LHeC Ring-Linac options

various operation modes & performance reaches

1st ECFA-CERN LHeC Workshop

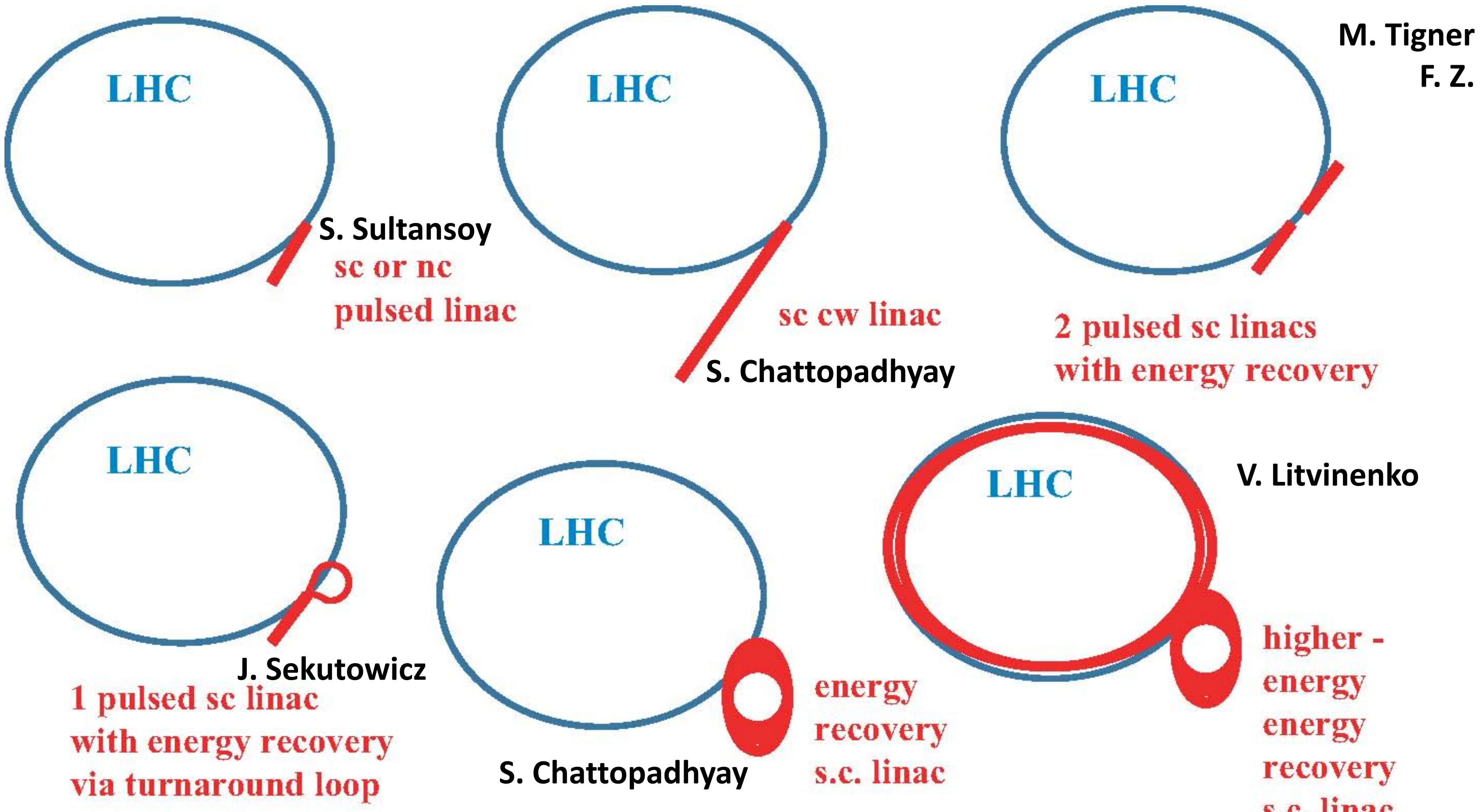
Divonne, 2 September 2008

F. Zimmermann, F. Bordry, H.-H. Braun, O.S. Bruning, H. Burkhardt, A. de Roeck, R. Garoby, T. Linnecar, K.-H. Mess, J. Osborne, L. Rinolfi, D. Schulte, R. Tomas, J. Tuckmantel, *CERN, Switzerland*; **A. Eide**, *EPFL, Switzerland*; **R. Calaga, F.J. Willeke**, *BNL, U.S.A.;* **S. Chattopadhyay**, *Cockcroft I.,UK*; **B.J. Holzer**, *DESY*; **J. Dainton, M. Klein**, *Liverpool U., UK*; **A. Vivoli**, *LAL, France*; **S. Sultansoy**, *TOBB ETU*, Turkey; **A.K. Ciftci**, *Ankara U*, Turkey; **H. Aksakal**, *Nigde U, Turkey;* **J. Skrabacz**, *UNM, U.S.A.*

LR e-p motivation

- colliding 7 TeV p's with 25-140 (-300) GeV e-'s:
  - → extending LHC discovery reach
  - → enabling LHC precision physics
- history: - Ankara workshop 1997, Turkish JP, 22, 7 (1998)
  - -S. Sultansoy, Aachen 2003, EPJ C33: S1064 (2004)
  - -D.Schulte,F.Zimmermann, EPAC'04 (CLIC-1/LHC p s-bunch)
  - -H. Aksakal et al, NIM A576: 287 (2007) (CLIC & ILC vs LHC)
  - - S. Chattopadhyay: ***cw!, ERL!*** (2007), A. Eide's report (2008)
  - -V. Litvinenko, CERN AB Form 11 March 2008
  - -F. Zimmermann et al, EPAC'08
  - -J. Skrabacz' report (2008)
- e- linac offers several distinct advantages
  e.g.: separation from LHC, high beam quality, synergies

LR scenarios



s.c. linac , long trains of bunches, 25-ns or 50-ns spacing, matching LHC p beam (*PLACET: stable);* long pulse or cw → high luminosity; optional energy recovery → higher luminosity; 1.3 GHz (ILC) or 700 MHz (SPL)

construction cost

rough estimate for cost / (unit length) extracted from XFEL, ILC and ELFE designs:

✓**linac: 160k$/m**

- with an effective gradient of 11.8 MV/m (XFEL)

✓**arc section: 50k$/m**

- 300 M$ per ILC Damping Ring

✓**drift straight: 10k$/m**

- vacuum + perhaps some diagnostics?, taken as ~20% of cost of arc section from ELFE design

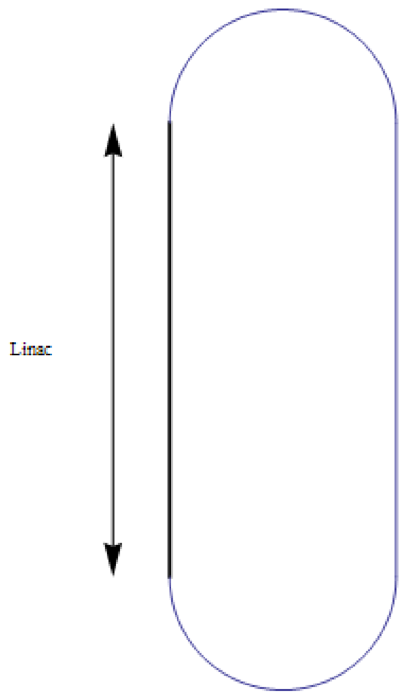
✓**ILC tunnel cost: ~5k$/m**

- already taken to be included in above numbers
- otherwise important only for the straight drifts, potentially raising the drift cost to 15k$/m

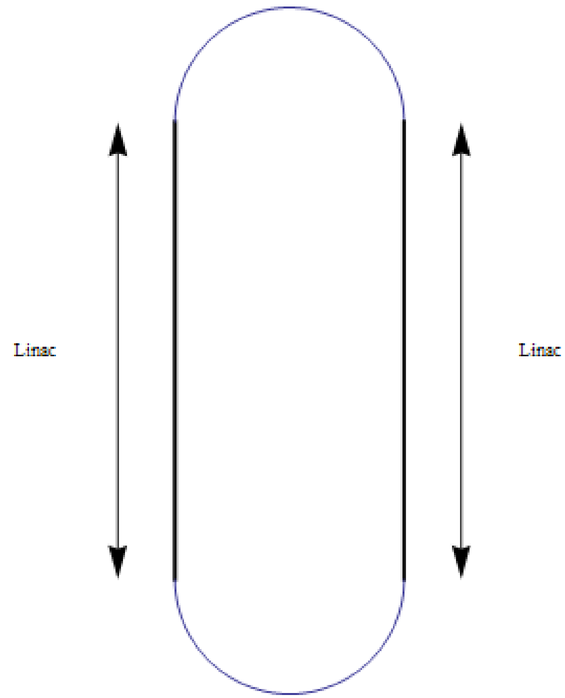
baseline layout

J. Skrabacz

Design for 1 Acceleration per Revolution



Design for 2 Accelerations per Revolution



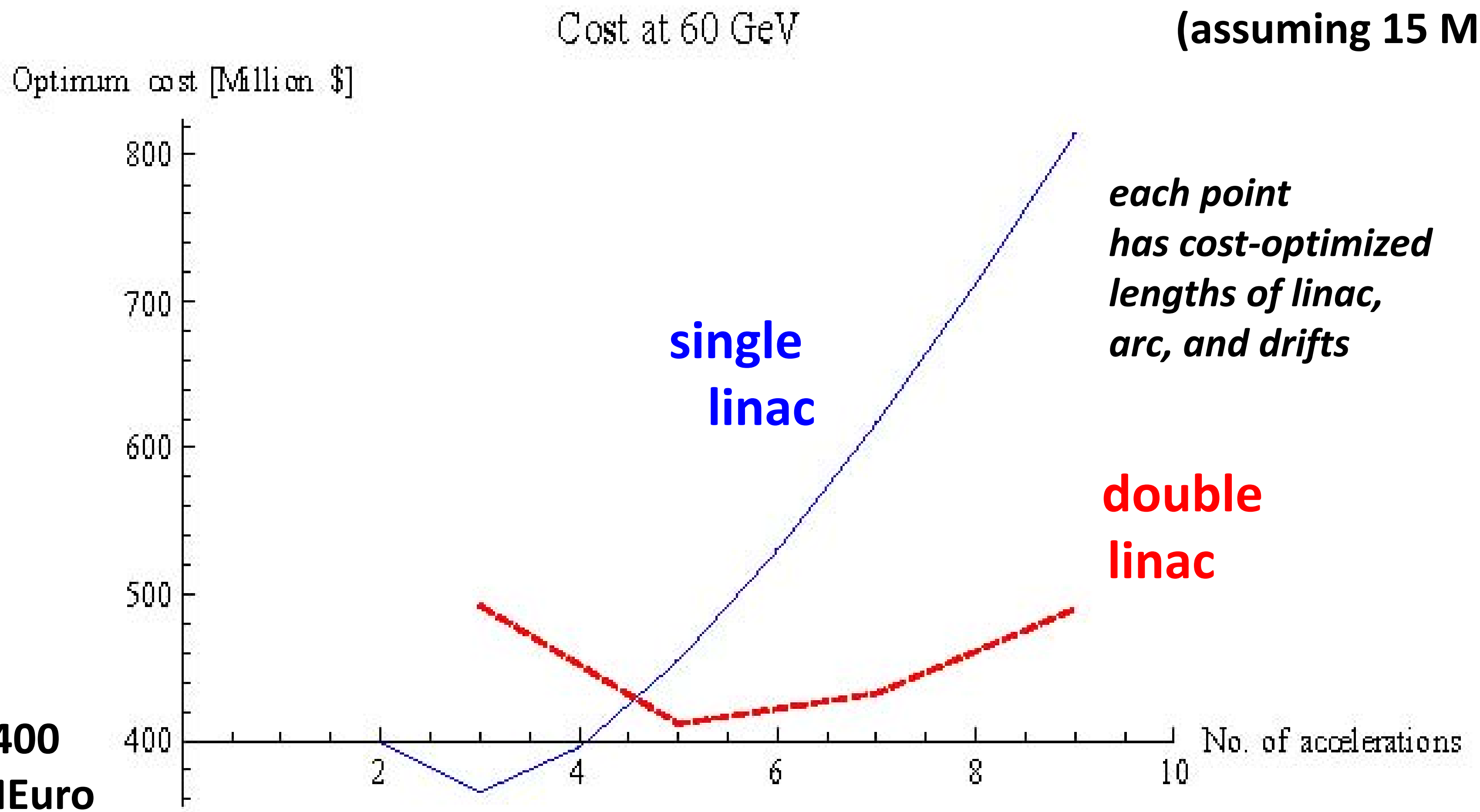
Design for 2 Accelerations per Revolution

Single or double acceleration? How many revolutions for optimum energy gain? Can we reduce emittance growth and cost?

racetrack shape with acceleration in one or both straight sections

construction cost at 60 GeV

J. Skrabacz
(assuming 15 MV/m)

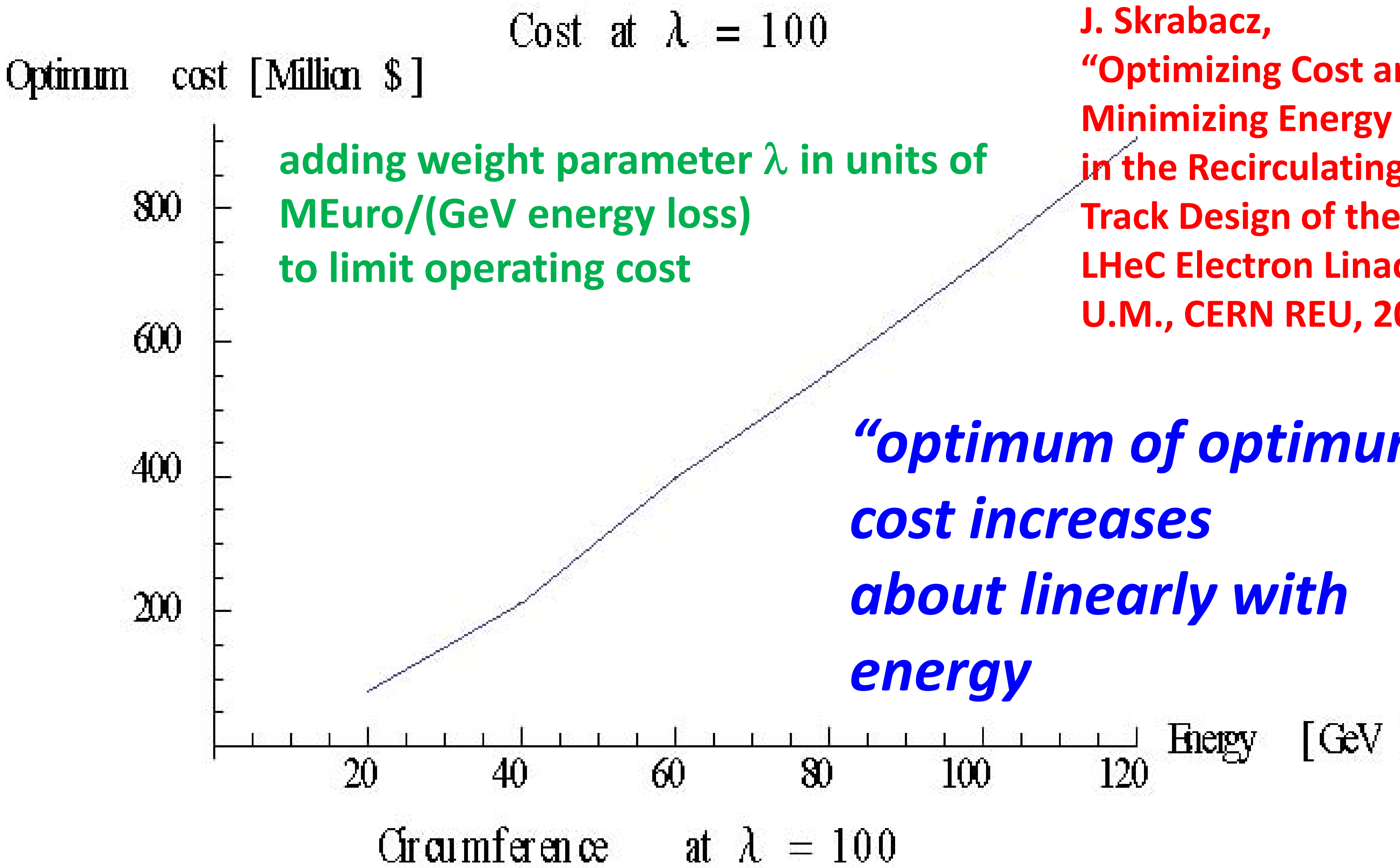


~400 MEuro

2-3 circulations are optimum at 60 GeV (w/o restraining energy loss)

optimized cost vs energy

J. Skrabacz



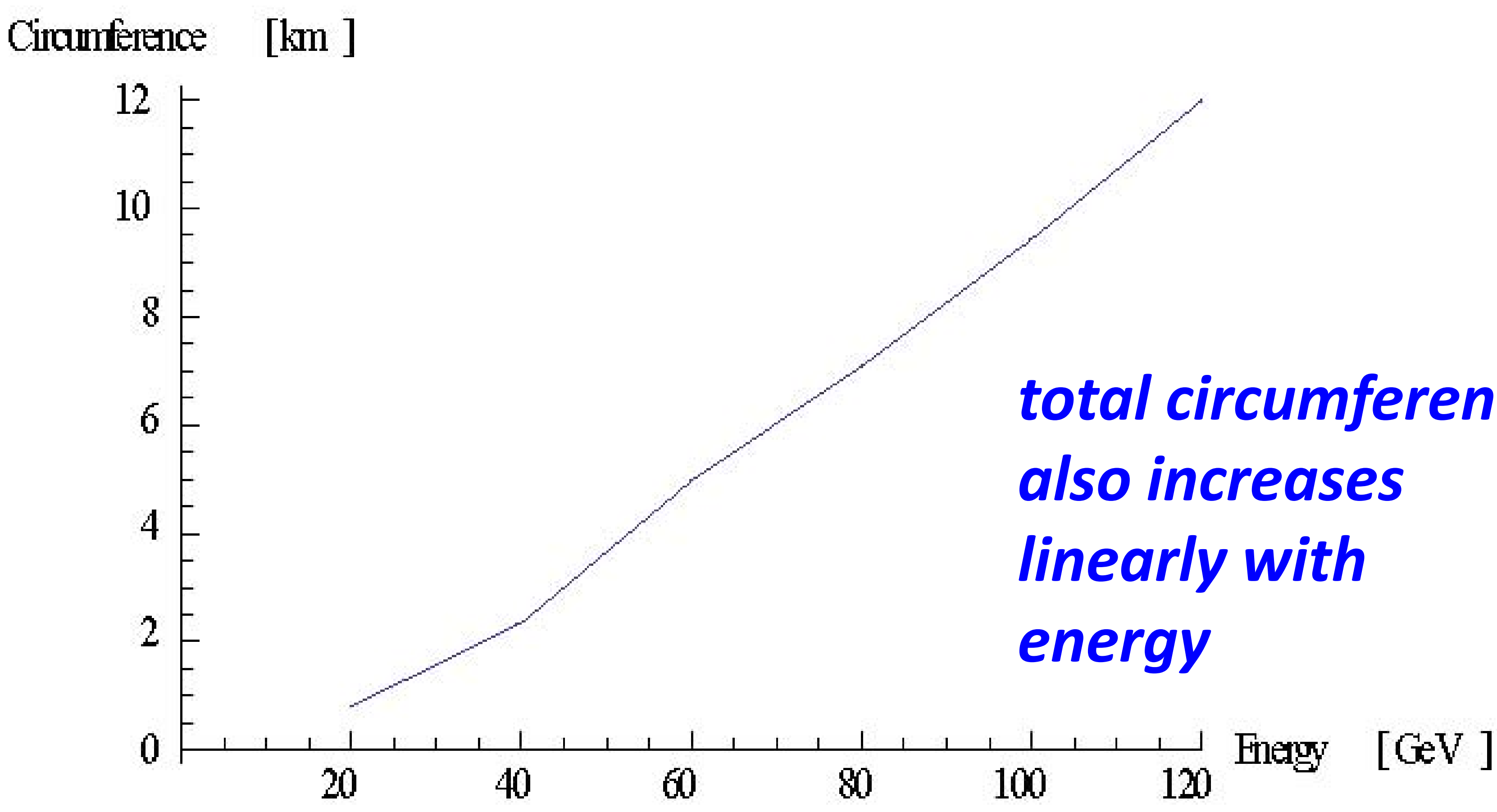
adding weight parameter λ in units of MEuro/(GeV energy loss) to limit operating cost

J. Skrabacz, "Optimizing Cost and Minimizing Energy Loss in the Recirculating Race-Track Design of the LHeC Electron Linac," U.M., CERN REU, 2008

"optimum of optimum" cost increases about linearly with energy

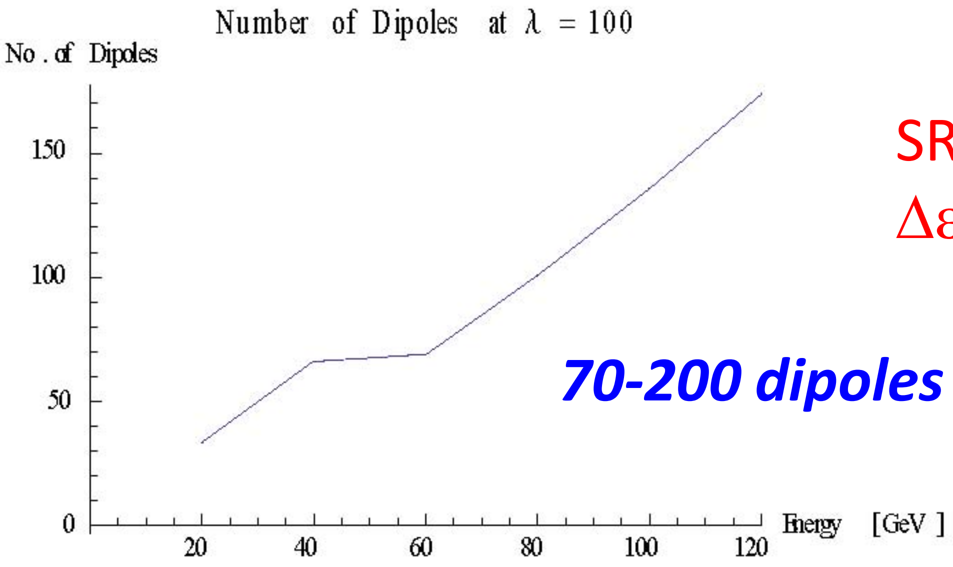
opt. circumference vs energy

J. Skrabacz



total circumference also increases linearly with energy

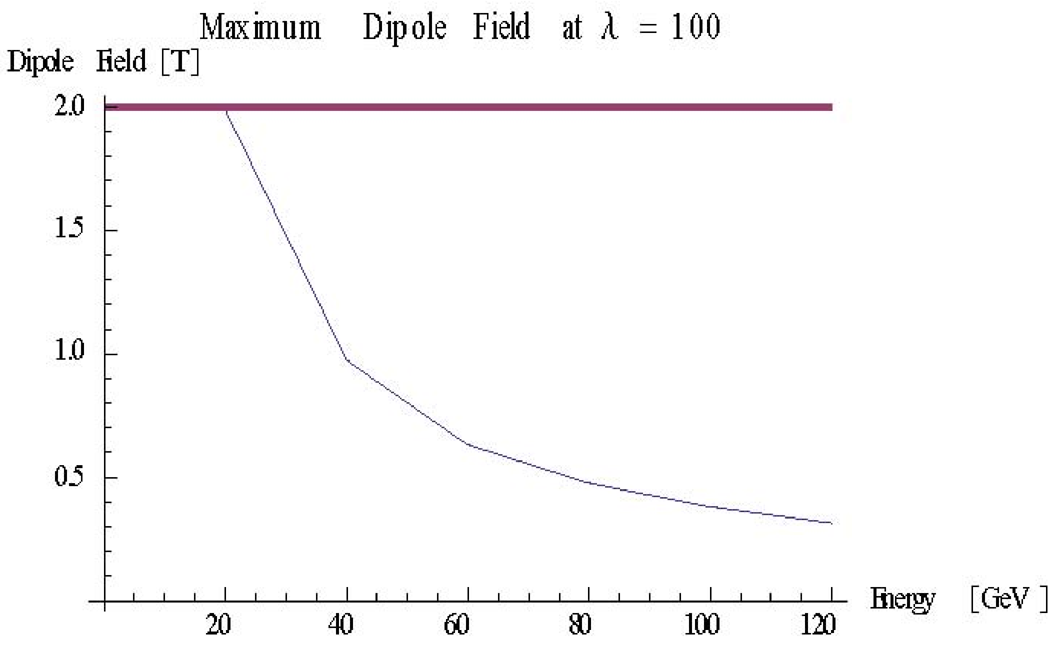
dipoles & B-field vs energy



J. Skrabacz

SR emittance growth limited to $\Delta\varepsilon\gamma < 100\ \mu m$

70-200 dipoles / turn



dipole field < 2 T

optimum #turns vs energy

J. Skrabacz

	Acc/Rev	No. Revs
E = 20 GeV	1	3
E = 40 GeV	1	2
E = 60 GeV	1	1
E = 80 GeV	1	1
E = 100 GeV	1	1
E = 120 GeV	1	1

from 60 GeV onwards single recirculation is optimum!

above ~140 GeV single linac!

$\lambda=100$

better shapes?

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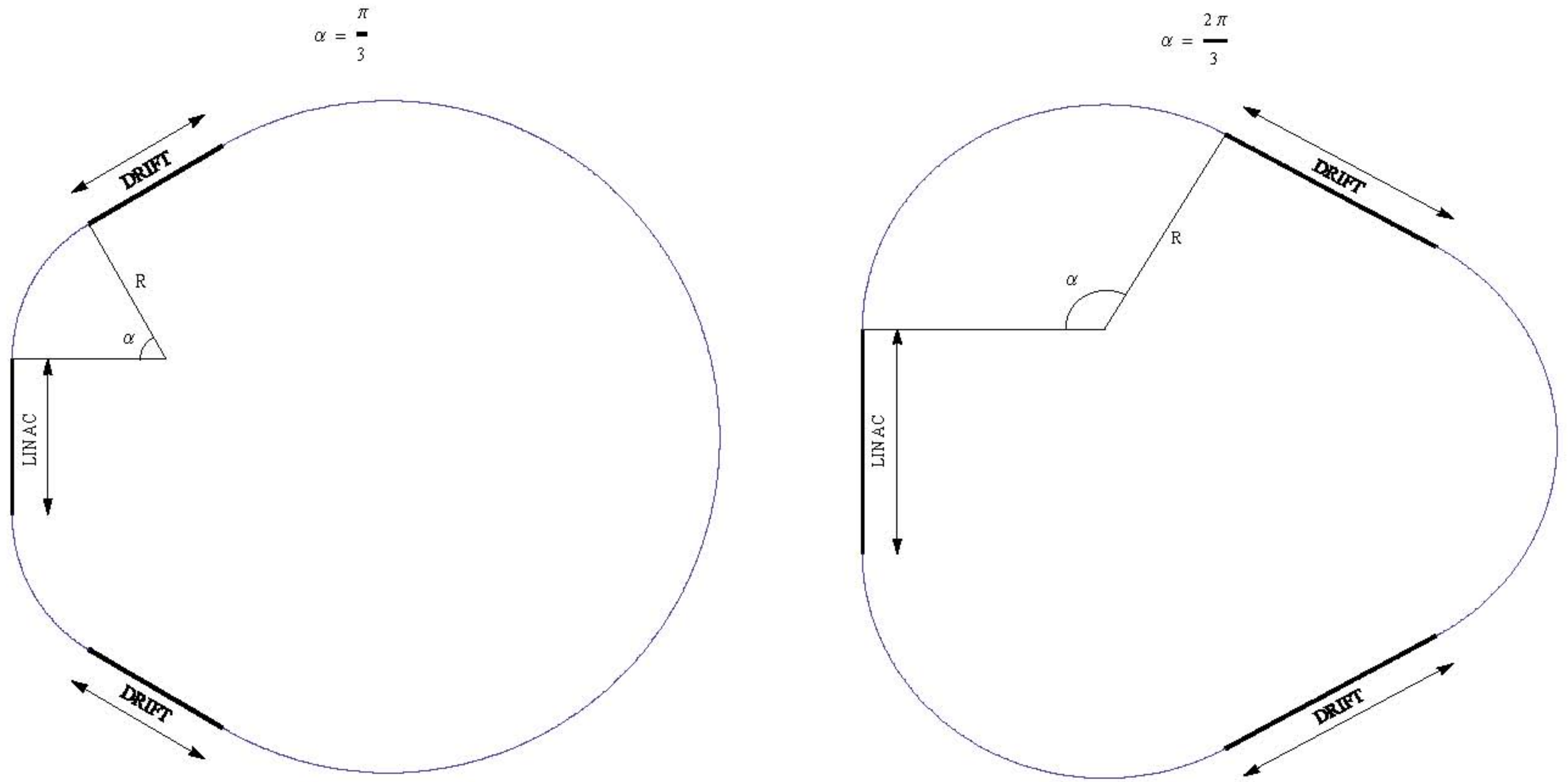


“ballfield” designs with additional shape parameters might reduce energy loss, emittance growth, or cost

ballfield vs racetrack

60 GeV **λ = 10**

J. Skrabacz

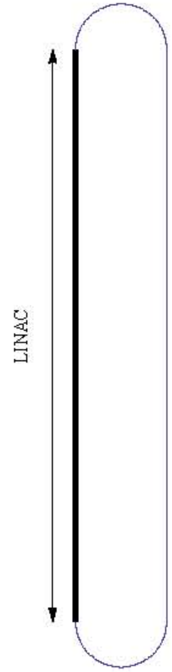
Race Track

Optimal radius = 86.6367 m
Optimal length = 1.08704 km
Total circumference = 2.71844 km
Total energy loss to radiation = 5.73243 GeV
Total cost of design = $271.885 million
Effective cost of design = $329.21 million

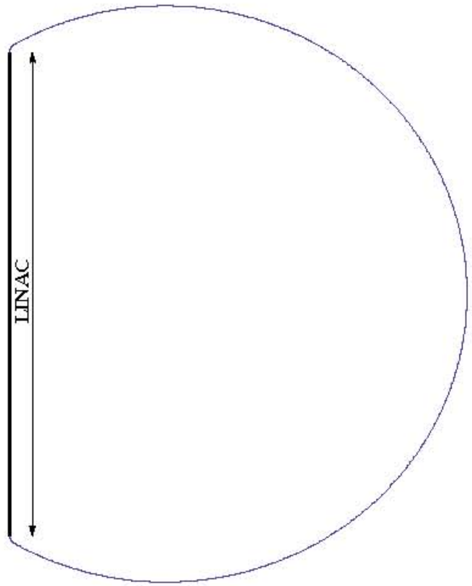
Ball Field

Optimal small radius = 39.0311 m
Optimal linac length = 2.00547 km
Optimal drift length = 0 km
Total circumference = 7.10074 km
Total energy loss to radiation = 0.674109 GeV
Total cost of design = $575.639 million
Effective cost of design = $ 582.38 million

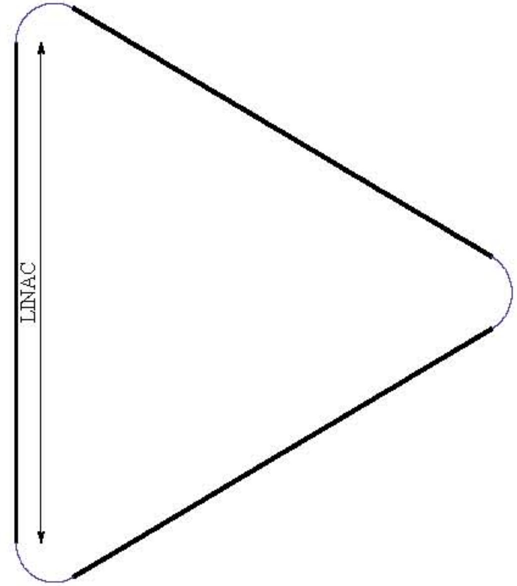
Optimal small radius = 84.8961 m
Optimal linac length = 1.087 km
Optimal drift length = 1.07737 km
Total circumference = 3.7868 km
Total energy loss to radiation = 5.7299 GeV
Total cost of design = $271.839 million
Effective cost of design = $ 329.138 million



$\alpha = \frac{\pi}{3}$



$\alpha = \frac{2\pi}{3}$



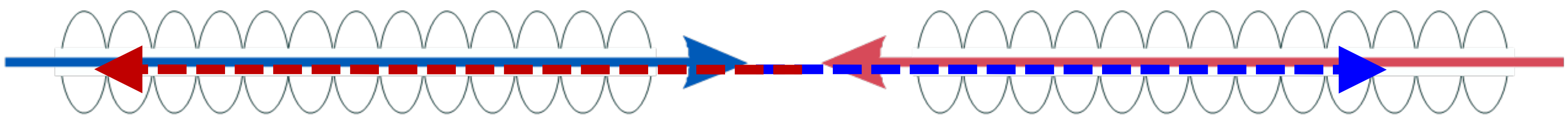
extreme ballfield is competitive

energy recovery options

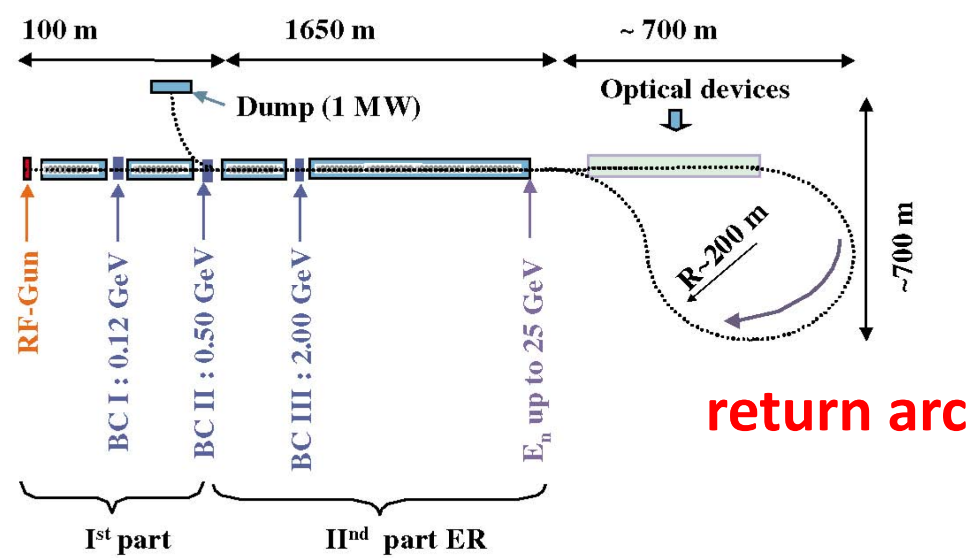
Jlab: **recirculating linac**, 99.5% of energy recovered at 150 MeV and 10 mA, ~98% recovery at 1 GeV and 100 μA with beam swung between 20 MeV to 1 GeV, plans for multi-GeV linacs withcurrents of ~100 mA

S. Chattopadhyay

M. Tigner, "A possible apparatus for electron clashing-beam experiments," Nuovo Cim.37:1228-1231 (1965).



J. Sekutowicz et al, "Proposed continuous wave energy recovery operation of an XFEL," Phys.Rev.ST Accel.Beams 8:010701,2005, up to 98% efficient



Maury on s.c. ERL collider

M. Tigner,
Nuovo Cimento **37** (1965) 1228

A Possible Apparatus for Electron-Clashing Experiments (*).

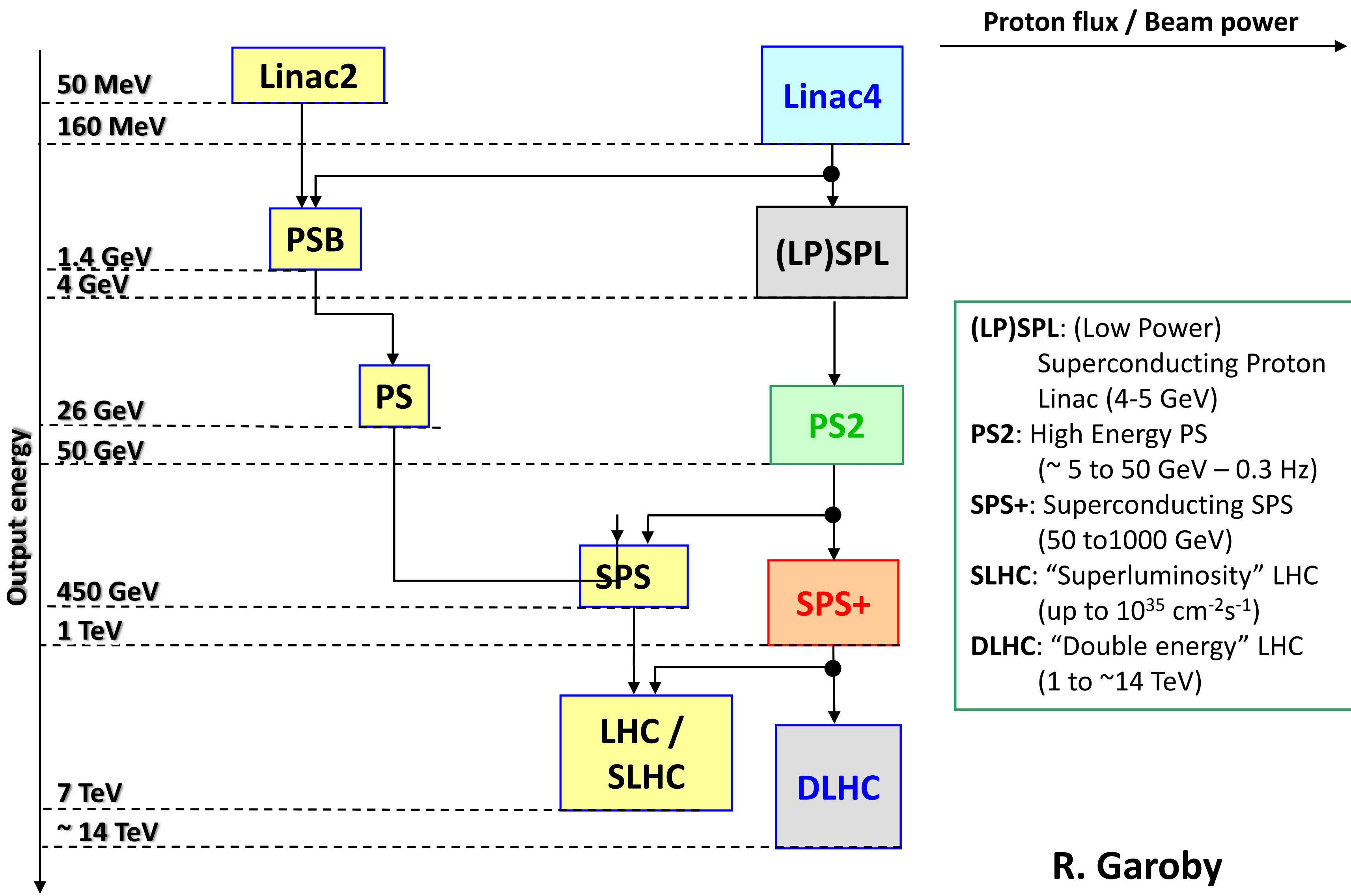
M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

"While the storage ring concept for providing clashing-beam experiments ([1]) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable."

introducing the ideas of "s.c. linac" and "energy recovery" - an "artifice", he wrote, that "might also be useful in experiments other than the clashing-beam type"

CERN p accelerator upgrade



(LP)SPL: (Low Power)
Superconducting Proton
Linac (4-5 GeV)

PS2: High Energy PS
(~ 5 to 50 GeV – 0.3 Hz)

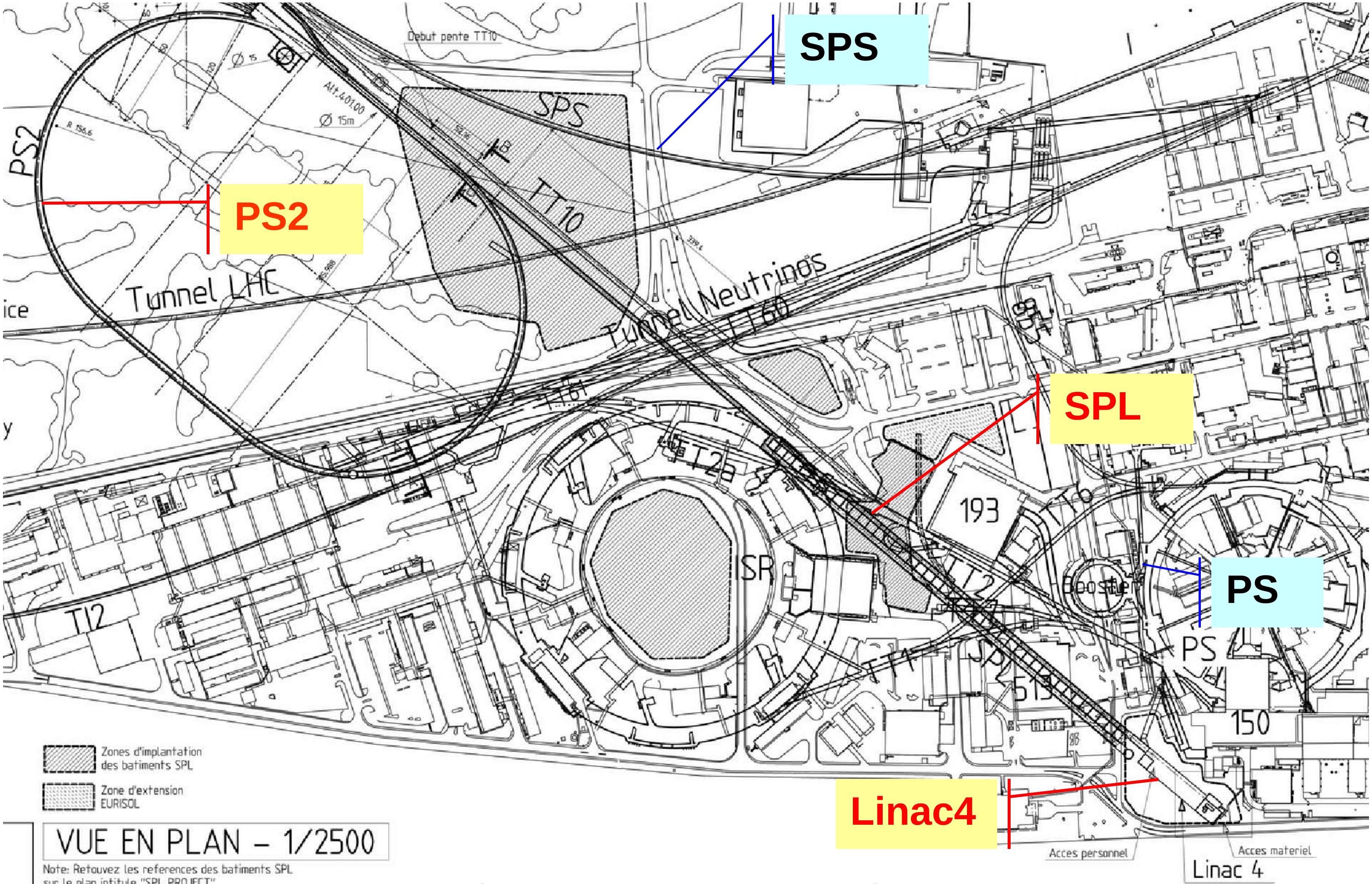
SPS+: Superconducting SPS
(50 to1000 GeV)

SLHC: "Superluminosity" LHC
(up to 10^{35} $cm^{-2}s^{-1}$)

DLHC: "Double energy" LHC
(1 to ~14 TeV)

R. Garoby

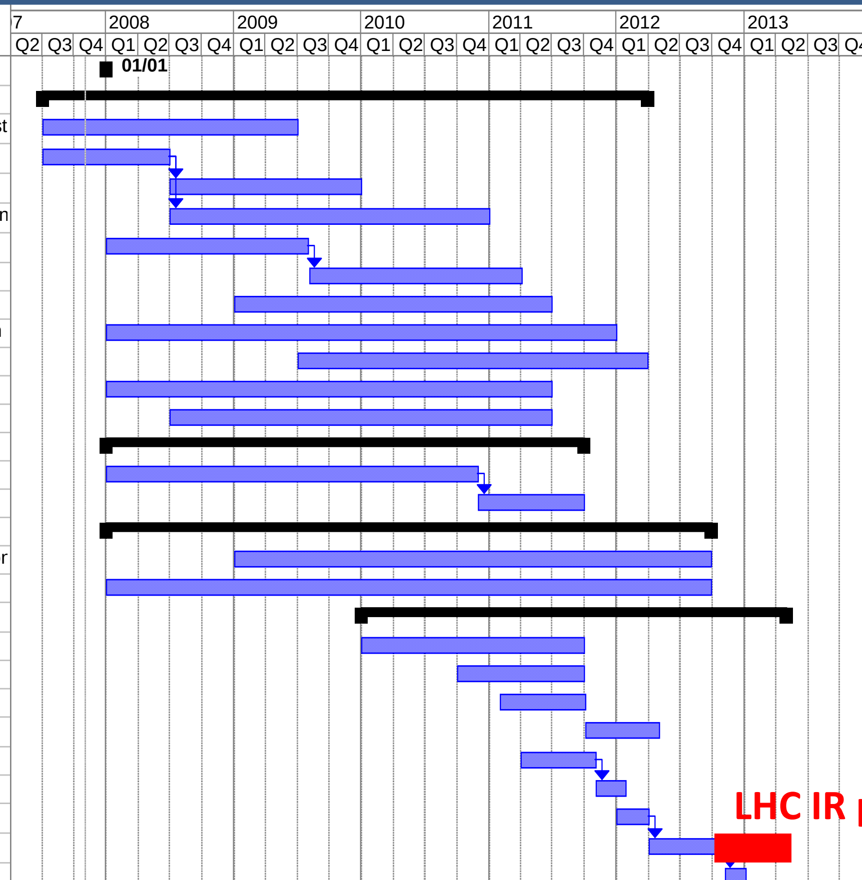
layout of the new injectors



R. Garoby, CARE-HHH BEAM07, October'07; L. Evans, LHCC, 20 Feb '08

injector & IR upgrade schedule

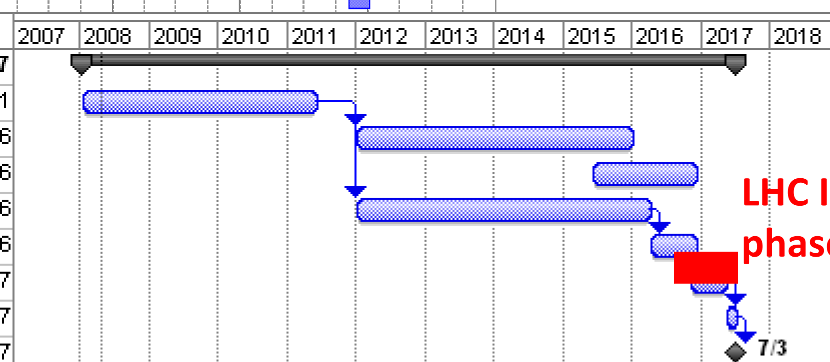
ID	WBS	Task Name
1		**Linac4 project start**
2	2	**Linac systems**
3	2.1	Source and LEBT construction, test
4		Drawings, material procurement
5	2.2	RFQ construction, test
6	2.4	Accelerating structures construction
7		Klystron prototyping
8	2.6.2	Klystrons construction
9	2.6.1	LLRF construction
10	2.7	Beam Instrumentation construction
11	2.8	Transfer line construction
12	2.9	Magnets construction
13	2.10	Power converters construction
14	5	**Building and infrastructure**
15	5.1	Building design and construction
16	5.2,3,	Infrastructure installation
17	3	**PS Booster systems**
18	3.1	PSB injection elements construction
19	3.2	PSB beam dynamics analysis
20	4	**Installation and commissioning**
21	4.1	Test stand operation (3 + 10 MeV)
22	4.2	Cavities testing, conditioning
23		Cabling, waveguides installation
24		Accelerator installation
25		Klystrons, modulators installation
26		Hardware tests
27		Front-end commissioning
28	4.5	Linac accelerator commissioning
29		Transfer line commissioning



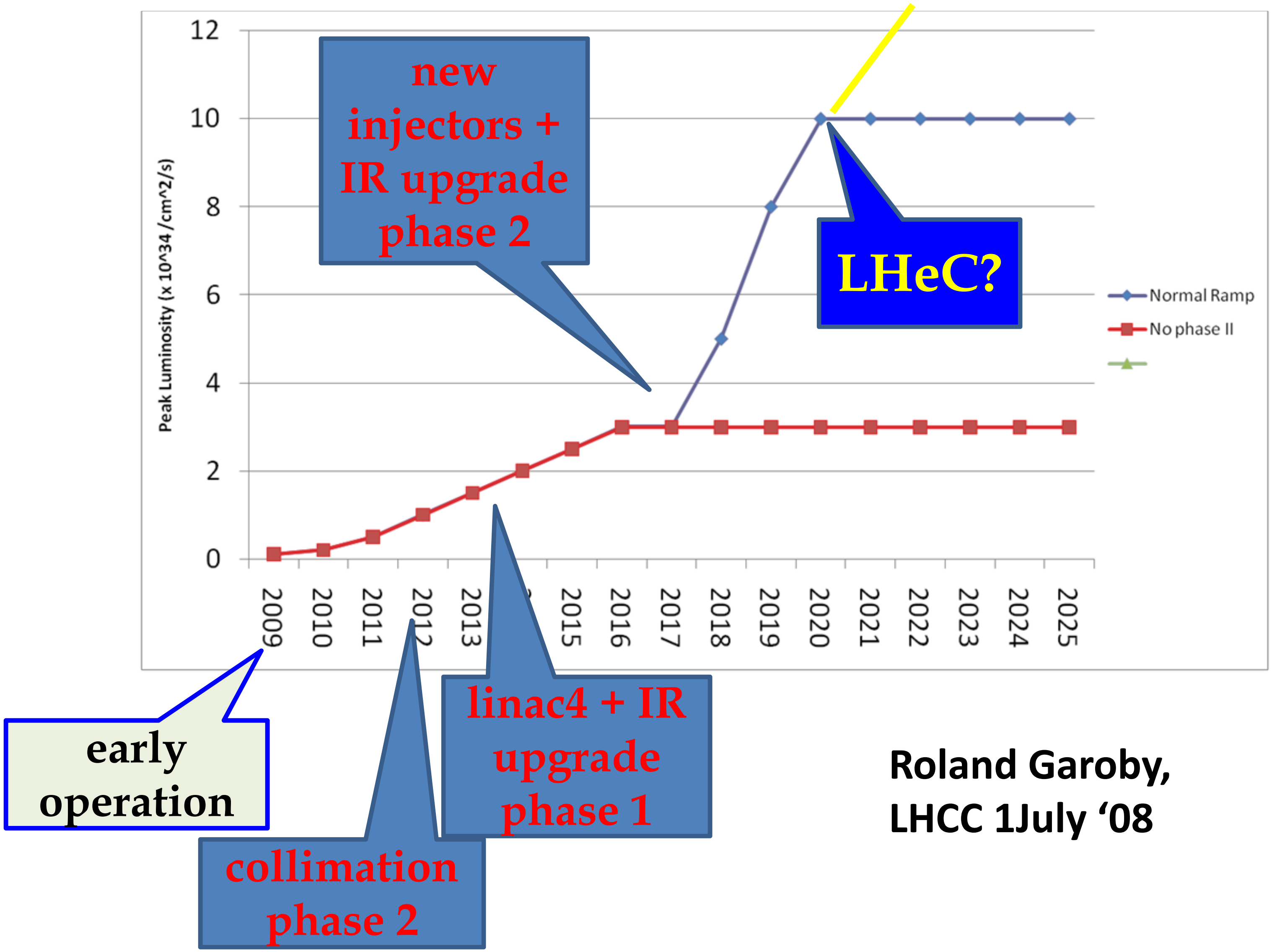
R. Garoby,
LHCC 1 July 2008

in 2017 may expect SPL, PS2 and LHC phase-2 IR & beam parameters

ID	Task Name	Start	Finish
1	**SPL + PS2**	**Mon 1/7/08**	**Mon 7/3/17**
2	Design	Mon 1/7/08	Wed 6/1/11
3	SPL Construction	Mon 1/2/12	Fri 1/1/16
4	SPL beam commissioning	Mon 6/1/15	Fri 12/2/16
5	PS2 construction	Mon 1/2/12	Fri 4/1/16
6	PS2 beam commissioning	Mon 4/4/16	Fri 12/2/16
7	SPS modification	Fri 11/4/16	Fri 5/5/17
8	SPS beam commissioning	Mon 5/8/17	Fri 6/30/17
9	Start operation for physics	Mon 7/3/17	Mon 7/3/17



peak LHC luminosity vs. year



Roland Garoby,
LHCC 1July '08

two p beam scenarios

Table 1: Proton beam scenarios

	$N_{b,p}$	T_{sep}	$\epsilon_p \gamma_p$	β_p^*
LHC	1.7×10^{11}	25 ns	3.75 μm	0.25 m
LHC*	5×10^{11}	50 ns	3.75 μm	0.10 m

ultimate bunch charge or phase-2 LPA charge

nominal spacing or phase-2 LPA (ES*) spacing

nominal emittance

phase-1 or phase-2 ES/FCC beta function

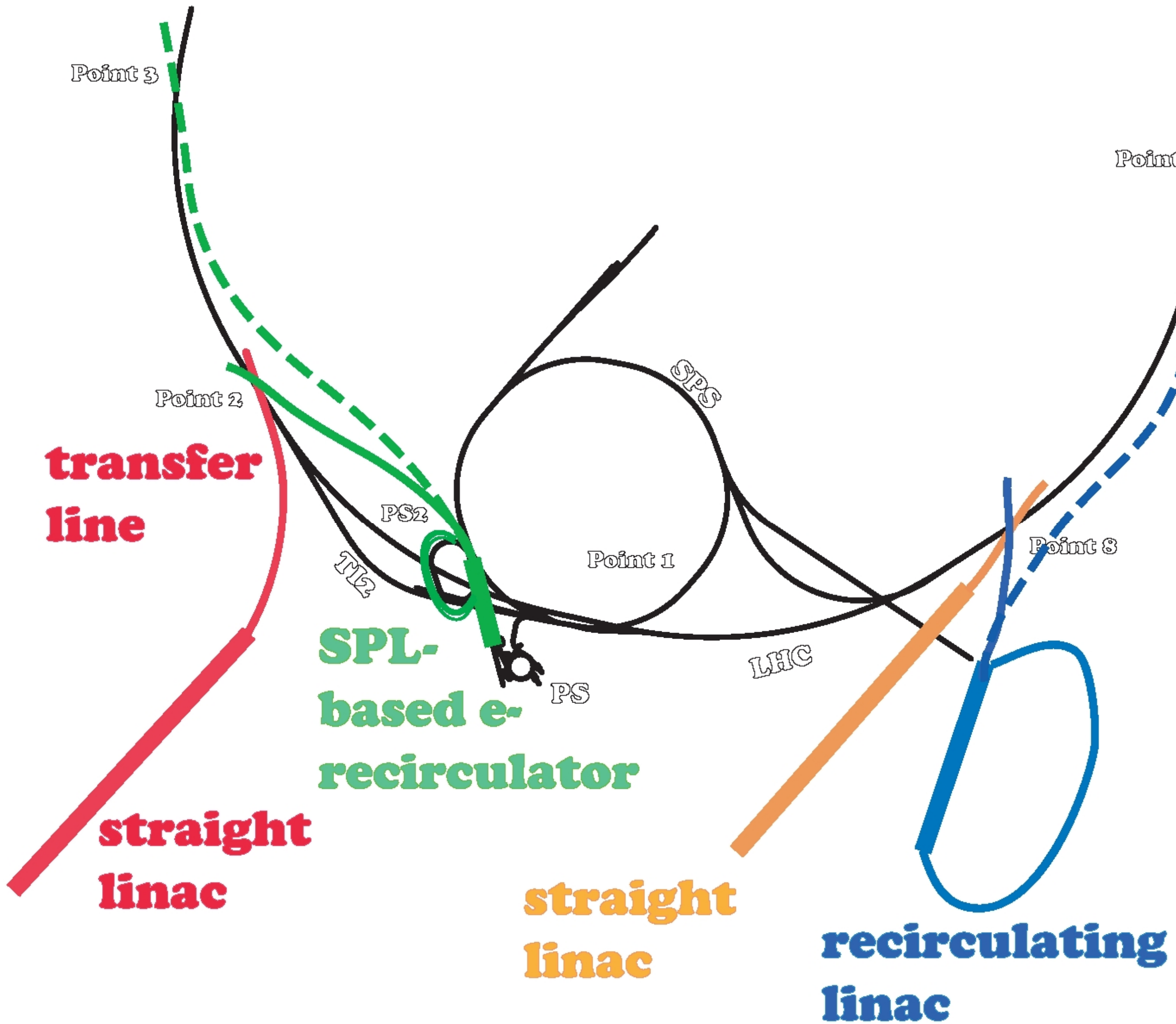
F. Zimmermann, "LHC Upgrade Scenarios," PAC'07

β^*=0.1 m could be realized in various ways:

- ✓ focusing only one p beam, relaxing aperture constraints
- ✓ dedicated ep runs, allowing for larger chromatic correction
- ✓ reducing the free length *l** between last quadrupole and ep IP
- ✓ hypothetical availability of stronger Nb_3Sn or NbAl magnets

example linac layouts at CERN

J. Osborne,
F. Z.



cryogenics electric power

$$P_{cr} = A\frac{E}{g} + BDEg$$

static heat load, dynamic heat load

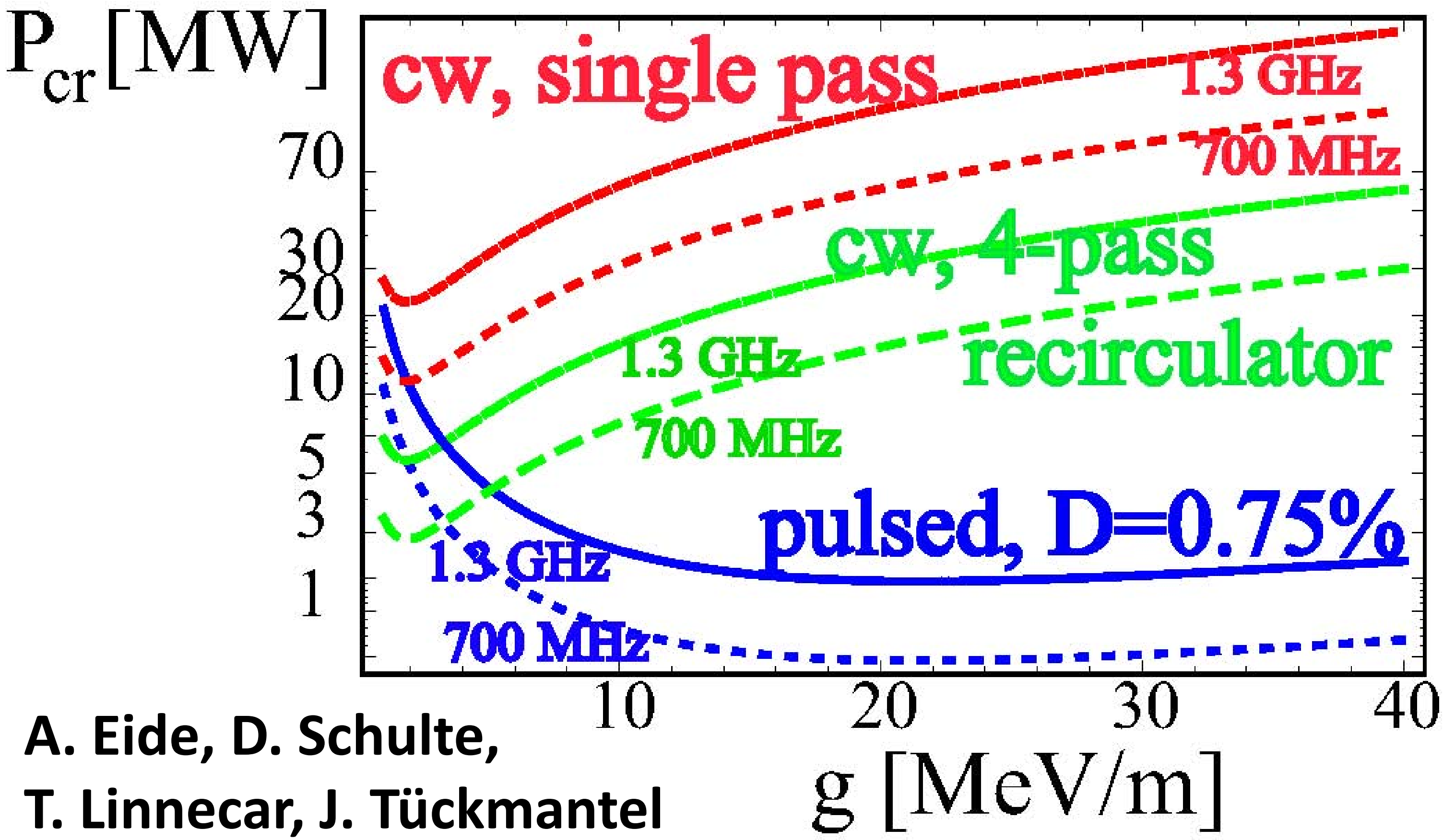
$A \approx 350\ \mathrm{W/m}$

$B \approx 10^{-10}\ \mathrm{Wm/(eV)^2}$

$$D \approx \begin{cases} 1 \text{ for cw mode} \\ 0.0075 \text{ for pulsed operation} \end{cases}$$

A. Eide: "Electrical Power of Ring-Linac Options for LHeC," T4 Report, 2008

cryogenics electric power vs. acc. gradient:



cw operation requires low gradient < 10 MV/m

recirculation and 700 MHz frequency further lower cryo-power needs

A. Eide, D. Schulte, T. Linnecar, J. Tückmantel

RF & total electric power

$$P_{rf} = P_{beam} \frac{1-\eta_{ER}}{\eta_{rf\rightarrow beam}\eta_{wp\rightarrow rf}}$$

A. Eide,
H. Braun

$\eta_{wp\rightarrow rf}$ ~ 50% for s.c. linacs

$\eta_{rf\rightarrow beam}$ ~ 100% in cw mode

$\eta_{rf\rightarrow beam}$ ~ $T_b/(T_b+(T_{rf,ref}-T_{b,ref})I_{ref}/I\,)$ in pulsed mode

η_{ERL} ~ 95% with ERL option (pessimistic); 0 else

$$P_{total} \approx P_{cr} + P_{rf}$$

total el. power   cryo power   rf power

IP parameters

both beams are taken to be round;

e- beam is assumed to be matched to p beam:

$\sigma_p^* = \sigma_e^*$

luminosity:

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\varepsilon_p} \frac{1}{\beta_p^*} I_e H_{hg}\left(\frac{\beta_e^*}{\sigma_{z,p}}, \frac{\varepsilon_e}{\varepsilon_p} \right)$$

average e- beam current (limited by available el. power, linac technology & beam dynamics)

proton brightness (limited by s.c. in injectors and LHC pp beam-beam)

p β function limited by IR layout, chromatic correction, and also by the e- hourglass reduction factor

H. Braun, F. Z.

e-p hourglass factor & p β^* limit

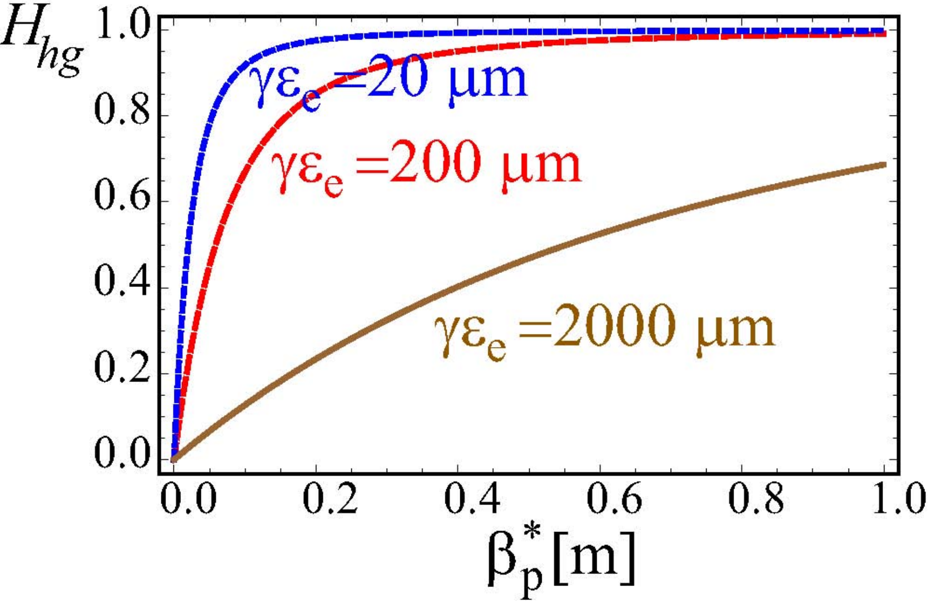
$$H_{hg}(x,r) = 2\sqrt{\pi}\, x r e^{4z^2r^2/(1+r^2)} \operatorname{erfc}\left(\frac{2xr}{\sqrt{1+r^2}}\right)$$

new formula!! (first presented at EPAC'08)

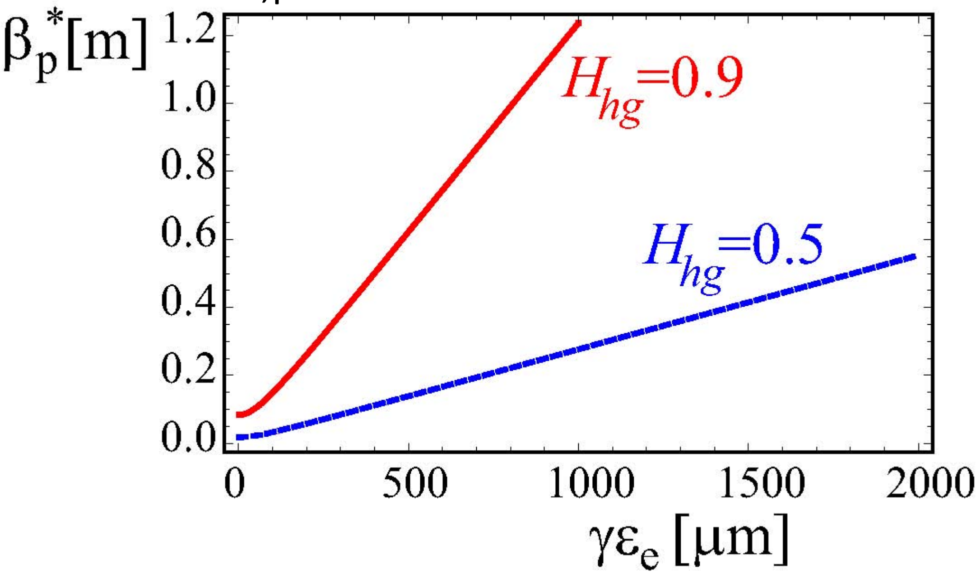
$x=\beta_e^*/\sigma_{z,p}$ $\quad r=\varepsilon_e/\varepsilon_p$

Note: linac $\gamma_e\varepsilon_e$ ~ 10-100 mm
smallest LEP $\gamma_e\varepsilon_e$ ~2 mm at 60 GeV

H_{hg} vs. β_p^* for three values of $\gamma_e\varepsilon_e$ assuming E=60 GeV & $\sigma_{z,p}$=7.5 cm

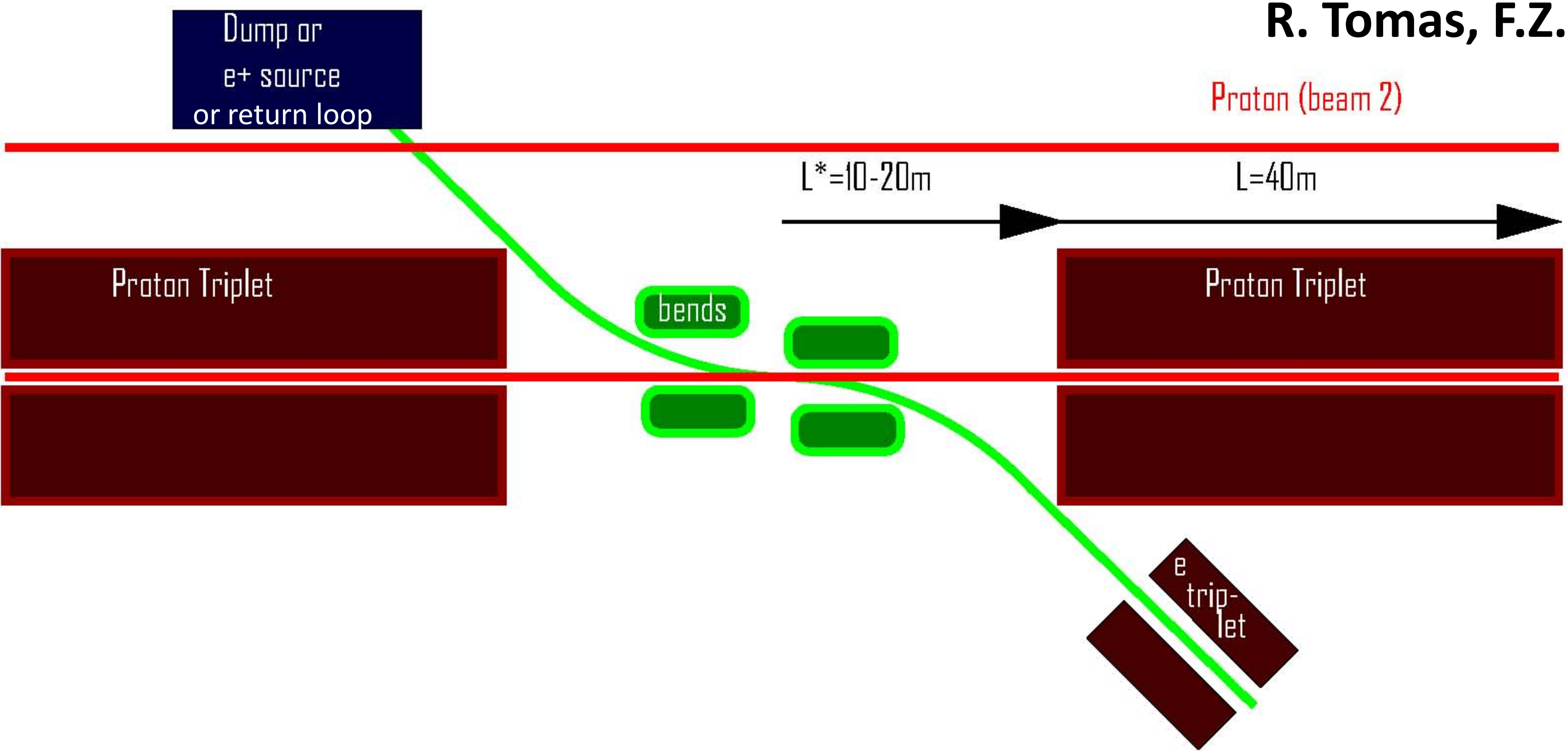


β^*_p vs. $\gamma_e\varepsilon_e$ for two values of H_{hg} assuming E=60 GeV & $\sigma_{z,p}$=7.5 cm



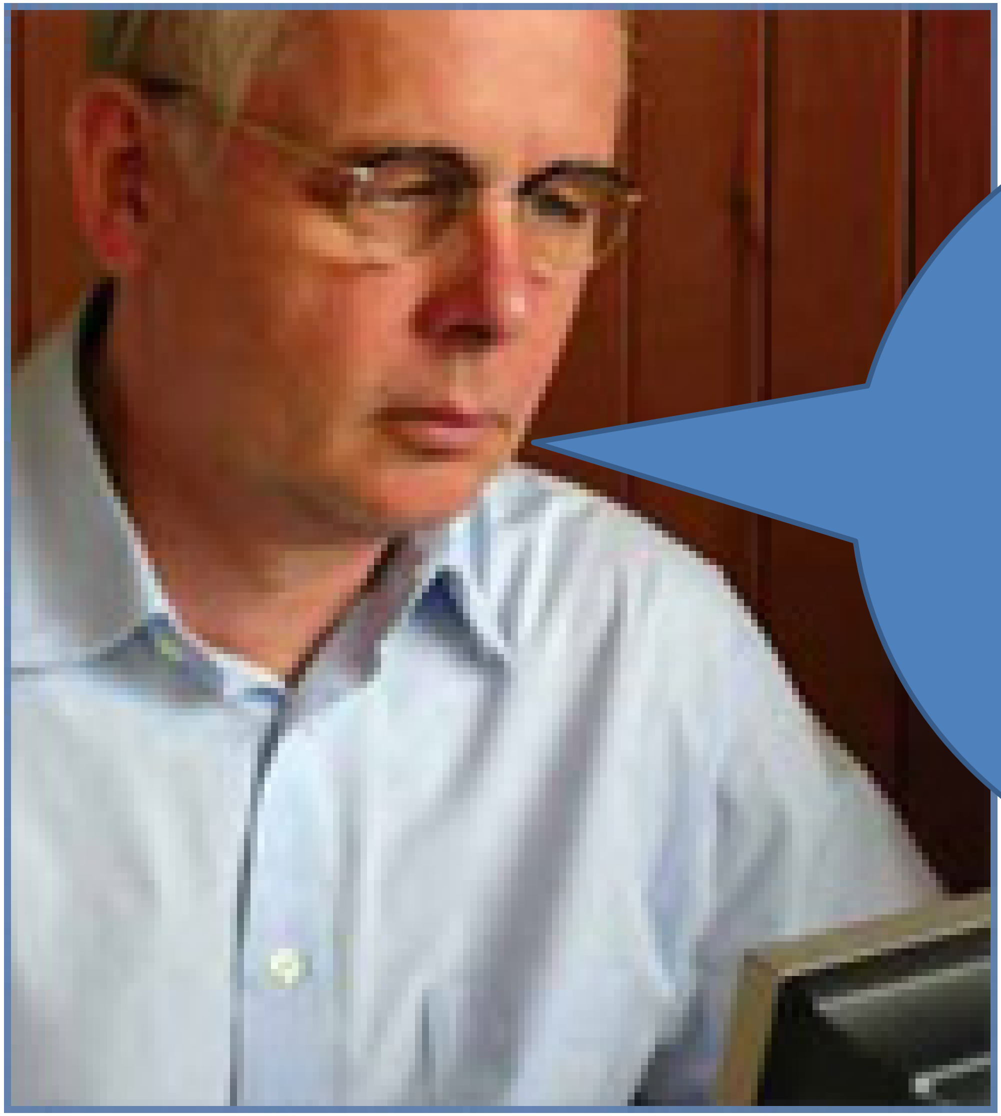
interaction region

R. Tomas, F.Z.



small e- emittance → relaxed β_e^* → $L_e^* > L_p^*$, can&must profit from ↓β_p^*
single pass & low e-divergence → parasitic collisions of little concern;
→ head-on e-p collision may be realized by long separation bends;
→ no crab cavity required up to 50 GeV or higher; later weak cc's

but questions will be asked ...

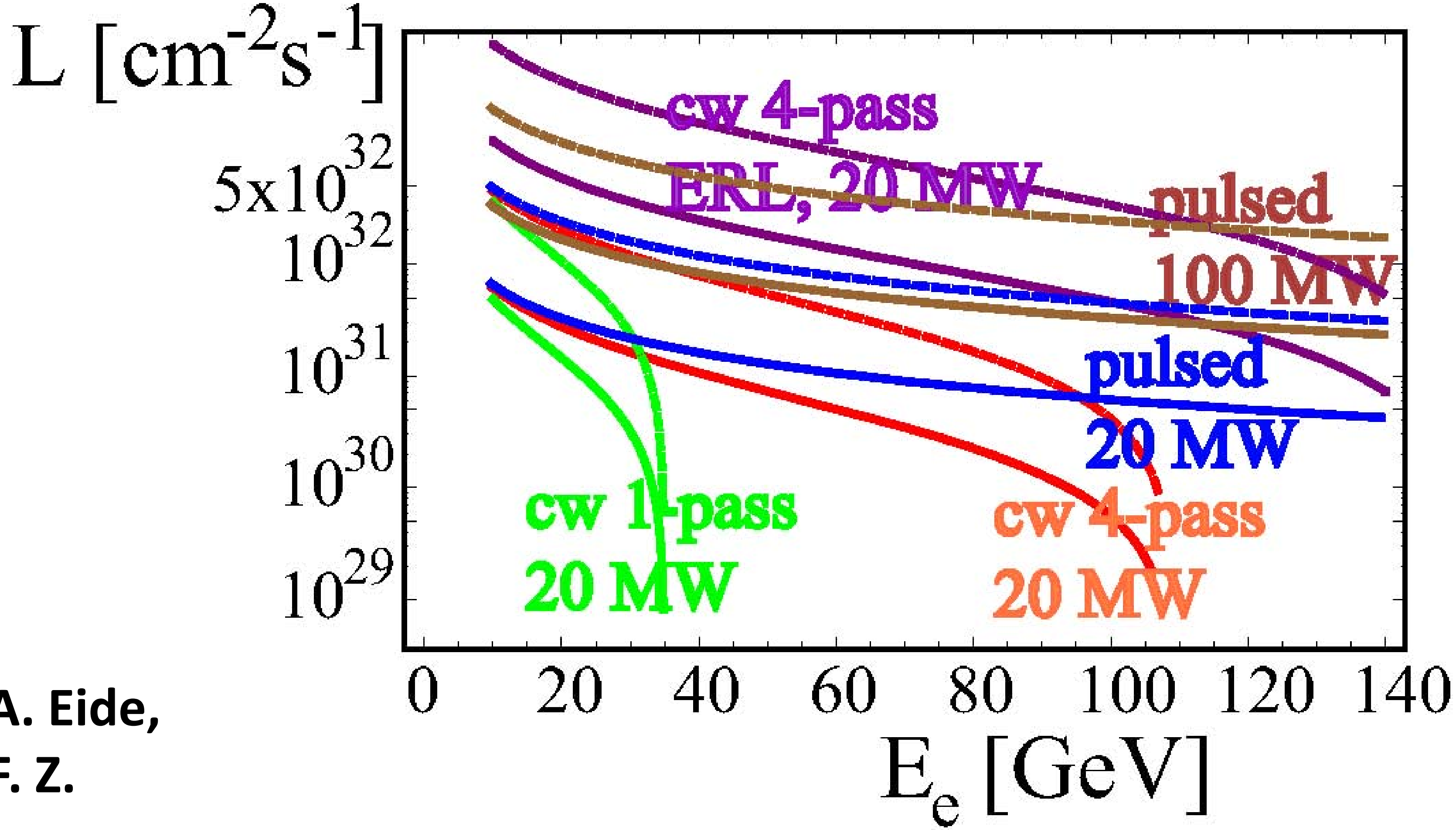


can we build a cost-effective linac-ring LHeC?

… and answers provided

yes we can!

luminosity reach



A. Eide,
F. Z.

luminosity vs. e- energy for cw & pulsed linac

detailed e- beam parameters

Table 2: Electron-beam parameters for various (s.c.) linac-ring LHeC scenarios. The β^* values are calculated for a normalized e- emittance of 20 μm. Parameters marked by asterisks refer to 'LHC*' of Table 1.

energy [GeV]	20	20	60	60	60	120
option	cw 4-pass	cw 4-p. ERL	cw 4-pass	cw 4-p. ERL	pulsed	pulsed
bunch population $N_{b,e}$ [10^9]	0.06, 0.12*	1.3, 2.6*	0.1, 0.2*	0.3, 0.6*	17, 34*	7, 14*
average current [μA]	400	8650	74	2050	820	340
beam power at IP [MW]	8.0	172	4.5	120	49	48
IP beta function [m]	0.25, 0.098*	0.25, 0.098*	0.74, 0.30*	0.74, 0.30*	0.74, 0.30*	1.72, 0.69*
luminosity [10^{31} cm^{-2}s^{-1}]	2.7, 20*	58, 430*	0.5, 3.7*	14, 100*	5.5, 41*	2.3, 17*
total electrical power [MW]	20	20	20	20	100	100

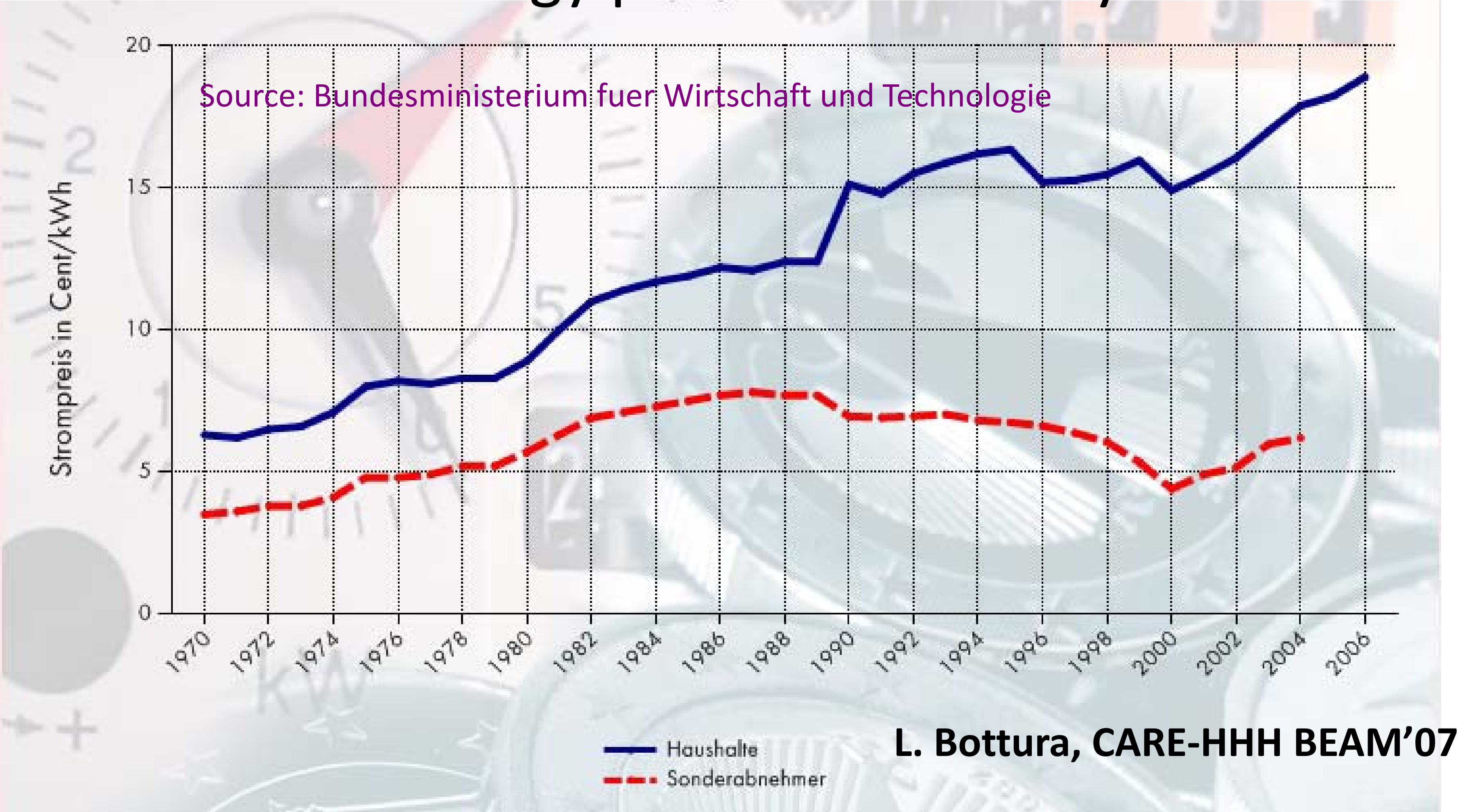
beware: luminosity for ring-ring collider is often quoted for 20 MW beam (not electrical!) power!

→ linac-ring collider can deliver luminosities of 10^{32} to $5\text{x}10^{33}$ cm^{-2}s^{-1} at 60 GeV e- energy with 100 MW total wall-plug power

operating cost

presently ~1 MEuros per MW per year (INFN)

evolution of energy prices in Germany:



L. Bottura, CARE-HHH BEAM'07

e- source

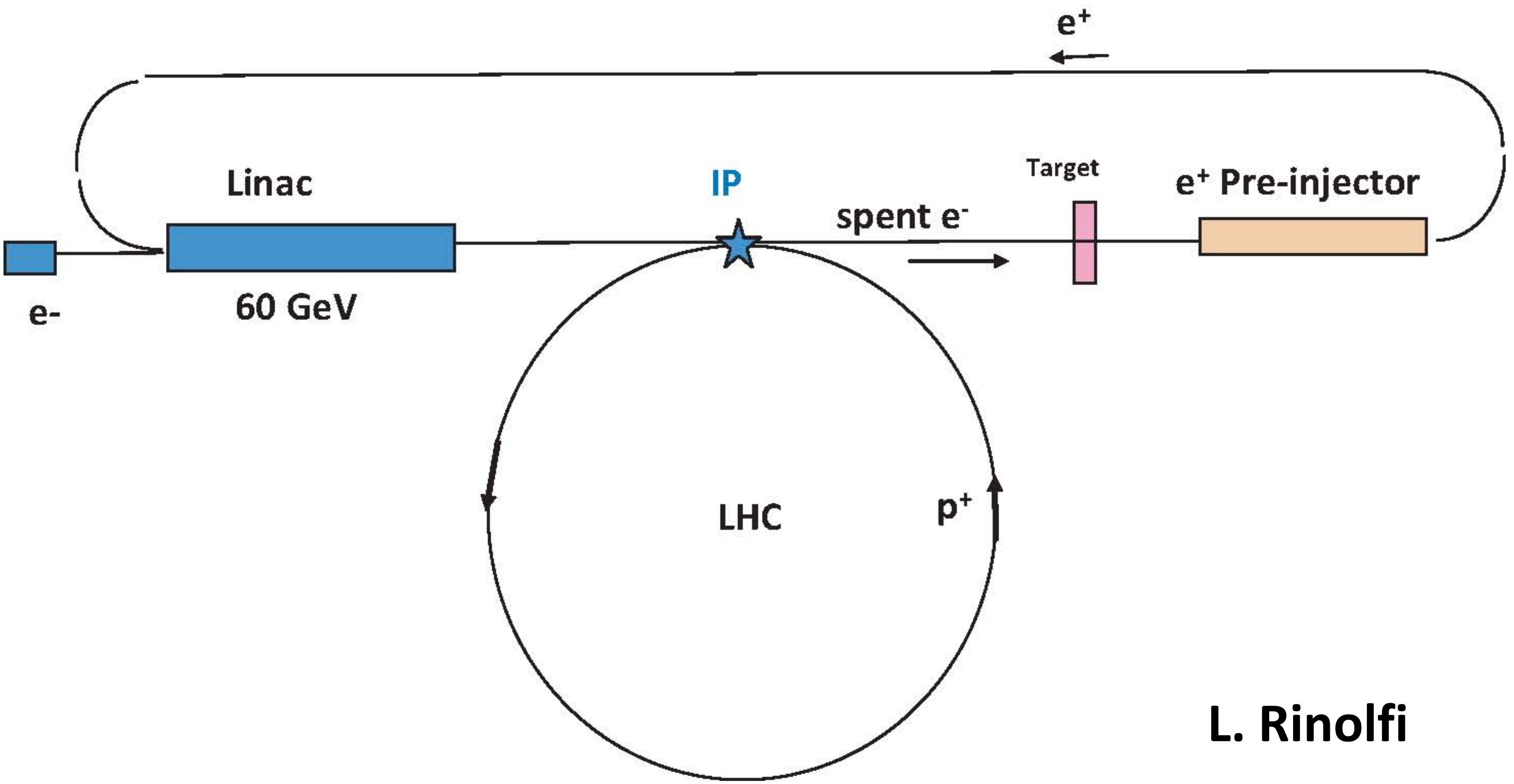
the e- beam can be produced from a polarized dc gun (e.g. SLC, E-158, or NLC type), with 90% polarization

depending on the bunch charge a normalized emittance between 10 and 100 μm is expected after bunching and acceleration

this is much (~3 orders of magnitude) smaller than might be hoped for in a ring at 70 GeV beam energy

H. Braun, L. Rinolfi, F. Z.

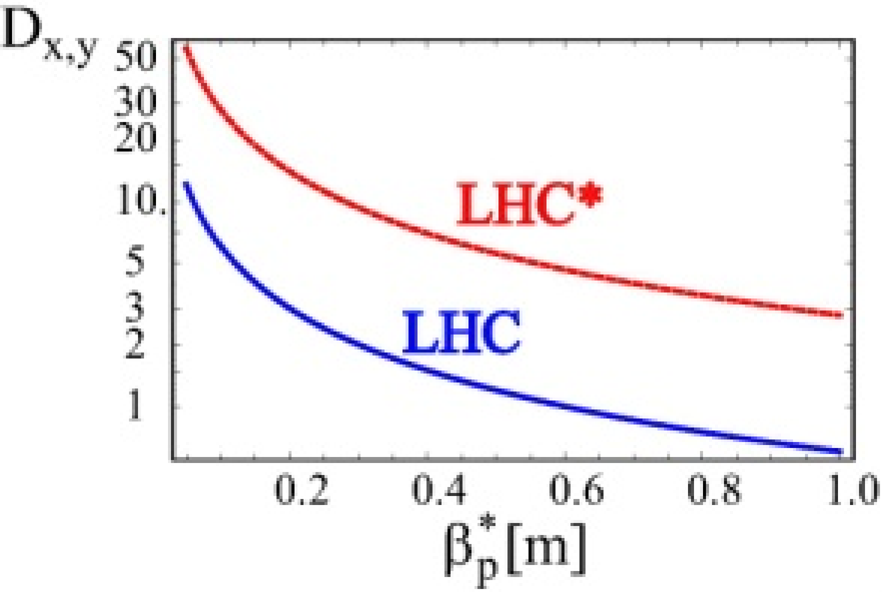
e+ production



L. Rinolfi

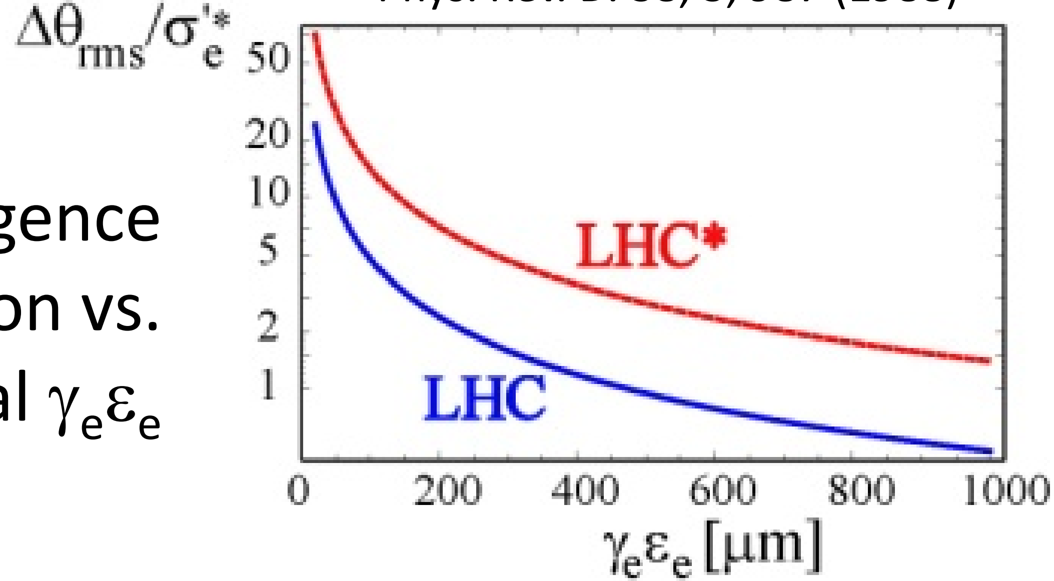
schematic linac-ring collider with integrated e+ production

collision effect on e-



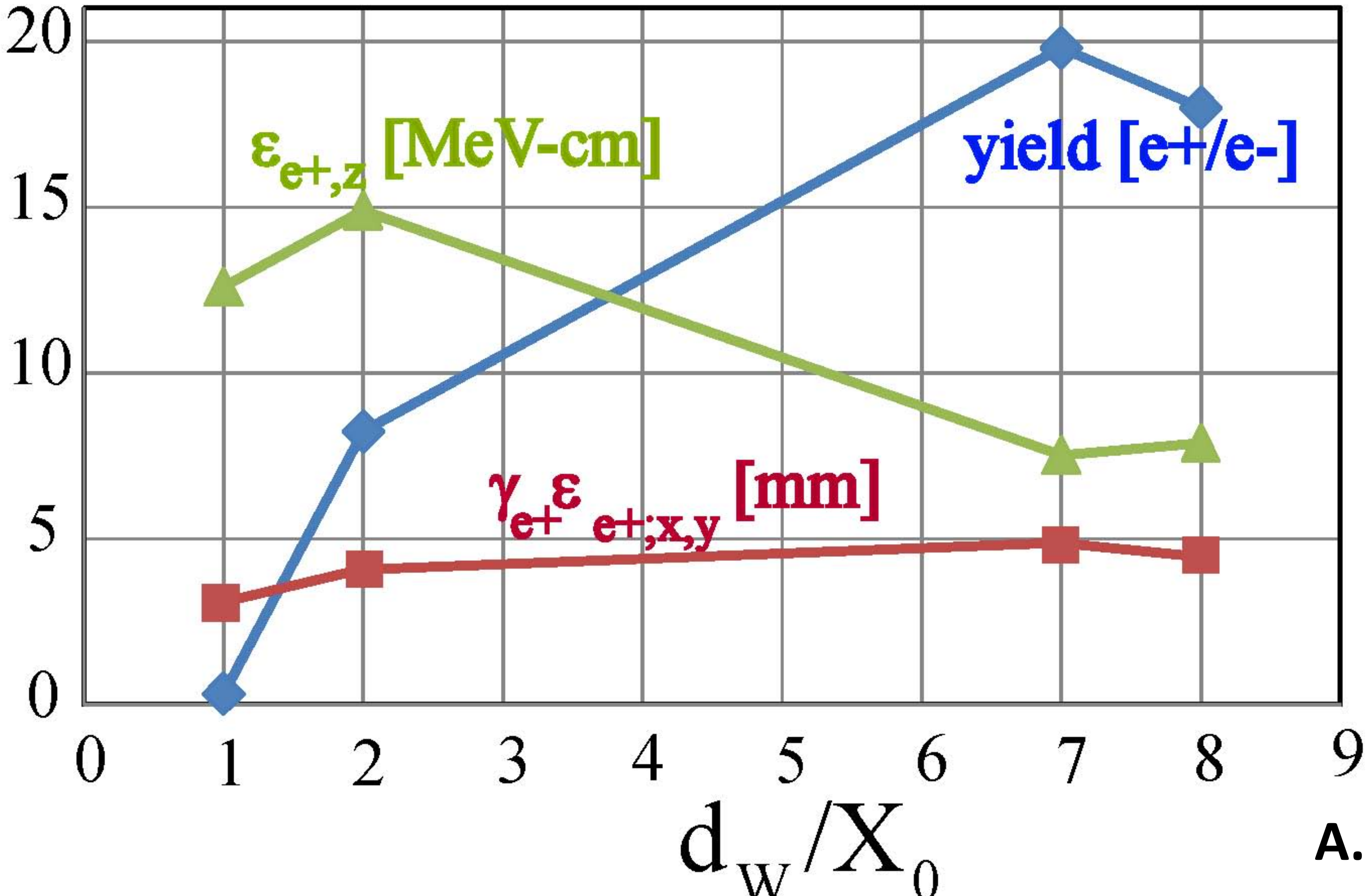
e- disruption parameter vs. β^*_p

see also: P. Chen, K. Yokoya, Phys. Rev. D. 38, 3, 987 (1988)



relative rms divergence increase in collision vs. initial $\gamma_e \varepsilon_e$

e+ source yield



A. Vivoli

EGS4&PARMELA simulations of e+ yield for amorphous W target of varying thickness hit by 60-GeV e- beam ($\gamma_e \varepsilon_e$ =20μm, $\sigma_{x,y,e}$=20 μm, β=10m, $\sigma_{z,e}$=300 μm, $N_{b,e-}$=2x10^{10}); ILC capture section; <E_{e+}>~270 MeV

physics merits

- no interruption of LHC pp physics program
- ep collisions at much higher energy & luminosity than HERA
- e- beam energy can be increased in stages, w/o any fundamental limit
- possibility of 90% e- polarization
- additional possibility of γ-p or γ-N collisions via laser Compton back-scattering (this mode is incompatible with energy recovery)

accelerator merits

- tunnel construction fully separate from LHC
- low e- emittance allows profiting from smaller β_p^* to boost the luminosity; and it reduces SR from quadrupoles
- energy recovery could raise luminosity 20 times
- possibility of simplified IR optics & layout (e- triplet far away, head-on collision, no or weak crab cavities)
- possibility of staged construction & exploitation

optimistic “dream” schedule

2017 — SPL *p*

2019 — recirc. SPL e-, 20 GeV, L_{ep}~ 10^{32} $m^{-2}s^{-1}$, P_{wp}~ 20 MW

2021 — 60 GeV upgrade, ~$2x10^{32}$ $m^{-2}s^{-1}$, 100 MW

2023 — ERL upgrade (60 GeV), $5x10^{33}$ $m^{-2}s^{-1}$, 100 MW

2025 — 140 GeV upgrade, $2x10^{33}$ $m^{-2}s^{-1}$, 100 MW

2029 — 300 GeV, $2x10^{33}$ $m^{-2}s^{-1}$ 200 MW

accelerator synergies

- with SPL: possible double use; same structures & RF
- with CERN complex: use PS or PS2 (or LHC) tunnel
  for e- recirculating loops?
  (later: dual 25-140 GeV *p* recirculating linac?)
- with future linear collider (ILC or CLIC):
  - joint developments and testbed
  - re-use of linac structures, RF, tunnel
  - γ-type collider, e- & e+ source, dynamics, DR?
  - possibility of adiabatic smooth transition from
    highest-energy ERL ep collider to e+e- LC
- with LHC: use LHeC as high-energy “e- lens” to
  push LHC beam-beam limit and pp luminosity?

a few issues

- linac tends to have lower e- current than ring (cost); luminosity can be recovered by exploiting smaller β_p^* (thanks to smaller e- emittance) and possibly by energy recovery
- alternating/simultaneous e-/e+ operation if spent e- beam is used for e+ production; in pulsed mode e+ damping ring?
- may need to choose between most cost-effective solution (SPL based), energy-upgradability (independent recirculating linac), and LC-compatibility, - who decides best strategy?

conclusions

- LR LHeC offers a great physics & upgrade potential, plus interesting accelerator physics
- luminosities between 10^{31} and several 10^{33} $cm^{-2}s^{-1}$ depending on operation mode, beam energy, and electric power
- e- energies up to several 100 GeV
- LR LHeC can be seamlessly integrated into the present LHC, LHC injectors and longer-term CERN upgrade plans
- rough construction cost ~100 MEuro for 20 GeV, 1 GEuro for 100 GeV
- e- operation cost ~ 100 MEuro/100 MW/year

thank you for your attention!