Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

MC Comparative Cost Analysis: *Part I – Phenomenlogical Model*

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MCC

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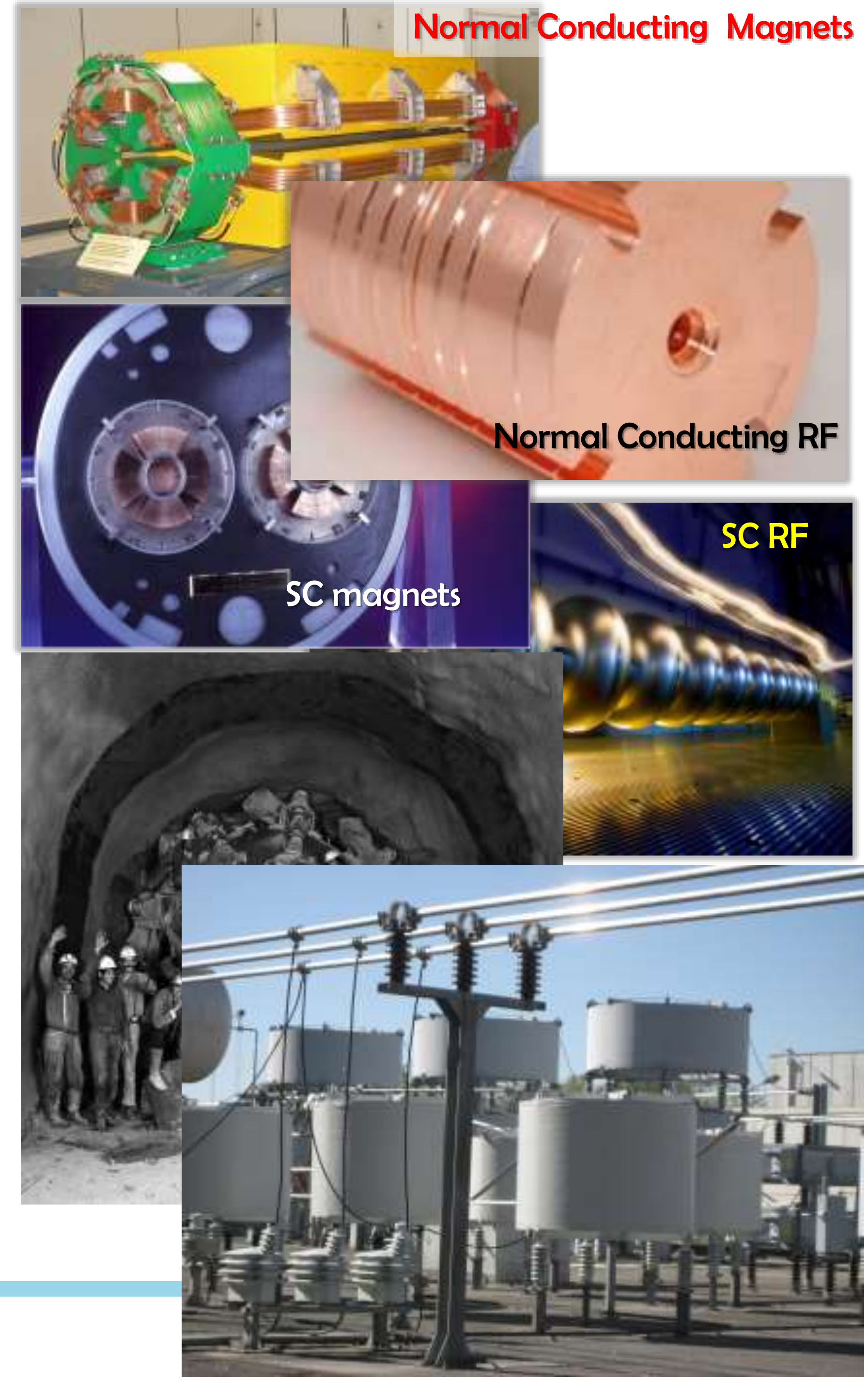
(Fast Forward) Summary Table

αβγ - Model

	Civil (km)	E_rf (TeV)	E_mag (TeV)	Site P (MW)	Cost* (LHCU)
XFEL	3.3	0.017	0	15	0.25 ±0.1
LHC* (green field)	45	0	14.5	230	1.4 ±0.4
LHC project	0_{+6}	0	14	120	**1.00**
ILC-Higgs	21_{+3}	0.25	0	129	0.9 ±0.3
CLIC - tt	11_{+6}	0.38	0	168	1.0 ±0.3
CLIC-3	54_{+6}	3	0	580	2.9 ±0.9
FCCee	100_{+20}	0.016	0.24	282	1.3 ±0.4
FCChh*(no FCCee)	100_{+20}	0.01	100	580	3.4 ± 1.1
FCChh after FCCee	0	0.01	100	580	2.8 ±0.9
MC-HF	0.3_{+3}	0.02	0.13	200	0.6 ±0.2
MC-3	4.5_{+7}	0.06	3	230	1.2 ±0.3
MC-10 base	10_{+7}	0.07	10	310	1.5 ±0.5
MC-10* max (M.P.)	10_{+59}	0.13	10	310	1.8 ±0.5
MC-14* rcs-LHC tun	0	0.03	14	340	1.4 ±0.4

Intro: *Cost*

- Cost is set by technology
  - *Accelerator technology* (magnets NC and SC, RF and SCRF)
  - *Civil construction technology*
  - *Power production, delivery and distribution technology*



2014 JINST 9 T07002

2014 Cost analysis:

17 “Data Points” - Costs of Big Accelerators:

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

Wide range :

- 4 orders in *E*nergy, >1 order in *P*ower, >2 orders in *L*ength
- Almost 2 orders in cost
  - (normalized to US TPC)

	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

Methodology of the αβγ – Model

- **Adjust all costs to TPC (US accounting)**
  - usually, btw 1.9 to 2.4 x European Accounting
- **Break TPC in just three parts (with sum = total)**
  - "Tunnels" (civil construction and siting)
  - "Accelerator systems" (SC and/or NC RF, Magnets)
  - "Power" (site, cryo, generators/converters/distribution, etc)
- **Scale each part with two parameters: $a_{L,E,P}$ and $b_{L,E,P}$**
  - *L* (in 10 km units), *E* (in TeV of cme), *P* (in 100 MW)

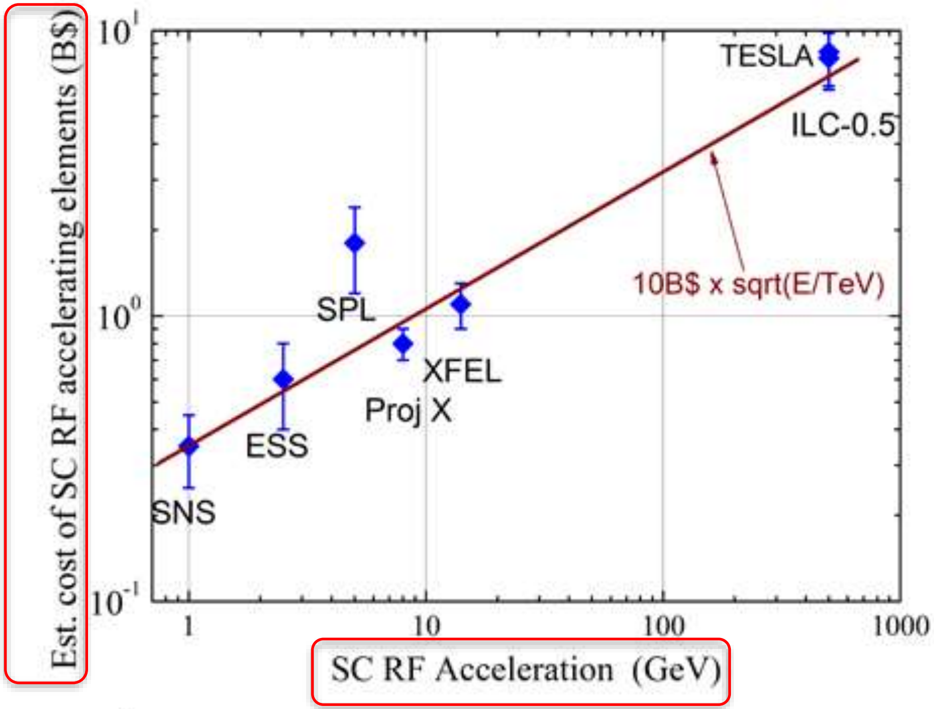
$$TPC = a_L \left(\frac{L}{10\,\mathrm{km}}\right)^{b_L} + a_E \left(\frac{E}{1\,\mathrm{TeV}}\right)^{b_E} + a_P \left(\frac{P}{100\,\mathrm{MW}}\right)^{b_P}$$

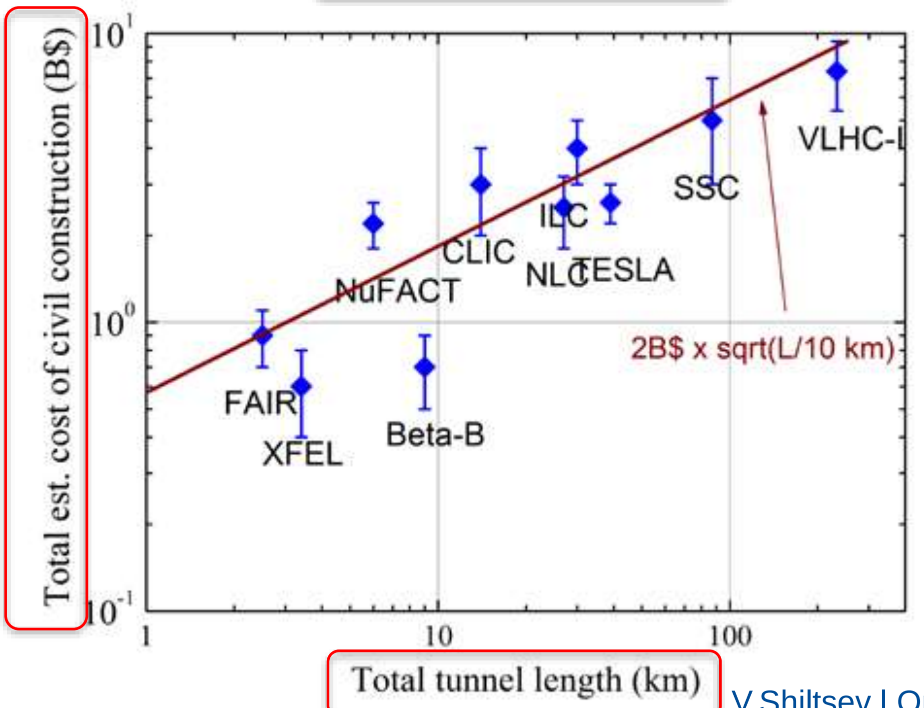
- **(Simplify to SQRT and round up… set all $b_{L,E,P}$ =1/2)**
  - as they were typically found btw 0.4 and 0.6

Illustrations

Comment:

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





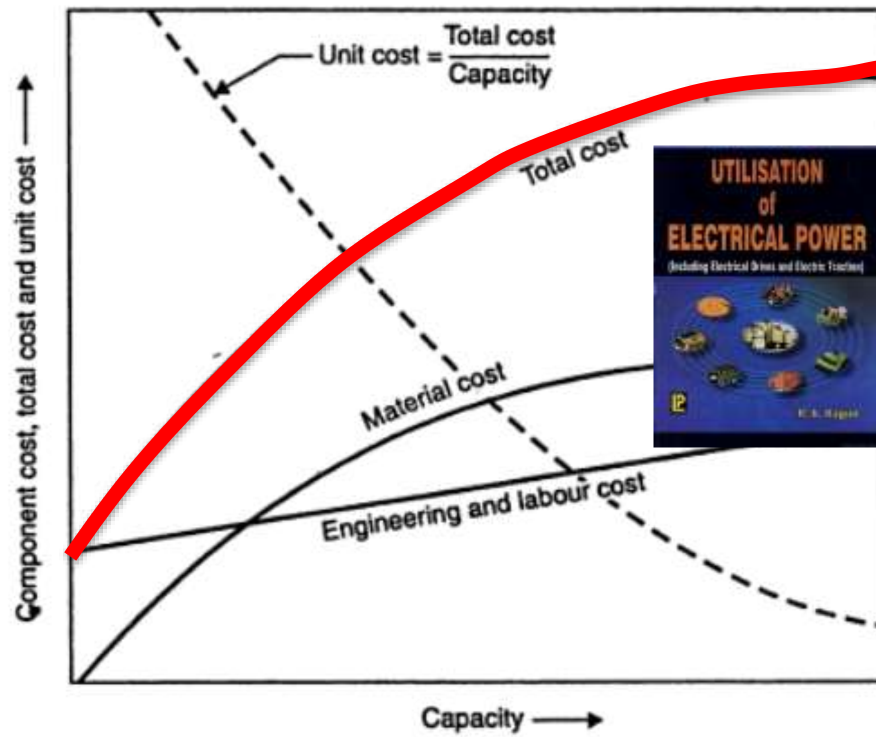


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

! 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 !**

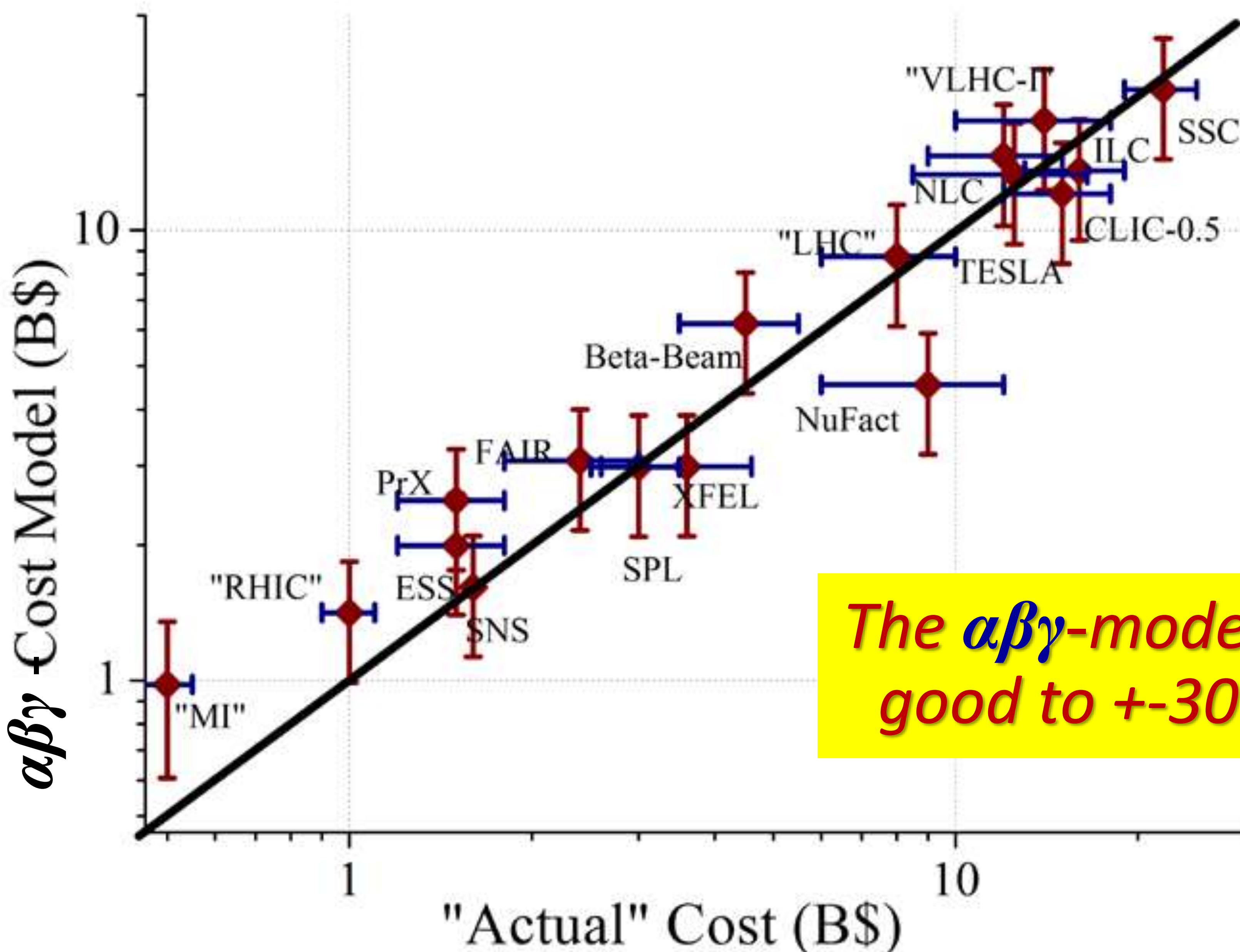
c) **There is hidden correlation btw *E* and technology progress**

d) **Pay attention to units**(10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 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)**

USE AT YOUR OWN RISK!

Total Cost vs *αβγ-Model* (Log-Log)



The αβγ-model is good to +-30%

Take LHC as an Example:

- ***αβγ* – Model:**
  - 40 km of tunnels
  - 14 TeV c.o.m SC magnets
  - ~150 MW of site power

$$2\sqrt{40/10} = 4$$

$$2\sqrt{14} = 7.5$$

$$2\sqrt{150/100} = 2.5$$

TOTAL PROJECT COST : **14B$ ± 4.5B$**

- **ITF T.Roser talk @ PLUB-II (USD 2021):**
  - existing injector complex **4.6 B$**
  - new accelerator systems **4.06 B$**
  - new infrastructure and civil **2.75 B$**
  - explicit labor **~1.4 B$**

Total: **12.8B$**

Future Colliders w.r.t. LHC

αβγ - Model

	Civil (km)	E_rf (TeV)	E_mag (TeV)	Site P (MW)	Cost* (LHCU)	Cost Reported
XFEL	3.3	0.017	0	15	0.25 ±0.1	1.7 BEUR
LHC* (green field)	27_{+28}	0	14.5	230	1.4 ±0.4	13-15 B?
LHC project	0_{+6}	0	14	120	**1.00**	8-10 B?
ILC-Higgs	21_{+3}	0.25	0	129	0.9 ±0.3	7 kOKU
CLIC - tt	11_{+6}	0.38	0	168	1.0 ±0.3	5.9 BCHF
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FCChh after FCCee	0	0.01	100	580	2.8 ±0.9	17 BCHF
MC-HF	0.3_{+3}	0.02	0.13	200	0.6 ±0.2	?
MC-3	4.5_{+7}	0.06	3	230	1.2 ±0.3	?
MC-10 base	10_{+7}	0.07	10	310	1.5 ±0.5	?
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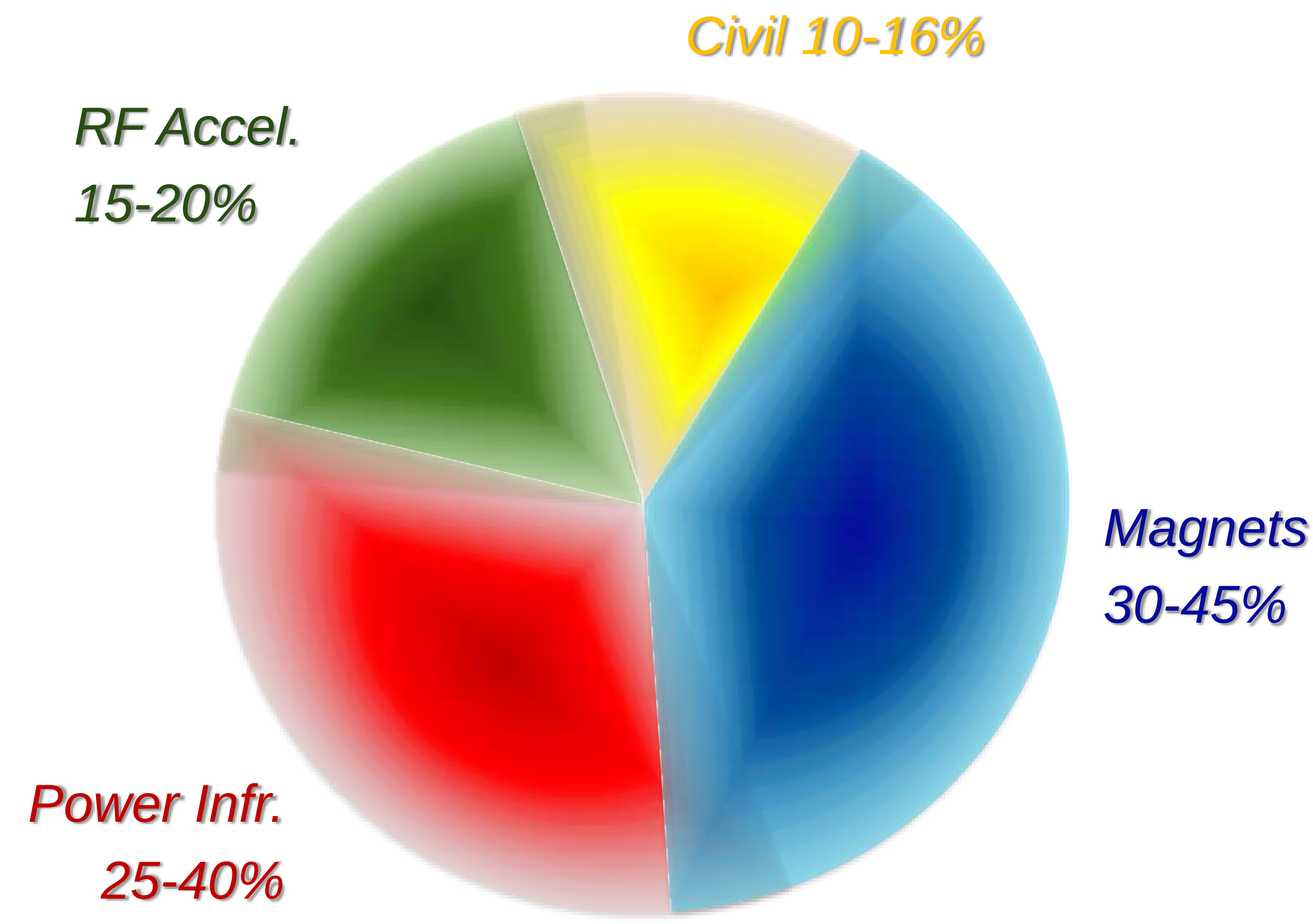
“αβγ – Model” : Notes

- Costs of future technologies are not well known:
  - plasma, lasers, crystals, “magic cheap” magnets, tunnels, HTS, etc
- Costs of civil construction and power systems are driven by larger economy (not by us)… “stable”
- Having injector/reuse infrastructure helps a lot (~1/3 of cost)
- Follows from the model:
  - *C*ost is weak function of luminosity (see next slide)
    - Also, LHC 10B$, HL-LHC 1B$ with x5 increase in luminosity
    - It’s OK to start high *E*, low *L*…CESR, Tevatron increased *L* >100x, LHC >10x
  - *C*ost is moderate function of length/circumference
  - *C*ost is strong function of *E*nergy and technology
- Of course, the model error bars are large (range of ~2) but at least allows approximately sort proposals in categories
    - E.g., “Less than LHCU”, “1-2 LHCU”, “More than 3 LHCU”, etc

“αβγ – Model” : 10 TeV Muon Collider



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"αβγ – Model" : Caveats

- "*Non-uniformity*": machine costs estimated by proponents and in variable methodologies
- Analysis was done in 2013:
  - *many more projects have been costed since then*: FCCee, FCChh, CepC, SPPC, LHeC, NICA, PIP-II, EIC, LCLS-II & HE, HL-LHC
  - *others updated or finished:* XFEL, SwissFEL, FRIB, ESS, FAIR, ILC, CLIC
  - *inflation 7yrs x 3% = 21%... varies by region*
- Analysis to be updated for the *Snowmass'21*:
  - *As part of the* AF Implementation Task Force
  - Scaling *and* relative weights of cost factors

BACK UP SLIDES