Crystal Ball :

On the Future High Energy Colliders *

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Content

Now & Past

LHC,Tevatron,
B-fact's, SSC…

"Near" Future

CepC, ILC,
LHeC, FCC-ee…

Future

FCC-pp, 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 right balance btw

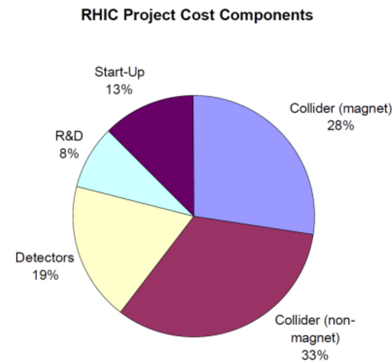
PHYSICS vs FEASIBILITY

- **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/present?
  - (besides that all built/existing machines are feasible)

"*Cost Feasibility*" Analysis

"*Known*" Costs for 17 Big Accelerators:

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



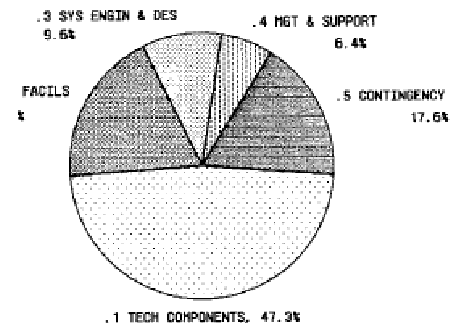
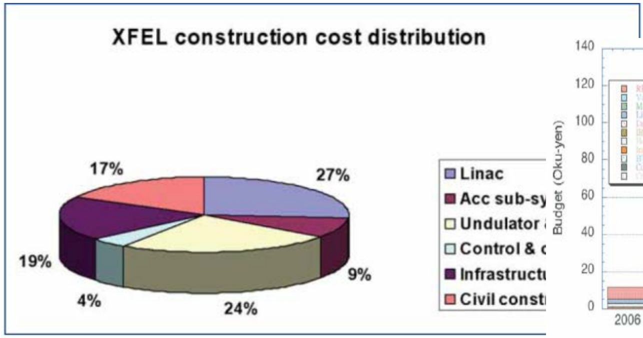
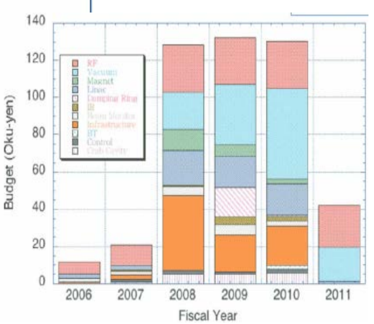
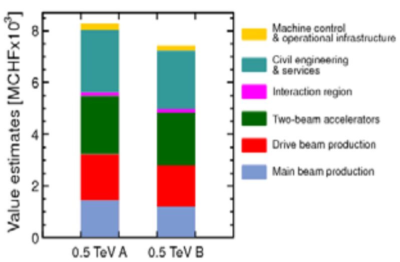
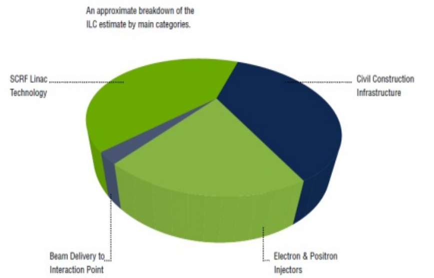


Figure 8.7-1. SSC cost estimate summary: Level 2 WBS categories.









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

2014 JINST 9 T07002
V.Shiltsev, A phenomenological cost model for high energy particle accelerators

Raw Data: *Confusion*

All are Different!

- **Parameters:**
  - energy ***E***
  - size/length ***L***
  - power ***P***
- **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…**

"European Accounting"

- (Tough it is not always easy) the "known" costs will be translated to the **TPC** … sets reference

TPC (US Accounting) vs *European Accounting*

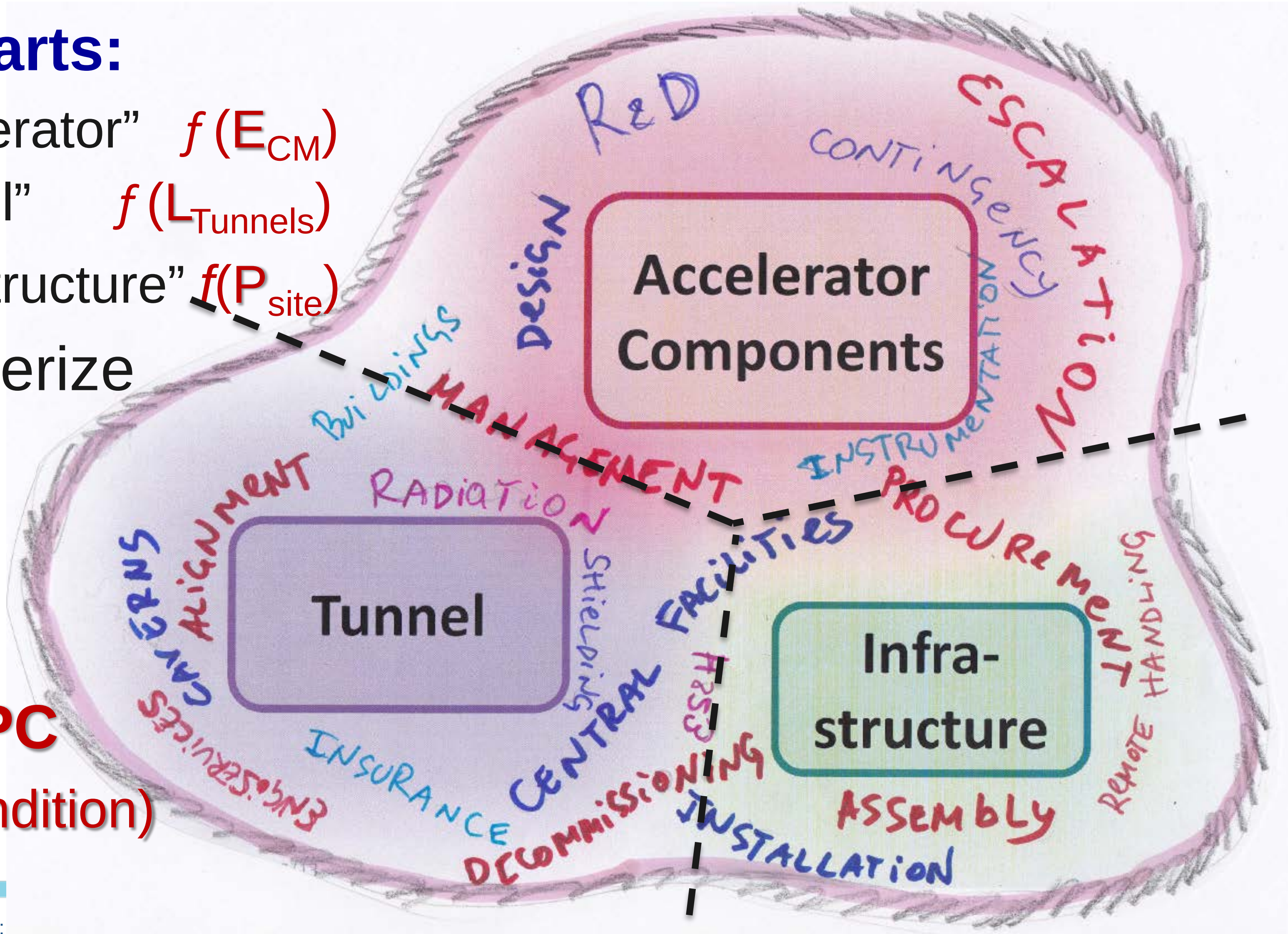
- To get the TPC one needs to include *SWF, OH, Escalation, Contingency, R&D, PED (often missed)*, and other *"missing elements"*

- 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** - ?

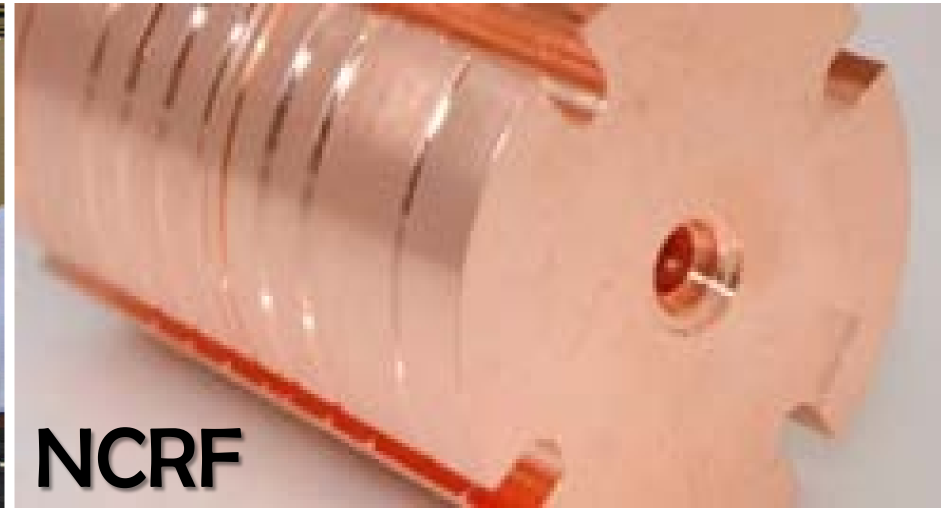
Use factor of 2-2.4 as typical

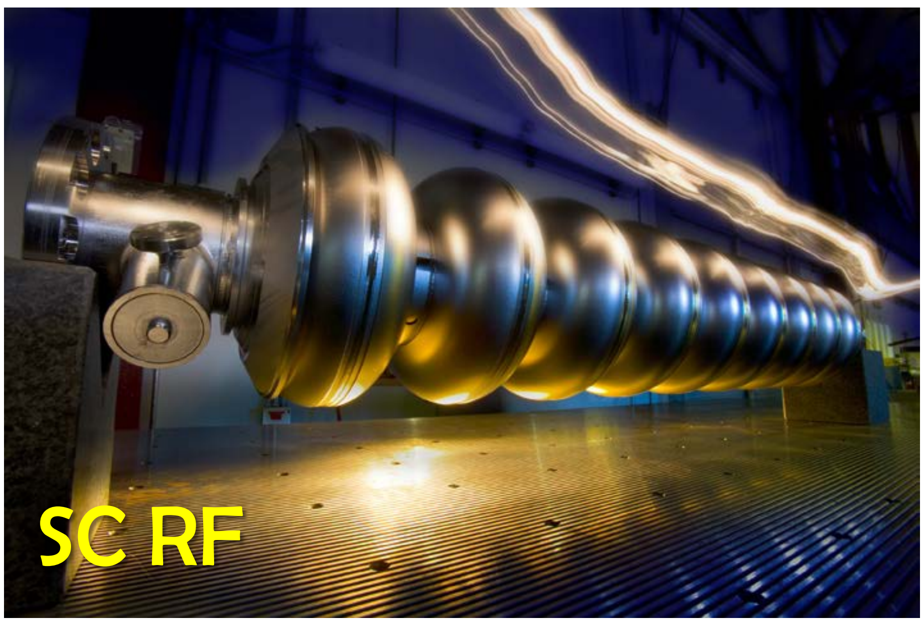
Approach: Though the TPC is complex mix → break it in just three parts

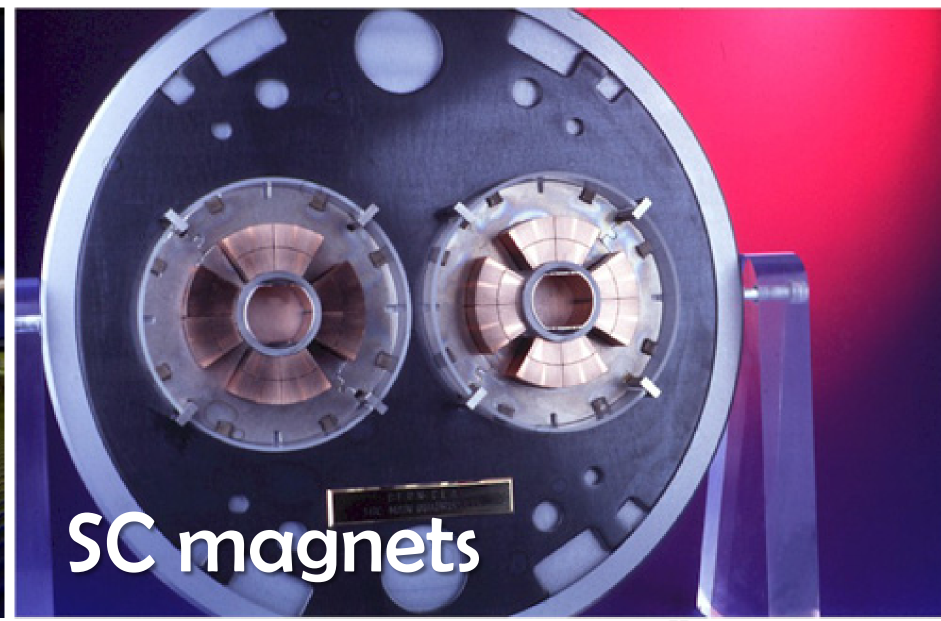
- **Three parts:**
  - "Accelerator" $f(E_{CM})$
  - "Tunnel" $f(L_{Tunnels})$
  - "Infrastructure" $f(P_{site})$
- Parameterize each by one parameter
- **Sum≡TPC** (unitarity condition)

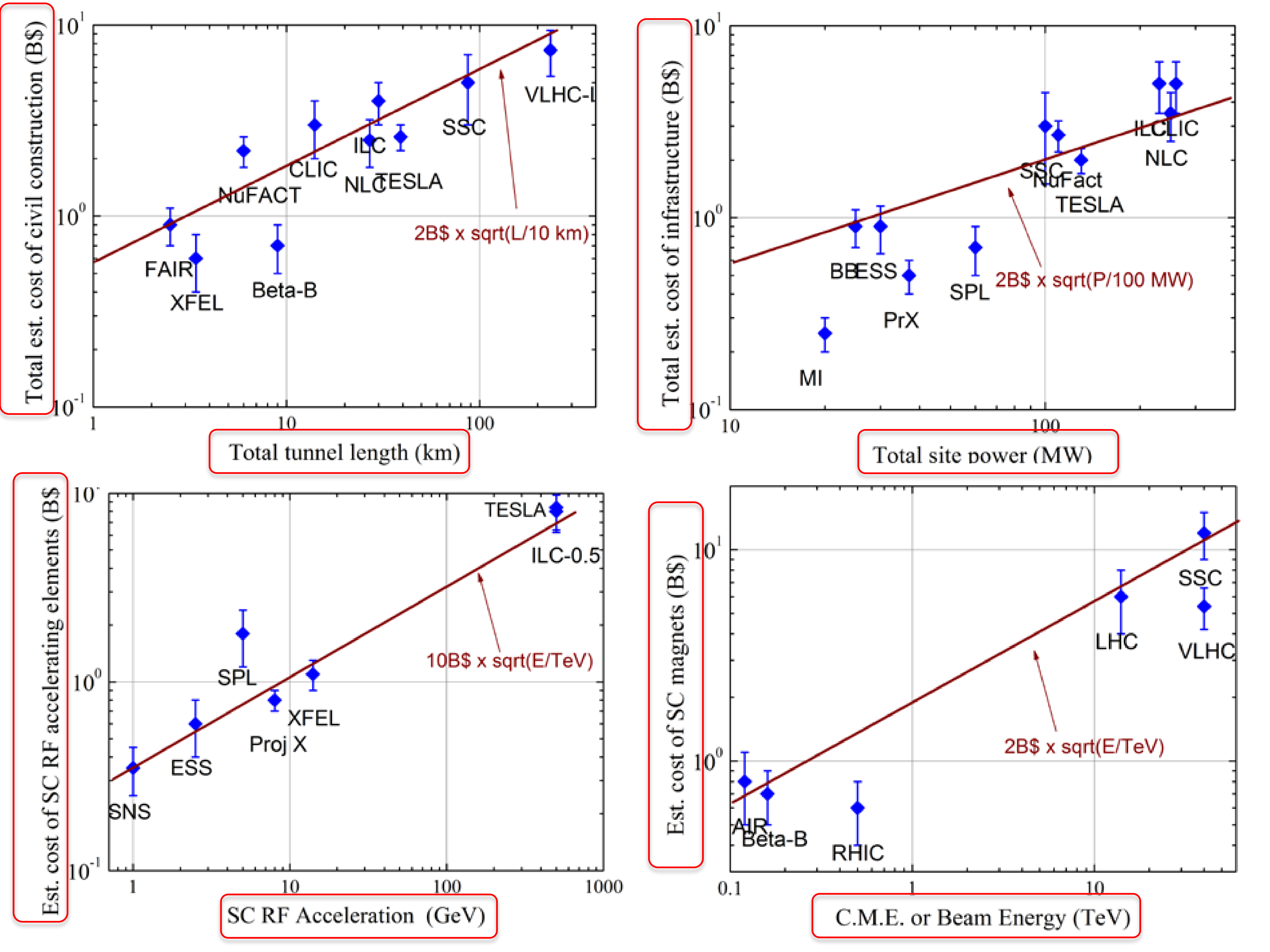


Our Key “Feasible” Technologies









Total est. cost of civil construction (B$)
Total tunnel length (km)
2B$ x sqrt(L/10 km)
FAIR
XFEL
NuFACT
Beta-B
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

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

"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$/sqrt(E/TeV)** for SC&NC RF
- **$\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)**

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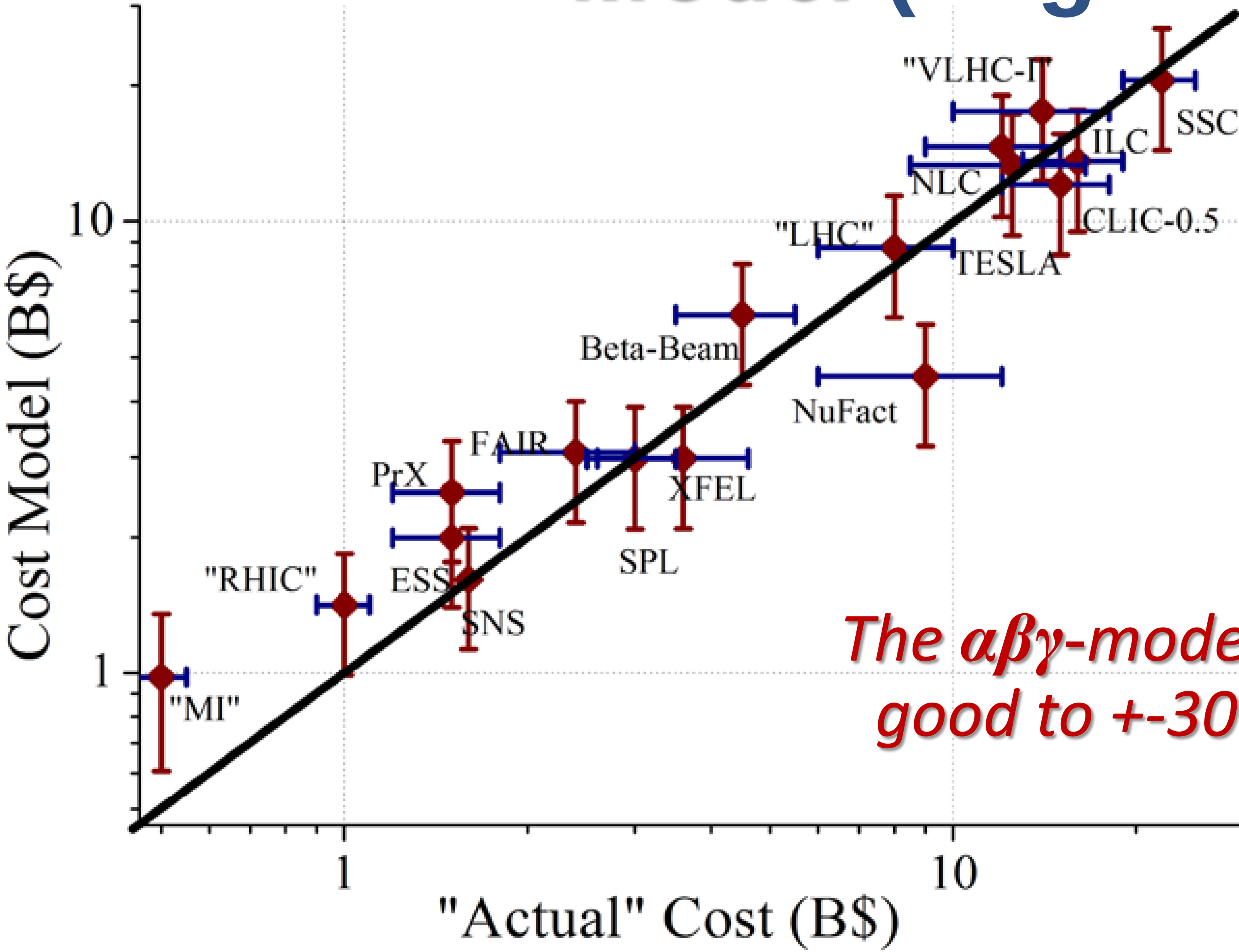
Total Cost vs *Model* (Log-Log)



The αβγ-model is good to +-30%

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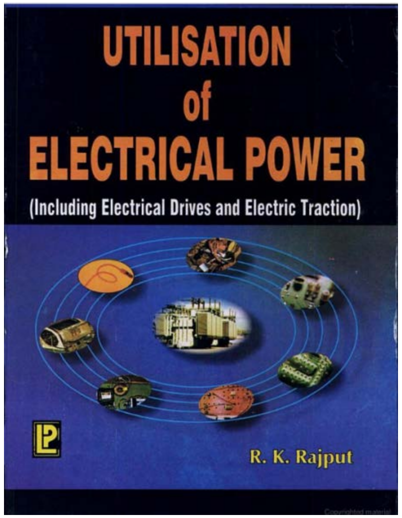
Comment on *sqrt*(Parameter)



Sqrt-functions are quite accurate over wide range because 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)

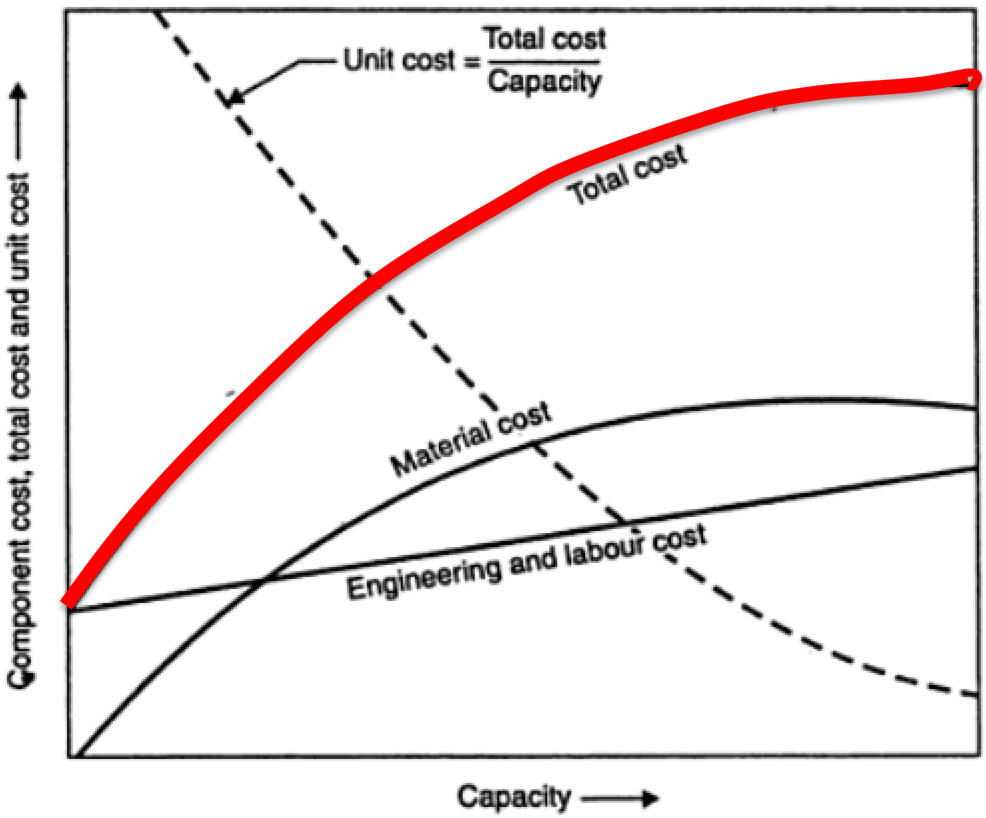


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

! WARNING !

The *αβγ* cost model:

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

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
FCC$_{ee}$	CERN	0.25	100	~300
CepC	China	0.25	55	~500
ILC	Japan	0.5	36	163
		TeV	*km*	*MW*

Energy Feasibility – No Doubt!

Feasibility of *Performance*

- **Luminosities : ~(2-5)10^{34}/IP**
  - **feasible, but there are issues**
    - Luminosity vs SRF power - trade off ($P=I\ \Delta E_{pass}$)
    - *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
    - etc.

Feasibility of Cost

- **ILC :**

European Accounting

  - **official est.: 7.8B$ + 13,000 FTEs**
    - ILC-Higgs ~70%: 5.5B$ +9,000 FTEs

αβγ: TPC = $2 \cdot 3^{1/2} + 10 \cdot 0.5^{1/2} + 2 \cdot 1.63^{1/2} = 3.5+7.1+3.1=$ **13.1B$** ±4B$

US Accounting

feasible ? – TBD soon

Feasibility of *Cost* (2)

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

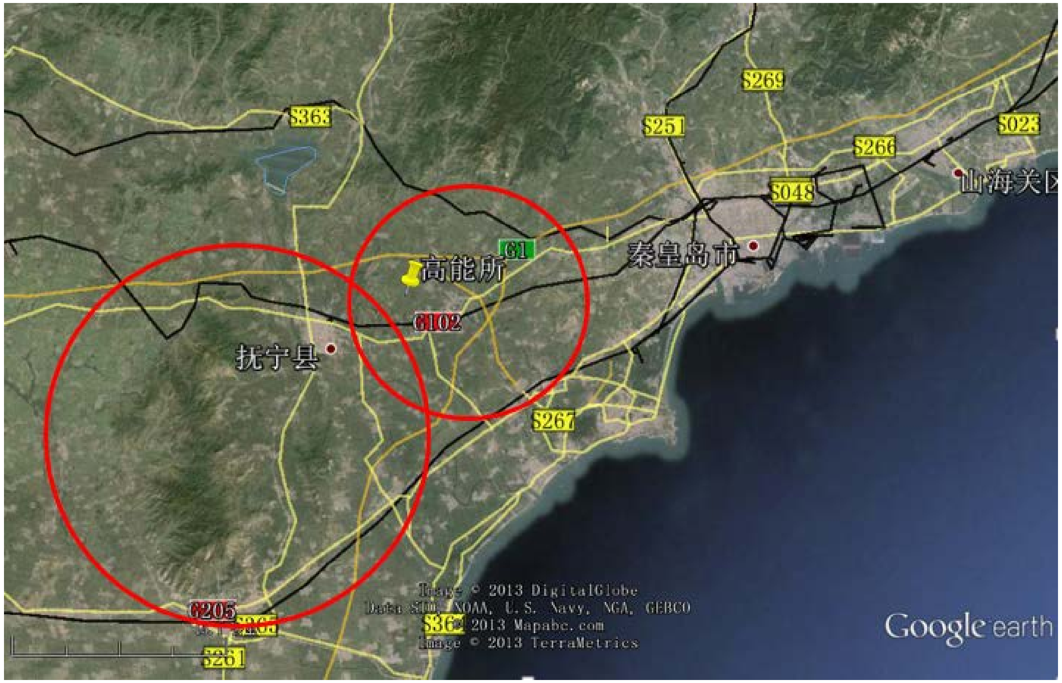
αβγ: $2\cdot10^{1/2}+(1\cdot0.25^{1/2} + 10\cdot.005^{1/2})$
$+\ 2\cdot3^{1/2} = 6.3+1.2+3.4 =$ **10.9 B$** ±4B$

- **CepC :** 54 km, 7 GeV SRF

αβγ: $2\cdot5.4^{1/2}+ (1\cdot0.12^{1/2}+10\cdot.007^{1/2})$
$+2\cdot5^{1/2} = 4.5+1.2+4.5=$ **10.2 B$** ±3B$

“Unfair Competitive Advantage”

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



Case study: modern light sources

SSRF (China)

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

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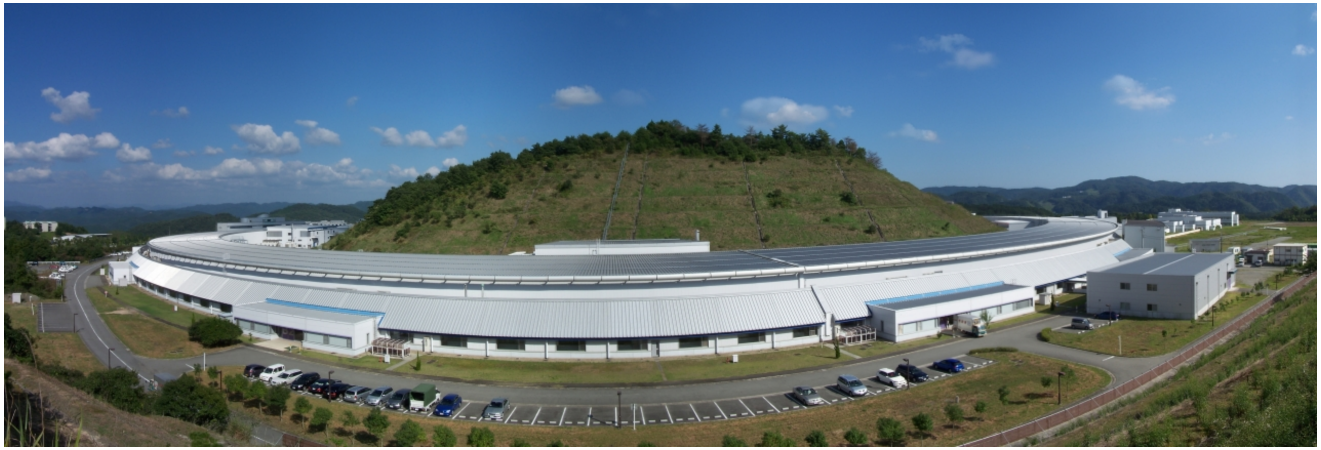
SPRING-8 (Japan)

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

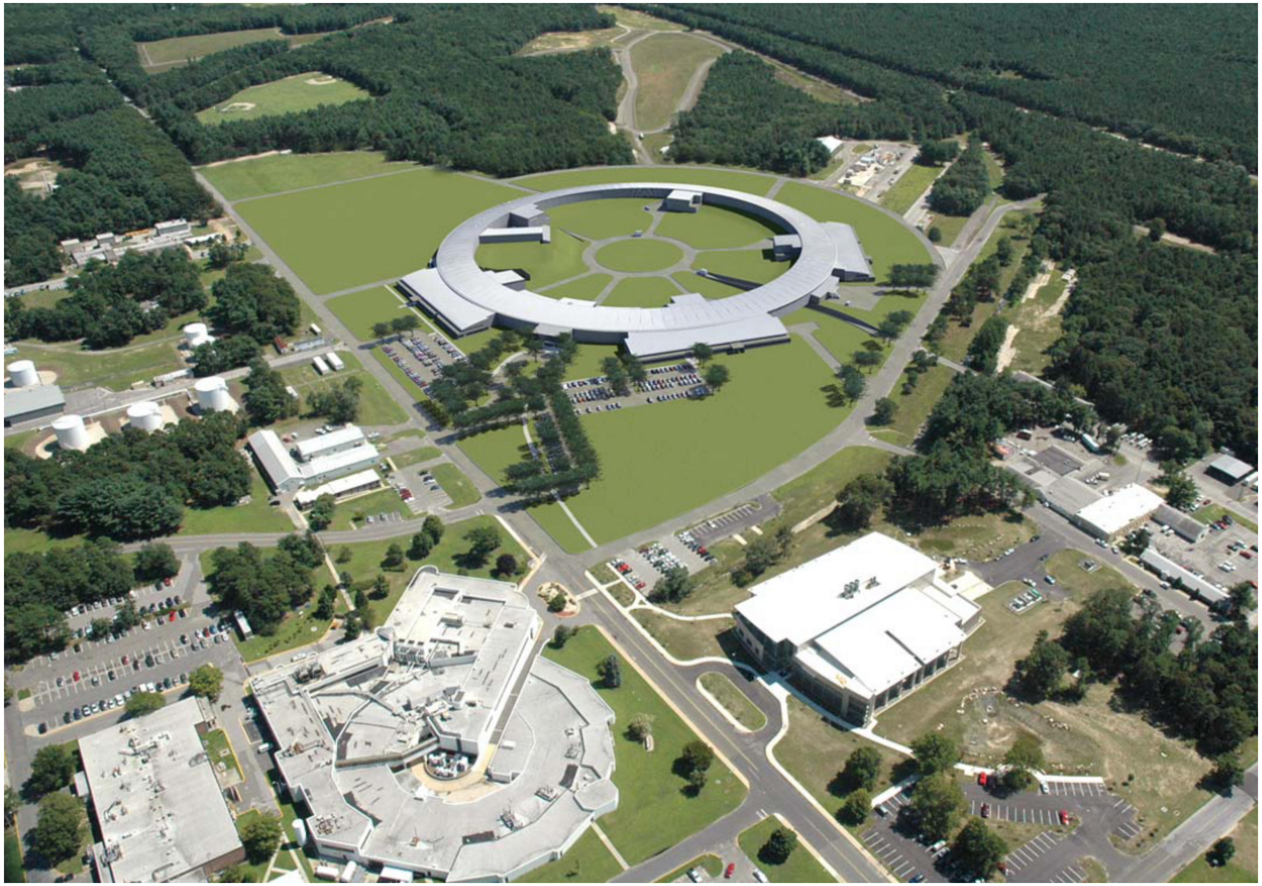


DIAMOND (UK)

- 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)



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Compare Costs of Light Sources

	Cost then	Cost now	Cost USD	Scale to SQRT(1km)
SSRF (China)	1.2B RMB (2007)	1.44 RMB	230 M$	350 M$
SPRING-8 (Japan)	110 BY (1999)	110 BY	924 M$	772 M$
DIAMOND (GBR)	383 M£ (2006)	500 M£	780 M$	1040 M$
NSLS-II (USA)	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_{pp}	CERN	100	100	400
SppC	China	50+	54	300
		TeV	*km*	*MW*

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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

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Feasibility of *Performance*

- **CLIC:** *e+e-* **~5 10^{34}**
  - **very tough ****
- **Muon Coll:** *μ+μ-* **~2 10^{34}**
  - **impossible now *****
- **FCC/SppC:** *pp* **~5 10^{34}**
  - **very tough ****

(each ***** is about 1 order of magnitude)

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Feasibility of Cost (1)

- **Muon Collider-6TeV : ?**

40 km of tunnels

6 TeV of SC magnets

50 GeV of SCRF linac / RLA

250 MW of site power

* if Proton Driver exists
* if ~7 km tunnel exists

αβγ: Cost = $2\cdot4^{1/2} + (2\cdot\mathbf{6}^{1/2} + 10\cdot0.05^{1/2}) + 2\cdot2.5^{1/2} = 4+4.9+2.2+3.2=$ **14.4B$** ±5B$

Feasibility of Cost (2)

- **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$**±8B$

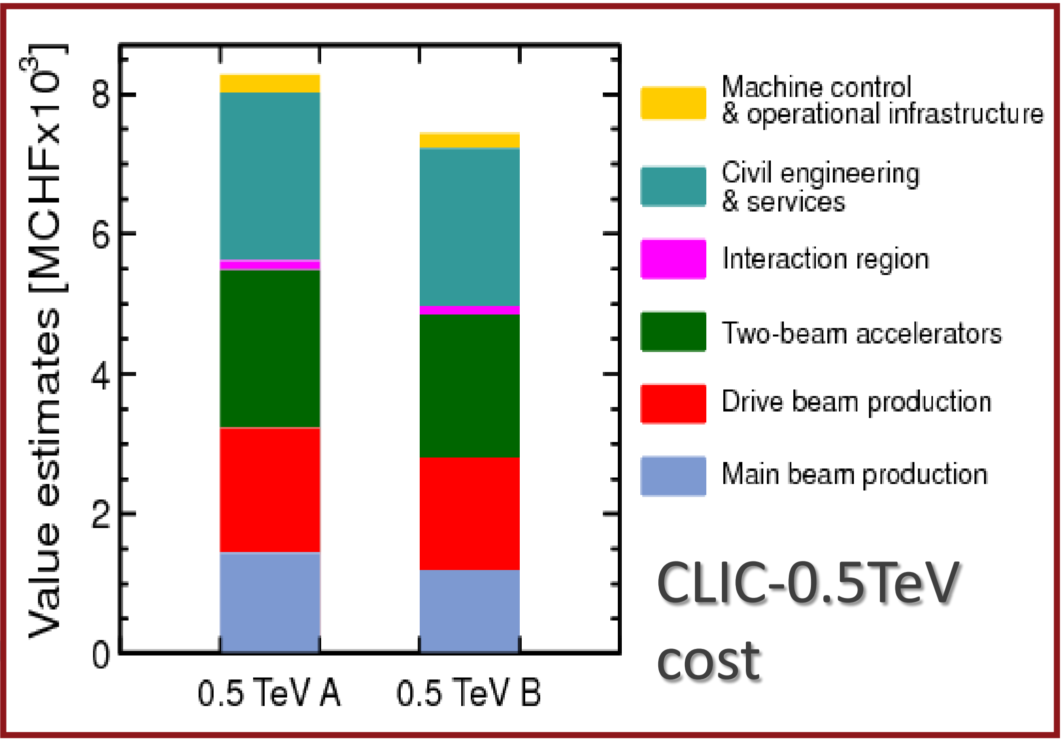
***BTW*: CLIC-0.5TeV**

est. 7.4 BCHF

European Accounting

αβγ: TPC = 13B$

US Accounting



Feasibility of *Cost* (3)

- **100 TeV *pp* : no (?)**

50-100 km of tunnels

70-100 TeV of SC magnets

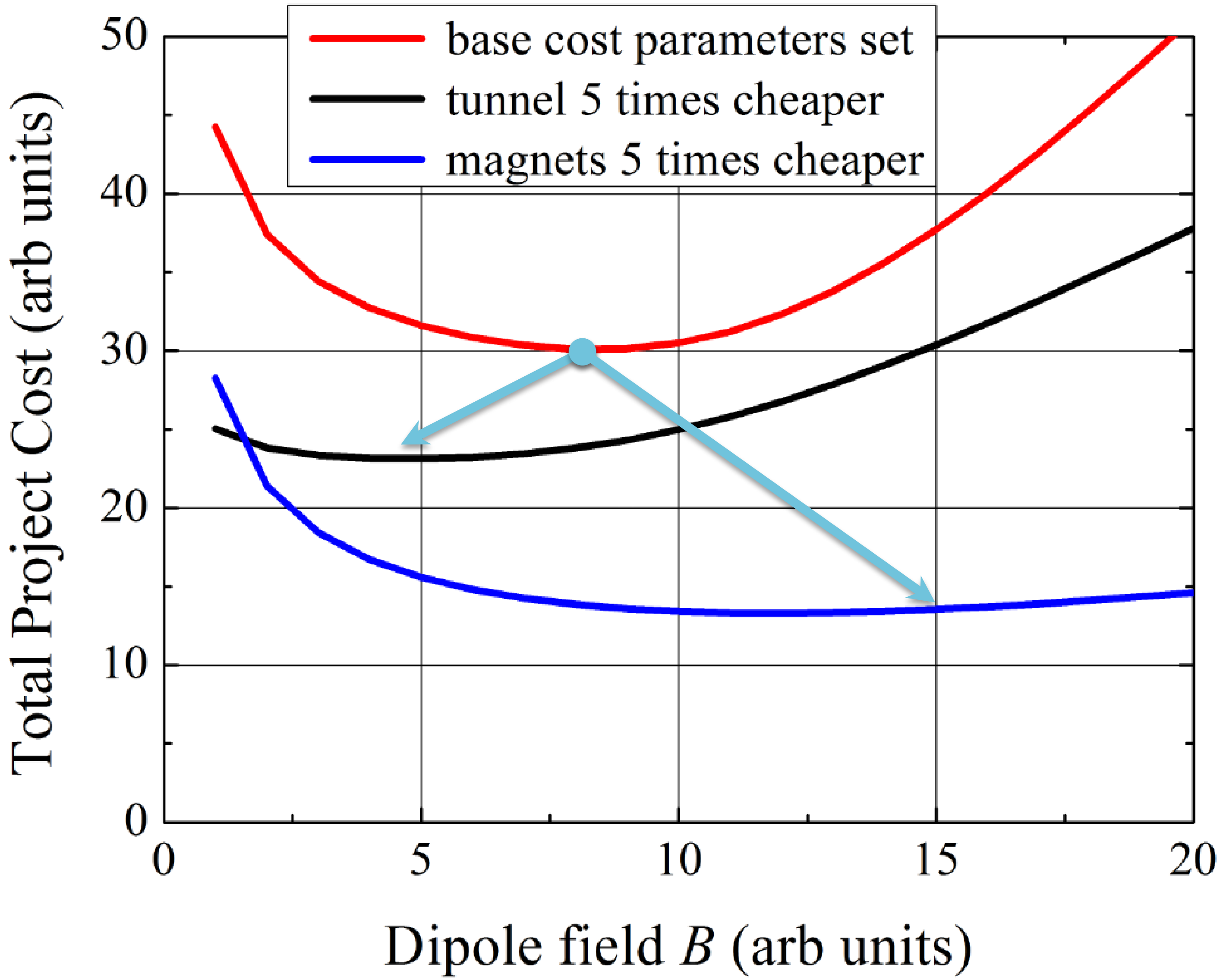
400 MW of site power

αβγ: $2\cdot(5\text{-}10)^{1/2} + 2\cdot\mathbf{(70\text{-}100)}^{1/2} + 2\cdot4^{1/2}$

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

(less ~10B$ if injector exists)

100 TeV *pp* : Qualitative Cost Dependencies



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

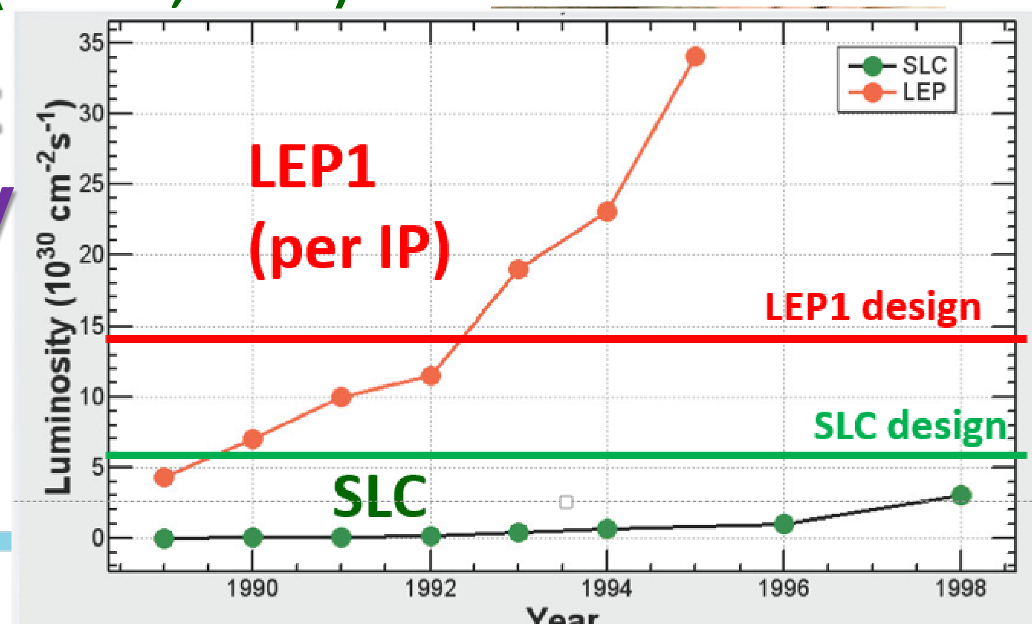
- Long-term research and development toward **significant (~3-4) cost reduction** of high-field ~15 T accelerator quality magnets
- Key areas:
  - push Nb_3Sn technology, new magnet designs, quench & splice engineering, better materials & conductors, etc
- There're examples in the past :
  - Significant cost reduction per *kA*m,* increase in *critical current densities*
  - …but that required 1-2 **decades** (see back up slides)

Two Comments:

1. **Availability of experts** :
   - **"Oide Principle"** : ***1 Accelerator Expert can spend intelligently only ~1 M$ a year***
   - + it takes significant time to get the team together (XFEL, ESS)

K.Oide (KEK)

2. **It takes time to get to design Luminosity**
   - **often 3-7 years**



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 circular ***e+e-*** collider above Higgs-F there will be no circular ***pp*** colliders beyond 100 TeV → **LINEAR**

circular collider

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

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

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)

SC magnets equiv. ~ 0.5 GeV per meter (LHC)

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

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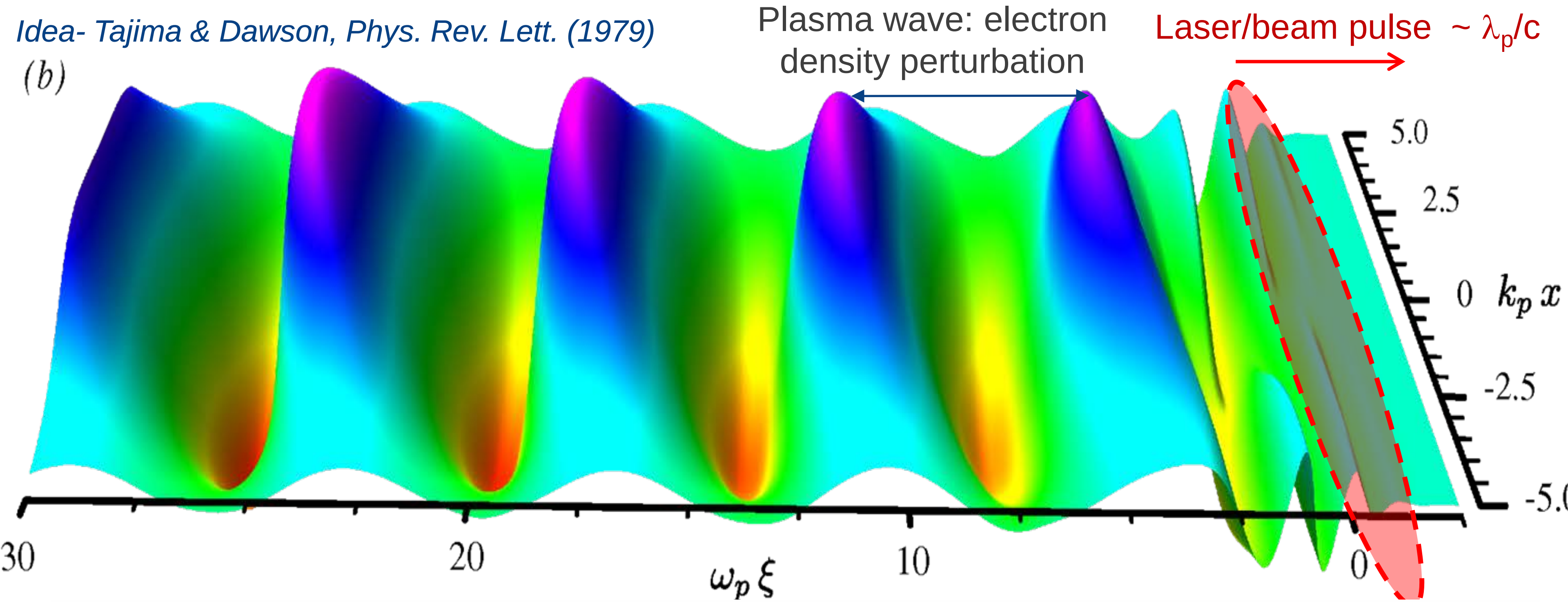
Plasma Waves



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

Option A:

Short intense e-/e+/p bunch

Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

Option B:

Short intense laser pulse

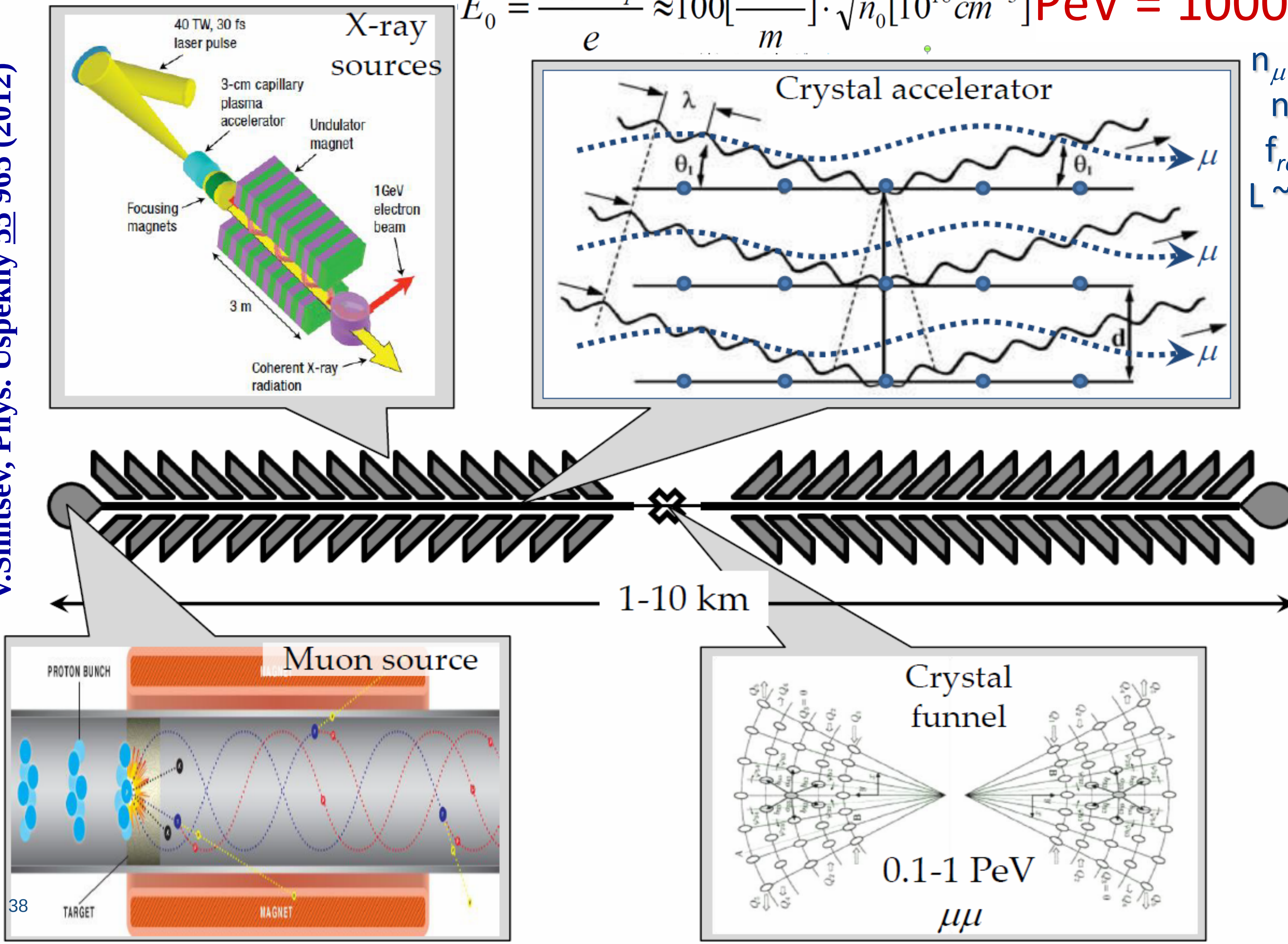
~10^{18}cm^{-3}, **50 GV/m** over 0.1m

Option C: Crystals & Muons

n~10^{22} cm^{-3}, **10 TeV/m →** PeV = 1000 TeV

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

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



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

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"Far Future" Colliders: Challenges

- Demonstrate Feasibility of **ENERGY**
  - now – only early indications
  - decade(s) of R&D at current pace (staging, etc)
- Demonstrate Feasibility of **COST**
  - too early to discuss seriously
  - at present x(3-10) more $$/TeV than SCRF
- Address Feasibility of **PERFORMANCE**
  - too early to guess, now - MANY orders of magnitude off
  - fundamental problem : **limited facility power**

$$\rightarrow P_b=I_bE \rightarrow I_b=P_b/E \rightarrow L \sim P_b/E$$

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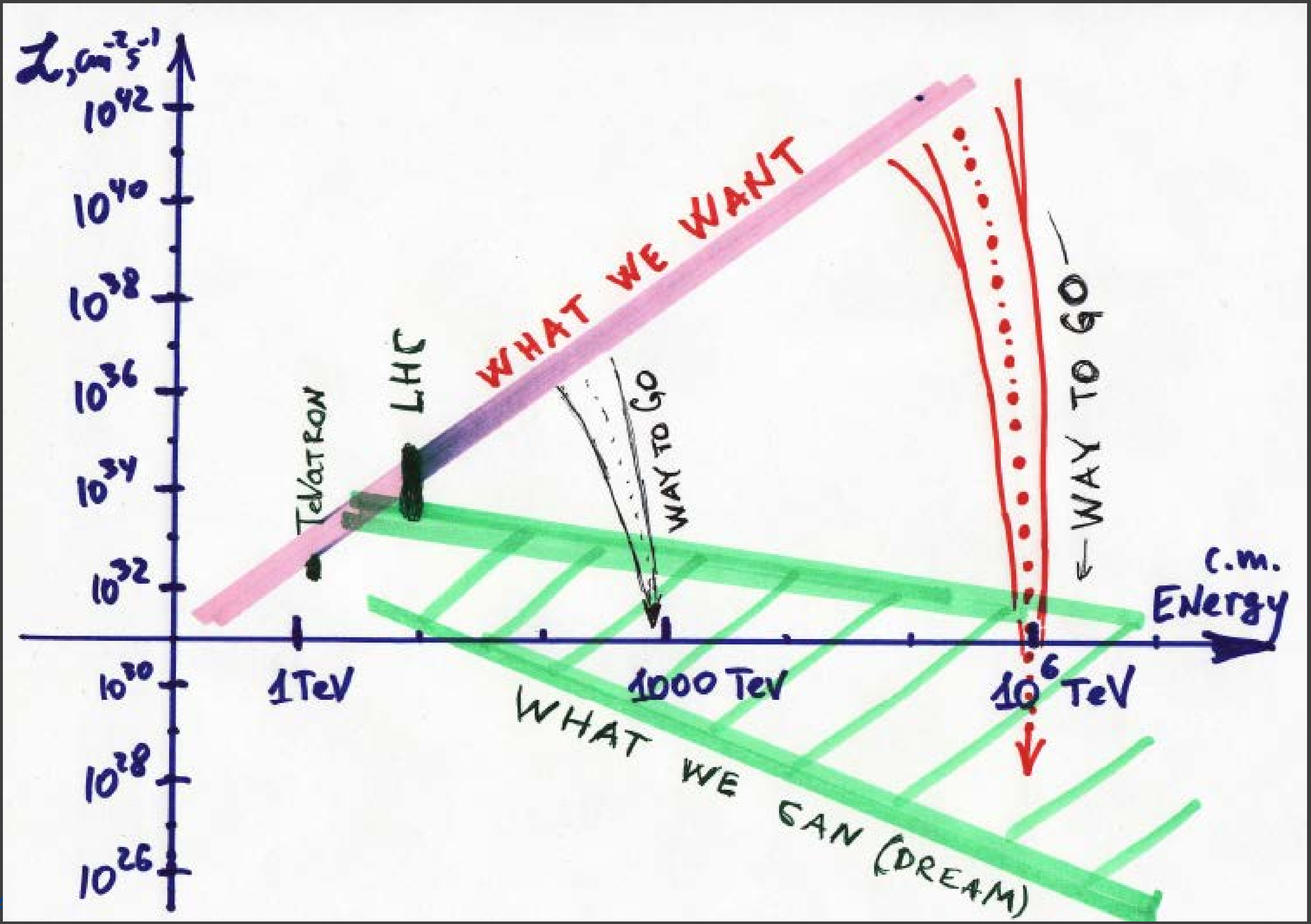
Paradigm Shift : *Energy* vs *Luminosity*



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

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in plasma/crystals
- **Bad News**
  - It will be

High

Energy

Low

Luminosity

Conclusions (1)

PAST AND PRESENT LESSONS

- Success of Colliders : 29 built over 50 yrs, *O*(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 are 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 4-5"***)

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 FCC/SppC - with cost and performance**
- **Key R&D for FCC/SppC 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, only: 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)**

Vielen Dank für Ihre Aufmerksamkeit !

Thank You for Your Attention!