LHeC : Linac-Ring Option

Hans-H. Braun / CERN

- General consideration
- Proton ring issues
- 70 GeV
- 140 GeV
- Polarisation and Positrons
- Comparison Ring-Ring v.s Linac Ring
- Conclusions

All considerations on LHeC linac-ring are in a very early stage, mainly parametric considerations to understand the potential of different options.

Present plan is to establish collaborations to narrow down possible design choices and to work on critical issues with a first resume at LHeC workshop in September.

Physics requirements (more input welcome)

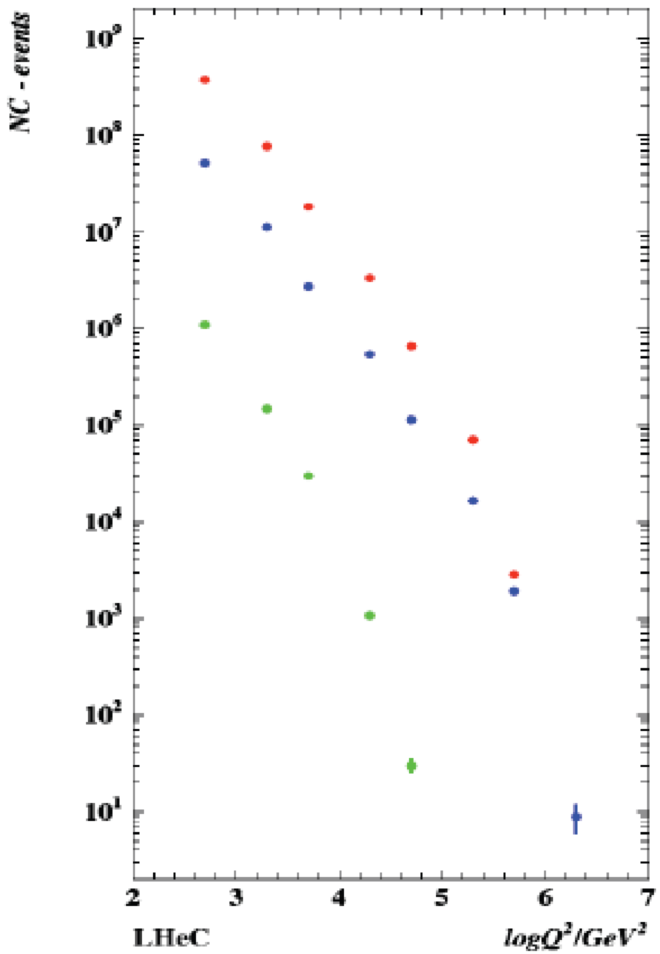
	Minimum performance to justify physics case	Desirable performance
E beam	50 GeV	70 GeV
L	$1 \cdot 10^{32}\ cm^{-2}s^{-1}$	$10 \cdot 10^{32}\ cm^{-2}s^{-1}$
Particle species	e^- & e^+	e^- & e^+
Polarisation	No	Yes

e-p option has to co-exist with p-p, but not necessarily for simultaneous running. Dedicated running periods with special p-beam conditions like for present LHC heavy ion program can be envisaged if integrated luminosity sufficient. But technical modifications for LHeC should not compromise performance for p-p runs.

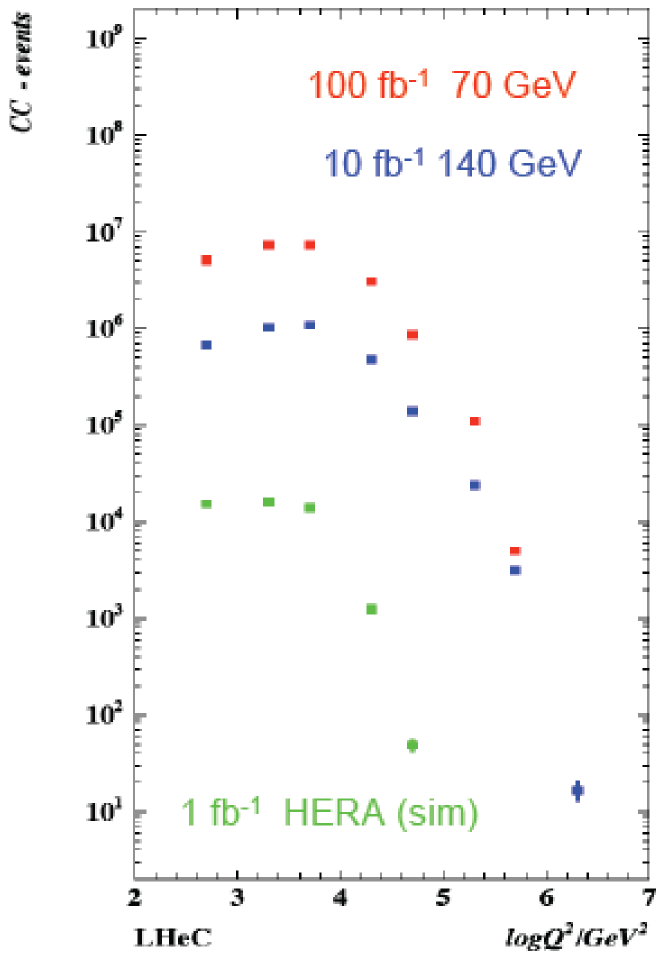
e-A option comes automatically, since LHC is already prepared for operation with Pb^{208}

DIS events

Neutral Currents ep ->eX



Charged Currents ep ->νX



The strong decrease of the DIS cross section with Q^2 requires highest possible luminosity.

Statistics at LHeC for up to $\sim 10^5$ GeV^2 is rich.

No statistics problem for low x physics - two versions of IR and instrumentation possible, though not really desired.

Highest scales: large energy counts for discovery range.

The LHeC is a huge step from HERA into the TeV range.

At very large Q^2 10 times less L is compensated by 2 E_e .

Typical achieved values for electron linacs

	Superconducting electron linacs	Normal conducting electron linac
Frequency	0.8-3 GHz	1.5-30 GHz
Accelerating field	5-30 MV/m	10-80 MV/m
Fill factor	70%	80%
Time structure	c.w. or pulsed with 0.5-5 ms pulse length	pulsed with 0.01– 10 μs pulse length
e^- per bunch	up to 10^{11}	up to 10^{11}
Beam current during pulse	up to 100 mA	up to 25 A
$\varepsilon\gamma$	1-100 μm	1-100 μm

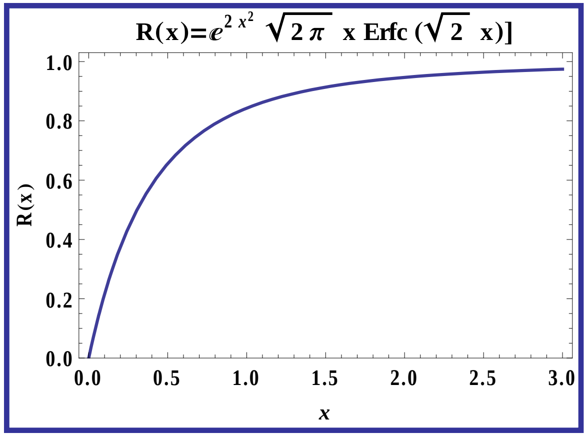
Luminosity for ring linac

$$L = \frac{N_P N_E f \; R\left(\beta^*_{XP}, \beta^*_{XE}, \beta^*_{YP}, \beta^*_{YE}, \sigma_{ZE}, \sigma_{ZP}, \alpha_{COLL}\right)}{2\pi \sqrt{\left(\beta^*_{XP}\varepsilon_{XP} + \beta^*_{XE}\varepsilon_{XE}\right)\left(\beta^*_{YP}\varepsilon_{YP} + \beta^*_{YE}\varepsilon_{YE}\right)}}$$

with $\varepsilon_{\mathrm{E}} \leq \varepsilon_{\mathrm{P}}, \sigma_{\mathrm{ZE}} << \sigma_{\mathrm{ZP}}$ and assuming round beams, $\alpha_{\mathrm{COLL}} = 0$

$$L \approx \frac{N_P N_E f}{4\pi \beta^*_P \varepsilon_P} R\left(\frac{\beta^*_P}{\sigma_{ZP}}\right) \xleftarrow{\text{hourglass effect}}$$

$$= \underbrace{\frac{N_P}{4\pi \beta^*_P \varepsilon_P} R\left(\frac{\beta^*_P}{\sigma_{ZP}}\right)}_{\text{p-beam parameters}} \underbrace{\frac{P_{e-Beam}}{m_e c^2 \gamma_e}}_{\text{e-beam parameters}}$$



LHC P-beam parameters ("ultimate")

E	7 TeV
N	$1.70 \cdot 10^{11}$
$\beta^*_{X,Y}$	0.50 m
$\varepsilon_{NX,Y}$	3.75 μm
σ_Z	7.55 cm
Bunch spacing	25 ns

$$L \approx \boxed{\frac{N_P}{4\pi\beta^*_P\varepsilon_P} R\left(\frac{\beta^*_P}{\sigma_{ZP}}\right)} \frac{P_{e-Beam}}{m_e c^2 \gamma_e}$$

LHeC case	electron beam power
70 GeV, $10^{32}\mathrm{cm^{-2}s^{-1}}$	210 MW
70 GeV, $10^{33}\mathrm{cm^{-2}s^{-1}}$	2100 MW

Improvement of LHC proton parameters essential to get more reasonable e-linac P_{Beam} !

- Reduce proton β^*
- Increase proton bunch charge
- Reduce proton emittance

Improvement of LHC proton parameters I

➢ ***Reduction of proton β^****

Goal of present LHC IR upgrade R&D is to reduce β^* from 55 cm to 25 cm for IR1 (ATLAS) and IR5 (CMS).

For LHeC a IR with smaller L^* could be envisaged, this allows for even smaller β^* . We assume in the following β^*=10cm.

see also

Proceedings of PAC07, Albuquerque, New Mexico, USA THPAN072

A CONCEPT FOR THE LHC LUMINOSITY UPGRADE BASED ON STRONG BETA* REDUCTION COMBINED WITH A MINIMIZED GEOMETRICAL LUMINOSITY LOSS FACTOR

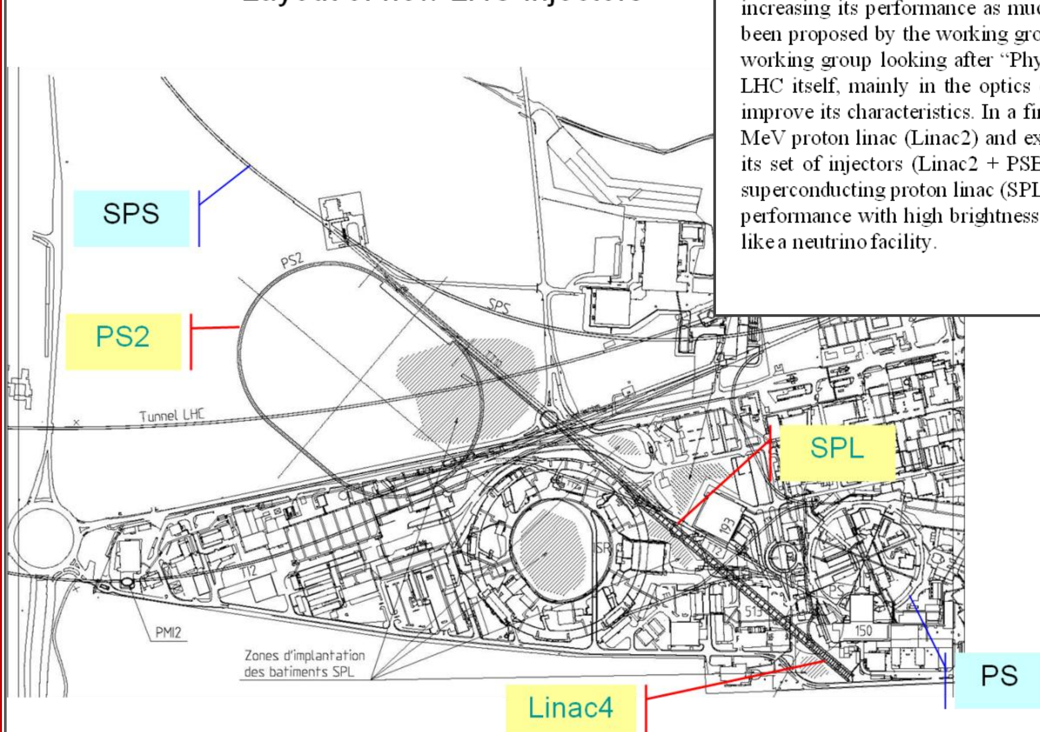
J-P. Koutchouk, R. Assmann, E. Métral, E. Todesco, F. Zimmermann, CERN, Geneva, Switzerland
R. De Maria, G. Sterbini, CERN, Geneva & EPFL, Lausanne, Switzerland

Improvement of LHC proton parameters II

- ***Increased proton bunch charge***

New LHC p-injector chain with LINAC 4, SPL and PS2 will allow to double N_B at injection of LHC. We assume therefore $N_B = 3.4 \cdot 10^{11}$

Layout of new LHC injectors



Plans for Upgrading the CERN Proton Accelerator Complex

R. Garoby, *HEP 2007 – 19-25 July 2007 – Manchester/GB*

With the construction of the Large Hadron Collider (LHC) in its final phase at CERN, it is now time to prepare for increasing its performance as much as possible and for preparing for the future needs of physics. A basic plan has been proposed by the working group on "Proton Accelerators of the Future", using the input from an ad'hoc physics working group looking after "Physics Opportunities with Future Proton Accelerators". Apart from upgrades in the LHC itself, mainly in the optics of the insertions, the proposal is to renew the injector complex and significantly improve its characteristics. In a first phase, a new 160 MeV H- linac (Linac4) will be built to replace the present 50 MeV proton linac (Linac2) and extensive consolidation will be made. In a second phase, the present 26 GeV PS and its set of injectors (Linac2 + PSB) are planned to be replaced with a ~50 GeV synchrotron (PS2) with a ~4 GeV superconducting proton linac (SPL) as injector. The SPS itself will be upgraded for injection at 50 GeV and for better performance with high brightness beams. These proposals will be described as well as their potential for other uses like a neutrino facility.

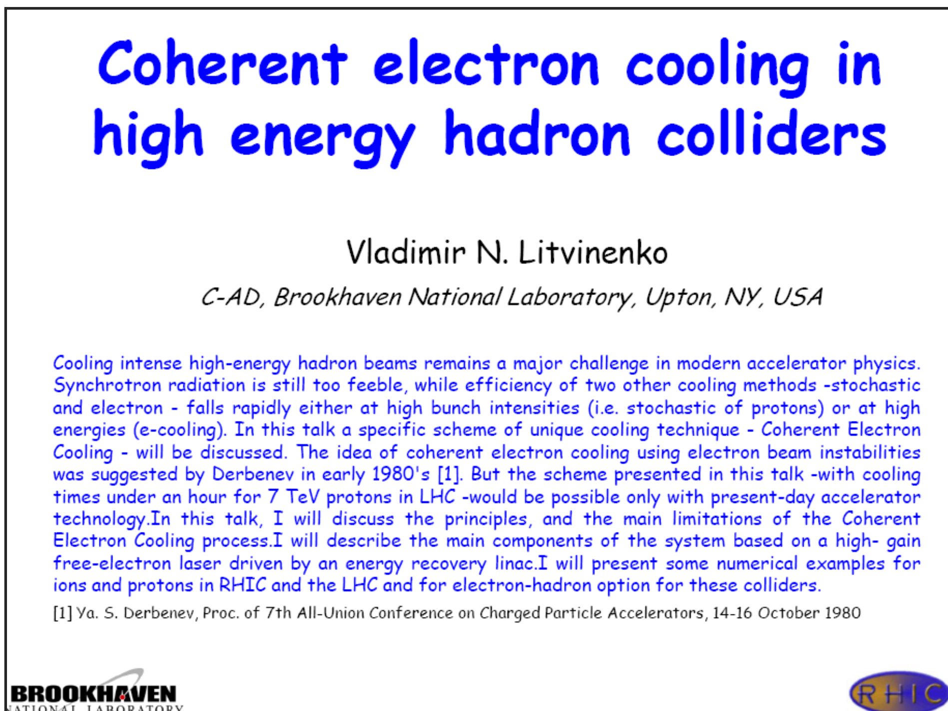
Improvement of LHC proton parameters III

➢ ***Reduced proton emittance***

Not very interesting for LHC p-p performance, but schemes for high energy proton beam cooling are under study elsewhere (BNL, FNAL) .

We assume that either with those schemes or with new LHC injectors

P- emittance can be reduced by a factor 2



Coherent electron cooling in high energy hadron colliders

Vladimir N. Litvinenko

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Cooling intense high-energy hadron beams remains a major challenge in modern accelerator physics. Synchrotron radiation is still too feeble, while efficiency of two other cooling methods -stochastic and electron - falls rapidly either at high bunch intensities (i.e. stochastic of protons) or at high energies (e-cooling). In this talk a specific scheme of unique cooling technique - Coherent Electron Cooling - will be discussed. The idea of coherent electron cooling using electron beam instabilities was suggested by Derbenev in early 1980's [1]. But the scheme presented in this talk -with cooling times under an hour for 7 TeV protons in LHC -would be possible only with present-day accelerator technology.In this talk, I will discuss the principles, and the main limitations of the Coherent Electron Cooling process.I will describe the main components of the system based on a high- gain free-electron laser driven by an energy recovery linac.I will present some numerical examples for ions and protons in RHIC and the LHC and for electron-hadron option for these colliders.

[1] Ya. S. Derbenev, Proc. of 7th All-Union Conference on Charged Particle Accelerators, 14-16 October 1980

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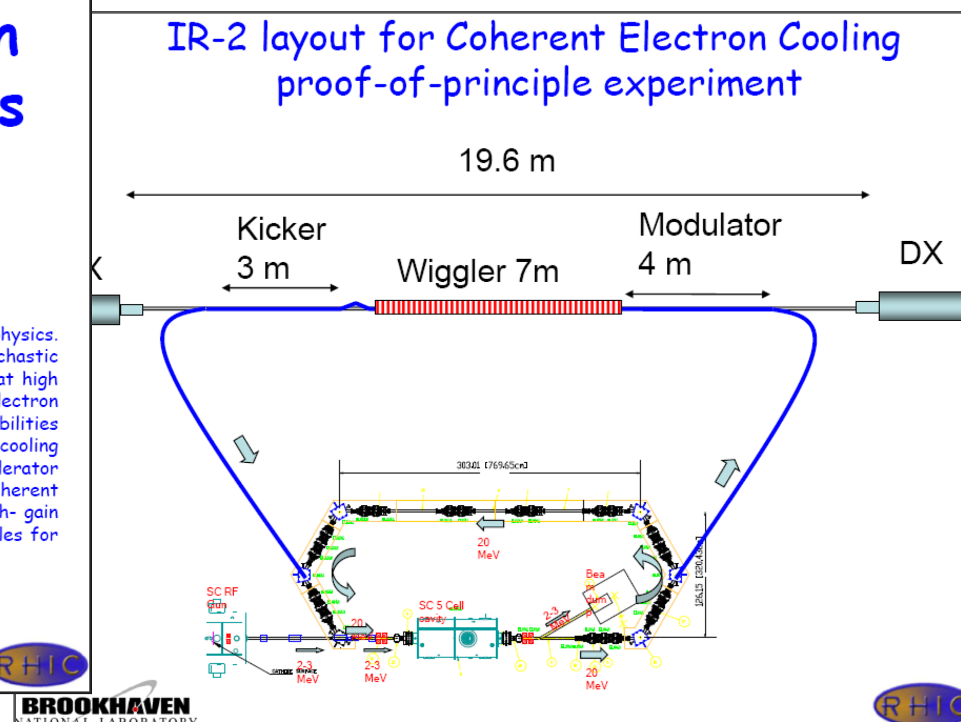
RHIC



assumed LHeC p-beam parameters

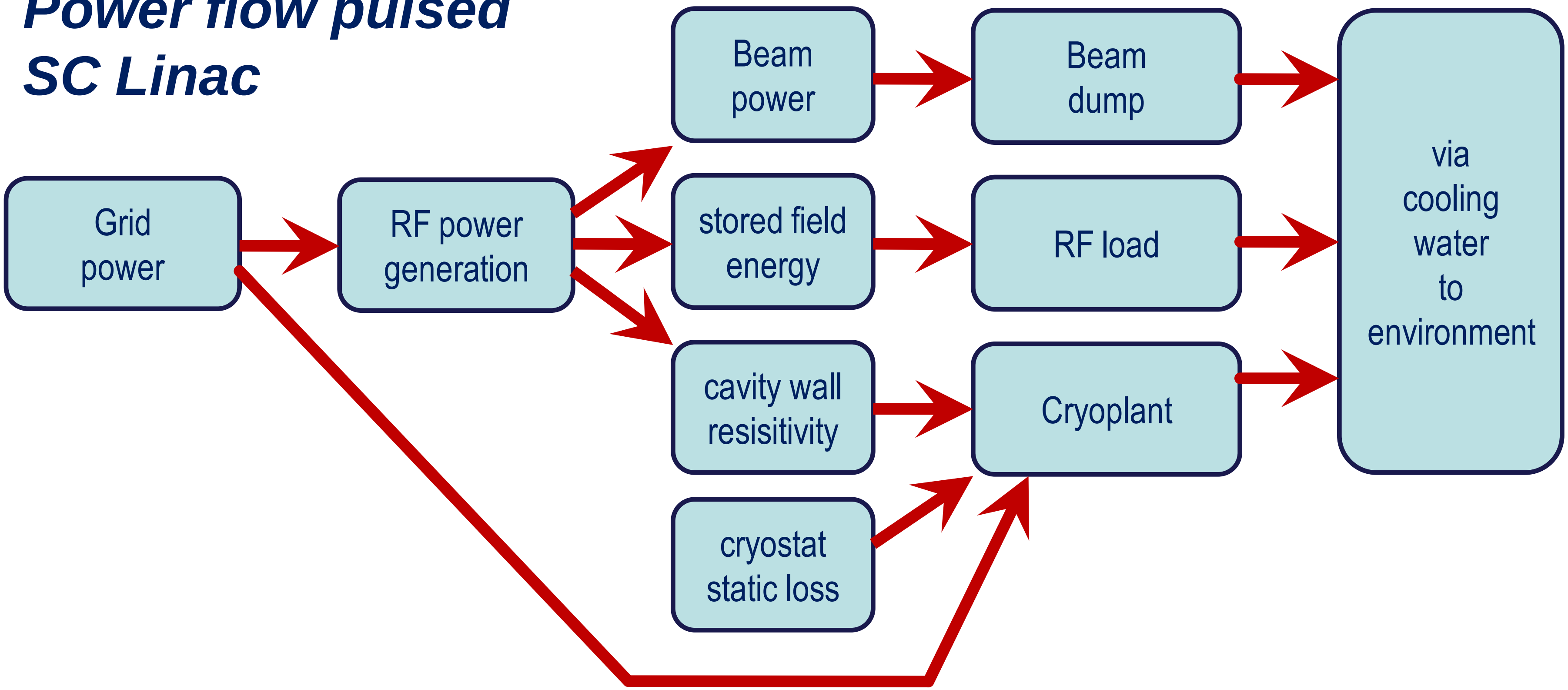
E	7 TeV
N	$3.40 \cdot 10^{11}$
$\beta^*_{X,Y}$	0.10 m
$\varepsilon_{X,Y} \cdot \gamma$	1.9 μm
σ_Z	7.55 cm
Bunch spacing	25 ns

with β^*=10cm, N_B =$3.4 \cdot 10^{11}$, ε_P=1.9μm

LHeC case	electron beam power
70 GeV, 10^{32}cm^{-2}s^{-1}	8.4 MW
70 GeV, 10^{33}cm^{-2}s^{-1}	84 MW

still very high,
but not completely
out of scale

Power flow pulsed SC Linac

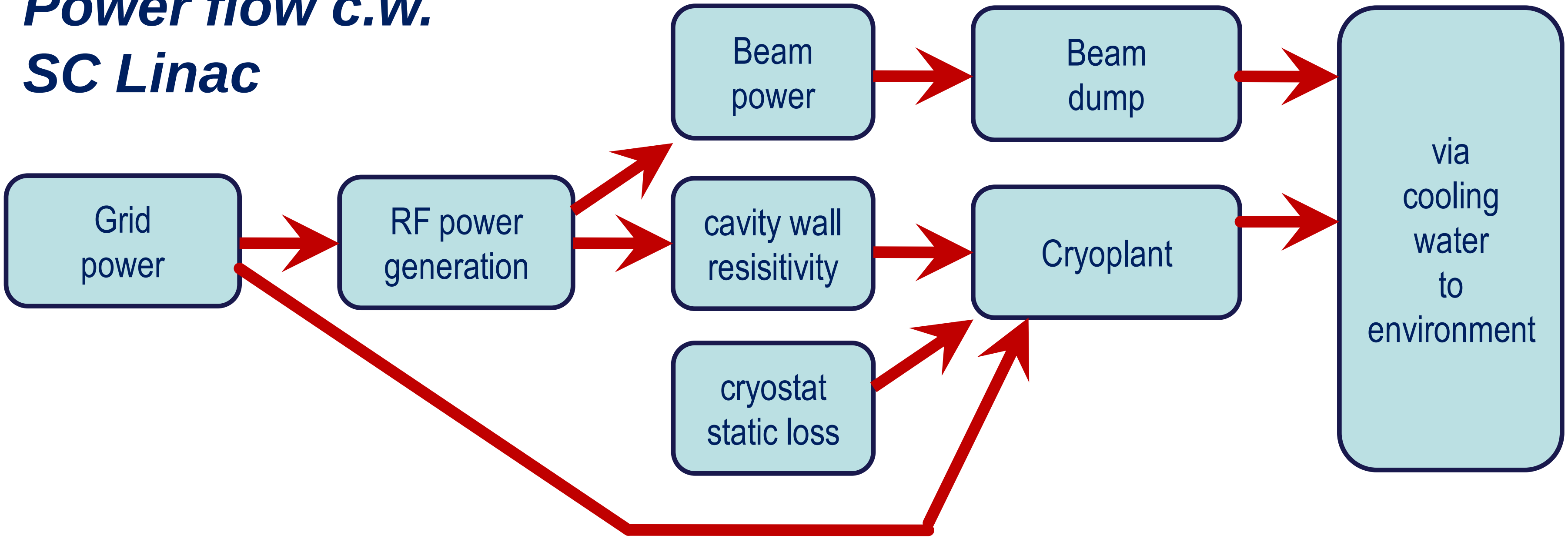


Example X-FEL 8 cavity Module (L=12.2m)

Gain beam power (196MV*5mA*0.65ms*10Hz)	6.4 kW
Grid power for RF stored field energy	19.3 kW
Grid power for RF for beam acceleration	16.8 kW
Grid power for static cryogenic losses	14.3 kW
Grid power for dynamic cryogenic losses ~E^2	13.1 kW
overall efficiency	***10%***

All overheads included !

Power flow c.w. SC Linac



Example X-FEL 8 cavity Module (L=12.2m), c.w.		pulsed case
Gain beam power (196MV*32.5 μA)	6.4 kW	6.4 kW
Grid power for RF stored field energy	0 kW	19.3 kW
Grid power for RF for beam	16.8 kW	16.8 kW
Grid power for static cryogenic losses	14.3 kW	14.3 kW
Grid power for dynamic cryogenic losses	857 kW	13.1 kW
overall efficiency	***0.72%***	***10%***

Example X-FEL 8 cavity Module (L=12.2m), c.w. optimised for good power efficiency, gradient reduced to 11.8 MV/m, high c.w. current		c.w. 23.6 MV/m	nominal pulsed 23.6MV/m
Gain beam power (98 MV*5mA)	490 kW	6.4 kW	6.4 kW
Grid power for RF stored field energy	0 kW	0 kW	19.3 kW
Grid power for RF for beam acceleration	1300 kW	16.8 kW	16.8 kW
Grid power for static cryogenic losses	14.3 kW	14.3 kW	14.3 kW
Grid power for dynamic cryogenic losses ~E^2	214 kW	857 kW	13.1 kW
overall efficiency	***32%***	***0.72%***	***10%***

Good power efficiency in c.w. operation only achievable with high beam current and moderate accelerating field !

But for given Luminosity and energy beam current is given, i.e. I_B=1.2 mA for L=$10^{33}cm^{-2}s^{-1}$

Solution: recirculation as in CEBAF, S-DALINAC

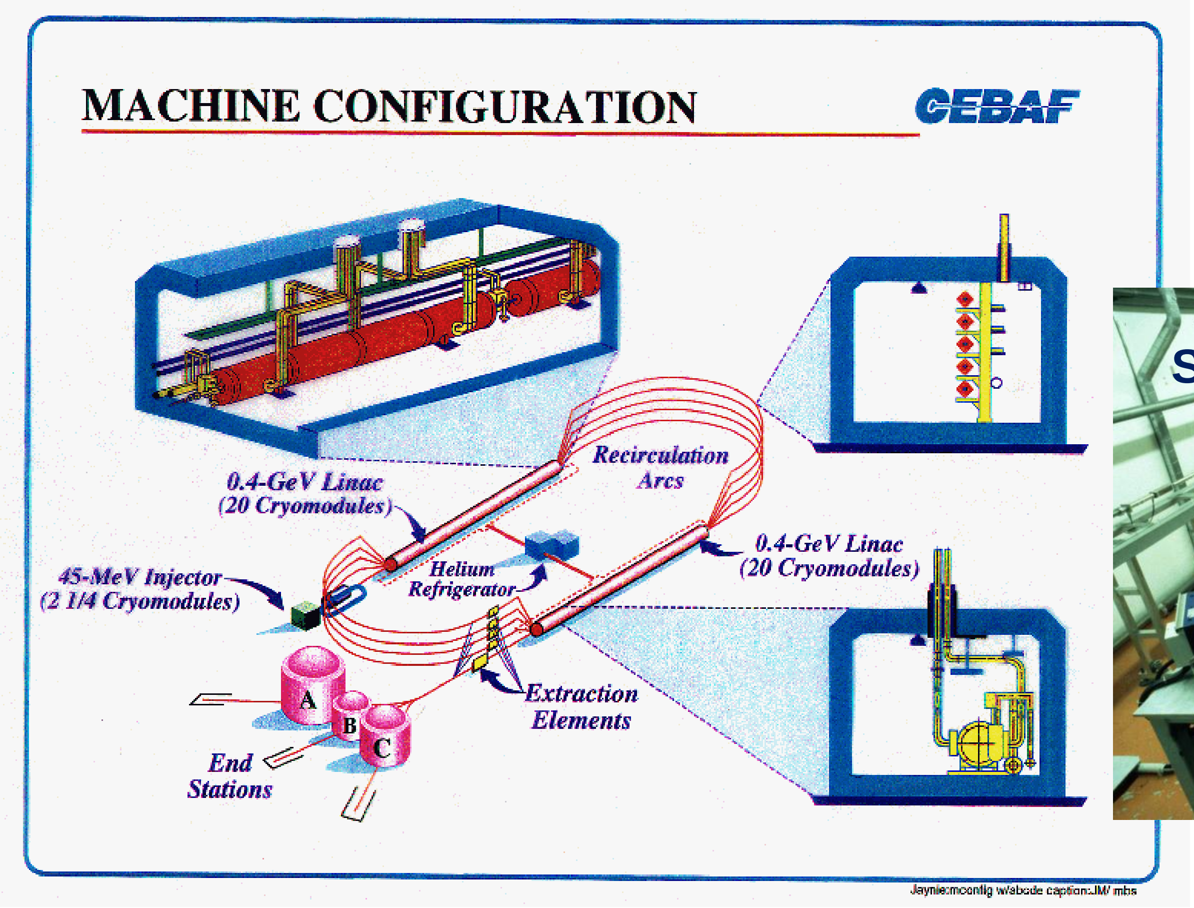
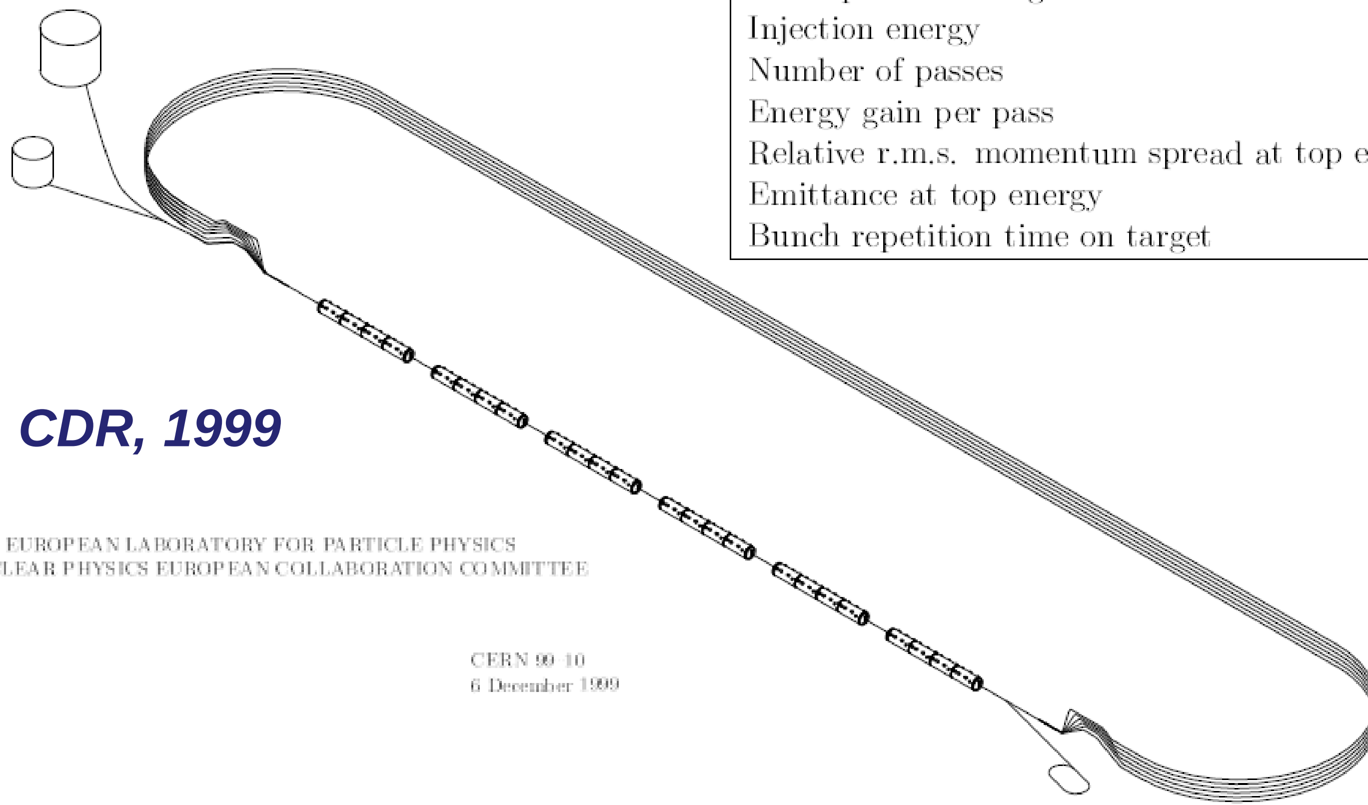


Table 1: ELFE performance parameters.

Top energy	25 GeV
Beam current on target	100 μA
Beam power on target	2.5 MW
Injection energy	0.8 GeV
Number of passes	7
Energy gain per pass	3.5 GeV
Relative r.m.s. momentum spread at top energy	$\leq 10^{-3}$
Emittance at top energy	≤ 30 nm
Bunch repetition time on target	2.8 ns



ELFE CDR, 1999

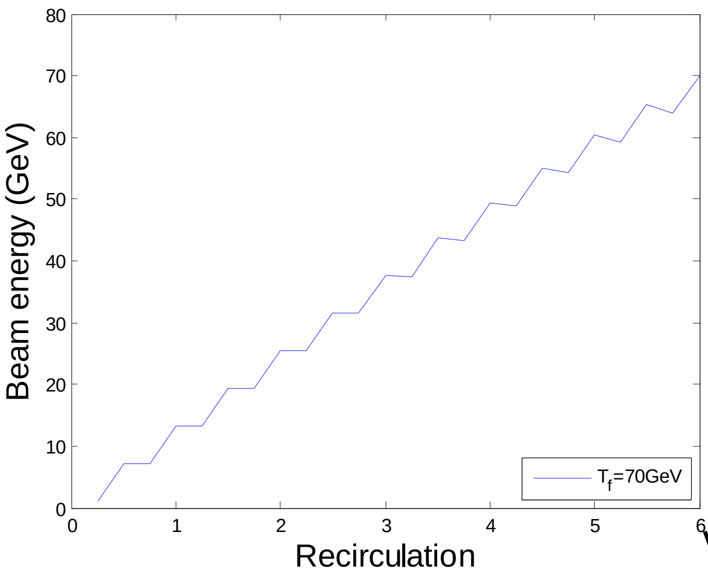
CERN – EUROPEAN LABORATORY FOR PARTICLE PHYSICS
NuPECC – NUCLEAR PHYSICS EUROPEAN COLLABORATION COMMITTEE

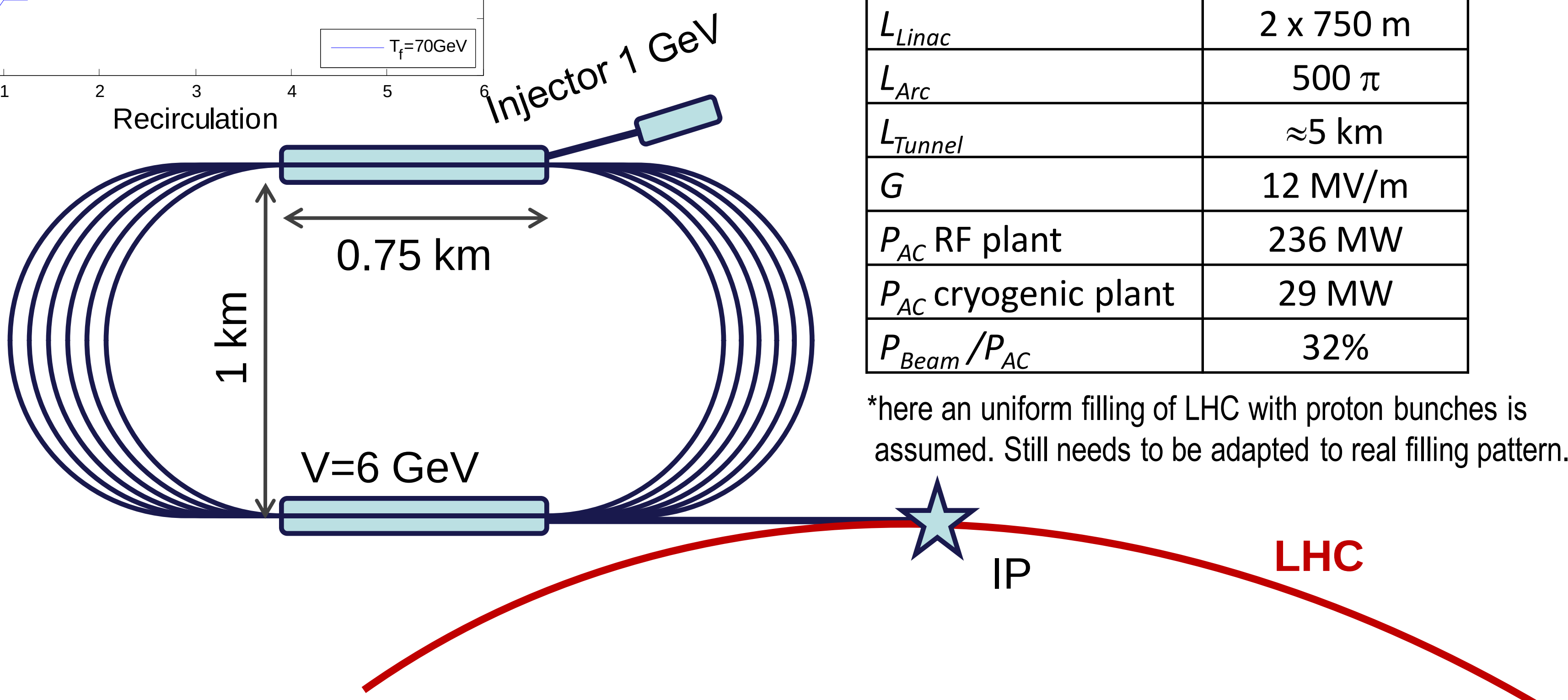
CERN 99-10
6 December 1999

ELFE AT CERN

K. Aulenbacher, B. Aune, J. Aysto, J.-L. Baldy, H. Burkhardt (Ed.),
F. Bradamante, E. Cennini, S. Claudet, C. Détraz, E. De Sanctis, H. Fonvieille,
H. Frischholz, S. Galès, M. Garçon, G. Gemme, R. Genand, G. Geschonke,
P. Grafstrom, N. Hilleret, M. Hoffmann, P. Hoyer, K. Hübner, D. Husmann,
J. Inigo-Golfin, M. Jablonka, K.H. Kaiser, E. Keil, G.-E. Körner, S. Kox,
J.-M. Laget, J. Lindroos, J. Martino, Y. Muttoni, R. Parodi, J. Payet,
J. Pedersen, G. Ricco, M. Sassowsky, H. Schmickler, G. Smirnov, G.R. Stevenson,
I. Sick, F. Tazzioli, A. Tkatchenko, R. Van de Vyver and Th. Walcher

Recirculated superconducting c.w. Linac for LHeC





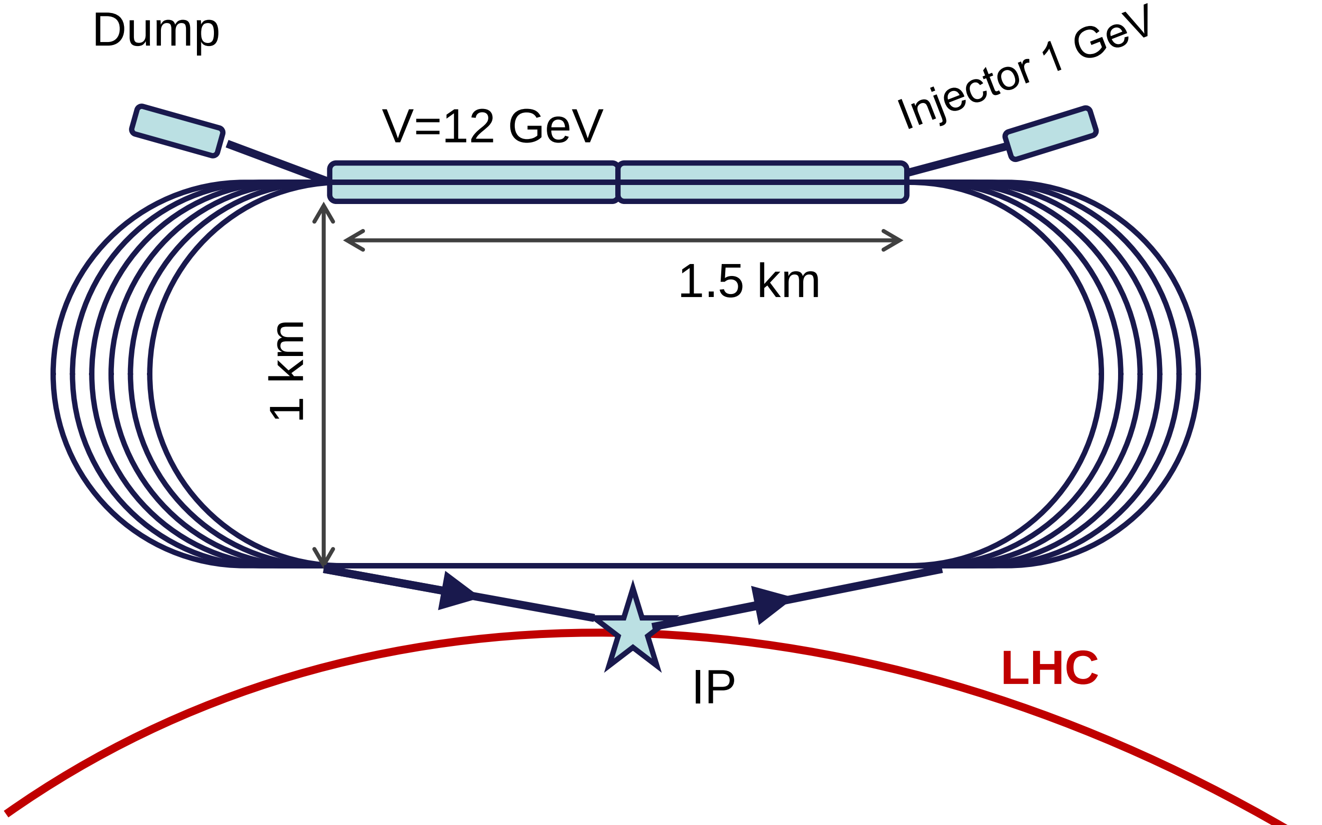
Tentative parameter set for $10^{33}cm^{-2}s^{-1}$

E	70 GeV
$E_{Injector}$	1 GeV
I_{Beam}	1.2mA
N_B	1.87 10^8
Bunch spacing*	25ns
P_{Beam}	84 MW
P_{SR}	5.6 MW
$N_{Recirculation}$	6
V_{Linac}	2 x 6.14 GeV
L_{Linac}	2 x 750 m
L_{Arc}	500 π
L_{Tunnel}	$\approx$5 km
G	12 MV/m
P_{AC} RF plant	236 MW
P_{AC} cryogenic plant	29 MW
P_{Beam}/P_{AC}	32%

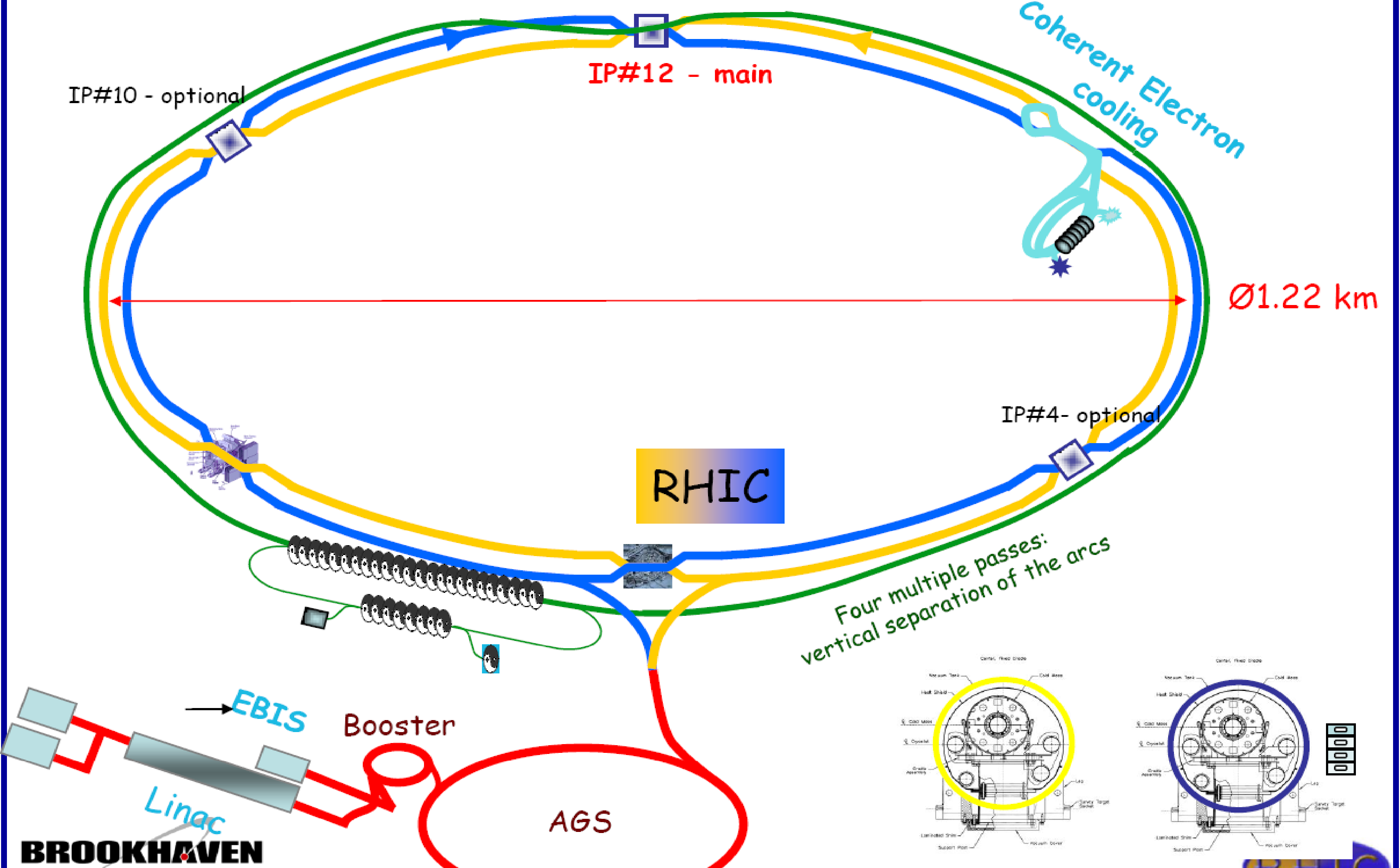
*here an uniform filling of LHC with proton bunches is assumed. Still needs to be adapted to real filling pattern.

Can this be combined with energy recovery scheme to reduce RF power and beam dump requirements ?

Not easily, because of energy imbalance due to SR losses
but this needs further studies.

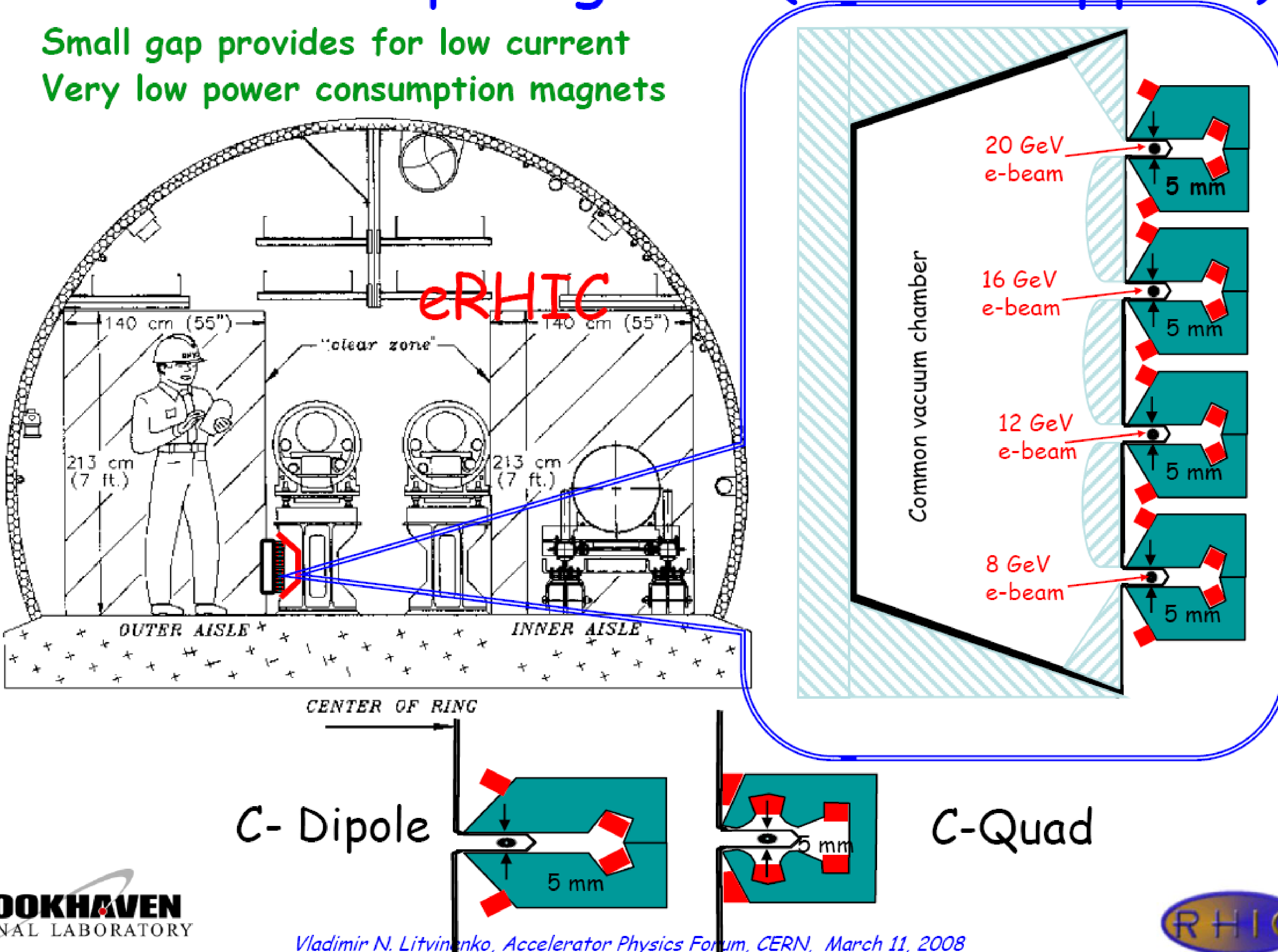


Linac-Ring Design based on 5-20⁺ GeV ERL: main choice



eRHIC loop magnets (LDRD support)

- Small gap provides for low current
- Very low power consumption magnets



ERL based LHeC with cooling: 30 x luminosity

6.3 GW c.w. beam power

	Electrons	Protons
Energy	70 GeV	7 TeV
N per bunch	$0.14\ 10^{11}$	$1.7\ 10^{11}$
Rep rate, MHz	40	
Beam current, mA	90	1090
Norm emittance, μm	3	0.3
β*, m	0.5	1.3
ξ* D	12.7 4.56	**0.0057**
Luminosity	**3.77×10^{34} cm^{-2} sec^{-1}**	
Loss for SR, MW	67	Kink Λ=0.93

Energy loss per 180^0 arc

$$\Delta E_{SR} = C_\gamma \frac{E^4}{2R}$$

Recirculations can proceed until

$$\Delta E_{SR} \approx \frac{V}{4}$$

with V the acceleration voltage in one linac.

Thus the maximum attainable energy is given by

$$\mathrm{E}_{\mathrm{MAX}} = \sqrt[4]{\frac{R\,V}{2C_\gamma}} + V$$

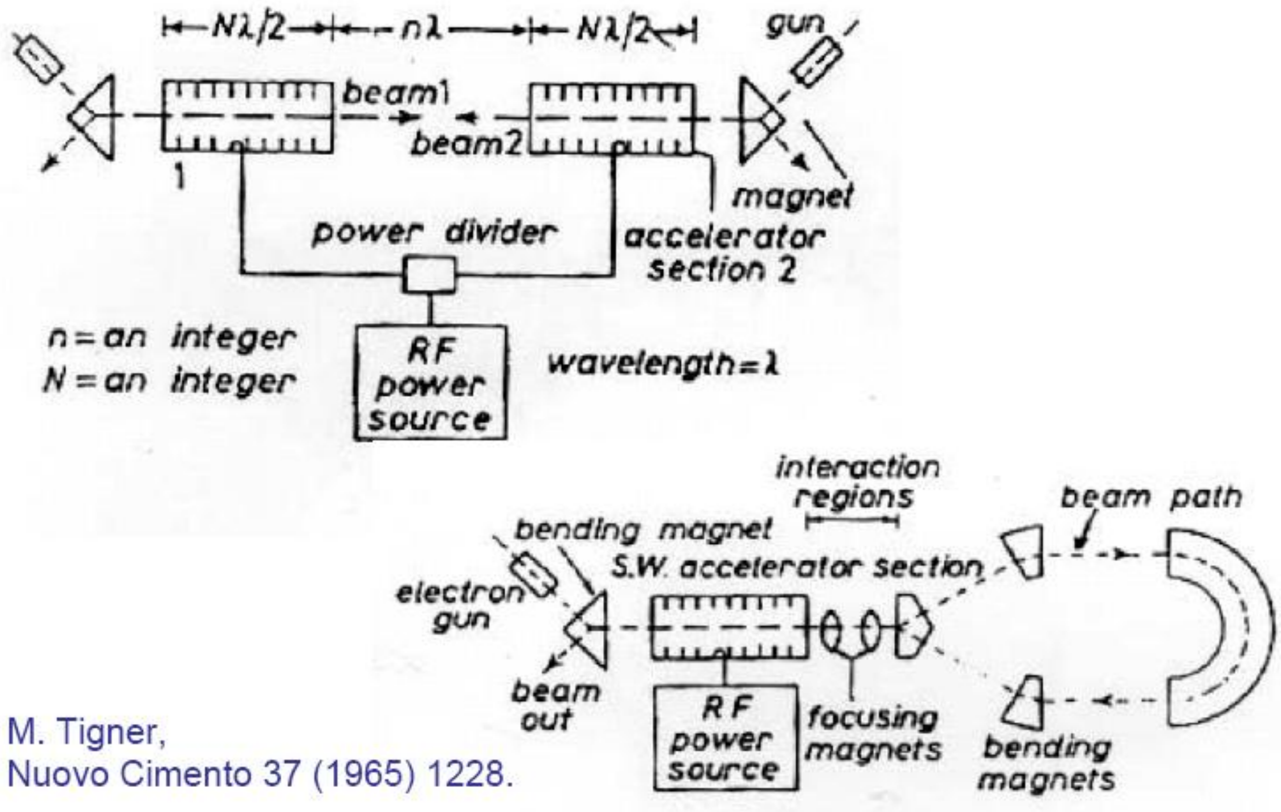
with reasonable numbers for R and V this limits the achievable Energy ≤ 80 GeV

because of 4^{th} root this is not very sensitive to precise choice of R, V

For energies > 100 GeV only straight, pulsed linac,
either superconducting or normal conducting can be considered

To be remembered: *ERL's don't necessarily need arcs !*
(as pointed out by Swapan Chattopaday and Frank Zimmermann for LHeC context)

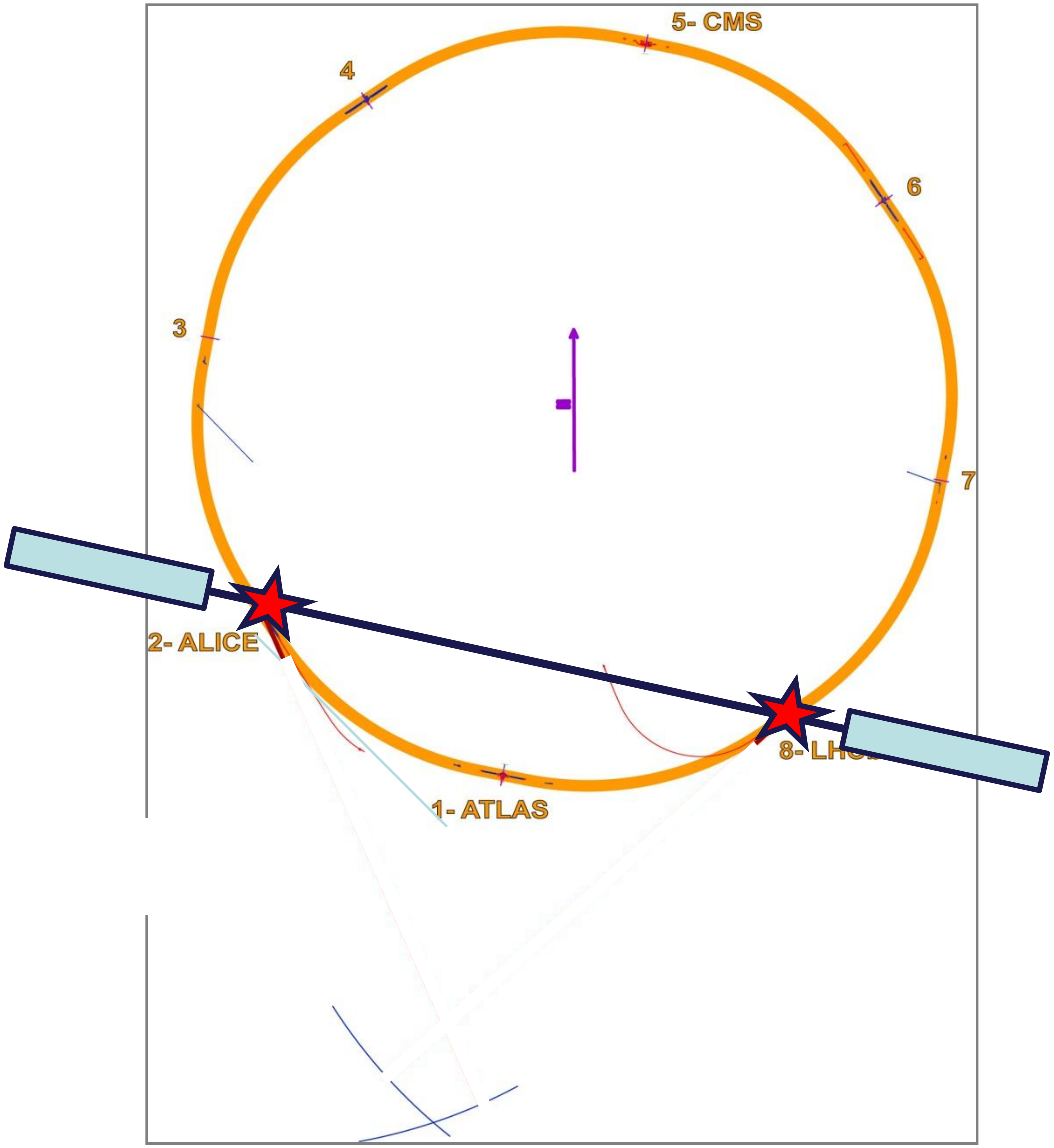
History of ERL



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

Fig. 3.

e$^{\pm}$ Linac - p/A ing
Energy recover
straight version



Parameters for pulsed Linacs for 140 GeV, $10^{32}cm^{-2}s^{-1}$

SC technology

NC technology

	X FEL 20 GeV	LHeC 140 GeV, $10^{32}cm^{-2}s^{-1}$	LHeC 140 GeV, $10^{32}cm^{-2}s^{-1}$
I_{Beam} during pulse	5 mA	11.4 mA	0.4 A
N_E	$0.624 \cdot 10^{10}$	$5.79 \cdot 10^{10}$	$6.2 \cdot 10^{10}$
Bunch spacing	0.2 μs	0.8 μs	25 ns
Pulse duration	0.65 ms	1.0 ms	4.2 μs
Repetition rate	10 Hz	10 Hz	100 Hz
G	23.6MV/m	23.6MV/m	20.0 MV/m
Total Length	1.27 km	8.72 km	8.76 km
P_{Beam}	0.65 MW	16.8 MW	16.8 MW
Grid power for RF plant	4 MW	59 MW	96 MW
Grid power for Cryoplant	3 MW	20 MW	-
P_{Beam}/P_{AC}	10%	21%	18%

Some remarks/questions

- All the schemes discussed so far require p-bunch parameters which are not compatible with LHC p-p running, i.e. require dedicated LHeC running periods.

- For the normal conducting linac case only proton bunches in about 5% of LHC circumference would collide.
  Luminosity comes in strong bursts of 4μs every 10 ms.
  How does this work for the detector ?

Some past work which has to be re-analysed in view of the new requirements

CERN-AB-2004-079
CLIC Note 608

QCD EXPLORER BASED ON LHC AND CLIC-1

D. Schulte, F. Zimmermann
CERN, Geneva, Switzerland

Abstract

Colliding 7-TeV LHC super-bunches with 75-GeV CLIC bunch trains can provide electron-proton collisions at very high centre-of-mass energies, opening up a new window into QCD. At the same time, this QCD explorer would employ several key components required for both an LHC upgrade and CLIC. We here present a possible parameter set of such a machine, study the consequences of the collision for both beams, and estimate the attainable luminosity.

arxiv.org/pdf/hep-ex/0504008

HC AND VLHC BASED ep COLLIDERS: e-LINAC vs e-RING

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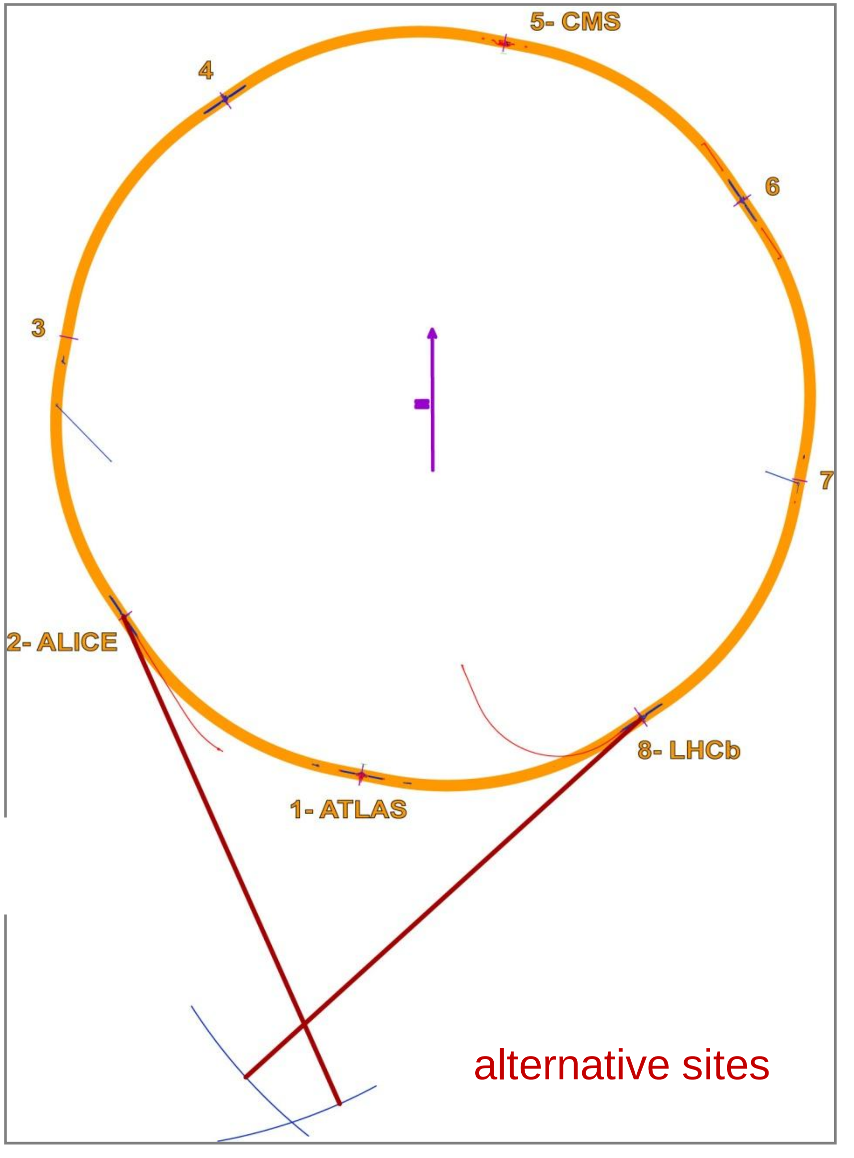
Abstract

Linac-ring analogues of the LHC and VLHC based standard type ep collider proposals are discussed. It is shown that sufficiently high luminosities can be obtained with TESLA-like linacs, whereas essential modifications are required for CLIC technology. The physics search potential of proposed ep colliders is demonstrated using pair production of heavy quarks as an example.

Keywords: Lepton, hadron, luminosity, ep collider.

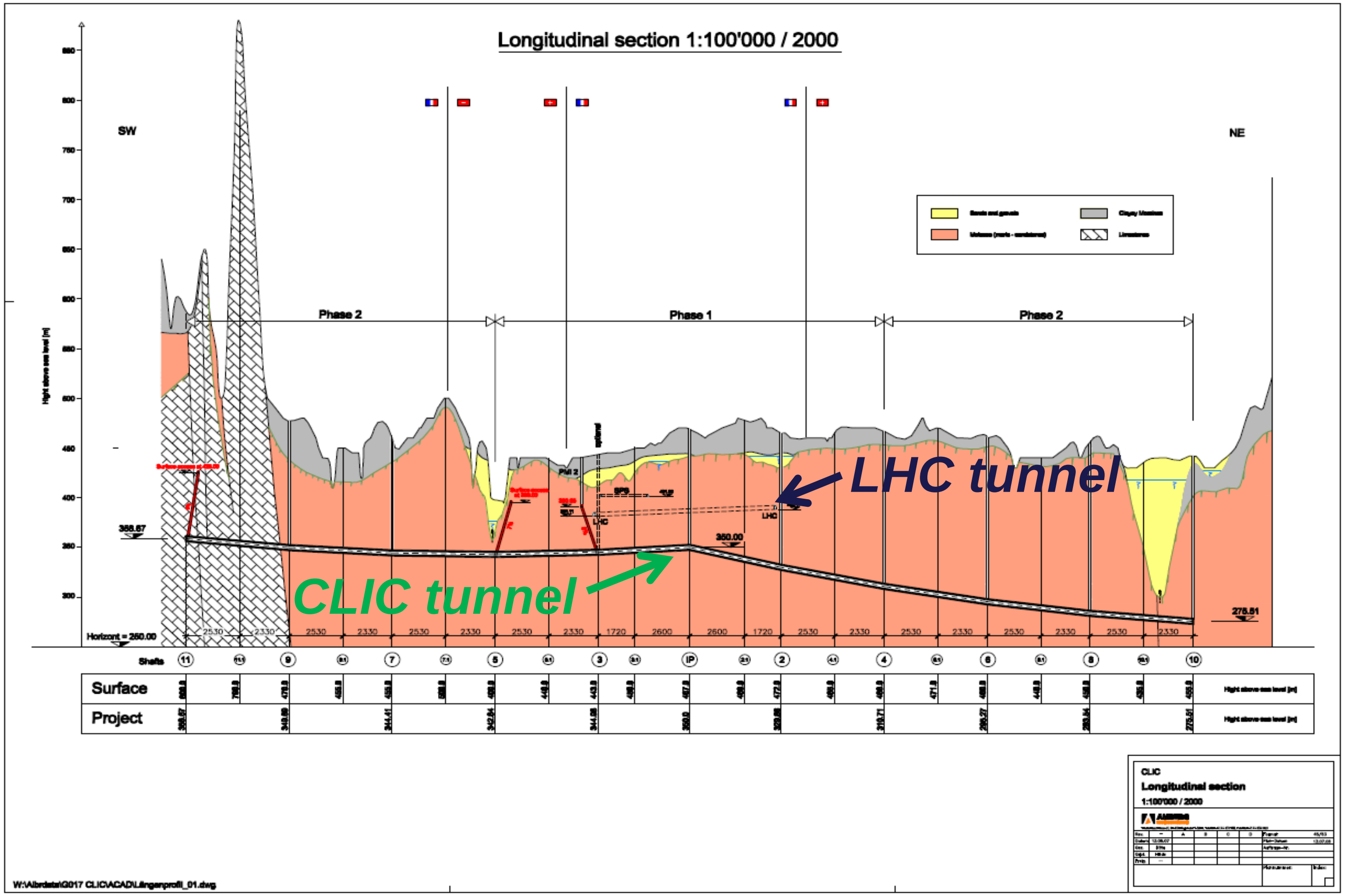
Pacs: 12.38.-t; 29.17.+w; 29.20.Dh; 29.90.+r

e$^{\pm}$ Linac - p/A Ring locations



Can tunnel for LHeC Linac be build as first part of a LC tunnel at CERN ?

Tunnel studies for CLIC and ILC at CERN both have tunnels which are deeper underground than LHC and seen from top they both pass close to LHC ring center. Therefore they are not suited to send e^- beam tangential to LHC ring.



Injector issues, electrons

- The electron, positrons are used only once in IP, therefore particle production rate for Linac-Ring option much higher than for Ring-Ring option.

- Contrary to Ring Ring option beam polarisation has to be created from in source

Source flux requirements	
Luminosity	$\dot{N}_{e-}$
$10^{32}cm^{-2}s^{-1}$	$1\cdot10^{15}\ s^{-1}$
$10^{33}cm^{-2}s^{-1}$	$1\cdot10^{16}\ s^{-1}$

JLab has demonstrated production of polarised e^- with $> 6\cdot10^{15}\ s^{-1}$ and >85% polarisation !

THPMS064 Proceedings of PAC07, Albuquerque, New Mexico, USA

LIFETIME MEASUREMENTS OF HIGH POLARIZATION STRAINED-SUPERLATTICE GALLIUM ARSENIDE AT BEAM CURRENT >1 MILLIAMP USING A NEW 100kV LOAD LOCK PHOTOGUN*

J. Grames#, P. Adderley, J. Brittian, J. Clark, J. Hansknecht, D. Machie, M.Poelker, M.L. Stutzman, R. Suleiman, K. Surles-Law, Jefferson Laboratory, Newport News, VA 23606, U.S.A.

Transport of polarised beam from source to IP with negligible loss of beam polarisation has been demonstrated in many facilities (SLC , CEBAF, MAMI, …)

Injector issues, positrons

Source flux requirements	
Luminosity	$\dot{N}_{e+}$
10^{32}cm^{-2}s^{-1}	$1\cdot10^{15}$ s^{-1}
10^{33}cm^{-2}s^{-1}	$1\cdot10^{16}$ s^{-1}

Problem 1

SLC has demonstrated e^+ production of $\approx 10^{13}$ s^{-1} (unpolarised)
Linear colliders require $\approx 10^{14}$ s^{-1}. *This is already considered difficult to achieve !*
Positron recovery possible ?

There is ongoing R&D to produce polarized e^+ at rates required for LC's.
Two schemes under investigation: Helical undulator & Compton ring

Problem 2

Beam emittance of beam from e.m. shower target is typically 2 orders of magnitude larger than electron source emittance.

$\Rightarrow$ *emittance damping is required to match e^+ beam size to P-beam size at IP.*
Damping ring ?

Comparison Linac-Ring and Ring-Ring

	Linac-Ring	Ring-Ring
Energy / GeV	40-140	40-80
Luminosity / 10^{32} cm^{-2} s^{-1}	1-10	10
Mean Luminosity, relative	2	1 [dump at L_{peak} /e]
Lepton Polarisation	60-85%	30% [?]
Tunnel / km	5-9	2.5=0.5 * 5 bypasses
Biggest challenge	positrons	Civil Engineering Ring+Rf installation
Biggest limitation	luminosity (ERL ?)	maximum energy
IR	not considered yet one design? (eRHIC)	allows ep+pp 2 configurations [lox, hiq]

Conclusions

- Ring-Linac solution can only achieve desired Luminosities with proton beam parameters adapted/upgraded for this purpose. A part of these proton upgrades is already part of the LHC upgrade R&D.
- For ≤70 GeV a SC Linac with recirculation seems most attractive. If energy recovery is applicable and economically viable needs further studies. This has to be compared with ring-ring in terms of cost, power consumption and interference with p-p program.
- For substantially higher energies recirculated Linac and Ring-Ring are virtually excluded. Straight pulsed linac is only solution. If SC or NC linac technology is better choice needs further study. L >10^{32} $cm^{-2}s^{-1}$ seems extremely difficult for this case.
- Positrons are a major R&D issue for ring-linac

Specific R&D for Ring-Linac

- Positron production, polarization and perhaps recovery
- IR region design
- High power e^- beam handling
- p-beam optimisation for ring-linac
- e^- beam disruption in IP
- p-beam stability, in particular for collision with pulsed linacs
- Matching of p-beam time structure to cw and pulsed e^- beams
- RF design of linacs
- Tunnel design

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