# How to shape the future of high-energy physics – Part 3: Accelerator

Frank Zimmermann

CERN Academic Training, 3 November 2021

# high energy particle accelerators

G. Hoffstaetter

*then ~1930*

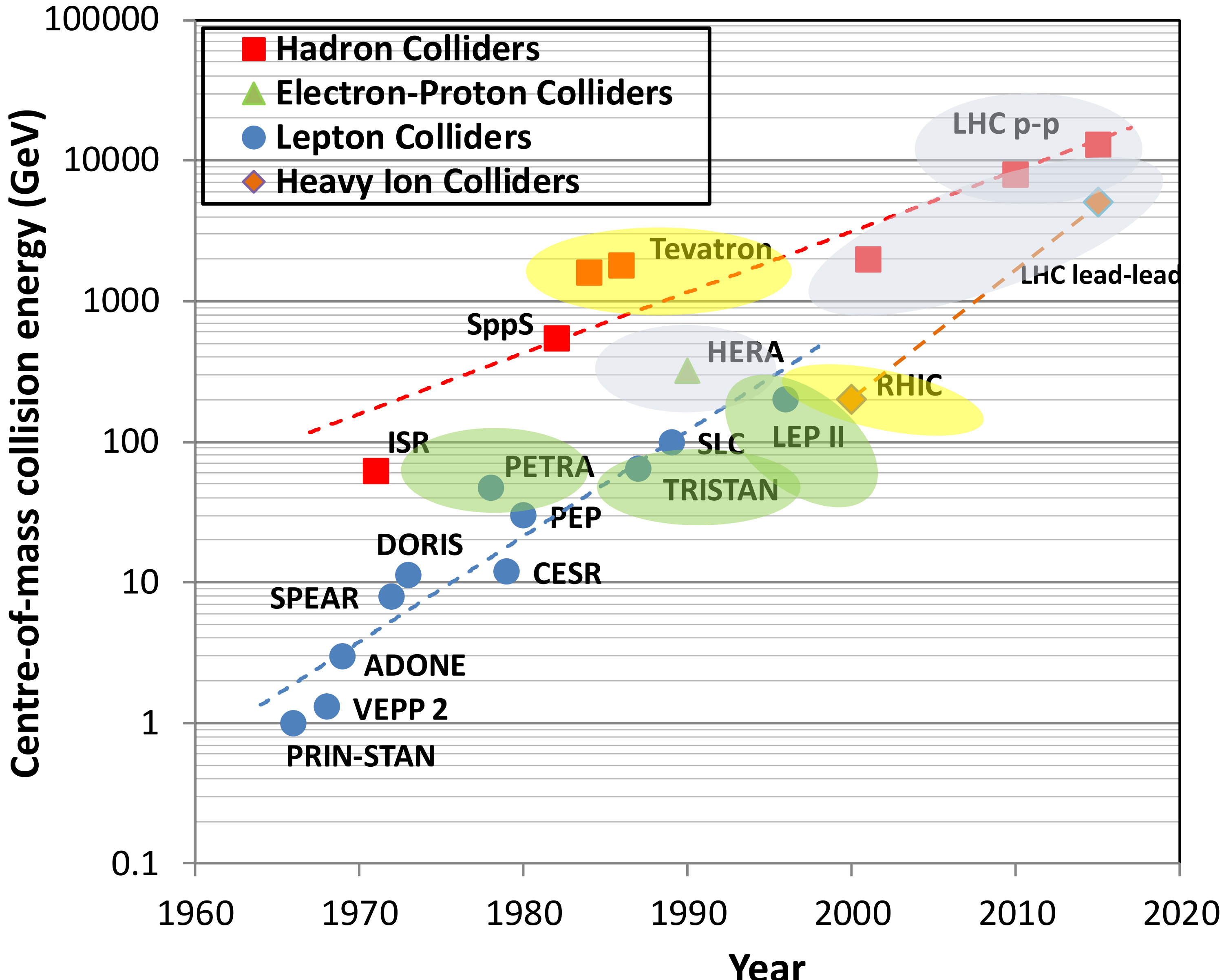
first cyclotron
E.O. Lawrence
11 cm diameter
1.1 MeV protons

*now*

Large Hadron Collider
9 km diameter, 7 TeV protons

# colliders constructed and operated

A. Ballarino



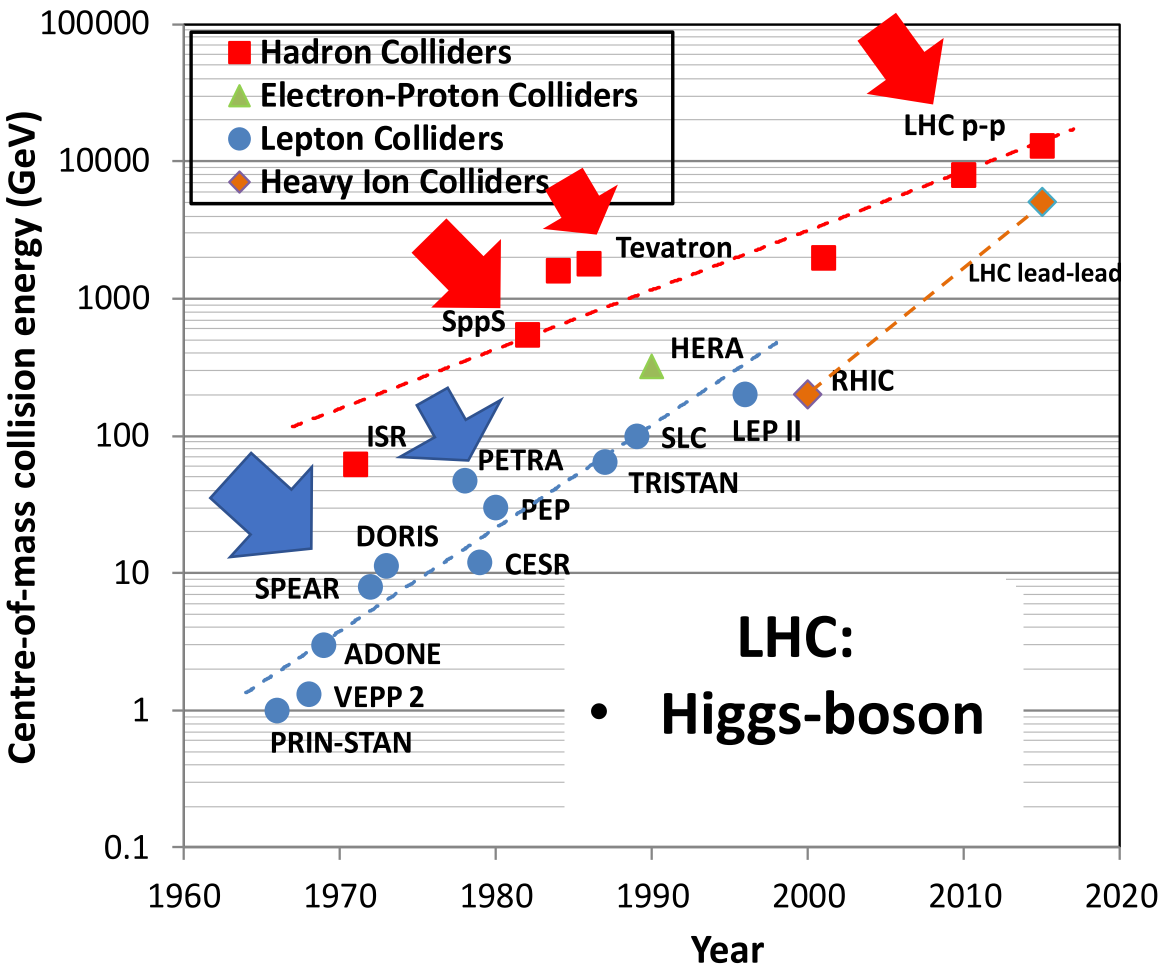

Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnets & RF

**advances by new technologies and new materials**

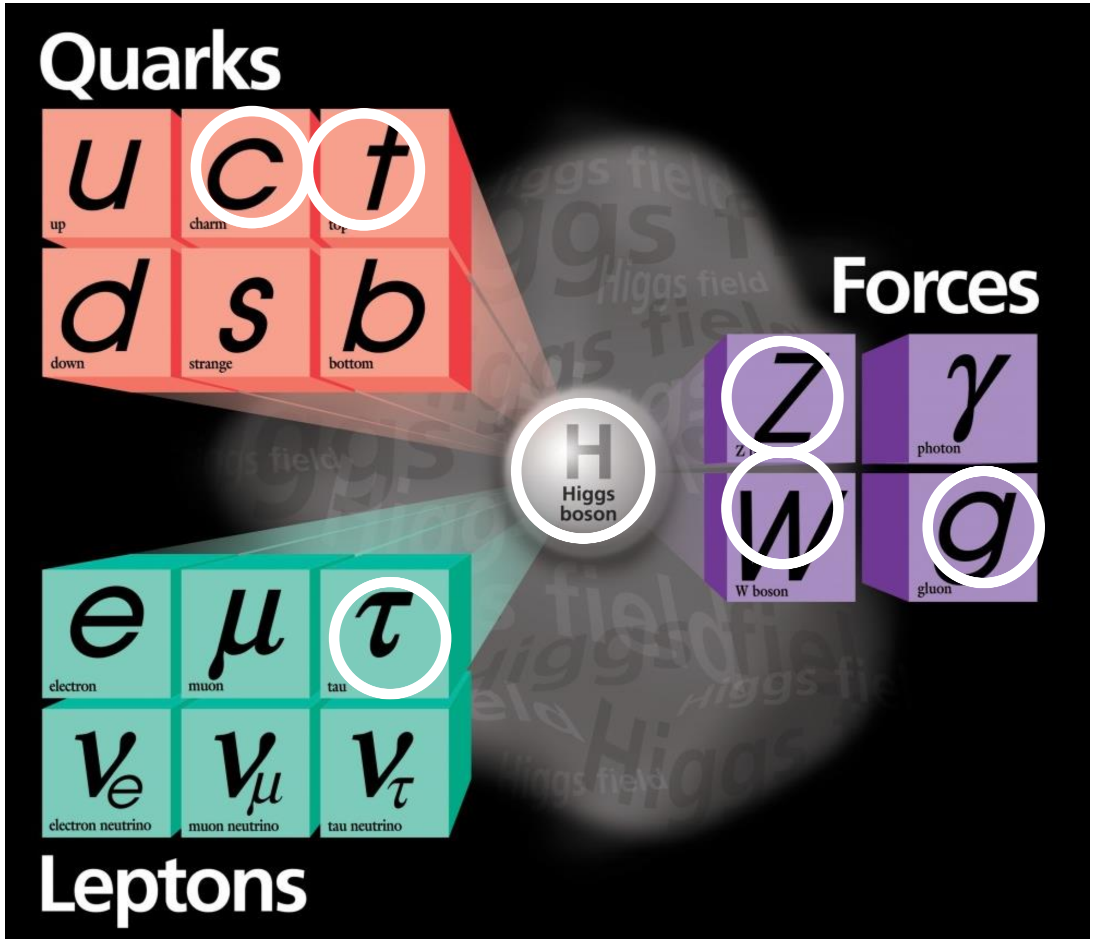
# discoveries with colliders




**LHC:**
- **Higgs-boson**

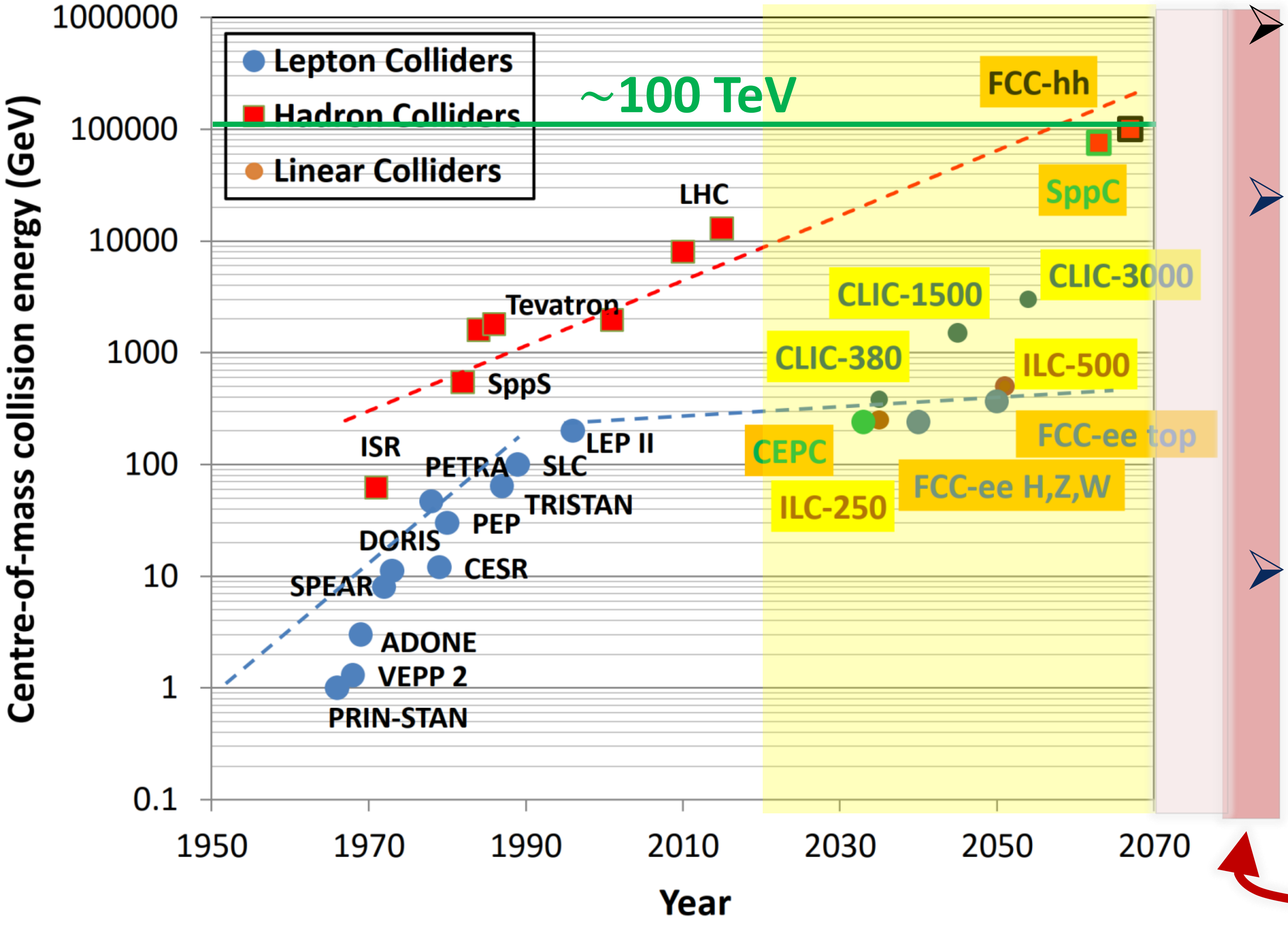
**Standard Model Particles and forces**

A. Ballarino




**colliders are powerful instruments in HEP for particle discoveries and precision measurements**

# next-generation high energy colliders under study




- **Linear e⁺e⁻ colliders** (CLIC, ILC)
  $E_{CM}$ up to ~ **3 TeV**
- **Circular e⁺e⁻ colliders** (CEPC, FCC-ee)
  $E_{CM}$ up to ~ **400 GeV**
  limited by $e^{\pm}$ synchrotron radiation
  $\Delta E/\text{turn} \propto \gamma^4/\rho$
  → **precision measurements**
- **Circular p-p colliders** (SppC, FCC-hh)
  $E_{CM}$ up to ~ **100 TeV**
  energy (momentum) limited by $p = eB\rho$
  → **direct discoveries energy frontier**

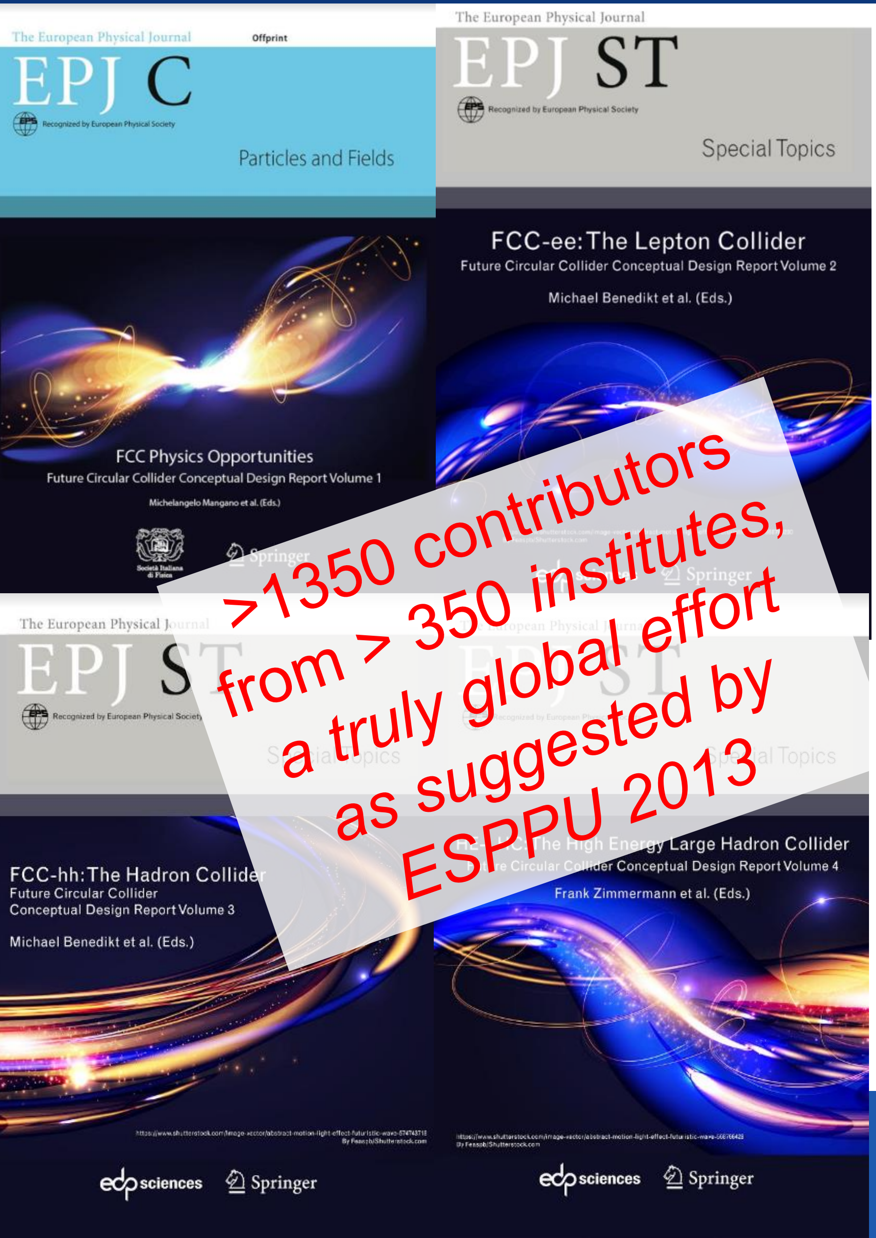
**next-next(-next) generation:**
**ERL based colliders?**
**muon colliders ?**
**plasma-based colliders?**

proposed locations of future energy frontier colliders



FUTURE CIRCULAR COLLIDER

# FCC design (since 2014)




## FCC-Conceptual Design Reports (end 2018) input:

- **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
- CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4) [Springer]**

  EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 , EPJ ST 228, 4 (2019) 755-1107 , EPJ ST 228, 5 (2019) 1109-1382

EPJ is a merger and continuation of *Acta Physica Hungarica, Anales de Fisica, Czechoslovak Journal of Physics, Fizika A, Il Nuovo Cimento, Journal de Physique, Portugaliae Physica* and *Zeitschrift für Physik*. 25 European Physical Societies are represented in EPJ, including the DPG.

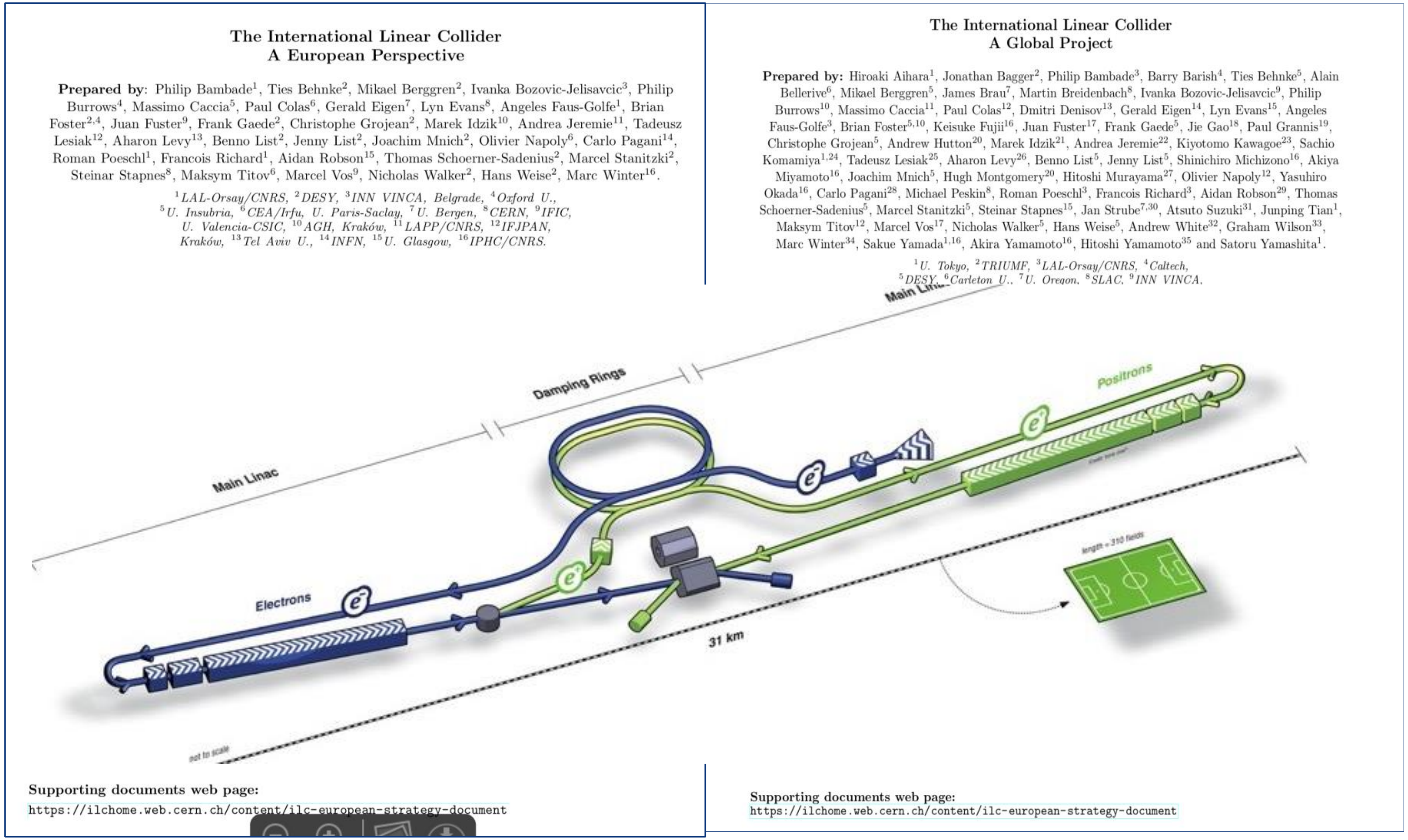
## Summary documents input to EPPSU 2019/20

- **FCC-integral, FCC-ee, FCC-hh, HE-LHC**, at http://fcc-cdr.web.cern.ch/

C= 97.75 km (CDR)

4 modes: 91 GeV: 259 MW; 160 GeV: 277 MW; 240 GeV: 282 MW, 365 GeV: 354 MW (CDR)

# ILC (based on TESLA design, since 1990)


The International Linear Collider
A European Perspective

Prepared by: Philip Bambade[1], Ties Behnke[2], Mikael Berggren[2], Ivanka Bozovic-Jelisavcic[3], Philip Burrows[4], Massimo Caccia[5], Paul Colas[6], Gerald Eigen[7], Lyn Evans[8], Angeles Faus-Golfe[1], Brian Foster[2,4], Juan Fuster[9], Frank Gaede[2], Christophe Grojean[2], Marek Idzik[10], Andrea Jeremie[11], Tadeusz Lesiak[12], Aharon Levy[13], Benno List[2], Jenny List[2], Joachim Mnich[2], Olivier Napoly[6], Carlo Pagani[14], Roman Poeschl[1], Francois Richard[1], Aidan Robson[15], Thomas Schoerner-Sadenius[2], Marcel Stanitzki[2], Steinar Stapnes[8], Maksym Titov[6], Marcel Vos[9], Nicholas Walker[2], Hans Weise[2], Marc Winter[16].

[1]LAL-Orsay/CNRS, [2]DESY, [3]INN VINCA, Belgrade, [4]Oxford U., [5]U. Insubria, [6]CEA/Irfu, U. Paris-Saclay, [7]U. Bergen, [8]CERN, [9]IFIC, U. Valencia-CSIC, [10]AGH, Kraków, [11]LAPP/CNRS, [12]IFJPAN, Kraków, [13]Tel Aviv U., [14]INFN, [15]U. Glasgow, [16]IPHC/CNRS.

Supporting documents web page:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document

The International Linear Collider
A Global Project

Prepared by: Hiroaki Aihara[1], Jonathan Bagger[2], Philip Bambade[3], Barry Barish[4], Ties Behnke[5], Alain Bellerive[6], Mikael Berggren[5], James Brau[7], Martin Breidenbach[8], Ivanka Bozovic-Jelisavcic[9], Philip Burrows[10], Massimo Caccia[11], Paul Colas[12], Dmitri Denisov[13], Gerald Eigen[14], Lyn Evans[15], Angeles Faus-Golfe[3], Brian Foster[5,10], Keisuke Fujii[16], Juan Fuster[17], Frank Gaede[5], Jie Gao[18], Paul Grannis[19], Christophe Grojean[5], Andrew Hutton[20], Marek Idzik[21], Andrea Jeremie[22], Kiyotomo Kawagoe[23], Sachio Komamiya[1,24], Tadeusz Lesiak[25], Aharon Levy[26], Benno List[5], Jenny List[5], Shinichiro Michizono[16], Akiya Miyamoto[16], Joachim Mnich[5], Hugh Montgomery[20], Hitoshi Murayama[27], Olivier Napoly[12], Yasuhiro Okada[16], Carlo Pagani[28], Michael Peskin[8], Roman Poeschl[3], Francois Richard[3], Aidan Robson[29], Thomas Schoerner-Sadenius[5], Marcel Stanitzki[5], Steinar Stapnes[15], Jan Strube[7,30], Atsuto Suzuki[31], Junping Tian[1], Maksym Titov[12], Marcel Vos[17], Nicholas Walker[5], Hans Weise[5], Andrew White[32], Graham Wilson[33], Marc Winter[34], Sakue Yamada[1,16], Akira Yamamoto[16], Hitoshi Yamamoto[35] and Satoru Yamashita[1].

[1]U. Tokyo, [2]TRIUMF, [3]LAL-Orsay/CNRS, [4]Caltech, [5]DESY, [6]Carleton U., [7]U. Oregon, [8]SLAC, [9]INN VINCA.

Supporting documents web page:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document



Inputs to 2019/20 Strategy process

S. Stapnes

Papers & documents in:
https://ilchome.web.cern.ch/content/ilc-european-strategy-document

More about ILC:
https://ilchome.web.cern.ch

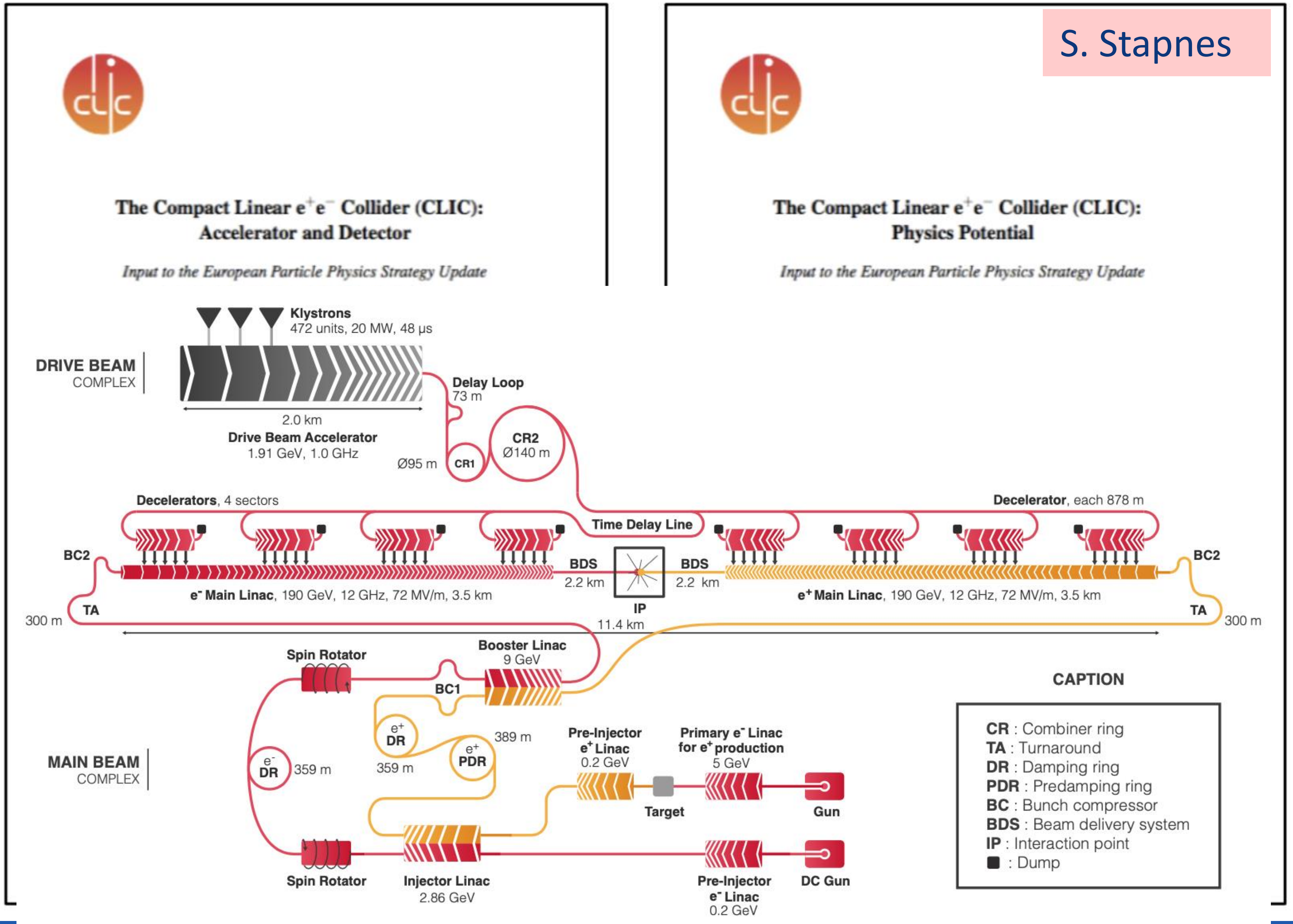
3 stages:

250 GeV: 20.5 km, 129 MW

500 GeV: 31.0 km, 163 MW

1 TeV: 40 km, 300 MW

# CLIC design (studied & optimized since 1985)




S. Stapnes

Inputs to 2019/20 Strategy process

These papers and supporting documents in: https://clic.cern/european-strategy

More about CLIC: https://clic.cern

**3 stages:**

380 GeV: 11.4 km, 168 MW

1.5 TeV: 29.0 km, 364 MW

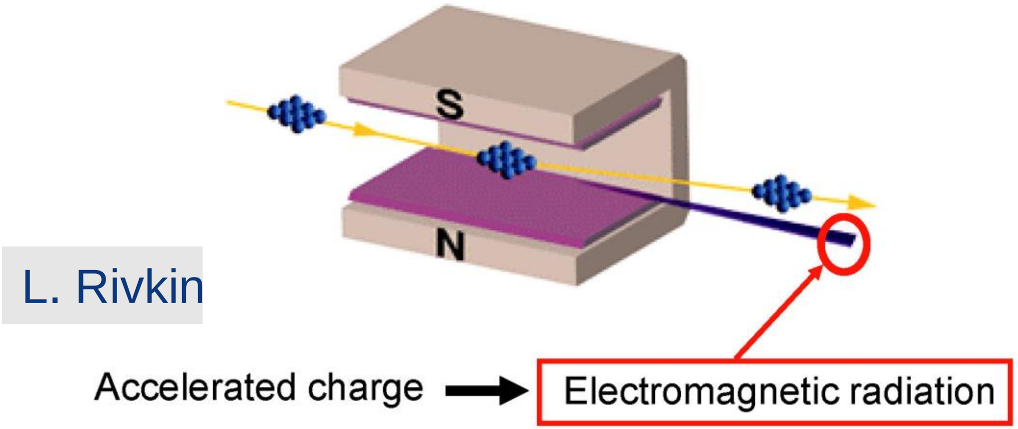
3 TeV: 50.1 km, 589 MW

# five major challenges driving the strategy

1. synchrotron radiation
2. bending magnetic field
3. accelerating gradient
4. (rare) particle production – $e^+$ and $\mu$
5. cost and sustainability

# challenge #1: synchrotron radiation (SR)

## circular colliders




**energy loss per particle per turn** $$U_0 = \frac{e^2}{3\varepsilon_0}\frac{\gamma^4}{\rho}$$

**SR power** $$P_{SR} = \frac{I_{beam}}{e} U_0$$

**e±:** $P_{SR}$ $=$ 23 MW for LEP (former e+e- collider in the LHC tunnel),
100 MW for FCC-ee (imposed as design constraint),

**protons:** $P_{SR}$ $=$ 0.01 MW for LHC,
5 MW for FCC-hh – this requires >100 MW cryoplant power

# SR in the arcs: possible mitigations (challenge #1)

**mitigations:**

- **large bending radius ρ**

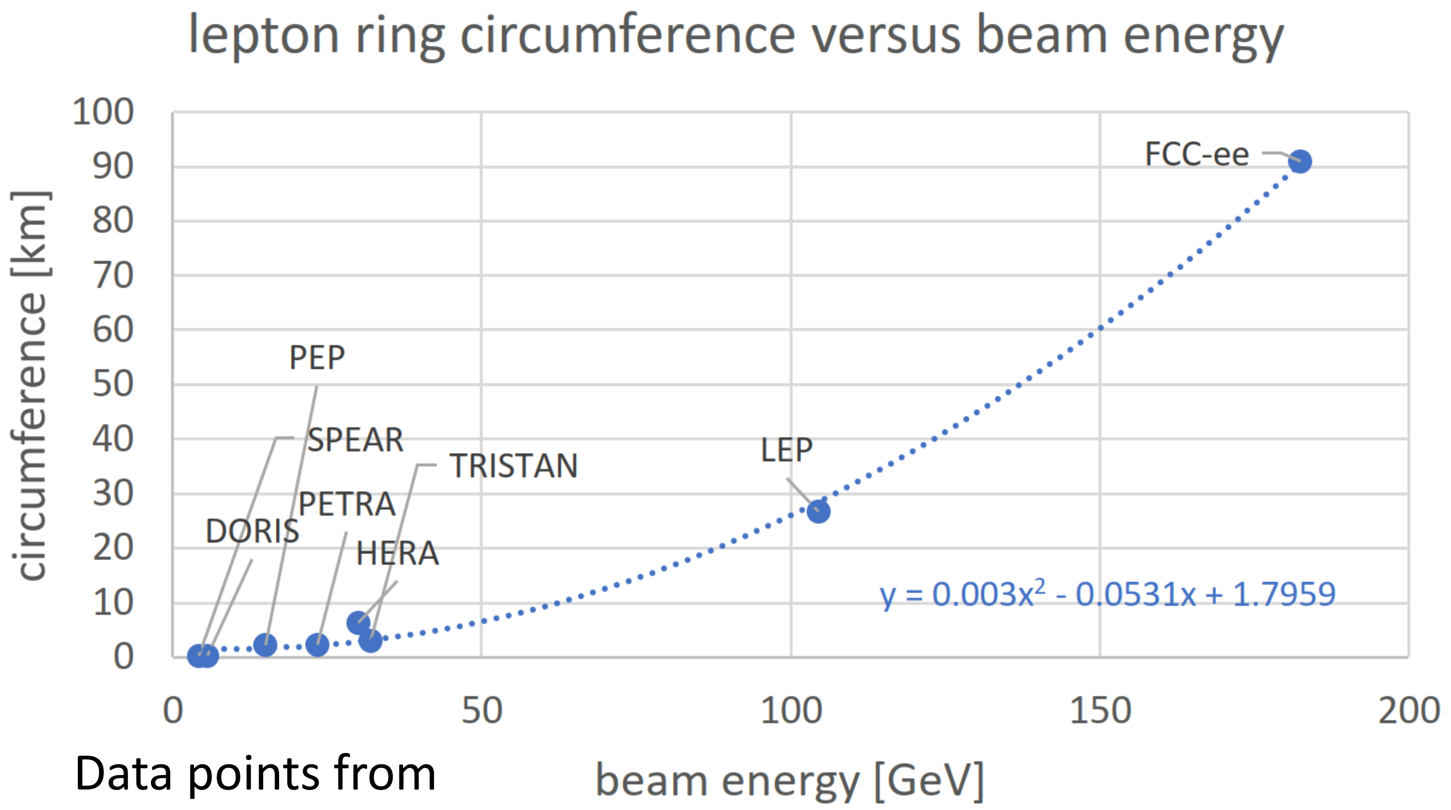
  → large circular collider → *next slide*
- **linear collider**

  - "almost" no arcs, but beamstrahlung → *next next slides*
- **muon collider**

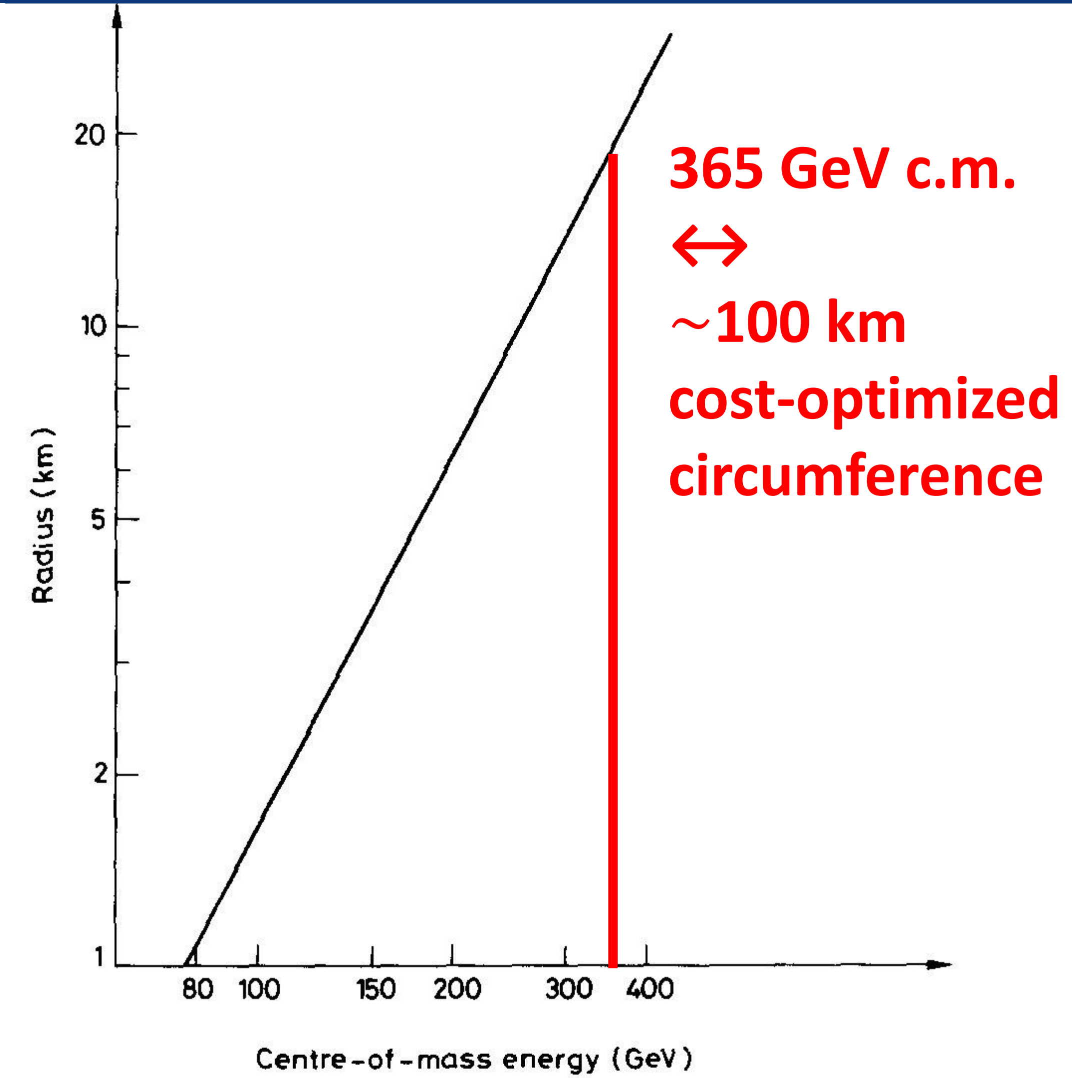
  - μ ~200 heavier than $e^{\pm}$ → ~$10^9$x less radiation at same energy and radius, but μ's decay → *later*
- **shaping beam vacuum chamber or the beam itself**

  - tiny vacuum chamber in large ring, $\lambda_{sh} \approx 2\sqrt{d^3/\rho}$ with *d:* pipe diameter
  - beam shaping to suppress radiation; a DC beam does not radiate! explored in EU projects ARIES & I.FAST → *not part of ESPPU 20*

# SR → size of circular $e^+e^-$ colliders (challenge #1)




Data points from
S. Myers, "*FCC - Building on the Shoulders of Giants*", submitted to EPJ+ (2021)



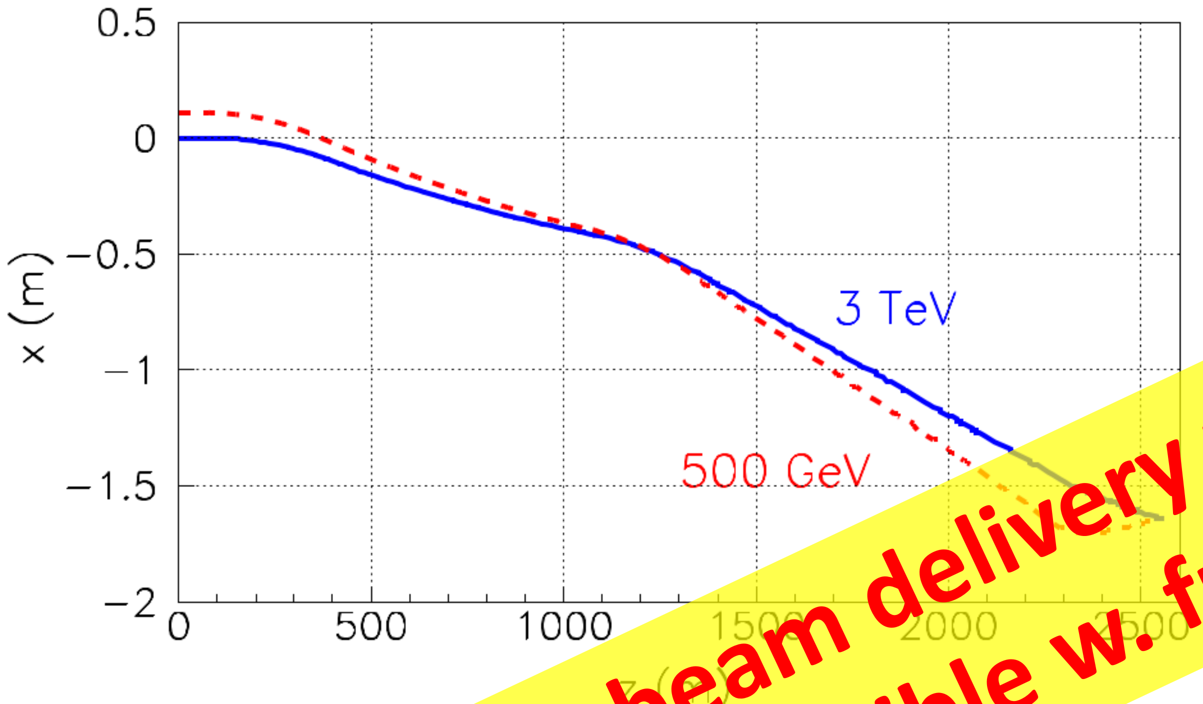

B. Richter, "*Very High Energy Electron-Positron Colliding Beams for the Study of Weak Interactions*", NIM 136 (1976) 47-60

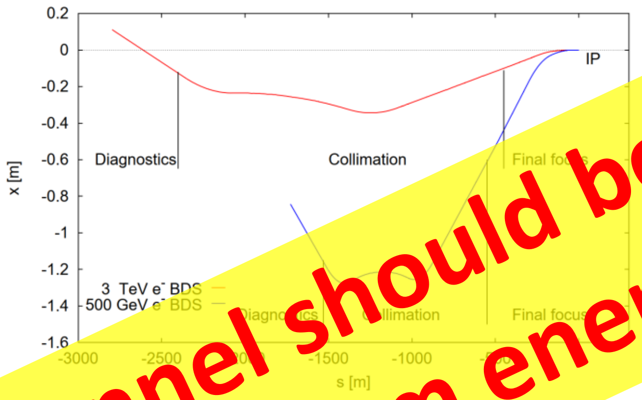
**Serendipitously, 90-100 km is exactly the size required for a 100 TeV hadron collider and optimum tunnel size in the Lake Geneva basin !**

# SR → linear collider beam delivery (challenge #1)

## linear colliders

SR in bending magnets of the beam-delivery system




Other footprints of CLIC 3-TeV and 500-GeV beam delivery systems (G. Zamudio, R. Tomas, 2011, CLIC-Note-882 )

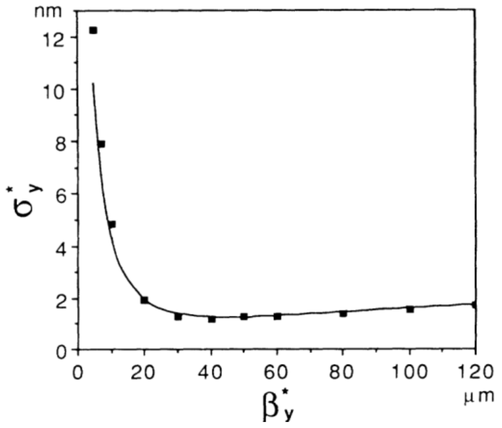
Historical footprints of CLIC 3-TeV and 500-GeV beam delivery systems (M. Aleksa et al. 2003, CLIC-Note-551 )

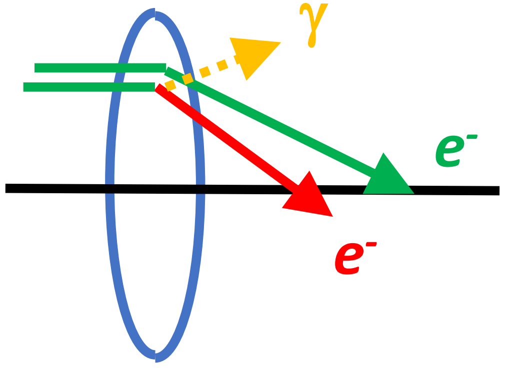
SR in bending magnets caused a factor ~2 loss in luminosity in 2003 CLIC BDS design at 3 TeV; similarly for the SLC at 91 GeV c.m. (!)

**beam delivery tunnel should be compatible w. future beam energies**

SR in final quadrupole magnet ("Oide effect") limits collision spot size

K. Oide, Phys. Rev. Lett. 61, 1713 (1988)



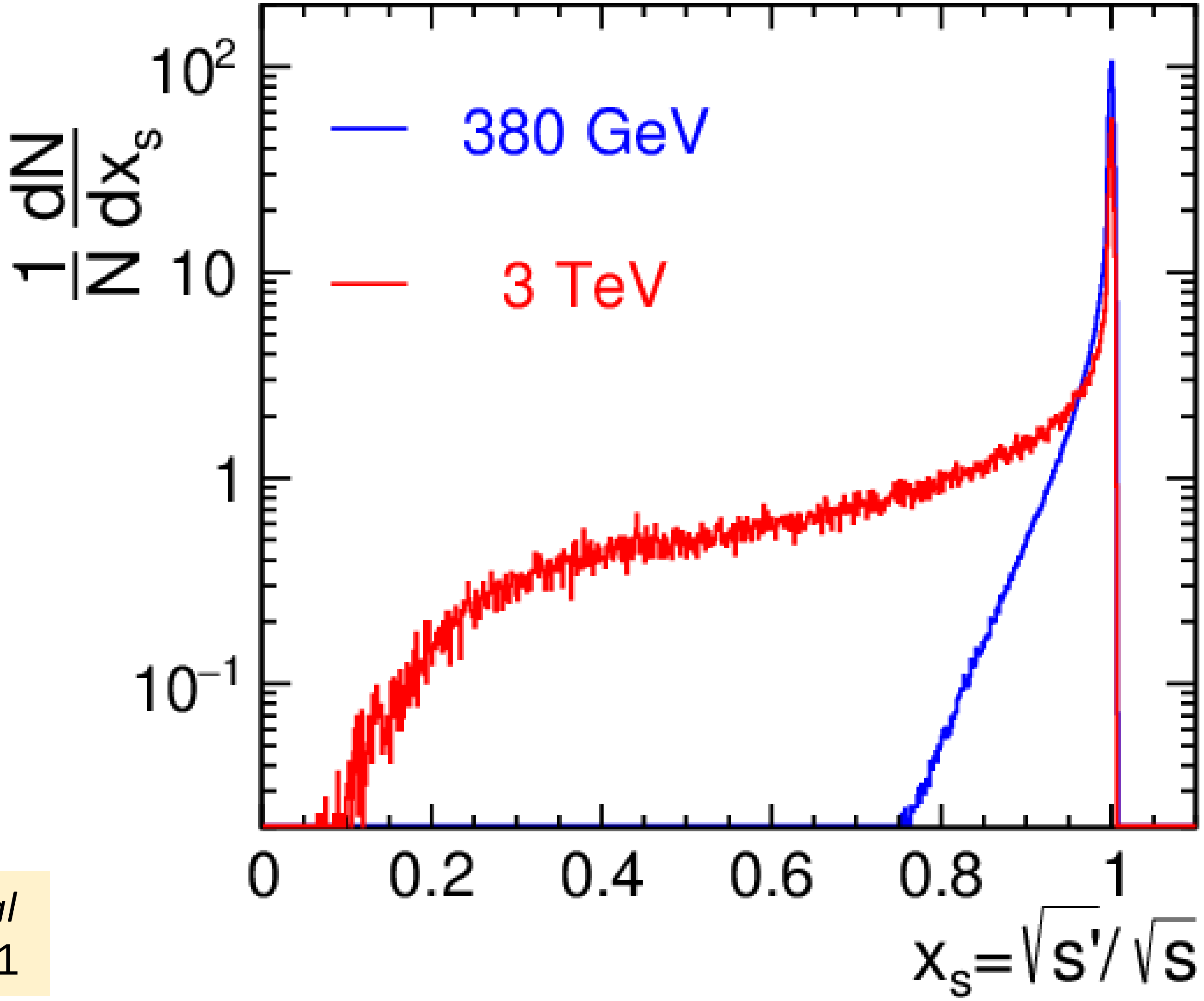




final quadrupole lens

# challenge #1: synchrotron radiation - cont'd

**linear colliders**

synchrotron radiation in the strong field of the opposing beam (="**beamstrahlung**") degrades the luminosity spectrum




CLIC at 380 GeV: 60% of total luminosity within 1% of target energy

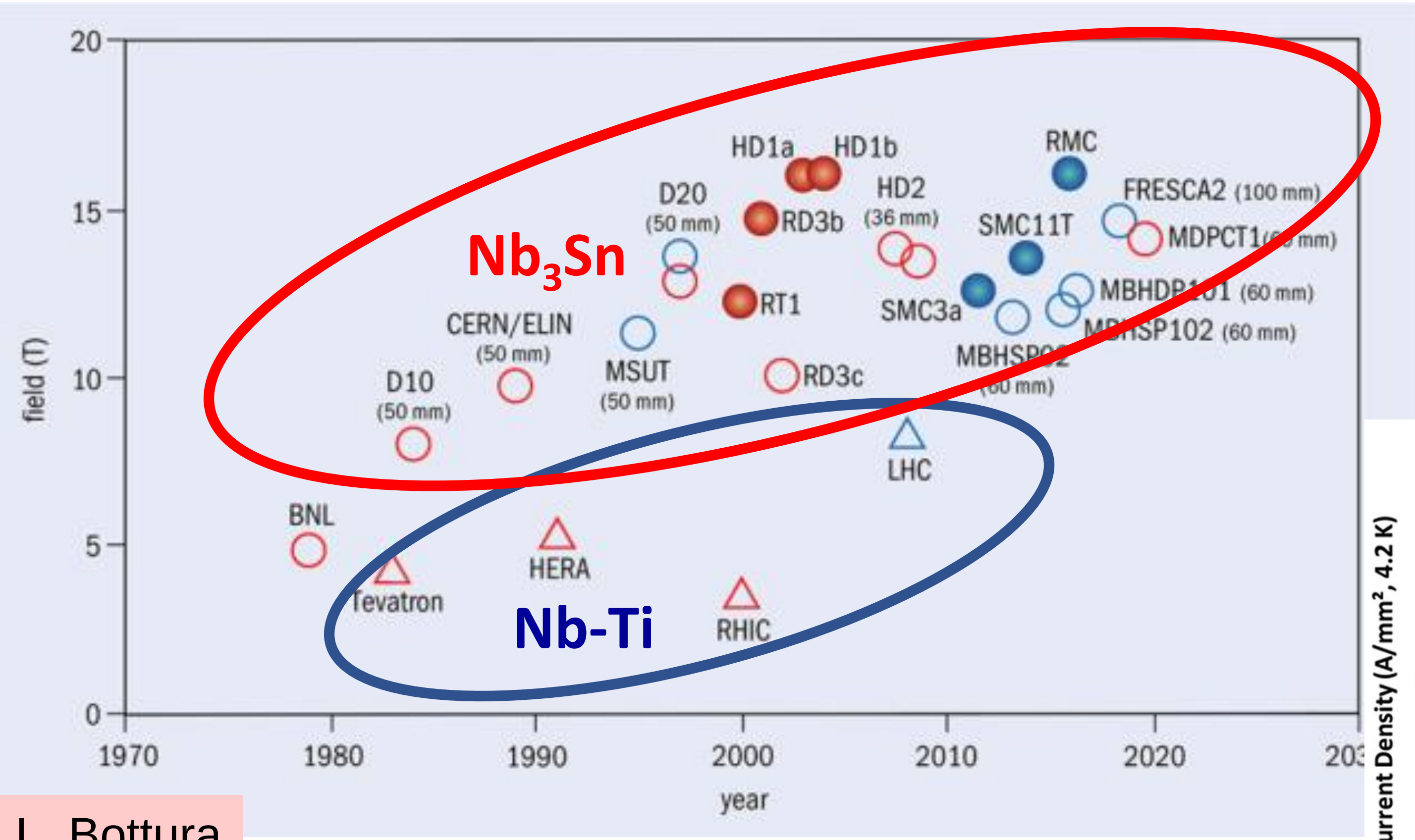
CLIC at 3 TeV: only 33% of total luminosity within 1% of target

$e^+e^-$ collisions in linear colliders lose their distinct energy precision

D. Schulte

H. Abramowicz, *et al* - arXiv:1807.02441

# challenge #2: bending magnetic field



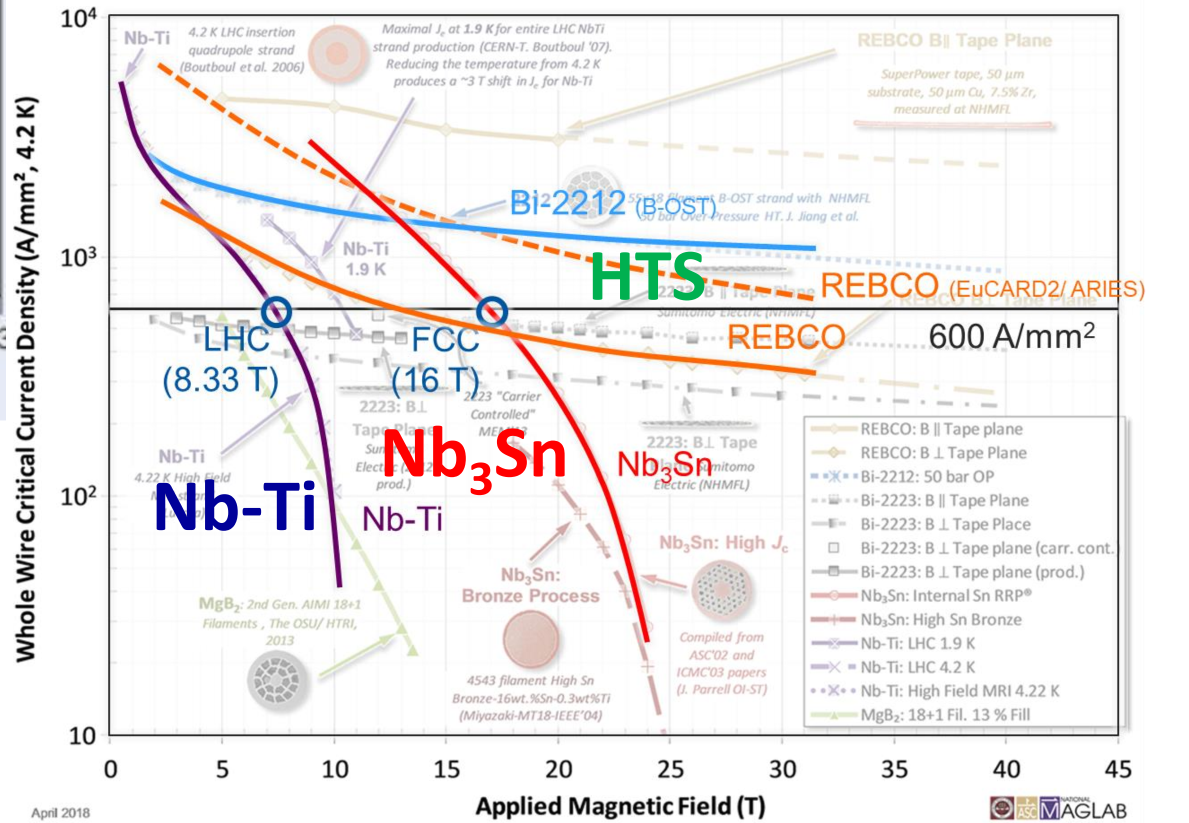

L. Bottura

Record fields attained with dipole magnets of various configurations and dimensions, and either at liquid (4.2 K, red) or superfluid (1.9 K, blue) helium temperature.

**→ hadron collider energy reach**

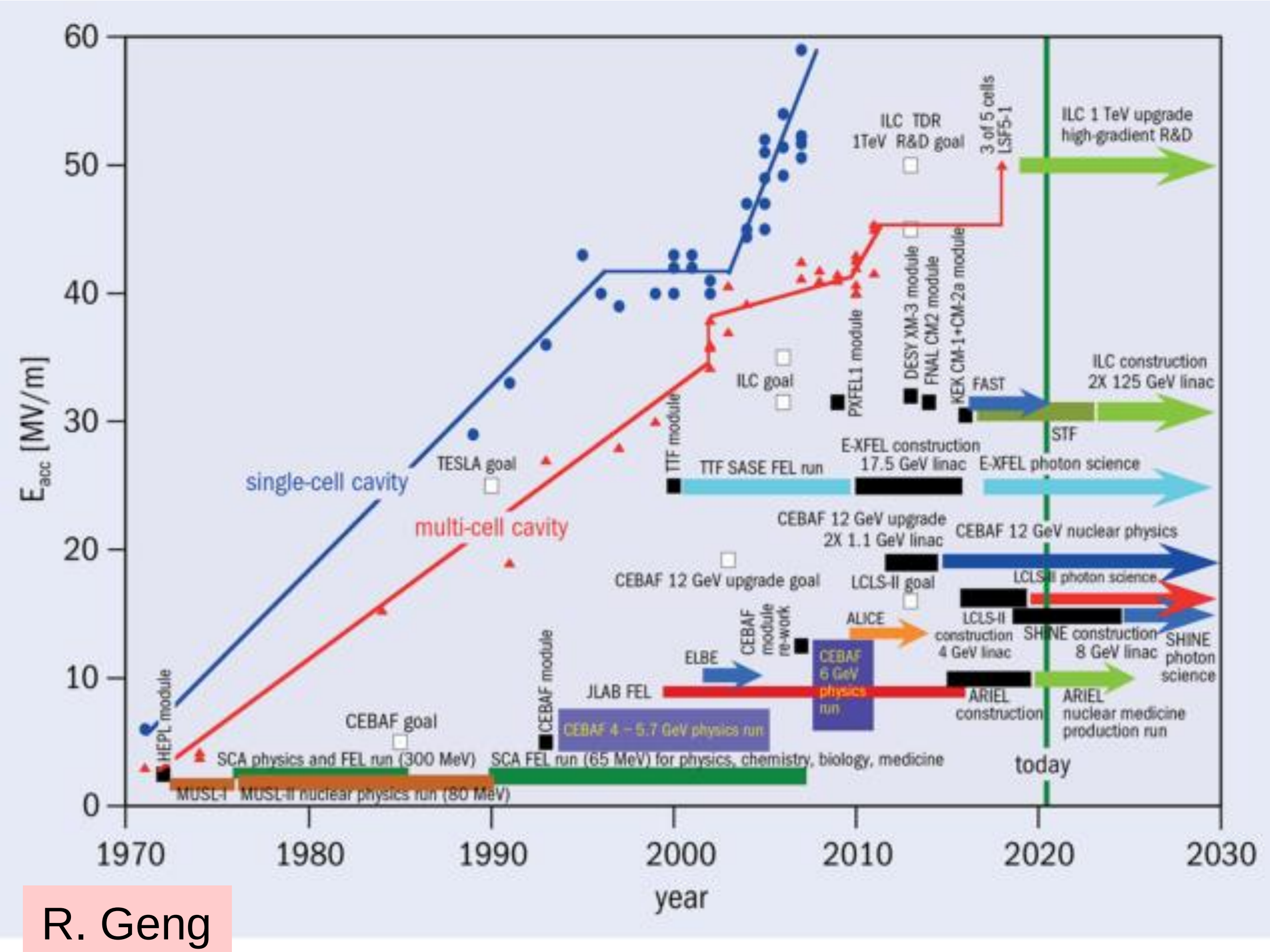
Superconducting wire critical current density versus magnetic field.

P. Lee



# challenge #3: accelerating gradient

**Gradient growth** Superconducting RF linac accelerating gradient achievements and applications since 1970. CERN Courier 2020




R. Geng

## RF Accelerators

R. Aßmann

> 30,000 operational – many serve for Health

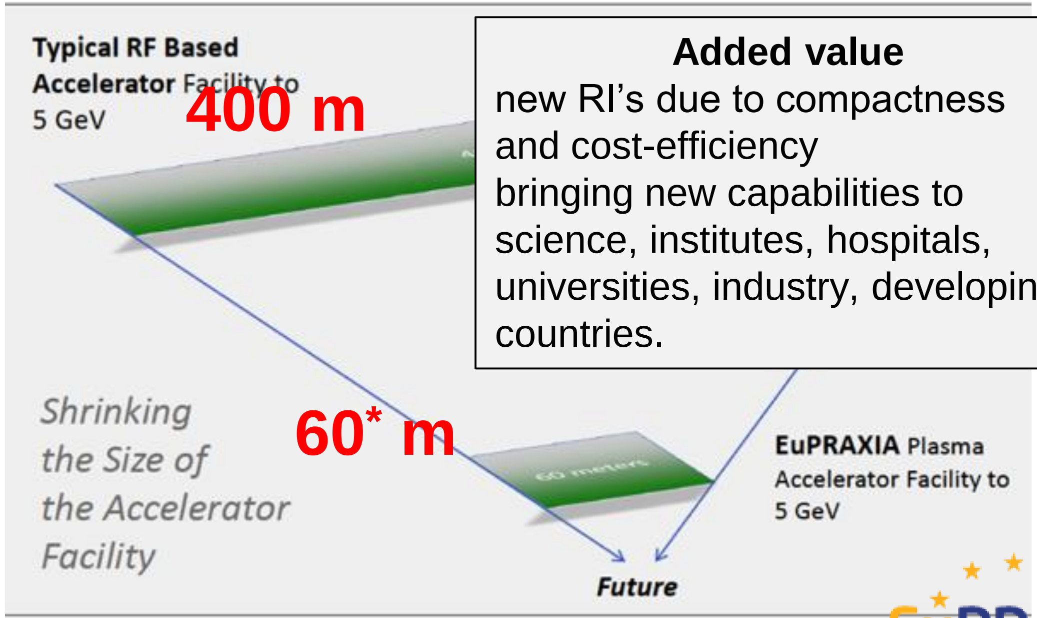
**30 million Volt per meter**

RF: 90 years of success story for society

## Plasma Accelerators

first user facility to be realized

**100,000 million Volt per meter**

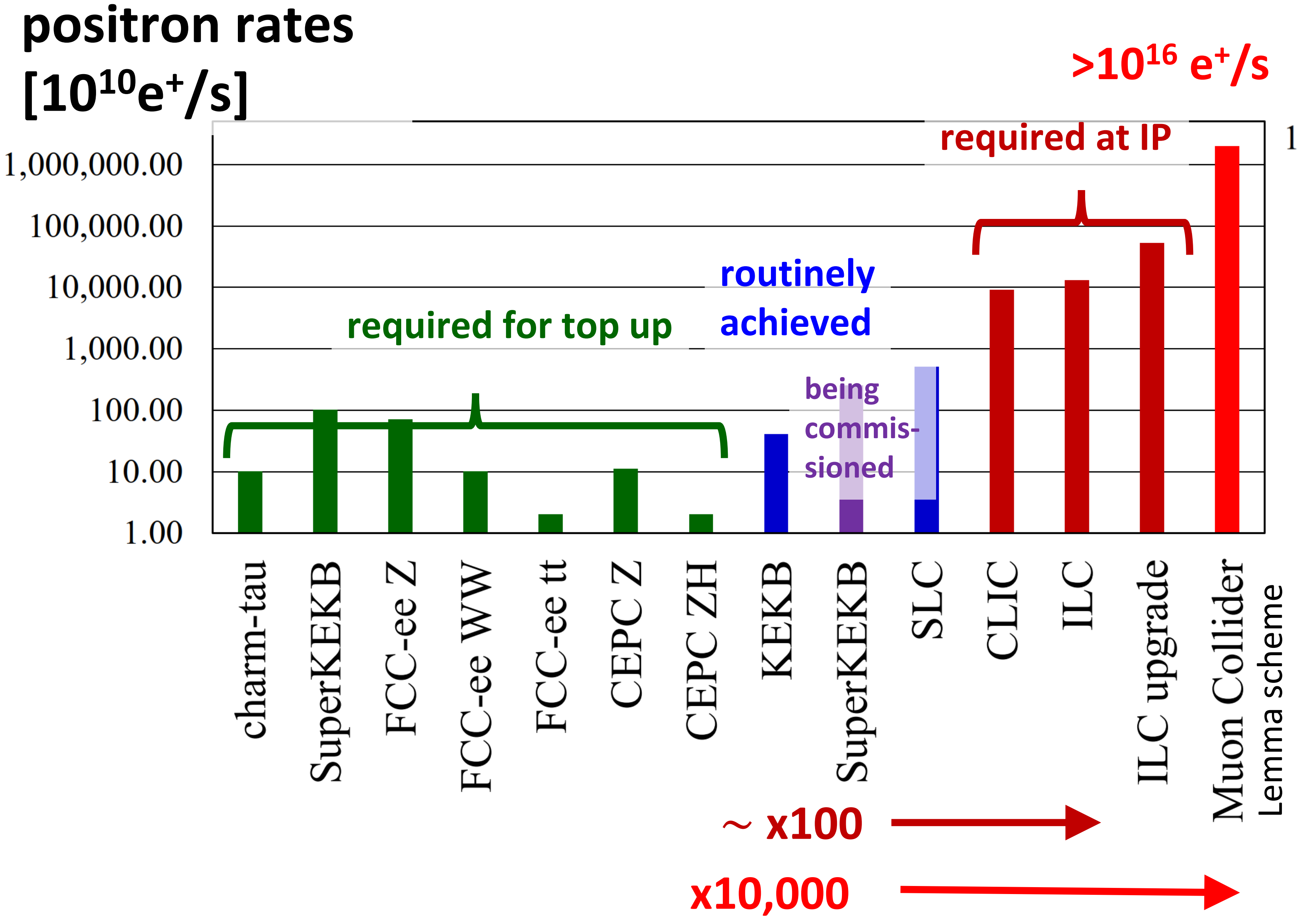


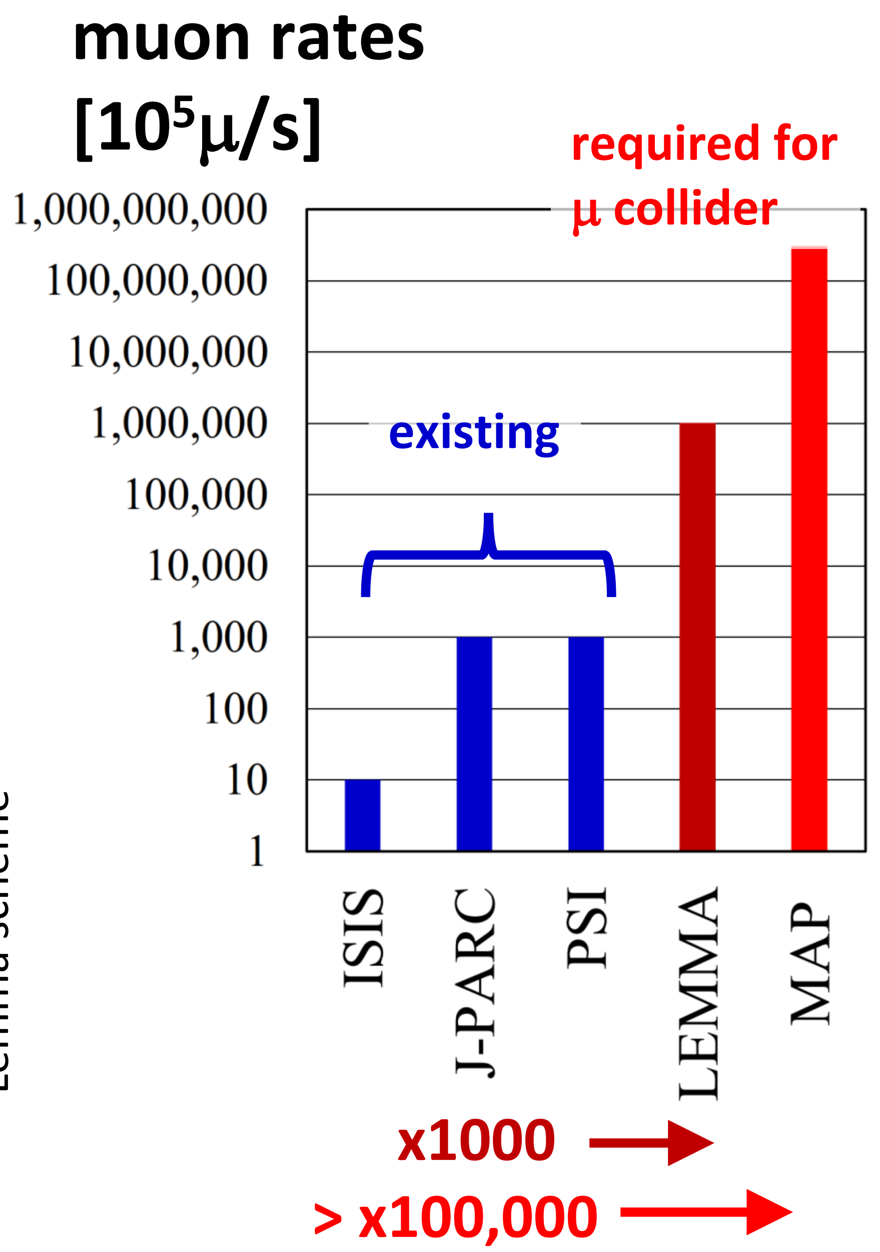

**Added value**
new RI's due to compactness and cost-efficiency
bringing new capabilities to science, institutes, hospitals, universities, industry, developing countries.

*realistic design including all required infrastructure for powering, shielding,

EuPRAXIA

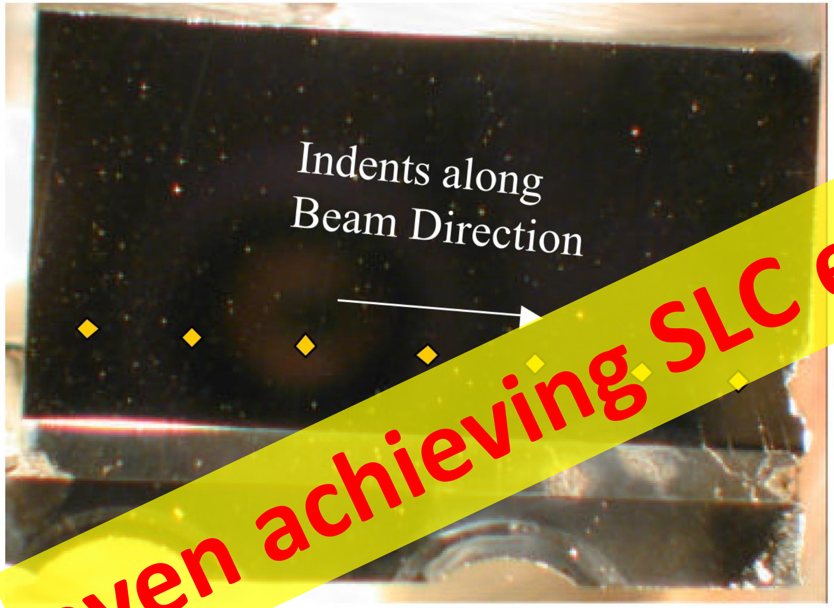
# challenge #4: particle production – $e^+$, μ

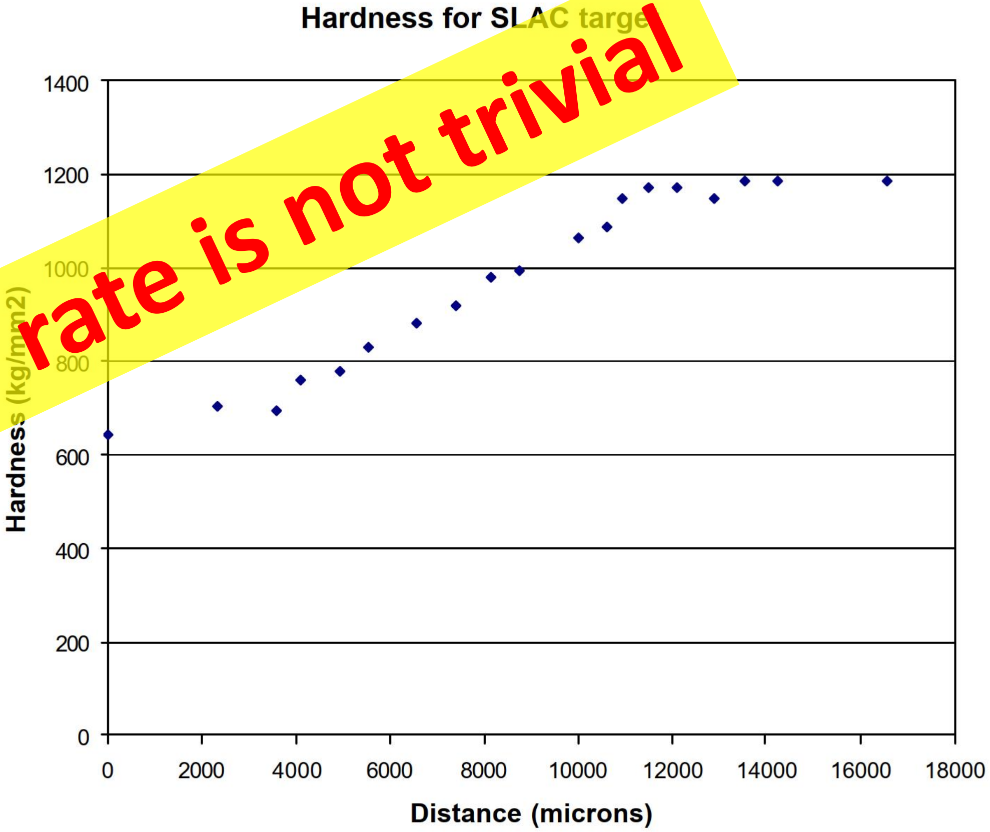


# failure of SLC $e^+$ target after 5 years of operation (challenge #4)

SLC target analysis at LANL: Failed SLC positron target was cut into pieces and metallographic studies were carried out to examine level of deterioration of material properties due to radiation exposure.




**even achieving SLC $e^+$ rate is not trivial**

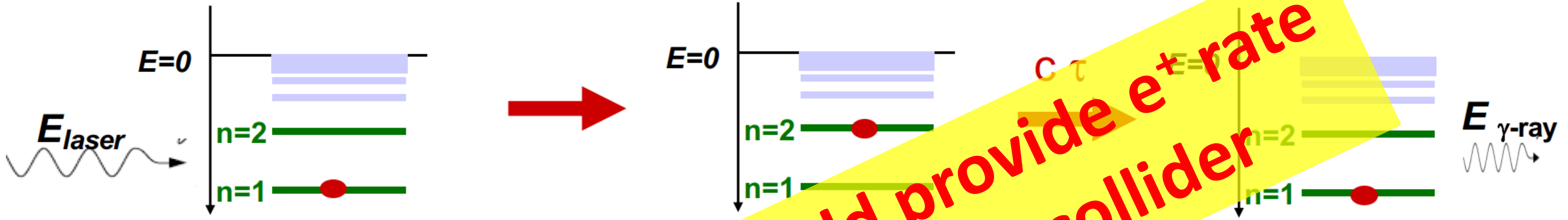
Radiation damage, work hardening, or temperature cycling?

*David Schultz*

*Snowmass, July 10, 2001*

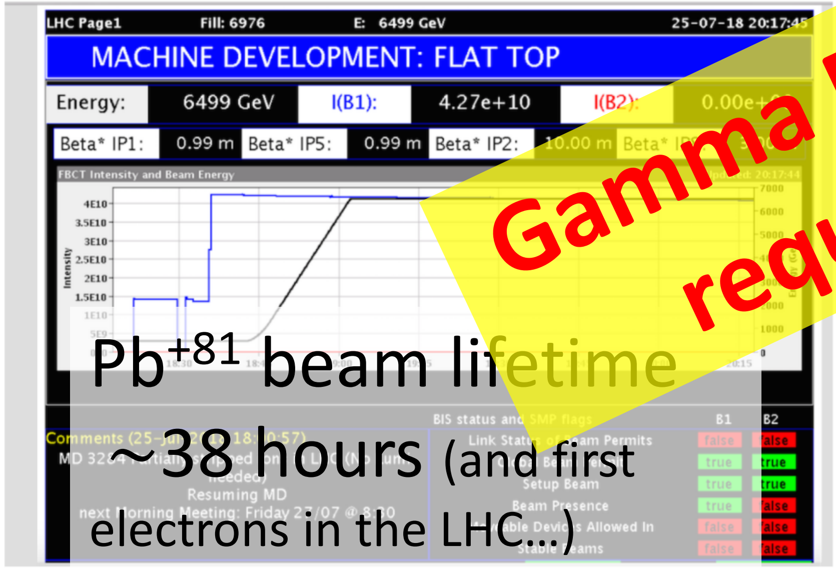
# particle production: Gamma factory (challenge #4)

resonant scattering of laser photons off partially stripped heavy-ion beam in LHC (or FCC): high-stability laser-light-frequency converter




$$\nu^{max} \rightarrow (4\gamma_L^2)\,\nu_{laser}$$

**Gamma Factory could provide $e^+$ rate required for LEMMA μ collider**




Pb$^{+81}$ beam lifetime ~38 hours (and first electrons in the LHC…)

proposed applications:

intense source of $e^+$ ($10^{16}$-$10^{17}$/s) , μ ($10^{11}$-$10^{12}$/s), π, etc. – **sufficient for LEMMA type μ collider**

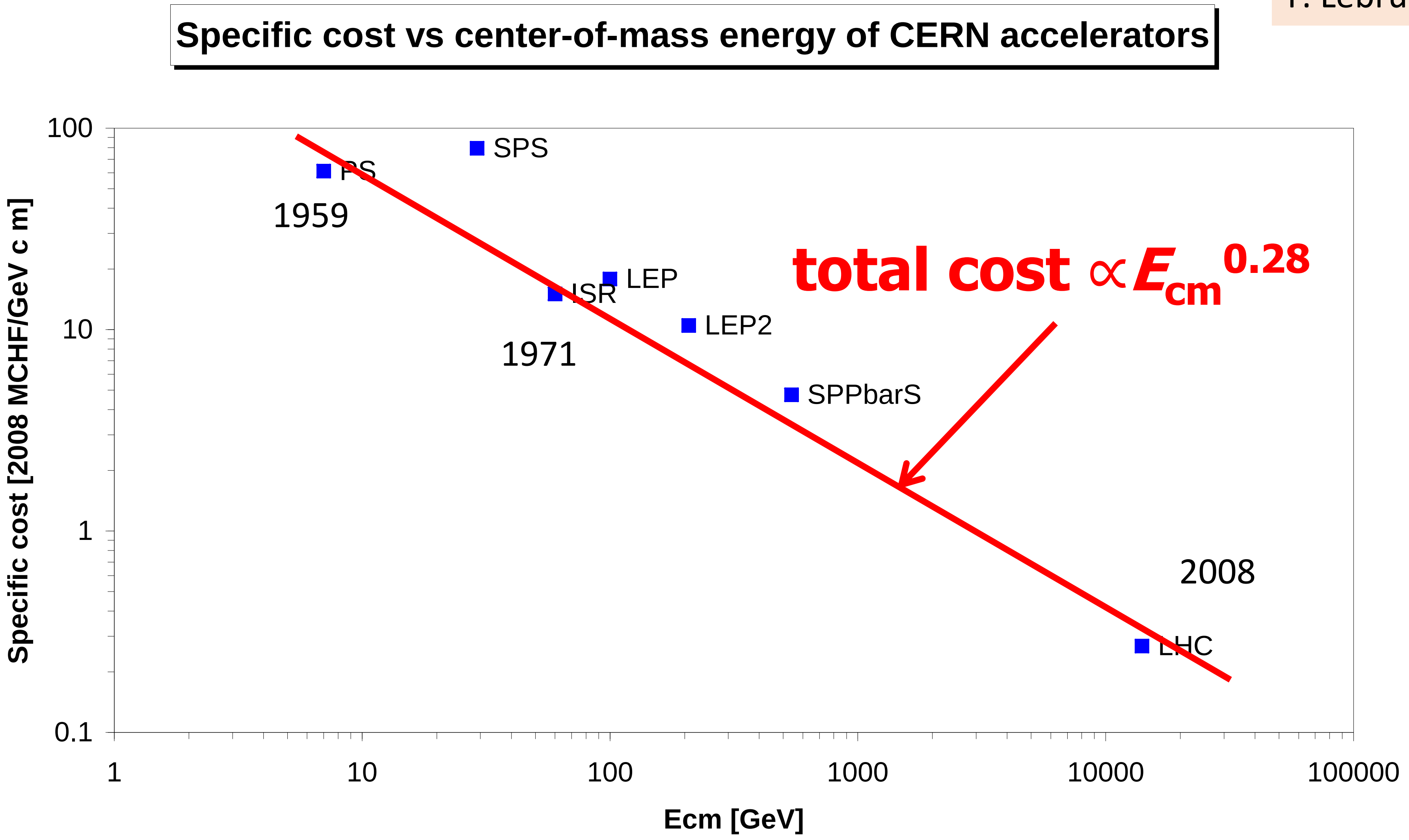
doppler laser cooling of high-energy beams

HL-LHC w. laser-cooled isocalar ion beams

W. Krasny

# challenge #5: cost / sustainability

P. Lebrun, RFTech 2013




*new concepts and new technologies*

cost per collision energy greatly reduced

# ESPP Update 2020 “High-priority future initiatives” - 1

- An **electron-positron Higgs factory is the highest-priority next collider**. For the longer term, the European particle physics community has the ambition to operate a **proton-proton collider at the highest achievable energy**.

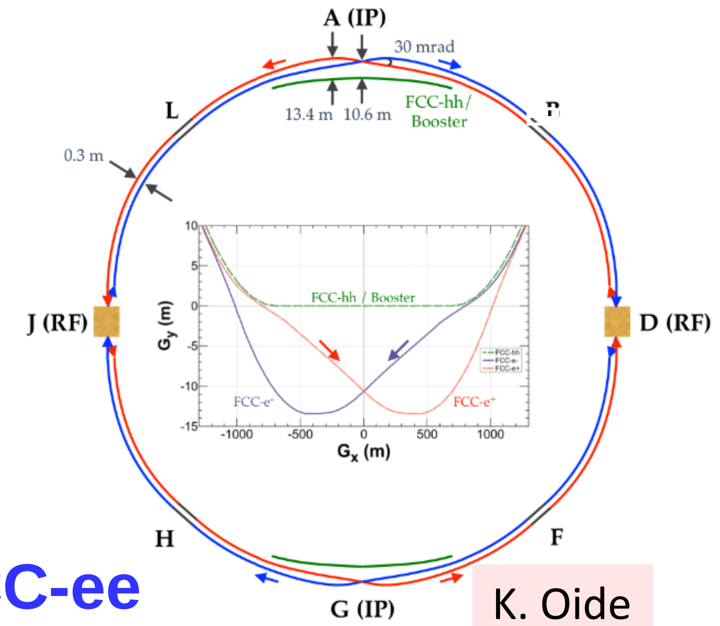
- “Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an **electron-positron Higgs and electroweak factory as a possible first stage**.
- Such a **feasibility study of the colliders and related infrastructure** should be established as a global endeavour and be **completed on the timescale of the next Strategy update**..”

→ launch of Future Circular Collider Feasibility Study in summer 2021

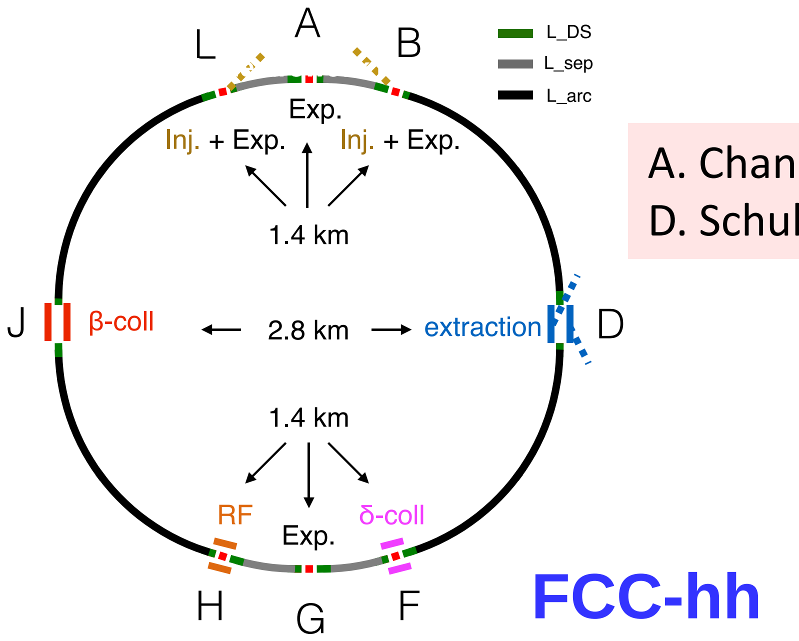
# The Future Circular Collider integrated program inspired by successful LEP – LHC programs at CERN

**comprehensive long-term program maximizing physics opportunities**

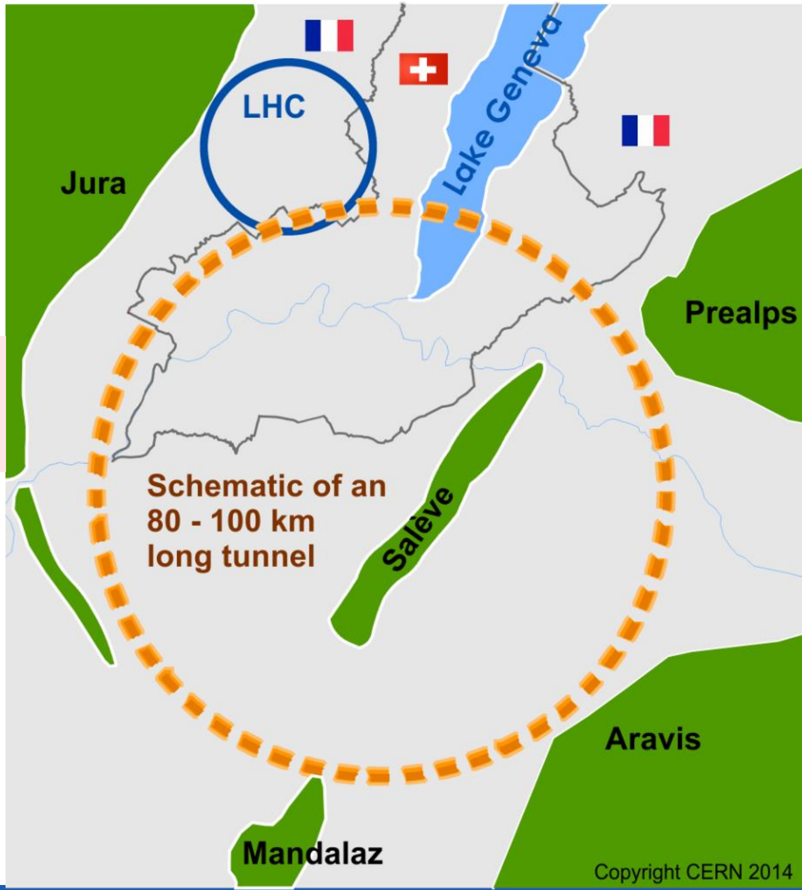
- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures
- building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after HL-LHC




K. Oide



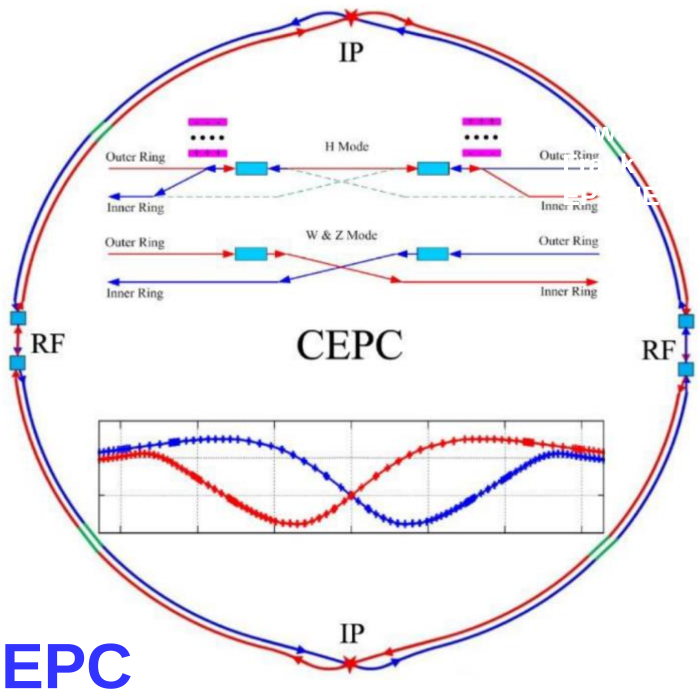

A. Chance, D. Schulte



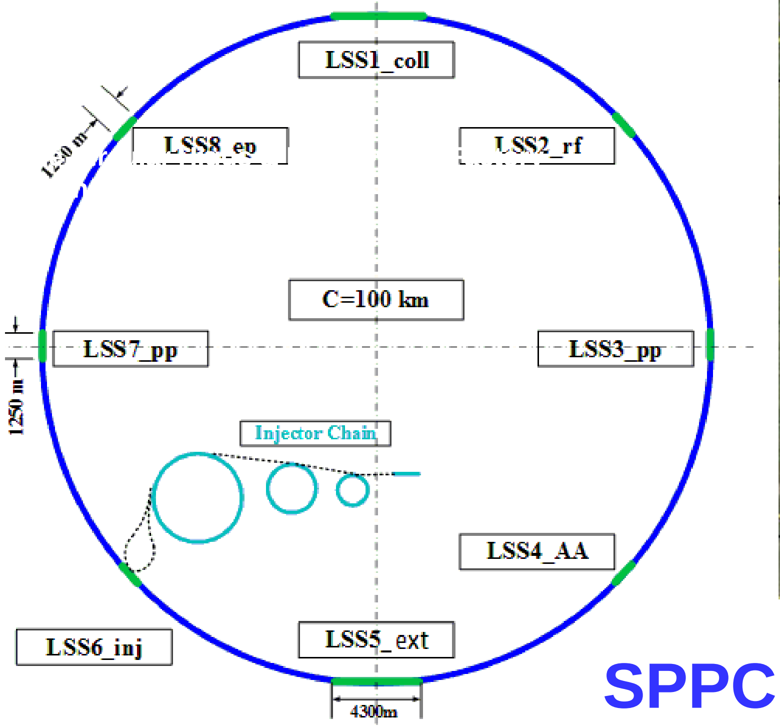
# independent R&D in China → "same" solution

**comprehensive long-term program maximizing physics opportunities**

- **stage 1: CEPC (Z, W, H, optionally $t\bar{t}$ ?) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: SPPC (~75 TeV) as natural continuation at energy frontier**
- complementary physics
- common civil engineering and technical infrastructures, **green field construction**




**CEPC**




**SPPC**


J. Gao, Y. Wang

# FCC-ee basic design choices

K. Oide et al. PRAB **19**, 111005 (2016)

**double ring** $e^+e^-$ collider

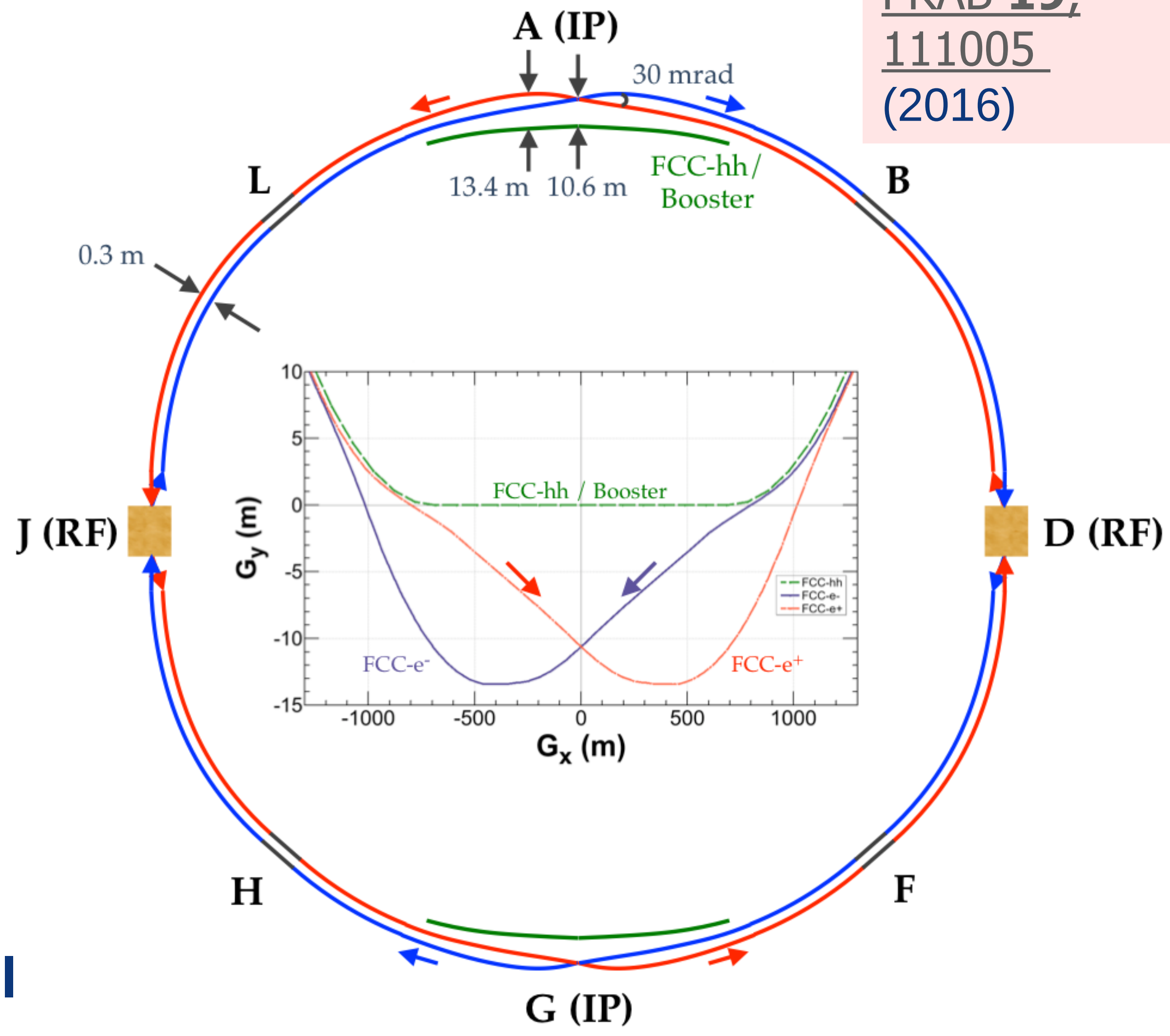
**common footprint with FCC-hh,**
except around IPs

**asymmetric IR layout and optics** to limit synchrotron radiation towards the detector

**2 IPs, large** horizontal crossing angle **30 mrad, crab-waist collision optics**
(**alternative layouts with 4 IPs under study**)

**synchrotron radiation power 50 MW/beam**
at all beam energies

**top-up injection** scheme for high luminosity requires **booster synchrotron in collider tunnel**

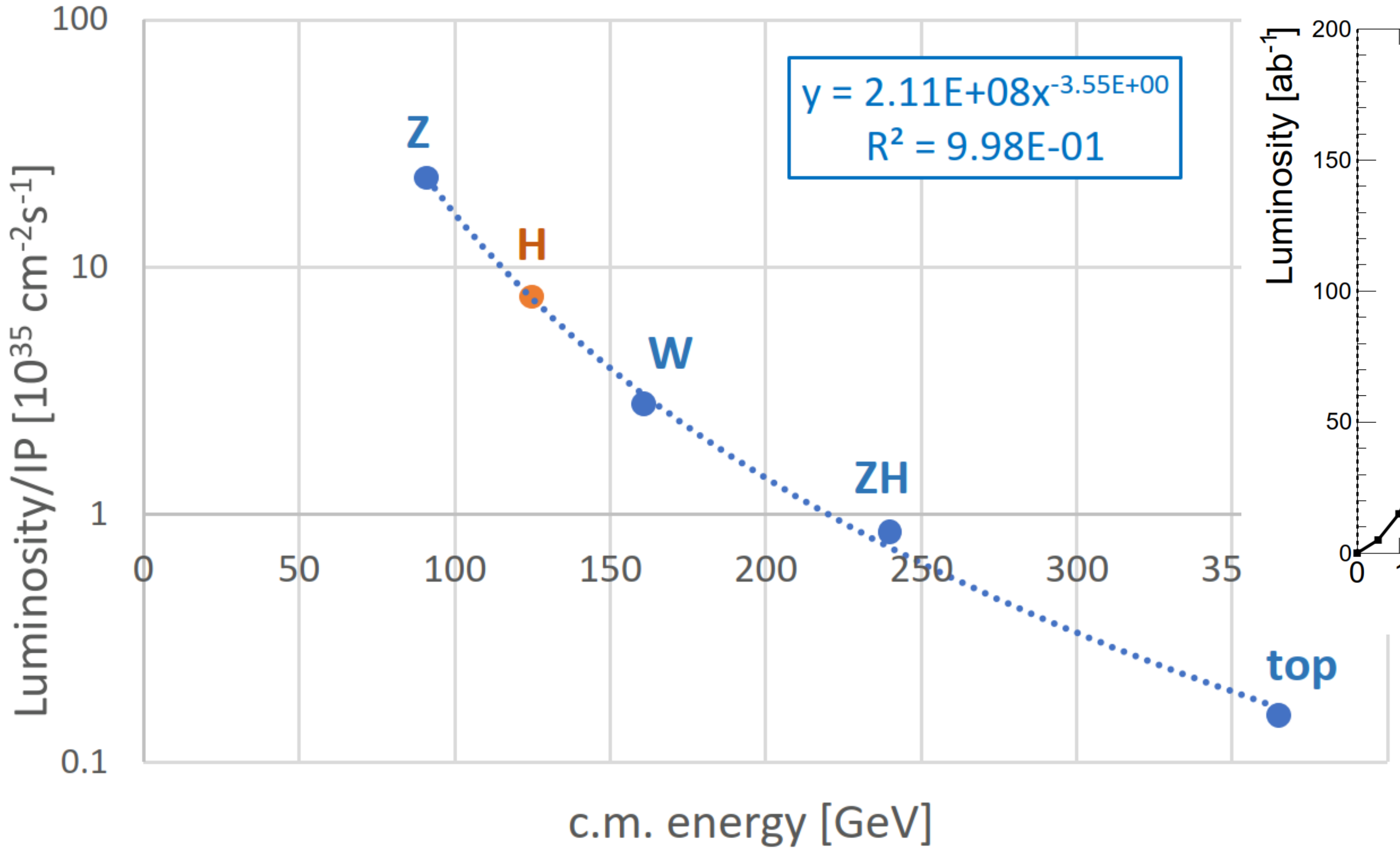


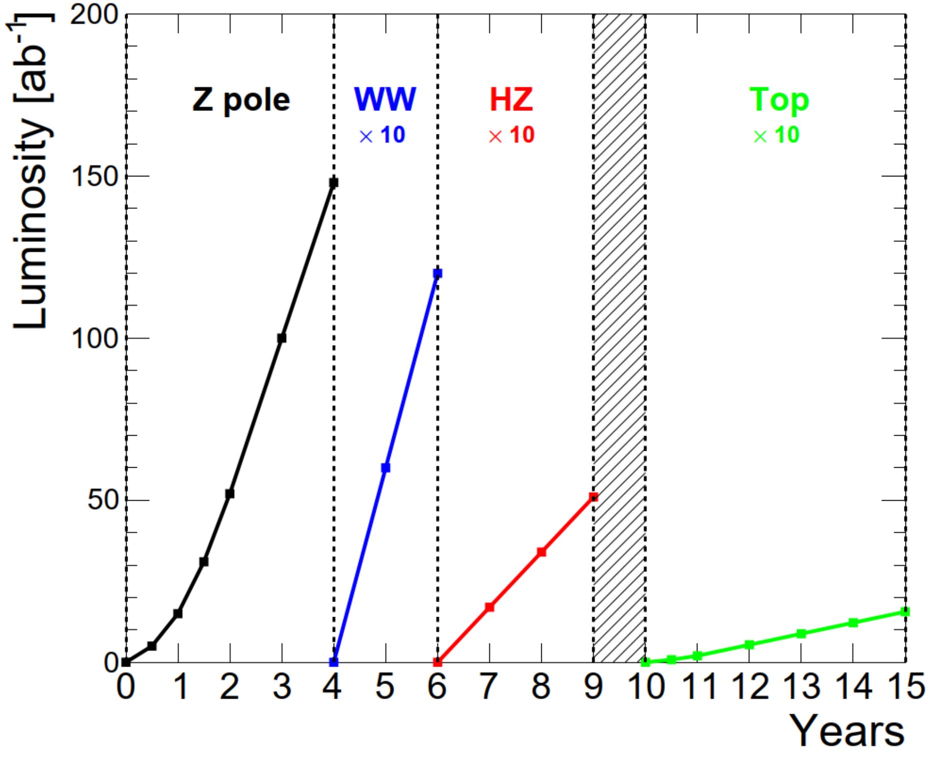
# FCC-ee CDR baseline parameters with 2 IPs

| parameter | Z | WW | ZH | $t\bar{t}$ | LEP2 |
|---|---|---|---|---|---|
| **energy/beam [GeV]** | **45.6** | **80** | **120** | **182.5** | 105 |
| bunches/beam | 16640 | 2000 | 328 | 48 | 4 |
| beam current [mA] | 1390 | 147 | 29 | 5.4 | 3 |
| **luminosity/IP x $10^{34}$ $cm^{-2}s^{-1}$** | **230** | **28** | **8.5** | **1.6** | 0.0012 |
| energy loss/turn [GeV] | 0.036 | 0.34 | 1.72 | 9.2 | 3.34 |
| **synchrotron power [MW]** | **100** | | | | 22 |
| RF voltage [GV] | 0.1 | 0.75 | 2.0 | 4.0 + 6.9 | 3.5 |
| rms bunch length (SR,+BS) [mm] | 3.5, 12 | 3.0, 6.0 | 3.2, 5.3 | 2.0, 2.5 | 12, 12 |
| rms emittance $\varepsilon_{x,y}$ [nm, pm] | 0.27, 1 | 0.84, 1.7 | 0.63, 1.3 | 1.5, 2.9 | 22, 250 |
| longit. damping time [turns] | 1273 | 236 | 70 | 20 | 31 |
| vert. IP beta function $\beta_y$* [mm] | 0.8 | 1.0 | 1.0 | 1.6 | 50 |
| beam lifetime, rad. Bb + BS [min] | 68 | 59 | 12 | 12 | 434 |

# bunches reduced at higher energy, much smaller $\beta$* & emittance than LEP, beamstrahlung affects $\sigma_z$ and $\tau$

# luminosity per IP for 4 (5) modes of operation



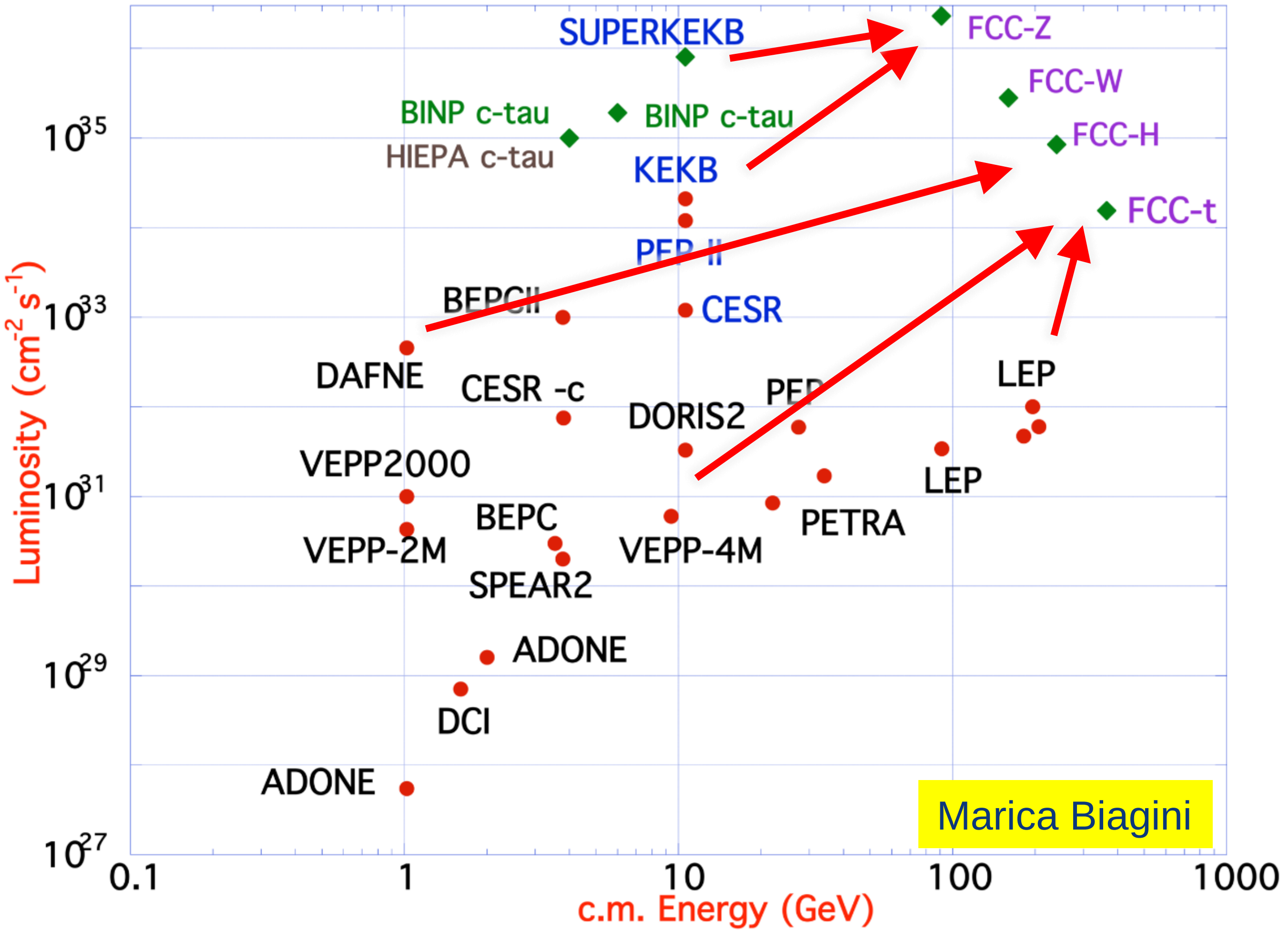




**physics run plan**

A. Blondel,
P. Janot, et al.

# FCC-ee design concept

## based on lessons and techniques from past colliders (last 40 years)




*B-factories:* KEKB & PEP-II:
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

S-KEKB: low $\beta_y$*, crab waist

LEP: high energy, SR effects

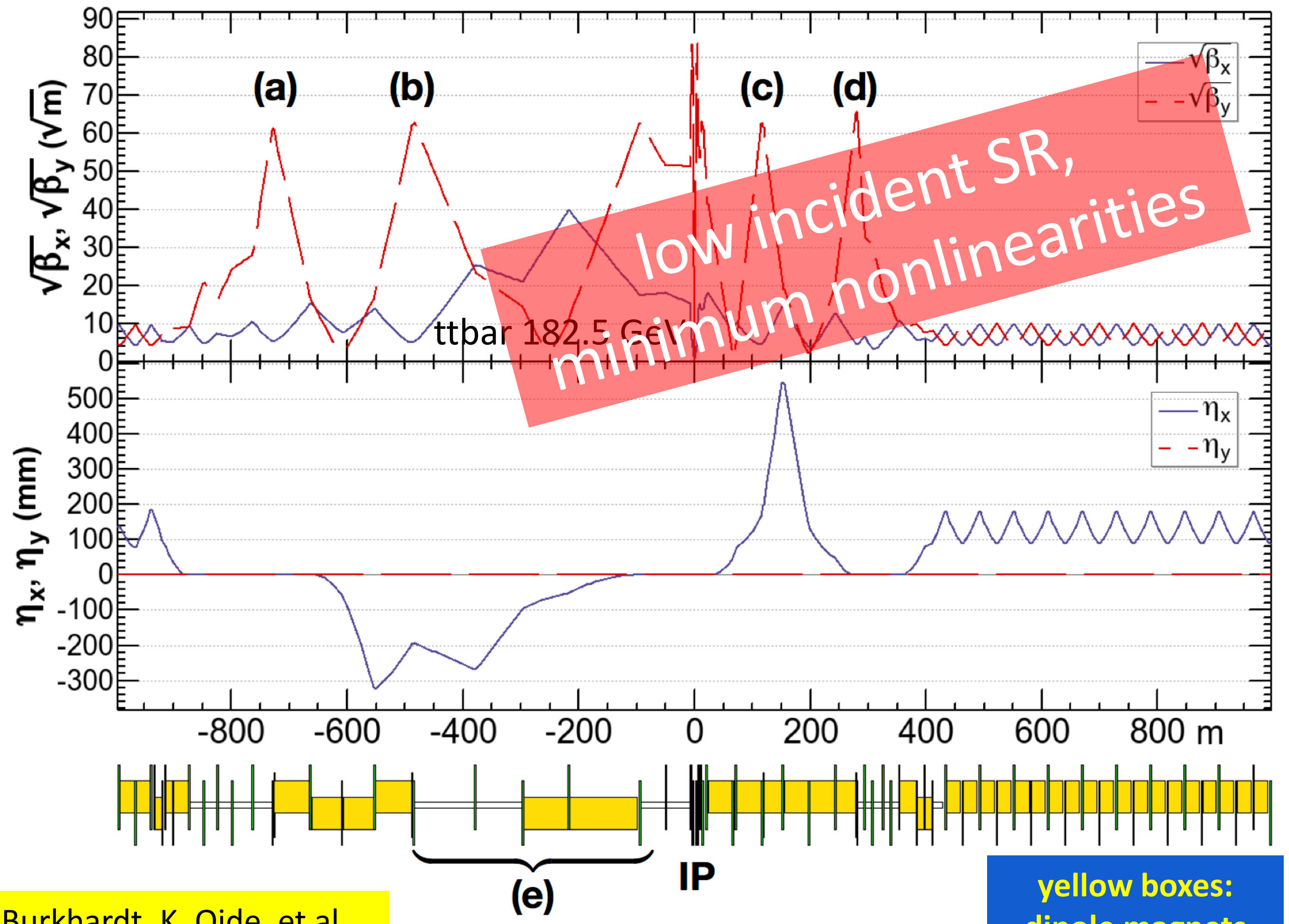
VEPP-4M, LEP: precision E calibration

KEKB: $e^+$ source

HERA, LEP, RHIC: spin gymnastics

**combining successful ingredients of several recent colliders → highest luminosities & energies**

# *new:* FCC-ee asymmetric crab-waist IR optics




yellow boxes: dipole magnets

**Novel asymmetric IR optics** to suppress synchrotron radiation toward the IP, **$E_{critical}$ <100 keV from 450 m from IP (e) – lesson from LEP**

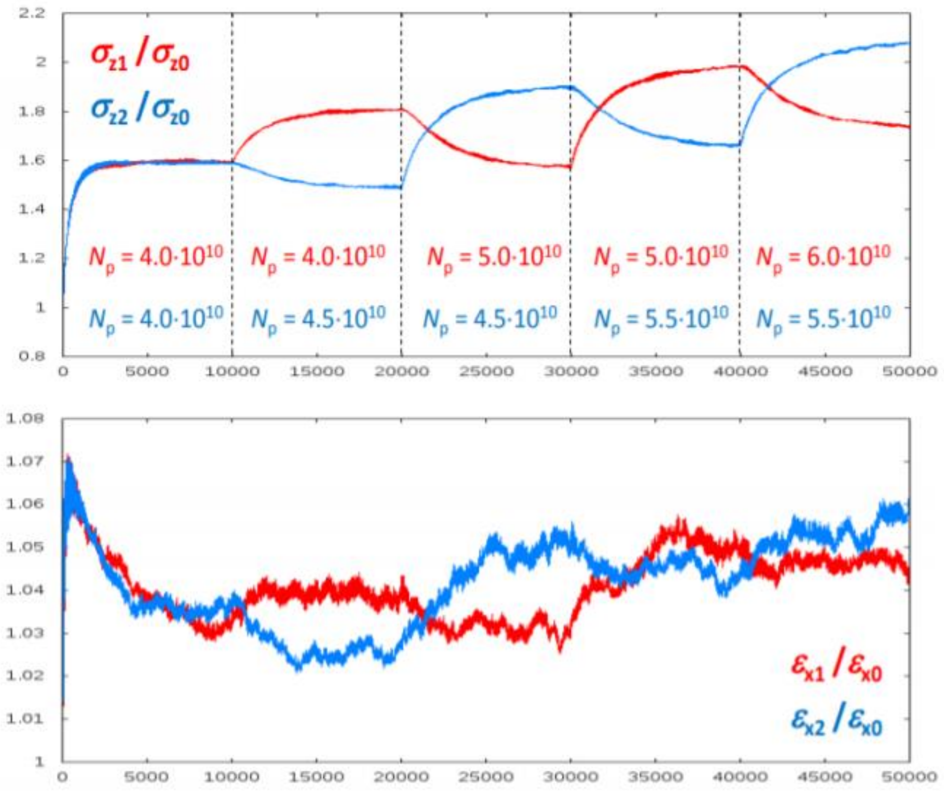
**4 sextupoles (a – d) for local vertical chromaticity correction combined with crab waist,** optimized for each working point – **novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

K. Oide et al., Design of beam optics for the future circular collider $e^+e^-$ collider rings, **Phys. Rev. Accel. Beams 19**, 111005 (2016).

H. Burkhardt, K. Oide, et al.

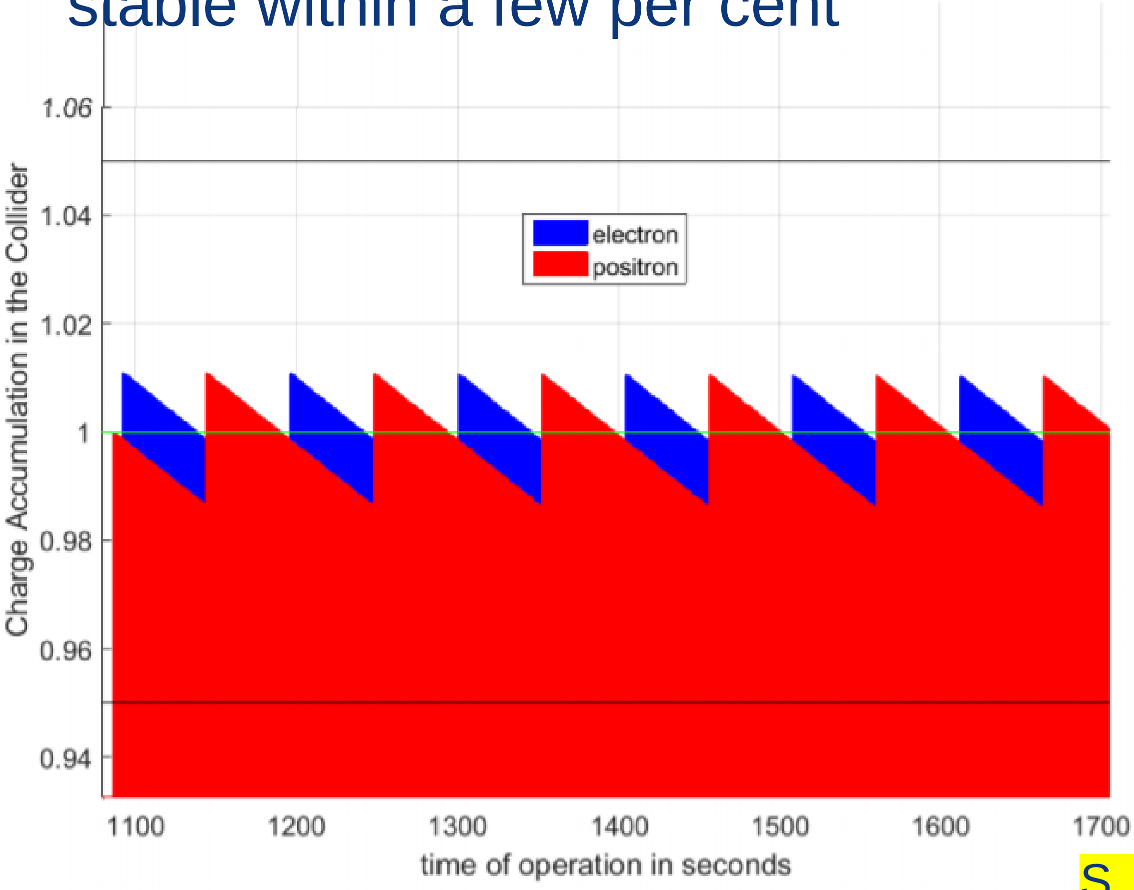
# *new*: “bootstrapping” & top-up injection

injection from zero, alternating between beams to avoid beam-beam flip-flop effect




D. Shatilov

alternating replenishment of the two colliding beams, keeping beam currents stable within a few per cent

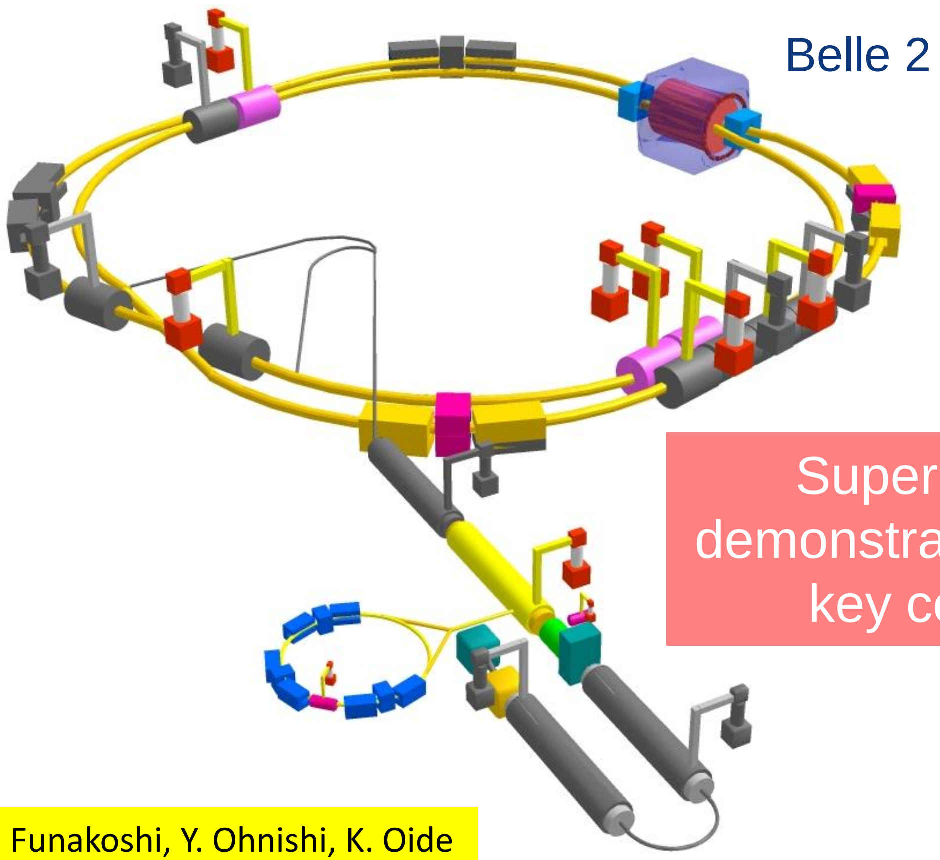



S. Ogur

average luminosity ~ peak luminosity

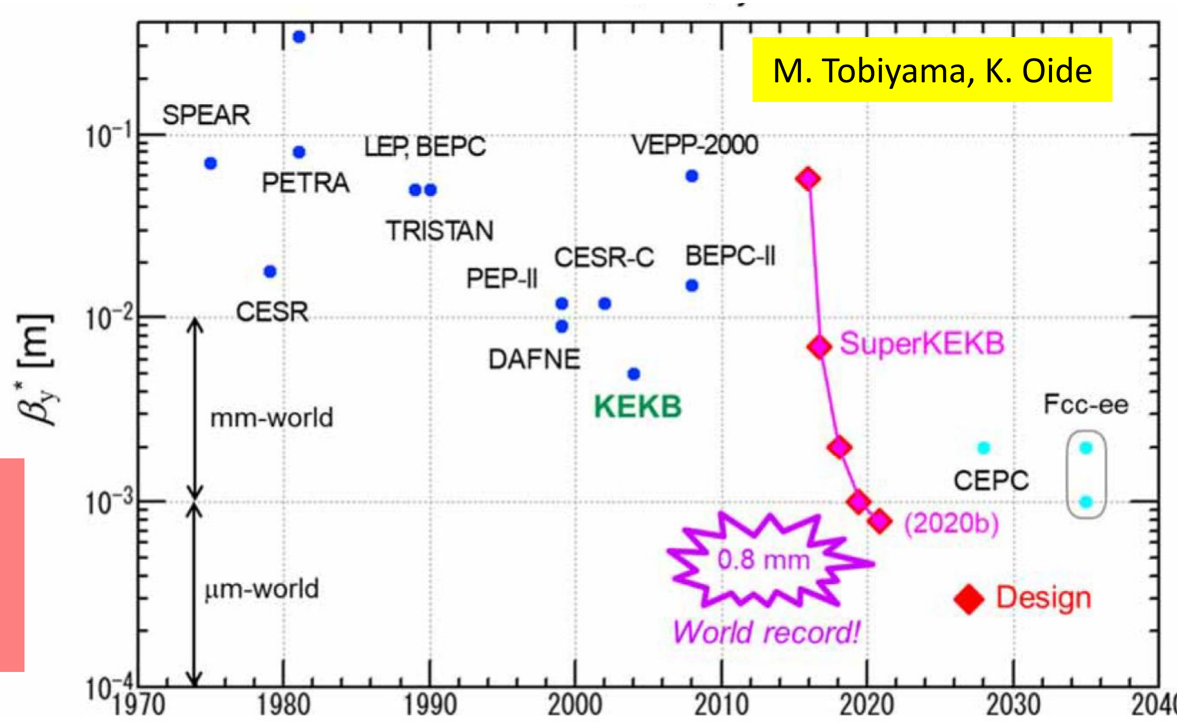
# SuperKEKB – "FCC-ee demonstrator"

**Double ring $e^+e^-$ collider *B*-factory** at 7($e^-$) & 4($e^+$) GeV; **design luminosity ~8 x $10^{35}$ cm$^{-2}$s$^{-1}$**;
**design $\beta_y^*$ ~ 0.3 mm; beam lifetime ~5 min**; **top-up** inj.; **~ 2.5 $10^{12}$ $e^+$/s ; under commissioning**




Y. Funakoshi, Y. Ohnishi, K. Oide

SuperKEKB is demonstrating FCC-ee key concepts




**$\beta_y^*$ = 0.8 mm achieved in both rings – using the FCC-ee-style "virtual" crab-waist collision scheme**

new world record *L* = 3.12 x $10^{34}$ cm$^{-2}$s$^{-1}$ on 22 June '21

# KEKB, SuperKEKB ’21, SuperKEKB design

| parameter | KEKB w Belle | | SuperKEKB 2021 w Belle II | | design | |
|---|---|---|---|---|---|---|
| | | | $\beta_y^*$ = 1.0 mm CW | | | |
| | LER | HER | LER | [illegible] | [illegible] | [illegible]ER |
| E [GeV] | 3.5 | 8 | 4 | [illegible] | [illegible] | [illegible] |
| $\beta_x^*$ (mm) | 1200 | 1200 | [illegible] | [illegible] | [illegible] | [illegible] |
| $\beta_y^*$ (mm) | 5.9 | [illegible] | [illegible] | [illegible] | [illegible] | **0.30** |
| $\varepsilon_x$ (nm) | 18 | [illegible] | [illegible] | [illegible] | [illegible] | 4.6 |
| $\varepsilon_y$ (pm) | [illegible] | [illegible] | [illegible] | [illegible] | **8.6** | **12.9** |
| I (mA) | [illegible] | [illegible] | [illegible] | [illegible] | **3600** | **2600** |
| $n_b$ | [illegible] | | [illegible] | | 2500 | |
| $I_b$ (mA) | [illegible] | [illegible] | [illegible] | **0.585** | 1.44 | 1.04 |
| $\xi_y$ * | [illegible] | [illegible] | **[illegible]046** | **0.030** | 0.069 | 0.060 |
| $L_{sp}$ ($10^{30}$cm[illegible] | [illegible] | | 67.6 | | 214 | |
| L ($10^{34}$cm$^{-2}$s$^{-1}$) | [illegible].11 | | 3.12 | | 80 | |

**50% more luminosity than KEKB with half the beam currents → greatly 6x improved “efficiency” – concepts validated – , but still long way to go**

# SuperKEKB – lessons learnt & present limits

## FCC-ee demonstrator

- FCC-ee type **“virtual crab waist” collisions** (K. Oide, Phys. Rev. Accel. Beams 19, 111005) work well at S-KEKB
- **smallest $\beta_y^*$ considered for FCC-ee: 1 mm and 0.8 mm**
- $e^+$ prod. rate similar to FCC-ee’s – feasibility shown ; **top-up injection w. <10 min beam lifetime**

## SuperKEKB challenges

- **design luminosity optimistic**: ~2x higher than simulated for ideal case w/o impedance & w/o errors
- **bunch currents and esp. beam currents lower than design**: LER TMCI threshold (impedance model!); bunch lengthening (imp. model) sudden beam losses in the LER (noise?); poor injection efficiency (emittance growth in HER transfer line - CSR?!); beam-beam blow up; collimation & machine protection (aperture bottlenecks near experiment); collision stability; lack of beam diagnostics; aging equipment (inherited from TRISTAN) ; aging accelerator experts (many working far beyond retirement age)
- **vertical emittances 4-10x too large, even at low current & w/o collision**
- **$\beta_y^*$ still 3-4 times larger than design**: detector background, limited IR aperture & large emittance of inj. beam

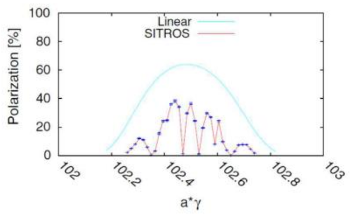
**New International Task Force was formed two months ago to address these challenges**

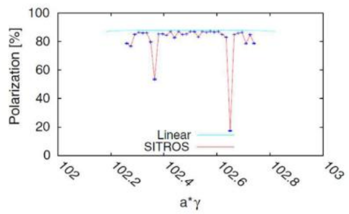
# precise energy calibration by res. depolarisation

Z pole with polarisation wigglers

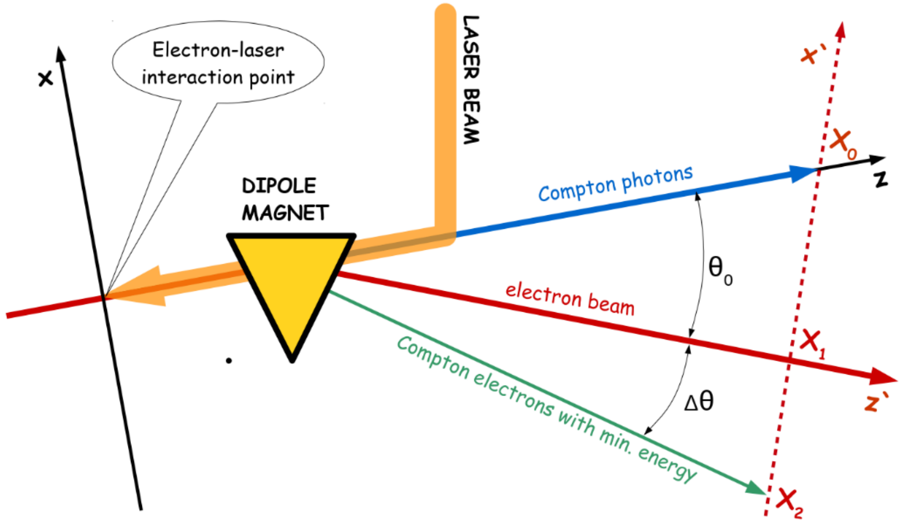
E. Gianfelice-Wendt, *Investigation of beam self-polarization in the future $e^+e^-$ circular collider*, **Phys. Rev. Accel. Beams 19**, 101005 (2016).

orbit correction + harmonic bumps



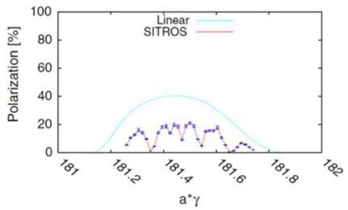

**Z pole: 8 asymmetric wigglers per beam** lower the polarisation rise time to 12 hours allowing a level of 10% (5%) beam polarisation, sufficient for the energy calibration by RDP, to be obtained in 90 (45) minutes. **W pair threshold**: **spontaneous polarisation** with a rise-time of around 10 hours without wigglers.

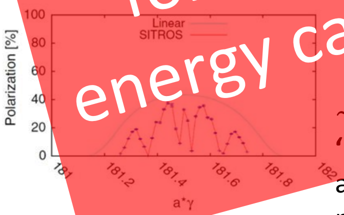



N. Muchnoi, arXiv:1803.09595 (2018).

WW threshold

orbit correction + harmonic bumps



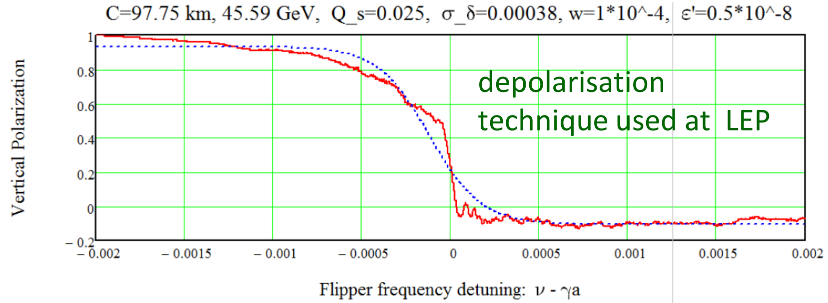




for Z and W: precise energy calibration at $10^{-6}$ level

**RF located in one point ! Largest remaining systematic error:** vertical closed-orbit distortions - at the Z, 100 µm error will induce a possible systematic shift of around 45 keV.

~200 **non-colliding 'pilot' bunches** injected at start of fill and polarised using wigglers

simulated frequency sweep with depolariser




luminosity-averaged centre-of-mass uncertainty:

~100 keV at Z pole
~300 keV at W pair threshold

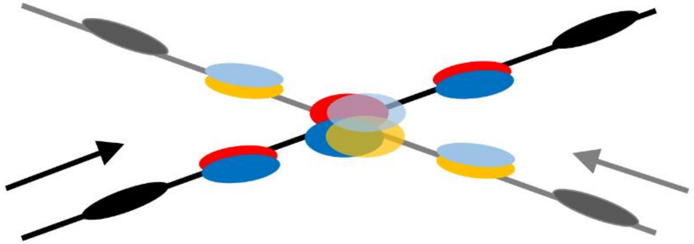
A. Blondel, P. Janot, J. Wenninger et al.

# monochromatized direct Higgs production at 125 GeV c.m. to measure $e^-$ Yukawa coupling ?

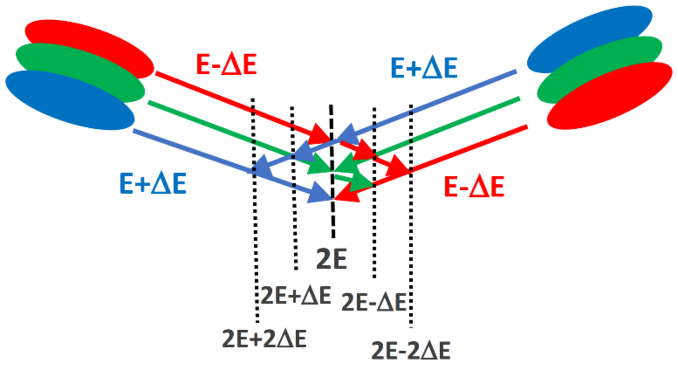
$D_x^* \neq 0$

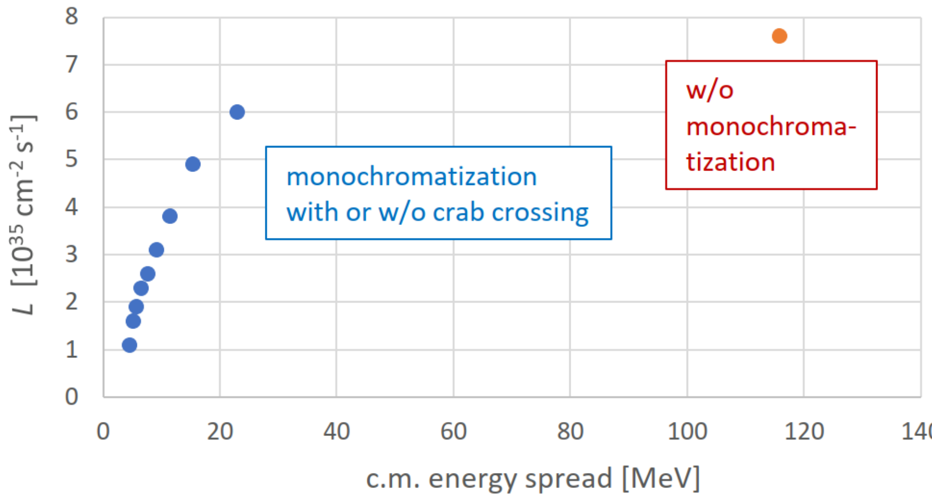
M.A. Valdivia Garcia, A. Faus-Golfe, A. Blondel, F. Zimmermann et al.

w crab cavities

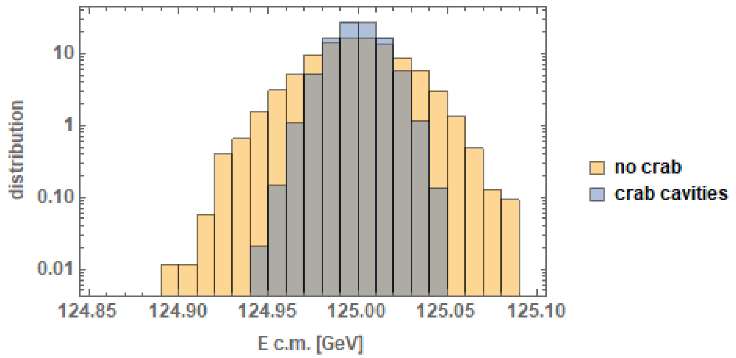


w/o crab cavities

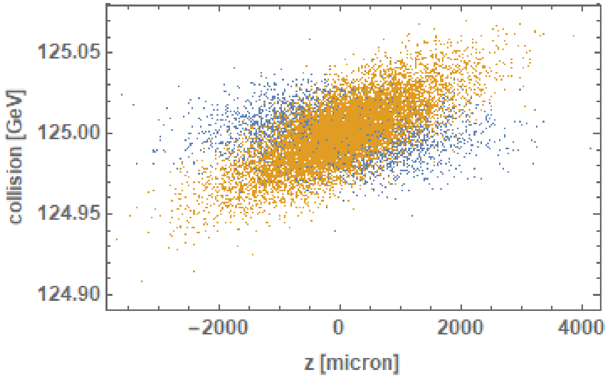



*including beamstrahlung*




integrated resonance scan



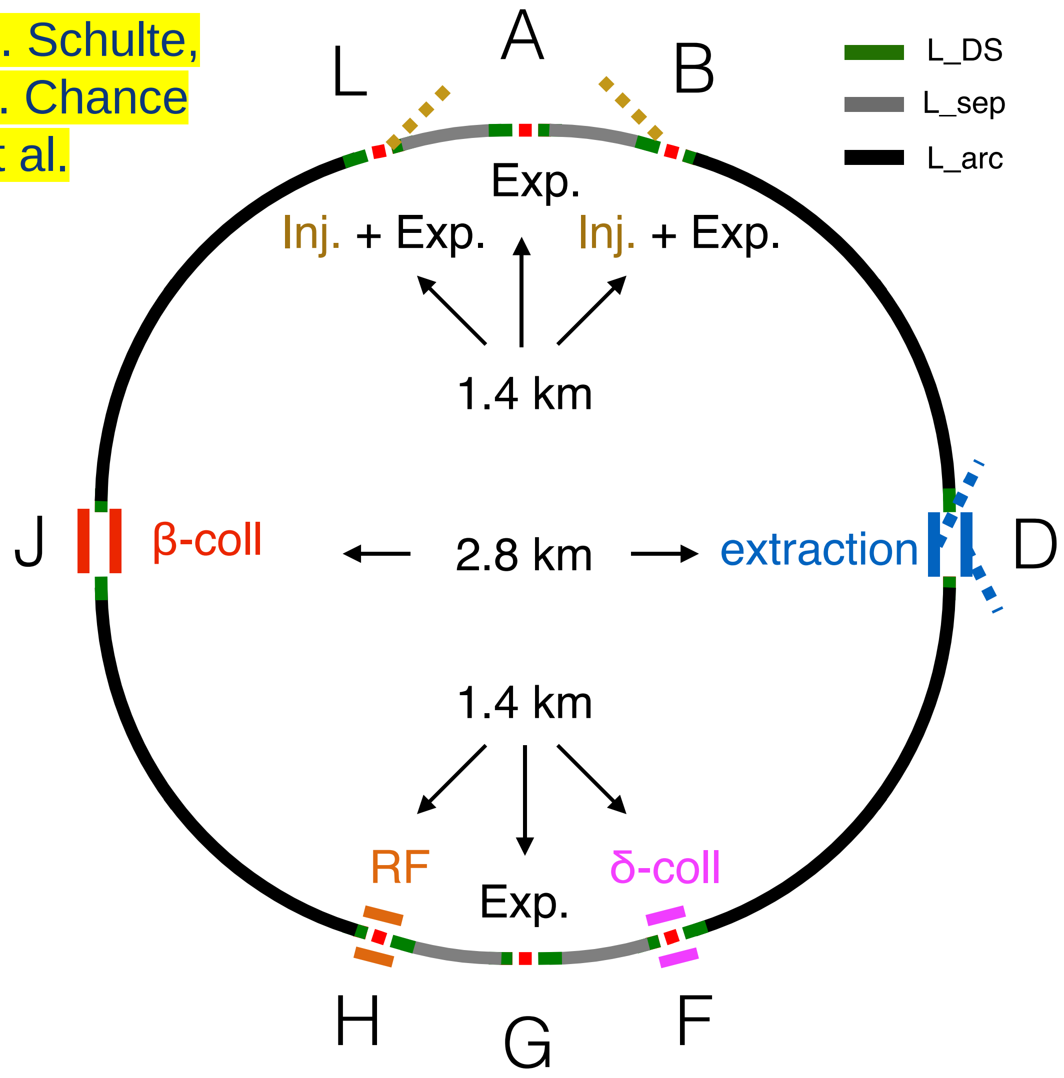

**a few times higher Higgs production rate thanks to monochromatization**

**possibly the only available approach to measure the electron Yukawa coupling !**

FUTURE CIRCULAR COLLIDER

# FCC-hh basic design choices for CDR

D. Schulte, A. Chance et al.



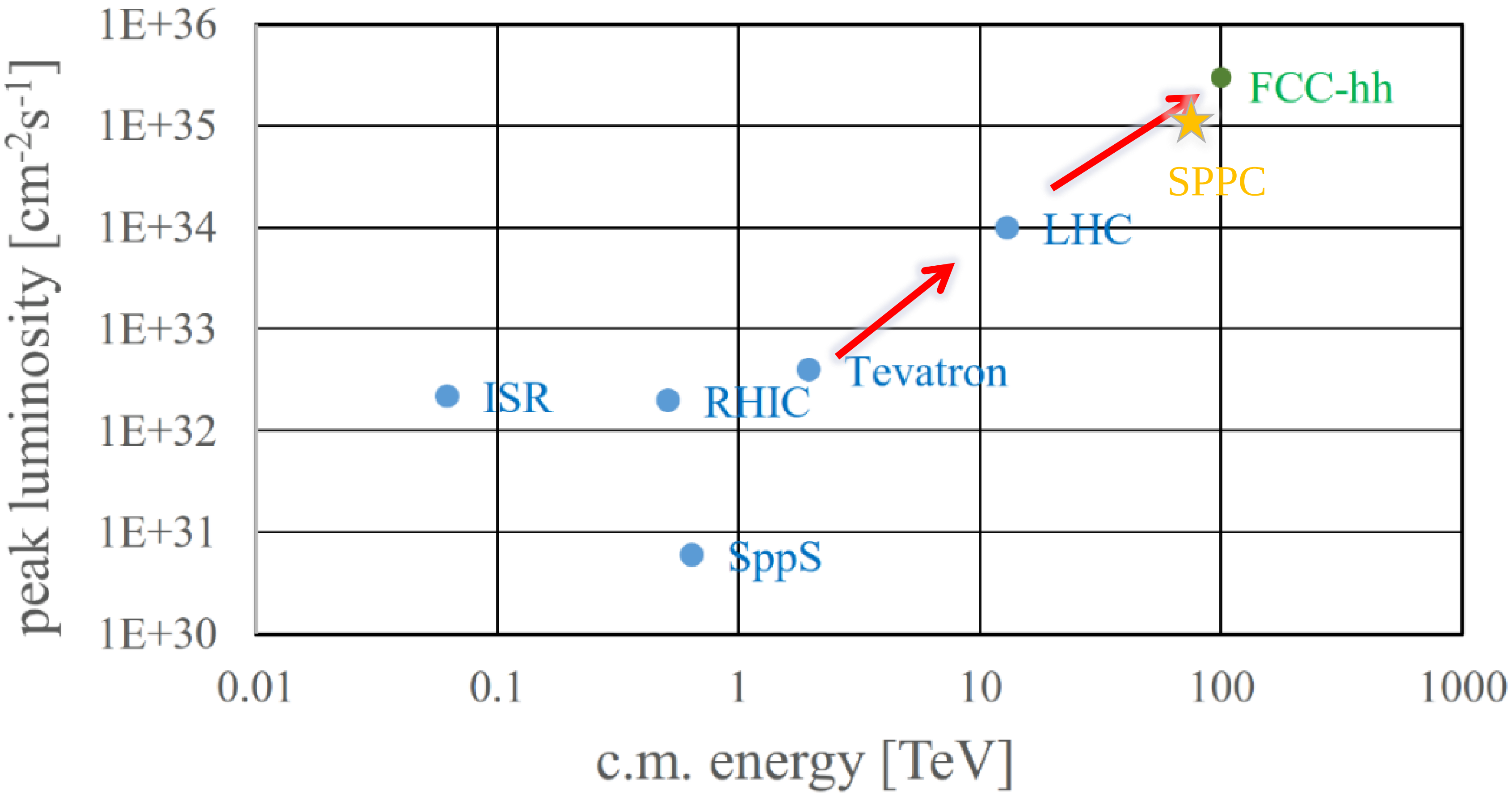

- **dual aperture superconducting magnets**
- **two high-luminosity experiments (A & G)**
- **two other experiments (L & B)** combined with **injection upstream** of experiments
- **two collimation insertions**
  - betatron cleaning (J)
  - momentum cleaning (F)
- **extraction/dump insertion (D)**
- **RF insertion (H)**
- **Injection from LHC (~3 TeV) or scSPS (~1.2 TeV)**
- **Alternative layouts under study**

~4x size & 2x field strength → ~8x energy of LHC

# FCC-hh (pp) parameters

| parameter | FCC-hh | | HL-LHC | LHC |
|---|---|---|---|---|
| **collision energy cms [TeV]** | **100** | | 14 | 14 |
| **dipole field [T]** | **16** | | 8.33 | 8.33 |
| **circumference [km]** | **97.75** | | 26.7 | 26.7 |
| beam current [A] | 0.5 | | 1.1 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 | 25 | 25 |
| **synchr. rad. power / ring [kW]** | **2400** | | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.15 (min.) | 0.55 |
| normalized emittance [mm] | 2.1 | | 2.5 | 3.75 |
| **peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$]** | **5** | **30** | 5 (lev.) | 1 |
| **events/bunch crossing** | **170** | **1000** | 132 | 27 |
| stored energy/beam [GJ] | 8.4 | | 0.7 | 0.36 |

# FCC-hh & SPPC: performance




**order of magnitude performance increase** in **energy & luminosity**

**100 TeV cm collision energy** (vs 14 TeV for LHC)

**FCC-hh : 20 $ab^{-1}$ per experiment collected over 25 years** of operation, SPPC: ~ 10 $ab^{-1}$ over 25 years (vs 3 $ab^{-1}$ for LHC)

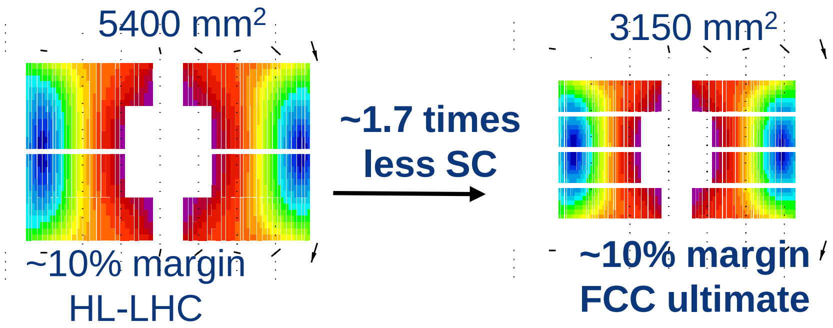
similar performance increase as from Tevatron to LHC

**key technology: high-field magnets**

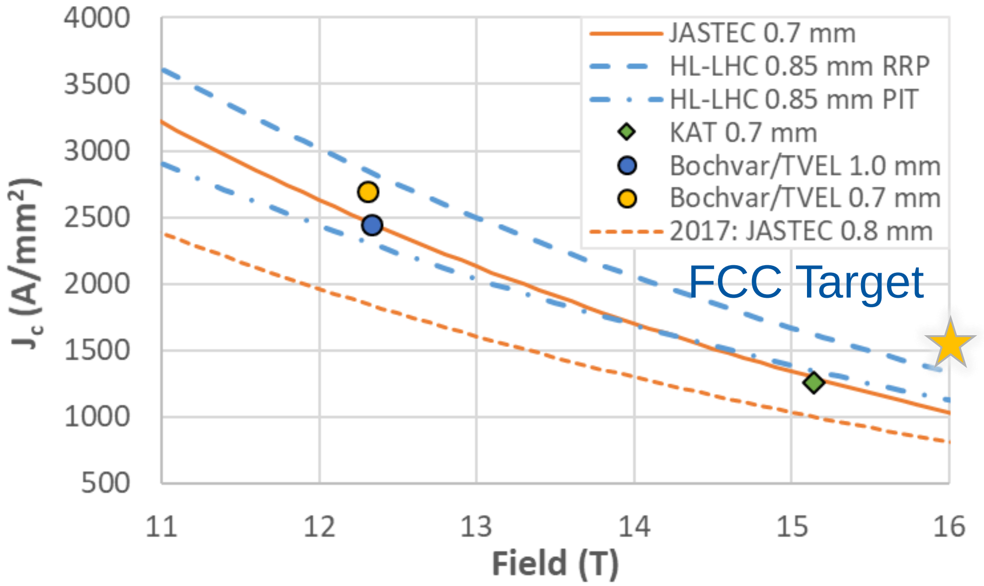
# worldwide FCC $Nb_3Sn$ program

**Main development goal is wire performance increase:**

- **$J_c$ (16T, 4.2K) > 1500 A/mm² →50% increase wrt HL-LHC wire**
- **Reduction of coil & magnet cross-section**




After 1-2 years development, **prototype $Nb_3Sn$ wires from several new industrial FCC partners already achieve HL-LHC $J_c$ performance**




## FCC conductor development collaboration:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **Bruker, Germany, Luvata Pori, Finland**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea, Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy, University of Freiberg**, **Germany**

## 2019/20 results from US, meeting FCC $J_c$ specs:

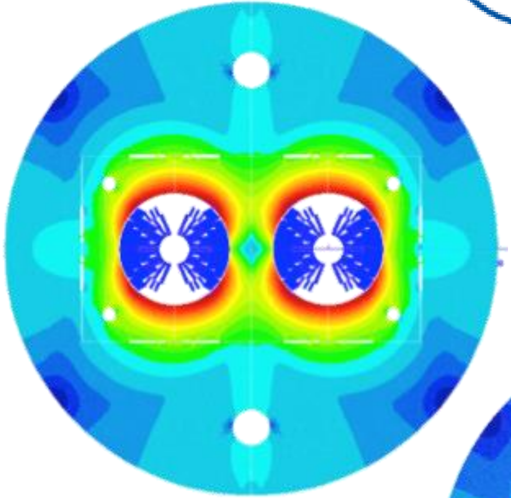
- **Florida State University:** high-$J_c$ $Nb_3Sn$ via Hf addition
- **Hyper Tech /Ohio SU/FNAL**: high-$J_c$ $Nb_3Sn$ via artificial pinning centres based on Zr oxide.

FUTURE CIRCULAR COLLIDER

# 16 T dipole design activities and options

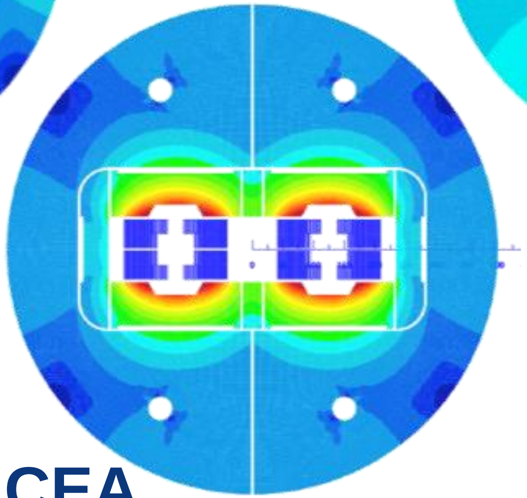
H2020 EuroCirCol A key to New Physics

Cos-theta



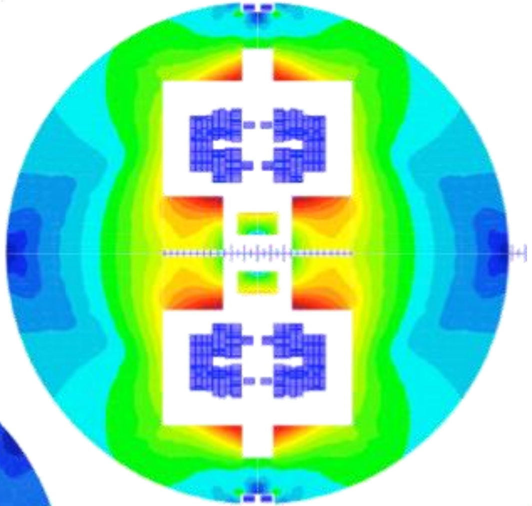
INFN

Blocks



CEA

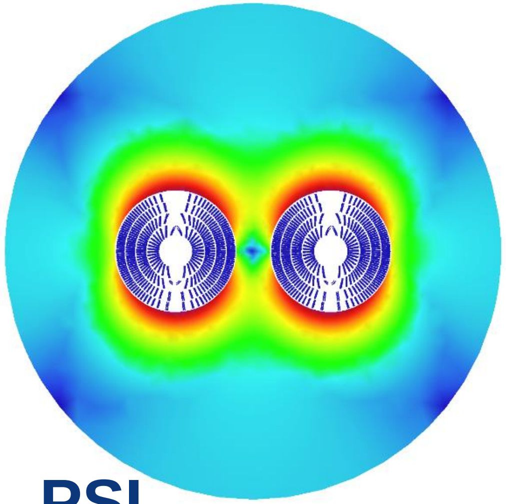
Common coils



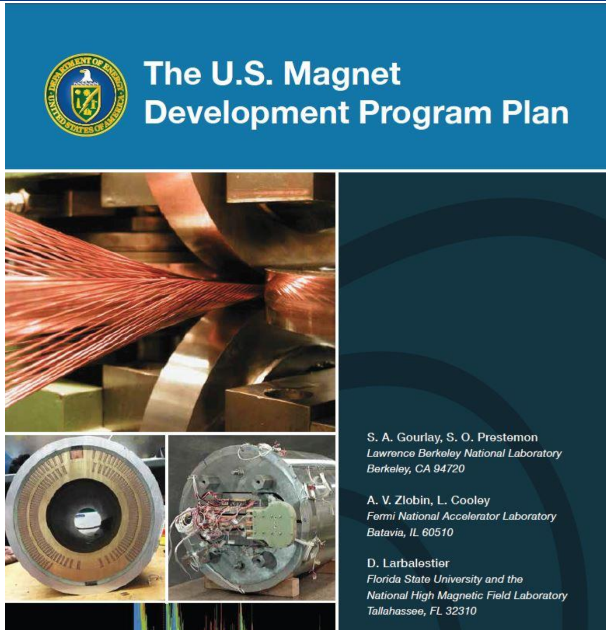
CIEMAT

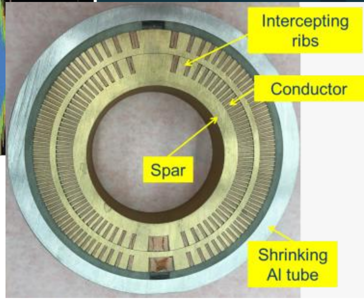
Swiss contribution

Canted Cos-theta

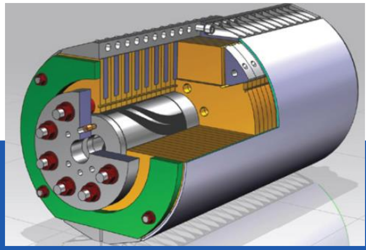


PSI



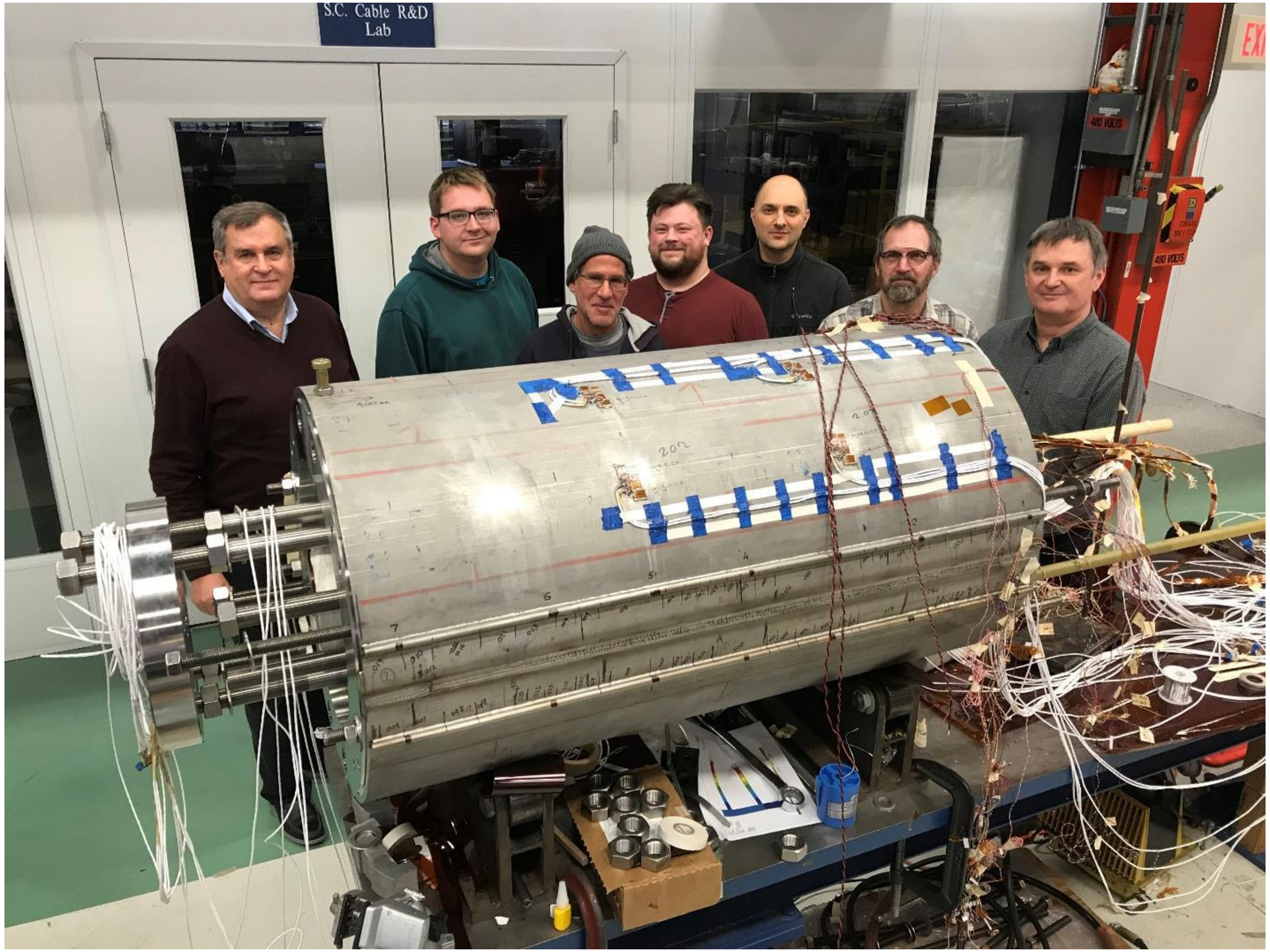

LBNL

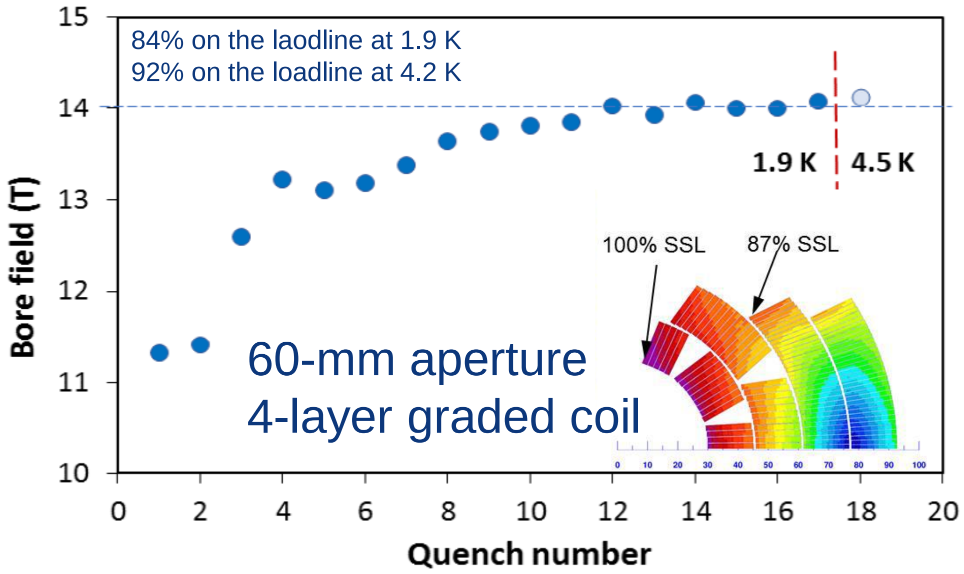


FNAL

**Short model magnets (1.5 m lengths) will be built until 2025**

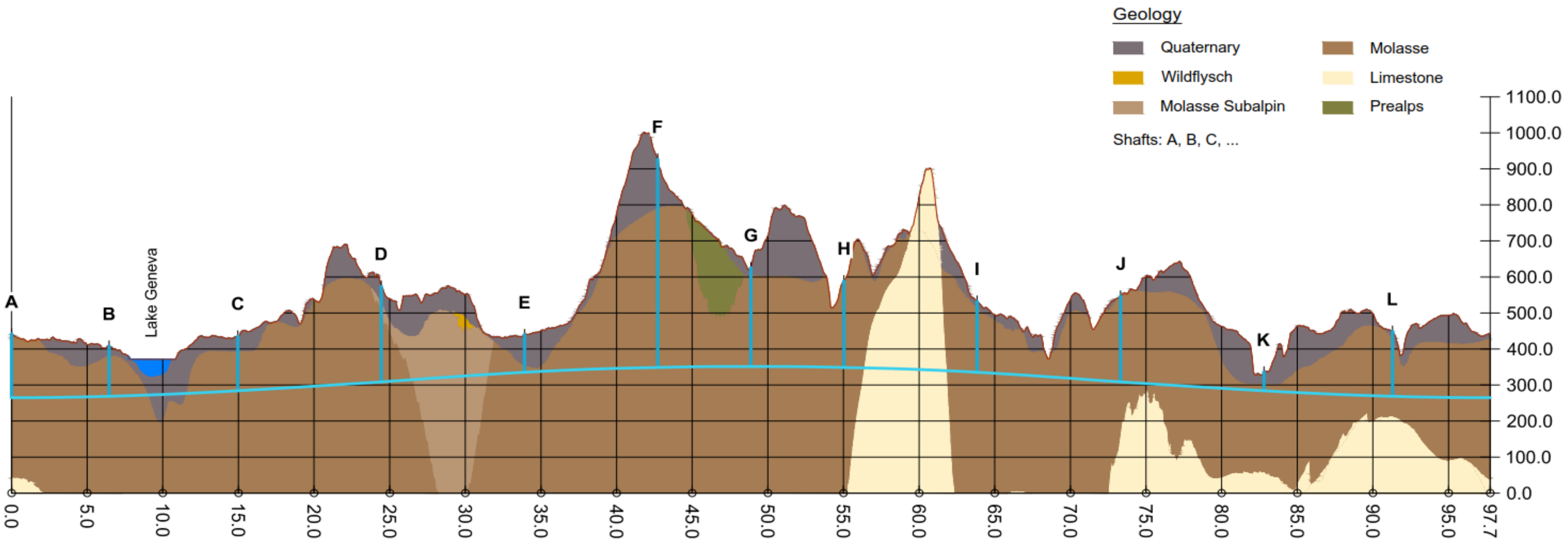
# US – MDP: 14.5 T magnet tested at FNAL

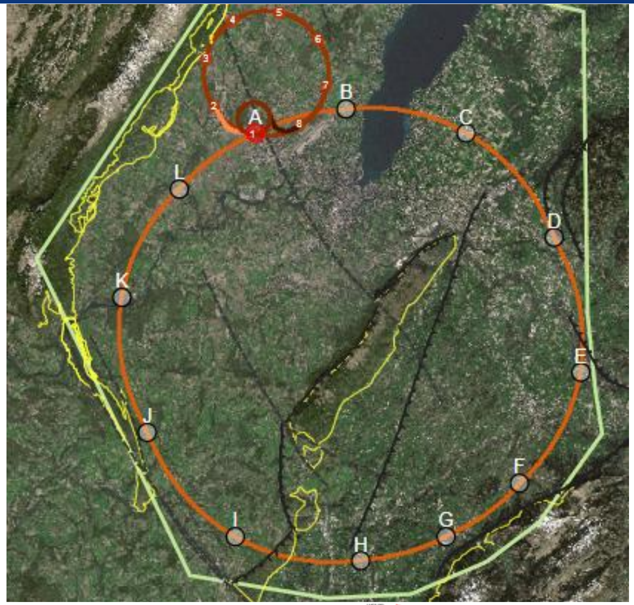


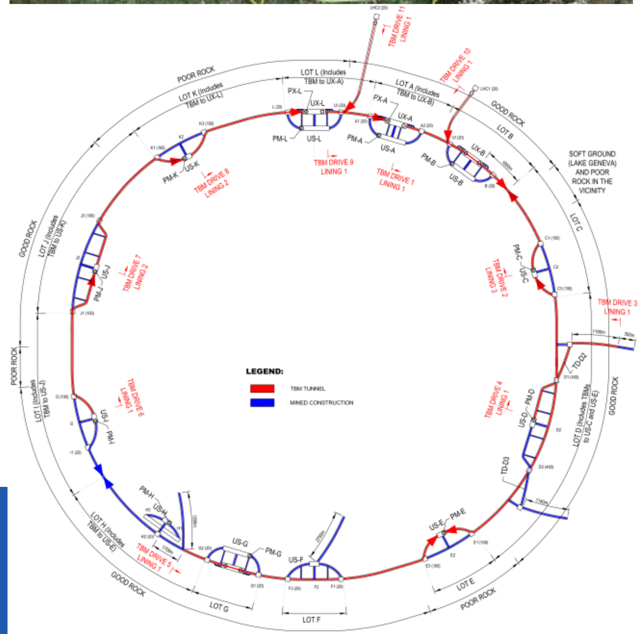




- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in June 2020 with additional pre-stress reached 14.5 T

# FCC implementation - footprint baseline



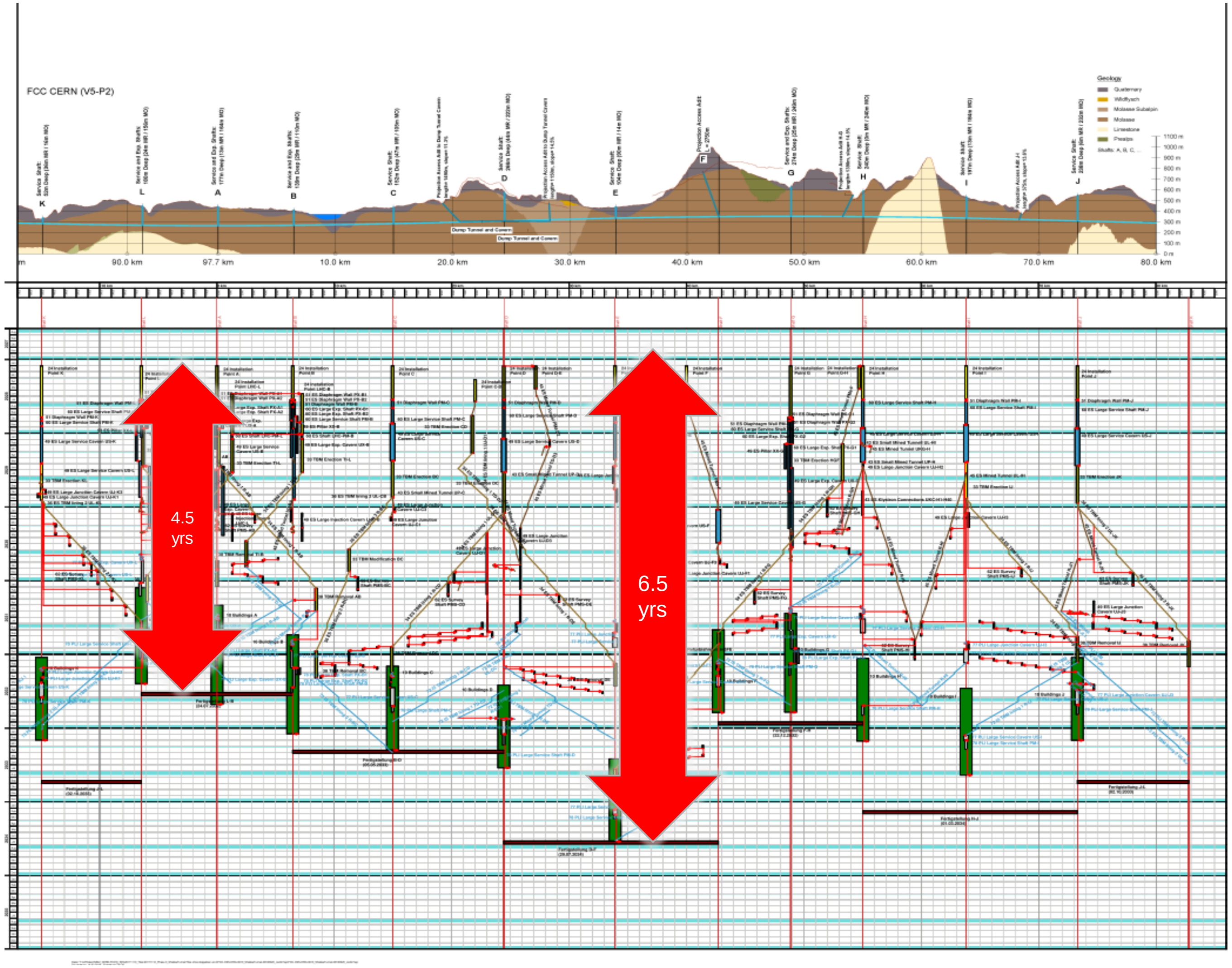



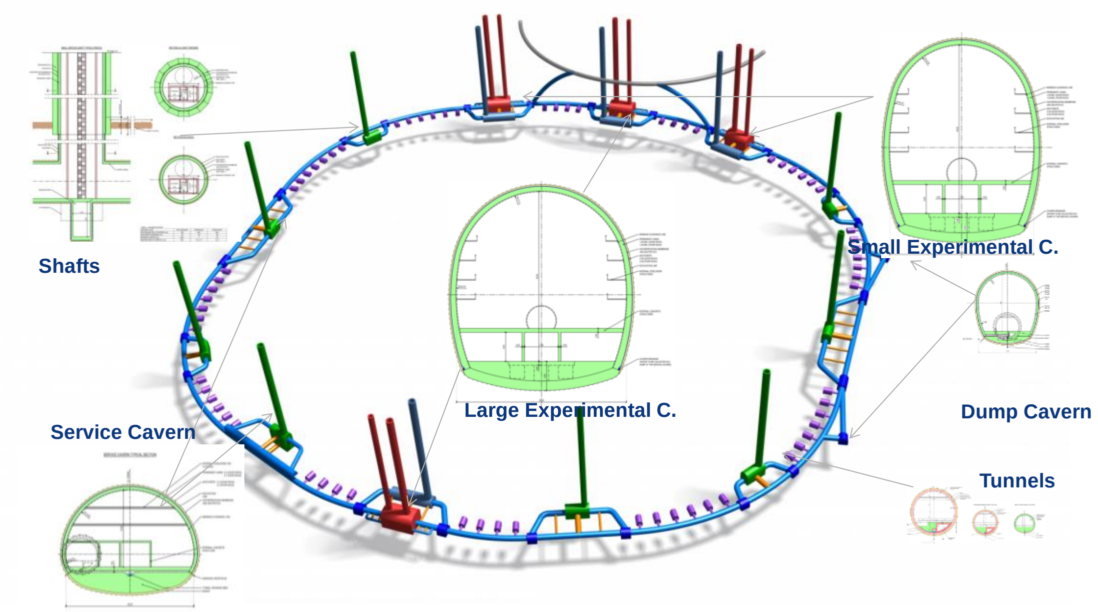

**present baseline position was established considering:**

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

- **90 – 100 km circumference**
- **12 surface sites with ~5 ha area each → recent studies on 8 surface s.**

# Civil engineering studies

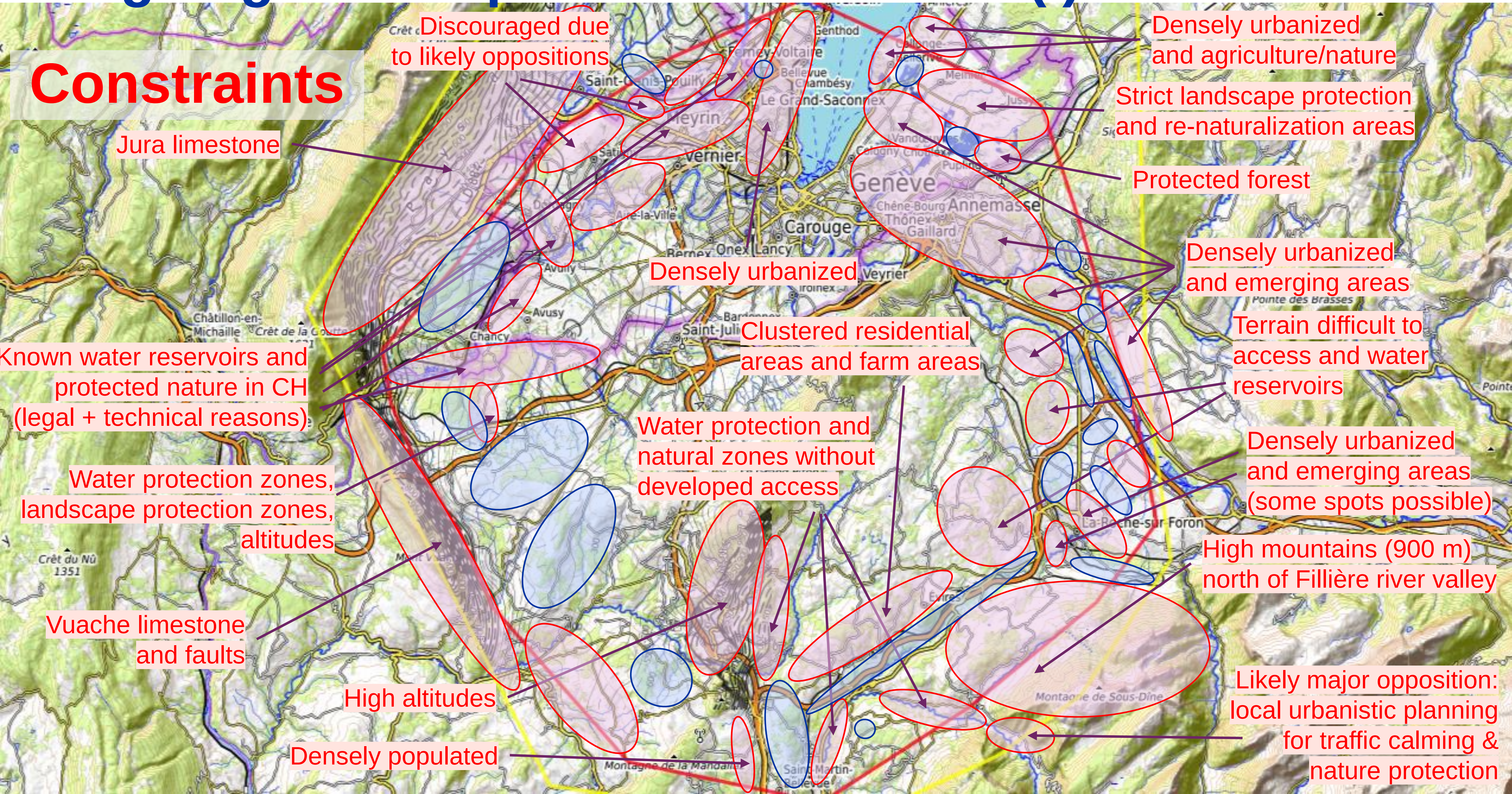



- **Total construction duration 7 years**
- **First sectors ready after 4.5 years for start of technical infrastructure installation**

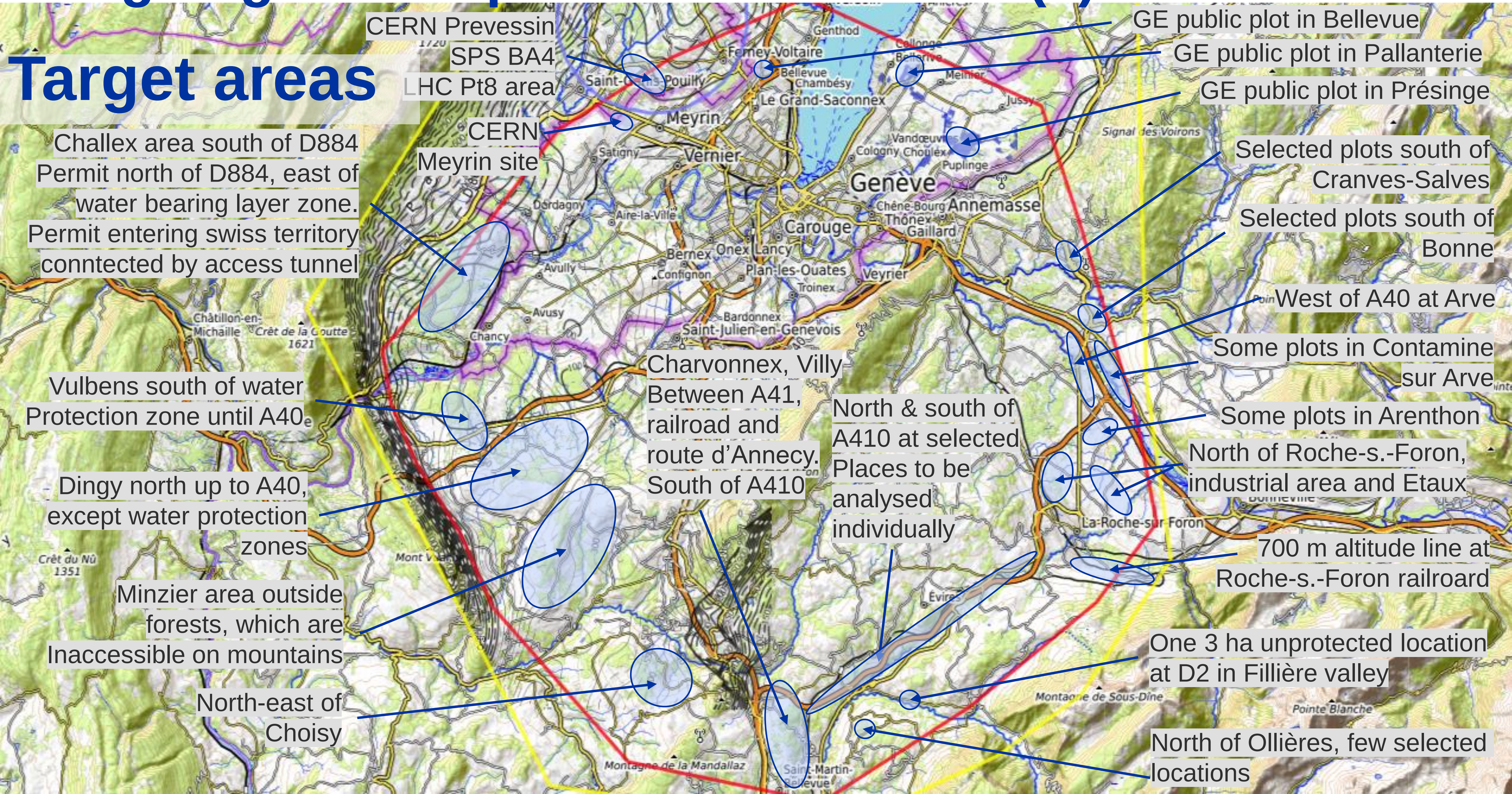
# Ongoing work – placements studies (i)

J. Gutleber, V. Mertens



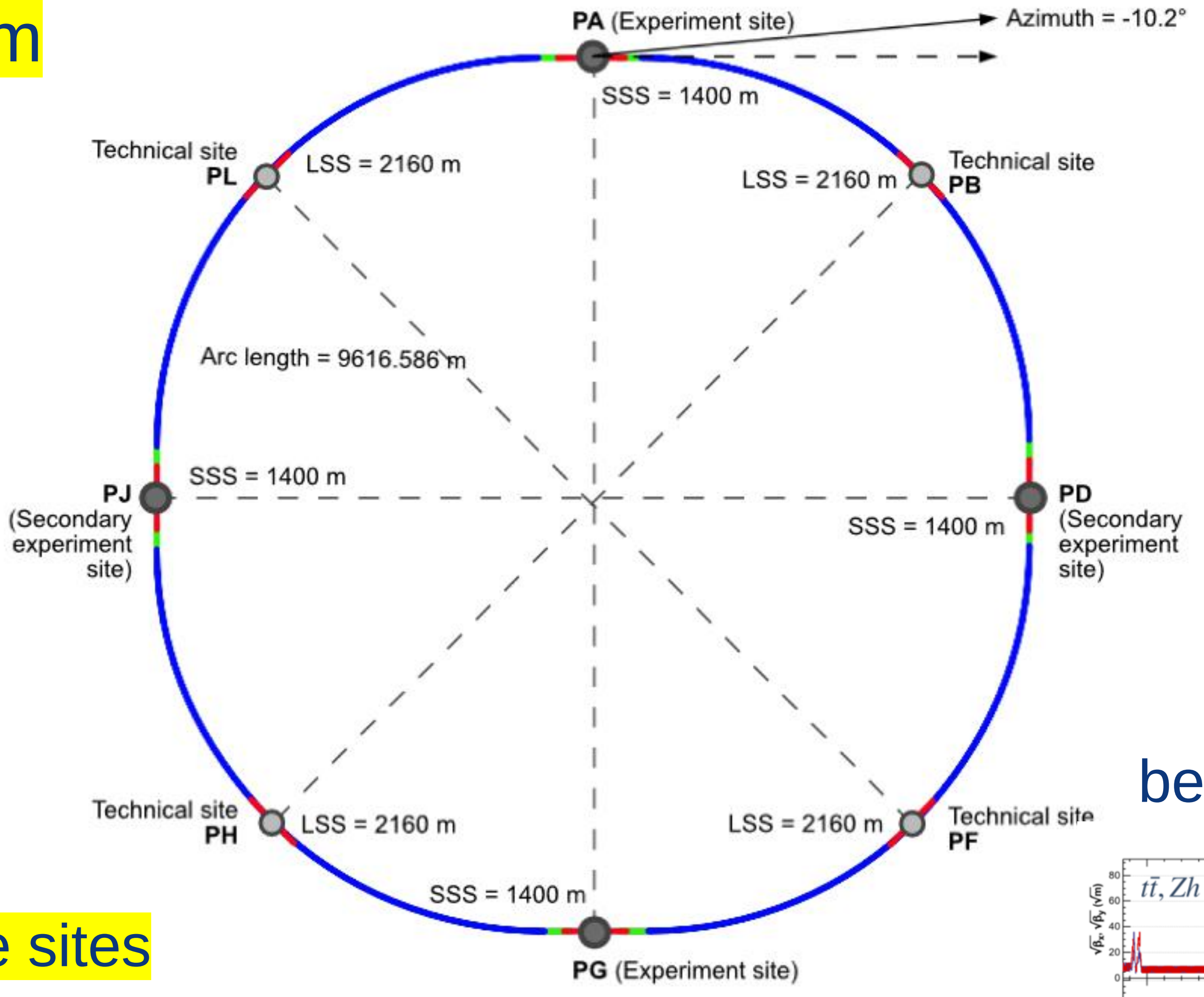
# Ongoing work – placements studies (ii)

J. Gutleber, V. Mertens



# new “lowest risk” placement/optics allows 4 exp’s

C=91 km



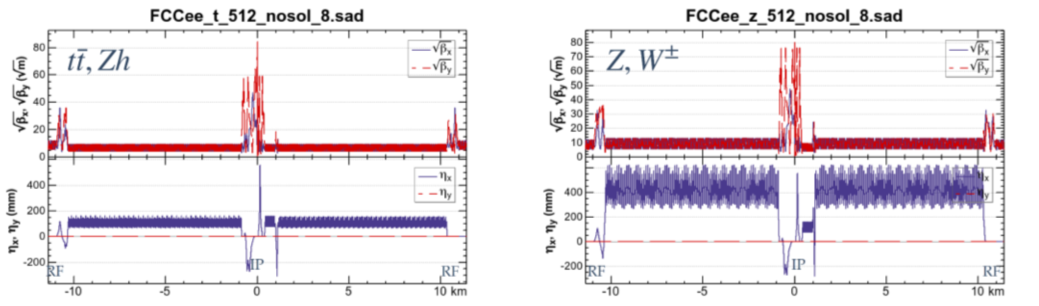

J. Gutleber

perfect symmetry
and
**perfect 4-fold superperiodicity**

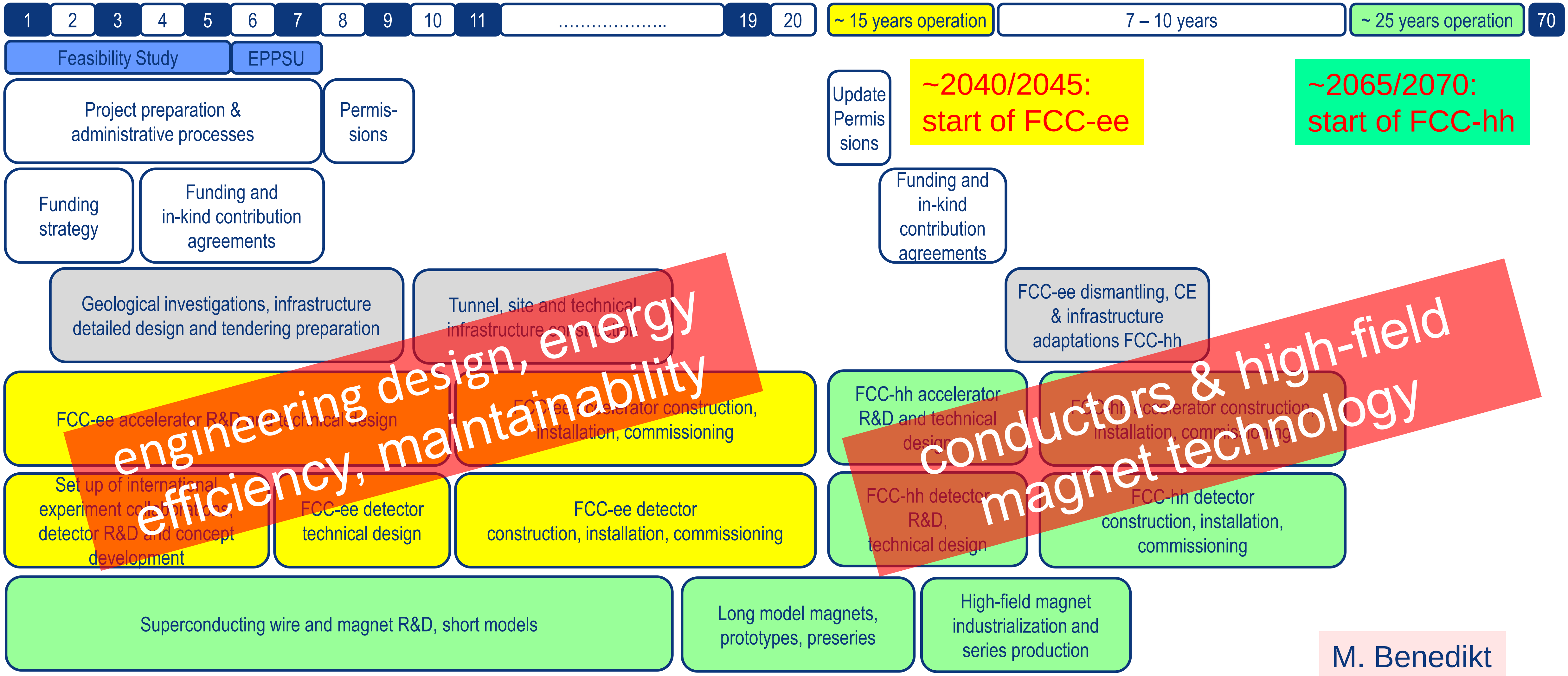
8 surface sites

beam optics for ¼ ring

K. Oide



# FCC integrated project technical schedule



# ESPPU 2020 “Environmental and societal impact”

- The environmental impact of particle physics activities should continue to be carefully studied and minimised. A detailed plan for the **minimisation of environmental impact** and for the **saving and re-use of energy** should be part of the approval process for any major project.

# FCC-ee figures of merit – cost & sustainability

## Luminosity vs. capital cost

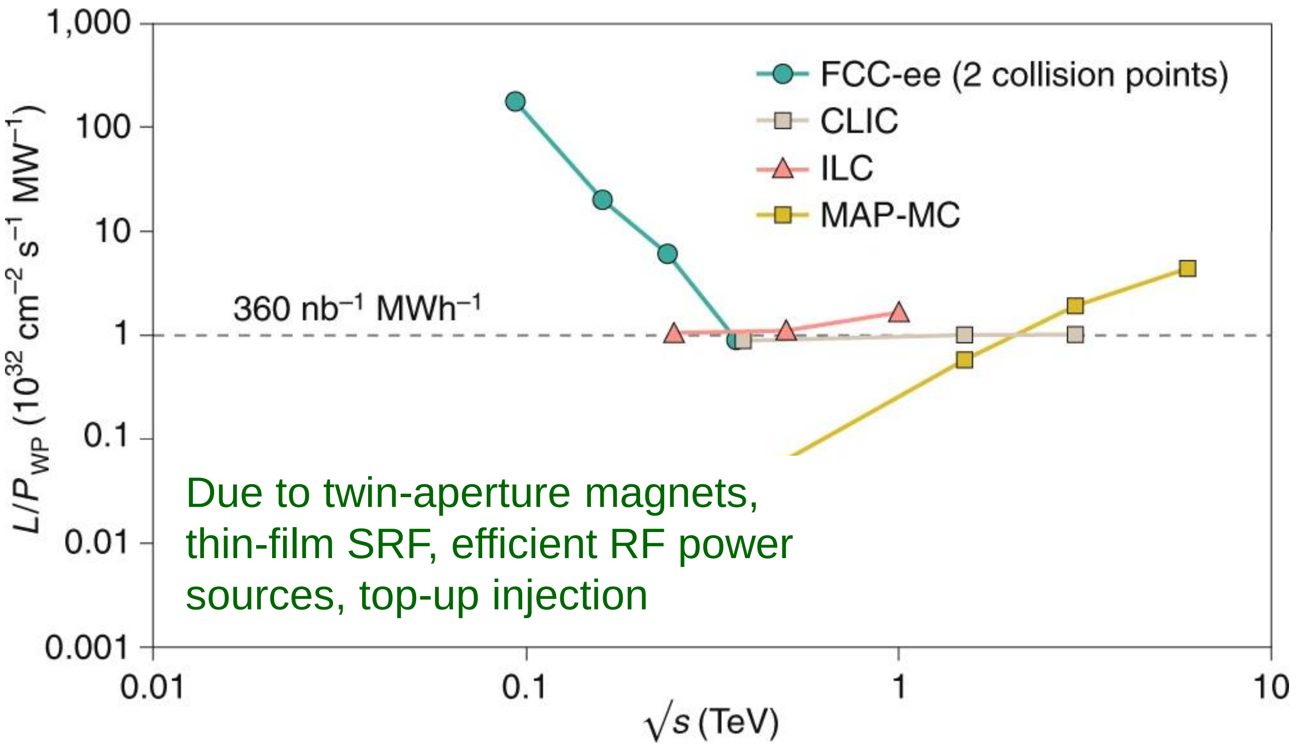
- for the H running, **with 5 $ab^{-1}$ accumulated over 3 years and $10^6$ H produced**, the total investment cost (~10 BCHF) corresponds to
  → **10 kCHF per produced Higgs boson**

- for the Z running with **150 $ab^{-1}$ accumulated over 4 years and $5\times10^{12}$ Z produced,** the total investment cost corresponds to
  → **10 kCHF per $5\times10^6$ Z bosons**

This is the number of Z bosons collected by each experiment during the entire LEP programme !

**Capital cost per luminosity dramatically decreased compared with LEP !**

## Luminosity vs. electricity consumption

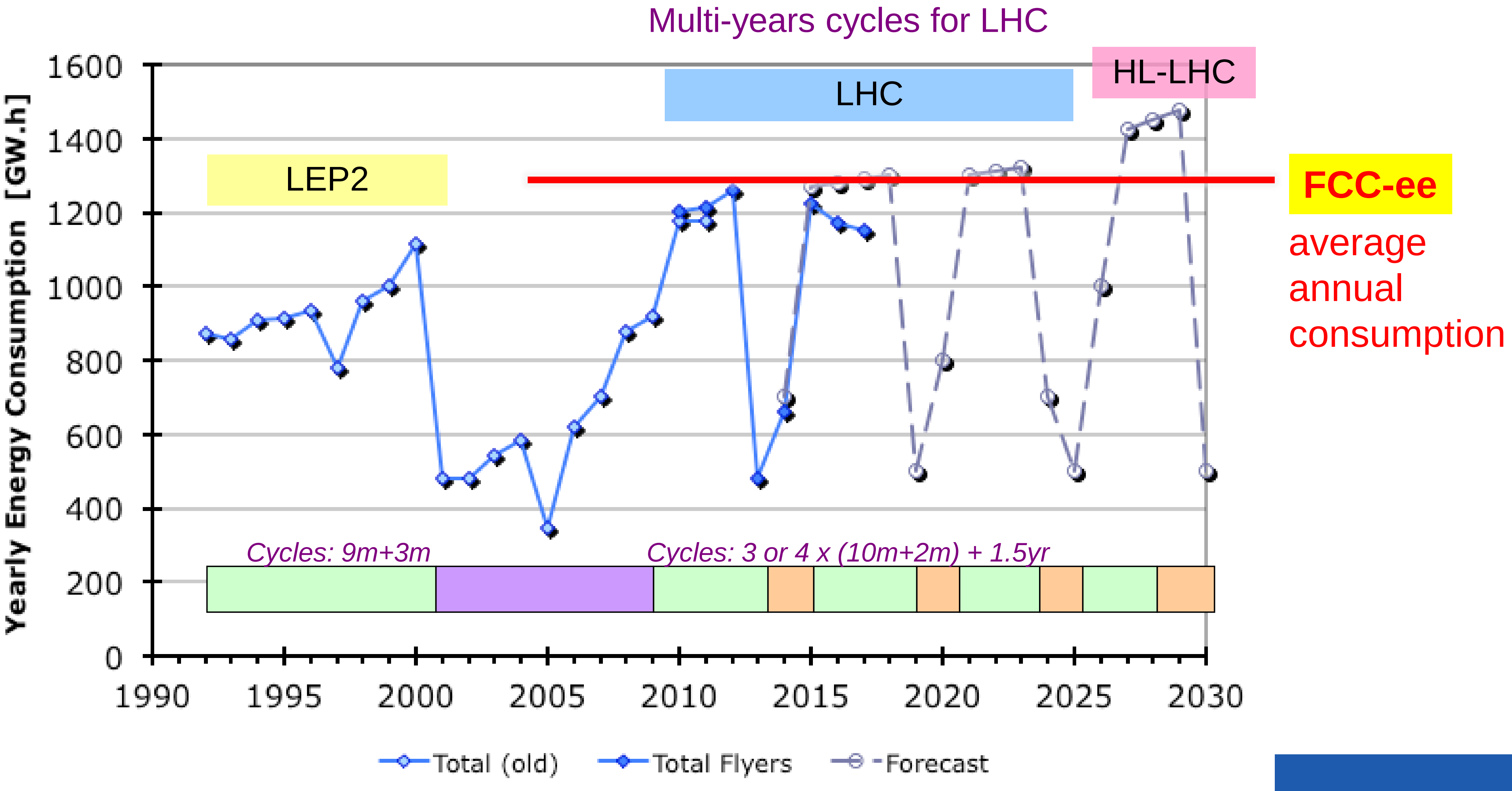



**Highest lumi/power of all proposals**
**Electricity cost ~200 CHF per Higgs boson**



M. Benedikt, A. Blondel, P. Janot, et al., **Nature Physics 16**, 402-407 (2020), and **European Strategy** for Particle Physics Preparatory Group, *Physics Briefing Book* (CERN, 2019)

# energy consumption – example CERN today




V. Mertens

# RF as main power consumer

continually supplying circulating beam with

$P_{SR}$=100 MW power (SR losses) requires

wall-plug power $P_{wall}=P_{SR}/\eta$ , note beam current $I_b \propto L \propto P_{SR}$

with $\eta$=conversion efficiency wall-plug → beam

## FCC strategy:

- RF system optimized for each energy
- high-gradient high-Q SC cavities (low cryo power)
- highly efficient RF power sources

# FCC-ee RF staging scenario (CDR)

FUTURE CIRCULAR COLLIDER

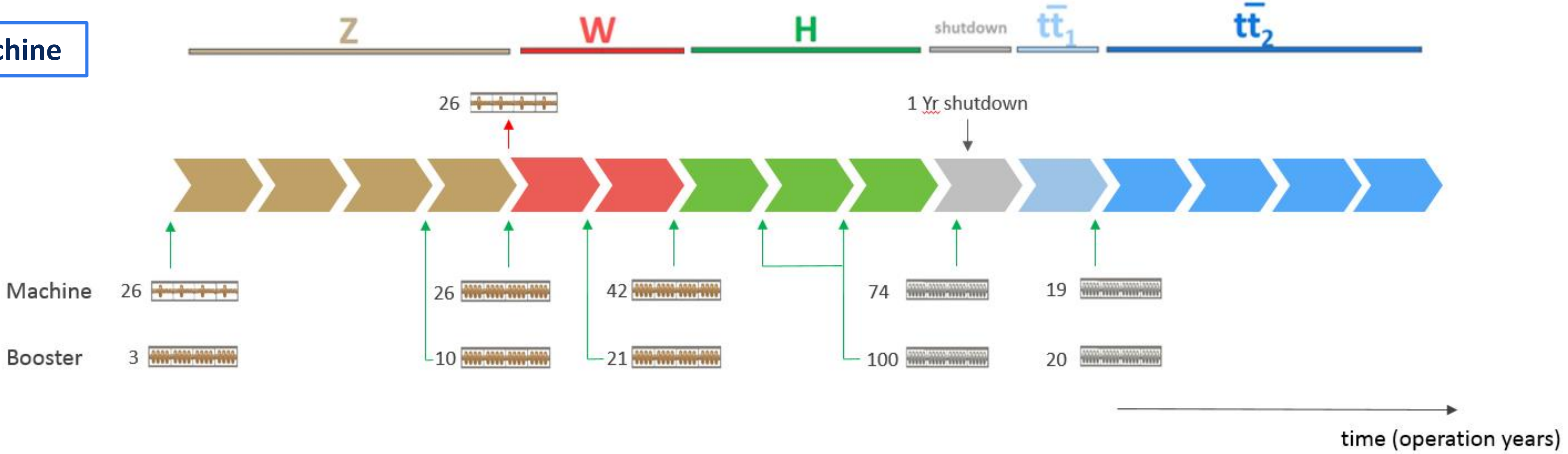
"Ampere-class" machine

| WP | $V_{rf}$ [GV] | #bunches | $I_{beam}$ [mA] |
|---|---|---|---|
| Z | 0.1 | 16640 | 1390 |
| W | 0.44 | 2000 | 147 |
| H | 2.0 | 393 | 29 |
| ttbar | 10.9 | 48 | 5.4 |

"high-gradient" machine

three sets of RF cavities to cover all options for FCC-ee & booster:

- high intensity (Z, FCC-hh): 400 MHz mono-cell cavities (4/cryom.)
- higher energy (W, H, t): 400 MHz four-cell cavities (4/cryomodule)
- ttbar machine complement: 800 MHz five-cell cavities (4/cryom.)
- installation sequence comparable to LEP ( ≈ 30 CM/shutdown)

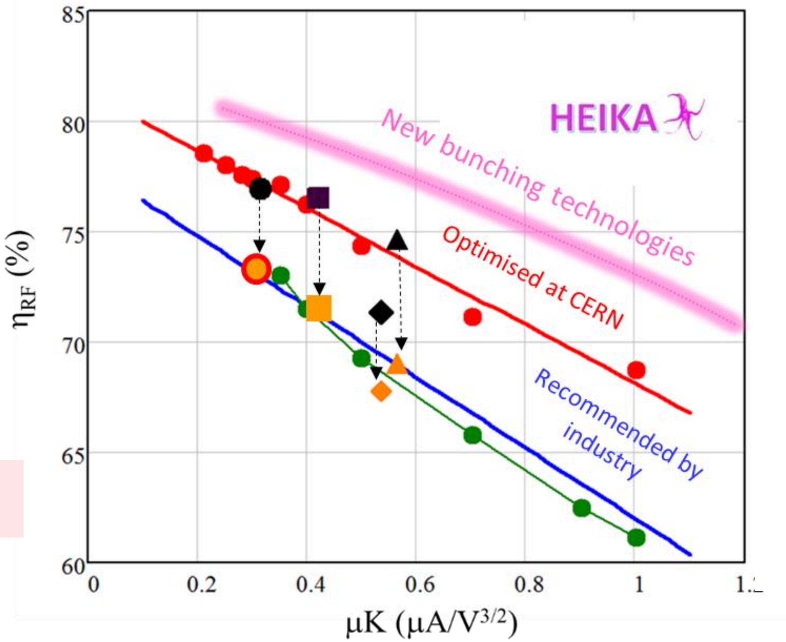



O. Brunner

# “green” energy efficient technologies

FUTURE CIRCULAR COLLIDER

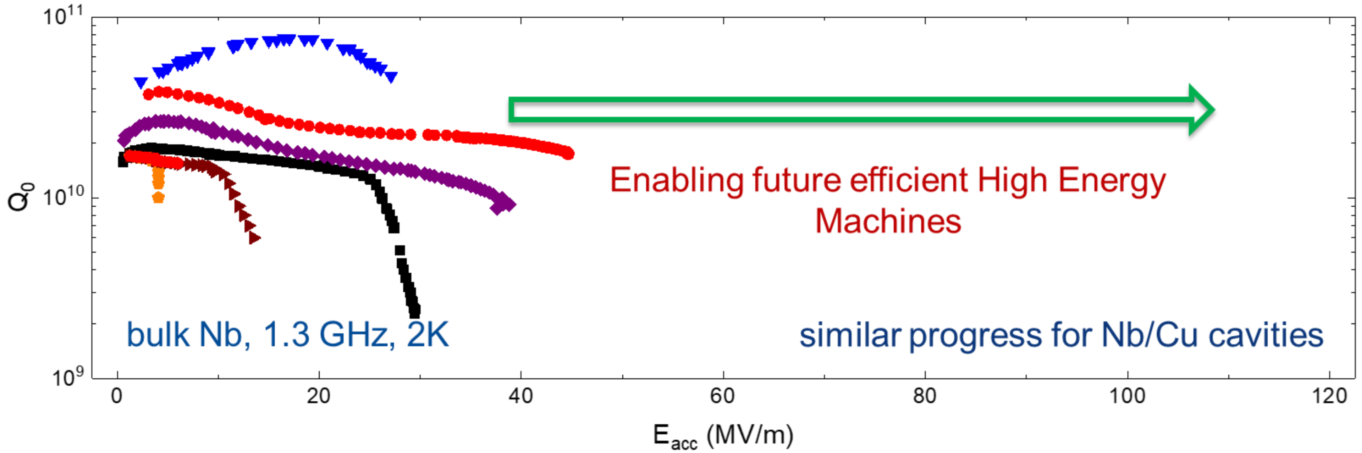
more efficient RF power sources



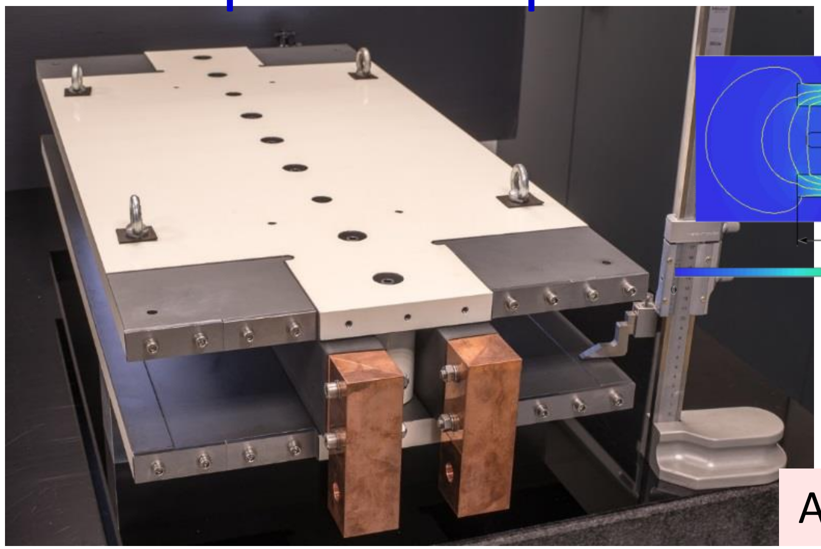

I. Syratchev

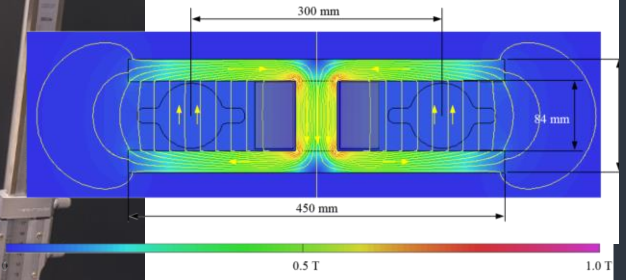
more efficient SC cavities

A. Grasselino

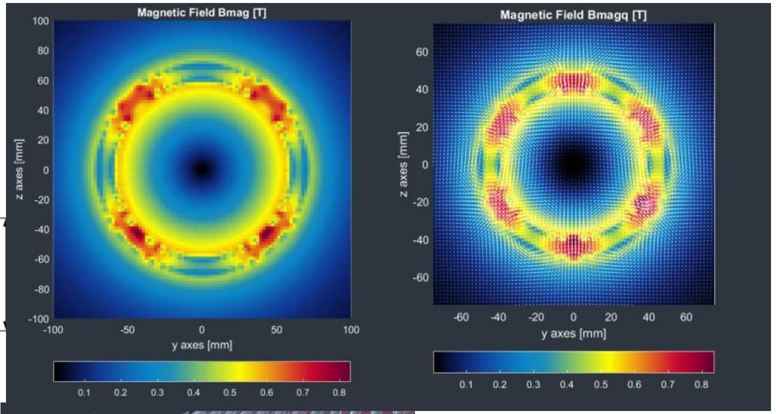



twin aperture dipoles for FCC-ee

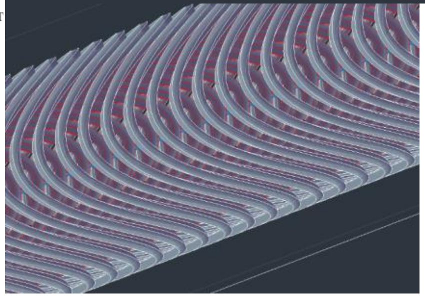





A. Milanese




M. Koratzinos



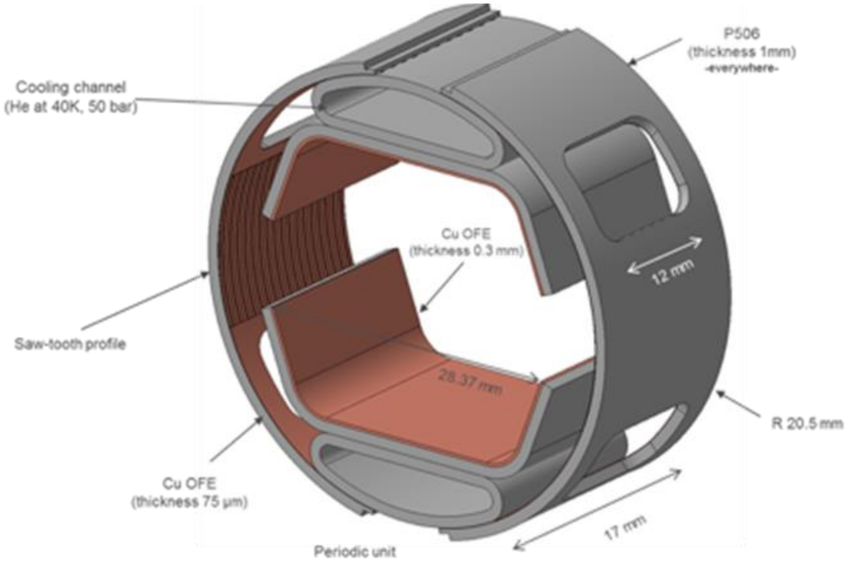
CCT HTS quadrupoles & sextupoles for FCC-ee

# synchrotron radiation (SR) and cryogenics

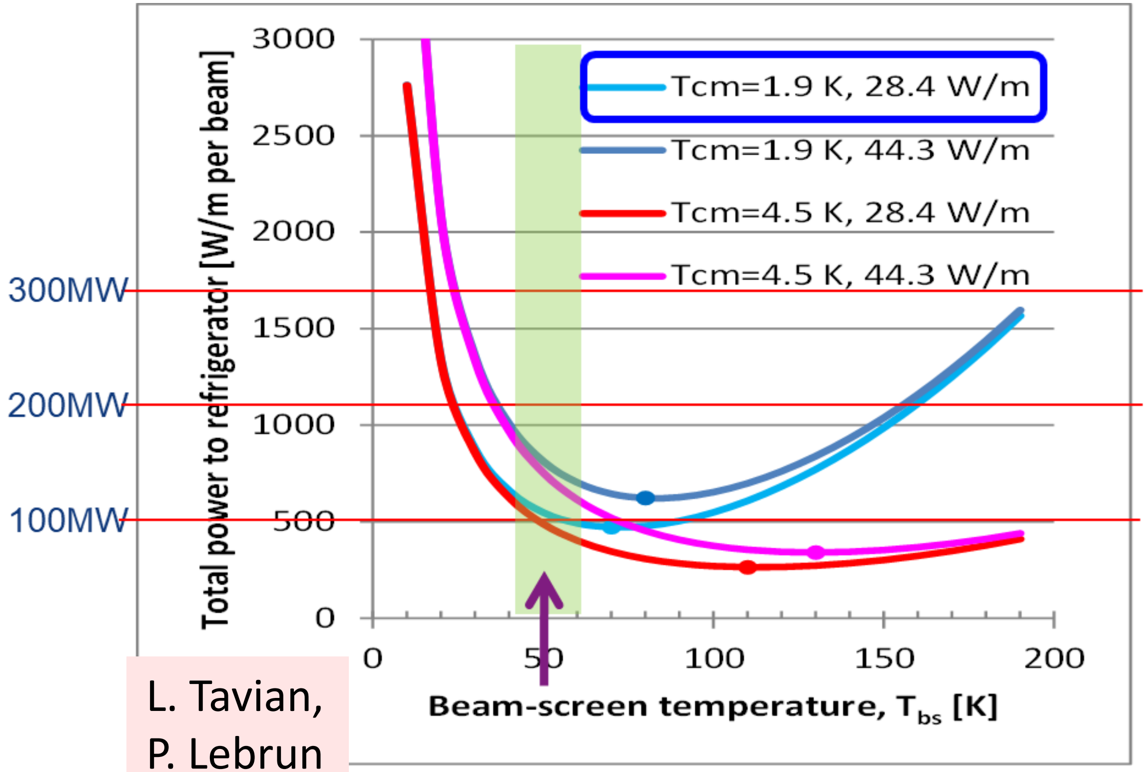
**FCC-ee ~100 MW at all beam energies (design constraint)**

**FCC-hh ~ 5 MW total SR power in arcs from proton beams**, emitted inside the cold magnets

**→strategy: SR absorption on "beam screen" (BS) at T >> 1.9 K**




I. Bellafont, F. Perez, R. Kersevan et al.




L. Tavian,
P. Lebrun

FCC-hh BS temperature choice through overall optimisation:

- cryoplant power consumption
- vacuum system performance
- impedance and beam stability

# ESPP Update 2020 “High-priority future initiatives” - 2

- the particle physics community should ramp up its **R&D effort focused on advanced accelerator technologies**, in particular that for **high-field super-conducting magnets**, including **high-temperature superconductors**

**→ directly relevant for energy frontier hadron collider (FCC-hh), for HTS applications at FCC-ee (certain collider magnets, $e^+$ target solenoid, etc.), & future muon collider**

- the technologies under consideration include **high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs**. The European particle physics community must **intensify accelerator R&D** and sustain it …. A **roadmap should prioritise the technology**,…

CERN Council

LDG

Accelerator

R&D Roadmap

5 expert panels:

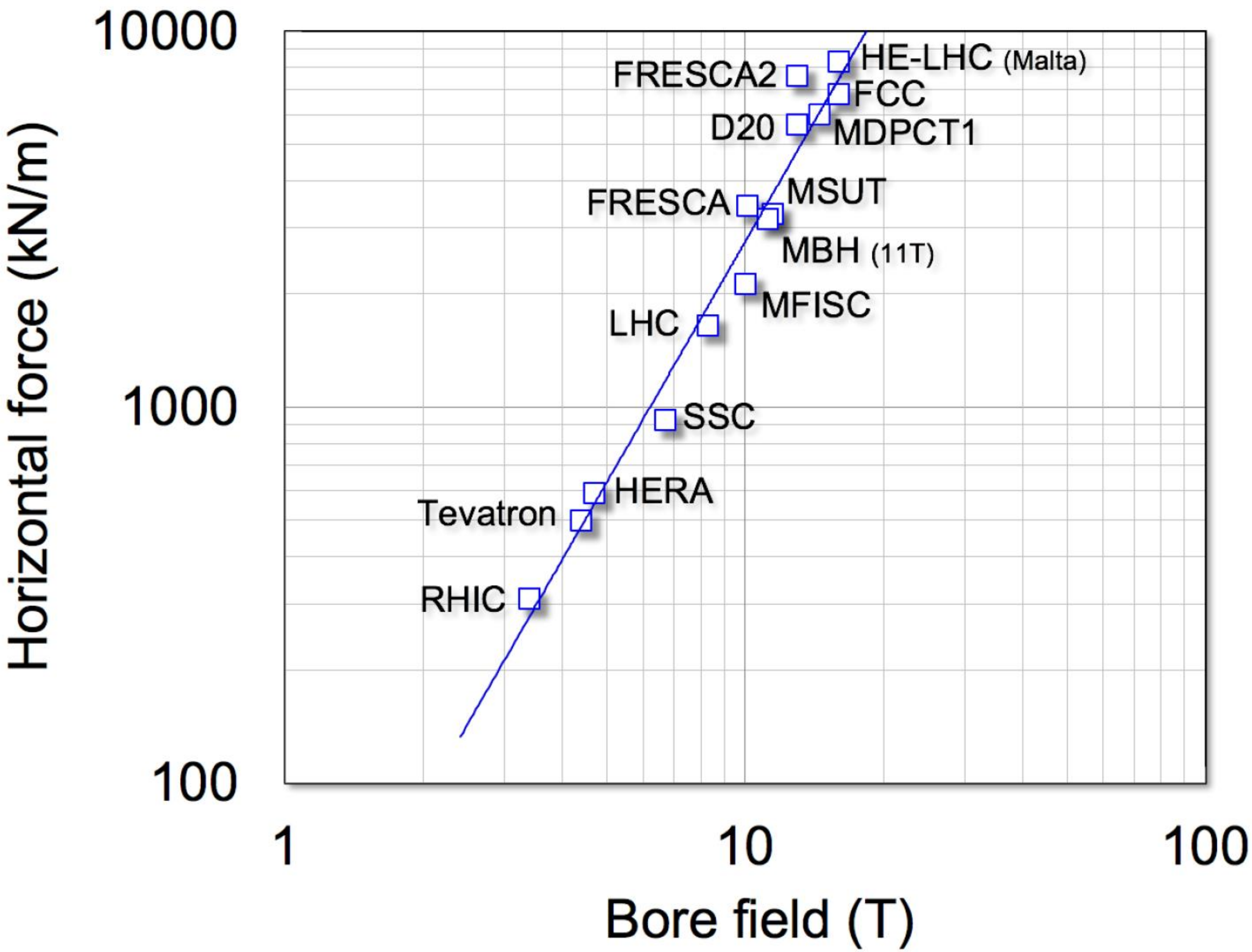
- High-field magnets
- High-gradient acceleration
- RF structures
- Muon beams
- Energy recovery linacs

chairs

- nets: P. Vedrine (IRFU)
- ma: R. Assmann (DESY)
- S. Bousson (IJCLab)
- Muons: D. Schulte (CERN)
- ERL: M. Klein (Liverpool)
- Diverse and international panel membership

D. Newbold

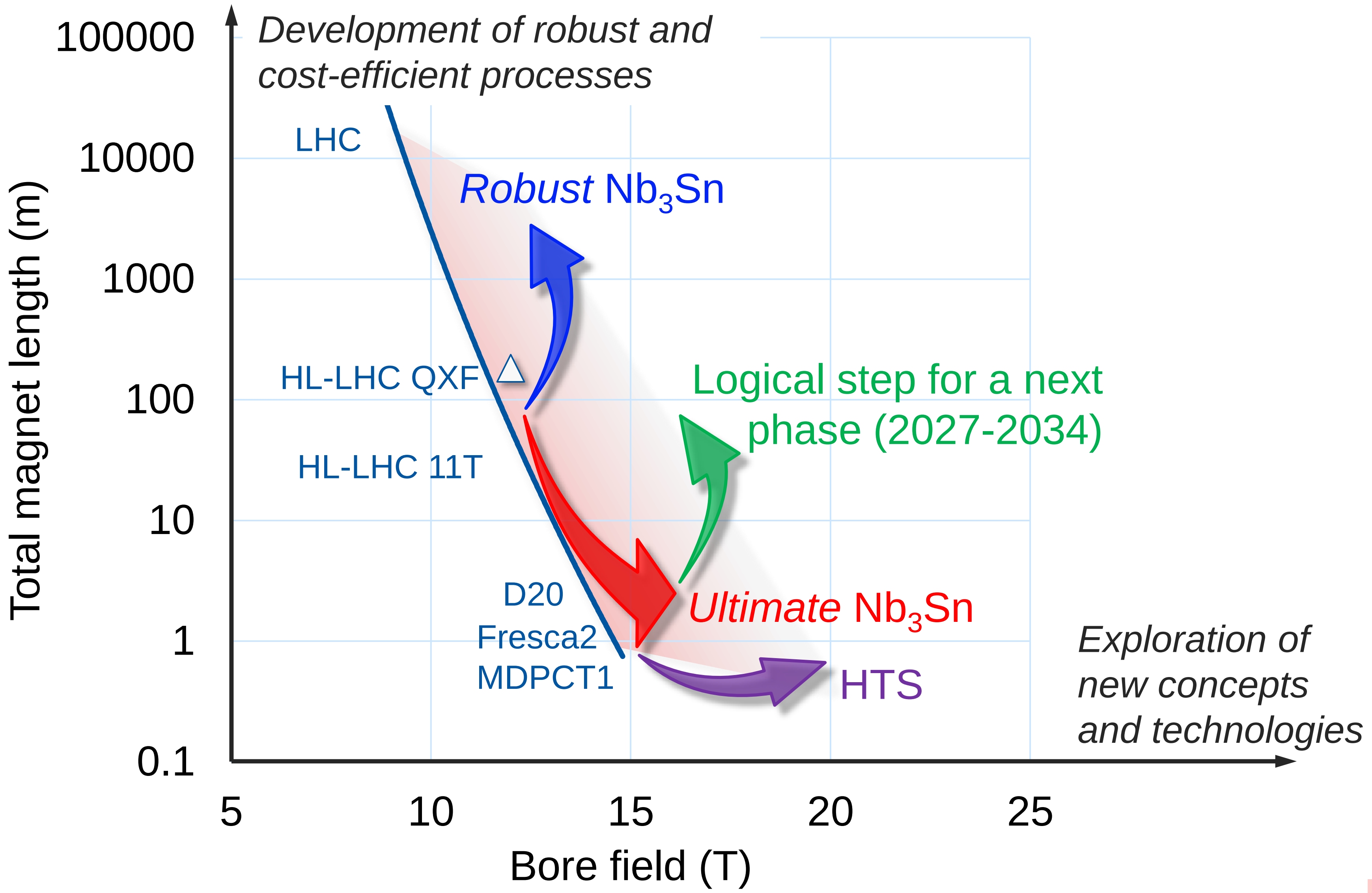
# High-Field Magnets – Challenge Force Management




horizontal forces per quadrant in dipole accelerator magnets (built and tested or design studies)

Luca Bottura et al., LDG draft report

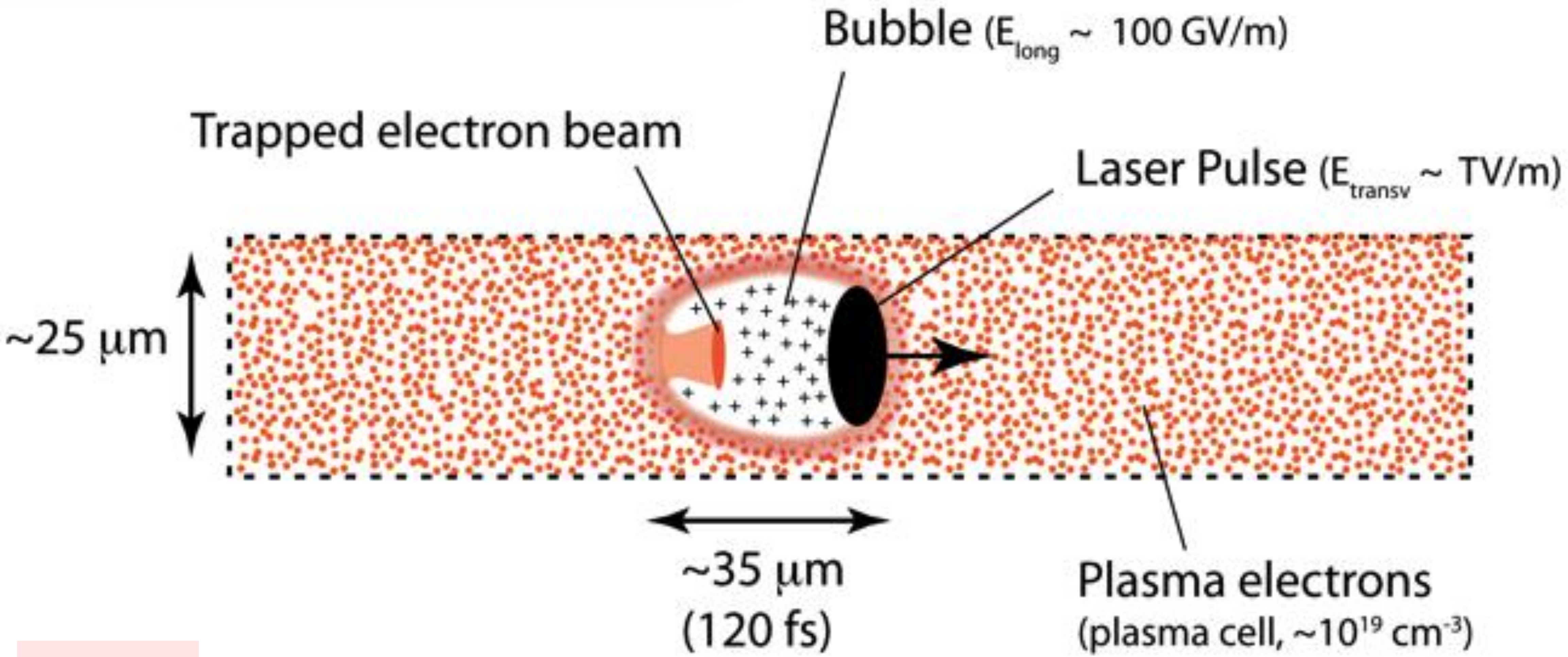
# High-Field Magnets - R&D Program Goals




Luca Bottura

# High-Gradient Acceleration (Plasma/Laser)

This accelerator fits into a human hair




R. Assmann

# High-Gradient Acceleration (Plasma/Laser) – cont'd

A plasma cell compared with the superconducting accelerator FLASH (credit DESY)

# High-Gradient Acceleration (Plasma/Laser) – cont'd

State of field: Rapidly progressing (e.g. first FEL SASE lasing) – low energy RI's planned (outside HEP) – national, European, international efforts – wish to **advance HEP concepts**

**MAIN CHALLENGES**

### Electron beam with collider quality

1-10 GV/m acceleration, 15,000 nC/s charge delivered, sub-micron transverse emittances, $10^{-4}$ rel. energy spread, spin polarization.
**Deliverables** on injectors, numerical simulations, repetition rate, efficiency, beam loading, emittance preservation, energy spread control, polarization, staging, … were proposed.

### Solution for positron acceleration

with parameters similar to electron bunches.
**Deliverables** on numerical simulations, proof-of-principle experiments were proposed.

### Conceptual design advanced collider

with physics case, self-consistent machine parameter set, realistic assessment of feasibility issues, performance, size and cost.
**Deliverables** on a coordinated international design study, including beam delivery, luminosity and interaction region design, were proposed.

### Intermediate steps towards a particle physics collider and synergy

with progress in photon science and lower energy applications.
**Deliverables** for intermediate implementation steps were proposed.

E. Gschwendtner, R. Assmann

# plasma acceleration of positrons ? (required for $e^+e^-$ collider)

"ballistic injection": a ring-shaped laser beam and a coaxially propagating Gaussian laser beam are employed to create donut and center bubbles in the plasma, resp.

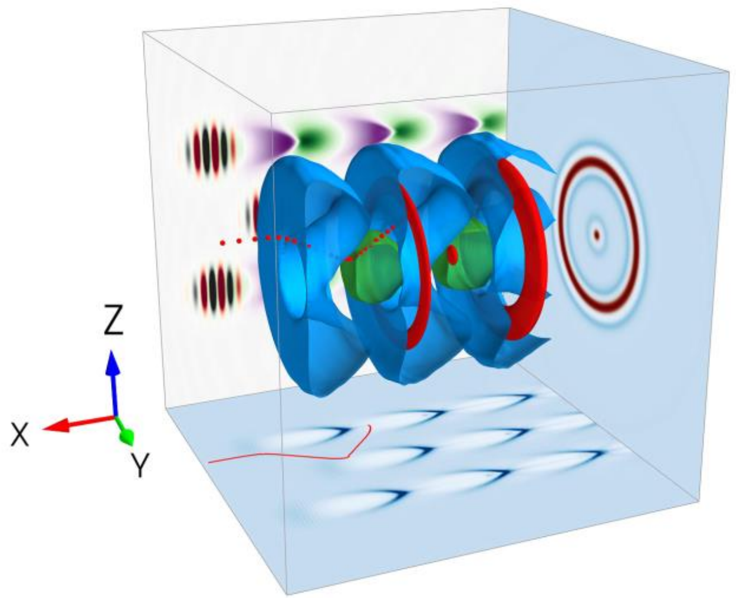
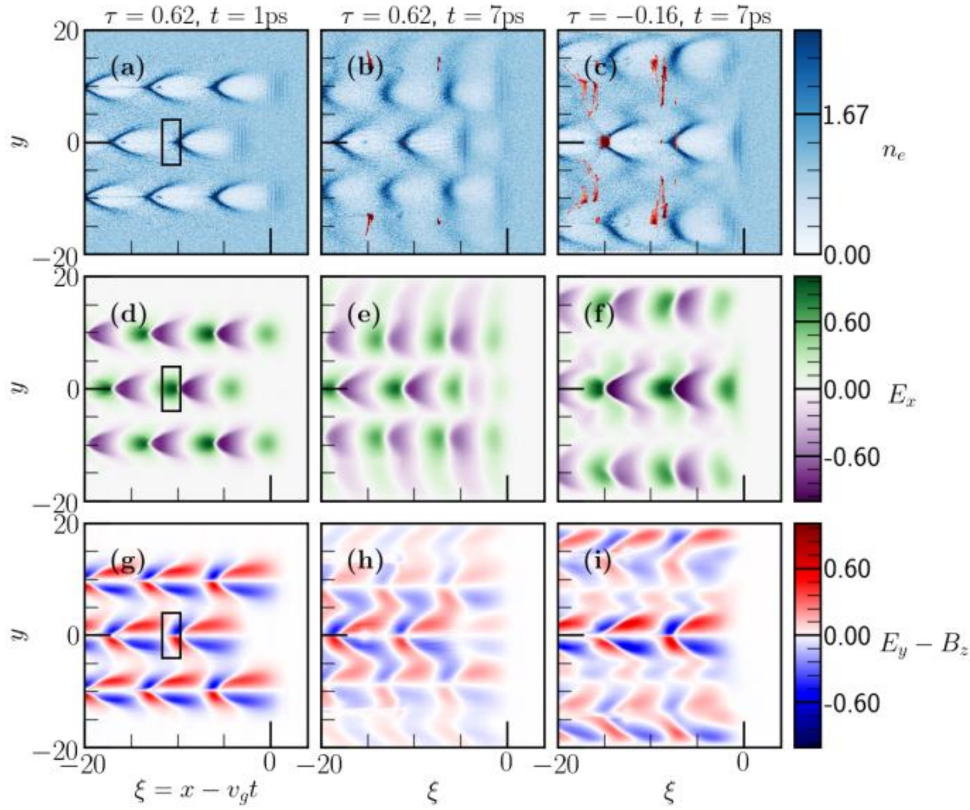



FIG. 1. The concept of the positron ballistic injection scheme. The blue and green colors are contour surfaces of electron densities of donut and center bubbles, respectively. The red color represents injected positrons. The $x$–$y$ and $x$–$z$ planes are transverse slices of the density distribution and the longitudinal electric field $E_x$. The red curve in the $x$–$y$ plane is the trajectory of an injected positron (corresponding to the projection of red balls in the 3D model). The leading oscillating colors (amber and grey) denote the laser beams in the $x$–$z$ plane. The $y$–$z$ plane is the projection of electron density (blue) and injected positron density (red).




PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 091301 (2020)

**New injection and acceleration scheme of positrons in the laser-plasma bubble regime**

Z. Y. Xu,[1] C. F. Xiao,[1] H. Y. Lu,[1,2,3,*] R. H. Hu,[1,†] J. Q. Yu,[1,‡] Z. Gong,[1] Y. R. Shou,[1] J. X. Liu,[1] C. Z. Xie,[1] S. Y. Chen,[1] H. G. Lu,[1] T. Q. Xu,[1] R. X. Li,[4] N. Hafz,[5] S. Li,[5] Z. Najmudin,[6] P. P. Rajeev,[7] D. Neely,[7] and X. Q. Yan[1,3]

Z.Y. Xu

# High gradient RF structures & systems

2nd Accelerator R&D Roadmap Workshop, 12 October 2021

**14:20** → 14:50 **High-field Magnets** 30m

- delivery plans

Speakers: Luis Garcia-Tabares (Centro de Investigaciones Energéti cas Medioambientales y Tecno) , Pierre Vedrine (Université ...-Saclay (FR))

LDG - HFM Status n... | LDG - HFM Status n...

**14:50** → 15:20 **High-gradient RF Structures and Systems** 30m

- delivery plans

Speakers: Hans Weise (DESY) , Sebastien Bousson (IJCLab - ...

**15:20** → 15:50 **High-gradient Plasma and Laser Accel...** 30m

- delivery plans

Speakers: Edda Gsch... ...olfgang Assmann (DESY) , Ralph Wolfgang Assmann (Deutsches Elektronen-Synchrotron (DE))

2021-10-12_e... | ...-10-12_expert-...

information highly protected

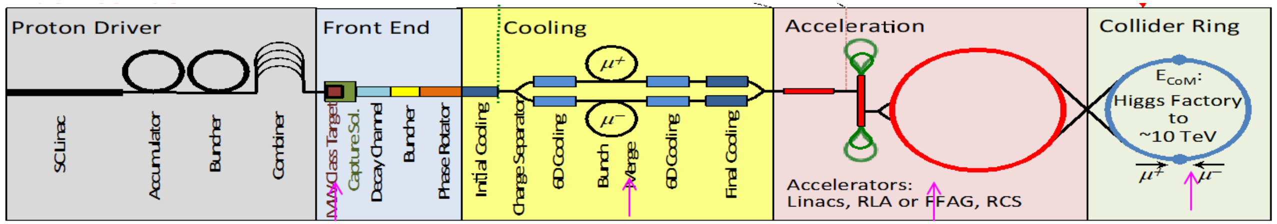
The following may be included: **(1) SRF**: higher Q of bulk Nb, field emission, SC films, SRF couplers (FPC and HOM), substrate fabrication & engineering; **(2) NCRF**: manufacturing, RF in strong magnetic field; **(3) High RF power and LLRF**: klystrons & solid-state, FE-FRT, mm-wave & gyro, AI; **(4) Facilities & infrastructures**

# Muon Collider

~$1.6 \times 10^9$ x less SR than $e^+e^-$, no beamstrahlung problem

two production schemes proposed

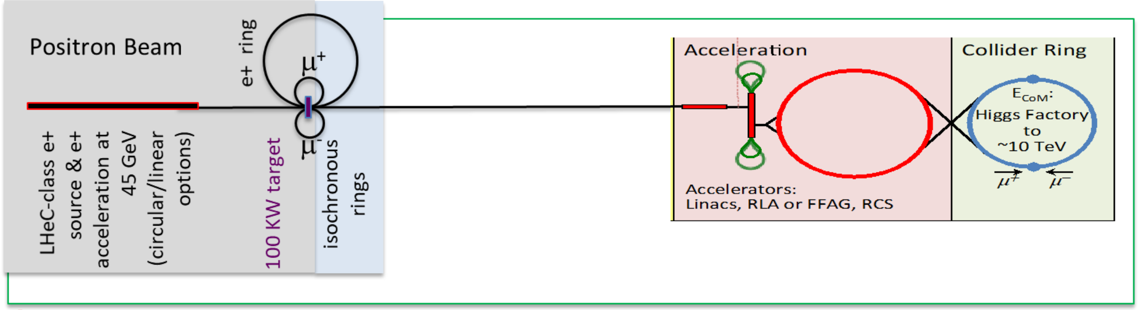
US-MAP (2015) *p*-driven




key challenges

- ~$10^{13}$-$10^{14}$ μ / sec tertiary particle $p \rightarrow \pi \rightarrow \mu$:
- fast cooling ($\tau$=2μs) by $10^6$ (6D)
- fast acceleration mitigating μ decay
- background from μ decay

Italian LEMMA (2017) $e^+$-annihilation




key challenges: ~$10^{11}$ μ / sec from $e^+e^- \rightarrow \mu^+\mu^-$

key R&D: $10^{15}$ $e^+$/sec, 100 kW class target, NON destructive process in e+ ring

needs large 45 GeV $e^+$ ring like FCC-ee, possible upgrade path to **FCC-μμ**

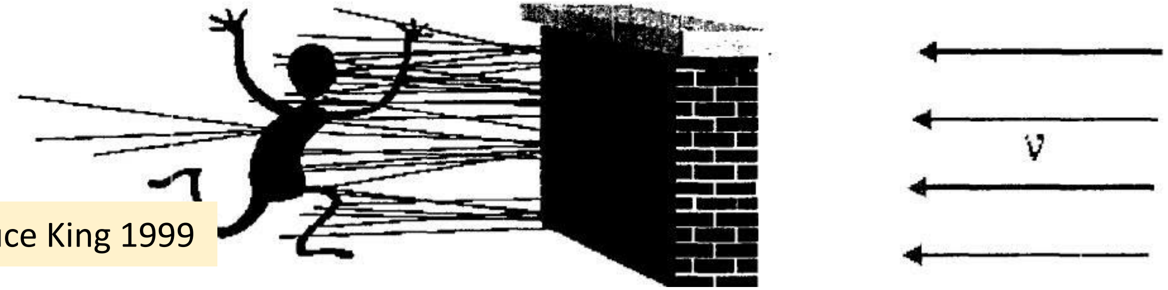
μ's decay within a few 100 - 1000 turns:

→ rapid acceleration

(perhaps plasma?)

→ ν radiation hazard

(limits maximum μ energy)



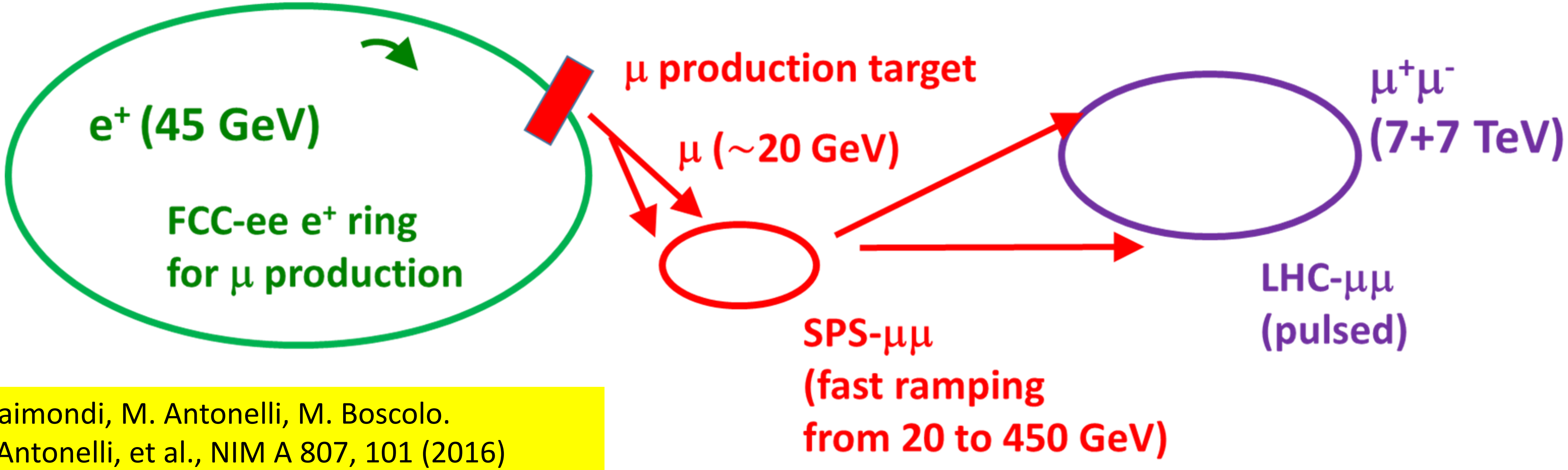

Bruce King 1999

$\sigma_\nu \propto E$, **flux** $\propto E^2$ (Lorentz boost)

solution beyond 10 TeV unclear

# post FCC-ee option: feeding 14 TeV μ collider

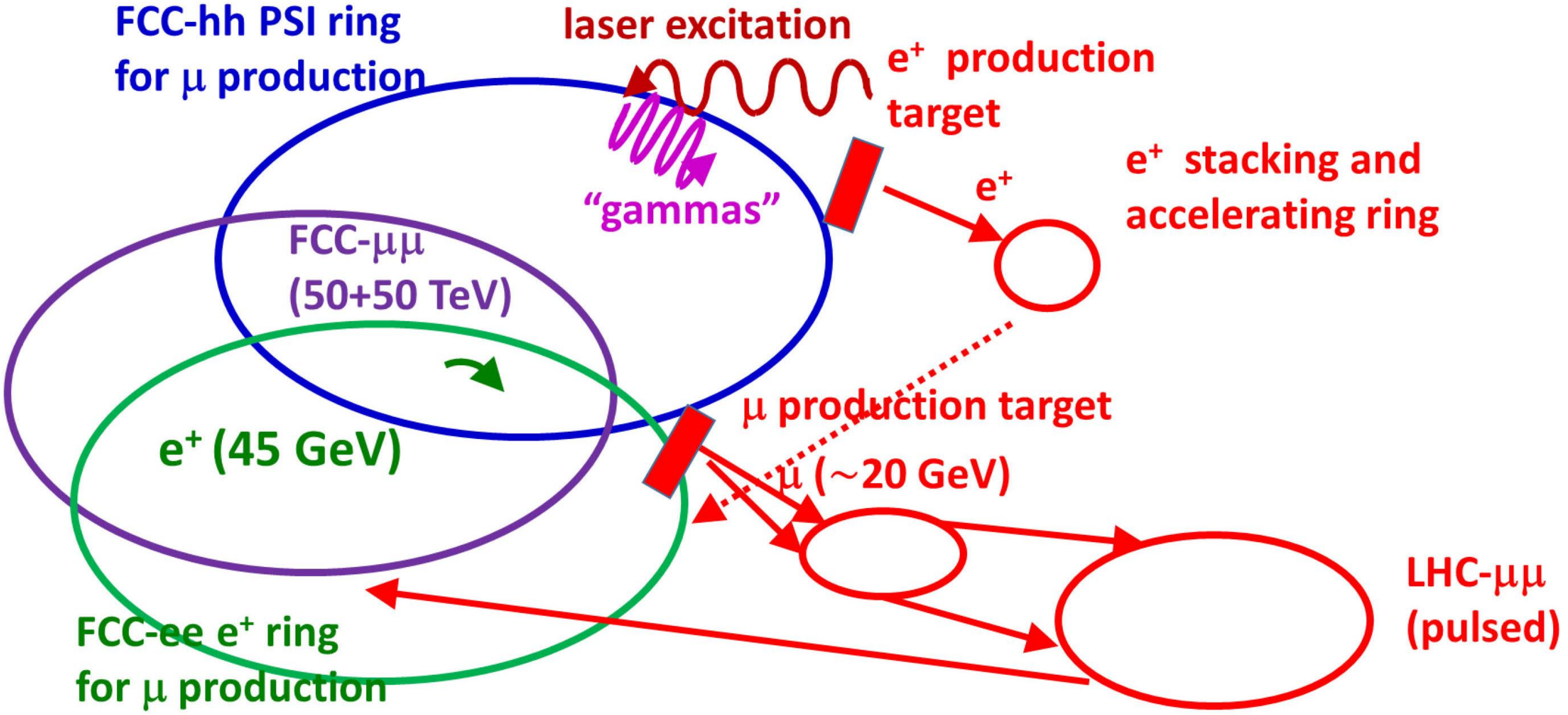
14 TeV μ collider LHC-μμ with FCC-ee μ± production




P. Raimondi, M. Antonelli, M. Boscolo.
M. Antonelli, et al., NIM A 807, 101 (2016)
M. Boscolo et al., PRAB 23, 051001 (2020)

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

# after FCC-hh: FCC-μμ, a 100 TeV μ collider?

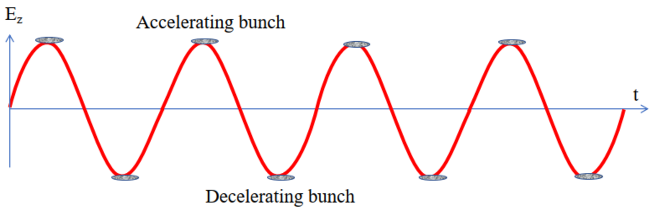



W. Krasny, https://arxiv.org/abs/1511.07794

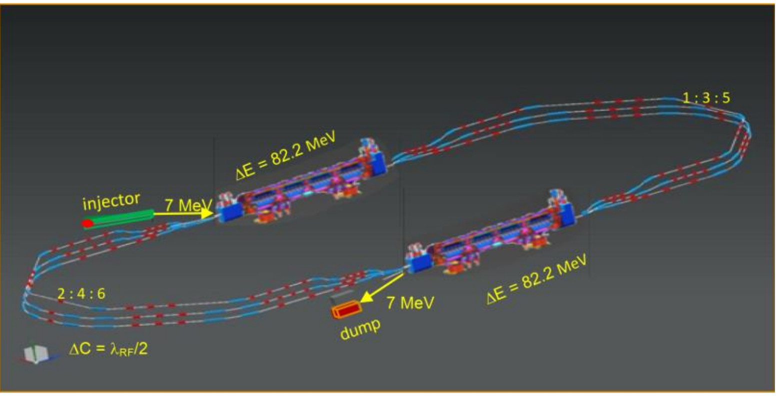
PSI: partially stripped ion ("Gamma Factory")

F. Zimmermann 2018 *J. Phys.: Conf. Ser.* **1067** 022017

# Energy Recovery Linacs (ERLs) – Landscape

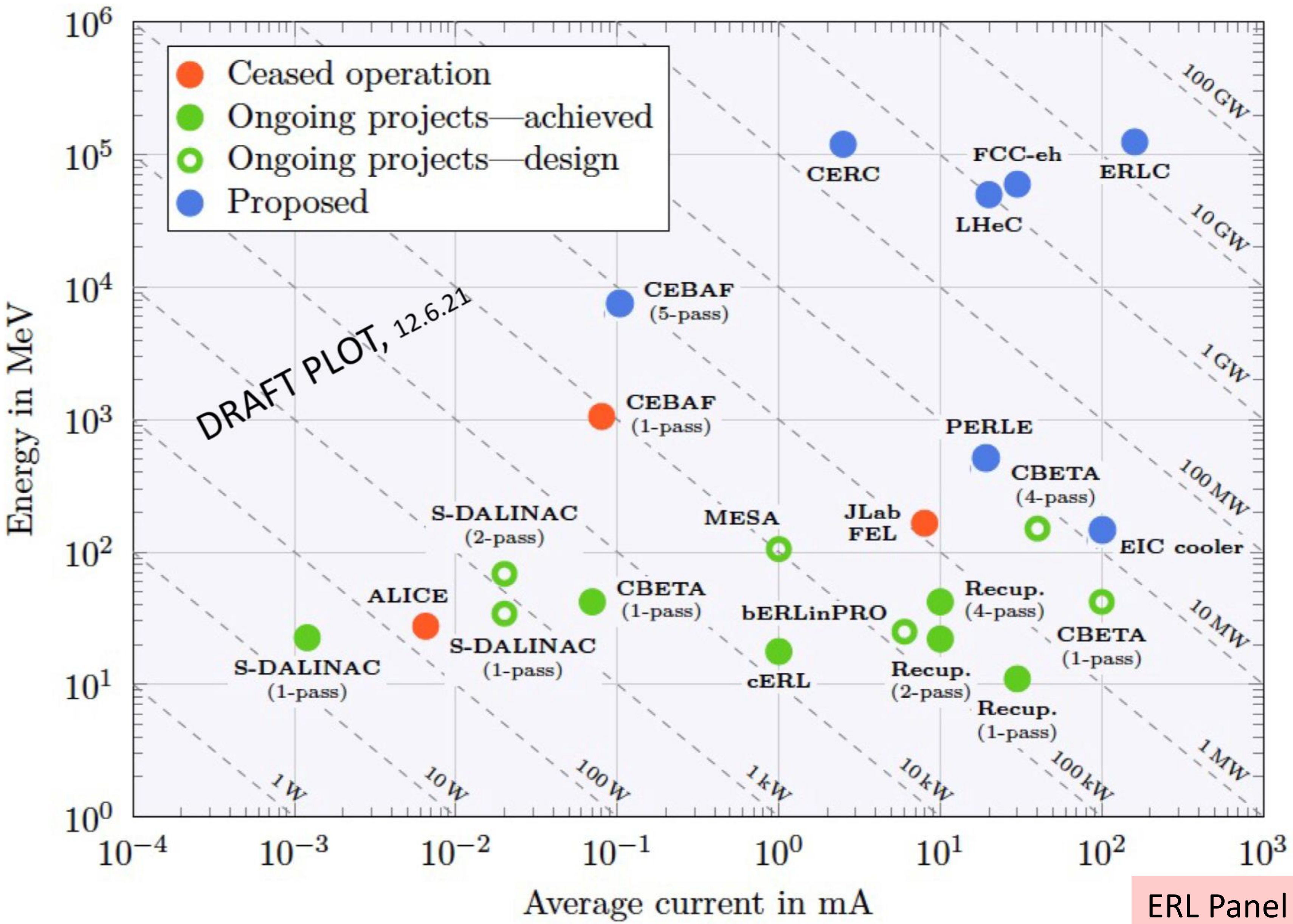



V. Litvinenko, T. Roser, M. Chamizo



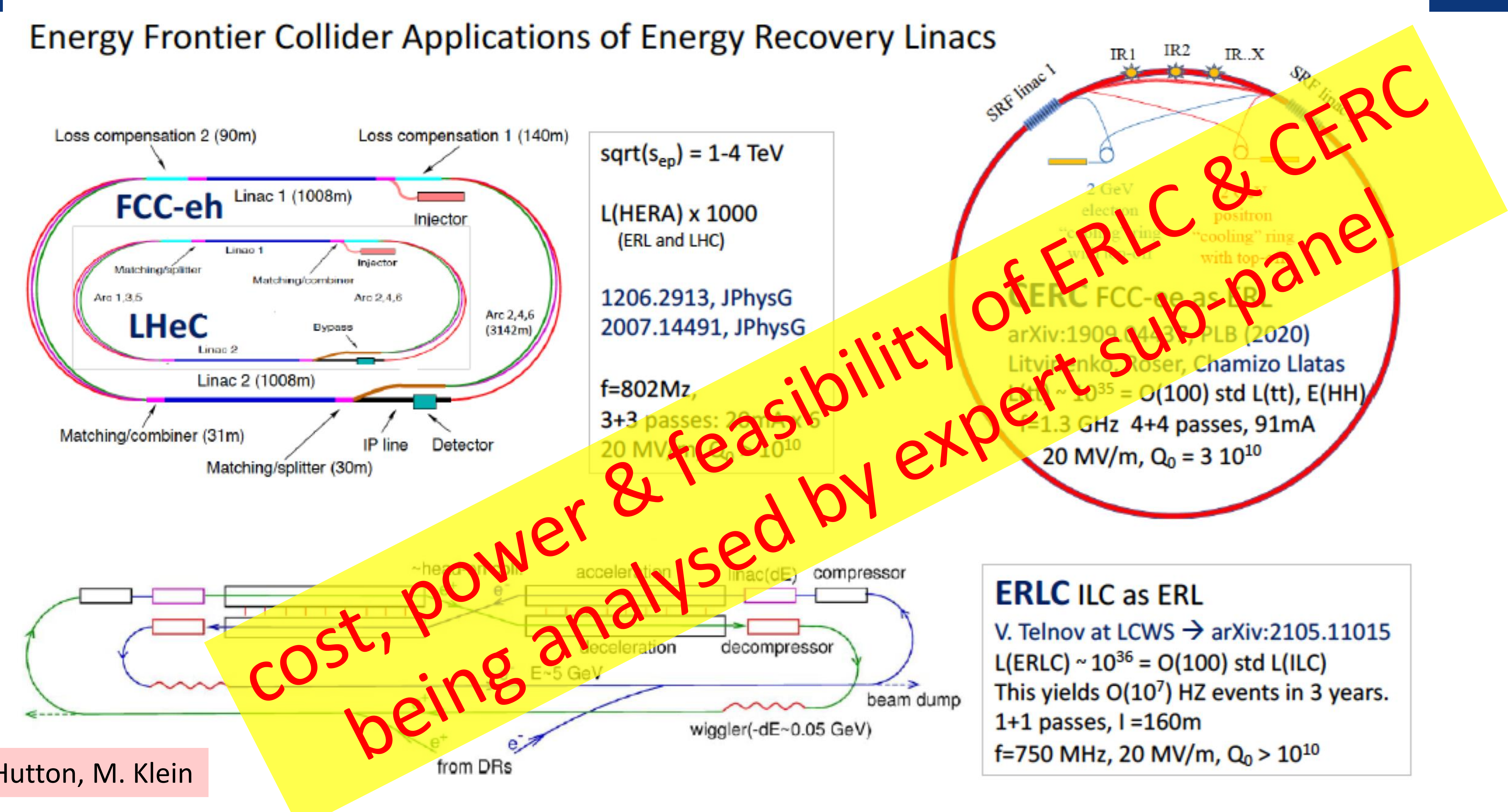

test Facility PERLE at IJClab
(high current, multi-turn)
would complement MESA, CBETA,
bERLinPRO and EIC cooler

M. Klein




ERL Panel

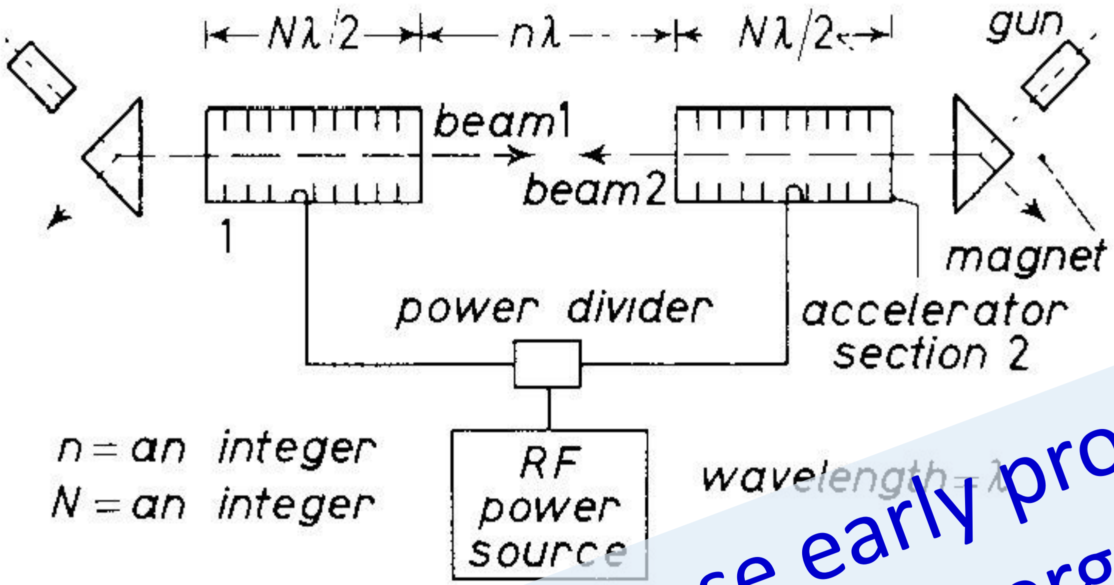
# Possible Future Colliders based on ERLs




A. Hutton, M. Klein

# reappraisal of historical ERL proposals

early linear-collider proposals

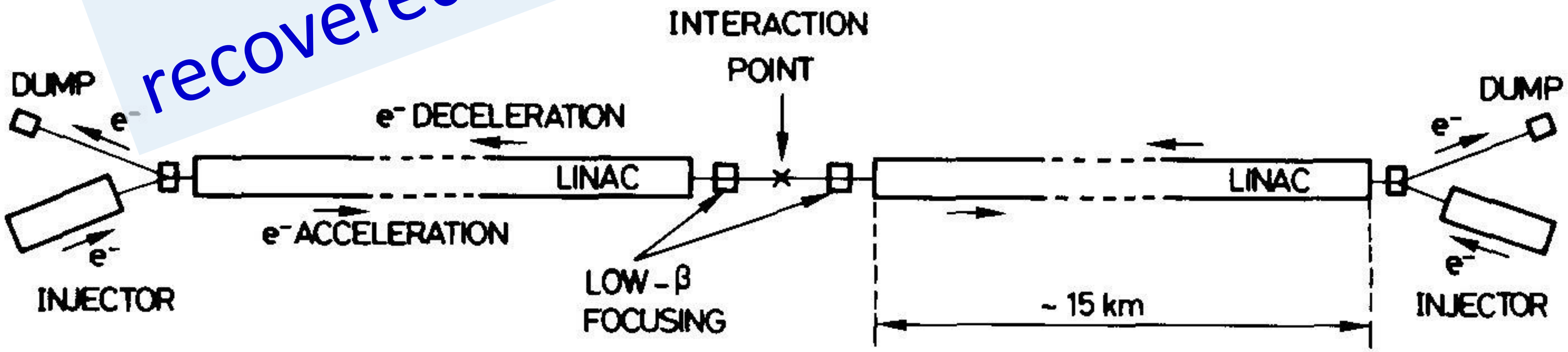



**1-6 GeV c.m.**

Maury Tigner, "*A Possible Apparatus for Clashing-Beam Experiments*", Nuovo Cimento 37, 1228 (**1965**)

these early proposal always recovered the energy of the spent beam!

Ugo Amaldi, "*A possible scheme to obtain e-e- and e+e- collisions at energies of hundreds of GeV*", Physics Letters B61, 313 (**1976**)




**300 GeV c.m.**

# comparison of ERL collider proposals then and now

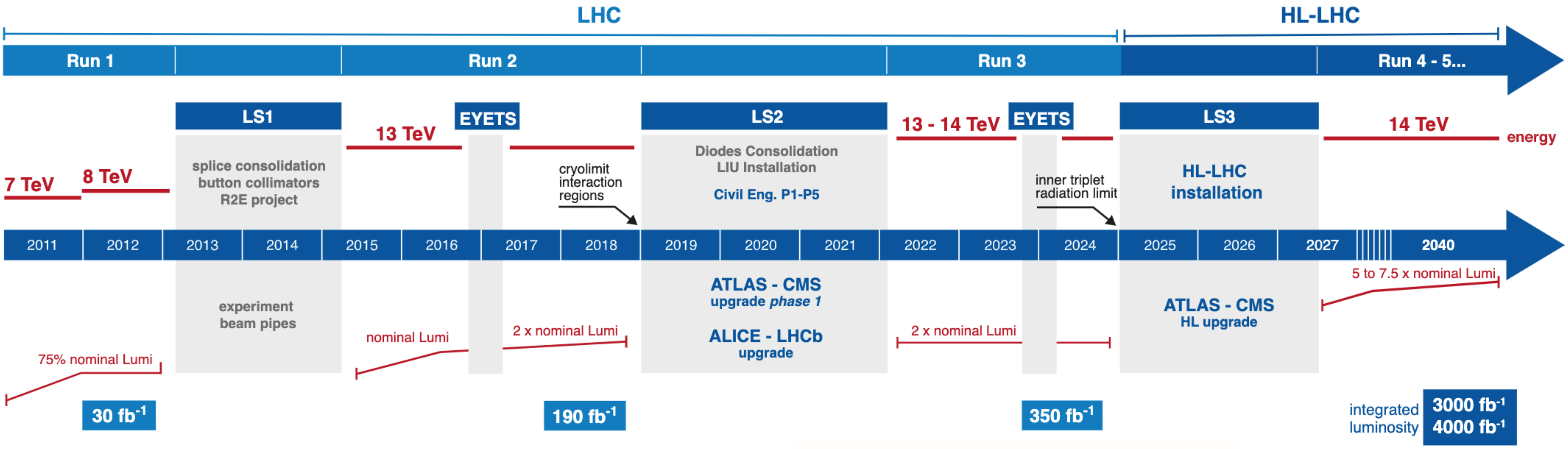
| | Tigner 1965 | Amaldi 1976 | Gerke – Steffen 1979 | Litvinenko-Roser-Chamizo 2019 | | Telnov 2021 | |
|---|---|---|---|---|---|---|---|
| c.m. energy [GeV] | 1-6 | 300 | 200 | 240 | 600 | 250 | 500 |
| average beam current [mA] | 120 | 10 | 0.3 | 2.5 | 0.16 | 100 | 100 |
| vertical rms IP beam size [nm] | 40,000 (round) | 2,000 (round) | 900 (round) | 6 | 5 | 6.1 | 7.4 |
| luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 0.0003 | 0.01 | 0.004 | 73 | 8 | 90 | 64 |

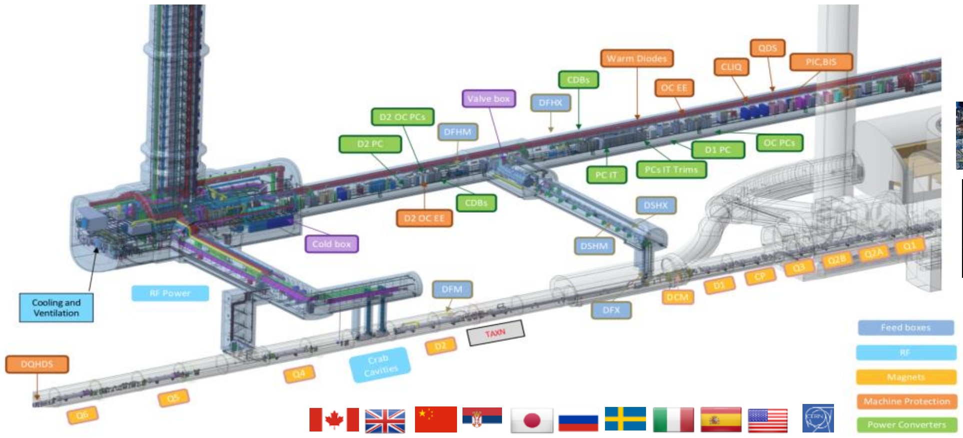
**Main differences: flat instead of round beams, much smaller (vertical) beam sizes, higher beam current → ~10,000x higher luminosity**

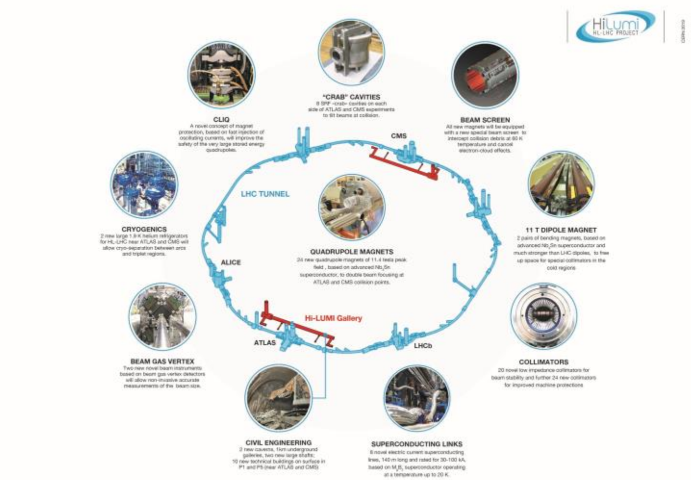
# ESPP Update 2020 "Major Developments from 2013" - 1

- … a significantly enhanced physics potential is expected with the HL-LHC. The **required high-field superconducting $Nb_3Sn$ magnets have been developed**. The **successful completion of the high-luminosity upgrade of the machine** and detectors should remain the focal point of European particle physics, together with continued innovation in experimental techniques. The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.

# LHC & HL-LHC





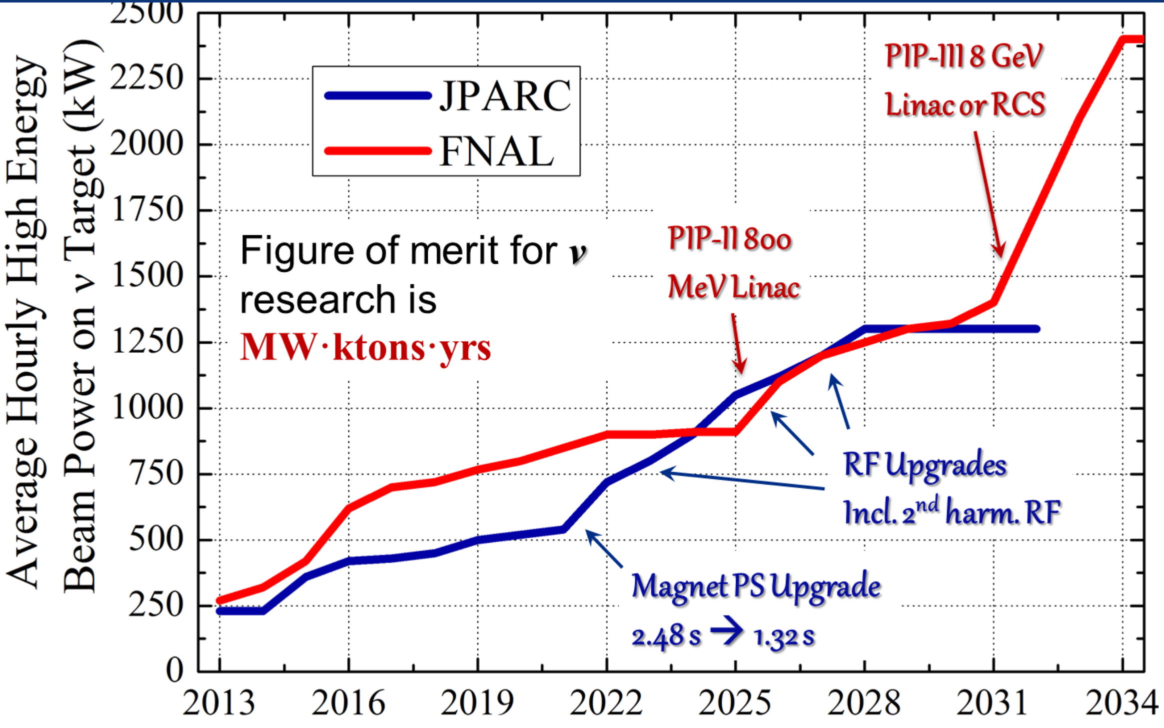

~1.2 km of accelerator will be upgraded

# ESPP Update 2020 "Major Developments from 2013" - 2

- Europe, and CERN through the **Neutrino Platform**, should **continue to support long baseline experiments in Japan and the United States**. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).

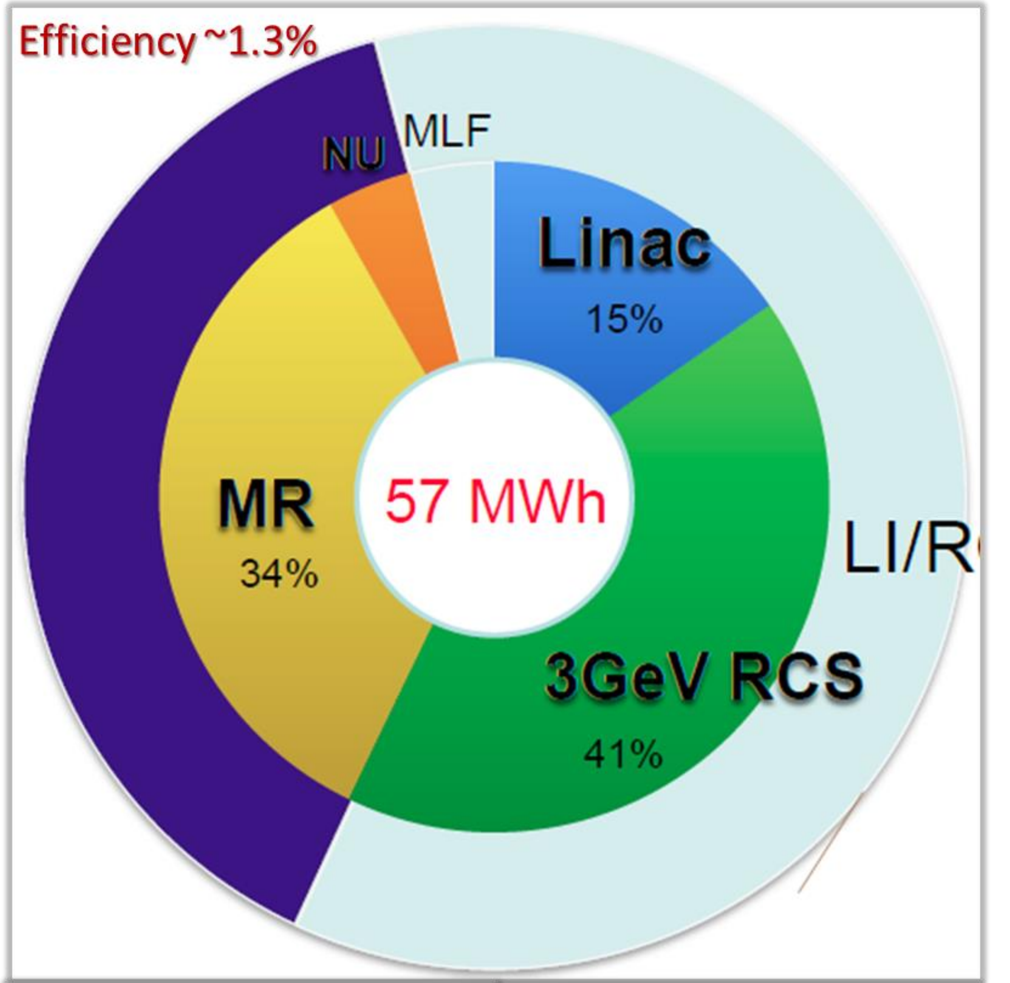
# super-beam facilities & upgrades

**Fermilab & J-PARC Power Upgrades**



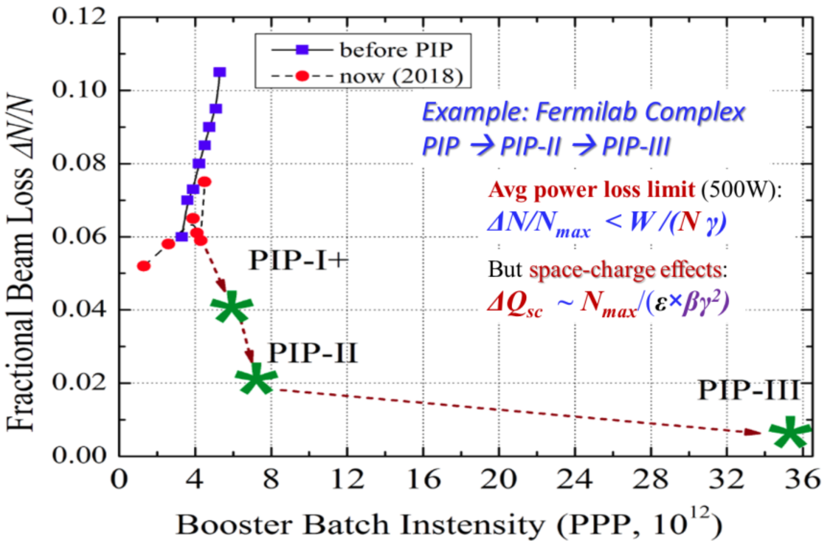

**power efficiency challenge**

J-PARC : 0.5 MW beams vs ~40 MW site power




- MR Magnets: 10.4 MWh per hour
- MR RF: 3.8 MWh per hour
- RCS Magnets: 9.6 MWh per hour
- RCS RF: 7 MWh per hour

**protons per pulse challenge**




V. Shiltsev

# expected inputs for ESPP Update 2027

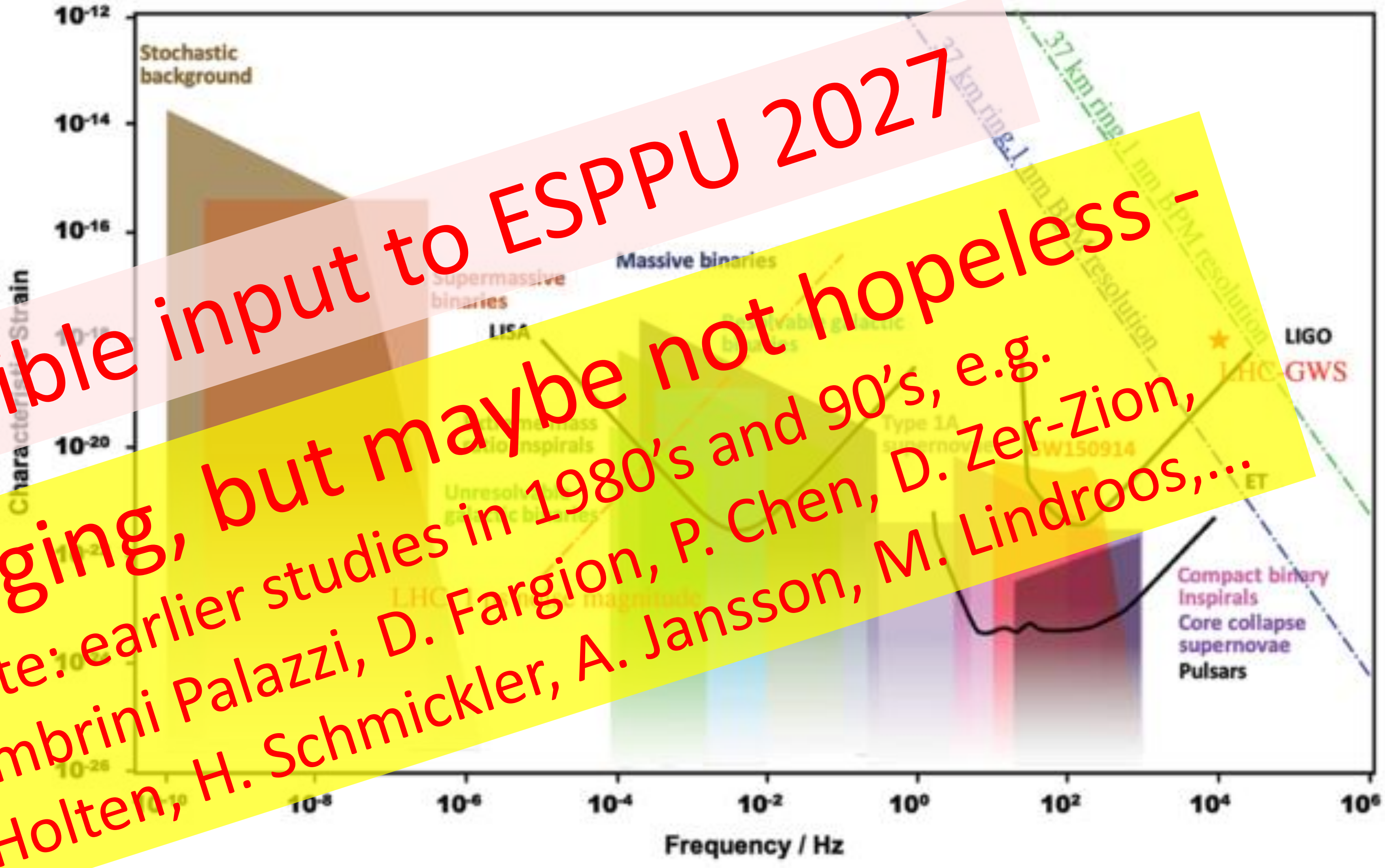
- **FCC Feasibility Study Report**
- LDG Accelerator **Roadmap R&D results**
- other new developments and proposals → *next slide*

# storage rings as tools to detect or generate gravitational waves

ARIES workshop 2021


Accelerators meet gravitational waves
Courier

J. Ellis et al (2021),
https://arxiv.org/abs/2105.00992




Sources and sensitivities GW sources (shaded) and detector sensitivities (lines), incl. space-based interferometer LISA, ground-based LIGO and Einstein Telescope. Accelerator-based detection methods and sources are superimposed based on optimistic assumptions.

possible input to ESPPU 2027

challenging, but maybe not hopeless -

note: earlier studies in 1980's and 90's, e.g.
G. Diambrini Palazzi, D. Fargion, P. Chen, D. Zer-Zion,
J. Van Holten, H. Schmickler, A. Jansson, M. Lindroos,...

thank you !

# …surely great times ahead!