



# LHeC Accelerator Overview

Frank Zimmermann

LHeC Workshop 2012

Chavannes-de-Bogis

## Many contributors:

Jose Abelleira, Chris Adolfsen, Husnu Aksakal, Rob Appleby, Mei Bai, Desmond Barber Nathan Bernard, Alex Bogacz, Luca Bottura, Chiara Bracco, Hans Braun, Oliver Brüning, Eugene Bulyak, Helmut Burkhardt, Swapan Chattopadhyay, Ed Ciapala, Kenan Ciftci, Reina Ciftci, John Dainton, Anders Eide, Emre Eroglu, Miriam Fitterer, Hector Garcia, Brennan Goddard, Yue Hao, Friedrich Haug, Bernhard Holzer, Erk Jensen, Miguel Jimenez, John Jowett, Dmitry Kayran, Max Klein, Peter Kostka, Vladimir Litvinenko, Karl Hubert Mess, Zafer Nergiz, John Osborne, Tatiana Pieloni, Alessandro Polini, Vadim Ptitsin, Louis Rinolfi, Lucio Rossi, Stephan Russenschuck, Daniel Schulte, Ilkyoung Shin, Peter Sievers, Mike Sullivan, Saleh Sutansoy, Hugues Thiesen, Luke Thompson, Rogelio Tomas, Davide Tommasini, Dejan Trbojevic, Joachim Tückmantel, Alessandro Variola, Ferdinand Willeke, Vitaly Yakimenko, Fabian Zomer, ... ++

# Large Hadron electron Collider (LHeC)

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



<http://cern.ch/lhec>



## 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



### LHeC Study Group

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

Thanks to all and to  
CERN, ECFA, NuPECC

About 150 Experimentalists and Theorists from 50 Institutes  
Tentative list

**LHeC CDR completed (~600 pages);**

# LHeC CDR

## Accelerator

### Part:

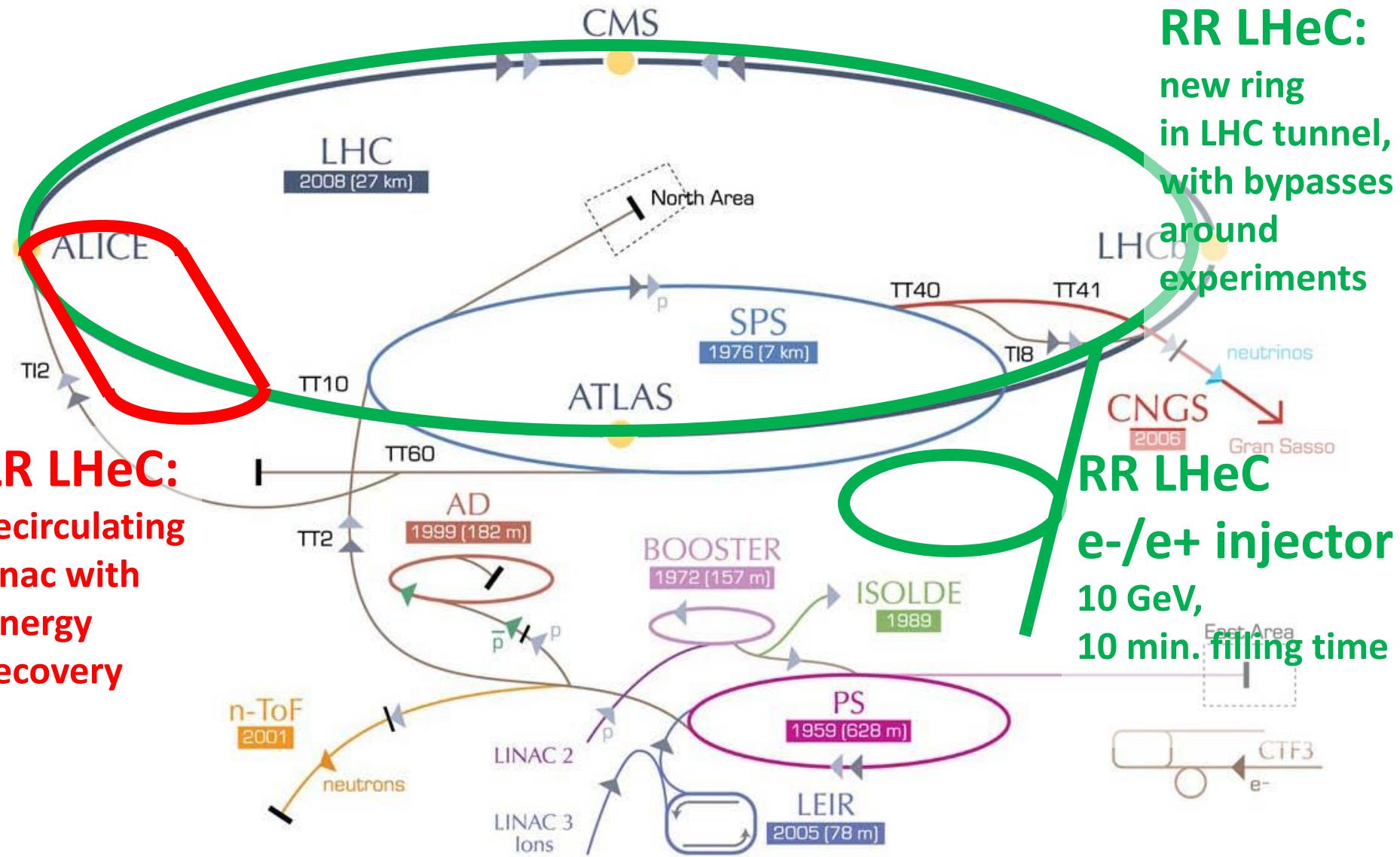
#### table of contents;

#### 4 chapters;

#### 226 pages

<b>III Accelerator</b>	<b>204</b>
<b>7 Ring-Ring Collider</b>	<b>205</b>
7.1 Baseline parameters and configuration	205
7.2 Geometry	206
7.2.1 General layout	206
7.2.2 Electron ring circumference and e-p synchronization	206
7.2.3 Idealized ring	207
7.2.4 Bypass options	208
7.2.5 Bypass point 1	209
7.2.6 Bypasses point 5	209
7.2.7 Matching proton and electron ring circumference	209
7.3 Layout and optics	210
7.3.1 Arc cell layout and optics	210
7.3.2 Insertion layout and optics	210
7.3.3 Bypass layout and optics	211
7.3.4 Chromaticity correction	211
7.3.5 Working point	212
7.3.6 Aperture	212
7.4 Interaction region layout	226
7.4.1 Beam separation scheme	227
7.4.2 Crossing angle	229
7.4.3 Beam optics and luminosity	231
7.5 Design requirements	232
7.5.1 Detector coverage and acceptance	232
7.5.2 Lattice matching and IR geometry	233
7.6 High luminosity IR layout	234
7.6.1 Parameters	234
7.6.2 Layout of the electron lattice	234
7.6.3 Separation scheme	235
7.7 High acceptance IR layout	235
7.7.1 Parameters	235
7.7.2 Layout	237
7.7.3 Separation scheme	238
7.8 Comparison of the two layouts	238
7.8.1 Crab cavities	239
7.9 Long straight section	240
7.9.1 Dispersion	240
7.9.2 Geometry	240
7.9.3 Electron optics in the LSS	241
7.9.4 Synchrotron radiation	241
7.9.5 LHC integration	242
7.10 The non-colliding proton beam	243
7.10.1 Design elements	243
7.10.2 Solution	244
7.10.3 Summary	246
7.11 Synchrotron radiation and absorbers	247
7.11.1 Introduction	247
7.11.2 High luminosity	249
7.11.3 High detector acceptance	255
7.12 Beam-beam effects in the LHeC	262
7.12.1 Head-on beam-beam effects	262
7.12.2 Long range beam-beam effects	265
7.13 Performances as an electron-ion collider	266
7.13.1 Heavy nuclei, e-Pb collisions	266
7.13.2 Electron-deuteron collisions	267
7.14 Spin polarisation – an overview	268
7.14.1 Self polarisation	268
7.14.2 Suppression of depolarisation – spin matching	271
7.14.3 Higher order resonances	271
7.14.4 Calculations of the $e^\pm$ polarisation in the LHeC	272
7.14.5 Spin rotator concepts for the LHeC	274
7.14.6 Further work	275
7.14.7 Summary	276
7.15 Integration and machine protection issues	277
7.15.1 Space requirements	277
7.15.2 Impact of the synchrotron radiation on tunnel electronics	283
7.15.3 Compatibility with the proton beam loss system	283
7.15.4 Space requirements for the electron dump	284
7.15.5 Protection of the p-machine against heavy electron losses	284
7.15.6 How to combine the machine protection of both rings?	285
7.16 LHeC injector for the Ring-Ring option	285
7.16.1 Injector	285
7.16.2 Required performance	286
7.16.3 Source, accumulator and acceleration to 0.6 GeV	287
7.16.4 10 GeV injector	288
<b>8 Linac-Ring Collider</b>	<b>290</b>
8.1 Basic parameters and configurations	290
8.1.1 General considerations	290
8.1.2 ERL performance and layout	291
8.1.3 Polarization	299
8.1.4 Pulsed linacs	299
8.1.5 Higher-energy LHeC ERL option	301
8.1.6 $\gamma p/A$ Option	301
8.1.7 Summary of basic parameters and configurations	303
8.2 Interaction region	303
8.2.1 Layout	304
8.2.2 Optics	304
8.2.3 Modifications for $\gamma p$ or $\gamma A$	311
8.2.4 Synchrotron radiation and absorbers	311
8.3 Linac lattice and impedance	318
8.3.1 Overall layout	318
8.3.2 Linac layout and lattice	320
8.3.3 Beam break-up	326
8.3.4 Imperfections	338
8.3.5 Touschek scattering	339
8.4 Performance as a Linac-Ring electron-ion collider	339
8.4.1 Heavy nuclei, e-Pb collisions	339
8.4.2 Electron-deuteron collisions	340
8.5 Polarized-electron injector for the Linac-Ring LHeC	342
8.6 Spin rotator	342
8.6.1 Introduction	342
8.6.2 LHeC spin rotator options	342
8.6.3 Polarimetry	345
8.6.4 Conclusions and outlook	346
8.7 Positron options for the Linac-Ring LHeC	347
8.7.1 Motivation	347
8.7.2 LHeC Linac-Ring $e^+$ requirements	348
8.7.3 Mitigation schemes	349
8.7.4 Cooling of positrons	350
8.7.5 Production schemes	350
8.7.6 Conclusions on positron options for the Linac-Ring LHeC	356
<b>9 System Design</b>	<b>357</b>
9.1 Magnets for the interaction region	357
9.1.1 Introduction	357
9.1.2 Magnets for the ring-ring option	357
9.1.3 Magnets for the Linac-Ring option	358
9.2 Arc accelerator magnets	364
9.2.1 RR option, dipole magnets	364
9.2.2 RR option, quadrupole magnets	367
9.2.3 LR option, dipole magnets	372
9.2.4 LR option, quadrupole magnets	372
9.2.5 LR option, corrector magnets for the two 10 GeV linacs	376
9.3 Ring-Ring RF Design	377
9.3.1 Design parameters	377
9.3.2 Cavities and klystrons	380
9.4 Linac-Ring RF design	381
9.4.1 Design parameters	381
9.4.2 Layout and RF powering	381
9.4.3 Arc RF systems	381
9.5 Crab crossing for the LHeC	383
9.5.1 Luminosity reduction	385
9.5.2 Crossing schemes	385
9.5.3 RF technology	385
9.6 Ring-Ring power converters	387
9.6.1 Overview	387
9.6.2 Powering considerations	387
9.6.3 Power converter topologies	387
9.6.4 Main power converters	388
9.6.5 Insertion and by-pass quadrupole power converters	390
9.6.6 Power converter infrastructure	391
9.7 Linac-Ring power converters	391
9.7.1 Overview	391
9.7.2 Powering considerations	391
9.7.3 Linac quadrupole and corrector power converters	391
9.7.4 Recirculation main power converters	393
9.7.5 Power converter infrastructure	393
9.7.6 Conclusions on power converters	394
9.8 Vacuum	395
9.8.1 Vacuum requirements	395
9.8.2 Synchrotron radiation	396
9.8.3 Vacuum engineering issues	398
9.9 Beam pipe design	402
9.9.1 Requirements	402
9.9.2 Choice of materials for beampipes	402
9.9.3 Beampipe Geometries	405
9.9.4 Vacuum instrumentation	405
9.9.5 Synchrotron radiation masks	405
9.9.6 Installation and integration	405
9.10 Cryogenics	406
9.10.1 Ring-Ring cryogenics design	406
9.10.2 Linac-Ring cryogenics design	410
9.10.3 General conclusions cryogenics for LHeC	412
9.11 Beam dumps and injection regions	414
9.11.1 Injection region design for Ring-Ring option	414
9.11.2 Injection transfer line for the Ring-Ring Option	414
9.11.3 60 GeV internal dump for Ring-Ring Option	419
9.11.4 Post collision line for 140 GeV Linac-Ring option	421
9.11.5 Absorber for 140 GeV Linac-Ring option	422
9.11.6 Energy deposition studies for the Linac-Ring option	422
9.11.7 Beam line dump for ERL Linac-Ring option	423
9.11.8 Absorber for ERL Linac-Ring option	423
<b>10 Civil Engineering and Services</b>	<b>424</b>
10.1 Overview	424
10.2 Location, geology and construction methods	424
10.2.1 Location	424
10.2.2 Land features	426
10.2.3 Geology	426
10.2.4 Site development	426
10.2.5 Construction methods	427
10.3 Civil engineering layouts for Ring-Ring	427
10.4 Civil engineering layouts for Linac-Ring	430
10.5 Summary	430

# Large Hadron electron Collider



# performance targets



e- energy  $\geq 60$  GeV

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

total electrical power for e-:  $\leq 100$  MW

e $^+$ p collisions with similar luminosity

simultaneous with LHC  $pp$  physics

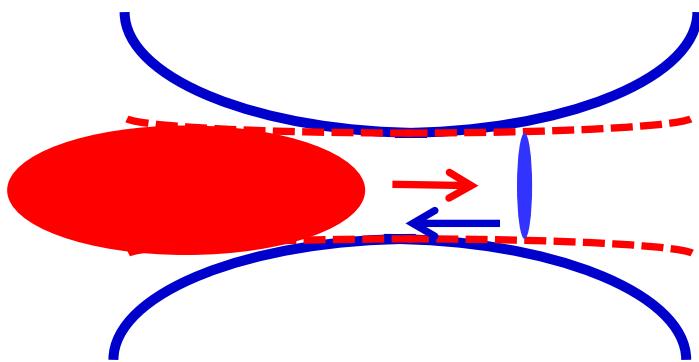
e $^-$ /e $^+$  polarization

detector acceptance down to 1°

# colliding unequal beams

ring-ring

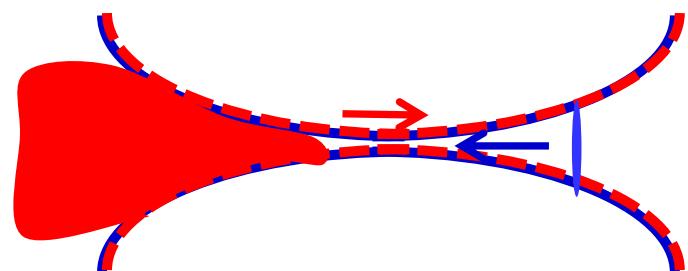
$$\varepsilon_e \gg \varepsilon_p$$



minimum beta function  
and beam size  
limited by hourglass effect;  
small crossing angle acceptable;  
little disruption

ring-linac

$$\varepsilon_e \approx \varepsilon_p$$



smaller beta function  
and beam size possible;  
head-on collision required;  
significant disruption

$$H_{hg} = \frac{\sqrt{\pi} z e^{z^2} \operatorname{erfc}(z)}{S} ; z \equiv 2 \frac{(\beta_e^*/\sigma_{z,p})(\varepsilon_e/\varepsilon_p)}{\sqrt{1+(\varepsilon_e/\varepsilon_p)^2}} S ; S \equiv \sqrt{1 + \frac{\sigma_{z,p}^2 \theta_c^2}{8 \sigma^{*2}}}$$

# R-R LHeC road map to $10^{33} \text{ cm}^{-2}\text{s}^{-1}$

*luminosity of RR collider:*

(flat beams)

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\epsilon_p} \frac{H_{hg}}{\sqrt{\beta_{y,p}^* \beta_{x,p}^*}} I_e H_D$$

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

$\gamma\epsilon=3.75 \mu\text{m}$

$N_b=1.7\times10^{11}$

bunch spacing  
25 or 50 ns

maximize geometric factor with nonzero crossing angle and hourglass effect (small  $\beta^*$ )

$\beta_{x,y(p)}^*=4, 1 \text{ m}$

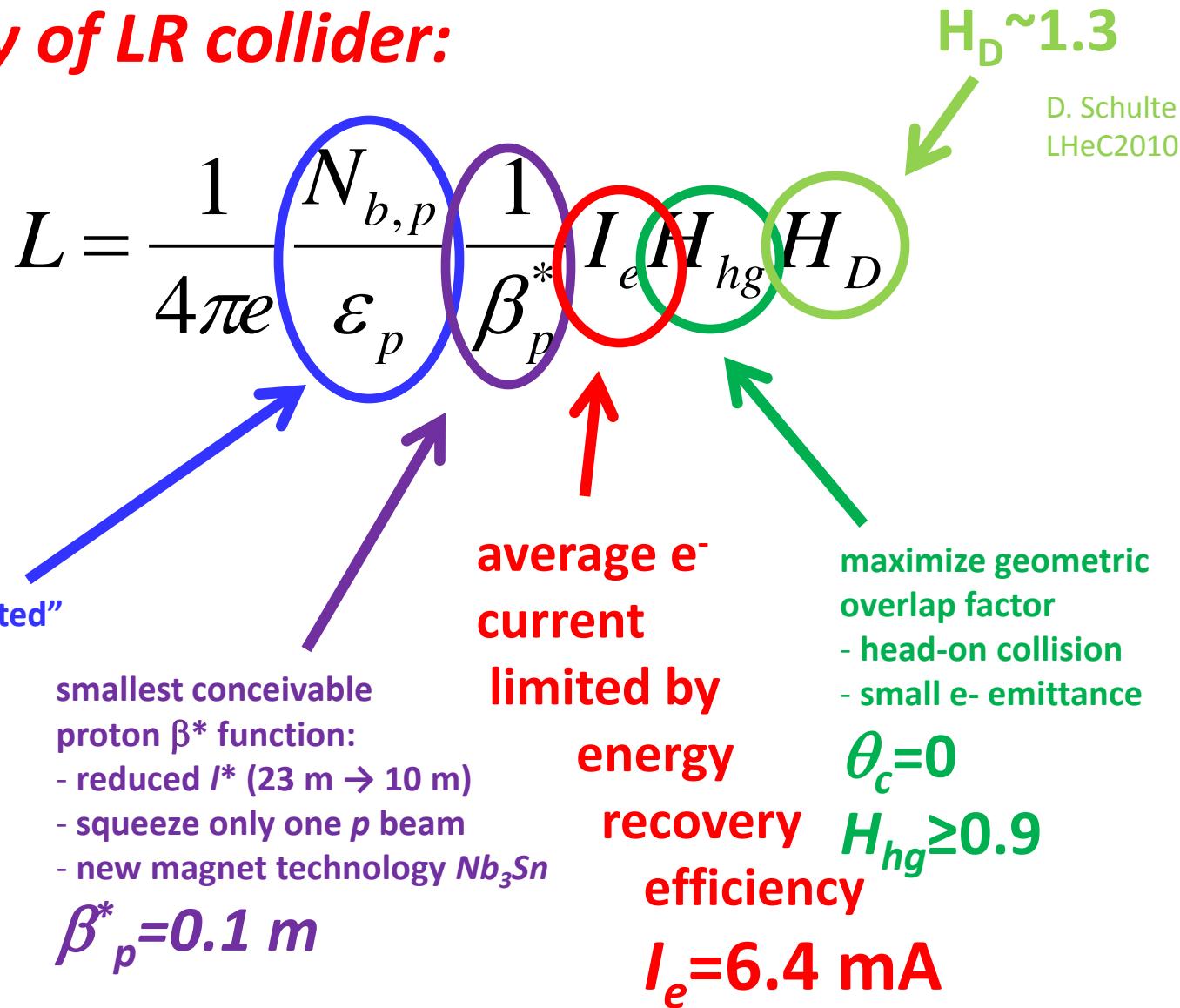
$I_e=100 \text{ mA}$

$H_D \sim 1$

# *L-R LHeC road map to $10^{33} \text{ cm}^{-2}\text{s}^{-1}$*

## ***luminosity of LR collider:***

(round beams)



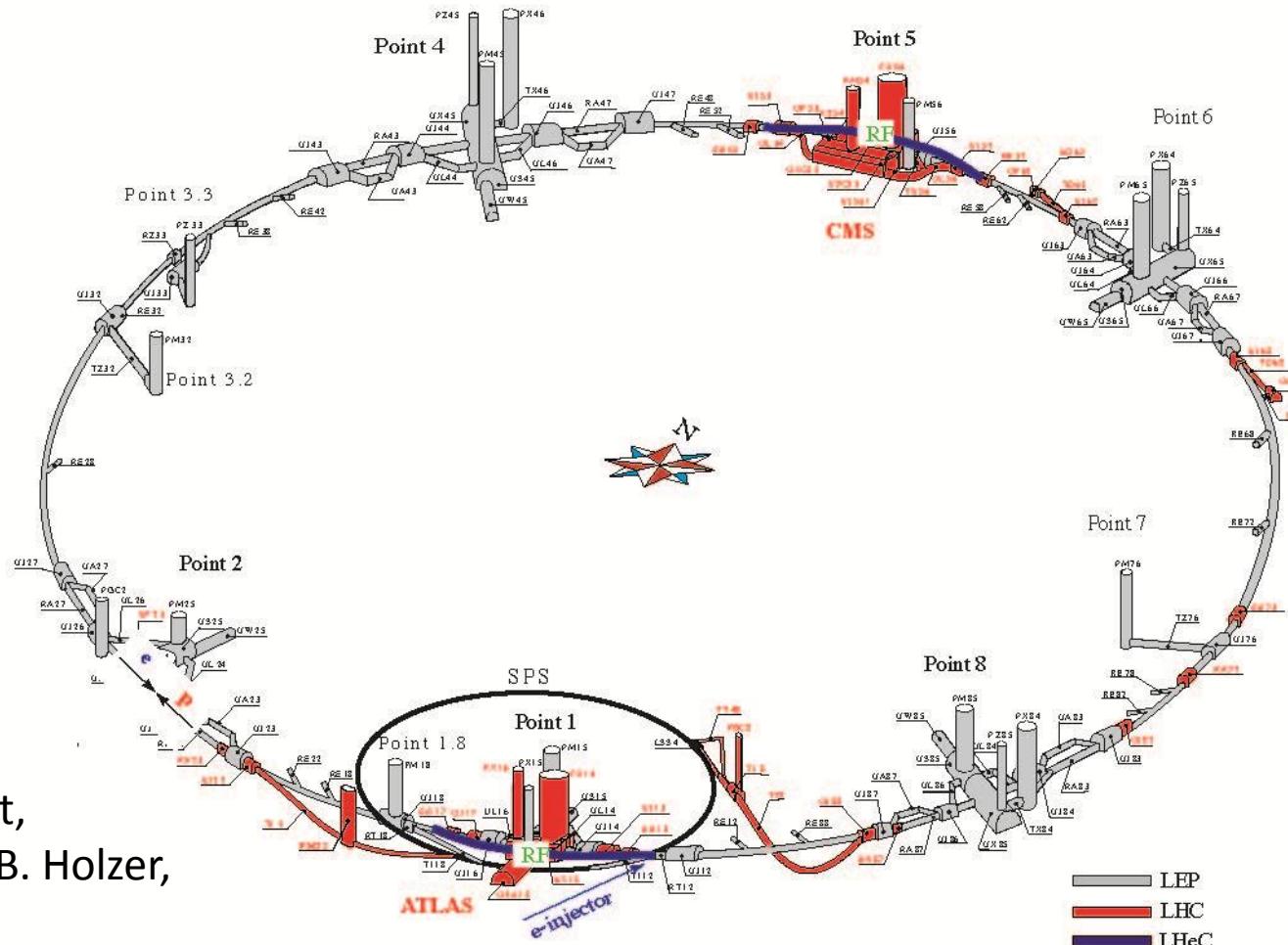
# LHeC design parameters



\*) pulsed, but high energy ERL not impossible

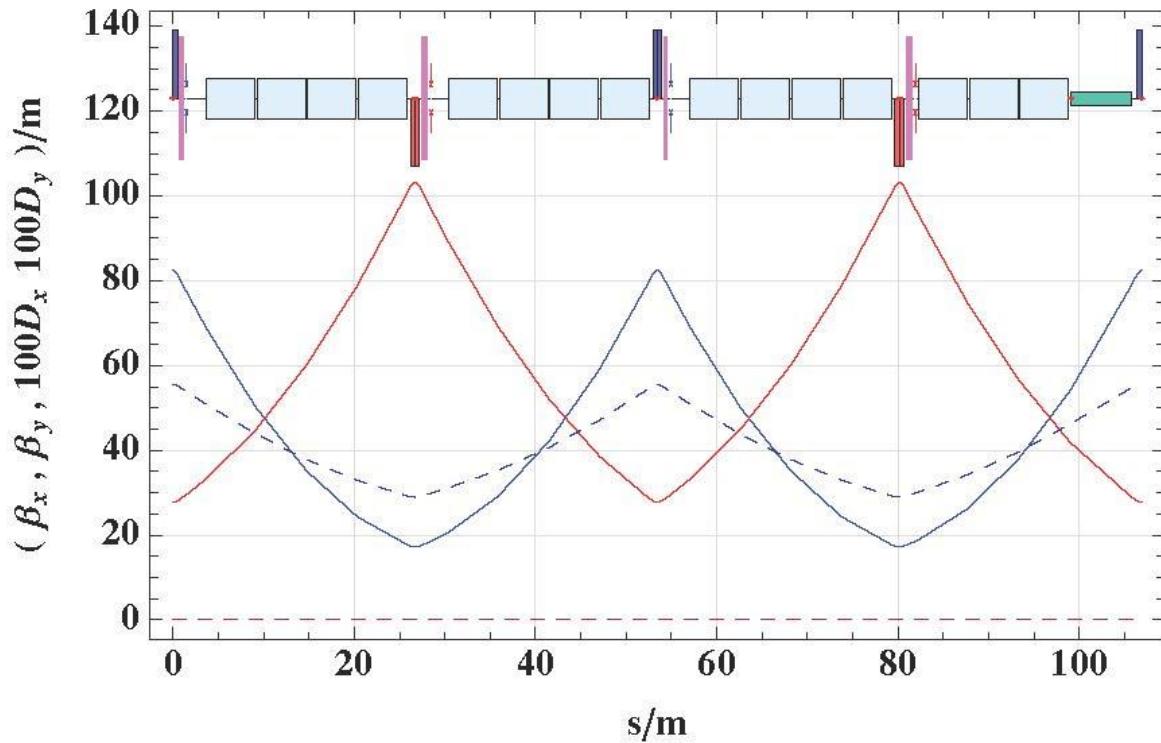
electron beam	RR	LR	LR*	proton beam	RR	LR
e- energy at IP[GeV]	60	60	140	bunch pop. [ $10^{11}$ ]	1.7	1.7
$ep$ luminosity [ $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ]	8	10	0.4	tr.emit. $\gamma\varepsilon_{x,y}$ [ $\mu\text{m}$ ]	3.75	3.75
$eN$ luminosity [ $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ]	0.45	1	0.04	spot size $\sigma_{x,y}$ [ $\mu\text{m}$ ]	30, 16	7
polarization for e- ( $e^+$ ) [%]	40 (40)	90 (0)	90 (0)	$\beta^*_{x,y}$ [m]	4.0, 1.0	0.1
bunch population [ $10^9$ ]	20	1.0	0.8	bunch spacing [ns]	25	25
e- bunch length [mm]	6	0.3	0.3	50 ns & $N_b=1.7\times 10^{11}$ probably conservative		
bunch interval [ns]	25	25	25	design also for deuterons (new) and lead (exists)		
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.59, 0.29	0.05	0.1	$\beta^* \sim 0.025 \text{ m}$ possible in IP3 or 7 using ATS optics (S. Fartoukh); + also going to 2 $\mu\text{m}$ emittance (H. Damerau, W. Herr), $\rightarrow L \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ within reach!		
rms IP beam size $\sigma_{x,y}$ [ $\mu\text{m}$ ]	45, 22	7	7	RR = Ring – Ring LR = Linac – Ring		
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.4, 0.2	0.12	0.14	higher- $L$ design exists		
full crossing angle [mrad]	0.93	0	0			
geometric reduction $H_{hg}$	0.87	0.91	0.94			
disruption enhancement	1.0	1.3	$\sim 1.0$			
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]	100	6.4	5.4			
tot. wall plug power[MW]	100	100	100			

# LHeC Ring-Ring Layout



Two **LHeC bypasses shown in blue** - each 1.3 km long. **RF in the central straight sections** of the two bypasses (<500 m total). The bypass around Point 1 also hosts the injection.

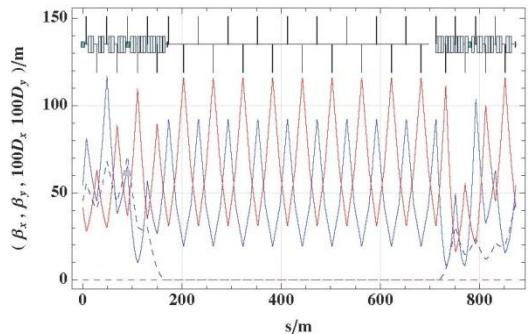
# LHeC Ring-Ring Arc Optics



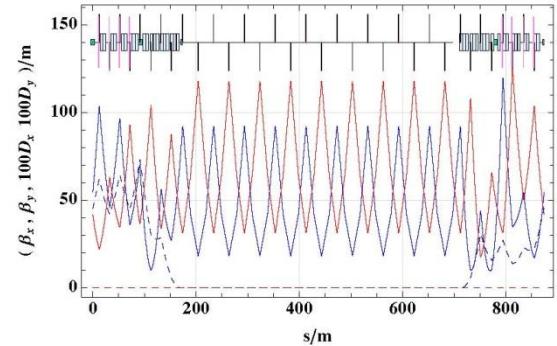
2 LHeC FODO cells = 1 LHC FODO cell

H. Burkhardt,  
M. Fitterer,  
B. Holzer,  
J. Jowett

$$\varepsilon_{x,\text{LHeC}} < 1/3 \varepsilon_{x,\text{LEP1.5}}$$

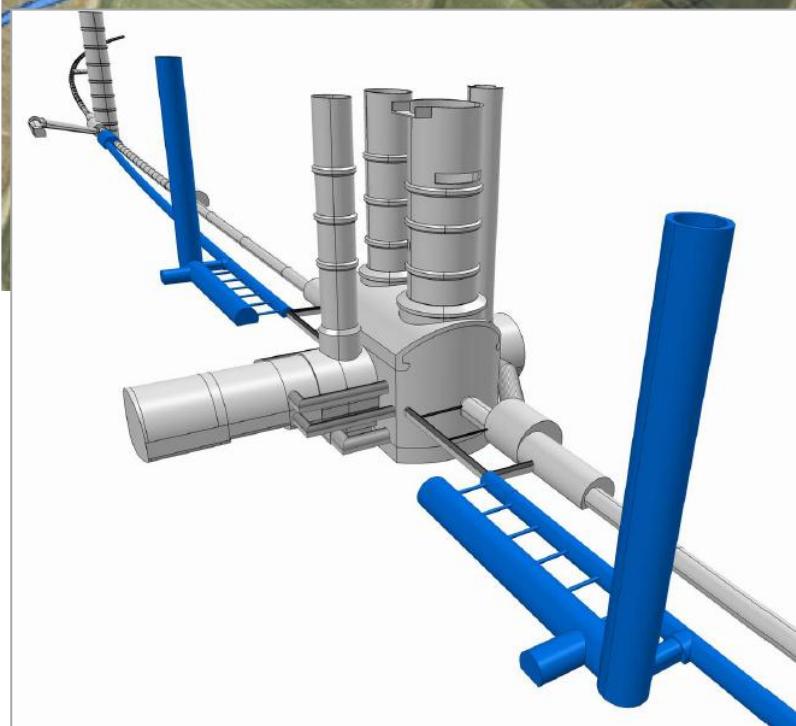
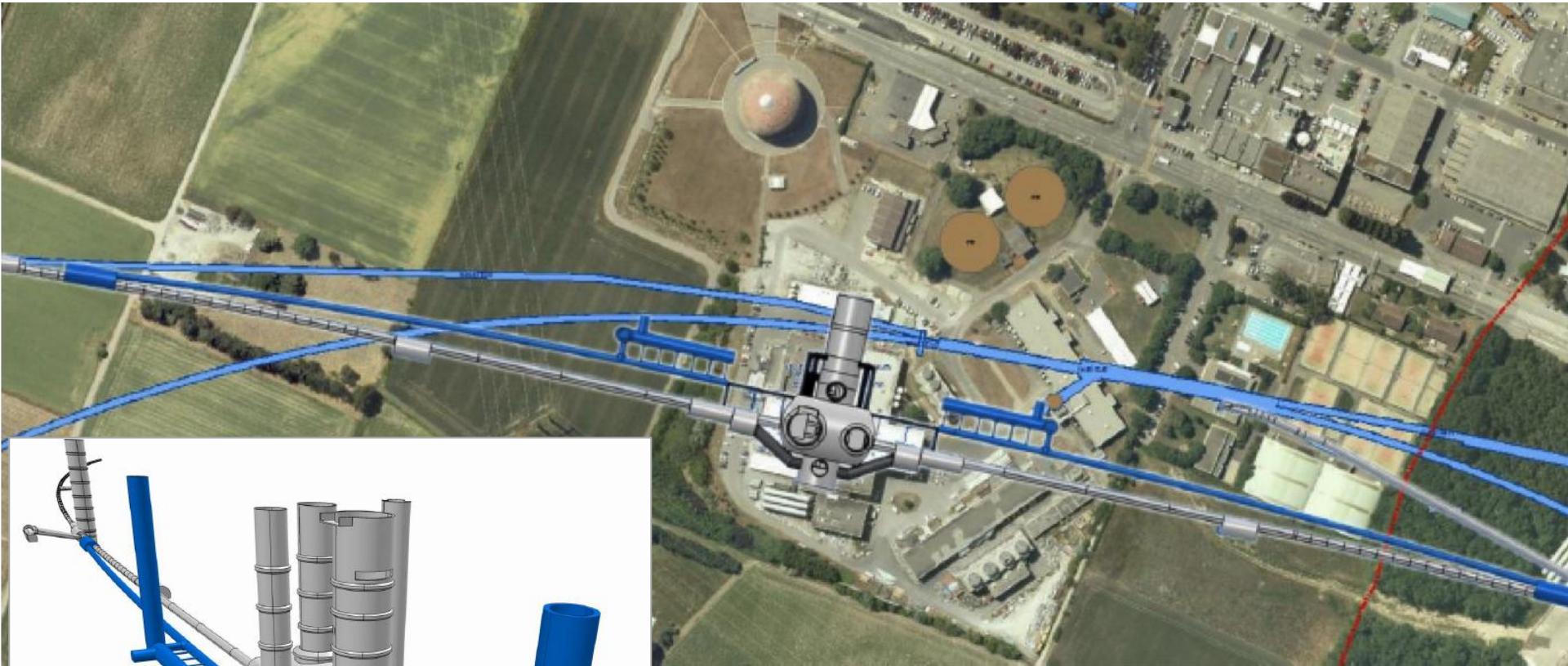


even IR



odd IR

# LHeC R-R: Bypassing LHC detectors

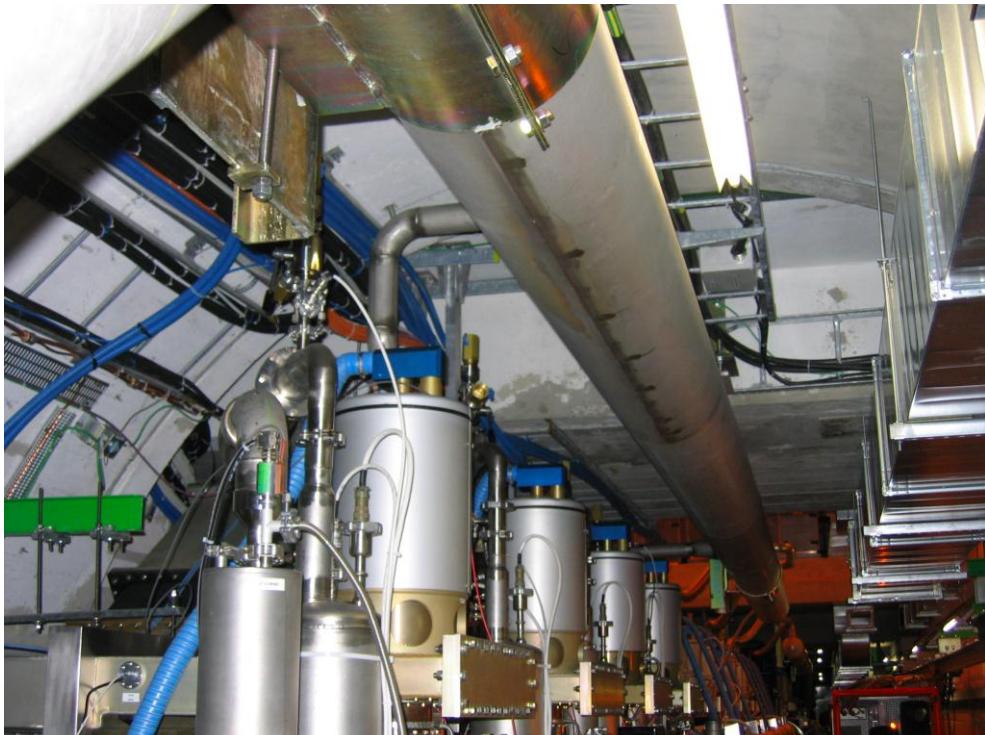


Without using the survey gallery  
the ATLAS bypass would need to  
be 100m away from the IP or on  
the inside of the tunnel!

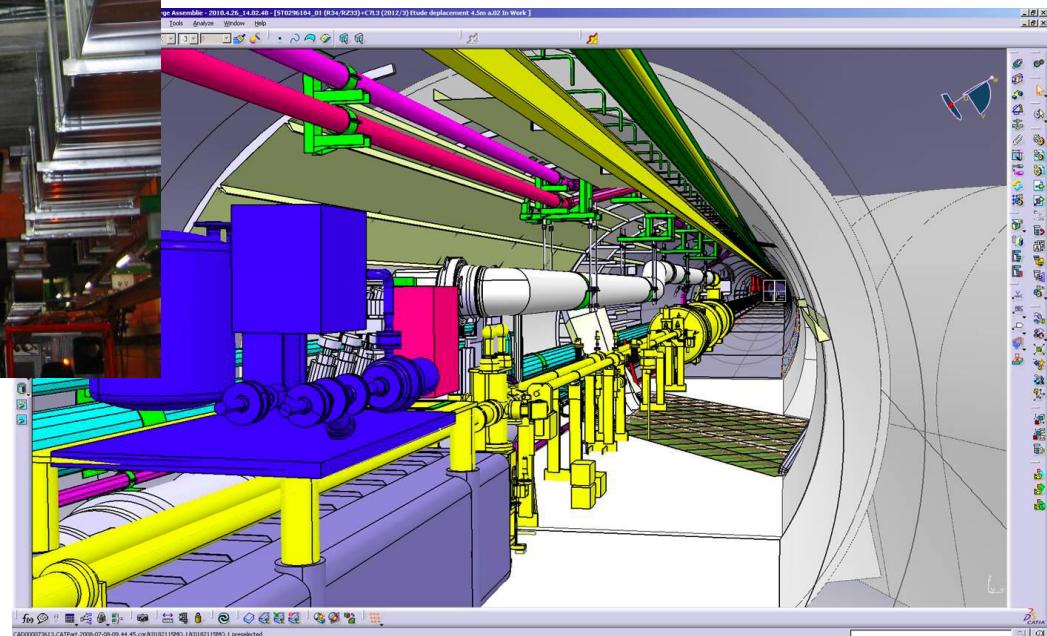
For the CDR the  
bypass concepts  
were decided to be  
confined to  
ATLAS and CMS

ca. 1.3 km long bypass  
ca. 170m long dispersion free area for RF

# LHeC R-R: Integration in LHC tunnel



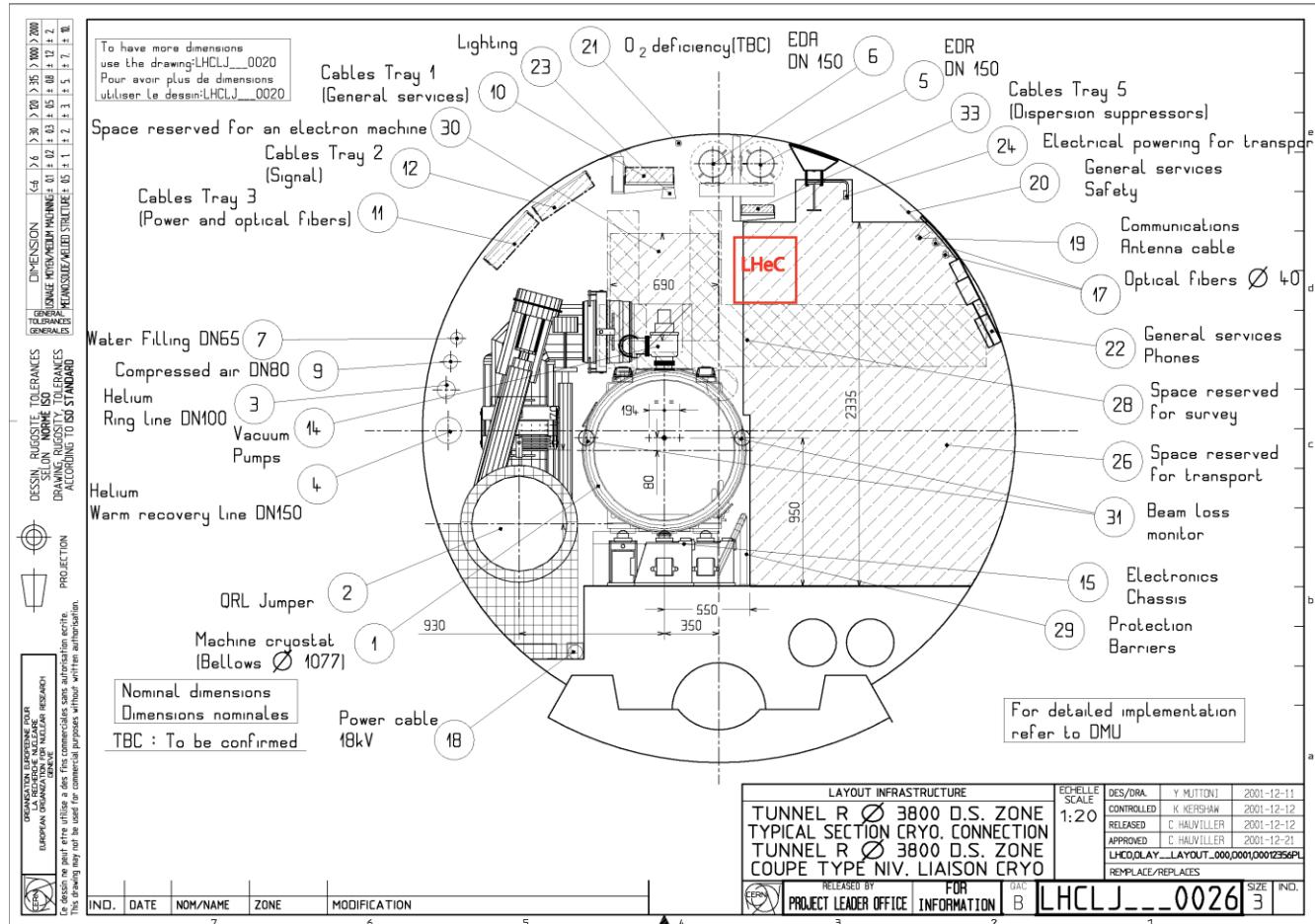
RF Installation in IR4



Cryo link in IR3

# LHeC R-R: Matching LHC circumference

requires:  
support  
structure  
with  
efficient  
montage  
and  
compact  
magnets



to transport LHC cryo equipment e<sup>-</sup> ring may need to be shifted 30 cm to the outside ; semi-automatic movement & expansion joints

# LHeC R-R dipole magnets: 400 mm long CERN model

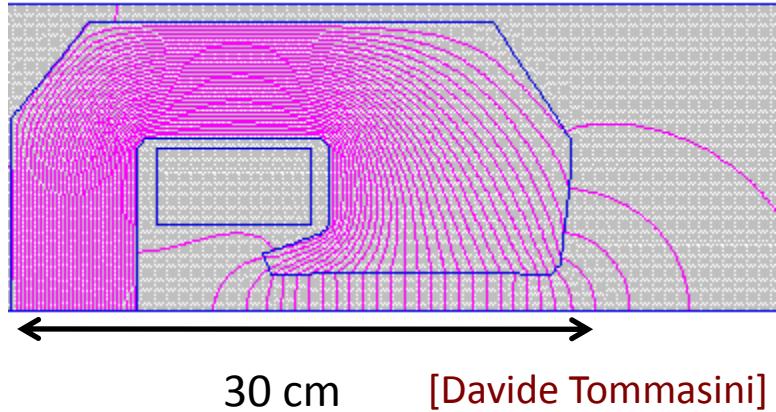
- interleaved ferromagnetic laminations
- air cooled
- two turns only, bolted bars
- 0.4 m models with different types of iron



REPRODUCIBILITY OF MAGNETIC FIELD OVER 8 CYCLES

Model	Low field	High fields
Maximum Relative Deviation from Average		
Model 1 (NiFe steel)	$5 \cdot 10^{-5}$	$4 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$6 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$4 \cdot 10^{-5}$	$6 \cdot 10^{-5}$
Standard Deviation from Average		
Model 1 (NiFe steel)	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
Model 2 (Low carbon steel)	$4 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
Model 3 (Grain oriented 3.5% Si steel)	$2 \cdot 10^{-5}$	$4 \cdot 10^{-5}$

Manufacture & tests of 3 models



## Magnet Parameters of the full length magnet

Beam Energy [GeV]	70
Magnetic Length [m]	5.45
Magnetic field [Gauss]	127-763
Number of magnets	3080
Vertical aperture [mm]	40
Pole width [mm]	150
Number of coils	2
Number of turns/coil	1
Current [A]	1500
Conductor section [mmxmm]	92x43
Conductor material	aluminum
Magnet Inductance [mH]	0.15
Magnet Resistance [mΩ]	0.2
Power per magnet [W]	450
Cooling	air
Weight [tons]	1.5

# LHeC Ring-Ring Challenges



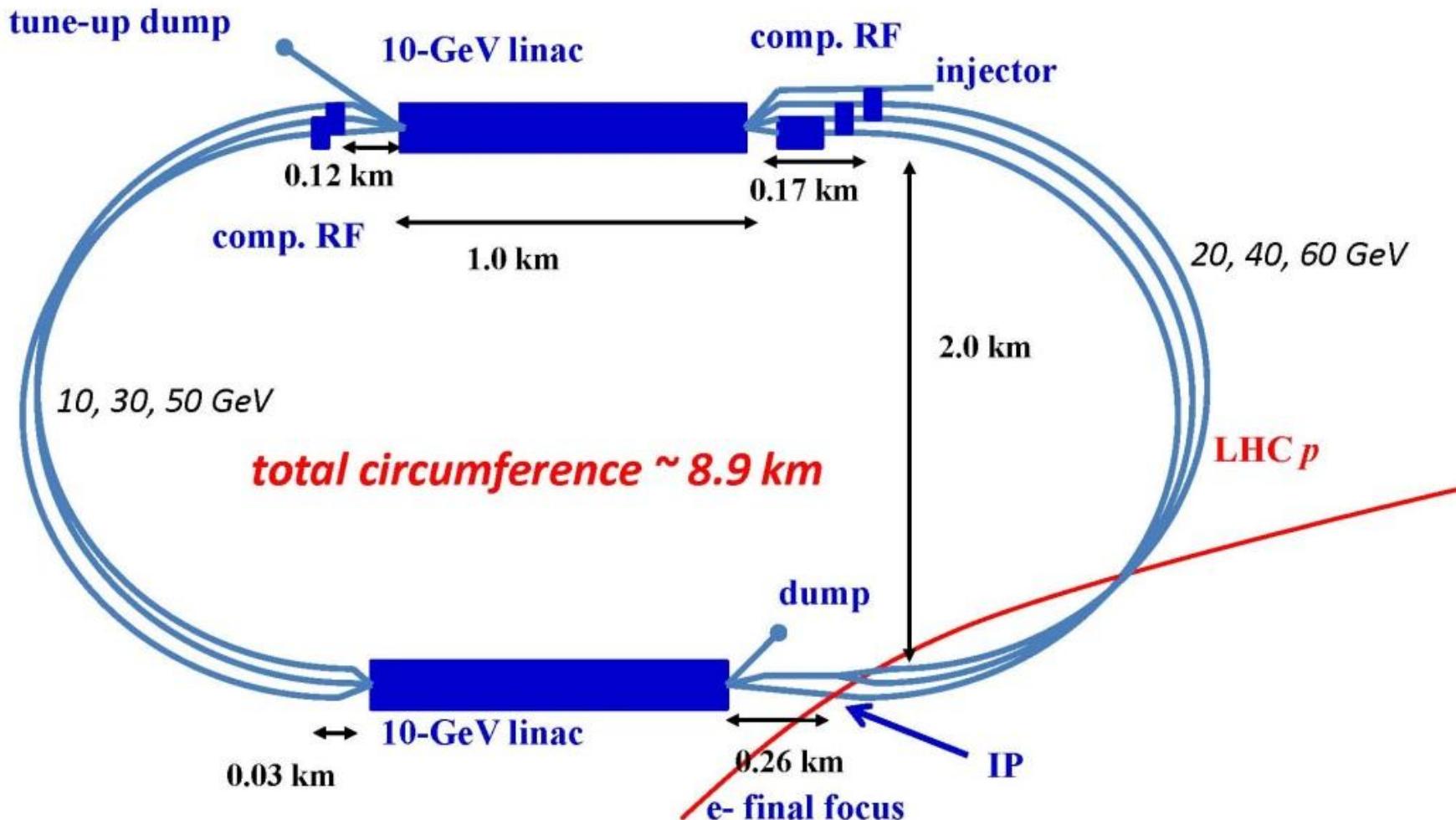
- bypassing the main LHC detectors
  - CMS: 20 cm distance to cavern, 1.3 km bypass, 300 m for RF installation
  - ATLAS: using the survey gallery, 1.3 km bypass, 170 m for RF installation; similar schemes for LHCb & ALICE
- integration into the LHC tunnel
  - cryo jumpers taken into account in arc-cell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

# LHeC Ring-Ring Conclusions

- Low-emittance optics compatible with LHC
- Light arc magnet prototypes from Novosibirsk and CERN show that required field quality and reproducibility is achievable
- No fundamental problem found for R-R LHeC
- But RR still needs a full 3-D integration study!
- Planning integration into LS2 and LS3 might be challenging!
- 40% polarization to be demonstrated

# LHeC Linac-Ring Option: ERL layout

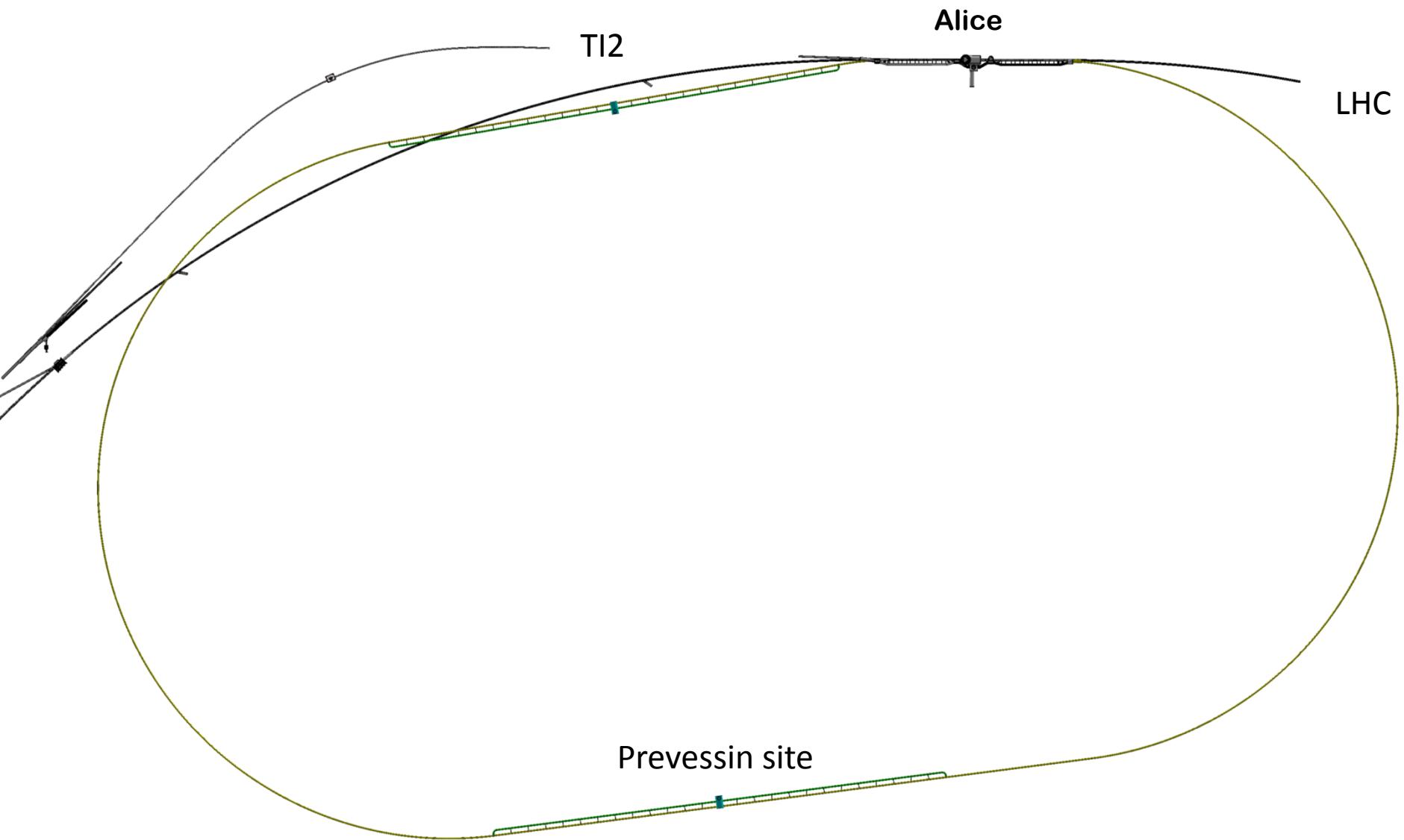
two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e-'s collide w. LHC protons/ions



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

(C=1/3 LHC allows for ion clearing gaps)

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



# underground layout / integration with LHC; example: Point 2

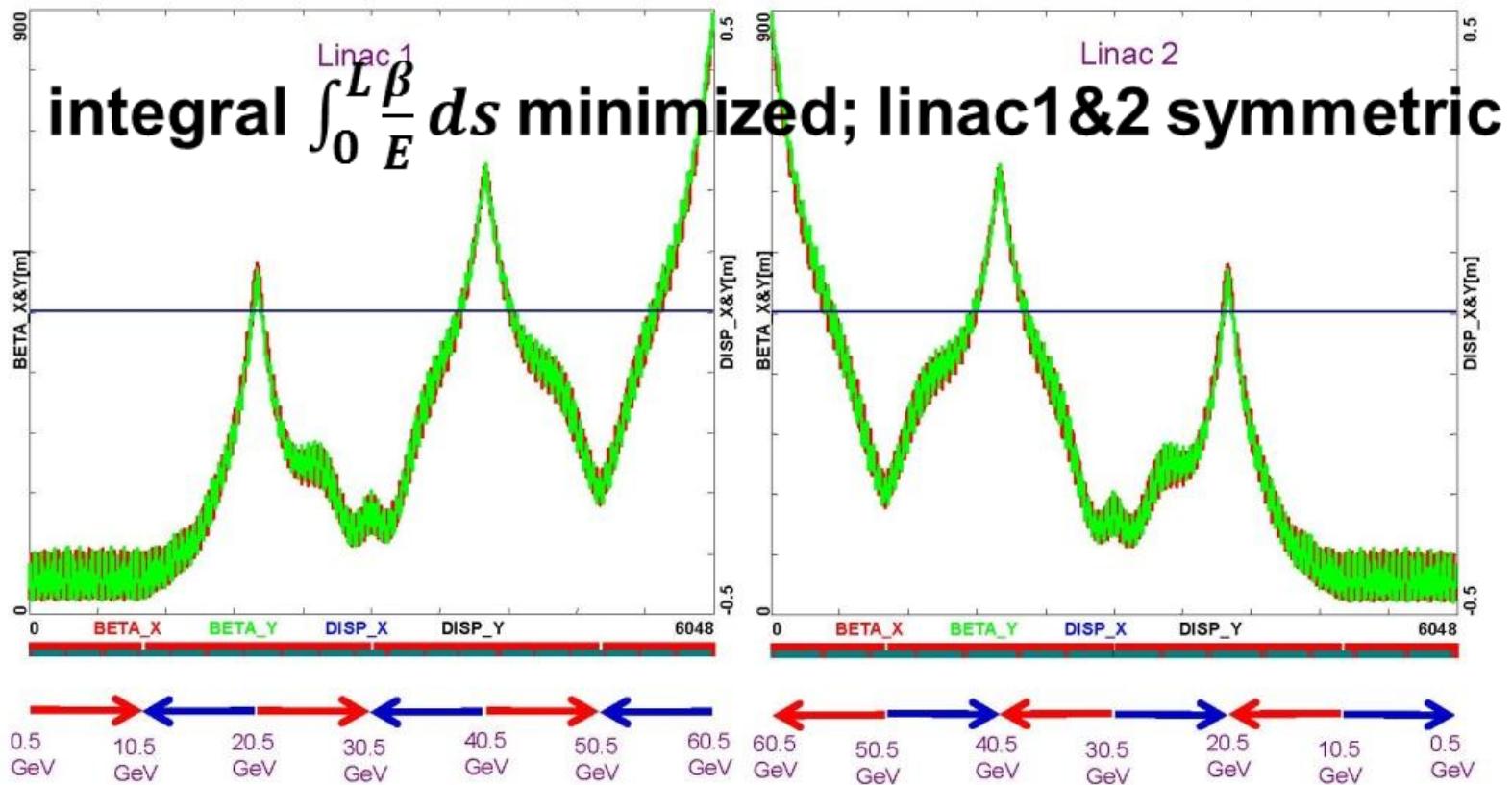


Alice

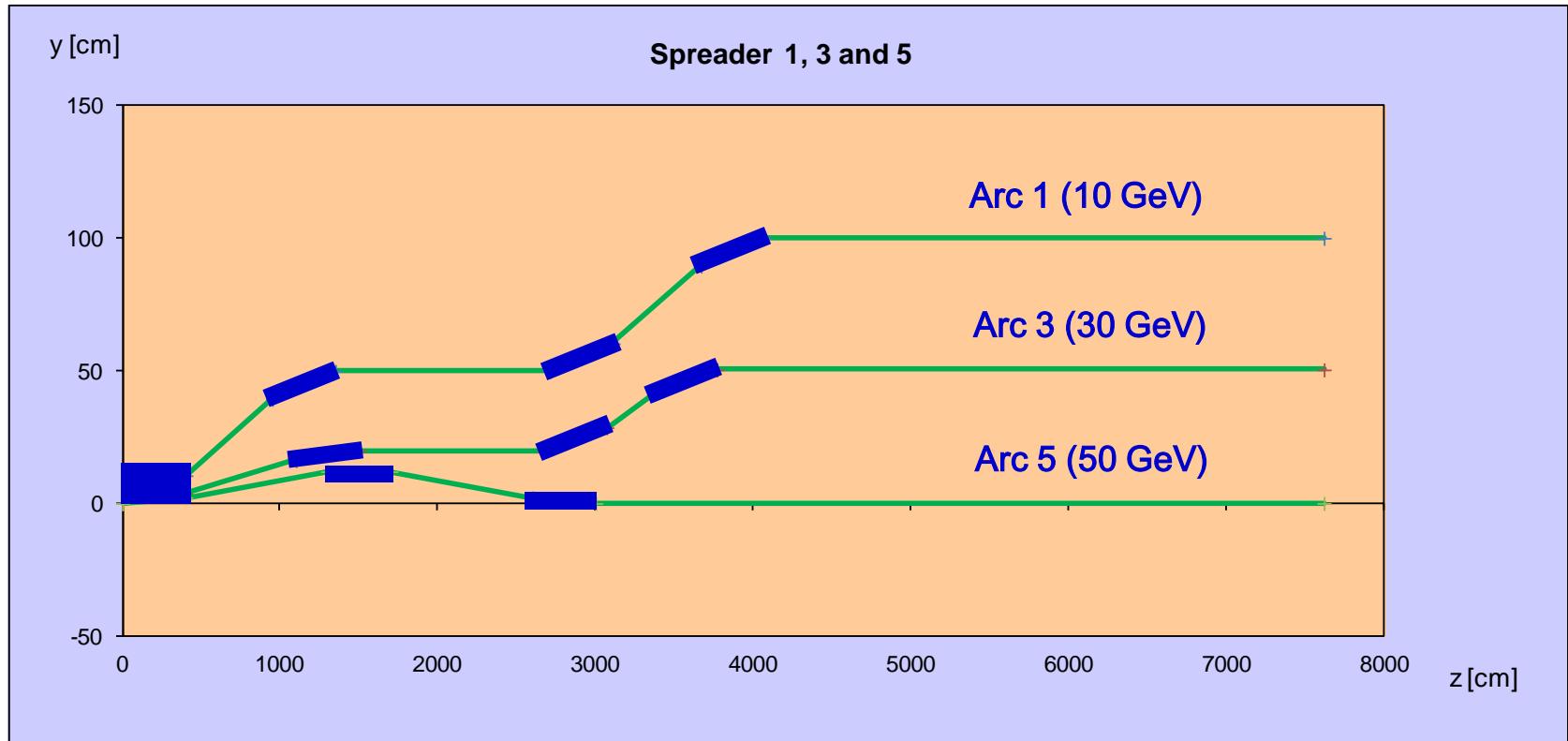
TI2

# LHeC L-R Option: ERL Linac Optics

## Linac 1 and 2 – Multi-pass ER Optics



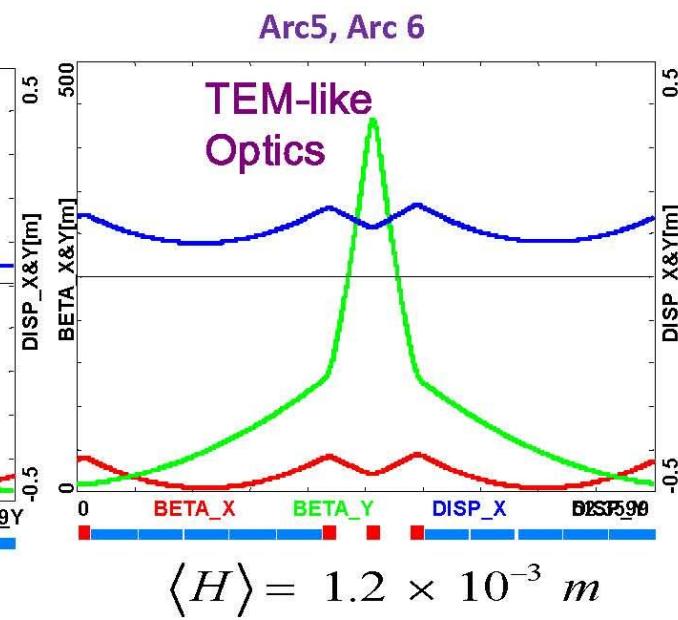
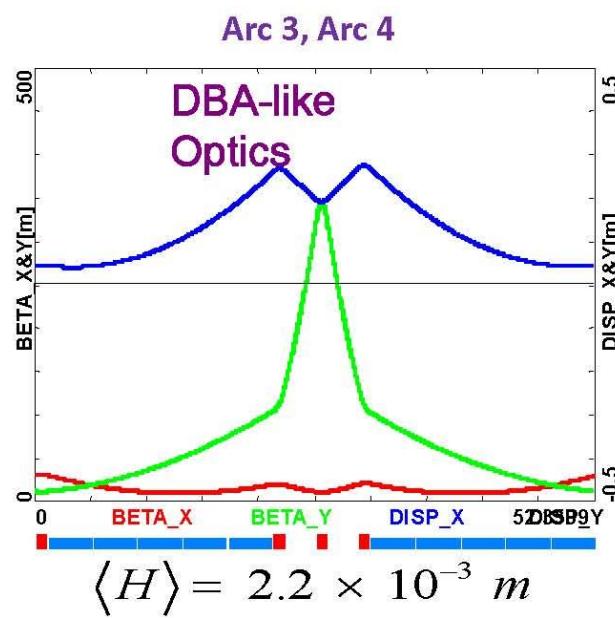
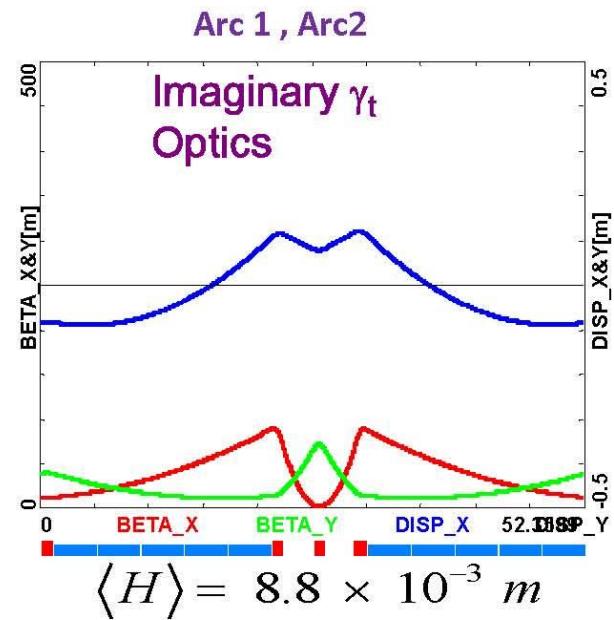
# LHeC L-R: Vertical Separation of Arcs & Spreader Optics



Alex Bogacz

# LHeC L-R Option: ERL Arc Optics

flexible momentum compaction cell; tuned for small beam size (low energy) or low  $\Delta\varepsilon$  (high energy)

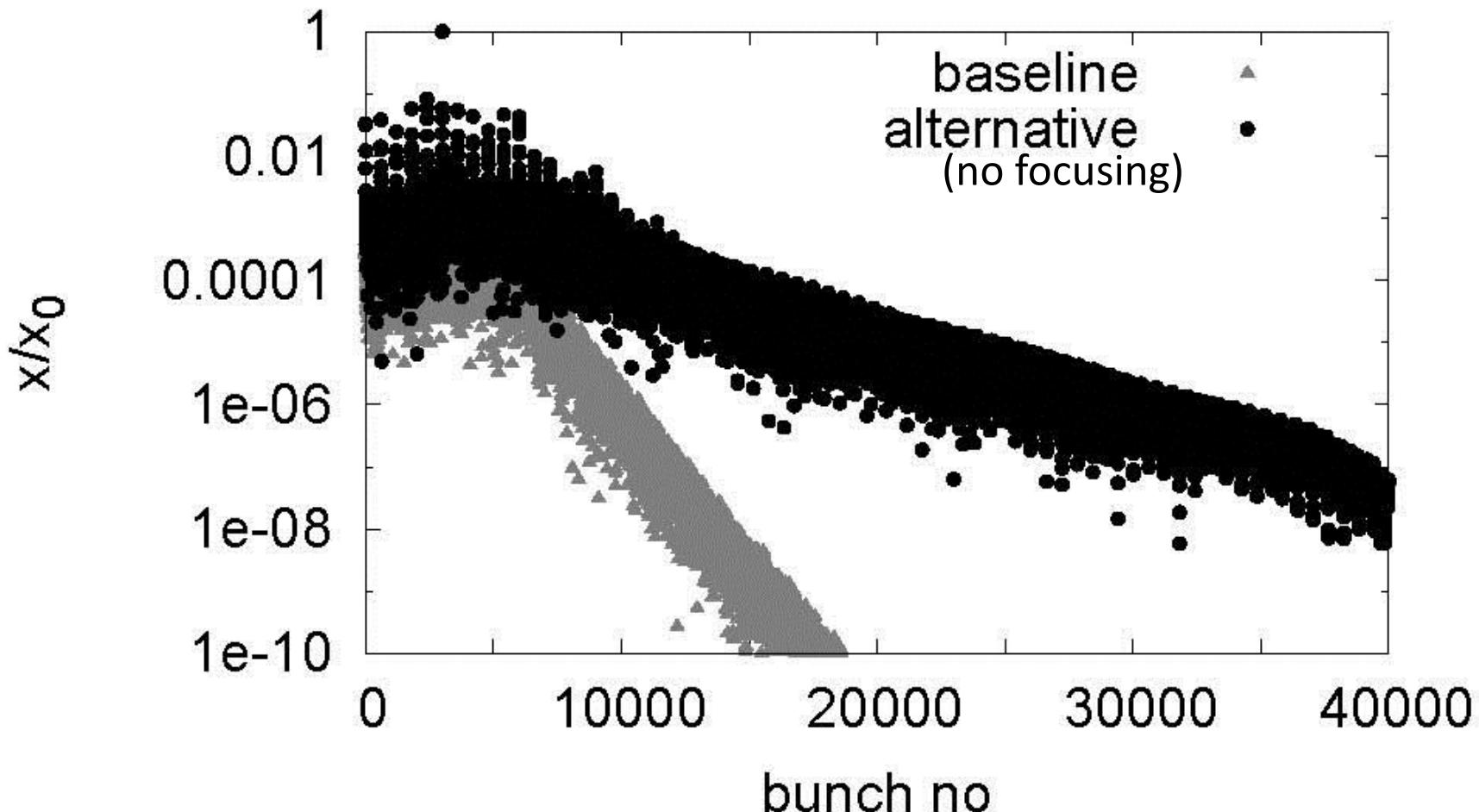


limit chamber size  
( $>12\sigma$  at 25 mm diameter)

limit emittance growth

# LHeC L-R Option: ERL Beam Dynamics

BBU: beam stability requires both damping  
( $Q \sim 10^5$ ) & detuning ( $\Delta f/f_{\text{rms}} \sim 0.1\%$ ) , 720 MHz



# 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  $\sim 1/2$  LHC
  - less current than other ERL designs (CESR-ERL, eRHIC)
- **return arcs**
  - total circumference  $\sim 9$  km, 3 passes
  - same magnet design as for RR option, >4500 magnets
  - installation fully decoupled from LHC operation
- **e<sup>+</sup>p luminosity: e<sup>+</sup> production & recycling**
  - IP e+ rate  $\sim 100$  times higher than for CLIC or ILC
  - several schemes proposed to achieve this

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

	Ring	Linac
magnets		
number of dipoles	3080	3600
dipole field [T]	0.013 – 0.076	0.046 – 0.264
number of quadrupoles	968	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 $R/Q$ [ $\Omega$ ]	114	285
cavity $Q_0$	—	$2.5 \cdot 10^{10}$
cooling power [kW]	5.4@4.2 K	30@2 K

# electrical power

	ring-ring	linac-ring
cryogenics	1 MW	21 MW
RF (microphonics + SR)	79 MW	58-80 MW*
injector	?	7 MW
magnets	2 MW	4 MW
total	82 MW	91-113 MW

\*Erik Jensen, Chamonix'12

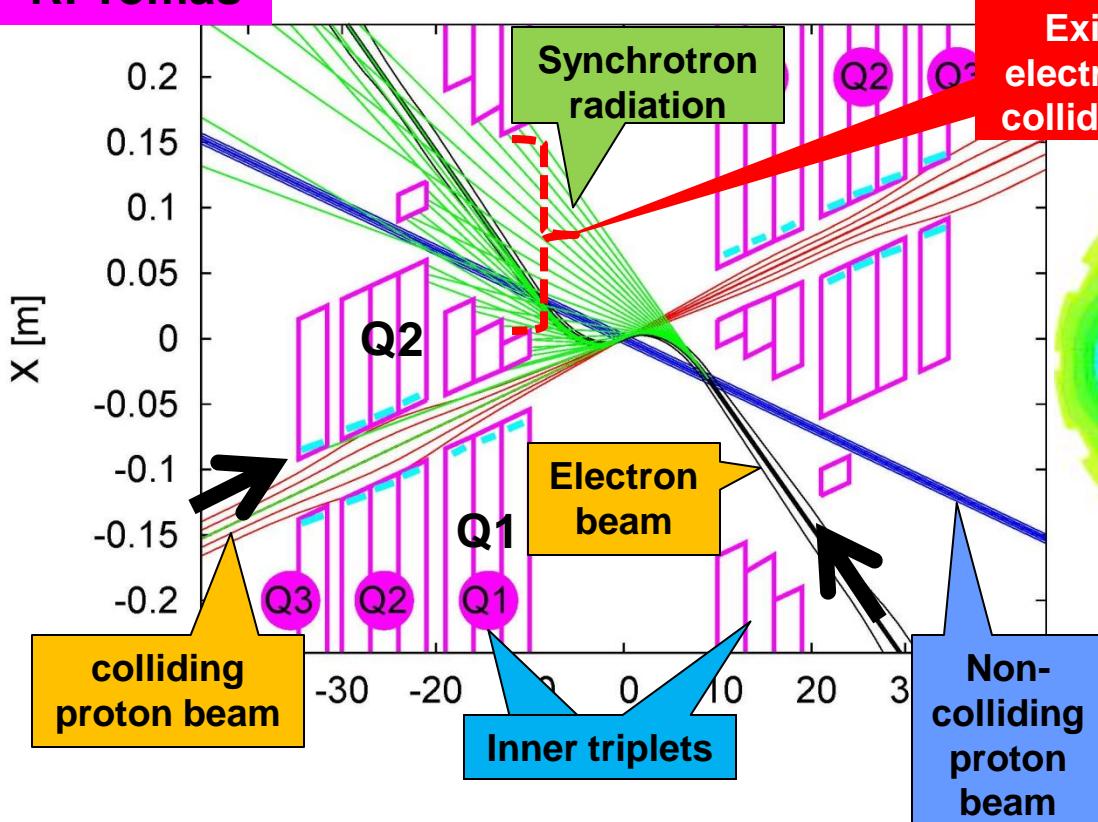
# LHeC L-R & R-R Joint IR Challenges

- interaction region layout for 3 beams
  - exit holes & optics, R-L: detector integrated dipole
- final quadrupole design
  - Q1 half quadrupole design
  - synergy with HL-LHC developments ( $\text{Nb}_3\text{Sn}$ )
- IR synchrotron radiation shielding
  - IR SR  $\sim 50$  kW for both;  $E_c \sim 163$  (R-R) or 718 keV (R-L)
  - minimize backscattering into detector
  - shielding of SC quadrupoles
  - SC masking to be further optimized (vac & det. bkgd)
  - spin rotator (including SR)

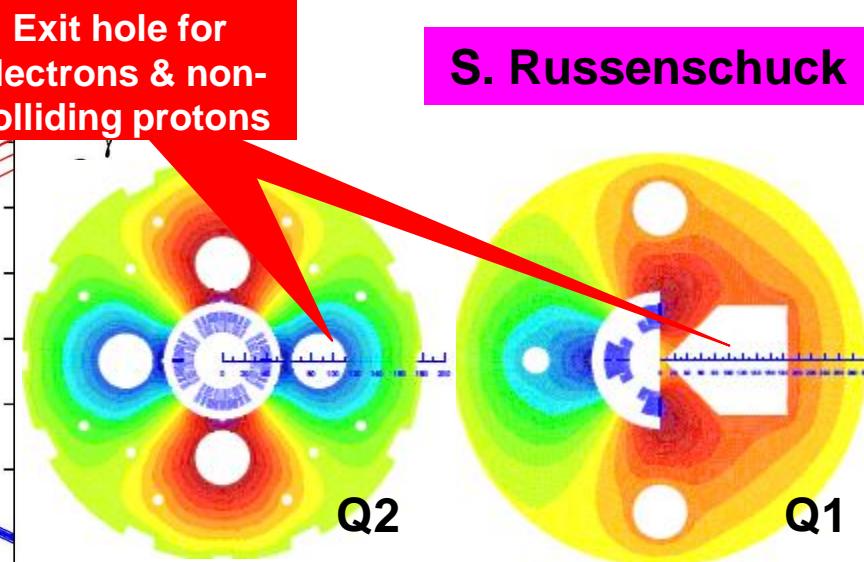


# LR LHeC IR layout & SC IR quadrupoles

R. Tomas



S. Russenschuck



High-gradient SC IR quadrupoles based on Nb<sub>3</sub>Sn 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

Nb<sub>3</sub>Sn (HFM46):  
5700 A, 175 T/m,  
4.7 T at 82% on LL  
(4 layers), 4.2 K

46 mm (half) ap.,  
63 mm beam sep.

0.5 T, 25 T/m

Nb<sub>3</sub>Sn (HFM46):  
8600 A, 311 T/m,  
at 83% LL, 4.2 K

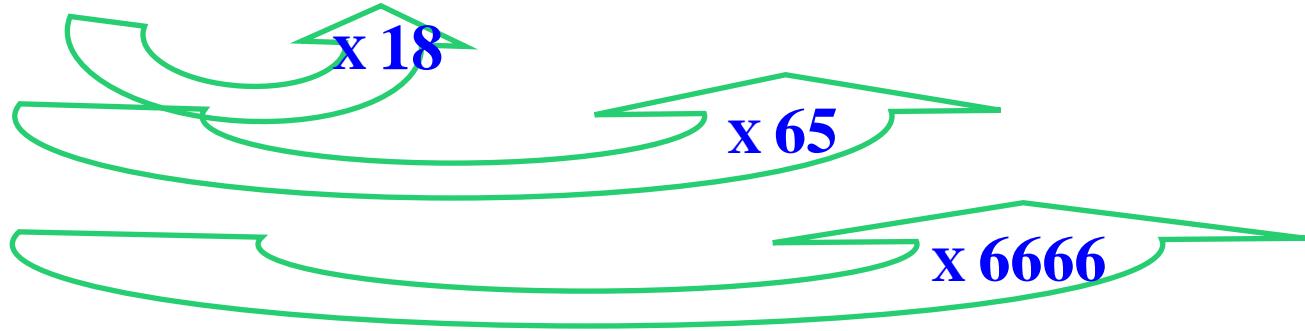
23 mm ap.. 87  
mm beam sep.

0.09 T, 9 T/m

# LHeC Linac-Ring e<sup>+</sup> source

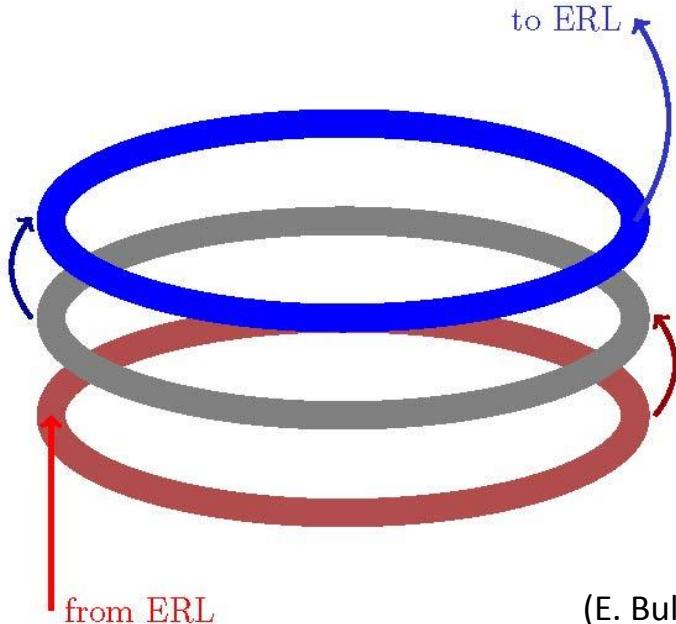


	<b>SLC</b>	<b>CLIC (3 TeV)</b>	<b>ILC (RDR)</b>	<b>LHeC</b>
Energy	1.19 GeV	2.86 GeV	5 GeV	60 GeV
e <sup>+</sup> / bunch at IP	$40 \times 10^9$	$3.72 \times 10^9$	$20 \times 10^9$	$2 \times 10^9$
e <sup>+</sup> / bunch before DR inj.	$50 \times 10^9$	$7.6 \times 10^9$	$30 \times 10^9$	N/A
Bunches / macropulse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



# linac e+ source options

- recycle e+ together with energy, multiple use,  
damping ring in SPS tunnel w  $\tau_{\perp} \sim 2$  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)



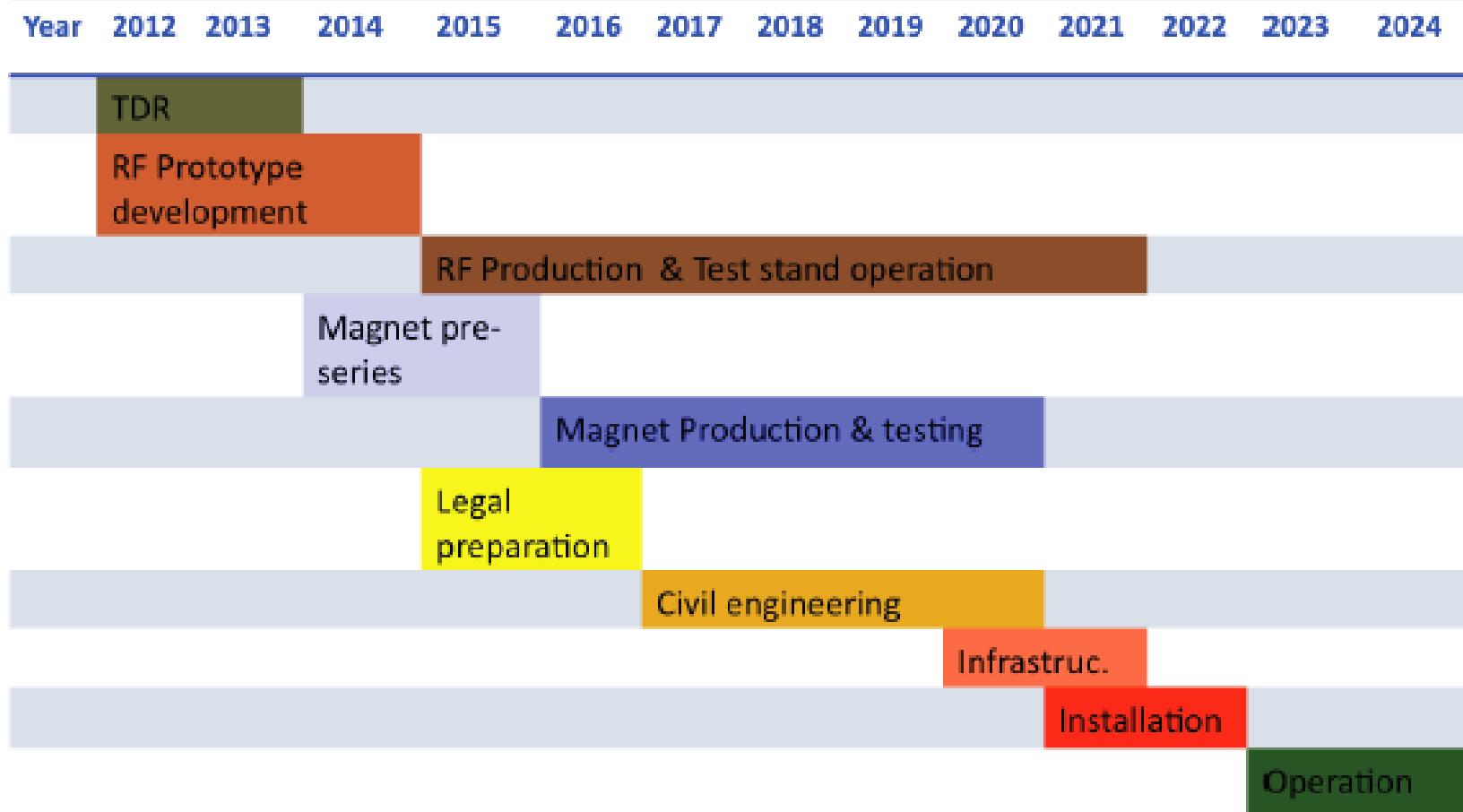
extraction ring ( $N$  turns)  
fast cooling ring ( $N$  turns)  
accumulator ring ( $N$  turns)

(E. Bulyak)

# 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**

# draft LHeC time schedule (11/2011)



-Only 2 long shutdowns planned before 2022

-Only 10 years for the LHeC from CDR to project start.

LS3 --- HL LHC

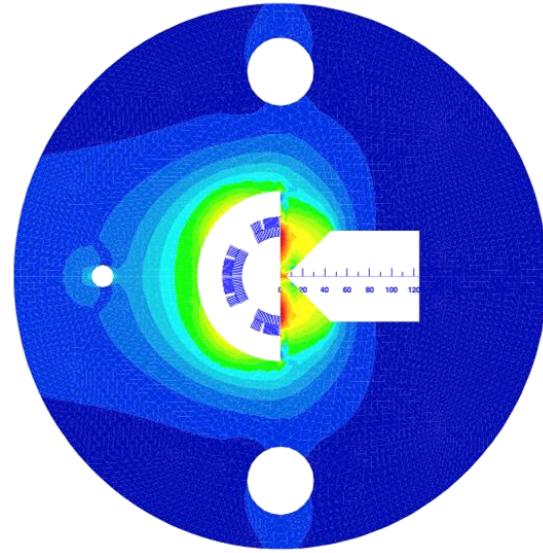
# LHeC Priority R&D



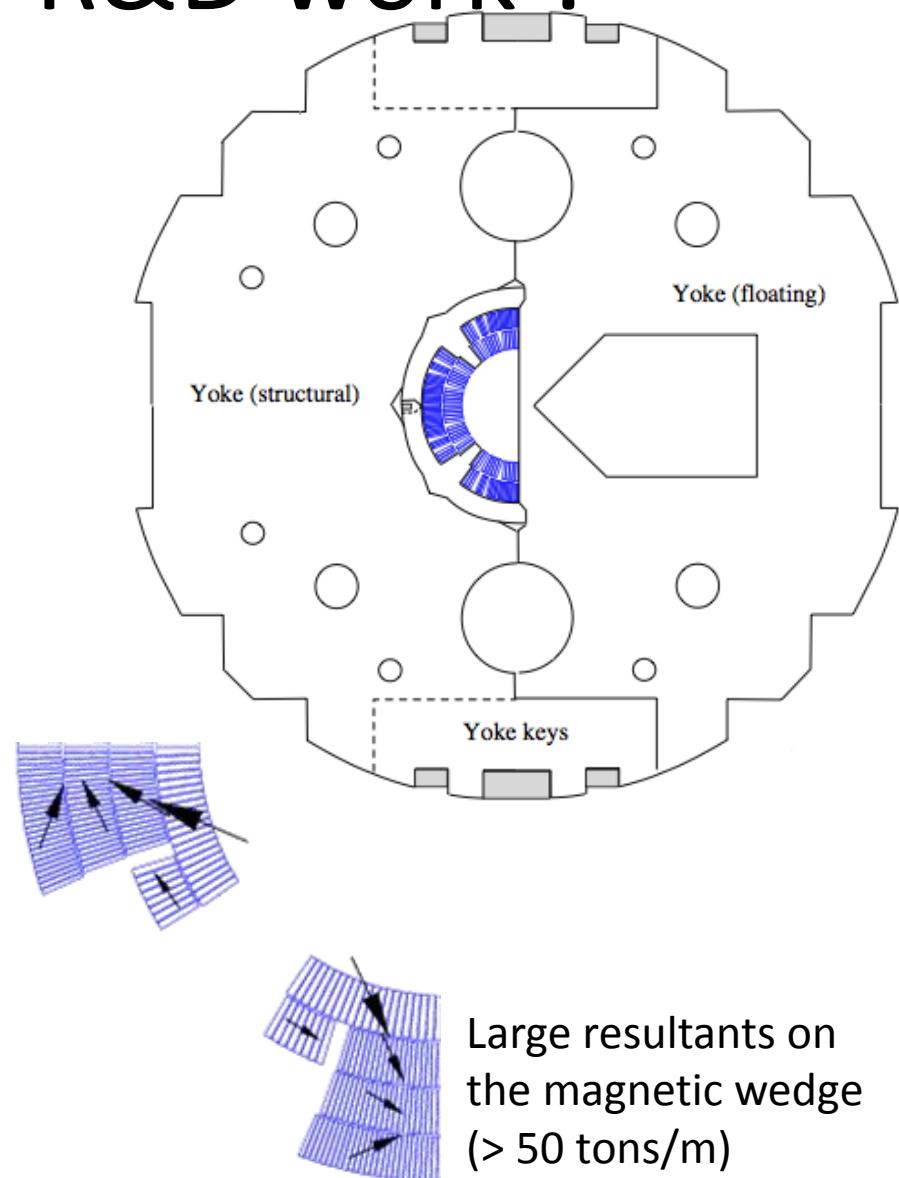
## R&D activities:

- 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

# LHeC IR quad R&D work ?



- Half-quad with field-free region, assembled using MQXC coils
  - 2.5 FTE
  - 500 kCHF
  - approx. 2 years till test

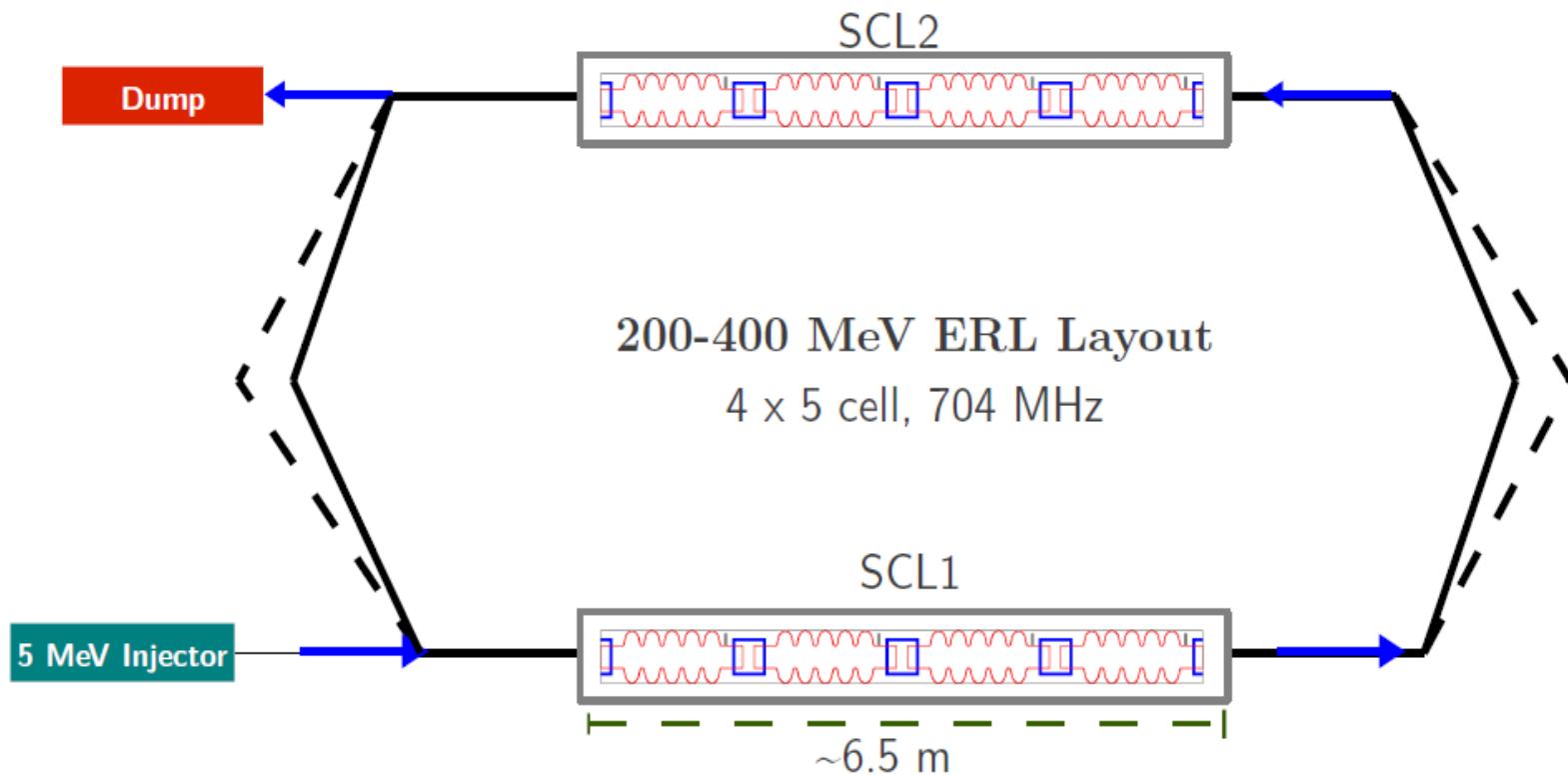


# ERL Test Facility at CERN

- ERL demonstrator
- e-cooling (@PS/SPS energies)
- ultra-short electron bunches
- strong synergy with SPL-ESS & BNL activities
- High energies & CW (100 – 400 MeV)
- Multi-cavity cryomodule layout (validation + gymnastics)
- MW class power coupler tests in non-ERL mode (vector feedback?)
- Complete HOM characterization and instability studies
- FEL & gamma-ray source

# ERL Test Facility at CERN

Potential layout:



# LHeC key decision points

2012: choice of IR: Point 2 (~~or 7 or 3?~~)

2012: choice between linac and ring

20xx: decision to go ahead with  
production

# thank you for your attention!

“LHeC” in google scholar / year

