LHeC and HE-LHC: accelerator layout and challenges

project layouts; main accelerator-physics & technology challenges; required LHC modifications; global schedules with decision points

Frank Zimmermann

Chamonix LHC Performance Workshop 2012

Many thanks to:

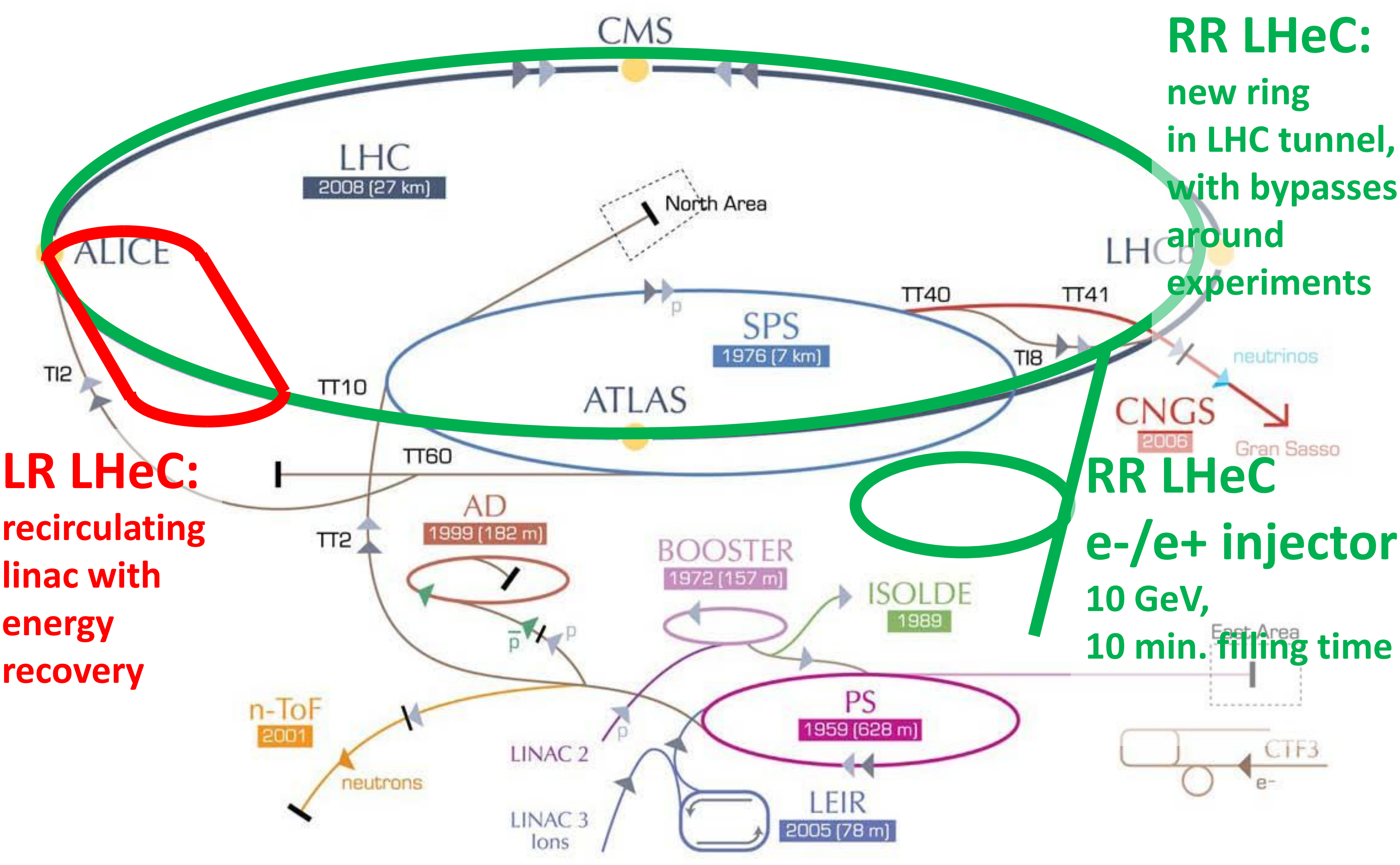
Jose Abelleira, Ralph Assmann, Nathan Bernard, Alex Bogacz, Chiara Bracco, Oliver Brüning, Helmut Burkhardt, Swapan Chattopadhyay, Ed Ciapala, John Dainton, Octavio Dominguez, Anders Eide, Miriam Fitterer, Brennan Goddard, Friedrich Haug, Bernhard Holzer, Miguel Jimenez, John Jowett, Max Klein, Peter Kostka, Vladimir Litvinenko, Peter McIntyre, Karl Hubert Mess, Steve Myers, Alessandro Polini, Louis Rinolfi, Lucio Rossi, Stephan Russenschuck, GianLuca Sabbi, Daniel Schulte, Mike Sullivan, Laurent Tavian, Ezio Todesco, Rogelio Tomas, Davide Tommasini, Joachim Tückmantel,…

Key references:

O. Brüning, LHeC Accelerator, ECFA Meeting at CERN, 25.11.2011

E. Todesco, High Energy LHC, 2nd EuCARD Meeting, Paris, 11.05.2011

Large Hadron electron Collider



Large Hadron electron Collider (LHeC)

DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group
THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

http://cern.ch/lhec

LHeC Study Group

J. Abelleira Fernandez[10,15], C.Adolphsen[39], S.Alekhin[40,11], A.N.Akai[01], H.Aksakal[30], P.Allport[17], J.L.Albacete[37], V.Andreev[25], R.B.Appleby[23], N.Armesto[38], G.Azuelos[26], M.Bai[47], D.Barber[11], J.Bartels[12], J.Behr[11], O.Behnke[11], S.Belyaev[10], I.BenZvi[47], N.Bernard[16], S.Bertolucci[10], S.Bettoni[10], S.Biswal[32], J.Bluemlein[11], H.Boettcher[11], H.Braun[48], S.Brodsky[39], A.Bogacz[28], C.Bracco[10], O.Bruening[10], E.Bulyak[08], A.Bunyatian[11], H.Burkhardt[10], I.T.Cakir[54], O.Cakir[53], R.Calaga[47], E.Ciapala[10], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[29], J.C.Collins[46], J.Dainton[17], A.De.Roeck[10], D.d'Enterria[10], A.Dudarev[10], A.Eide[43], E.Eroglu[45], K.J.Eskola[14], L.Favart[06], M.Fitterer[10], S.Forte[24], P.Gambino[42], T.Gehrmann[50], C.Glasman[22], R.Godbole[27], B.Goddard[10], T.Greenshaw[17], A.Guffanti[09], V. Guzey[28], C.Gwenlan[34], T.Han[36], Y.Hao[47], F.Haug[10], W.Herr[10], B.Holzer[10], M.Ishitsuka[41], M.Jacquet[33], B.Jeanneret[10], J.M.Jimenez[10], H.Jung[11], J.M.Jowett[10], H.Karadeniz[54], D.Kayran[47], F.Kocac[45], A.Kilic[45], K.Kimura[41], M.Klein[17], U.Klein[17], T.Kluge[17], G.Kramer[12], M.Korostelev[23], A.Kosmicki[10], P.Kostka[11], H.Kowalski[11], D.Kuchler[10], M.Kuze[41], T.Lappi[14], P.Laycock[17], E.Levichev[31], S.Levonian[11], V.N.Litvinenko[47], A.Lombardi[10], C.Marquet[10], B.Mellado[07], K.H.Mess[10], S.Moch[11], I.I.Morozov[31], Y.Muttoni[10], S.Myers[10], S.Nandi[26], P.R.Newman[03], T.Omori[44], J.Osborne[10], Y.Papaphilippou[10], E.Paoloni[35], C.Pascaud[33], H.Paukkunen[38], E.Perez[10], T.Pieloni[15], E.Pilicer[45], A.Polini[04], V.Ptitsyn[47], Y.Pupkov[31], V.Radescu[13], S.Raychaudhuri[27], L.Rinolfi[10], R.Rohini[27], J.Rojo[24], S.Russenschuck[10], C.A.Salgado[38], K.Sampei[41], E.Sauvan[19], M.Sahin[01], U.Schneekloth[11], A.N.Skrinsky[31], T.Schoerner Sadenius[11], D.Schulte[10], H.Spiesberger[21], A.M.Stasto[46], M.Strikman[46], M.Sullivan[39], B.Surrow[05], S.Sultansoy[01], Y.P.Sun[39], W.Smith[20], I.Tapan[45], P.Taels[02], E.Tassi[52], H.Ten.Kate[10], J.Terron[22], H.Thiesen[10], L.Thompson[23], K.Tokushuku[44], R.Tomas.Garcia[10], D.Tommasini[10], D.Trbojevic[47], N.Tsoupas[47], J.Tuckmantel[10], S.Turkoz[53], K.Tywoniuk[18], G.Unel[10], J.Urakawa[44], P.VanMechelen[02], A.Variola[37], R.Veness[10], A.Vivoli[10], P.Vobly[31], R.Wallny[51], G.Watt[10], G.Weiglein[12], C.Weiss[28], U.A.Wiedemann[10], U.Wienands[39], F.Willeke[47], V.Yakimenko[47], A.F.Zarnecki[49], F.Zimmermann[10], F.Zomer[33]

About 150 Experimentalists and Theorists from 50 Institutes
Tentative list

Thanks to all and to
CERN, ECFA, NuPECC

draft LHeC CDR completed (~600 pages); TDR by 2014

performance targets

e- energy ≥60 GeV

luminosity ~10^{33} $cm^{-2}s^{-1}$

total electrical power for e-: ≤100 MW

e^+p collisions with similar luminosity

simultaneous with LHC *pp* physics

e^-/e^+ polarization

detector acceptance down to 1^o

LHeC design parameters

electron beam	RR	LR	LR*
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	17	10	0.44
polarization [%]	40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
repetition rate [Hz]	N/A	N/A	10
beam pulse length [ms]	N/A	N/A	5
ER efficiency	N/A	94%	N/A
average current [mA]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

*) pulsed, but high energy ERL not impossible

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit. $\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1
bunch spacing [ns]	25	25

50 ns & N_b=1.7x10^{11} probably conservative

design also for deuterons (new) and lead (exists)

RR= Ring – Ring
LR =Linac –Ring

β^*~0.025 m possible in IP3 or 7 using ATS optics (S. Fartoukh); + also going to 2 μm emittance (H. Damerau, W. Herr), → L~10^{34} $cm^{-2}s^{-1}$ within reach!

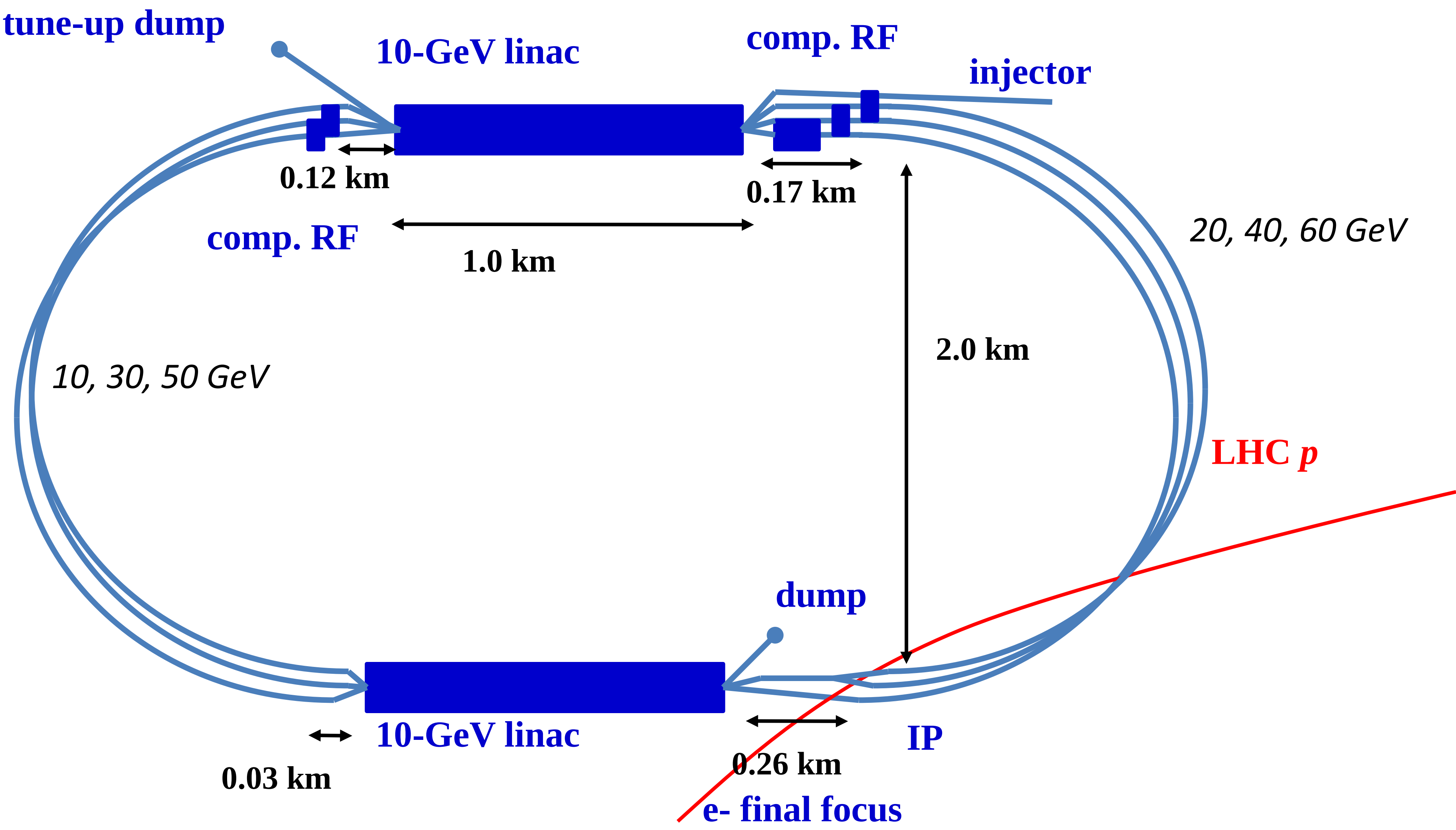
LHeC Ring-Ring Challenges

- bypassing the main LHC detectors
  - CMS: 20 cm distance to cavern, 1.3 km bypass, 300 m for RF installation
  - ATLAS: using the survey gallery, 1.3 km bypass, 170 m for RF installation; similar schemes for LHCb & ALICE
- integration into the LHC tunnel
  - cryo jumpers taken into account in arc-cell design
- installation matching LHC circumference
  - avoiding Hirata-Keil resonances, arcs ~4000 magnets
  - no show stopper found; 3D integration needed
  - compact magnet design & prototypes (BINP)
- installation within LHC shutdown schedule

LHeC Linac-Ring Challenges

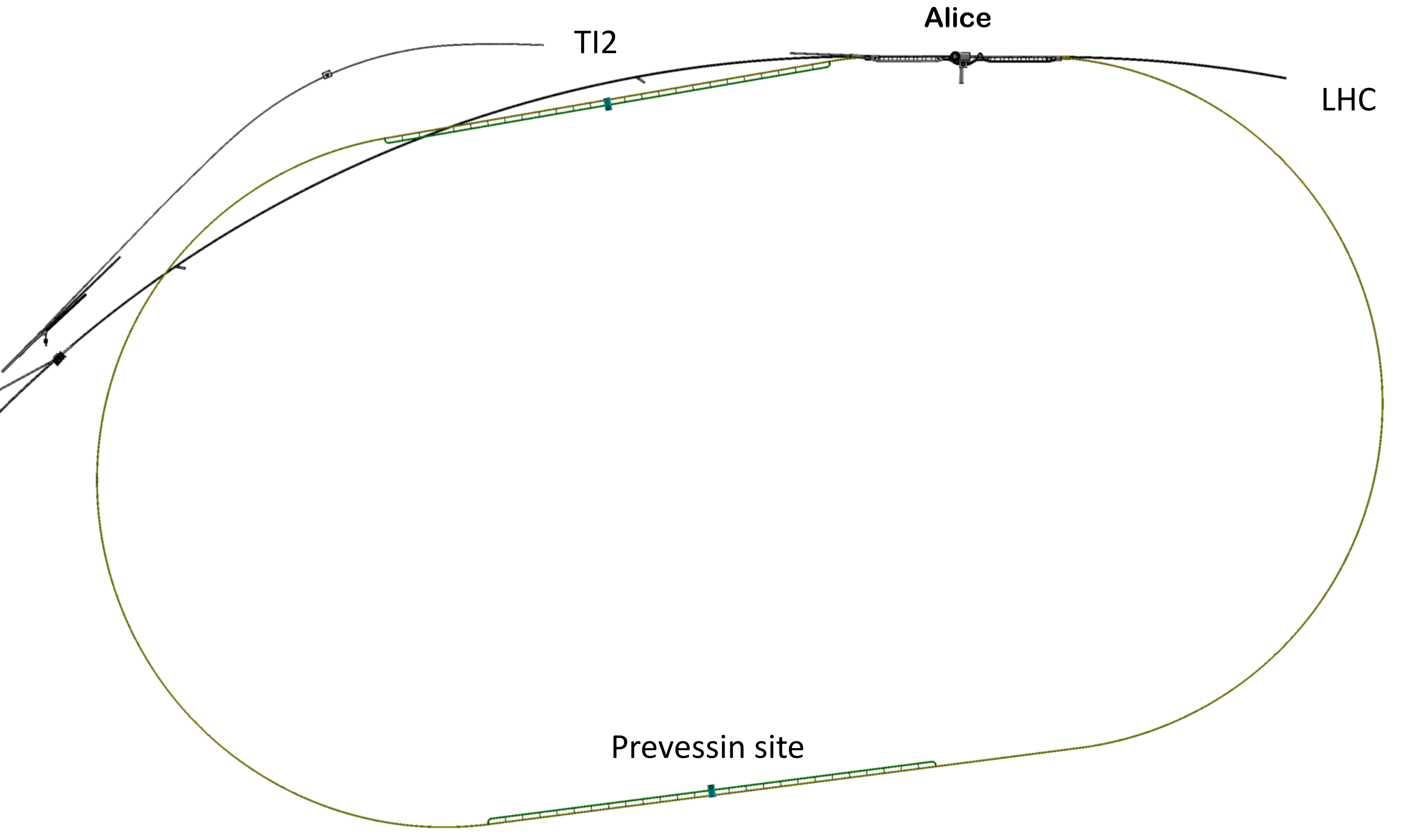
- 2 x 10 GeV SC Energy Recovery Linacs
  - SC linac: synergies with ESS, SPL, XFEL, JLAB, ILC, eRHIC
  - linac size similar to XFEL at DESY; cryo power ~1/2 LHC
  - less current than other ERL designs (CESR-ERL, eRHIC)
- return arcs
  - total circumference ~ 9 km, 3 passes
  - same magnet design as for RR option, >4500 magnets
  - installation fully decoupled from LHC operation
- e^+p luminosity: e^+ production & recycling
  - IP e+ rate ~100 times higher than for CLIC or ILC
  - several schemes proposed to achieve this

ERL configuration



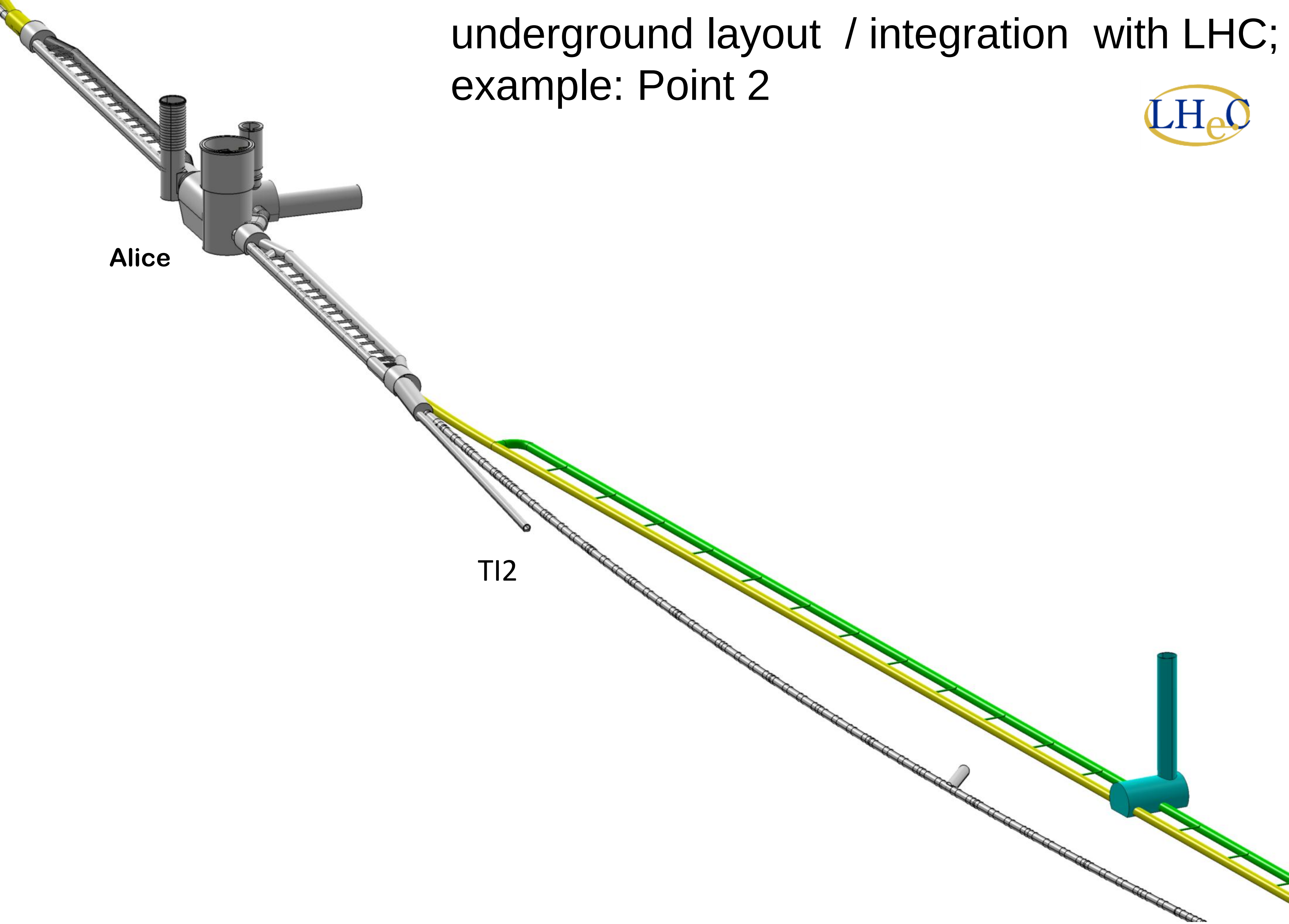
total circumference ~ 8.9 km

LHeC RL option: underground layout / integration with LHC; example: Point 2



J.Osborne / A.Kosmicki CERN/GS

underground layout / integration with LHC; example: Point 2



J.Osborne / A.Kosmicki CERN/GS

L-L&R-L LHeC arc magnets & RF cavities

Table 2: Components of the Electron Accelerators

	Ring	Linac
magnets		
beam energy	60 GeV	
number of dipoles	3080	3600
dipole field [T]	0.013 – 0.076	0.046 – 0.264
total nr of quads	866	1588
RF and cryogenics		
number of cavities	112	944
gradient [MV/m]	11.9	20
RF power [MW]	49	39
cavity voltage [MV]	5	21.2
cavity R/Q [Ω]	114	285
cavity Q_0	–	$2.5\ 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K

LHeC

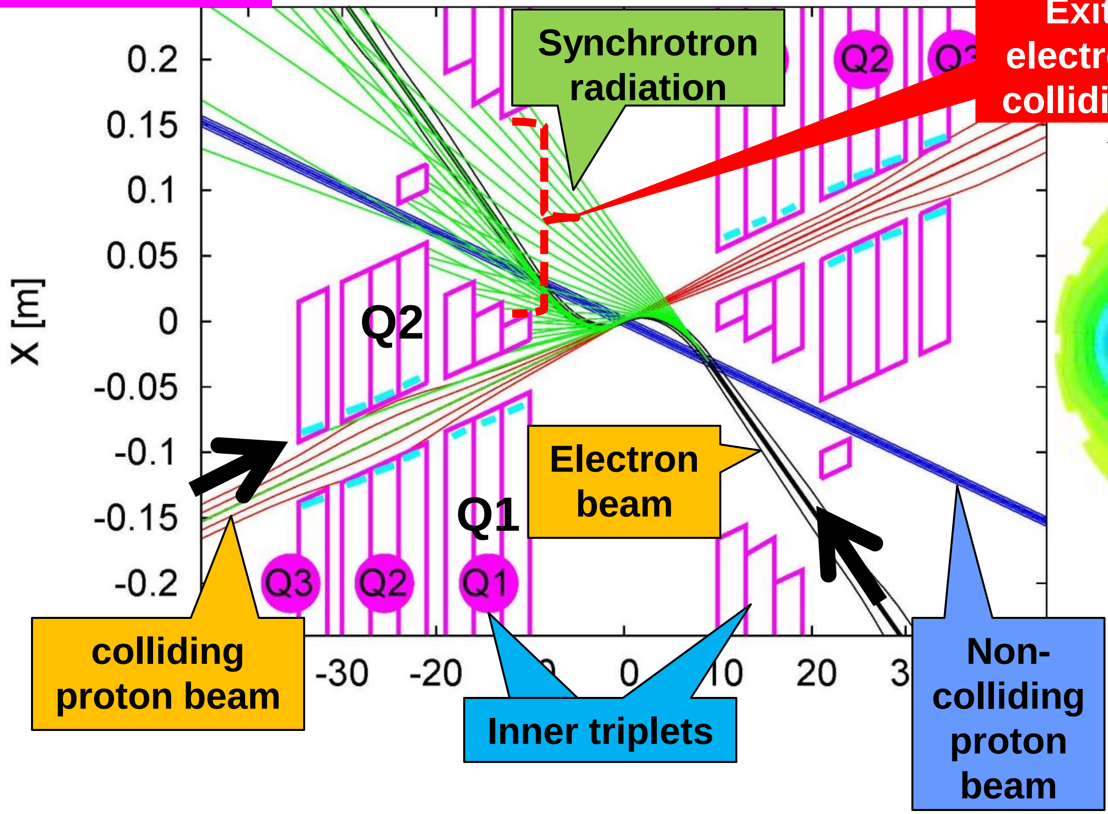
LHeC L-R & R-R Joint IR Challenges

- interaction region layout for 3 beams
  - exit holes & optics
- final quadrupole design
  - Q1 half quadrupole design
  - synergy with HL-LHC developments (Nb_3Sn)
- IR synchrotron radiation shielding
  - SR from last quadrupoles and/or combination dipole
  - minimize backscattering into detector
  - shielding of SC quadrupoles
  - SC masking to be further optimized (vacuum & detector background)

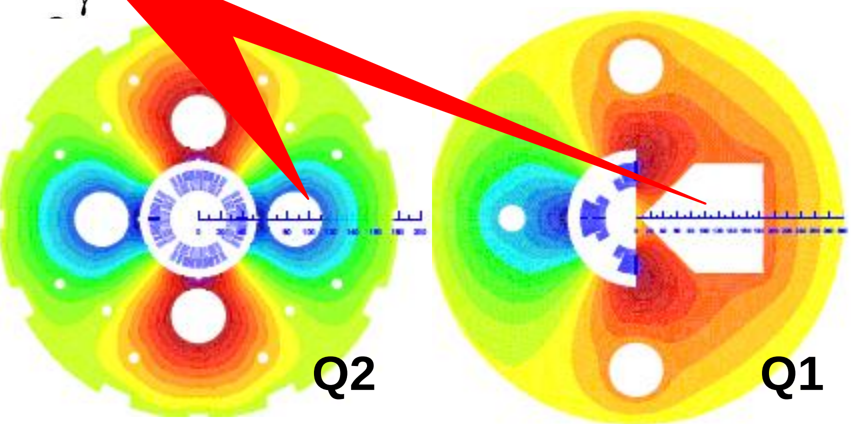
LHeC

LR LHeC IR layout & SC IR quadrupoles

R. Tomas



S. Russenschuck



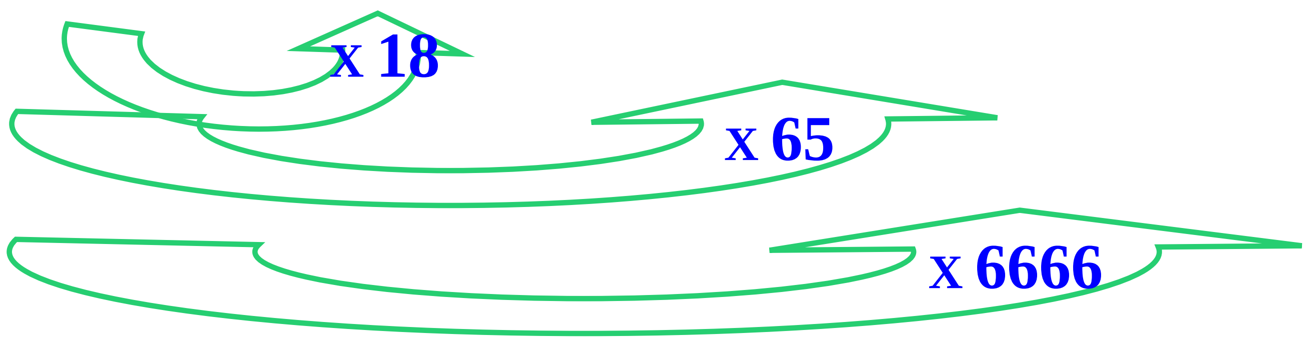
Nb3Sn (HFM46): 5700 A, 175 T/m, 4.7 T at 82% on LL (4 layers), 4.2 K	Nb3Sn (HFM46): 8600 A, 311 T/m, at 83% LL, 4.2 K
46 mm (half) ap., 63 mm beam sep.	23 mm ap.. 87 mm beam sep.
0.5 T, 25 T/m	0.09 T, 9 T/m

High-gradient SC IR quadrupoles based on Nb3Sn for colliding proton beam with common low-field **exit hole for electron beam and non-colliding proton beam**

detector integrated dipole: 0.3 T over +/- 9 m

LHeC Linac-Ring e^+ source

	SLC	**CLIC (3 TeV)**	**ILC (RDR)**	**LHeC**
Energy	1.19 GeV	2.86 GeV	5 GeV	60 GeV
e^+/ bunch at IP	40×10^9	$3.72\text{x}10^9$	20×10^9	$2\text{x}10^9$
e^+/ bunch before DR inj.	50×10^9	$7.6\text{x}10^9$	30×10^9	N/A
Bunches / macropulse	1	312	2625	N/A
Macropulse repet. rate	120	50	5	CW
Bunches / second	120	15600	13125	$20\text{x}10^6$
e^+ / second	**0.06×10^{14}**	**1.1×10^{14}**	**3.9×10^{14}**	**400×10^{14}**

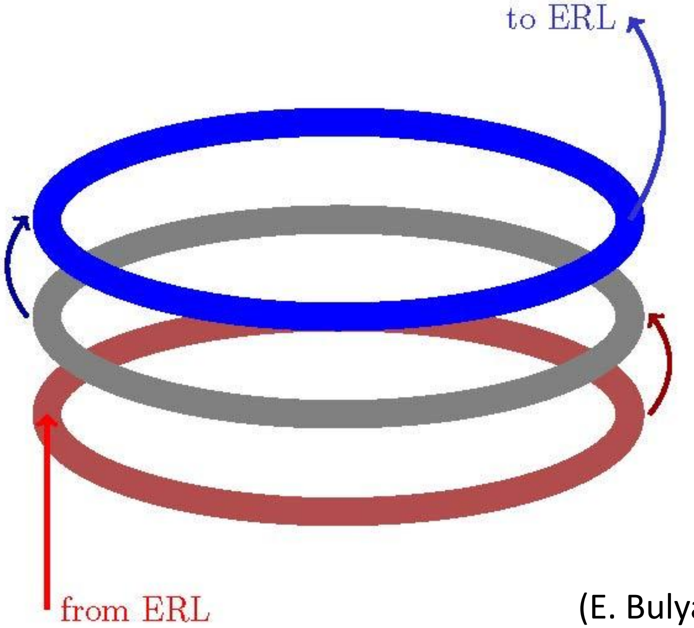


L. Rinolfi

linac e+ source options

- recycle e+ together with energy, multiple use,

  damping ring in SPS tunnel w $\tau_\perp$~2 ms (D. Schulte) (Y. Papaphilippou)
- Compton ring, Compton ERL, coherent pair production, or undulator for high-energy beam
- 3-ring transformer & cooling scheme (H. Braun, E. Bulyak, T. Omori, V. Yakimenko)



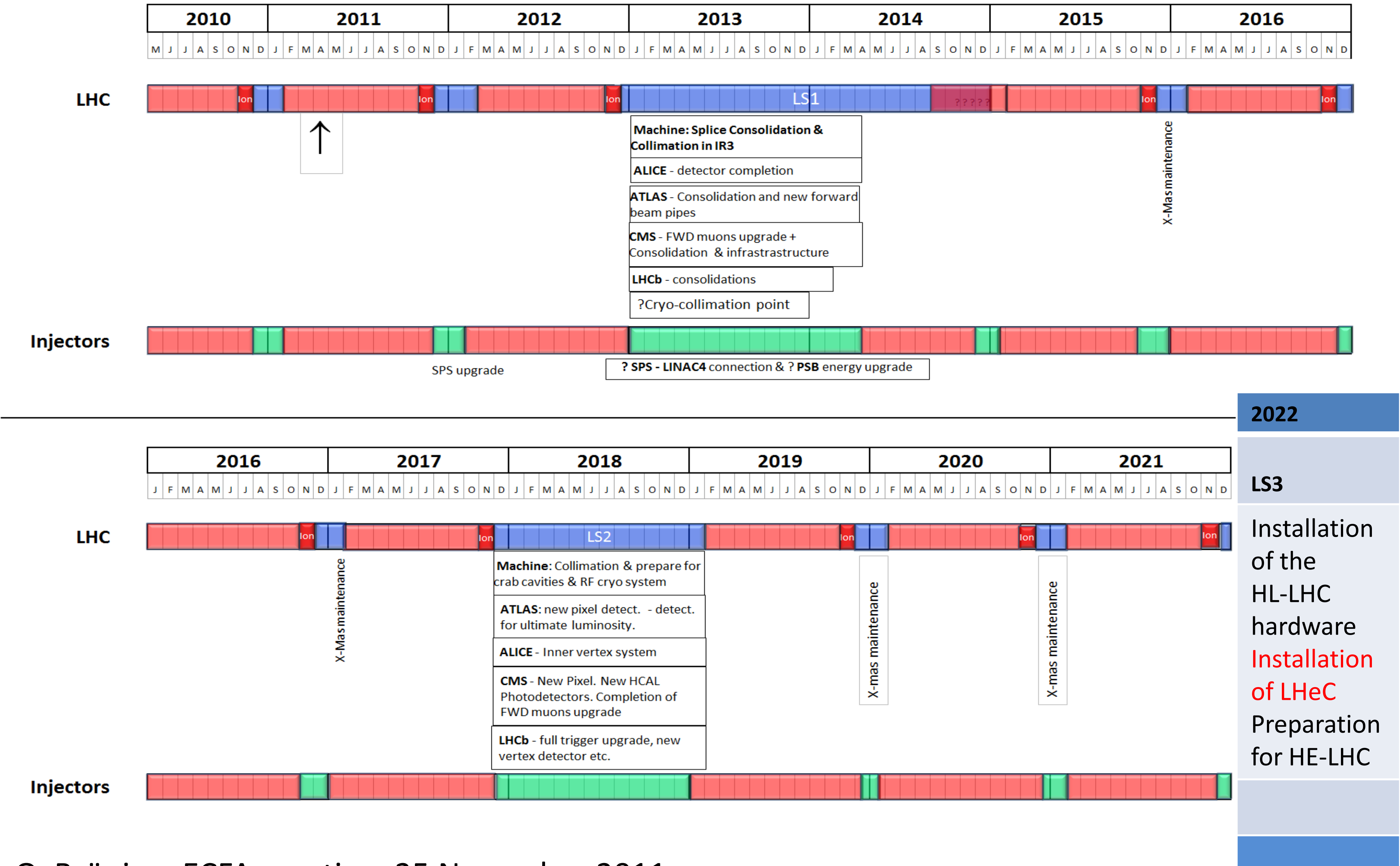
extraction ring (*N* turns)

fast cooling ring (*N* turns)

accumulator ring (*N* turns)

(E. Bulyak)

CERN Medium Term Plan



O. Brüning, ECFA meeting, 25 November 2011

LHeC Planning and Timeline

CERN Medium Term Plan →

- Only 2 long shutdowns before 2022
- Only 10 years from LHeC CDR to start of operation

LHeC planning:

- **R&D work must start** as soon as possible
- Develop **detailed TDR** after feedback from CDR review

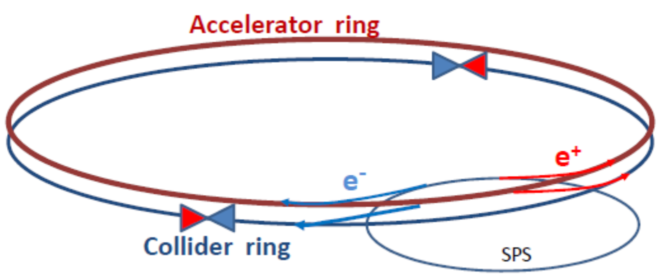
→ concentrate future effort on only one option: **L-R or R-R**

some arguments for linac or ring

- energy-recovery linac
  - novel far-reaching energy-efficient technology
  - **no interference with LHC operation & HL-LHC work**
  - **synergies w SPL, CEBAF+, ESS, XFEL, eRHIC, SPL, ILC, …**
  - new technology, **great investment** for future (e.g. neutrino factory, linear collider, muon collider, 20-GeV SC proton linac, HE-LHC injector, higher-energy LHeC, proton-driven plasma acceleration,…)
- ring
  - **conventional, little risk, less demanding *p* optics**
  - **synergies with LEP3 Higgs factory in LHC tunnel**

parenthesis - LEP3 Higgs factory

- e^+e^- collider in LHC tunnel, few bunches / beam
- 50 MW SR power per beam; ex. *LHeC optics*
- $>10^{34}$ $cm^{-2}s^{-1}$ in ATLAS & CMS, τ_{beam}~few minutes
- $>10^4$ Z-H events per year

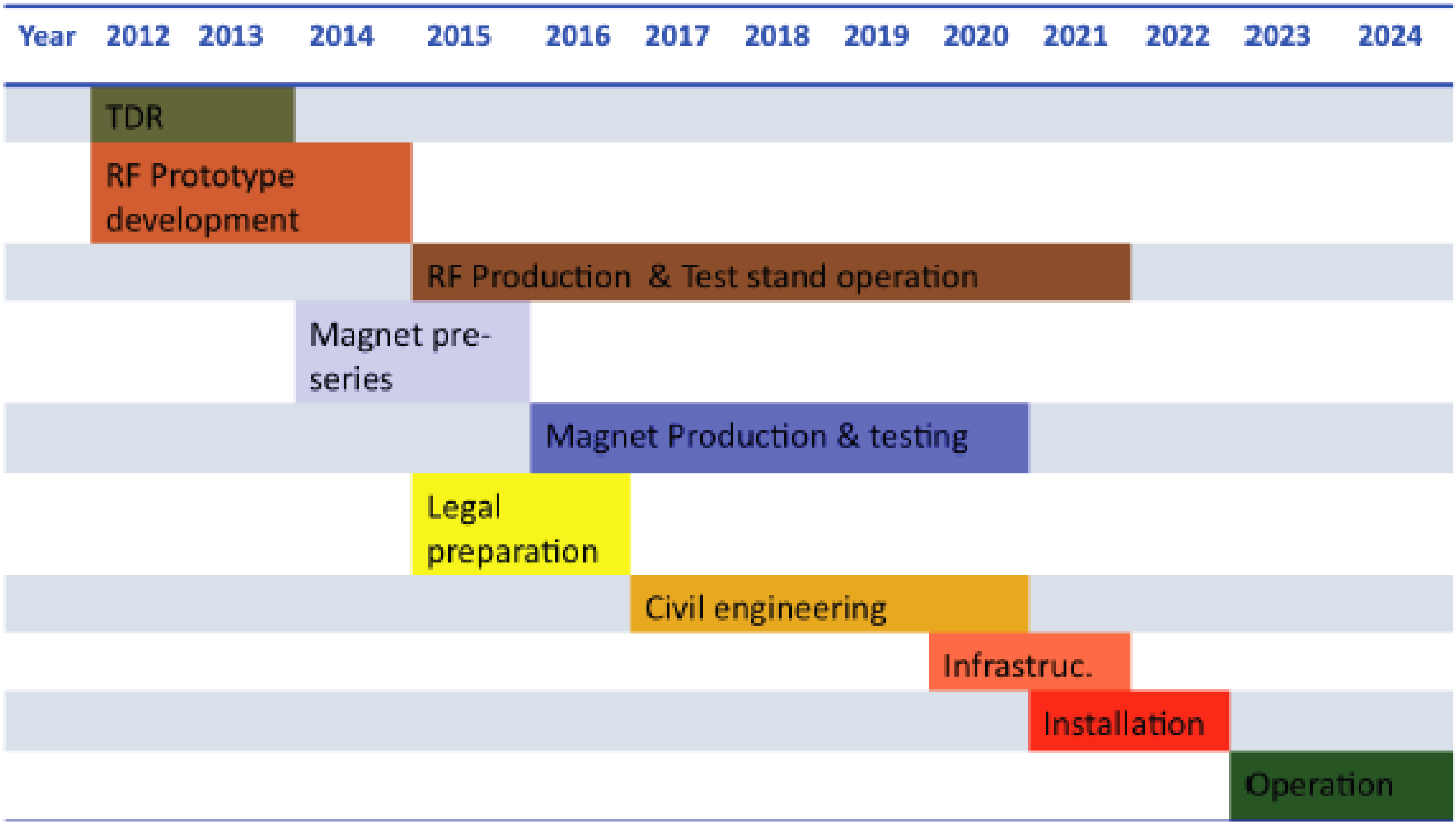


two ring scheme with top-up injection into collider ring

Alain Blondel, Frank Zimmermann, *A High Luminosity e+e- Collider in the LHC tunnel to study the Higgs Boson,* CERN-OPEN-2011-047, arXiv:1112.2518v1 [hep-ex]

	LEP	LHeC ring design	LEP3
E_b beam energy	104.5 GeV	60 GeV	120 GeV
beam current	4 mA (4 bunches)	100 mA (2808 bunches)	7.2 mA (3 bunches)
total #e- / beam	2.3e12	5.6e13	4.0e12
horizontal emittance	48 nm	5 nm	20 nm
momentum compaction	$1.85x10^{-4}$	$8.1x10^{-5}$	$8.1x10^{-5}$
SR power / beam	11 MW	44 MW	50 MW
$\beta_{x,y}$*	1.5, 0.05 m	0.18, 0.10 m	0.15 0.0012 m
rms IP beam size	270, 3.5 micron	30, 16 micron	55, 0.4 micron
hourglass loss factor	0.98	0.99	0.65
energy loss per turn	3.408 GeV	0.44 GeV	6.99 GeV
total RF voltage	3641 MV	500 MV	9000 MV
beam-beam tune shift (/IP)	0.025, 0.065	N/A	0.126, 0.130
average acc.field	7.5 MV/m	11.9 MV/m	18 MV/m
effective RF length	485 m	42 m	505 m
RF frequency	352 MHz	721 MHz	1300 MHz
rms bunch length	1.61 cm	0.688 cm	0.30 cm
peak luminosity / IP	$1.25x10^{32}$ $cm^{-2}s^{-1}$	N/A	$1.33x10^{34}$ $cm^{-2}s^{-1}$
beam lifetime	6.0 h	N/A	12 minutes

Baseline LHeC Time Schedule



LS3 --- HL LHC

O. Brüning, ECFA meeting, 25 November 2011

LHeC Priority R&D

R&D activities:

-**Superconducting RF with high Q** & strategic partnerships ➔ 1.3 GHz versus 720 MHz

-Normal conducting compact magnet design ✔

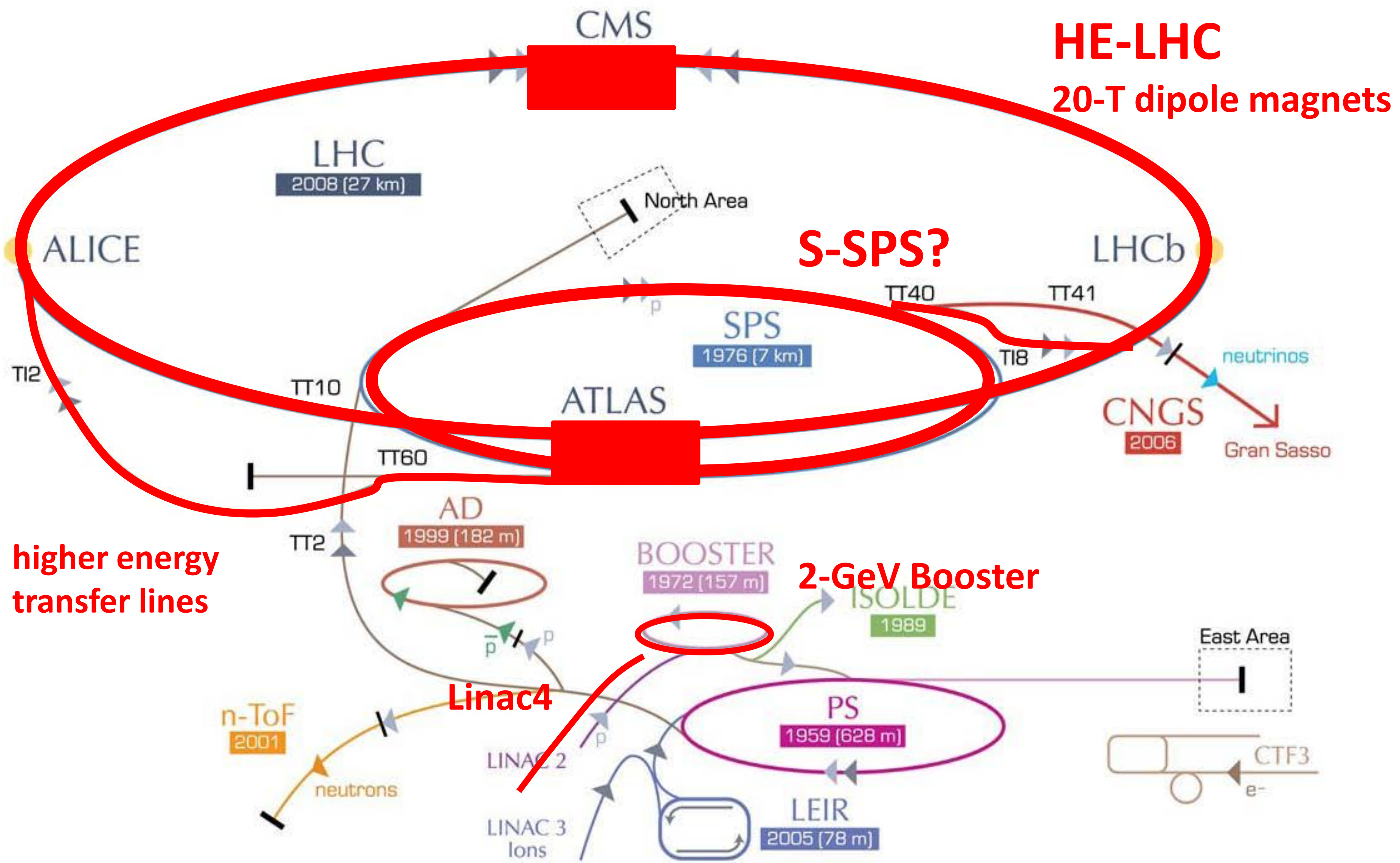
-**Superconducting 3-beam IR magnet design**

➔ synergy with HL-LHC triplet magnet R&D

-**Test facility for Energy Recovery operation** and/or for compact injector complex

- **R&D on high intensity polarized positron sources**

High Energy LHC



performance targets

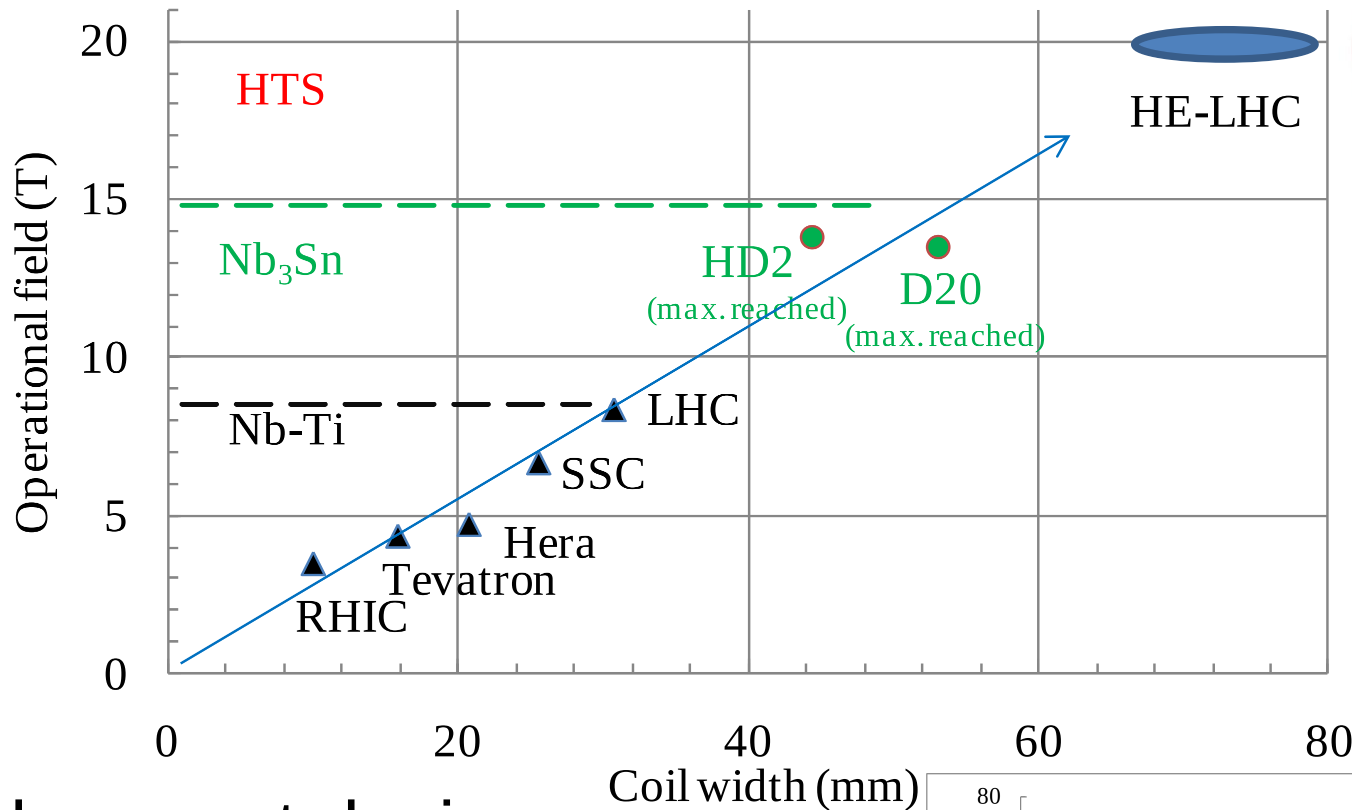
proton beam energy 16.5 TeV in LHC tunnel

peak luminosity 2×10^{34} $cm^{-2}s^{-1}$

also heavy ion collisions at equivalent energy

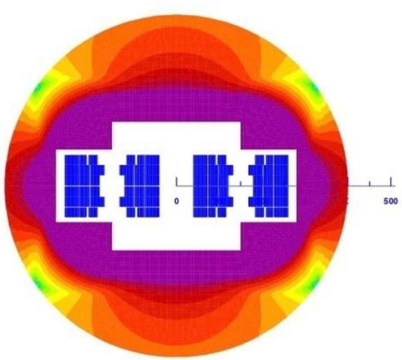
eventually high-energy ep ollisions?

HE-LHC key component: 20-T magnet

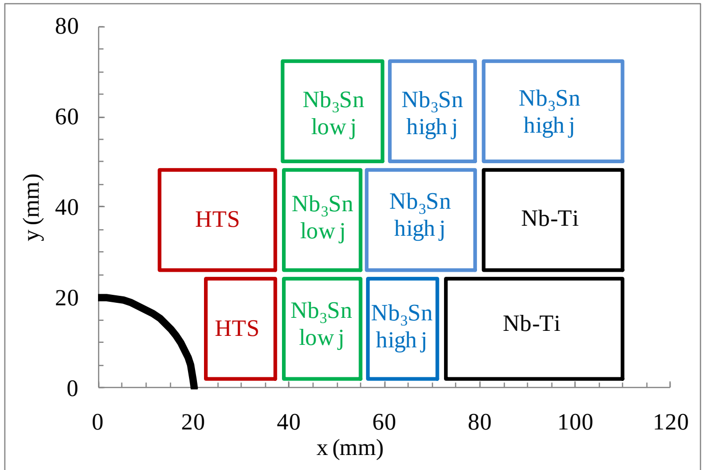


E. Todesco
P. McIntyre

hybrid magnet design



Nb-Ti	26%
Nb3Sn -h	35%
Nb3Sn -l	23%
HTS (Bi2212)	17%



High Energy-LHC (HE-LHC) Activities

CERN working group in 2010

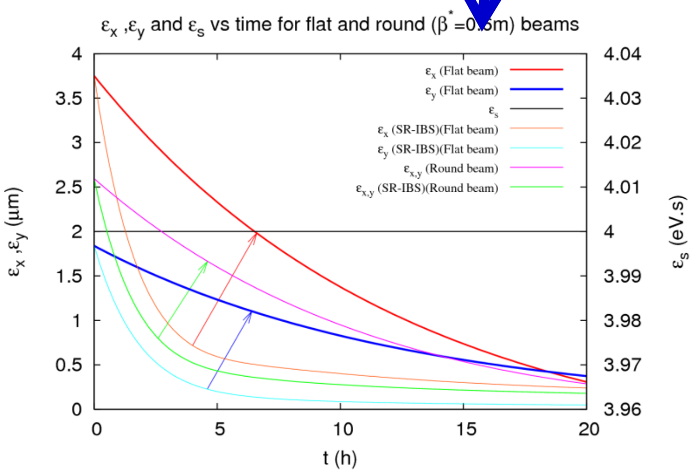
EuCARD AccNet workshop HE-LHC'10, 14-16 October 2010

Proceedings CERN Yellow Report 2011-3

<u>key topics</u>

beam energy 16.5 TeV; 20-T magnets, cryogenics: **synchrotron-radiation heat, radiation damping & emittance control,** vacuum system: synchrotron radiation, **new injector:** energy > 1 TeV, parameters

	LHC	HE-LHC
beam energy [TeV]	7	16.5
dipole field [T]	8.33	20
dipole coil aperture [mm]	56	40
#bunches	2808	1404
IP beta function [m]	0.55	1 (x), 0.43 (y)
number of IPs	3	2
beam current [A]	0.584	0.328
SR power per ring [kW]	3.6	65.7
arc SR heat load dW/ds [W/m/ap]	0.21	2.8
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0
events per crossing	19	76



O. Dominguez, F. Zimmermann

beam dynamics: new easy regime

HE-LHC Challenges

High Energy LHC

- 20-T dipole magnets
  - cost & feasibility; "acrobatic" price estimates for 2025
    - Nb_3Sn 4x more expensive than Nb-Ti
    - HTS 4x more expensive than Nb_3Sn; price for 1200 magnets: **5-6B$**
    - 20 T or 15 T (available today)?
  - stored energy and magnet protection

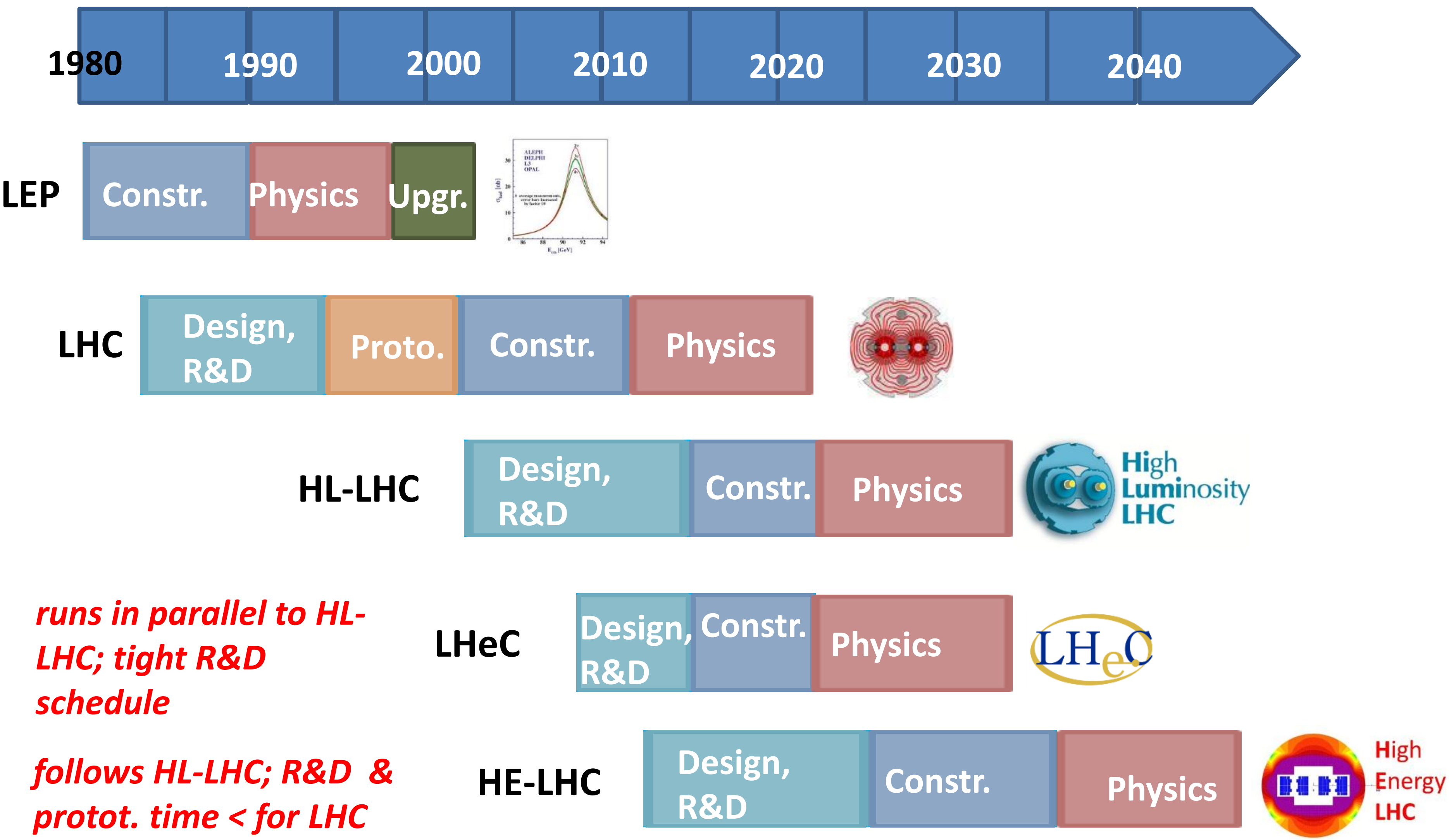
L. Rossi, April 2006, EDMS Nr 754391

- injector
  - S-SPS w 5-6 T dipole or 2-T superferric ring in LHC tunnel
  - LHC injector complex still working in 2030-40?
- synchrotron radiation handling & heat load

L. Tavian

  - beam screen 6x more heat load than LHC (40-60 K?)
  - cold mass 50% higher; h-l near limit of LHC cryo capacity

time line of CERN HEP projects

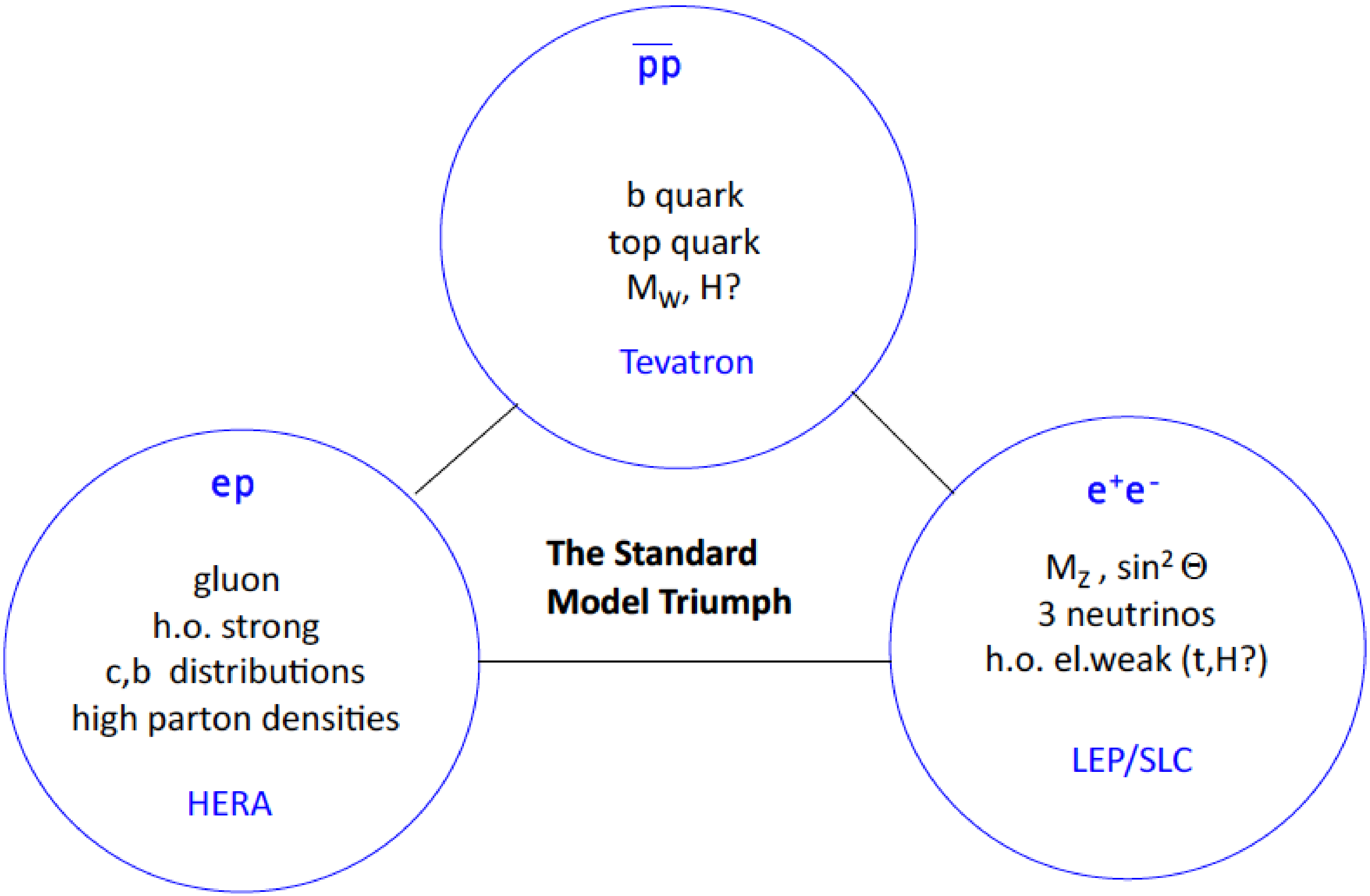


Source: L. Rossi. LMC 2011 (modified)

key decisions points

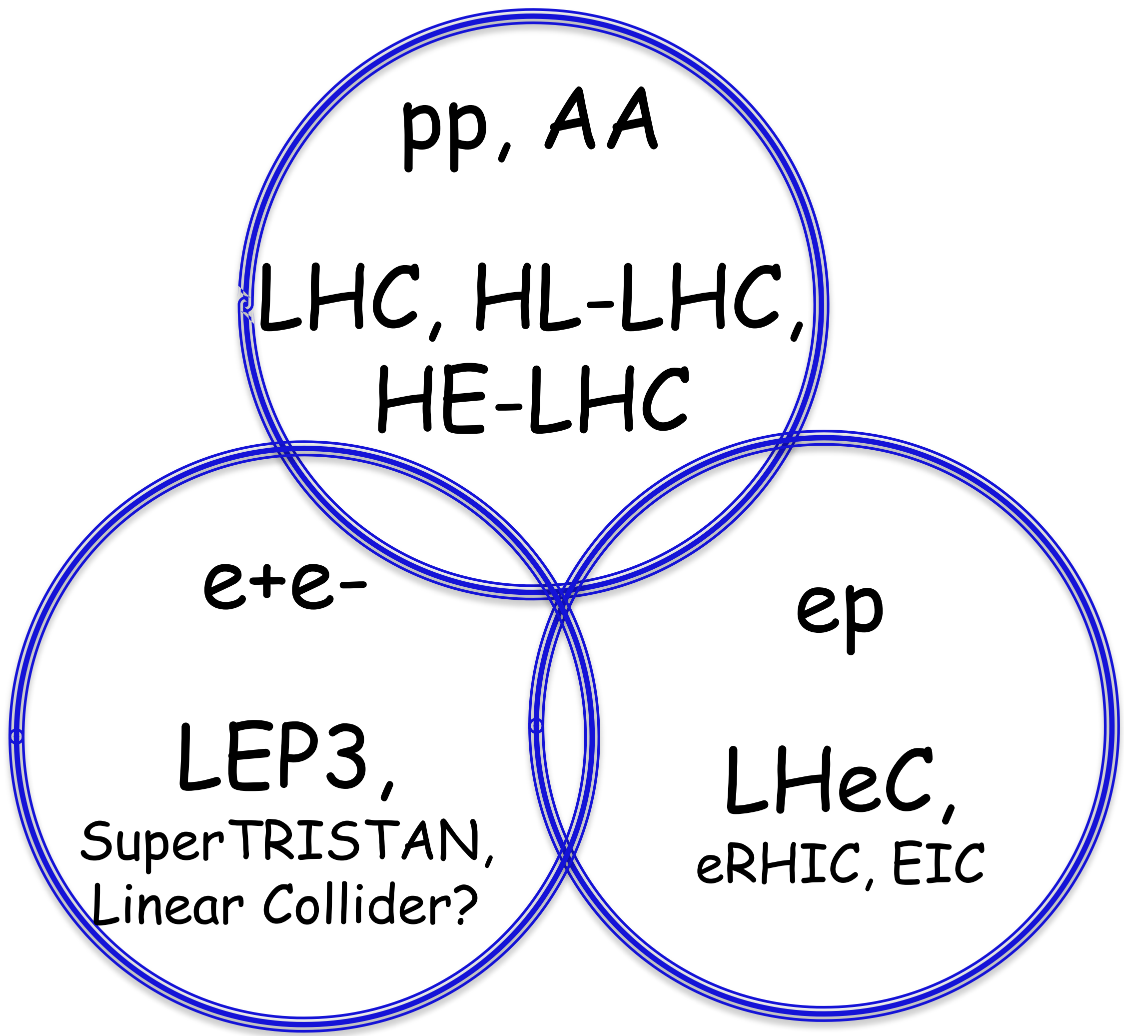
- LHeC
  - 2012: choice between linac and ring
  - 2013: choice of IR (Point 2?, Point 7 or 3?)
  - 2014: decision to go ahead with production
- HE-LHC
  - 2016: decision to use or not to use HTS (L. Rossi)
  - 2024: decision to go ahead with production

The Fermi Scale [1985-2010]



Max Klein

The sub-Fermi Scale (2010-2040)?



all can be done with LHC "upgrades"!

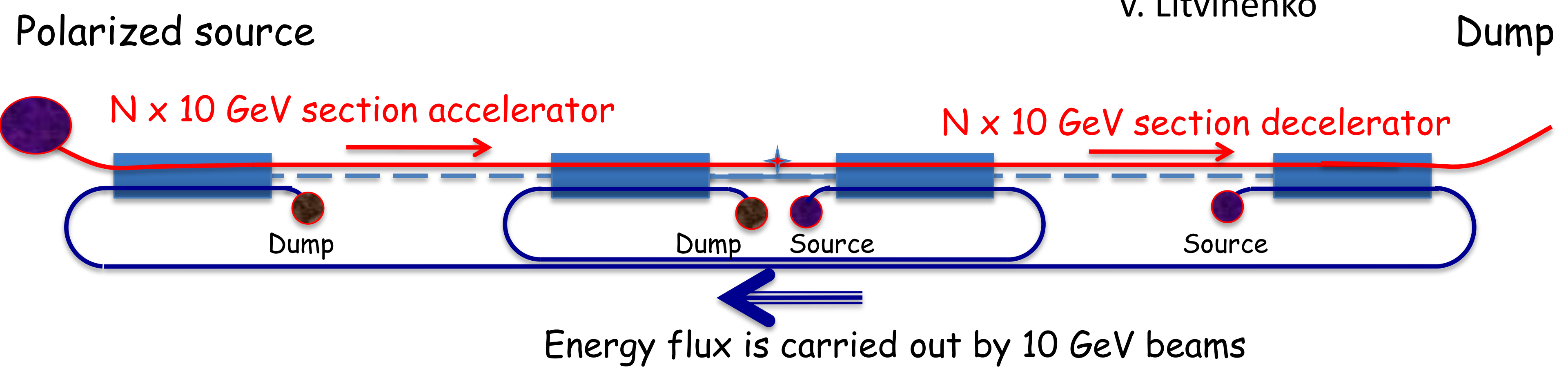
beyond 2040

further great upgrades on the horizon:

- HL-HE-LHC (10^{35} cm^{-2}s^{-1} at 33 TeV c.m.)
- HE-LHeC (150 GeV e^- x 16.5 TeV p^+)

high energy ERL using "CLIC" technology

V. Litvinenko



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reserve transparencies

EuCARD Newsletter article

European Coordination for Accelerator Research and Development Newsletter

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EuCARD >> News >> Newsletters >> Issue 8 >> Article 2

Proposed increase in energy takes LHC even further into the future

Accelerator scientists from around the world came together in Malta in October to discuss the possibility of increasing the energy of the present LHC. Organised by AccNet within EuCARD, the High Energy (HE) LHC workshop was convened to discuss the possible future LHC upgrade to a 16.5 TeV beam machine.

Participants in the HE-LHC'10 workshop. *Image courtesy of Kazuhito Ohmi. Thumbnail image on main page courtesy of CERN.*

LHeC road map to 10^{33} cm^{-2}s^{-1}

luminosity of LR collider:

(round beams)

$H_D \sim 1$

$$L = \frac{1}{4\pi e}\frac{N_{b,p}}{\varepsilon_p}\frac{1}{\beta_p^*} I_e H_{hg} H_D$$

highest proton beam brightness "permitted" (ultimate LHC values)

$\gamma\varepsilon$=3.75 μm

N_b=1.7x10^{11}

bunch spacing 25 or 50 ns

smallest conceivable proton β* function:
- **reduced *l** (23 m → 10 m)**
- **squeeze only one *p* beam**
- **new magnet technology *Nb_3Sn***

β*=0.1 m

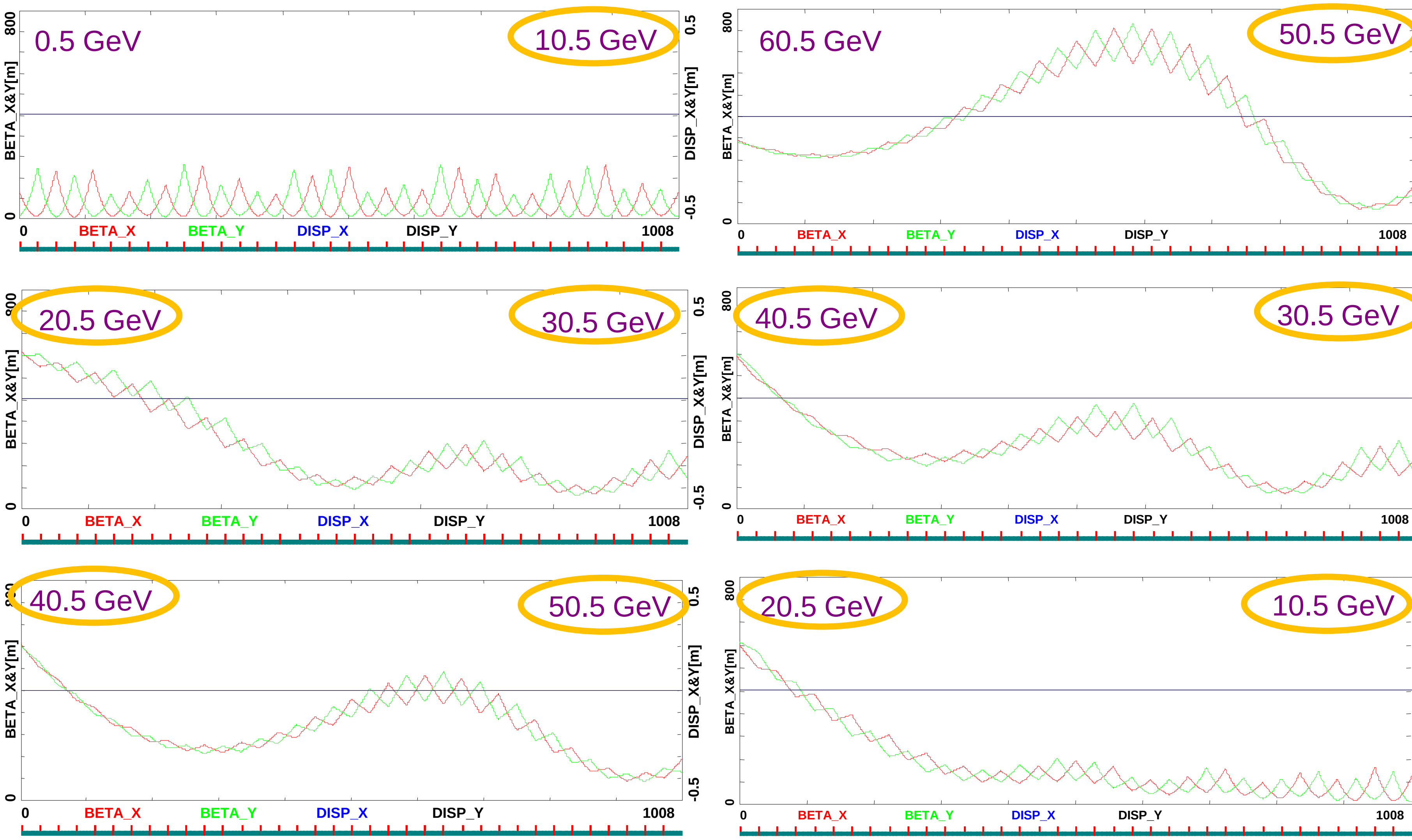
average e^- current !

maximize geometric overlap factor
- **head-on collision**
- **small e- emittance**

θ_c=0

H_{hg}≥0.9

Linac 1 – multi-pass + ER Optics



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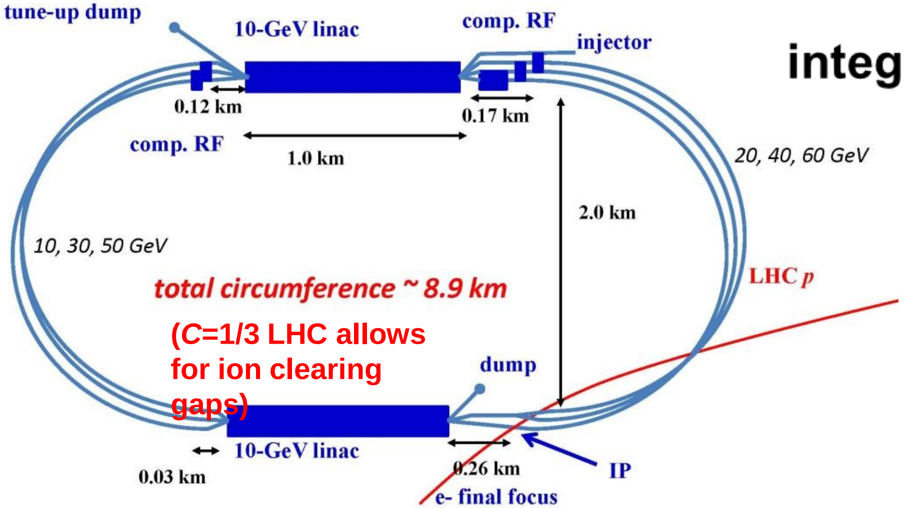
LHeC Linac-Ring Optics & Beam Dynamics

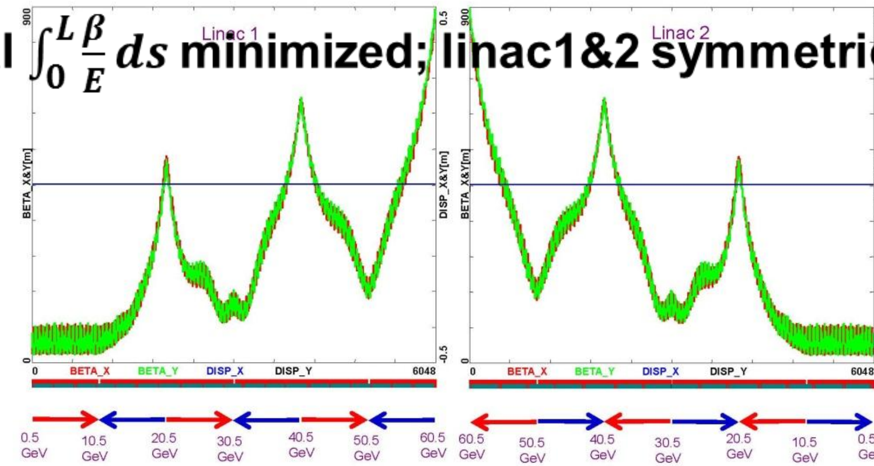
A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-'s collide w. LHC protons/ions



Linac 1 and 2 – Multi-pass ER Optics

integral $\int_0^L \frac{\beta}{E} ds$ minimized; linac1&2 symmetric



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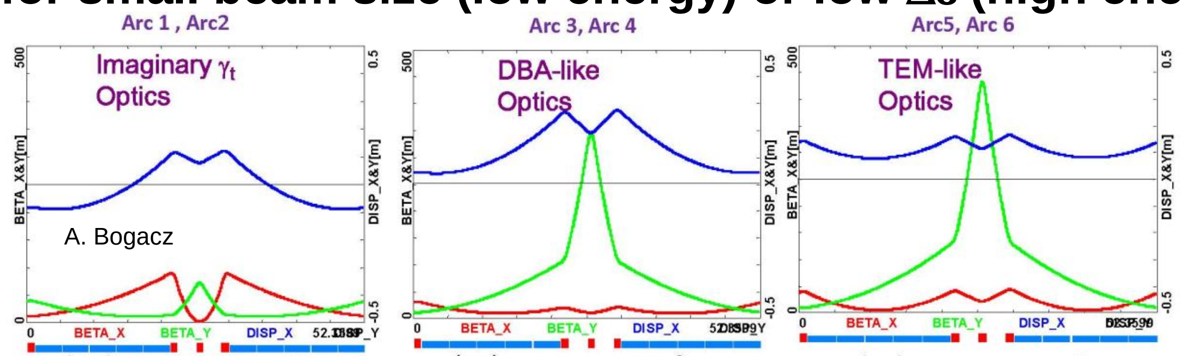
arc optics: flexible momentum compaction cell; tuned for small beam size (low energy) or low Δε (high energy)

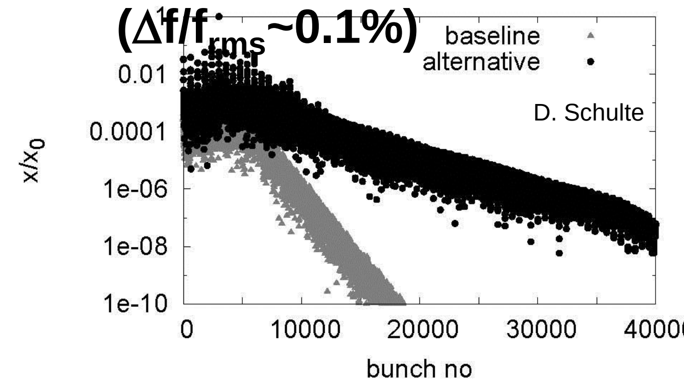


$\langle H \rangle = 8.8 \times 10^{-3}\ m$ — **limit chamber size (>12 σ at 25 mm diameter)**

$\langle H \rangle = 2.2 \times 10^{-3}\ m$

$\langle H \rangle = 1.2 \times 10^{-3}\ m$ — factor of 18 smaller than FODO — **limit emittance growth**

BBU: beam stability requires both damping ($Q\sim10^5$) & detuning ($\Delta f/f_{rms}\sim0.1\%$)



linac RF parameters

	ERL 720 MHz	ERL 1.3 GHz	Pulsed
duty factor	cw	cw	0.05
RF frequency [GHz]	0.72	1.3	1.3
cavity length [m]	1	~1	~1
energy gain / cavity [MeV]	18	18	31.5
R/Q [100 Ω]	400-500	1200	1200
Q_0 [10^{10}]	**2.5-5.0**	**2? (1)**	**1**
power loss stat. [W/cav.]	5	<0.5	<0.5
power loss RF [W/cav.]	**8-32**	**13? (27)**	**<10**
power loss total [W/cav.]	13-37 (!?)	13-27	11
"W per W" (1.8 k to RT)	700	700	700
power loss / GeV @RT [MW]	**0.51-1.44**	**0.6-1.1**	**0.24**
length / GeV [m] (*filling*=0.57)	97	97	56

ERL electrical site power

cryo power for two 10-GeV SC linacs: 28.9 MW

MV/m cavity gradient, 37 W/m heat at 1.8 K

700 "W per W" cryo efficiency

RFTech guidance requested!

RF power to control microphonics: 22.2 MW

10 kW/m (eRHIC), 50% RF efficiency

RF for SR energy loss compensation: 24.1 MW

energy loss from SR 13.2 MW, 50% RF efficiency

cryo power for compensating RF: 2.1 MW

1.44 GeV linacs

microphonics control for compensating RF: 1.6 MW

injector RF: 6.4 MW

500 MeV, 6.4 mA, 50% RF efficiency

magnets: 3 MW

grand total = 88.3 MW

L-R LHeC IP parameters

	protons	electrons
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
geometric emittance $\varepsilon_{x,y}$ [nm]	0.50	0.43
IP beta function $\beta^*_{x,y}$ [m]	0.10	0.12
rms IP beam size $\sigma^*_{x,y}$ [μm]	7	7
rms IP divergence $\sigma'_{x,y}$ [μrad]	70	58
beam current [mA]	≥430	6.6
bunch spacing [ns]	25 or 50	50
bunch population	1.7×10^{11}	2×10^{9}
crossing angle	0.0	

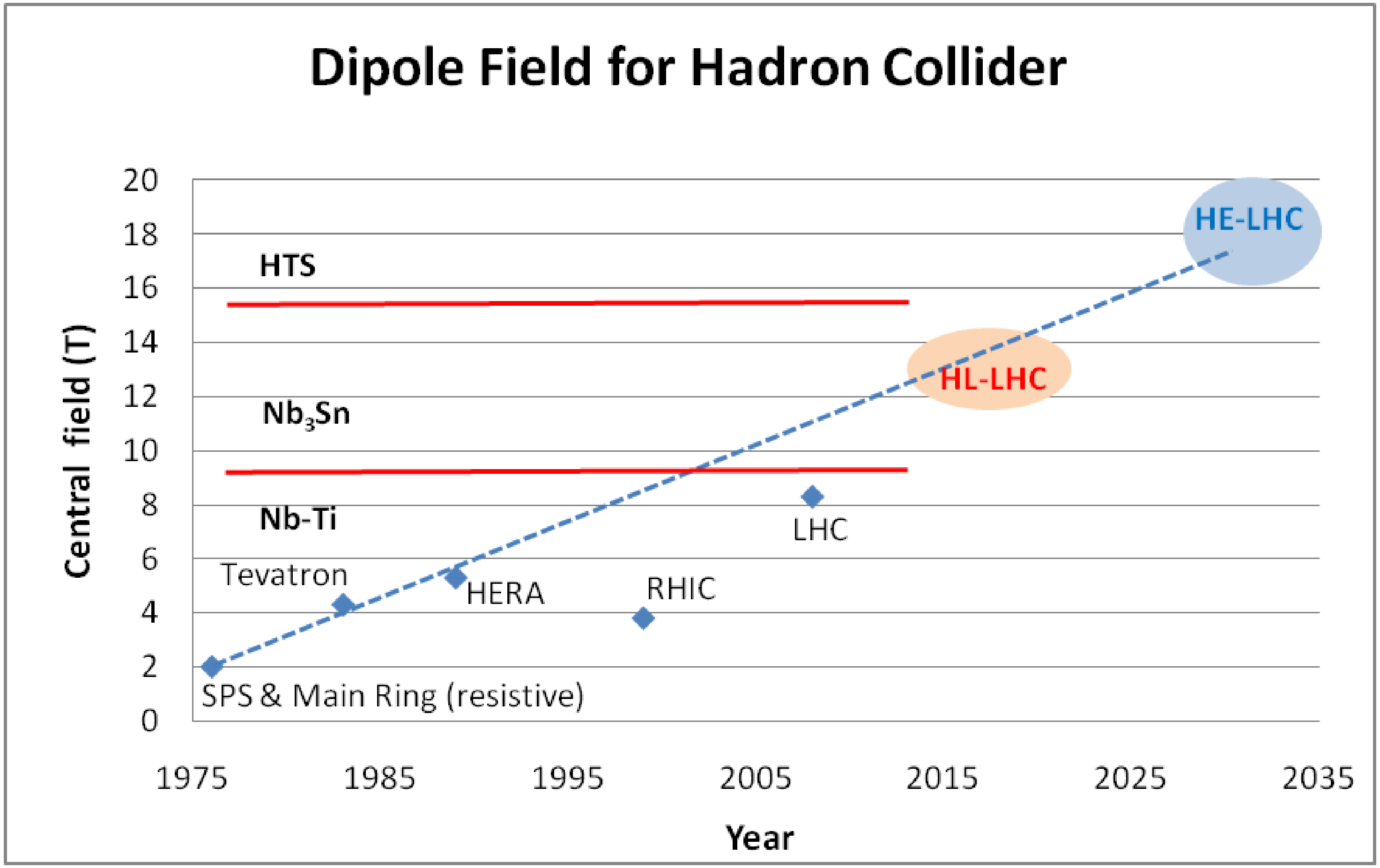
LHeC status

- design study for a Large Hadron Electron Collider (LHeC) ongoing since fall 2008
- jointly supported by CERN, by the European Committee for Future Accelerators (ECFA) and by the Nuclear Physics European Collaboration Committee (NuPECC)
- CDR draft complete last summer (2011)
- reviewed by distinguished external referees

→ CERN Council European particle-physics strategy

HL-LHC paves the way for the future

SCRF (Crab Cavity), SC link 1 GW rate, HF SC magnets



L. Rossi