LHeC

- Design Considerations
- Two options: -Ring-Ring collider

  -Linac-R[illegible]er with Energy Recovery
- IR Layout
- Plan[illegible]imeline
- Next steps

On behalf of the LHeC Collaboration!

LHeC Proposal endorsed by ECFA (30.11.2007)

As an add-on to the LHC, the LHeC delivers in exce… the electron-quark cms system. It accesses hi… 'beyond' what is expected to be the unitarity l… thus fundamental and deserves to be further wo… respect to the findings at the LHC and the final re… and of HERA.

First considerations of a rin… …ing accelerator layout lead to an unprecedent… energy and luminosity in lepton-hadron ph… the latest developments in accelerator and … y.

It is th… …old two workshops (2008 and 2009), under th… …CFA and CERN, with the goal of having a … …gn Report on the accelerator, the experiment and … A Technical Design report will then follow if appropriate.

Maximum Exploitation of the LHC infrastructure investment!

Unanimously supported by rECFA and ECFA plenary in November 2007

NuPECC – Roadmap 5/2010: New Large-Scale Facilities

Design Considerations

LHC hadron beams: E_p=7 TeV; CM collision energy: E^2_{CM} = 4 E ... 0GeV

Integrated $e^{\pm}p$: O(100) fb^{-1} ≈ 100 * L(HERA) → synchro...

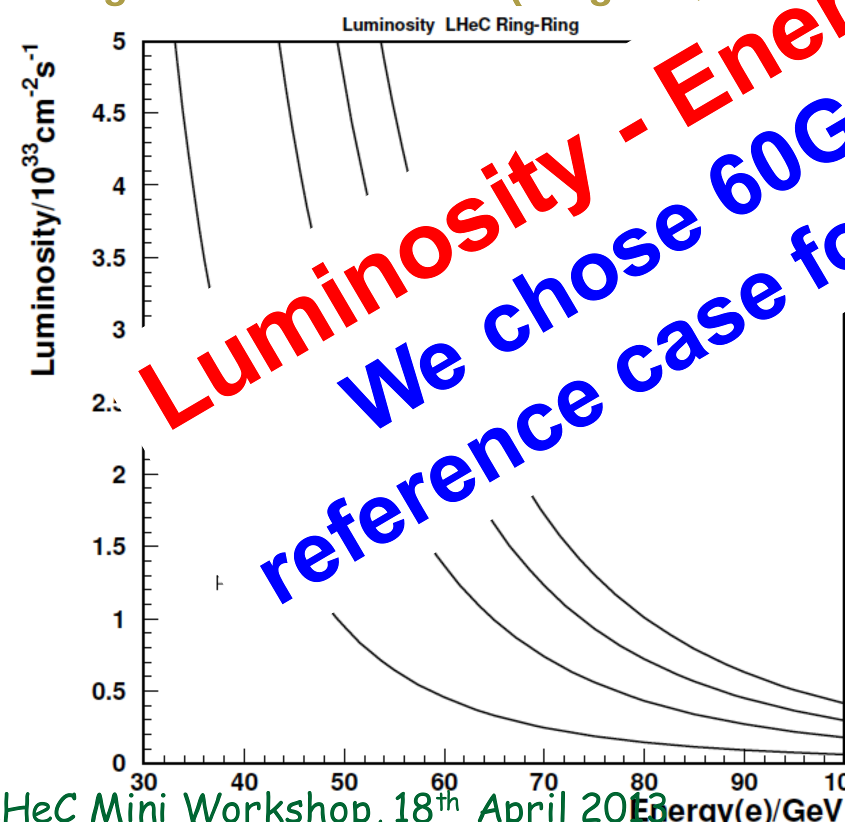
Luminosity O (10^{33}) $cm^{-2}s^{-1}$ with 100 MW power c... 0 MW

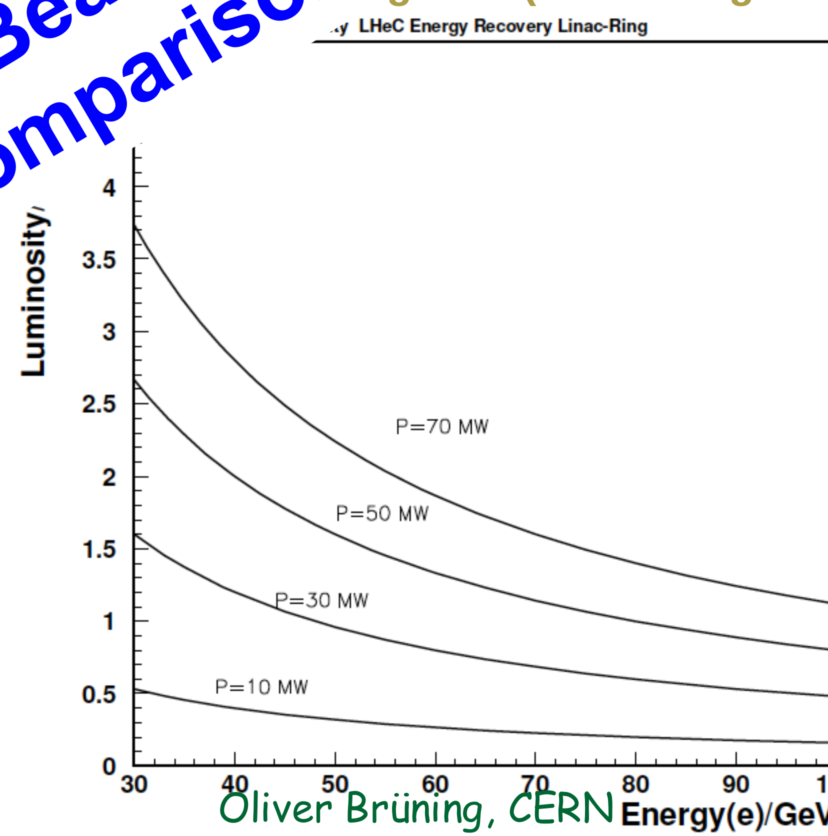
Start of LHeC operation together with HL-... in 2022)

Luminosity - Energy & Power tradeoff

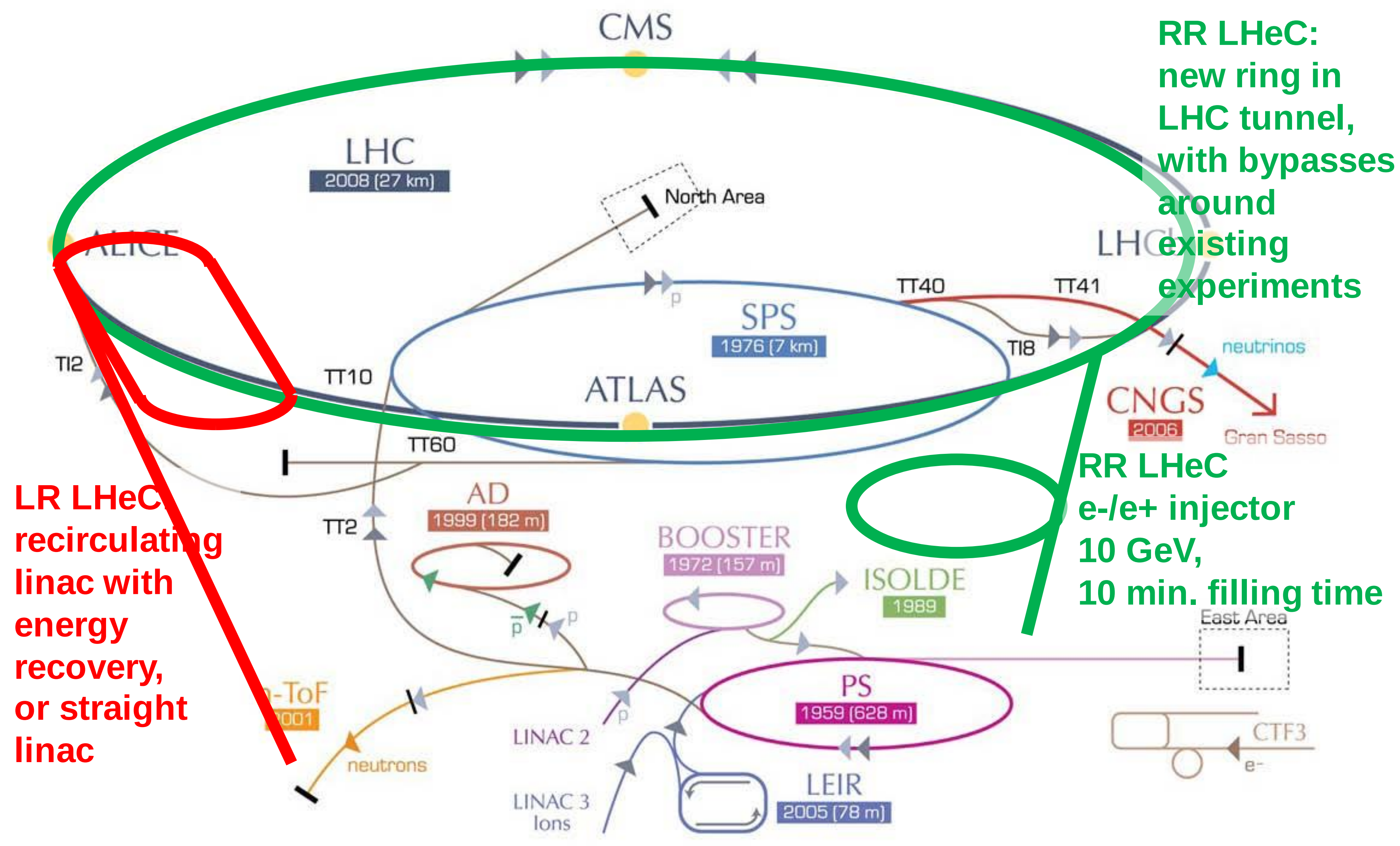
We chose 60GeV Beam Energy as reference case for comparison in the CDR

e Ring in the LHC tunnel (Ring-Ring ... ERL (Linac-Ring -LR)

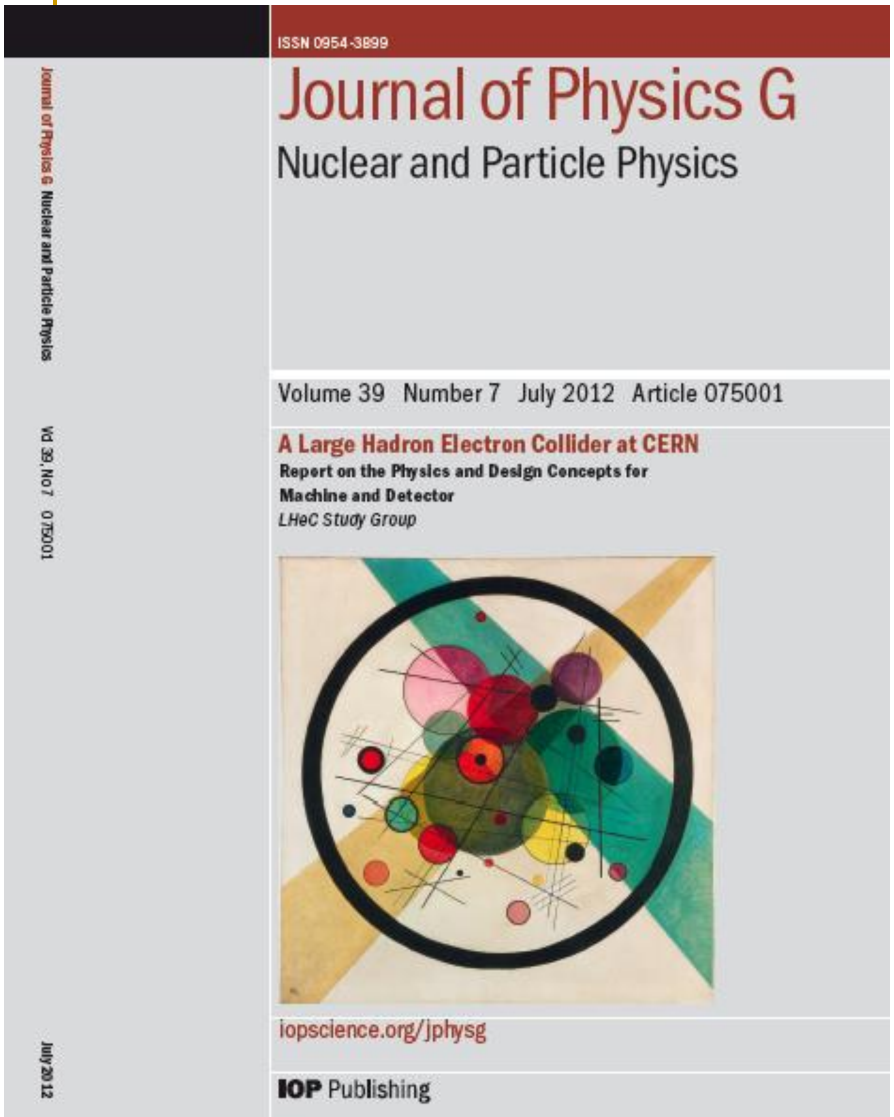




LHeC options: RR and LR



LHeC CDR



1. Design for synchronous ep and pp operation (including eA) → after LS3 which is about 2025 – no firm schedule exists for HL-LHC, but it may operate until ~2035

2. LHeC is a new collider: the cleanest microscope of the world, a complementary Higgs facility, a unique QCD machine with a striking discovery potential, with possible applications as γγ → H or injector to TLEPP or others AND an exciting new accelerator project

3. CERN Mandate to develop key technologies for the LHeC for project decision after start of LHC Run II and in time for start parallel to HL LHC phase

CERN Mandate

The mandate for the technology development **includes studies and prototyping of the following key technical components**:

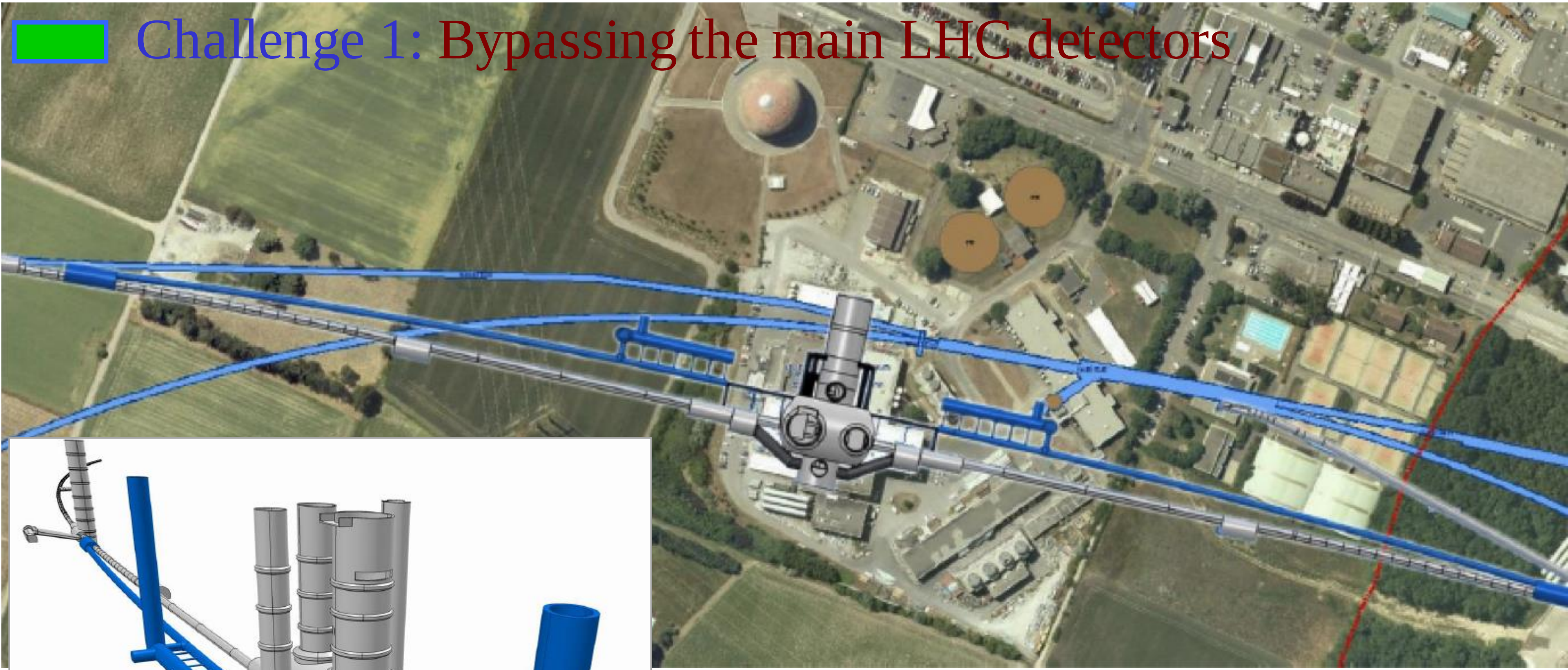
- Superconducting RF system for CW operation in an Energy Recovery Linac (high Q_0 for efficient energy recovery) S
- uperconducting magnet development of the insertion regions of the LHeC with three beams. The studies require the design and construction of short magnet models
- Studies related to the experimnetal beam pipes with large beam acceptance in a high synchrotron radiation environment
- The design and specification of an ERL test facility for the LHeC.
- The finalization of the ERL design for the LHeC including a finalization of the optics design, beam dynamics studies and identificationof potential performance limitations

The above technological developments require close collaboration between the relevant technical groups at CERN and external collaborators. Given the rather tight personnel resource conditions at CERN **the above studies should exploit where possible synergies with existing CERN studies.**

S.Bertolucci at Chavannes workshop 6/12 based on
CERN directorate's decision to include LHeC in the MTP

LHeC: Ring-Ring Option

Challenge 1: Bypassing the main 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

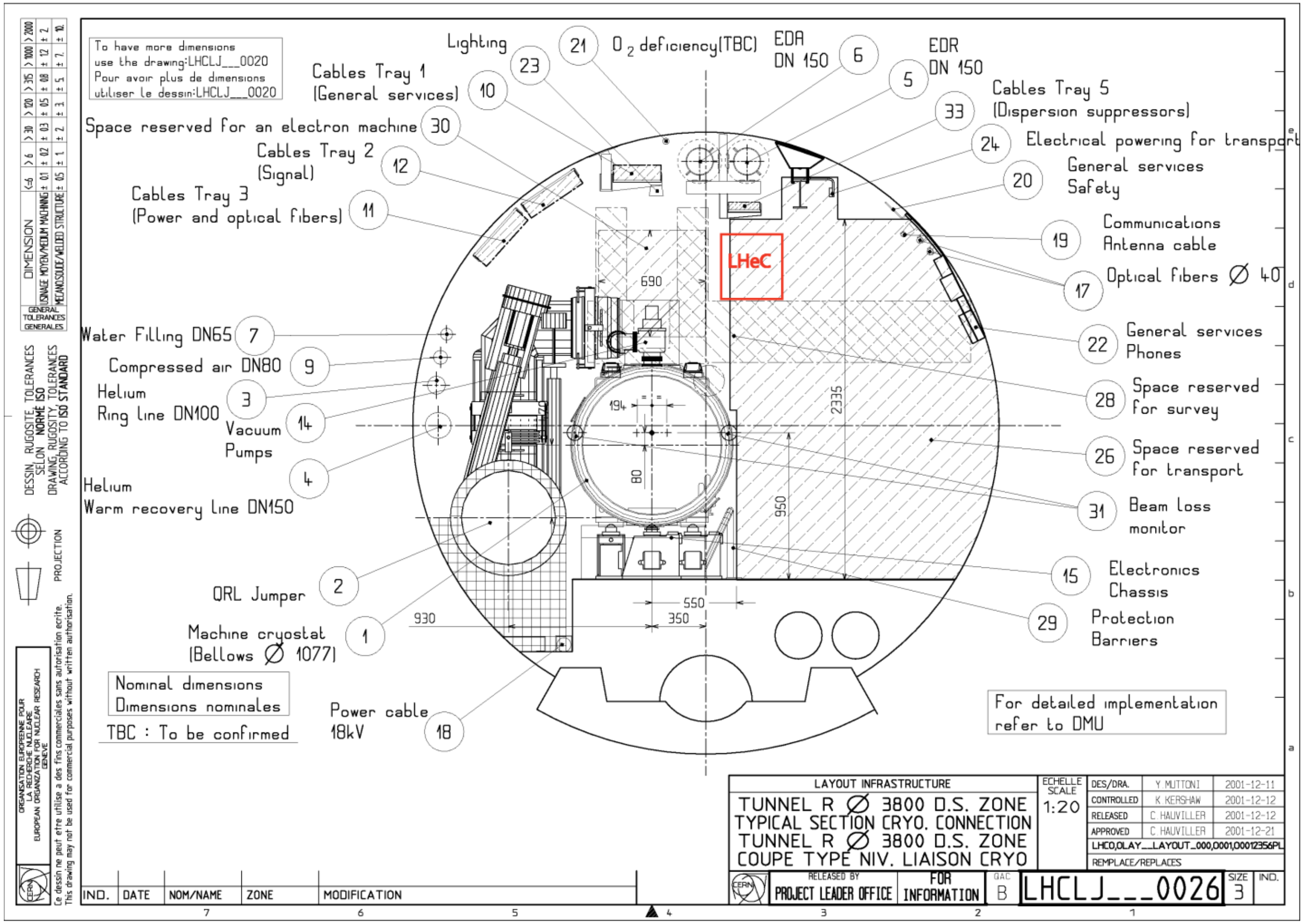
ca. 1.3 km long bypass

ca. 170m long dispersion free area for RF

LHeC: Ring-Ring Option

Challenge 3: Installation with LHC circumference:

requires: support structure with efficient montage and compact magnets



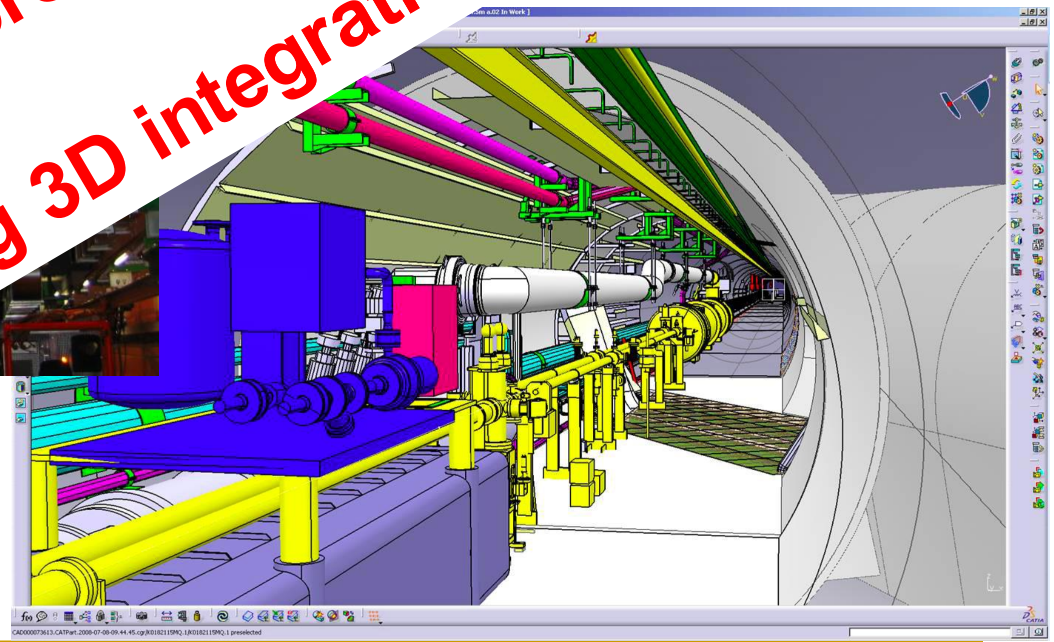
LHeC: Ring-Ring Option

Challenge 2: Integration in the LHC tunnel

No principal problem found yet!

(Still missing 3D integration study)

link in IR3



LHeC Ring-Ring dipole 400 mm long CERN m…

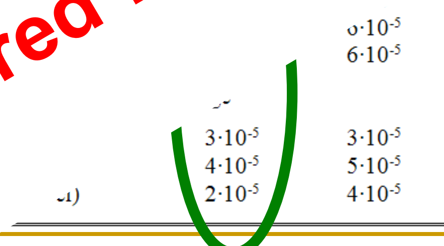
- interleaved ferromagnetic laminations
- air cooled
- two turns only, bolted bars
- 0.4 m models with different types of iron

Similar prototype development from Novosibirsk

→ Prototype of light magnet design shows that required field quality and reproducibility is feasible!

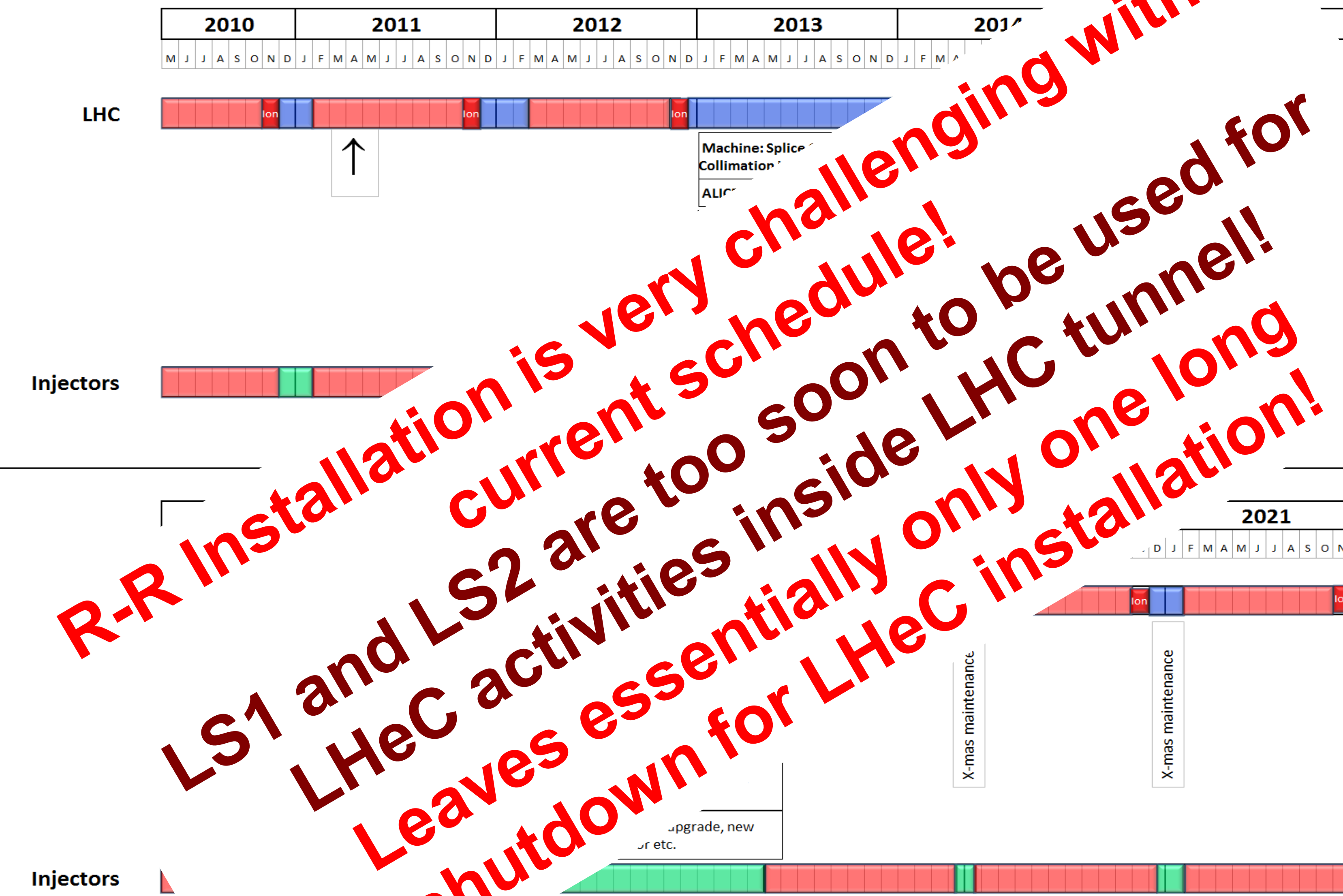
…nasini]

	…gth magnet
	70
	5.45
…s]	127-763
…gnets	3080
…perture [mm]	40
… 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



…ture & tests of 3 models

Current 10 Year Plan for LHC Operation



R-R Installation is very challenging within current schedule!

LS1 and LS2 are too soon to be used for LHeC activities inside LHC tunnel!

Leaves essentially only one long shutdown for LHeC installation!

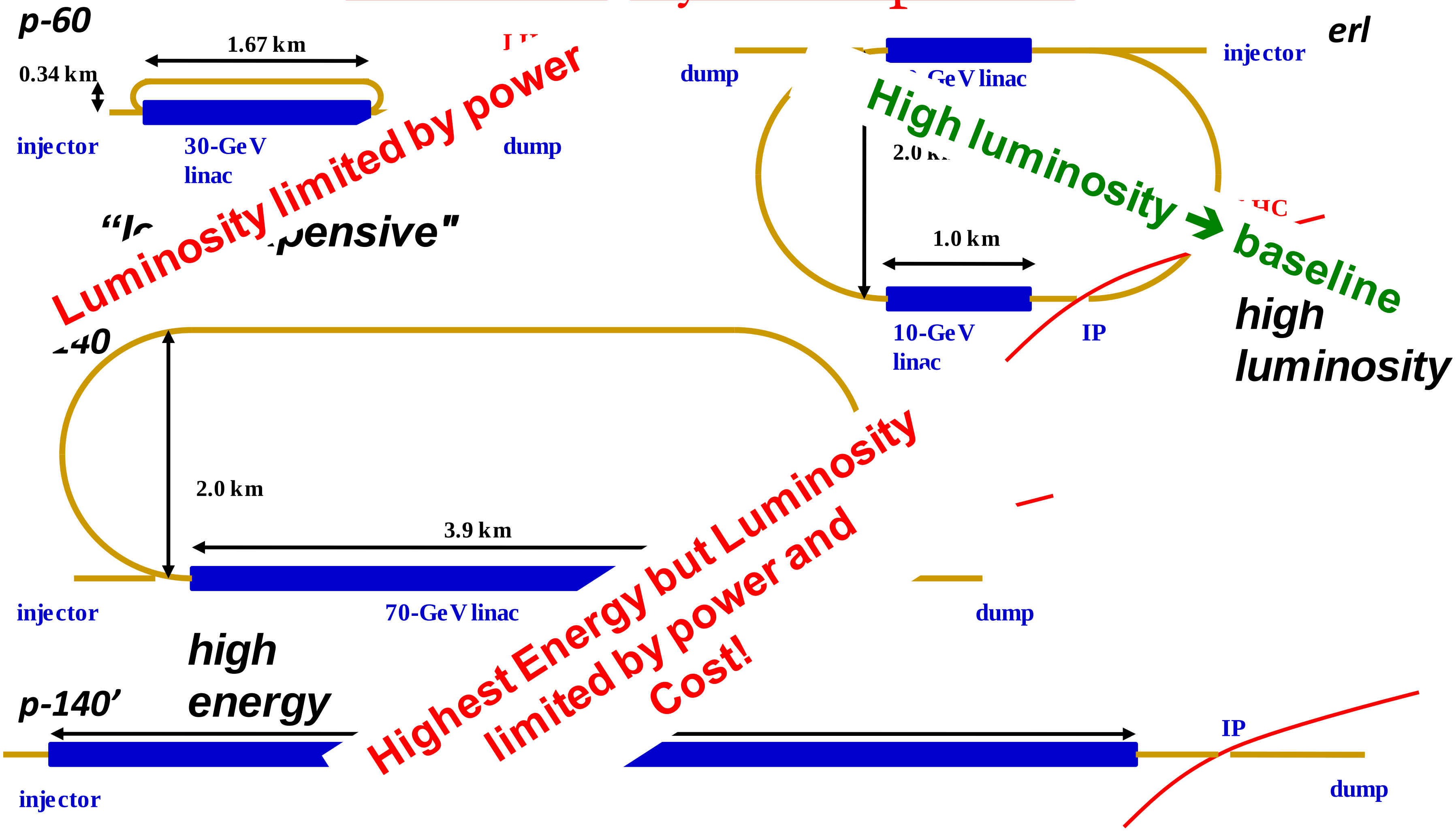
2022

LS3

Installation of the HL-LHC hardware
Installation of LHeC
Preparation for HE-LHC

LHeC: Linac-Ring Option Considered

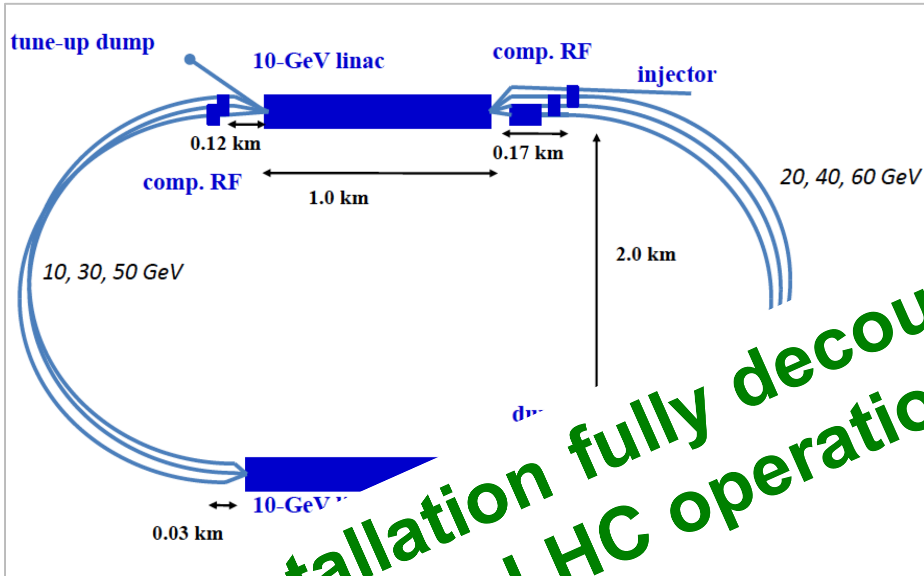
Various Layout Options



LHeC: Baseline Linac-Ring Option

LHeC

Challenge 1: Super Conducting Linac with Energy Recovery & high current (> 6mA)



Two 1 km long SC lin[…] CW operation

➚ requires Cryogenic system comparable to LHC system!

Installation fully decoupled from LHC operation!

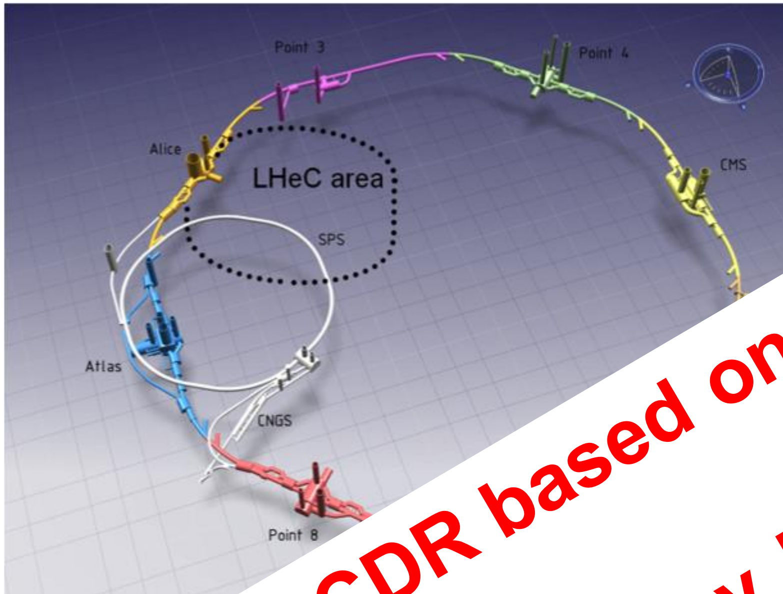
Challen[…]atively large return arcs

➔ ca. 9 k[…] underground tunnel installation

➔ total of 19 km bending arcs

➔ same magnet design as for RR option: > 4500 magnets

LINAC – Ring: connection to the L...



LHeC CDR based on 721 MHz cavity design

But RF Frequency has been re-optimized after publication of the CDR!

800 MHz chosen after CDR

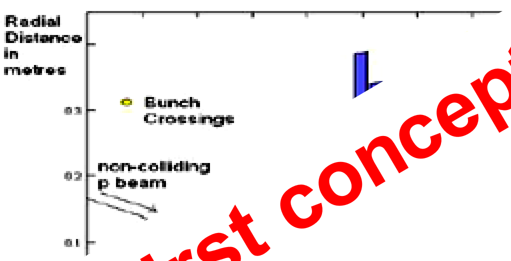
...ack)
...e LHC for
...ess at CERN
Territory
U=U(LHC)/3=9km

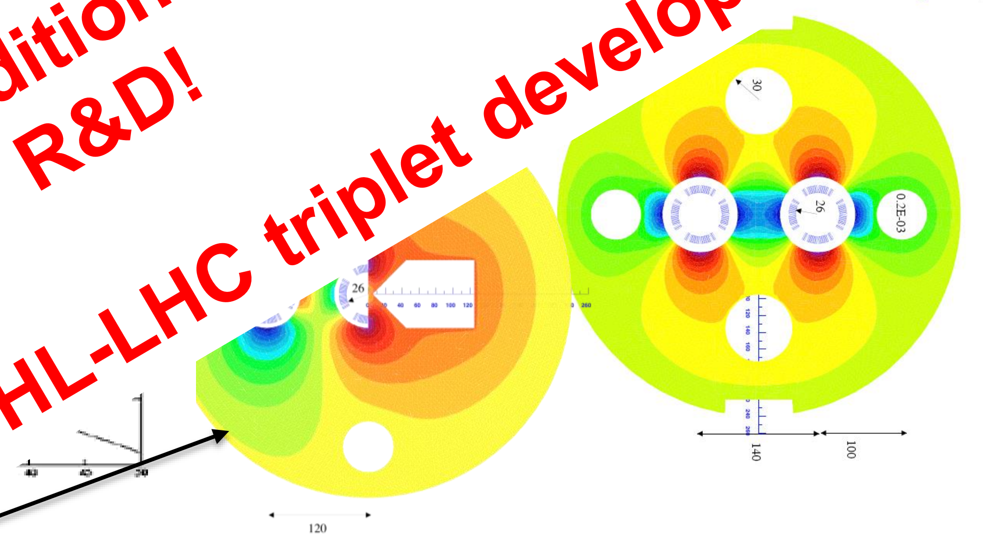
...dules per linac
...Hz, 21 MV/m CW
...imilar to SPL, ESS, XFEL, ILC, eRHIC, Jlab
-24 - 39 MW RF power
-29 MW Cryo for 37W/m heat load
-4500 Magnets in the 2 * 3 arcs:
600 - 4m long dipoles per arc
240 - 1.2m long quadrupoles per arc

Interaction Region: Accommodatin... ...ns

Small crossing angle of about 1mrad to avoid ... 77)
(Dipole in detector? Crab cavities? Desi...
Synchrotron radiation –direct and b... .)

Focus of current activity





First conceptual SC magnet designs exist

But still requires additional design work and R&D!

Synergies with HL-LHC triplet development!

1st ... ...d deflect)
sepa... ...n, MQY cables, 4600 A

2nd quad: 3 beams in horizontal plane
separation 8.5cm, MQY cables, 7600 A

LHeC Planning and Timeline

- We assume the LHC will reach end of its lifetime with the end of the HL-LHC project:

  -Goal of integrated luminosity of 3000 fb^{-1} with 200fb^{-1} to 300fb^{-1} production per year ➔ ca. 10 years of HL-LHC operation

  -Current planning based on HL-LHC start in 2022

  ➔ end of LHC lifetime by 2032 to 2035

- LHeC operation:

  -Luminosity goal based on ca. 10 year exploitation time (➔100fb^{-1})

  -LHeC operation beyond or after HL-LHC operation will imply significant operational cost overhead for LHC consolidation

LHeC Options: Executive Summary

LHeC

Ring-Ring option:

-We know we can do it: → LEP 1.5

-Challenge 1: integration in tunnel and co-existence with LHC HW

-Challenge 2: installation within LHC shutdown schedule

Linac-Ring option:

-Installation decoupled from LHC operation and shutdown planning

-Infrastructure investment with potential exploitation beyond LHeC

-Challenge 1: technology → high current, high energy SC ERL

-Challenge 2: Positron source

LHeC CDR:

Total of ca. 500 pages: D…

•Details remain to be addressed

•Decision to focus R&D work on LR technologies over coming 4 years

→Main Conclusion so far: LHeC can be realized in parallel with HL-LHC if necessary studies are not delayed!

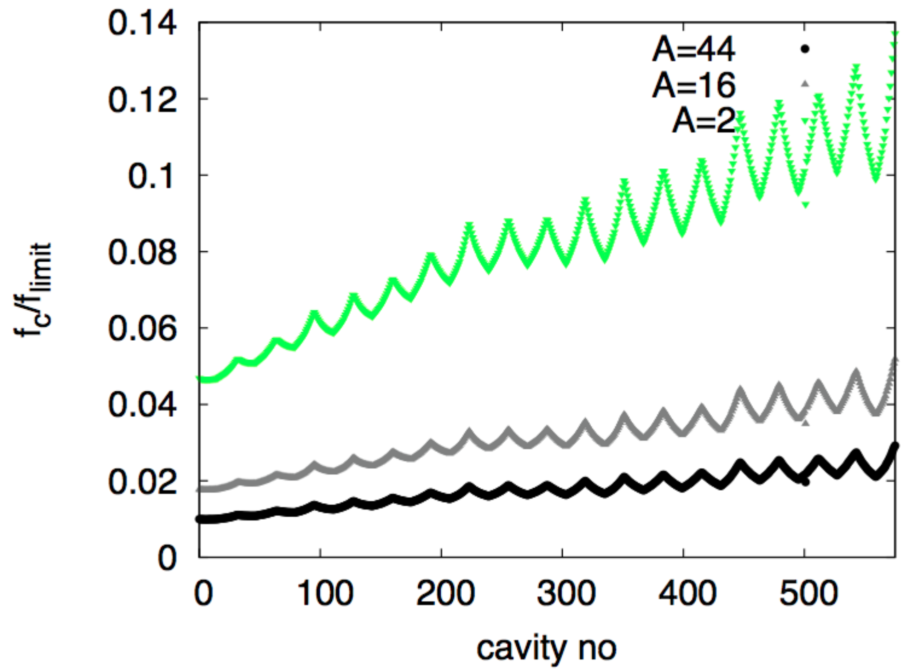
Post CDR Studies: ERL Beam Dynamics

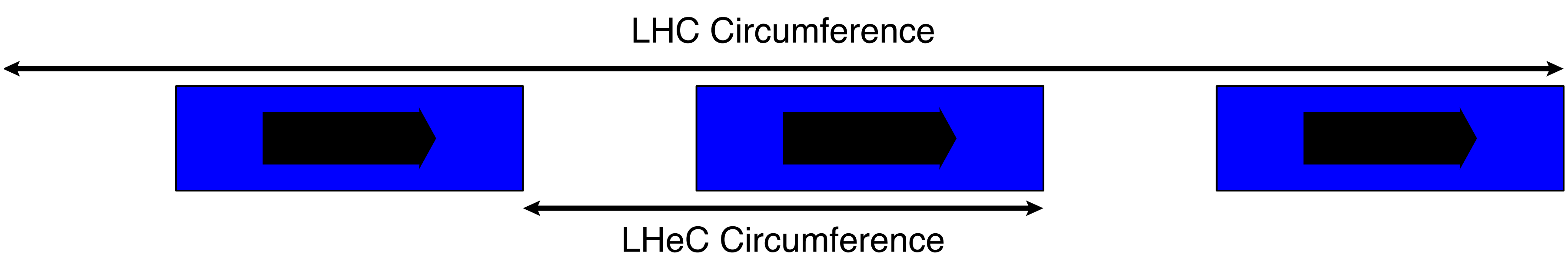
Daniel Schulte

Beam Pulses:

- Parameter list does not consider gaps in LHC beam
  - Fewer bunches with more charge
- Fast beam-ion instability may require a long gap
  - All ions are trapped in continuous beam ($f_c < f_{limit}$)
  - Beam will become unstable before neutralisation is reached
- Fix LHeC circumference to be 1/n of LHC
  - Each LHC bunch always or never collides with electron bunches

- Increase bunch charge by 50% to 3 10^9
  - Needs to be reviewed





Post CDR Studies: ERL Beam Dynamics

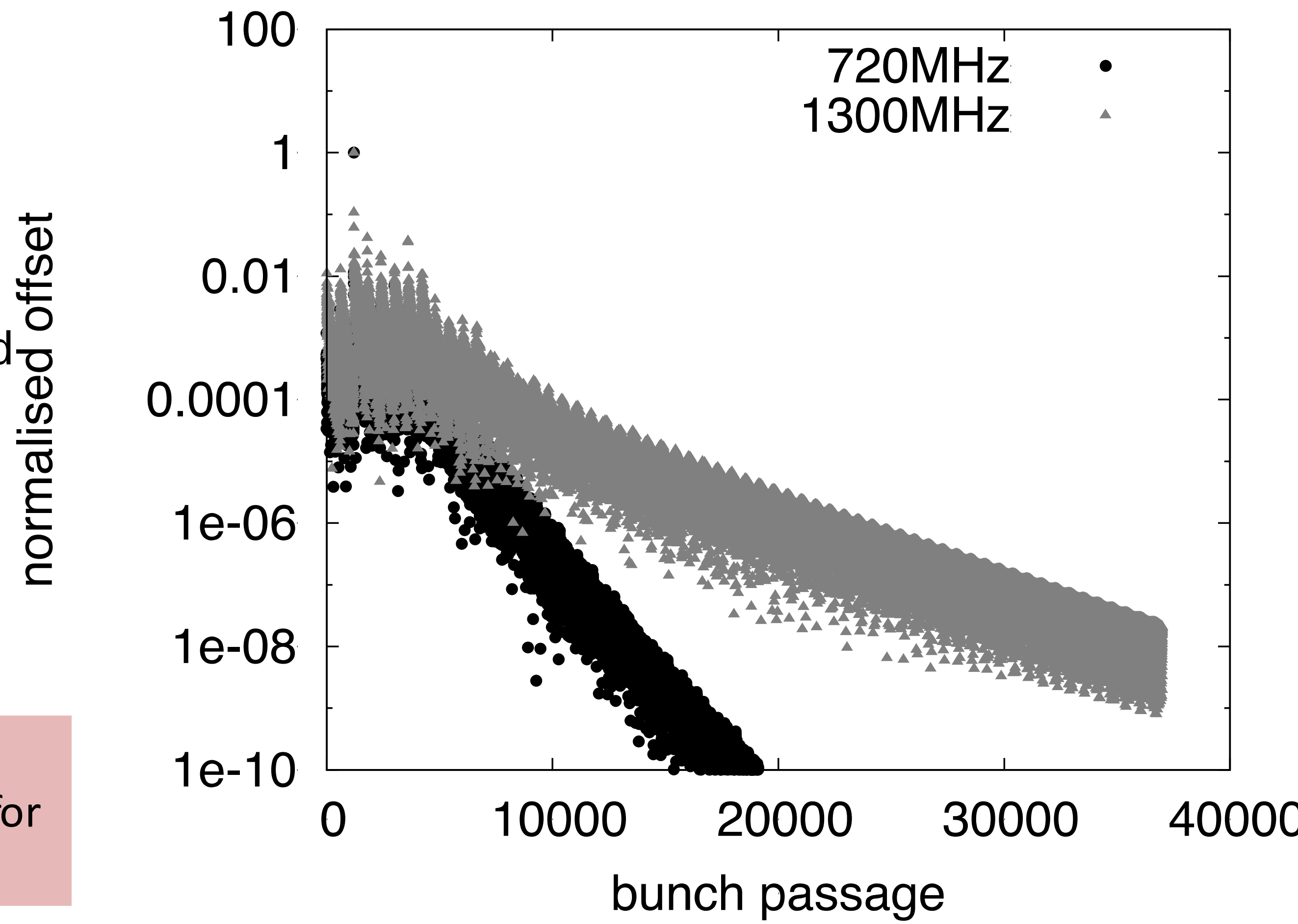
Beam Instabilities:

Daniel Schulte @ LHeC Seminar 12. March 2013

Increased bunch charge
To allow for ion-clearing gaps
N=3 10^9

Note: bunches were placed in the gaps

F_{rms}=1.05 for ILC cavity
F_{rms}=1.001 for SPL cavity



Beam is stable for both cases but more margins for lower RF frequency

→ Optimum choice for LHeC RF frequency?

Post CDR Studies: ERL Beam Dynamics

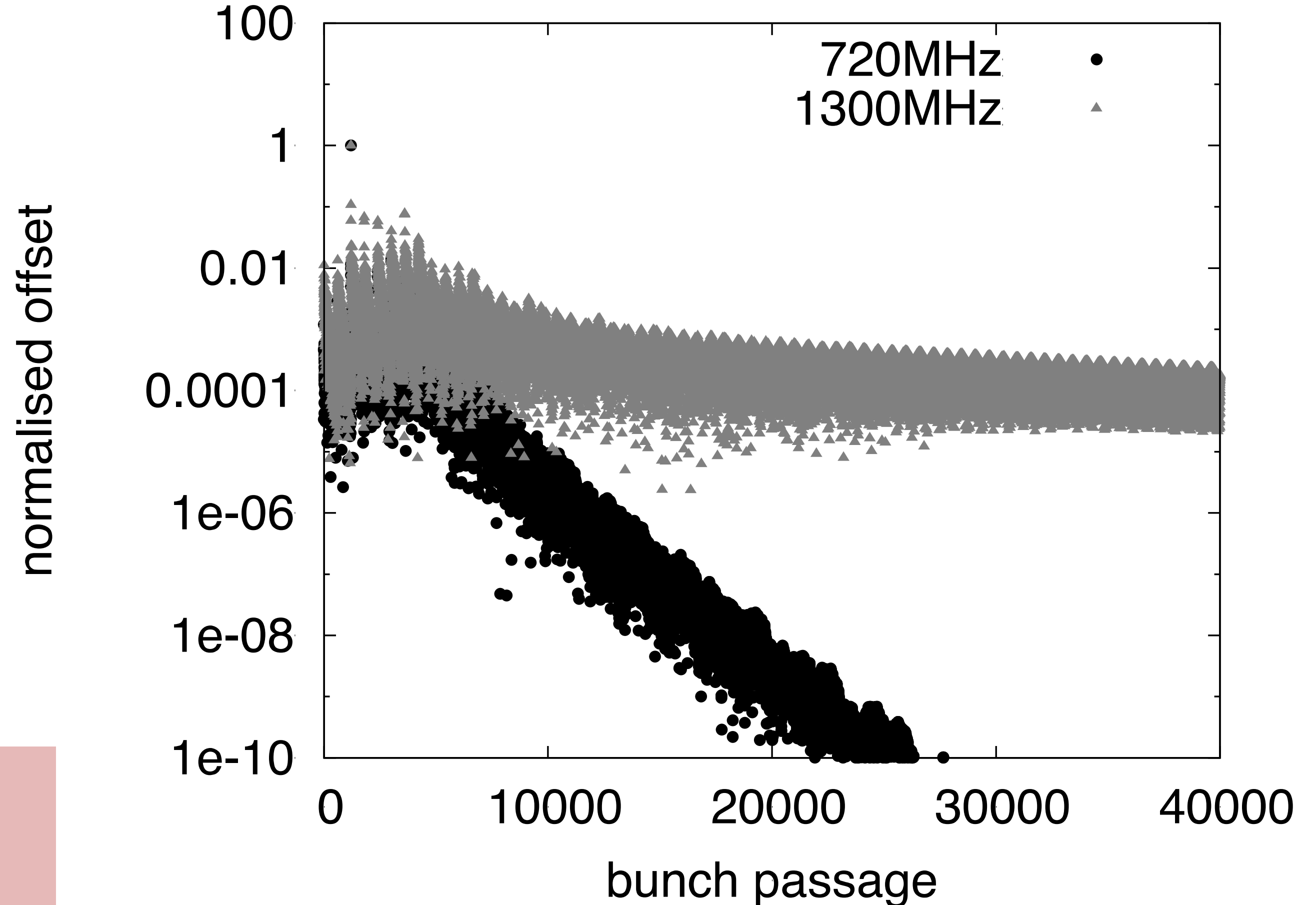
Beam-Beam effects:

Daniel Schulte @ LHeC Seminar 12. March 2013

$N=3\ 10^9$
Beam-beam effect included as linear kick

Result depends on seed for frequency spread
"worst" of ten seed shown

F_{rms}=1.135 for ILC cavity
F_{rms}=1.002 for SPL cavity



Beam is stable but very small margin with 1.3GHz cavity

→ Optimum choice for LHeC RF frequency?

Post CDR Studies: RF Frequency

LHeC

Review of the SC RF frequency:

-HL-LHC bunch spacing requires bunch spacing with multiples of 25ns (40.079 MHz)

Frequency choice: *h* * n* 40.079 MHz

Symmetry in ERL: n=3 → h * 120.237 MHz

h=6: 721 MHz or h=11: 1.323GHz

SPL & ESS: 704.42 MHz; ILC & XFEL: 1.3 GHz

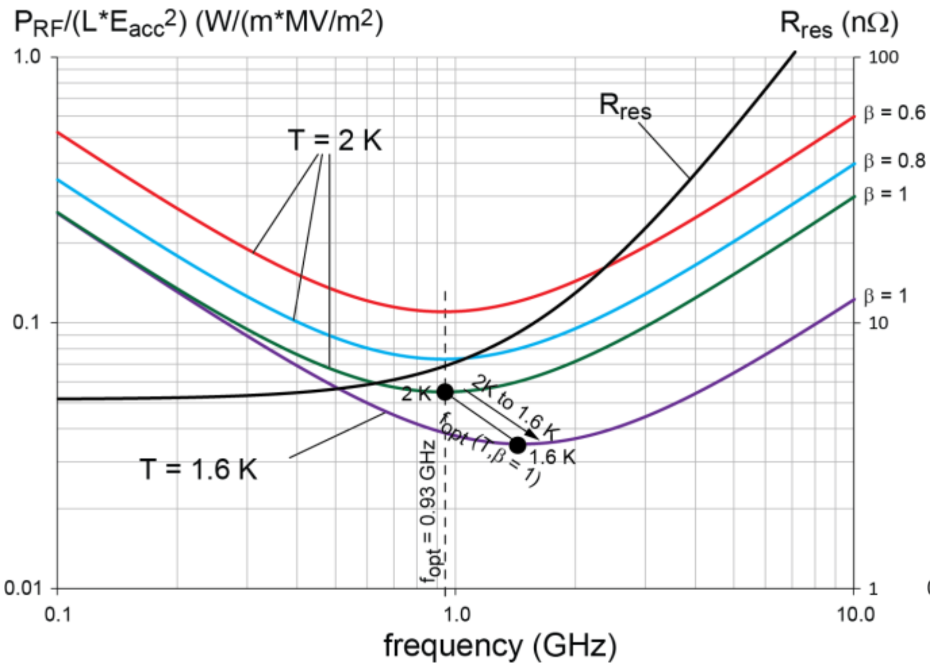
Frequencies are quite different (20MHz) from existing technologies!

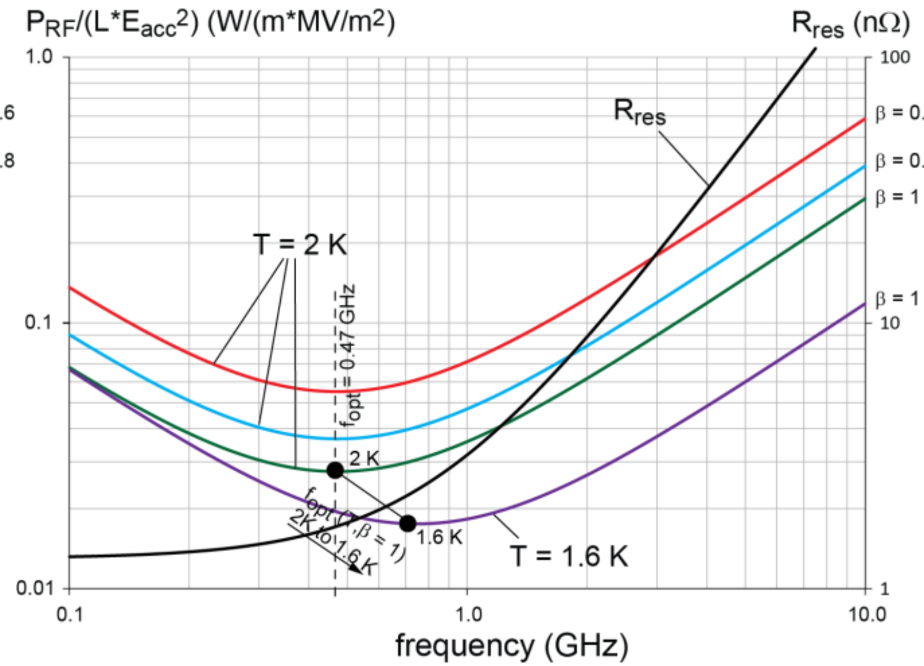
But having the harmonic number be a multiple of the ERL symmetry is not a strong requirement → asymmetric bunch patterns

Optimum RF Frequency: Power Considerations

Results from F. Marhauser

Erk Jensen at Daresbury meeting 12 March 2013





Small-grain (normal) Nb:
Optimum frequency at 2K between 700 MHz and 1050 MHz
Lower T shift optimum f upwards

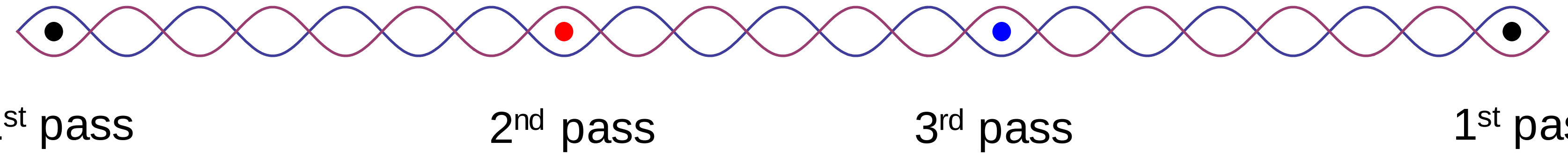
Large-grain Nb:
Optimum frequency at 2K between 300 MHz and 800 MHz
Lower T shift optimum f upwards

Optimum RF Frequency: around 800 MHz

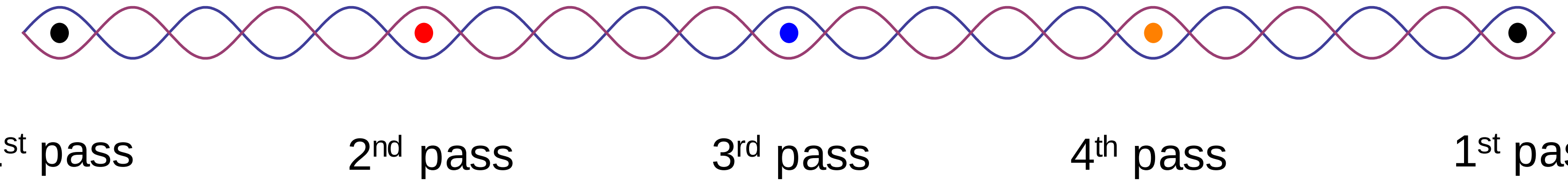
Erk Jensen @ March 2013 LHeC Seminar

- F_{RF} = 20* 40.079 MHz ➔ 801.58 MHz

➔Buckets with slightly unevenly spaced bunches



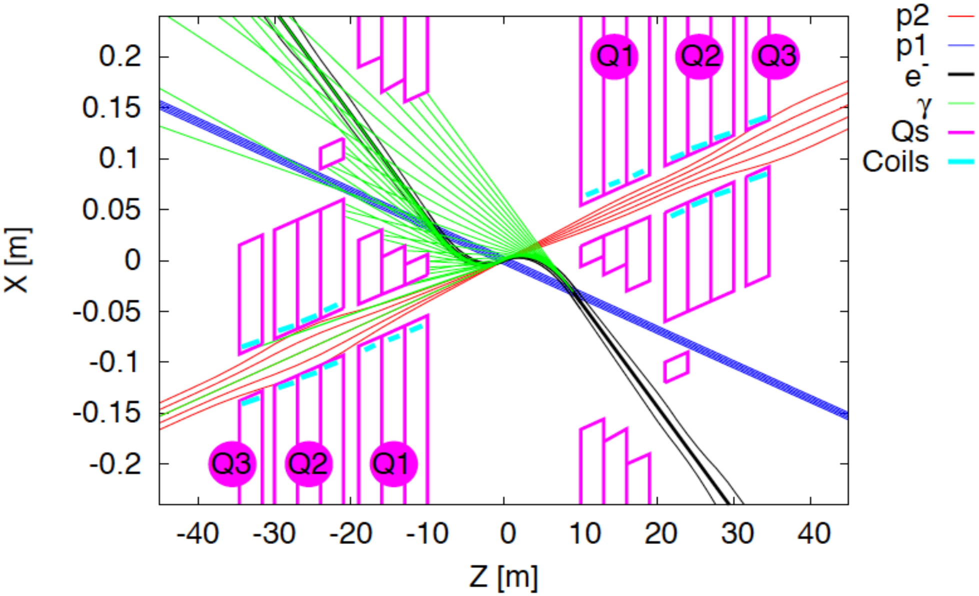
➔One could vary the number of passes through the ERL:



➔Synergy with HL-LHC: Higher Harmonic RF System and TLEP!

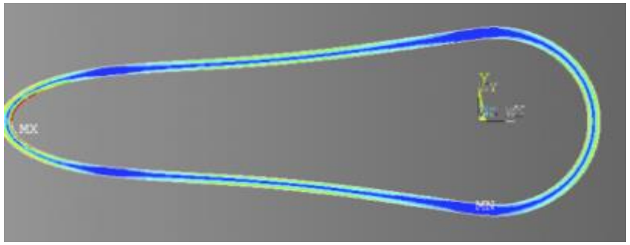
Next Steps: Interaction Region Design

LHeC



Beam pipe: in CDR 6m, Be, ANSYS calculations

Composite material R+D, prototype, support..
→ Essential for tracking, acceptance and Higgs



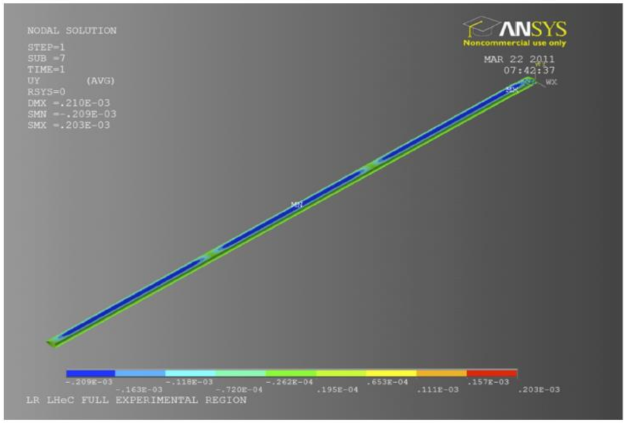


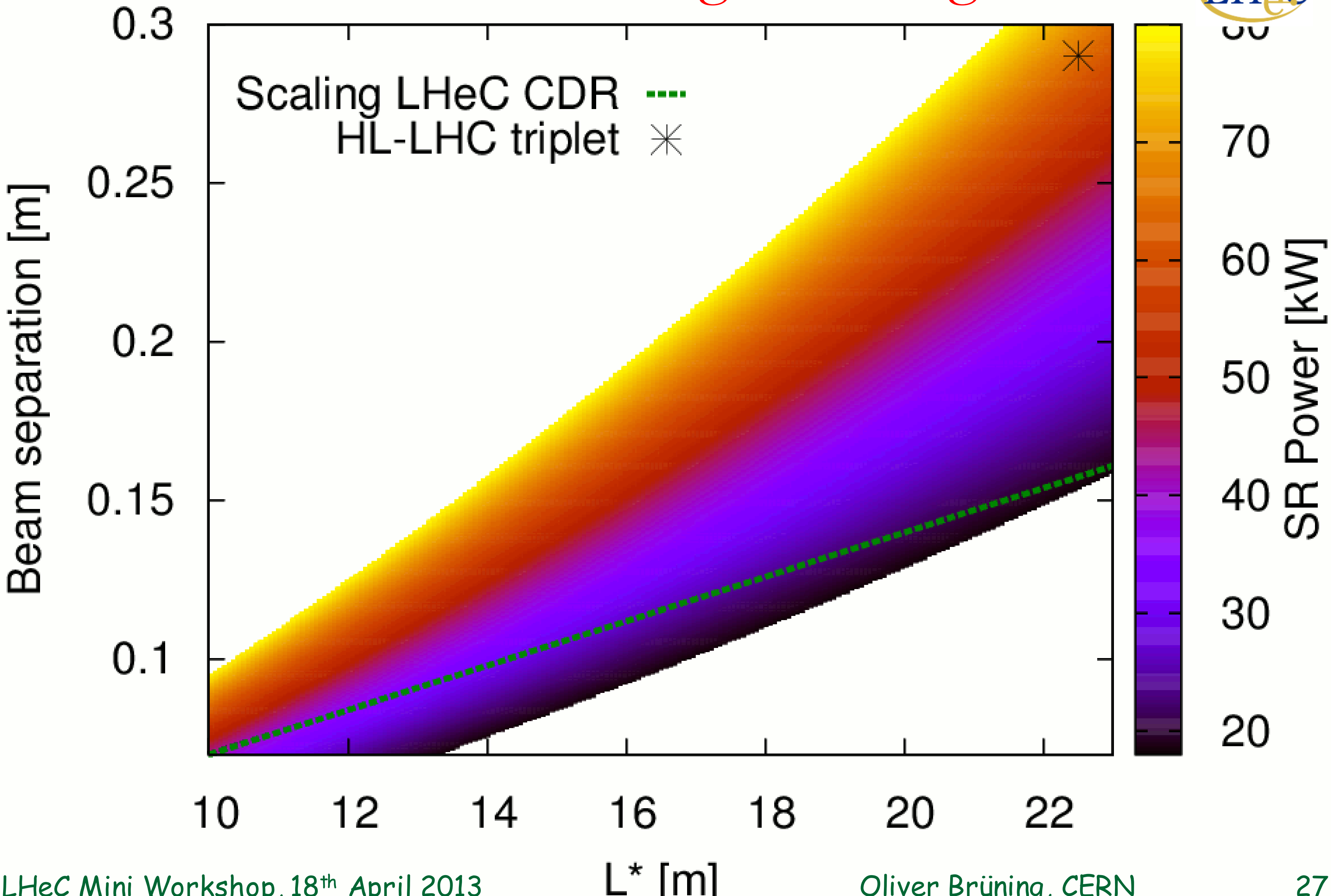
Figure 9.32: 3-D view of the LR geometry showing contours of bending displacement [m].

Have optics compatible with LHC ATS optics and β*=0.1m
Head-on collisions mandatory →
High synchrotron radiation load, dipole in detector

Adapt LHeC to LHC ATS optics
Specification of Q1 – NbTi prototype

Revisit SR (direct and backscattered),
Masks+collimators
Beam-beam dynamics and 3 beam operation studies

Interaction Region Design



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  -LHeC operation beyond or after HL-LHC operation will imply significant operational cost overhead for LHC consolidation

LHeC Tentative Time Schedule

Year	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
	RF Proto Type Development												

LHeC Project is still on track for startup with HL-LHC:

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

(Other smaller projects like ESS and PSI XFEL plan for 8 to 9 years [TDR to project start] and the EU XFEL plans for 5 years from construction to operation start)

HERA required ca.10 years from proposal to completion

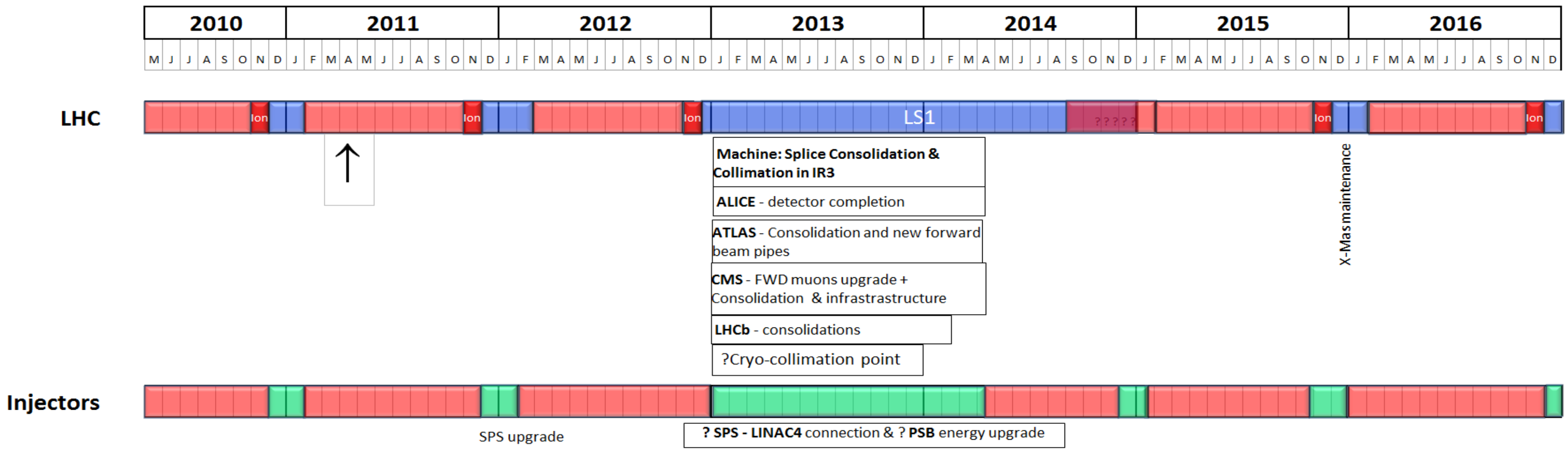
On schedule for launching SC RF development

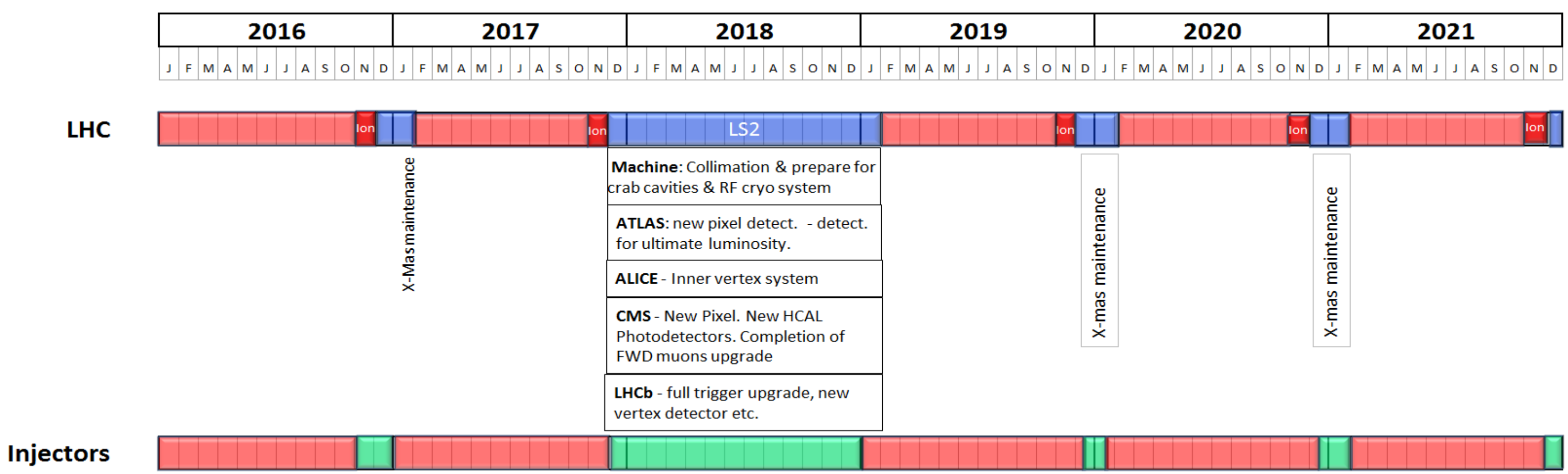
➔ Synergies with HL-LHC and TLEP

LS3 --- HL LHC

(LEP, LHC and LINAC4 at CERN and the European XFEL at DESY and the PSI XFEL). In

New rough draft 10 year plan





2022

LS3

Installation of the HL-LHC hardware

Installation of LHeC

Preparation for HE-LHC

LHeC: Post CDR Plans

LHeC

Launch SC RF and ERL R&D and Establish collaborations:

- -SC RF R&D has direct impact on cryo power consumption
  - -Synergy with HL-LHC and TLEP!
- -ERL is a hot topic with many applications
  - -Synergy with national research plans: e.g. MESA

Magnet R&D activities:

- -Normal conducting compact magnet design ✔
- -Superconducting IR magnet design
  - ➔ Detailed magnet design depends on IR layout and optics
  - ➔ Optics & IR magnet design influence experimental vacuum beam pipe

LHeC: Post CDR Plans

- Develop an ERL test facility @ CERN:
  - -Beam Dynamics for ERL operation ➔ develop expertise at CERN
  - -Synergy with other research plans: SC RF and TLEP

Next Steps: RF Prototype and Test Facility

LHeC

- Develop 2 RF Cryomodule Prototypes over the nest 3 years

  -LHeC RF frequency choice driven by power considerations

  ➔ Choice of ERL RF frequency: 801.58 MHz

  ➔ Synergy with HL-LHC and Higher Harmonic RF system!

- Design an ERL test facility @ CERN:

  -Optimize magnet design for ERL return arcs

- Optimize and Iterate on LHeC ERL layout:

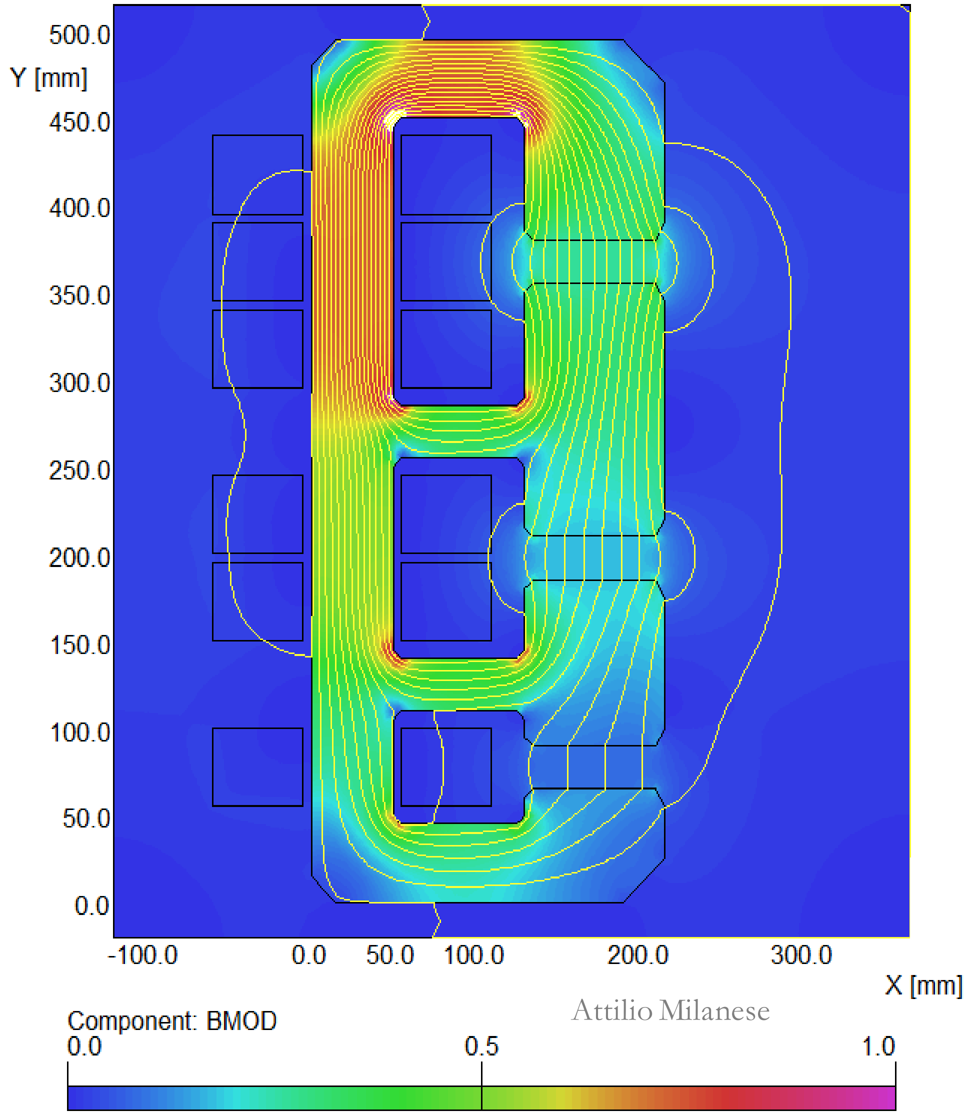
  -Optimization of linac configuration & of number of passages

  -Optimization of Civil Engineering layout

  -Optimization of Interaction Region (L^*) and Synchroton Light

Reserve Transparencies

Next Steps: Test Facility and Magnets



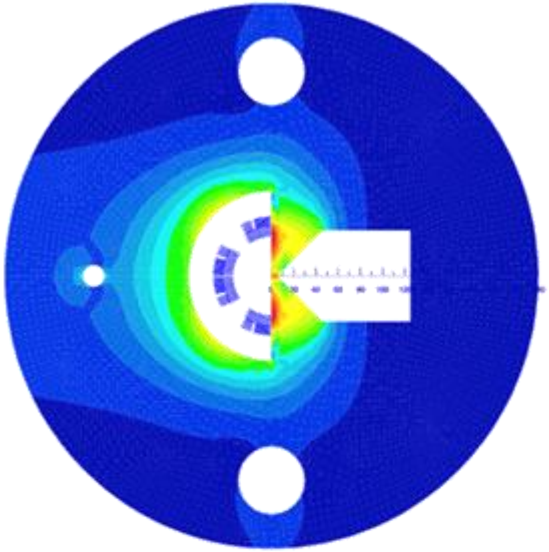
Attilio Milanese

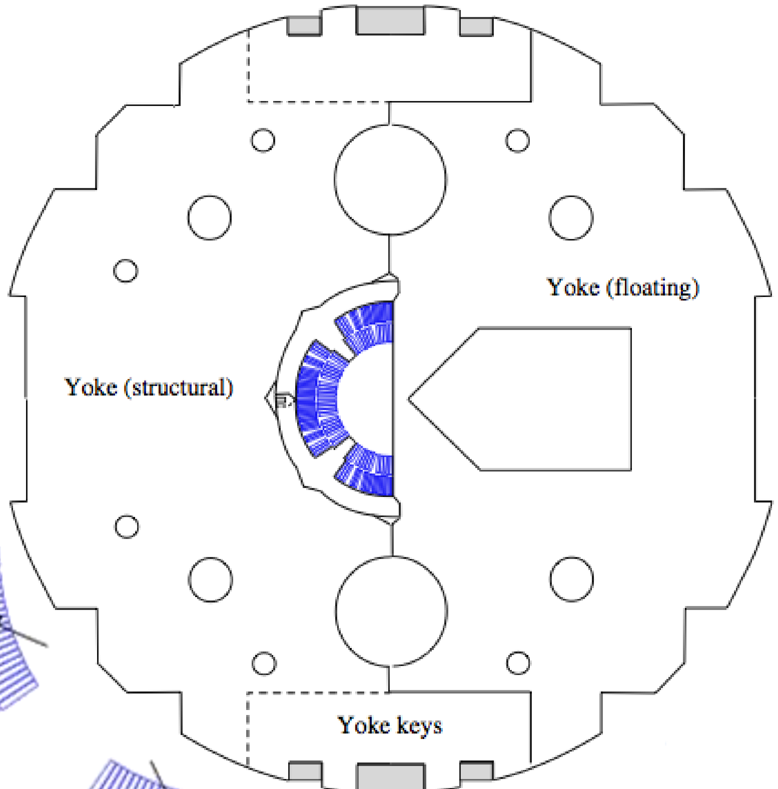
First conceptual cross-section

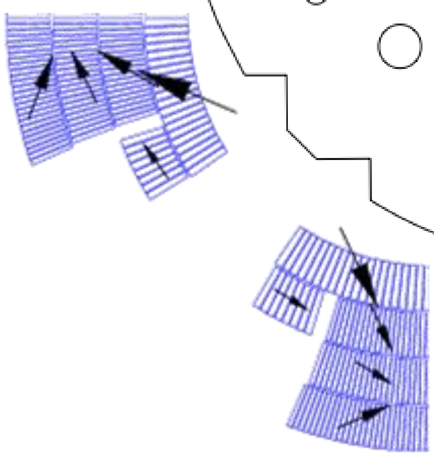
flux density in the gaps	0.264 T 0.176 T 0.088 T
magnetic length	4.0 m
vertical aperture	25 mm
pole width	85 mm
number of magnets	584
current	1750 A
number of turns per aperture	1 / 2 / 3
current density	0.7 A/mm[2]
conductor material	copper
resistance	0.36 mΩ
power	1.1 kW
total power 20 / 40 / 60 GeV	642 kW
cooling	air

Next Steps: LHeC IR Quadrupole

Luca Bottura @ Chamonix 2012





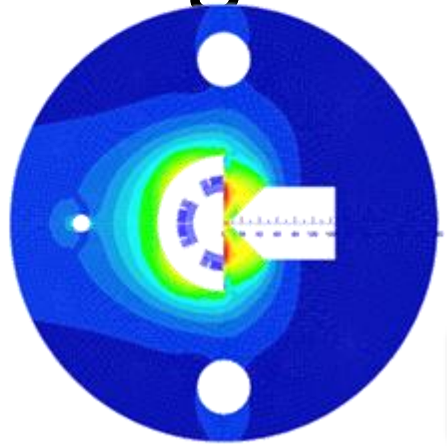


- Half-quad with field-free region, assembled using MQXC coils
  - 2.5 FTE
  - 500 kCHF
  - approx. 2 years till test

Large forces on the magnetic wedge (> 50 tons/m)

IR magnets

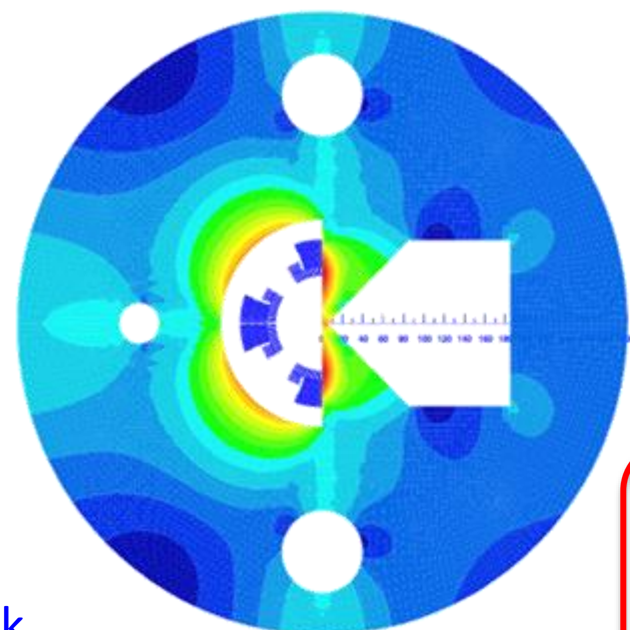
- Ring-ring
  - G=140 T/m
  - A=70 mm
  - **B_{fringe} = 30 mT**
  - **O(15) kW SR power in the proton aperture**

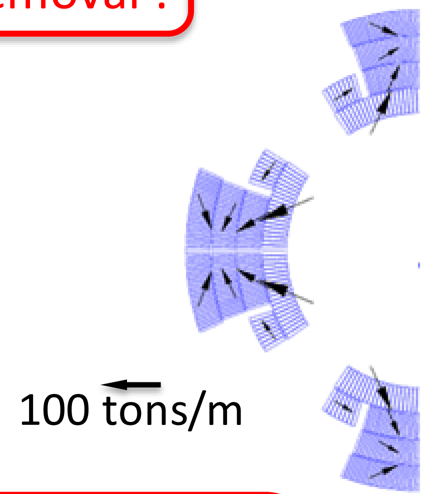


NbTi suitable for this *medium gradient* option

Mechanics ?
Heat removal ?

- Linac-Ring
  - **G=250-300 T/m**
  - **A=90 mm**
  - B_{fringe} = 500 mT
  - **O(2) kW SR power in the proton aperture**

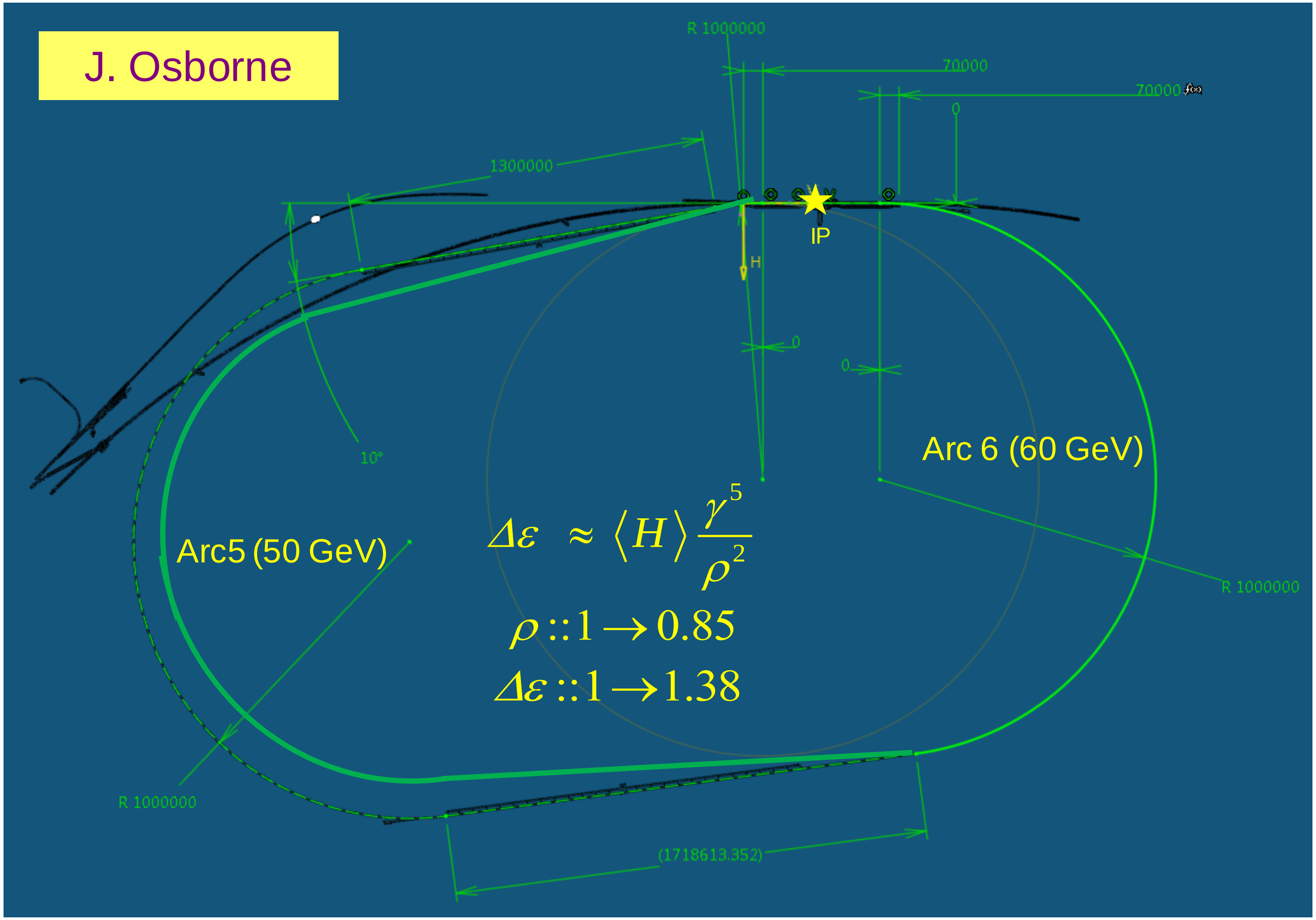




NbTi or Nb3Sn ?
Large aperture ?
Mechanics ?
Heat removal ?

By courtesy of S. Russenschuck

Next Steps: ERL Layout Finalization

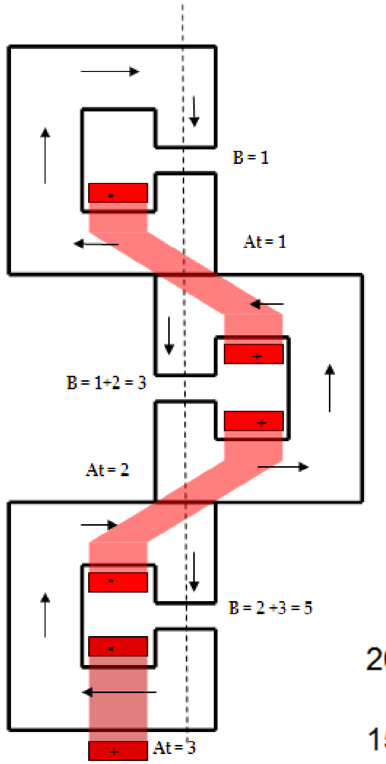


John Osborne

Next Steps: Test Facility and Magnets

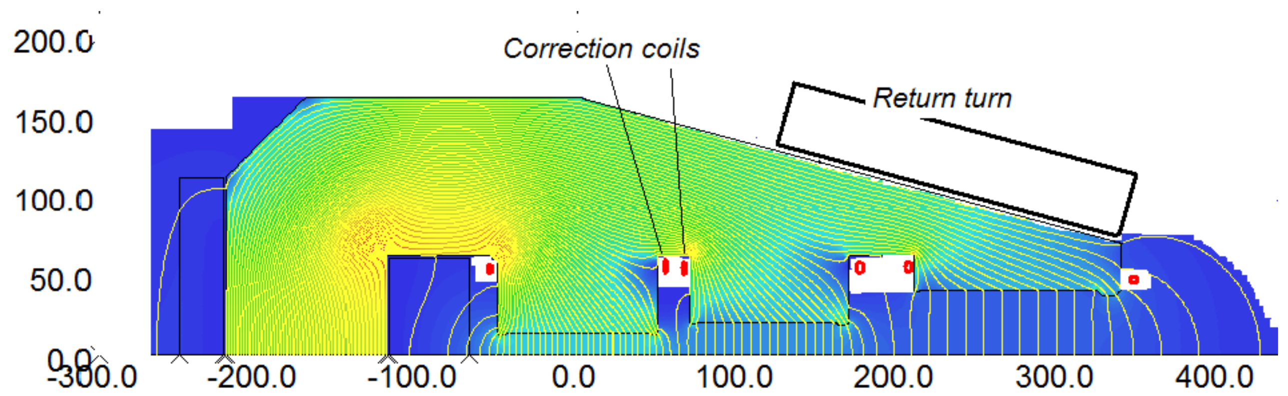
Intend to build Collaboration of CERN Magnet Group for the dipole and possibly further arc magnets for the Test Facility (two turns) and the LHeC.

Initial designs for Linac magnets in CDR and further discussions/thoughts from Daresbury, CERN and BINP colleagues.



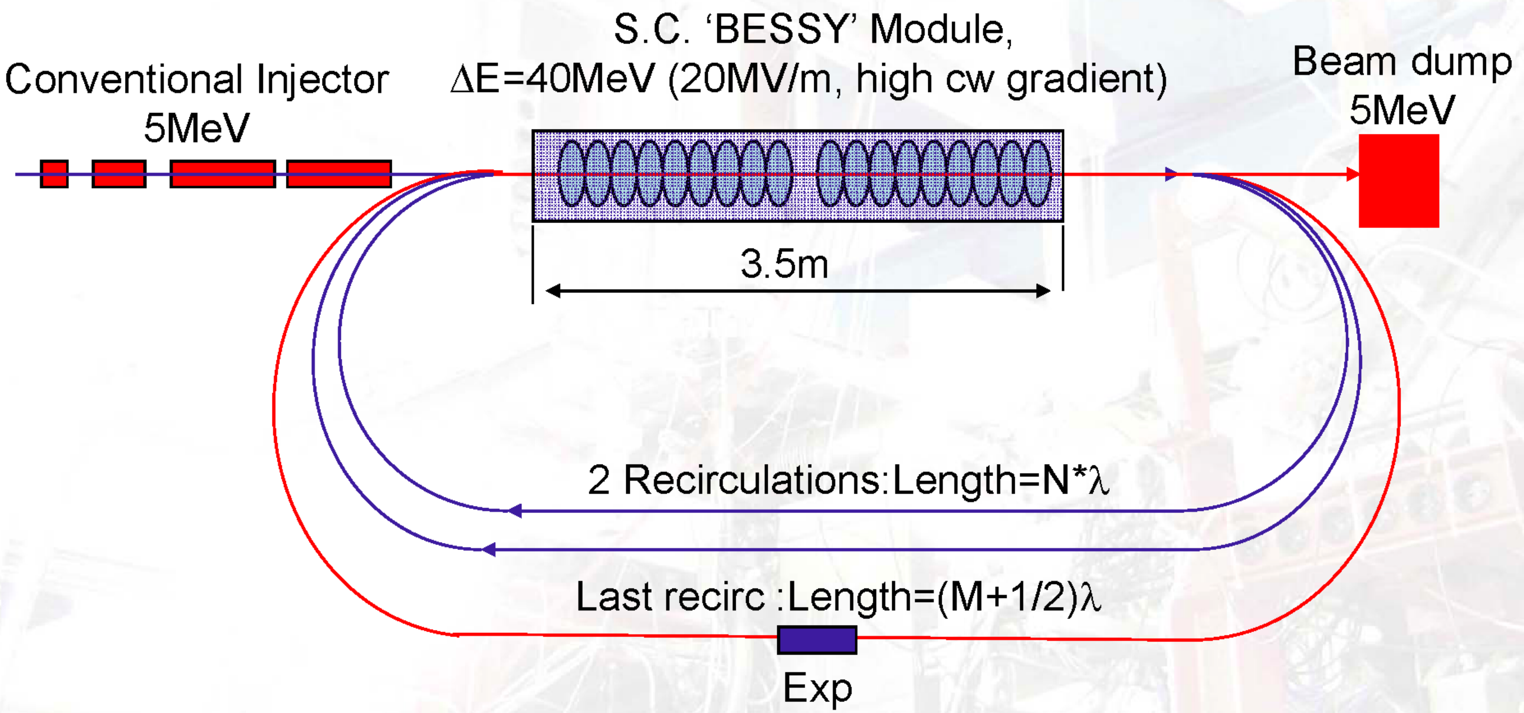
Neil Marks 7/12

Attilio Milanese and Yuri Pupkov 11/12



MESA

Mainzer Energieeffiziente Supraleitende Anlage
Mainz Energy recovering Superconducting Accelerator



Parameters: (red beam for experiments)
E_{max}= 5-125 MeV; I_{av}=10mA (cw) ; ε_{norm}=10μm, P_{dump}≤50kW, Cost <10M€
Footprint < 20*10m.

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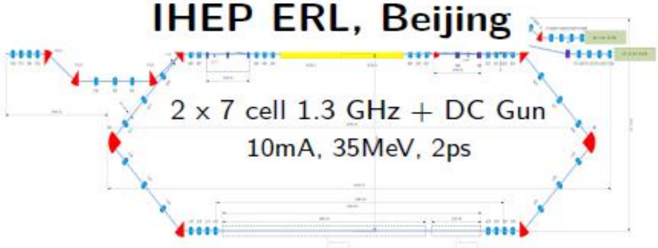
Kurt Aulenbacher: MESA: A new tool....

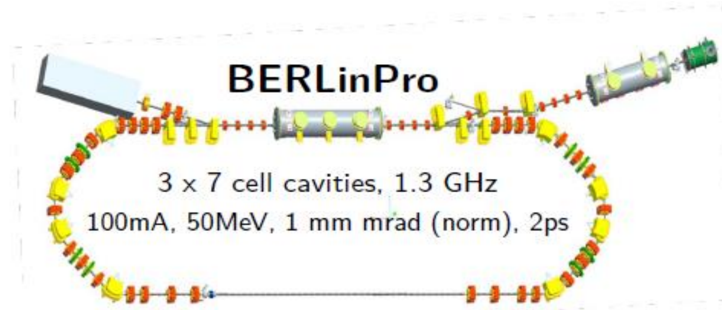
02.04.2009

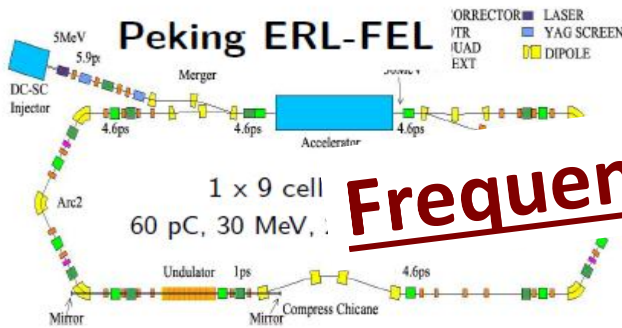
ERL Facilities around the World

LHeC

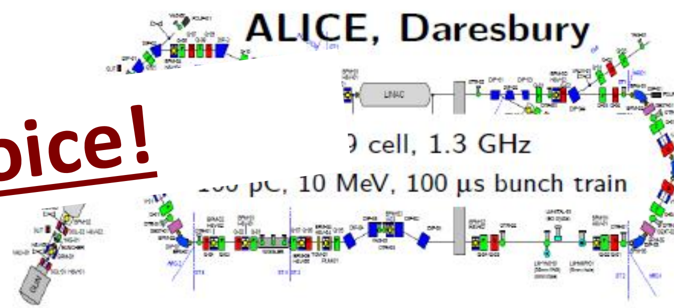
Planned Test Facilities and Installations:

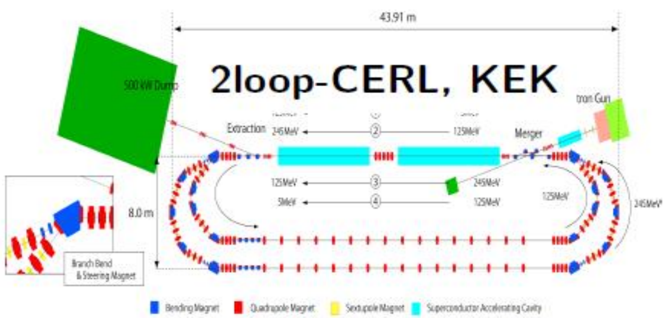






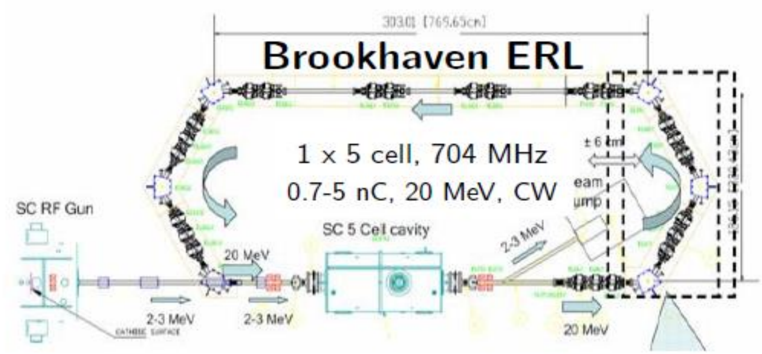
Frequency choice!





9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps

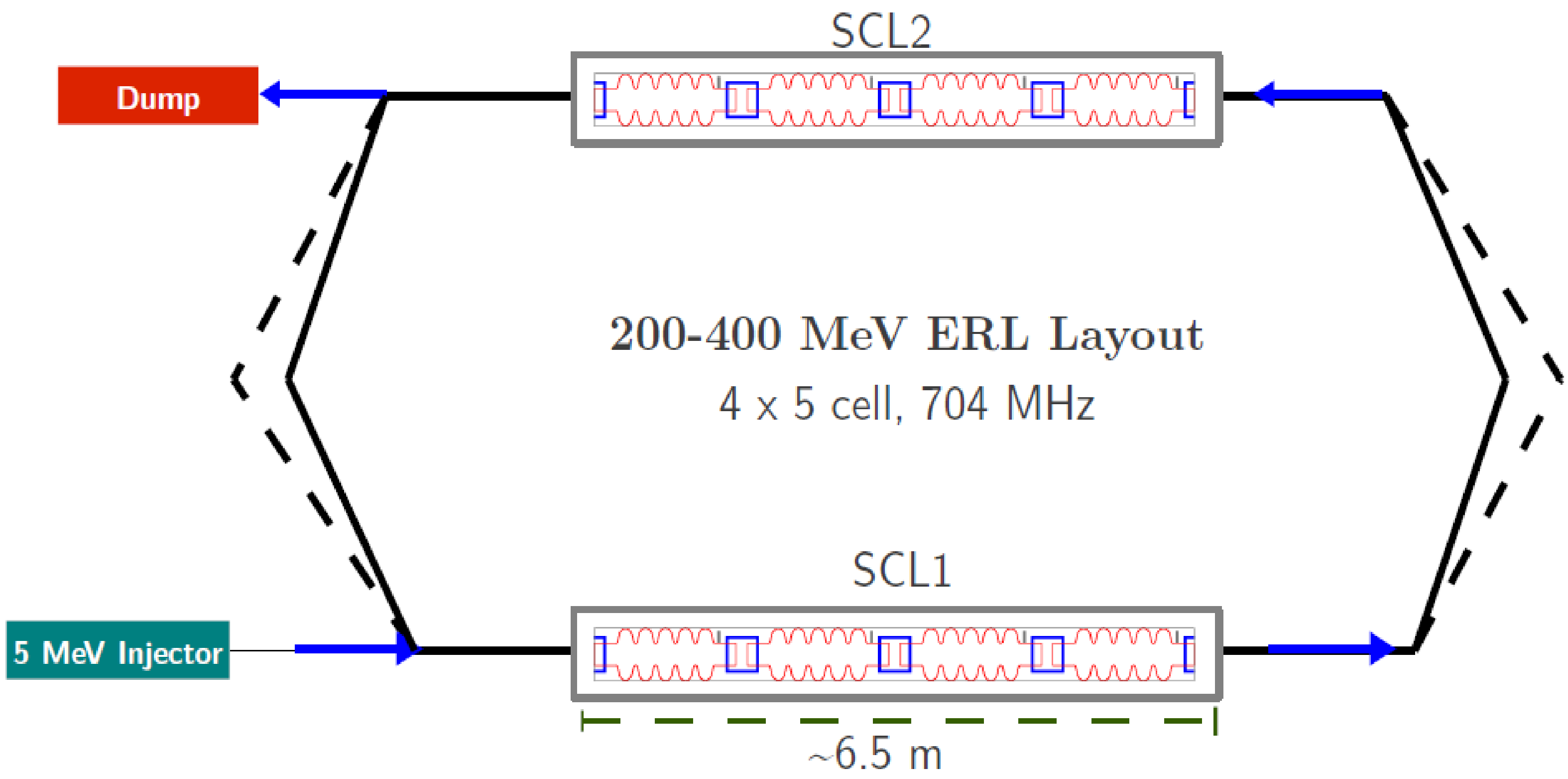


Erk Jensen

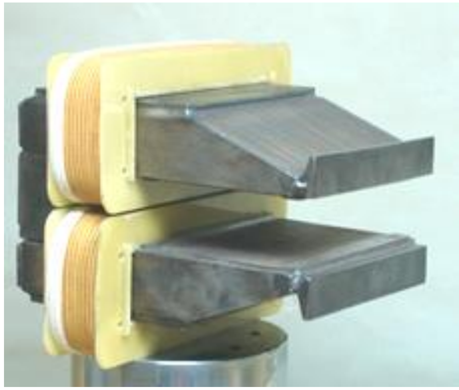
ERL Test Facility at CERN

LHeC

- Potential layout:



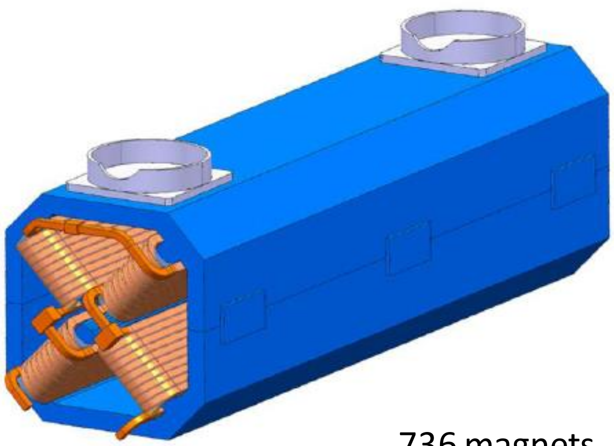
Ring: Dipole + Quadrupole Magnets



BINP & CERN prototypes

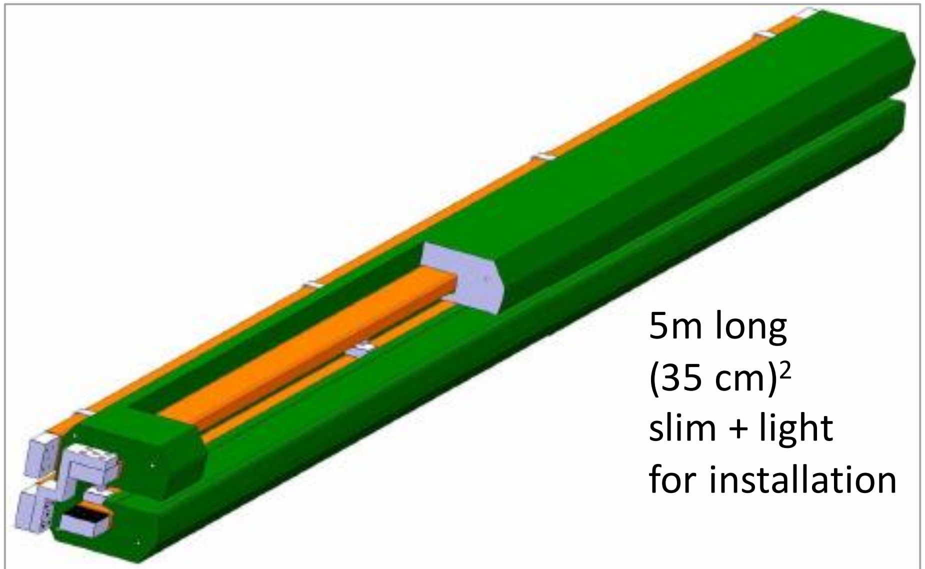
Parameter	Value	Units
Beam Energy	10-60	GeV
Magnetic Length	5.35	Meters
Magnetic Field	0.127-0.763	Tesla
Number of magnets	3080	
Vertical aperture	40	mm
Pole width	150	mm
Number of turns	2	
Current @ 0.763 T	1300	Ampere
Conductor material	copper	
Magnet inductance	0.15	milli-Henry
Magnet resistance	0.16	milli-Ohm
Power @ 60 GeV	270	Watt
Total power consumption @ 60 GeV	0.8	MW
Cooling	air or water	depends on tunnel ventilation

Table 3.2: Main parameters of bending magnets for the RR Option.



736 magnets
1.2 m long

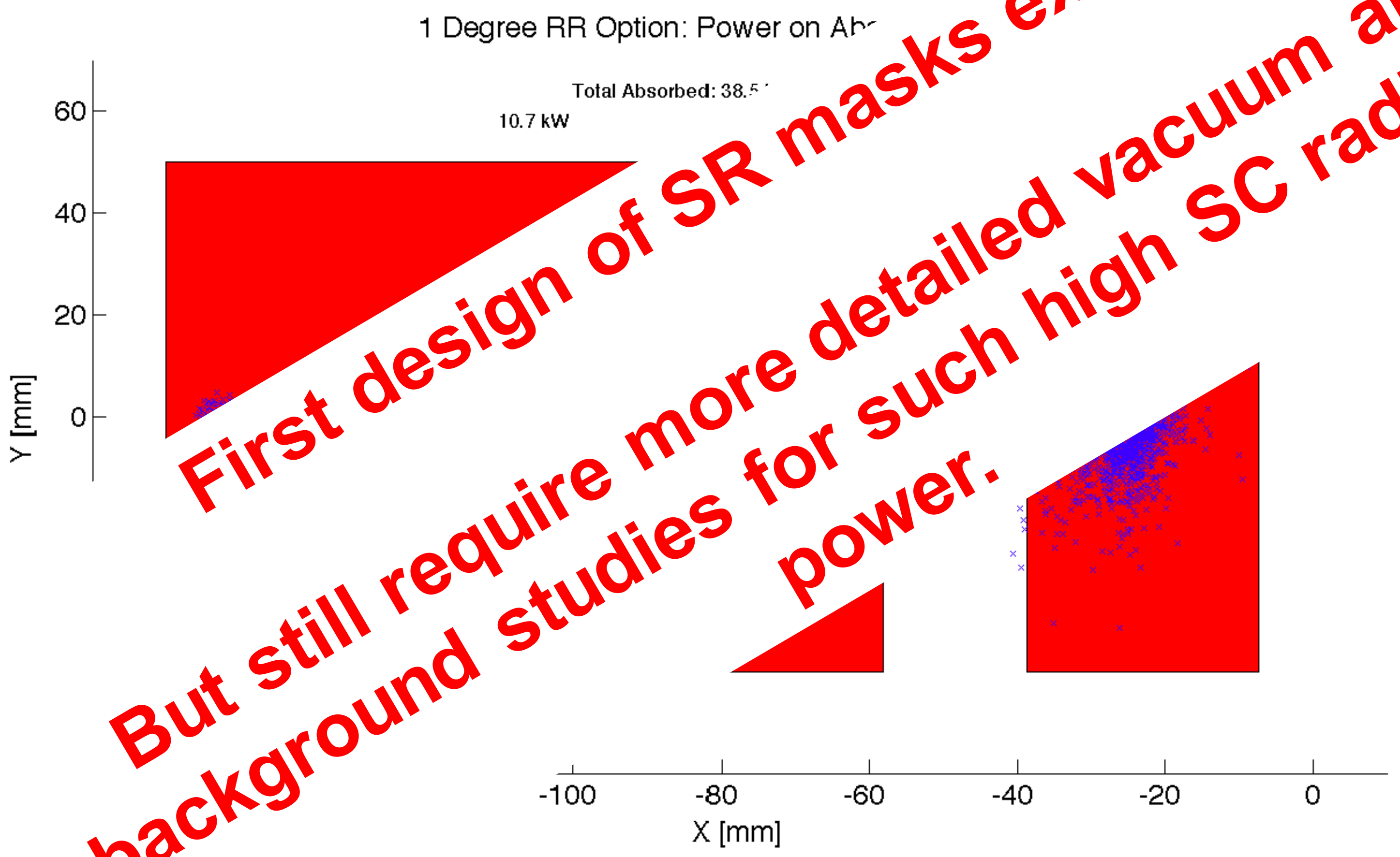
Arc quadrupole magnets for the RR Option



5m long
$(35\ \text{cm})^2$
slim + light
for installation

Interaction Region: Synchrotron R[...]tion

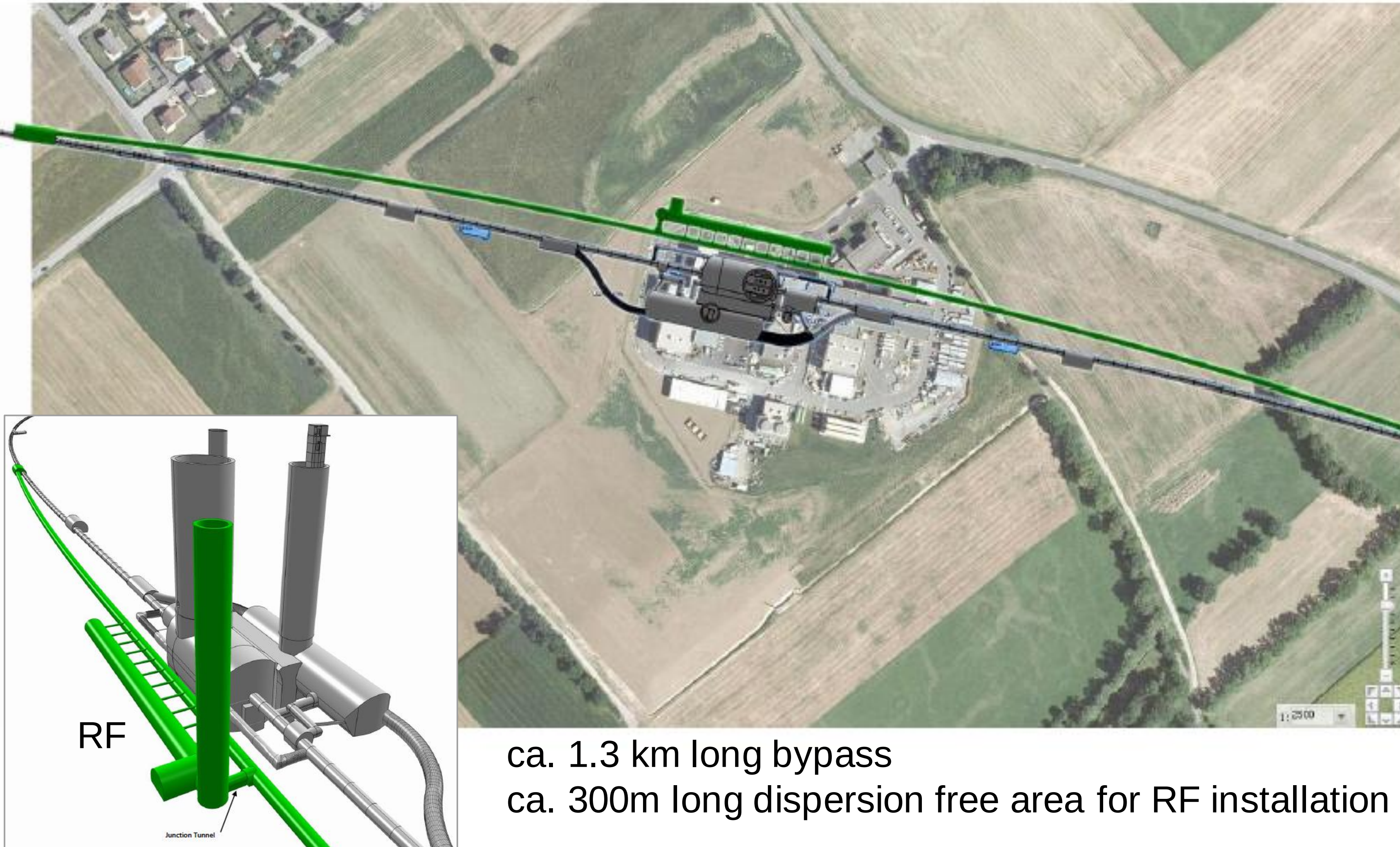
Significant power: > 20 kW. Example Ring-Ring



First design of SR masks exists.

But still require more detailed vacuum and background studies for such high SC radiation power.

Bypassing CMS: 20m distance to Cavern



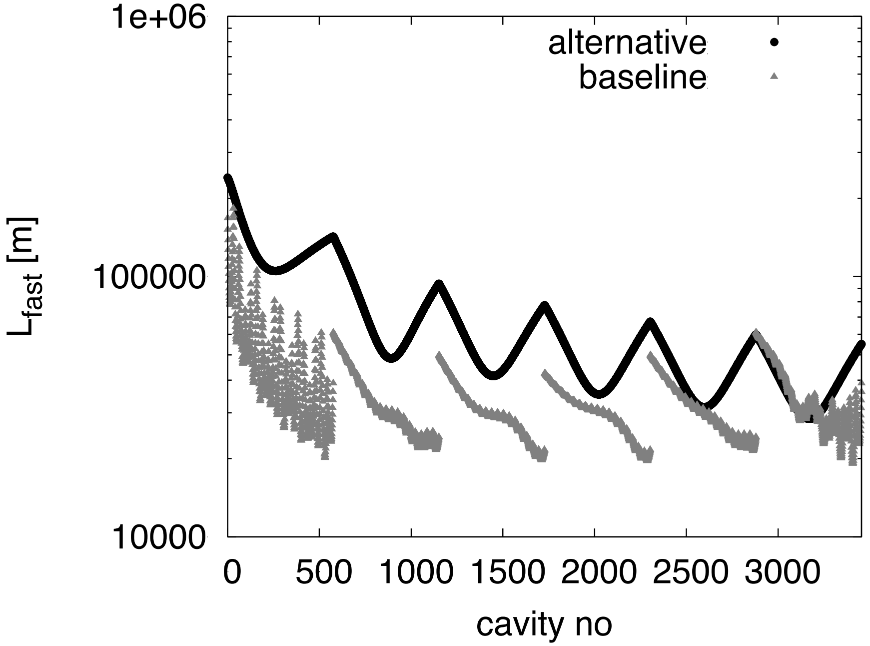
ca. 1.3 km long bypass

ca. 300m long dispersion free area for RF installation

LINAC: Beam Dynamics Issues

- Has been studied for the linacs only
  - Arcs need to be included
  - Only analytics estimates used
- Continuous beam would trap ions in the linacs
  - This would lead to unstable beam
- One 10µs long gap in beam prevents long-term tracking
  - Rise time of instability during the train between gaps seems to be acceptable (10 turns)

- Full study needed
  - Arcs will make instability worse
  - Ions are not completely lost during one passage of the gap
  - But the frequency of the induced instability varies along the machine, which helps



Design Parameters

electron beam	RR**	LR	LR*
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} $cm^{-2}s^{-1}$]	0.9	10	[illegible]
polarization [%]	40	90	[illegible]
bunch population [10^9]	20	[illegible]	[illegible]
e- bunch length [mm]	6	[illegible]	[illegible]
bunch interval [ns]	[illegible]	[illegible]	[illegible]
transv. emit. $\gamma\varepsilon_{x,y}$ [m…	[illegible]	[illegible]	[illegible]
rms IP beam si…	[illegible]	[illegible]	[illegible]
e- IP beta…	[illegible]	[illegible]	[illegible]
full…	[illegible]	[illegible]	[illegible]
geo…	[illegible]	[illegible]	[illegible]
repeti…	[illegible]	[illegible]	[illegible]
beam pu…	[illegible]	[illegible]	5
ER efficie…	[illegible]	[illegible]	N/A
average cur…	[illegible]	6.6	5.4
tot. wall plug …	[illegible]	100	100

	LR
	1.7
	3.75
	7

Final parameter set to be developed as we gain experience with LHC operational (beam-beam, spacing etc)

The goal here is to demonstrate that realistic sets exist for both LHeC versions

…servative

… also for deuterons …ew) and lead (exists)

RR= Ring – Ring
LR =Linac –Ring

Ring uses 1° as baseline: L/2
Linac: clearing gap: L*2/3

LHeC - Participating Institutes: A very rich collaboration

LHeC

CERN

SLAC NATIONAL ACCELERATOR LABORATORY

NTNU Norwegian University of Science and Technology

clic

The Cockcroft Institute of Accelerator Science and Technology

Jefferson Lab Thomas Jefferson National Accelerator Facility

ANKARA ÜNİVERSİTESİ

NİĞDE ÜNİVERSİTESİ 1992

ULUDAĞ ÜNİVERSİTESİ 1975

TOBB ETU

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Legnaro

DESY

Physique des accélérateurs

ECFA

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

UNIVERSITY OF LIVERPOOL

BROOKHAVEN NATIONAL LABORATORY

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