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Goals of a National Accelerator R&D Program Toward Large *pp* Colliders

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P5 Report on 100 TeV *pp* collider physics

"…A very high-energy proton-proton collider is the most powerful future tool for direct discovery of new particles and interactions under any scenario of physics results that can be acquired in the P5 time window. Colliders of energy up to 100 TeV, with a circumference of about 100 km with an option of *e*+*e*–, are presently under study at CERN, in China, and in the U.S. ***Extensive R&D is required to make such a collider feasible at a reasonable cost. The U.S. is the world leader in R&D on high-field superconducting magnet technology, which will be a critical enabling technology for such a collider.*** Future R&D follows naturally from the directed R&D now conducted by the LARP program for the HL-LHC. "

P5 Recommendation

"*Recommendation 24*: Participate in global conceptual design studies and critical path R&D for future very high-energy proton-proton colliders. Continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs."

Guidance from the GARD Subpanel Chair – *need input on:*

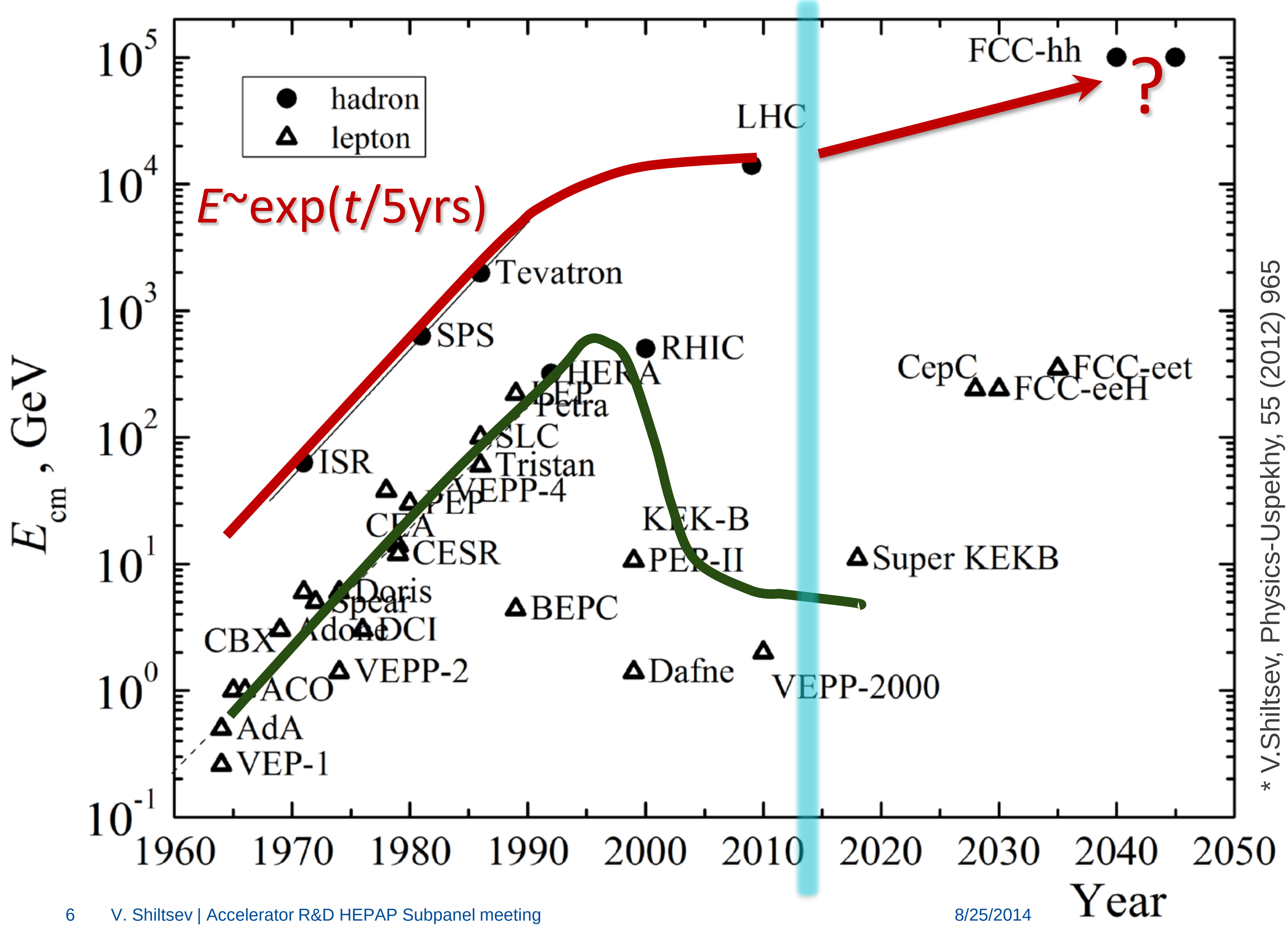
1. Appropriate goals for medium- and long-term R&D in the US
2. The scope of the current medium- and long-term R&D and how well it is aligned with the goals
3. What’s needed to achieve these goals (resources, management, existing/expected infrastructure)
4. The training of accelerator scientists and technologists
5. The elements of the program in the scenario of increased funding, esp. in the long-term

Q #1(Goals): Basis for recommendations

- Overview of past and current efforts in the US and overseas
- Main challenges for ~100 TeV scale *pp* collider studies in the next decade
- Reasonable balance between domestic and world priorities, between mid- and long-term, between theory, modeling, experiment and training, and between science and technology.

→ Recommendation on the goals

Colliders: Glorious Past – 29 built incl. 5 *pp*



* V.Shiltsev, Physics-Uspekhy, 55 (2012) 965

Overview of *pp* Colliders

	Years	*E_com*	*C*	*“Then Year Cost”*
ISR	1971-84	63 GeV	1.0 km	~50MCHF(~0.45BCHF 2008)
Isabelle	1983	0.4 TeV	3.8 km	0.2 B$ (tot ~0.65B$)
SppS	1981-84	630GeV	6.9 km	~0.2BCHF (~2BCHF 2008)
Tevatron	1985-2011	2TeV	6.3 km	0.45B$
UNK	1991	0.4+3 TeV	21 km	0.6BRu (~2B$ for 3+3TeV)
SSC	1993	40 TeV	87 km	~11 B$
RHIC	2000-	0.5 TeV	3.8 km	0.66 B$
VLHC-I	2001	40 TeV	233 km	4.1 B$ (not incl Stg-II 175 TeV)
LHC	2009-	8-14 TeV	27 km	6.5 BCHF
SppC	2036?	50-70 TeV	50-70km	<20BRMB ? (3.3B$)
FCC	2040?	100 TeV	80-100km	?

The lessons:

1. Advantage 1 : feasibility of energy reach - SC magnet technology in principle guarantees the energy frontier
2. Advantage 2 : feasibility of performance (luminosity) – *pp* colliders never missed the design *L*-targets yet, accelerator physics issues understood well so far
3. Dis-advantage : feasibility of acceptable cost – *pp* colliders always pushed the envelope, science/$ often questioned, and several counter-measures invented:
   - Staging : *E* → *E* (UNK, VLHC); *e+e-* → *pp* (LHC, FCC, SppC)
   - Count on evolution, reuse predecessor : Tevatron, RHIC, LHC
   - Technology/design/cost optimization (see next slides)
4. Other (smaller) dis-advantages of scale (for any large acc.):
   - going under private land (esp., in the US)
   - lack of experts ("*Oide law*" – "in 1 year 1 expert to spend 1M$")

Global Context : A 100 TeV *pp* Studies

FCC=Future “C” Collider

“C” =	CERN	China	Chicago
Energy, TeV	100	50-90	175
Luminosity, 1e34	5	20-30	2
Circumference, km	100-83	50-70	233
Dipole field, T	16-20	12-19	11.2
Facility power, MW	n/a	n/a	100
CDR/Cost Study	2018	2020	(2001) - ?
Project R&D	tbd	2030	?

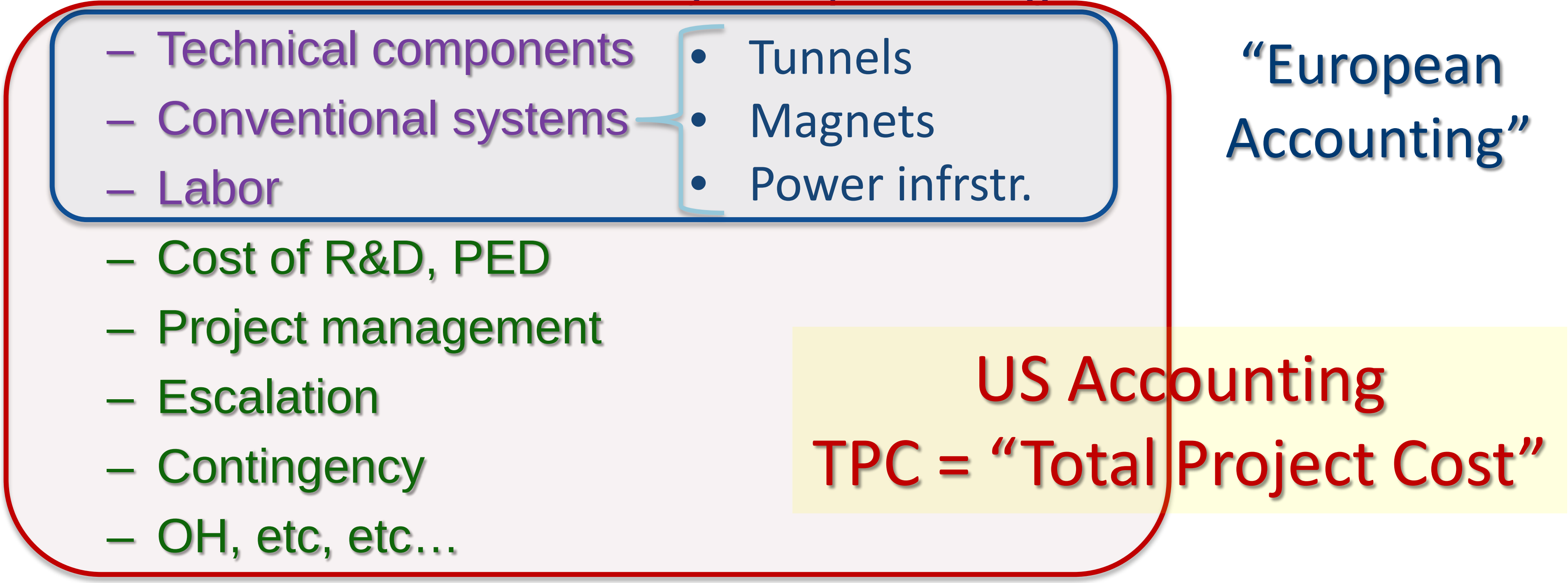
* also 100TeV pp in Arxiv.org:1306.2369

R&D Time Scale and Hi-Level Goals

- So there are 10-15 years ahead to lay foundation of a feasible future 100 TeV scale *pp* collider
  - the time scale points to the need of long-term R&D and steady support
- Overarching R&D goals:
  - to address feasibility of acceptable cost
  - better understand the performance reach
    - and explore cost/performance trade-offs

Comments on the cost

- What we call COST is very complex thing



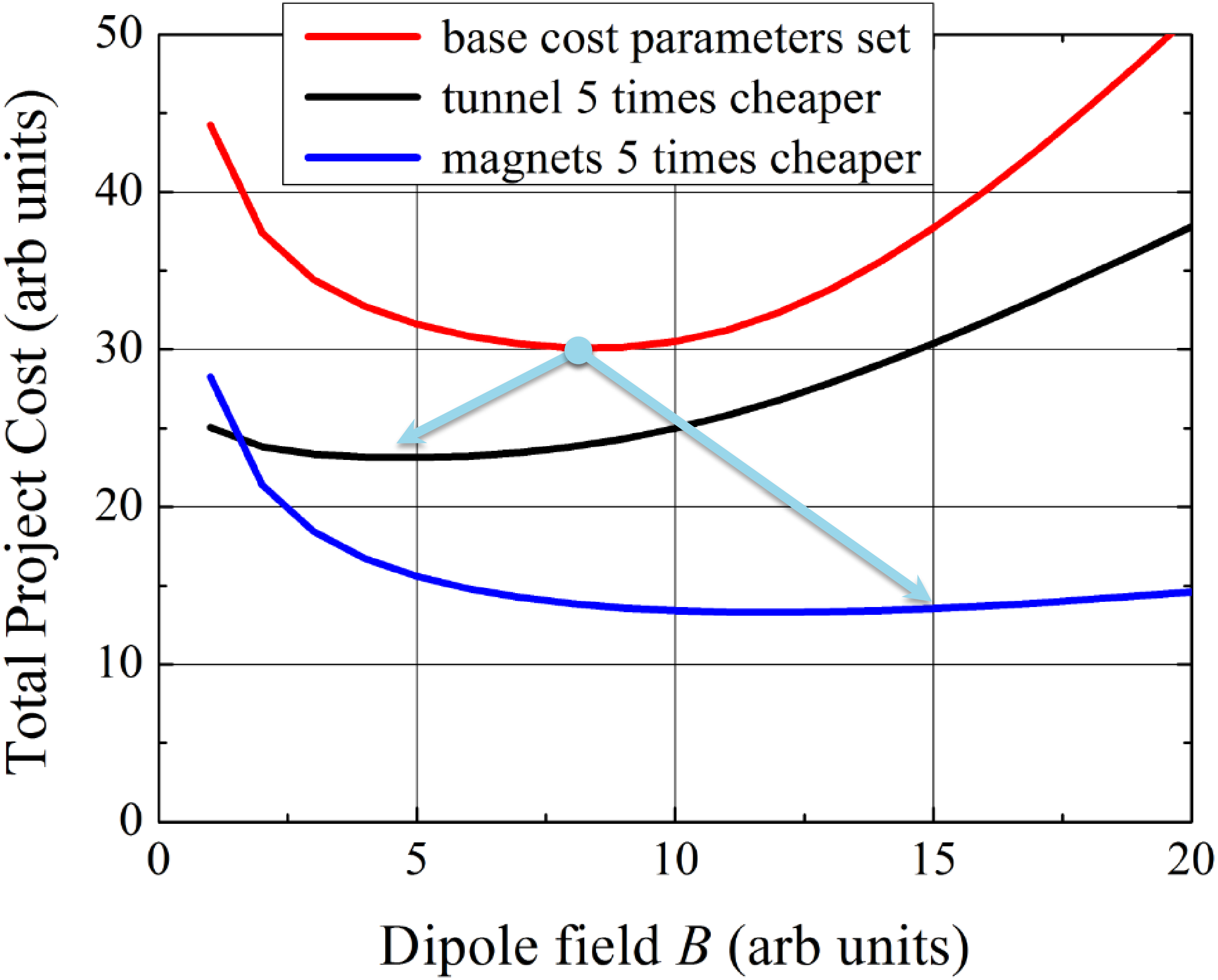
  - Technical components
  - Conventional systems
    - Tunnels
    - Magnets
    - Power infrstr.
  - Labor
  - Cost of R&D, PED
  - Project management
  - Escalation
  - Contingency
  - OH, etc, etc…

"European Accounting"

US Accounting
TPC = "Total Project Cost"

- The cost is to a degree probabilistic:
  - *"...costing a new project in advanced technology is not just accounting, but rather an attempt to organize complexity and uncertainty*" (P.Lebrun)

100 TeV *pp* : Qualitative Cost Dependencies



* for illustration purposes only,
see also V.Shiltsev, 2014 JINST 9 T07002

Areas of Studies

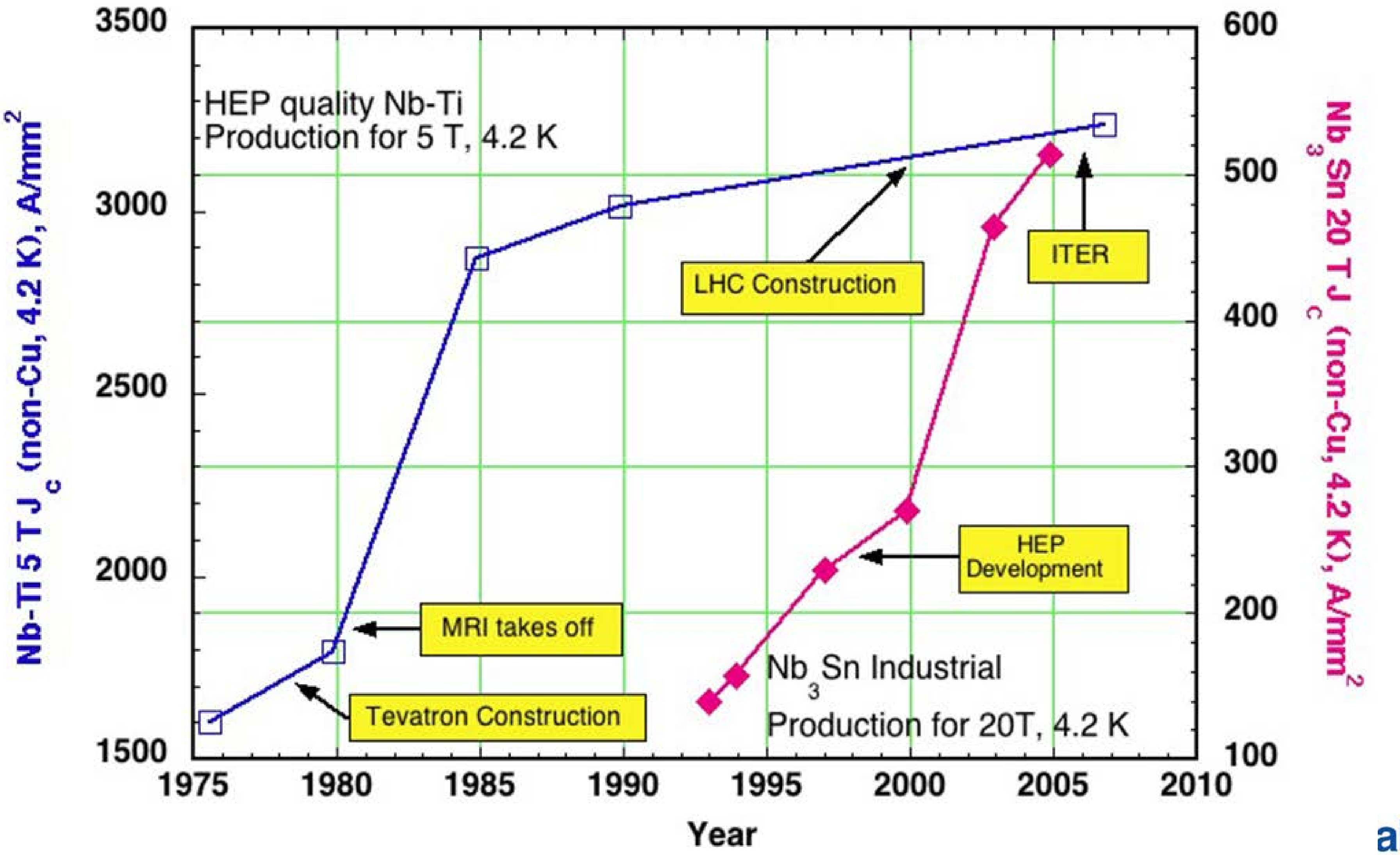
- R&D on Magnets:
  - Most suitable for the US: world-leading expertise in SC magnets R&D and construction, synergy with LARP & HL-LHC
- R&D on Performance and Site Power:
  - Contribute to global studies: tap off acc. sci. expertise, synergy with LARP & Int.Fr. R&D
- R&D on Tunnels:
  - Better suited for other regions (CERN, China)… in US considerable knowledge already exists on the geology and tunneling for SSC and VLHC sites

R&D Goal #1: SC Magnets

- Long-term research and development toward significant (~3-4) cost reduction of high-field accelerator-quality magnets suitable for a future 100 Tev scale proton-proton collider
- In coordination with the accelerator design teams (to understand the specs) as well as with magnet design and development partners (to avoid duplication of efforts)
- Key areas:
  - push performance and reduce cost of conductor (Nb3Sn, HTS), structural materials and components; explore new magnet design concepts; optimize magnet production, installation and operation technologies and costs, etc.

Substantial improvements need time

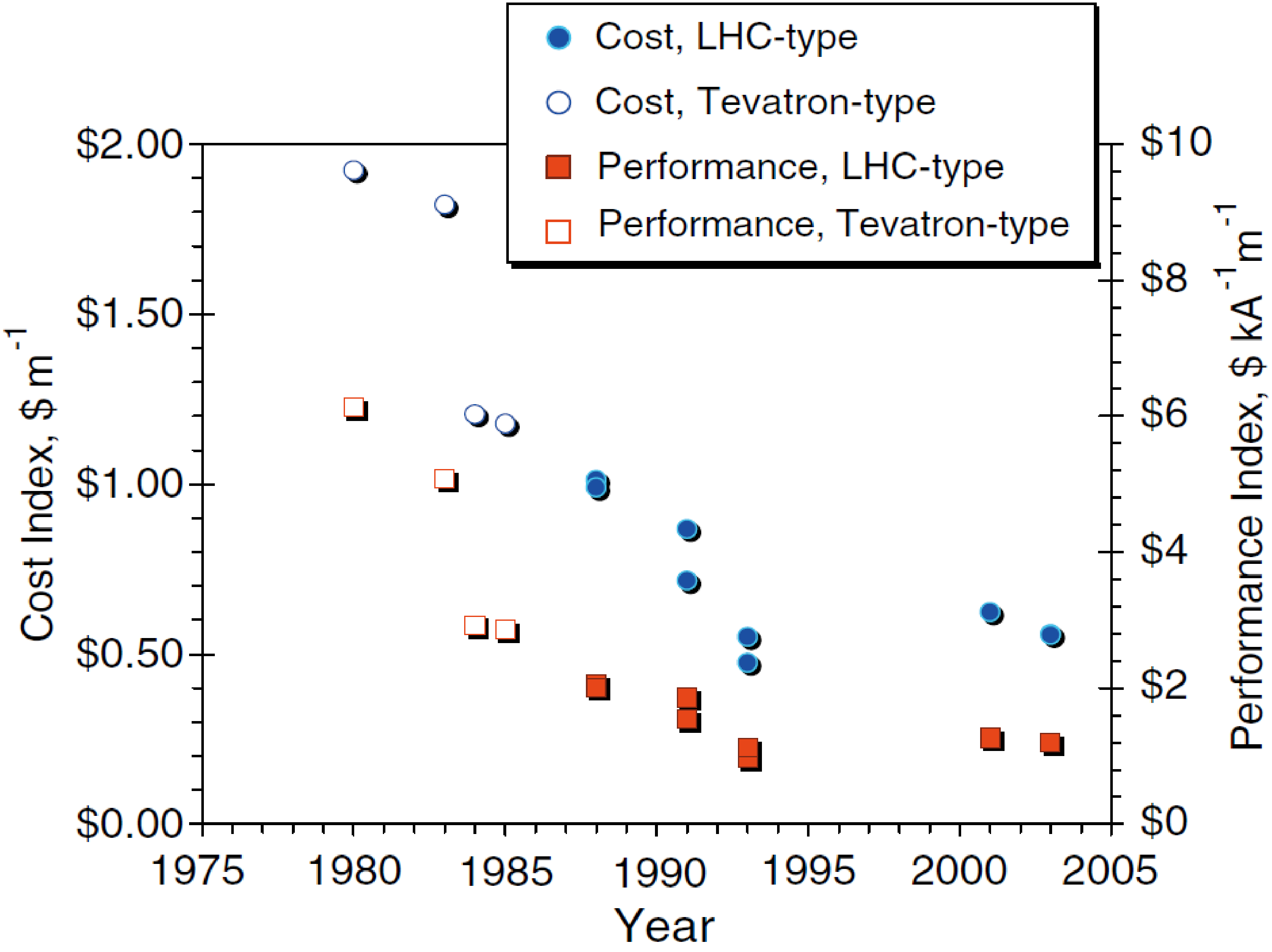
Decadal improvements in SC critical currents NbTi, Nb3Sn



* Courtesy A.Zlobin

Substantial improvements need time

Decadal improvements in SC NbTi cable cost per m, per A*m

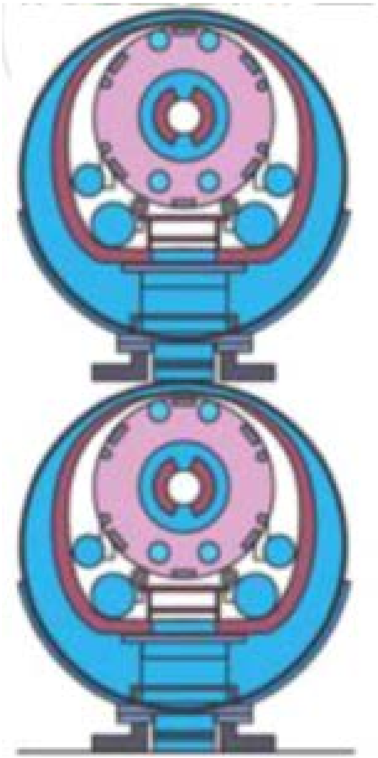


* Courtesy A.Zlobin

Substantial improvements need time

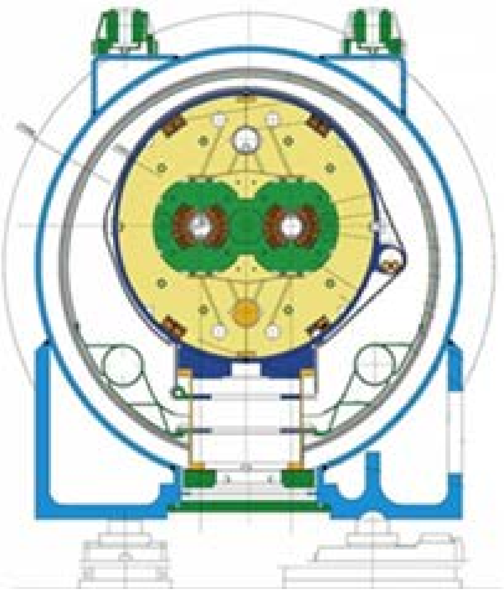
Decadal improvements in SC magnet design

1990’s



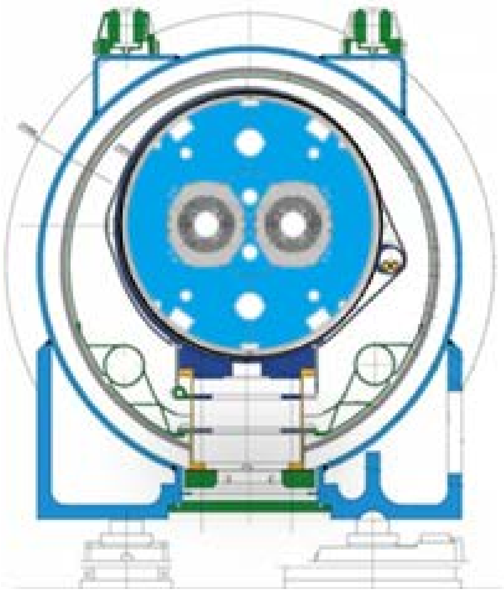
SSC, 50 mm
6.6 T, 4.3 K

2000’s



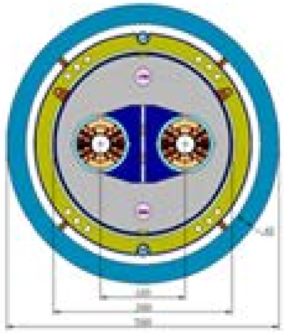
LHC, 56 mm
8.3 T, 1.9 K

2010’s



LHC, 60 mm
11 T, 1.9 K

2020-30’s ?



VLHC, 43 mm
10 T, 4.5 K

* Courtesy A.Zlobin

R&D Goal #2: Performance and Design

- Launch limited scope long-term research on selected topics of importance for optimization of the most cost-effective machine design
- In coordination with (much bigger) global design studies in Europe and Asia
- Assure the best benefits from synergies with:
    - LARP
    - activities in *Accelerator Science and Modeling* thrust and *R&D Toward Multi-MW Beams*
    - R&D in other Offices (BES, NP)

“Burning Issues” of the Machine Design

- How to handle MW of SR power
- How to handle 10’s of kW of the IR debris power (compared to 1 kW in the LHC)
- Transverse instabilities at injection energy
- Collimation & machine protection
- Low-beta optics with flat beams and means to control the beam-beam effects
- Injector complex: energy, emittances, cooling, high proton flux, SRF, etc
- Coordination with *e+e-* stage design

Synergies

- There is vast expertise in the US in all these areas:
  - BNL, FNAL, LBNL, SLAC, MSU, Cornell, IU, TAMU, etc
- One must assure that results of several advanced R&D are taken as input:
  - LARP supports studies on crab cavities, high bandwidth beam FB system, hollow electron beam collimation, beam-beam modeling and compensation
  - Beam optics, instabilities and high-performance simulation tools in the Accelerator Science and Modeling thrust
  - Novel schemes such as *Coherent Electron Cooling* and RHIC *electron lenses for beam-beam compensation* (supported by Nuclear Physics) and *Optical Stochastic Cooling* at IOTA/ASTA at FNAL
  - All experimental accelerator research on instabilities and loss control at IOTA/ASTA (*integrable optics* and *space-charge compensation*) in the proposed ***R&D towards Multi-MW beams and targets*** thrust

Q #3: Resources and Management (1)

Part A: High-field Accelerator-quality Low-Cost Magnets

- Resources needed: closer to ~10M$/yr nation-wide ("*ca* 2011" level, above the current level ~6 M$)
  - careful coordination with LARP and the HL-LHC project is a must in order to maintain core scientific and engineering talent over the next decade (see G.Apollinari's talk next)
- Management: continue to manage national program under "*SC Magnets and Materials*" GARD thrust
  - "White Paper" prepared jointly by LBNL, FNAL, BNL, NHFML and TAMU is a very nice starting point of longer-term cooperative magnet R&D for a 100 TeV *pp*
  - surely, more detail planning is needed to follow the proposed refocus

Q #3: Resources and Management (2)

Part B: Design Studies Toward Cost Effective Machine

- Resources needed: some 1-1.5 M$ /yr for next ~4-5 years with possible expansion if any current global study will initiate machine-oriented R&D program
  - careful coordination with LARP's "Accelerator Science" is needed
  - attract University groups, in addition to Nat'l labs
- Management: manage as activity within "*Accelerator Science, Modeling and Design*" GARD thrust
  - Coordinate the design study efforts with International partners via Workshops, joint publications, collaborations

An Example: *FCC Design Study* at CERN

Proposal for FCC WBS top level

preliminary

- **Future Circular Collider**
  - **Physics and Experiments**
    - Hadron Collider Physics
    - Hadron Collider Experiments
    - Lepton Collider Physics
    - Lepton Collider Experiments
    - Lepton-Hadron Collider Physics
    - Lepton-Hadron Collider Experiment
  - **Accelerators**
    - Hadron Injectors
    - Hadron Collider
    - Lepton Injectors
    - Lepton Collider
    - Lepton-Hadron Collider
    - Technology R & D
  - **Infrastructures and Operation**
    - Civil Engineering
    - Technical Infrastructures
    - Operation and Energy Efficiency
    - Integration
    - Computing and Data Services
    - Safety, RP and Environment
  - **Implementation and Planning**
    - Project Risk Assessment
    - Implementation
    - Cost Estimates
  - **Study and Quality Management**
    - Study Administation
    - Communications
    - Conceptual Design Report

CERN's FCC : Lower Level WBS *hh*

100(s) of WBS lines

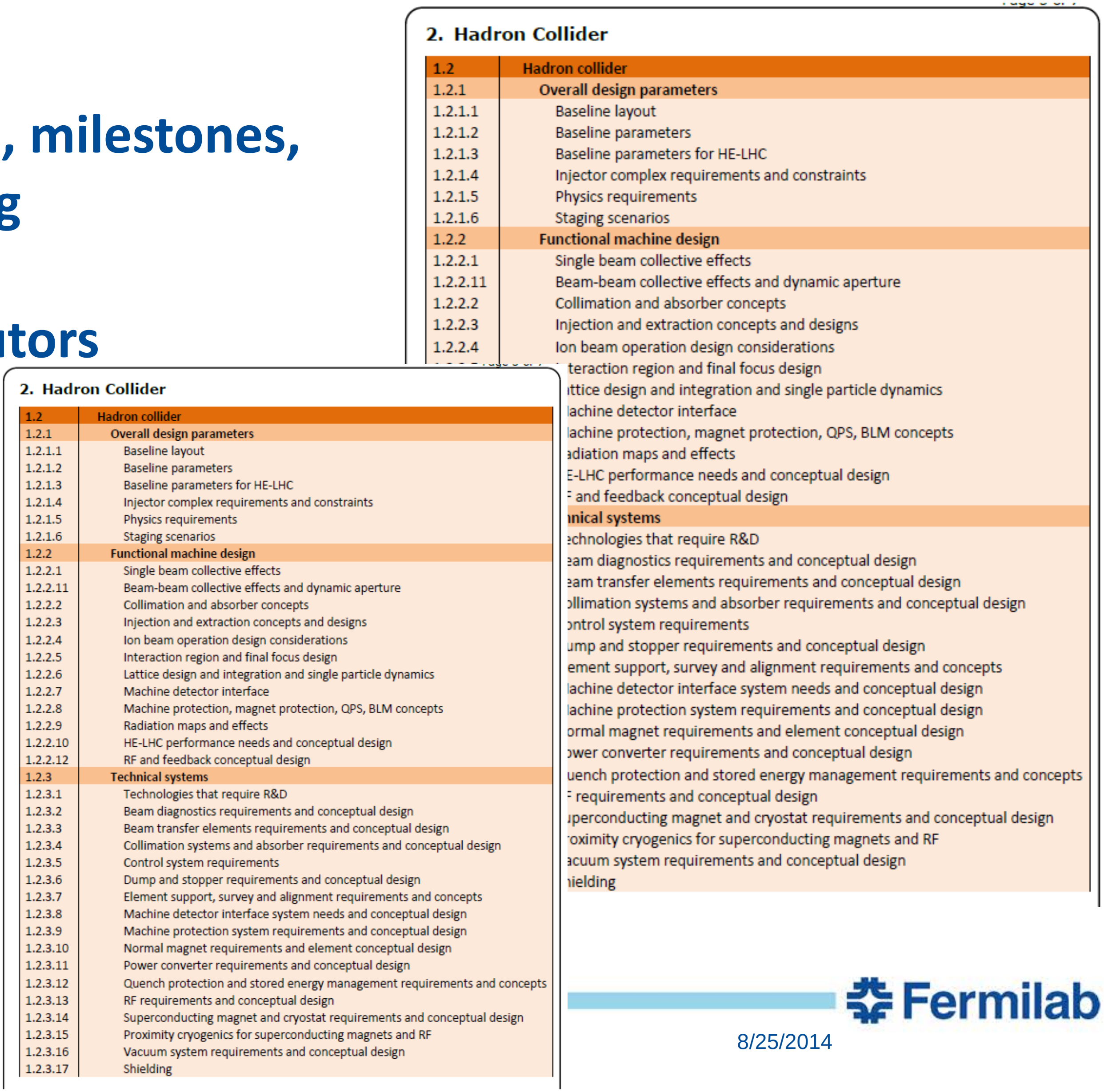
Project-like: timelines, milestones, deliverables, reporting

International contributors and conveners needed for technical areas and study organiz'n :

co-leadership model

One from CERN

One from smw.else



2. Hadron Collider

1.2	**Hadron collider**
1.2.1	**Overall design parameters**
1.2.1.1	Baseline layout
1.2.1.2	Baseline parameters
1.2.1.3	Baseline parameters for HE-LHC
1.2.1.4	Injector complex requirements and constraints
1.2.1.5	Physics requirements
1.2.1.6	Staging scenarios
1.2.2	**Functional machine design**
1.2.2.1	Single beam collective effects
1.2.2.11	Beam-beam collective effects and dynamic aperture
1.2.2.2	Collimation and absorber concepts
1.2.2.3	Injection and extraction concepts and designs
1.2.2.4	Ion beam operation design considerations
1.2.2.5	Interaction region and final focus design
1.2.2.6	Lattice design and integration and single particle dynamics
1.2.2.7	Machine detector interface
1.2.2.8	Machine protection, magnet protection, QPS, BLM concepts
1.2.2.9	Radiation maps and effects
1.2.2.10	HE-LHC performance needs and conceptual design
1.2.2.12	RF and feedback conceptual design
1.2.3	**Technical systems**
1.2.3.1	Technologies that require R&D
1.2.3.2	Beam diagnostics requirements and conceptual design
1.2.3.3	Beam transfer elements requirements and conceptual design
1.2.3.4	Collimation systems and absorber requirements and conceptual design
1.2.3.5	Control system requirements
1.2.3.6	Dump and stopper requirements and conceptual design
1.2.3.7	Element support, survey and alignment requirements and concepts
1.2.3.8	Machine detector interface system needs and conceptual design
1.2.3.9	Machine protection system requirements and conceptual design
1.2.3.10	Normal magnet requirements and element conceptual design
1.2.3.11	Power converter requirements and conceptual design
1.2.3.12	Quench protection and stored energy management requirements and concepts
1.2.3.13	RF requirements and conceptual design
1.2.3.14	Superconducting magnet and cryostat requirements and conceptual design
1.2.3.15	Proximity cryogenics for superconducting magnets and RF
1.2.3.16	Vacuum system requirements and conceptual design
1.2.3.17	Shielding

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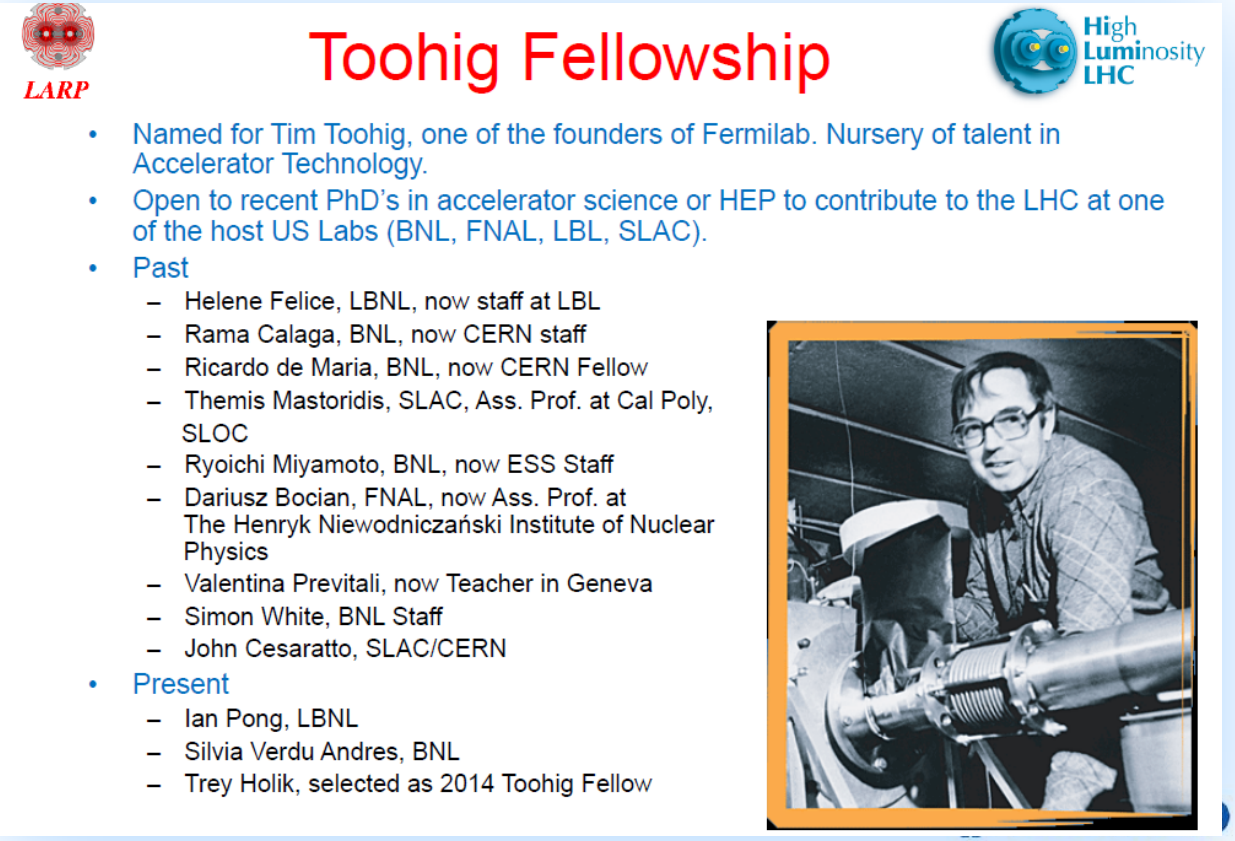
“MoU: Why not?”

- The MOU assumes the level of responsibility which we can not afford at this moment
- Assumes stable funding which can not be guaranteed
- Assumes that the US is fully behind the proposed concept at this early stage – and we are not there yet
- CERN’s FCC Study is relatively short-term (to end in ~3 yrs) CERN-specific design project while GARD is supposed to support mid- to longer-term efforts
- There are other opportunities, and modes of collaboration:
  - Eg SppC study in China – we should be equally open to contributing to that option (BTW : it offers different, more flexible and longer term model of coordination)
  - Even without formal MOU we still can be of great help to any global study via organization of or attendance at Workshops, joint publications, individual visits, technical coordination boards, etc

Q4 : Training and education

- There are unique opportunities for the training of scientists and engineers in accelerator physics and technologies:
  - via broader involvement of University groups
  - support of the Toohig Fellowship after LARP transition to HiLumi (in about 3-4 years)



Toohig Fellowship

- Named for Tim Toohig, one of the founders of Fermilab. Nursery of talent in Accelerator Technology.
- Open to recent PhD's in accelerator science or HEP to contribute to the LHC at one of the host US Labs (BNL, FNAL, LBL, SLAC).
- Past
  - Helene Felice, LBNL, now staff at LBL
  - Rama Calaga, BNL, now CERN staff
  - Ricardo de Maria, BNL, now CERN Fellow
  - Themis Mastoridis, SLAC, Ass. Prof. at Cal Poly, SLOC
  - Ryoichi Miyamoto, BNL, now ESS Staff
  - Dariusz Bocian, FNAL, now Ass. Prof. at The Henryk Niewodniczański Institute of Nuclear Physics
  - Valentina Previtali, now Teacher in Geneva
  - Simon White, BNL Staff
  - John Cesaratto, SLAC/CERN
- Present
  - Ian Pong, LBNL
  - Silvia Verdu Andres, BNL
  - Trey Holik, selected as 2014 Toohig Fellow

Q5 : Increased Funding Scenario

- Establish experimental program toward most cost effective SR absorption in cryogenic environment (affects cost of the required site power infrastructure)
- Initiate R&D program on the cost-reduction of the tunneling with industry (affects civil construction cost)
- Explore additional/alternative options for the magnet design (target magnet cost reduction) and corresponding design studies

Summary

- As expressed in the P5 report, a ~100 TeV scale *pp* collider is favorably considered for a long-term future by broader HEP community
- Program of transformational accelerator R&D toward feasibility of such collider should be focused on the substantial reduction of the magnet cost and performance optimization
- The level of support needed to achieve these goals:
  - ~10M$/year for the magnet R&D
  - ~1-1.5M$ for a limited scope design studies
- All these activities should be carried in close coordination with our international partners