European Coordination for Accelerator Research and Development

PUBLICATION

LEP3 and TLEP

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EuCARD-PRE-2012-007

LEP3 and TLEP

Frank Zimmermann

HF2012, FNAL, 15 November 2012

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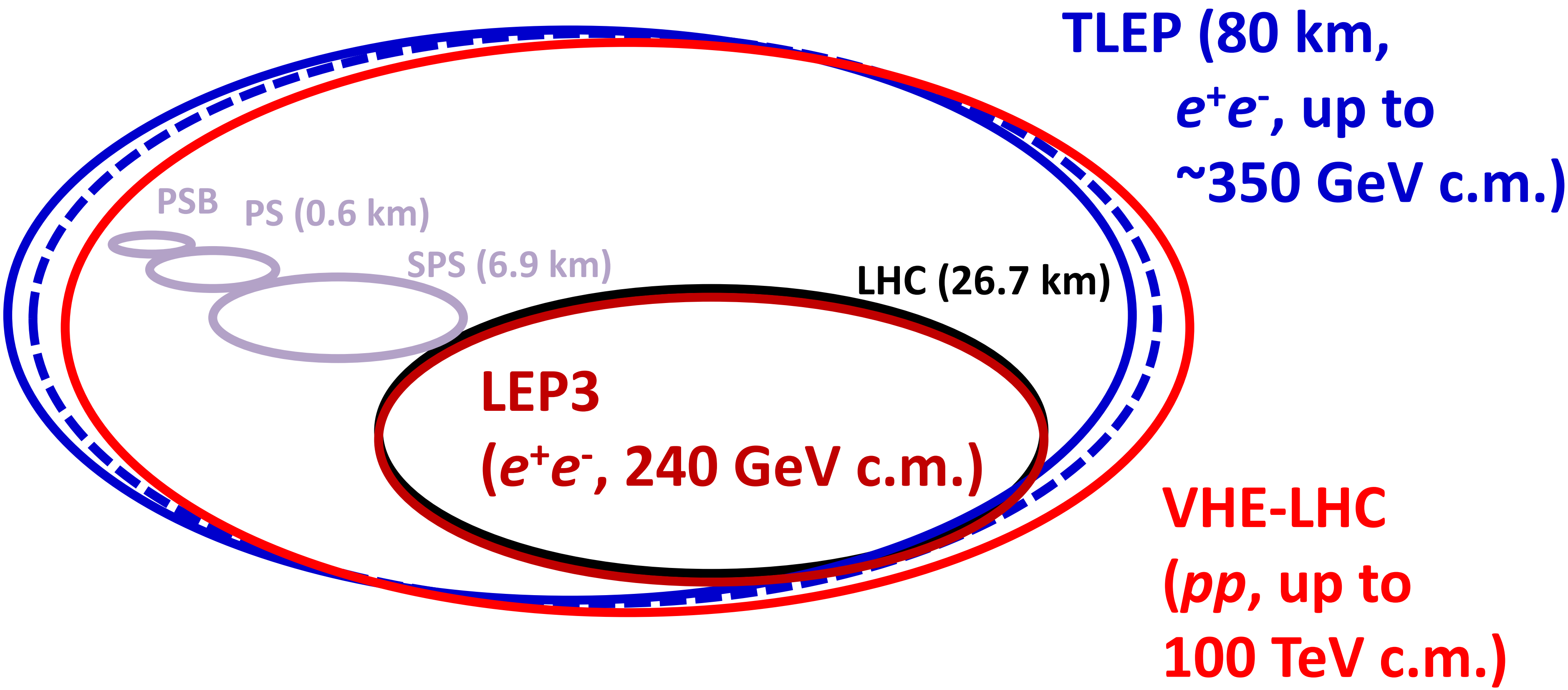
work supported by the European Commission under the FP7 Research Infrastructures project EuCARD, grant agreement no. 227579

circular Higgs factories at CERN & beyond



also: $e^{\pm}$ **(200 GeV) – *p* (7 & 50 TeV)** collisions

a long-term strategy for HEP!

two options

- installation in the LHC tunnel "LEP3"

  + inexpensive (<0.1xLC)

  + tunnel exists

  + reusing ATLAS and CMS detectors

  + reusing LHC cryoplants

  - interference with LHC and HL-LHC

- new larger tunnel "TLEP"

  + higher energy reach, 5-10x higher luminosity

  + decoupled from LHC/HL-LHC operation & construction

  + tunnel can later serve for HE-LHC (factor 3 in energy from tunnel alone) with LHC remaining as injector

  - 4-5x more expensive (new tunnel, cryoplants, detectors)

LEP3, TLEP

(e^+e^- -> ZH, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow Z$,[$e^+e^- \rightarrow t\bar{t}$])

key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
luminosity at 350 GeV c.m.	-	0.7×10^{34} cm^{-2}s^{-1}
luminosity at 240 GeV c.m.	10^{34} cm^{-2}s^{-1}	5×10^{34} cm^{-2}s^{-1}
luminosity at 160 GeV c.m.	5×10^{34} cm^{-2}s^{-1}	2.5×10^{35} cm^{-2}s^{-1}
luminosity at 90 GeV c.m.	2×10^{35} cm^{-2}s^{-1}	10^{36} cm^{-2}s^{-1}

at the *Z* pole repeating LEP physics programme in a few minutes…

other LEP3 parameters

arc optics

- same as for LHeC: $\varepsilon_{x,LHeC}<1/3\ \varepsilon_{x,LEP1.5}$ at equal beam energy,
- optical structure compatible with present LHC machine (not optimum!)
- small momentum compaction (short bunch length)
- assume $\varepsilon_y/\varepsilon_x$ ~5×10^{-3} similar to LEP (ultimate limit ε_y ~ 1 fm from opening angle)

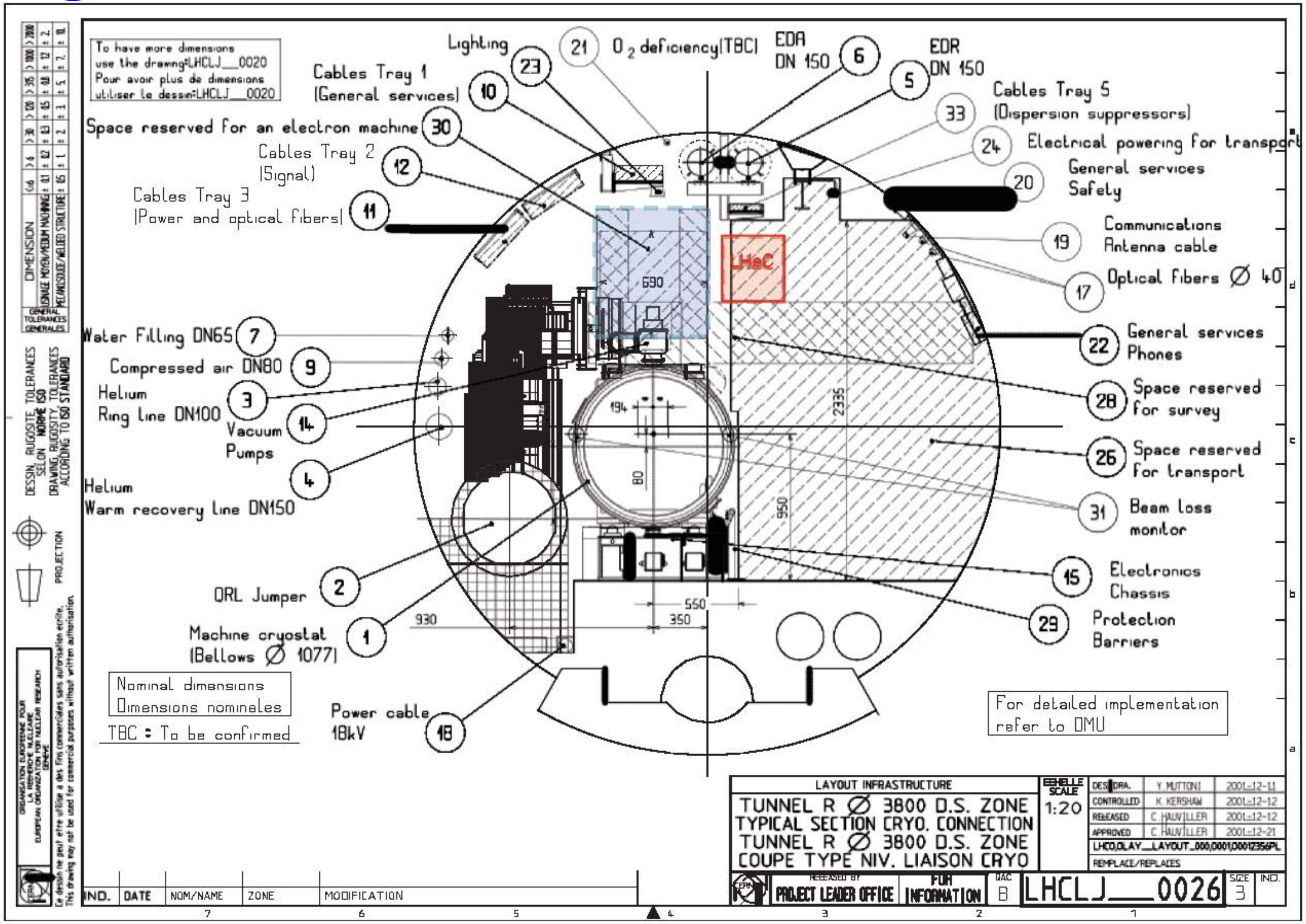
RF

- RF frequency 1.3 GHz or 700 MHz
- ILC/ESS-type RF cavities high gradient (20 MV/m assumed, 2.5 times LEP gradient)
- total RF length for LEP3 at 120 GeV similar to LEP at 104.5 GeV
- short bunch length (small β^*_y)
- cryo power ≤LHC

synchrotron radiation

- energy loss / turn: $E_{loss}[\mathrm{GeV}]=88.5\times10^{-6}\,(E_b[\mathrm{GeV}])^4/\rho[\mathrm{m}]$.
- higher energy loss than necessary
- arc dipole field = 0.153 T
- compact magnet
- critical photon energy = 1.4 MeV
- 50 MW per beam (total wall plug power ~200 MW ~ LHC complex)→4×10^{12} $e^{\pm}$/beam

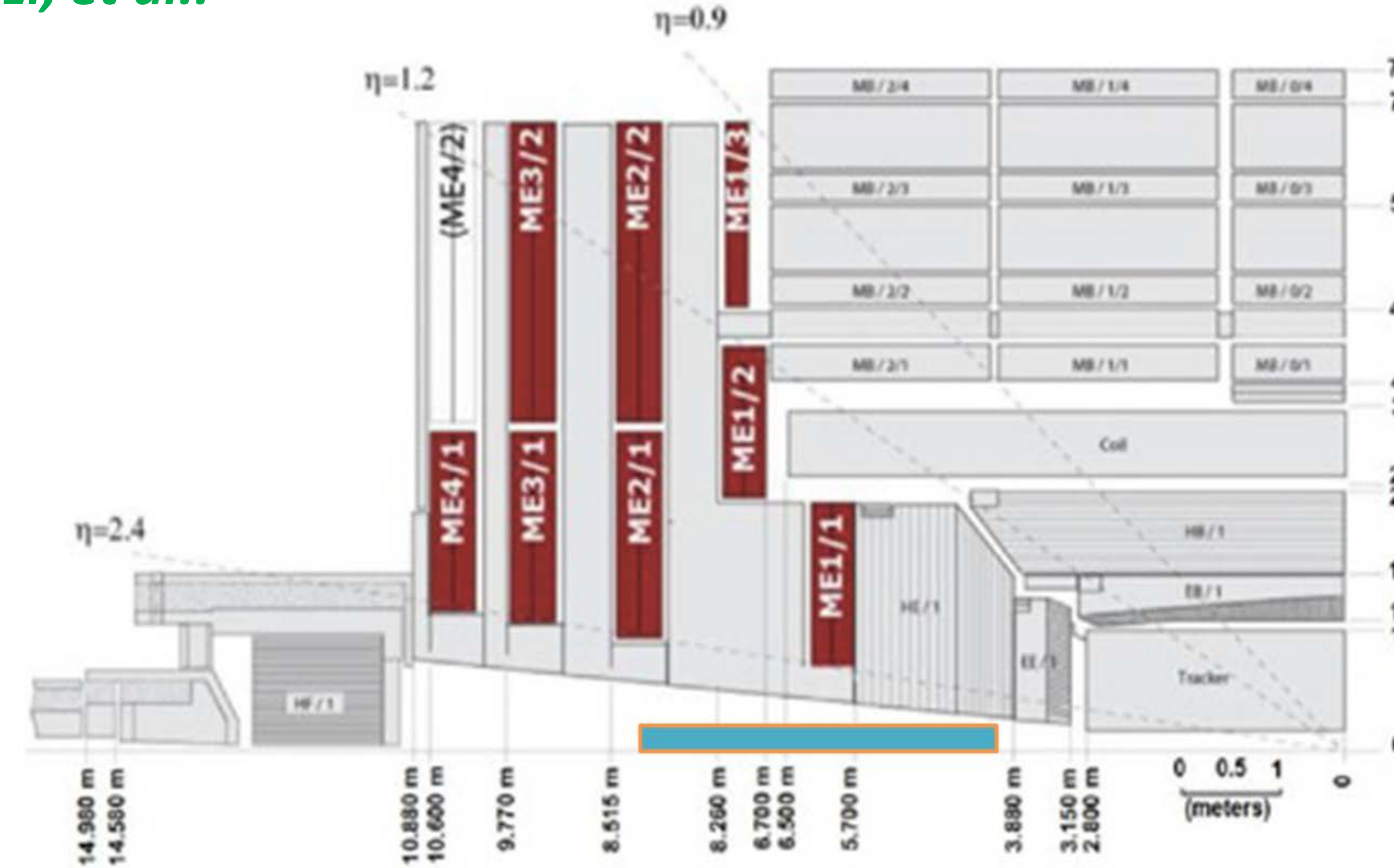
putting LEP3 into the LHC tunnel?



LHC tunnel cross section with space reserved for a future lepton machine like LEP3 [blue box above the LHC magnet] and with the presently proposed location of the LHeC ring [red]

integrating LEP3 IR in CMS detector?

Azzi, et al..

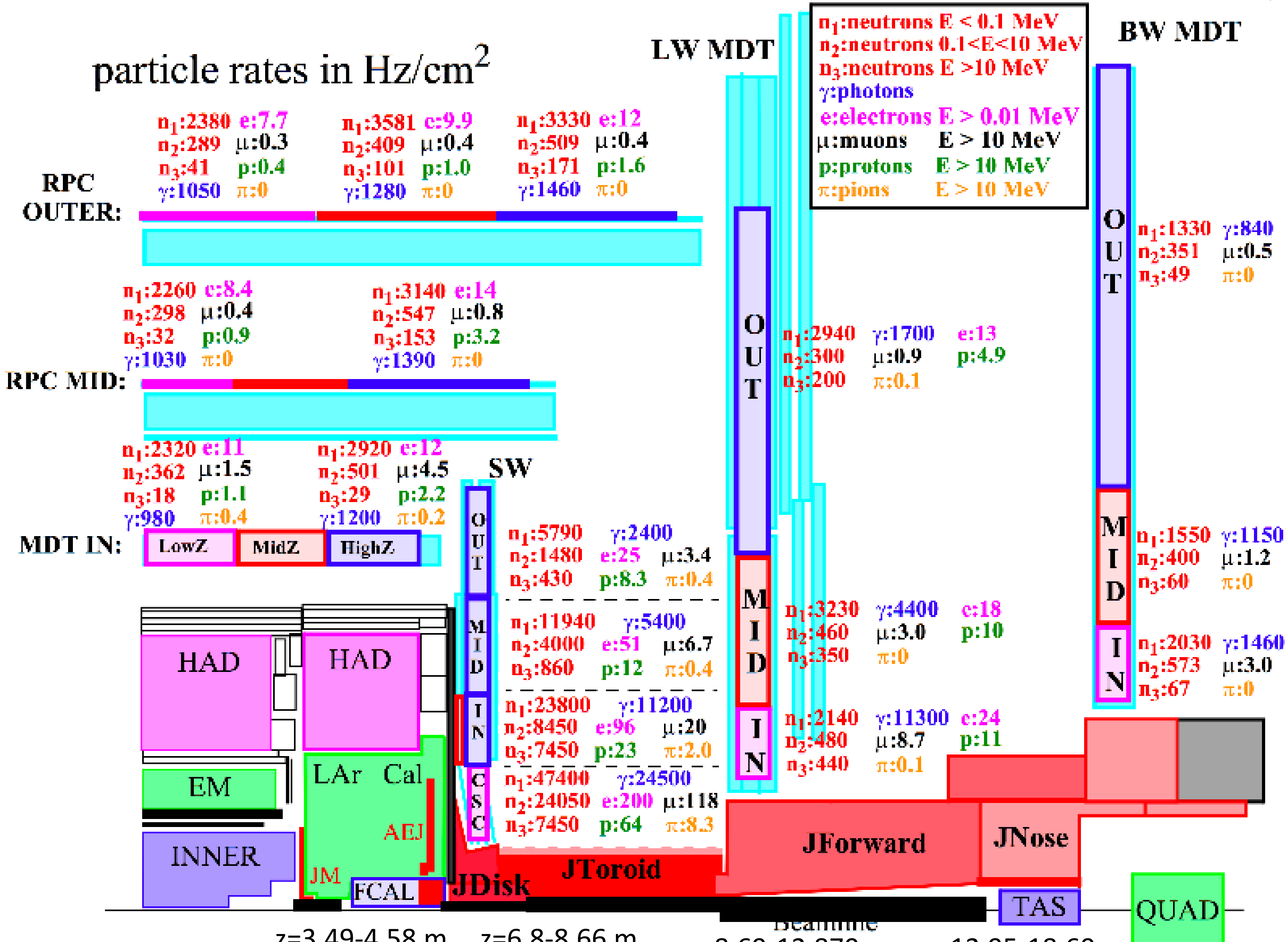


QUADS insertions in the CMS detector

A. Blondel, ATLAS Meeting 4 Oct. 2012

integrating LEP3 IR in ATLAS detector?

based on
M. Nessi
CARE-HHH
IR'07



z=3.49-4.58 m
r_{max}=18 cm

z=6.8-8.66 m
r_{max}=43 cm

z=8.69-12.870 m
r_{max}=87 cm

z=12.95-18.60 m
r_{max}=150 cm

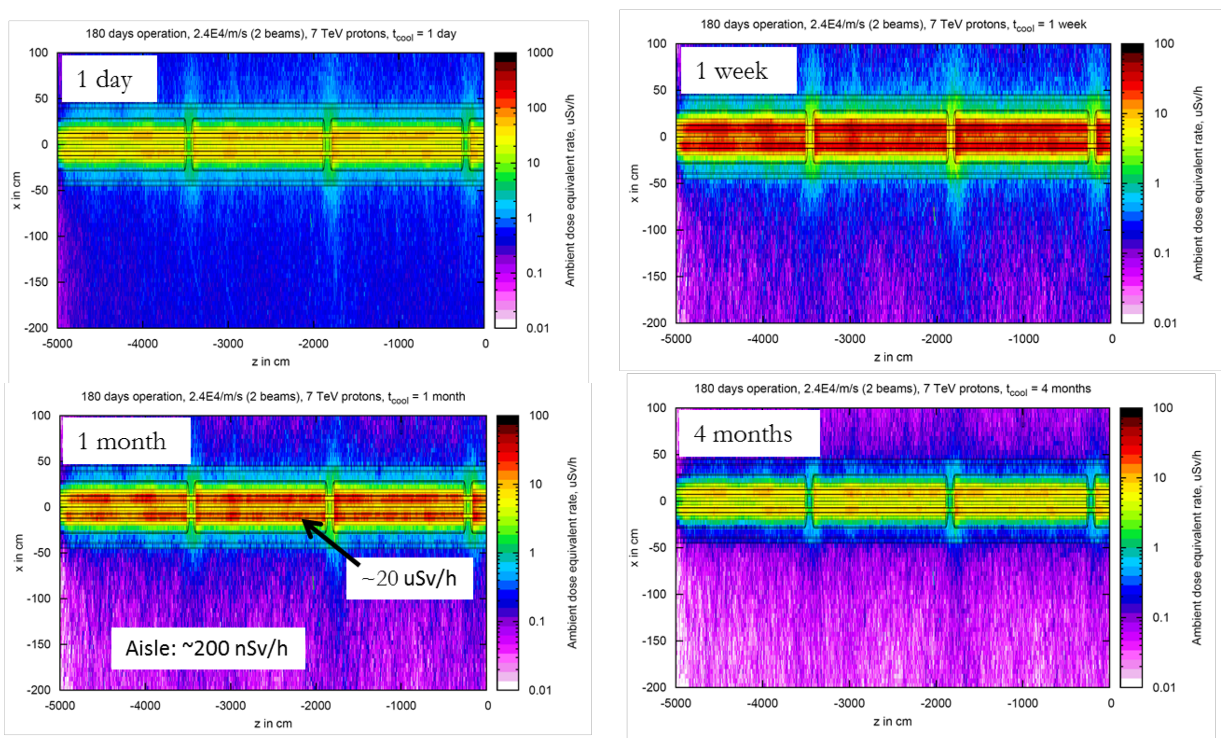
activation of LHC tunnel after (HL-) LHC operation

Activation of Arcs

Assumption:

2.4×10^4 protons/m/s (both beams), 7TeV, lost for 180 days continuously
(corresponds to an H_2-equivalent beam gas density of 4.5×10^{14} /m^3)

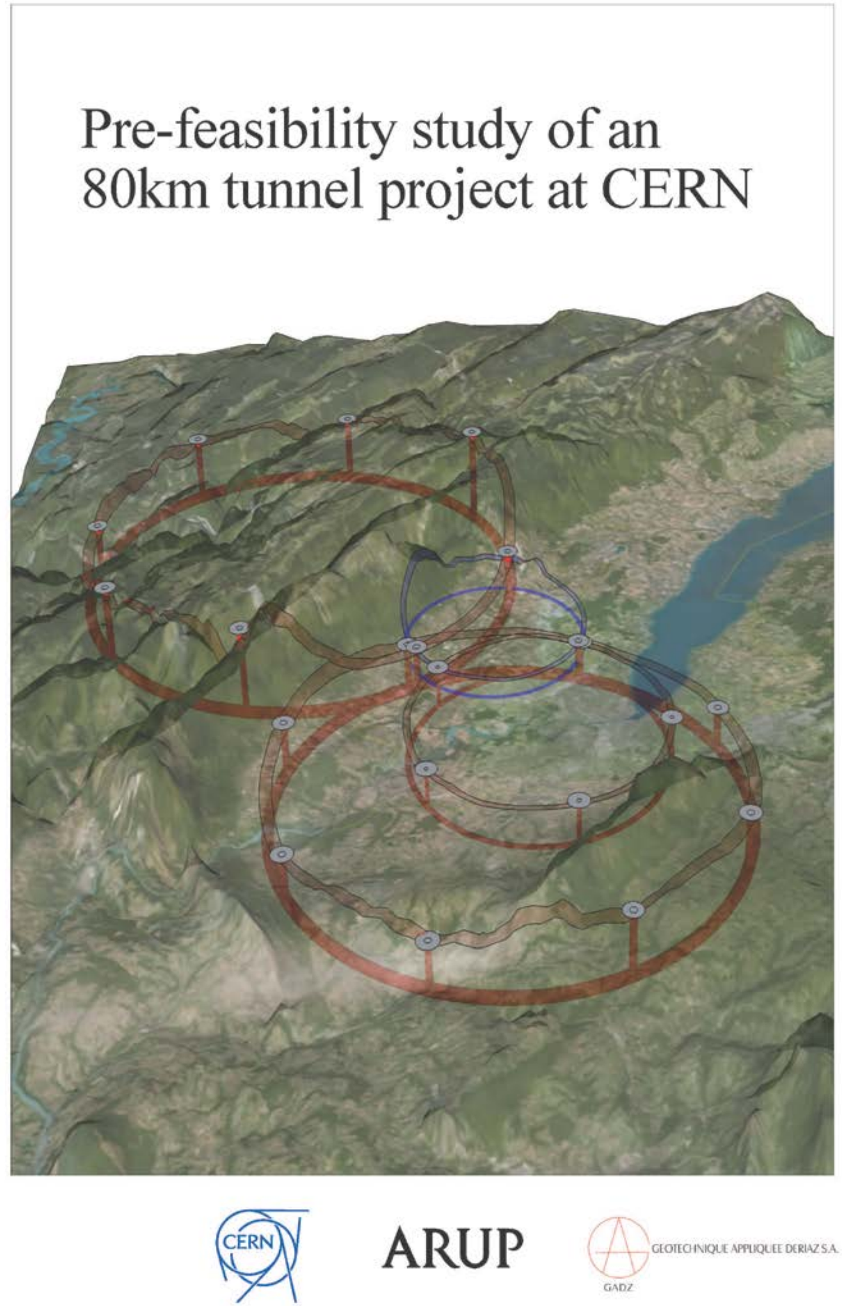
nominal



"Operation of HE-LHC will not increase the radiological risk to workers and public when compared to LHC-ultimate and HL-LHC (based on best present knowledge)"

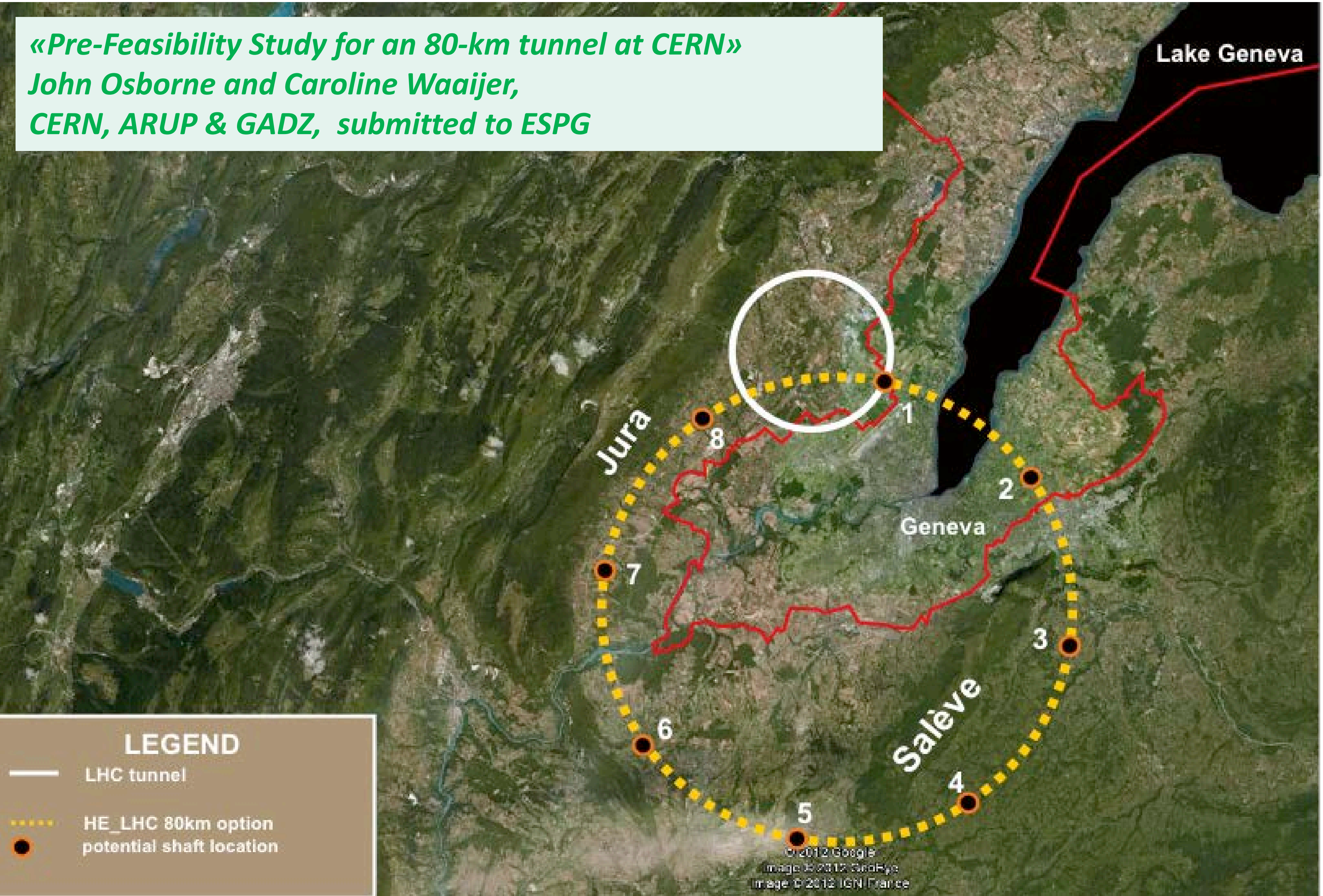
D. Forkel-Wirth et al, "Radioprotection issues after 20 years of LHC operation," Proc. EuCARD-AccNet mini-workshop on a Higher-Energy LHC "HE-LHC'10," 14-16 Oct. 2010, Malta, CERN Report CERN-2011-003

a new tunnel for TLEP in the Geneva area?



TLEP tunnel in the Geneva area – “best” option

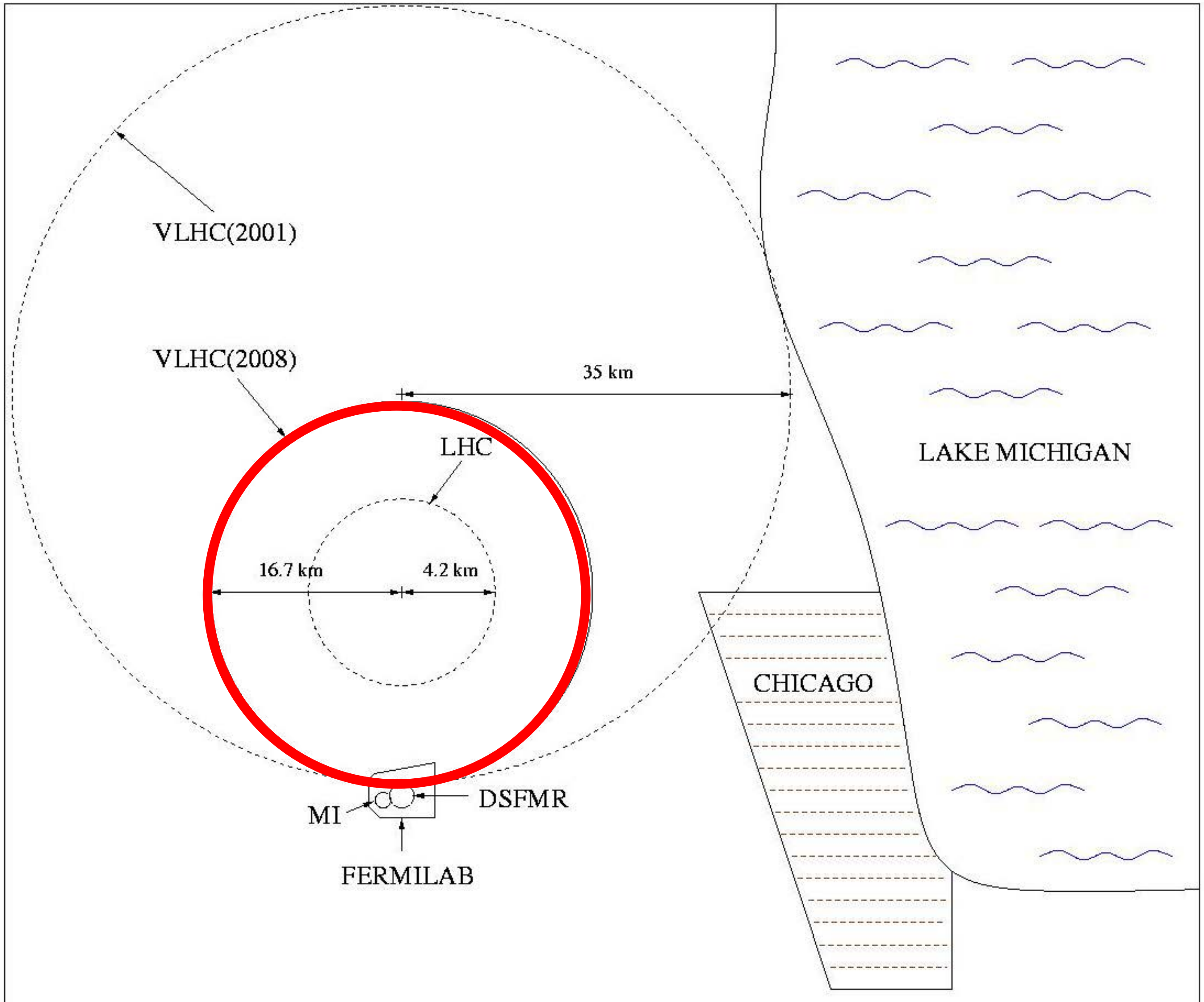
«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG




SuperTRISTAN 40
薬王院
八郷植物センター
TLEP tunnel in the KEK area?
12.3 km
KEK
SuperTRISTAN in Tsukuba: 40 km ring
Proposal by K. Oide, 13 February 2012


80 km ring in KEK area
12.7 km
KEK
Mt Tsukuba
筑波山
Miyawaki
宮脇
Tsutsujigaoka
つつじヶ丘
Mt Fuji
富士山
Ishioka
City Office
Makabe Branch
City Office
Chiyoda Branch
市役所千代田庁舎
City Office
Niihari Branch
Toyosato
Hospital
足尾山
丸山
きのこ山
フラワーパーク
筑波国際CC
つくばねCC
筑波東急GC
千代田PA
Map data ©2012 Google, ZENRIN -

105 km tunnel near FNAL



(+ FNAL plan B from R. Talman)

H. Piekarz, "… and … **path to the future of high energy particle physics**," JINST 4, P08007 (2009)

luminosity formulae & constraints

$$L = \frac{f_{rev} n_b N_b^2}{4\pi\sigma_x\sigma_y} = (f_{rev} n_b N_b)\left(\frac{N_b}{\varepsilon_x}\right)\frac{1}{4\pi}\frac{1}{\sqrt{\beta_x\beta_y}}\frac{1}{\sqrt{\varepsilon_y/\varepsilon_x}}$$

$$(f_{rev} n_b N_b) = \frac{P_{SR}\,\rho}{8.8575\times10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^{-3}}E^4}$$ *SR radiation power limit*

$$\frac{N_b}{\varepsilon_x} = \frac{\xi_x 2\pi\gamma(1+\kappa_\sigma)}{r_e}$$ *beam-beam limit*

$$\frac{N_b}{\sigma_x\sigma_z}\frac{30\,\gamma r_e^2}{\delta_{acc}\,\alpha} < 1$$ *>30 min beamstrahlung lifetime (Telnov) → N_b, β_x*

→minimize $\kappa_\varepsilon=\varepsilon_y/\varepsilon_x$, $\beta_y \sim \beta_x(\varepsilon_y/\varepsilon_x)$ and respect $\beta_y \geq \sigma_z$

LEP3/TLEP parameters -1

soon at SuperKEKB: β_x^*=0.03 m, β_Y^*=0.03 cm

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e−/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [µm]	270	30	71	78	43	63
σ^*_y [µm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.59	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3

SuperKEKB: $\varepsilon_y/\varepsilon_x$=0.25%

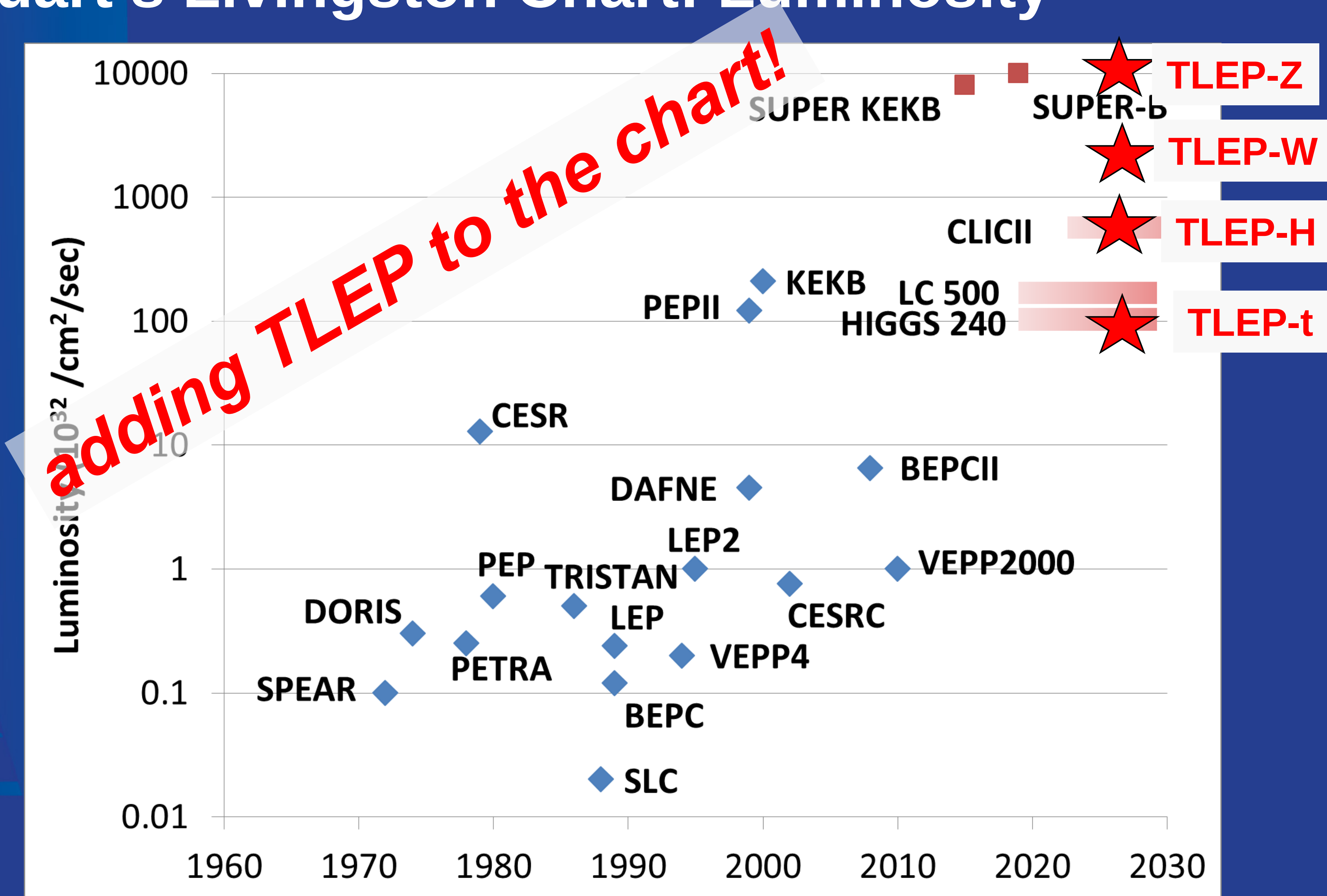
LEP3/TLEP parameters -2

LEP2 was not beam-beam limited

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	5.7	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	2.19	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	700	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.31	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	94	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	18	74	32	54
Υ_{BS} [10^{-4}]	0.2	0.05	9	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	31	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	44	6.2	65	95

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)

Stuart's Livingston Chart: Luminosity



beam lifetime

LEP2:

- beam lifetime ~ 6 h
- dominated by radiative Bhahba scattering with cross section σ~0.215 barn

LEP3:

- with L~10^{34} $cm^{-2}s^{-1}$ at each of two IPs:

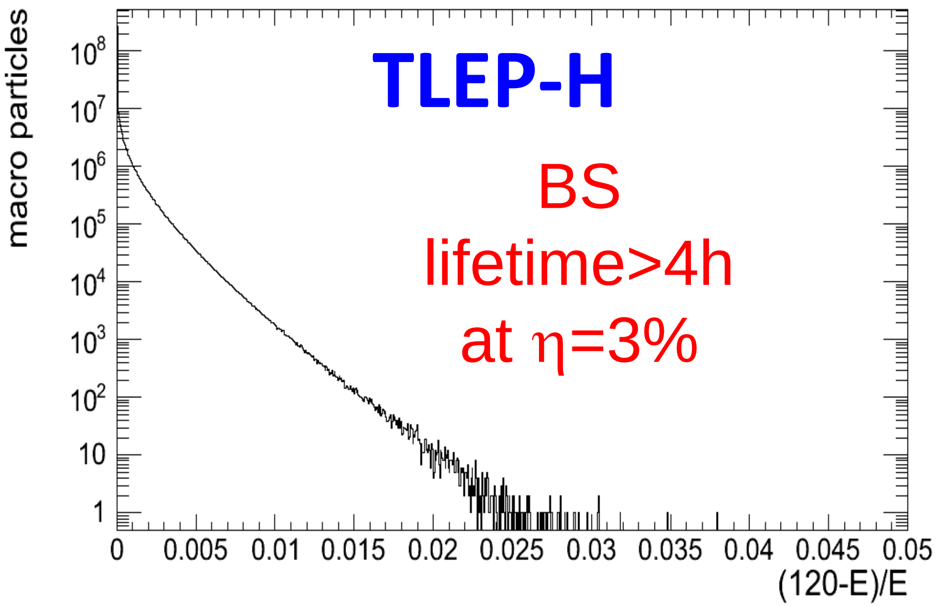
  $\tau_{beam,LEP3}$~18 minutes from rad. Bhabha
- **additional beam lifetime limit due to beamstrahlung** requires: (1) large momentum acceptance ($\delta_{max,RF} \geq 3\%$), and/or (2) flat(ter) beams and/or (3) fast replenishing

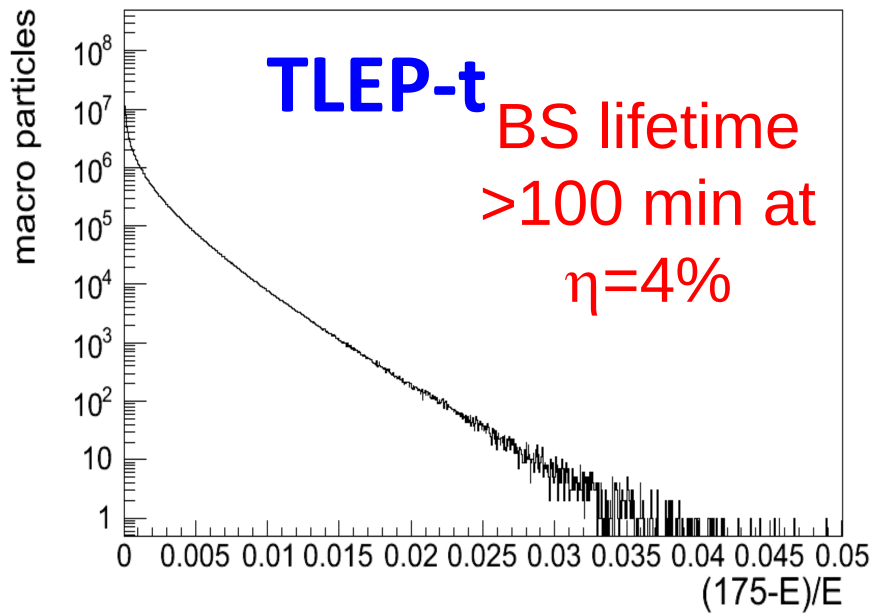
  (Valery Telnov, Kaoru Yokoya, Marco Zanetti)

energy spectrum after 1 collision

- GUINEA-PIG simulation with 360M macroparticles
- lifetime depends exponentially on energy acceptance η

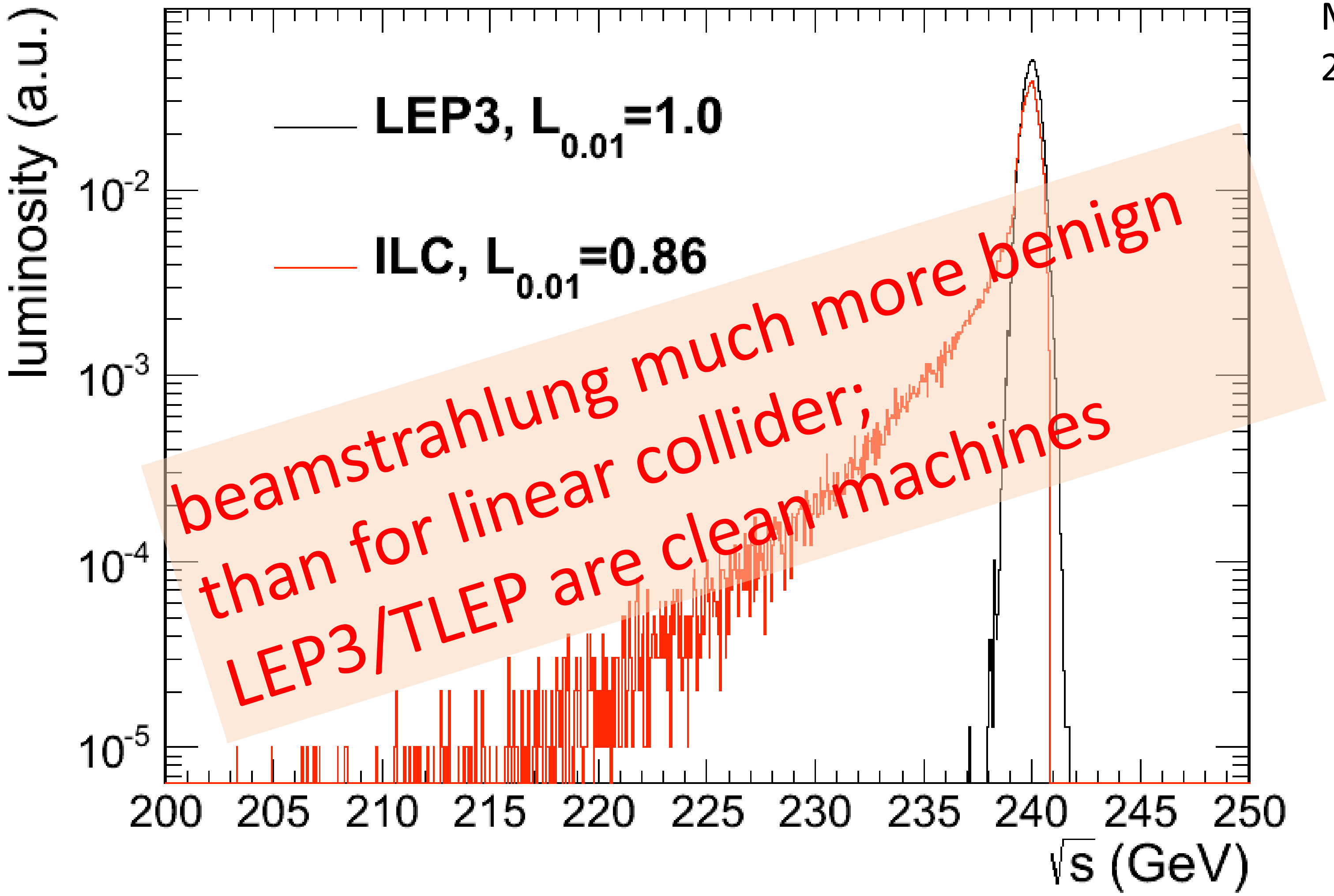
M. Zanetti, MIT
2nd LEP3 Day





- as for LEP3, TLEP BS lifetime well above required threshold
- in particular there is some margin for TLEP-H

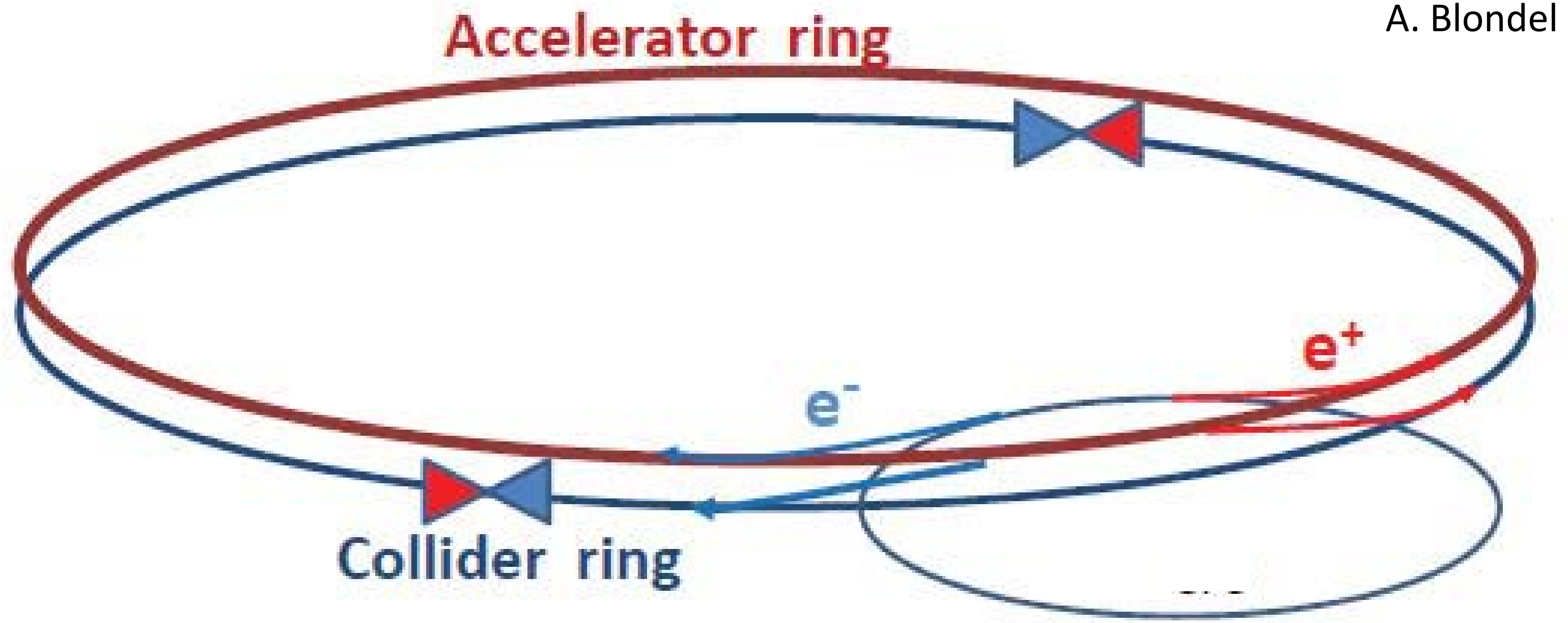
note: beamstrahlung effect at LEP3 much smaller than for ILC, ~monochromatic luminosity profile



M. Zanetti, MIT
2nd LEP3 Day

LEP3/TLEP: **double ring w. top-up injection** supports short lifetime & high luminosity

A. Blondel



a first ring accelerates electrons and positrons up to operating energy (120 GeV) and injects them at a few minutes interval into the low-emittance collider ring, which includes high luminosity $\geq 10^{34}$ cm^{-2} s^{-1} interaction points

top-up injection: *e^+* production

top-up interval << beam lifetime

→ average luminosity ≈ peak luminosity!

LEP3 needs about 4×10^{12} e^+ every few minutes, or of order 2×10^{10} e^+ per second

for comparison:

LEP injector complex delivered ~10^{11} e^+ per second (5x more than needed for LEP3!)

top-up injection: magnet ramp

SPS as LEP injector accelerated $e^{\pm}$ from 3.5 to 20 GeV (later 22 GeV) on a very short cycle:

acceleration time = 265 ms or about 62.26 GeV/s

Ref. K. Cornelis, W. Herr, R. Schmidt, "Multicycling of the CERN SPS: Supercycle Generation & First Experience with this mode of Operation," Proc. EPAC 1988

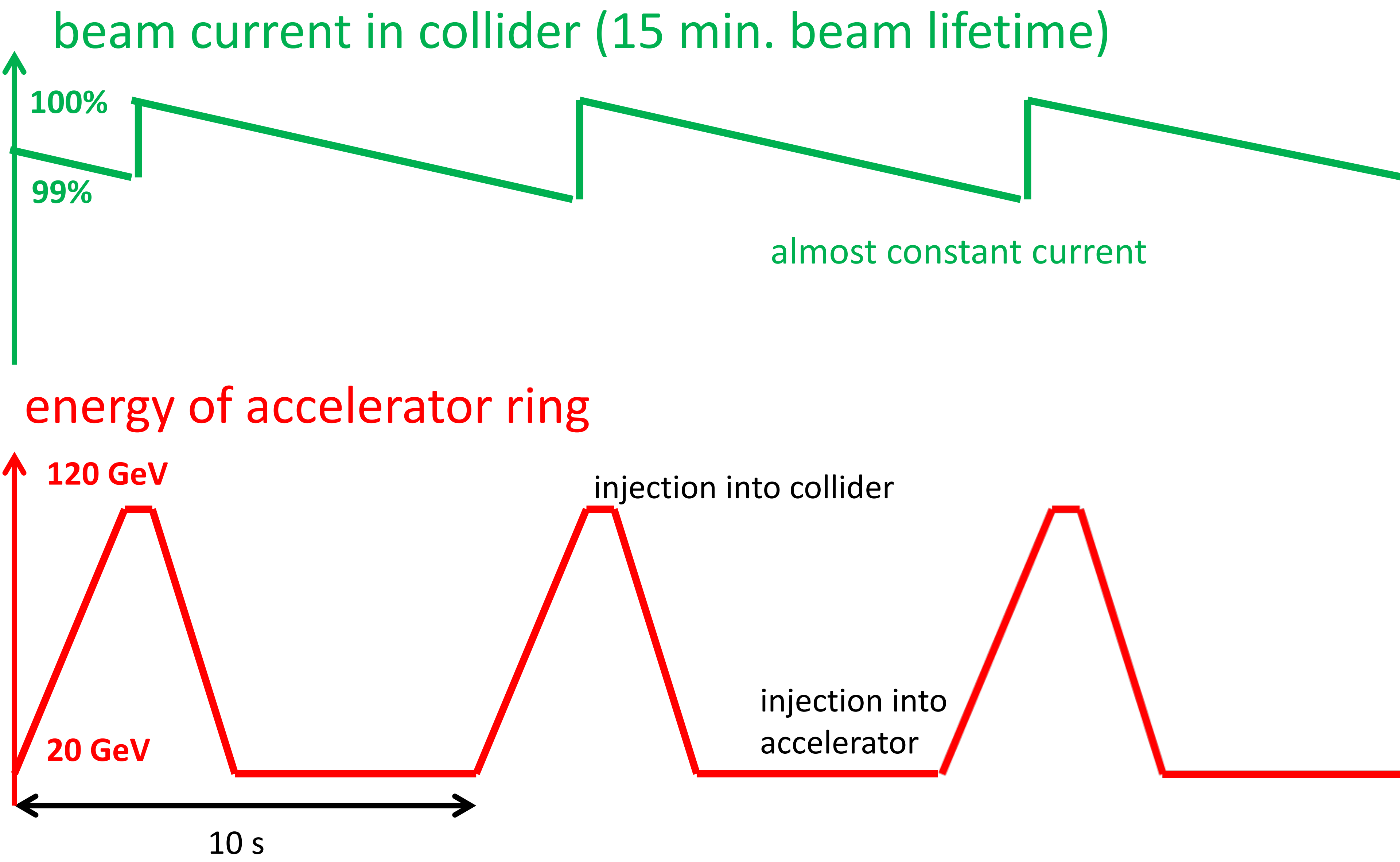
LEP3/TLEP: with injection from SPS into top-up accelerator at 20 GeV and final energy of 120 GeV →

acceleration time = 1.6 seconds

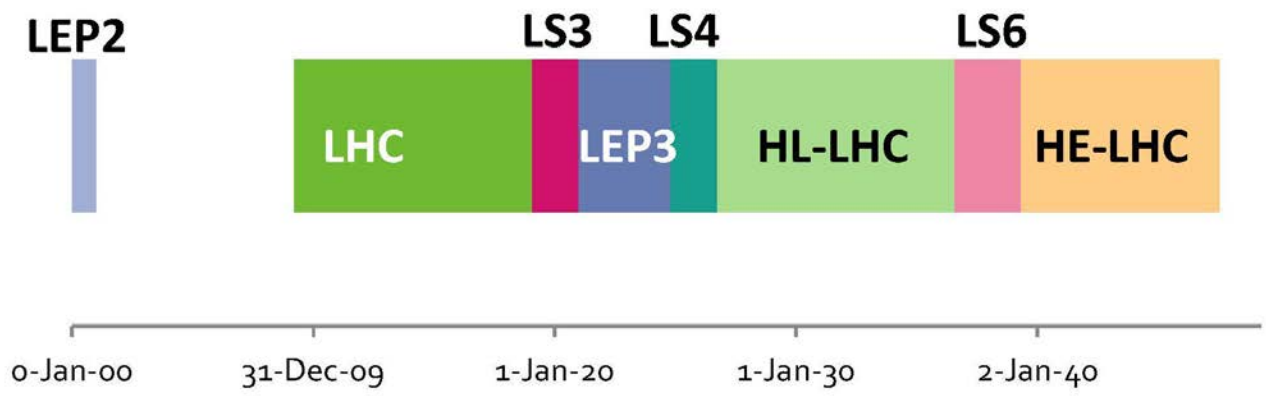
total cycle time = 10 s looks conservative (→ **refilling ~1% of the LEP3** beam, for τ_{beam}~18 min)

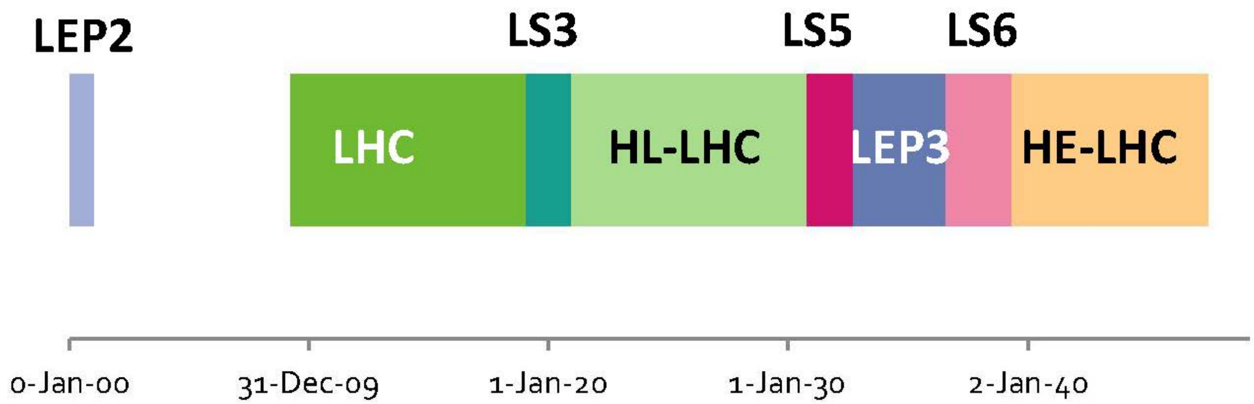
Ghislain Roy & Paul Collier

top-up injection: schematic cycle



two schematic time schedules for LEP3



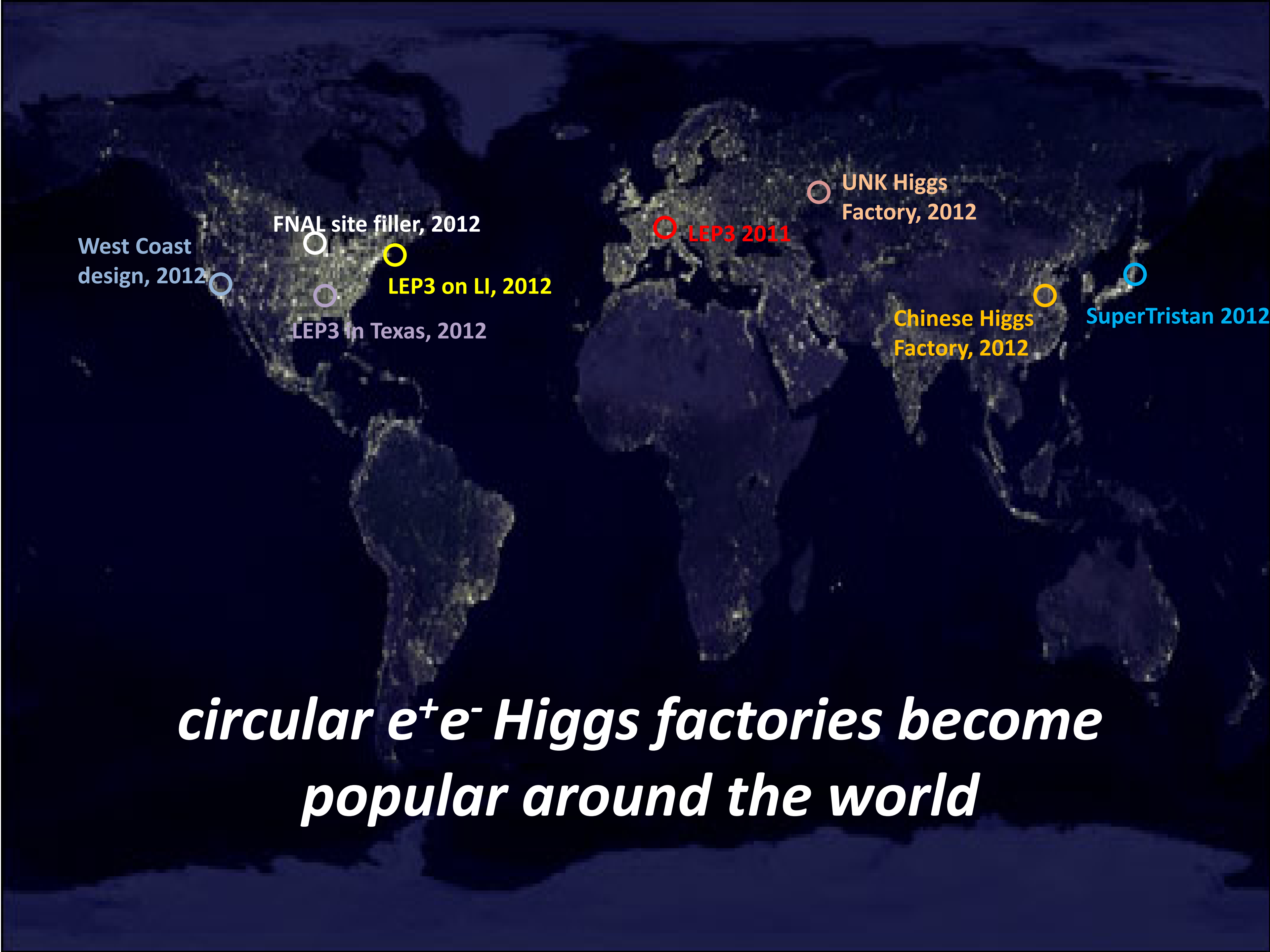


(LEP3 run time likely to be longer than shown)

of course TLEP would be constructed independently and could pave a direct path to VHE-LHC

LEP3/TLEP R&D items

- choice of RF frequency: 1.3 GHz (ILC) or 700 MHz (ESS)? & RF coupler
- SR handling and radiation shielding (LEP experience)
- beam-beam interaction for large Q_s and significant hourglass effect
- IR design with large momentum acceptance
- integration in LHC tunnel (LEP3)
- Pretzel scheme for TERA-Z operation

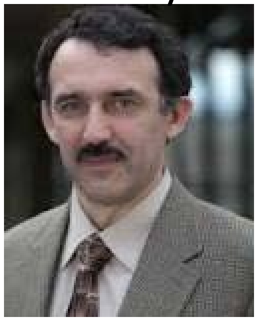


circular e^+e^- Higgs factories become popular around the world

LEP3/TLEP baseline w established technology

I had thought (and still think) that the possible use of **cheap, robust, established technology is a great asset for LEP3/TLEP**

A. Seryi



However, in Cracow and here at FNAL the **argument** has been put forward **that any future collider should be a *Hi-Tech facility*** (i.e. 18 GV SRF not enough, 350 GeV SRF being much better! - In other words a reasoning that we should fill a large tunnel with expensive objects instead of with cheap magnets as for LEP/LEP2)

by the way, LEP2 technology worked well

Parameter	Design LEP1 / LEP2	Achieved LEP1 / LEP2
Bunch current	0.75 mA	1.00 mA
Total beam current	6.0 mA	8.4 / 6.2 mA
Vertical beam-beam parameter	0.03	0.045 / 0.083
Emittance ratio	4.0 %	0.4 %
Maximum luminosity	16 / 27 10^{30} $cm^{-2}s^{-1}$	34 / 100 10^{30} $cm^{-2}s^{-1}$
IP beta function β_x	1.75 m	1.25 m
IP beta function β_y	7.0 cm	4.0 cm
Max. beam energy	95 GeV	104.5 GeV
Av. RF gradient	6.0 MV/m	7.2 MV/m

A. Blondel, P. Janot

LEP3/TLEP(/VHE-LHC) "Hi-Tech options"

examples:

novel SC cavities for LEP3/TLEP collider

fast ramping HTS magnets
for LEP3/TLEP double ring

VHE-LHC 20-T high-field magnets

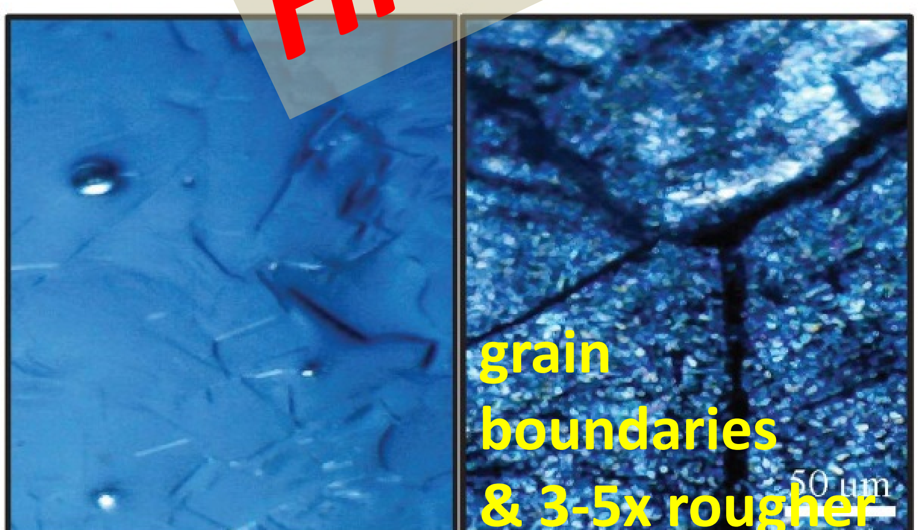
SC cavities based on material other than bulk *Nb*: thin *Nb* films, Nb_3Sn, HTS

E. Jensen, LHeC 2012; JLAB, IPAC12

- extensive studies at CERN (T. Junginger) and JLAB
- CERN/Legnaro/Sheffield cavities - first prototypes tested at Legnaro in 2012! HiPIMS* technique, SIS** concept,…
- sputtered *Nb* will reduce cost and may show better performance; even more HTS SIS** cavities
- Nb_3Sn could be studied at CERN (quad resonator) in collaboration with other labs

Hi-Tech cavities!

*High-power impulse magnetron sputtering, **Superconductor-Insulator-Superconductor



micrographs of sample surface of a micrometer thin niobium film sputtered on top of a copper substrate (left) and a bulk niobium sample (right)

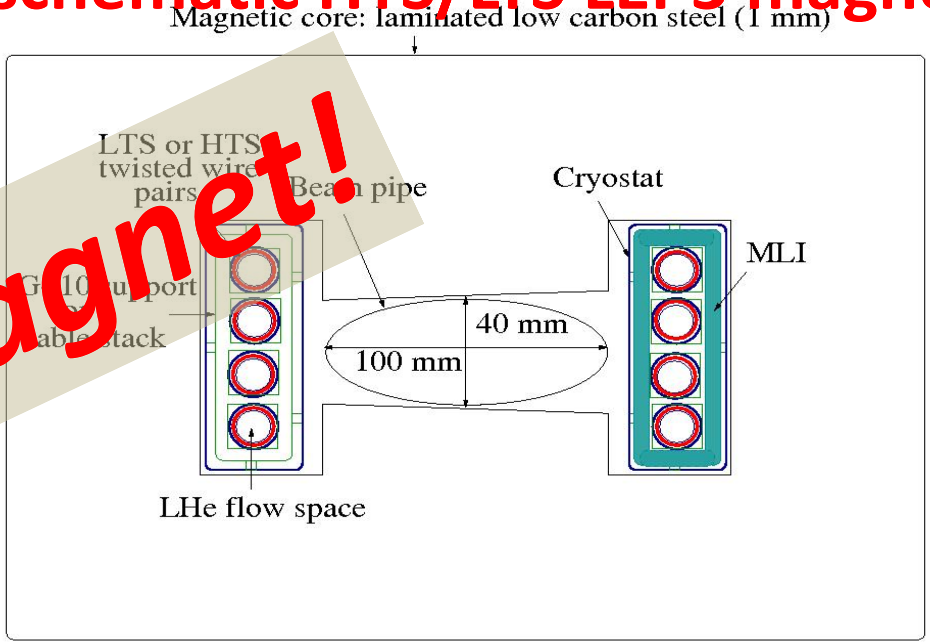
T. Junginger et al, IPAC2011

transmission-line HTS/LTS magnets

H. Piekarz,
1st EuCARD LEP3 Day

SC magnets require typically 10 x less space than NC magnet of the same field and gap; the magnet weight is very significantly reduced.

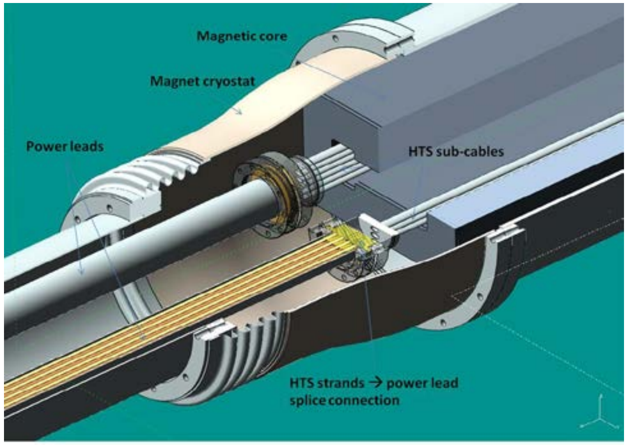
schematic HTS/LTS LEP3 magnet



Hi-Tech magnet!

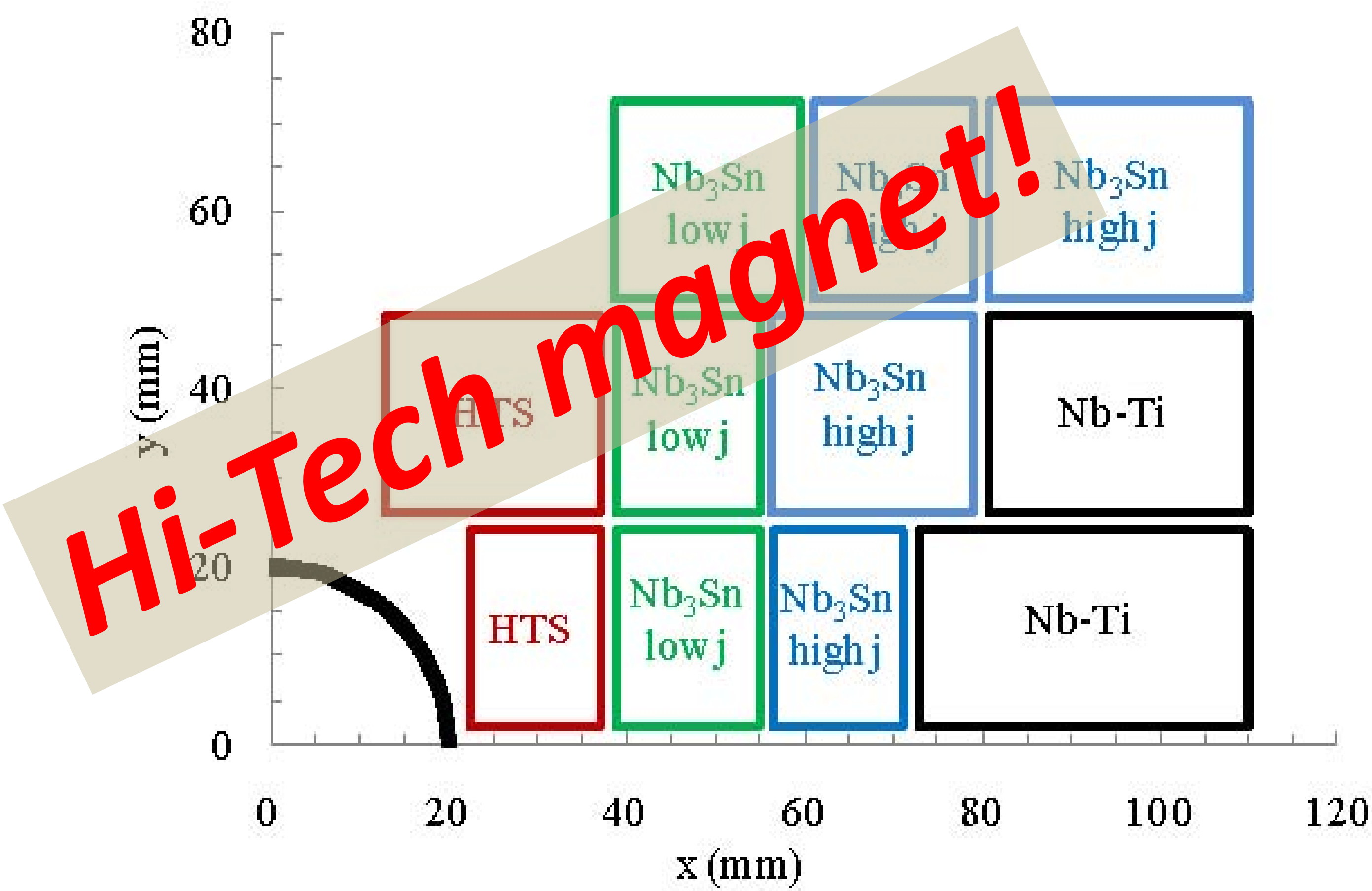
HTS prototype dipole at FNAL

Test: B_{max} = 0.5 T, I_{max} = 27 kA, dB/dt_{max} = 10 T/s , T_{max} ~ 25 K



acceleration time ~0.1 s, total cycle ~1 s; fast SC magnets might support 1 minute lifetime in collider ring!

(V)HE-LHC 20-T hybrid magnet



E. Todesco,
L. Rossi,
P. McIntyre

block layout of *Nb-Ti* & *Nb_3Sn* & *HTS* (*Bi*-2212) 20-T dipole-magnet coil. Only one quarter of one aperture is shown.

vertical rms IP spot sizes in nm

in regular font: achieved

in italics: design values

LEP2	3500
KEKB	940
SLC	500
LEP3	***320***
TLEP-H	***220***
ATF2, FFTB	150? (*35*), 65
SuperKEKB	*50*
SAPPHiRE	***18***
ILC	*5*
CLIC	*1*

LEP3/TLEP will learn a lot from SuperKEKB and ATF2!

LEP3/TLEP punchline

a ring e^+e^- collider LEP3 or TLEP appears to provide an economical & robust solution with very high statistics at several IPs for studying the X(125) with excellent precision & for performing many high-resolution measurements on H, W, Z (+top quark) within our lifetimes [A. Blondel]*;*

LEP3/TLEP would be THE choice for e^+e^- collision energies up to 400 GeV;

TLEP could be part of a long-term HEP strategy aiming for 100 TeV pp CoM energy

having the tunnel is everything!

Conclusions:

LEP3 may be the **cheapest possible option to study the Higgs** (cost ~1BEuro scale), feasible, **“off the shelf”, but** perhaps **not easy**

TLEP is **more expensive** (~5 BEuro?), but **clearly superior in terms of energy & luminosity**, and **extendable towards VHE-LHC**, preparing ≥50 years of exciting e^+e^-, *pp*, *ep/A* physics at highest energies

LEP3 and TLEP offer interesting energy-frontier physics at **moderate cost and/or with long-term perspective**, using robust technology

LEP3 and TLEP deserve a detailed design study

(incidentally, the only appearance of a Roman in the history of mathematics)

“NOLI TURBARE CIRCULOS MEOS!“

Archimedes of Syracuse, 287 – 212 BC

thank you for listening!

References for LEP3/TLEP:

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