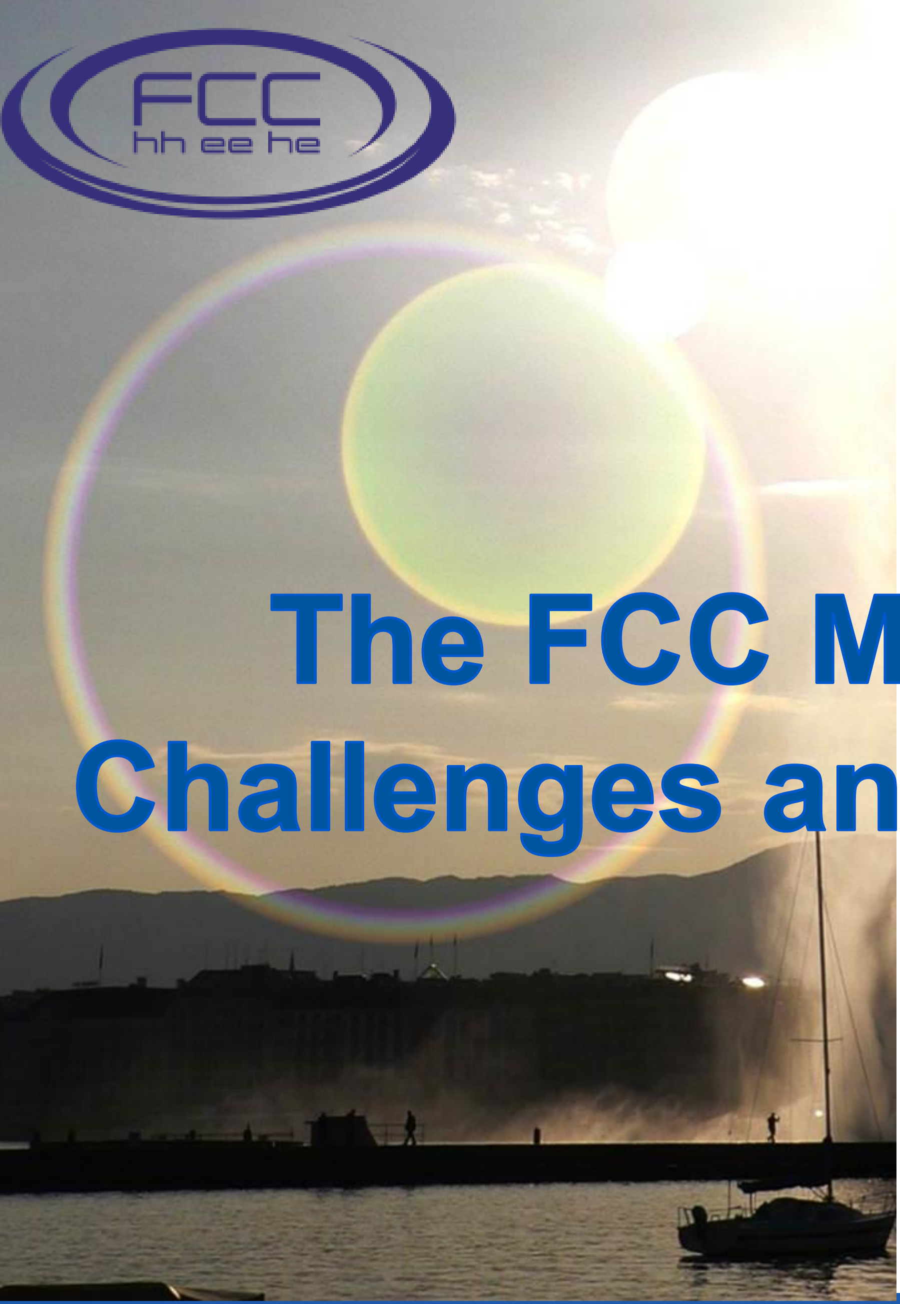

FCC hh ee he

1st Workshop on Accelerator Magnets in HTS
Hamburg 21-23 May 2014

EuCARD²   - Future - - Magnets -   WAM

The FCC Magnet Program: Challenges and Opportunities for HTS

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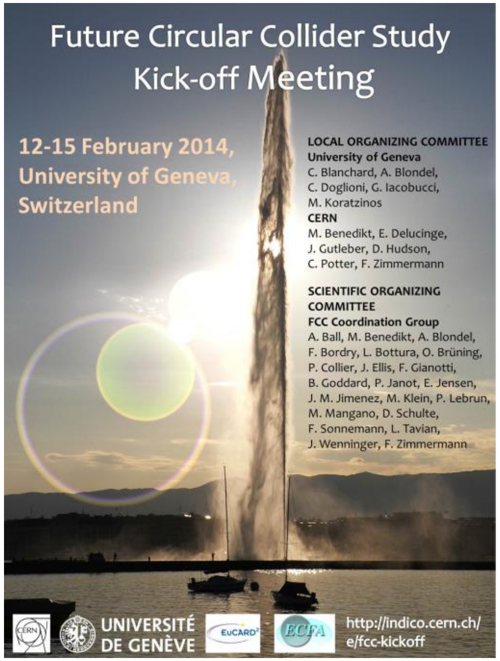
CERN

Outline

- The Future Circular Collider Design Study (NOTE: a full presentation will be given by M. Benedikt later in the workshop)
- Demands and challenges
- Opportunities

What is the FCC ?

- The *Future Circular Collider* is a ***Design Study*** that CERN has launched in February 2014 to respond to the request from the EU Strategy Group on Particle Physics:



"to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update **(NOTE: to take place in 2018)**

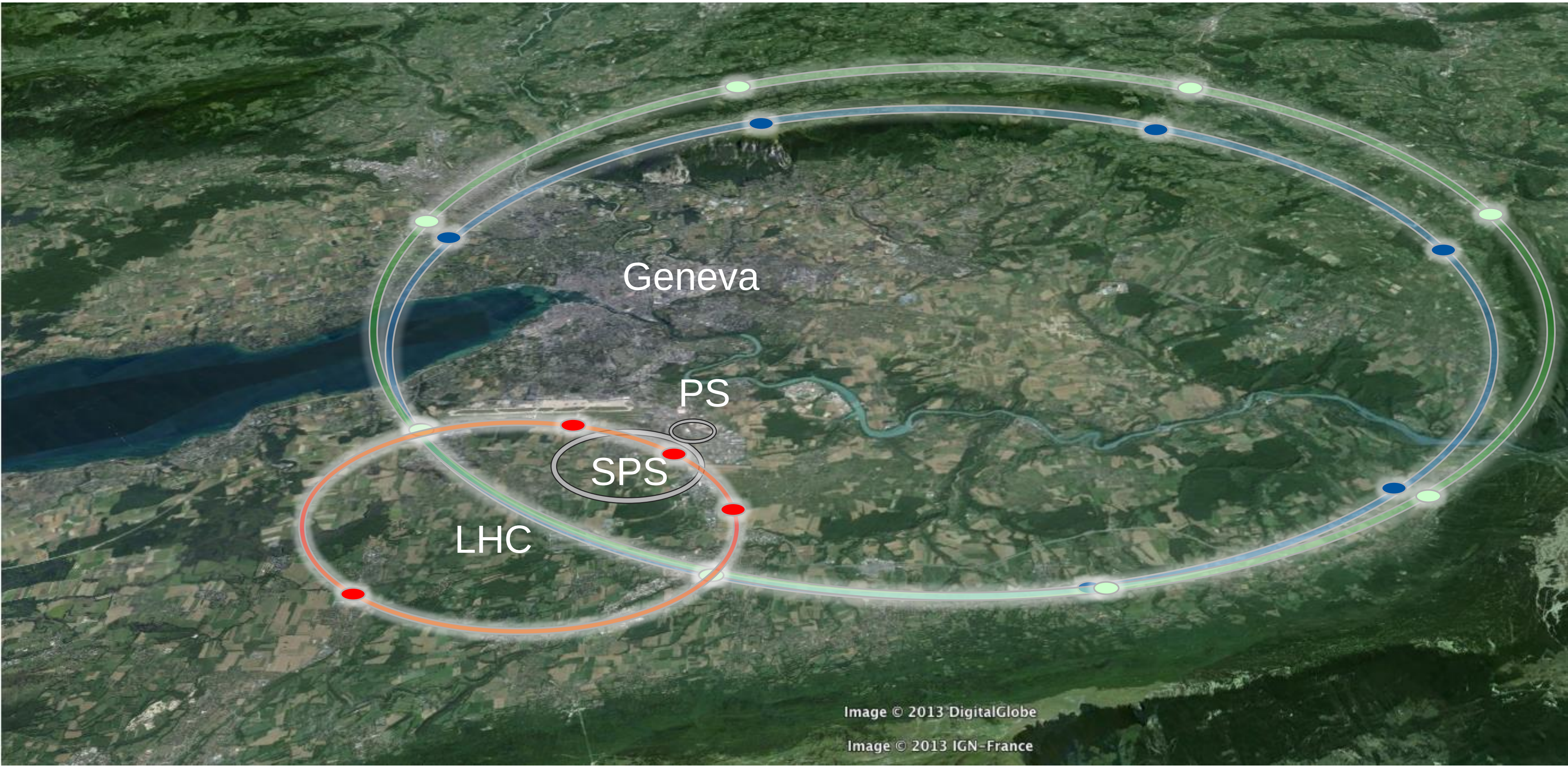
…

d) CERN should undertake design studies for accelerator projects in a global context,

…

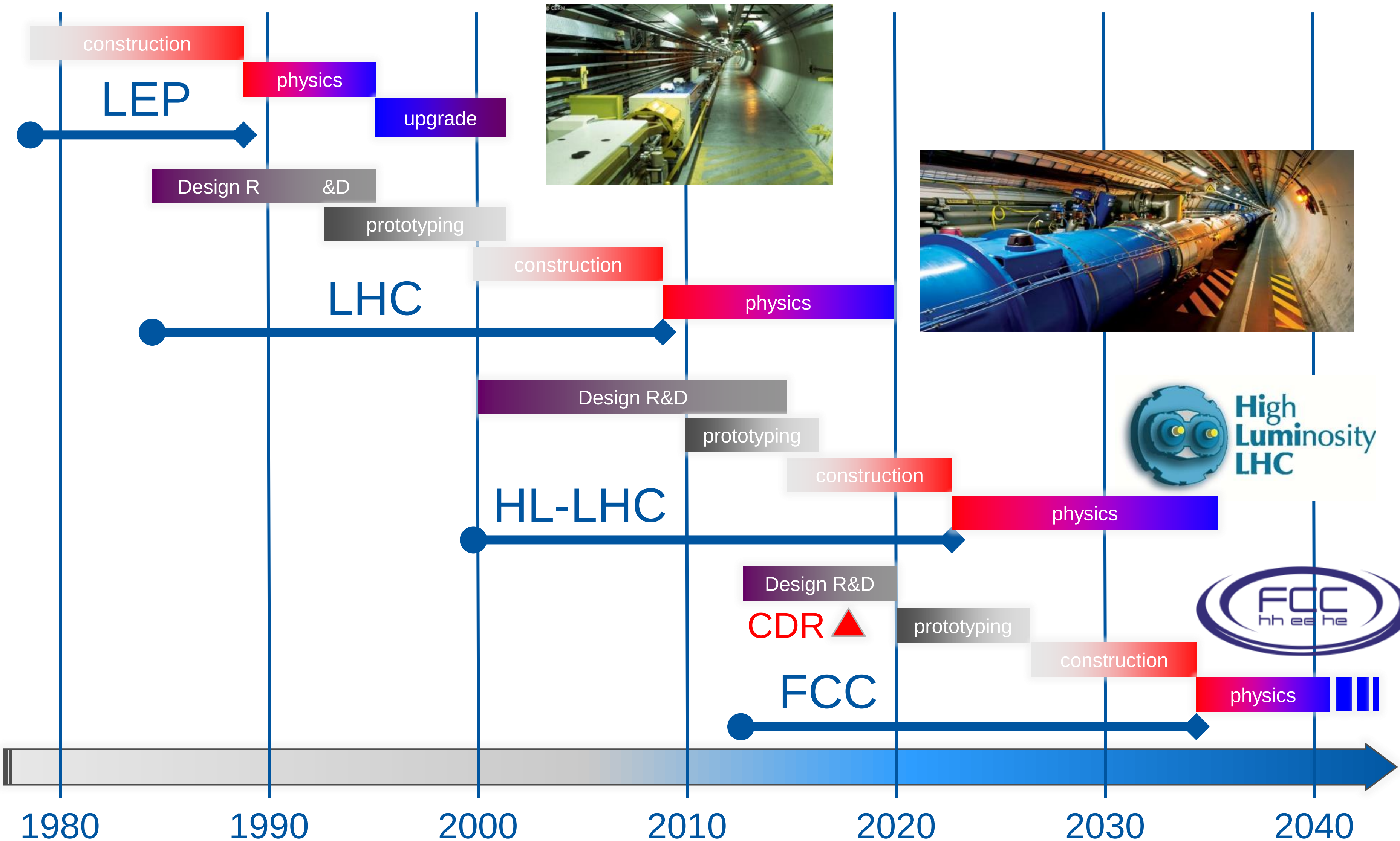
*with emphasis on **proton-proton** and electron-positron **high-energy frontier machines**. These design studies should be coupled to a **vigorous accelerator R&D programme, including high-field magnets** and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

Some possible FCC-hh *geometries*

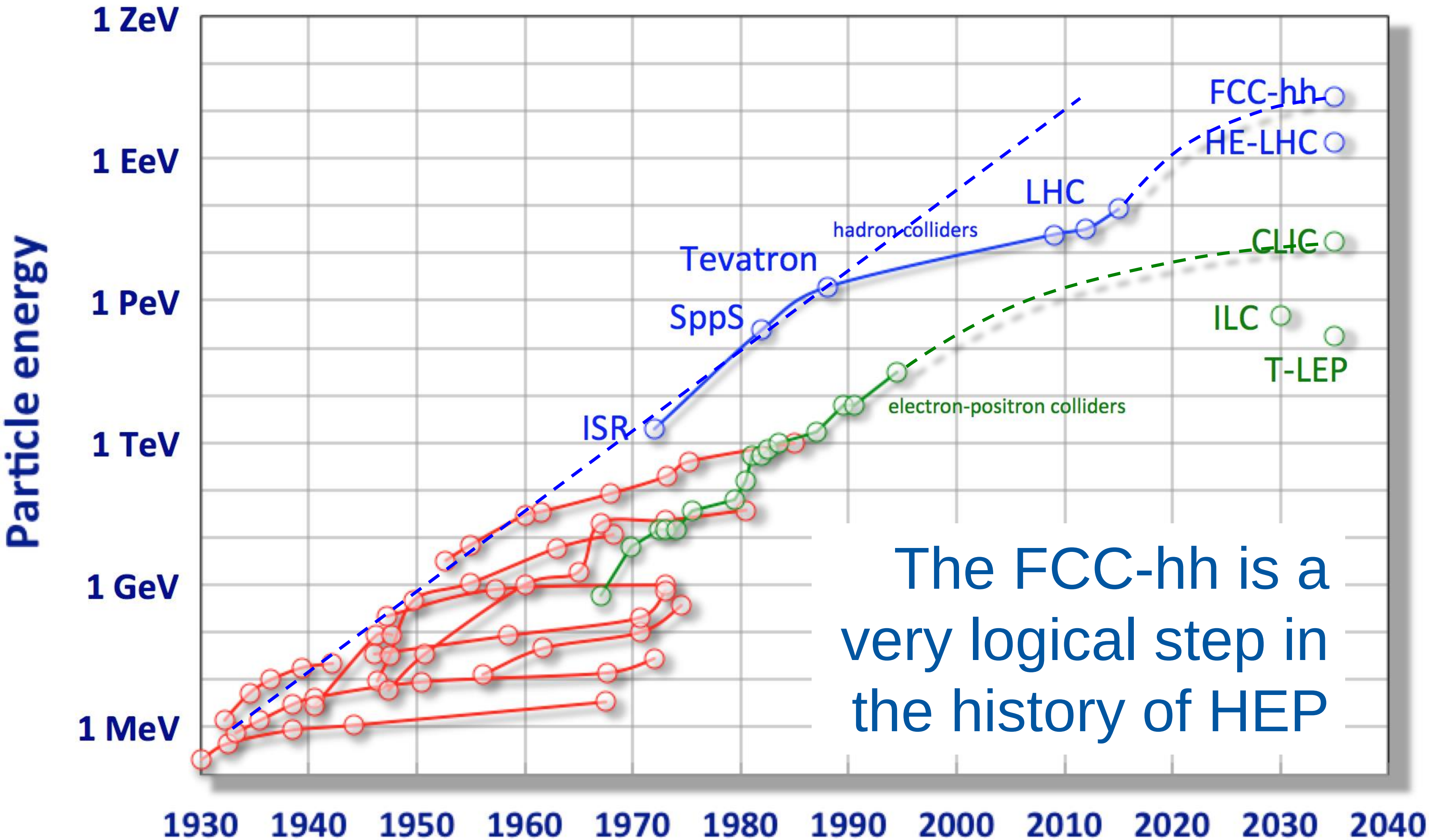


LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)

A *possible* timeline (for an FCC @ CERN)



The FCC in the Livingston plot



The FCC-hh is a very logical step in the history of HEP

Scope of the FCC magnet design

- FCC-hh main ring
  - FODO cell: dipoles (MB) and quadrupoles (MQ)
  - Interaction Region: dipoles (Dx) and quadrupoles (QX)
  - Other insertions, matching sections, etc.
- FCC-hh injector
  - Option 1 - FCC booster: use the existing CERN injector complex (maximum 450 GeV), accelerate and inject in the collider (3 TeV desirable)
  - Option 2 - FCC injector complex: use either the SPS or LHC tunnels to build a new injector for the FCC collider
- FCC-ee and FCC-eh (trivial ?)

NOTE: in red where I think that HTS has opportunities

Remember: two simple recipes

- Dipoles

Beam energy — Bending radius — Dipole field

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

  - Achieve the largest feasible and economic B to reduce the accelerator radius

- Quadrupoles

Beam *size* — Emittance — Lorentz factor

$$\sigma = \sqrt{\frac{\beta\varepsilon}{\gamma}}$$

Beta function — FODO cell length

$$\beta[m] \approx 3.4L[m]$$

Integrated quadrupole gradient

$$G\ell_q[T] = \frac{\sqrt{2}E[GeV]}{0.3L[m]}$$

  - Achieve the largest feasible integrated gradient to reduce the magnet bore size

FCC magnet catalog – LTS option

		B / G (T) / (T/m)	B_{peak} (T)	dB/dt (mT/s)	Bore (mm)	Length (units x m)
FCC	MB	**16**	**16.8**	16	40	**4578** x 14.3
	MQ	375	10	10	40	762 x 6.6
	QX	200	12.5	12.5	90	Optics ?
	D1	12	13	13	60	4x2 x 12
	D2	10	10.5	10.5	60	4x3 x 10
Booster in the FCC	MB	1.1	2	2	50	**4578** x 14.3
injector in the LHC	MB	5	5.25	20	50	1232 x 14.3
injector in the SPS	MB	12	12.5	100	50	892 x 4.7

FCC magnet catalog – HTS option

		B / G (T) / (T/m)	B_{peak} (T)	dB/dt (mT/s)	Bore (mm)	Length (units x m)
FCC	MB	**20**	**21**	16	40	**3662** x 14.3
	MQ	375	10	10	40	610 x 6.6
	QX	200	12.5	12.5	90	Optics ?
	D1	12	13	13	60	4x2 x 12
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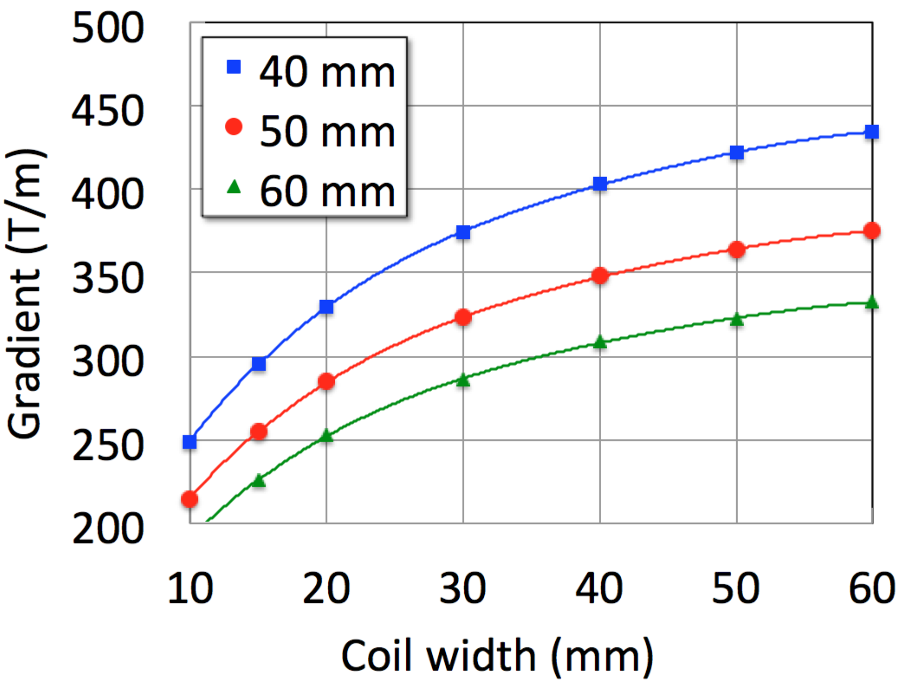
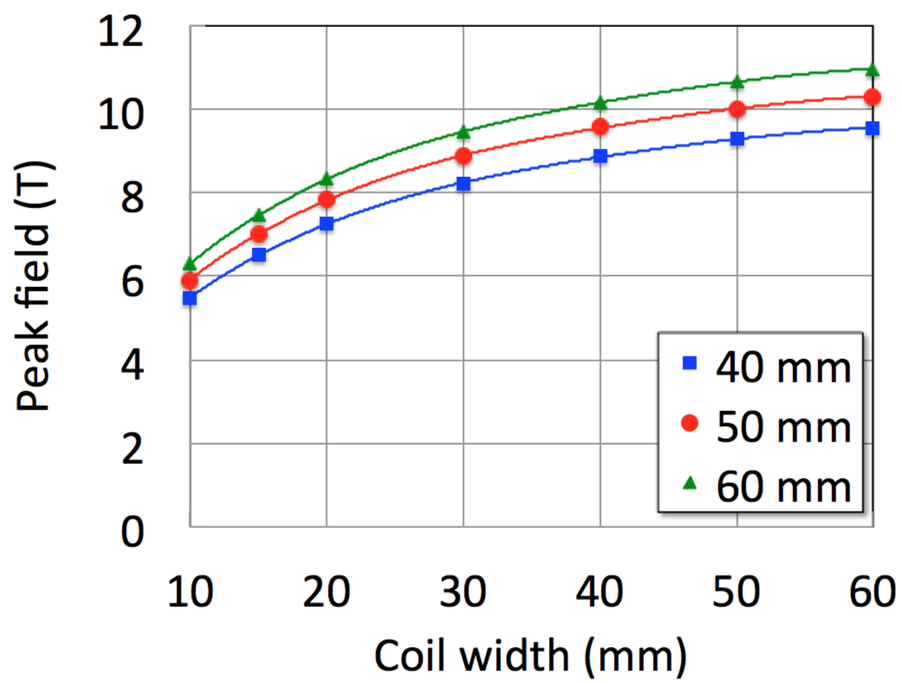
NOTE: in red where HTS has opportunities

Quadrupoles, a different “race”

Retraced from: E. Todesco, L. Rossi, PRSTAB 9 102401 (2006)





Adding more conductor the gain in gradient saturates. The peak field only increases marginally, **and remains in the range of 10 T**

At reasonable J_E (400-600 A/mm^2) the space is not enough to pack sufficient conductor close to the bore

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Some of the major FCC challenges

- Field levels (16 to 20 T)
  - How-to (materials, margin, cables, …)
  - Forces and stresses
  - Protection

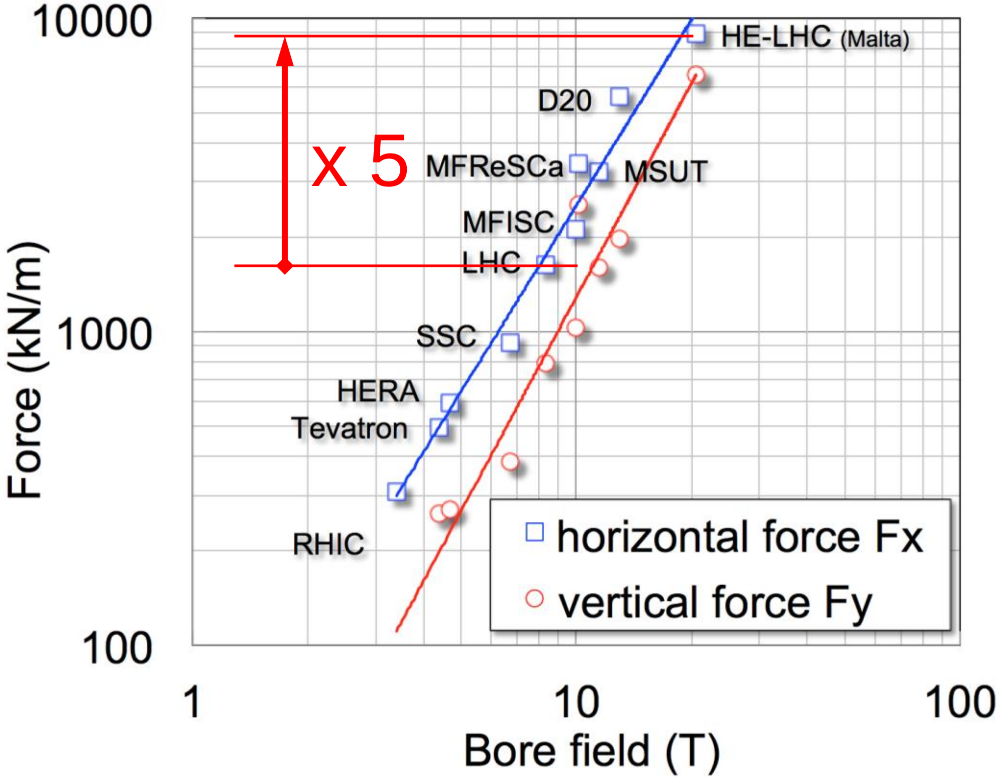
- Scale and cost
  - Very large number of magnets
  - Material quantities

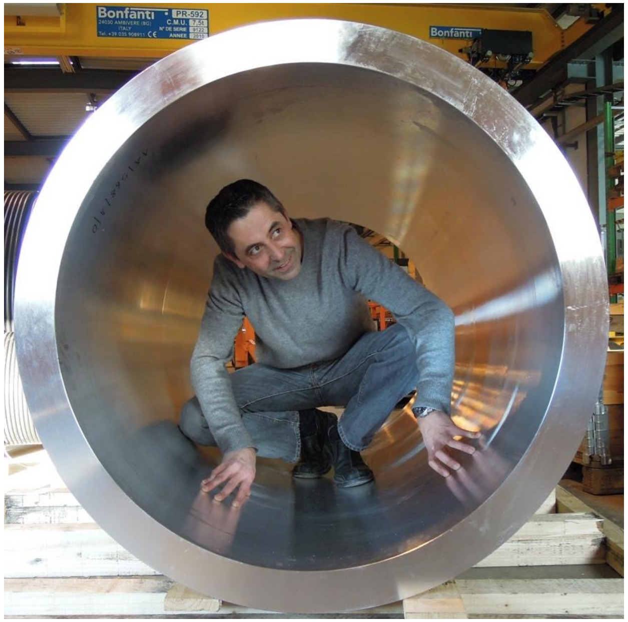
- Electrical consumption

Forces (and mechanics)

- The electromagnetic loads in a 20 T dipole would be a factor 5 to 8 larger than in the LHC dipoles

Scaling of force on coil quadrant in recent production and R&D dipoles

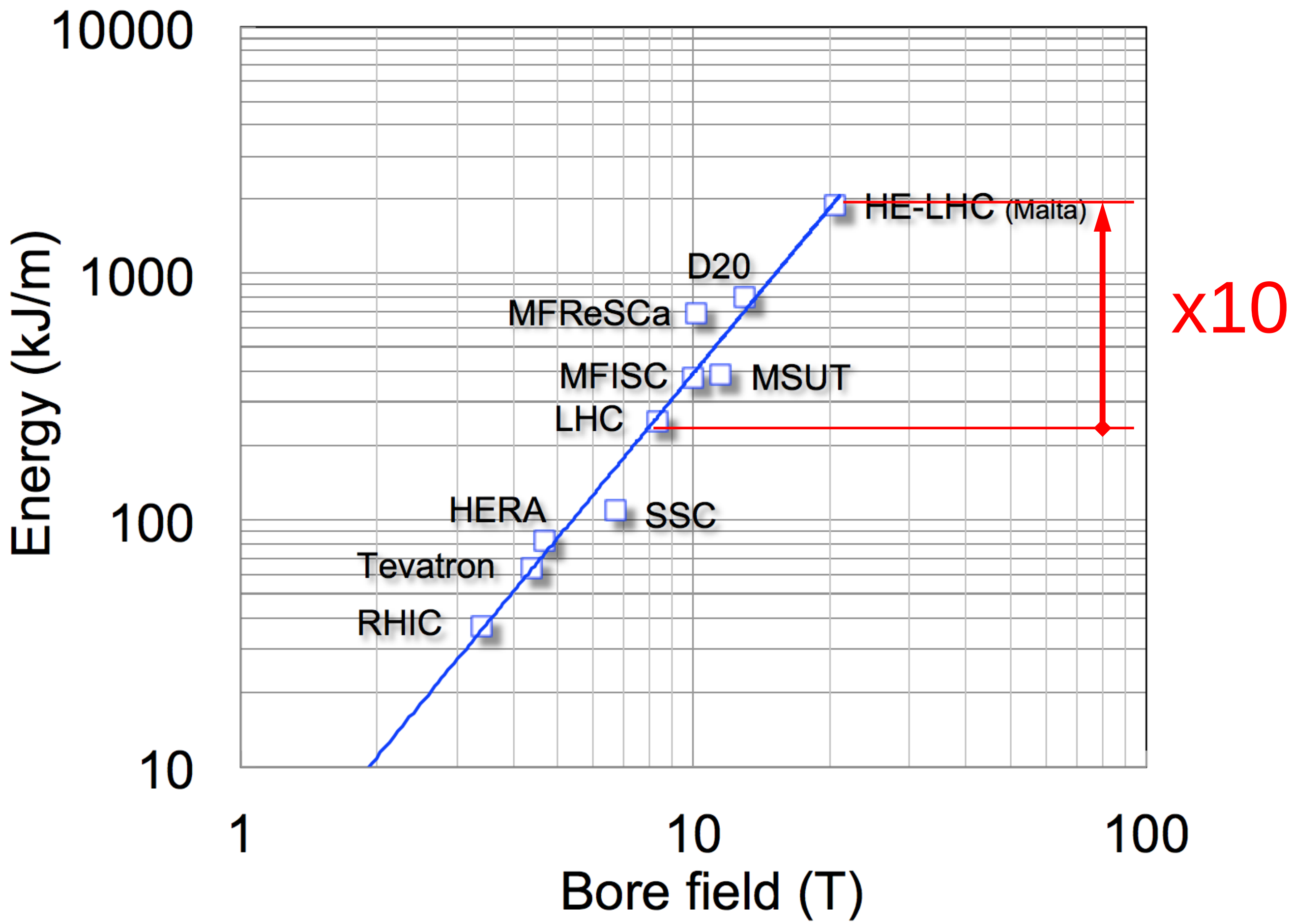




The supporting shell for a 15T-class magnet, with apologies to J.-C. Perez, CERN

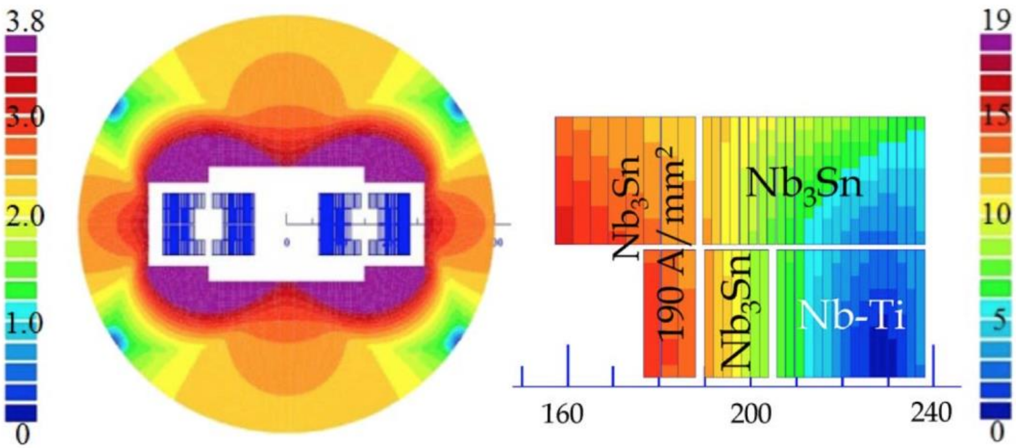
Magnet protection ?!?

Scaling of the energy per unit length of magnet
in recent production and R&D dipoles



Scales and quantities

From: E. Todesco, IEEE TAS, 24(3), 2014, 4004306

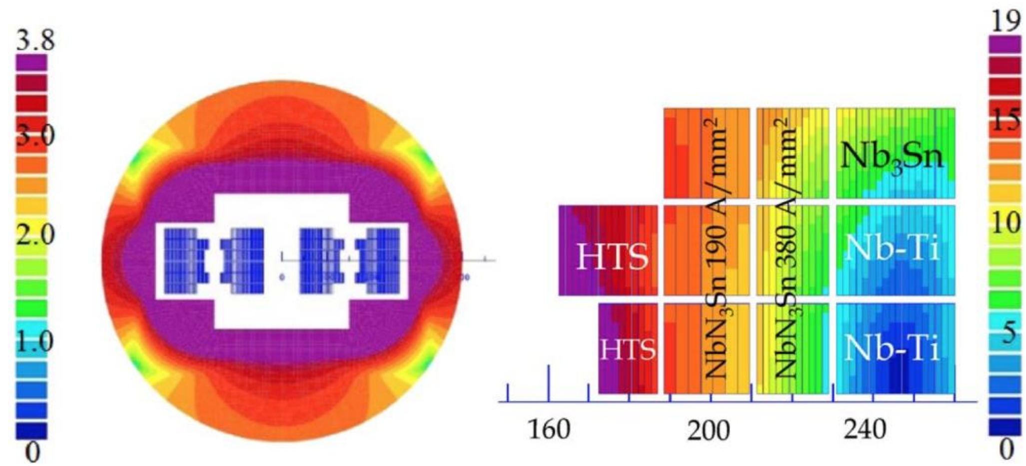


15 T “Snowmass” design
4578 units (+ 160 spares)

1000 tons of LHC-grade Nb-Ti
3500 tons of HEP-grade Nb_3Sn

20 T “Malta revised” design
3662 units (+ 120 spares)

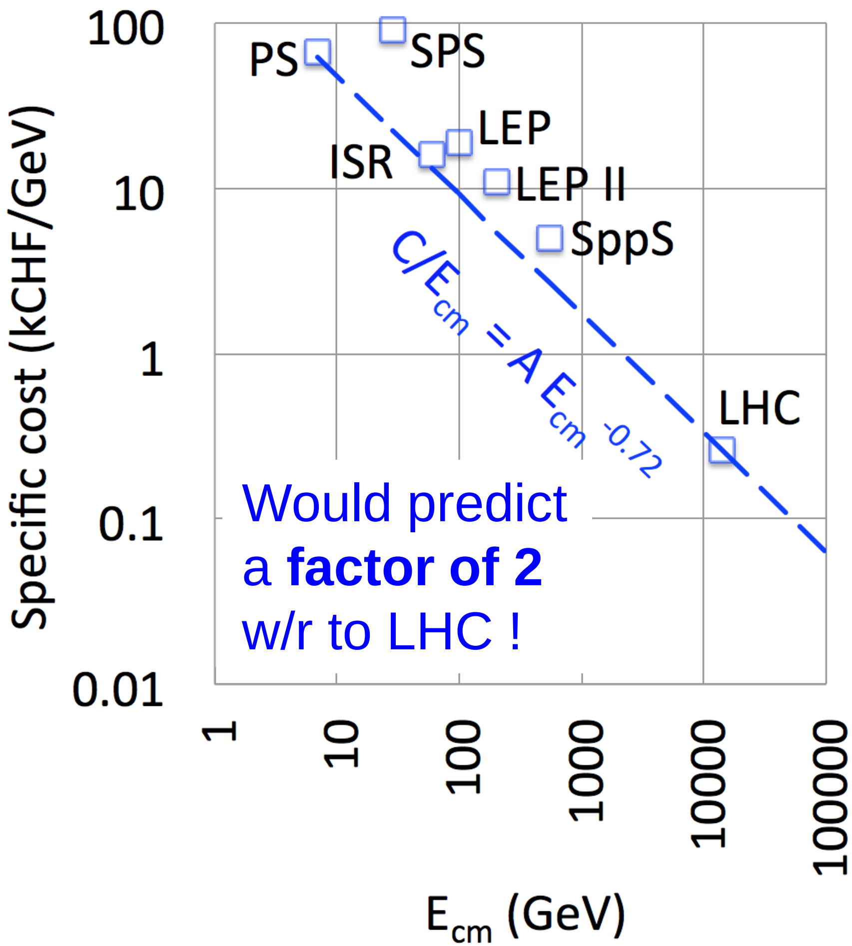
1000 tons of LHC-grade Nb-Ti
3000 tons of HEP-grade Nb_3Sn
750 tons of HTS



We are not talking about cost – Still…

- The FCC-hh would be a machine 3 times as long as the LHC
- Historically, the specific cost of accelerator magnet systems has dropped substantially
- Can the favorable specific cost reduction be achieved by
  - Production scale effect ?
  - **Technology innovation ?**

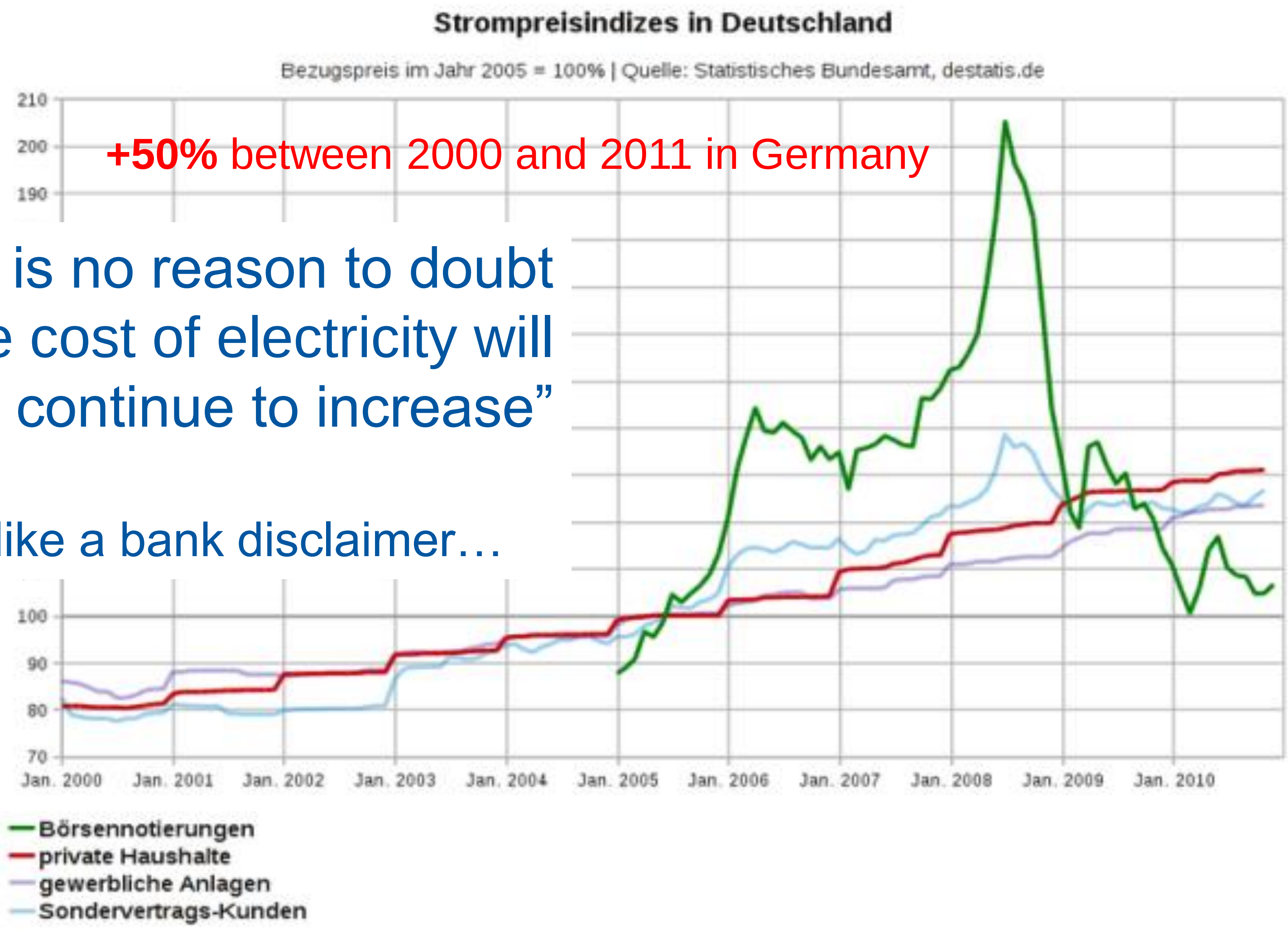
Retraced from original plot by Ph. Lebrun, CERN



NOTE: in red where HTS has opportunities

Can HTS ever be as cheap (or expensive) as Nb_3Sn ?

Electricity prices

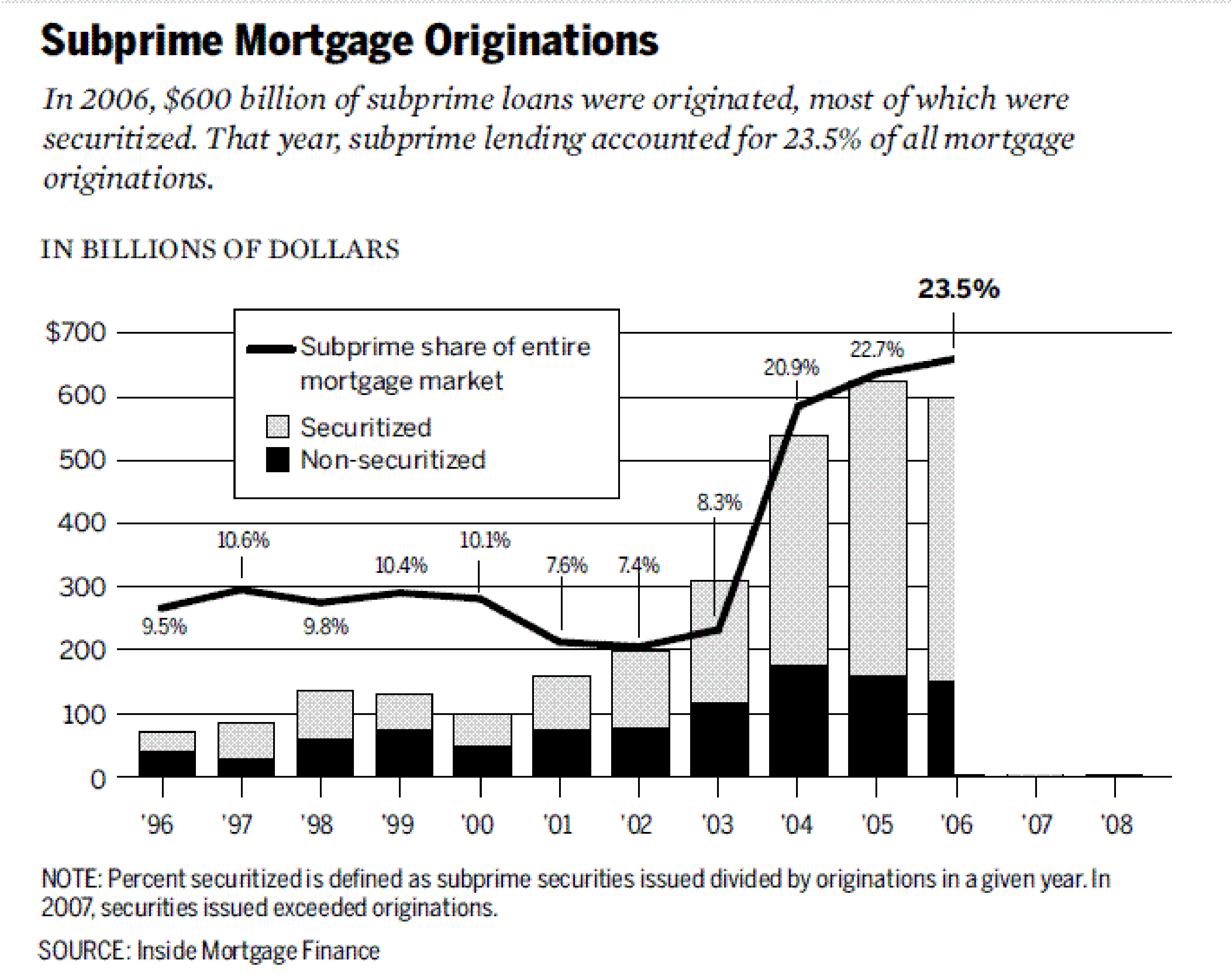


+50% between 2000 and 2011 in Germany

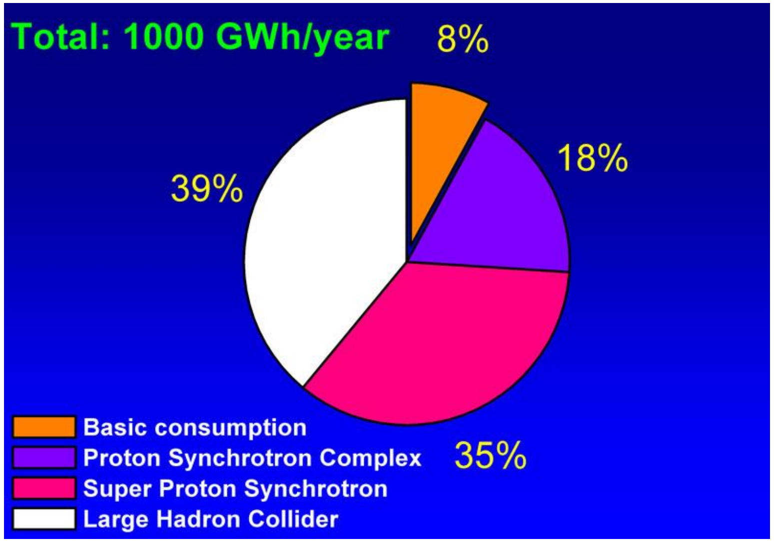
"There is no reason to doubt that the cost of electricity will continue to increase"

Sounds like a bank disclaimer…

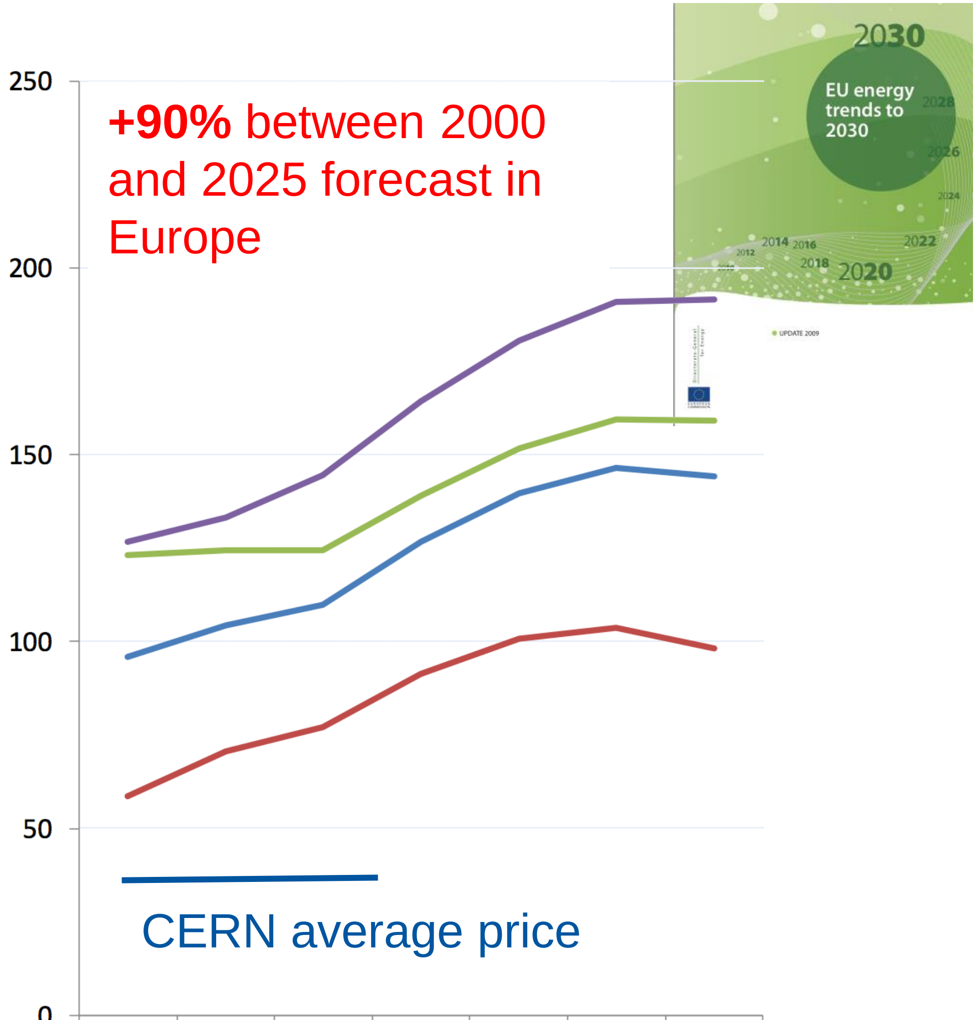
I would not count on this…



At CERN…

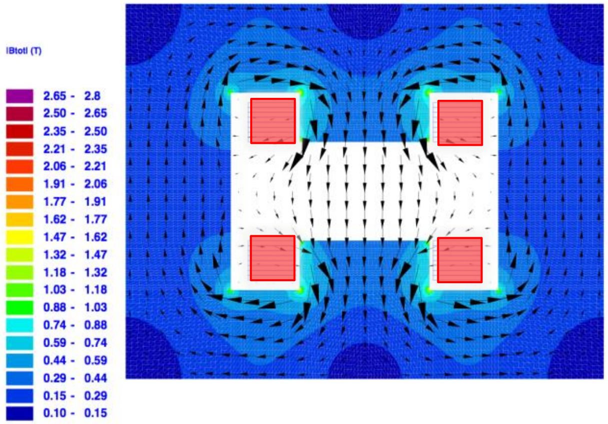


- CERN has an average use of the order of 150 MW and an annual consumption of 1000 GWh

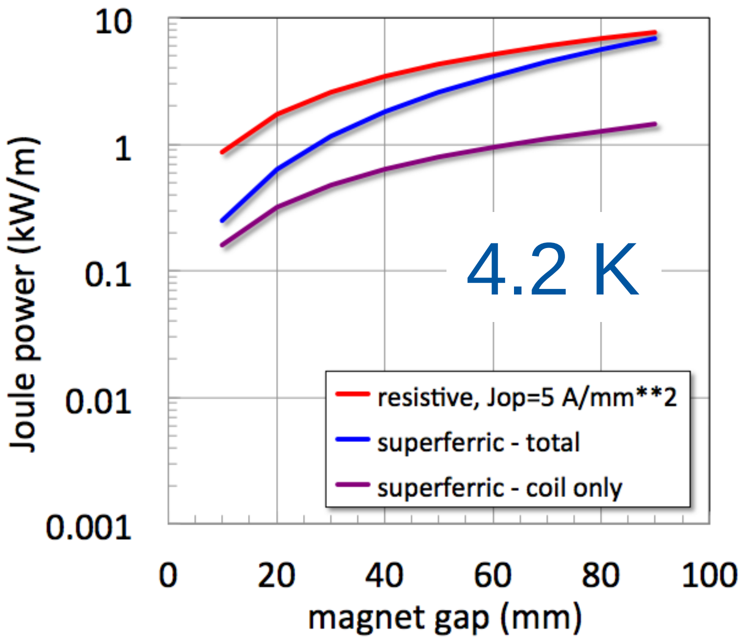


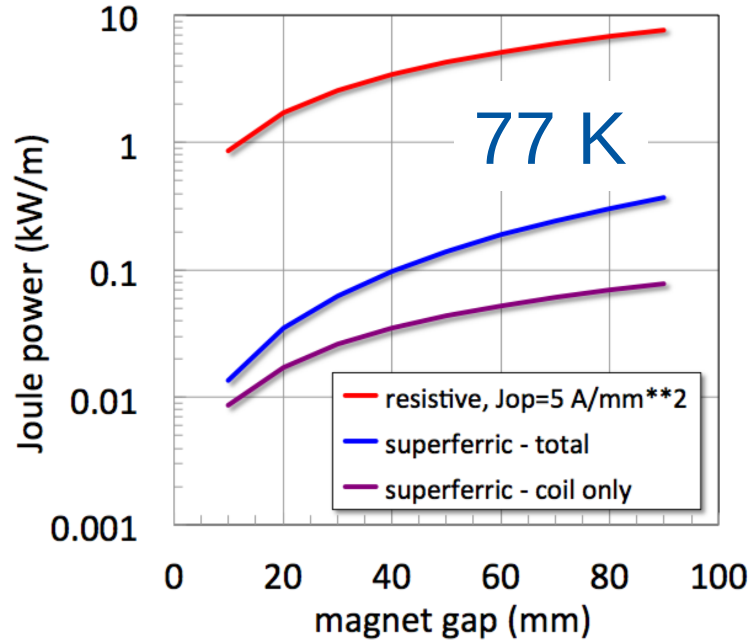
	2000	2005	2010	2015	2020	2025	2030
Average	96	104	110	127	140	146	144
Industry	59	71	77	92	101	104	98
Services	123	124	124	139	152	159	159
Households	127	133	144	164	180	191	192

Trade-off with resistive magnets

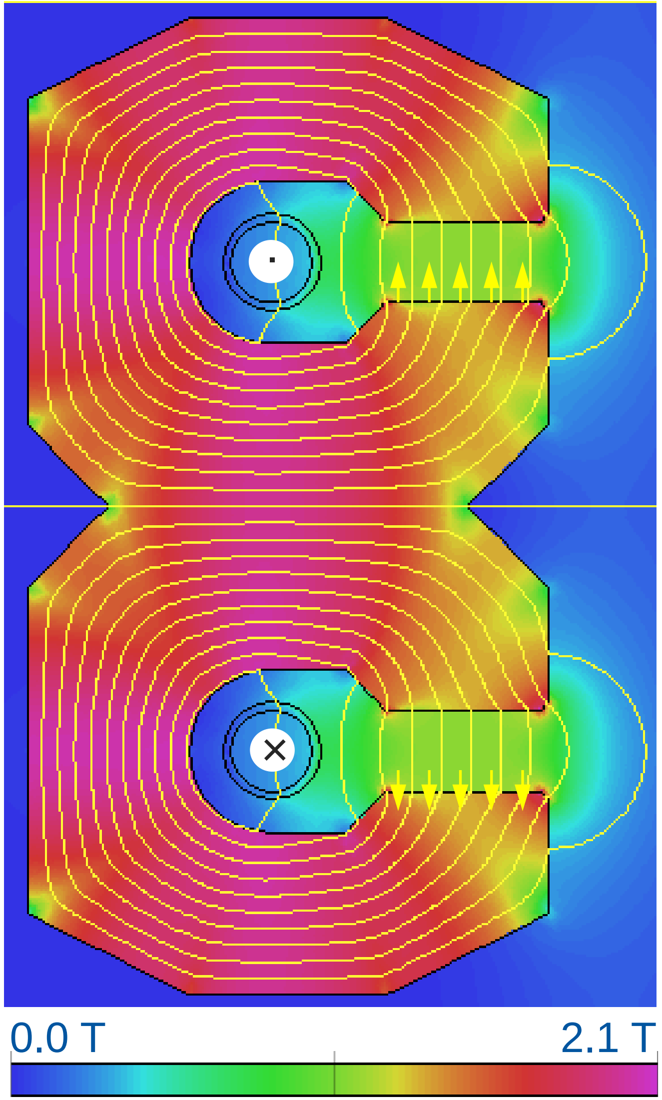


A superconducting magnet will be competitive if we achieve a wall-plug power per unit magnet length *much below* 2…4 kW/m





HEB magnets in a 100 km tunnel



- **HTS, transmission line,** iron dominated, superferric, 2-in-1 dipole
- Tentative parameters:
  - vertical full gap 50 mm
  - good field region ±20 mm
  - overall diameter of “super-cable”, including cryostat, 100 mm
- 50 kA-turns for 1.1 T (3.4 TeV)
- At low current, the apertures could be used in bipolar operation as a lepton booster

Study by A. Milanese, IPAC 2014

A summary

- HTS for field (MB)
  - Attain o(20) T, reducing length and civil engineering in the main dipoles, and providing ad-hoc solutions for specific regions (e.g. function similar to the LHC 11 T Nb_3Sn dipole). Only HTS can do this
- HTS for operating margin (D1)
  - The FCC IR and collimator regions will be a “hell of a place”, with particles and energies never experienced before. Radiation tolerance, heat removal and temperature margin will be paramount to reliable operation. HTS can do this
- HTS for low consumption (booster/injector)
  - The FCC injector complex requires high energy efficiency to maintain the installed power at a reasonable level (e.g. the LHC SPS uses today o(50) MW). HTS at 20…77 K is a good candidate for this
- HTS for power transmission
  - The scale of the accelerator requires high-current lines over km lengths. HTS, combined with advances in cryogenic distribution, would be the ideal solution

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