SC RF cavity technology: the possibility of mass scale production, a global review

- Remarkable production experience exists for elliptical type cavities made from solid Niobium   (around 500 units)
  - Mainly by European companies
  - Around 40complete modules (single and multi-cells) have been fabricated by European industry, partially turn-key conditions
- TESLA (20,000) and XFEL (1,000) pushed industrial effort for mass scale production
  - ILC just starts this effort in USA and Japan
- This talk gives a **global** overview on the present state of knowledge about mass scale production and related costs
- Short comments on “lessons learned from LHC magnet production”

Technical systems: Cavity / module

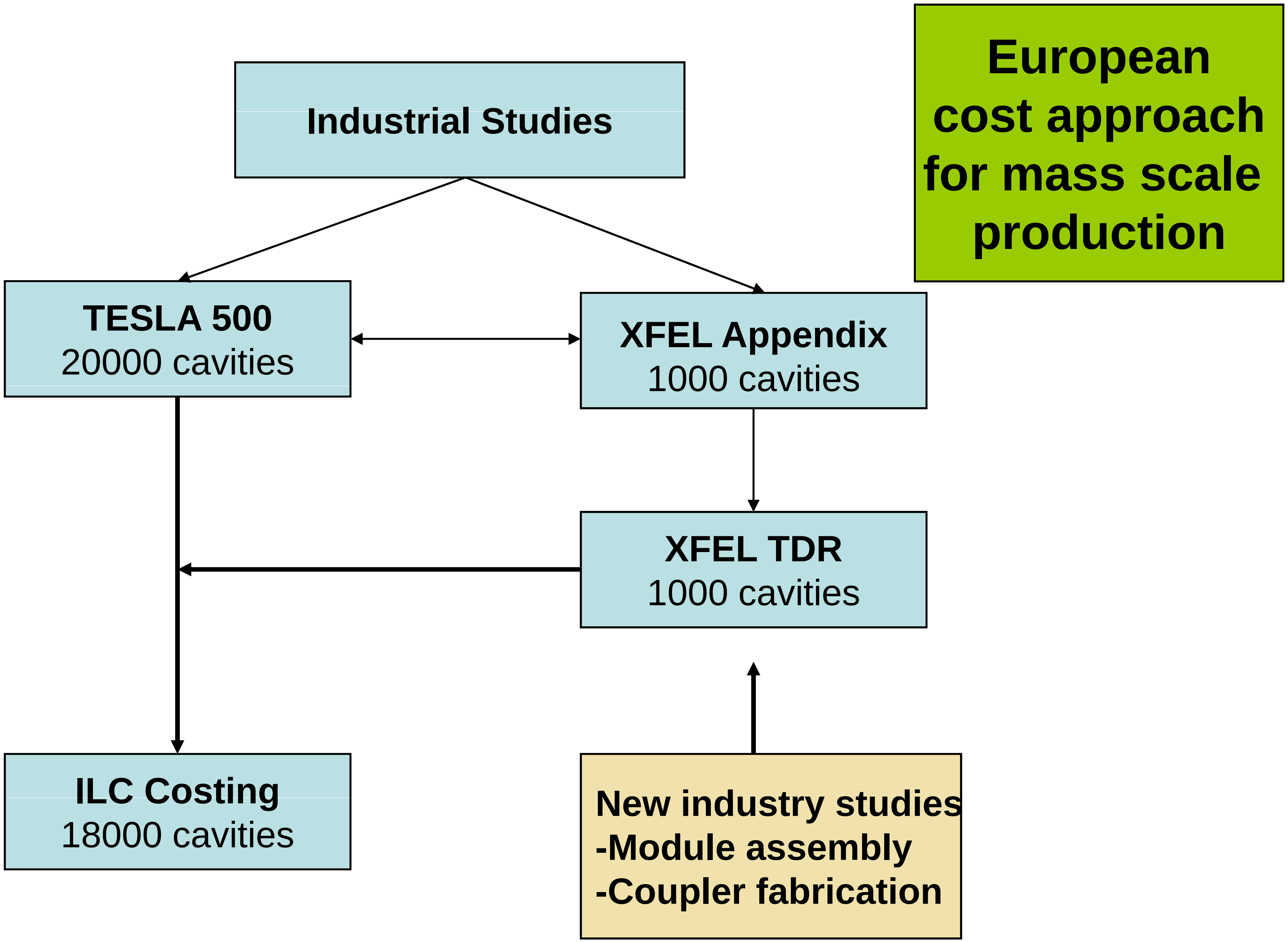
- Overview on industrialization / costing activities for mass scale production
  - European industrialization, costing method
    - Overview industrial methods
    - General comments on industrialization
  - Short report on American activities
  - Short report on Asian activities
- Conclusion

Technical systems: Cavity / Modules

- Elements in cavity / module system
  - Niobium material
  - Cavity fabrication
    - Input coupler
    - HOM coupler
    - Tuning system
  - Cavity treatment
  - Module assembly

European Approach to industrial mass production

- Industrial studies for TESLA (20000 cavities) at 2001
- Appendix to TESLA: XFEL part at 2001
  - 1000 cavities
- Revised XFEL TDR at 2006
  - Corrections for
    - Increased material costs
    - Risk assessment for costs
    - Inflation
- For ILC: Corrections / modifications to TESLA costs based on findings in XFEL part



D.Proch, LCWS 2007

European cost / mass production evaluation by Industrial Studies

- **Analyze production of TTF components**
  - Describe present fabrication process
  - Determine cost drivers, critical procedures
  - Define core technology, outsourcing possibility

- **Implementation of mass production methods**
  - Evaluate investment of machinery, tooling, roboting
  - Cost optimize flow of fabrication
  - Describe layout for “core tech” factory

European cost / mass production evaluation by Industrial Studies, cont.

- **Complete planning of new "core tech" factory**
  - Determine costs for buildings, investment, man power, ramp up & production & ramp down, overhead, consumables, QC,…
  - Get bits for outsourced parts
  - Sum up total cost of component fabrication

- **NO** learning curve assumed (e.g. -10% for doubling the production)
- But assumption: stable production after about 50 cavities, couplers,…
  - **Is verified e.g. by LHC magnet production: assembly time reached stable (and predicted) level after about 40 magnets**

- **This cost model is valid because it was developed by experienced companies. Additional studies would require time, money and competent industry.**

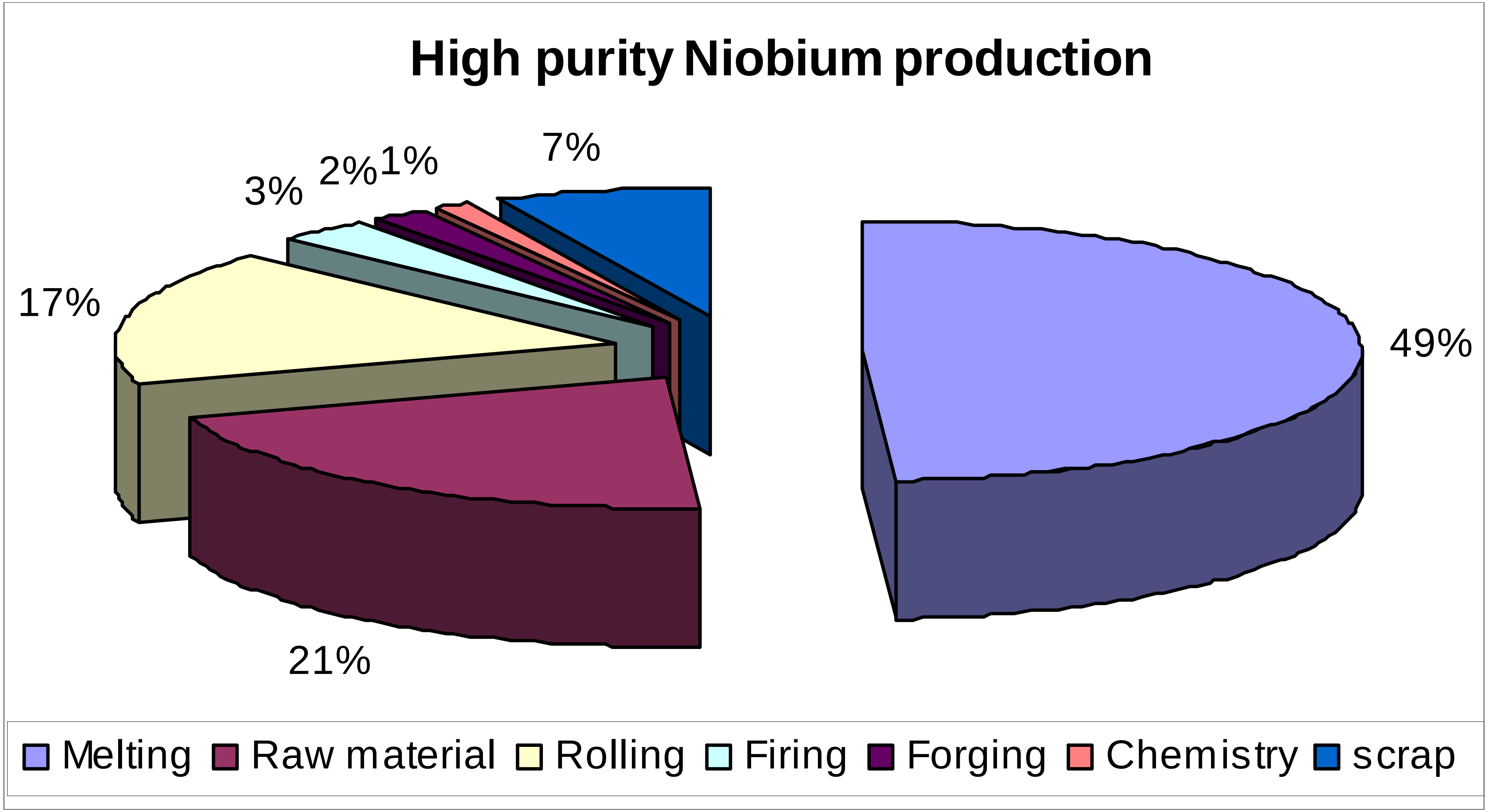
Components with European Industrial Studies

- Niobium fabrication, done
- Cavity fabrication, done
- Cavity treatment, done
- Module assembly, done
  - Revised study is in progress, see talk by R.Lange
- Input coupler fabrication
  - Study in progress, see talk by W.D.Moeller
- Industrial investigation of QA for EP electrolyte (my talk from yesterday)

500KW electron beam cold hearth

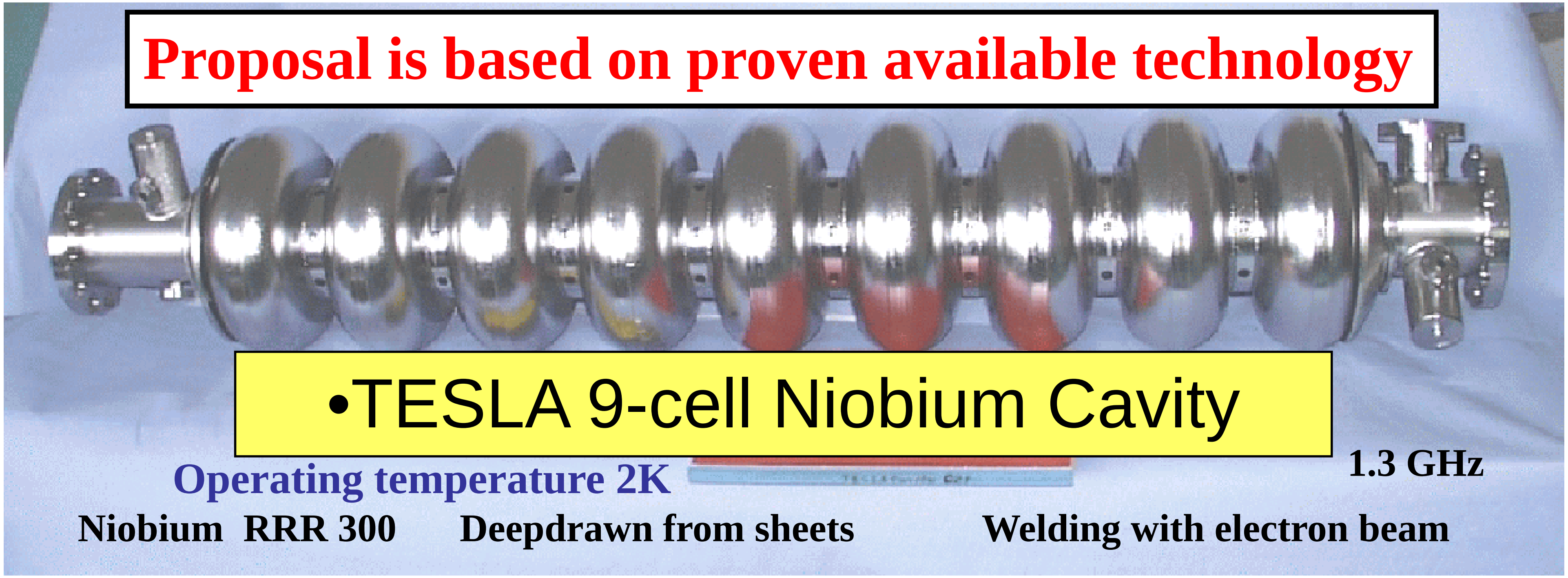
Comments to mass production / cost evaluation of high purity Niobium

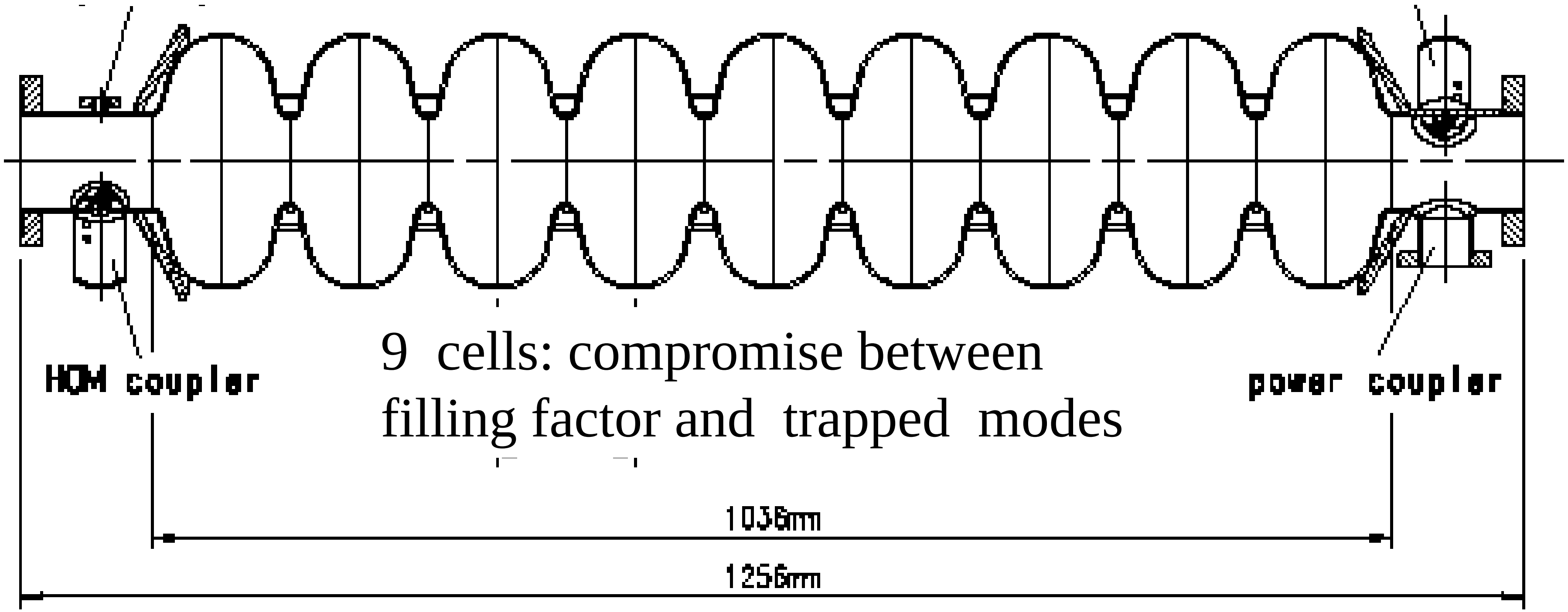
- **Nb Material** (high purity, RRR 300)
  - No shortage of raw Nb material (40.000 tons annual production, ILC needs around 500 tons
  - But limited number of high purity melting facilities
    - Today there are 4 qualified companies, but only one is capable of producing full yield for ILC
  - Marginal savings in mass production (from industrial study)
    - Size of melting furnace is limited
    - But some saving can be realized by
      - Disc rather than rectangular sheet (scrap can be recovered)
      - Other material produced ready for fabrication, e.g. flange material
    - **Latest developments in large/single crystal cavities promise cost reductions, needs more experience / studies**



D.Proch, LCWS 2007

Proposal is based on proven available technology





9 cells: compromise between filling factor and trapped modes

Cavity production

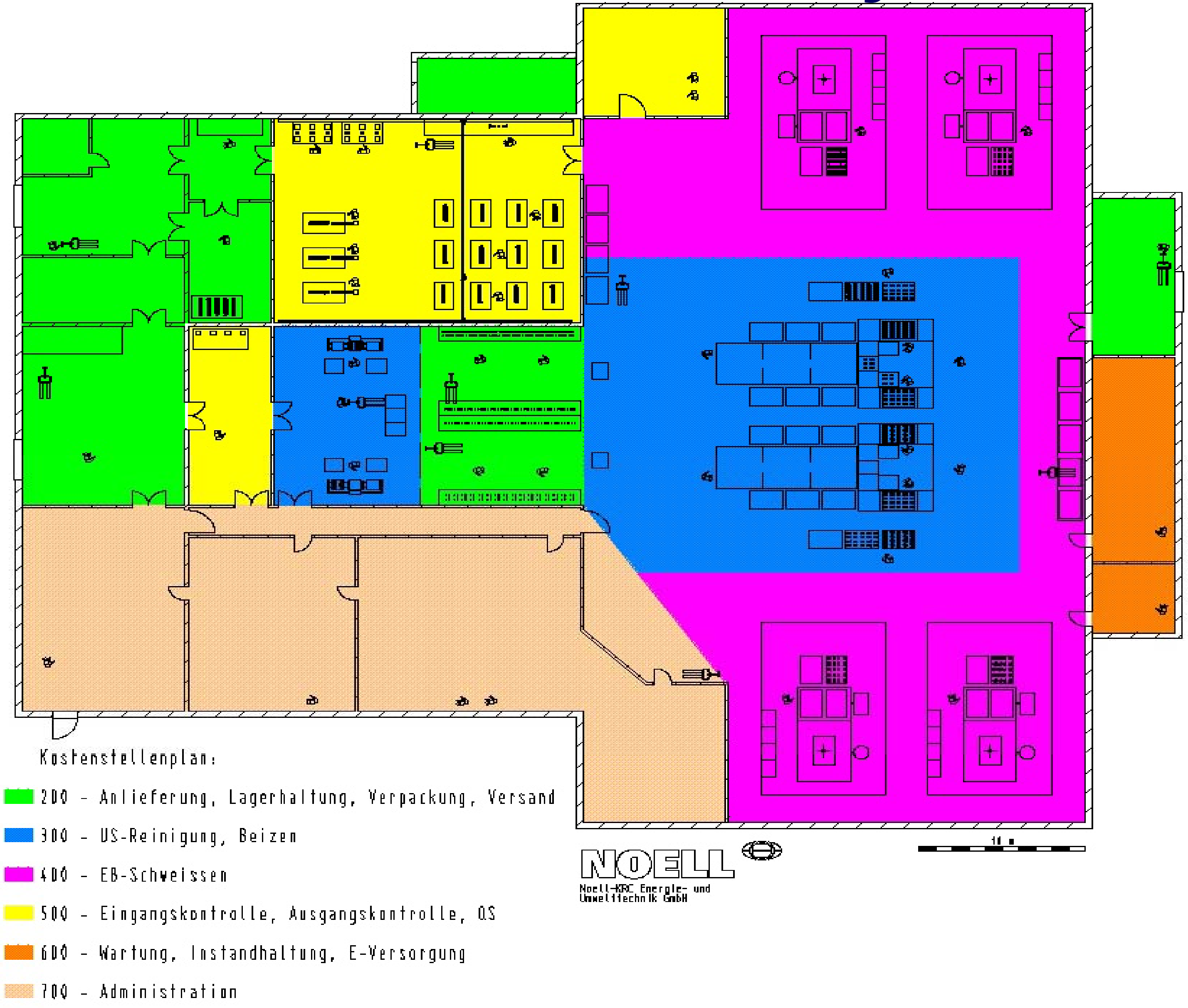
Comments to industrialization / cost evaluation

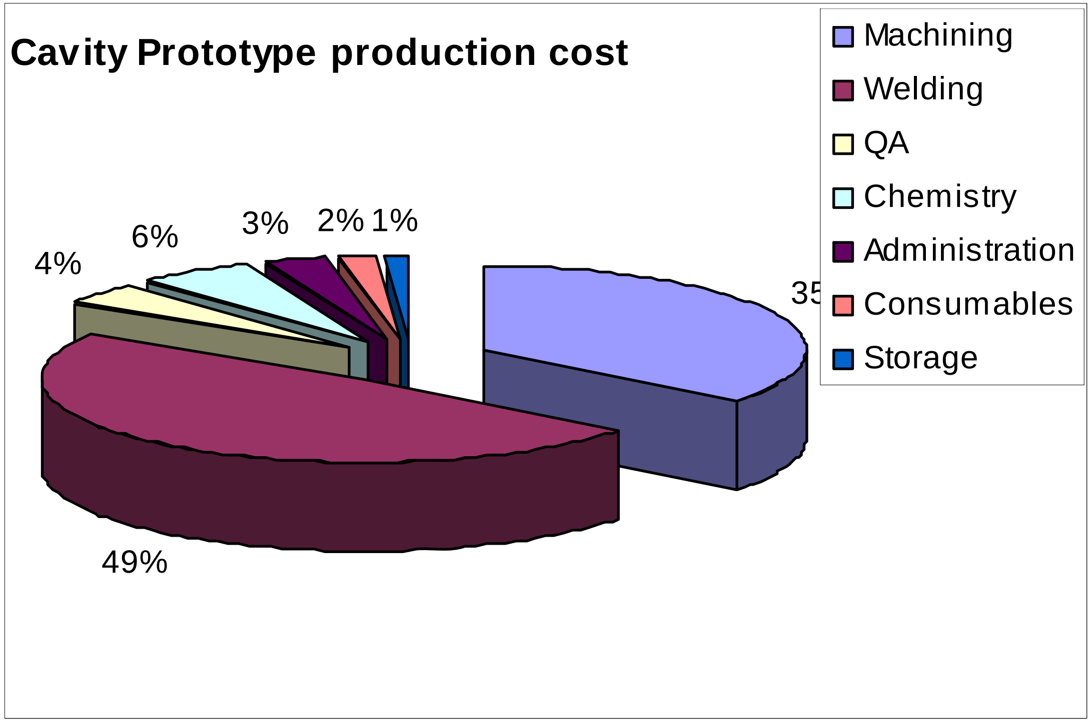
- **Cavity fabrication**
  - Experienced companies in Europe
    - More than 500 type TESLA cavities have been fabricated so far
    - Fabrication process is well understood and stable
    - Cost drivers: EB welding process (50% total cost)
      - Cure: reduced pump down time by multiple vacuum chambers welder
      - Cure: mass production welding tooling
    - Cost saving in large scale production is well understood

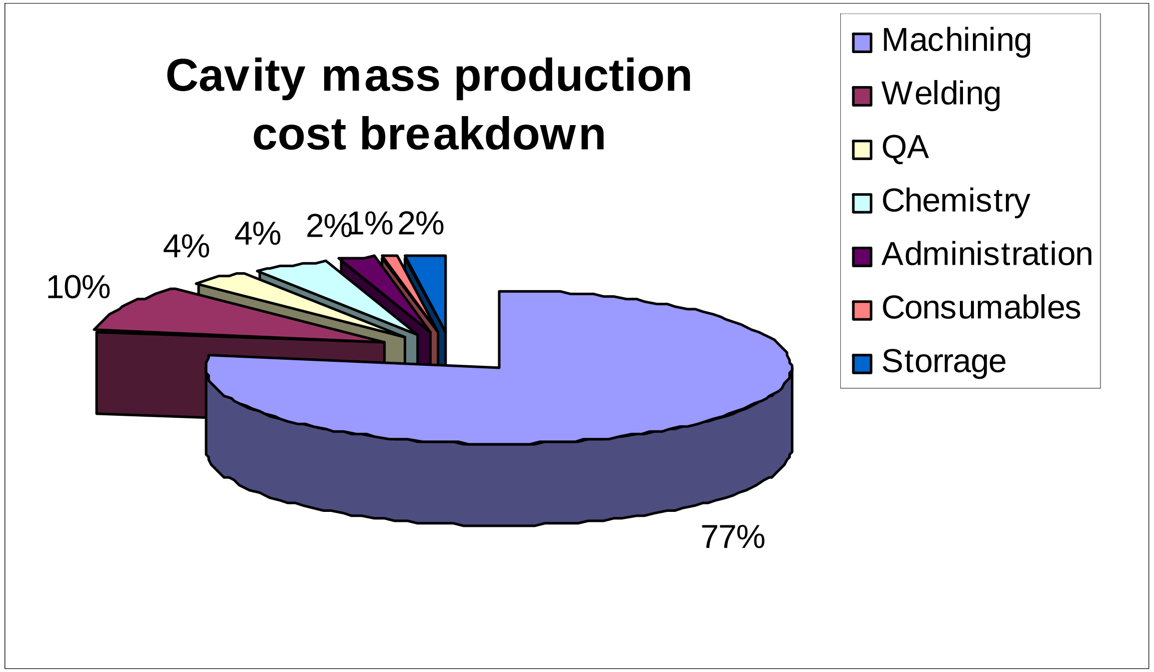
Reduction of cavity fabrication cost

- **3 vacuum chamber welding machine:**
  - Pump down and cool down in separate chamber
  - Welding in middle chamber
- Tooling for welding many parts in one cycle
- **Outsource machining of parts**

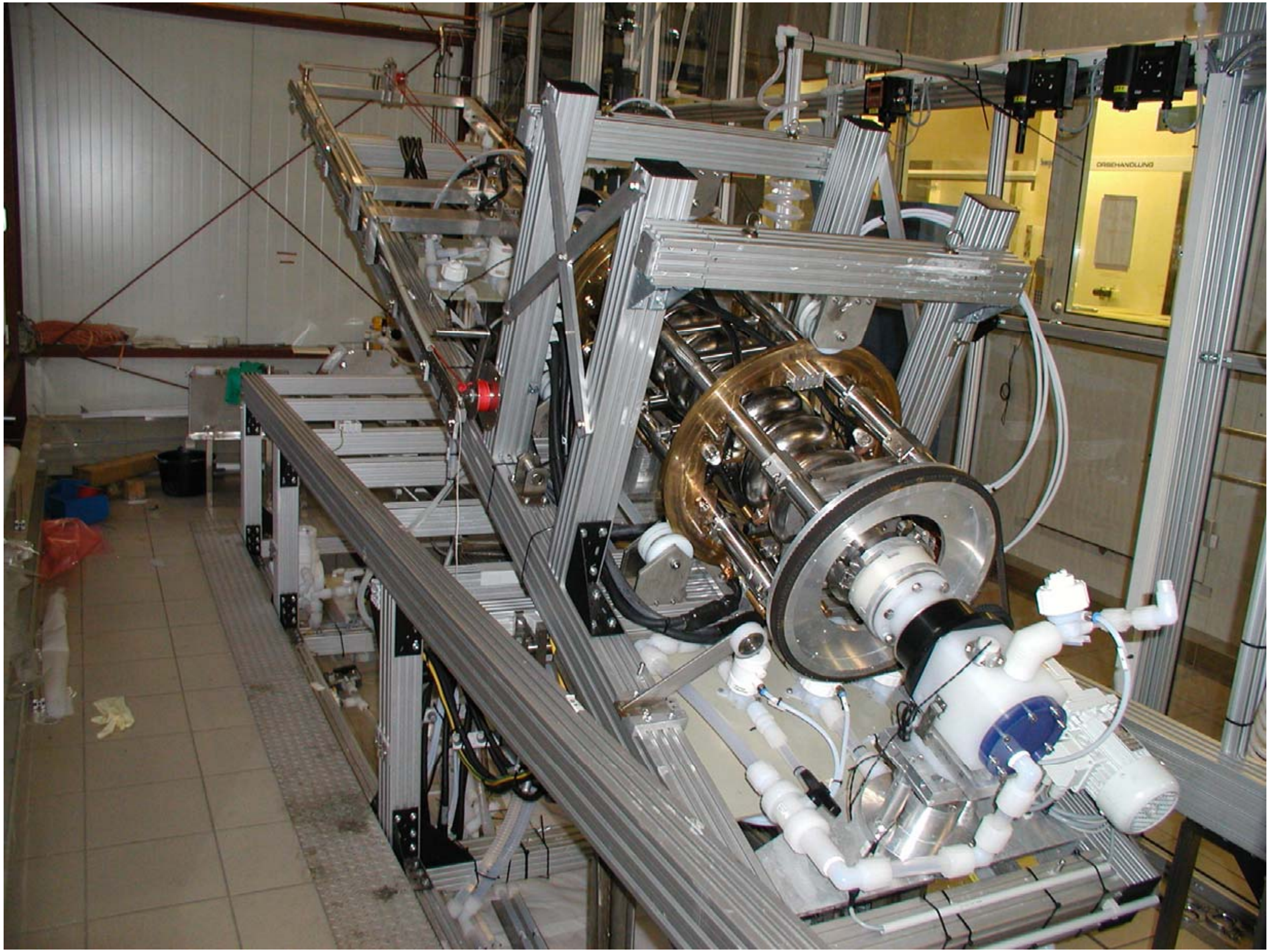
Production facility




Cavity Prototype production cost
Machining
Welding
QA
Chemistry
Administration
Consumables
Storage
4%
6%
3%
2%
1%
35
49%


Cavity mass production cost breakdown
Machining
Welding
QA
Chemistry
Administration
Consumables
Storrage
10%
4%
4%
2%
1%
2%
77%

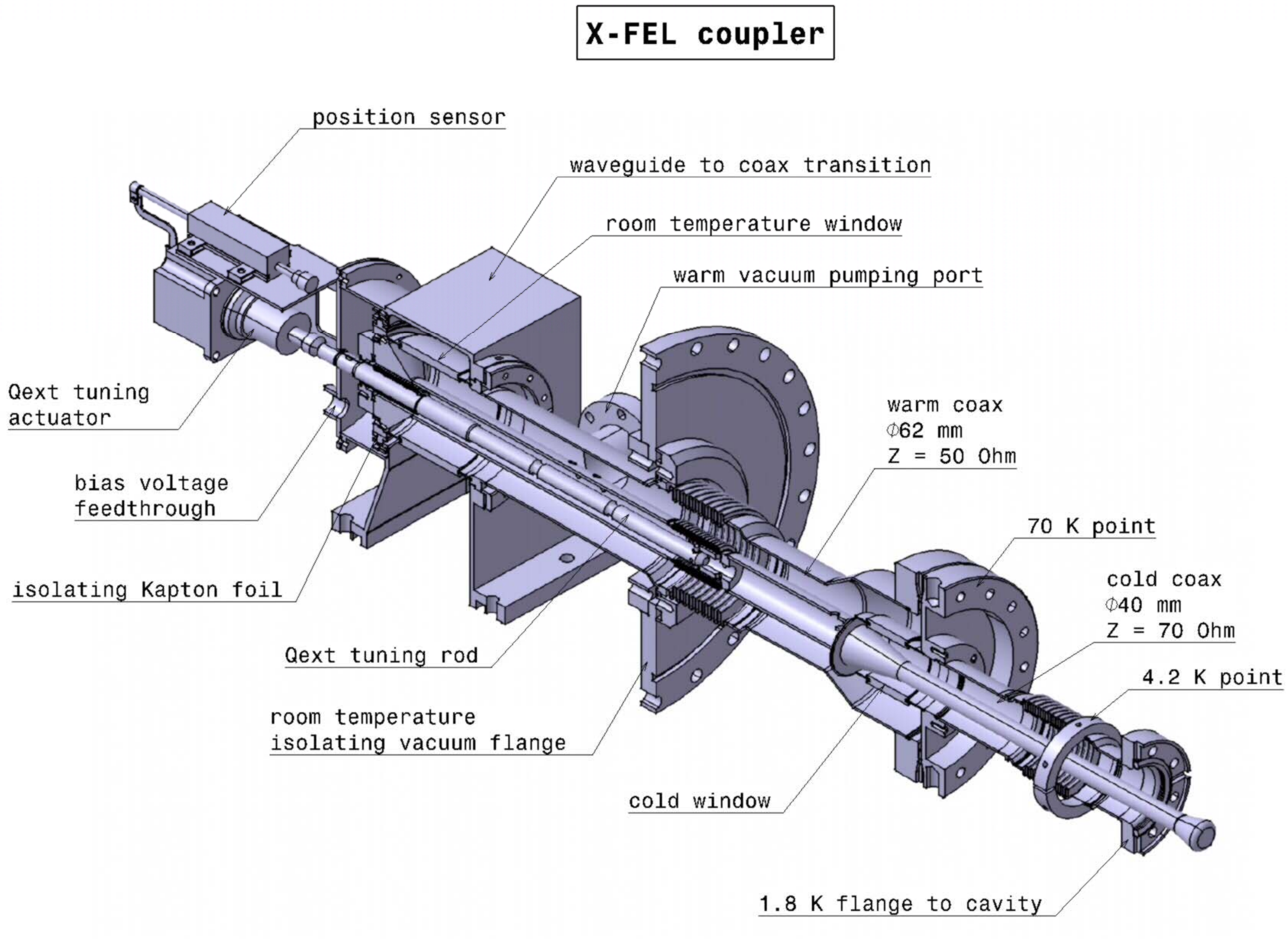
DESY Electro-polishing machine



Comments to industrialization / cost evaluation

- **Cavity treatment**
  - Standard treatment is EP, 800°C / 130°C bake, high pressure water cleaning, clean-room assembly
  - Technology transfer of EP to industry just started
    - In preparation for XFEL two orders were placed to install and operate EP facilities for 9-cell cavities (ACCEL, Henkel)
    - This EP installation should be operational end 2007
    - In total 30 9-cell cavities will be treated by about 100 um EP
    - Final treatment (small EP, baking, HPW) will be done at DESY
  - Industrial involvement for the complete cavity preparation for high gradient performance is still missing

Baseline design

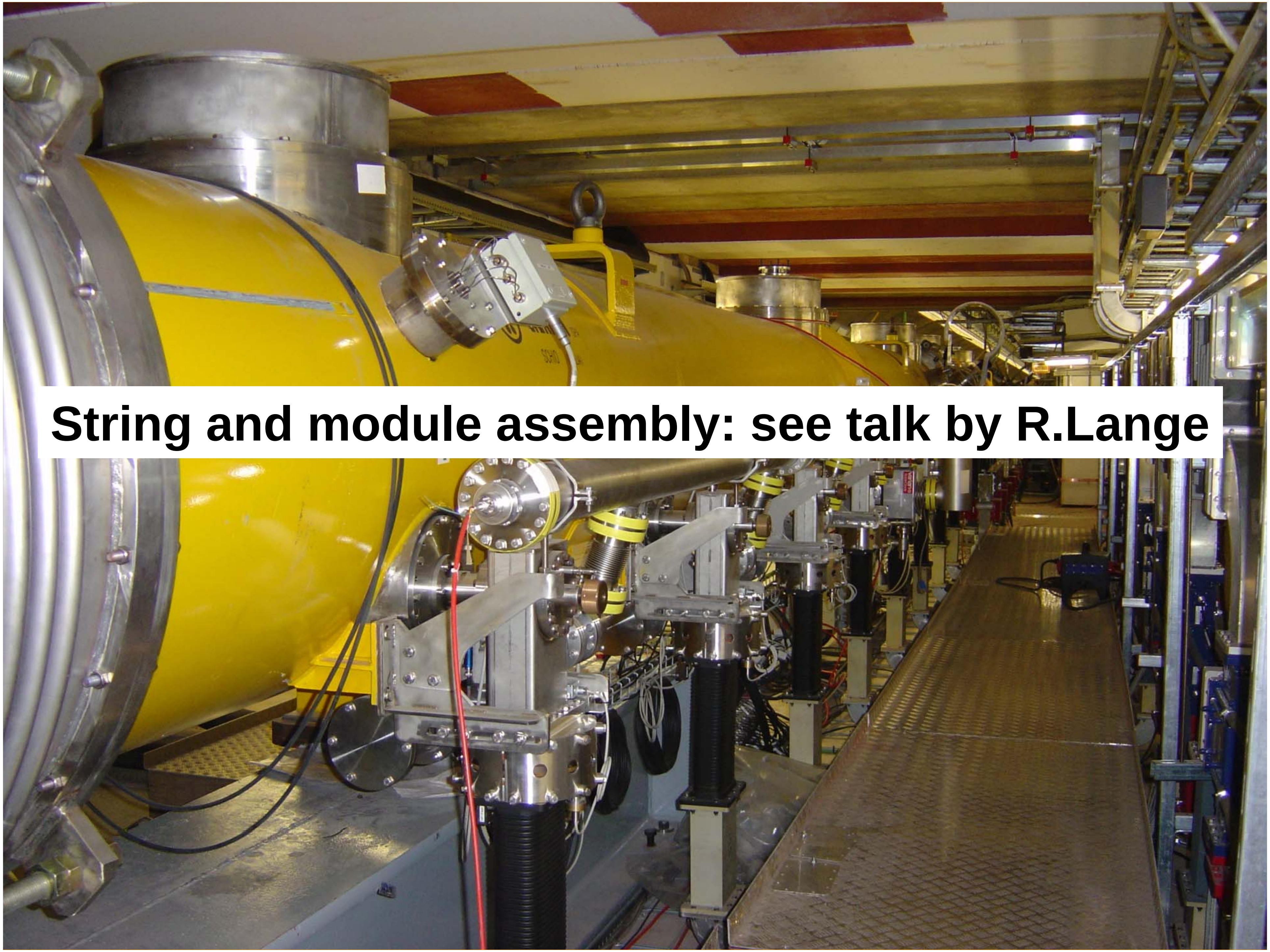


Comments to industrialization / cost evaluation

- **Input coupler**
  - Cost is high, comparable with cavity fabrication !!
  - Present industrial fabrication around 80 couplers. Industry identified cost savings which were included, e.g. standardized tube sizes
  - Ongoing industrial study (XFEL) on mass production will deliver a reliable cost number
- Detailed info by next talk from W.D.Moeller

Cavity Preparation; String and Module Assembly

String and module assembly: see talk by R.Lange



American industrialization / costing method

- There is fabrication experience in some laboratories from earlier projects
- American industry was only involved to minor extend
- A new industrial study on cavity, module and HLRF mass production is just finished
  - Production scheme is not yet optimized
  - Ideas for cost reduction in module design exist
  - No experience of US mass fabrication companies in Nb material machining

Asian industrialization / costing method

- In Japanese culture industry has been involved in early stage in accelerator projects, e.g. Tristan, KEKB
- Industry is a major driver in EP (electro polishing) and coupler development
- In house (KEK) cryo-module development is under way (STF)

Summary & Conclusion: Mass scale production of SC accelerator systems

- Industrial expertise exists in SC cavity and for most of the SC sub-systems (auxiliaries)
- European Industry has a world leading position
  - Japanese industry has specialized expertise
  - US industry just starts in SC technology
- SC cavity technology is based on poly-crystalin Nb material
  - Large grain / single crystal Nb material could reduce cost (and increase performance ?) in the future

Can we learn from LHC magnet production for XFEL / ILC ?

- Can we compare SC magnets with SC cavities?
  - Magnets and cavities are embedded in a cryogenic system (2K)
  - Both rely on intrinsic properties of SC material (QA of Nb sheets; QA of SC wire (and mag. properties if iron)
  - Magnets need final 100% cold test, the lowest magnet performance determines machine energy
  - Cavities need 100% vertical test, performance scatter in module can be compensated
  - Magnets: stringent alignment, residual fields are crucial, but can be measured at room temperature
  - Cavities: clean room conditions and final treatment are crucial
- Common: Both SC components are at the edge of technology
- Common: Fabrication technology is not available „of the shelf“

QA: Laboratory Equipment (300 K tests)

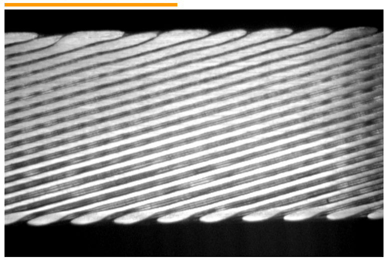
LHC project

LHC project

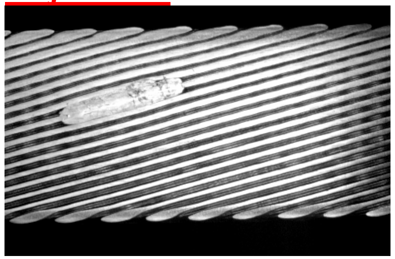
QA: LABORATORY EQUIPMENT (300 K TESTS)

Examples of defects detected **C. I. S.**

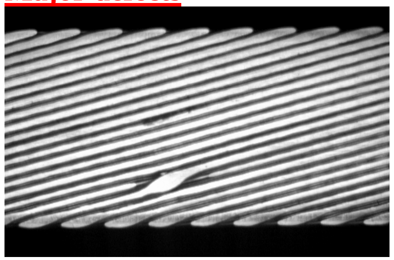
Minor defect



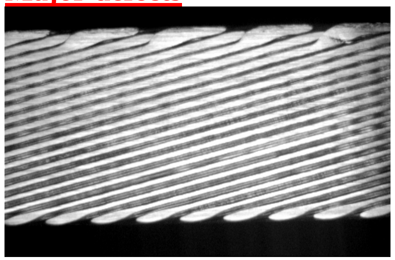
Major defect

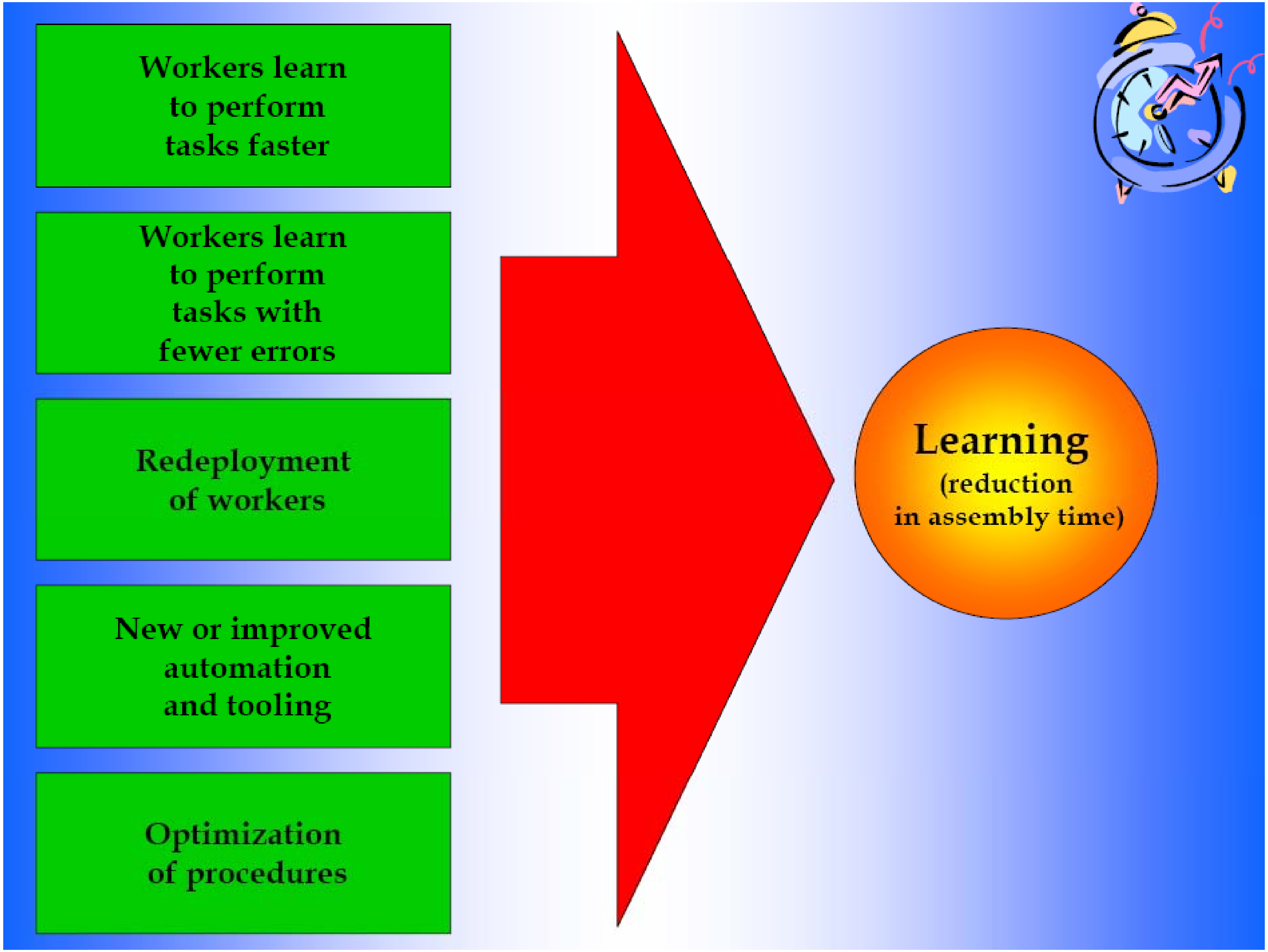


Major defects



Major defects

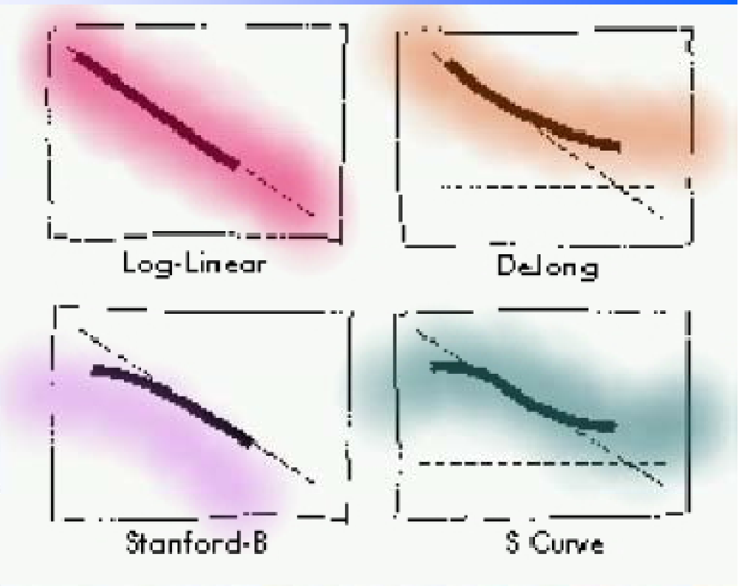




D.Proch, LCWS 2007

4 models to study effect of learning on production time

- Log-Linear: $t_n = t_1 n^b$
- Stanford-B: $t_n = t_1 (n + c_{ex})^b$
- De Jong: $t_n = c_{in} + t_1 n^b$
- S-Curve: $t_n = c_{in} + t_1 (n + c_{ex})^b$



$b<1$

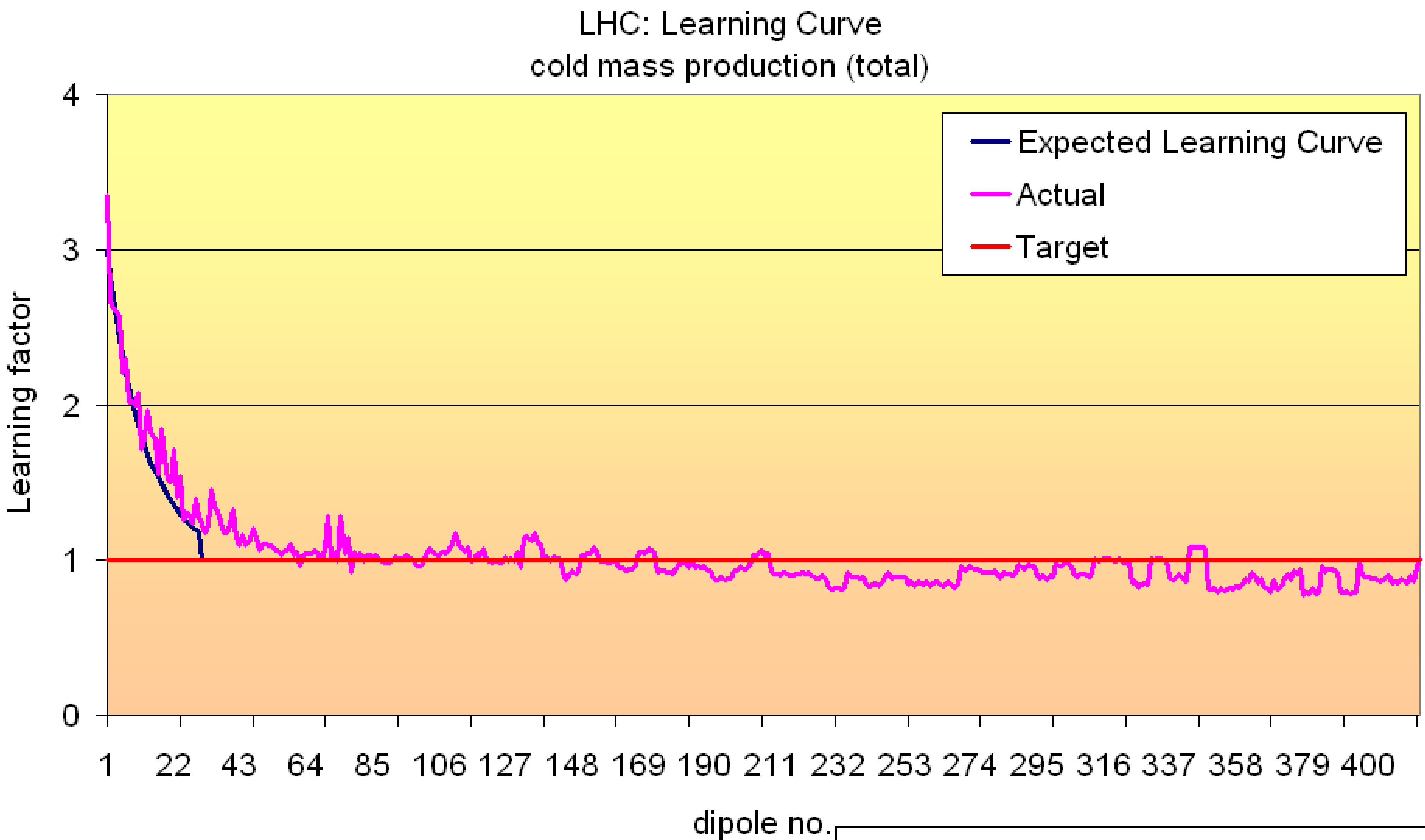
c_{ex} :previous experience

c_{in} :incompressible time (tool limit)

Learning percentage:

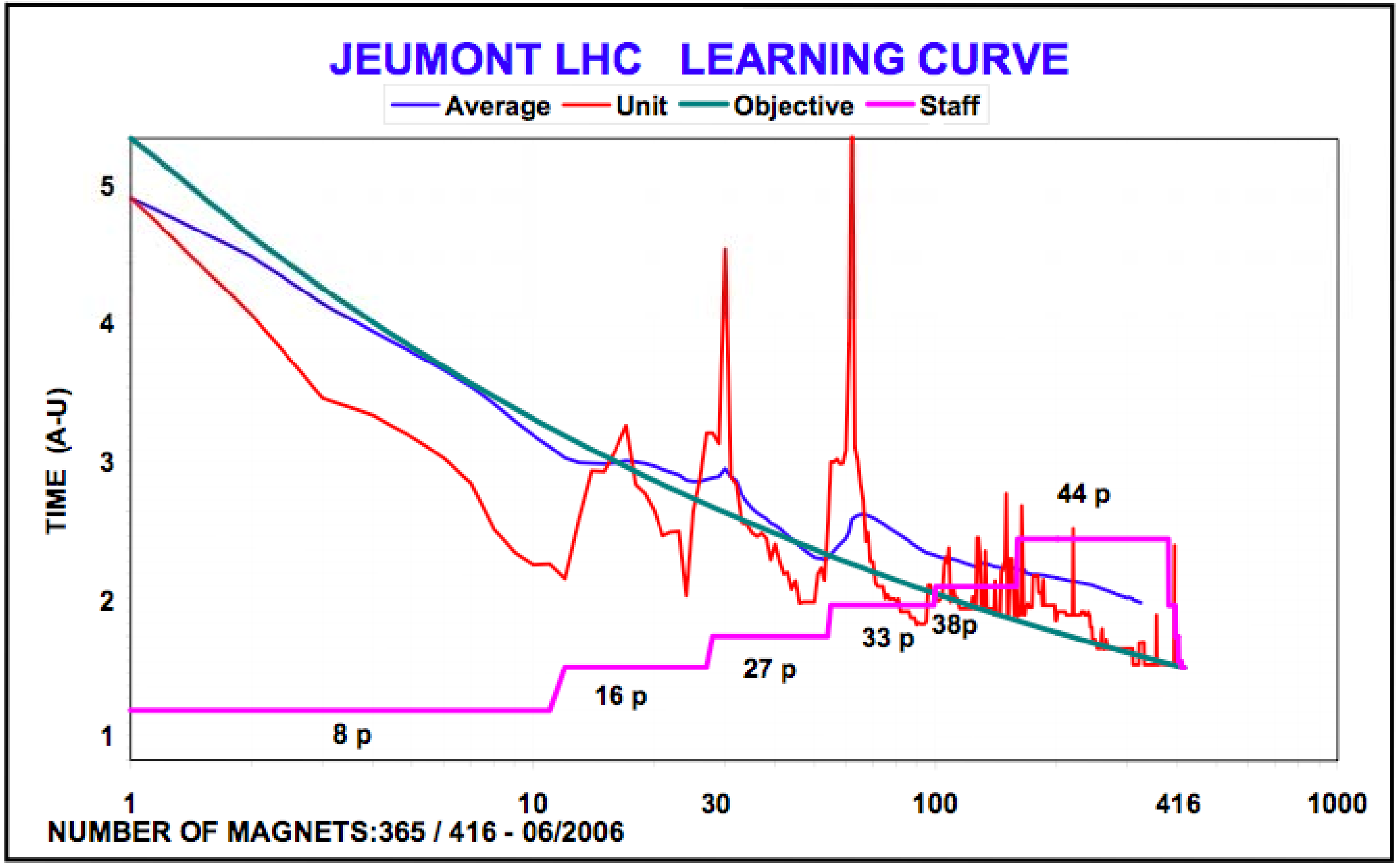
$t_n / t_{2n} = 1/2^b$

LHC: Learning Curve
COLLARED COIL PRODUCTION

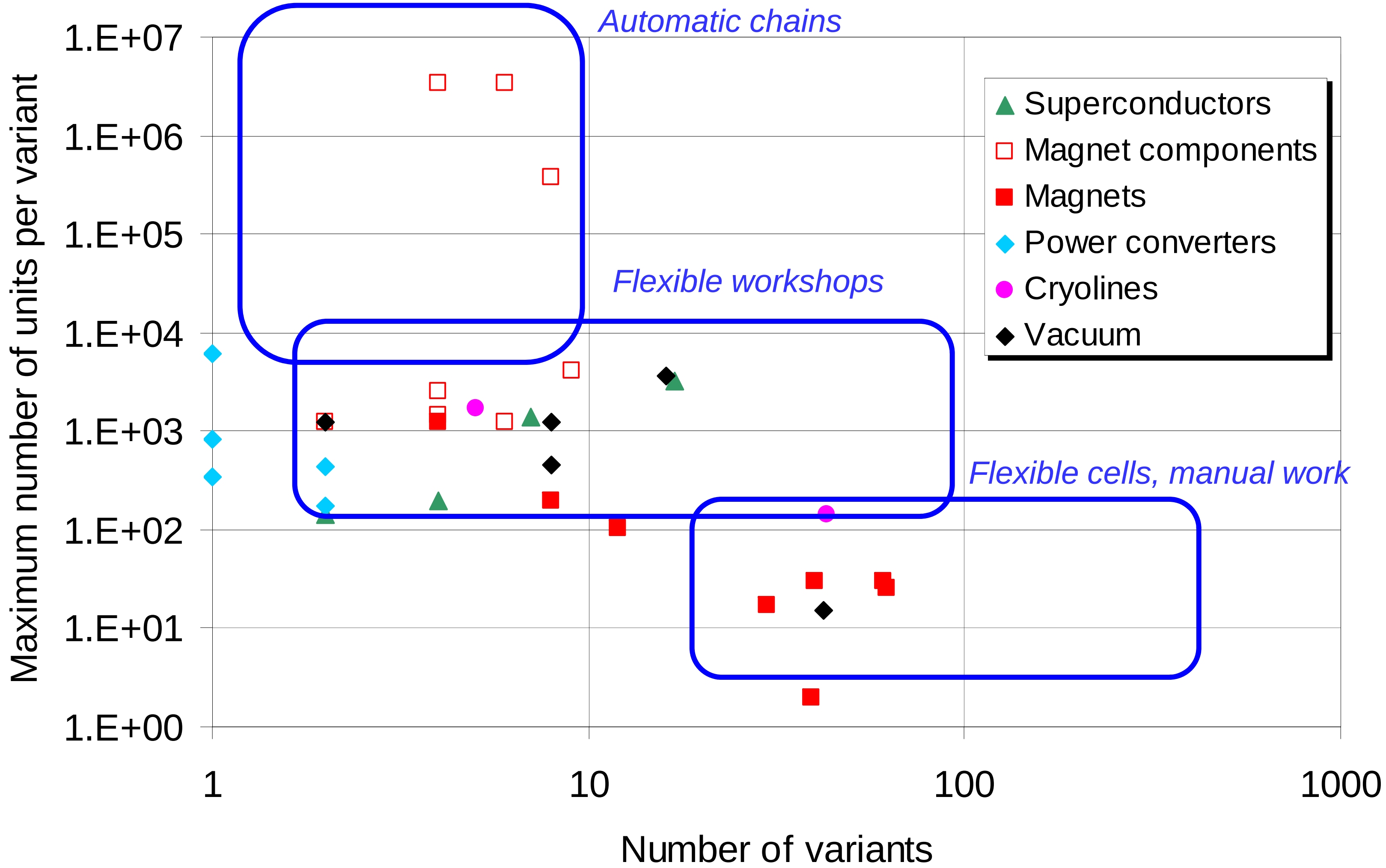


Courtesy of Babcock Noell, Germany

Courtesy of Jeumont, France



Series production of LHC components



Courtesy of Ph. Lebrun

Conclusion: What can we learn from LHC magnet production for XFEL / ILC planning

- SC magnet and cavity fabrication is not (yet) of the shelf technology
  - Very tight supervision of companies is recommended
  - XFEL production will improve the situation, but can companies preserve this expertise until ILC construction?
- Cryostat assembly time (=cost) levels around 50 units
- QA on some components for ILC (e.g. Nb sheet scanning) might require automatic chains
- A pre-series production (after proto-typing) will establish the required expertise at companies for realistic bidding without too high risk margin.
  - A cooperative spirit should be established between scientific laboratories and production companies in early time