



High-Energy LHC: Machine Design & Accelerator Physics Challenges

Vladimir SHILTSEV, FCC International Advisory Council

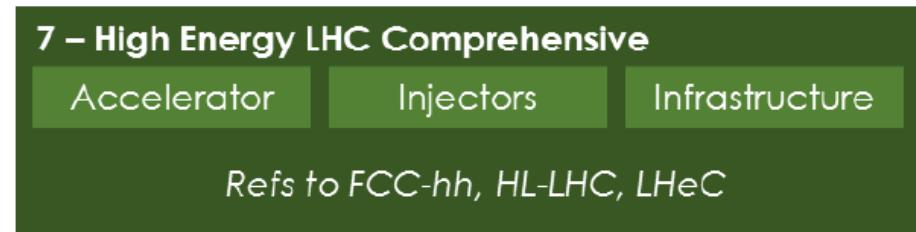
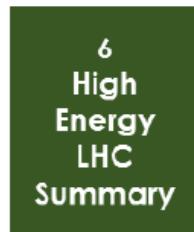
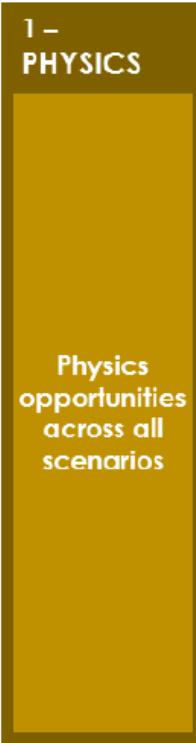
HL/HE LHC meeting, Fermilab

4 Apr 2018

HE-LHC : “...in the shadow of FCC-hh”

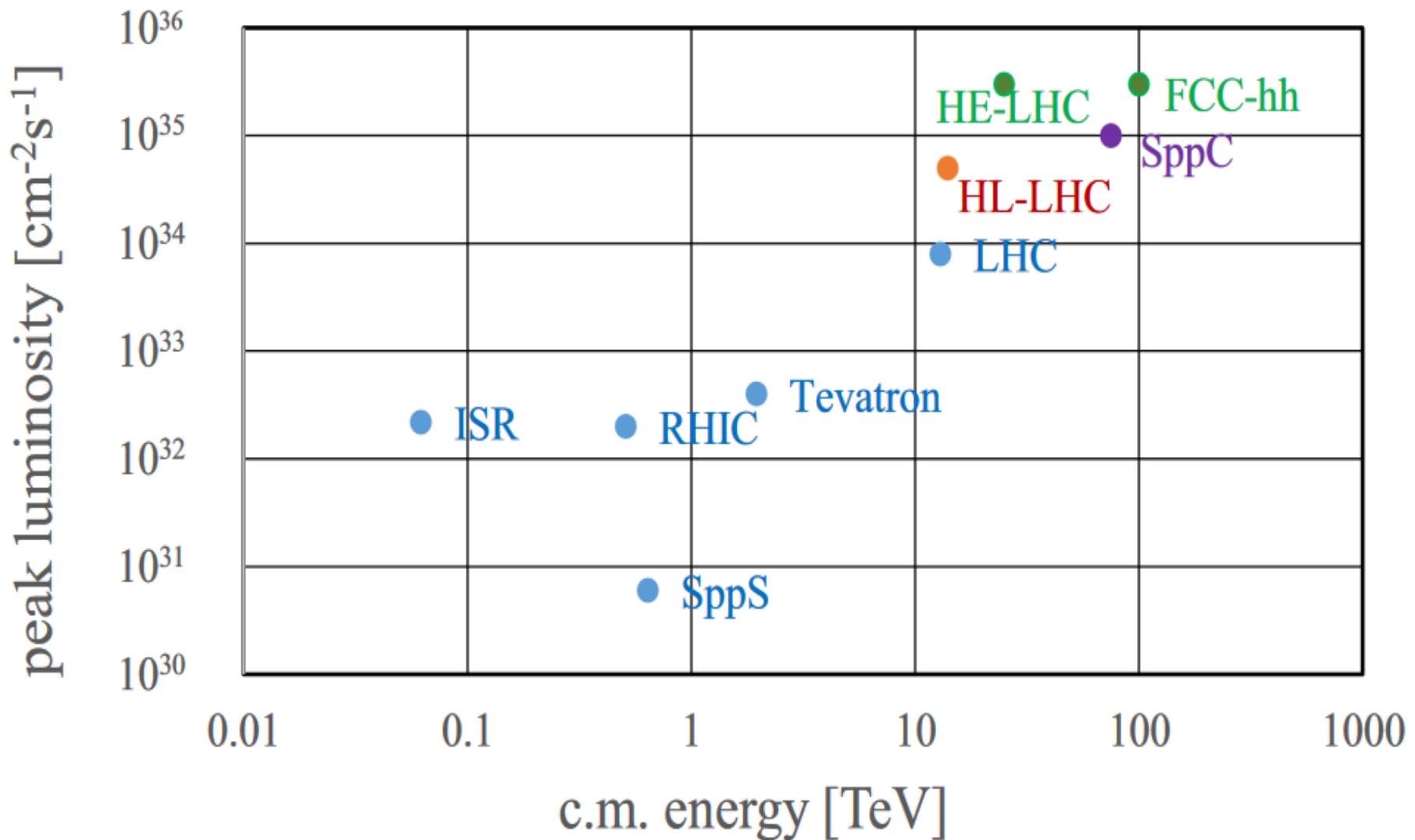


Conceptual Design Report



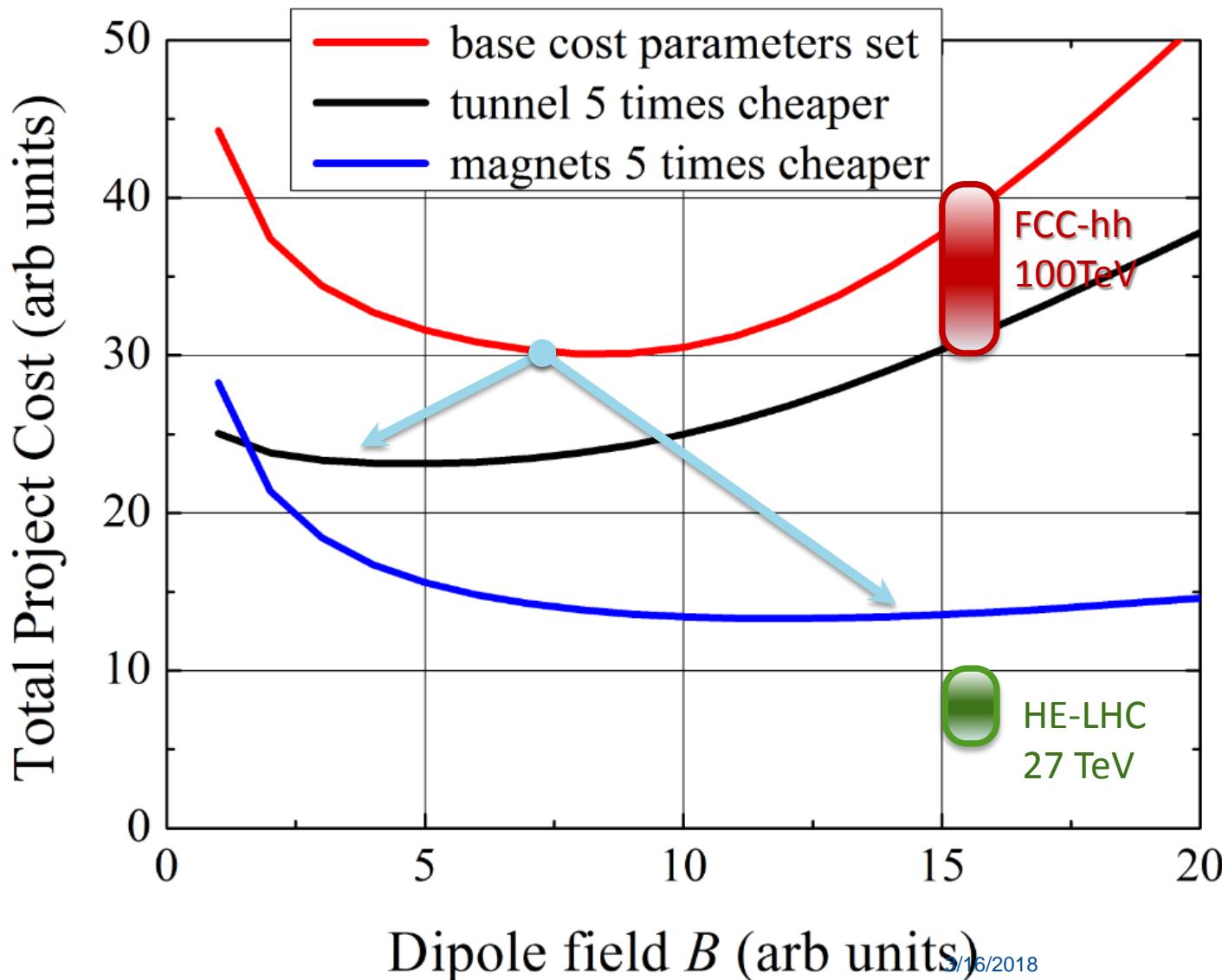
- required for end 2018, as input for European Strategy Update
- common physics summary volume
- three detailed volumes FCC-hh, FCC-ee, HE-LHC
- three summary volumes FCC-hh, FCC-ee, HE-LHC

Luminosity vs E_{cm}



Why not stick with FCC-hh ?

100 TeV pp : Qualitative Cost Dependencies



* for illustration purposes only

HE-LHC design goals and basic choices

physics goals:

- 2x LHC collision energy with FCC-hh magnet technology
- c.m. energy = 27 TeV $\sim 14 \text{ TeV} \times 16 \text{ T} / 8.33\text{T}$
- target luminosity $\geq 4 \times \text{HL-LHC}$ (cross section $\propto 1/E^2$)

key technologies:

- FCC-hh magnets (curved!) & FCC-hh vacuum system
- HL-LHC crab cavities & electron lenses

beam:

- HL-LHC/LIU parameters (25 ns baseline, also 5 ns option)

Hadron Collider Parameters - 1

parameter	FCC-hh	HE-LHC	(HL) LHC
collision energy cms [TeV]	100	27	14
dipole field [T]	16	16	8.33
circumference [km]	100	27	27
straight section length [m]	1400	528	528
# IP	2 main & 2	2 & 2	2 & 2
beam current [A]	0.5	1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2 (0.44)
bunch spacing [ns]	25	25 (5)	25 (5)
rms bunch length [cm]	7.55	7.55	(8.1) 7.55
peak luminosity [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	30	25
events/bunch crossing	170	1k (200)	~800 (160)
stored energy/beam [GJ]	8.4	1.3	(0.7) 0.36
beta* [m]	1.1-0.3	0.25	(0.20) 0.55
norm. emittance [μm]	2.2 (0.4)	2.5 (0.5)	(2.5) 3.75

Challenges FCC:

- Cost of 100 km magnets and civil
- 16 T magnets
- ~1000 pileup
- Collimation/protection



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Challenges HE-LHC:

- Cost of 27 km magnets
- 16 T magnets
- ~800 pileup
- High current

Hadron Collider Parameters - 2

parameter	FCC-hh	HE-LHC	(HL) LHC
rms IP beam size [μm]	6.7 (3) – 3.5 (1.5)	6.6 (3.0)	(8.2) 16.7
half crossing angle [μrad]	37 - 70	131 (60)	(255) 143
Piwinski angle	0.42 – 1.51	1.50 (1.50)	(2.52) 0.65
crab cavities needed	NO - YES	YES (YES)	(YES) NO
synchr. rad. power / ring [kW]	2400	101	(7.3) 3.6
beam-screen half aperture [mm]	13.2	13.2 or 14	17
beam-screen temperature [K]	50	20 or 50	20
SR power / length [W/m/ap.]	28.4	4.6	(0.33) 0.17
ΔE / turn [keV]	4600	93	6.7
long. emit. damping time [h]	0.54	1.8	12.9
initial beam lifetime [h]	18	3	(15) 40
total / inelastic cross section [mbarn]	156 / 109	125 / 91	112 / 82
injection energy [TeV]	3.3	1.3	0.45
hor.,vert. arc half aperture [mm]	15,13.2	15, 13.2 (19, 14)	22, 17

Challenges FCC:

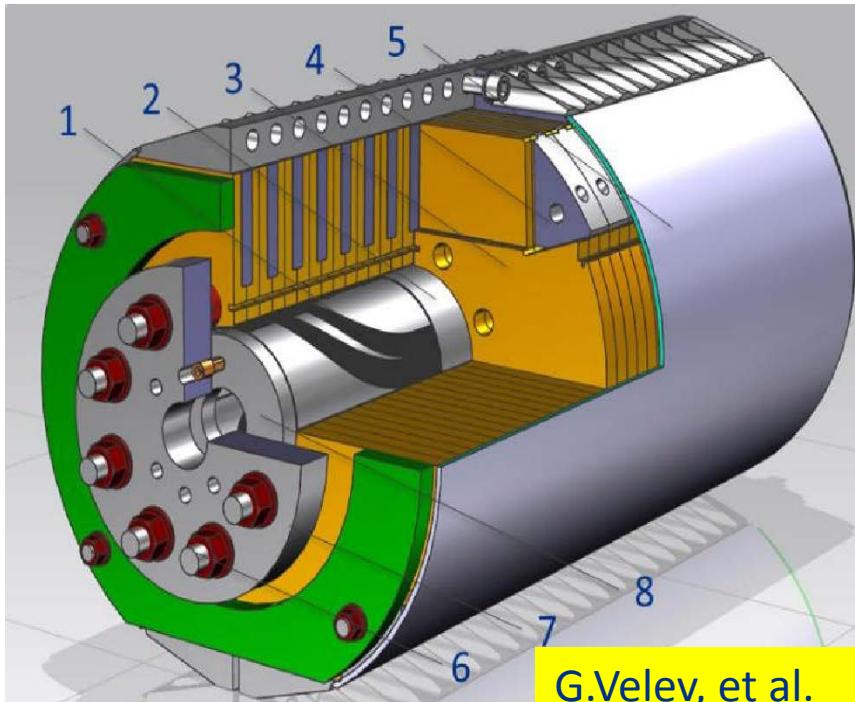
- Need new 3.3 TeV injector
- x100 LHC radiation power /meter

Challenges HE-LHC:

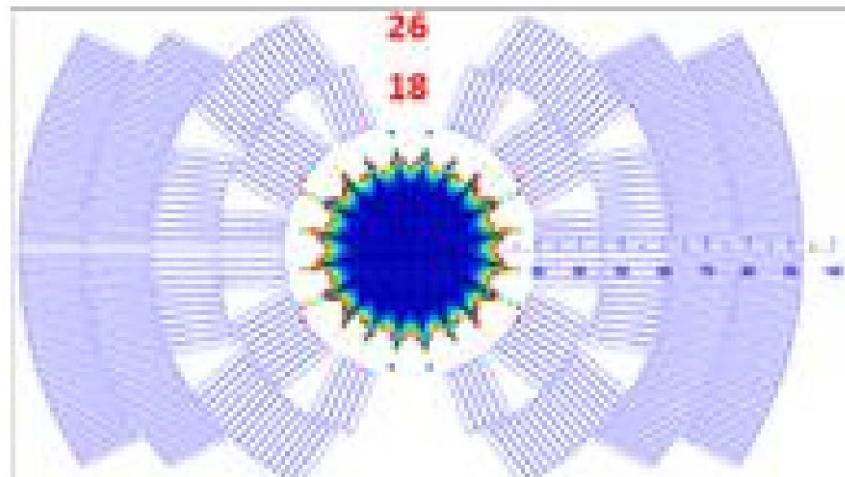
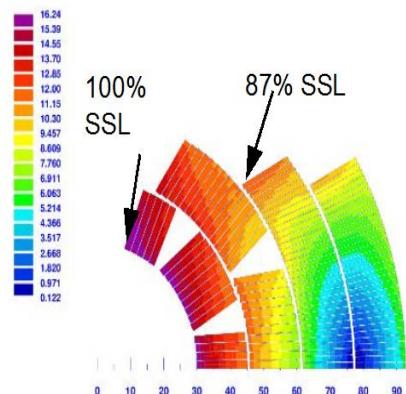
- Need new 1.3 TeV injector/beamlines
- x15 LHC radiation power /meter

Challenge #0: 16 T Magnets

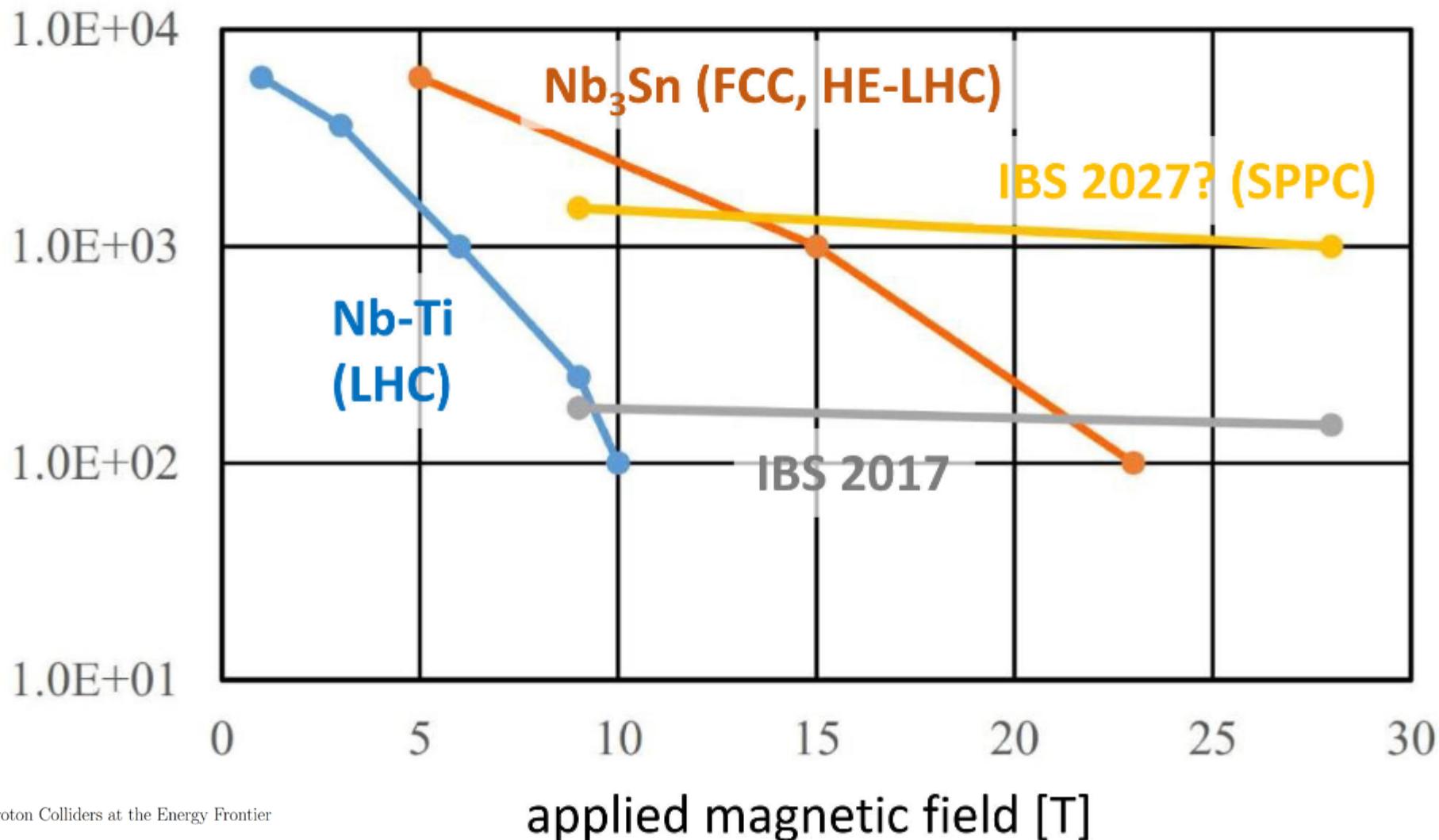
- The strongest field achieved in the accelerator type dipole is 13.7 T in **1997**, D20 (LBNL)
- Current status of the SCs
 - Nb₃Sn (still need ~20% increase in J_c to 1500 A/mm² at 4K, 16 T)
 - HTS (Bi-2212, REBCO, IBS) - \$\$\$
- Magnet Program at Fermilab
 - 11-12 T magnets are reality for HL-LHC
 - Working on 15T demo (~1m long)



G.Velev, et al.

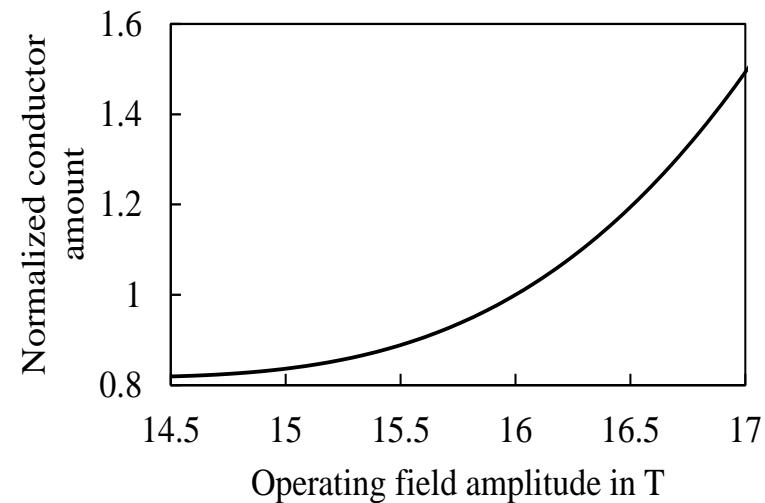


whole wire critical current density [A/mm², 4.2 K]

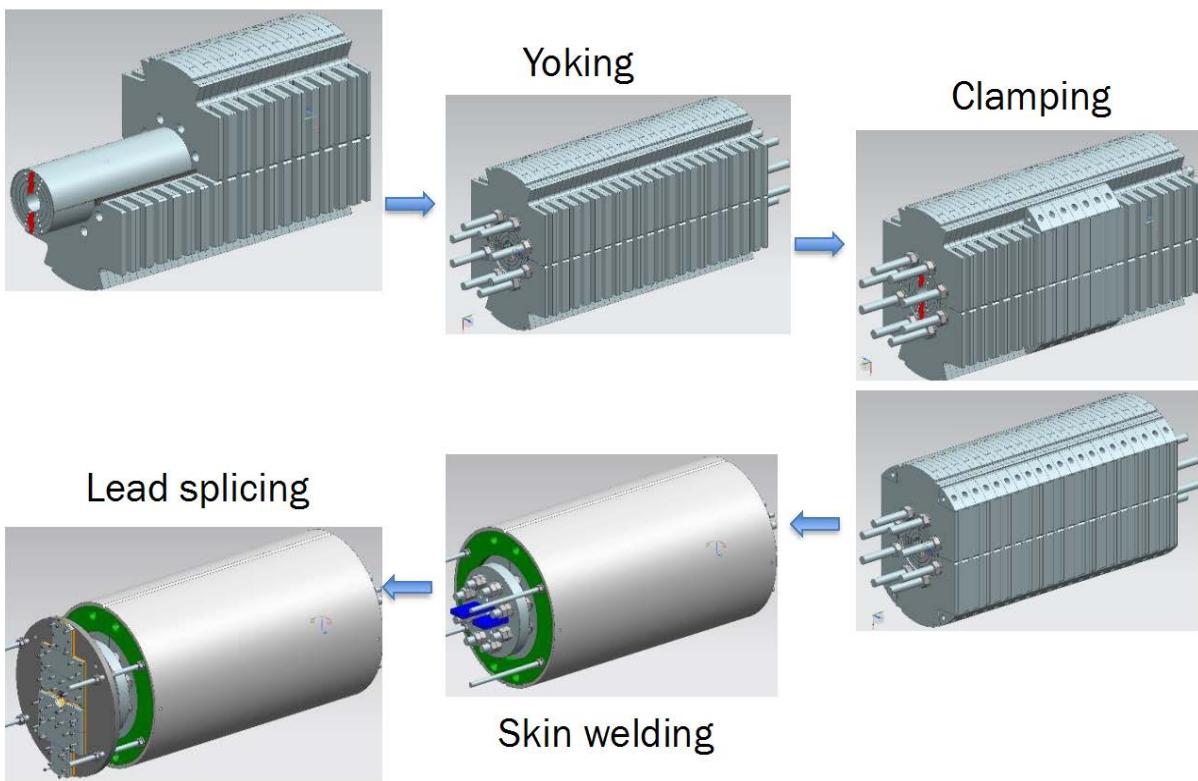


Superconductor Cost

- Today if we take NbTi (the accelerator “workhorse”) as a base = 1 unit cost
 - NB3Sn - 3 times more expensive
 - Bi-2212 - 100 times, 70% Ag matrix
 - REBCO ~ 80-90 more expensive, production technology limited
 - IBS - material are cheap, production technology cost unknown
- According to the present cost model the target cost for a 16 T magnet for HE-LHC built to the cos-θ design would be:
 - Conductor cost: 670 kEUR/magnet
 - Assembly cost: 600 kEUR/magnet
 - Parts cost: 420 kEUR/magnet
 - Total cost: 1690 kEUR/magnet
 - HE-LHC: 1232 dipoles (~2BEuro total),
FCC-hh: 4664 dipoles, (~8BEuro)
~16 T (15.71 T), aperture 50 mm,
Inter-beam distance 204 mm



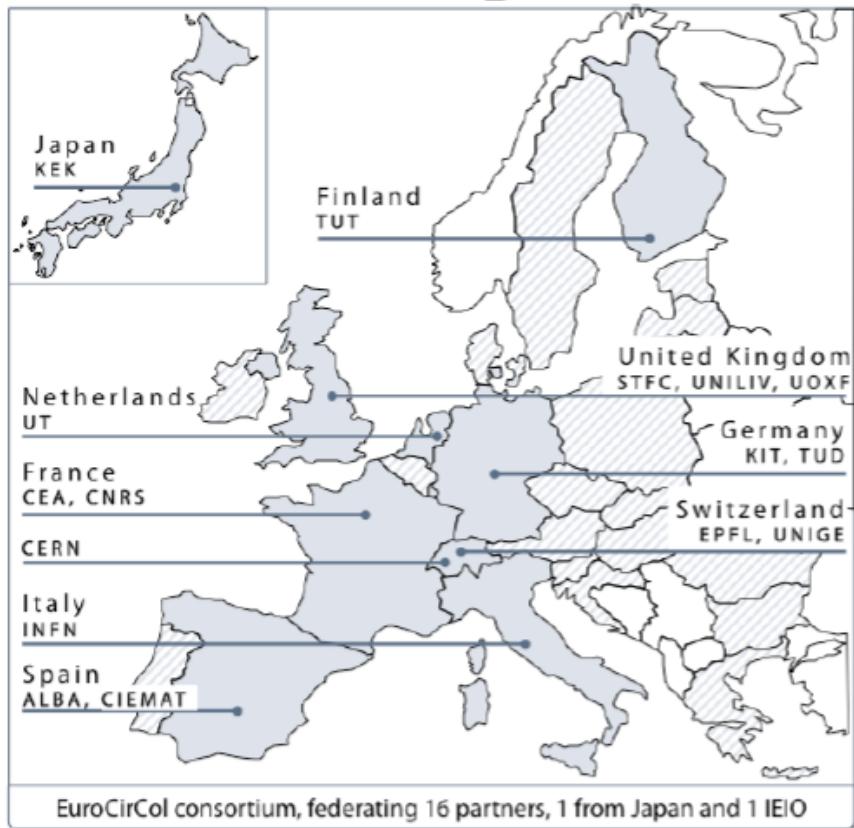
Fermilab's “15T Demonstrator” (Test in Sep'18)





EU H2020 DS 'EuroCirCol' on 16 T dipole & vacuum system design

UNIVERSITY OF TWENTE.



European Union
Horizon 2020
program

- Support for FCC
- 3 MEURO co-funding



TECHNISCHE
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Karlsruher Institut für Technologie



ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE



MANCHESTER
1824

F.Zimmermann

Scope: FCC-hh
(&HE-LHC) collider

- Optics Design
- Cryo vacuum system design
- 16 T dipole design, construction folder for demonstrator magnets

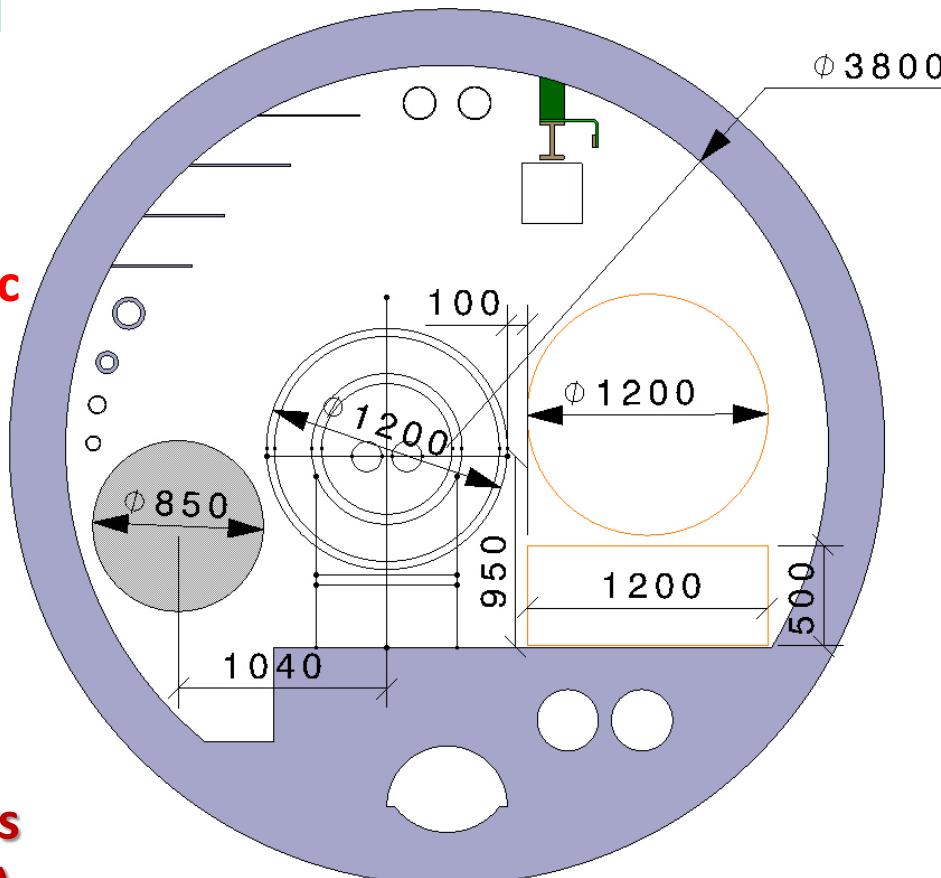
Extra challenge: Integrating HE-LHC in the LHC tunnel

tunnel diameter 3.8 m much smaller than FCC-hh's 5.5 m

use existing LHC tunnel
without tunnel
enlargement;
→ push for “compact”
16 T magnets (magnetic cryostats?)

QRL diameter: 850 mm
(LHC 750 mm), max.
outer magnet cryostat size: 1200-1250 mm

**Also, 15m long magnets
need saggita ~ 9 mm (!)**

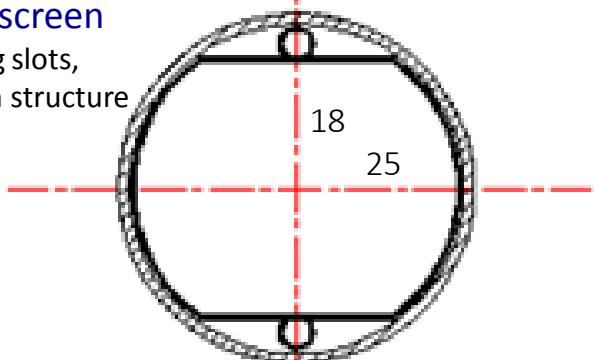


M. Benedikt
V. Mertens,
V. Parma,
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L. Tavian,
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F. Valchкова-
Georgieva,
V. Venturi,
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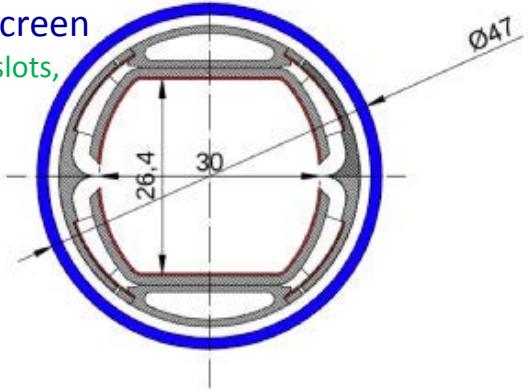
Challenge #1: Beampipe for 5W/m

arc beam-screen options

LHC beam screen
with pumping slots,
and sawtooth structure



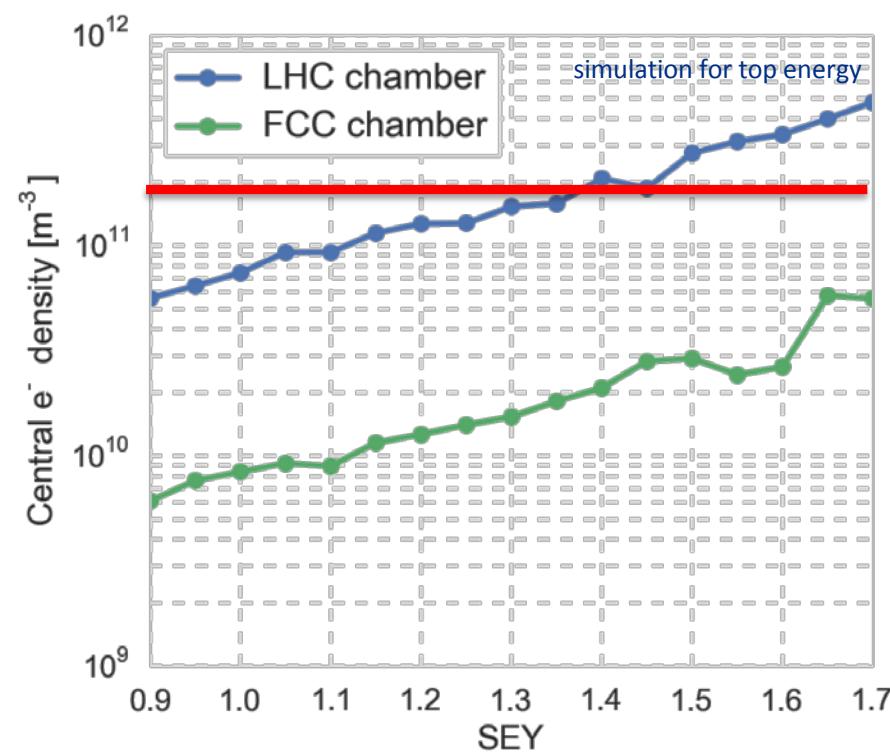
HE-LHC beam screen
shielded pumping slots,
less electron cloud



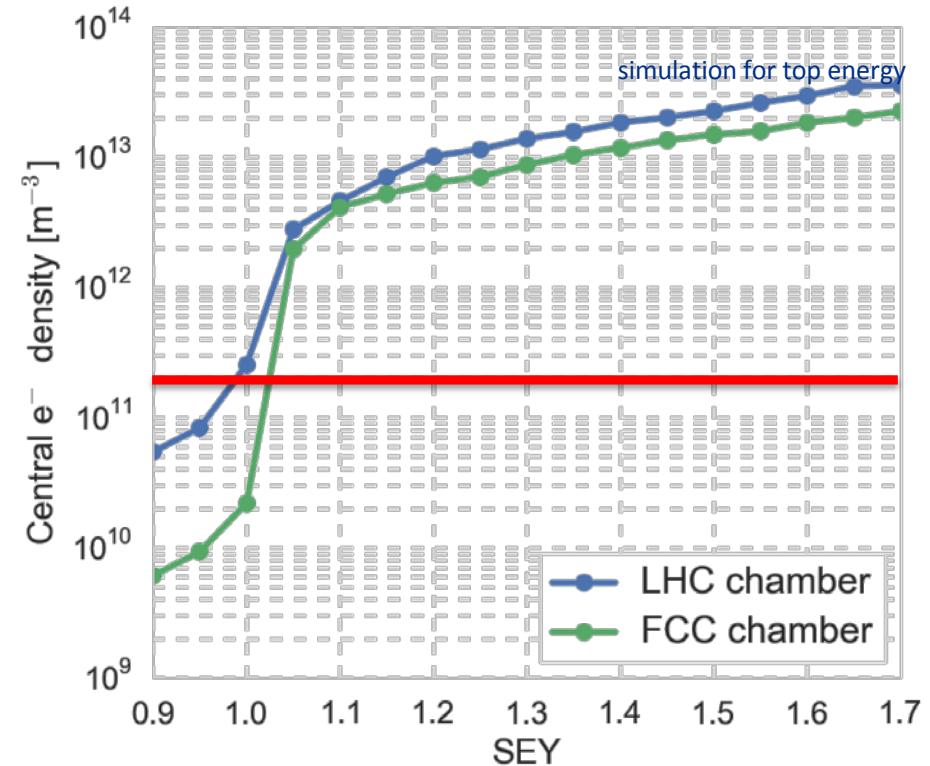
accelerator	450 GeV	1.3 TeV
LHC w LHC tolerances	$n_1 = 6.7$	-
HL-LHC w HL-LHC tol's	13.5	-
HE-LHC 24x60 degree	8.2	13.9
HE-LHC 18x60 degree	4.7	7.9

Related Issue: HE-LHC electron cloud

25 ns beam



5 ns beam

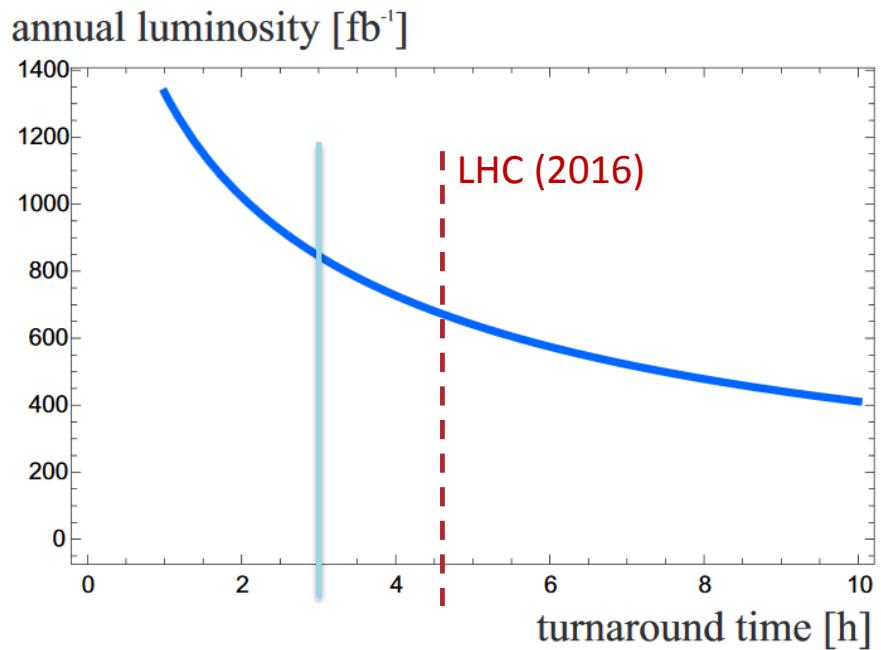
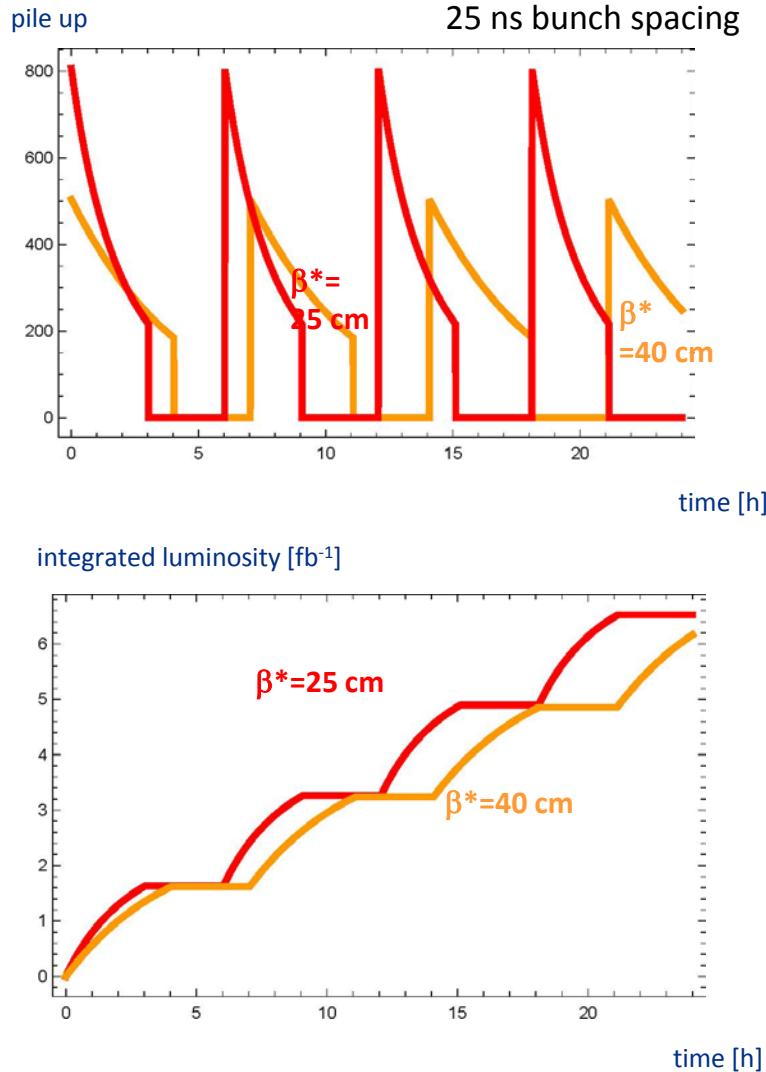


FCC type chamber efficient, 5 ns requires very low SEY

e-cloud inst. threshold		25 ns injection	5 ns injection
formula	$\rho_{e,\text{th}}(\text{m}^{-3})$	1.4×10^{11}	1.4×10^{11}
simulation with B	$\rho_{e,\text{th}}(\text{m}^{-3})$	3×10^{11}	$3-4 \times 10^{11}$
simulation wo B	$\rho_{e,\text{th}}(\text{m}^{-3})$	$1-2 \times 10^{11}$	$1-2 \times 10^{11}$

L. Mether,
K. Ohmi,
G. Guillermo
ab

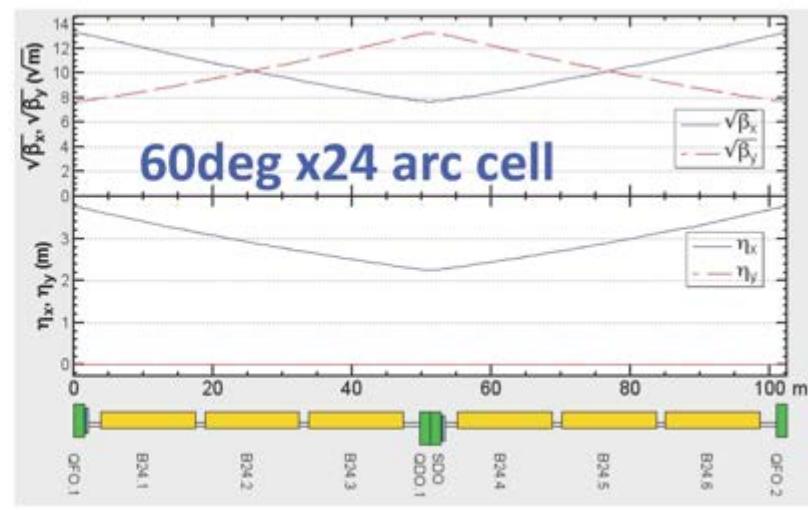
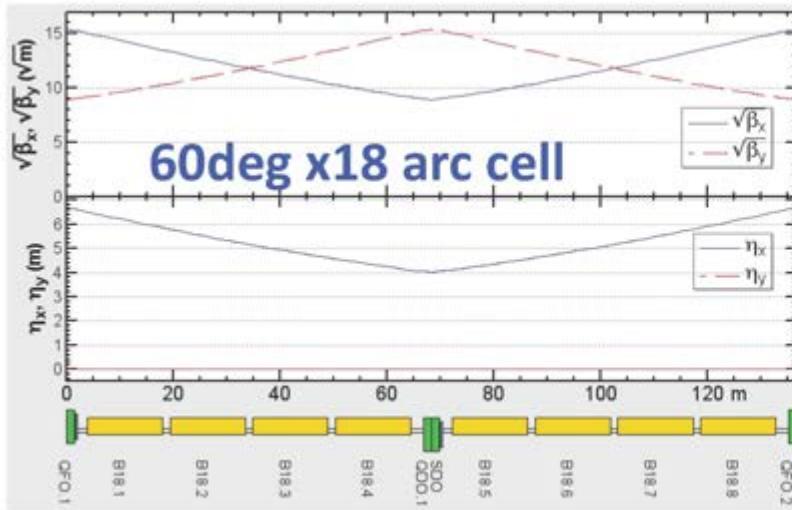
Challenge #2: 3 h Turnaround Time



with 160 days of physics,
70% availability, 3 h turnaround time

$\beta^* = 25 \text{ cm}: 820 \text{ fb}^{-1}/\text{year}$
 $\beta^* = 40 \text{ cm}: 700 \text{ fb}^{-1}/\text{year}$

#3: Optimization HE-LHC Focusing Optics



	24 x 60 deg	18 x 60 deg	20 x 90 deg
dipole length, m	13.56	14.1	12.39
number of dipoles	1280	1280	1424
dipole field, T	16.3	15.68	16.04
cell quad gradient, T/m	289.5	215.9	340.0
sextupole gradient*, T/m ²	2056.7	1102.7	3366.0

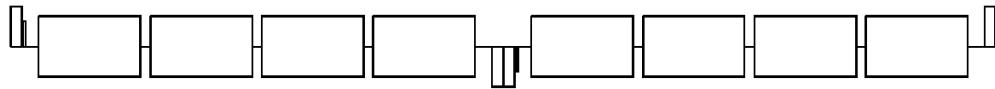
*sextupole strengths calculated for injection optics

Y. Nosochkov,
D. Zhou

~0.3 T margin for dipole field;
lowest quadrupole and sextupole
gradients

Optimal HE-LHC 18-cell 60 deg arc cell

- $L_{\text{cell}} = 136.594 \text{ m}$, eight 14.1 m long dipoles
- 28% higher beta and 3.3x higher dispersion compared to LHC

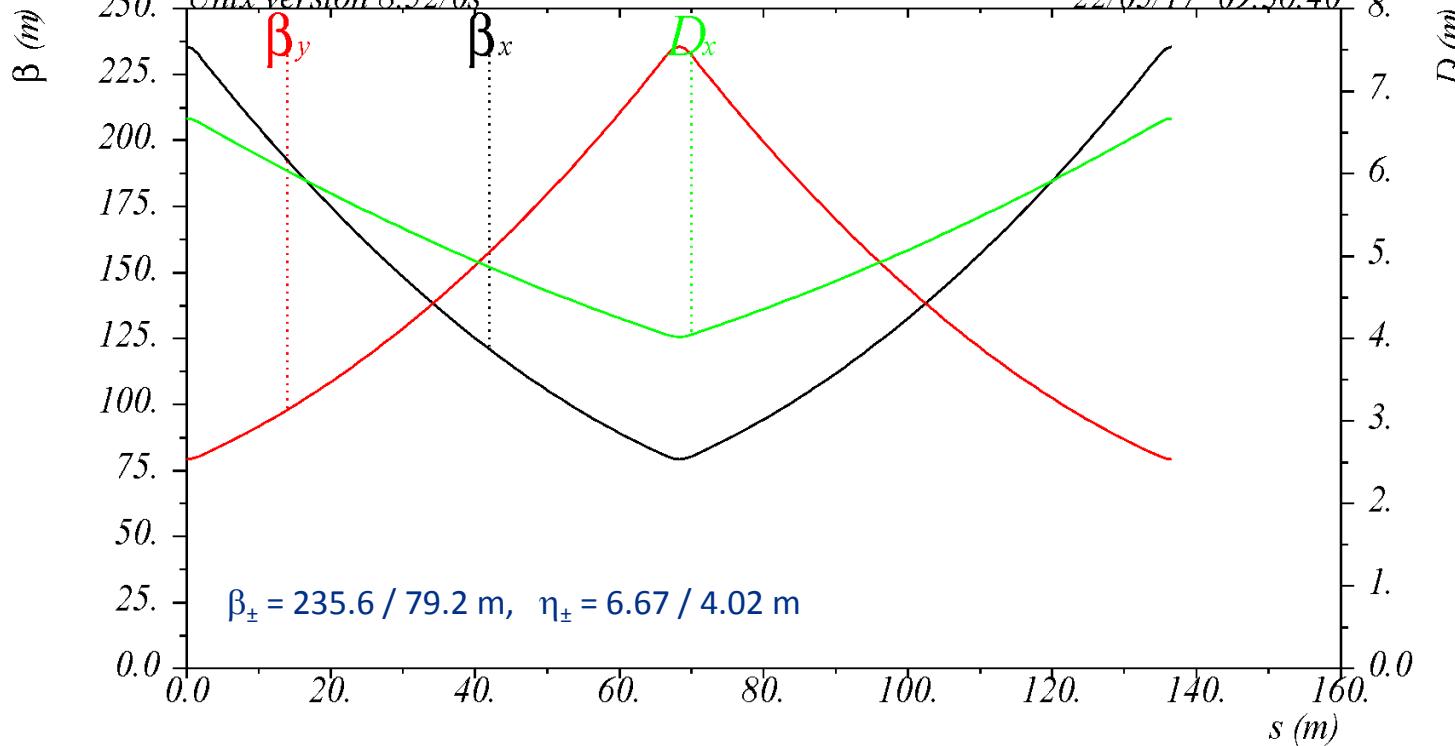


60 degree arc cell

HE-LHC 18-cell 60-degree injection lattice, v.100, $Q = [37.28, 39.31]$

Unix version 8.52/0s

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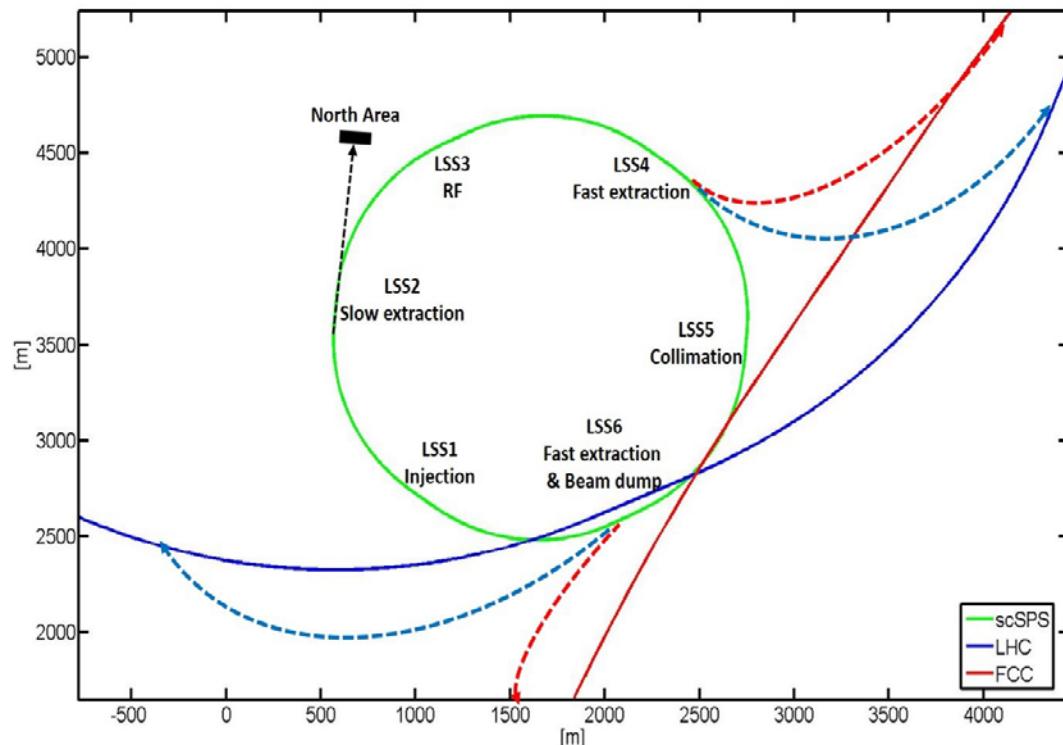


much enhanced dispersion → injection energy > 1 TeV

#4: scSPS as HE-LHC injector

- keep SPS geometry (6 LSS)
- replace SPS by new superconducting single aperture machine
- peak **magnetic field 6 T** → extract at 1.3 TeV - fast ramping
- scSPS energy swing ~50
- scSPS design as injector option for FCC-hh

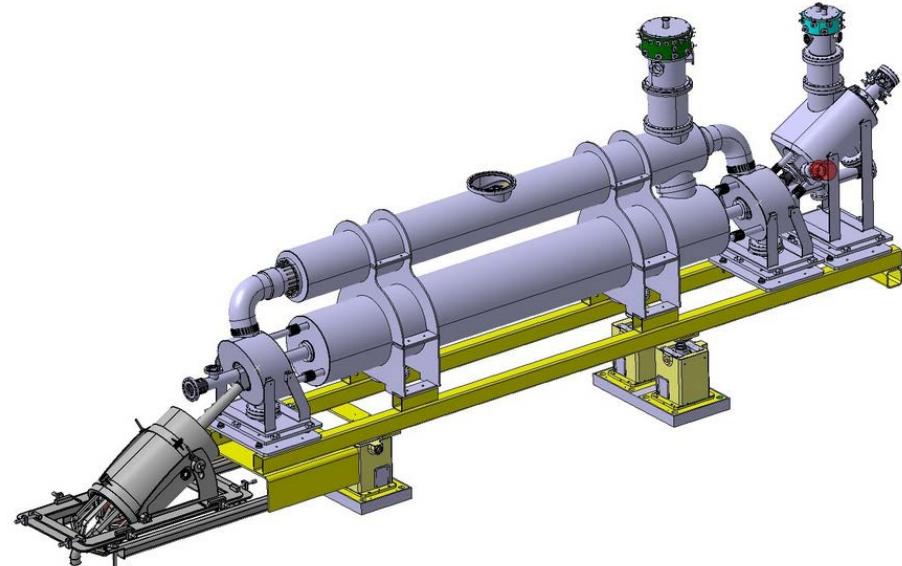
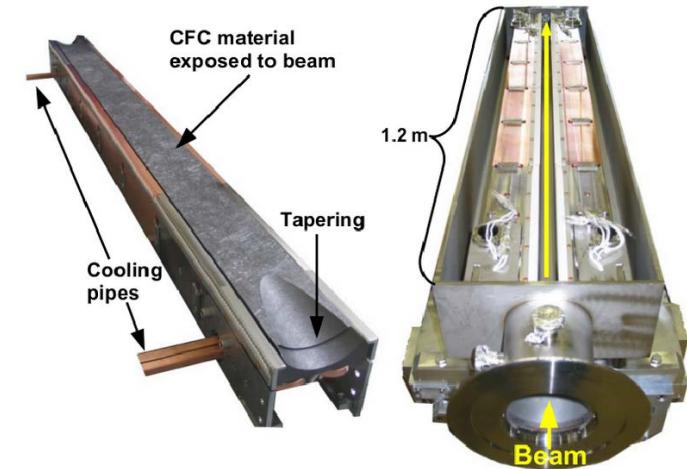
scSPS helps for HE-LHC optics,
physical & dynamic aperture,
impedance effects & extraction, ...



Parameter	Unit	Value
Injection energy	GeV	26
Extraction energy	GeV	1300
Maximum dipole field	T	6
Dipole field at injection	T	0.12
Number of dipoles		372
Number of quadrupoles		216
Ramp rate	T/s	0.35 - 0.5
Cycle length	min	1
Number of bunches per cycle		640
Number of injections into scSPS		8 (80b)
Number of protons per bunches		$\leq 2.5 \times 10^{11}$
Number of extraction per cycle		2 (2x320 b)
Number of cycles per FCC filling		34
FCC filling time	min	34 - 40
Max stored beam energy	MJ	33

#5: HE-LHC collimation challenge

- must fit into existing straights
→ scaling solution of FCC-hh
not applicable
→ reduced collimator gaps
- separation with NC magnets
requires too much space
→ shielded SC separation
dipoles
→ consider hollow e-lenses
(under study for HL-LHC)



Summary

- 27 TeV cme HE-LHC seems to be financially and technologically viable option for energy frontier pp collider
- Biggest uncertainty is the cost, field and quality of 16 T dipoles, focus of the growing int'l R&D effort:
 - 15-20% improvement in the Nb_3Sn conductor J_c is needed to reach the requirements for 16T dipole
 - Fermilab is assembling the first-in-the-world 15T demonstrator
 - Is 1.7MEuro/magnet real?
- Though there are beam physics and other accelerator technology issues, they 'll probably be addressed in the CDR
 - Injection energy and scSPS, beam screen design, beam optics, beam collimation, overall integration,

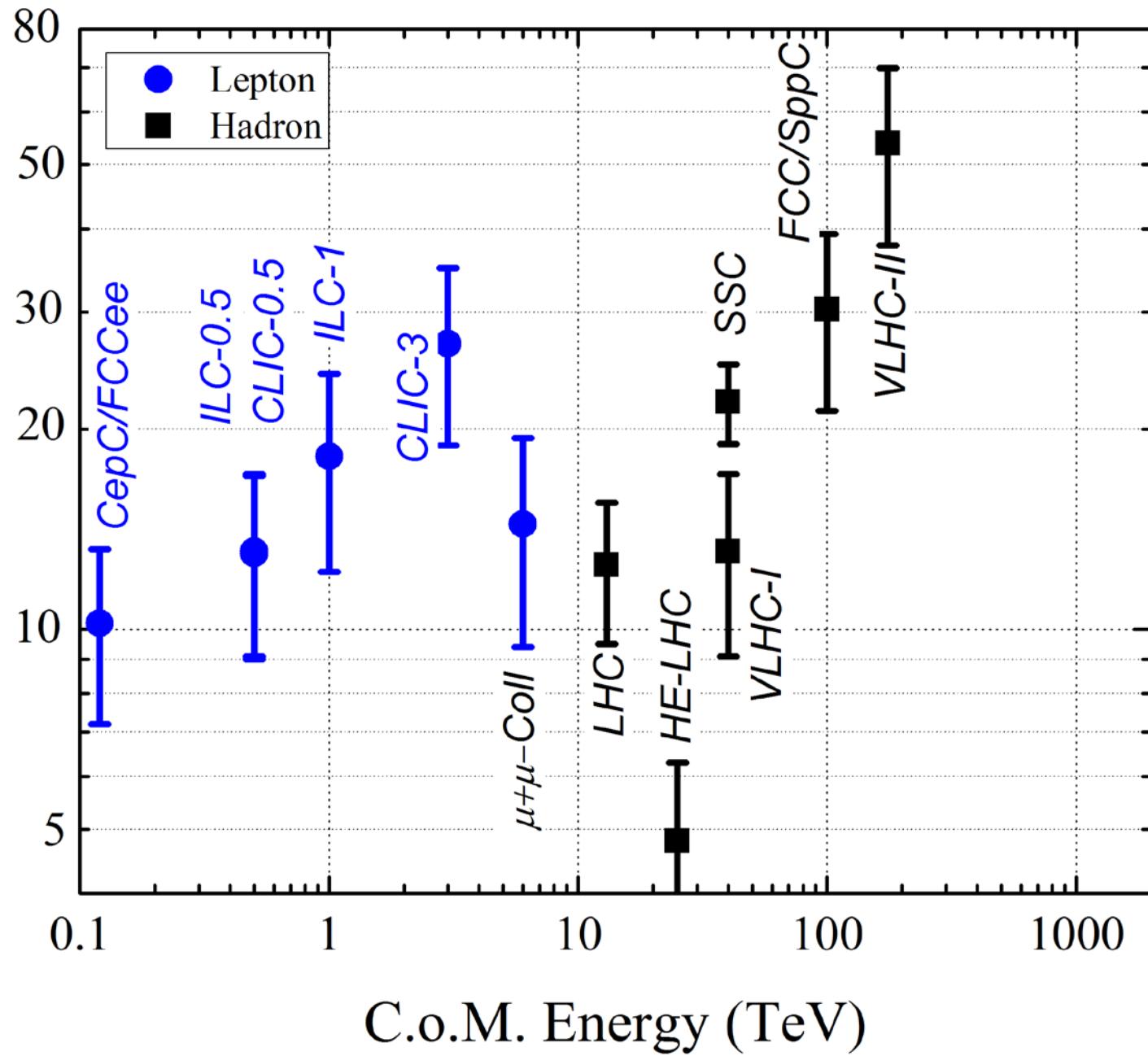
Thank You !





Back-Up Slides

Cost Estimate (2016 B\$ TPC)



! WARNING!

$\alpha\beta\gamma$ - Cost Estimate Model:

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

- a) $\pm 33\%$ estimate, for a “green field” accelerators
- b) “US-Accounting” = TPC ! ($\sim 2 \times$ European Accounting)
- c) Coefficients (units: 10 km for L , 1 TeV for E , 100 MW for P)
 - $\alpha \approx 2 \text{B\$}/\text{sqrt}(L/10 \text{ km})$
 - $\beta \approx 10 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for SC/NC RF
 - $\beta \approx 2 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for SC magnets
 - $\beta \approx 1 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for NC magnets
 - $\gamma \approx 2 \text{B\$}/\text{sqrt}(P/100 \text{ MW})$

USE AT YOUR OWN RISK!

Take LHC as an Example:

- **$\alpha\beta\gamma$ – 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\$

- ## • CERN LHC Factbook (2009)

- 6.5 BCHF, incl. **5 BCHF** for accelerator
(European Accounting)

– x 2 to US TPC → **10 BCHF=10B\$**

Cost of existing injector complex
~30-40% **3-4 B\$**

TPC : ~13-14B\$

(of which CERN paid 10 over ~8 yrs)

