International Linear Collider Reference Design Report

DESY-Seminar
Deutsches Elektronen-Synchrotron DESY
Hamburg und Zeuthen · June 19 & 20, 2007

Wilhelm Bialowons and Lutz Lilje · DESY & GDE

Based on “Reference Design Report “ by Kaoru Yokoya, International Cost Review, May 23, 2007

Outline (1)

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- Beam Delivery system
- Value Estimate
- Summary and Outlook

ILC Reference Design Report

~700 Contributers from 84 Institutes


ILC-REPORT-2007-01
AAI-PUB-2007-002
CHEP A07-001 (CHEP/KNU)
CLNS 07/1991
Cockcroft-07-04
DESY 07-046
FERMILAB-TM-2382-AD-CD-DO-E-FESS-TD
JAI-2007-001
JINR Dubna-E9-2007-39
JLAB-R-2007-01
KEK Report 2007-1
LNF-07/9(NT)
SLAC-R-857

DRAFT

INTERNATIONAL LINEAR COLLIDER

REFERENCE DESIGN REPORT

2007

APRIL, 2007


LIST OF CONTRIBUTORS

3:00pm, May 4, 2007

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ii ILC-Reference Design Report

http://www.linearcollider.org

What's RDR

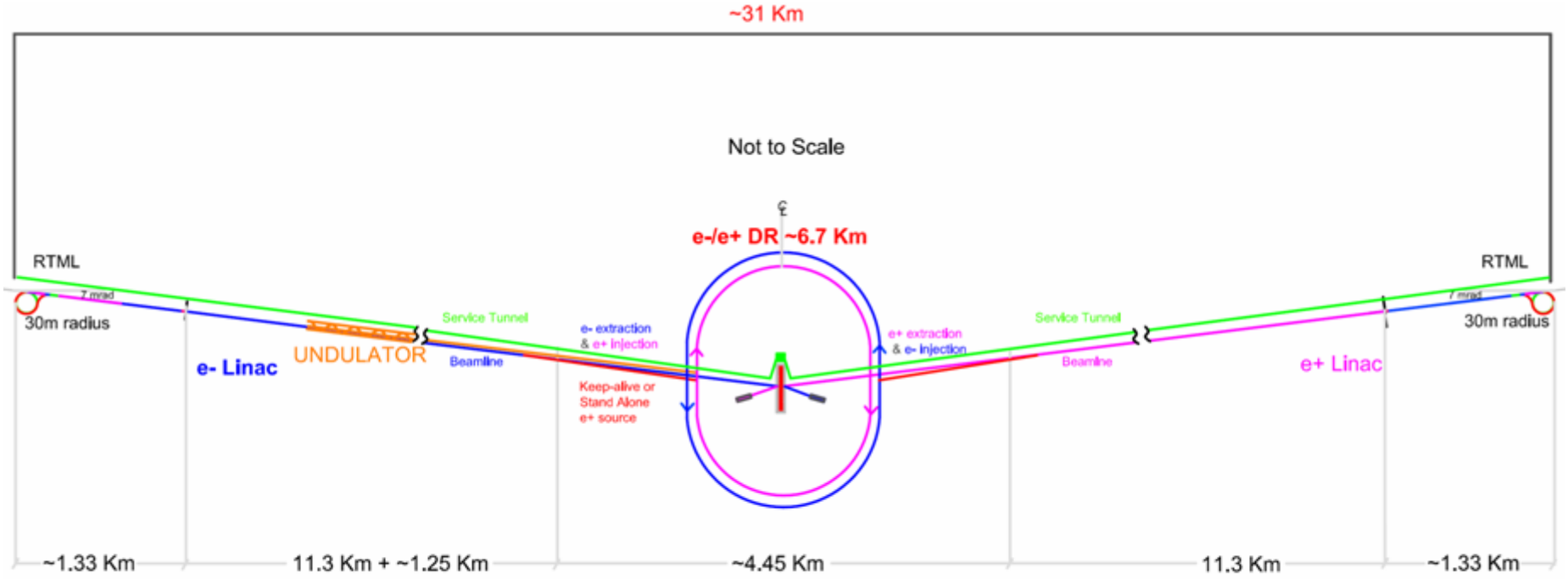
- Conceptual design report
- With first-stage cost (value, labor) estimation
- Engineering details not yet contained
- Not all based on the present technology
  - Forward-looking
  - R&D needed
- History
  - BCD (Baseline Configuration Document) published in December 2005 at Frascati meeting
  - Rules for cost estimation established in March 2006 at Bangalore meeting
  - First cost compilation in July 2006 at Vancouver meeting
    - Cost reduction effort started
  - RDR draft published in February 2007 at Beijing meeting

Machine Requirements

- Center-of-Mass Energy up to 500 GeV
  - upgradeable to 1 TeV.
- Integrated luminosity in the first 4 years > 500 fb^{-1} (500 GeV equivalent)
  - This corresponds to the peak luminosity ~$2x10^{34}$ $cm^{-2}s^{-1}$
    - taking into account the availability and buildup of luminosity after construction.
- Ability of energy scan in 200-500 GeV

Overall Layout

1st Stage: 500 GeV



Schematic Layout of the 500 GeV Machine

Basic Global Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	~$2x10^{34}$	$cm^{-2}s^{-1}$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

Beam Parameters for 500 GeV cms

	Nominal	Low Q	Large Y	Low P	
Number of Particles	2	1	2	2	10^{10}
Number of bunches	2625	5120	2625	1320	
Bunch interval (buckets)	369(480)	189(246)	369(480)	480(624)	ns( )
Average current	9.0	9.0	9.0	6.8	mA
Norm.emittance at IP x/y	10/0.04	10/0.03	10/0.08	10(0.036)	μm
Beta at IP x/y	20/0.4	11/0.2	11/0.6	11/0.2	mm
Rms beamsize at IP x/y	639/5.7	474/3.5	474/9.9	474/3.8	nm
Rms bunch length	300	200	500	200	μm
Disruption param x/7	0.174/19.4	0.108/14.6	0.520/24.9	0.211/26.1	
Beamstrahlung param Υ	0.048	0.050	0.038	0.097	
Energy loss by beamstr.	2.4	1.7	2.7	5.5	%
# of photons of beamstr.	1.32	0.91	1.77	1.72	
Pinch enhancement	1.71	1.48	2.18	1.64	
Geometric luminosity	1.20	1.35	0.935	1.21	10^{34}
Luminosity	2.0	2.0	2.0	2.0	10^{34}

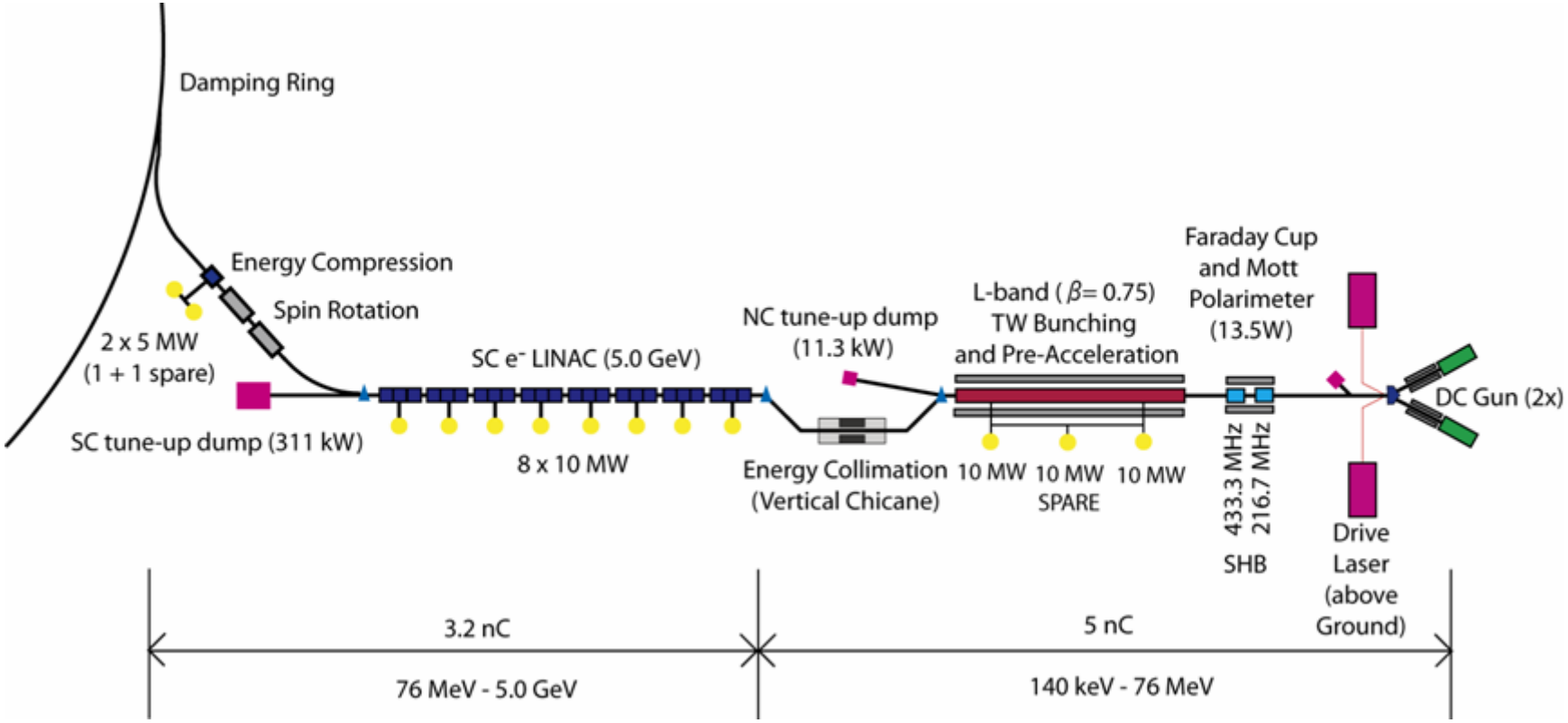
Range of Parameters

	min	-	nominal	-	max	
Number of particles	1	-	2	-	2	10^{10}
Number of bunches	1320	-	2625	-	5120	
Linac bunch interval	189	-	369	-	480	ns
DR bunch interval	3.08	-	6.15	-	12.3	ns
Bunch length	200	-	300	-	500	μm
Vertical emittance	0.03	-	0.04	-	0.08	μm
Beta at IP (x)	11	-	11	-	20	mm
Beta at IP (y)	0.2	-	0.4	-	0.6	mm

Electron Source

- Requirements
  - Beam structure
    - ~2600 bunches, ~1 ms, $2x10^{10}$ at DR
    - >80 % polarization
- Polarized e- gun
  - Used in SLC for many years
  - Improvements since then
  - Laser for long pulse needed
- Acceleration
  - NC up to 76 MeV
  - SC to 5 GeV

Electron Source System

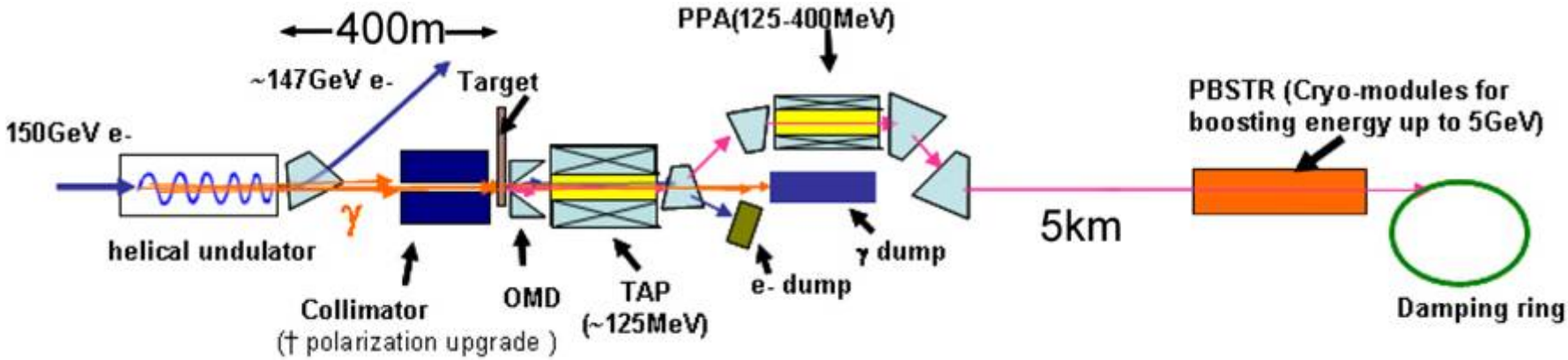


Positron Source

- 3 possible positron generation schemes have been proposed
  - A) Standard method: a few GeV electron on target
  - B) Undulator scheme: use photons from >100 GeV electron through undulator
  - C) Compton scheme: use photons from a few GeV electron through laser-Compton scattering
- B) has been selected as the baseline
  - C) is immature
  - Cost saving by A) is not significant. Physics descoping (no positron polarization)

Positron Source

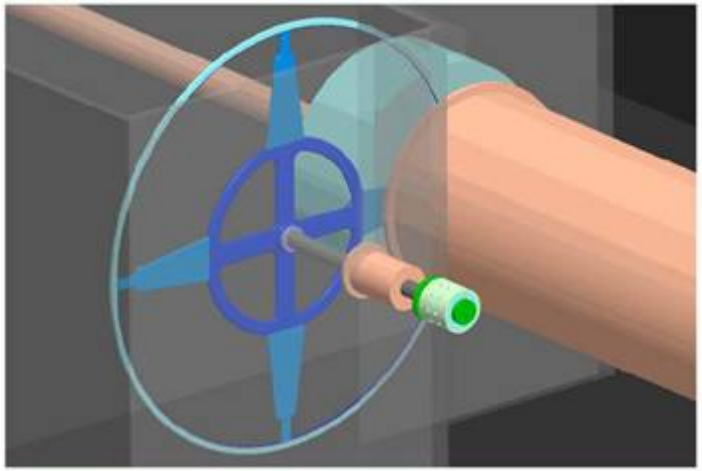
- Undulator scheme
  - Electron beam at 150 GeV

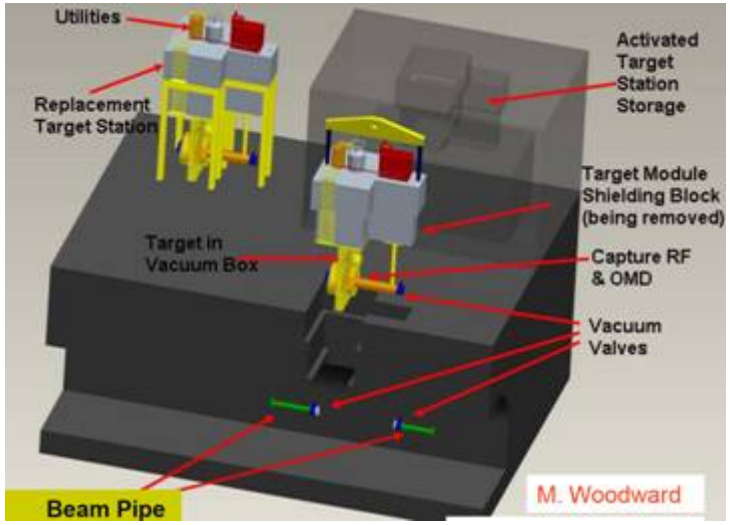


  - Undulator
    - Helical, superconducting
    - length 147 m (longer for polarized e+)
    - K = 0.92, λ = 1.15 cm, (B = 0.86 T)
  - Needs 'keep-alive source'
    - 10 % intensity
    - Share 5 GeV linac

Positron Source R&D items

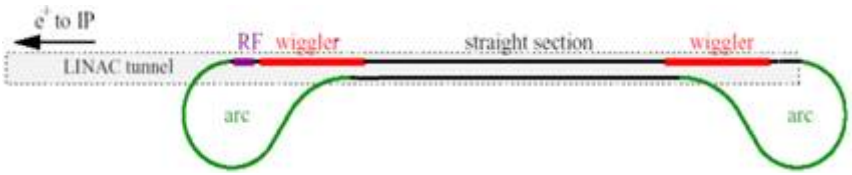
- Undulator fabrication
  - Superconducting
  - Helical
  - pitch 1.15 cm
  - K=0.92 (0.86 T)
  - beam aperture 5.85 mm
- Target
  - titanium alloy
  - diameter 1 m, 1.4 cm thick
  - rotating at 100 m/s
  - Eddy current heating if in magnetic field
- Target region design
  - quick replacement
    - Redundant target-capture section in the previous design was eliminated for cost reduction

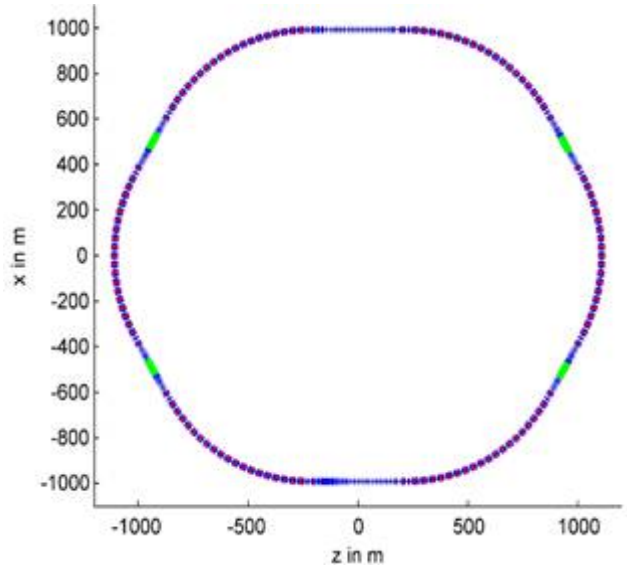




Damping Rings

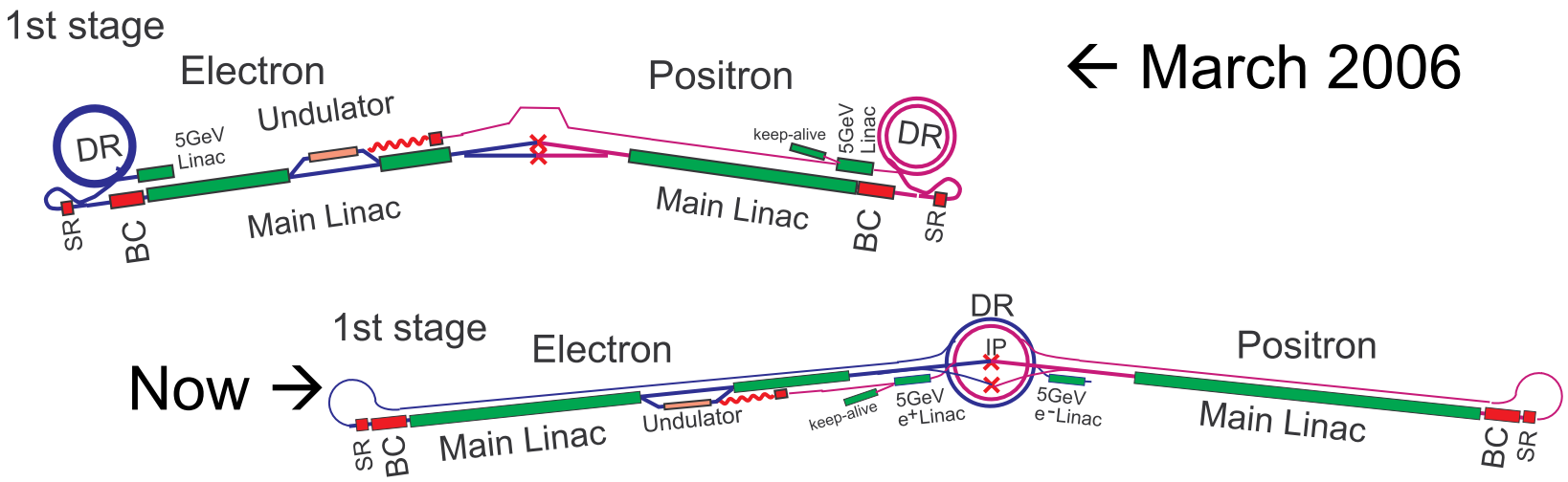
- Roles
  - Reduce transverse/longitudinal emittances
  - Beam stabilization
- Possible choices
  - Dog-bone
  - (nearly) Circular: ~3 km, ~6 km
- Baseline
  - 6.7 km circular ring
  - One for e+ and one for e-





Damping Ring Location

- Large cost savings since the original BCD
- 1e- and 2e+ → 1e- and 1e+
  - Progress in the electron-cloud problem
- Central injector system
  - Common tunnel for e+/e-, though transport to main linacs is longer



DR Remaining Issues

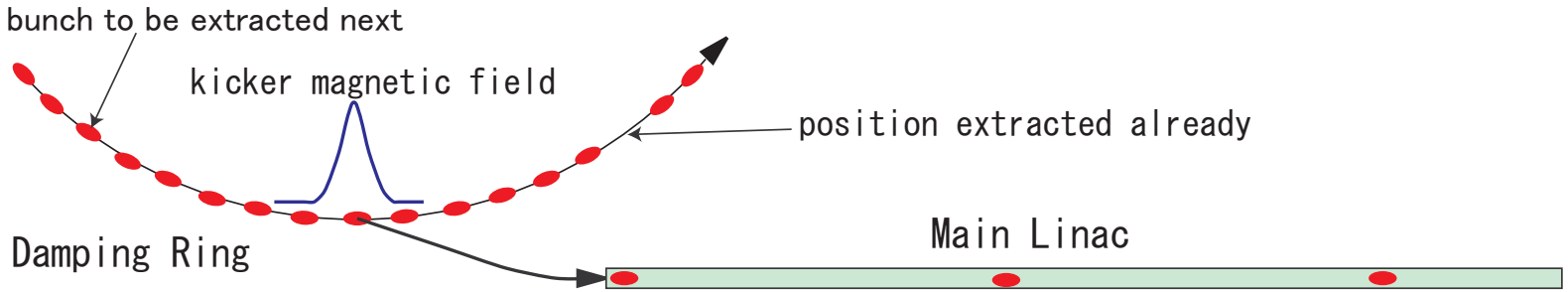
- Injection/extraction kickers
- Instabilities
  - Electron-cloud, Fast Ion, microwave, …
- Dynamic aperture
- Tuning for low emittance

Task Force S3 has been established for DR R&D

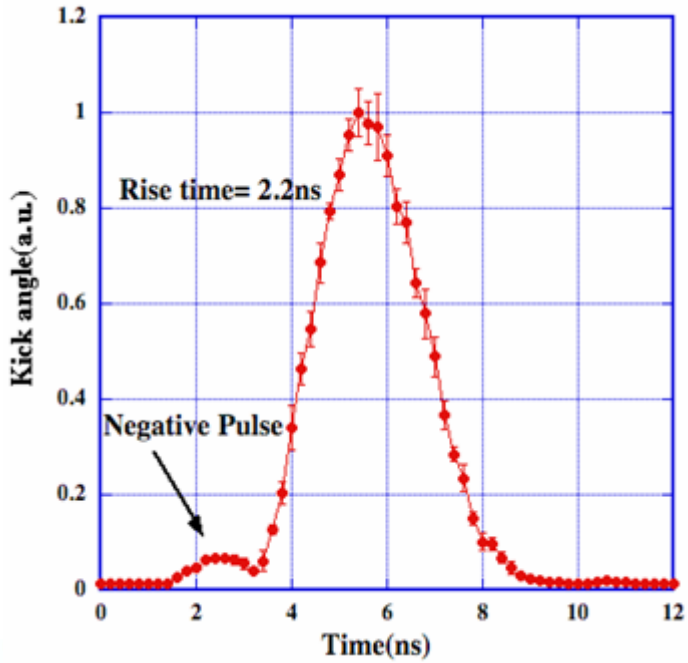
- Defining work packages
- Available machines
  - KEK-ATF
  - KEKB, CESR, HERA

Kicker System

- Must extract bunches one-by-one

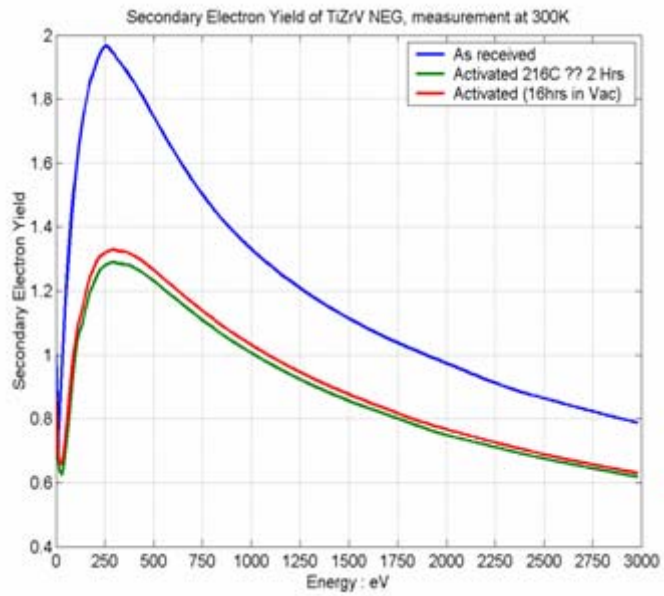


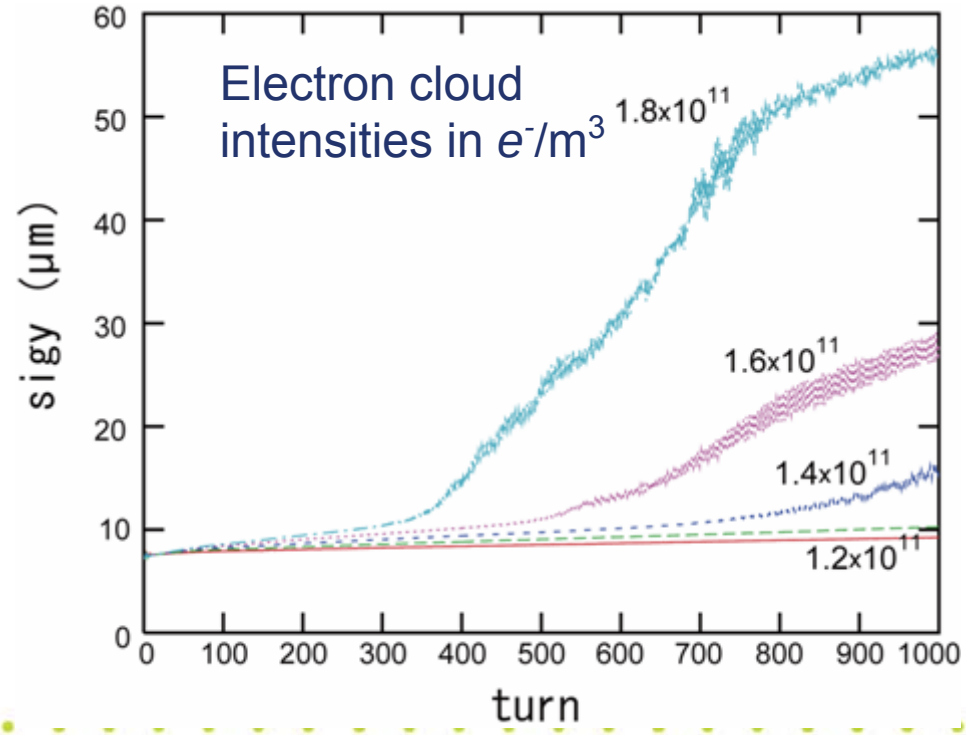
- Specification
  - rise, fall time < 3 ns
  - rep.rate 5.5 MHz
  - pulse length 1ms
  - stability < 0.1 %
    - can be relaxed by feedforward
- Fast kicker needed
  - A system with fast pulser and stripline developed at KEK.
  - Unit test done.



Electron Cloud

- Secondary electrons attracted by positron beam causes an instability
- Max. of Secondary Electron Yield (SEY) should be < 1.1
- Possible cures
  - Coating with NEG
  - Solenoids in free field region
  - Grooves on the chamber wall
  - Clearing electrode





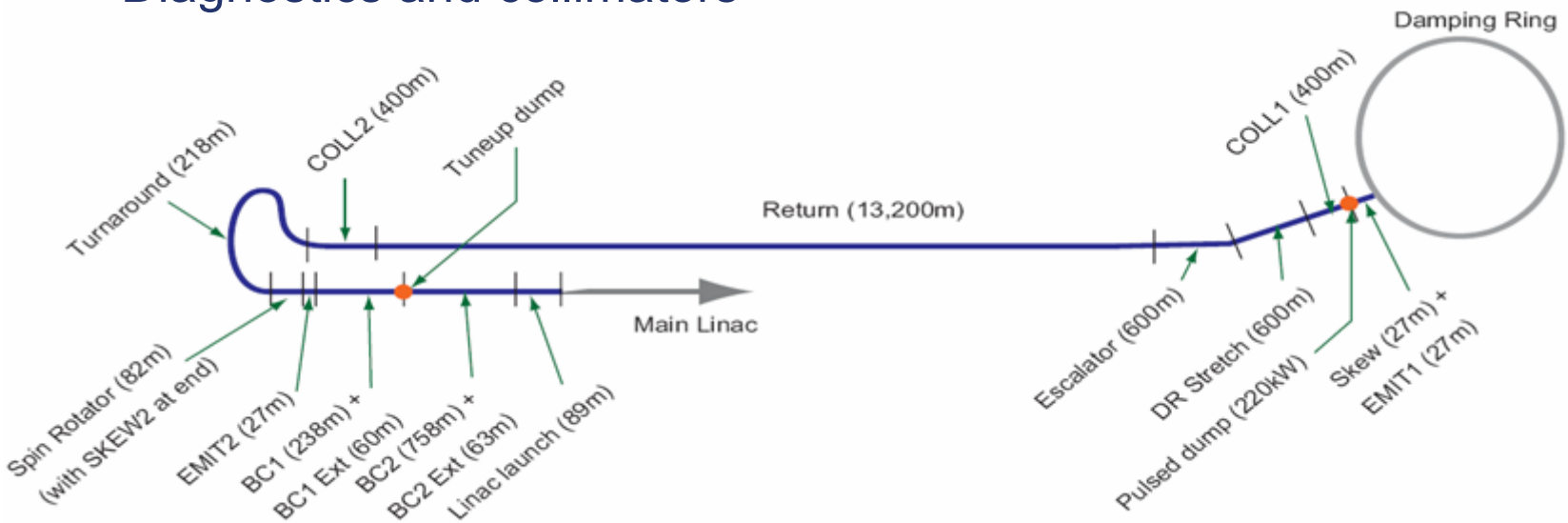
RTML (Ring To Main Linac)

Roles

- Transport from DR to Main Linac
- Bunch length compression
  - ~9mm → 200 to 300 μm
- Collimation
- Feed-forward
  - Eliminate beam oscillation from upstream
    - e.g. from DR kicker
- Spin rotation (vertical → horizontal)
- Diagnostics

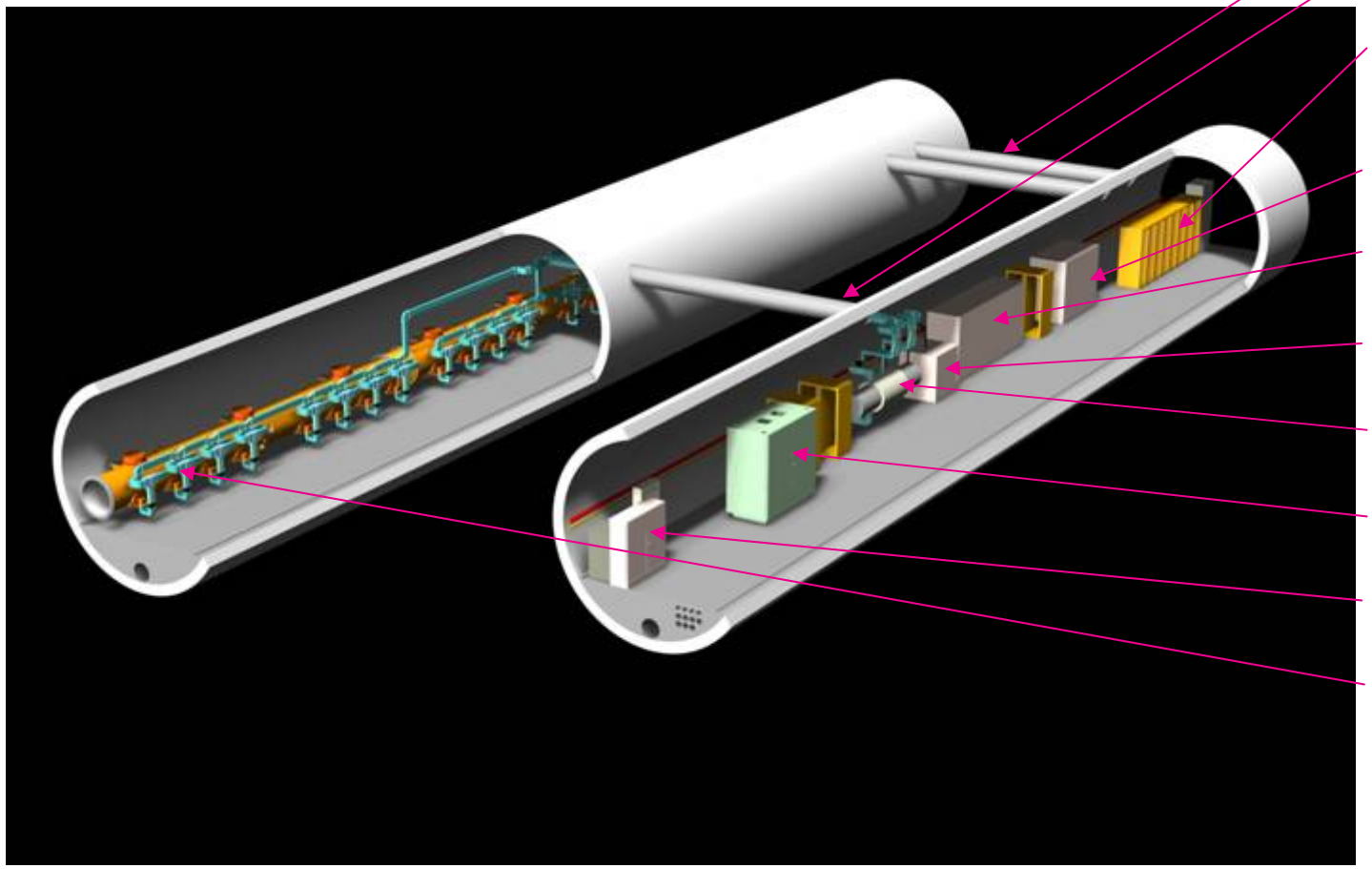
RTML

- ~14 km long transport
- Turn-around
  - needed also for feed-forward
- Spin Rotator
- Bunch compressor in 2 stages
  - 9mm→300μm (nominal parameters)
  - 9mm →200μm possible (Low Q parameters)
- Diagnostics and collimators



Main Linac Layout

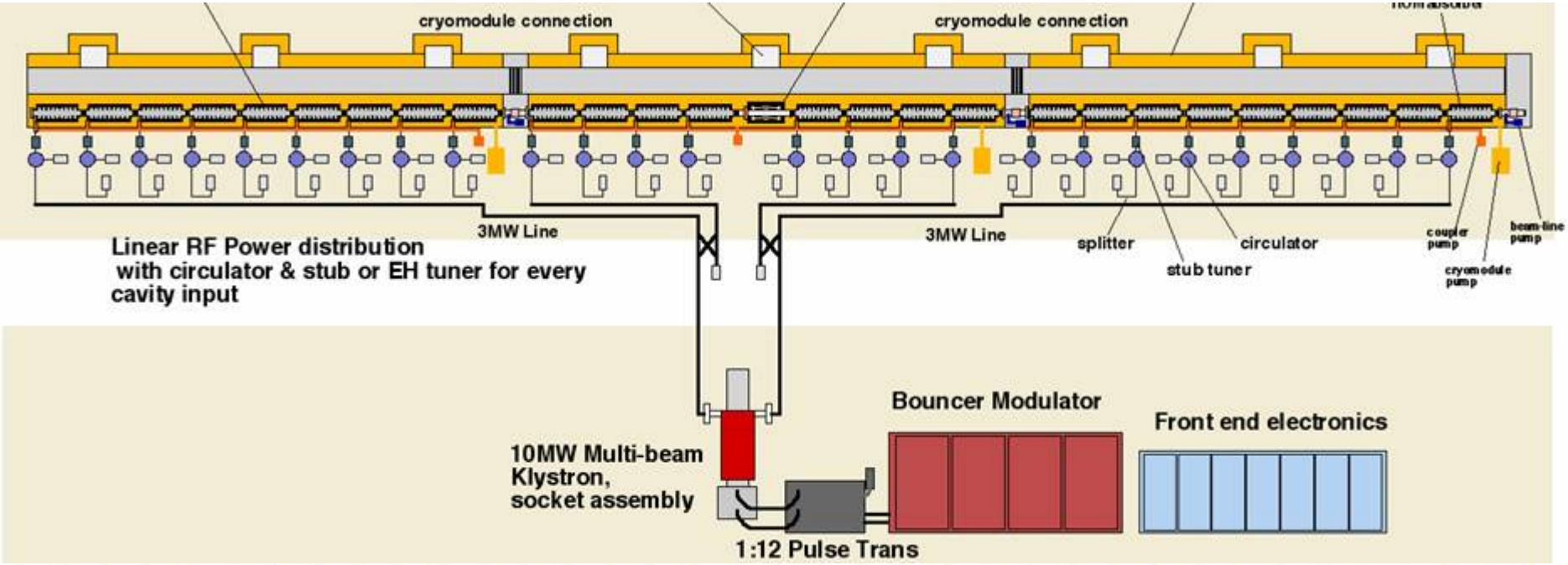
- Length ~11 km x 2
- Average gradient 31.5 MV/m
- 2 tunnels diameter 4.5 m



Dwg: J. Liebfritz

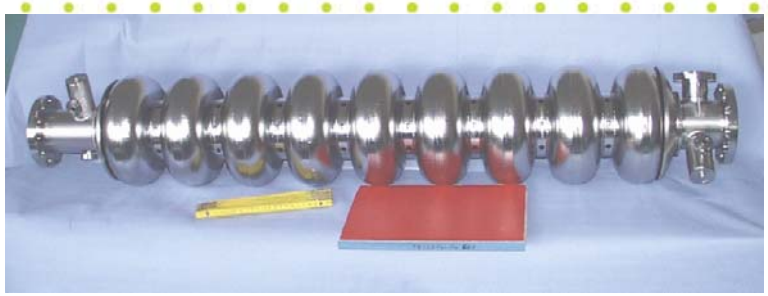
Main Linac RF Unit Overview

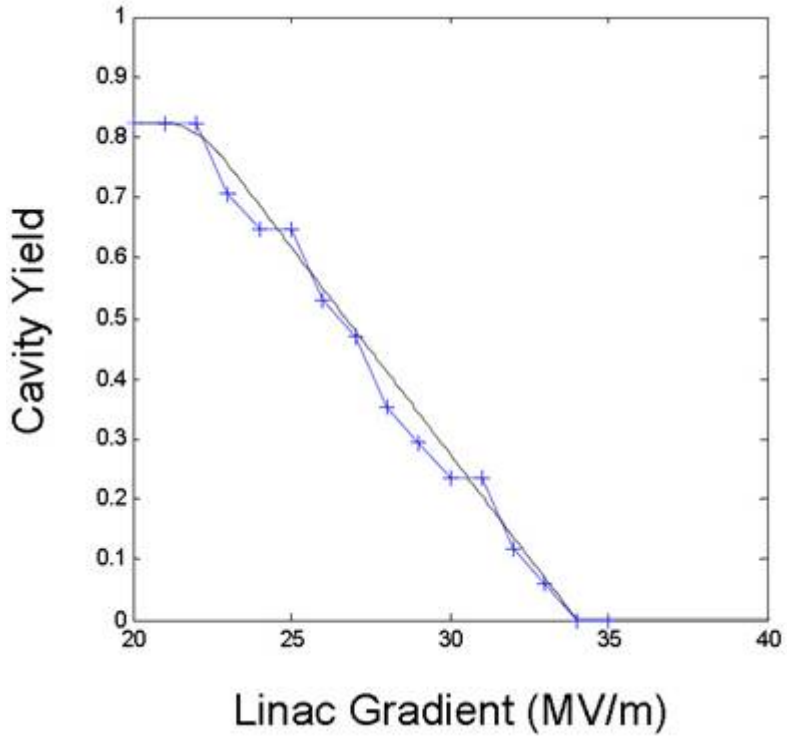
- Bouncer type modulator
- Multibeam klystron (10 MW, 1.6 ms)
- 3 Cryostats (9+8+9 = 26 cavities)
- 1 Quadrupole at the center



Cavities

- Baseline: TESLA-type 1.3 GHz
  - Identical to XFEL cavities
    - Only beamtubes shortened
- Accelerating gradient
  - Vertical test
    - >35 MV/m, Q>0.8x10^{10}
  - Average gradient in cryomodule
    - 31.5 MV/m, Q>1x10^{10}
- With the presently available technology
  - Average gradient lower than 31.5 MV/m
  - Spread of gradient large
  - If uniform distribution in 22<G<34 MV/m, average 28 MV/m
    - Cost increase ~7 %





High Gradient Reproducibility: S0 S1 Program

- Task Force created and R&D program set up
- S0: establish 35 MV/m in low power tests
  - Single-cell program
    - optimise final surface preparation (e.g. short electr polishing, alcohol rinse, ultrasound gegrease)
  - Tight-loop process
    - repeated surface treatment with small number of cavities including exchange of cavities among Asia-US-Europe in 2007
  - Production-like process
    - Many cavities with the same recipe
    - Large data set is (will be) available from the XFEL project
      - experience with TTF and FLASH
      - pre-production runs
        - » includes industrialisation e.g. Electropolishing at Industry
- Time line
  - Establish high yield well before EDR
- S1: Establishing 31.5 MV/m operational in accelerator modules

(A) CBP+CP+Anneal+EP(80μm) +HPR+Baking(120C*48hrs)

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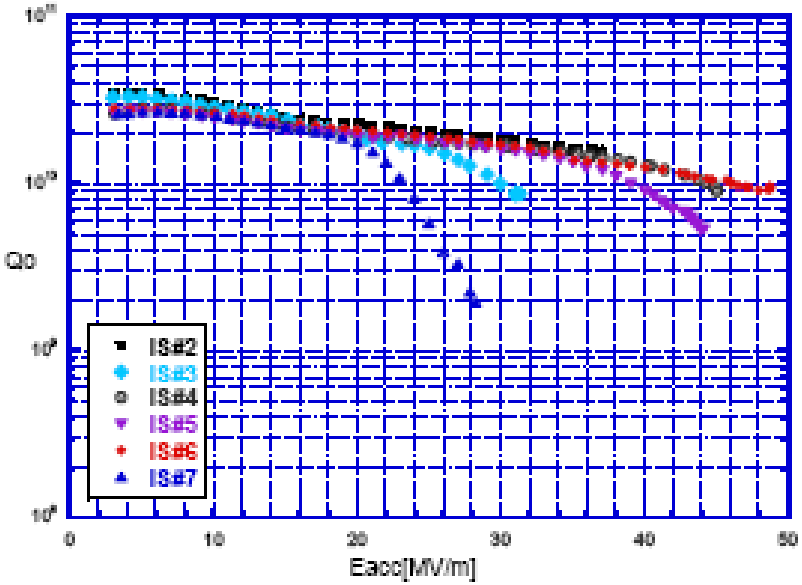

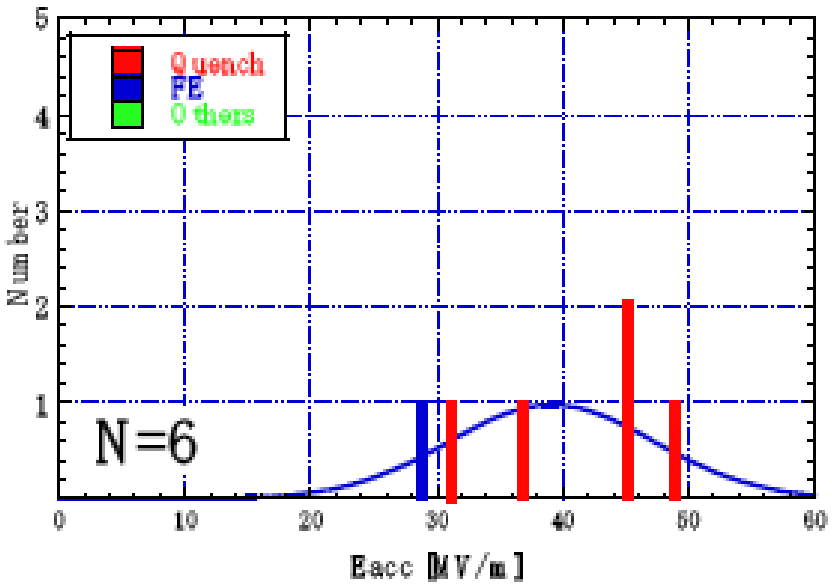

Ave. Eacc=39.1±8.2MV/m

Scattering:20%, Acceptability@40MV/m(ACD):50%

		IS#2	IS#3	IS#4	IS#5	IS#6	IS#7
EP(80)	Eacc	36.90	31.40	45.10	44.20	48.80	28.30
	Qo	1.53e10	8.66e9	9.07e9	5.38e9	9.64e9	1.94e9

(D) +EP(20μm)+EP(3μm, fresh, closed) +HF* +HPR+Baking (120C*48hrs)

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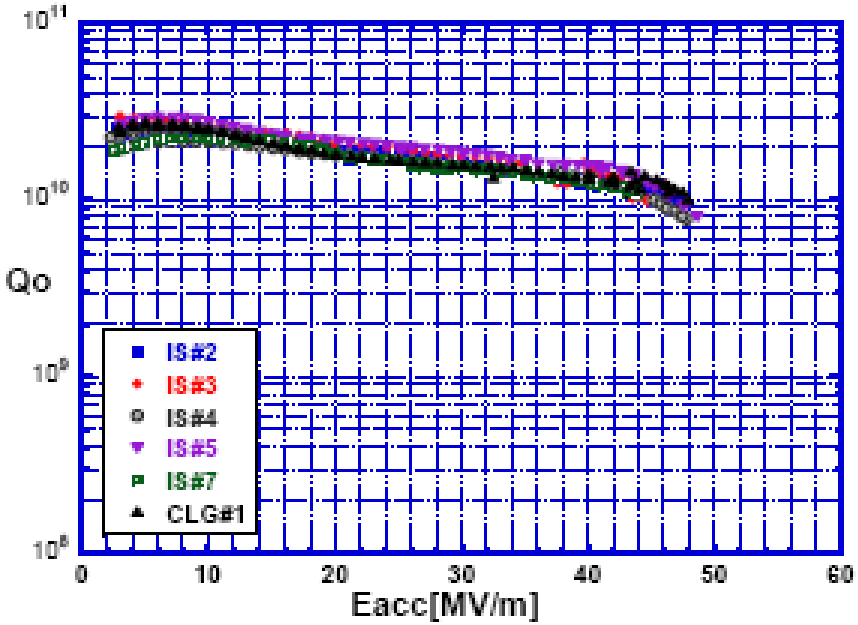
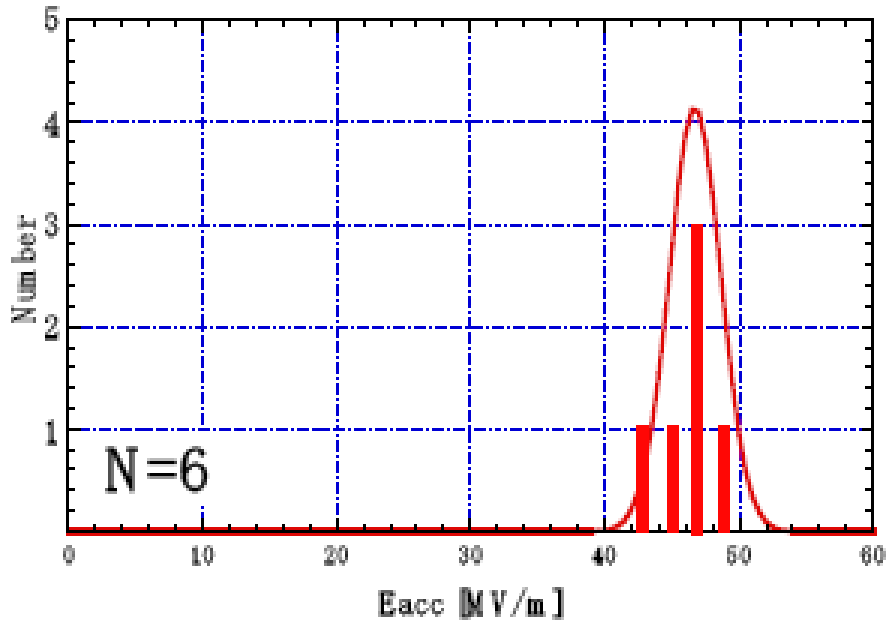


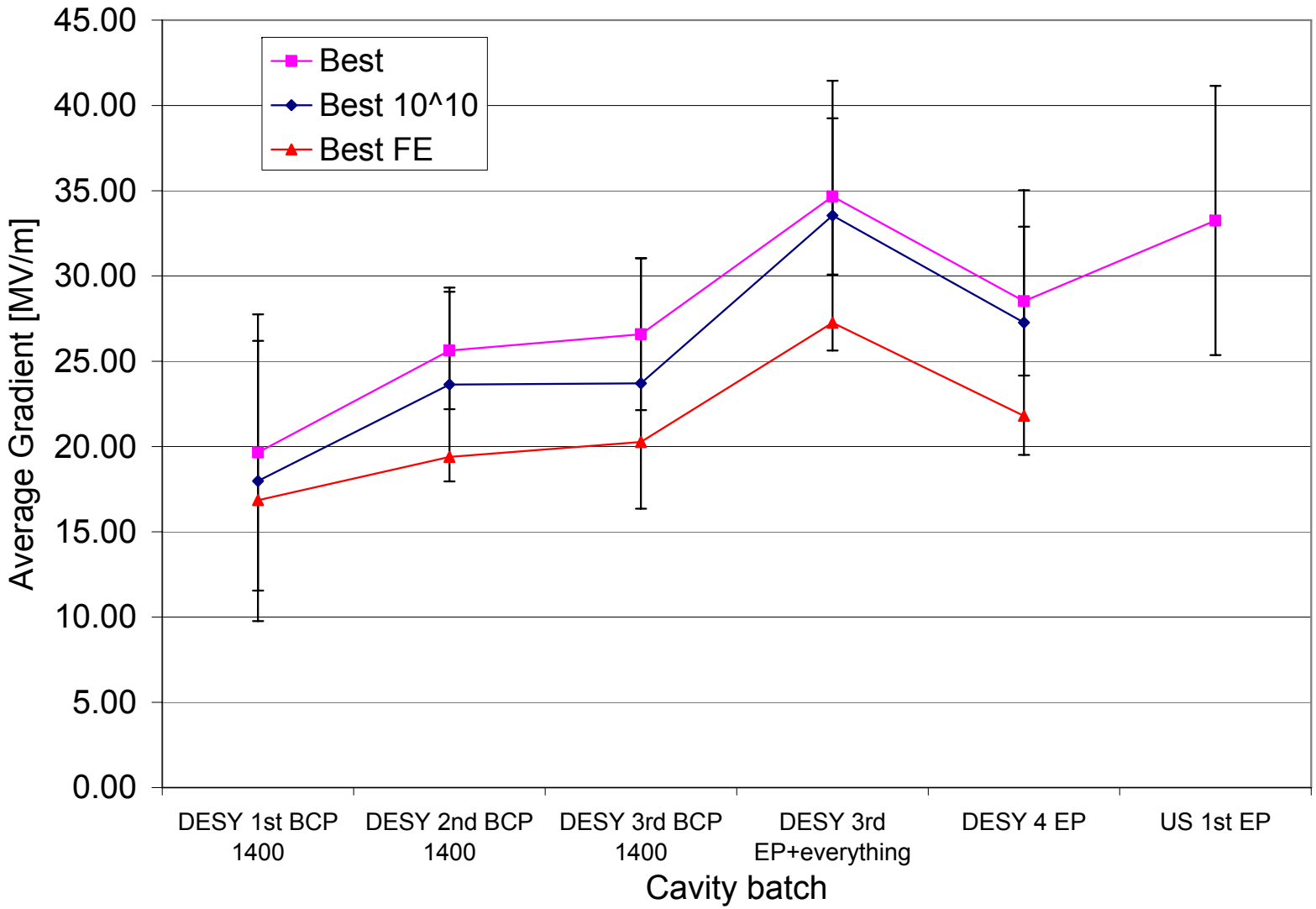


Ave. Eacc=46.7±1.9MV/m

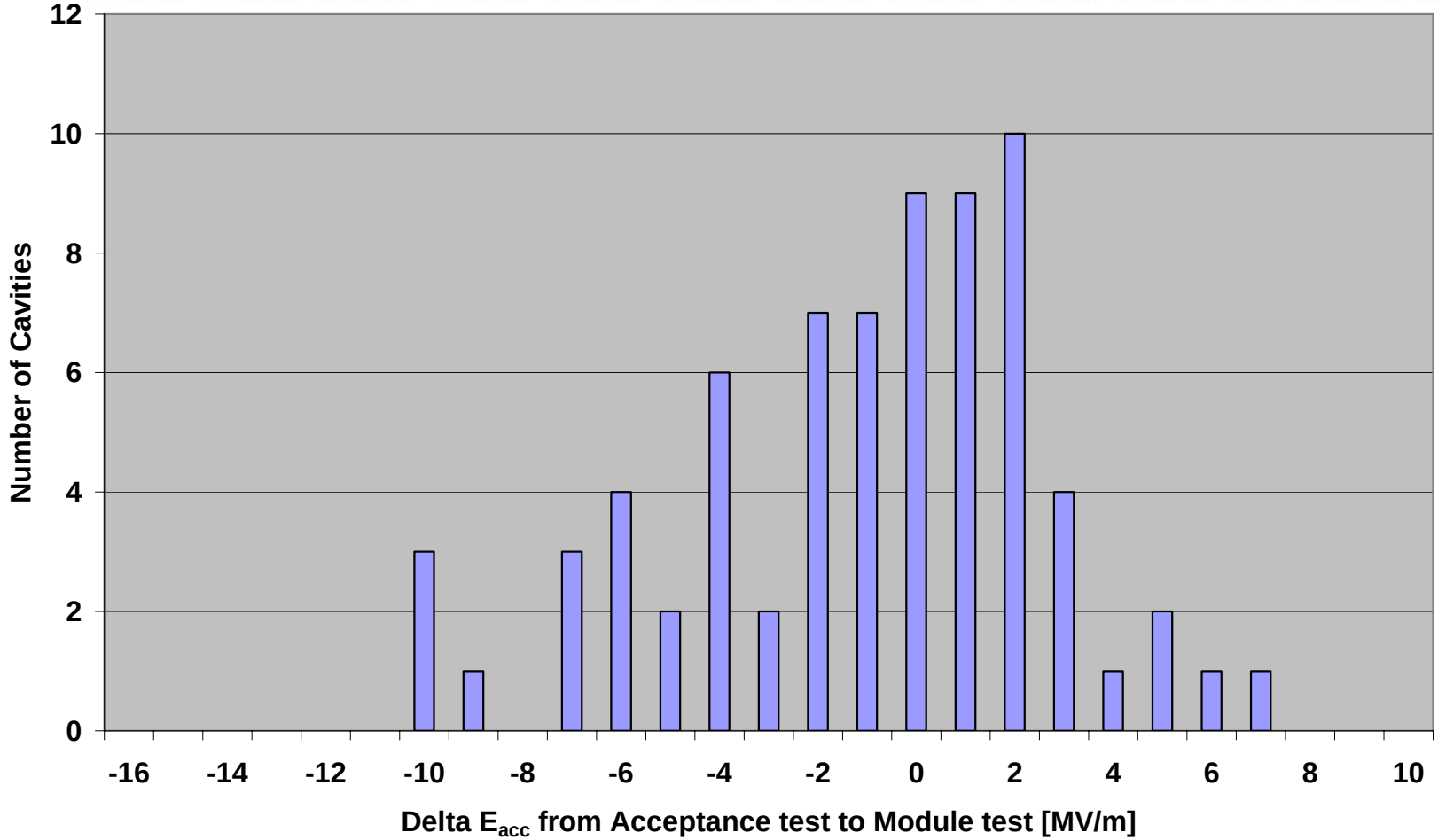
Scattering:4%, Acceptability@40MV/m(ACD):100%

		IS#2	IS#3	IS#4	IS#6	IS#7	CLG#1
+EP(20+3) +HF*	Eacc	47.07	44.67*	47.82	48.60*	43.93*	47.90*
	Qo	1.06e10	0.98e10	0.78e10	0.80e10	1.17e10	1.0e10

‘Qualified’ Vendor Productions: Best Test Results



S1 RF Performance: Compare Acceptance Test with Module Operational Accelerating Gradient



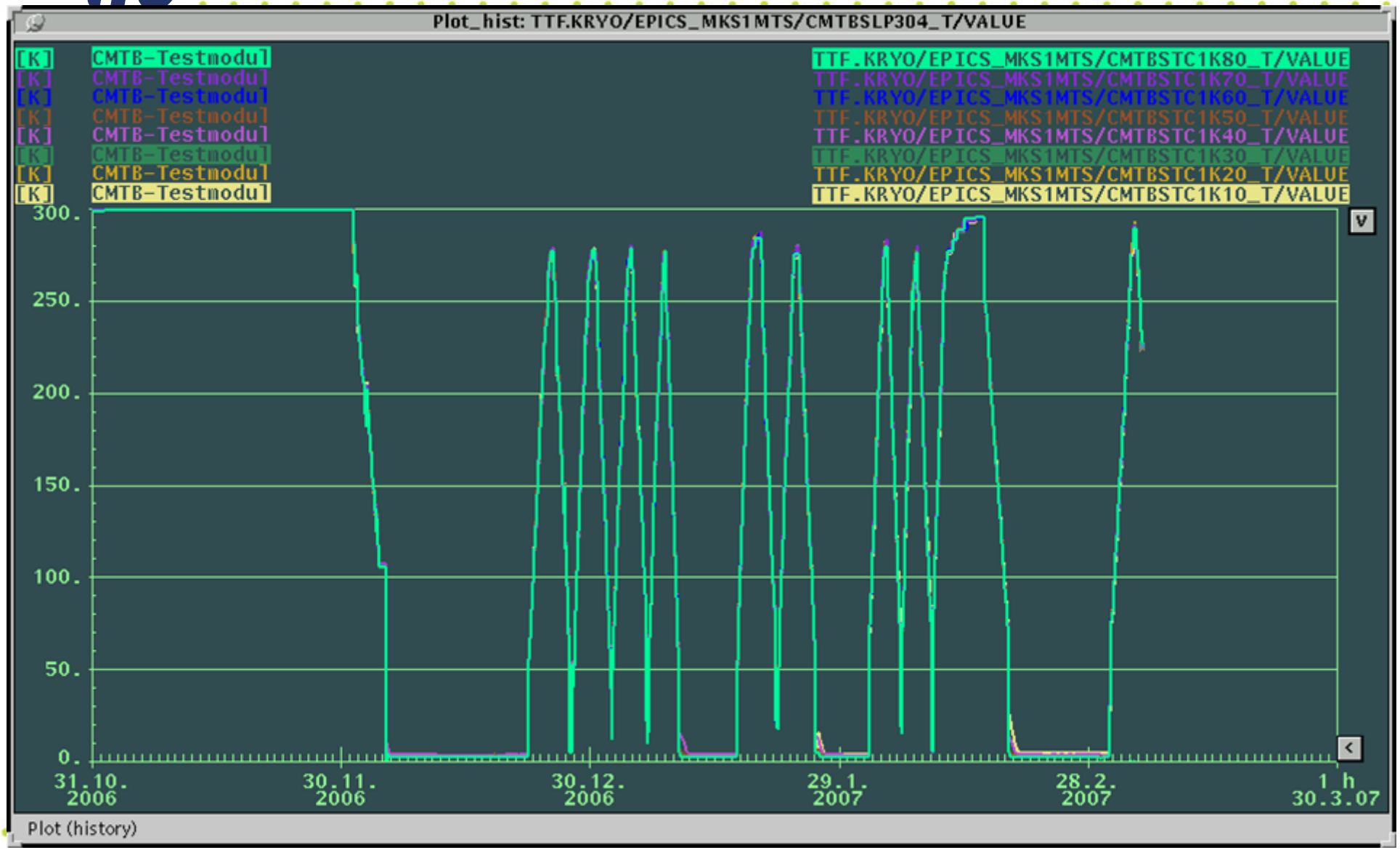
- This is the main motivation for S1
- Improvement on assembly procedures needed
  - Addressed in studies with industry also

XFEL assets: Module Test at DESY

- High gradient modules have been assembled
  - For installation in FLASH
- Test in dedicated test stand possible e.g.
  - Cavity performance
  - Thermal cycles
  - Heat loads
  - Coupler conditioning
  - Fast tuner performance
  - (LLRF tests)
- Part of the ongoing preparation work for XFEL

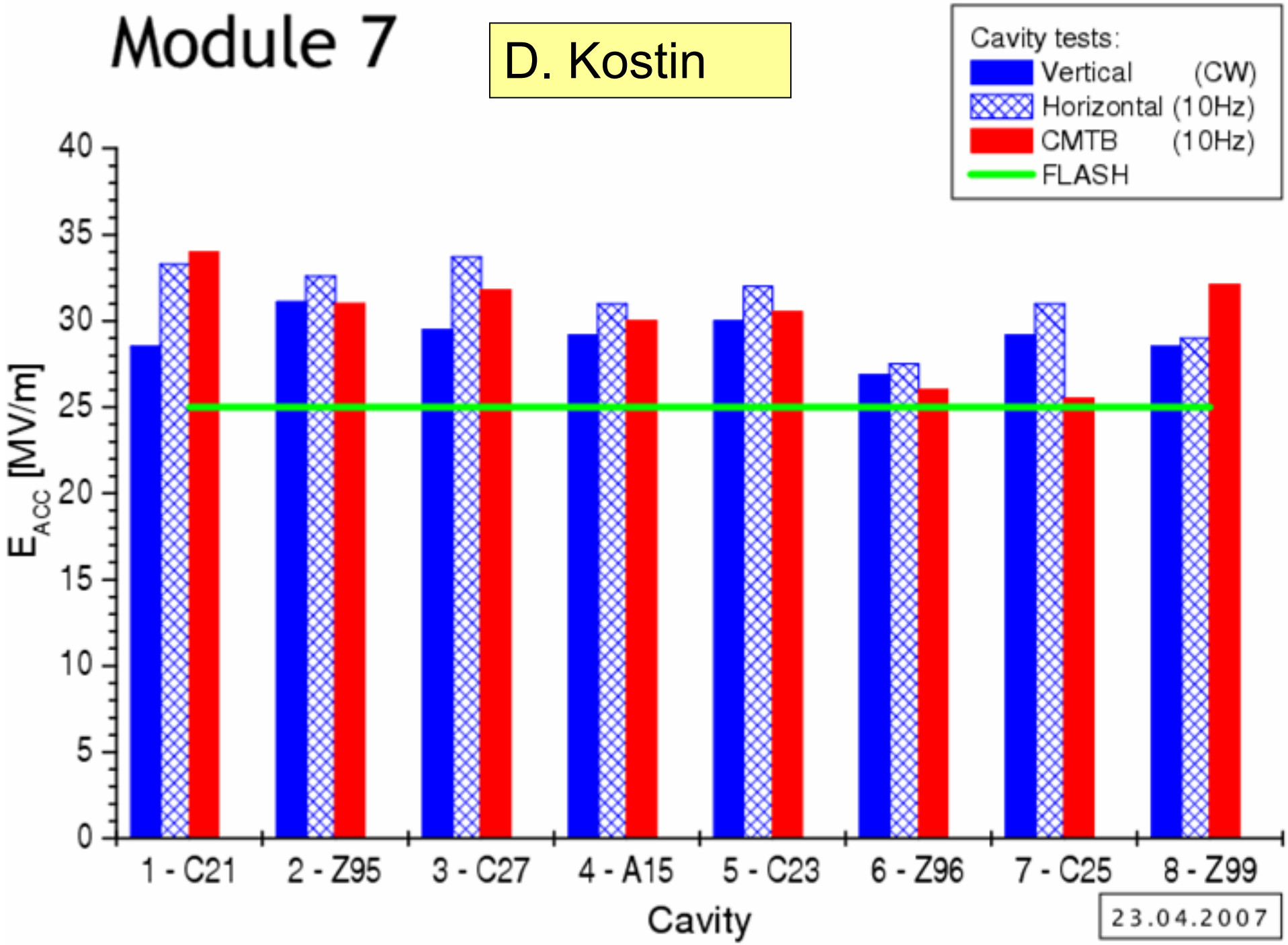
E.G. CMTB Module 6: 11 cool downs

R. Lange

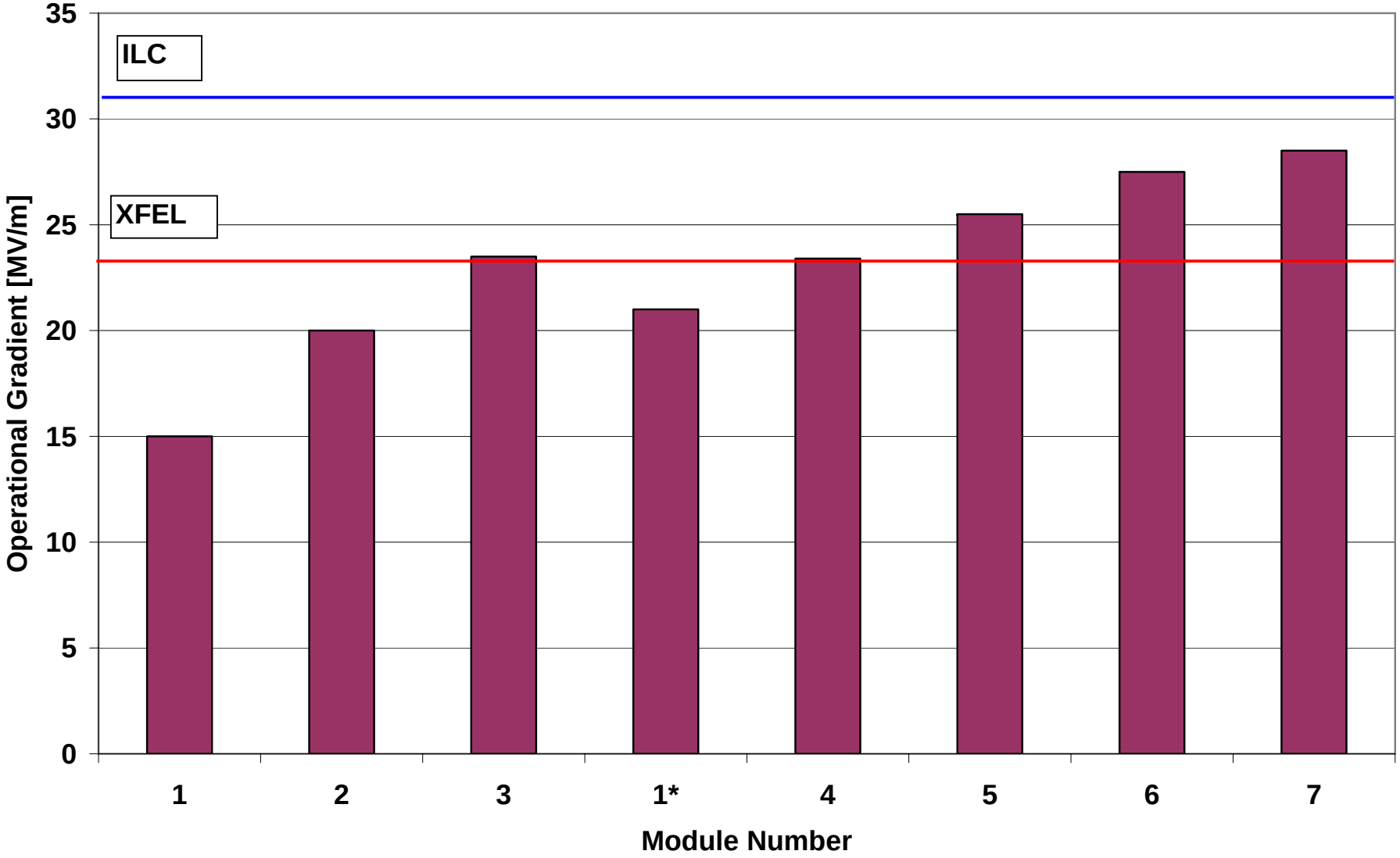


Module 7

D. Kostin



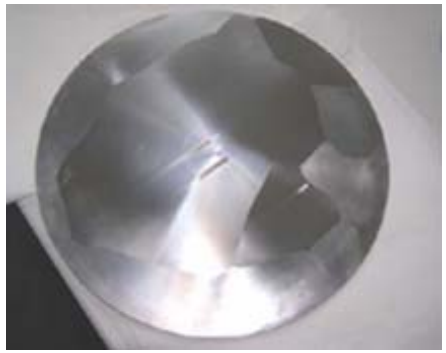
Accelerator Module Operational Gradients

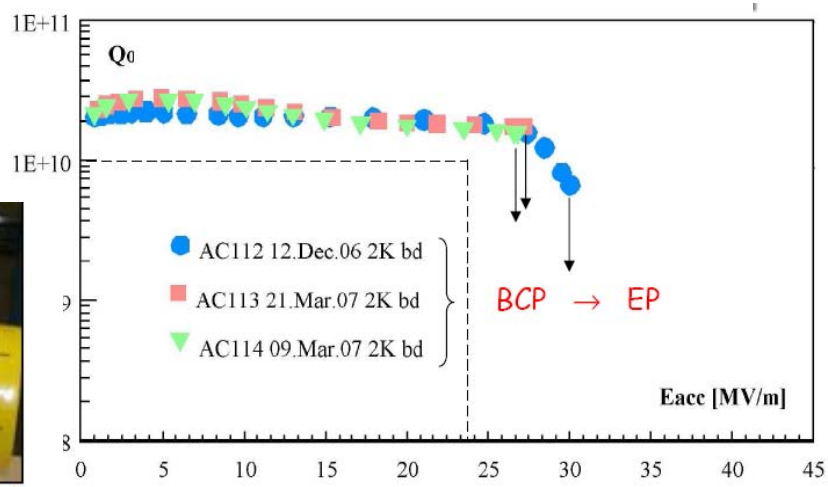


Alternatives:

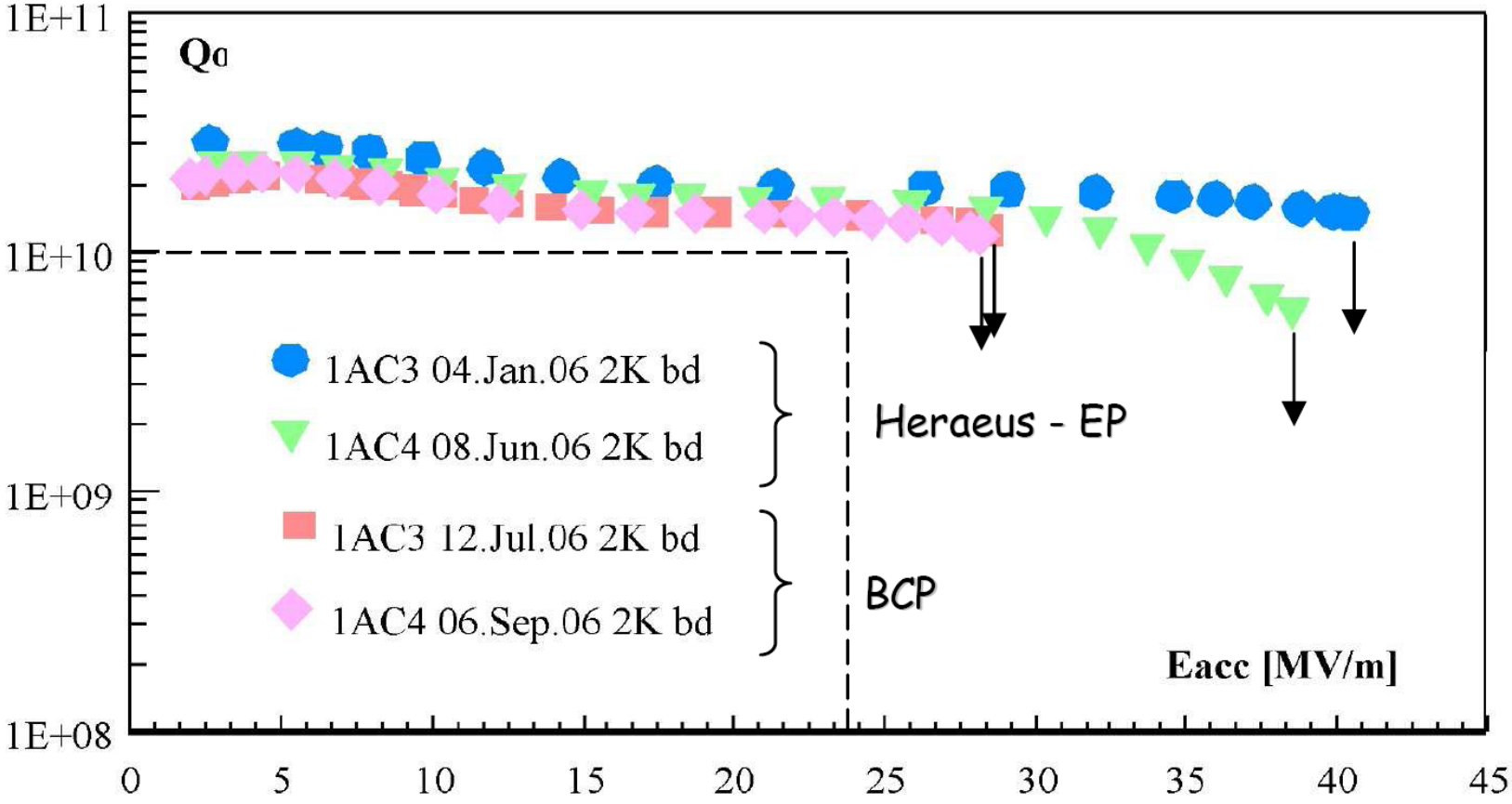
- LL-type cavity
  - Lower max. magnetic field at same accelerating gradient
    - Potentially higher gradient > 40 MV/m
  - Under development at KEK and JLab
    - Single-cell test successful with max. over 50MV/m
    - But 9-cell cavities are still poor with max. 29MV/m without HOMs

- Nb material:Large grain
  - Started at JLab
  - Single-cells
    - comparable performance to standard material
  - Full nine-cells fabricated XFEL preparation phase
    - so far only etched (BCP)
    - EP underway





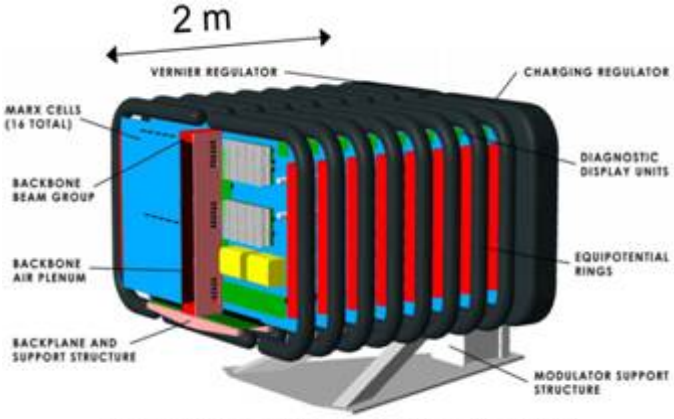
Large Grain Material: EP and BCP



D. Reschke et al.

Modulator

- Baseline
  - Bouncer-type modulator
    - Design at FNAL
      - Has been working for >10 years at TTF at DESY
      - No major technical issues
      - XFEL choice
  - Design improvements (within XFEL industrialisation)
    - More cost-efficient design under way
    - Redundancy of internal components for higher availability
- Alternative:
  - Marx Modulator
    - Under development at SLAC
    - Smaller size
    - No step-up transformer
    - Potentially high cost saving



MARX MODULATOR - MECHANICAL DETAIL

Klystrons

Thales

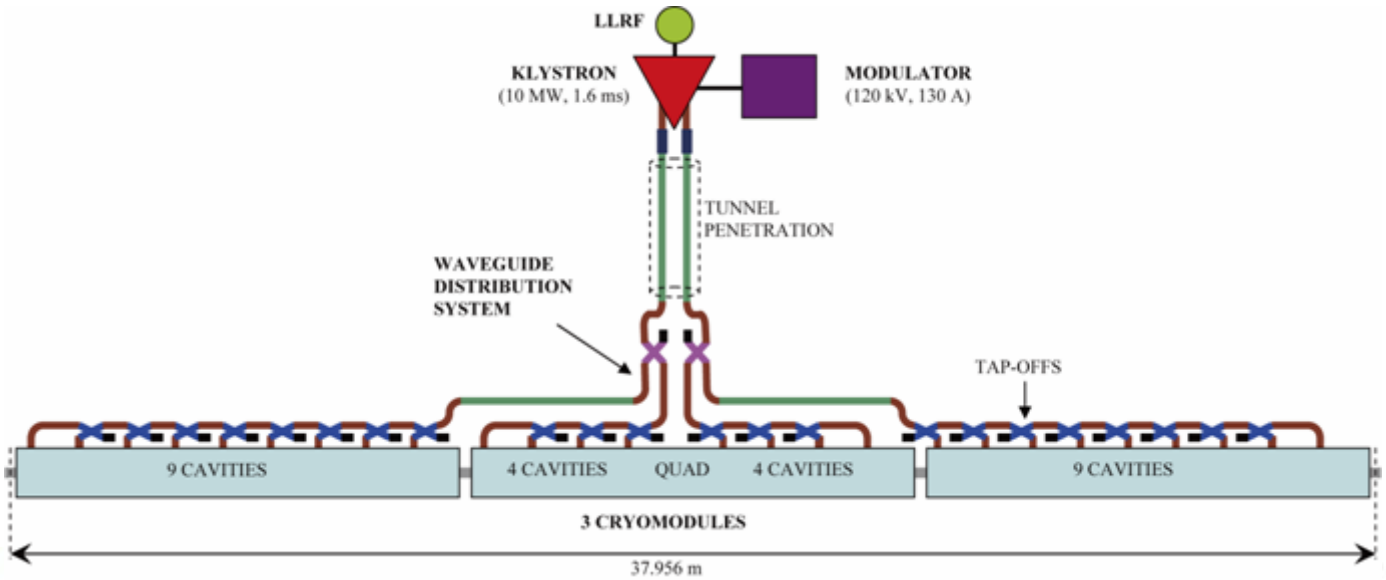
CPI

Toshiba

- Requirements:
  - 10 MW
  - 1.6 ms
  - 5 Hz
  - lifetime for full power >40000 hrs
- Baseline solution: Multi-beam klystron
  - Use multiple beams of low charge
  - Lower space-charge effects
  - Lower voltage (120 kV)
  - Higher efficiency (~65 %)
- Prototypes from 3 manufacturers for the European XFEL (higher repetition rate: 10 Hz)
  - Thales and Toshiba MBKs being successfully tested at DESY at full spec
    - for > 1000 hrs
    - Several klystrons under varying operating conditions at FLASH, PITZ and test stand
- Horizontally mounted klystron needed for small tunnel diameter
  - XFEL develops this with industry
- More lifetime testing going on (eventually also at SLAC)
  - At DESY all tubes which are now in operation do not show signs of degradation (no arcing, no perveance drops)

RF Distribution

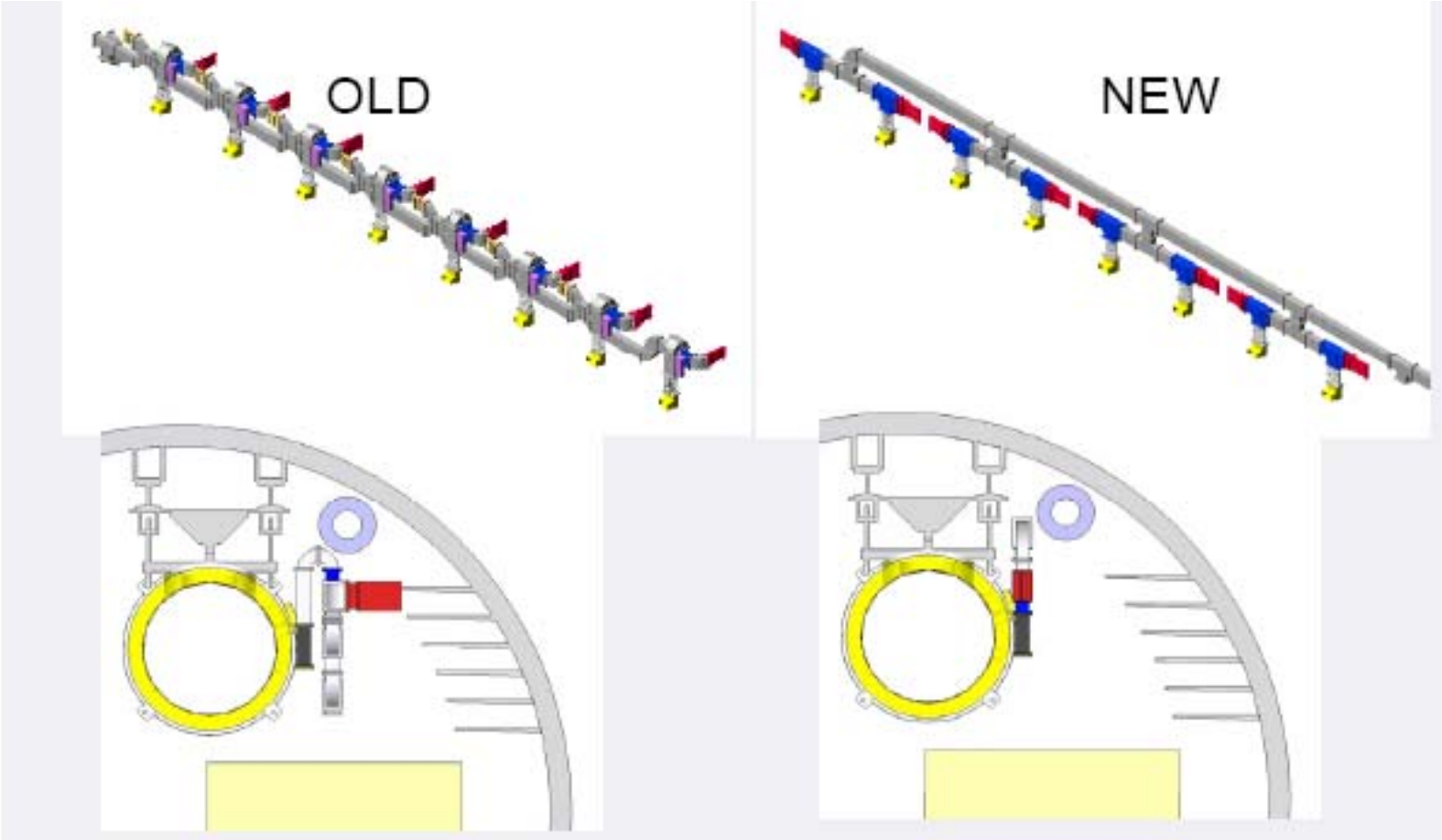
- 2 outputs from klystron → 2 waveguides of ~10 m long to the other tunnel
- Hybrid splitter (ratio 4:9)
- tap-offs (power fraction to individual cavities)
- circulator (protection against reflected power)
- 3-stub tuner (phase and coupling adjustment)
- Total power loss ~6.5 %
- Other design to replace circulator and 3-stub tuner is underway for lower cost and lower power loss



Alternative RF distribution for XFEL

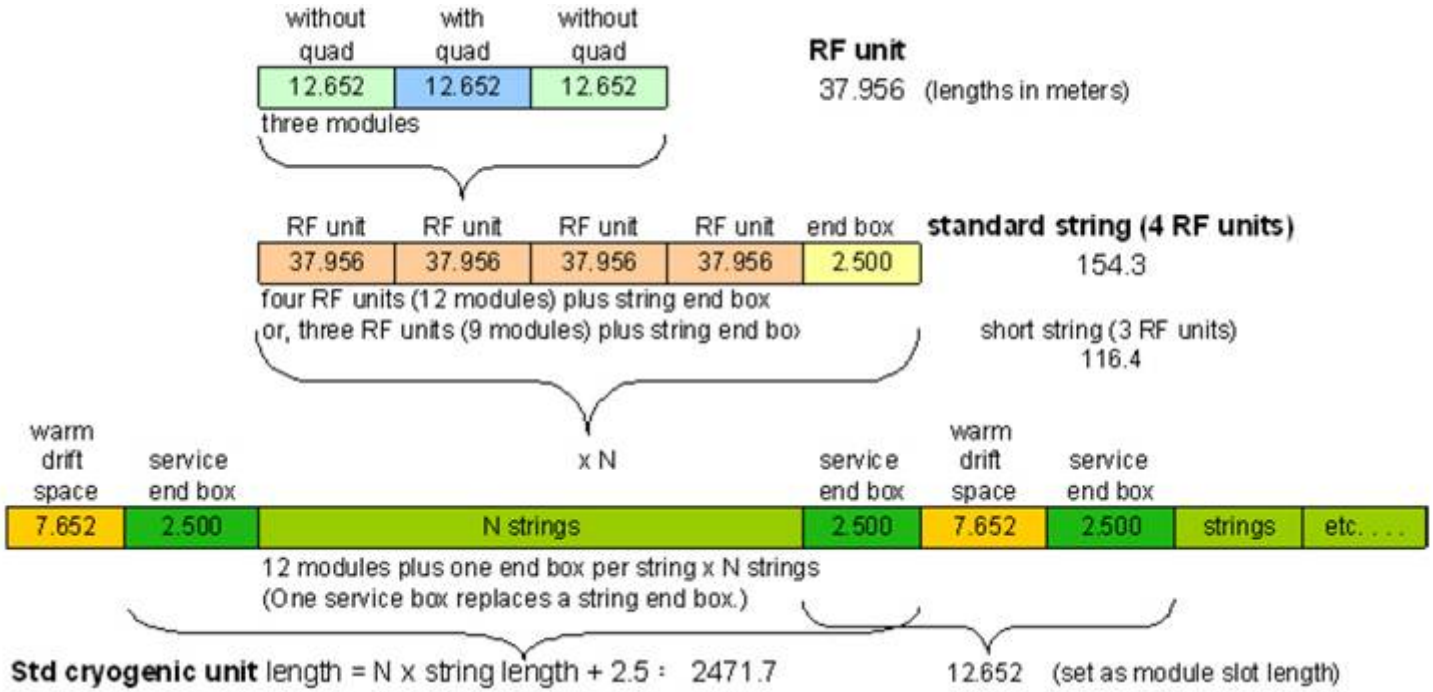
(V. Katalev, S. Choroba)

- Less parts, less space consuming
  - to be tested in FLASH ACC6 soon



Cryogenics System

- 1 cryogenic plant covers 2.5km linac length.
  - Installed power ~4.5MW
- Total 10 plants
  - ~45MW
  - comparable to LHC cryogenics system

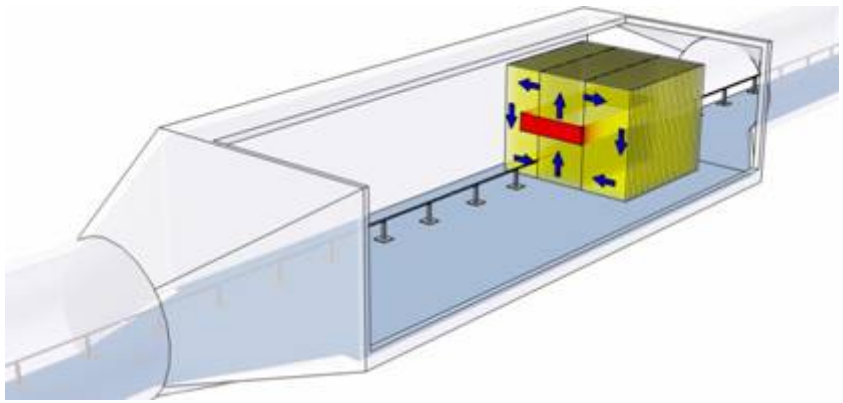


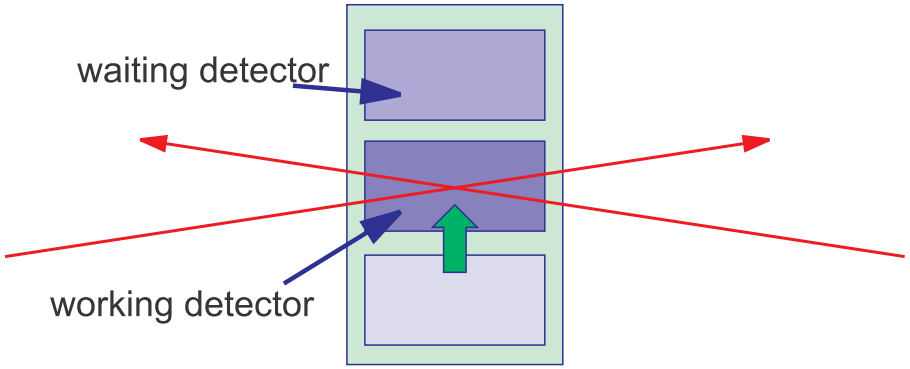
BDS (Beam Delivery System)

- From main linac exit to IP (Interaction Point) and to the beam dump
- Roles of BDS
  - Focus the beam to the desired spot size for collision
  - Remove beam-halo to minimize the background events
  - Protect the beamline and detectors against mis-steered beam
  - Diagnostics of the linac beam
  - Safely dump the spent beams

Cost Savings in BDS

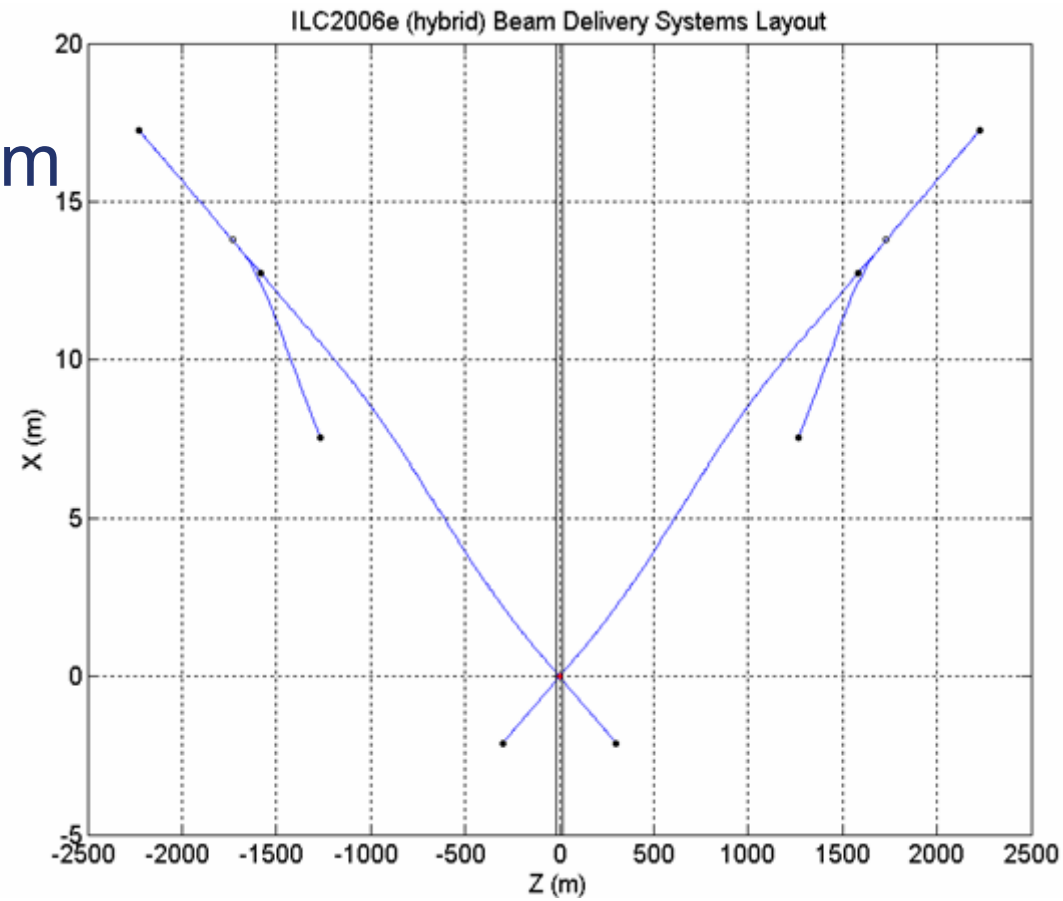
- 2IP with crossing angle 20 and 2mrad
  ➔ 2IP with crossing angle 14 and 14mrad
  (small angle scheme in the present design turned out to be significantly expensive)
  ➔ 1IP with crossing angle 14mrad
  with push-pull detector
- Remove 2nd muon wall





BDS (Beam Delivery System)

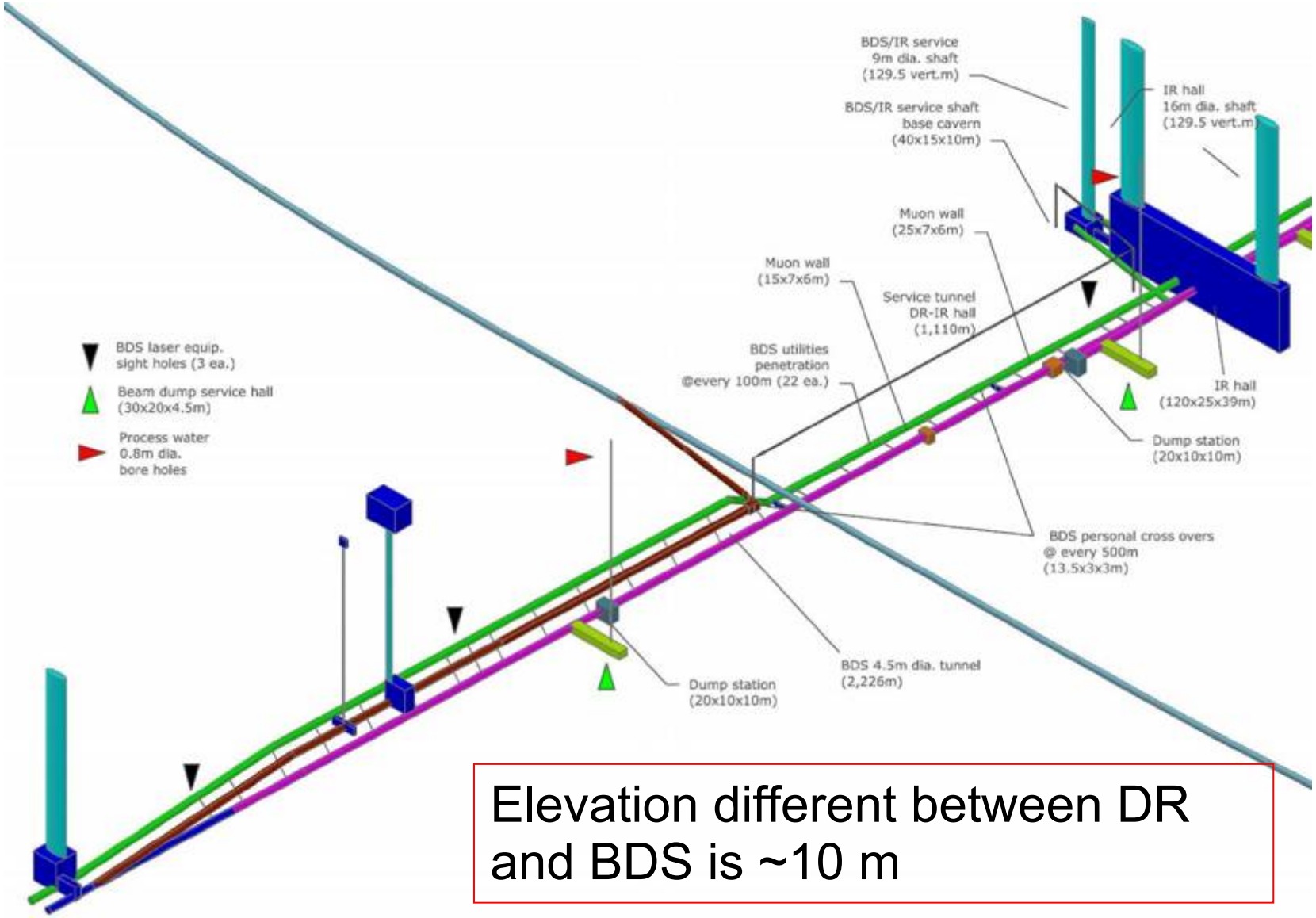
- Single IR and push-pull detector
- Total length 4.45 km
- 1 TeV upgrade by inserting some components (no geometry change)



Single IR with Push-Pull Detectors

- Large cost savings compared with 2 IR
  - ~200 M$ compared with 2IR with crossing angles 14 + 14 mrad
- Push-pull detectors
  - Task force from WWS and GDE formed
  - Conclusion is
    - No show-stoppers
    - But need careful design and R&D works
    - 2IR should be left as an `Alternative'

Layout of BDS+DR



Elevation different between DR and BDS is ~10 m

Value Estimate

- From Bangelore to Beijing
  - LCWS06 Bangalore, March 9 to13, 2006
    Value Estimate and Costing Rules
  - VLCW06 Vancouver, July 19 to 22, 2006
    First Cost Estimate
  - ILC06 Valencia, November 6 to 10, 2006
    Cost Reduction
  - BILCW07 Beijing, February 4 to 7, 2007
    Release of Draft Reference Design Report with Reliable Costs

Costing Rules

One common estimate of the "value" and labor including site dependent cost is made. The definition of the "value" is:

1. Cost estimate of the construction cost but no preparation cost.
2. Cost estimate on the basis of a world wide call for tender, i.e. the value of an item is the world market price if it exists.
3. The selection criterion is the best price for the best quality. value is world market price if exists
4. One vender supplies the total number of deliverables. Two vendors for the same package could be chosen for risk minimization. Then the parts depend on the bids.
5. If necessary parametric cost estimate is used for scaling of the cost, i.e. for cost improvement. The cost improvement is defined by the following equation:

   $P = P_1 N^a$ $P = P_1 N^a$, where P is the total price of N units

   where P is the total price of N units, P_1 is the first unit price and a the slope of the curve related to learning. The slope a is for large N also the ratio of the last unit price PN and the average unit price $<P>$.
6. No tax is included.
7. No escalation is used. The fixed date is January 2, 2007.
8. No contingency is calculated. The risk will be analyzed separately.
9. One currency with fixed exchange rates is used. The fixed exchange rates are:

   1 M€ = 1.2 M$ = 1.4 Oku¥. 1 M€ = 1.2 M$ = 1.4 Oku¥

10. Fixed raw material prices, i.e. for copper, steel and niobium, and fixed prices for power are used. The fixed prices are:
    Electrical work C/W = $ 0.1/kWh (incl. supply cost),
    Copper C/m = $ 1000/100 kg (up to factor three higher for degassed copper),
    Black steel C/m = $ 0.6 /kg (for stainless and magnet steel up to factor three higher).
11. The external labor is included in the value.
12. Internal (institute) labor will be estimated in person hours (1 person year = 1700 person hours).
13. The EDIA[1] is included in the item cost.

[1] In the U.S. EDIA is the acronym for Engineering, Design, Inspection and Administration. Industry calls this non-recurring engineering (NRE).

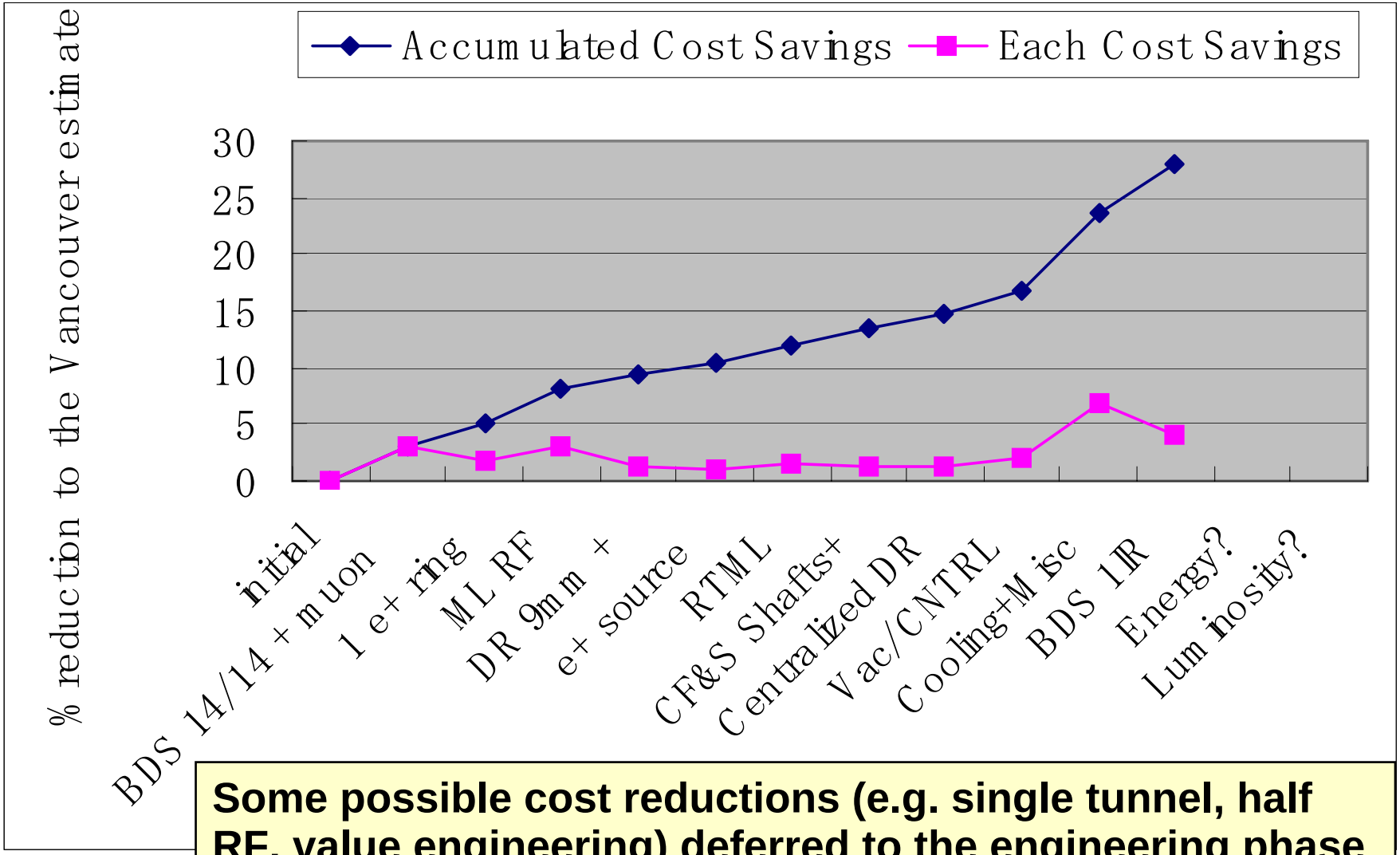
RDR Costing Guidelines March 11, 2006

High technology: Items such as cavities, cryomodules, and rf power sources, where there will be interest in developing expertise in all three regions, should be estimated separately for manufacture by each region. Costs should be provided for the total number of components …

System description	July 18, 2006 - Cost Estimates received for								Regional		
	common	e-	e+	DR	RTML	ML	BDS	Exp	Am	Asia	Eur
e- Source		√									
e+ Source			√								
DR				√							
RTML					√						
Main Linac											
BDS							√				
Com, Op, Reliab											
Control System	√	√	√	√	√	√	√				
Cryogenics		√	√	√ *	√	√	√ *				
Convent. Facilities	√	√	√	√	√	√	√ *	√	√	√	√
Installation	√	√	√	√	√	√	√				
Instrumentation	√	√	√	√	√	√	√				
Cavities				√					√		√
Cryomodules		√	√		√	√			√	√	√
RF	√	√	√	√	√	√			√	√	√
Magnets & PS				√ *			√ *				
Dumps & Collim		√	√	√	√		√				
Vacuum		√	√	√	√	√	√				
Accel Phys											

- First almost complete cost estimate
- Cost just too high!

√ = complete, √ * = almost complete, missing something minor



Some possible cost reductions (e.g. single tunnel, half RF, value engineering) deferred to the engineering phase

Scale of International Linear Collider

16,088 SC Cavities: 9 cell, 1.3 GHz

1848 CryoModules: 2/3 containing 9 cavities,
1/3 with 8 cavities + Quad/Correctors/BPM

613 RF Units: 10 MW klystron, modulator, RF distribution

72.5 km tunnels ~ 100-150 meters underground

13 major shafts $\geq$ 9 meter diameter

443 k cu. m. underground excavation: caverns, alcoves, halls

10 Cryogenic plants, 20 KW @ 4.5^{o} K each
plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)

92 surface "buildings", 52.7 K sq. meters = 567 K sq-ft total

240 M Watts connected power, 345 MW installed capacity

13,200 magnets – 18 % superconducting

Total ILC Value and Explicit Manpower

- Total ILC Value Cost **ILCU* 6.62 B**

ILCU 4.79 B shared + **ILCU 1.83 B** <site specific>#

plus 14.2 k person-years **Explicit Manpower**

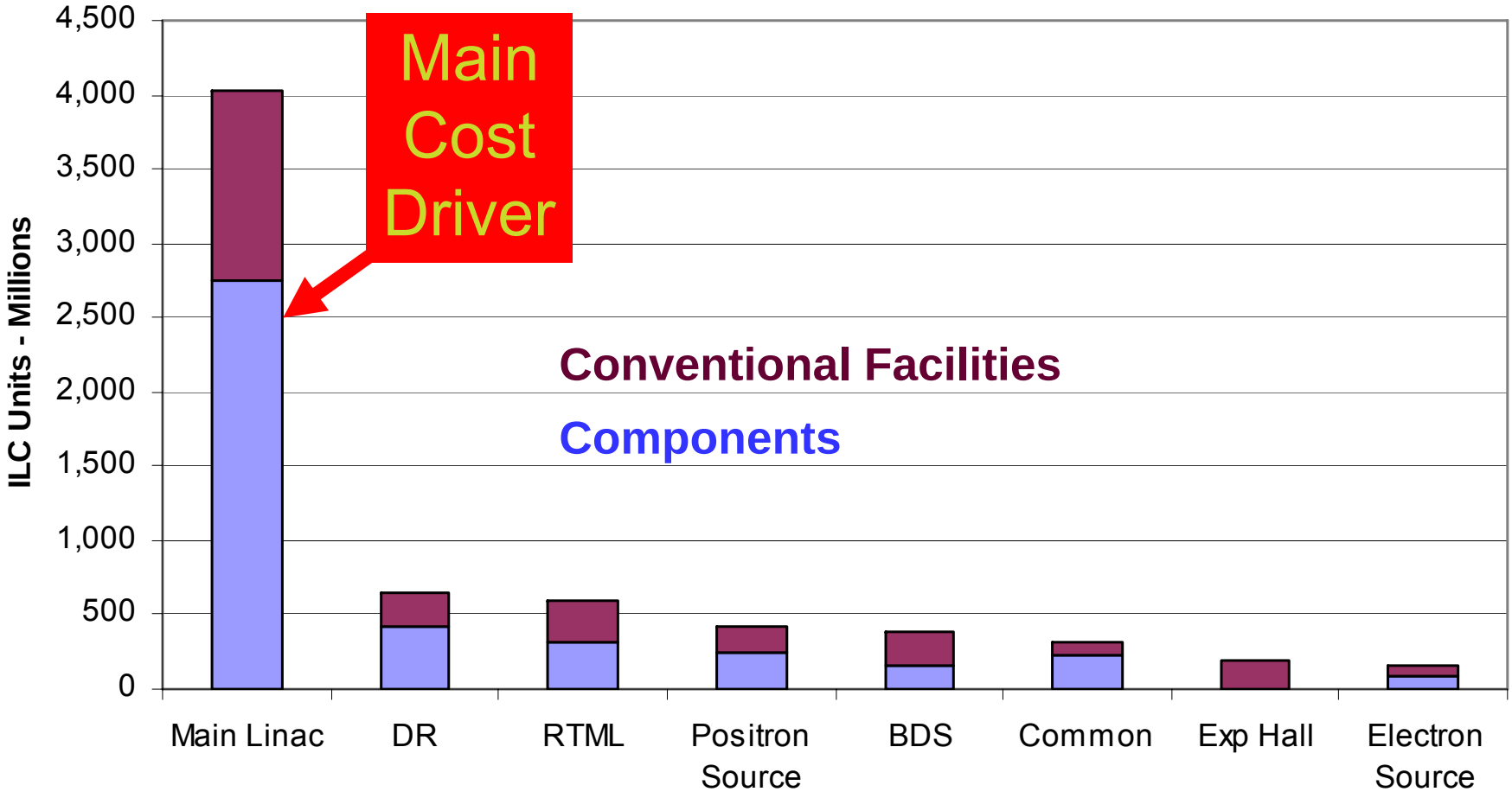
= 24.2 M person-hours

@ 1,700 person-hr/person-yr

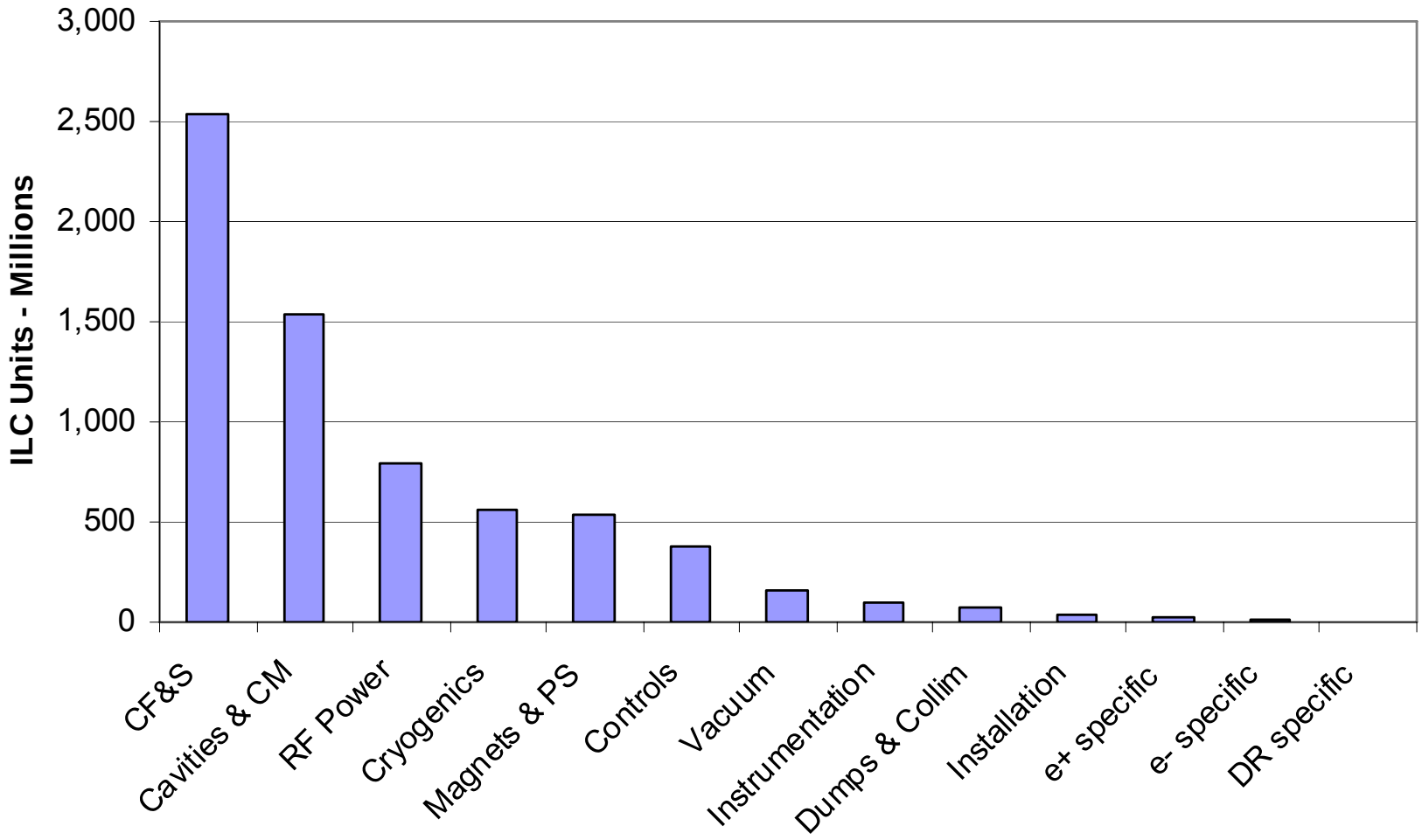
*ILCU(nit) = $ (January 2, 2007)

#<site specific> = average of the three site specific costs

ILC Value – by Area Systems



ILC Value – by Technical Systems

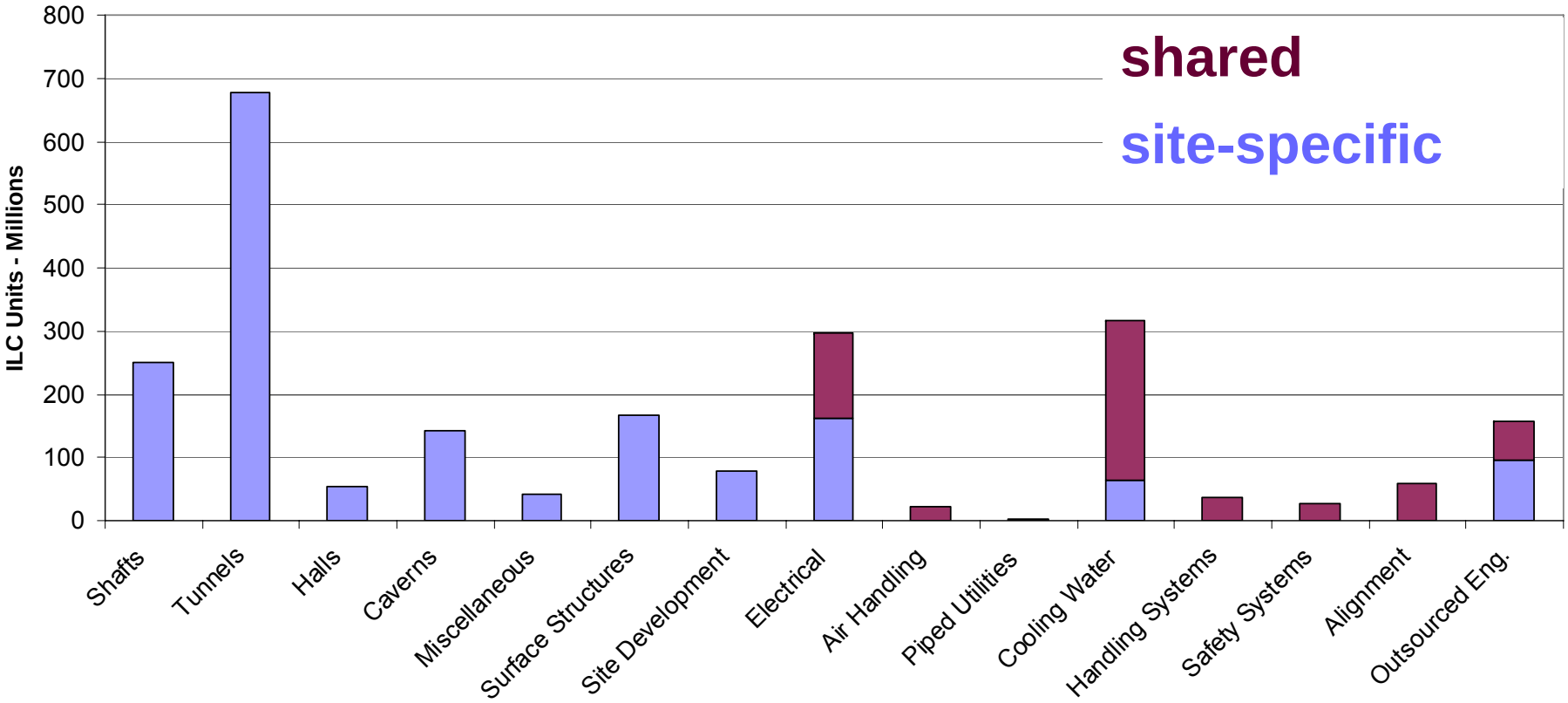


Conventional Facilities

ILCU(nit) = $ (January 2, 2007)

	total	civil only
Asia	ILCU 2.25 B	1.38 B
Americas	ILCU 2.54 B	1.65 B
Europe	ILCU 2.49 B	1.61 B

Conventional Facilities



ILC Cost Reviews

- Internal Review of the Cryomodule cost
- Internal Cost Review at SLAC with the participation of an External Review Panel on December 14 to 16, 2006
  - *"Methodology is an appropriate basis" for ILC costing*
- Machine Advisory Committee Review at Daresbury on January 10 to 12, 2007
  - *"… performance driven baseline configuration was successfully converted into a cost conscious design."*
- DOE Briefing on January 17, 2007
- FALC Meeting at London on January 22, 2007
- International Cost Review at Orsay on May 23 to 25

Comparison between TESLA and ILC Cost

Scale of ILC and TESLA

16,088 SC Cavities: 9 cell, 1.3 GHz (TESLA: ~36/26)

1848 CryoModules: 2/3 containing 9 cavities,
1/3 with 8 cavities + Quad/Correctors/BPM

613 RF Units: 10 MW klystron, modulator, RF distribution

ML: 562 RF Units (15 to 250 GeV); TESLA 572 (5 to 250 GeV)

72.5 km tunnels ~ 100-150 meters underground (TESLA 37 km)

13 major shafts $\geq$ 9 meter diameter (TESLA 19 shafts)

443 K cu. m. underground excavation: caverns, alcoves, halls

10 Cryogenic plants, 20 KW @ 4.5^{o} K each (TESLA 12 x 15 kW)
plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)

92 surface "buildings", 52.7 k sq. meters (TESLA ~30 k m^2)

240 MW connected power, 345 MW installed capacity (145/180)

13,200 magnets – 18% superconducting

Comparison between TESLA & ILC

	TESLA TDR / M€	Scaled TESLA TDR / M$	ILC RDR / M$	Difference / M$
Total Cost	**3136**	**5018**	**~6500**	**~1500**
Civil Facilities	676	1082	2437	1355
Underground Buildings		100 %	175 %	
Surface Buildings		100 %	240 %	
Consultant Engineering		100 %	1000 %	
Power Distribution		100 %	510 %	
Water Cooling		100 %	333 %	
Cryogenic System	162	260	567	307
Cryo Plant*		12 x 100 %	10 x 200 %	

*TESLA: 12 x 2.2 kW @ 2 K

ILC: 10 x 3.5 kW @ 2 K

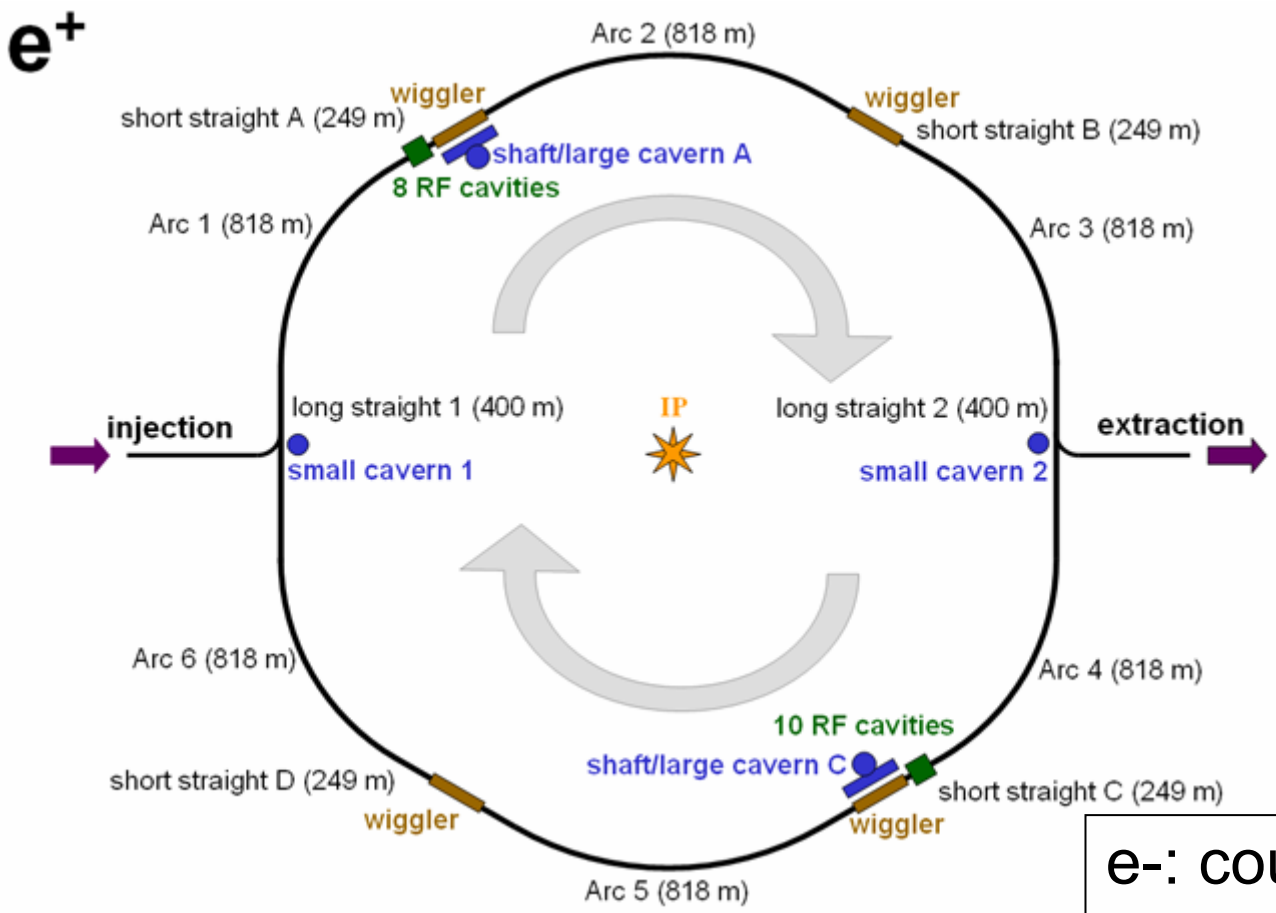
XFEL: 2.45 kW @ 2 K; 34.35 M€ for Cryogenic System

Summary and Outlook

- RDR Draft published in February 2007
  - Consistent design, though details are still lacking
  - Significant cost savings since the original version of BCD (Dec 2005)
  - Physics scope not reduced (energy, luminosity)
  - Risk assessments underway
- Final RDR to be published soon
- R&D and engineering design issues still remain
  - The next document will contain much more technical detail: Engineering Design Report due 2010
  - Currently work packages for R&D and Engineering are being set up
    - Move toward a 'real' project structure
  - Several of the baseline choices are being tested at the XFEL
    - E.g. klystrons, modulators, LLRF, RF couplers, cavity shape etc.
- The XFEL is a very important stepping stone towards the ILC!

Backup Slides

Schematic Layout



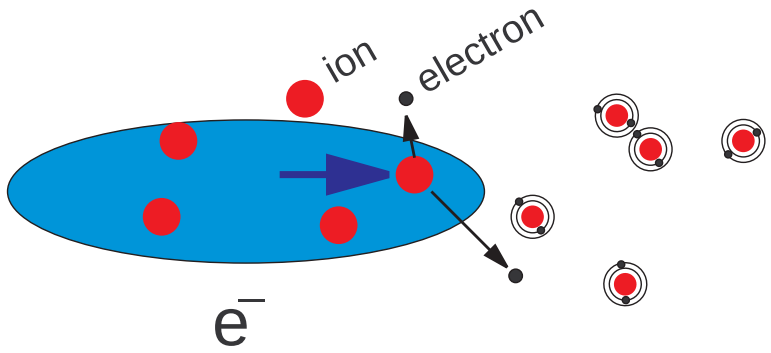
e-: counter-clockwise

2 vertical shafts

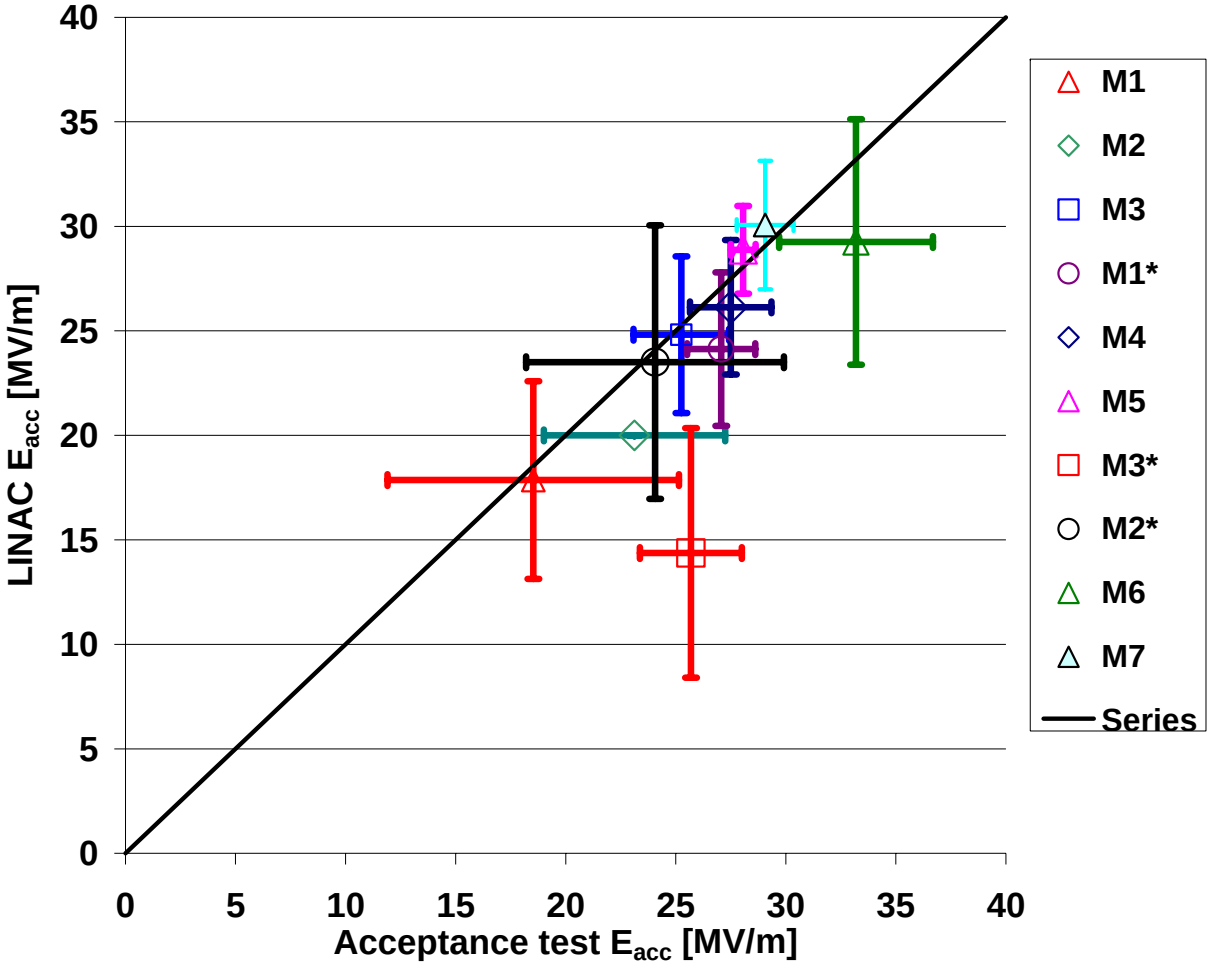
Andy Wolski

Fast Ion Instability

- (Non trapped) Ions created from ionization by electrons are attracted by electrons and cause instability
- Cures
  - Low vacuum pressure ~1 nTorr
  - Bunch-by-bunch feedback system
  - Gaps between bunch trains

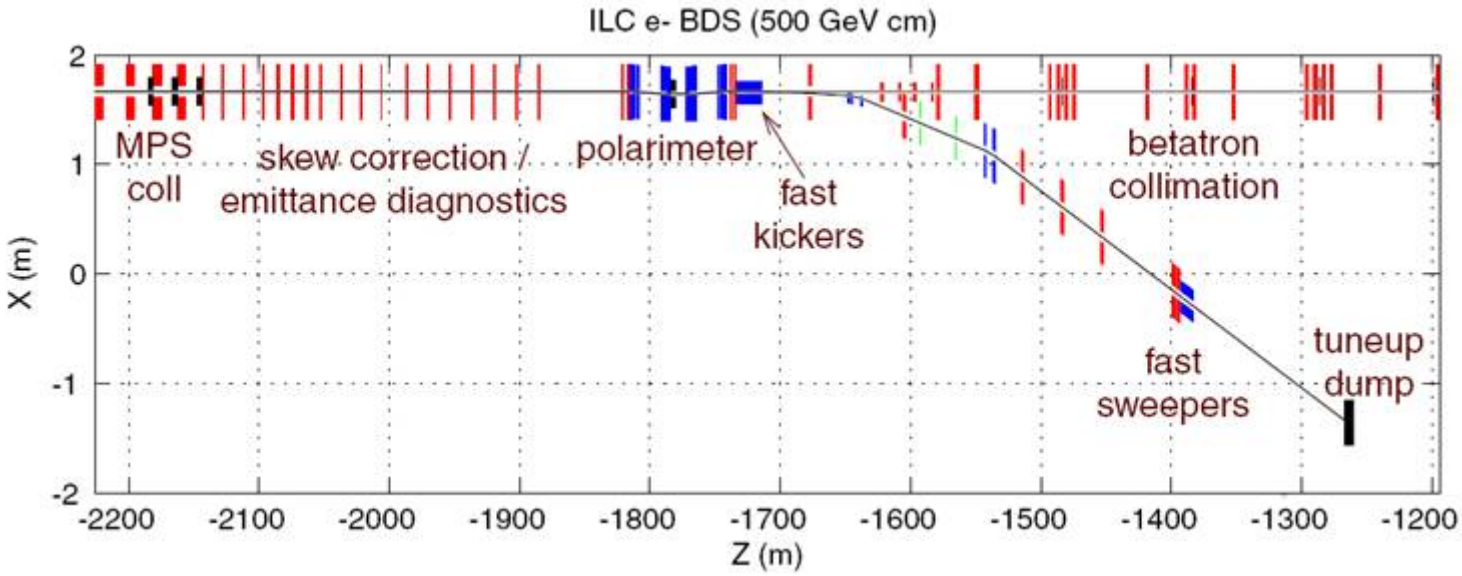


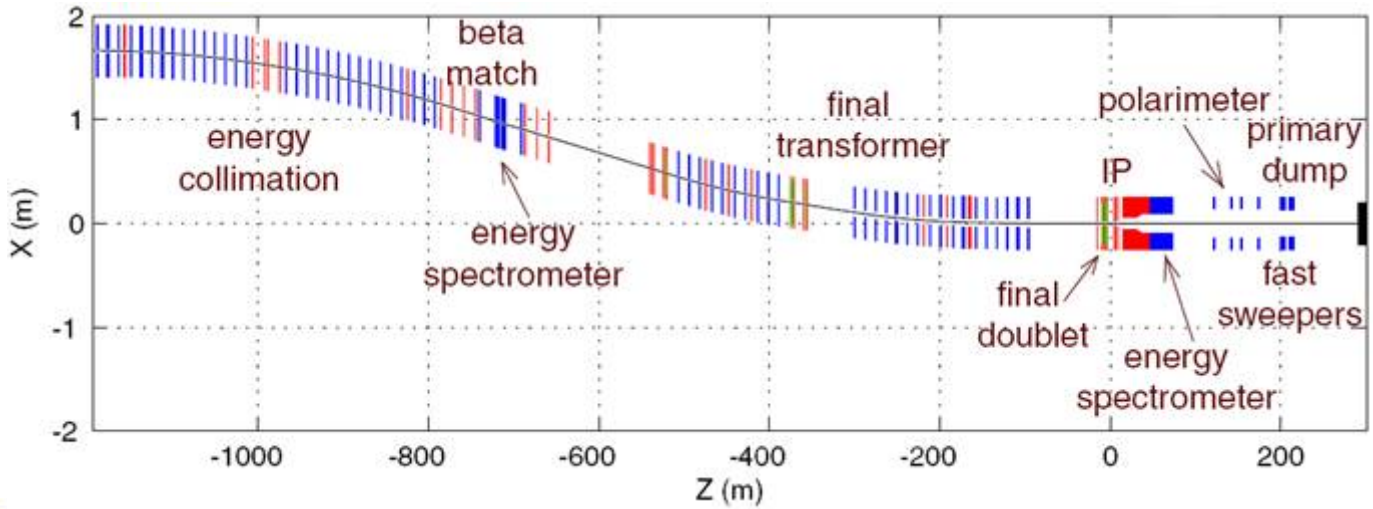
S1 RF Performance: LINAC vs. Vertical (Cavity Average Gradients)



- Several Modules met expectations
  - E.g. M4, M5, M7
- M6 did not
  - 2 cavities degraded
  - Large spread in gradients in acceptance test due to time pressure for installation into FLASH
- M3* is a very special case
  - Coupler disassembly wrong
  - Repair with non-standard treatment and no acceptance test on 4 out of 5 'repaired' cavities
  - Time Pressure: Module needed for installation

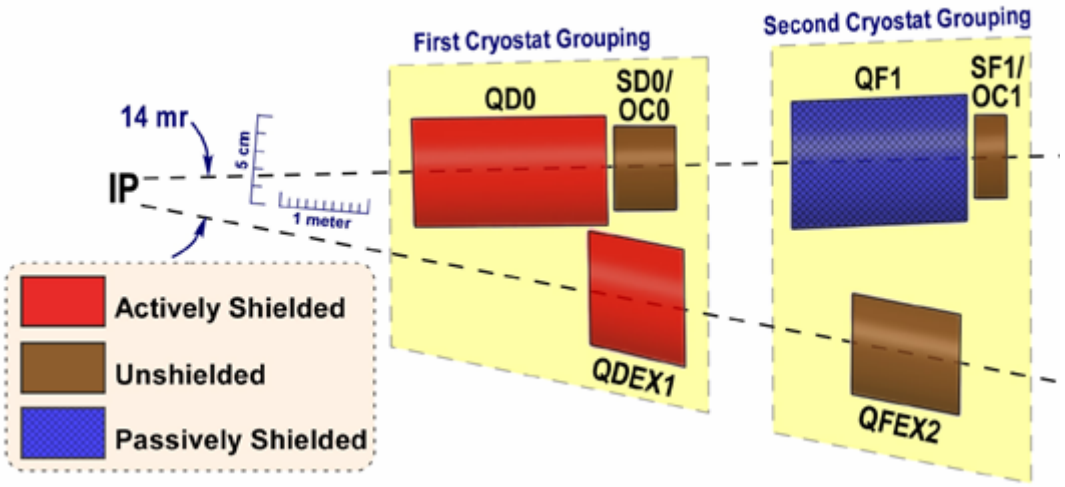
BDS Layout

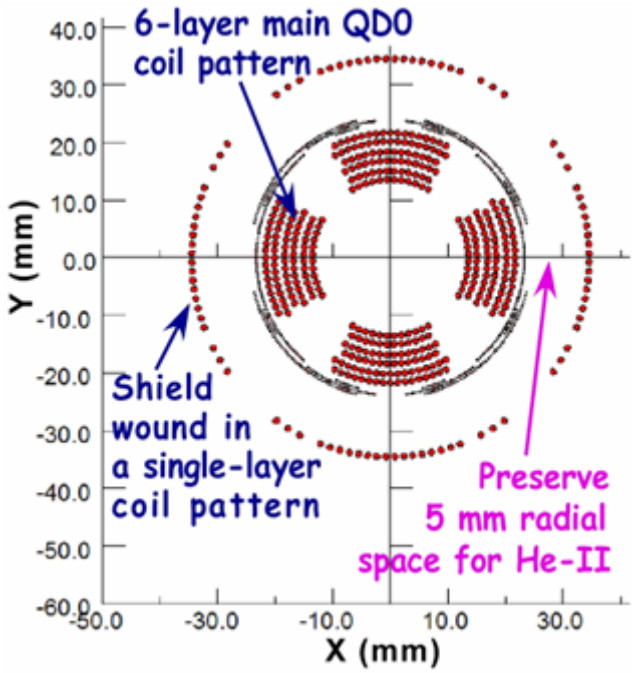

ILC e- BDS (500 GeV cm)
MPS
coll
skew correction /
emittance diagnostics
polarimeter
fast
kickers
betatron
collimation
fast
sweepers
tuneup
dump
X (m)
Z (m)


beta
match
energy
collimation
energy
spectrometer
final
transformer
polarimeter
primary
dump
IP
final
doublet
fast
sweepers
energy
spectrometer
X (m)
Z (m)

Interaction Region

- Crossing angle 14mrad
- Final quadrupole magnets
  - Superconducting (QD0 in detector magnetic field)
  - Out-going beam goes outside





Crab Crossing

- Large crossing angle 14mrad
- Need to deflect head and tail oppositely
- Crab cavity
  - 3.9 GHz SC
  - phase tolerance ~60 fs
  - prototype fabricated