'_{\max} L \approx 36 \ T, \quad B'_{\max} \approx 60 \ [T/m]$

- *Allow to tune up to μ=**90°** phase advance @ 250 GeV*
- *Additional ~ 20% overhead for lattice matching*

Correctors

- Correctors are required to:
  - bend beam in vertical plane to transport beam along earth curvature
  - Correct beam (quad) offsets *Δy*

$$(H \cdot L) = \frac{Energy\ [GeV]}{0.3} \cdot \left[\frac{\Delta y \cdot \sin(\mu / 2)}{s} + \frac{s}{R} \right] \quad [T \cdot m]$$

where ***s*** *- quad spacing,* ***R = 6400 km*** *- Earth radius.*

- Vertical corrector in each quad
- Horizontal corrector in every second quad package
  - **Note: In horizontal plane second term is equal zero (no curvature)**

Corrector strength

Maximum required strength of corrector is defined from the following assumptions:

- *Energy = 250 GeV; μ= 90°; (RDR: μ_x / μ_y = 75°/60°)*
- Quad offset: rms σ= 0.3 mm; *($3\sigma \approx 0.9$ mm)*
- Max beam offset ±3 mm at energy 250 GeV

$$\left(H \cdot L\right) = 0.075 \quad \left[T \cdot m\right]$$

(<10% of strength needs to deflect beam along the Earth curvature)

Max current: (at 250 GeV) = 40A
Stability: same as for quads.
Field change: by a few percent in 0.2 s, every 0.2 s
Change step: (equivalent ~1µm of quad center motion)

2.e-6 T*m at 15 GeV; 3.e-5 T*m at 250 GeV

Magnet strength Fast stability (K.Kubo) (quad and dipole correctors)

1. *Vertical position change due to magnet strength error.*

- ***Relative magnet strength*** < 2.e-5 ➔ 0.14*σ rms beam offset in IP.

(Random 0.14 σ offset of each beam will make average position offset 0.2 σ between two beams at IP, which will decrease luminosity about 3%, without beam-beam force.)

- Very tight but relevant only for **fast jitter**, faster than orbit feedback (~1 ms)

2. Emittance increase due to magnet strength error.

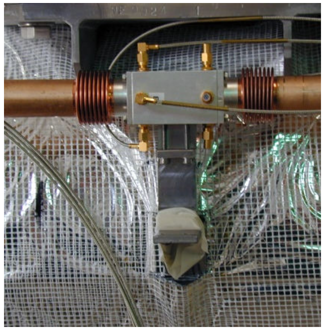
- ***Relative magnet strength*** < 1.7e-5 ➔ $\Delta\varepsilon/\varepsilon_0 < 0.063$

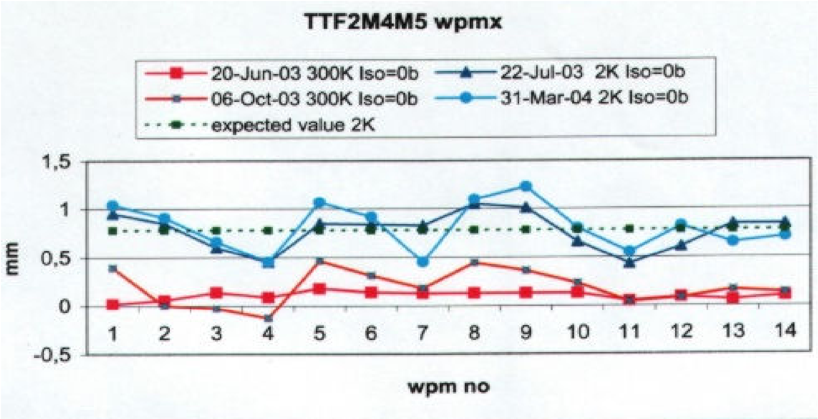
(Emittance increase by 0.063 will decrease luminosity about 3%, without beam-beam force.)

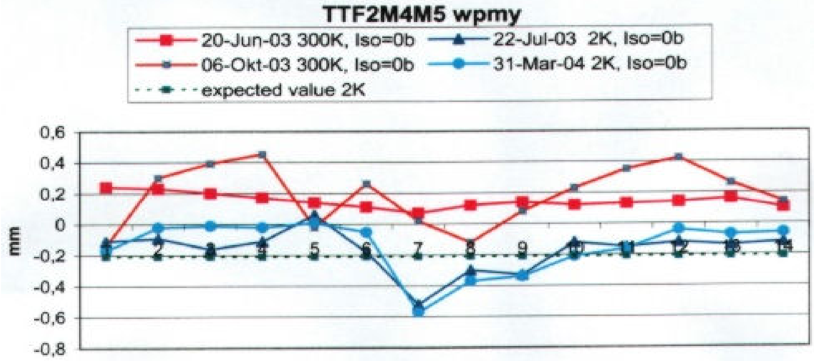
Alignment tolerances (installation)

Alignment tolerances are defined by CM design (DESY):

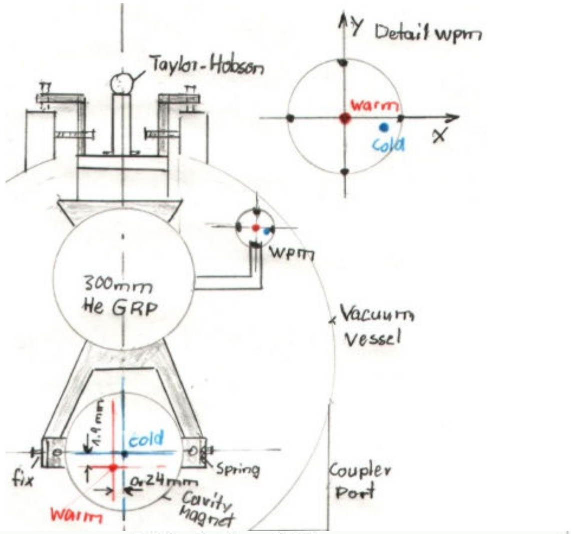
- Alignment strategy (state-of-the-art) during assembly
- Stability of the of the components during cool down/warm up
- Reproducibility, Alignment control system







- Still some work at the module interconnection
- Cavity axis to be properly defined



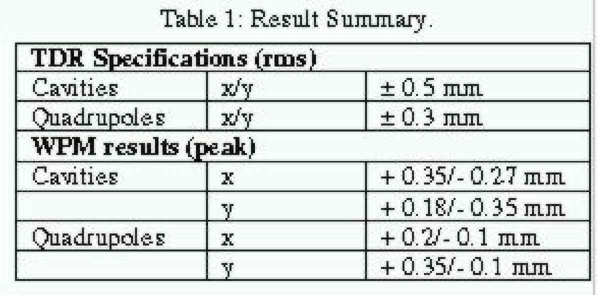


Table 1: Result Summary.

TDR Specifications (rms)		
Cavities	x/y	± 0.5 mm
Quadrupoles	x/y	± 0.3 mm
WPM results (peak)		
Cavities	x	+ 0.35/- 0.27 mm
	y	+ 0.18/- 0.35 mm
Quadrupoles	x	+ 0.2/- 0.1 mm
	y	+ 0.35/- 0.1 mm

ACC4 & ACC5 Met Specs

Quad center position stability

- Installation alignment of beamline components: Quad, cavities, BPM's
  ~300 mkm/300 mrad

- Few steps of Beam based alignment

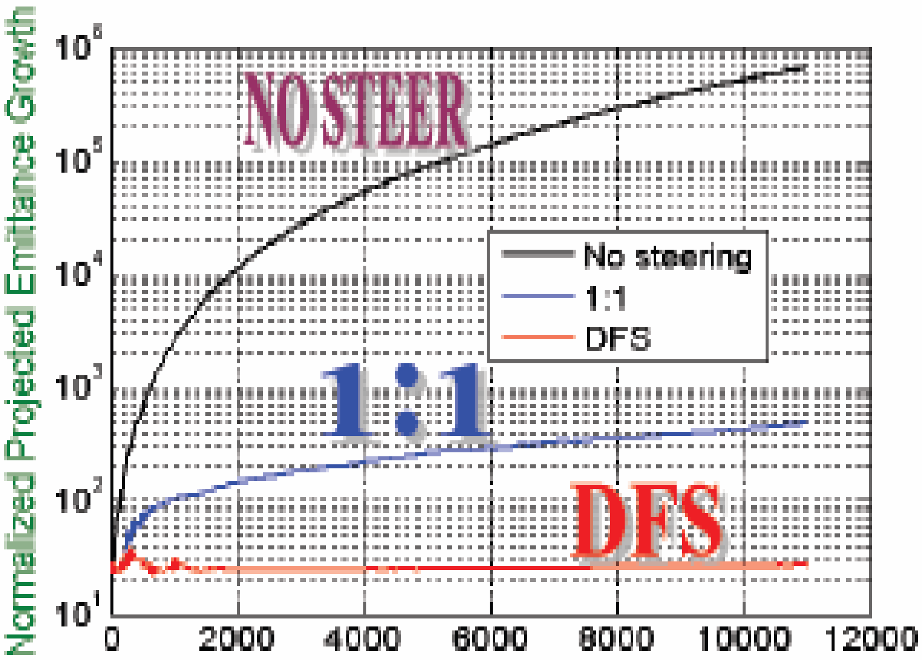
In first step:

- Magnet shunting (-20% in field) to define BMP misalignment ~ 1-2 μm
  - Required magnet center motion stability below 2 μm
- Ballistic alignment (BA) – switch field off
- Strength changes within a few sec.

2nd step:

- Dispersion Free Steering
- Dispersion matching steering
- Dispersion/wakefield Bumps
- Etc…

Tolerance	Vertical (y) plane
BPM Offset w.r.t. Cryostat	300 μm
Quad offset w.r.t. Cryostat	300 μm
Quad Rotation w.r.t. Cryostat	300 μrad
Structure Offset w.r.t. Cryostat	300 μm
Cryostat Offset w.r.t. Survey Line	200 μm
Structure Pitch w.r.t. Cryostat	300 μrad
Cryostat Pitch w.r.t. Survey Line	20 μrad
BPM Resolution	1.0 μm



Power supplies

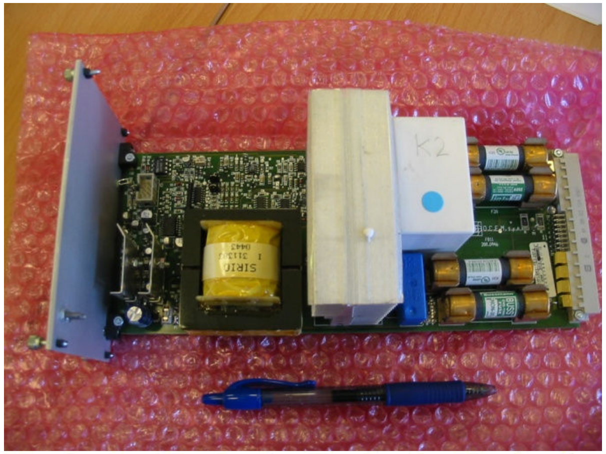
Switch-mode Bulk Power Supply

- *Line to load V matching transformer is downstream of high frequency > 20kHz switching element. Small size and light*
- *Each 30V, 400A 12kW*
- *Recommended*

ILC Development at SLAC by Paul Bellomo et. all

ATF2 (commissioned in 2008) – prototypes ILC
- 38 power supplies (1.5 kW to 6 kW),
- currents from 50 A to 200 A, voltages 30 V
- uses N+1 redundancy, with 50A power modules
- current stability 10-1000 ppm

PS for SC magnets:
- 100 A current leads
- Low losses
- Cheap



Quad specs

- ***Dimensions:***
  - **Beam pipe diameter = 78 mm; inner coil diameter ~ 90mm**
  - **Quad total length (z- slot) ≤ 0.66m (TESLA - 0.666 m)**
- ***Integrated gradient:*** *scales with energy*
  - **B'*L < 36 T (B' < 60 T/m, if L=660mm) - 1Q/3CM lattice at 250 GeV**
- ***Low peak current:*** 100A (40 A for trim coil)
  - **Optimal for DC power supply *(Paul Bellomo, SLAC)***
  - **reduce heat load from current leads (each quadrupole is powered separately), available and cheap current leads.**
- ***Stability requirements*:**
  - **faster than orbit correction (<1 ms) < 2.e-5**
  - **slower than orbit correction (>0.2 s) < 1.e-3**
- ***Higher harmonic tolerance***: not studied yet in details
  - **Skew quad < 3.e-4 (at reference radius 5mm)**
  - **High harmonics < 1.e-3 (at r = 5mm)**
  - **Fringe field in cavity region < 10 μT (at r=35mm, z~650 mm from quad center. Cavity has magnetic shielding**

Two families of quads ?

- ML quadrupoles should cover broad energy range: from 5 GeV to 250 GeV (factor of 50).

- It seems beneficial to have at least two families of quadrupole packages, optimized for low and high energy part of the Linac (performance and cost).
  - **Low energy: 5 – (40÷50) GeV**
  - **High Energy: (40÷50) – 250 GeV**

- Both families may use similar power supply and control electronics

- Note: Requirements for low energy quads are scaled with energy, where it is necessary

Magnets for High Energy (50-250 GeV)

Table of Specifications (Summary)

Quad	Beam pipe diameter Inner coil diameter Coil Length Integrated strength Gradient, max Operating T Nominal Current Max Field @ conductor	78 90 < 660 36 60 2 100 3.6	mm mm mm T T/m K A T
Field quality	Skew component Higher harmonics*	3.e-4 1.e-3	at *r = 5mm*
Dipole (trim) coil	Length (if separate) Field integral Max Field at conductor Max Current	< 350 0.075 3.6 40	mm T·m T A
Alignment tolerances (installation)	Center quad wt. pipe Angle (Pitch,Yaw, roll)	0.3 0.3	mm mrad
Alignment stability	Magnetic center motion (over --20% field variation) Pitch, yaw, roll (magnetic axis)	2 < 0.3	mkm mrad

(Some specs are copied from TESLA TDR as a reference)

SC magnets for Low-energy (5-50 GeV)

Table of Specifications (Summary)

Quad	Beam pipe diameter	78	mm
	Inner coil diameter	90	mm
	Coil Length	< 660	mm
	Integrated strength	7	T
	Gradient, max	12	T/m
	Operating T	2	K
	Nominal Current	100	A
	Max Field @ conductor	3.6	T
Field quality	Skew component	3.e-4	at
	Higher harmonics*	1.e-3	*r = 5mm*
Dipole coil	Length (if separate)	< 350	mm
	Field integral	0.015	T·m
	Max Field at conductor	3.6	T
	Max Current	40	A
Alignment tolerances (installation)	Center quad wt. pipe	0.3	mm
	Angle (Pitch,Yaw, roll)	0.3	mrad
Alignment stability	Magnetic center motion (over 20% field variation)	2	mkm
	Pitch, yaw, roll (magnetic axis)	< 0.3	mrad

Tolerances for higher harmonics are probably looser. Need to check.

Remarks from J.Tompkins (2007)

- Stability and Reproducibility: The center of quadrupoles and higher order elements must remain stable over time and with changes in magnet strength. The field obtained at a given current must also be stable with respect to the magnet powering history. These requirements translate into mechanical stability in all magnets, controlling hysteretic behavior in the magnet steel, and magnetization current effects in superconducting magnets.
- Reliability. A mean time between failures (MTBF) of the order of $>10^7$ hours is required for individual magnets to meet the overall availability assigned. To achieve this value for MTBF, every aspect of magnet design, fabrication and operation will be scrutinized in a series of MEA (Failure Modes and Effect Analysis) studies for a few representative magnets.

Conclusion

- Major specifications for ILC Main Linac Quadrupoles and Correctors are formulated, based on beam physics studies.

- Linac SC magnets with required parameters are feasible. Two prototypes built and tested
  - *SC quad built at CIEMAT and tested at SLAC*
  - *FNAL prototype*

- Proposed splittable design for ML magnet has advantages. R&D and prototyping are needed to confirm performance and efficiency.

- *Main issues:*
  - Optimal quad package configuration
  - Integrated field range (high:low)
  - Magnetic center motion stability in range of –20% field change
  - Combined or stand alone correctors
  - Fringing fields in SCRF areas from magnet package