Particle Accelerators Past and Future

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9 November 2016

This work represents the opinions of the author and not the DOE.

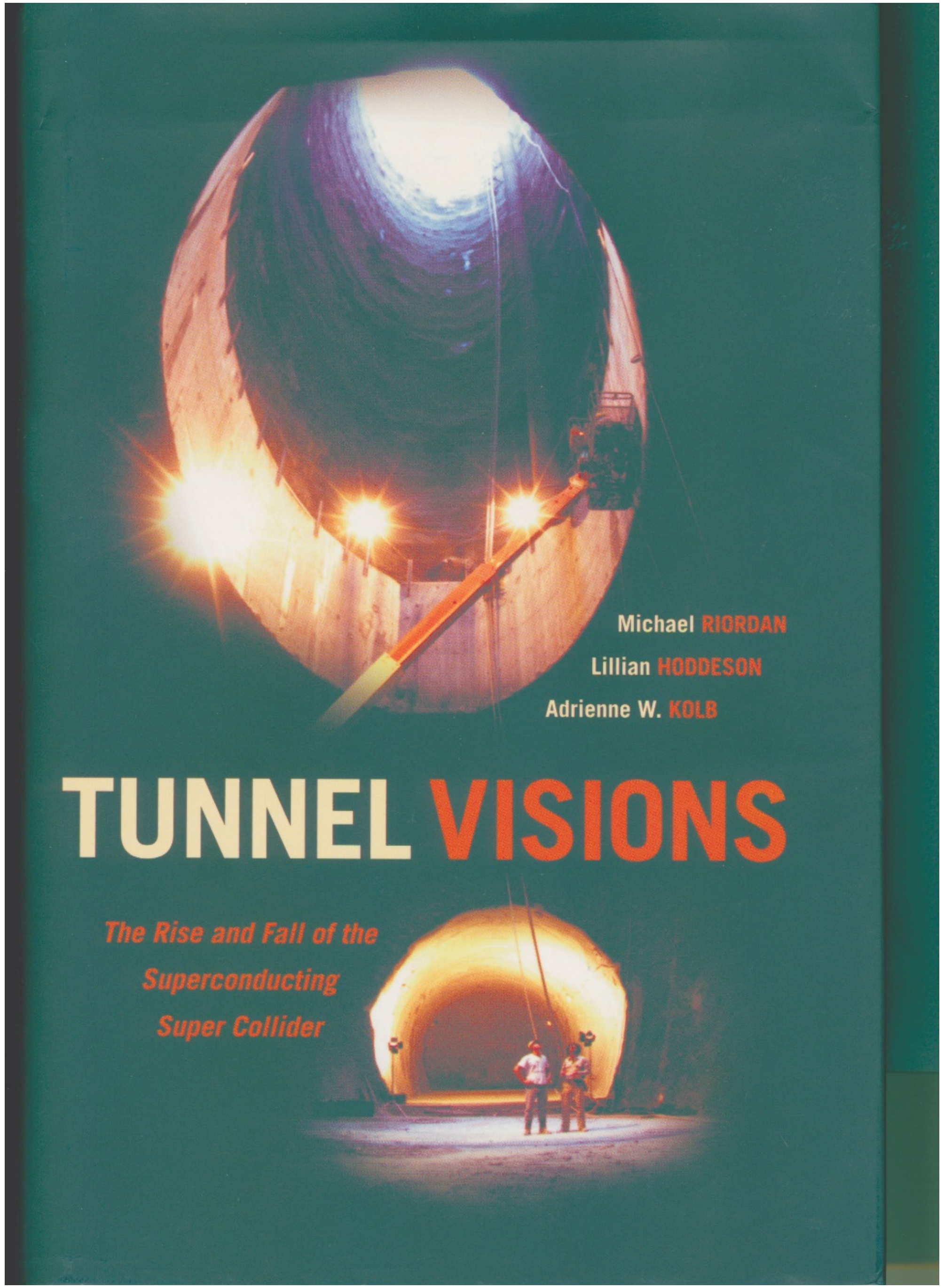
Physics Today, October 2016

Michael Riordan, Lillian Hoddeson and Adrienne W. Kolb,

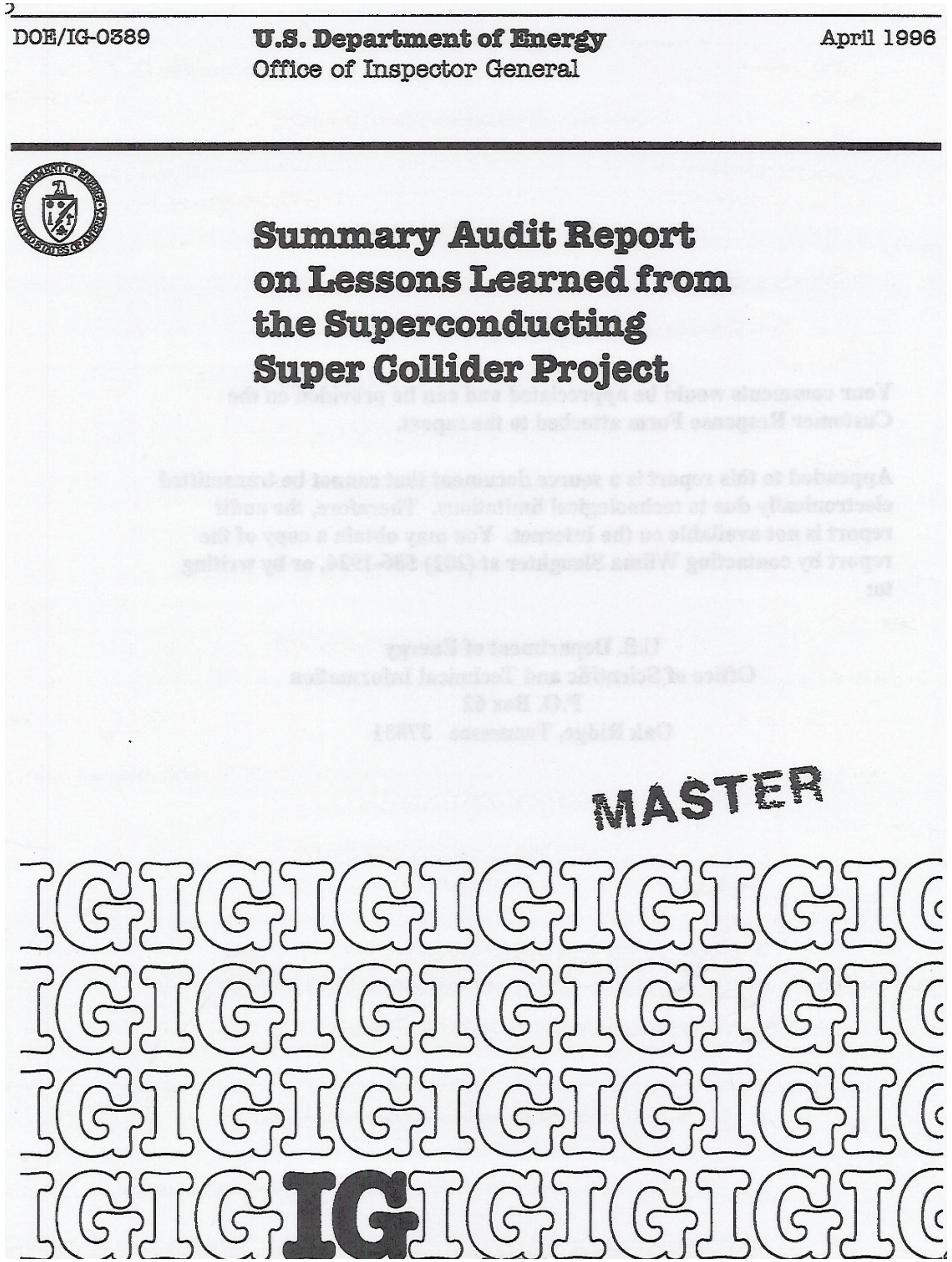
Tunnel Visions

University of Chicago Press, Chicago 60637

2015



U. S. Department of Energy
Office of the Inspector General
April 1996


DOE/IG-0389

U.S. Department of Energy
Office of Inspector General

April 1996

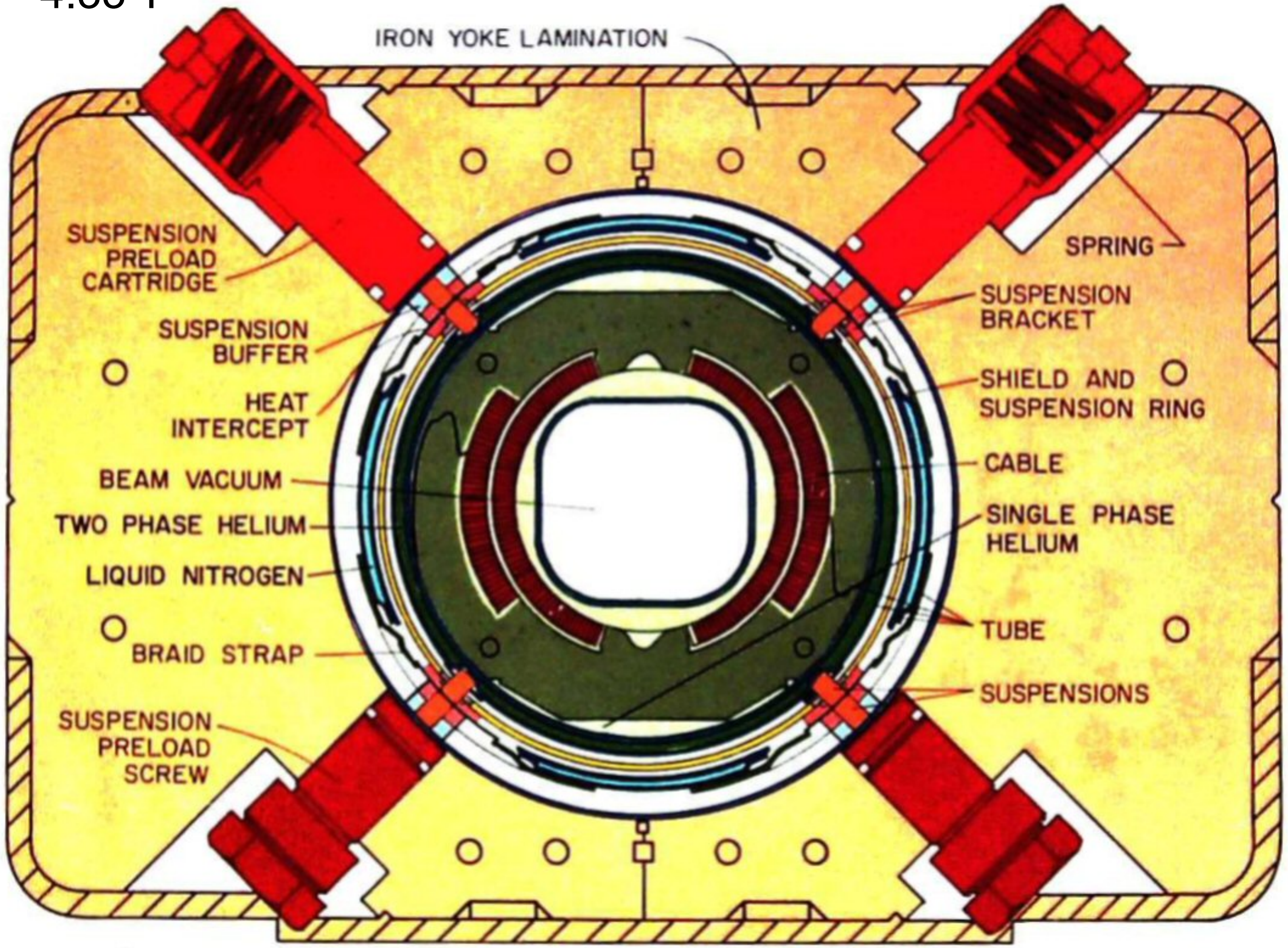
Summary Audit Report on Lessons Learned from the Superconducting Super Collider Project

MASTER


WE HAVE MET THE ENEMY AND HE IS US.
© 1971 WALT KELLY

Tevatron Dipole

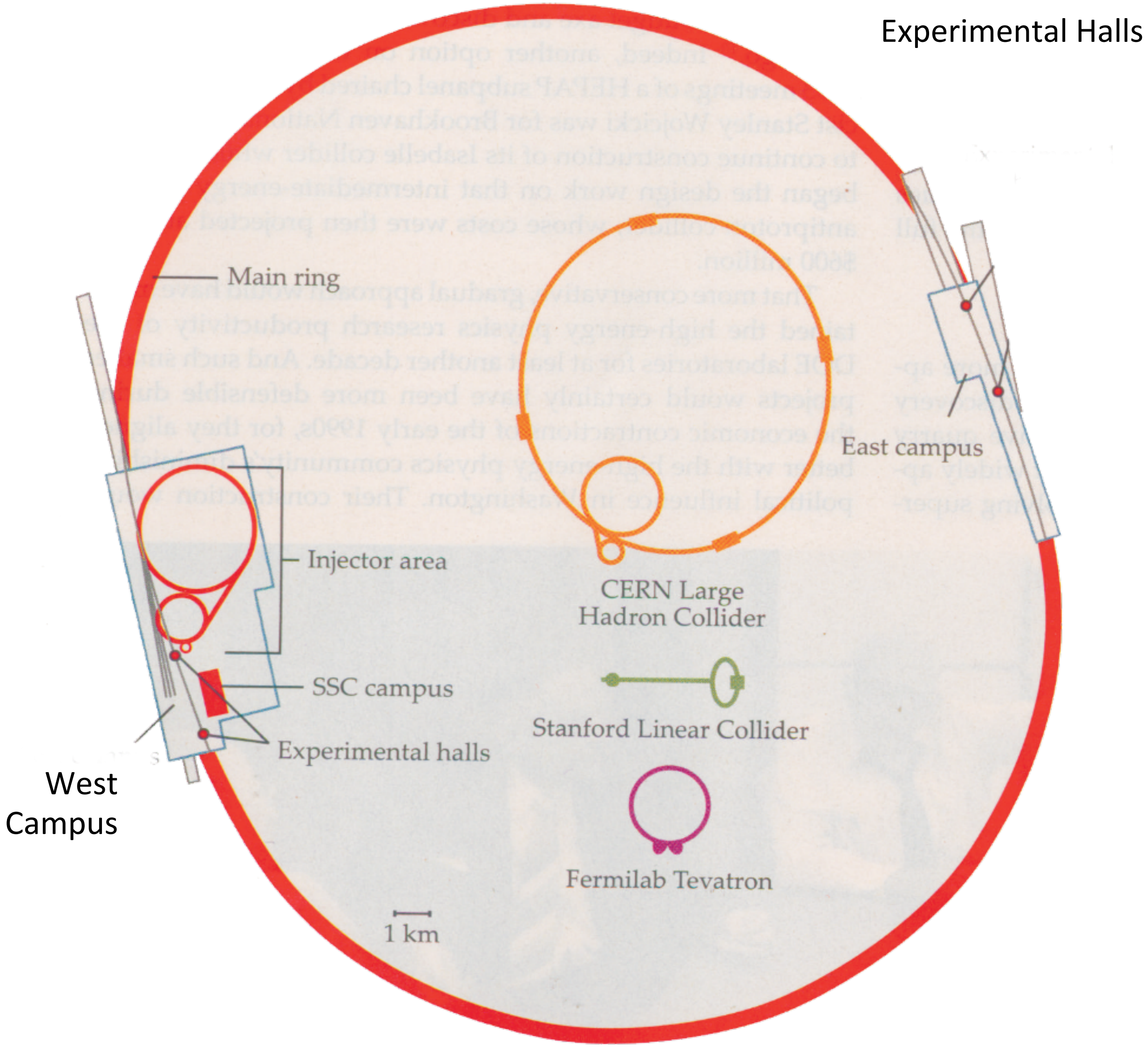
B operating = 4.33 T



Where did the SSC go Wrong?

- Fitting the technology and budget into a small sack.
- Technology was not timely resolved.
- Cost assumptions and scaling were in error.
    - Assumptions became dogma.
- Scale of the project required new management structures and systems that fit a DOE and not a DOD project.

SCALE



Experimental Halls
Main ring
Injector area
SSC campus
Experimental halls
West
Campus
East campus
CERN Large
Hadron Collider
Stanford Linear Collider
Fermilab Tevatron
1 km

Technology in Hand?

"In a few cases, those responsible for the design of projects were so sure of their own brilliance that they felt they could handle the use of new technology although others had failed. They invariably had serious problems and acquired humility the hard way."

"Understanding the Outcomes of Megaprojects," E. W. Merrow, RAND Corporation, March, 1988

Technology in Hand?

"None of the above discussion should be interpreted as being "anti-innovation." Rather, megaprojects are simply inappropriate vehicles for experimentation. If project economics cannot withstand appreciable cost growth, schedule slippage, and performance shortfalls, thoroughly proven technology should be used throughout or the project should be abandoned. If the project economics do not look favorable with conventional technology, new technology is very unlikely to provide the answer, although it may enable project champions to delude themselves, their sponsors, and lenders in the short run."

"Understanding the Outcomes of Megaprojects," E. W. Merrow, RAND Corporation, March, 1988

What specifically went wrong?

Technology assumptions

- We can make high field Nb-Ti magnets.
- We can operate close to the short sample limit.
- We can save money by reducing the bore.
- We can transfer the technology to industry.

Cost Estimates

- We can achieve a 20% learning curve.
- We will build a small cross section tunnel.

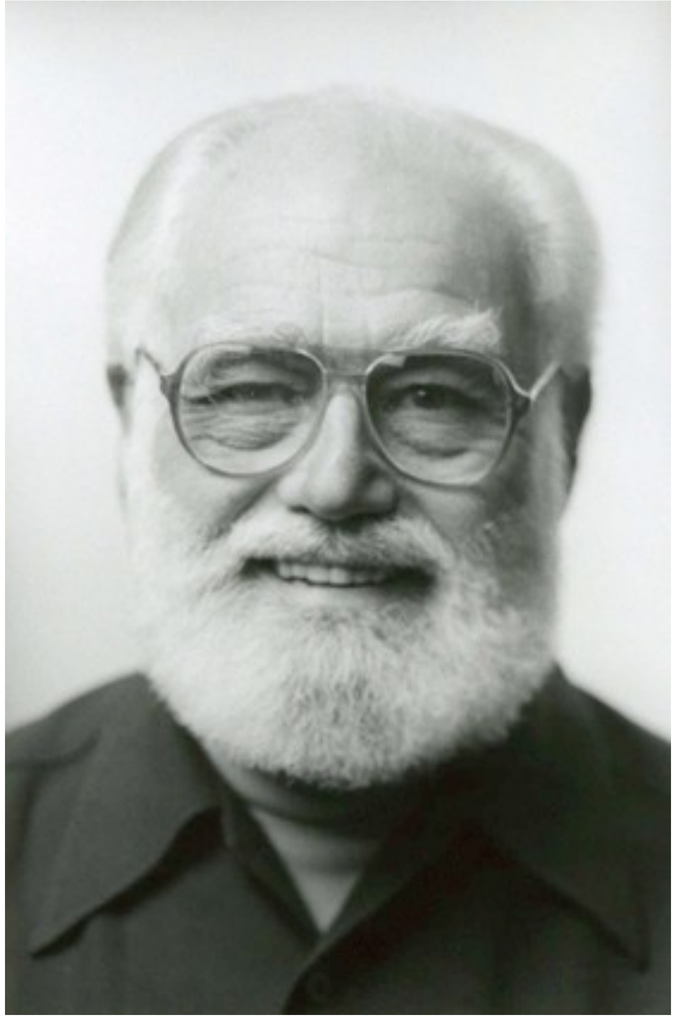
Cost and Schedule Control System

Business Management Systems

Facts vs. Assumptions

My first laboratory director, Professor Arthur Kantrowitz, then of Avco Everett Research Laboratory, would remind us to:

“Remember to separate the facts from the assumptions.”



Technical Assumptions

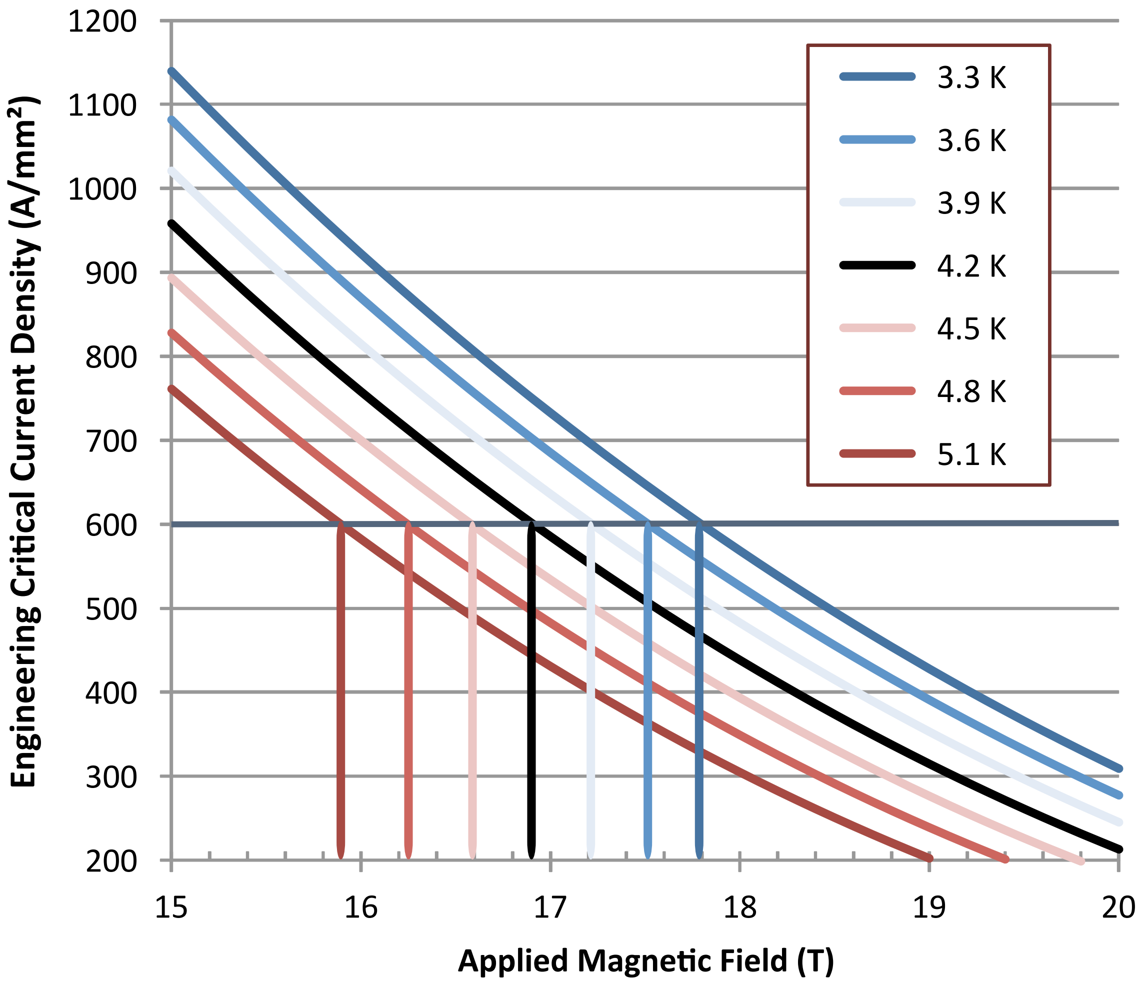
Arthur Kantrowitz

- Circle your assumptions
- Separate facts from assumptions

Technical Assumptions / Magnets

- Operate close to the short sample limit
- Cost assumptions of raw materials
- Cost of superconductor to fall
- Reduce the bore
- Technical transfer
  - Between Labs—NIH
  - To manufacturers

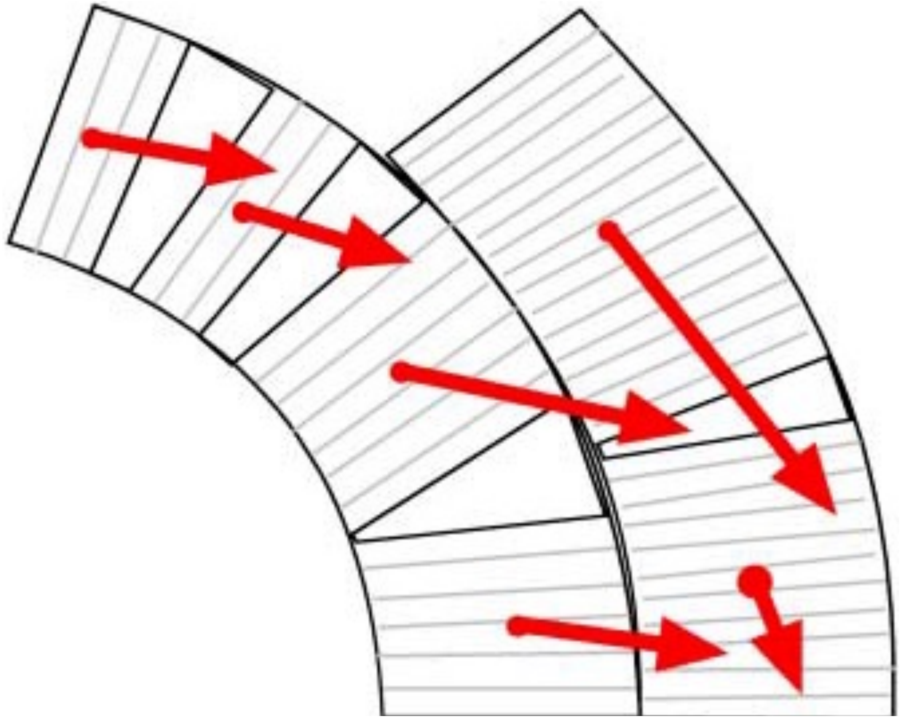
J_e Sensitive to Operating Temperature



4.2 K RRP® data scaled using Nb_3Sn Scaling Spreadsheet - Matthijs Mentink, Diego Arbelaez, Arno Godeke [LBNL]

Available from http://fs.magnet.fsu.edu/~lee/plot/plot.htm

Nb_3Sn (RRP®): Non-Cu J_c Internal Sn OI-ST RRP® 1.3 mm, Parrell, J.A.; Youzhu Zhang; Field, M.B.; Cisek, P.; Seung Hong; , "High field Nb_3Sn conductor development at Oxford Superconducting Technology," Applied Superconductivity, IEEE Transactions on , vol.13, no.2, pp. 3470- 3473, June 2003.
doi: 10.1109/TASC.2003.812360 and Nb_3Sn Conductor Development for Fusion and Particle Accelerator Applications J. A. Parrell, M. B. Field, Y. Zhang, and S. Hong, AIP Conf. Proc. 711, 369 (2004), DOI:10.1063/1.1774590.



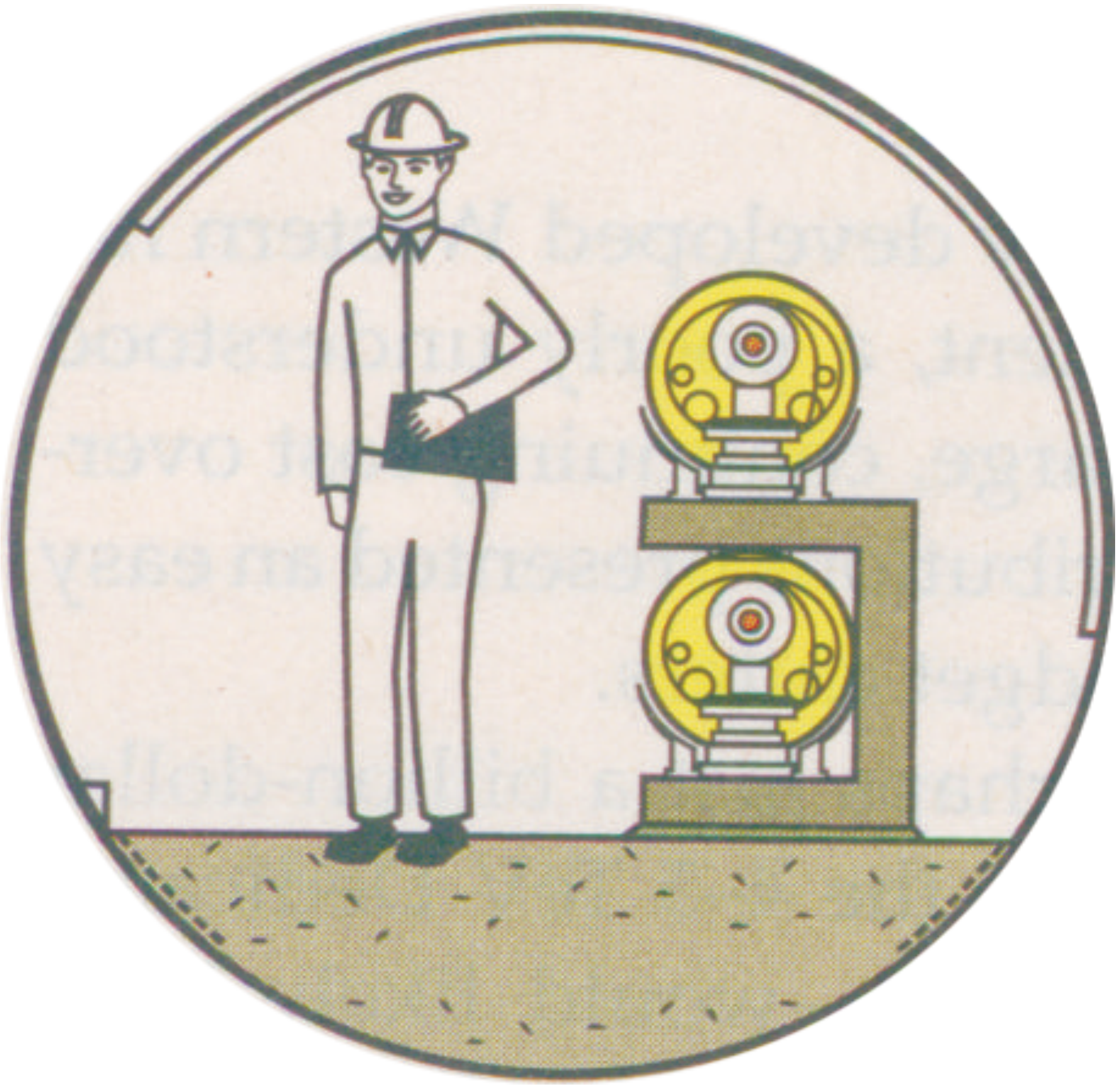
Cost Assumptions / Magnets

- Operate close to the short sample limit

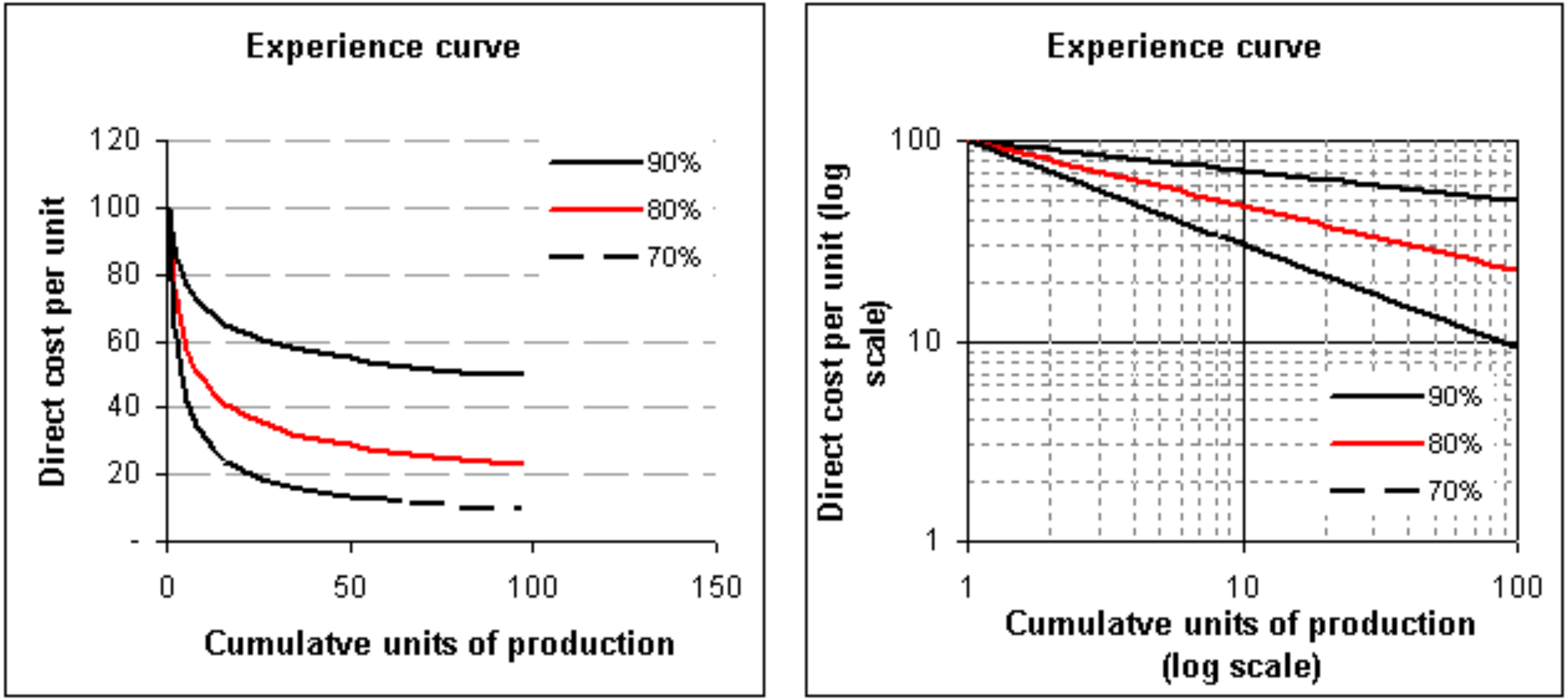
- Cost of superconductor to fall
- Not evident for HEP conductor in the past 25 years

- Reduce the bore
- Cost does not go to the origin

- Learning curve is 20%
  - Toyota is 8%
  - HERA is 8%



Tunnel Cross Section



Experience curve
120
100
80
60
40
20
-
Direct cost per unit
0
50
100
150
Cumulatve units of production
90%
80%
70%
Experience curve
100
10
1
Direct cost per unit (log scale)
1
10
100
Cumulatve units of production (log scale)
90%
80%
70%

Costing

Scientists and engineers should be very careful when using the "Learning Curve."

Cost Considerations

Can you live within a shrinking budget box?

Prototypes to Production

- R&D is done!
- A cultural change of team members
- Production design changes acceptable

Manufacturing Process

Built to print and build to ***process!***

When is the Low Bid NOT the Least Expensive?

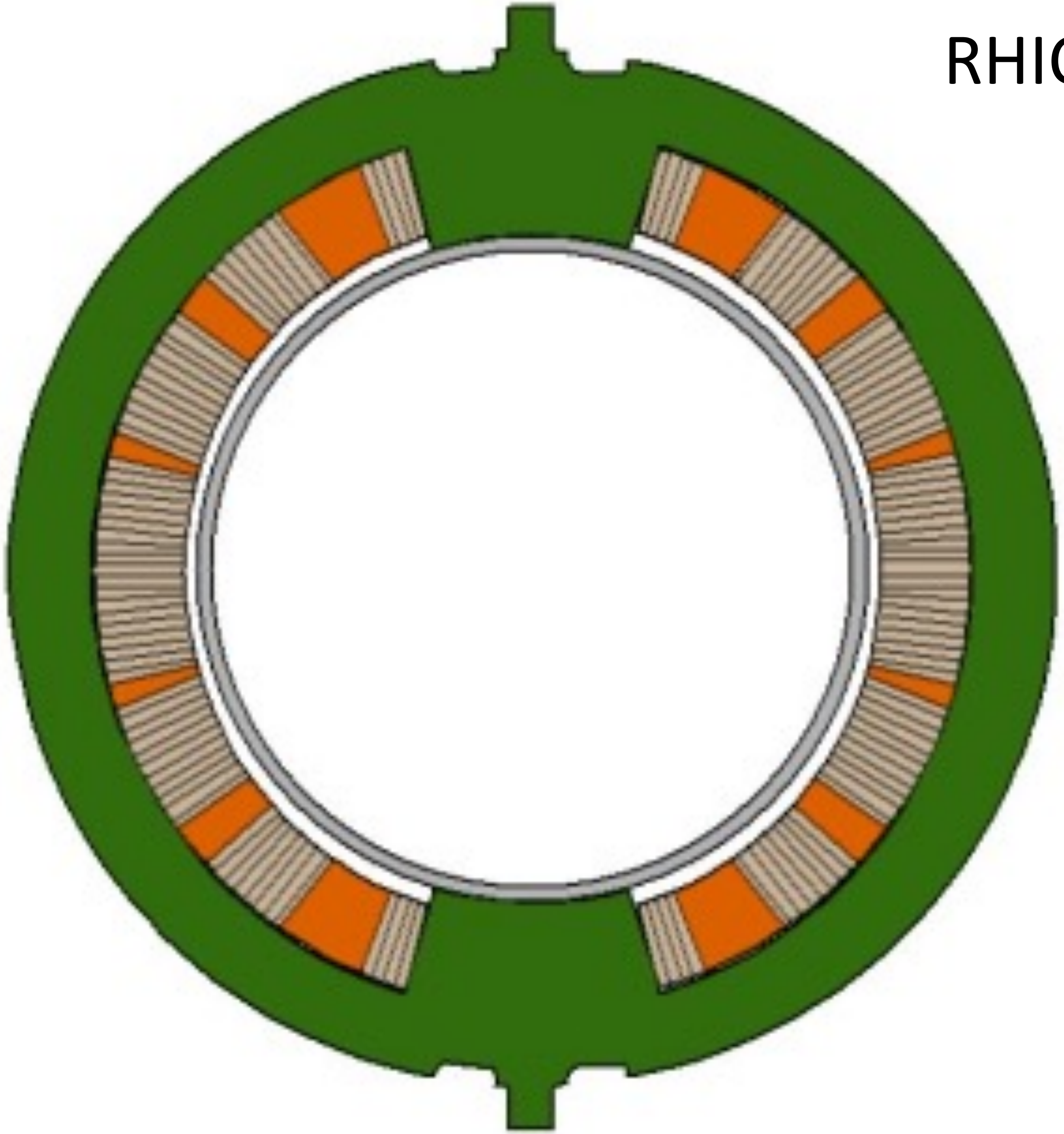
- Gross under bid
- No corporate track record
- Corporate performance record
- Corporate depth
  - Financial
  - Infrastructure
  - People

Getting to Project Start

RHIC and HERA

- Conservative magnet designs
- Made in industry
  - Excellent technology transfer!
- Turned on and operating!

RHIC Magnet Winding
Cross Section



CERNLHC

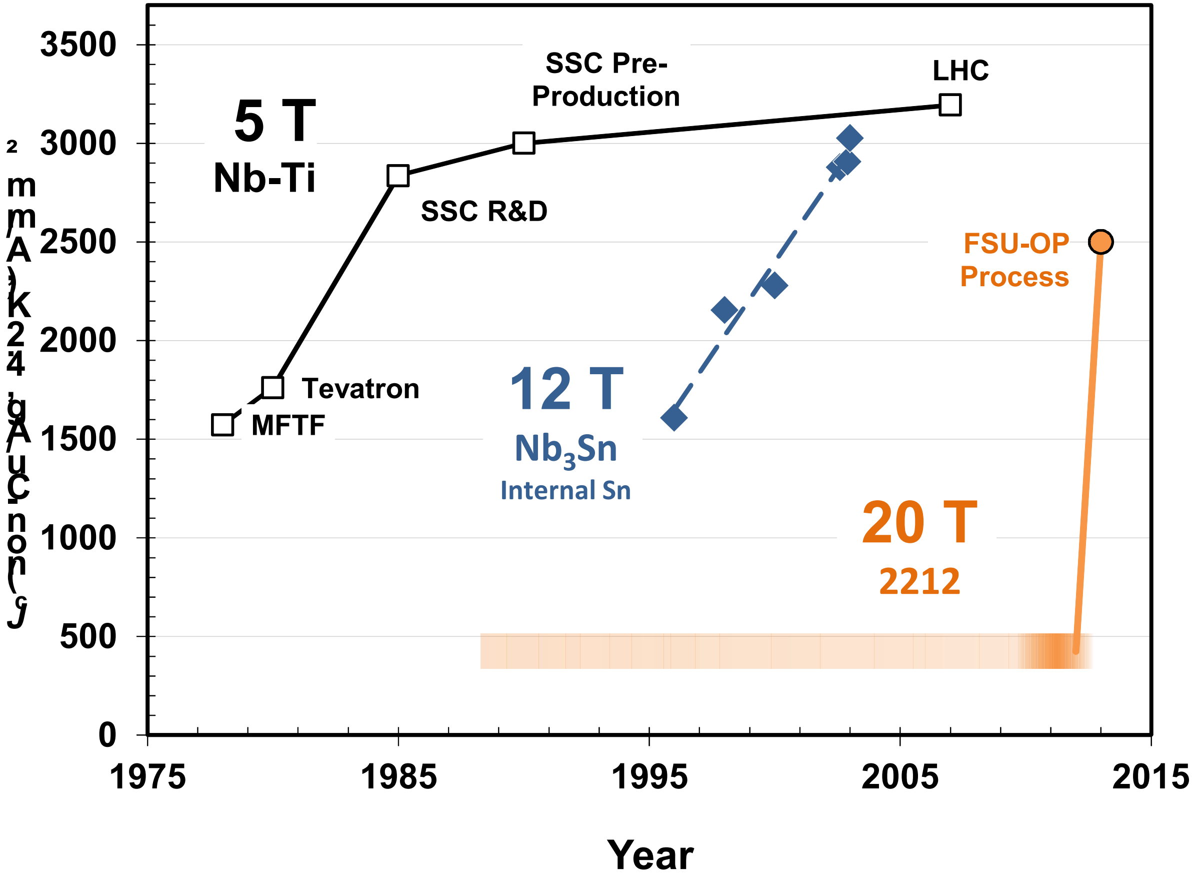
- Existing tunnel
- Decade of technical development
- Existing management infrastructure
- Cooperative development with industry
- Cold masses made in industry. Four vendors.
  - Pricing surprise!
- Final Cryostat assembly and testing at CERN
- The incident!

Development for the Next Generation

US DOE HEP DEVELOPMENT

- Nb_3Sn and HTS Development
- Nb_3Sn R&D Dipoles
- Nb_3Sn Quads

Progress in Nb-Ti, Nb_3Sn and Bi-2212 compared (magnet-relevant long length J_c(4.2 K) values only)



Note that all three conductors are round, multifilament, twisted and stabilized with high purity normal metal.

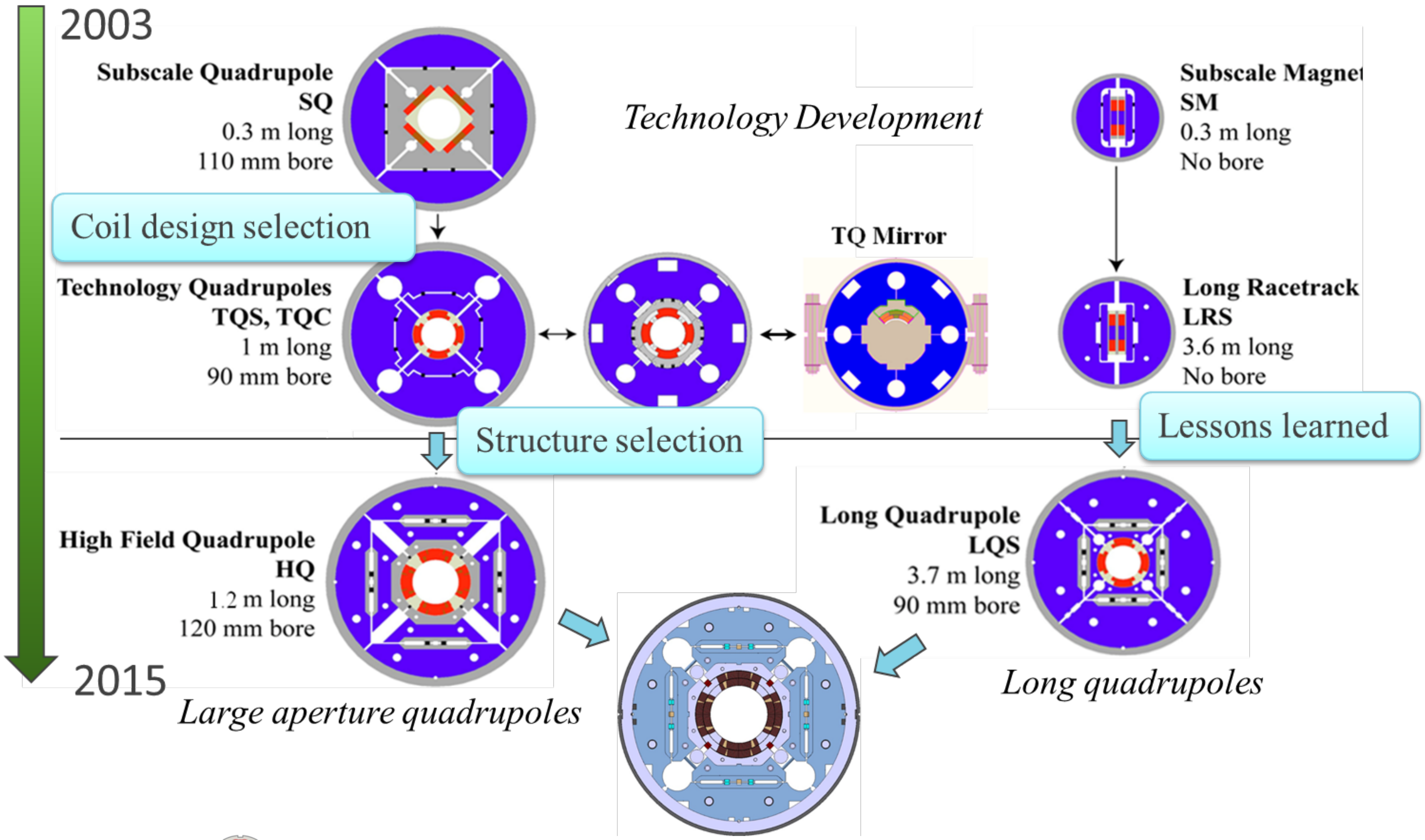
CERN Hi-Lumi

U.S. Contributions to the LHC

- **The LHC and its upgrades are a core part of the U.S. program**
  - DOE participated in the design, construction, and operation of the LHC and its detectors since the original 1997 International Cooperation Agreement between CERN, DOE, and NSF
  - The unique scientific capabilities of the LHC promise compelling science for decades to come

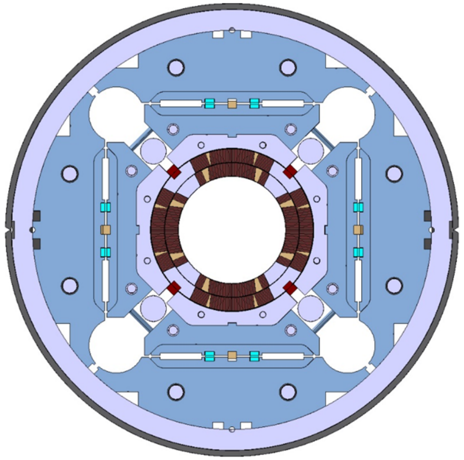
- **DOE contributions to the HL-LHC accelerator and detector upgrades will leverage our areas of technical expertise and capitalize on previous investments**
  - Long-term investments in the U.S. LHC Accelerator Research Program (LARP) enables accelerator contributions that will be key to the HL-LHC program
  - Long-term investments in silicon-based detector R&D enable U.S. leadership in the ATLAS and CMS inner trackers and the CMS high-granularity calorimeter

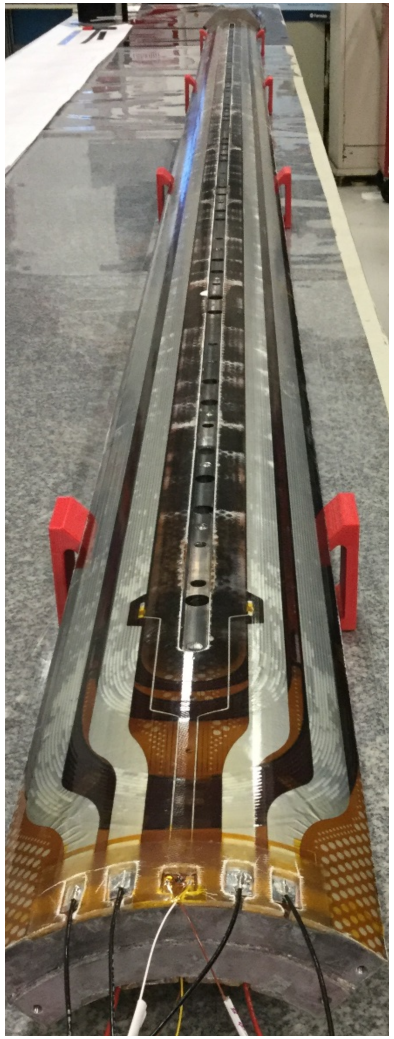
MQXF is based on LARP Nb_3Sn Development

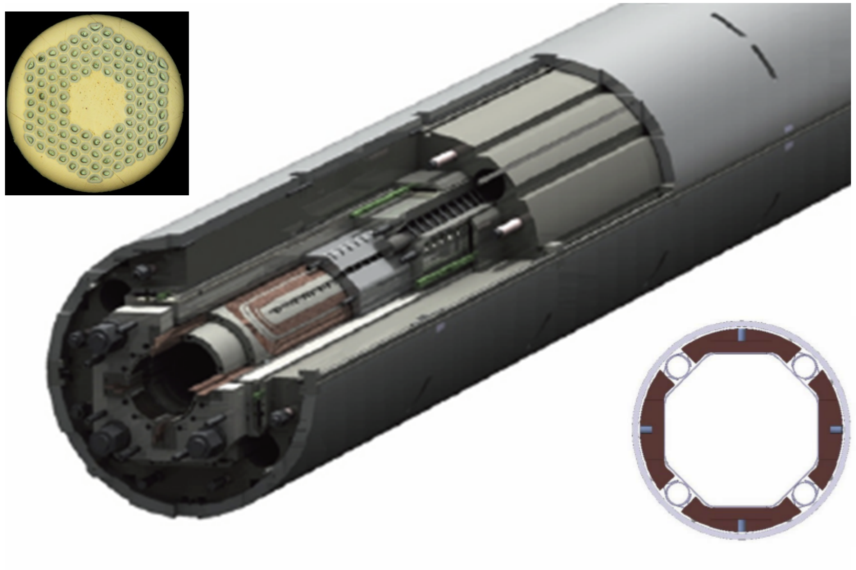


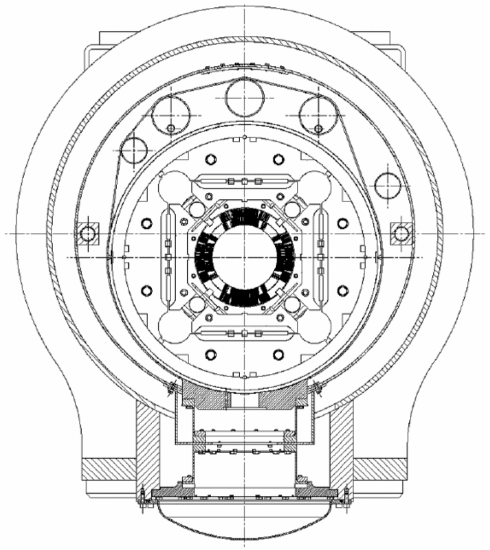
MQXF Quadrupole Parameters and Design

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nom. current	T	11.4
Stored energy at nom. curr.	MJ/m	1.2
Diff. inductance	mH/m	8.2



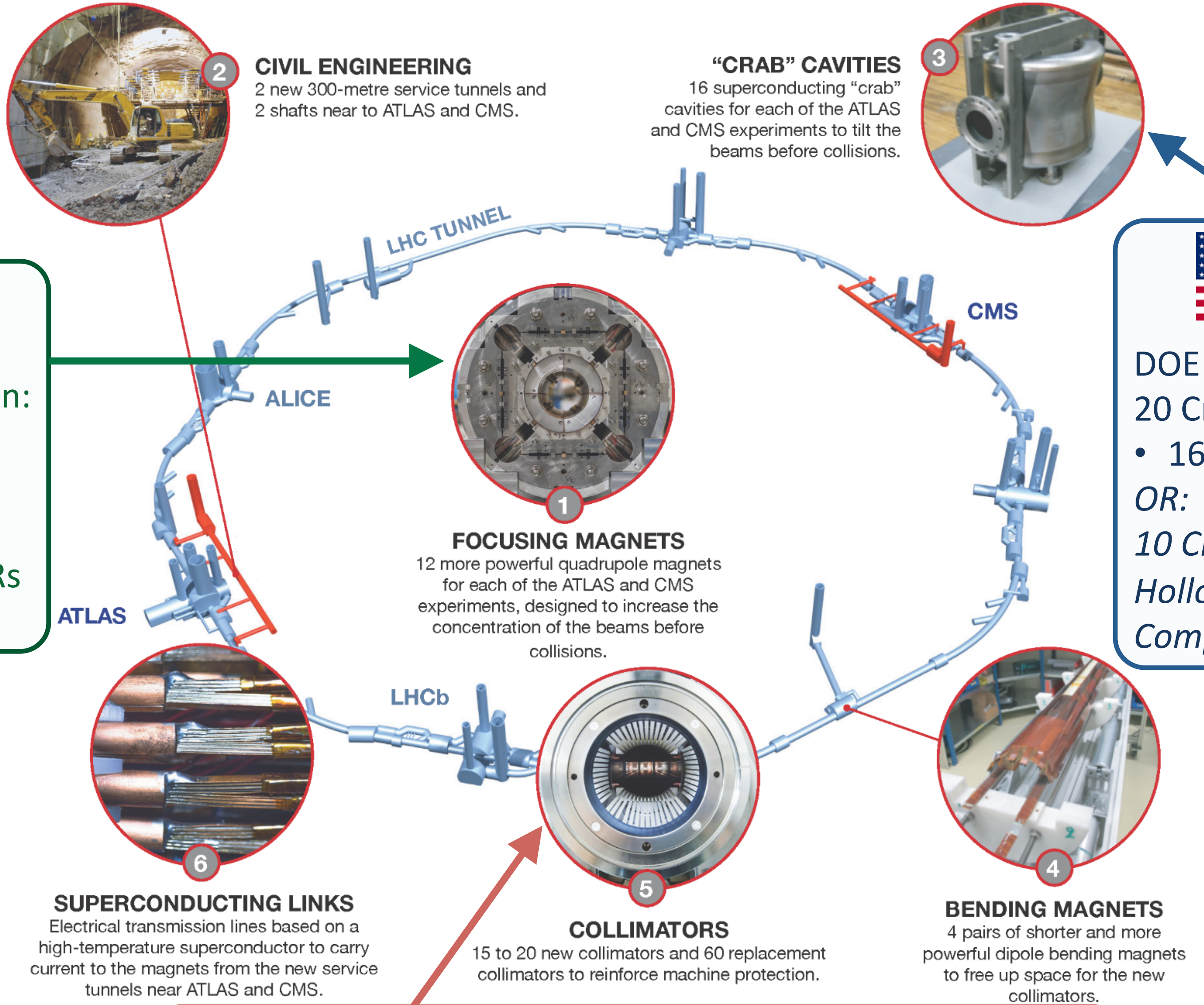






HL-LHC Accelerator Upgrades:
Enabling U.S. Science Participation

DOE contribution:
10 Cold Mass Assemblies
- 4 each for ATLAS/CMS IRs
- 2 spares



DOE contribution:
20 Crab Cavities
- 16 + 4 spares

OR:
10 Crab cavities & Hollow e-Lens Components

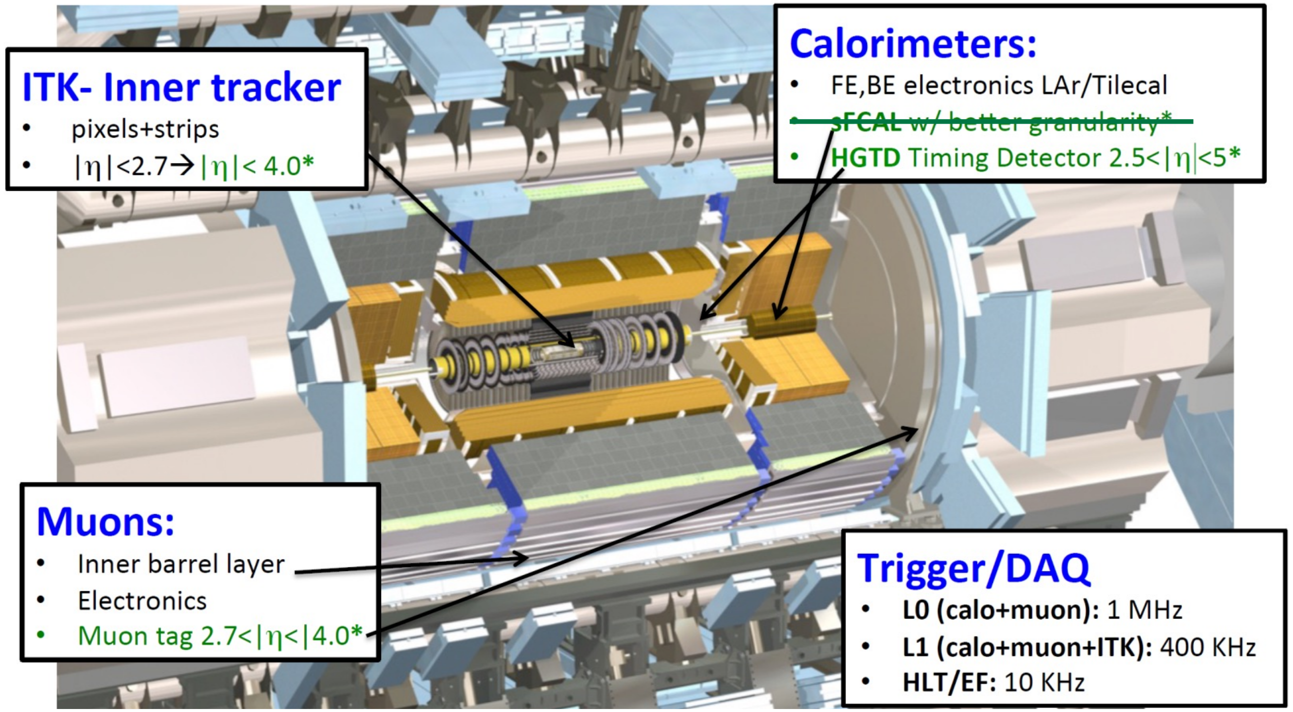
DOE contribution:
Hollow e-Lens Components (under discussion)

ATLAS HL-LHC Upgrade

- **U.S. ATLAS has defined the scope of its potential contributions to the HL-LHC upgrades**
  - Driven by future science discovery potential while leveraging the interests and experience of U.S. groups
  - Active coordination with international ATLAS — at all levels

- **DOE Scope:**
  - Barrel ITK (pixel & strip detector)
  - DAQ hardware (data flow elements)
  - LAr front end analog chip development

- **NSF Scope:**
  - Trigger and readout electronics for LAr, Tile, Muons



** Large eta scenarios, as described in the 2015 scoping document for the reference 275 MCHF CORE cost scenario*

CMS HL-LHC Upgrade

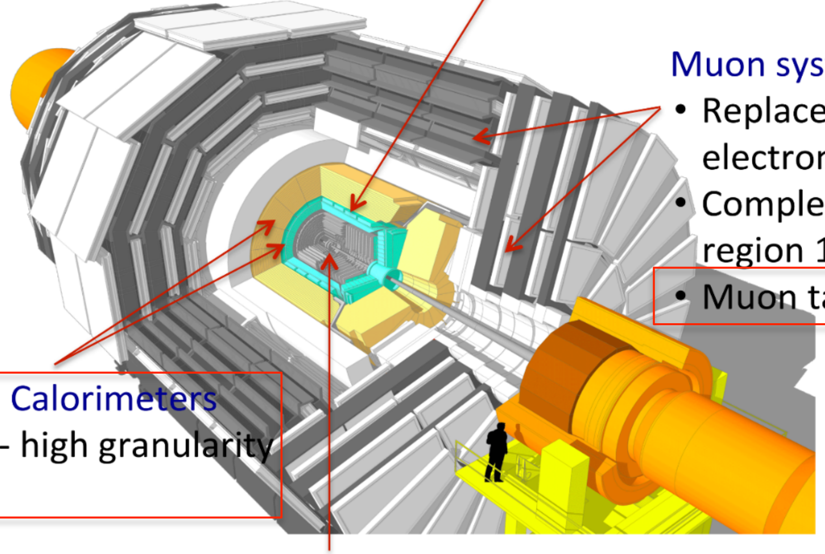
- **U.S. HL-LHC CMS upgrade scope driven by future science opportunities, expertise by U.S. scientists, and coordination with international CMS**

DOE / NSF

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics — NSF
- Lower operating temperature (8◦)

Muon systems
- Replace DT & CSC FE/BE electronics — NSF
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$ — NSF



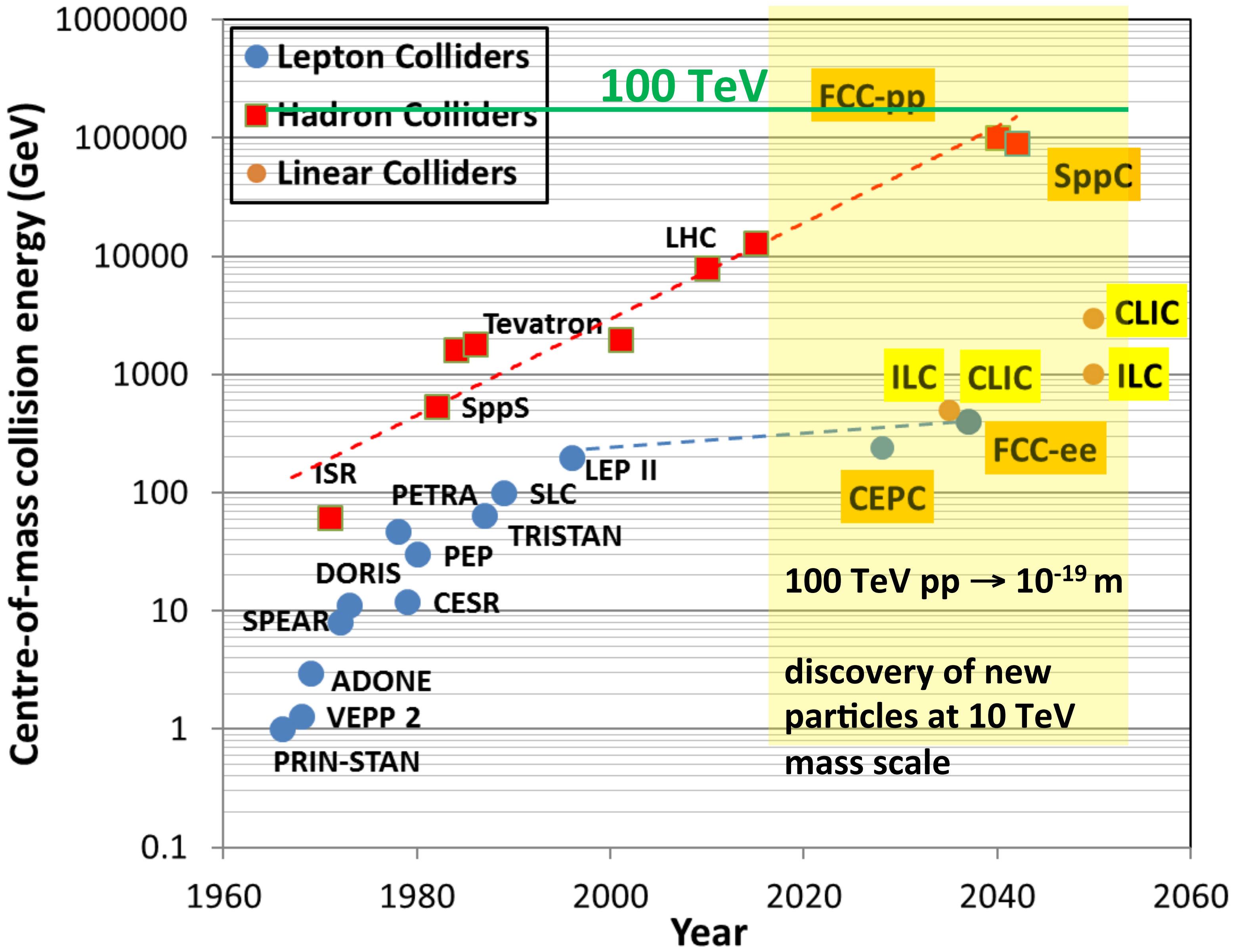
DOE

*Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Replace Tracker *
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger — DOE
- Extend coverage to η = 3.8 — NSF

☐ = Significant U.S. contributions

High Energy Colliders under study



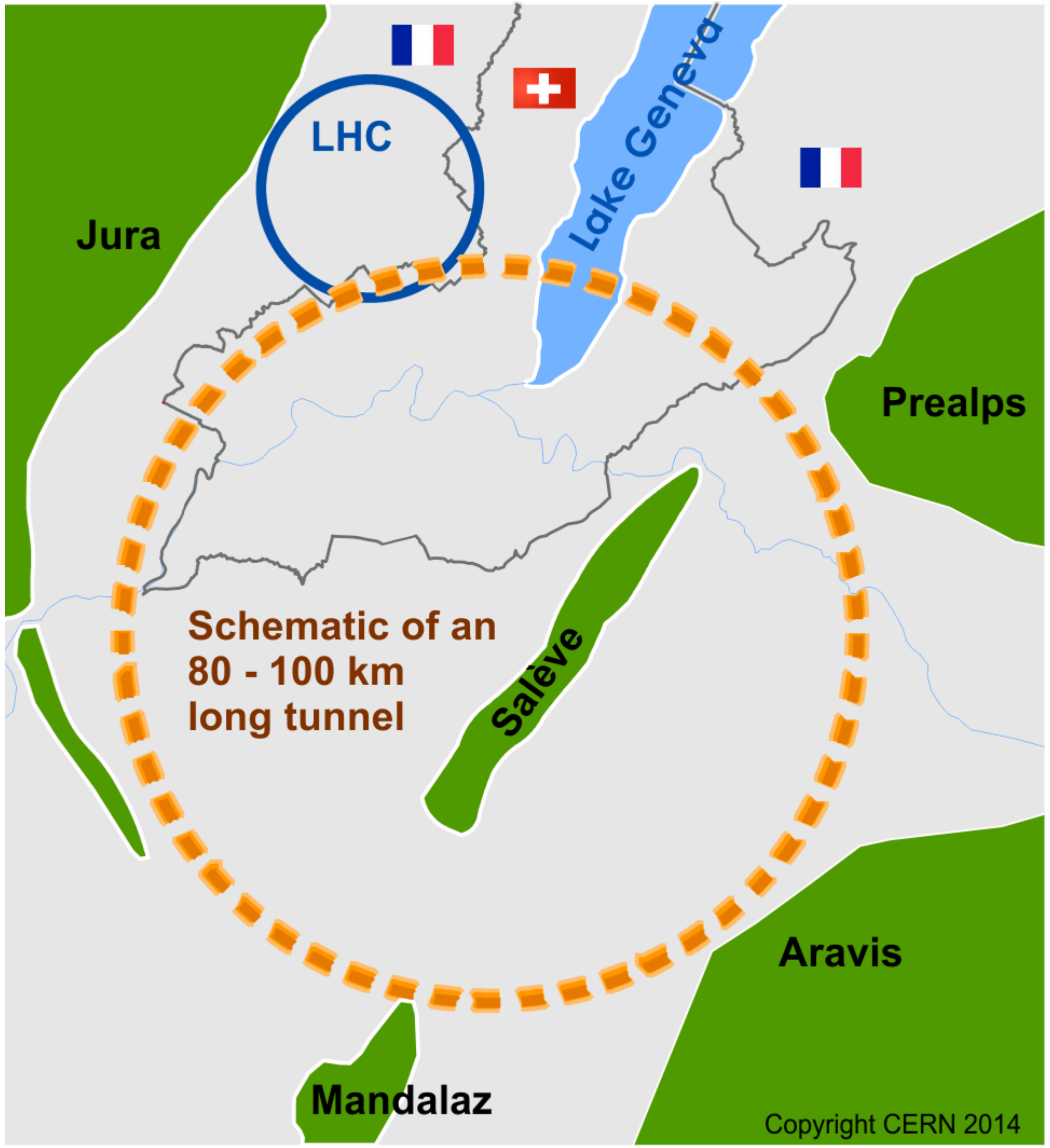
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

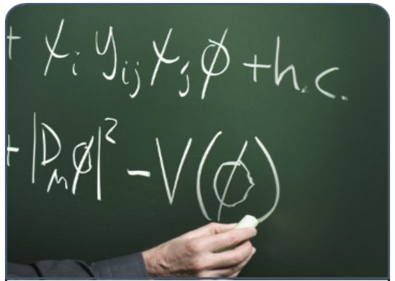
- ***pp*-collider (*FCC-hh*)** → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e*⁺*e*⁻ collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology

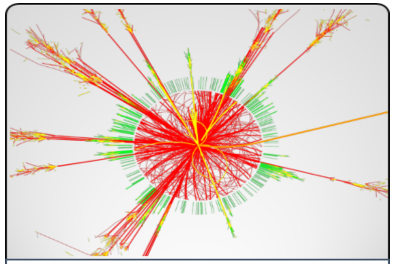


FCC Scope: Physics & Experiments



Physics Cases

Elaborate and document
- **Physics opportunities**
- **Discovery potentials**



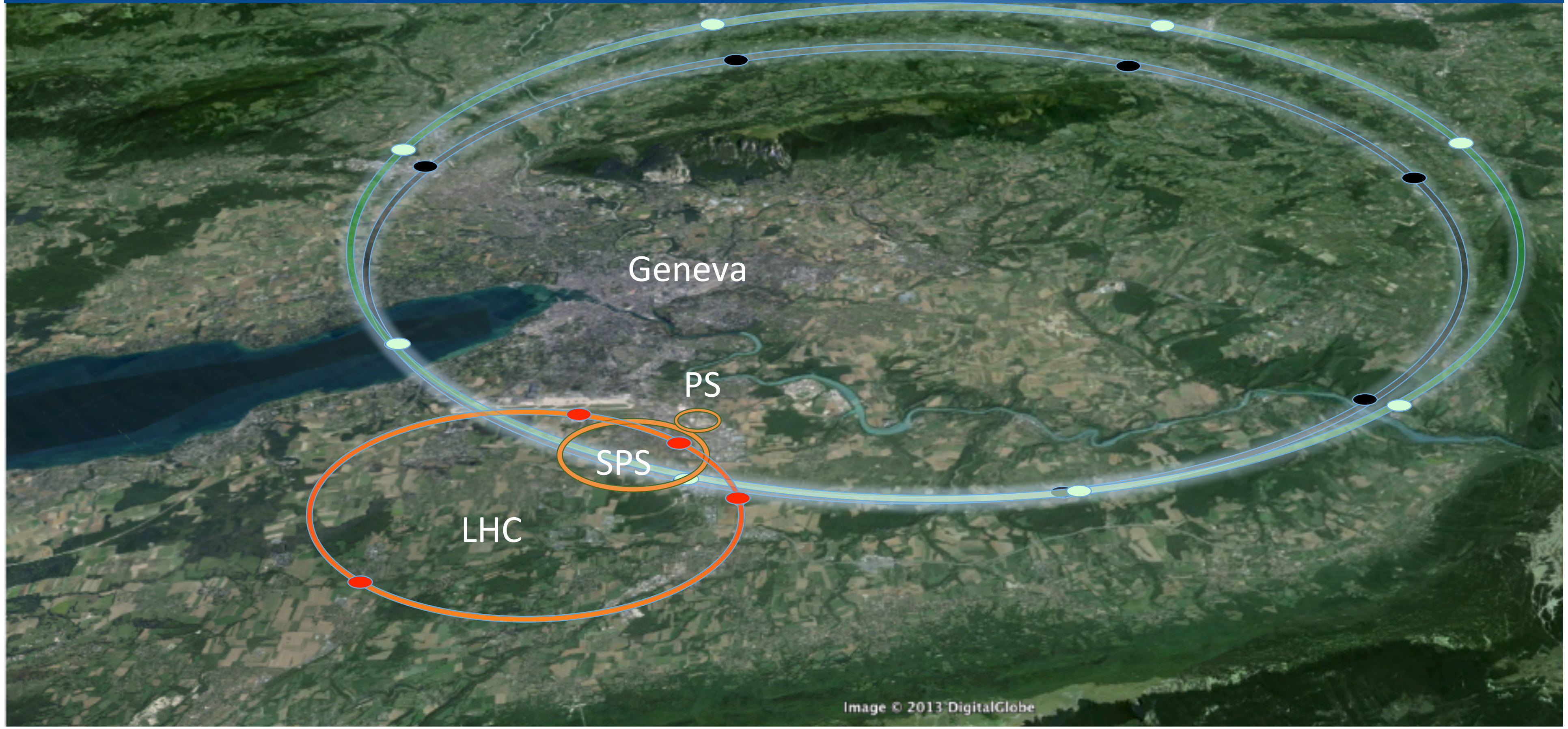
Experiments

Experiment concepts for hh, ee and he
Machine Detector Interface studies
R&D needs for **detector technologies**

Cost Estimates

Overall **cost model for collider scenarios** including infrastructure and injectors
Develop **realization concepts**
Forge **partnerships with industry**

FCC SC main magnet options and requirements



LHC	HE-LHC baseline	FCC-hh baseline	FCC-hh
27 km, 8.33 T	**27 km, 16 T**	**100 km, 16 T**	80 km, **20 T**
14 TeV (c.o.m.)	26 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	**2500 tons Nb_3Sn**	**10000 tons Nb_3Sn**	2000 tons HTS 8000 tons LTS

Main SC Magnet system
FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm

Dipoles: $4578\ units,\ 14.3\ m\ long,\ 16\ T \Leftrightarrow \int Bdl \sim 1\ MTm$

Stored energy ~ 200 GJ (GigaJoule) ~44 MJ/unit

Quads: $762\ magnets,\ \ 6.6\ m\ long,\ 375\ T/m$

LHC

Bore diameter: 56 mm

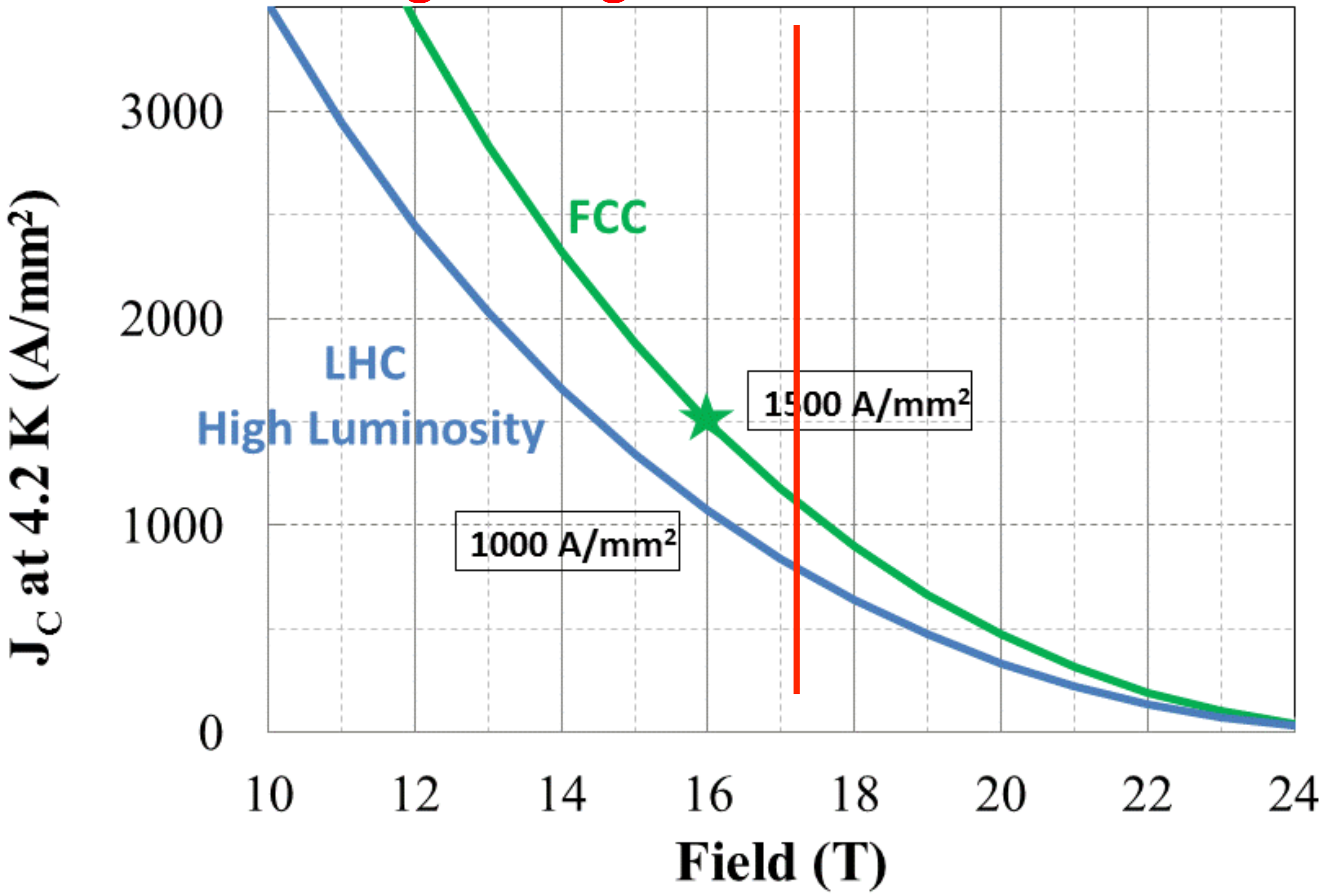
Dipoles: $1232\ units,\ 14.3\ m\ long,\ 8.3\ T \Leftrightarrow \int Bdl \sim 0.15\ MTm$

Stored energy ~ 9 GJ (GigaJoule) ~7 MJ/unit

Quads: $392\ units,\ \ 3.15\ m\ long,\ 233\ T/m$

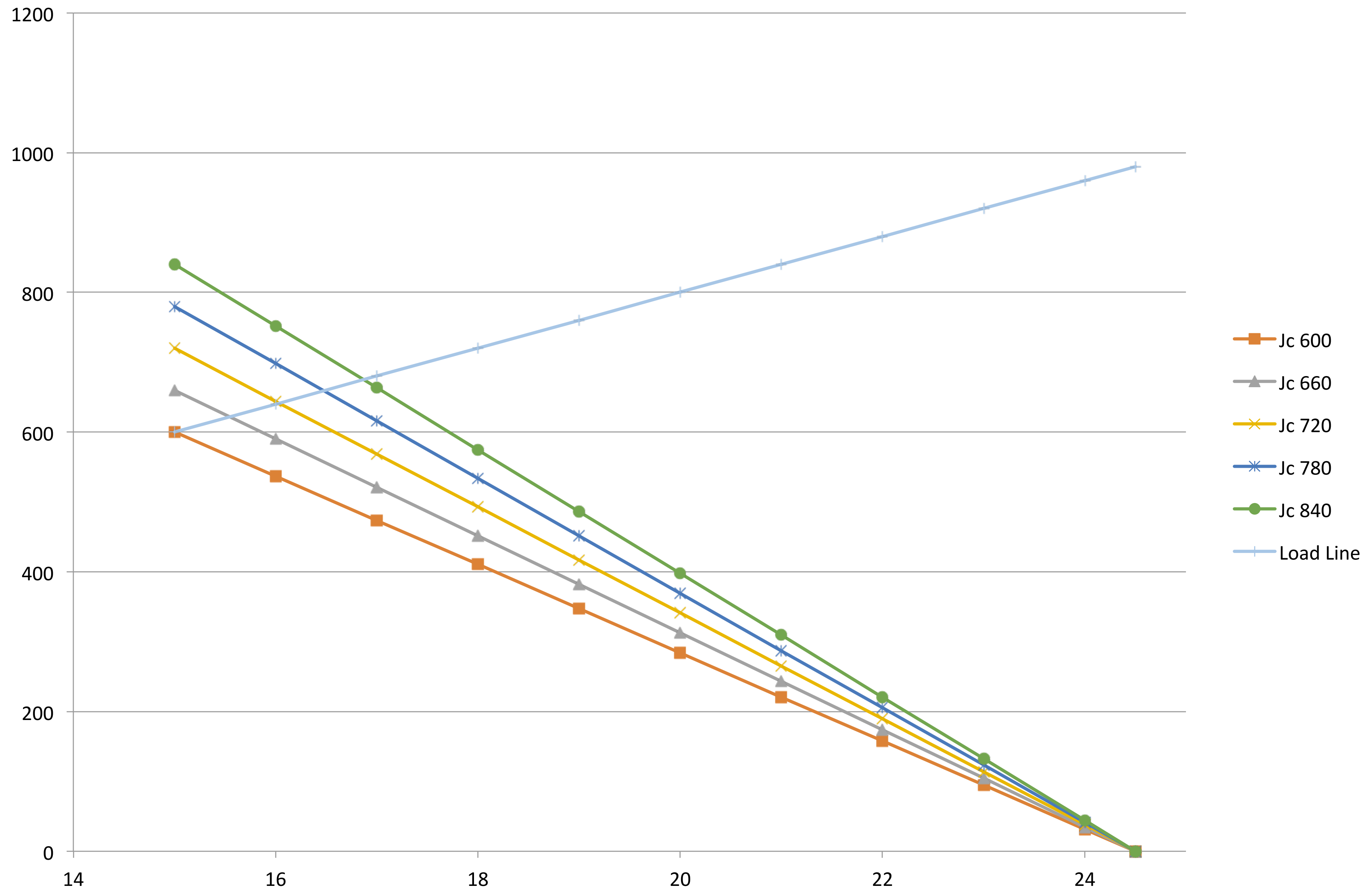
Nb_3Sn conductor program

Nb_3Sn is one of the major cost & performance factors for FCC-hh and must be given highest attention

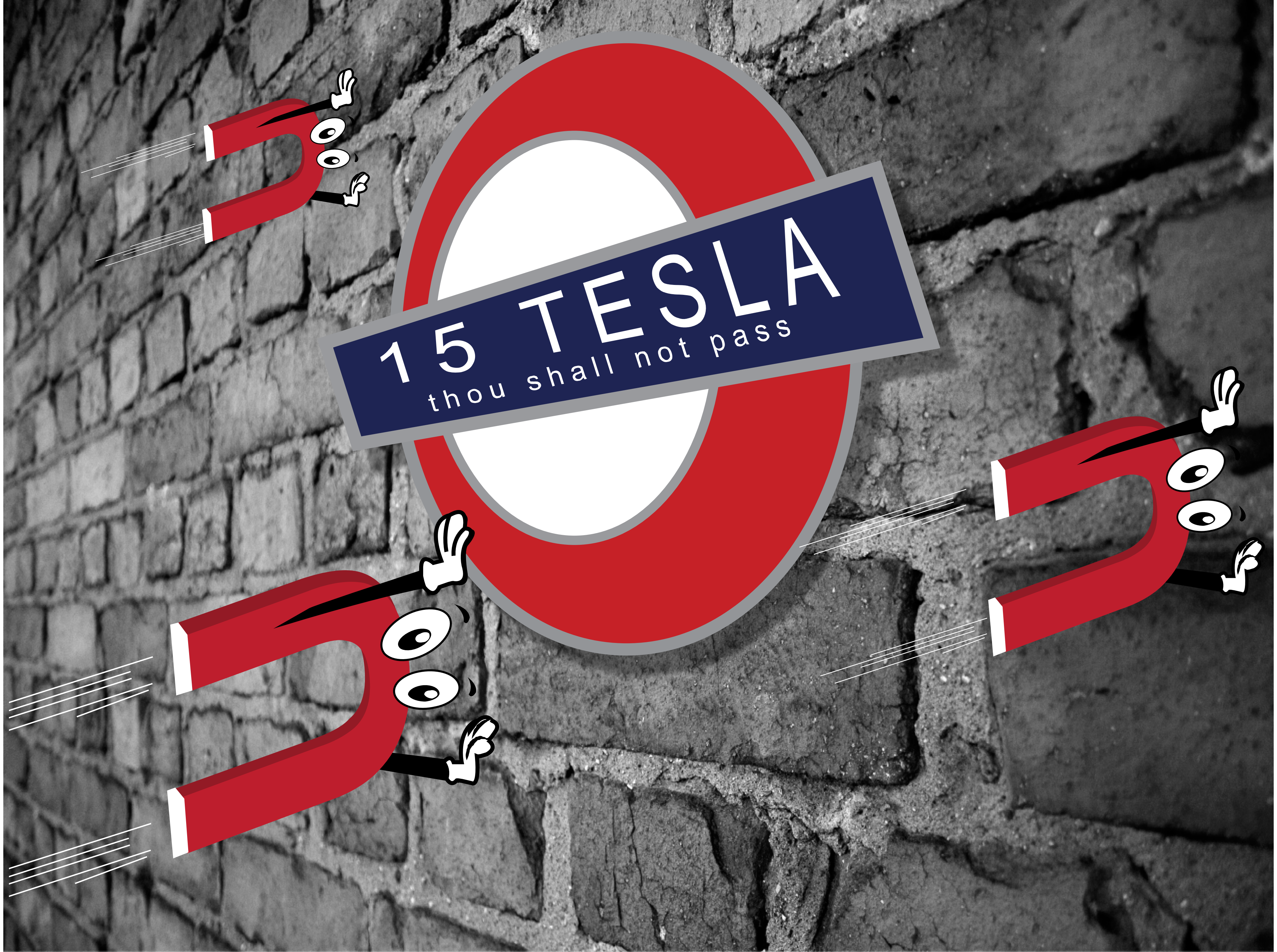


Main development goals until 2020:

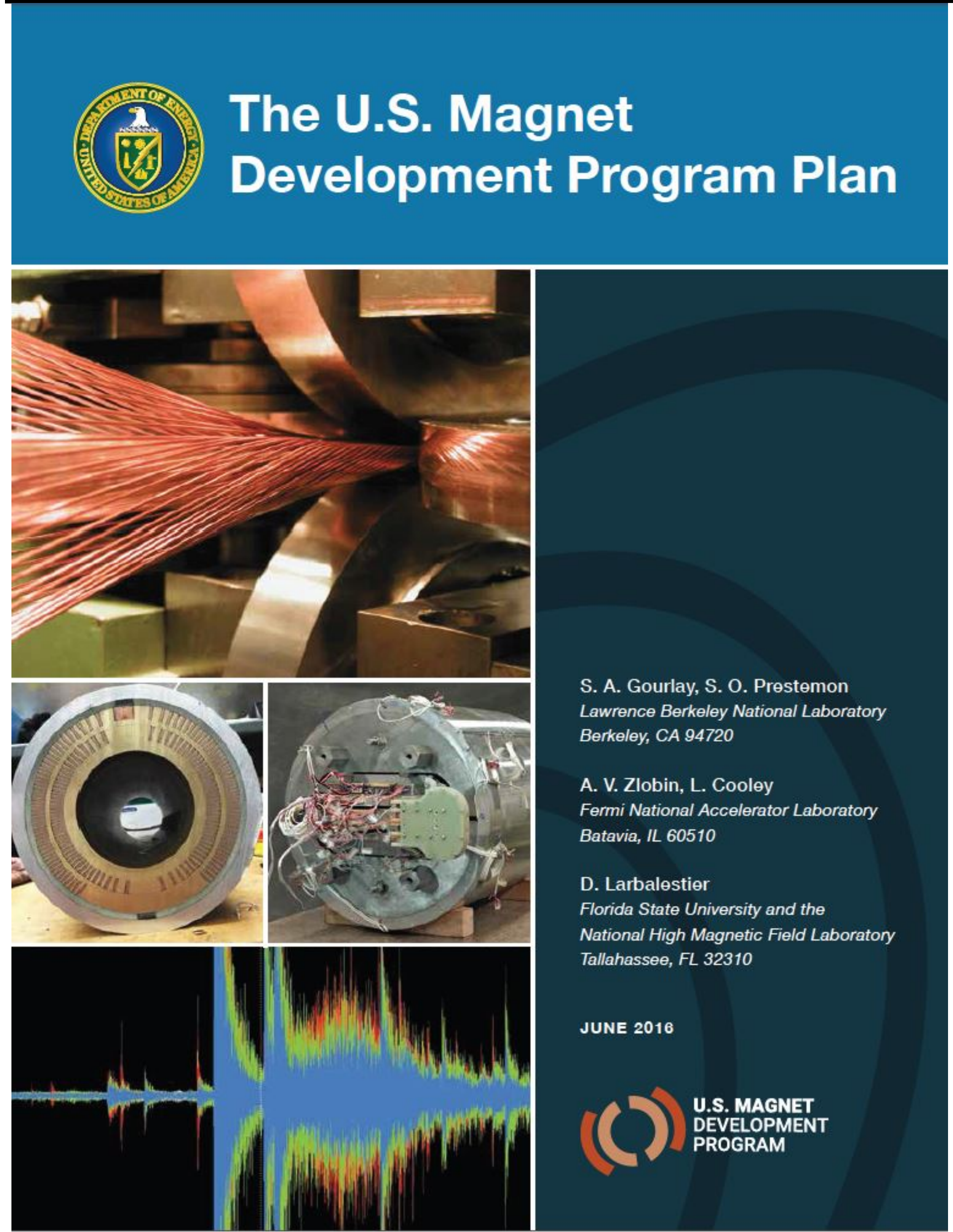
- **J_c increase (16T, 4.2K) > 1500 A/mm^2 i.e. 50% increase wrt HL-LHC wire**
- **Reference wire diameter 1 mm**
- **Potentials for large scale production and cost reduction**



1200
1000
800
600
400
200
0
14
16
18
20
22
24
Jc 600
Jc 660
Jc 720
Jc 780
Jc 840
Load Line


15 TESLA
thou shall not pass

US Program


The U.S. Magnet Development Program Plan

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JUNE 2016

U.S. MAGNET DEVELOPMENT PROGRAM

Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

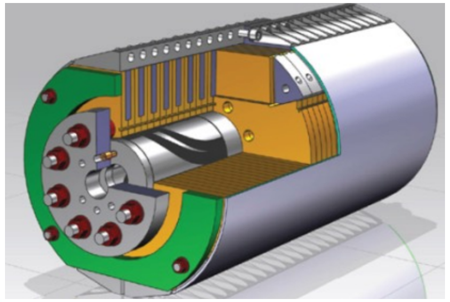
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

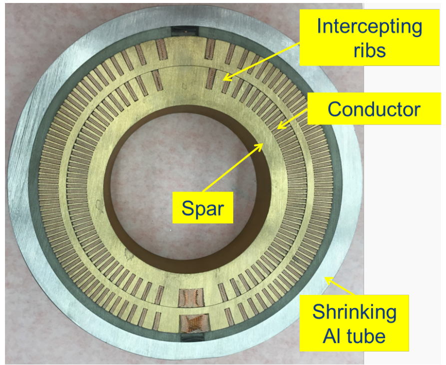
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Under Goal 1:

16 T cos theta dipole design

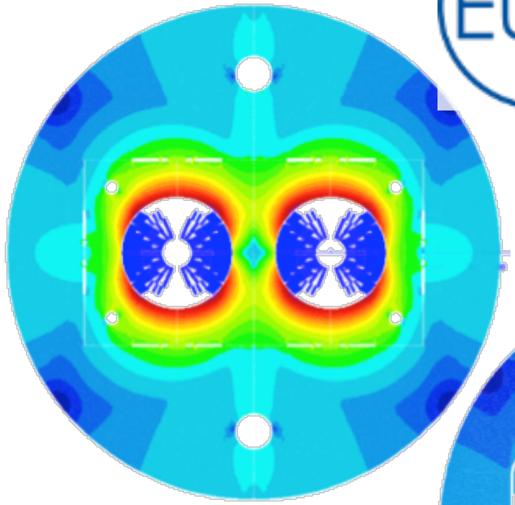


16 T canted cos theta (CCT) design

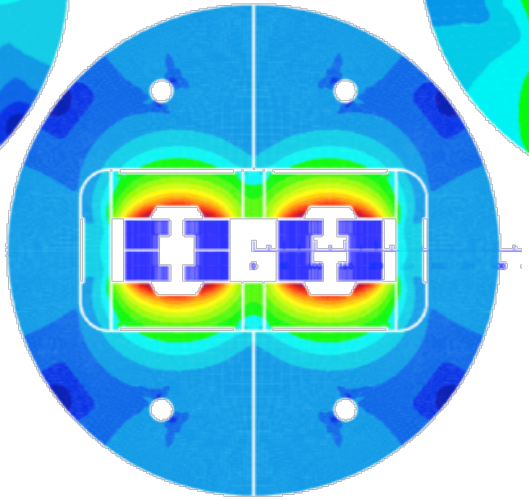


16 T dipole options under consideration

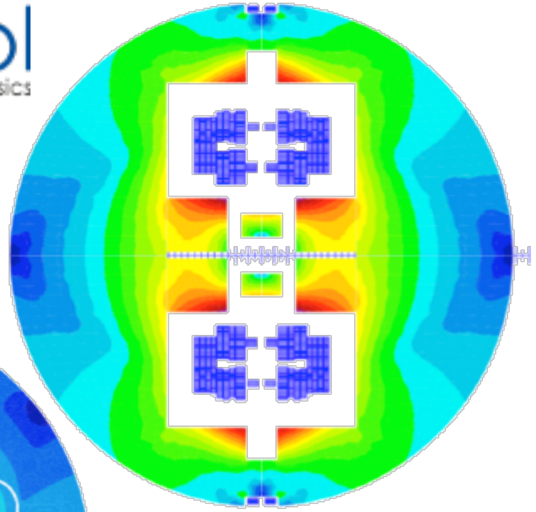
Cos-theta



Blocks



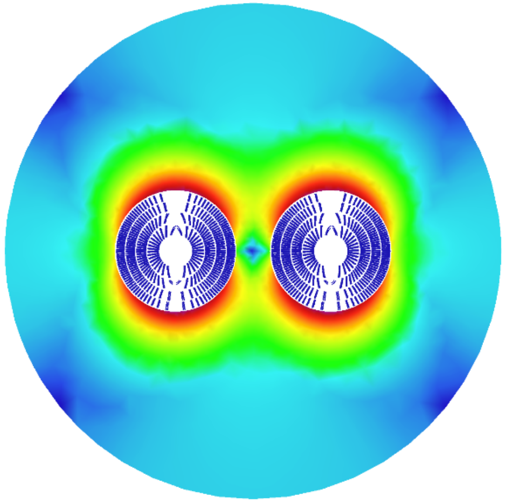
Common coils



Swiss contribution

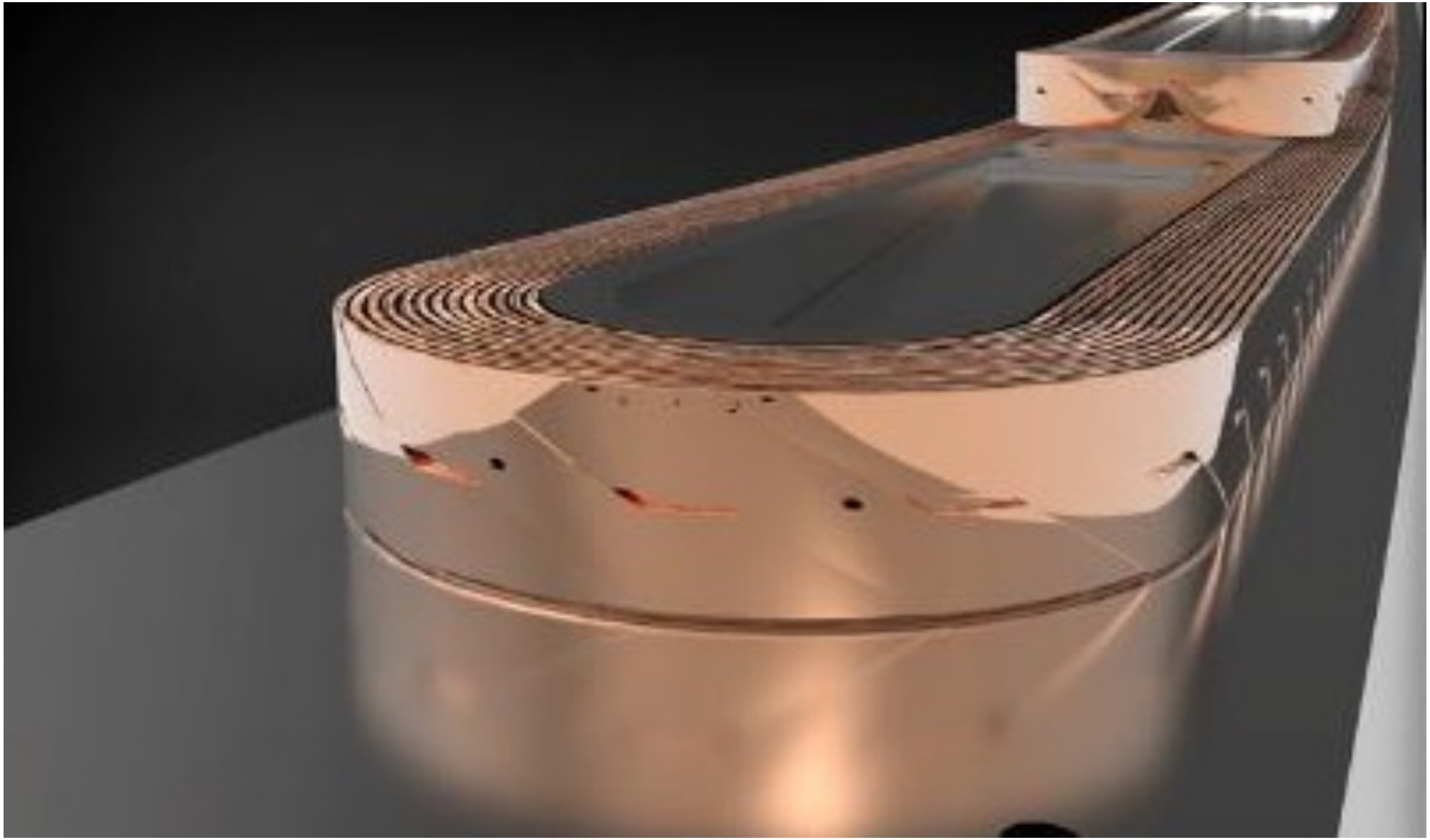
via PSI

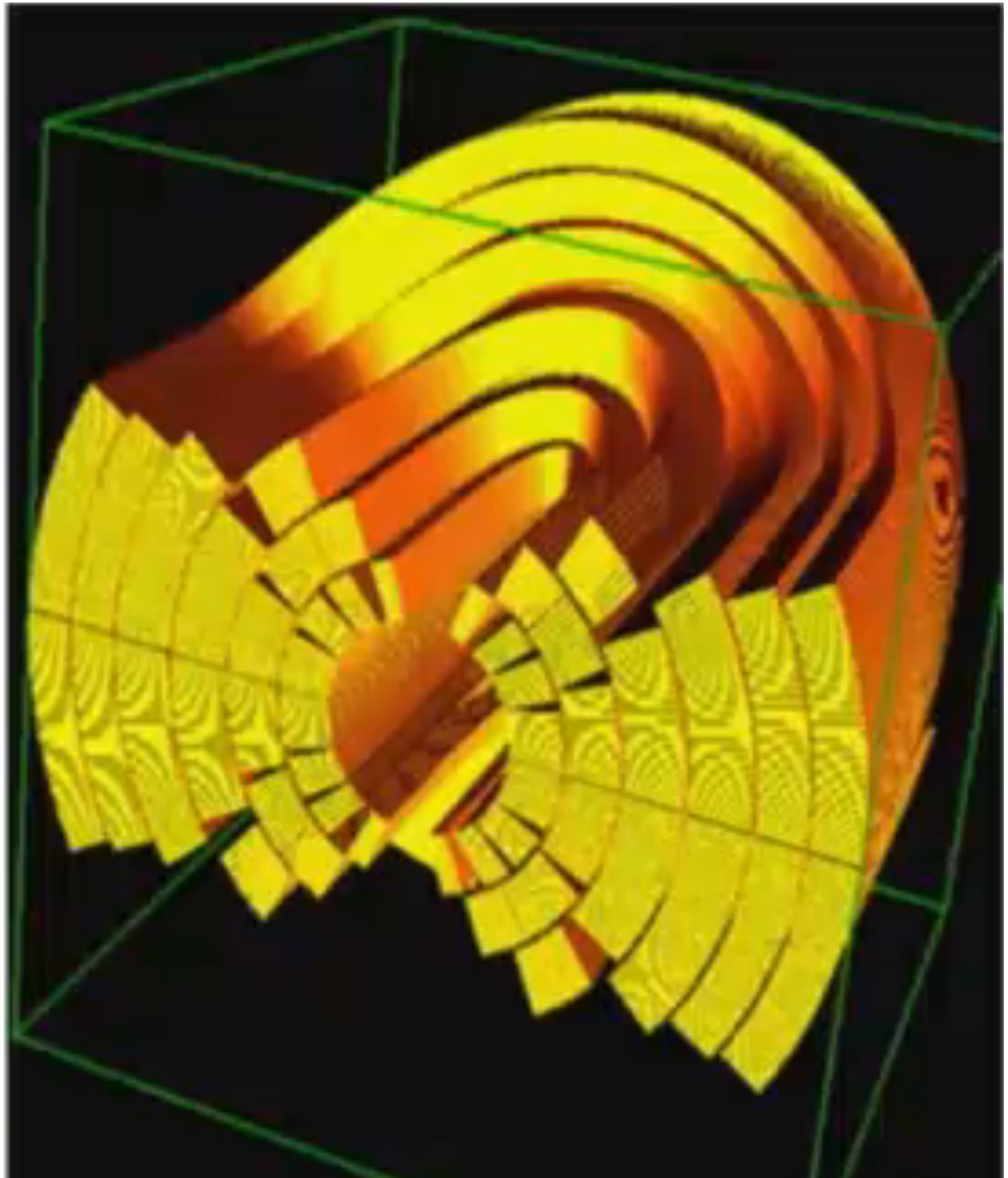
Canted Cos-theta



1LOr3C-02, 2PL-01, 2LPo1A-10, 2LPo1D-02, 2LPo1D-03, 2LPo1D-05, 2LPo1D-07, 2LPo1D-08

Down-selection of options end 2016 for more detailed design work





What is DOE-HEP Watching?

FCC

Where C = CERN or Chicago or China

ILC

Where I→*i*

Waiting for Japan


SHOW
ME THE
MONEY!