Accelerator Perspective *

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* any views or opinions presented here are solely those of the author and do not necessarily represent those of the entire international accelerator community, neither of the accelerator group of the Workshop… "words of wisdom"

QUESTIONS WE FACE:

--What are the scientific goals of a Higgs factory and of a next generation of pp collider?
-- What are the optimal design and technological challenges for the future colliders?
-- What are the sensitivities of the scientific goals that can be reached with these future colliders?
-- What are the requirements and challenges of instrumentation for accomplishing these measurements?
-- What lessons have been learned from the LHC?

Content

Now & Past

LHC,Tevatron,
B-fact's, SSC…

"Near" Future

CepC, TLEP,
ILC…

Future

FCC, SppC,
Muon Collider,
CLIC…

"Far" Future

.?.

Past and *Present* shape *Future*

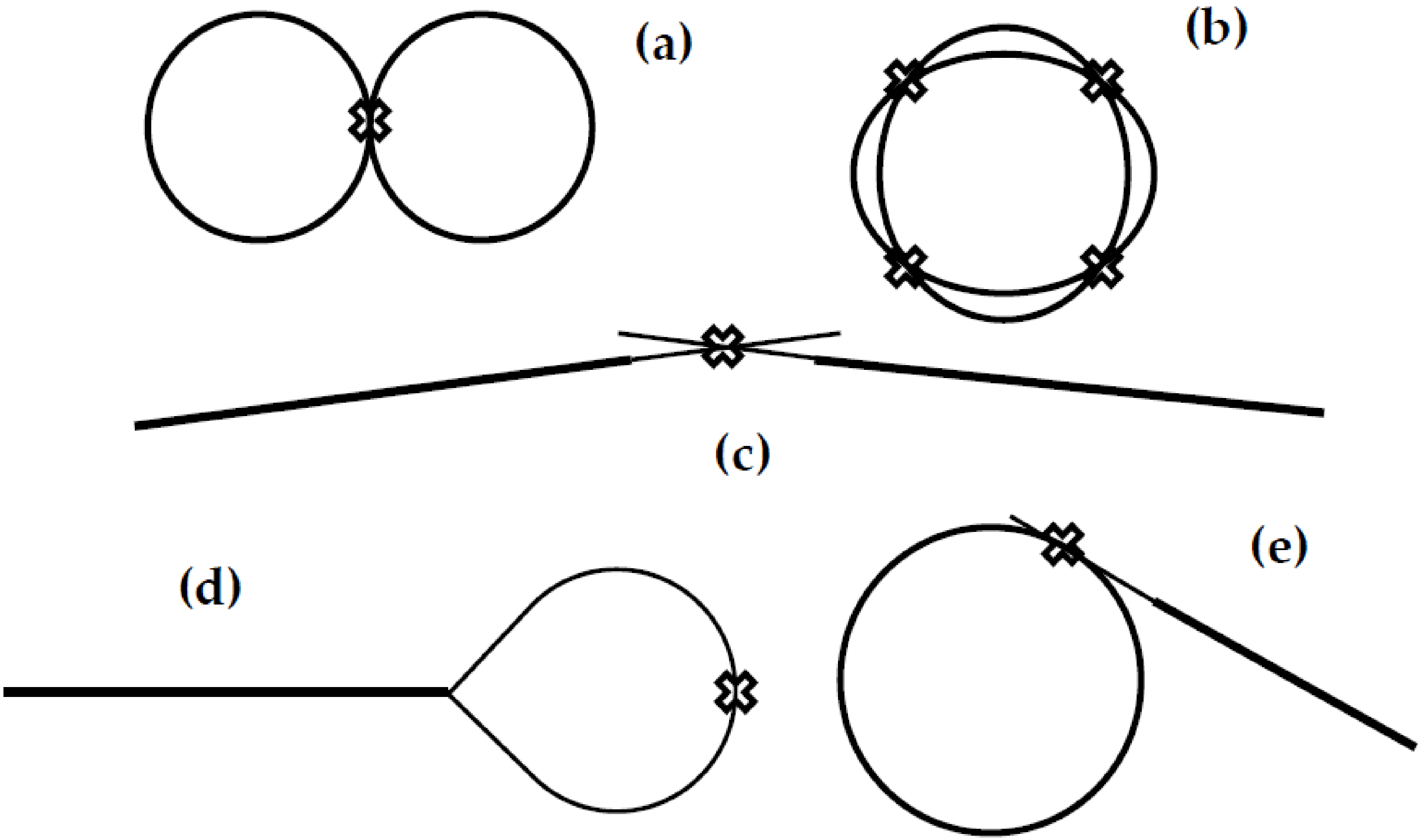
- When one wants to analyze options for future HEP accelerators, the question comes to

  PHYSICS vs **FEASIBILITY**

- (Leave **PHYSICS** to next speakers)
- **FEASIBILITY** of an accelerator is actually complex:
  - Feasibility of **ENERGY**
    - Is it possible to reach the *E* of interest / what's needed
  - Feasibility of **PERFORMANCE**
    - Will we get enough physics out there / luminosity
  - Feasibility of **COST**
    - Is it affordable to build and operate
- What can we learn/take from the past?

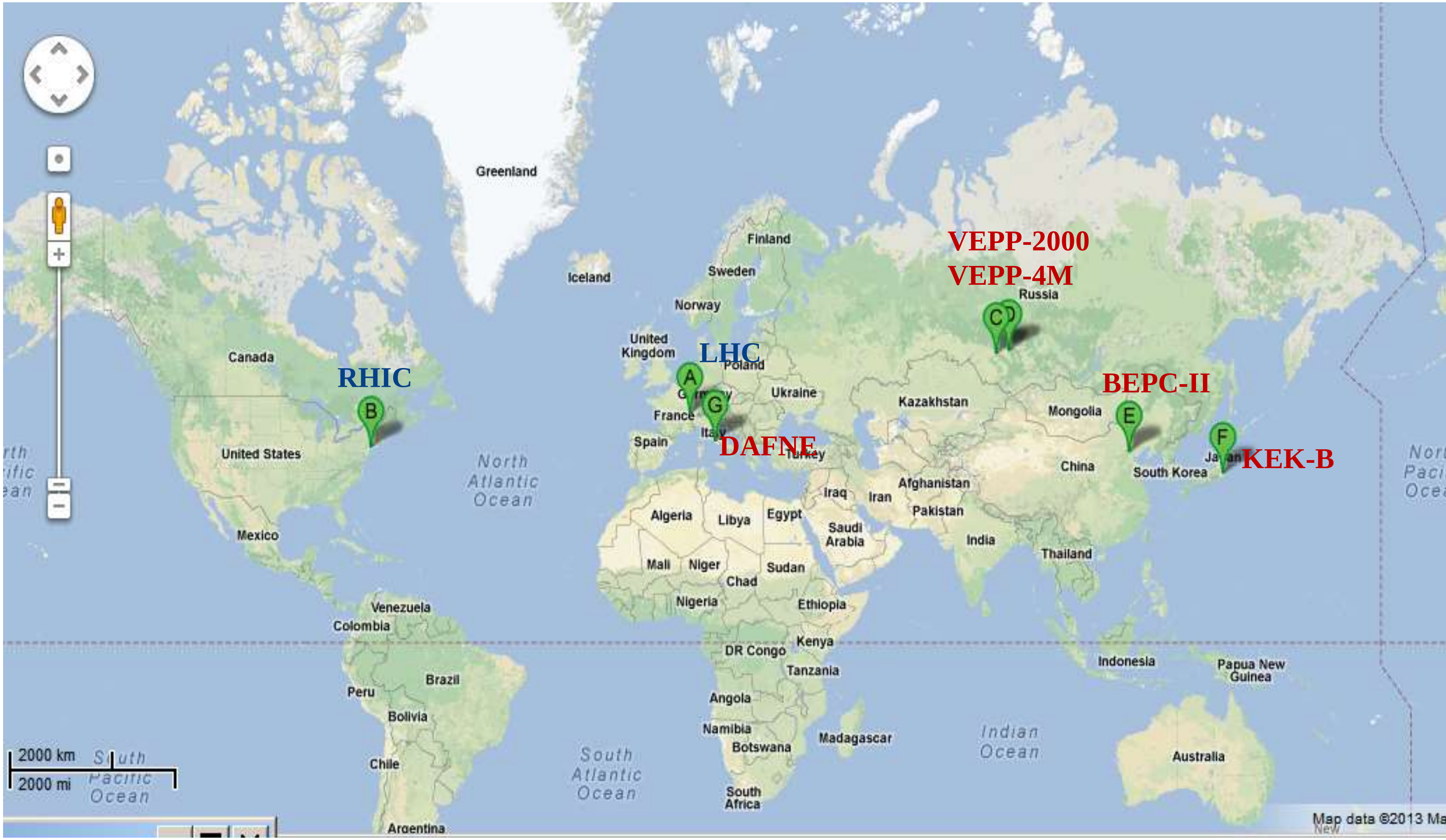
Colliders

- Over the past 5 decades, **COLLIDERS** dominated the ***Energy Frontier*** of particle physics

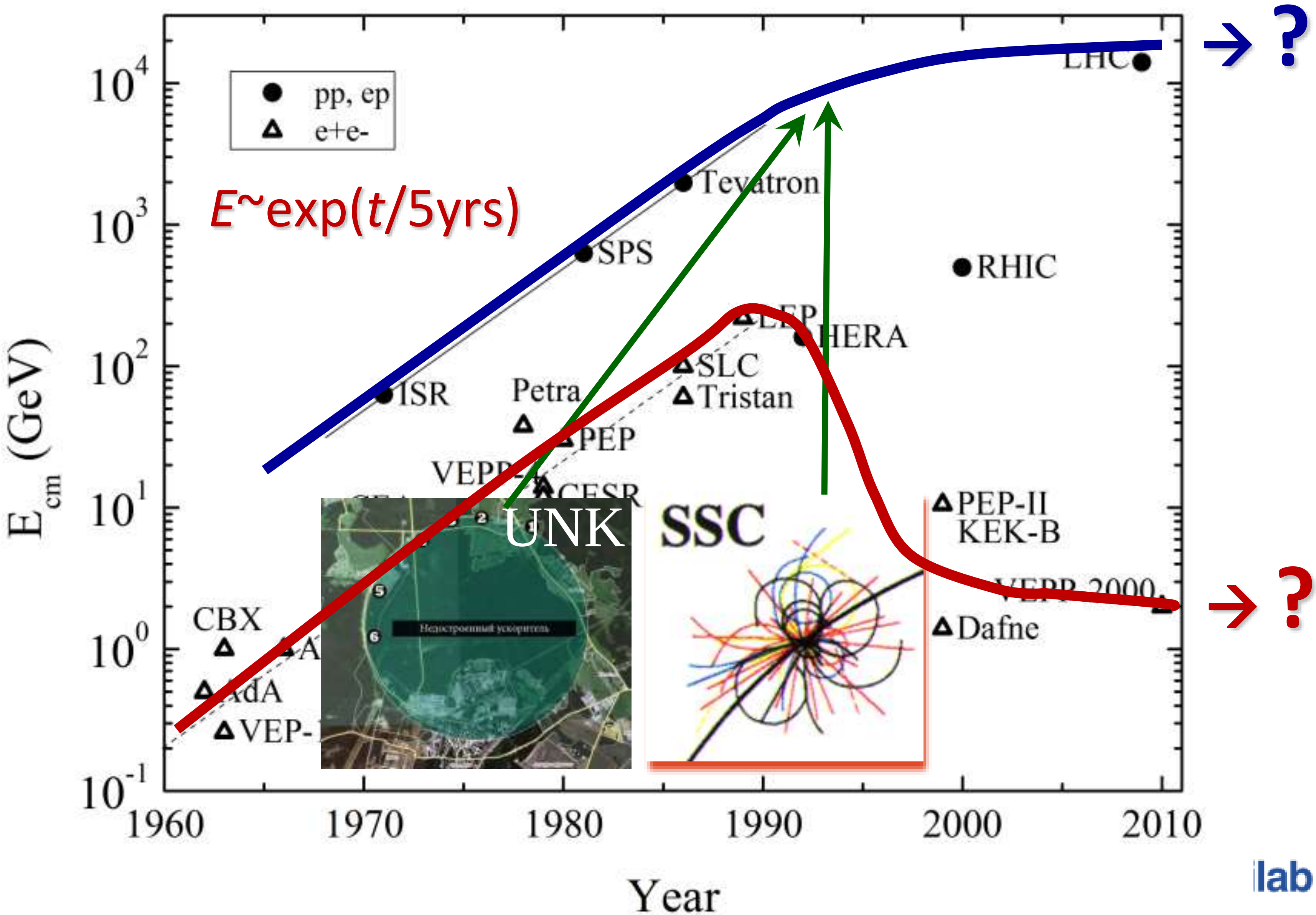


lab

29 Colliders Built… 7 Work "Now"



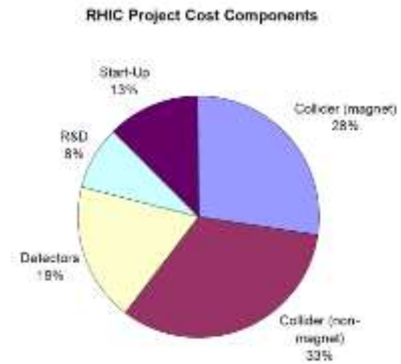
Colliders: Glorious Past



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

"Known" Costs for 17 Big Machines

- **Actual**
  - RHIC, MI, SNS, LHC
- **Under construction**
  - XFEL, FAIR, ESS
- **Not built/Future**
  - SSC, VLHC, NLC
  - ILC, TESLA, CLIC, Project-X, Beta-Beam, SPL, ν-Factory



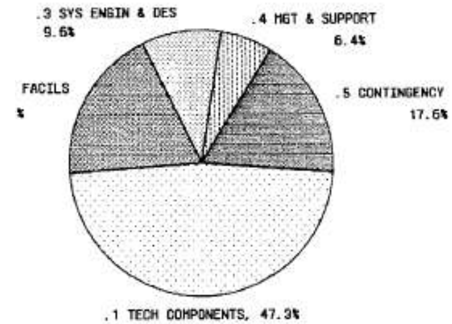
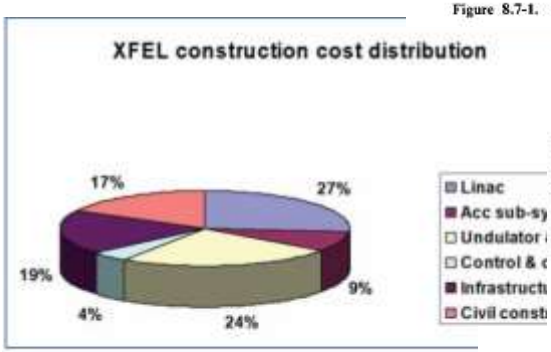
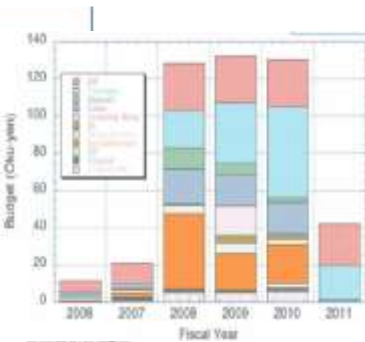
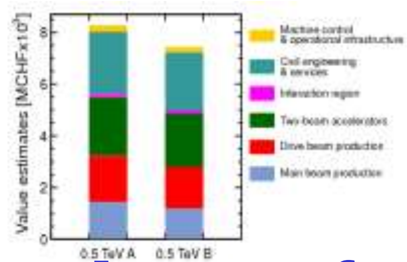
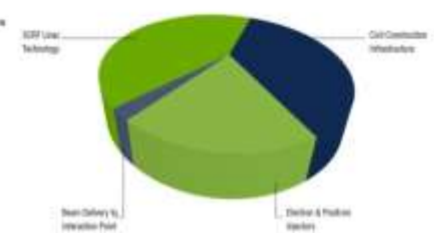


Figure 8.7-1. SSC cost estimate summary: Level 2 WBS categories.









Is it possible to parameterize the cost for known technologies ?

	Cost (B$) Year	Energy (TeV)	Accelerator technology	Comments	Length (km)	Site power (MW)	TPC range (Y14 B$)
SSC	11.8 B$ (1993)	40	SC Mag	Estimates changed many times [6–8]	87	~ 100	19–25
FNAL MI	260M$ (1994)	0.12	NC Mag	"old rules", no OH, existing injector [9]	3.3	~ 20	0.4–0.54
RHIC	660M$ (1999)	0.5	SC Mag	Tunnel, some infrastructure, injector re-used [10]	3.8	~ 40	0.8–1.2
TESLA	3.14 B€ (2000)	0.5	SC RF	"European accounting" [11]	39	~ 130	11–14
VLHC-I	4.1 B$ (2001)	40	SC Mag	"European accounting", existing injector [12]	233	~ 60	10–18
NLC	~ 7.5 B$ (2001)	1	NC RF	~ 6 B$ for 0.5 TeV collider, [13]	30	250	9–15
SNS	1.4 B$ (2006)	0.001	SC RF	[14]	0.4	20	1.6–1.7
LHC	6.5 BCHF (2009)	14	SC Mag	collider only — existing injector, tunnel & infrstr., no OH, R&D [15]	27	~ 40	7–11
CLIC	7.4–8.3B CHF(2012)	0.5	NC RF	"European accounting" [16]	18	250	12–18
Project X	1.5 B$ (2009)	0.008	SC RF	[17]	0.4	37	1.2–1.8
XFEL	1.2 B€ (2012)	0.014	SC RF	in 2005 prices, "European accounting" [18]	3.4	~ 10	2.9–4.0
NuFactory	4.7–6.5 B€ (2012)	0.012	NC RF	Mixed accounting, w. contingency [19]	6	~ 90	7–11
Beta-Beam	1.4–2.3 B€ (2012)	0.1	SC RF	Mixed accounting, w. contingency [19]	9.5	~ 30	3.7–5.4
SPL	1.2–1.6 B€ (2012)	0.005	SC RF	Mixed accounting, w. contingency [19]	0.6	~ 70	2.6–4.6
FAIR	1.2 B€ (2012)	0.003-.08	SC Mag	"European accounting" [20], 6 rings, existing injector	~ 3	~ 30	1.8–3.0
ILC	7.8 B$ (2013)	0.5	SC RF	"European accounting" [21]	34	230	13–19
ESS	1.84 B€ (2013)	0.0025	SC RF	"European accounting" [22, 23]	0.4	37	2.5–3.8

V.Shiltsev, A phenomenological cost model for high energy particle accelerators

2014 JINST 9 T07002

Raw Data: *Confusion*

All are Different!

- **Parameters:**
  - energy
  - size/length
  - power
- **Currencies**
- **Years**
- **Technologies**
- **Accounting**

What are we after ?

- In the US (now) – the figure of interest is TPC = "Total Project Cost" (in specified "Year $$")
- Includes ***everything***:
  - **Technical components**
  - **Conventional systems**
  - **Cost of R&D, PED**
  - **Program management**
  - **Escalation**
  - **Contingency**
  - **SWF, OH, etc, etc…**
- (Tough it is not always easy) the "known" costs will be translated to the **TPC** … sets reference

What is the COST of, e.g. SSC ?

- 1984 2.7-3.1B$ RDS, FY1984
- 1986 3.9-4.2B$ SSC CDR
- 1988 5.2B$ budget request
- 1989 5.9B$ URA contract
- 1990 7.8B$ SSCL site specif.
- 1992 8.3-8.9B$ var. DOE/HEPAP
- 1993 11.8B$ (1.2B$) TPC Congress

SSC 1990 (DOE/ER-0468P)

Construction Project	SCDR	Baseline	Δ
1.0 Technical Systems	2986	3168	+182
2.0 Conventional Systems	1052	1073	+21
3.0 Project Management Support, & Indirects	49		
Subtotal (FY90$)	4087		
Escalation	906		
Subtotal (AY$)	4993		
Contingency (AY$)	920		
Construction Total (TEC)	5913		
Other Related Costs			
4.0 R&D, Pre-Ops, & Support	976	[illegible]	[illegible]
5.0 Experimental Systems	752	760	+8
Subtotal (FY90$)	1728	1635	-93
Escalation	196	263	+67
Other Costs Total (AY$)	1924	1898	-26
Total Project Costs (TPC)	7837	8249	+412

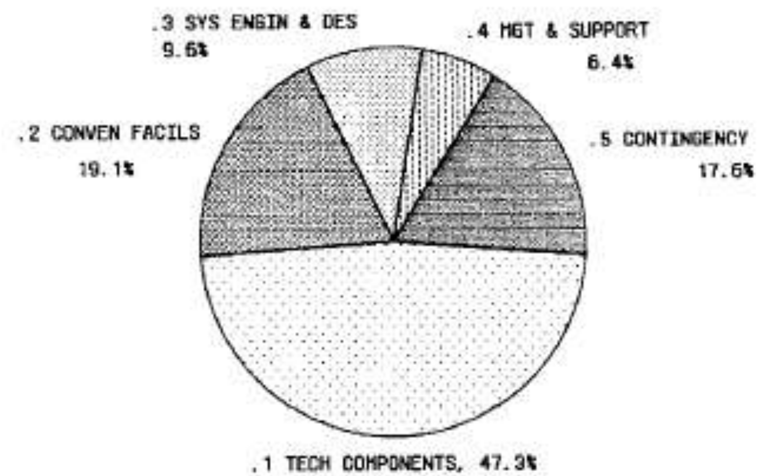


Figure 8.7-1. SSC cost estimate summary: Level 2 WBS categories.

11.8B$ in 1993 = ?? Today

CPI Inflation Calculator

$ 11.80

in 1993

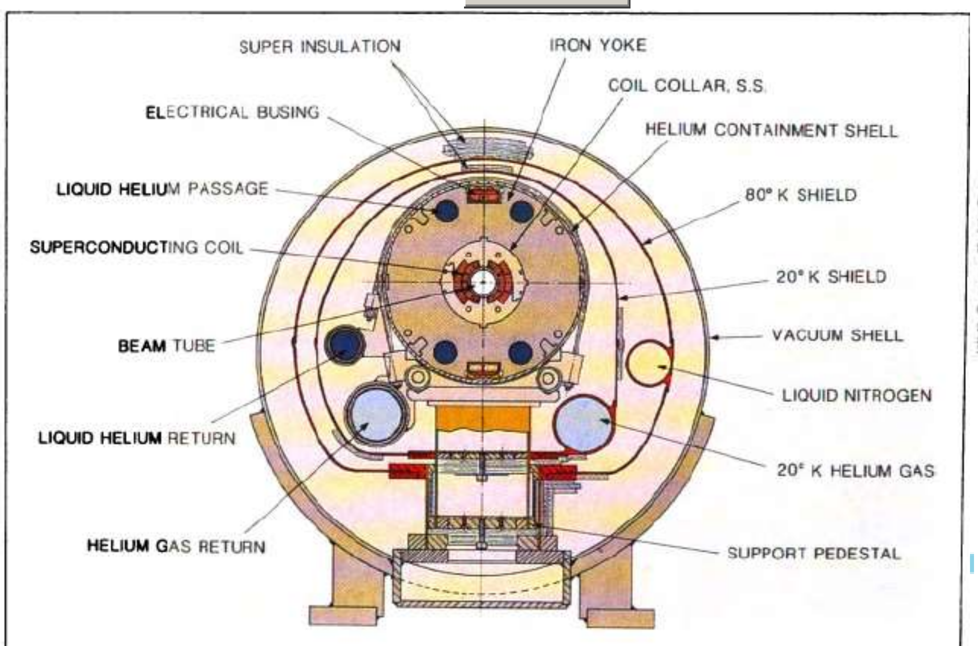
Has the same buying power as:

$18.99

in 2013

Calculate

CPI=1.61



11.8 (1993)=<u>19-25</u> (now)?

LHC: 7+7 TeV pp, 27 km, 120 MW

Construction costs (BCHF)	Personnel	Materials	Total
LHC Machine and areas	0.92	3.68	**4.60** *)
CERN share to Detectors	0.78	0.31	**1.09**
LHC injector upgrade	0.09	0.07	**0.16**
LHC computing (CERN share)	0.09	0.09	**0.18**
Total	**1.88**	**4.15**	**6.03**

*) *(including 0.43 BCHF of in-kind contributi*

[PDF] LHC the guide
cds.cern.ch/record/1092437/files/CERN-Brochure-2008-001-Eng.pdf
by C Lefevre - 2008 - Cited by 12 - Related articles

"…The construction of LHC was approved in 1995 with a budget of **2.6 billion Swiss francs**, with another 210 million francs towards the cost of the experiments … The total cost of the project is anticipated to be **between US$5 and US$10 billion**.[2] "

- **"European accounting":**
  - no OH, R&D, PED, etc
- So, how much did it actually cost?
  - 10 yrs of construction x ~3/4 of Annual budget of 1.2BCHF= 9B

- Two notes :
  - Injector complex and LEP tunnel **existed**
  - SC Magnets **~2/3 of the cost**

TPC (US Accounting) vs *European Accounting*

- To get the TPC one needs to include *SWF, OH, Escalation, Contingency, R&D, PED (often missed)*, and other *"missing elements"*

- TESLA (H.Edwards & P.Garbincius) ~ 1.95
- ITER (D. Lehman) ~ 2.3 (10% of 5B$=1.15B$)
- ILC (2008 DOE/OS) 16.5/6.7=**2.45** - ?

Use factor of 2-2.4 as typical

ILC : 0.5 TeV com, e+e-, 31 km, 230 MW

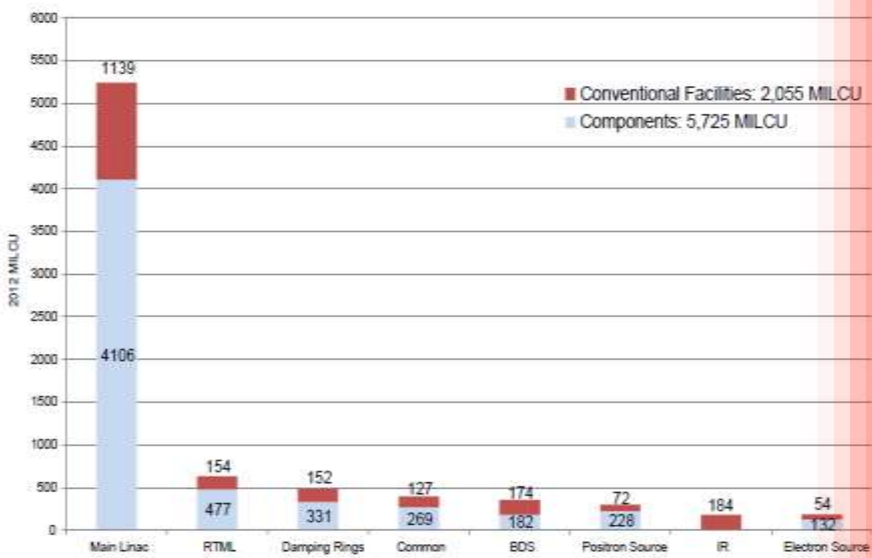


Figure 15.8. Distribution of the ILC value estimate by system and common infrastructure, in ILC Units. The numbers give the TDR estimate for each system in MILCU.

ScienceInsider

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Chu Pegs ILC Cost at $25 Billion

by Adrian Cho on 5 May 2009, 2:03 PM | 0 Comments

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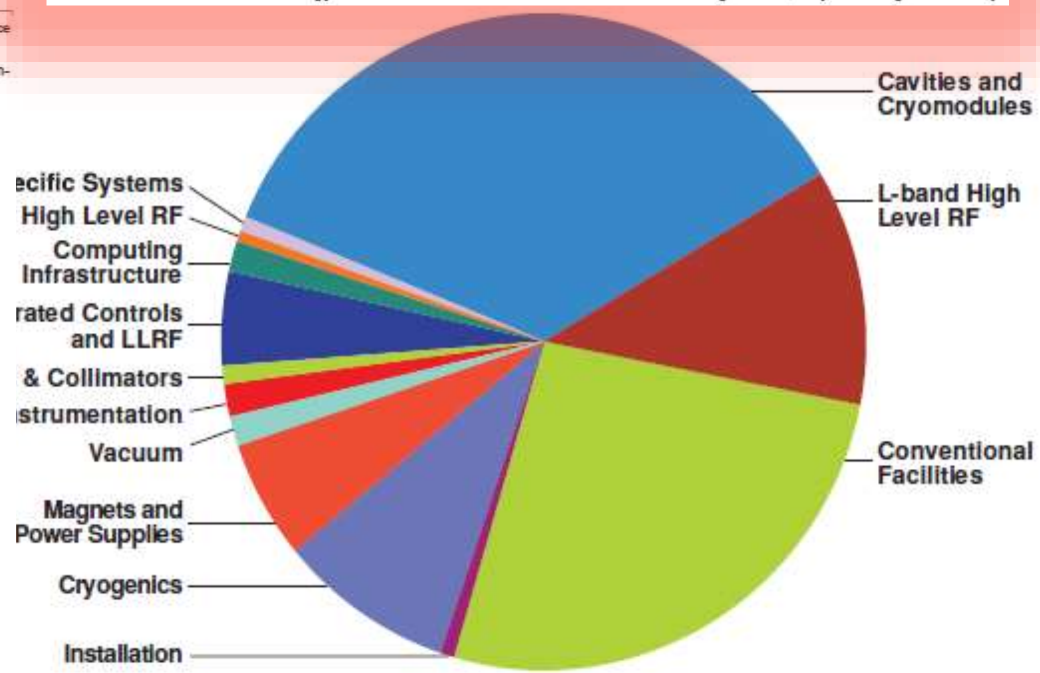
The International Linear Collider (ILC), a proposed 40-kilometer-long particle smasher, would cost a lot. But how much? U.S. Secretary of Energy Steven Chu and the leader of the project don't agree.

Yesterday, Chu said that "the total price tag will be about $25 billion." But Barry Barish, a physicist at the California Institute of Technology in Pasadena who directs the ILC Global Design Effort, says that figure is likely

- ILC RDR (2007)
  - 6.6B$ components
  - 14,000 FTEs
- ILC TDR (2013)
  - 7.8B$ components
  - 13,000 FTE (man yrs))



ILC-0.5 TPC = ?

- **Components: 7.8B$**
- **Manpower: 22e6 man hrs ~2,5B$**

Also:

- Detailed engineering design (~3 yrs) X B$
- Site development (bringing electrical power, roads, buildings to the site) Y B$
- Running associated lab for 10 years Z B$
  (safety, HR department, procurement, roads, maintenance, etc for green field site)
- Detectors XX B$
- Contingency YY B$
  (add 25% to have ~85% confidence level)

One ends up with ~(15-18)B$

- Note that **ILC-0.25 TeV** (Higgs Factory) cost is **~70%** of ILC-0.5 TeV

symmetry dimensions of particle physics

home departments science topics

Commentary: Ray Orbach

Photo: Reidar Hahn, Fermilab

Focus on the future

Over the next few years, the U
physics communities will see g
These, in turn, will pose profou
the right timescales to ensure
particle physics for the next se
major discovery throughout tha

Three events are notable:

- Within the next several years
highly successful experiment
Factory at SLAC. These two
field, and I congratulate the t
for their success in running th
luminosities.

HEPAP and Office of Science summed: ILC in the US "...delayed till ~2025 "

DIRECTOR'S CORNER

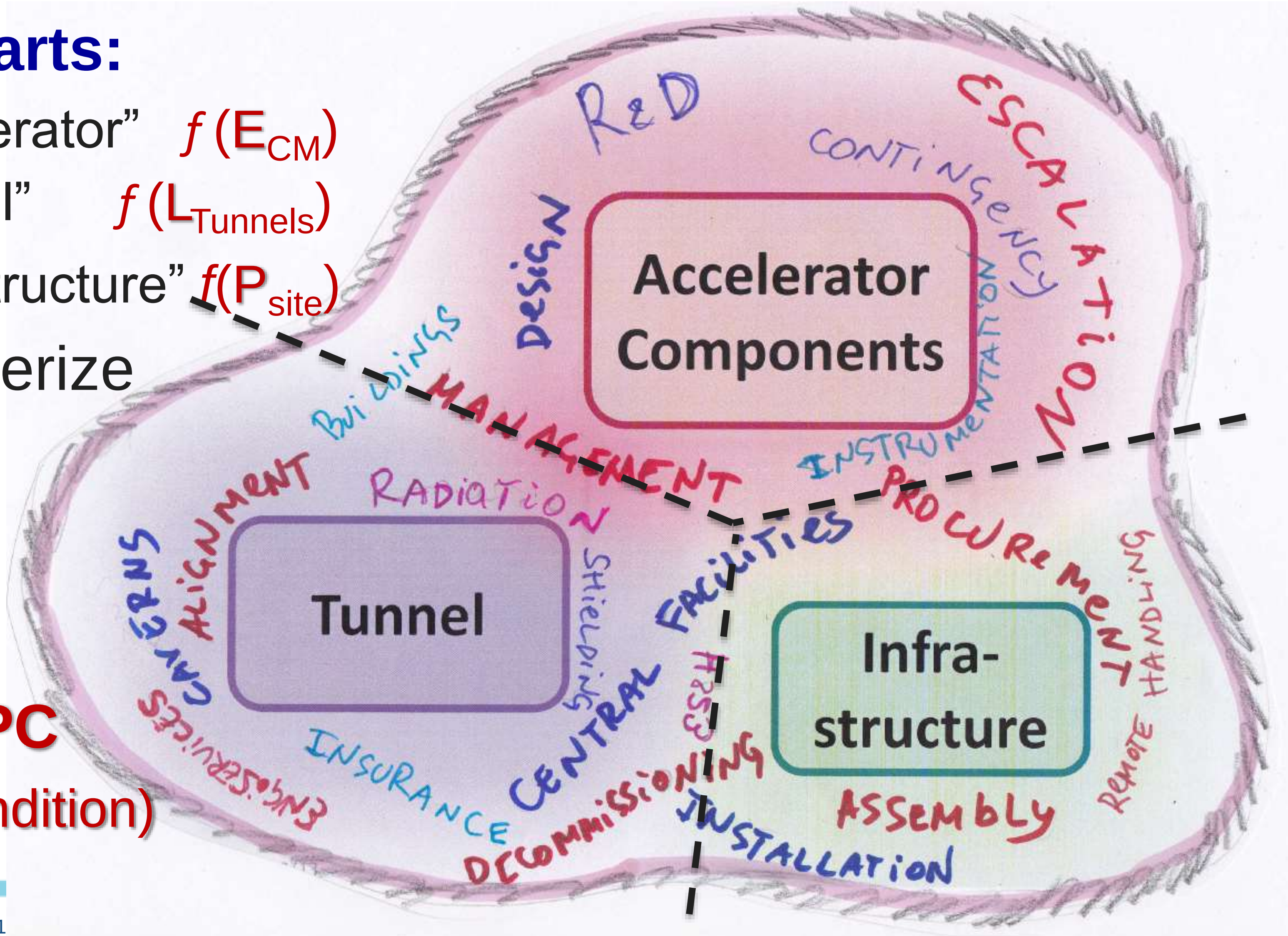
An ILC Higgs factory

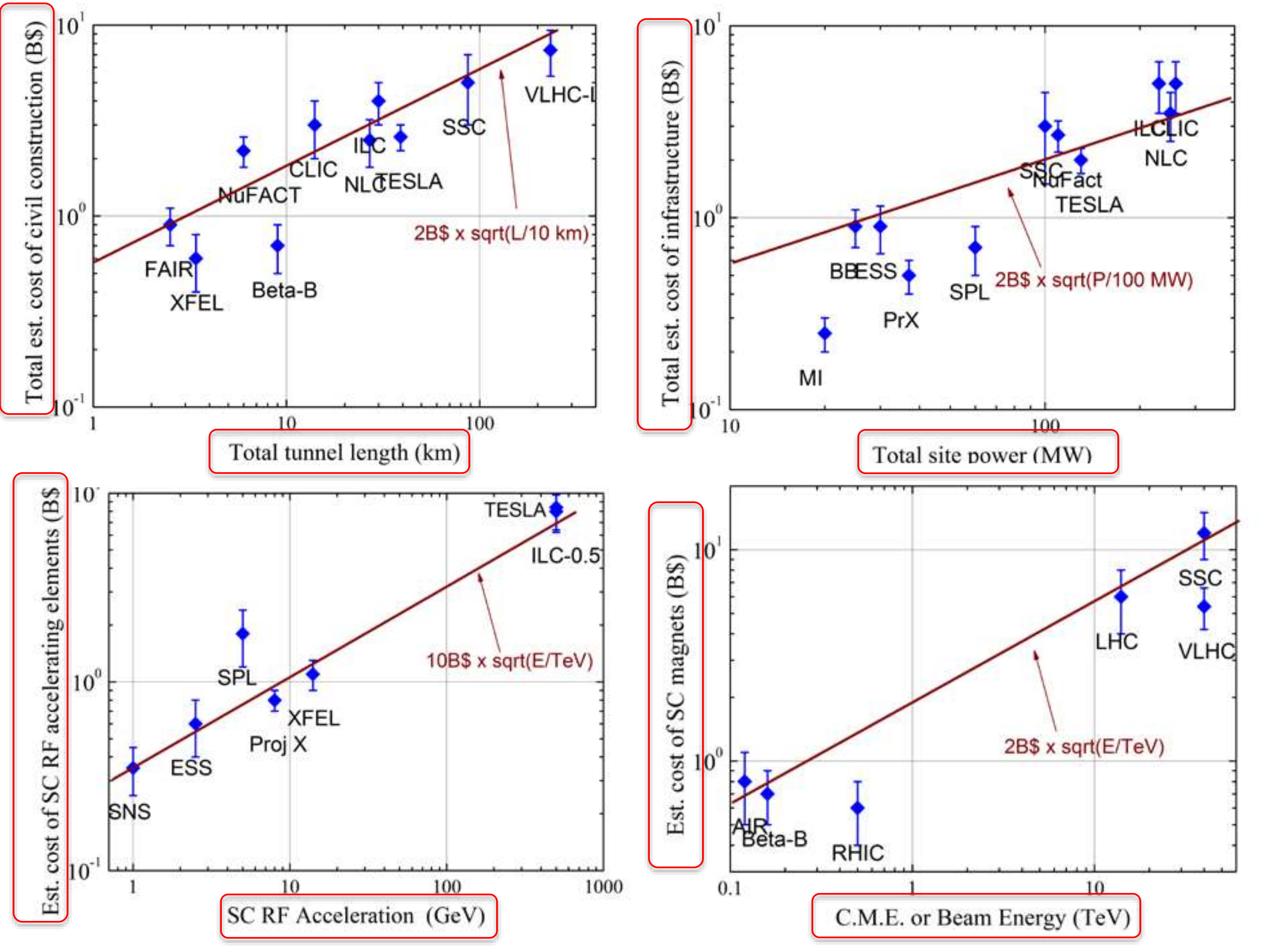
Based on some rather simplistic scaling, the cost of a dedicated 250-GeV machine would be ~70% of the cost of the 500-GeV machine. This may seem surprising until you realise that only about 60% of the total baseline cost is actually the linacs; the remaining 40% is for the sources, damping ring, beam delivery system and IR hall. A first look at the construction schedule also

Nick Walker | 27 September 2012

Approach: Though the TPC is complex mix → break it in just three parts

- **Three parts:**
  - "Accelerator" $f\,(E_{CM})$
  - "Tunnel" $f\,(L_{Tunnels})$
  - "Infrastructure" $f(P_{site})$
- Parameterize each by one parameter
- **Sum≡TPC** (unitarity condition)





Total est. cost of civil construction (B$)
Total tunnel length (km)
2B$ x sqrt(L/10 km)
FAIR
XFEL
Beta-B
NuFACT
CLIC
ILC
NLC
TESLA
SSC
VLHC-I
Total est. cost of infrastructure (B$)
Total site power (MW)
2B$ x sqrt(P/100 MW)
MI
BB
ESS
PrX
SPL
SSC
NuFact
TESLA
ILC
CLIC
NLC
Est. cost of SC RF accelerating elements (B$)
SC RF Acceleration (GeV)
10B$ x sqrt(E/TeV)
SNS
ESS
SPL
Proj X
XFEL
TESLA
ILC-0.5
Est. cost of SC magnets (B$)
C.M.E. or Beam Energy (TeV)
2B$ x sqrt(E/TeV)
AIR
Beta-B
RHIC
LHC
SSC
VLHC

Phenomenological Cost Model

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

"Total Project Cost in **the US accounting**"

"Tunnels" – Cost Civil Construction

"Energy" – Cost of Accelerator Components

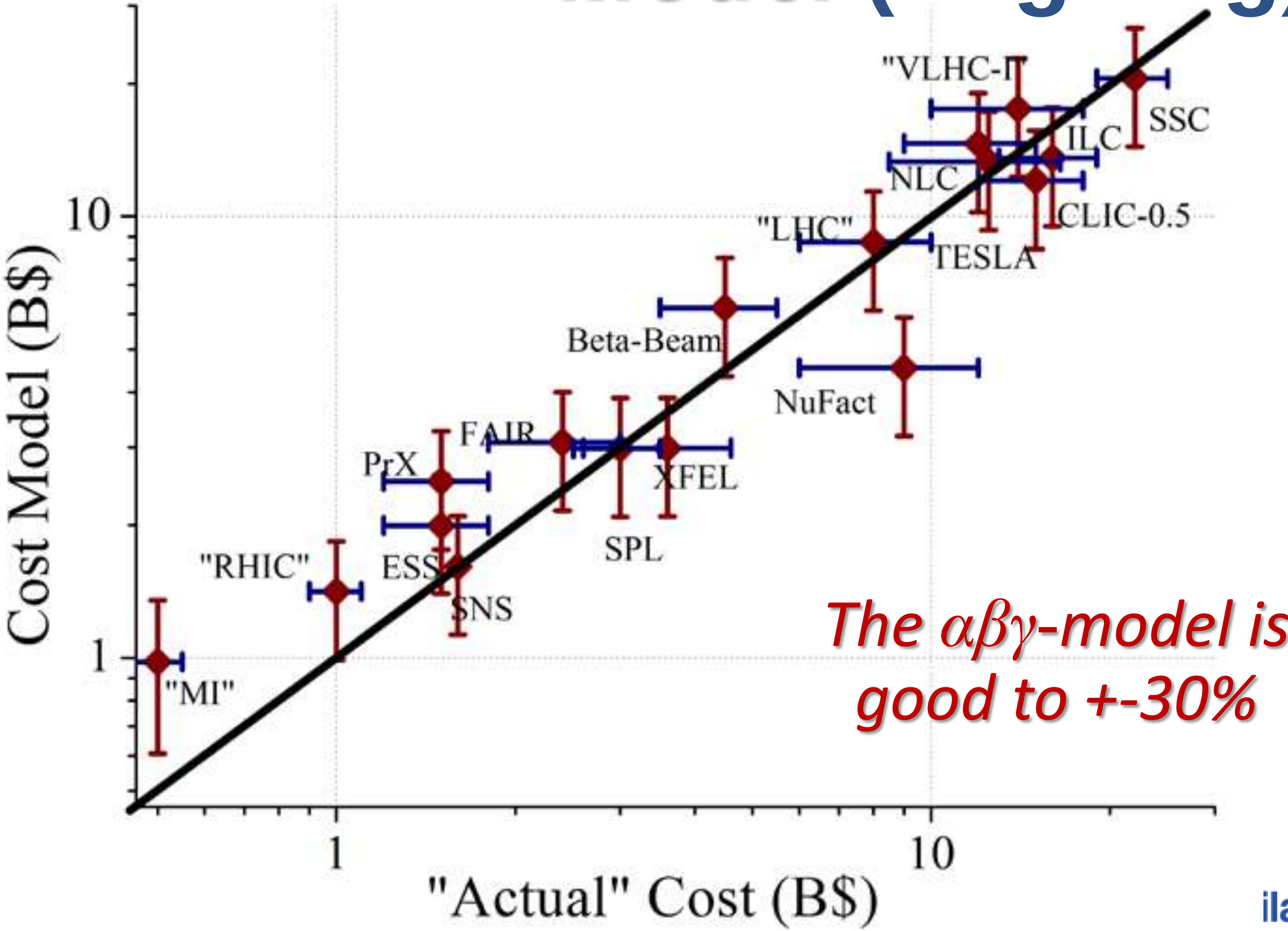
"Site Power"- Infrastructure

where α,β,γ – technology dependent constants

- **$\alpha \approx$ 2B$/sqrt(L/10 km)**
- **$\beta \approx$ 10B$/sqrt(E/TeV)** for SC RF
- **$\beta \approx$ 2B$ /sqrt(E/TeV)** for SC magnets
- **$\beta \approx$ 1B$ /sqrt(E/TeV)** for NC magnets
- **$\gamma \approx$ 2B$/sqrt(P/100 MW)**

Fermilab

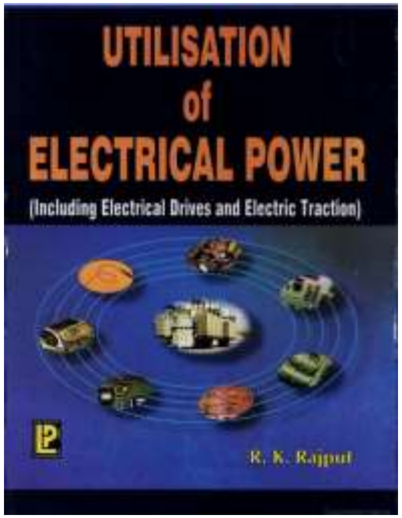
Total Cost vs *Model* (Log-Log)



ilab

Comment on *sqrt*(Parameter)

Sqrt-functions are quite accurate over wide range as such dependence well approximates the "initial cost" – effect :



- Pre-construction, shafts, buildings, etc –

  for "tunnels" (L=0)

- Injectors, transfer lines –

  for "accelerators" (E=0)

- Access, utilities, general infrastructure, preconstruction, etc –

  for "power" (P=0)

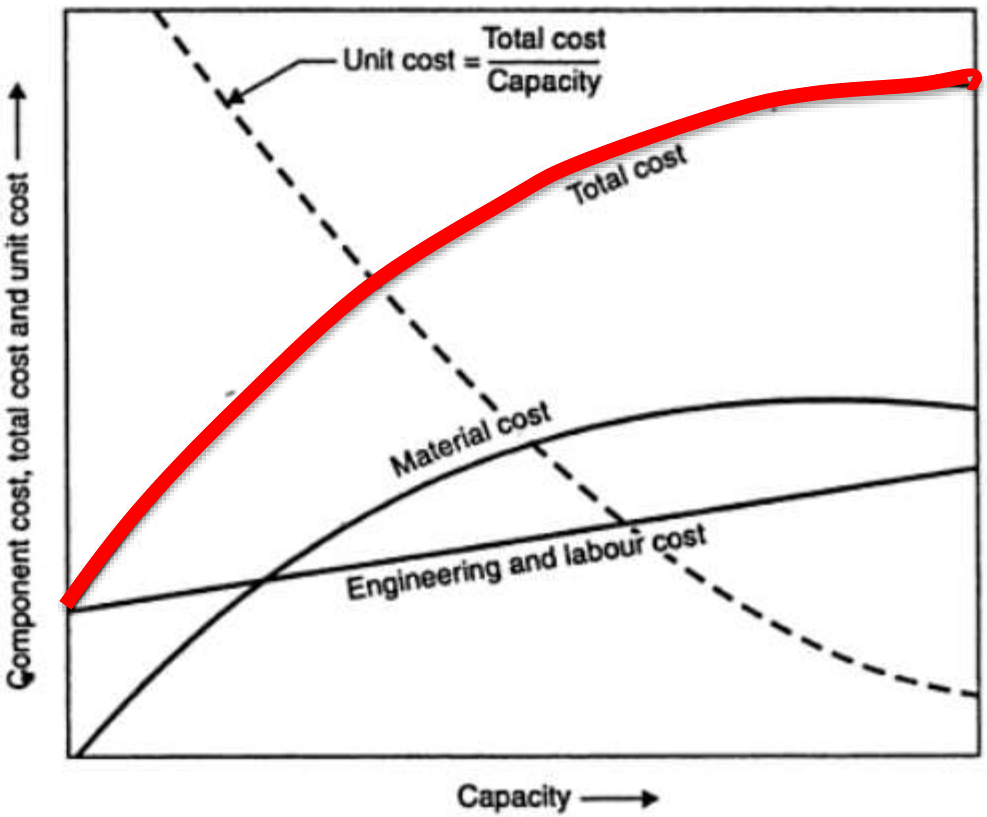


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

! WARNING !

The **αβγ** cost model:

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

a) **Is for a "green field" facility !**
b) **US-Accounting !**
c) **There is hidden correlation btw *E* and technology progress**
d) **Pay attention to units**(10 km for *L*, 1 TeV for *E*, 100 MW for *P*)
   – **α≈ 2B$/sqrt(L/10 km)**
   – **β≈ 10B$/sqrt(E/TeV)** for SC/NC RF
   – **β≈ 2B$ /sqrt(E/TeV)** for SC magnets
   – **β≈ 1B$ /sqrt(E/TeV)** for NC magnets
   – **γ≈ 2B$/sqrt(P/100 MW)**

USE AT YOUR OWN RISK!

Part II: "Near" Future Facilities

		E_{cm}	L	P
TLEP	CERN	0.25	100	~300
CepC	China	0.25	55	~300
ILC	Japan	0.5	36	233
		TeV	*km*	*MW*

Energy Feasibility – No Doubt!

Feasibility of *Performance* (1)

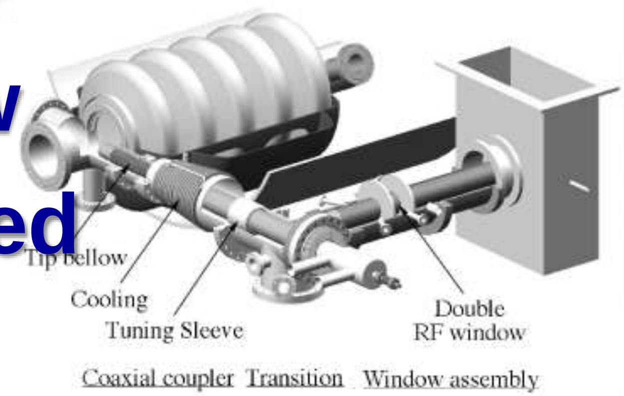
- **TLEP & CepC : ~(2-5)10^{34}/IP**
  - **feasible, but there are issues**
    - Luminosity vs SRF power - trade off ($P=I\ \Delta E_{turn}$)
    - 100 MW RF not easy * (klystrons, cryo, couplers, HOM mode dampers, etc)
    - *beam-strahlung*: lifetime, IR optics *
    - beam-beam effects
    - pretzel separation if one ring
    - Earth field effects if injection energy is low
    - Not easy injector: e+/e- source and booster

SRF Challenges: *Power to Beam*

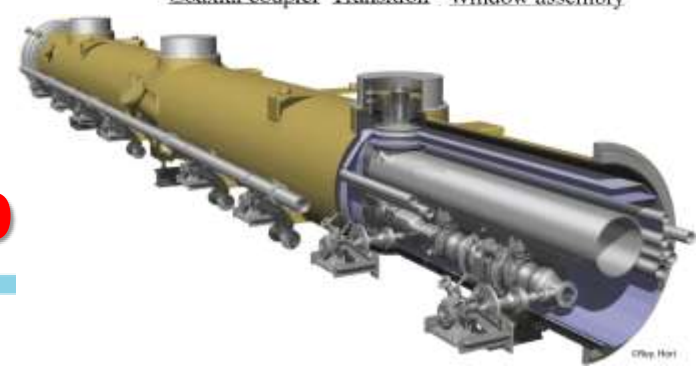
Nb, 1.3 GHz
SRF 15-20 MV/m cw, 35MV/m pulsed

5-10 GeV 10 mA 100 MW cw

- for CepC / TLEP
- SC RF: compare with



LEP	6GeV	6mA	18MW cw
CEBAF	12GeV	0.2mA	2.5MW cw
SNS	1GeV	1 mA	1 MW pulsed
LCLS-II	4GeV	0.25mA	1MW cw
ESS	2.5GeV	2mA	5 MW p
ILC	250GeV	0.05	12 MW p



SRF : Cryo Power CepC/TLEP vs ILC

$$P_{cryo} \propto V_{tot} G_{RF} \mathrm{D}/Q_0$$ or

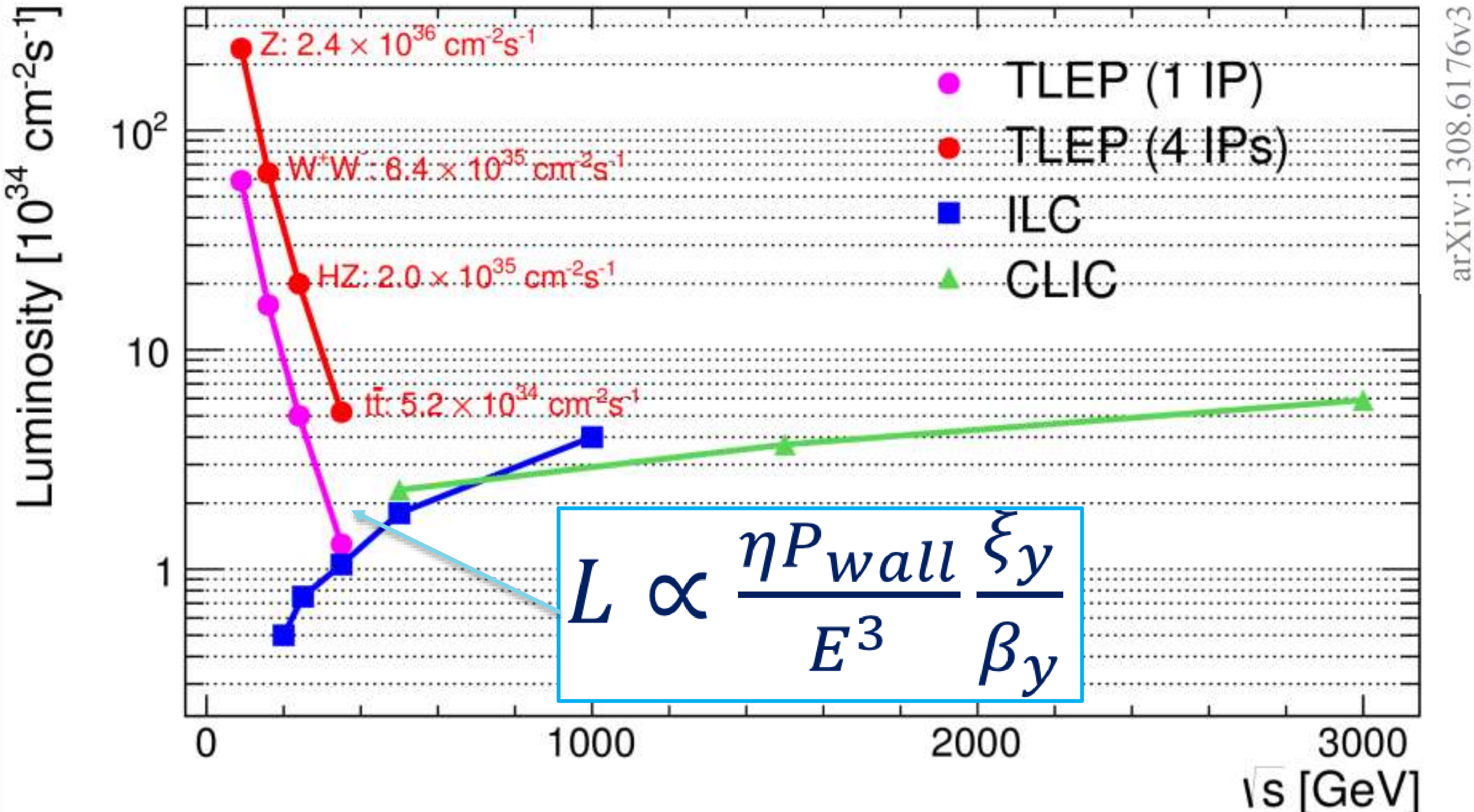
$$P_{cryo} \propto f_{RF} V_{tot} G_{RF} \mathrm{D}/Q_0$$

(if SC cavity losses dominated by BCS resistance)

	ILC-H	CepC/TLEP
RF voltage V_{tot}	**240 GV**	**6-12 GV**
RF gradient G_{RF}	**31.5 MV/m**	**15-20 MV/m**
effective RF length	**8 km**	**<800 m**
RF frequency f_{RF}	1.3 GHz	400 MHz (?)
Q_0: unloaded cavity Q	10^{10}	$2\text{-}4 \times 10^{10}$ (higher at lower G_{RF})
D: RF duty factor	**0.75% (pulsed)**	**100% (cw)**
total cryo power	**16 MW**	**10-25 MW**

total cryo power similar for both projects

CepC/TLEP Luminosity is set by RF power…



$$L \propto \frac{\eta P_{wall}}{E^3} \frac{\xi_y}{\beta_y}$$

see also R.Talman's tutorial

…or by beam-strahlung

Beamstrahlung

- The average energy loss and the number of photons per electron for the head-on collision with beam energy $E=\gamma mc^2$, bunch charge eN, rms bunch length σ_z, beam size σ_x, σ_y, are given by

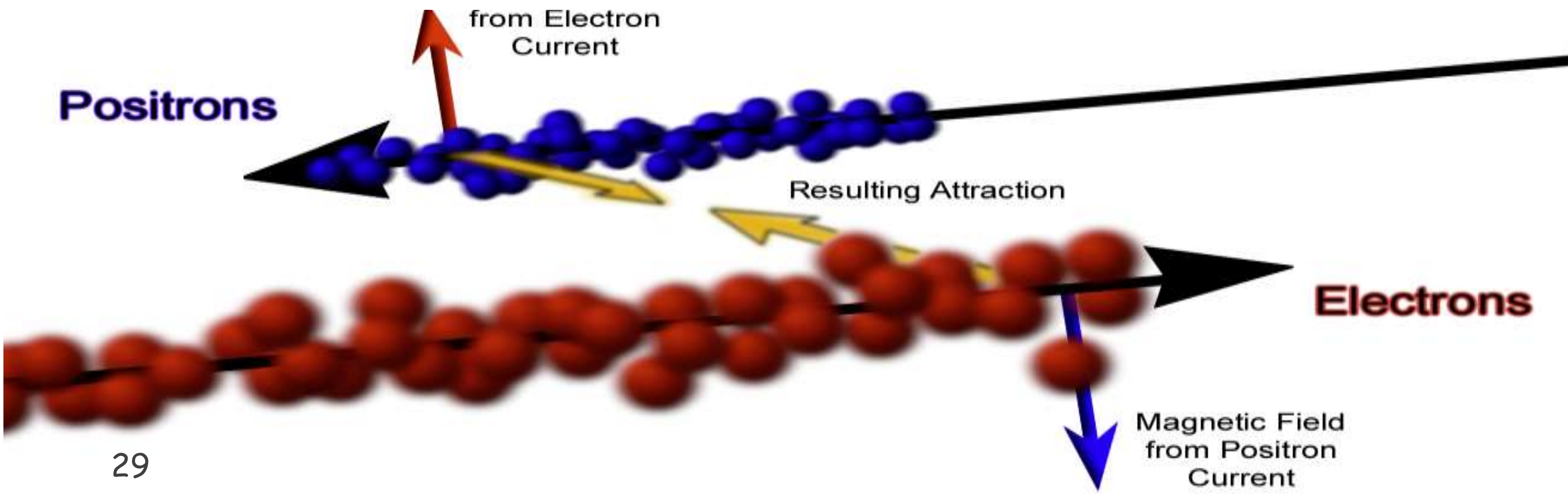
$$\delta_{BS} \equiv \frac{\langle \Delta E \rangle}{E} = 0.864 r_e^3 \gamma \left(\frac{N}{\sigma_z(\sigma_x + \sigma_y)} \right)^2 \sigma_z$$

$$n_\gamma = 2.12 \frac{\alpha r_e N}{\sigma_x + \sigma_y}$$

BB Field

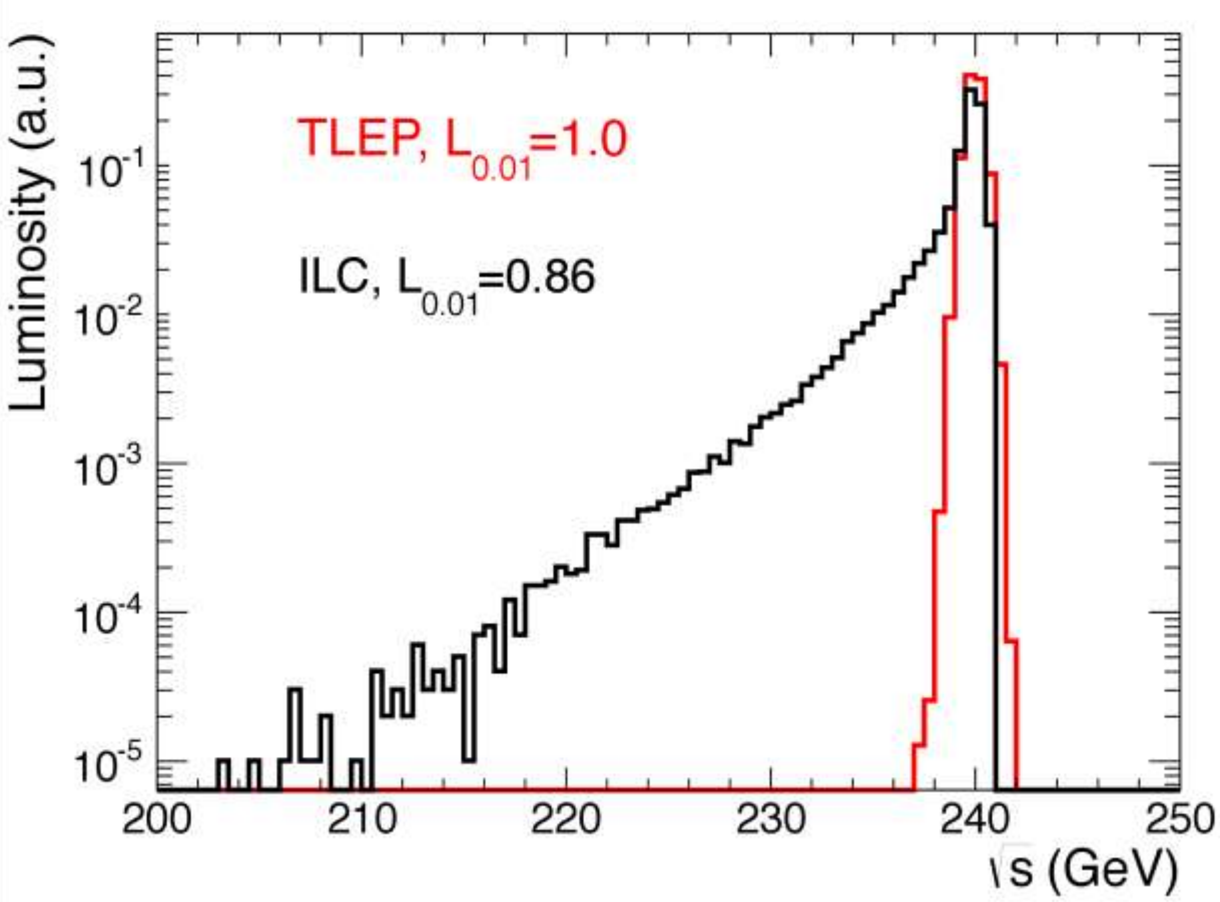
integration length

- For flat beams, $\sigma_x+\sigma_y \sim \sigma_x$



Beam-strahlung

- Limits lifetime in CepC/TLEP
- Large dE/E in ILC

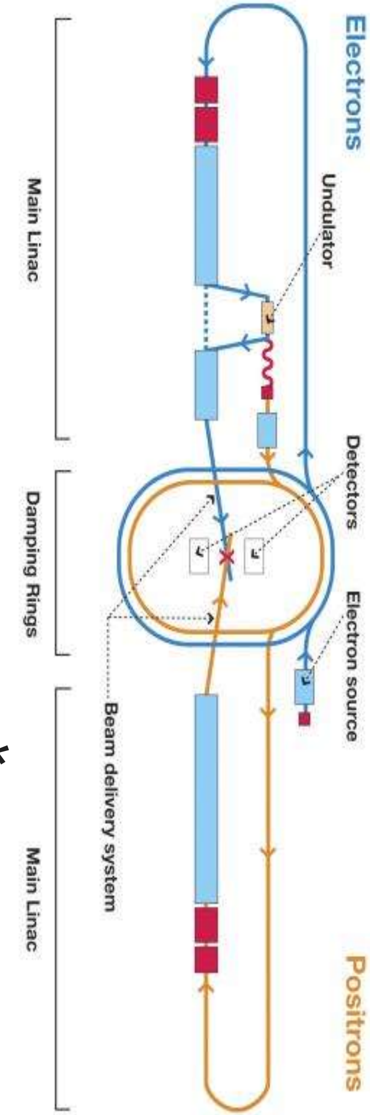


- **That rules out any multi-TeV *e+e-* $\mathcal{L}$>1e33 collider**

$$\frac{E_c}{E_0} = \frac{3\gamma r_e{}^2 N}{\alpha \sigma_x \sigma_z}$$

Feasibility of *Performance* (2)

- **ILC : ~2 10^{34}**
  - **tough* :**
    - emittances from the DRs
    - positron production
    - alignment/jitter of the linac
    - unprecedented final focus to few nm *
    - beam-beam effects
    - *beam-strahlung* *
    - (relatively novel type of accelerator)



Feasibility of ***Cost***

- **ILC :**

European Accounting

  – **official est.: 7.8B$ + 13,000 FTEs**

    - ILC-Higgs ~70%: 5.5B$ +9,000 FTEs

αβγ: TPC = $2 \cdot 3^{1/2} + 10 \cdot 0.5^{1/2} + 2 \cdot 2.33^{1/2} = 3.5 + 7.1 + 3.1 =$ **13.6B$** ±4B$

US Accounting

feasible ? – TBD soon

Feasibility of *Cost* (2)

- **TLEP :** 100 km, 5 GeV SRF

αβγ: $2\cdot10^{1/2}+(1\cdot0.25^{1/2}+10\cdot.005^{1/2})+2\cdot3^{1/2}=6.3+1.2+3.4=$ **10.9 B$** ±4B$

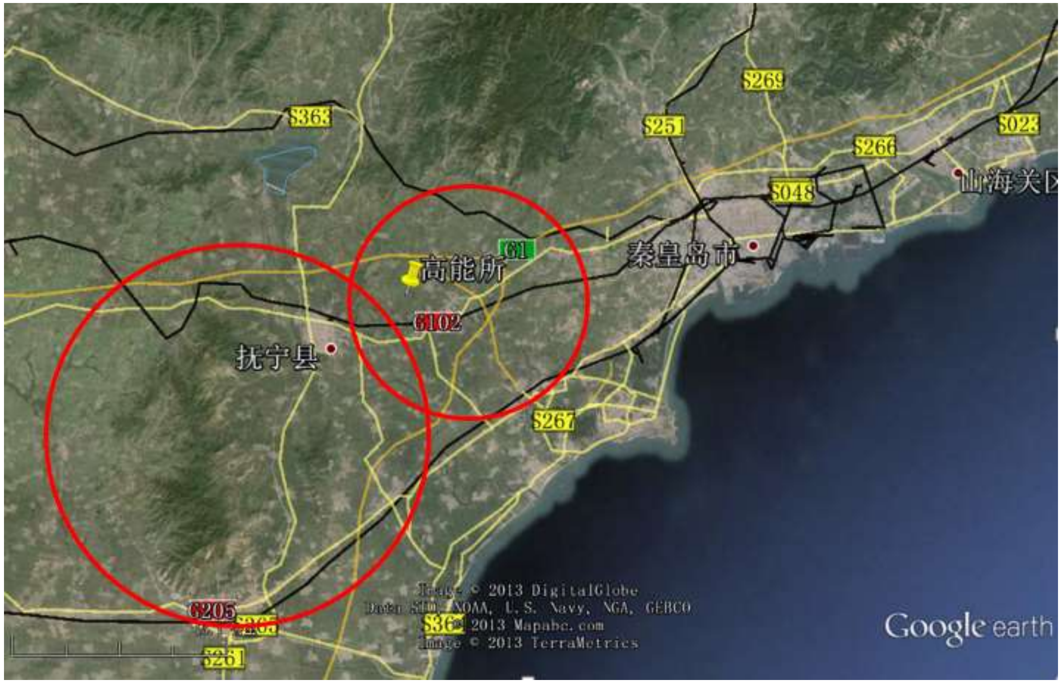
- **CepC :** 50 km, 7 GeV SRF

αβγ: $2\cdot5^{1/2}+(1\cdot0.12^{1/2}+10\cdot.007^{1/2})+2\cdot3^{1/2}=4.5+1.2+3.4=$ **9.1 B$** ±3B$

Fermilab

"Unfair Competitive Advantage"

- **CepC :** *the project to be built in* ***China***



Case study: modern light sources

Fermilab

SSRF (China)

- 432 m
- 3.5 GeV
- 1.2-billion RMB (US$176-million) – 2007
- China's biggest investment in a single science facility

SPRING-8 (Japan)

- 1436 m
- 8 GeV
- The initial construction cost was approximately 110 billion yen (1997). In addition, Hyogo Prefecture donated the site.

DIAMOND (UK)

- 562 m
- 3 GeV
- **<u>383 M £</u>** Diamond's construction is taking place in phases. Phase I cost £263 million and included the synchrotron machine itself, the surrounding buildings and the first seven experimental stations or beamlines. This phase was completed on time, on budget and to specifications in January 2007. Phase II funding of £120 million for a further 15 beamlines and a detector development programme was confirmed in October 2004 and completed in 2012. Diamond can potentially host up to 40 beamlines so there will be continual construction within the main building.(2006).

NSLS-II (US)

- 792 m
- 3 GeV
- **$912 M$** (2015)

Compare Costs of Light Sources

	Cost then	Cost now	Cost USD	Scale to SQRT(1km)
SSRF	1.2B RMB (2007)	1.44 RMB	230 M$	350 M$
SPRING-8	110 BY (1999)	110 BY	924 M$	772 M$
DIAMOND	383 M£ (2006)	500 M£	780 M$	1040 M$
NSLS-II	912 M$ (2015)	912 M$	912 M$	1024 M$

Part III: Future Colliders

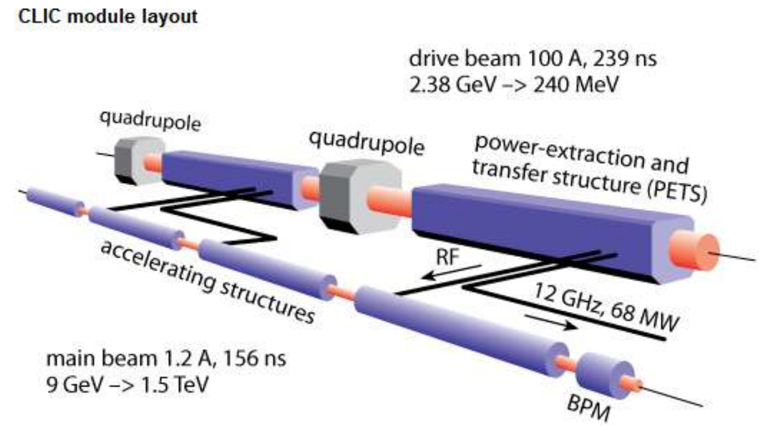
		E_{cm}	L	P
CLIC	CERN	3	60	560
Muon C.	US	6	20	230
FCC	CERN	100	100	400
SppC	China	50+	55	300
		TeV	*km*	*MW*

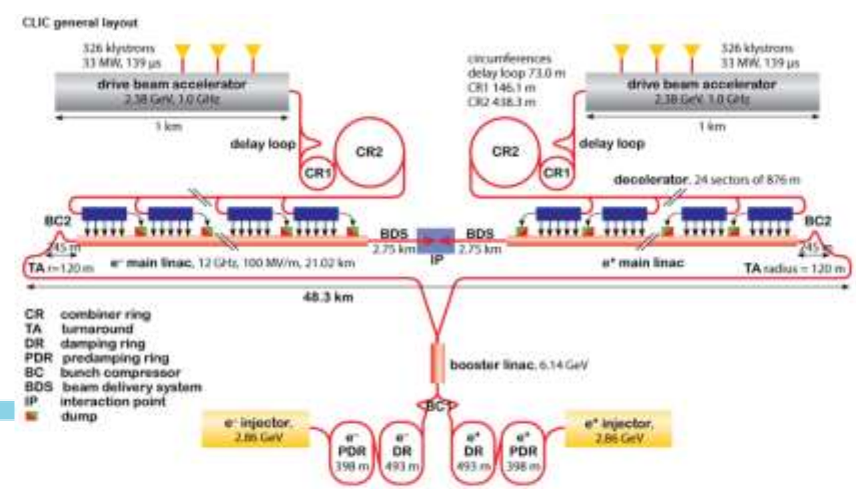
Feasibility of *Energy*

		100 MV/m @ 1e-7 spark
CLIC	**NC RF**	**tough**
Muon C.	**SCMag**	**no doubt**
FCC	**HF-SCMag**	**not (now)**
SppC	**HF-SCMag**	**not (now)**
		16-20 T magnets for >70 TeV

Feasibility of *Performance* (1)

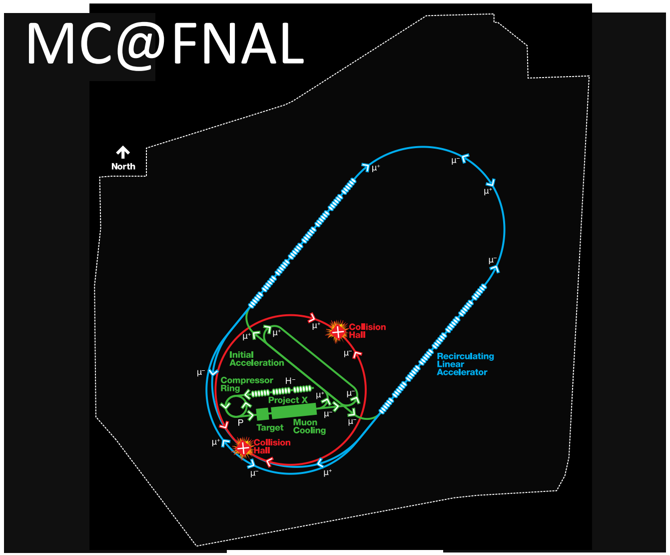
- **CLIC:** *e+e-* **~5 10^{34}**
  - **– very tough ****
    - emittances from the DRs
    - positron production
    - alignment/jitter of the linac
    - unprecedented final focus to few A *
    - *beam-strahlung* **
  - 15 accelerators
  - 560 MW of site power





Feasibility of *Performance* (2)

- **Muon Collider : ~2 10^{34}**
  - **– impossible now:**
    - requires 6D muon cooling
    - about **few $\times 10^{31}$ without it**
    - 4D cooling MICE experiment
  - But:
    - superb dE/E~0.1%
    - *s*-channel 40,000 × *e+e-*
    - *very compact/economical*

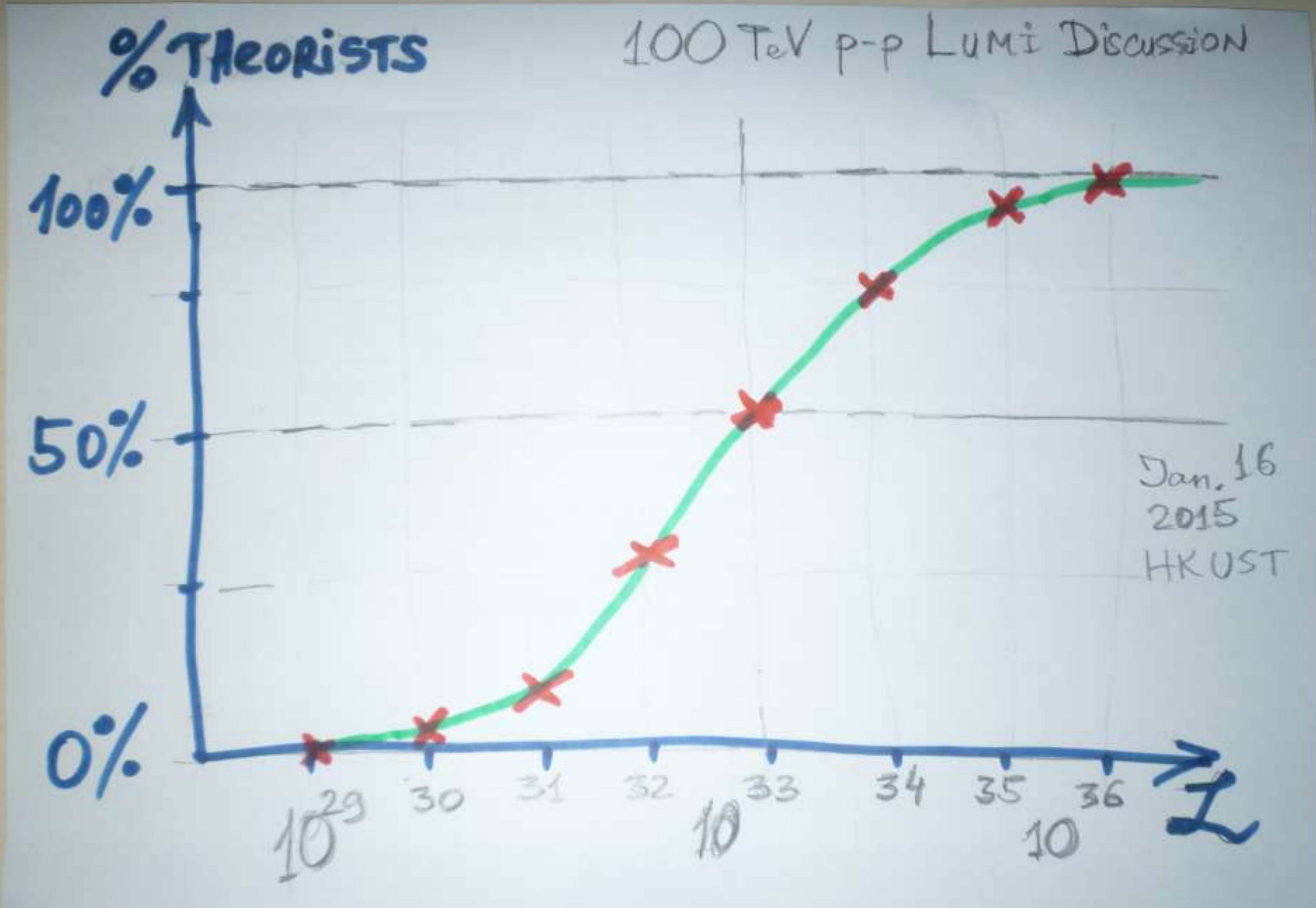


Feasibility of *Performance* (3)

- **SppC and FCC : ~5 10^{34}**
  - **– impossible now:**
    - SR power 5 MW
    - 25-50 W/m (vs 0.1-0.5)
    - Collimation 8GJ/beam
    - IR optics/beam-beam

$$L = \xi \frac{I}{e} \frac{\gamma}{\beta^*} \frac{1}{r_p} F$$

- But:
  - There are ideas for **SR** (liner, magnets)
  - Ideas for **beam-beam** (*e-lenses*) & **collimation**


100 TeV p-p Lumi Discussion
% THEORISTS
100%
50%
0%
Jan. 16
2015
HKUST
10^{29} 10^{30} 10^{31} 10^{32} 10^{33} 10^{34} 10^{35} 10^{36}
$\mathcal{L}$

Feasibility of *Cost* (1)

- **CLIC-3TeV : probably not**

αβγ: Cost = $2 \cdot 6^{1/2} + 10 \cdot 3^{1/2} + 2 \cdot 5.6^{1/2}$ =

$4.9+17.3+4.7=$ **26.9B$** ±8B$

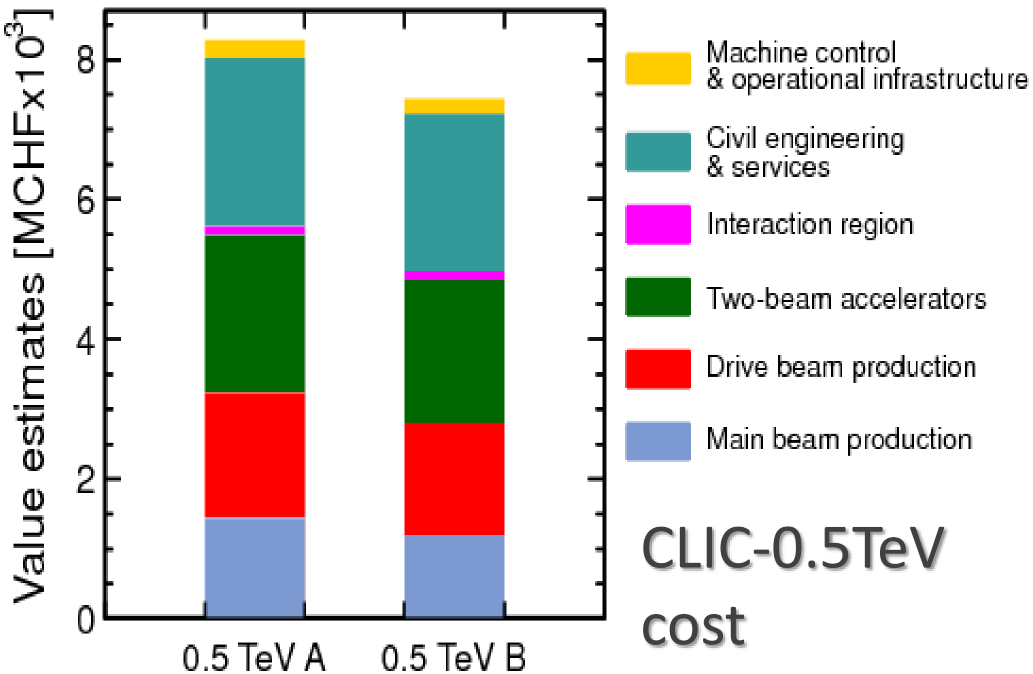
BTW: **CLIC-0.5TeV**

est. 7.4 BCHF

European Accounting

αβγ: TPC = 13B$

US Accounting



CLIC-0.5TeV cost

Feasibility of *Cost* (2)

- **Muon Collider-6TeV : no?**

40 km of tunnels

6 TeV of SC magnets

50 GeV of SCRF linac / RLA

250 MW of site power

αβγ: $\text{Cost} = 2\cdot 4^{1/2} + (2\cdot \mathbf{6}^{1/2} + 10\cdot 0.05^{1/2}) + 2\cdot 2.5^{1/2} = 4+4.9+2.2+3.2=$ **14.4B$** ±5B$

Feasibility of ***Cost*** (3)

- **100 TeV pp : no?**

50-100 km of tunnels

70-100 TeV of SC magnets

400 MW of site power

αβγ: $2 \cdot (5\text{-}10)^{1/2} + 2 \cdot \mathbf{(70\text{-}100)}^{1/2} + 2 \cdot 4^{1/2}$

$= (4.5\text{-}6.3)+(17\text{-}20)+4=$ **(25-30) B$** ±9B$

(less ~10B$ if injector exists)

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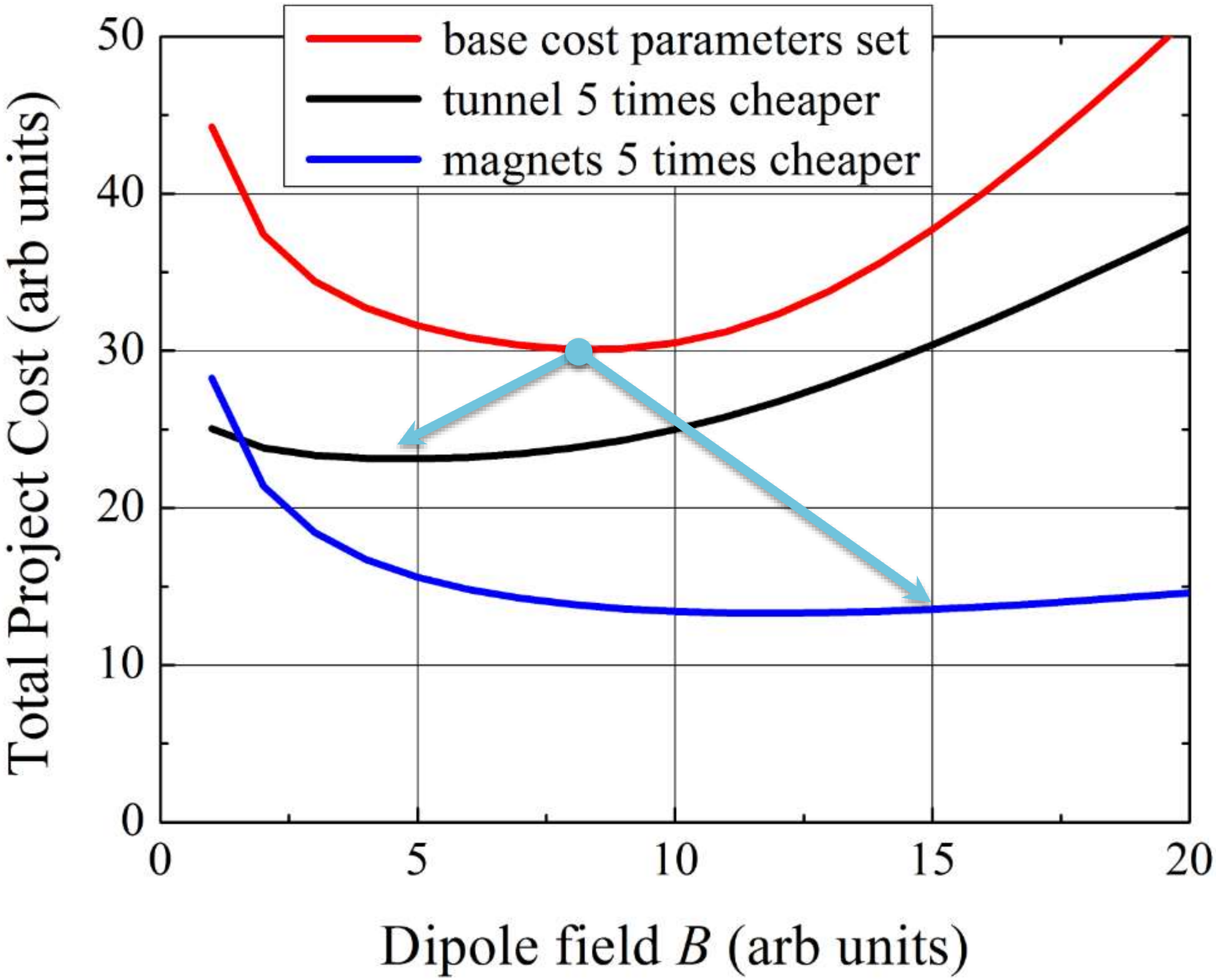
100 TeV pp : Qualitative Cost Dependencies



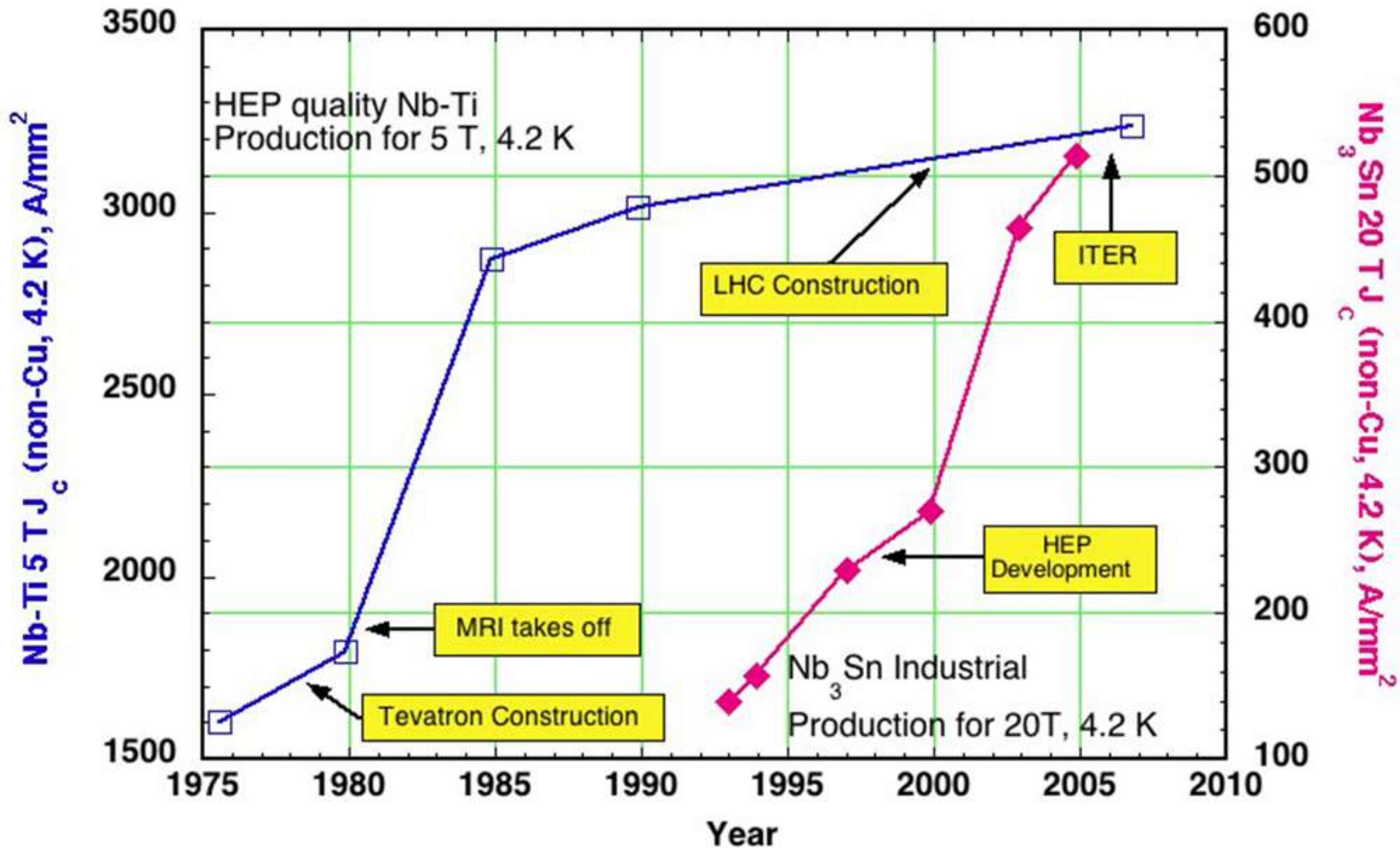
* for illustration purposes only

100 TeV pp R&D Goal #1: SC Magnets

- Long-term research and development toward significant (~3-4) cost reduction of high-field ~15 T accelerator quality magnets
- Global coordination :
  - Accelerator design teams (to understand and meet the specs)
  - Magnet design and development teams (to avoid duplication of efforts)
- Key areas (see also S.Gourlay tutorial):
  - push NB_3Sn technology, new magnet designs, quench & splice engineering, better materials & conductors, etc

Substantial improvements need time

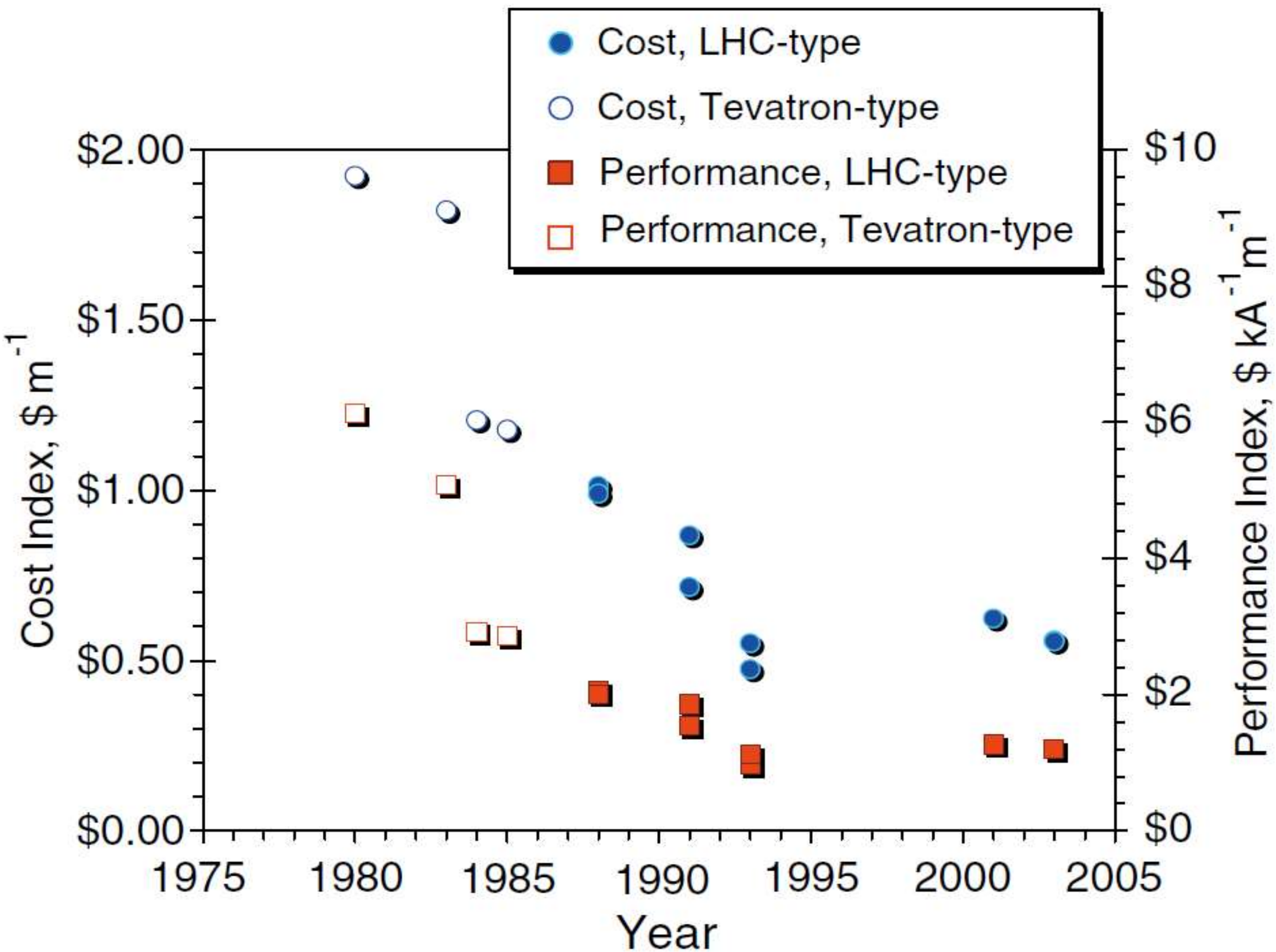
Decadal improvements in SC critical currents NbTi, Nb3Sn



* Courtesy A.Zlobin

Substantial improvements need time

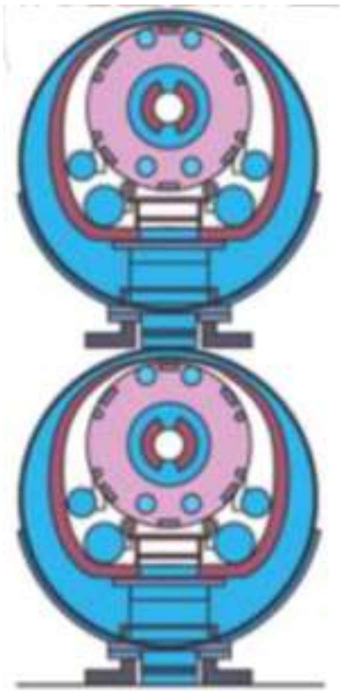
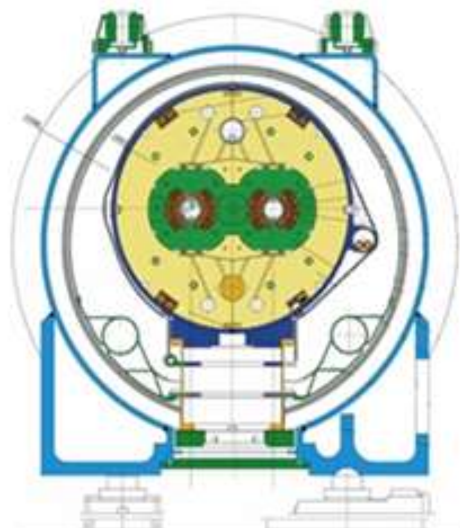
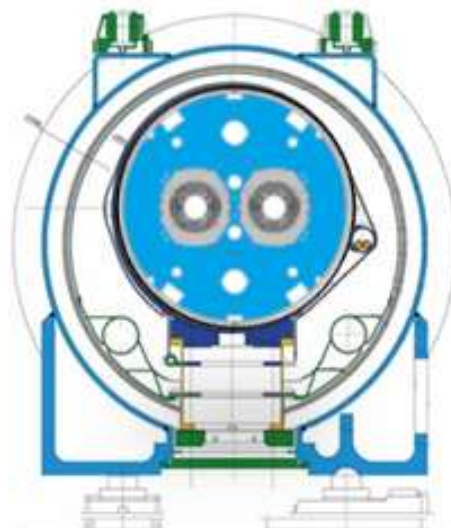
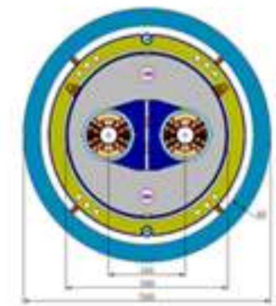
Decadal improvements in SC NbTi cable cost per m, per A*m



* Courtesy A.Zlobin

Substantial improvements need time

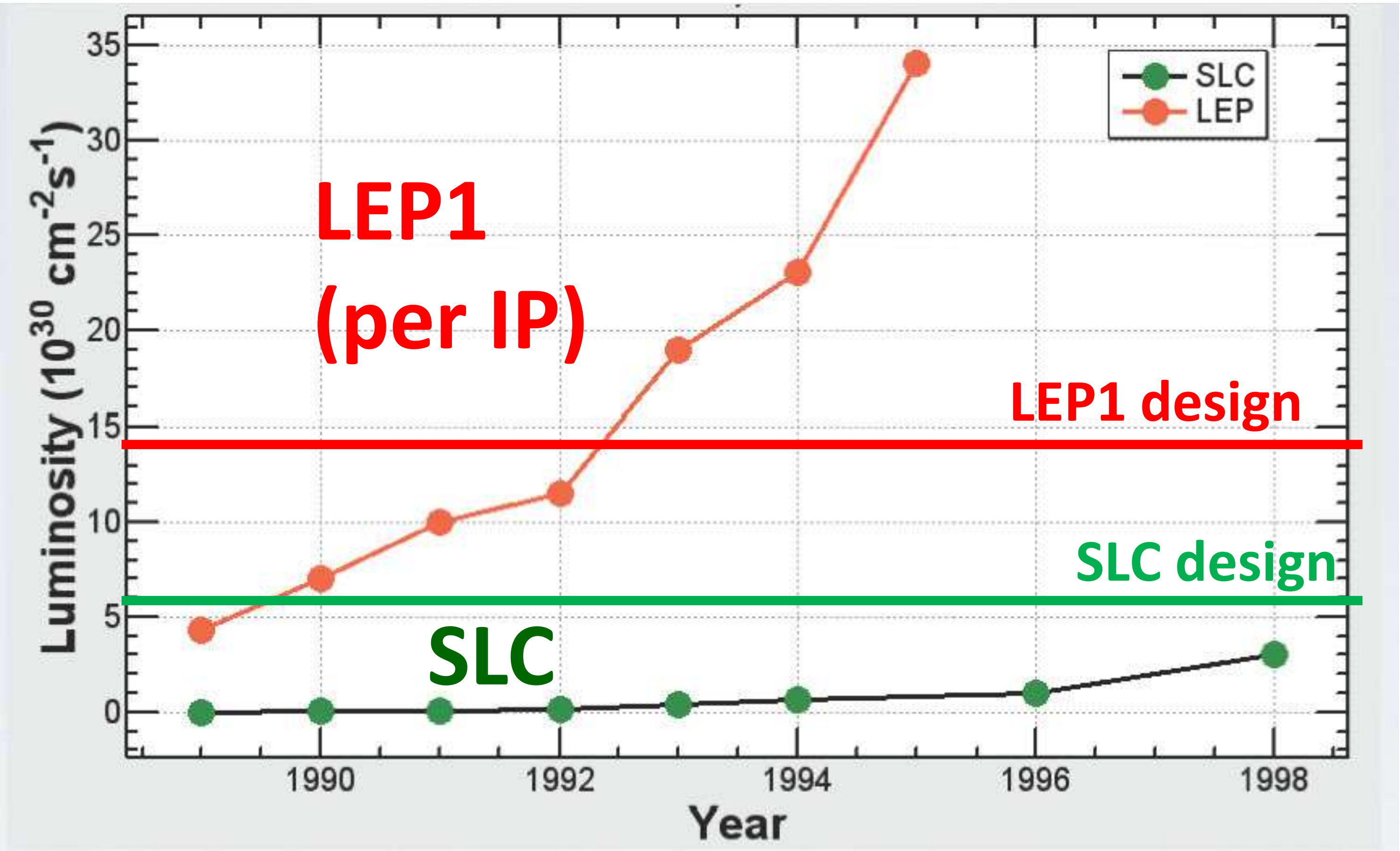
Decadal improvements in SC magnet design

1980's	1990's	2000's	2010's	2020-30's ?
				
Tev,76mm 4.5T,4.2K	SSC, 50 mm 6.6 T, 4.3 K	LHC, 56 mm 8.3 T, 1.9 K	LHC, 60 mm 11 T, 1.9 K	FCC, 43 mm 16T, 4.5K

* Courtesy A.Zlobin

Two Comments: #1

- It takes **time to get to design luminosity**… moreover, **it is not 100% guaranteed**



CERN-SL-2002- 009 (OP), SLAC–PUB–8042 [K. Oide, 2013]

Time to reach *Design Luminosity*

	Time to Design *L*	Final *L* / Design *L*
LEP-I	5 years	x2
SLC	Not achieved (9 years)	x0.5
LEP-II	0.3 year	x3
PEP-II	1.5 year	x4
KEK-B	3.5 year	x2
DAFNE	Not reached yet (9 years)	x0.9
TEV-Ib	1.5 year	x1.5
HERA-I	8 years	x1
RHIC-pp	10 years*	x1.2
TEV-II	3.5 years	x5
HERA-II	5 years	x1
LHC	Not reached yet (6 ** years)	x0.77

V.Shiltsev, Modern Physics Letters A Vol. 26, No. 11 (2011) 761–772

Comment #2

- Besides financial feasibility, one should take into account **availability of experts** :

K.Oide (KEK)

- **"Oide Principle"** : *1 Accelerator Expert can spend intelligently only **~1 M$ a year***
- some 1,000-1,200 total in the world now … e.g.

  ILC: 13,000 FTEs=1300 x 10 yrs
- it takes significant time to get the team together (XFEL, ESS)

Part IV: Is There "Far" Future ?

- Post-100 TeV "Energy Frontier" assumes
  - ❖ 300-1000 TeV   *(20-100 × LHC)*
  - ❖ "decent luminosity" (TBD)
- Surely we know:

1. For the same reason there is no ***e+e-*** collider above Higgs-F there will be no ***pp*** colliders beyond 100 TeV → **LINEAR**

2. Electrons radiate 100% beam-strahlung (<3 TeV) and in focusing channel (<10 TeV) → **μ+μ- or p-p**

circular collider

$$L \propto \frac{\eta P_{wall}}{E^3} \frac{\xi_y}{\beta_y}$$

linear collider

$$L \propto \frac{\eta_{\text{linac}} P_{wall}}{E} \frac{N_\gamma}{\sigma_y}$$

"Phase-Space" is Further Limited

- "Live within our means": for 20-100 × LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)

2T magnets ~ 50 MeV per meter

3. Only one option for >30 GeV/m is known now: <u>dense plasma</u>→ that excludes protons→ <u>only muons</u>

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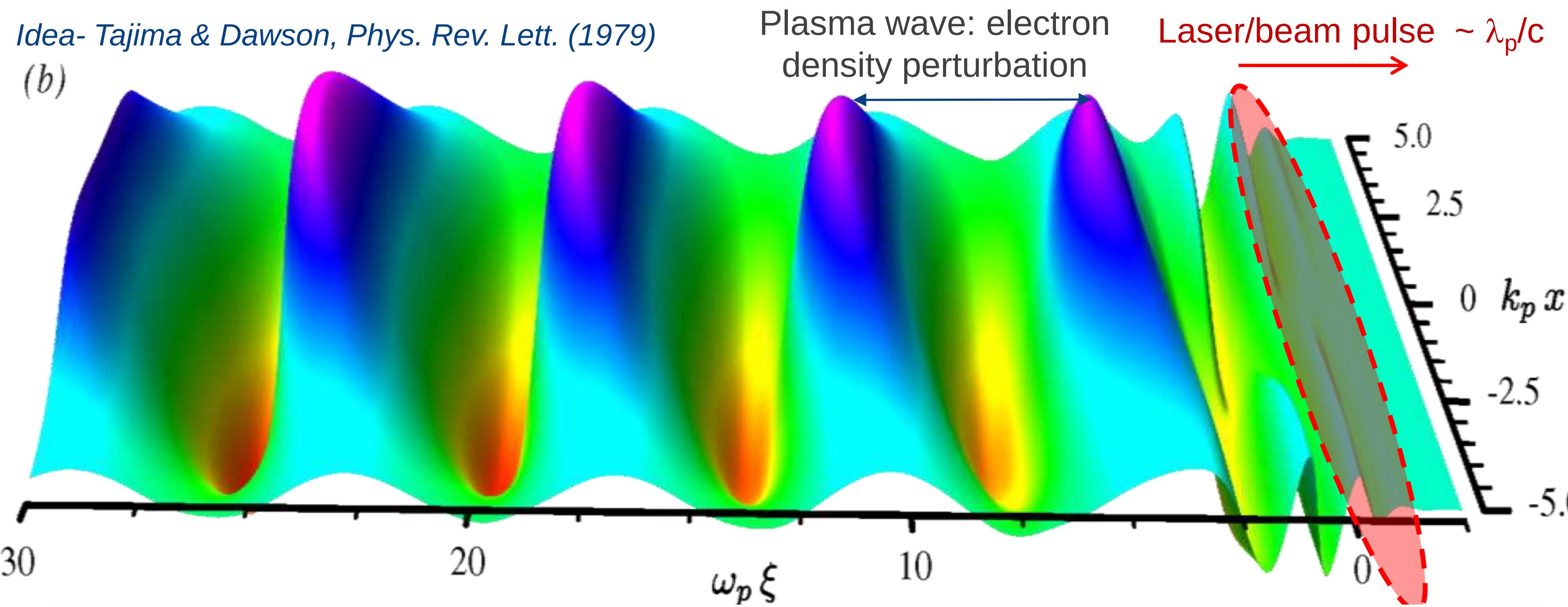
Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100\left[\frac{GeV}{m}\right] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option A:

Short intense e-/e+/p bunch

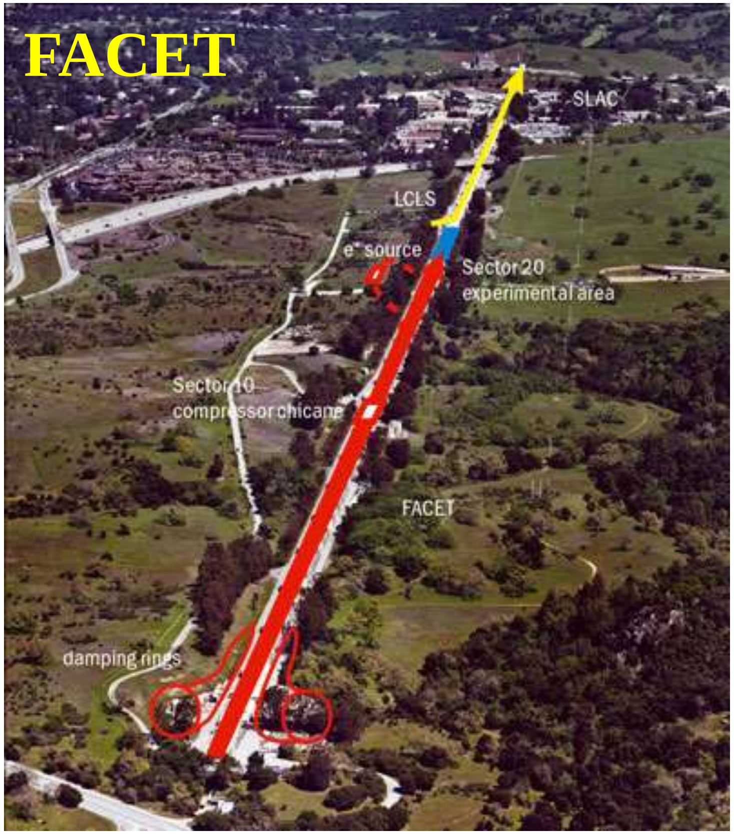
10^{18}cm^{-3}, **100 GV/m**, λ_p~30μm

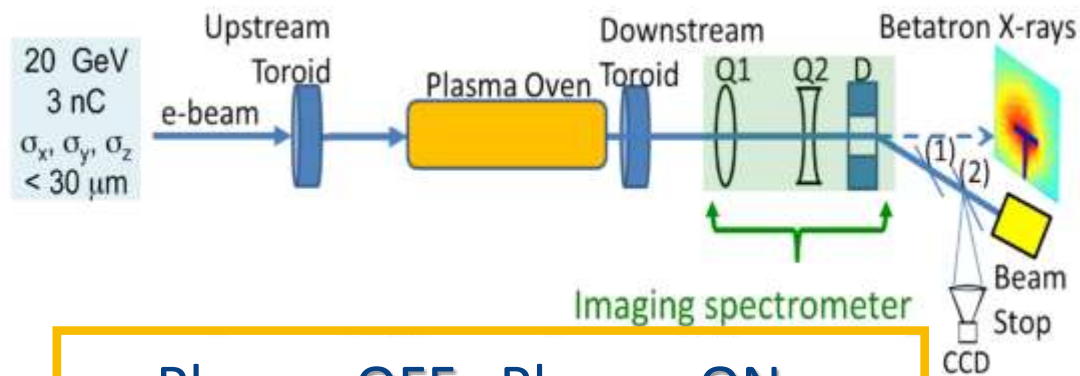
Option B:

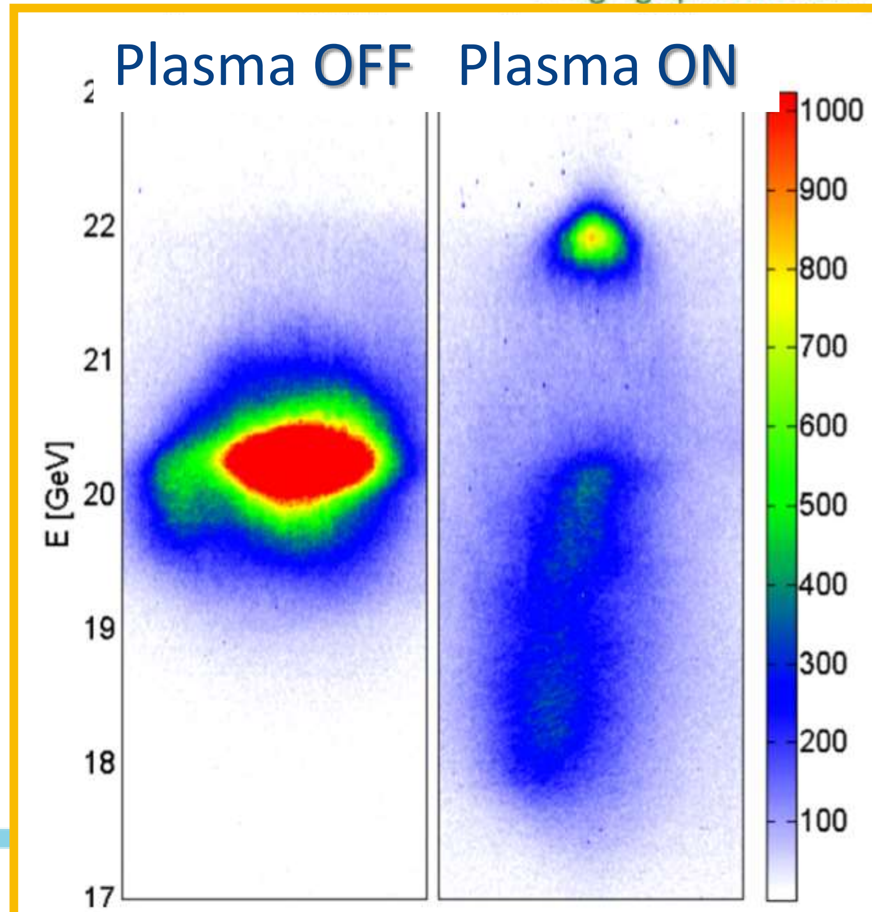
Short intense laser pulse

10^{17}cm^{-3}, **30 GV/m**, λ_p~100μm

Option A: Plasma Wakes by Beam







n~5e16 cm-3

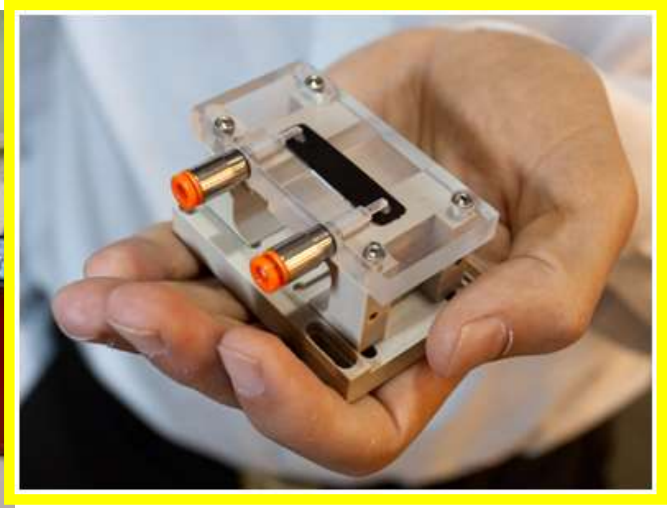
L=0.3 m

dE ~2 GeV

→ 6 GeV/m

electrons

Option B: Plasma Wakes by Laser

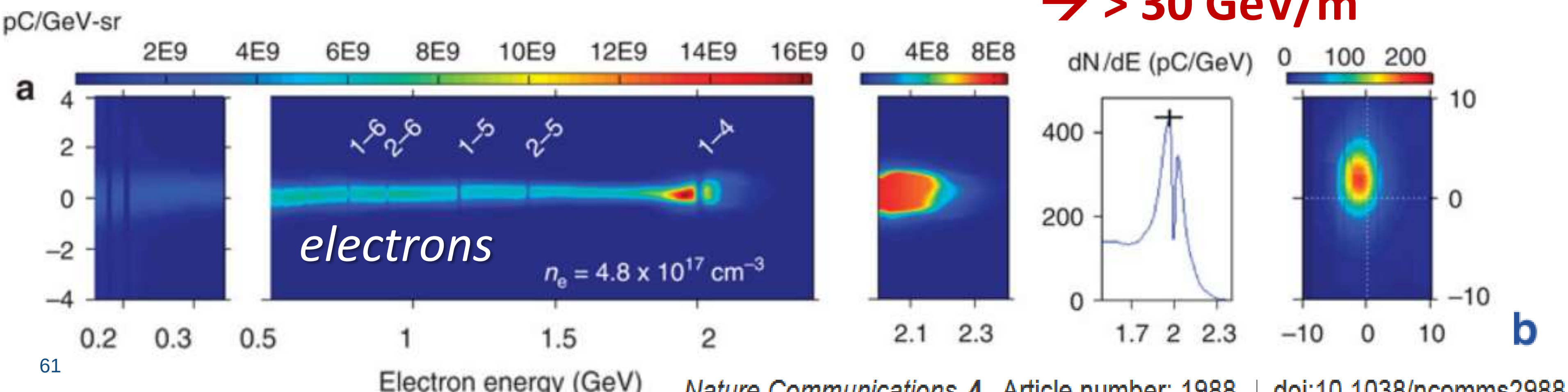


n~few e17 cm-3

L=0.03-0.1 m

dE ~2-5 GeV (PW lasers)

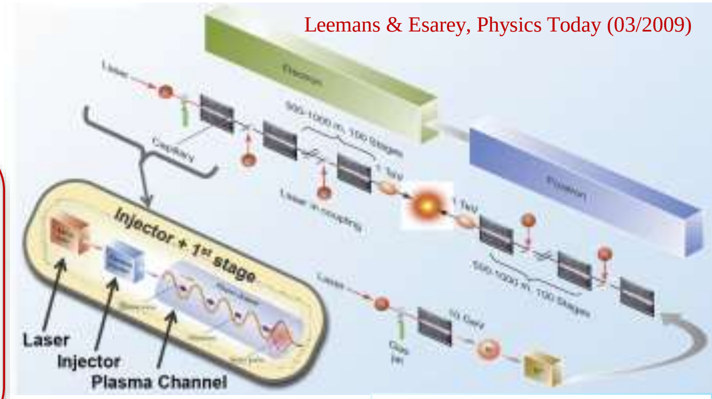
→ > 30 GeV/m



Nature Communications **4**, Article number: 1988 | doi:10.1038/ncomms2988

e+e- Plasma Collider Design Attempts

ISSUES AND QUESTIONS:



Leemans & Esarey, Physics Today (03/2009)

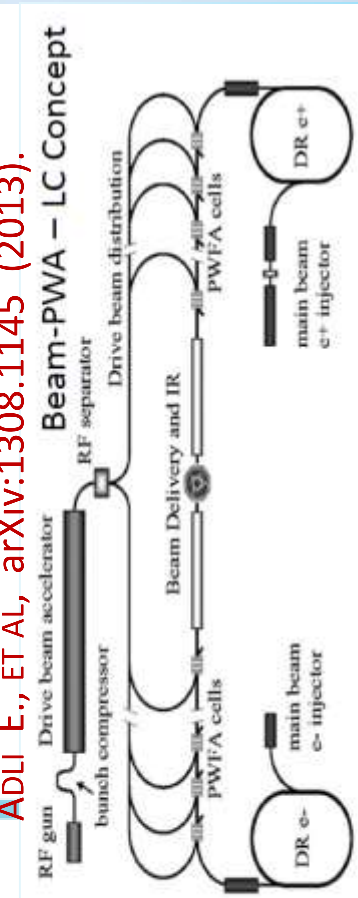
Staging is VERY inefficient – limits average acceleration gradient to ~1-2 GeV/m (beam) and ~10 GeV/m (laser)

Cost is prohibitive (now) : e.g., in the beam-option (A) the *αβγ*-model estimate the cost of 10 TeV facility (25 GeV SCRF drive-beam, 20 km of tunnels, 540 MW) as $2 \times (20/10)^{1/2} + 10 \times (25GeV/1TeV)^{1/2} + 2 \times (540/100)^{1/2}$ =**9B$** + 30-70% for plasma cells (= 12-15 B$?)....

- for laser-plasma ~15-30 M$/10 GeV (i.e. factor of ~20 above required)

Power MW: 130 for 1 TeV –> 540 for 10 TeV (est.)

Luminosity - unknown (many issues, dE/E 100% for *ee*)



ADLI E., ET AL, arXiv:1308.1145 (2013).

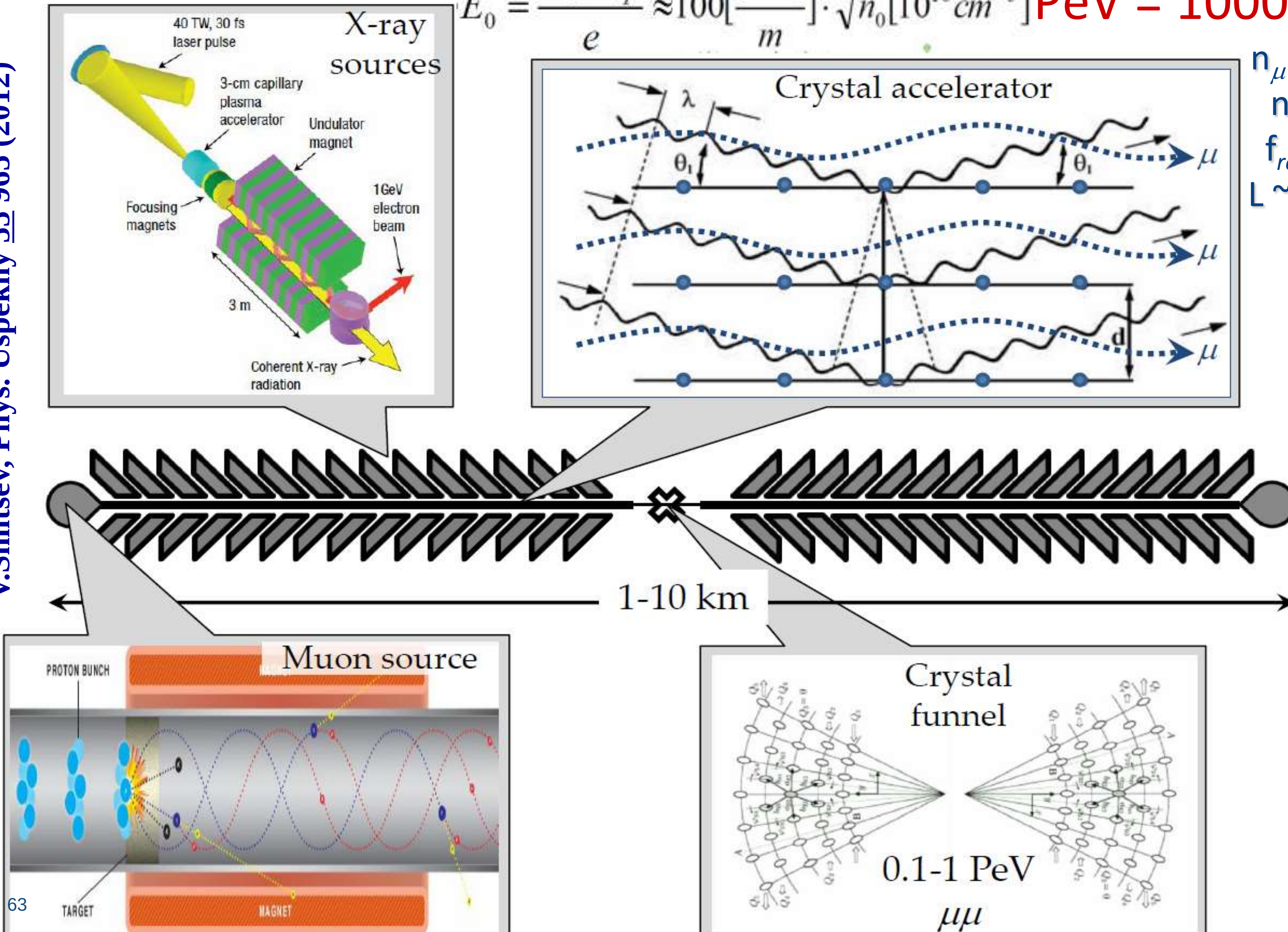
Option C: Crystals & Muons

n~10^{22} cm^{-3}, **10 TeV/m →**

$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$ PeV = 1000 TeV

n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~$10^{30\text{-}32}$

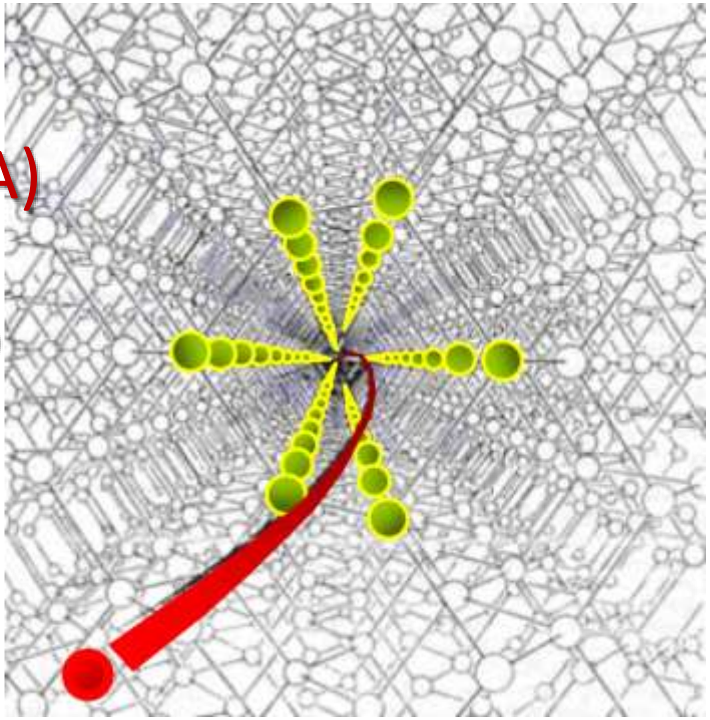
V.Shiltsev, Phys. Uspekhy 55 965 (2012)



ilab

Option C: Crystals & Muons

ISSUES AND QUESTIONS:



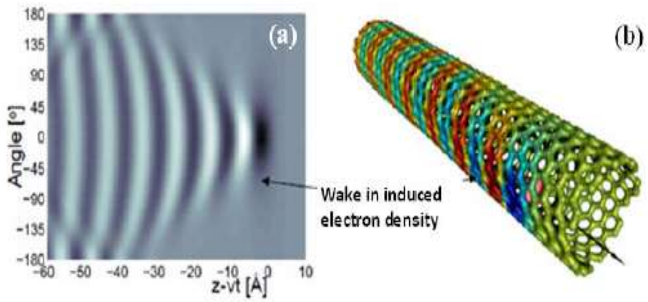
Can do(??) ~100+ GeV/m (test at ASTA)

- How to excite crystal?
- By Xrays? Sub-μm short bunches?

Cost/m unknown

Power MW: unknown

Luminosity - unknown (low)



yes – That will be the shortest accelerator
yes - Energy reach of **1-10 PeV** thinkable
yes - Muons "do not radiate"!!

Fermilab

New Paradigm for Collider Physics

$$E_{cm}$$

Size is limited <10 km → calls for the highest gradients → crystals → muons

$$L = f\frac{N_1 N_2}{A}$$

Luminosity calls for more particles in the smallest beam size

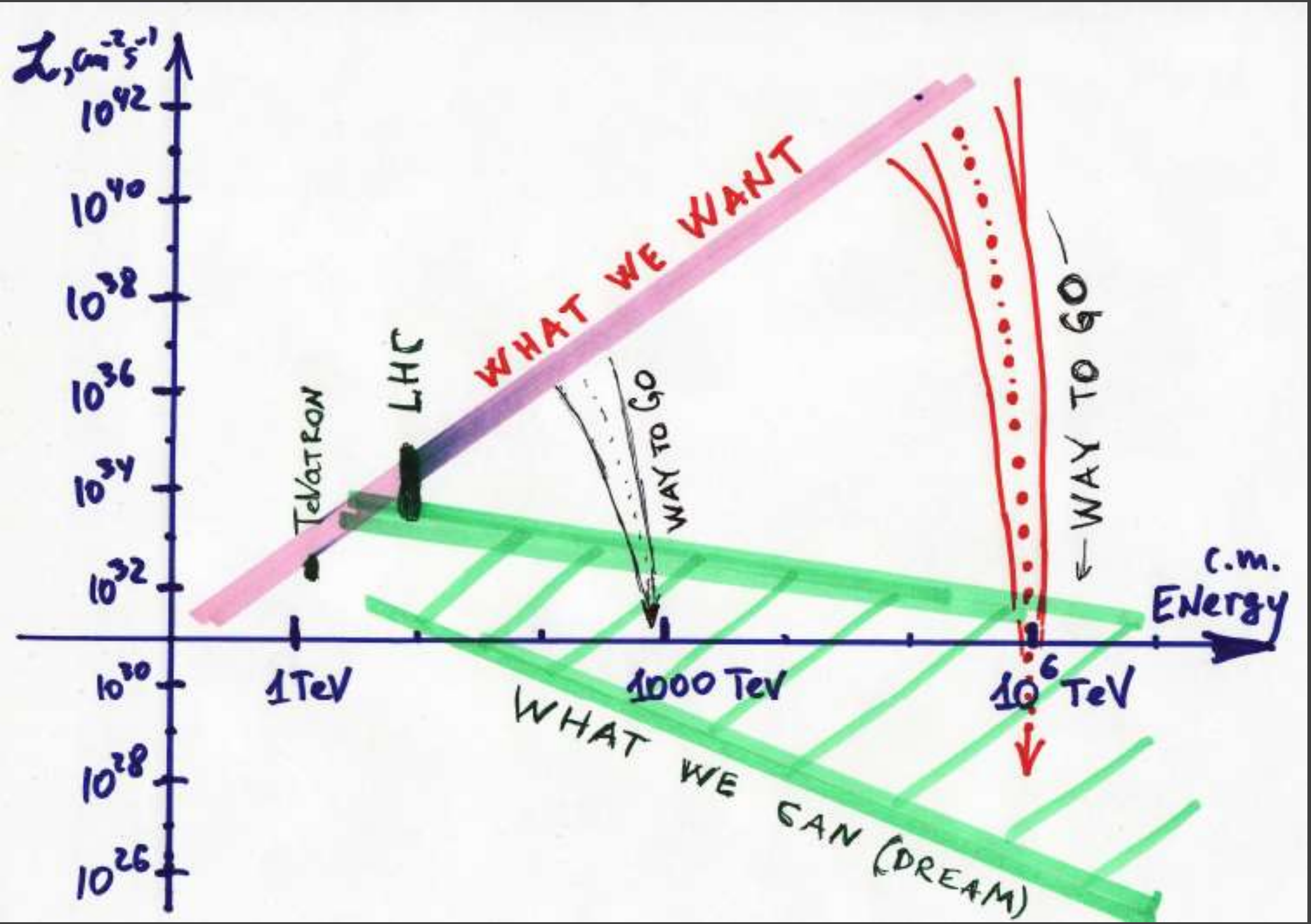
$$A \sim 1\ \text{Å}^2 = 10^{-16}\,\text{cm}^{-2}$$

This is the smallest beam size

$$P = f n_{ch} \cdot NE$$

The power is limited <10MW → ***N*** is small at high ***E*** → *L*

Paradigm Shift : *Energy* vs *Luminosity*



HEP's "Far" (or "Far-Far") Future

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in Crystals
- **Bad News**
  - It will be

High

Energy

Low

Luminosity

Conclusions (1)

PAST AND PRESENT LESSONS

- Success of Colliders : 29 built over 50 yrs, **~10 TeV** c.m.e.
- The progress has greatly slowed down due to **increasing size, complexity and cost** of the facilities.
- Accelerator technologies of RF and magnets well developed and costs understood **(*αβγ* - model)**

"NEAR" FUTURE DIRECTIONS (5-15 years)

- **CepC, TLEP** and **ILC** are not simple but **"~feasible"** in terms of **energy, luminosity** and possibly **cost**
- **CepC** seems to have **"unfair competitive advantage"** (cost)
- Start building the accelerator team **NOW** (~700-1000)
- Do not expect luminosity on ***"Day 1"*** (more like ***"Year 4"***)

Conclusions (2)

FUTURE ENERGY FRONTIER COLLIDERS (15-30 years)

- All have serious issues: 3 TeV CLIC - with performance and cost, 6 TeV Muon Collider - with performance, 70-100 TeV SppC/FCC - with cost
- Key R&D for SppC/FCC is to reduce the cost of ~16-20 T magnets by factor ~3-5 – it will take ~2 decades → start NOW
- Three regions are open for such collaboration

"FAR" FUTURE OUTLOOK (> 30 years)

- Not many options for 30-100 xLHC !!!
- Actually one: linear acceleration of muons in dense plasma
- In any case, that will be High Energy Low Luminosity facility (still ~10 orders of magnitude better than cosmics)

感谢您的关注

Thank You for Your Attention!