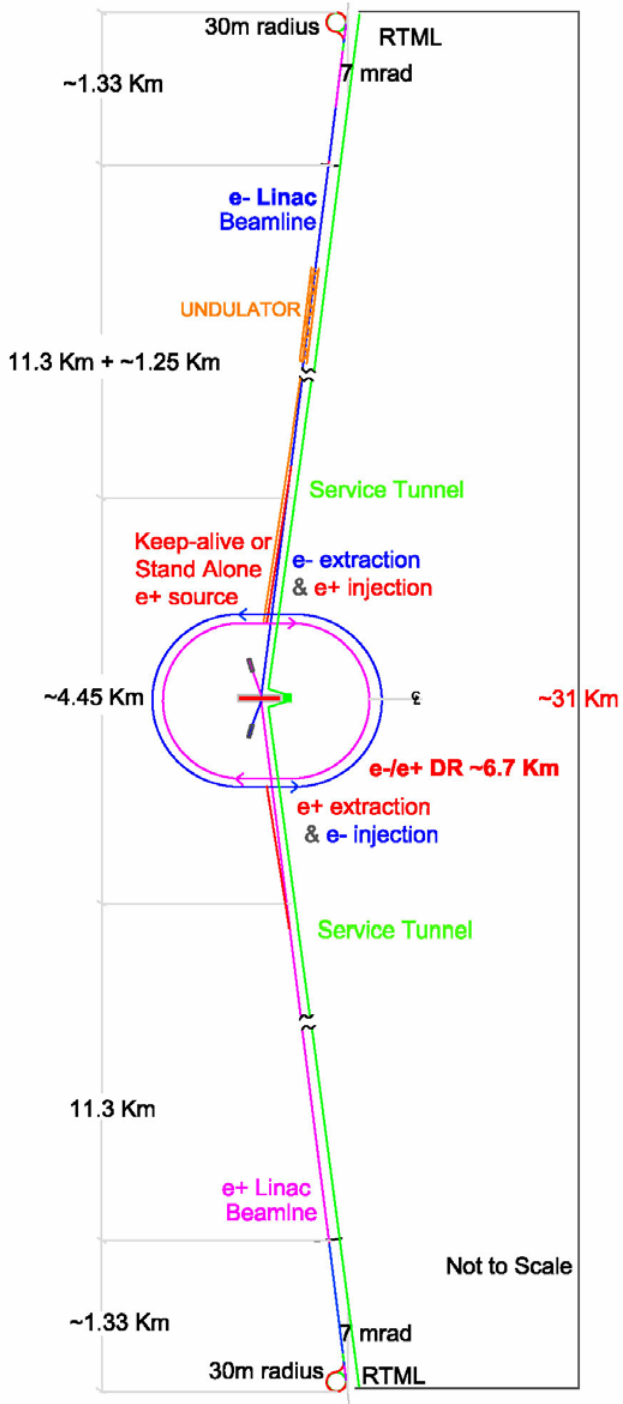
The Reference Design Report and cost estimate for the International Linear Collider

Marc Ross, Fermilab

Jan 31, 2007



Introduction

- **ICFA statement (based on input from the community):**
  - **the highest priority for a new machine for particle physics is a linear electron-positron collider with an initial energy of 500 GeV, extendible up to about 1 TeV, with a significant period of concurrent running with the LHC.**
- **This is the International Linear Collider.**

Physics:

- a continuous center-of-mass energy range between 200 and 500 GeV
- a peak luminosity of 2e34 and availability (75%) consistent with 500 fb-1 in the first four years
- > 80% electron polarization at the IP
- energy stability and precision < 0.1%
- option for 60% positron polarization
- options for e- e- and γγ collisions

Machine:

• beam current	9 mA
• pulse rate	5 Hz
• pulse length	1 ms
• number of bunches/pulse	1000 – 5400
• charge / bunch	1.6 – 3.2 nC
• accelerating gradient	31.5 MeV
• RF pulse length	1.6 ms
• beam power (2 ea)	10.8 MW
• typ beam size	640 x 5.7 nm
• AC power consumption	230 MW

Superconducting RF

- **Luminosity requires beam power;**
  - **Superconducting RF is the *most effective* way to create high power beams**
- **Proven design:**
  - **1.3 GHz niobium sheet metal cavities**
  - **ILC - each cavity delivers 285 KW to 9mA beam (nom)**
  - **ILC - fill time 38% total pulse**
  - **ILC - linac efficiency (RF to beam): 50%**
    - **Fill time, distribution and feedback overhead**
- **Large irises → minimal emittance growth with achievable tolerances**
  - **a manageable system**
  - **If we can achieve tighter assembly/tuning tolerances, can improve efficiency**

ILC Reference Design Report

- **Global effort – without a central lab providing coordination – has produced:**
  - **Baseline Configuration (2005)**
    - **Collection of basic design decisions**
  - **Reference Design and 'value' Cost estimate**
    - **International team-work "in action"**
- **The documents describe a design and associated strategy**
  - **The RDR will be used to prioritize R and D and engineering effort in order to have a** 'plan ready to submit for approval' **as soon as practical (3 years from now)**
    - **Plan is called 'Engineering Design Report'**
- **Completion of RDR in 2007 is a major milestone for the ILC Project Global Effort**

Staff and magic of the task

- Who did this?
- ILC has 6 'areas' –
  - sources, damping rings, compressors, SC linac, beam delivery
- Divided into 8 + 3 Technical + Global functional 'systems'
  - These are typical for such large accelerators
- Each row and each column is headed by 3 (min), one from each of 3 regions (EU, Americas, Asia)
  - Unprecedented degree of direct international involvement
- Rolled up through 'areas'
  - To facilitate performance tradeoff perspective
- Coordinated by management teams – each also internationally balanced
  - RDR management (Walker) + Cost engineer team
  - Executive (Barish)
  - Change Control Board (Toge)
  - Design / Cost Board (Garbincius)

Institutional participation: Northeast Illinois

- **Fermilab / Argonne direct role in RDR:**
  - Linac Area Leader: Nikolay Solyak
  - Controls Global: John Carwardine (ANL)
  - Conventional Facilities Global: Vic Kuchler
  - Cryogenics Global: Tom Peterson
  - Magnet Systems: John Tompkins
  - Vacuum Systems: John Noonan (ANL)
  - Instrumentation Systems: Marc Ross / Manfred Wendt
  - Cryomodule Systems: Harry Carter
- **Board representation:**
  - Design Cost Board: Peter Garbincius, Bob Kephart
  - Change Control Board: C. Shekar Mishra
  - R and D Board: Marc Ross

Snowmass 2005 decisions:

- These had substantial cost impact:
  - Performance parameter plane(s)
  - Civil layout
    - 1 tunnel or 2?
  - Gradient / cavity shape
    - TESLA shape or ?
  - Linac power technology
    - Klystron / modulator
  - Damping ring strategy
    - 2 rings or 3? / shape?
  - Beam delivery angles & layout
    - 2 / 20 mrad
  - Positron source
    - Undulator gamma-ray / Compton
    - location

What the RDR is:

- Comprehensive, conservative (with a few exceptions), coherent, constructable, costable Collider design
  - With a preliminary ‘value’ cost estimate
- Alternatives included:
  - e.g. cavity shape and metallic crystalline structure

What it is not

- Technically mature (Barish quote)
  - technical subsystem designs – for the most part quite conservative – are not ready
- Risk – assessed
  - most pressing item: quantitative assessment of risk
    - technical, (for example electron cloud, beam delivery)
    - component (cost), (for example cryomodule fab)
    - schedule (not yet)
  - in process for delivery summer 07
- DoE process – integrated
- A plan

Confidentiality issue

- Detailed cost compilations are not included!
- Cost driver:
  - SC RF high technology equipment does not have an established market cost
    - is under active industrial development – in all regions
    - magnets do
  - don't want to give the RDR a strong 'gain' term in the DESY XFEL project cost, for example.
  - (more later)
- How can this work be checked???
  - Parametric comparisons
  - International Cost review
    - extension of the DOE/SC 'Lehman' process
    - before summer 2007

Separation of RDR and RD

- Configuration control applied for RDR allows communication and common starting points
  - real success of the process
- RD is encouraged, but updates during RDR work were limited (in part) by CCB
  - This presentation will cover some 'update-needed' items; i.e. the challenges/weak points…
- It takes time to coordinate RD ($,¥,€) activities
  - establishment of a coherent inter-regional RD process is critical
  - RDR did not require this investment
- Now, we do.

next step: connection

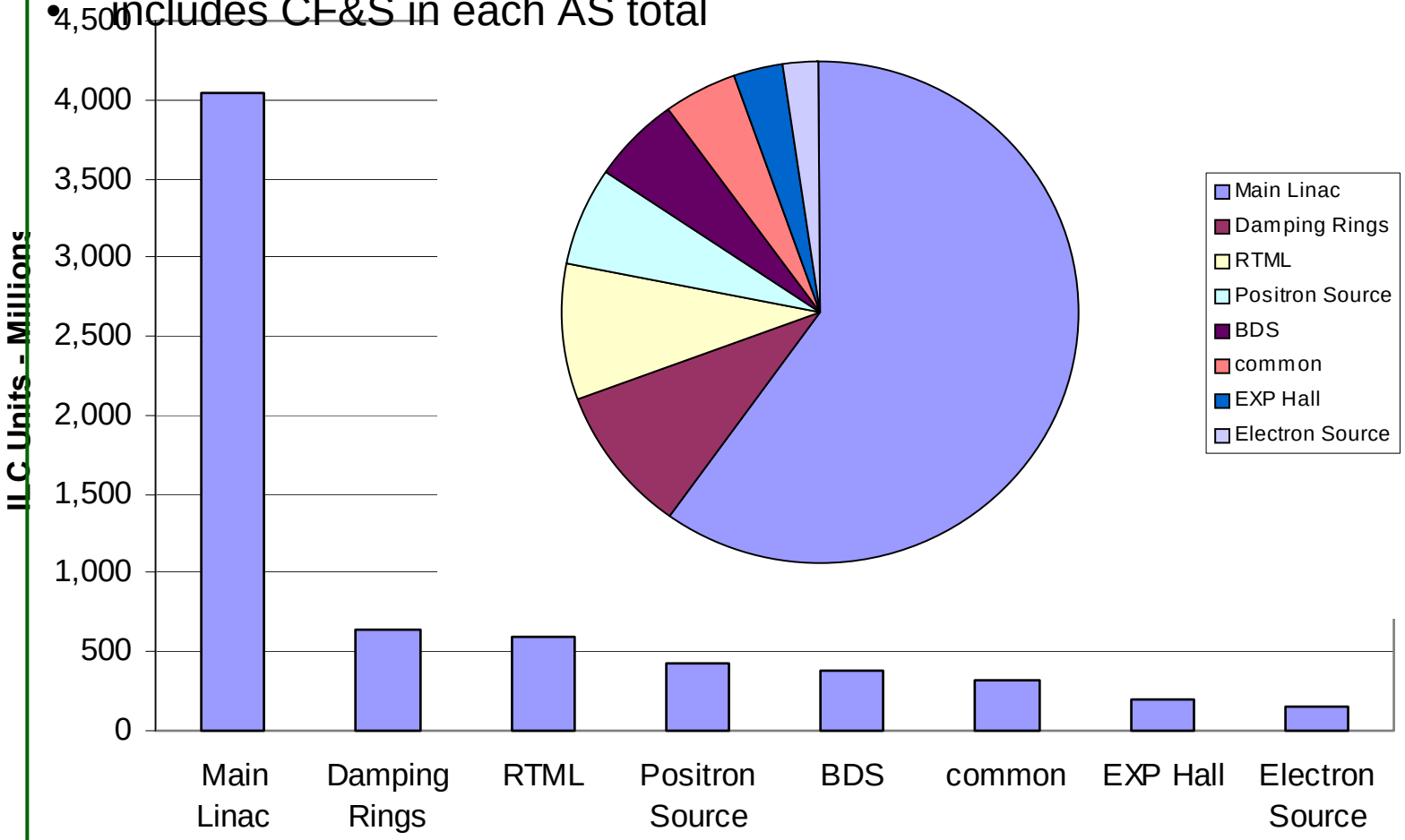
- EDR is the tool to achieve approval
  - we need to produce it as quickly and as cost-effectively as possible!
- Much (most?) development is of 'understood' technology
  - this is by design, and is one of the justifications used by the International Technology Recommendation Panel in August 2004
- Some challenges lie within RDR and must be mitigated during the EDR
  - Cost, cost, cost
  - Technical
  - Planning
  - International collaboration and Industrialization of critical components

Strategy for moving beyond RDR:

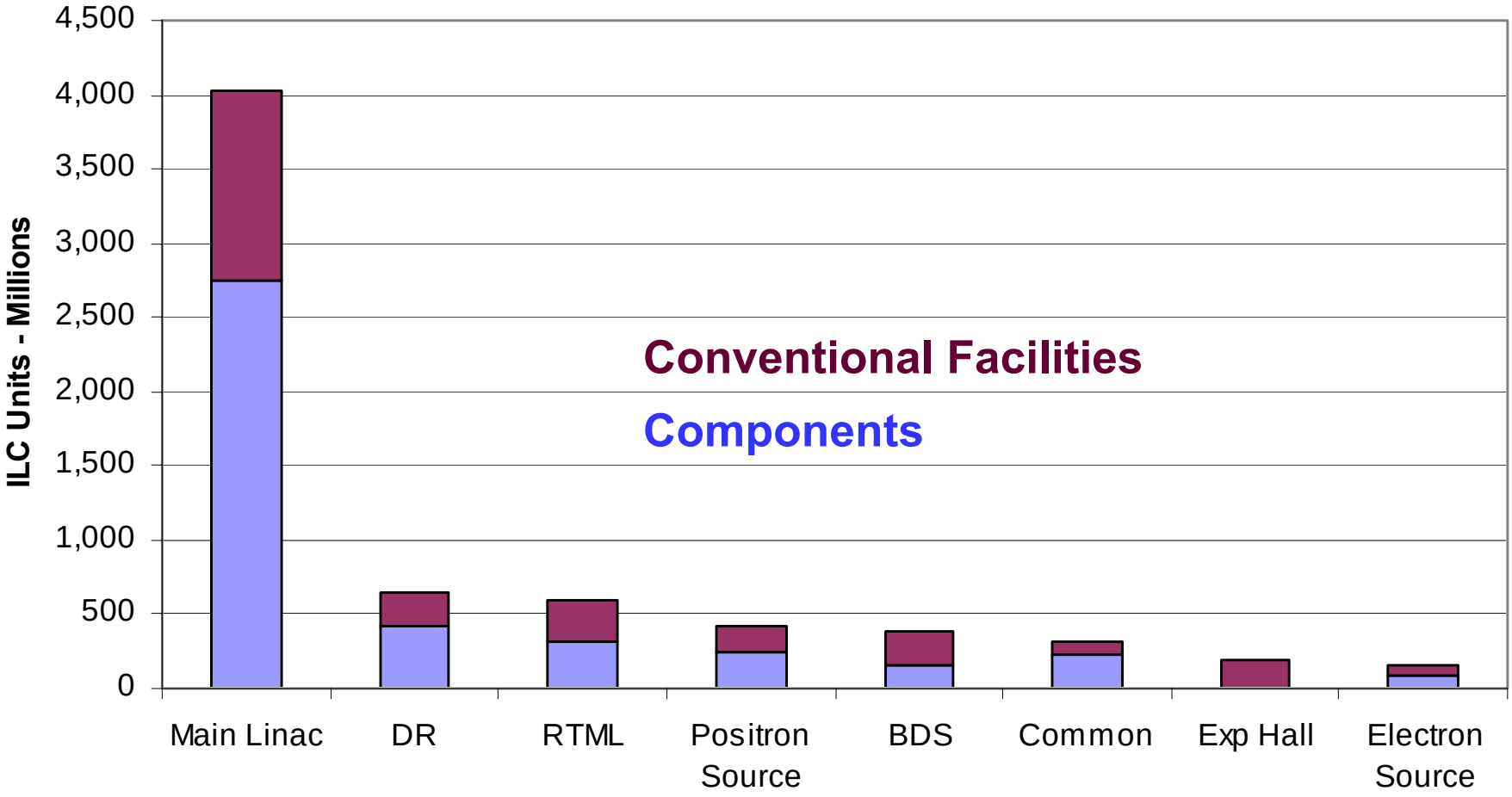
- Develop prioritization scheme based on risk mitigation
  - Engineering
  - RD
- Prioritization is actually straightforward
  - strategy
  - scheduling
  - funding
  - integrating (with related project efforts)
  - balancing (inter-regional)
- are not

ILC Value – by Area Systems

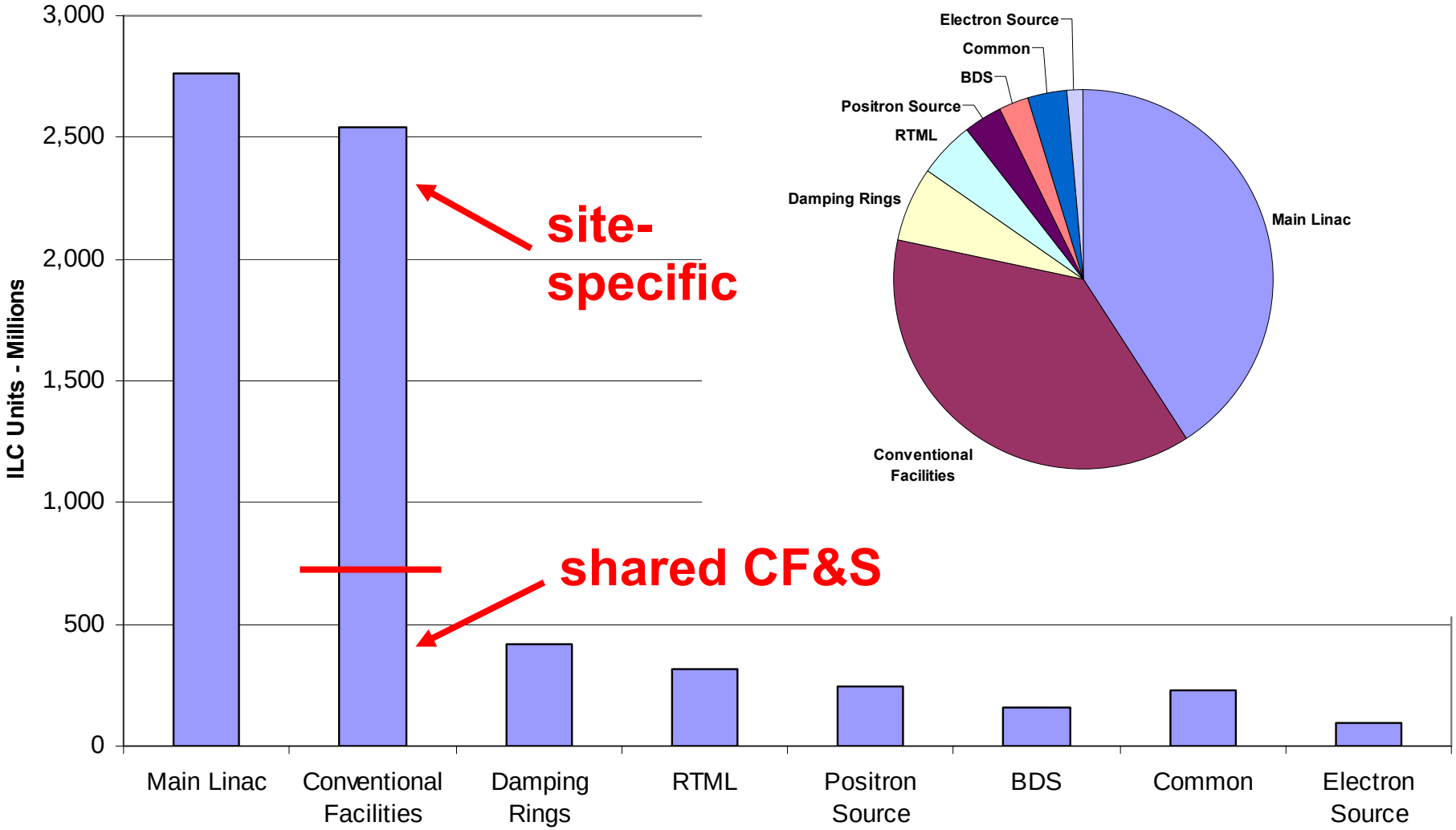
- includes CF&S in each AS total



ILC Value – by Area Systems



Value – CF&S + AS (non-CF&S)



Priorities for ILC

- (value estimate metrics:)
- Cost risk
  - Linac: 60%
    - main linac and its conventional
  - CFS: 38%
    - all conventional
  - Linac + CFS: 79%
    - main linac and all conventional
- Technical risk (e.g.):
  - SCRF "process"
  - damping ring, esp electron cloud instability
- Planning

cost of going to the energy frontier: beam power

- What are the issues?

RDR civil "footprint"

- 72.5 km tunnels ~ 100-150 meters underground
  - 93% overhead v/v actual tunnel needed for 'beam pipe'
  - Tevatron/MI? … ~0.
  - LEP/LHC ? 5%? PEP 5%
- 13 major shafts > 9 meter diameter
  - 1.6 km of large shafts
  - roughly ½ of LHC/LEP
- 443 K cu. m. underground excavation: caverns, alcoves, halls
  - 77 m cube
- 10 Cryogenic plants, 20 KW @ 4.5o K each
- plus smaller cryo plants for e-/e+ (1 each), DR (2), BDS (1)
- 92 surface "buildings" (for Americas' site), 52.7 K sq. meters
- 230 M Watts connected power, 345 MW installed capacity

Rdr power parameters / water

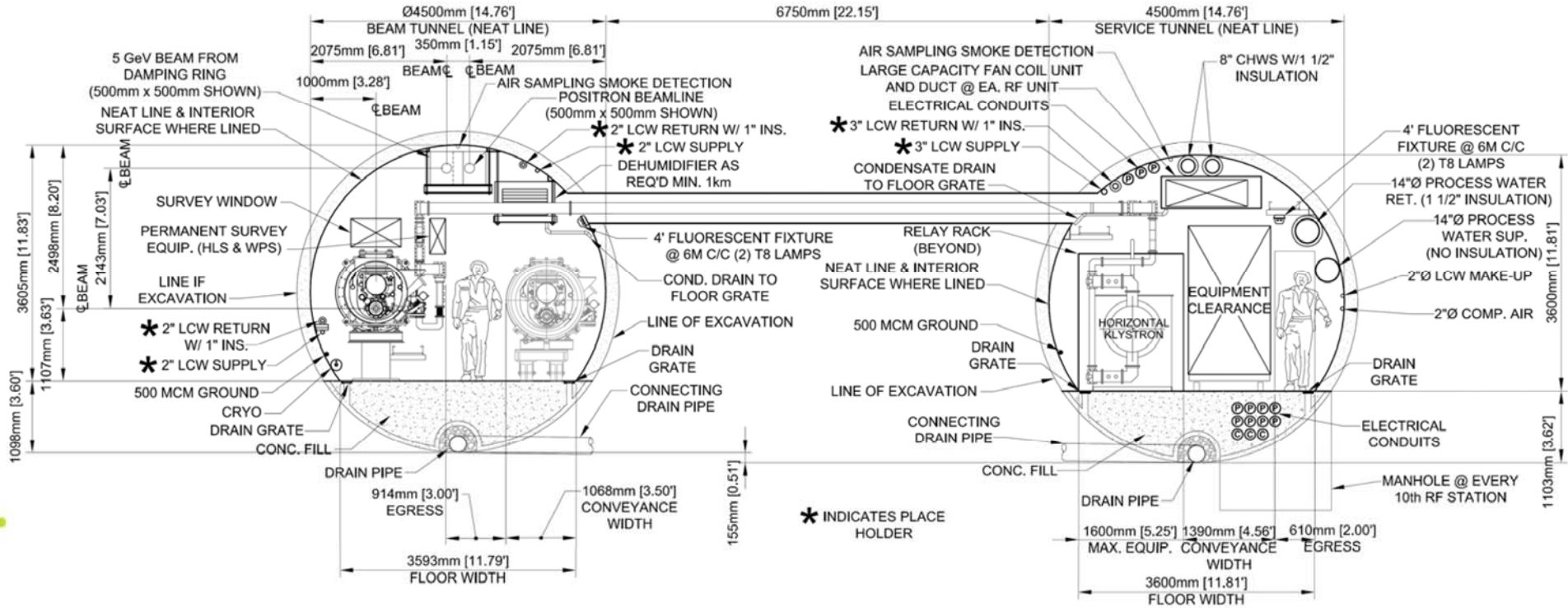
- power / water handling scheme is an indicator of design maturity
- Beam power at IP → 10.8 + 10.8 MW
  - 15 % efficient
  - 10% cooling overhead (100W to remove heat from 1 KW load)
- Good performance figures – but more to do
  - TESLA design (2001): ~ 80 MW lower for same luminosity

TABLE 4.3-1
Estimated Nominal Power Loads (MW) for 500 GeV Centre-of-Mass Operation

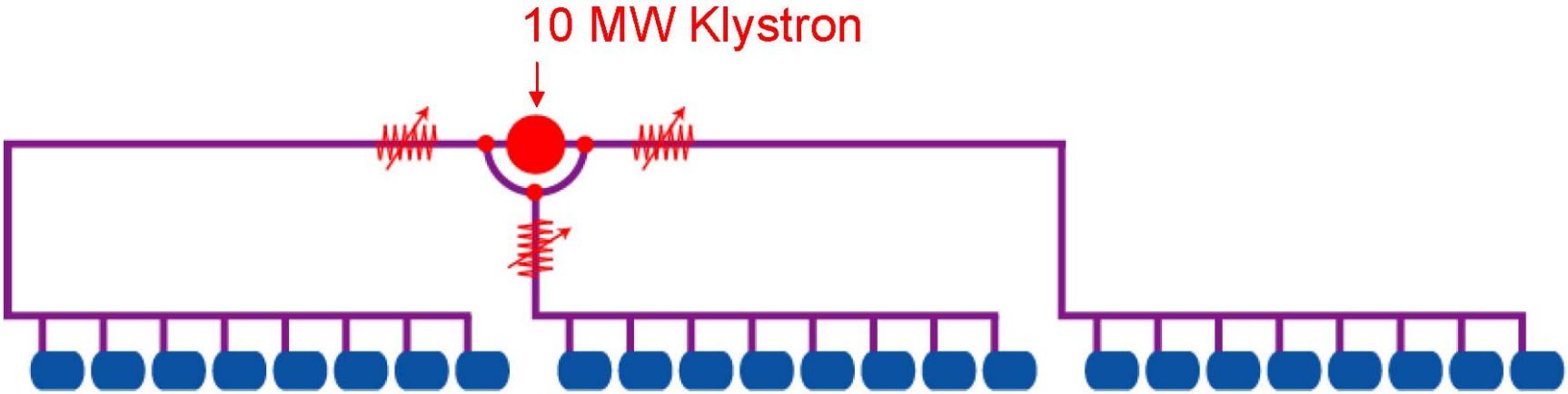
AREA SYSTEM	RF	CONV	NC MAGNETS	WATER SYSTEMS	CRYO	EMER	TOTAL (by area)
SOURCES e-	1.05	1.19	0.57	1.27	0.46	0.06	4.59
SOURCES e+	4.11	7.32	6.52	1.27	0.46	0.21	19.89
DR	14.0	1.71	6.78	0.66	1.76	0.23	25.15
RTML	7.14	3.78	2.84	1.34	0.0	0.15	15.24
MAIN LINAC	75.72	13.54	1.41	9.86	33.0	0.4	134.84
BDS	0.0	1.11	18.48	3.51	0.33	0.20	23.63
DUMPS	0.0	3.83	0.0	0.0	0.0	0.12	3.95
TOTAL (by system)	102.0	32.5	36.6	17.9	36.9	1.4	227.3

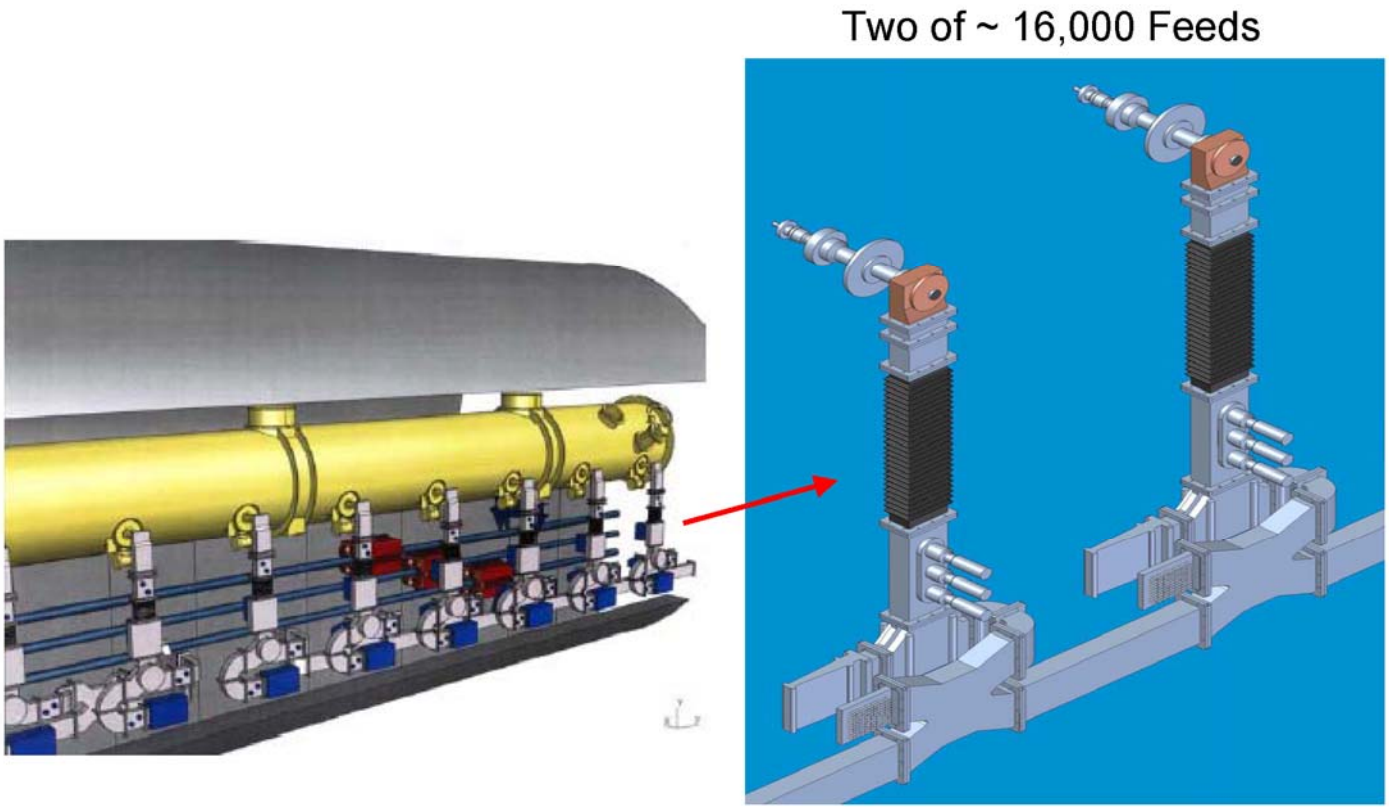
Main Linac Tunnels

- Design based on two 4.5m tunnels
  - Active components in service tunnel for access
  - Includes return lines for BC and sources
  - Sized to allow for passage during installation
  - Personnel cross-over every 500 meters



Tunnel function: RF power





Conventional Facilities

Regional Comparisons :

Quote 2007$ – Escalate 2006$ by 10.6% U.S (Turner); 2-3 % other regions

ASIA	TOTAL COST=	$2,247,562	CIVIL ONLY=	$1,377,765
AMERICA	TOTAL COST=	$2,540,439	CIVIL ONLY=	$1,648,052
EUROPE	TOTAL COST=	$2,493,066	CIVIL ONLY=	$1,608,407

Yen to US $	0.0085714
Euro to US $	1.2
Euro to Yen	140
US to Yen	116.7

S0 / S1 Task Force: Gradient

- (Led by ILC GDE R and D Board)
- Charge
  - *Provide the information needed for gradient choice*
  - Time scales: mid 08 / end 09.
    - Phased approach to match design / cost effort
  - S0 – cavity → gradient and yield in vertical test
    - Understand the achievable cavity gradient variation
  - S1 - cryomodule demonstration
- excellent cost / benefit
  - (?)
- How much more does the linac cost with lower, more variable-gradient cavities installed?

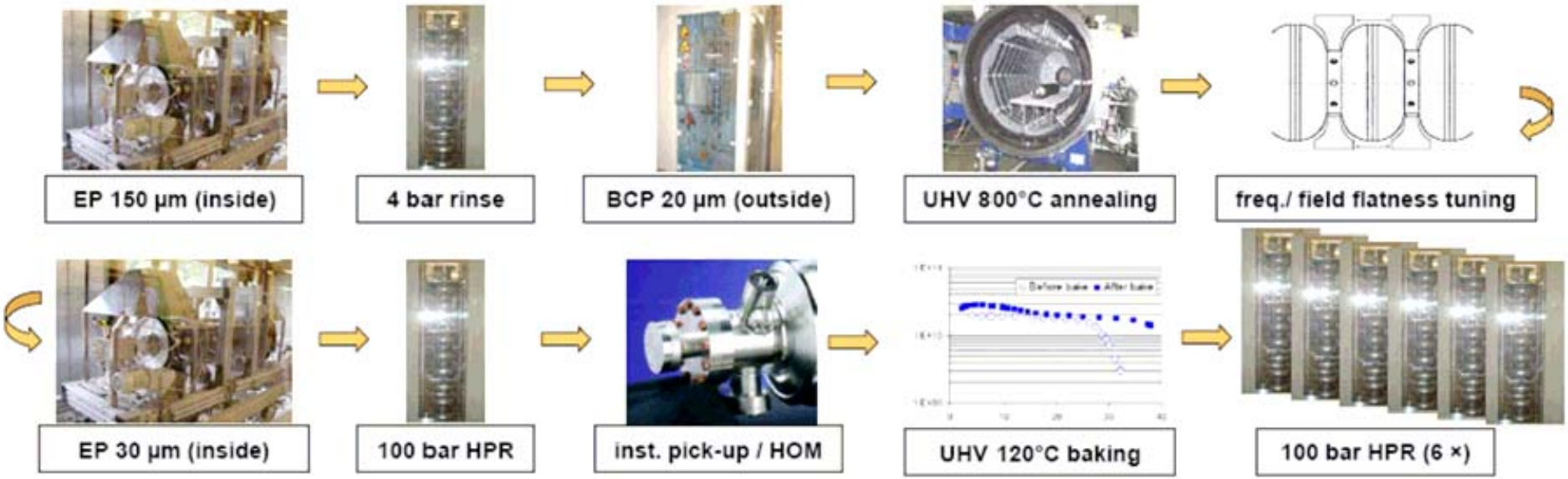
SCRF linac – basic building block

Figure 1.2-1: A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

- ~ 70 parts electron-beam welded at high vacuum
  - mostly stamped 3mm thick sheet metal
- pure niobium and niobium/titanium alloy
  - niobium cost similar to silver
- weight ~ 70 lbs
- 6 flanges

Finishing process

- **Chemical polishing, rinsing, clean room assembly**
- **Heat treatment (annealing**
- **mechanical tuning**

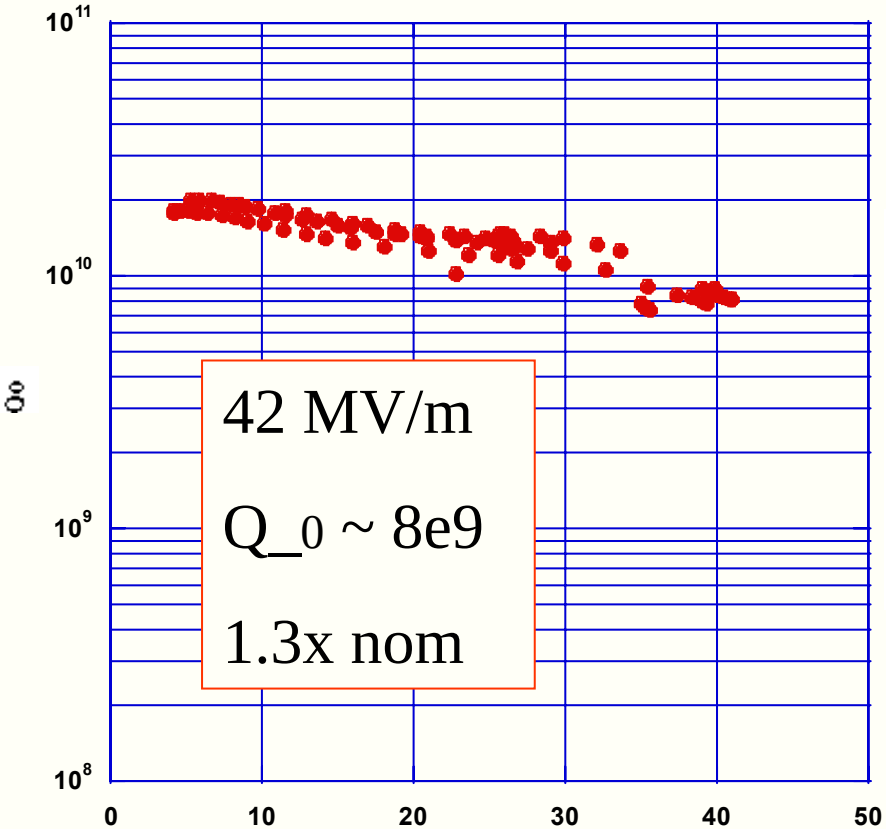


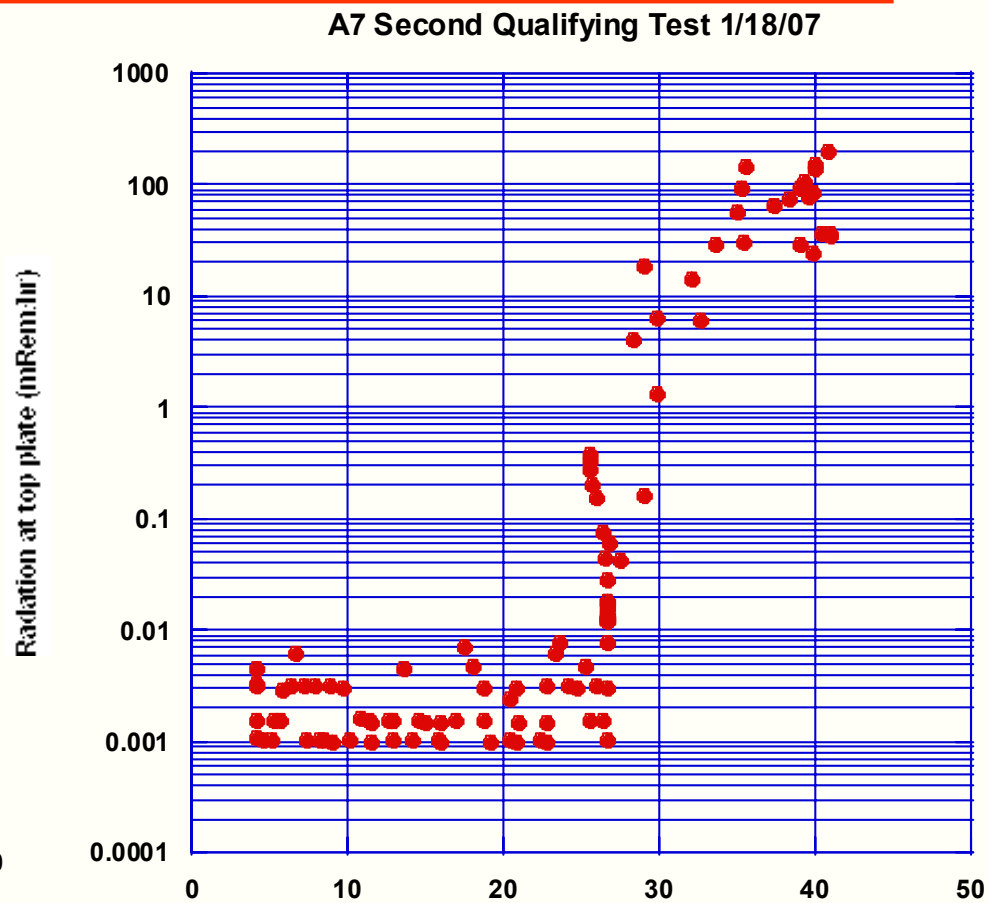
DESY/KEK developed technology

US cavity processing results: AC7

Fermilab

Thomas Jefferson National Accelerator Facility
John Mammosser, Jan. 18, 2007





Performance of FLASH Accelerator Modul

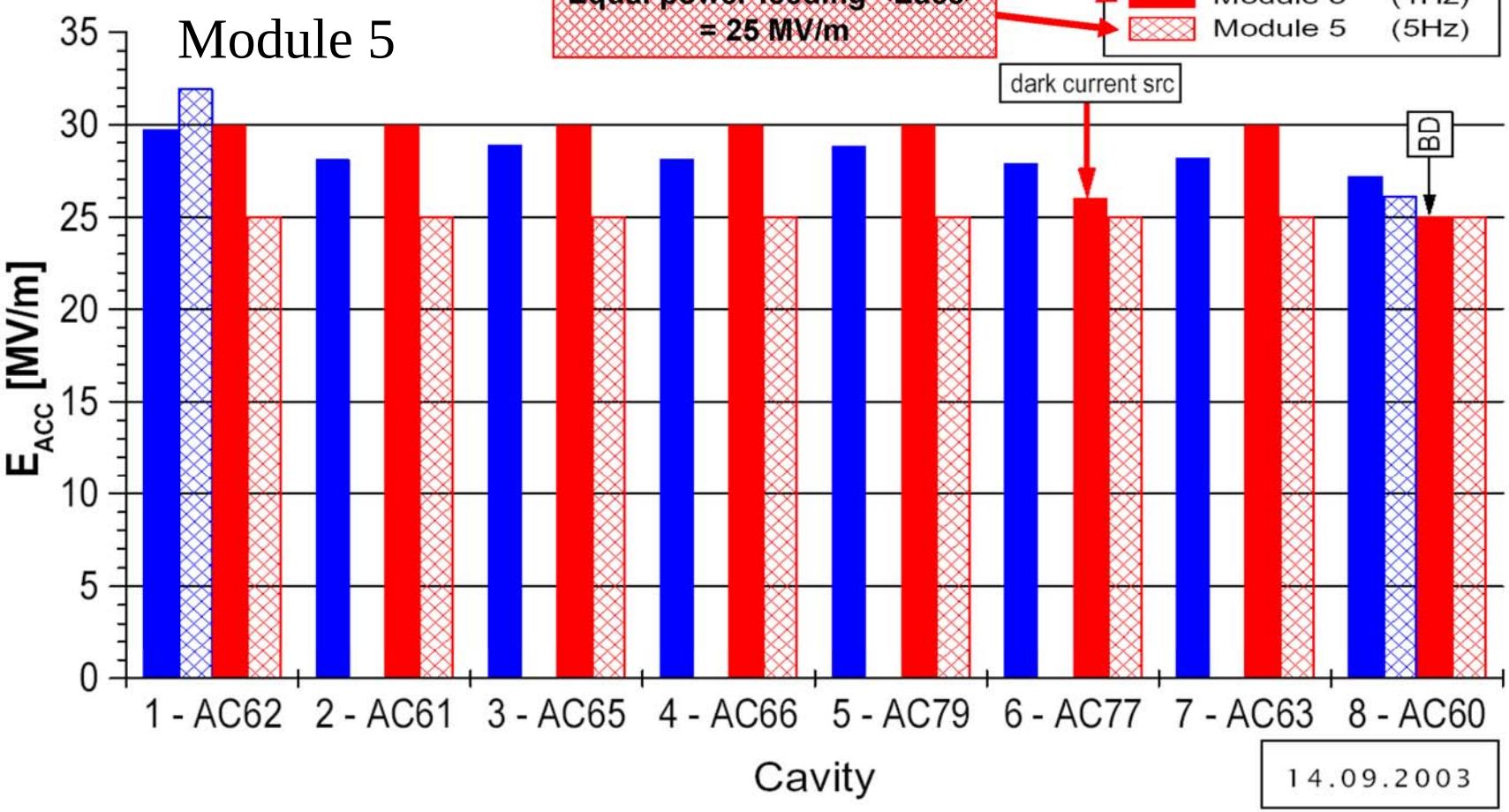
From H. Weise/ D. Kostin

A State-of-the-art module

- cryogenic type III
- latest coupler generation
- Etched (BCP) cavities

In single cavity measurements 6 out of 8 cavities reach 30 MV/m!

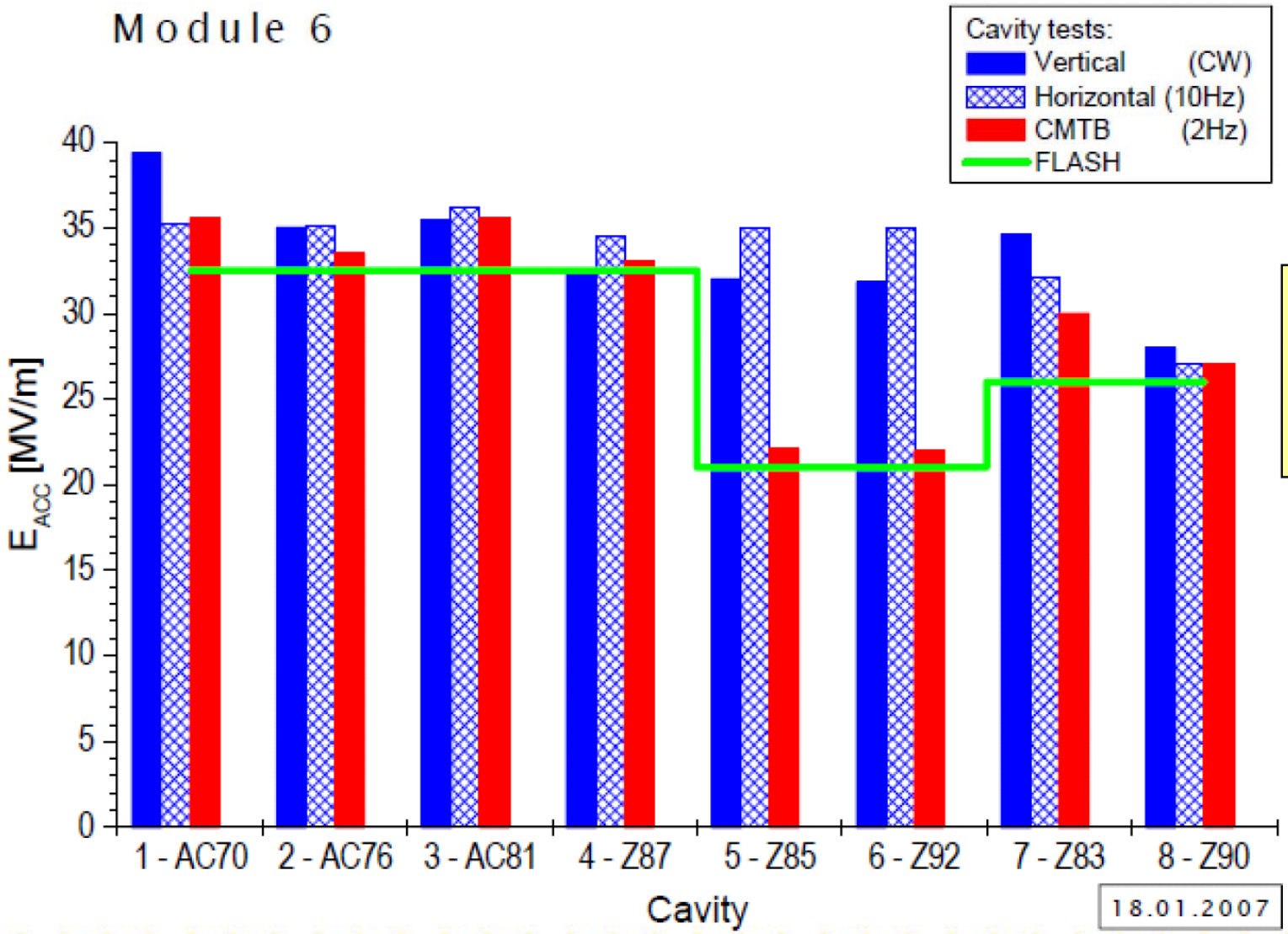
Equal power feeding <Eacc> = 25 MV/m



Cavity Performance

(courtesy D. Kostin – DESY)

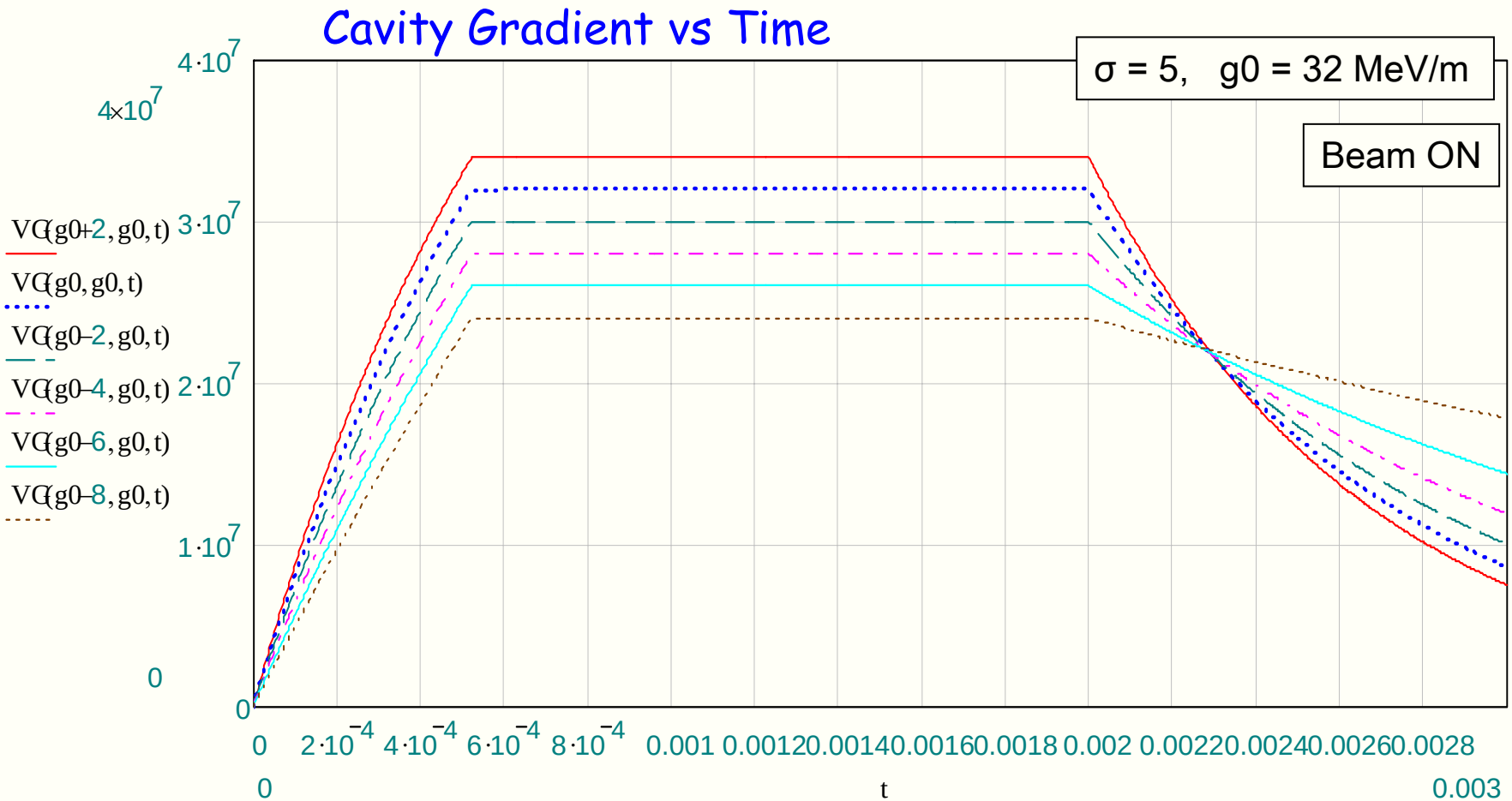
By L. Lilje (DE



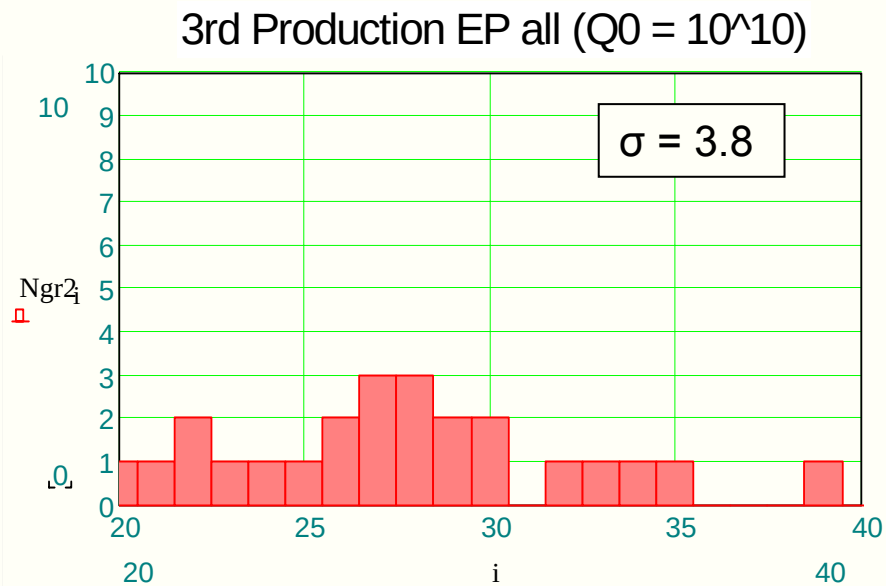
Average
gradien
28 MV/r

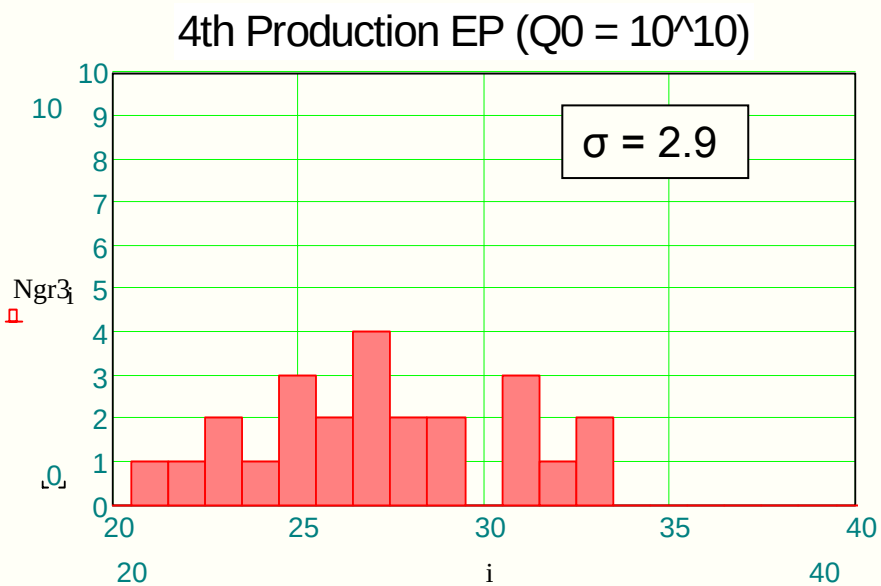
Cavity Operation – Beam ON

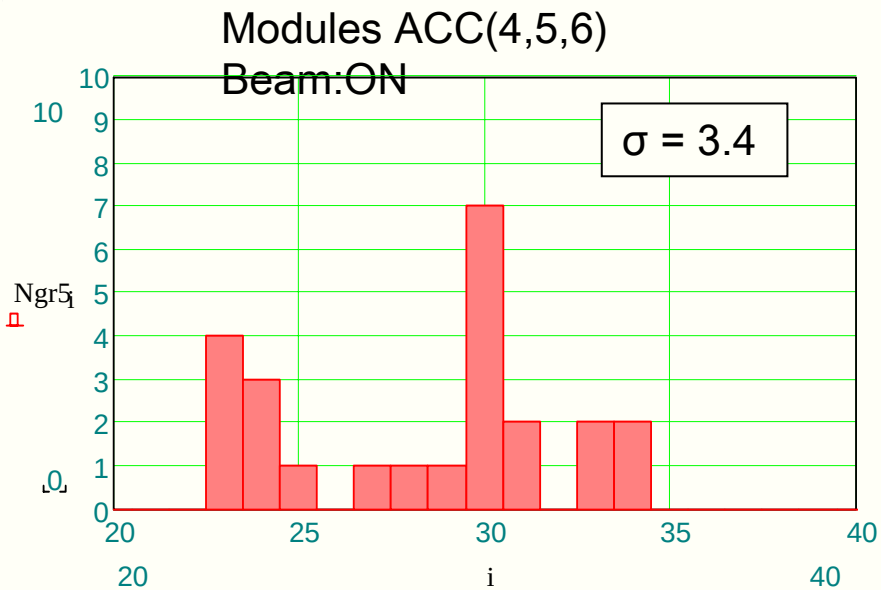
- **There are 2 controllable elements:**
  1. **the klystron power (common to 24); tap fraction for each cavity**
  2. **The rate at which power feeds into each cavity (coupler – Q_ext)**
- **There are 2 fundamental goals:**
  1. **Flat gradient as a function of time during the pulse for each ↓**
  2. **Maximum 'practical' field in each cavity**
- **Final: minimize wasted power; provide variability as needed for flexible ops**

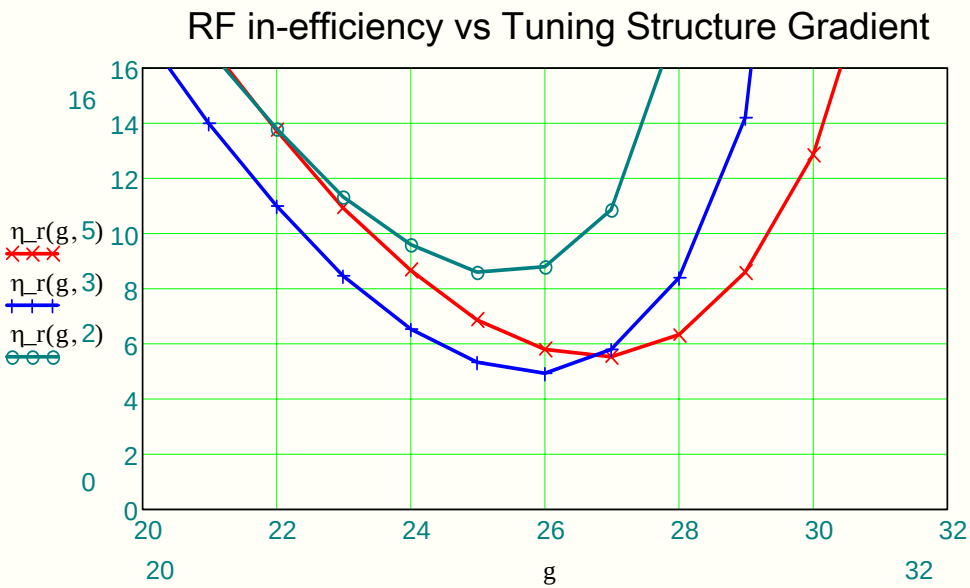


Cavity Gradient Distribution – and power inefficiency









Andrei Lunin and Nikolay Solyak

Linac Operation with Variable Tap-Offs (VTOs) and Large Gradient Spread

- Assume cavities produced with flat distribution of sustainable gradients (G) from 22 MV/m to 34 MV/m with <G> = 28 MV/m
- With Qeo optimized for Go = <G>, achieve flat cavity field at G with
  - Qe = Qeo * ln(2) / ln (1 + G/Go * Qeo/Qe)
  - Input Power = Po * (1/4) * (1 + G/Go * Qeo/Qe)^2 * (Qe/Qeo)
- Requires on average 6.8% more power per rf unit
- Maintain rf unit layout but increase linac length by 31.5/28 -1 = 12.5%
- At 31 MV/m, which is a 3-sigma variation in the mean gradient of an half rf unit, have same 16% tuning overhead as present design at 33 MV/m.
- Considering all changes, ILC cost increases by about 7%

- Chris Adolphsen, SLAC

toughest RDR task: Cryomodule

- (my opinion)
- Developing consensus on linac cryomodule cost
  - (RDR succeeded because most line items were much easier to handle)
- Sensitive item – driving item for confidentiality considerations
- Each region has "done it" in a lab context
  - Each region will develop vendors to assist
- In most plans (including XFEL), almost all of the work is 'outsourced' to companies who can make money (esp. due to the scale of the task) and do it more effectively than we could (would)
  - testing remains an 'in-house' activity
  - very similar to LHC

Specific Tasks – Cost

Cryomodule costs	fraction	sum
Cavity Fabrication	36%	36%
Power Couplers	10%	46%
Helium Vessel Fabrication	8%	54%
Magnetic Package (Quad)	7%	61%
Tuners	7%	68%
Assembly, Testing, Transport	5%	72%

(Next 7 items – to 1% level (22%)– Vacuum vessel,shields, interconnect, processing, dressing, pipes, supports, instrumentation)

Cavity String Assembly

The assembly of an 8 cavity string

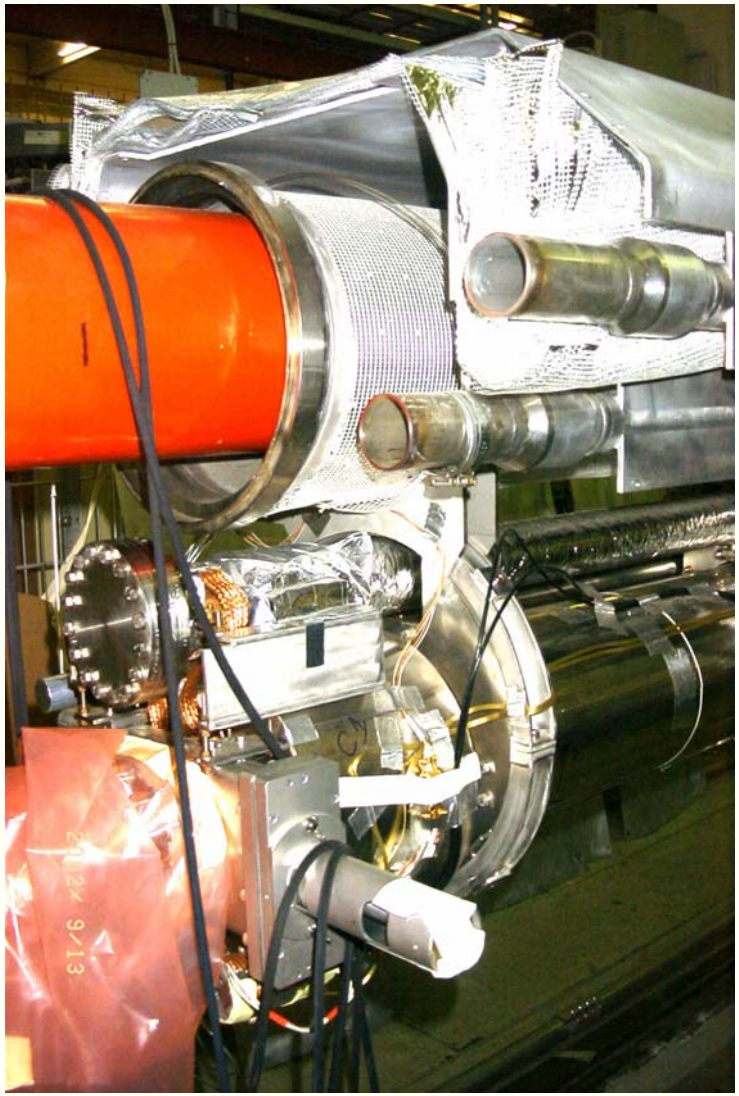
- is a standard procedure at DESY
- was done by technicians from the TESLA Technology Collaboration
- was the basis for two industrial studies.

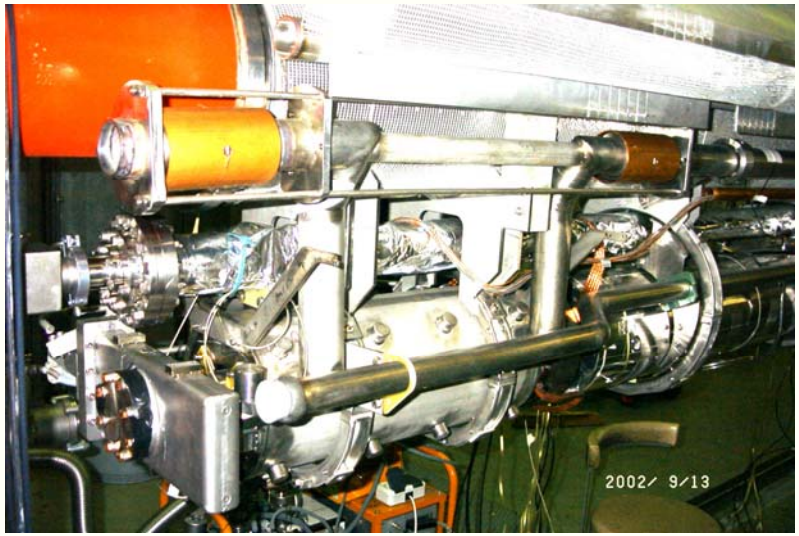
The transfer of this well known and complete procedure to industry has started.

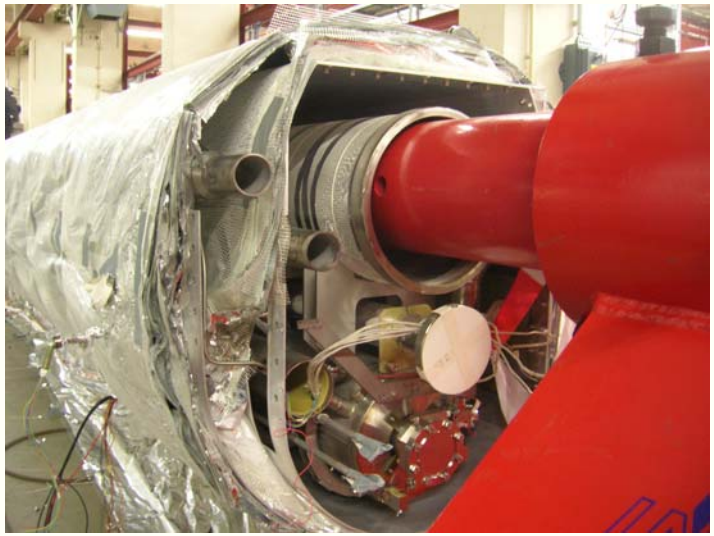
DESY will provide sub-components for the first string / module built in industry; this allows for an early training.

Cryomodule assembly: 1200+ parts

Fermilab







FNAL CM Assembly: T. Arkan

Role of XFEL - DESY

- The DESY X-ray Free Electron Laser is a '10%' model of ILC (~20 GeV)
  - ALMOST identical
  - Completion 2013 → reasonable, if not perfect, timing
  - Cost ~ 1B€, in european accounting, including user fac.
- Most XFEL project 'lessons' are applicable to ILC
  - (our priority is to understand the technology)
- We will learn the CM production management from DESY / XFEL team
  - They can benefit from the investment we make to 'educate' ourselves
- Development of US – based contractors in parallel, but with much smaller scope (0.5%)

ILC String Test: What's needed?

- **ILC scale:**
  - 16,088 SC Cavities: 9 cell, 1.3 GHz
  - 1848 CryoModules (LHC 1232 dipole cryounits)
  - 613 RF Units (#CM/3): 10 MW klystron, modulator, RF distribution
- **minimum size is a single RF unit with ILC like beam.**
  - many tests are statistical (testing); a longer string test with several RF units or multiple tests with one RF unit would be better
- **at least 1 RF unit with ~ final design should be tested before more than 1% are produced**

Damping Ring: the most challenging Accel. Phys.

Very High Priority R&D Objectives

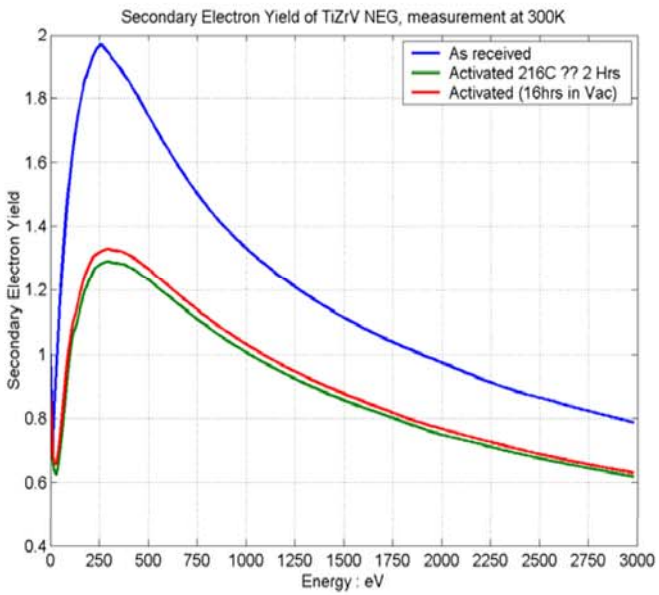
- 2.1.1.1 Lattice design for baseline positron ring
- 2.1.1.2 Lattice design for baseline electron ring
- 2.1.4.3 Demonstrate < 2 pm vertical emittance
- 2.2.1.2 Characterize single-bunch impedance-driven instabilities
- 2.2.3.1 Characterize electron-cloud build-up
- 2.2.3.2 Develop electron-cloud suppression techniques
- 2.2.3.3 Develop modeling tools for electron-cloud instabilities
- 2.2.3.4 Determine electron-cloud instability thresholds
- 2.2.4.1 Characterize ion effects
- 2.2.4.2 Specify techniques for suppressing ion effects
- 3.5.1.1 Develop fast high-power pulser for injection/extraction kickers

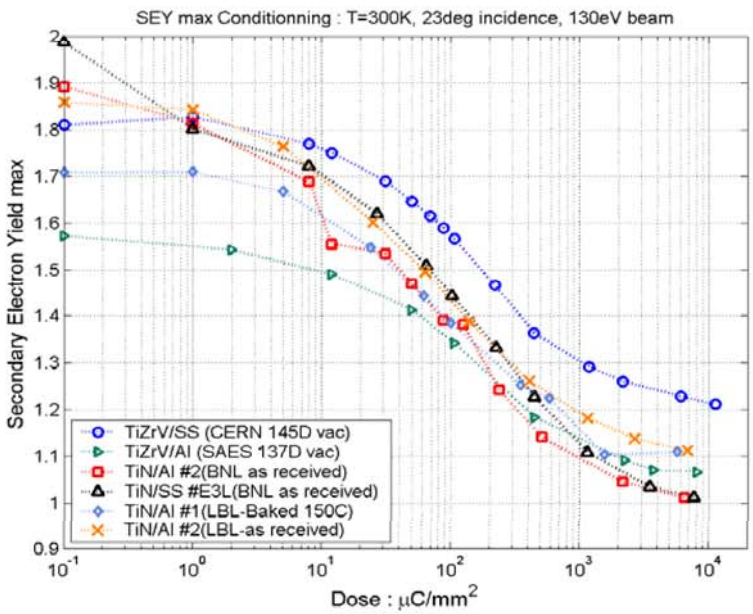
Damping Ring: Electron Cloud

- Electron cloud could drive instabilities in the positron beam, if allowed to develop to a sufficiently high level.
- The goal is to reduce the peak secondary electron yield (SEY) to below 1.2 in straights, bends and wigglers.
  - Benchmarked simulations indicate this will be sufficient to prevent the electron cloud reaching a density that would make the beam unstable.
- Several techniques are under investigation for suppressing the electron cloud build-up:
  - Solenoid windings in straights (demonstrated at the B factories).
  - Coating with low-SEY material, e.g. TiN or TiZrV (NEG): shown to be effective in lab studies, machine experience is needed.
  - Use of grooved chambers: shown to be effective in lab studies, machine experience is needed.
  - Clearing electrodes: simulation results look promising, experimental studies are needed.

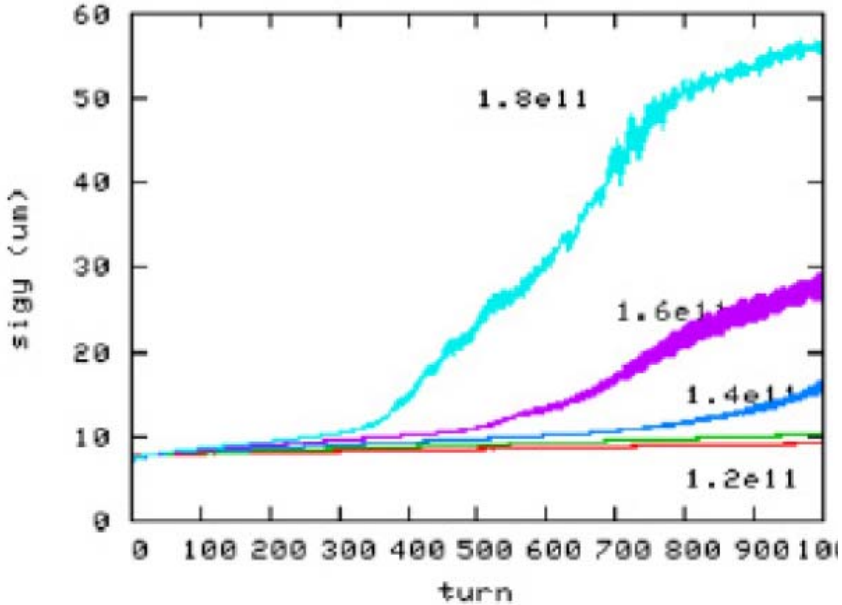
Electron Cloud

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



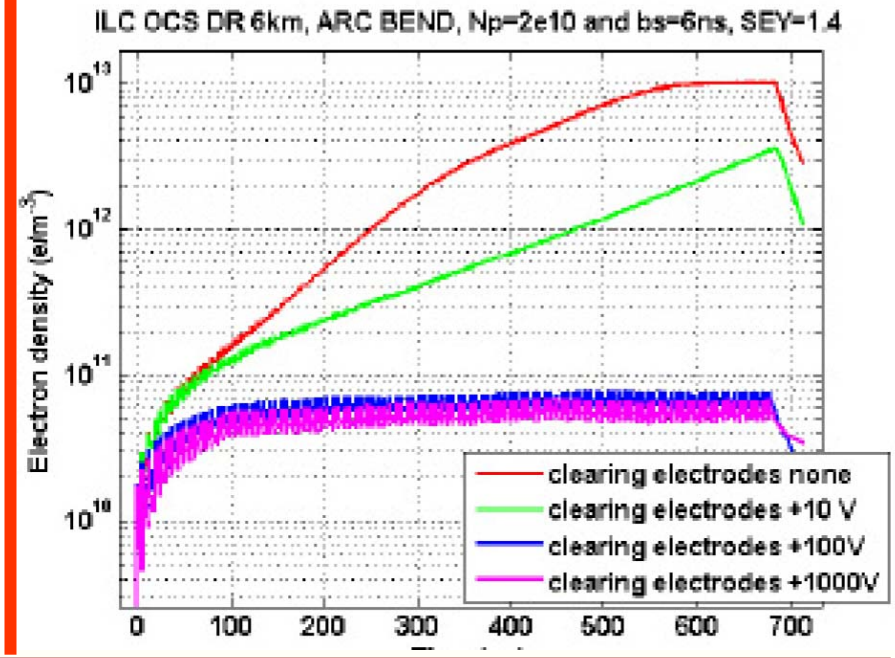


Electron Cloud - simulations

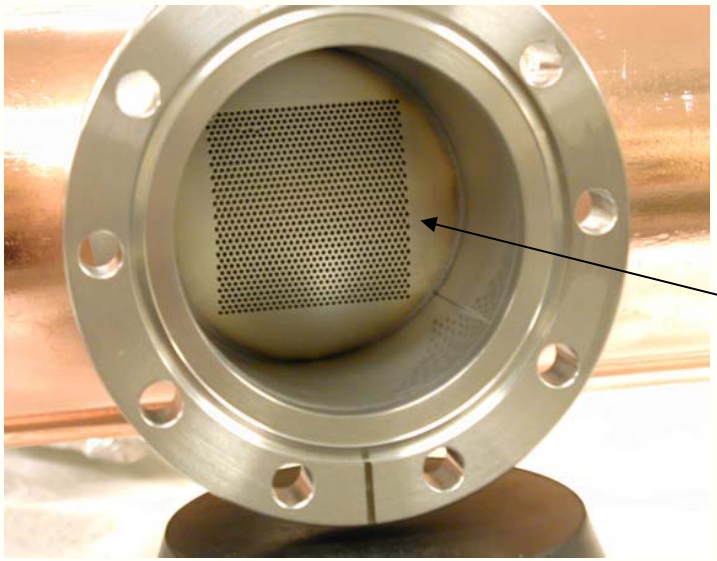


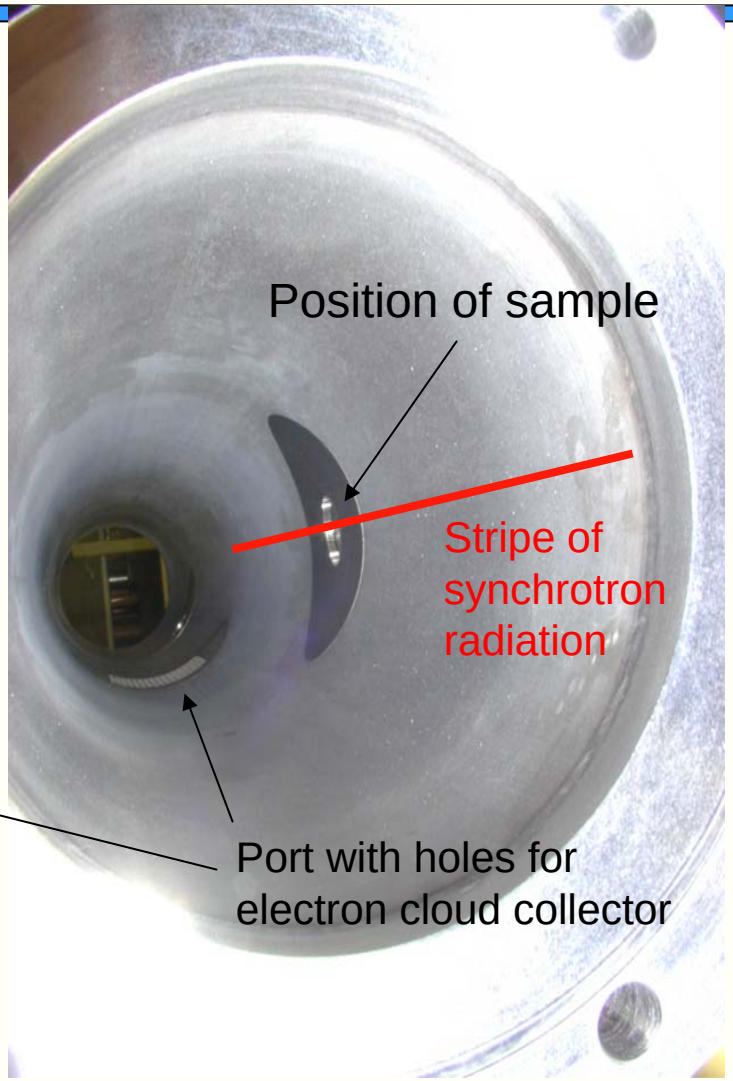
- beam size growth (incoherent) vs turn number (1 turn = 22us)
- for different cloud densities

- cloud density in an Arc Bend dipole vacuum chamber
- for different clearing field electrode voltages



Electron Cloud: Tests in PEP-II LER



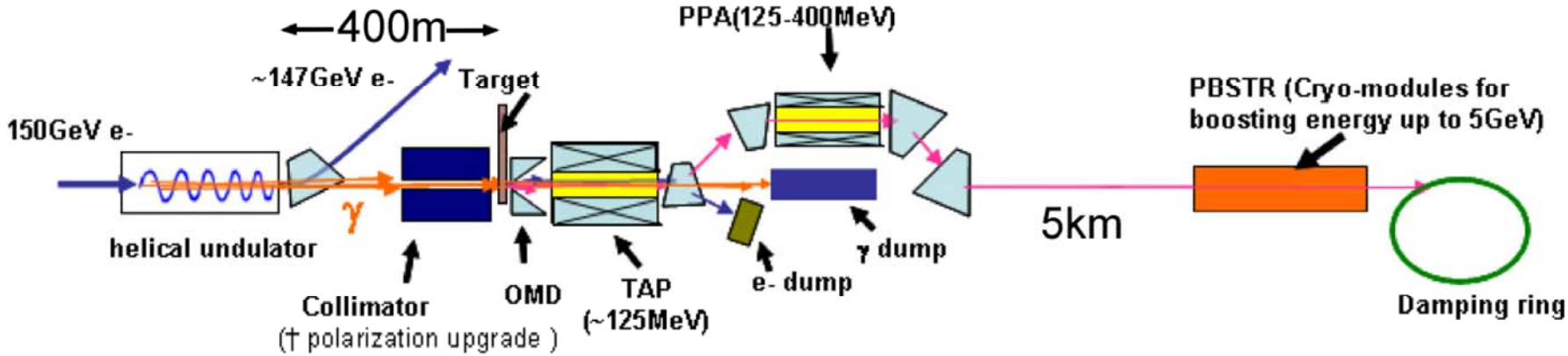


Electron Cloud: Tests in PEP-II LER

Extruded aluminum beam pipe with "fins" and coating.

Positron Source

- Undulator scheme
  - Electron beam at 150GeV

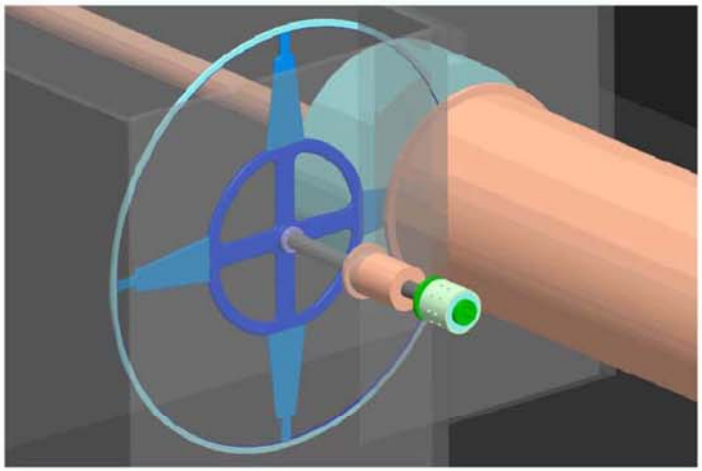


  - Undulator
    - Helical, superconducting
    - length ~100m (~200m for polarized e+)
    - K=0.92, λ=1.15cm, (B=0.86T)
  - Needs `keep-alive source'
    - 10% intensity
    - Share 5GeV linac

R&D items

e+

- Undulator fabrication (SC, pitch 1cm, 0.86T)
- Target (titanium alloy, diam.1m, 1.4cm think, rotating at 100m/s)
- Target region design



Beam Delivery R&D plans by institutes

	Accelerator design	IR design	SC magnets	Warm/ pulsed magnets	Crab system	Collimation & backgrounds	Vacuum design	Instrumentation	Feedback	Beam dumps	Stabilisation
SLAC											
BNL											
FNAL											
UBC/TRIUMF											
US Universities											
LC-ABD, UK											
LAL											
CEA											
LAPP											
CERN											
DESY											
KEK											
Kyoyo University											
Tohoku University											
Tokyo University											
IHEP, China											
Dubna											
BINP											
Any other?											

Draft

Presently working - may continue depending upon funding in few cases

May be/could do

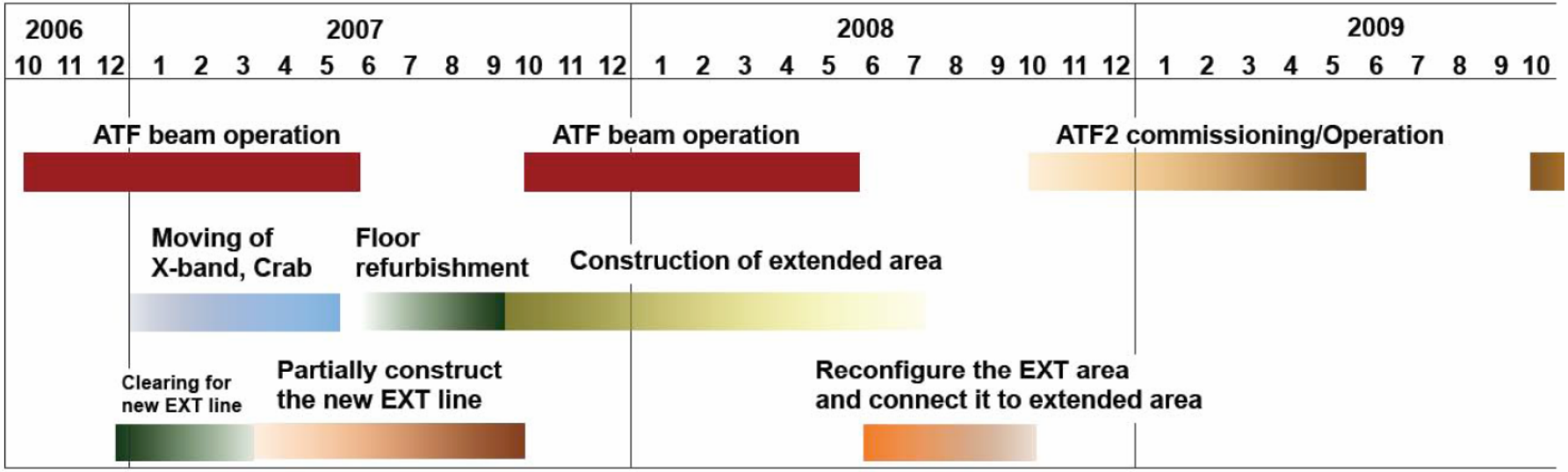
At detailed level, there are over 30 institutes

Beam Delivery R&D

- **Includes items which have major impact on operational performance & need substantial amount of R&D.**
  - IR superconducting magnets, their integration into the IR, and a design study to ensure their mechanical stability
  - push-pull design
  - crab cavities, and related systems to provide phase stability
  - collimator wakefield and their validation with codes
  - collimator beam damage and damage detection
  - Accelerator physics design
  - Design, construction, commissioning and operation of ATF2
  - laser wires beam diagnostic
  - intratrain feedback
  - MDI type hardware such as energy spectrometers and polarimeters
  - beam dump design and study of beam dump window survivability

Fermilab

ATF2 – Beam Delivery Test Facility at KEK



- **Construction of the extended shield area for final focus system can be done during the ATF beam operation.**
- Partial construction beside the current EXT line in shutdown week will release the work load for reconfiguration of the EXT line in summer of 2008.
- **ATF2 beam will come in October, 2008.**

Release of RDR in Beijing – Feb 8, 2007

Role of Fermilab

- **Research and Development of SRF across a broad front:**
  - **Fundamentals**
  - **Mass production technology**
  - **Accelerator operation**
  - **Cost reduction**

- **There are no entitlements in the accelerator building business**
  - **We have to demonstrate competence**
  - **Our partners are more advanced**
  - **Timing is critical → 50 KW electron beam in 2010 at NML**
- **Your participation is important**