Crystal Ball :

On the Future High Energy Colliders *

Vladimir Shiltsev
Fermilab, Batavia, IL , USA
Accelerator Physics Center
July 25, 2015

*FRA, LLC operates Fermilab under contract No. DE-AC02-07CH11359 with the U.S. DOE
**supported, in part, by the European Commission under the FP7 EuCARD-2, grant agreement 312453

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

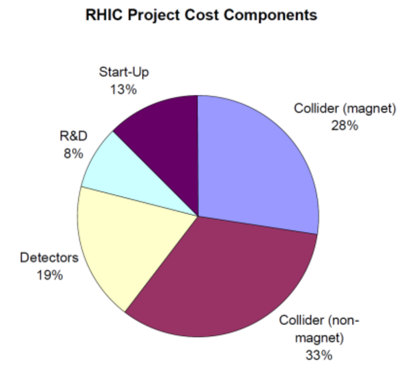
PHYSICS vs FEASIBILITY

- **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



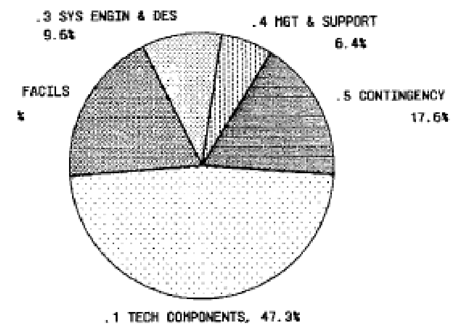
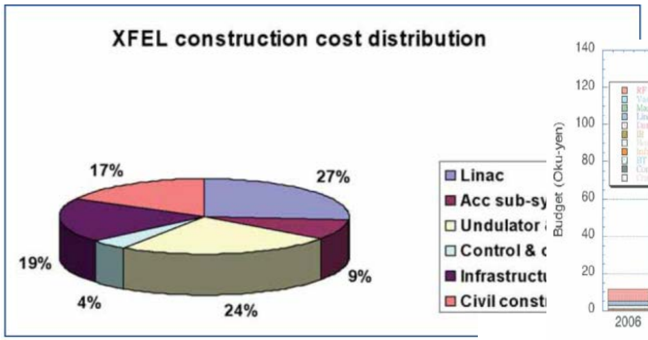
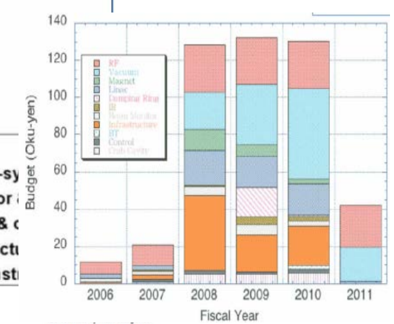
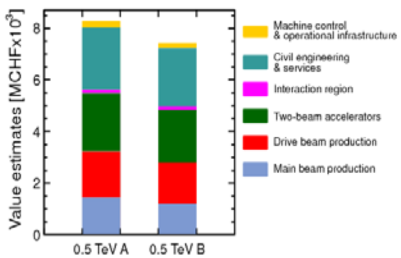
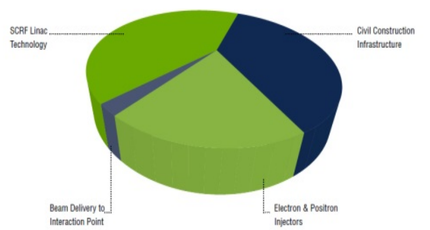


Figure 8.7-1. SSC cost estimate summary: Level 2 WBS categories.









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

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TPC (US Accounting) vs *European Accounting*

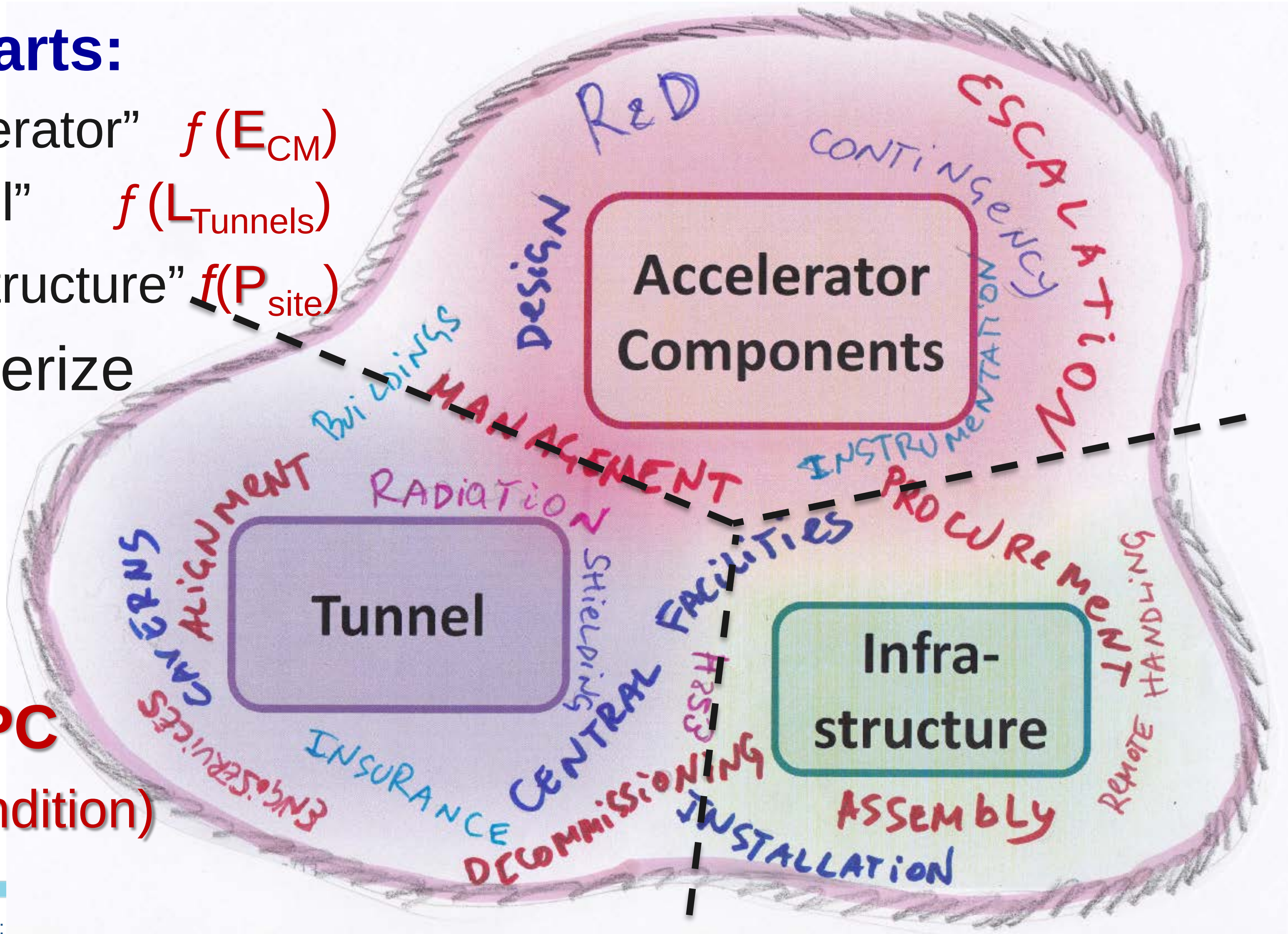
- To get the TPC one needs to include *SWF, OH, Escalation, Contingency, R&D, PED (often missed)*, and other *"missing elements"*

- 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** - ?

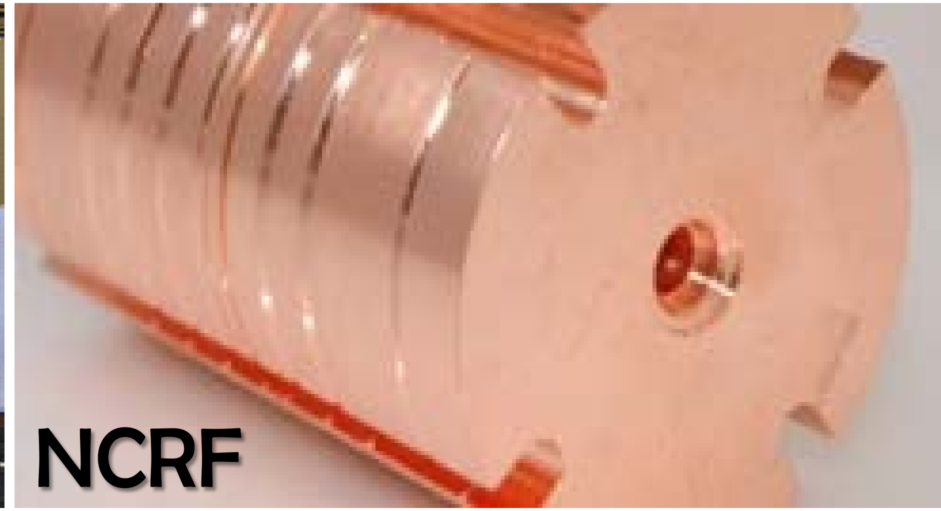
Use factor of 2-2.4 as typical

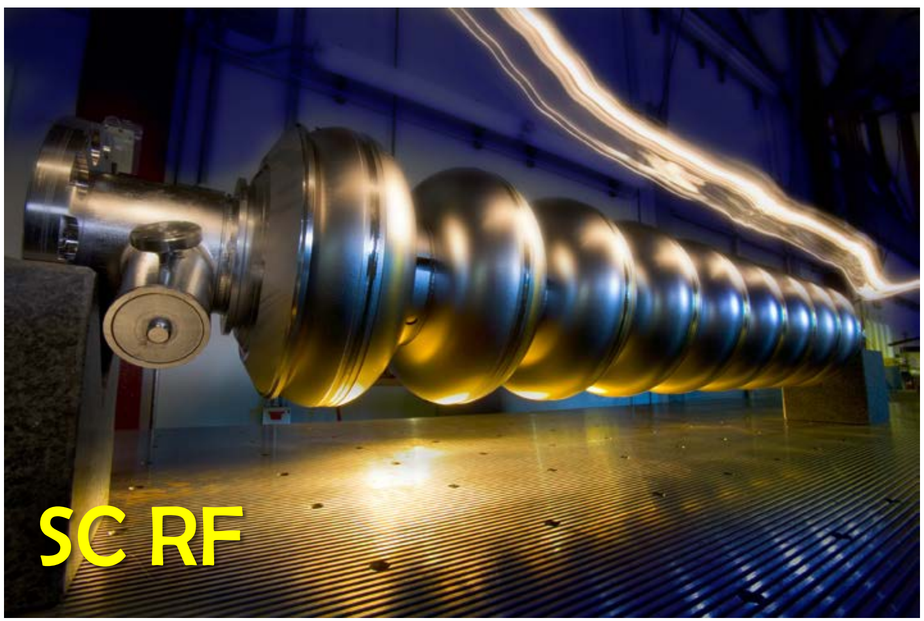
Approach: Though the TPC is complex mix → break it in just three parts

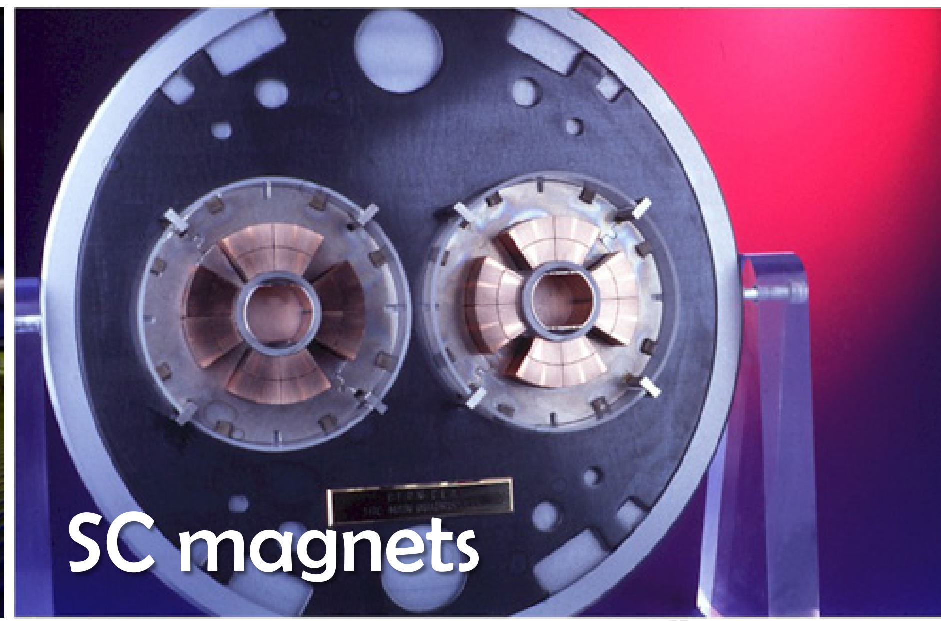
- **Three parts:**
  - "Accelerator" $f(E_{CM})$
  - "Tunnel" $f(L_{Tunnels})$
  - "Infrastructure" $f(P_{site})$
- Parameterize each by one para-meter
- **Sum≡TPC** (unitarity condition)

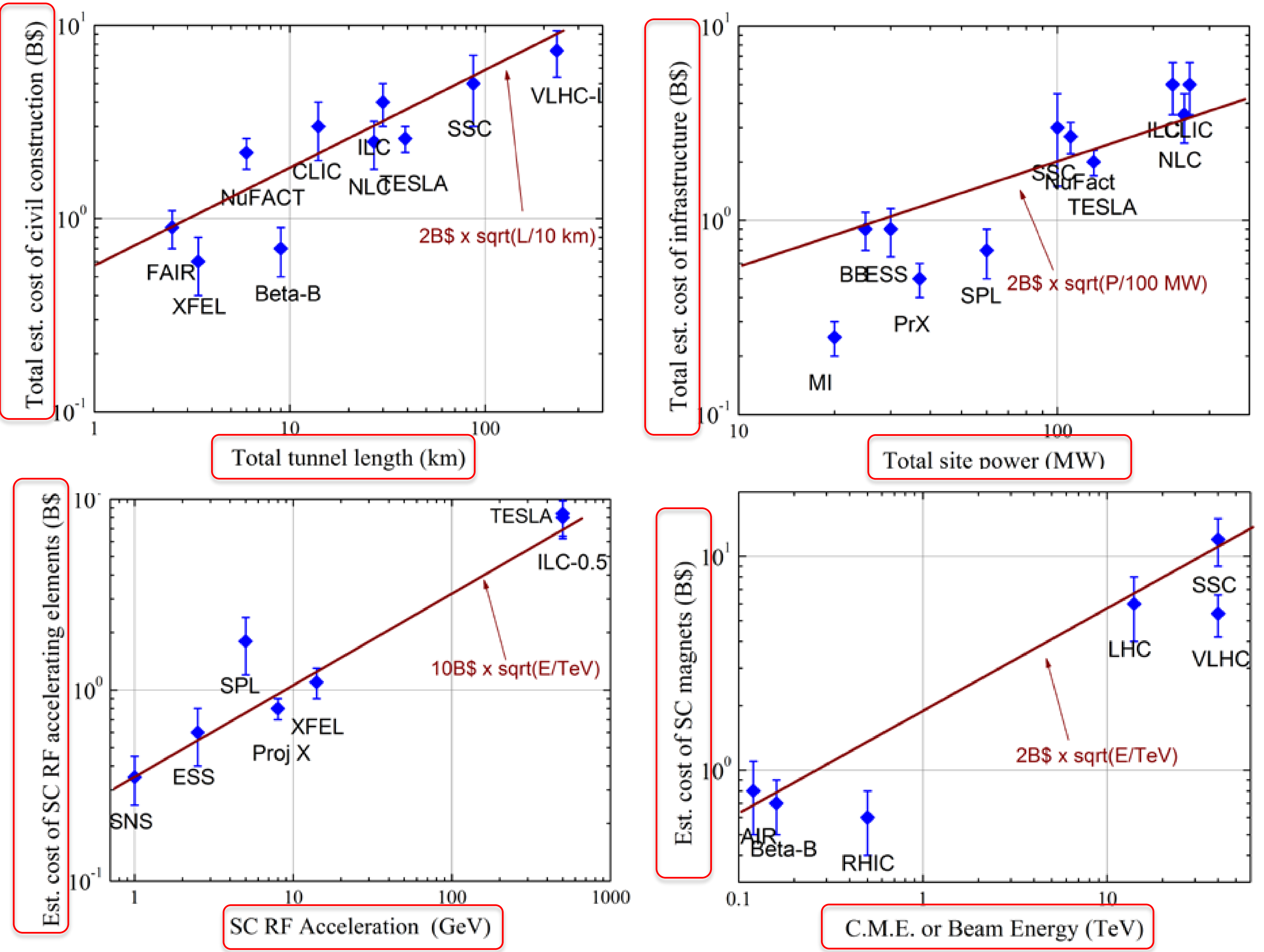


Our Key "Feasible" Technologies









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-L
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

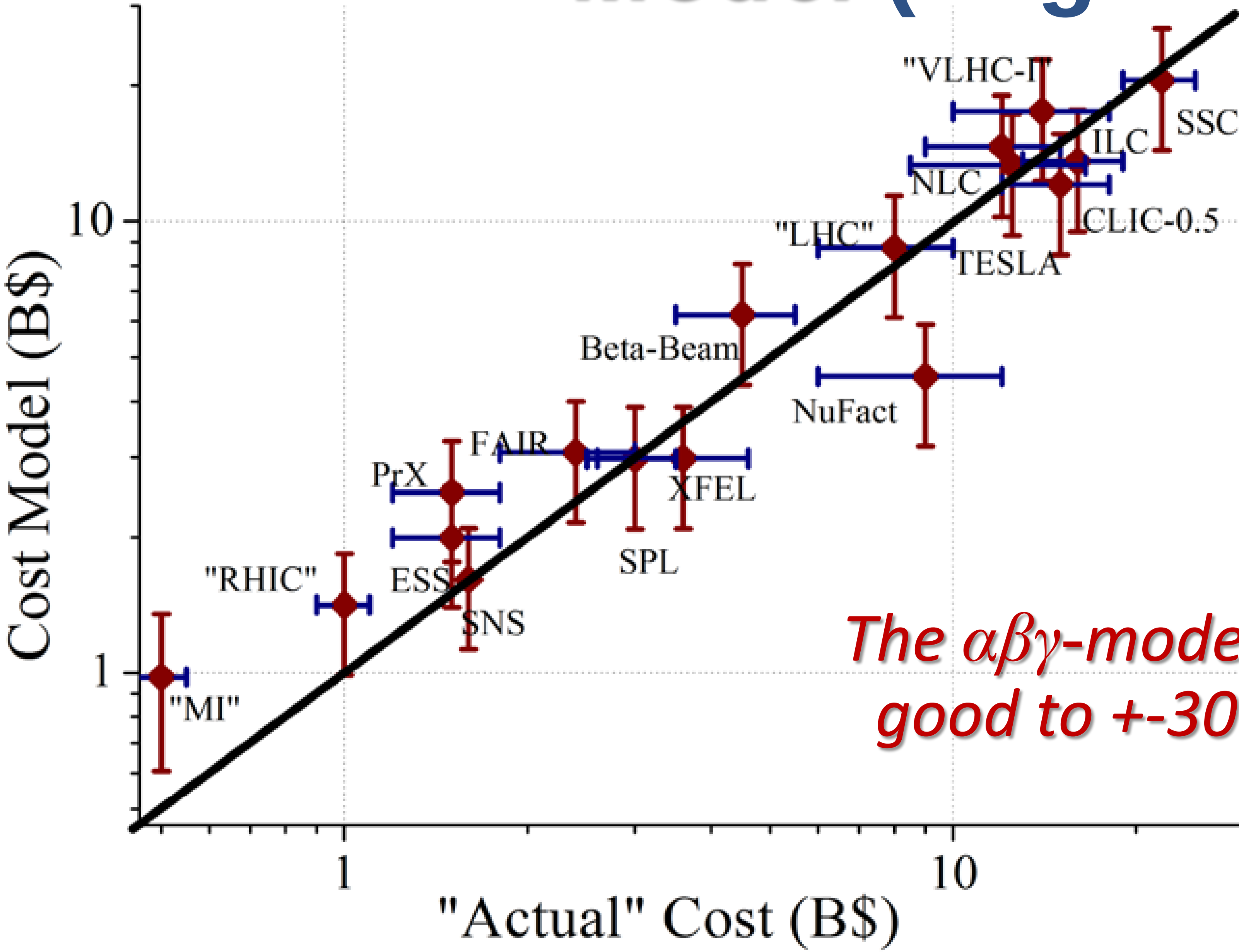
$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

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

Total Cost vs *Model* (Log-Log)



The αβγ-model is good to +-30%

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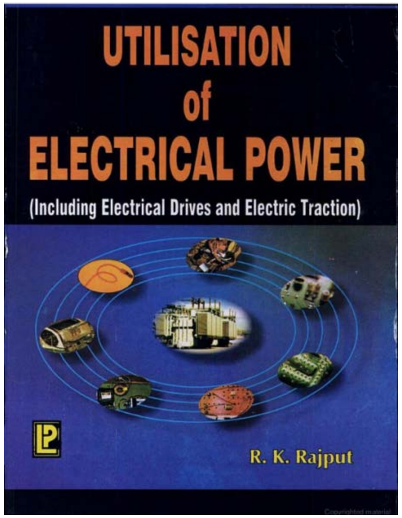
Comment on *sqrt*(Parameter)

Sqrt-functions are quite accurate over wide range 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)

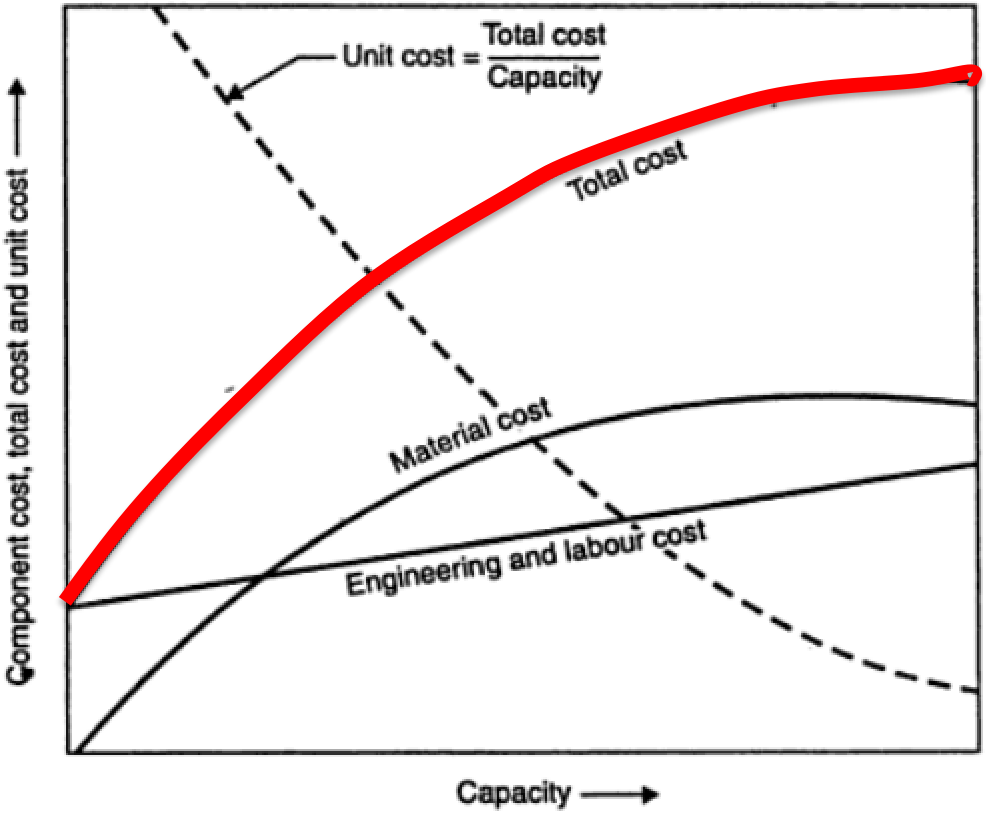


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

! WARNING !

The αβγ cost model:

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

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	233
		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 ΔE*$_{pass}$)
    - *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 = $2 \cdot 3^{1/2} + 10 \cdot 0.5^{1/2} + 2 \cdot 2.33^{1/2}$ = 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: $2\cdot 10^{1/2}+(1\cdot 0.25^{1/2} + 10\cdot .005^{1/2})$
$+ \ 2\cdot 3^{1/2} = 6.3+1.2+3.4 =$ **10.9 B$** ±4B$

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

αβγ: $2\cdot 5.4^{1/2}+ (1\cdot 0.12^{1/2}+10\cdot .007^{1/2})$
$+2\cdot 5^{1/2} = 4.5+1.2+4.5=$ **10.2 B$** ±3B$

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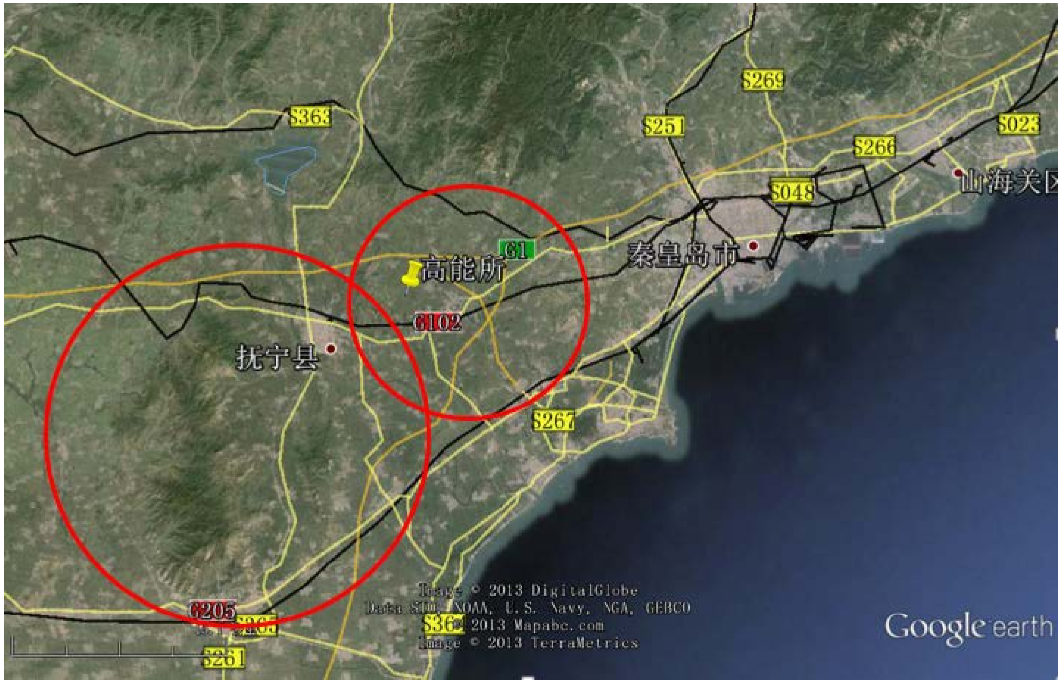
“Unfair Competitive Advantage”

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



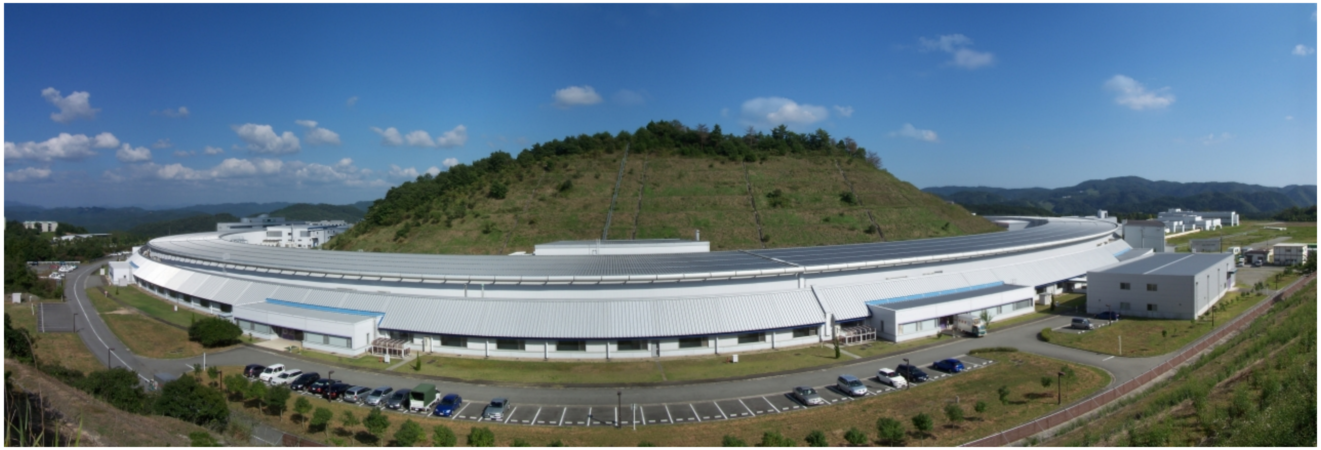
Case study: modern light sources

SSRF (China)

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

SPRING-8 (Japan)

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



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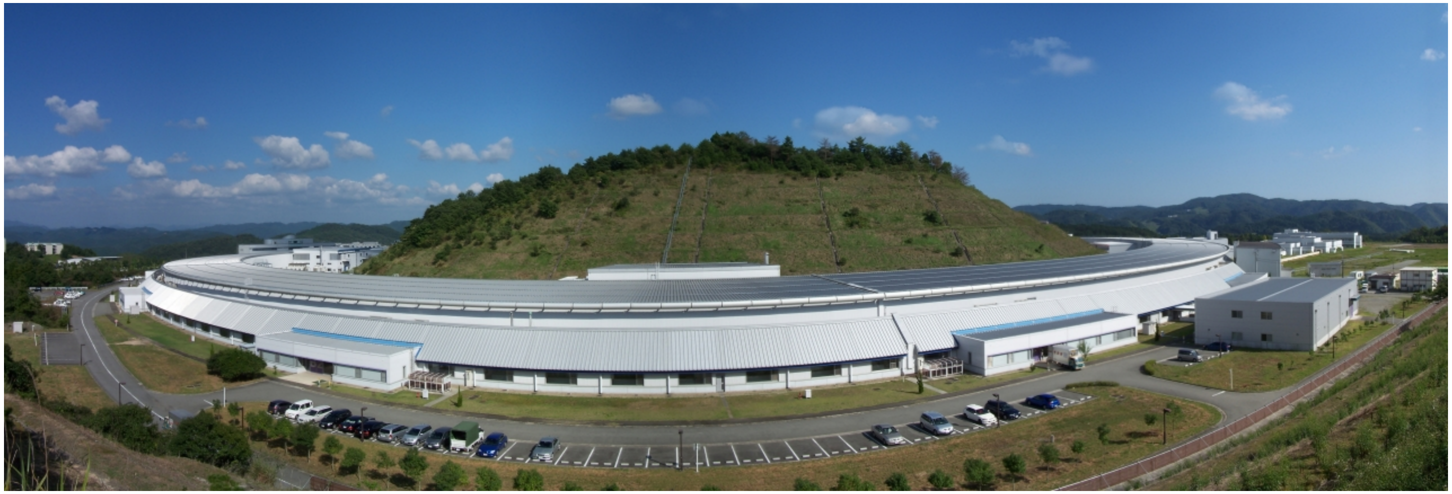
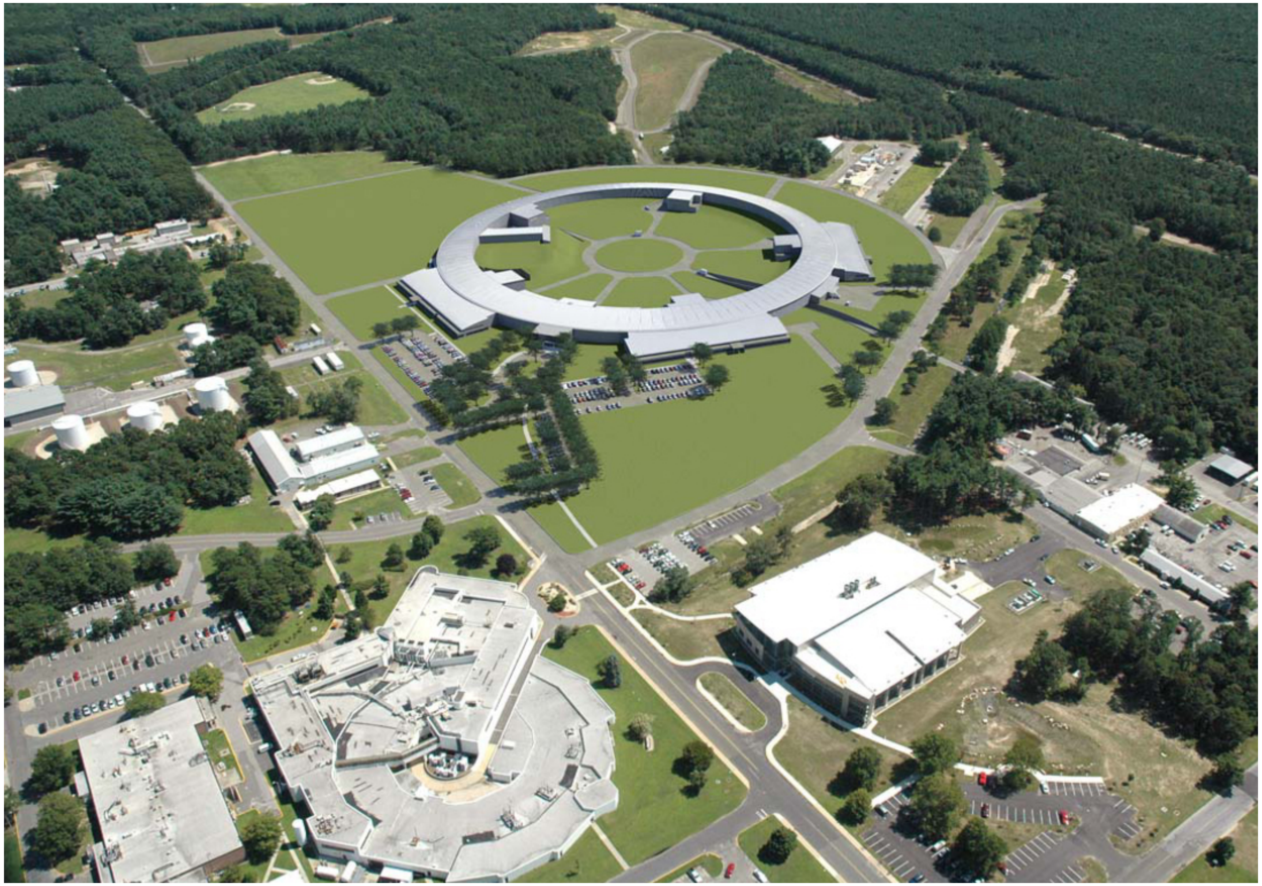
DIAMOND (UK)



- 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_{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)

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$**±8B$

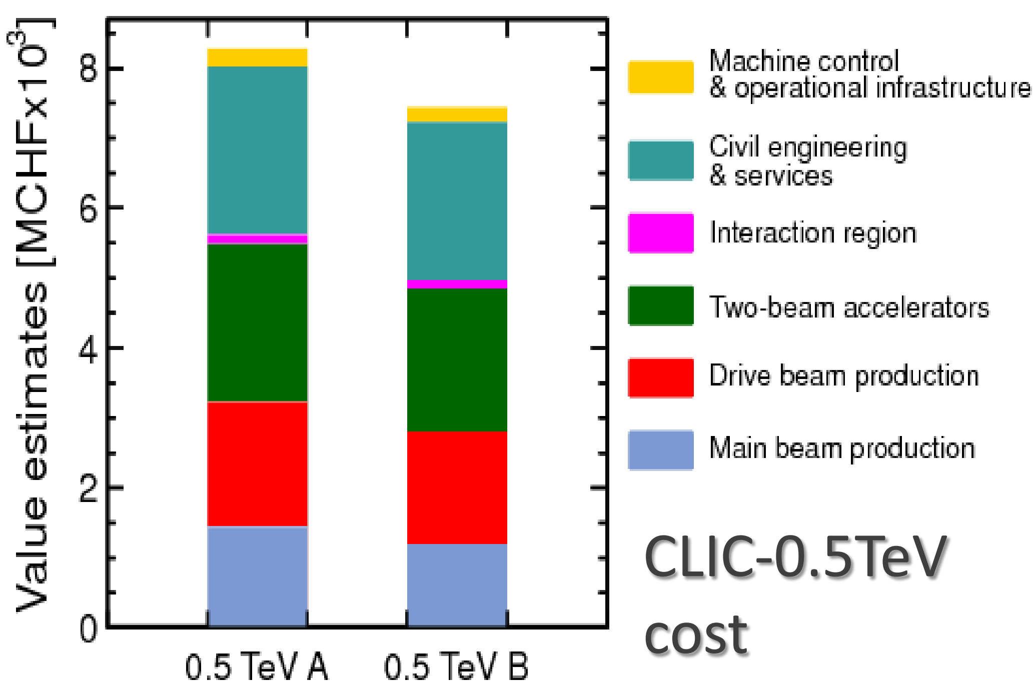
BTW: **CLIC-0.5TeV**

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: 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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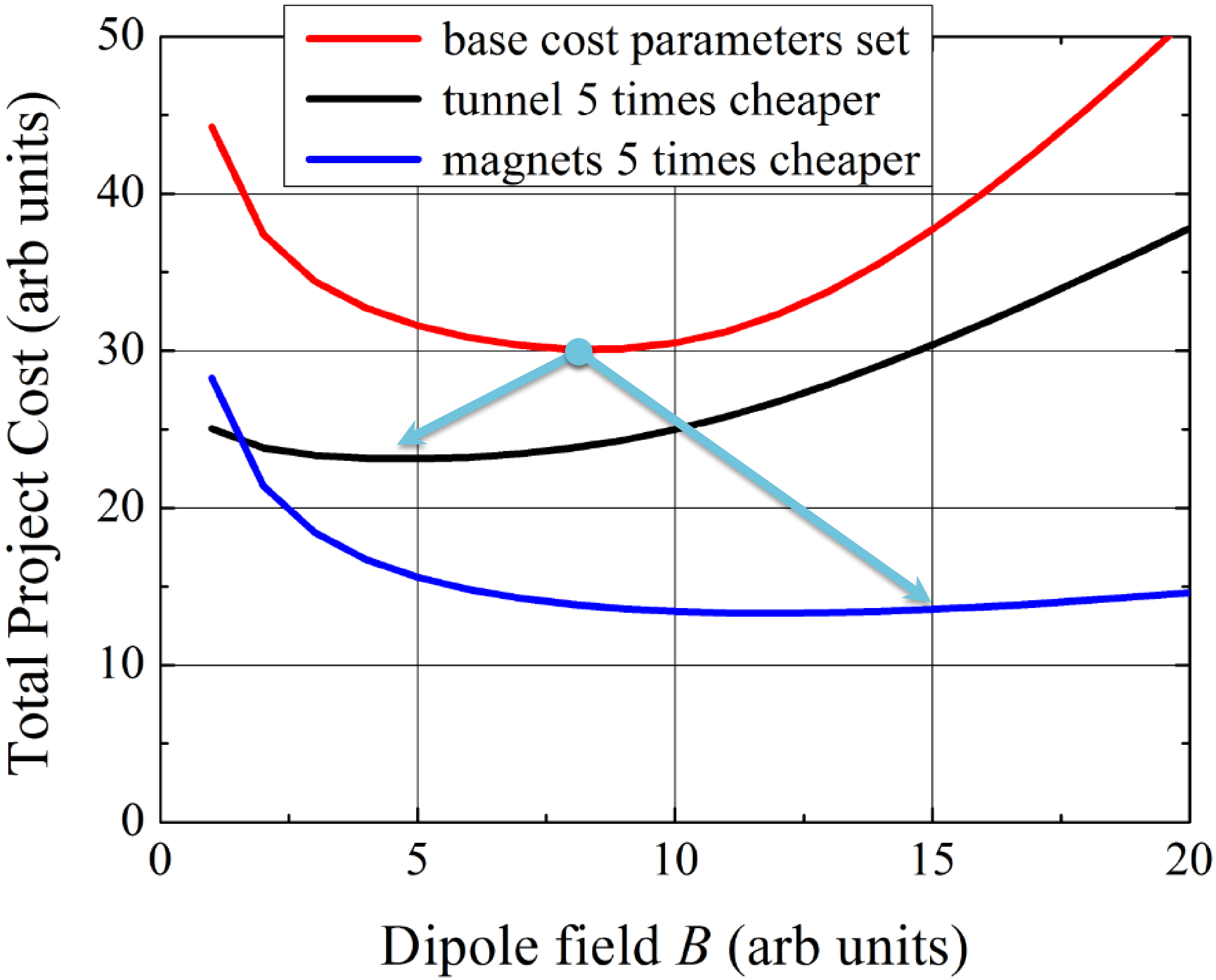
100 TeV pp : Qualitative Cost Dependencies



* for illustration purposes only

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

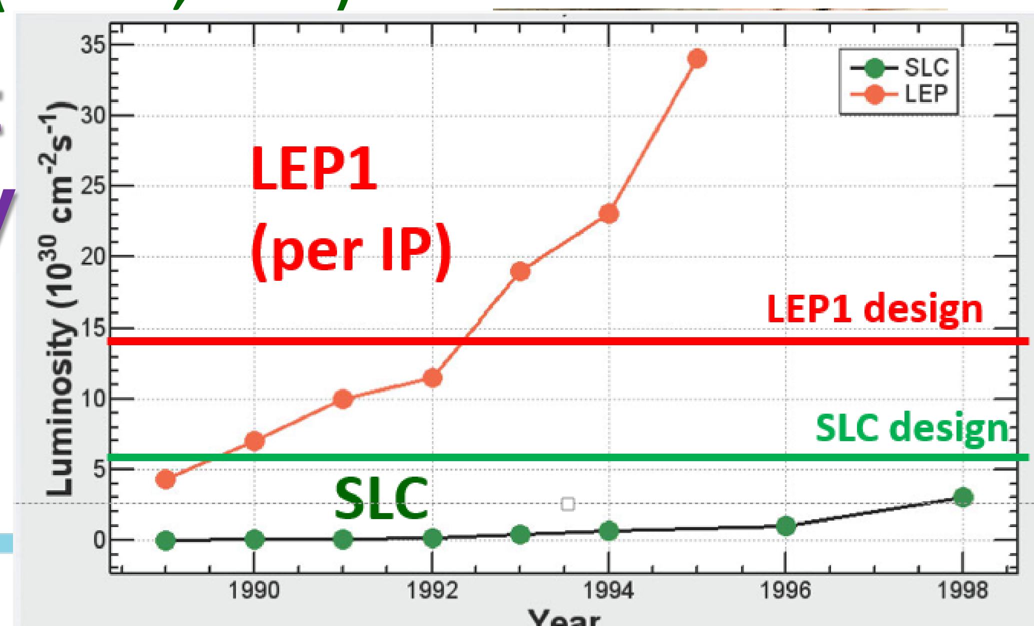
- Long-term research and development toward significant (~3-4) cost reduction of high-field ~15 T accelerator quality magnets
- Key areas:
  - push Nb_3Sn technology, new magnet designs, quench & splice engineering, better materials & conductors, etc
- There're examples in the past :
  - Significant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

circular collider

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**

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

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)**

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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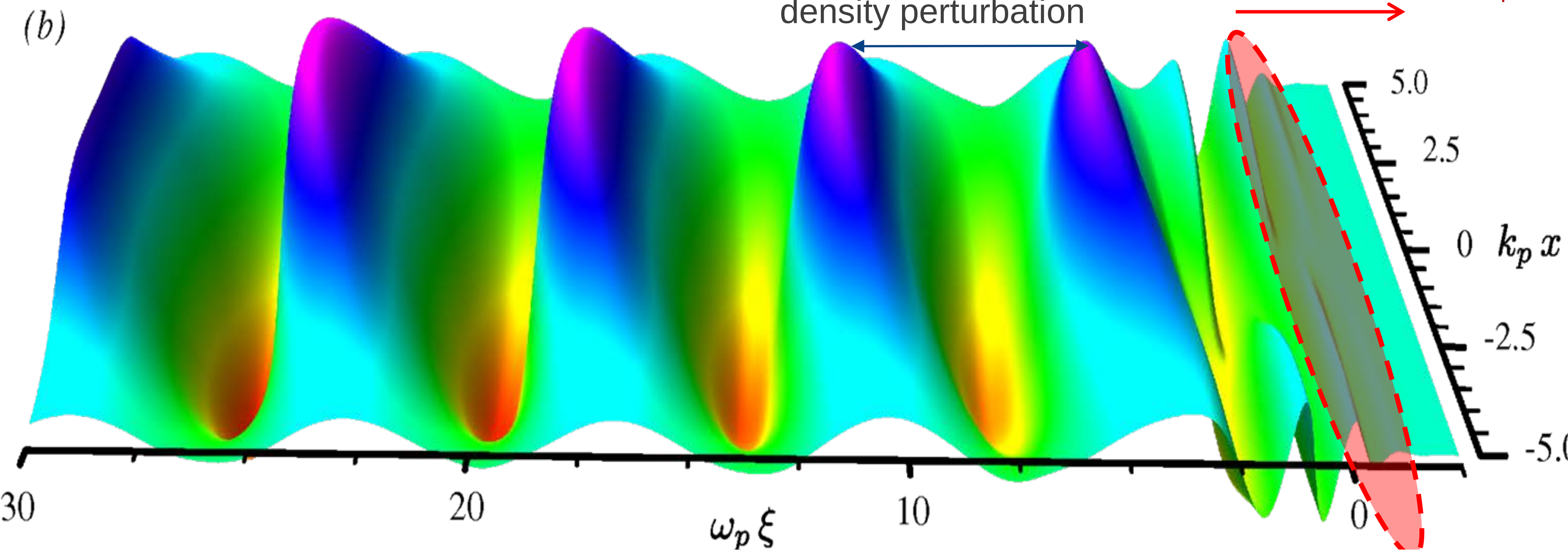
Plasma Waves

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



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

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

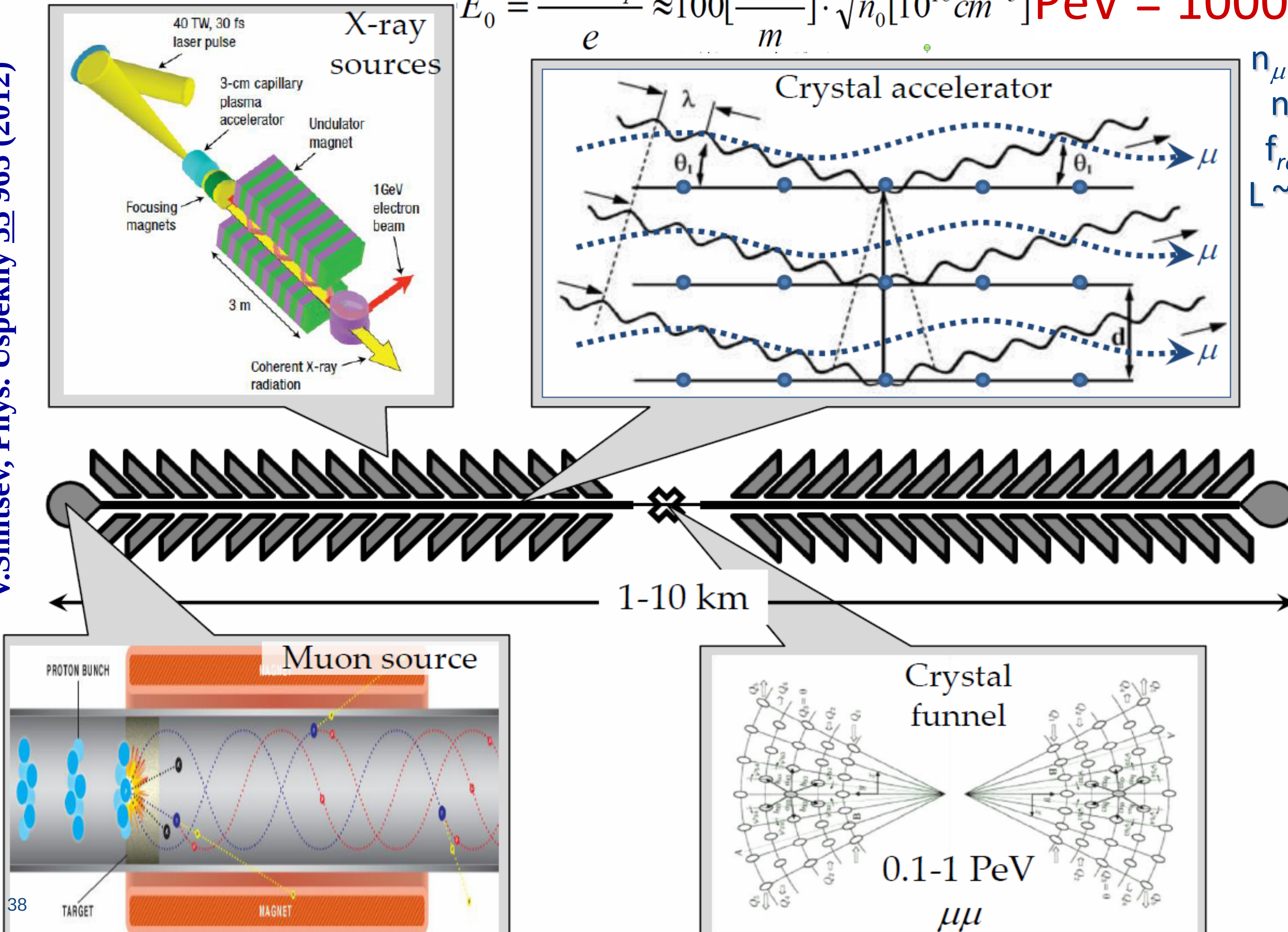
n~10^{22} cm^{-3}, **10 TeV/m →**

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

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)



“Far Future” Colliders: Issues

- Feasibility of **ENERGY**
  - now – only early indications
  - decade(s) of R&D at current pace (staging, etc)
- Feasibility of **COST**
  - too early to discuss seriously
  - at present x(3-10) more $$/TeV than SCRF
- 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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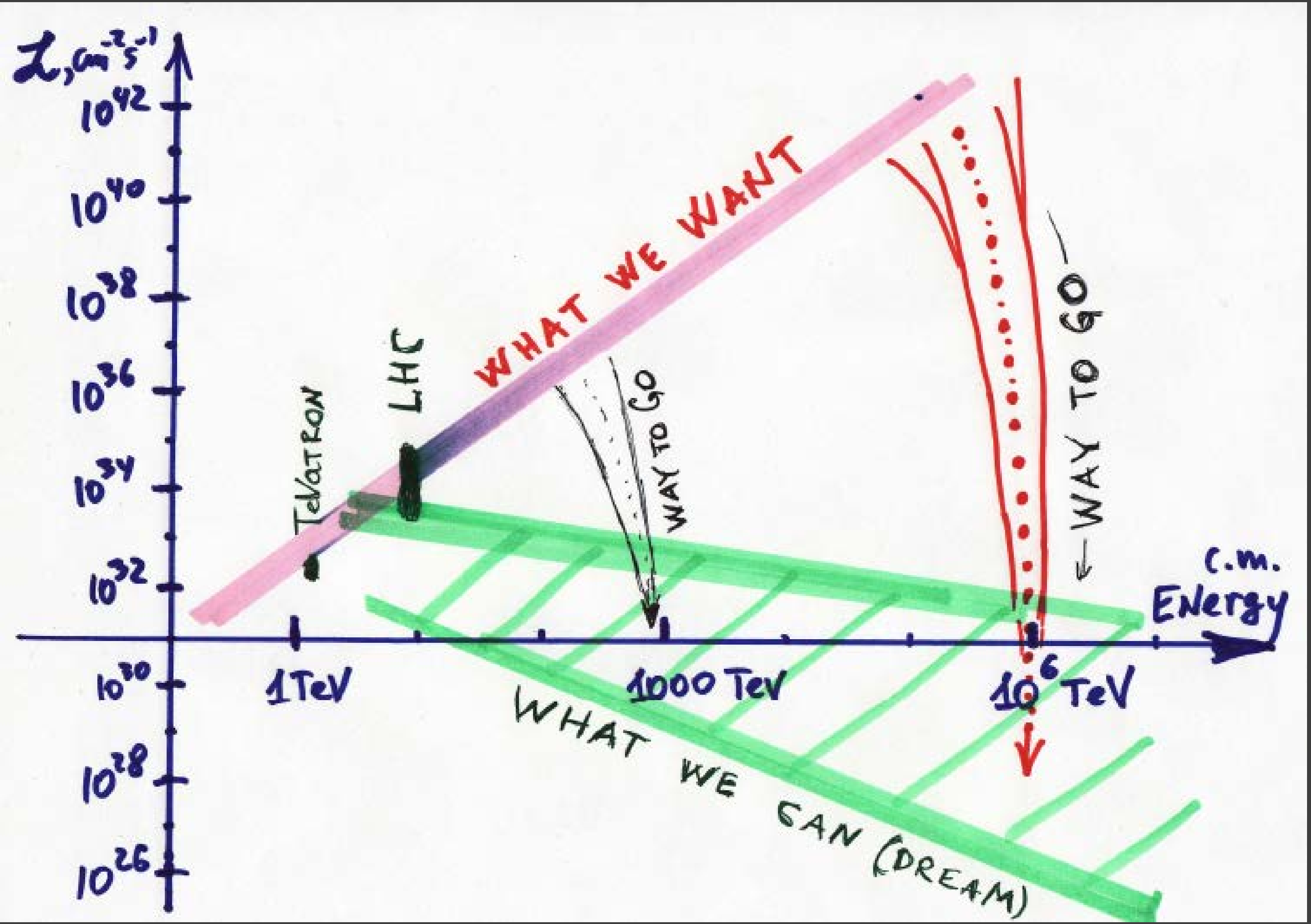
Paradigm Shift : *Energy* vs *Luminosity*



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 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 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)

Vielen Dank für Ihre Aufmerksamkeit !

Thank You for Your Attention!

Back up slides

	Known Estimate	*αβγ-Model*	Comments	$L_{[10km]}$	$E_{[1TeV]}$	$P_{[0.1GW]}$
eRHIC/MEIC *e-p(i)*	~0.8/1.3	1.1/1.7	2015 est.	0.1/0.5	~0.1	~0.1
Project X (SPL) *p*	1.8	2.2	Est. 2012	0.1	0.008	0.23
Neutrino Factory *p* → *μ*	4.7-6.5	4.6	Accounting not clear	0.6	0.012	1
LHeC *e-p*		5.1	LHC exists, 7x0.06 TeV	1.0	0.06	0.6
μ+μ- Higgs Factory		7.7	-2 if PD exists	0.7	0.12	1
Higgs *e-e+* FNAL site		7.8	C=16 km, 13 GV SRF	2.0	0.25	3
CepC/FCC*ee* Higgs Factory		10/11	7 GV SRF/5 GV SRF	6/10	0.25	3
ILC-0.25 TeV *e+e-* HF		10.2	~70% of ILC-0.5	~1.5	0.25	~1.2
μ+μ- Collider 3/6 TeV		12/15	-3+ if Prot. Driver exists	3/4	**3**/6	2.5
CLIC-0.5 TeV *e+e-*	7.4-8.3 E.a.	13.0	Coeff β_{CLIC} must be $>\beta_{ILC}$	2	0.5	2.5
VLHC-I 40 TeV *p-p*	11-14	13.1	2001 est (**4.1**)x3.5; - inj	23	40	2
ILC-0.5 TeV *e+e-*	(16.5)	13.6	2013 est = **7.8 Eur Acct**	3	0.5	2.3
Beam-PWA *ee* LC 3TeV		19-39	60 MW driver alone >8	1	3	2.8
CLIC-3 TeV *e+e-*		26.9	No public cost range	6	3	5.6
FCC 100 TeV *p-p*		30.3	Less ~10 if LHC injector	10	100	4
Laser-PWA 1/10 TeV *e+e-*		29/86.6	scaled today's laser cost	1	1/**10**	1.4
VLHC-II 175 TeV *p-p*		53.8		23	175	5

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

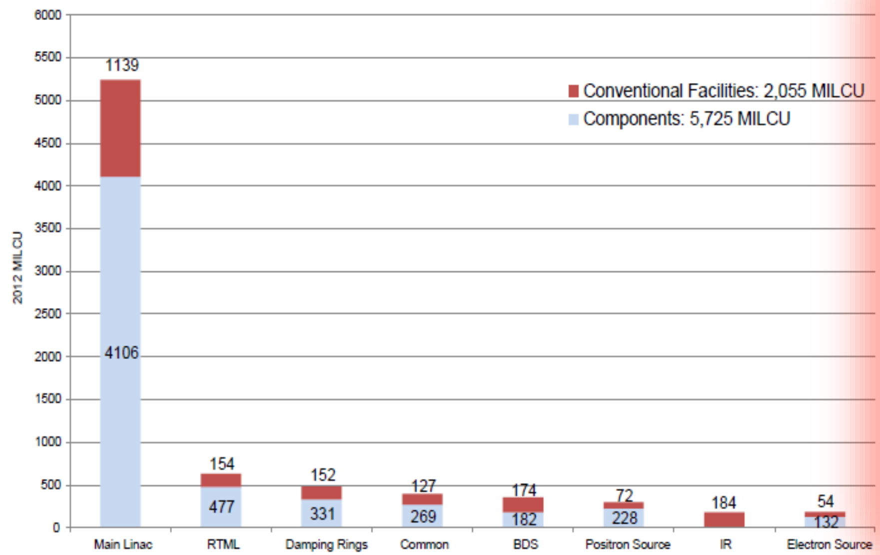


Figure 15.8. Distribution of the ILC value estimate by system and common infrastructure, in ILC Units. The numbers give the TDR estimate for each system in MILCU.

ScienceInsider

Breaking news and analysis from the world of science policy

Chu Pegs ILC Cost at $25 Billion

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

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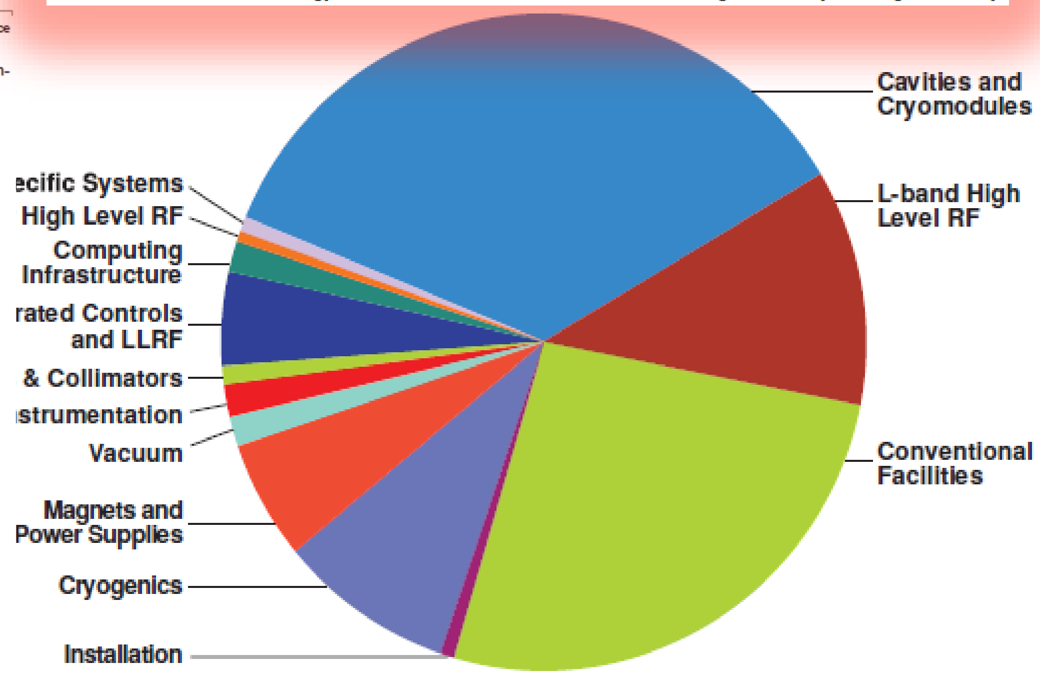
The International Linear Collider (ILC), a proposed 40-kilometer-long particle smasher, would cost a lot. But how much? U.S. Secretary of Energy Steven Chu and the leader of the project don't agree.

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 th

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 t luminosities.

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

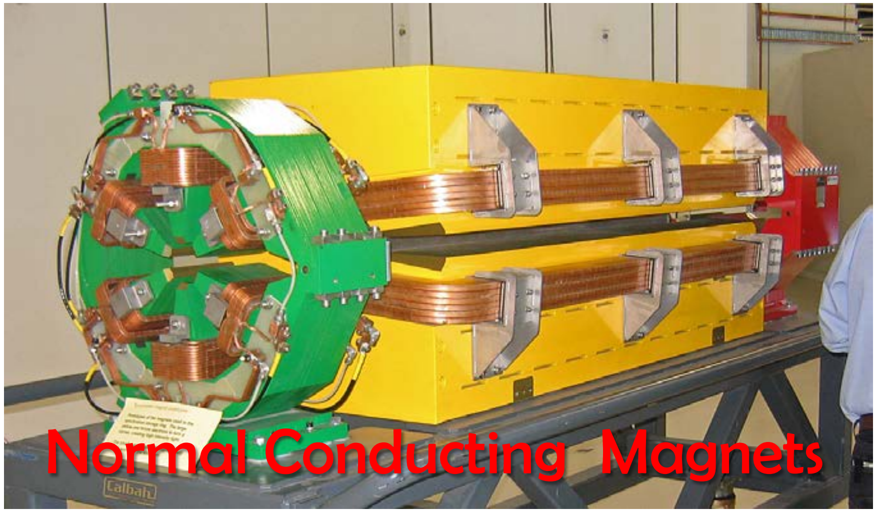
DIRECTOR'S CORNER

An ILC Higgs factory

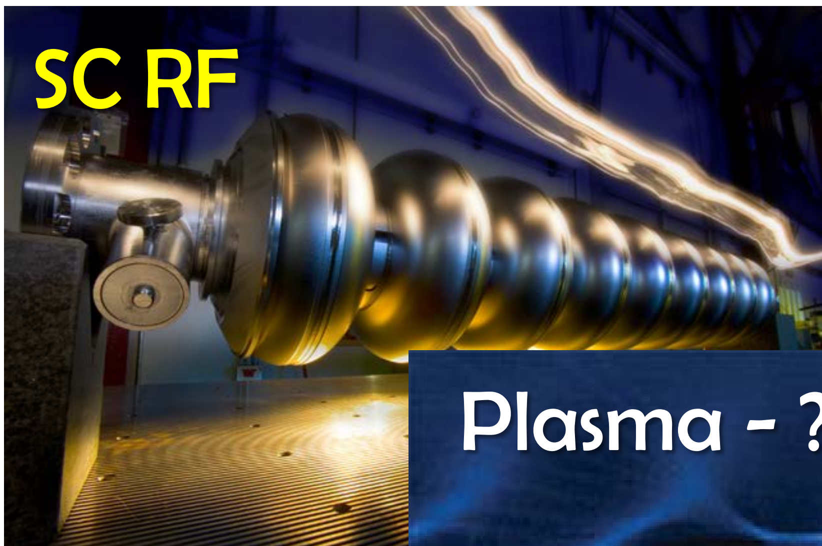
Based on some rather simplistic scaling, the cost of a dedicated 250-GeV machine would be ~70% of the cost of the 500-GeV machine. This may seem surprising until you realise that only about 60% of the total baseline cost is actually the linacs; the remaining 40% is for the sources, damping ring, beam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

Nick Walker | 27 September 2012

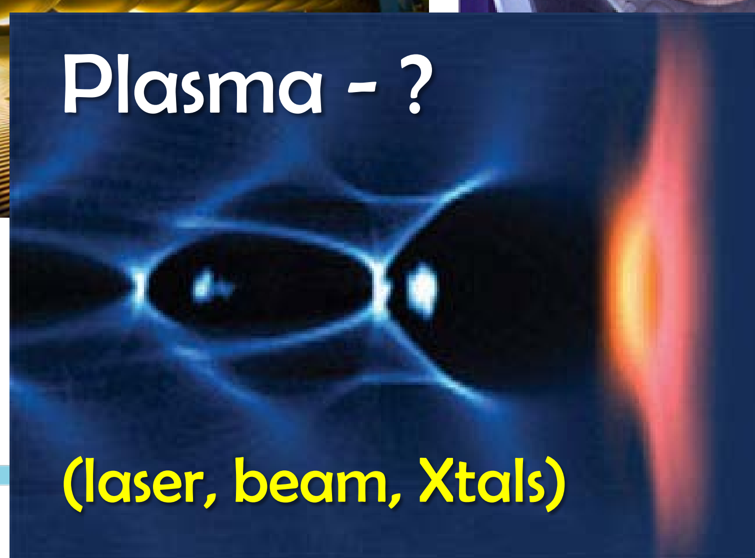
T


Normal Conducting Magnets


NCRF


SC RF

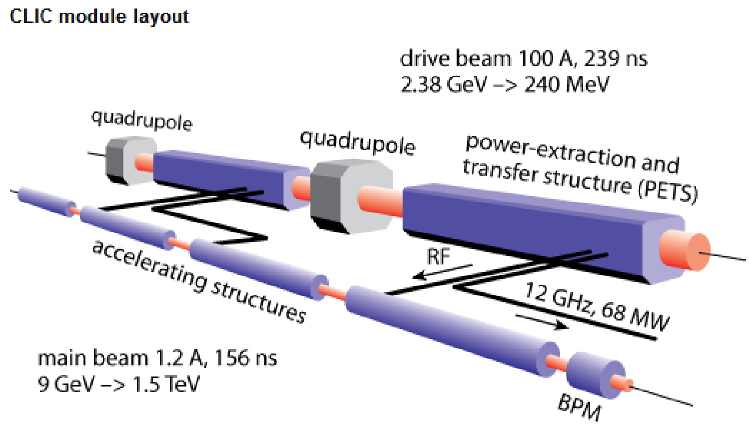

SC magnets

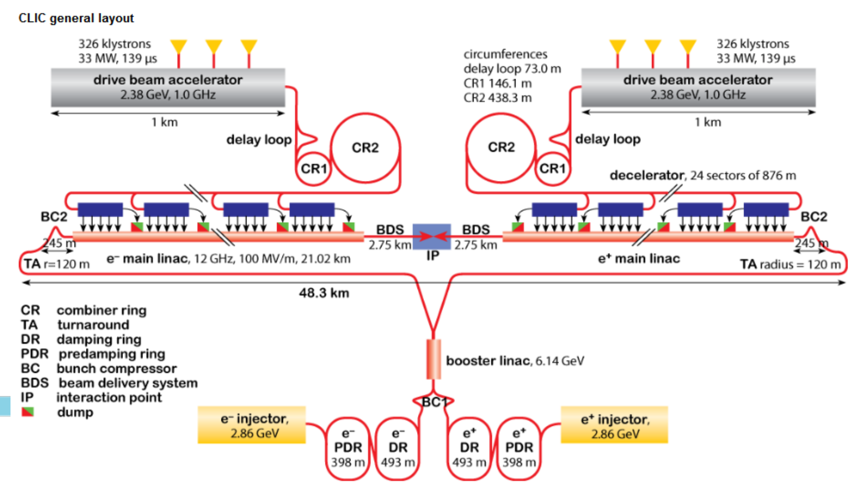

Plasma - ?
(laser, beam, Xtals)

Fermilab

Feasibility of *Performance* (1)

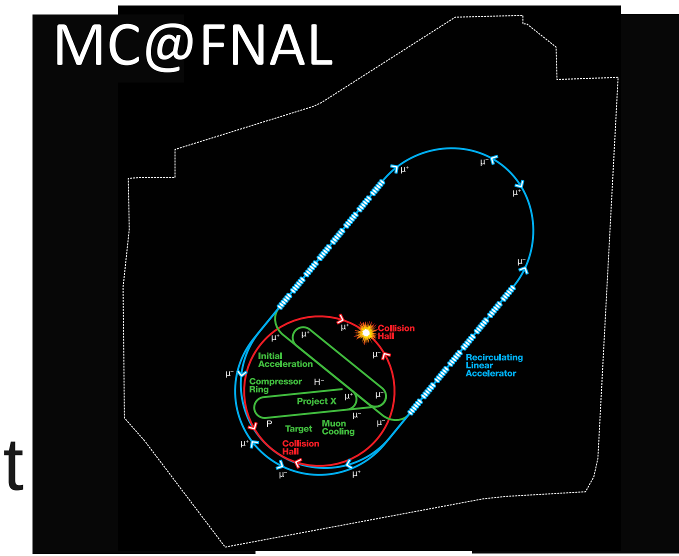
- **CLIC:** *e+e-* ~5 10^{34}
  - **very tough** **
    - emittances from the DRs
    - positron production
    - alignment/jitter of the linac
    - unprecedented final focus to few A *
    - *beam-strahlung* **
  - 15 accelerators
  - 560 MW of site power





Feasibility of *Performance* (2)

- **Muon Collider : ~2 10^{34}**
  - **– impossible now:**
    - requires 6D muon cooling
    - about **few × 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)

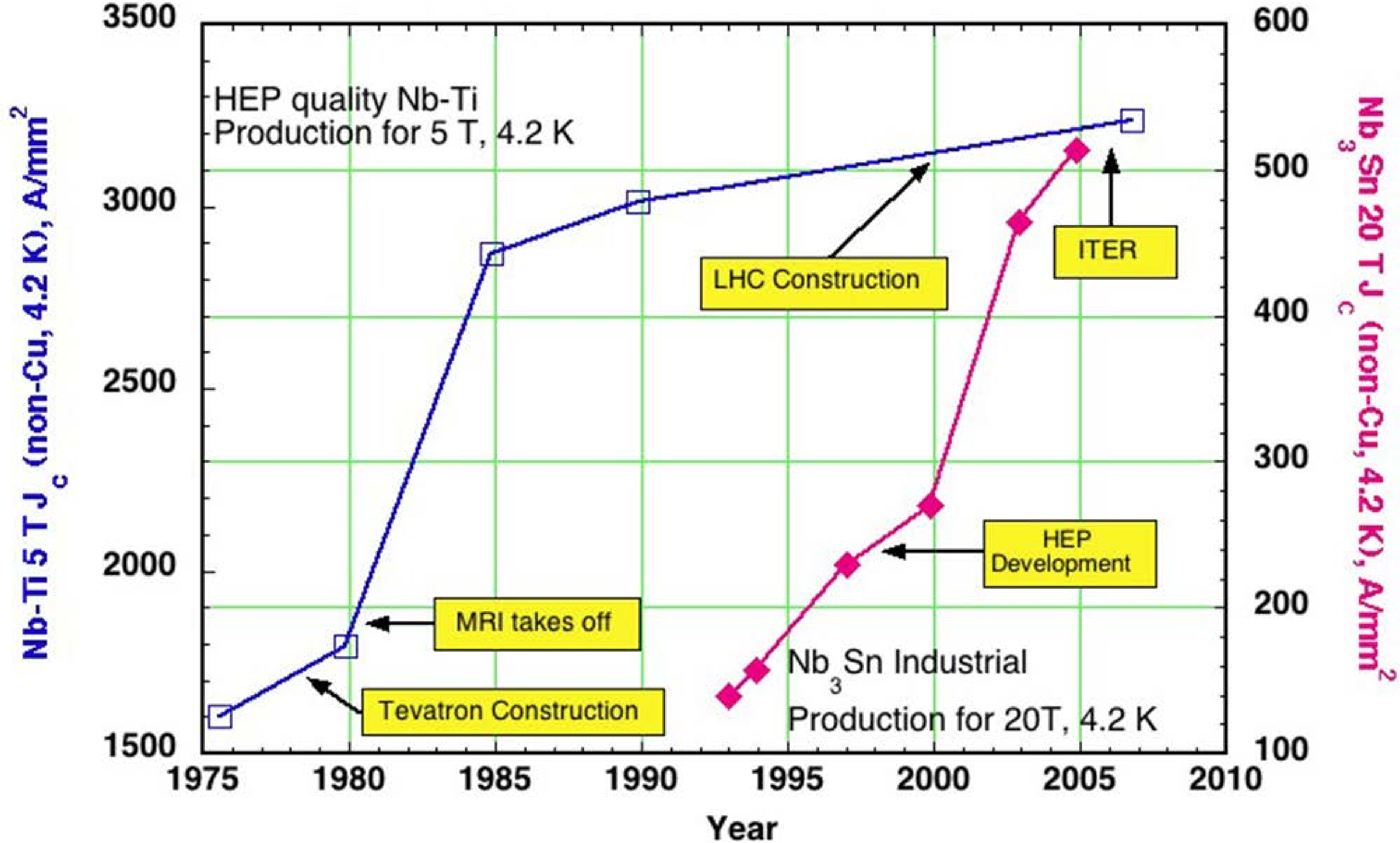
- **SppC and FCC : ~5 10^{34}**
  - **impossible now:**
    - SR power 5 MW
    - 25-50 W/m (vs 0.1-0.5)
    - Collimation 8GJ/beam
    - IR optics/beam-beam

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

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

Substantial improvements need time

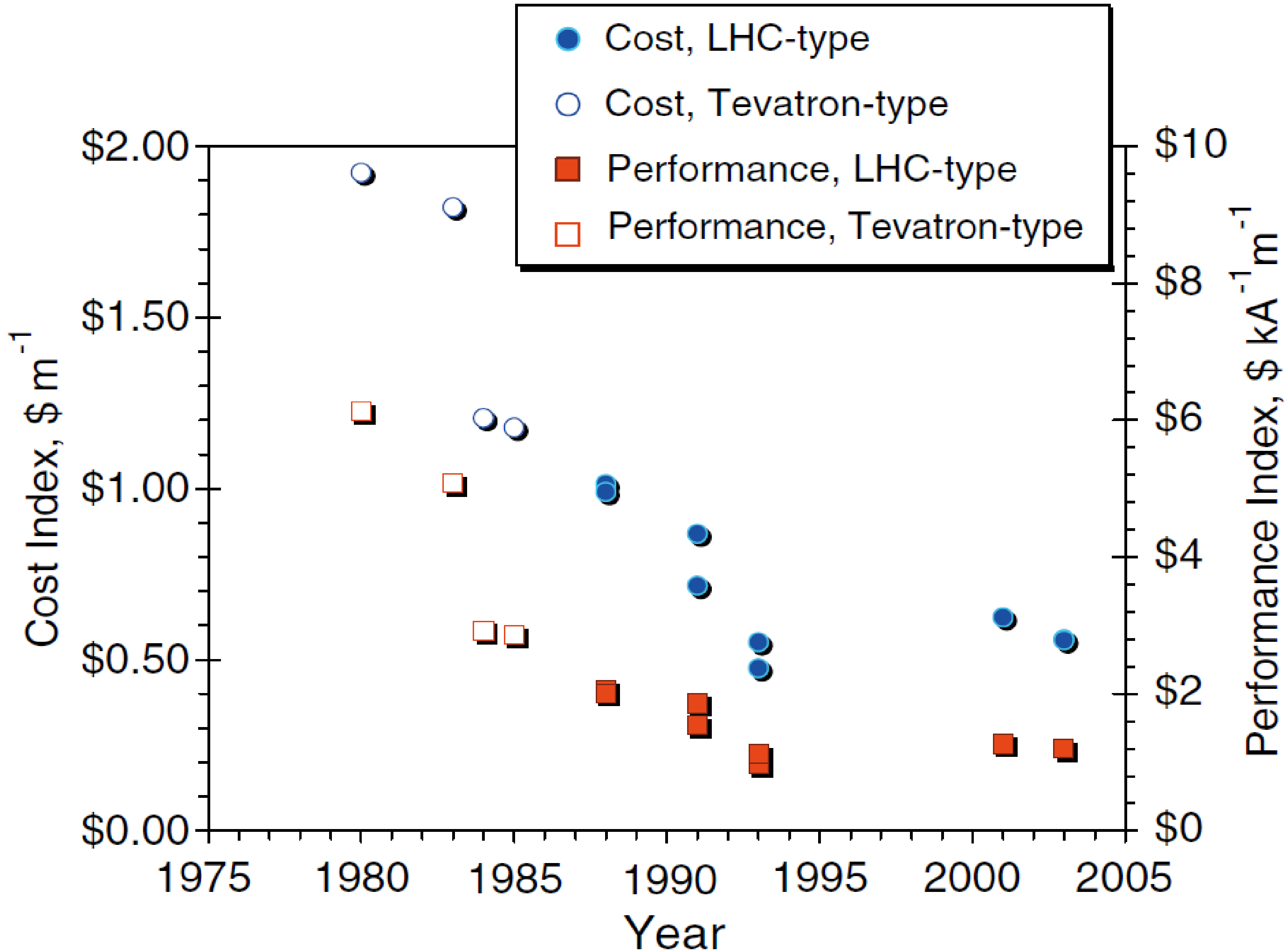
Decadal improvements in SC critical currents NbTi, Nb3Sn



* Courtesy A.Zlobin

Substantial improvements need time

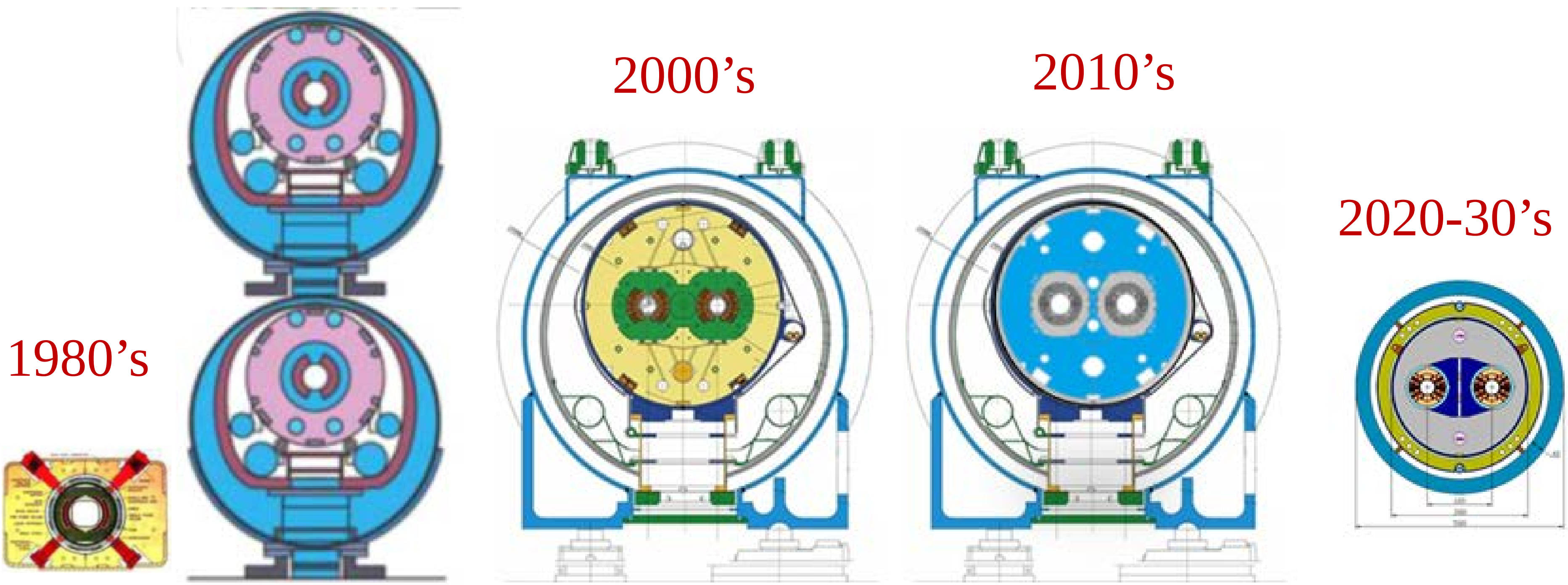
Decadal improvements in SC NbTi cable cost per m, per A*m



* Courtesy A.Zlobin

Substantial improvements need time

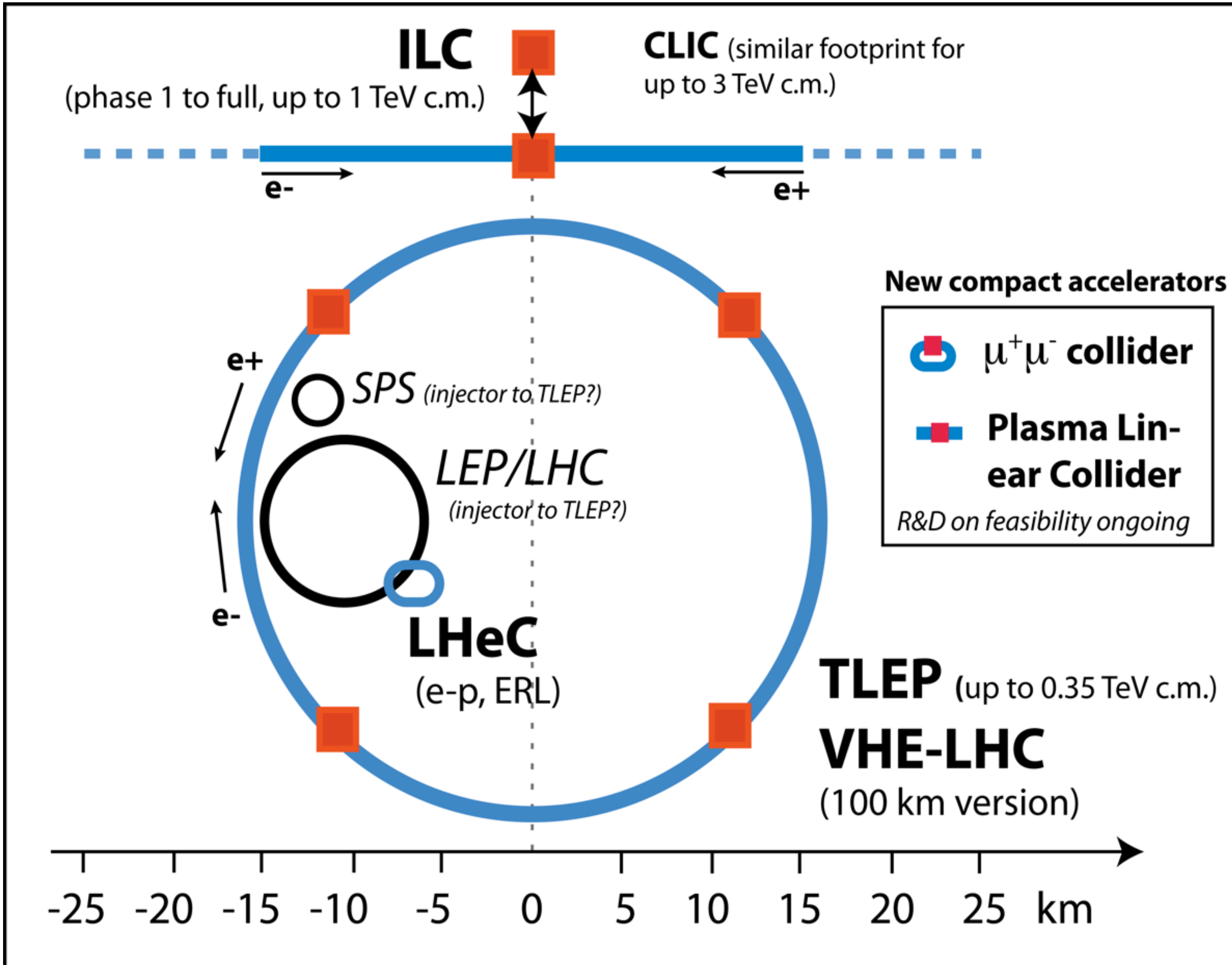
Decadal improvements in SC magnet design



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

Future Collider Options



R.Assmann, in *Challenges and Goals for Accelerators in the XXI Century*, O.Bruning, S.Myers (Eds, World Scientific , 2015)

Fermilab

IHEP-AC-2015-001

CEPC-SPPC

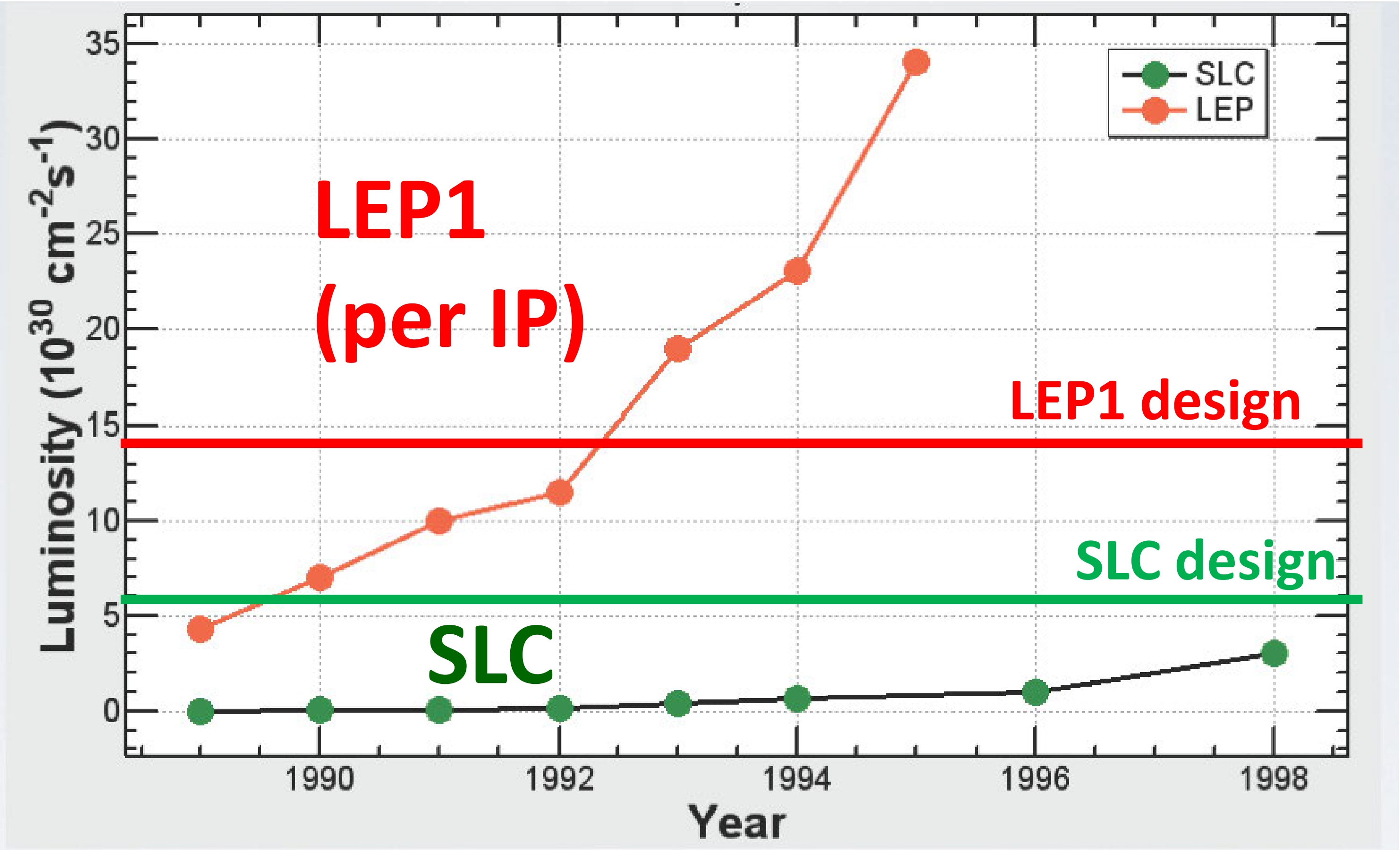
Preliminary Conceptual Design Report

March 2015

The CEPC-SPPC Study Group

Two Comments: #1

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



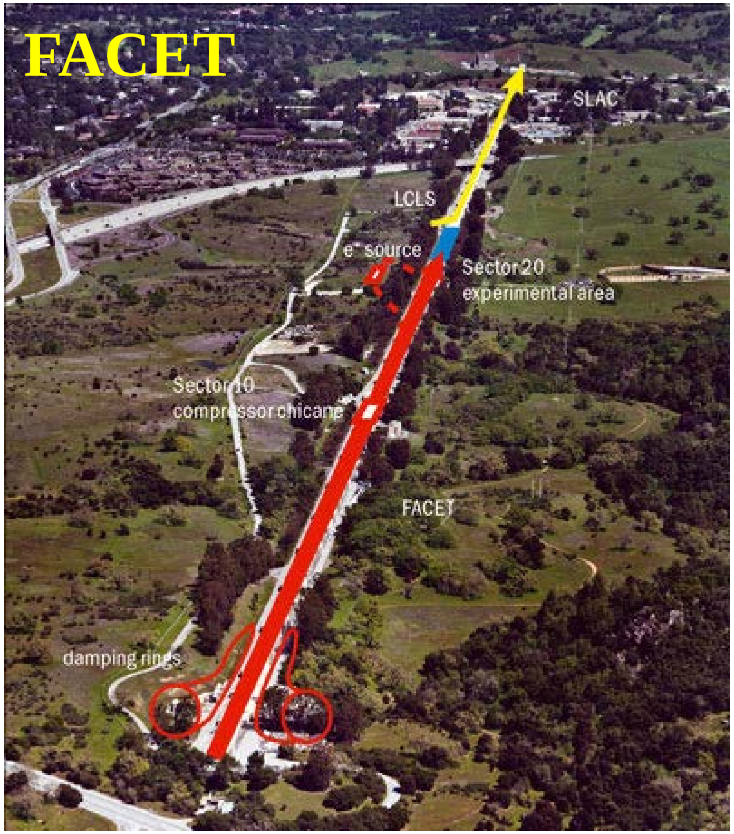
CERN-SL-2002- 009 (OP), SLAC–PUB–8042 [K. Oide, 2013]

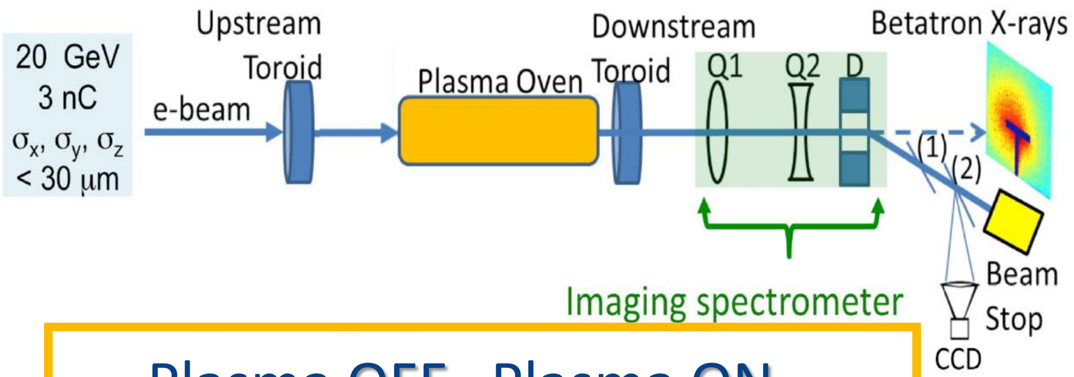
Time to reach *Design Luminosity*

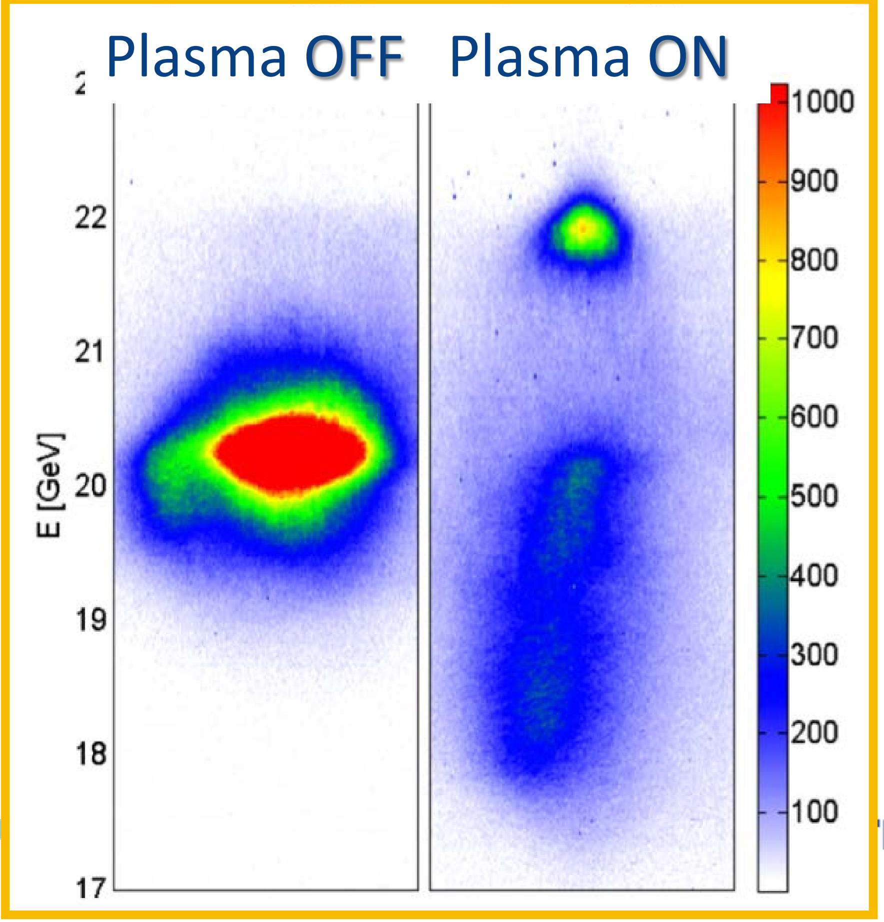
	Time to Design *L*	Final *L* / Design *L*
LEP-I	5 years	x2
SLC	Not achieved (9 years)	x0.5
LEP-II	0.3 year	x3
PEP-II	1.5 years	x4
KEK-B	3.5 years	x2
DAFNE-II	Not reached yet (5 years)	x0.9
TEV-Ib	1.5 year	x1.5
HERA-I	8 years	x1
RHIC-pp	10 years*	x1.2
TEV-II	3.5 years	x5
HERA-II	5 years	x1
LHC	Not reached yet (7 ** years)	x0.77

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

Option A: Plasma Wakes by Beam







n~5e16 cm-3

L=0.3 m

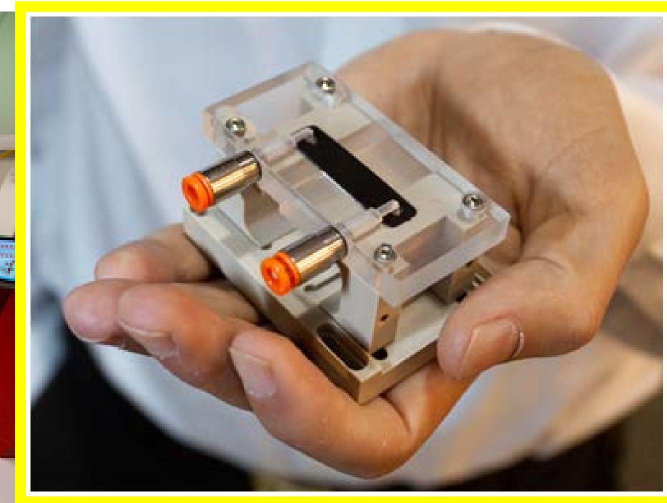
dE ~2 GeV

→ **6 GeV/m**

electrons

milab

Option B: Plasma Wakes by Laser

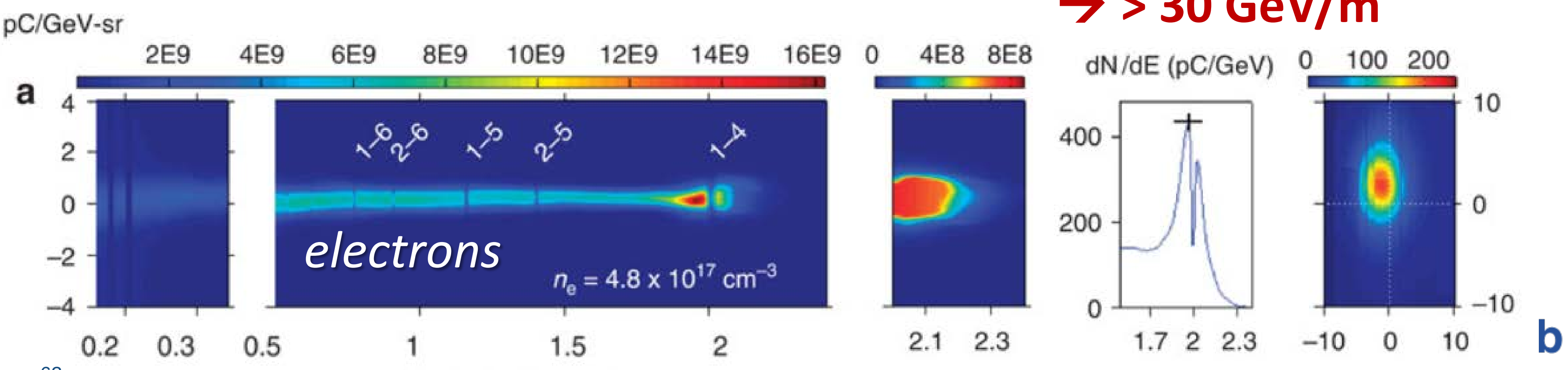


n~few e17 cm-3

L=0.03-0.1 m

dE ~2-5 GeV (PW lasers)

→ > 30 GeV/m

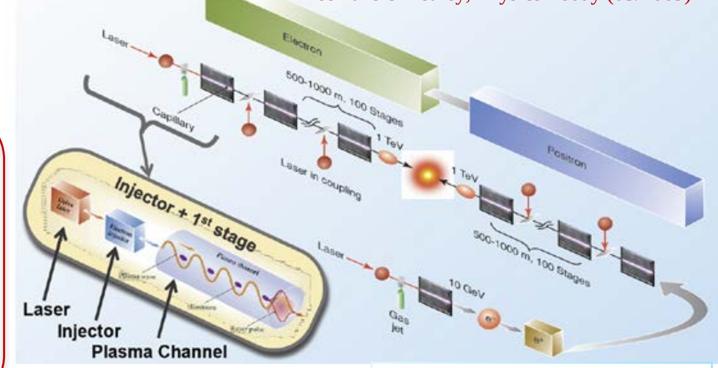


Nature Communications **4**, Article number: 1988 | doi:10.1038/ncomms2988

e+e- Plasma Collider Design Attempts

ISSUES AND QUESTIONS:

Leemans & Esarey, Physics Today (03/2009)



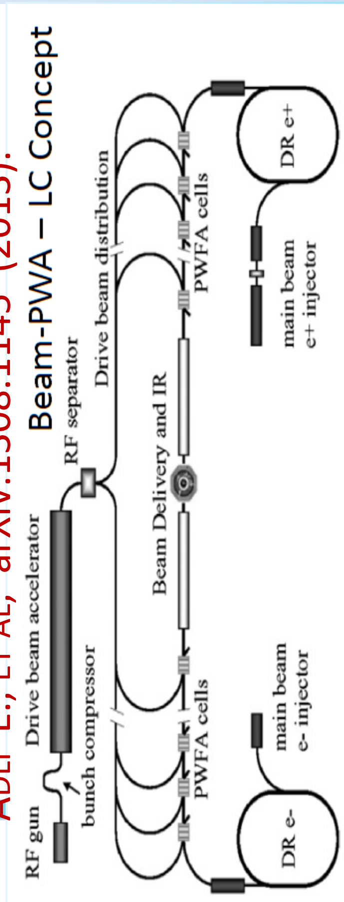
Staging is VERY inefficient – limits average acceleration gradient to ~1-2 GeV/m (beam) and ~10 GeV/m (laser)

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 ×(20/10)^1/2^+ 10 ×(25GeV/1TeV)^1/2^+2 ×(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.)

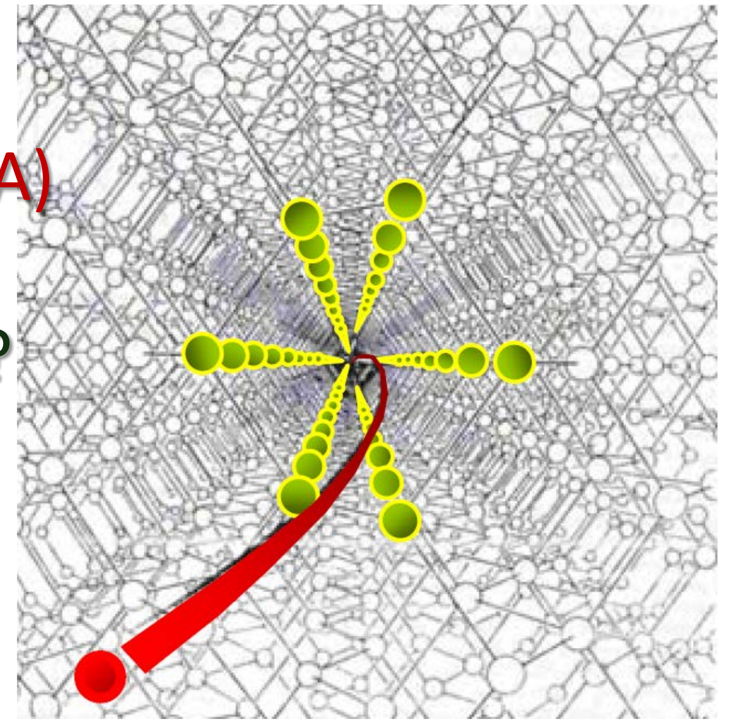
Luminosity - unknown (many issues, dE/E 100% for *ee*)

Adli E., et al, arXiv:1308.1145 (2013).



Option C: Crystals & Muons

ISSUES AND QUESTIONS:



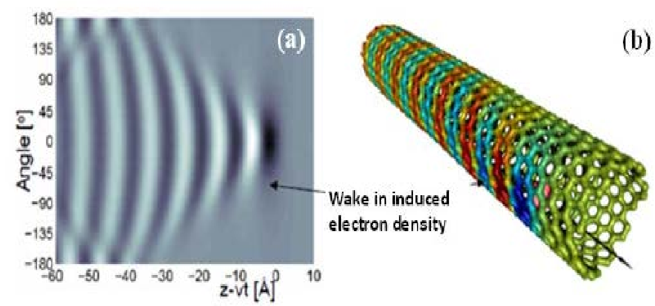
Can do(??) ~100+ GeV/m (test at ASTA)

- 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"!!

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*