Summary of the Ring Linac Session

An attempt

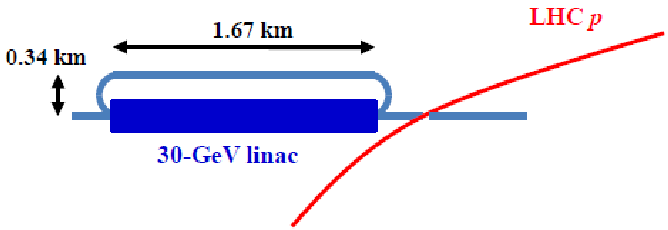
D. Schulte

On behalf of the LHeC ring-linac team

3rd CERN-ECFA-NuPECC Workshop on the LHeC
November 12-13, 2010

RF design for the linacs p-60

p-60

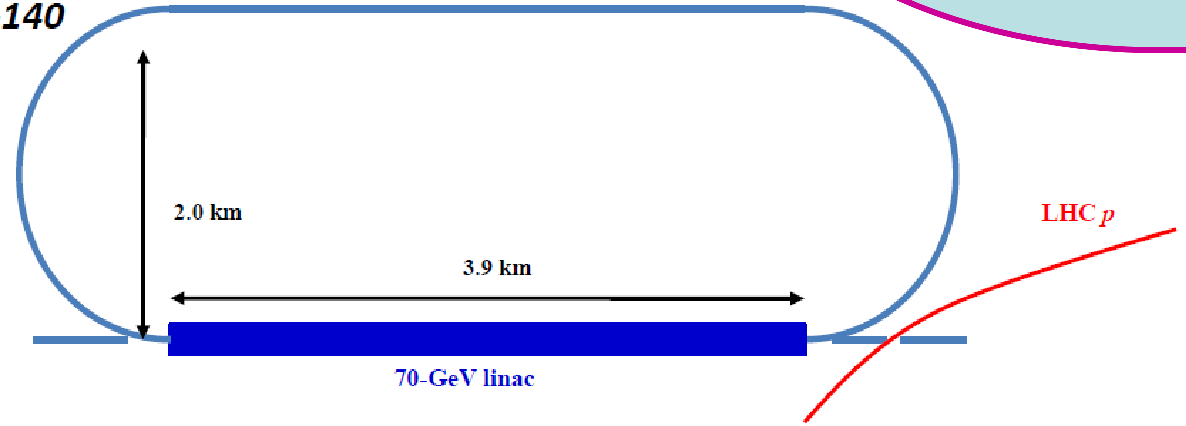


circumference = 4.4 km

erl

circumference = 8.3 km

p-140



circumference = 14.1 km

performance targets

F. Zimmermann

e- energy ≥60 GeV

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

total electrical power for e-: ≤100 MW

e^+p collisions with similar luminosity

simultaneous with LHC *pp* physics

e^-/e^+ polarization

detector acceptance down to 1°

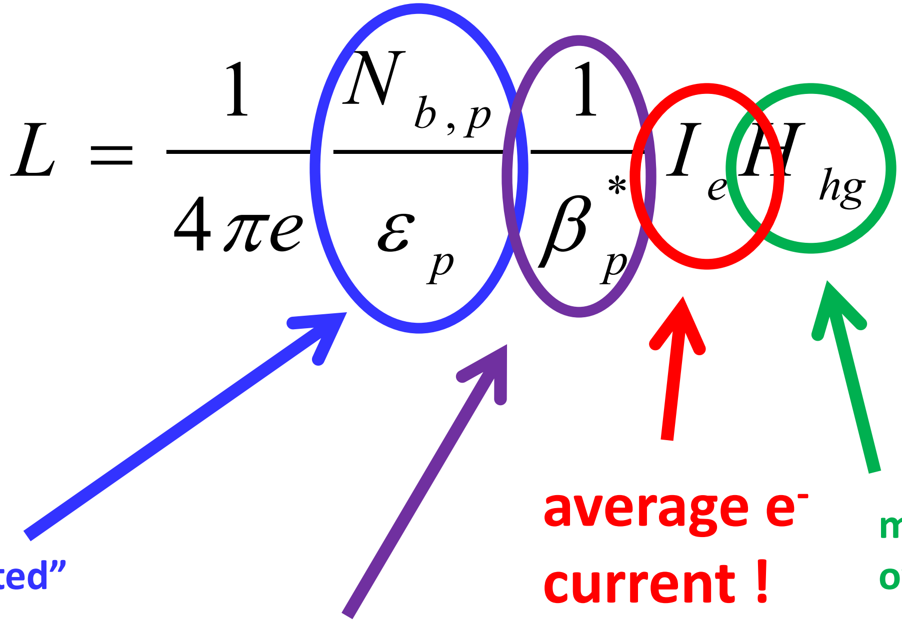
getting all this at the same time is very challenging

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

luminosity of LR collider:

F. Zimmermann

(round beams)



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

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

$\gamma\varepsilon$=3.75 μm

N_b=1.7x10^{11}

bunch spacing
25 or 50 ns

smallest conceivable
proton β* function:
- reduced *l** (23 m → 10 m)
- squeeze only one *p* beam
- new magnet technology *Nb₃Sn*

β*=0.1 m

average e$^-$
current !

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

θ_c=0

H_{hg}≥0.9

Luminosity

- 10^{33}cm^{-2}s^{-1} require 6.6mA electron current
  - At 60GeV this is about 400MW
  - With typical ineffciency at least 800MW
  - Energy recovery is needed

F. Zimmermann

- Simplified view (disregarding timing):

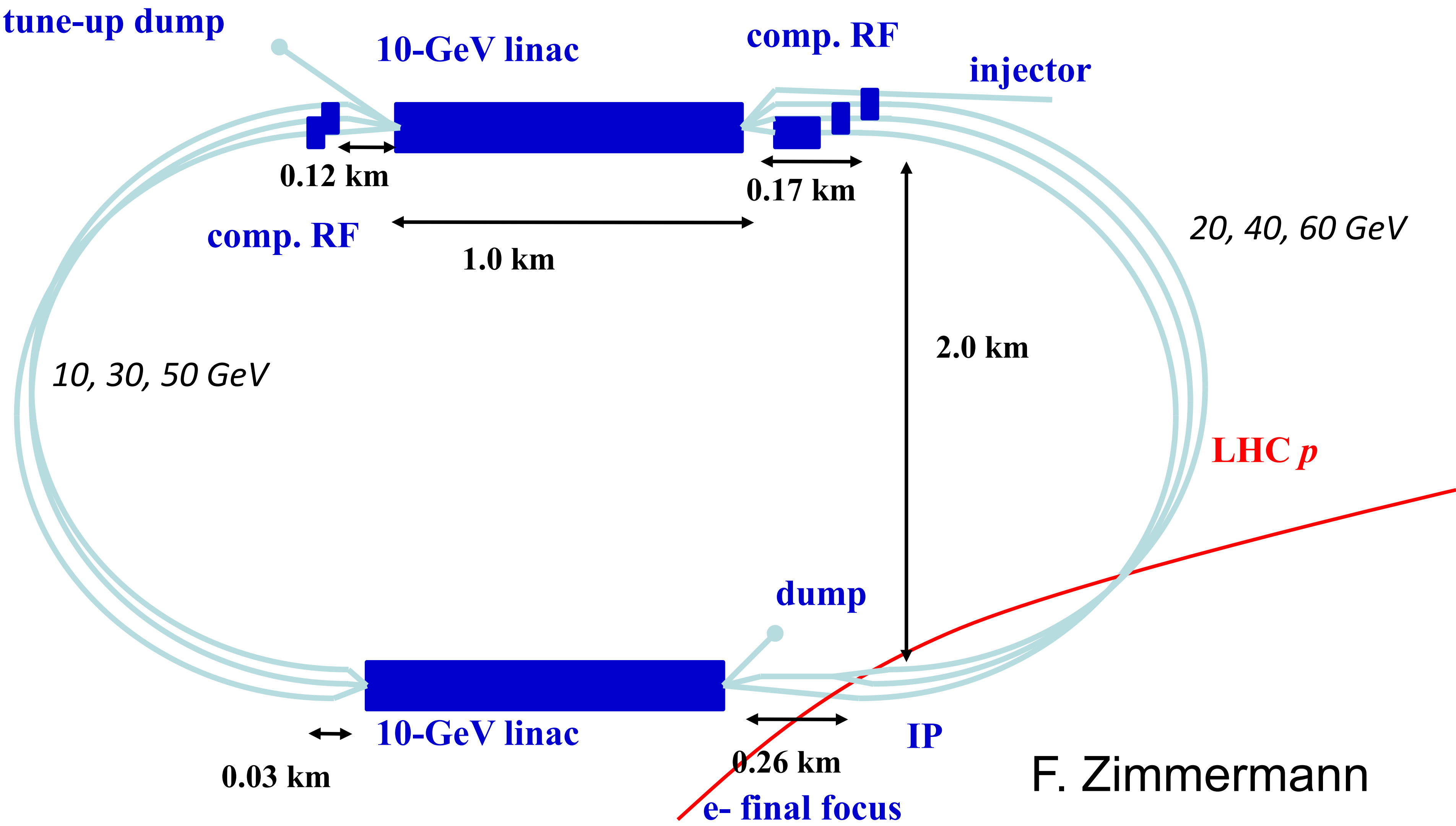
CLIC main beam ~ 0.01 mA (factor 600 missing)

lowering voltage, raise bunch charge & rep rate → 0.06 mA (NIMA 2007)

CLIC drive beam (30 mA, but 2.37 GeV)

ILC design current ~ 0.05 mA (factor ~100 missing)

ERL configuration



F. Zimmermann

total circumference ~ 8.9 km

ERL electrical site power

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

Depends on cavity performance Q_0, measurement needed

RF power to control microphonics: 22.2 MW

10 kW/m (eRHIC), experiment needed?

RF for SR energy loss compensation: 24.1 MW

energy loss from SR 13.2 MW, 50% RF efficiency, known

cryo power for compensating RF: 2.1 MW

microphonics control for compensating RF: 1.6 MW

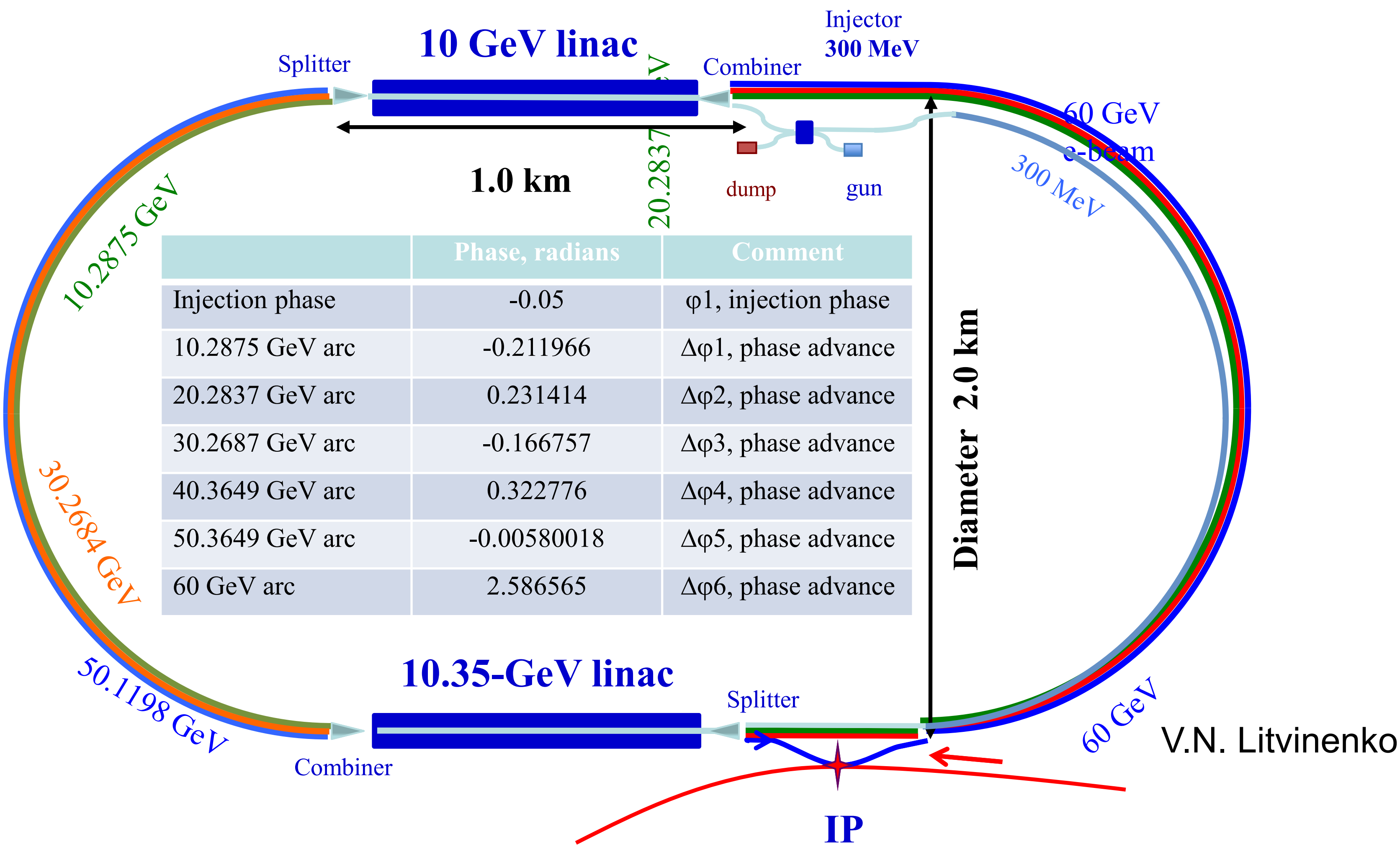
injector RF: 6.4 MW

magnets: 3 MW

grand total = 88.3 MW

New compensation scheme for SR losses with main linacs (VL)

Additional 0.4 GeV of the main RF linac (i.e. ~20 m)

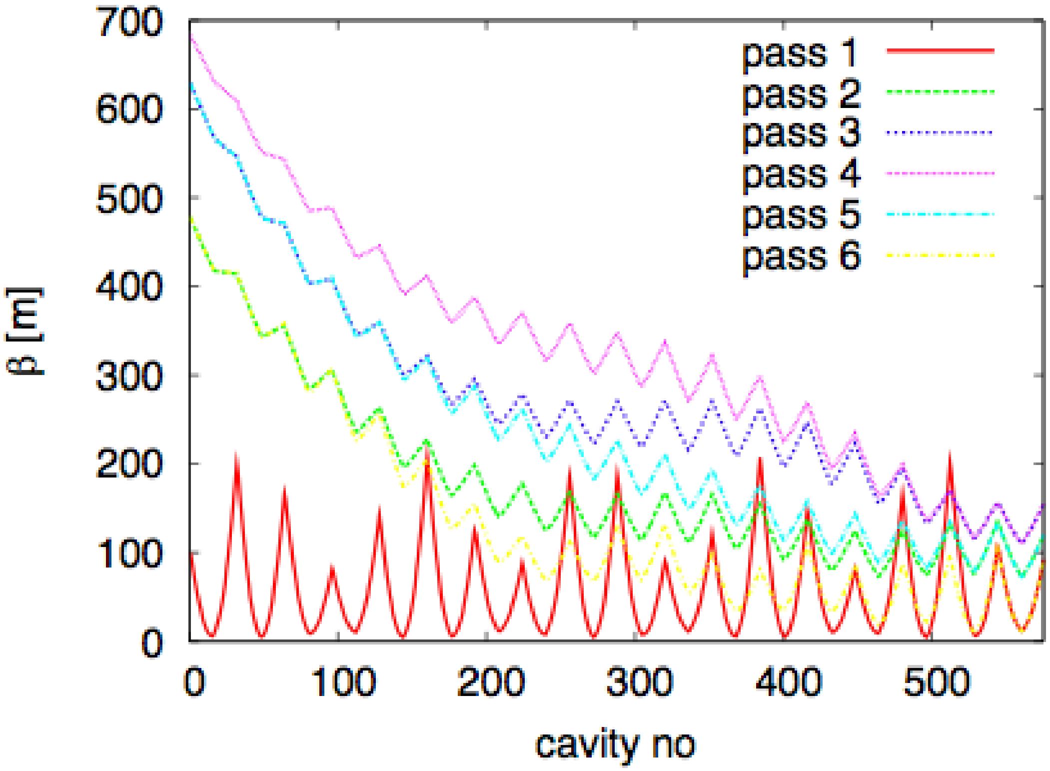


	Phase, radians	Comment
Injection phase	-0.05	φ1, injection phase
10.2875 GeV arc	-0.211966	Δφ1, phase advance
20.2837 GeV arc	0.231414	Δφ2, phase advance
30.2687 GeV arc	-0.166757	Δφ3, phase advance
40.3649 GeV arc	0.322776	Δφ4, phase advance
50.3649 GeV arc	-0.00580018	Δφ5, phase advance
60 GeV arc	2.586565	Δφ6, phase advance

The electron bunch passes through the main linacs twelve times in the following sequence of phases: -0.05, -0.261966, -0.0305519, -0.197309, 0.125467, 0.119667, 3.08786, 2.85644, 3.0232, 2.70042, 2.70622, 2.87589. Finally, linac 1 will compensate for 0.922 GeV of the energy loss, while the linac 2 will compensate for the remaining 1.144 GeV.

Main Linac Lattice Design

- Two approaches
  - option I, use focusing in the linac (A. Bogacz, F. Zimmermann, D.S.)
  - option II, no focusing in the linac (V.N. Litvinenko et al.)
- Option I
  - $12.8\,\mathrm{m}$-long cryomodules contain 8 cavities
  - two modules between quadrupoles ($28\,\mathrm{m}$ spacing)
  - gradient $\approx 17\,\mathrm{MV/m}$



- Optimisation strategy
  - chose constant phase advance for lowest energy beam
  - match transfer matrices through arcs to minimise

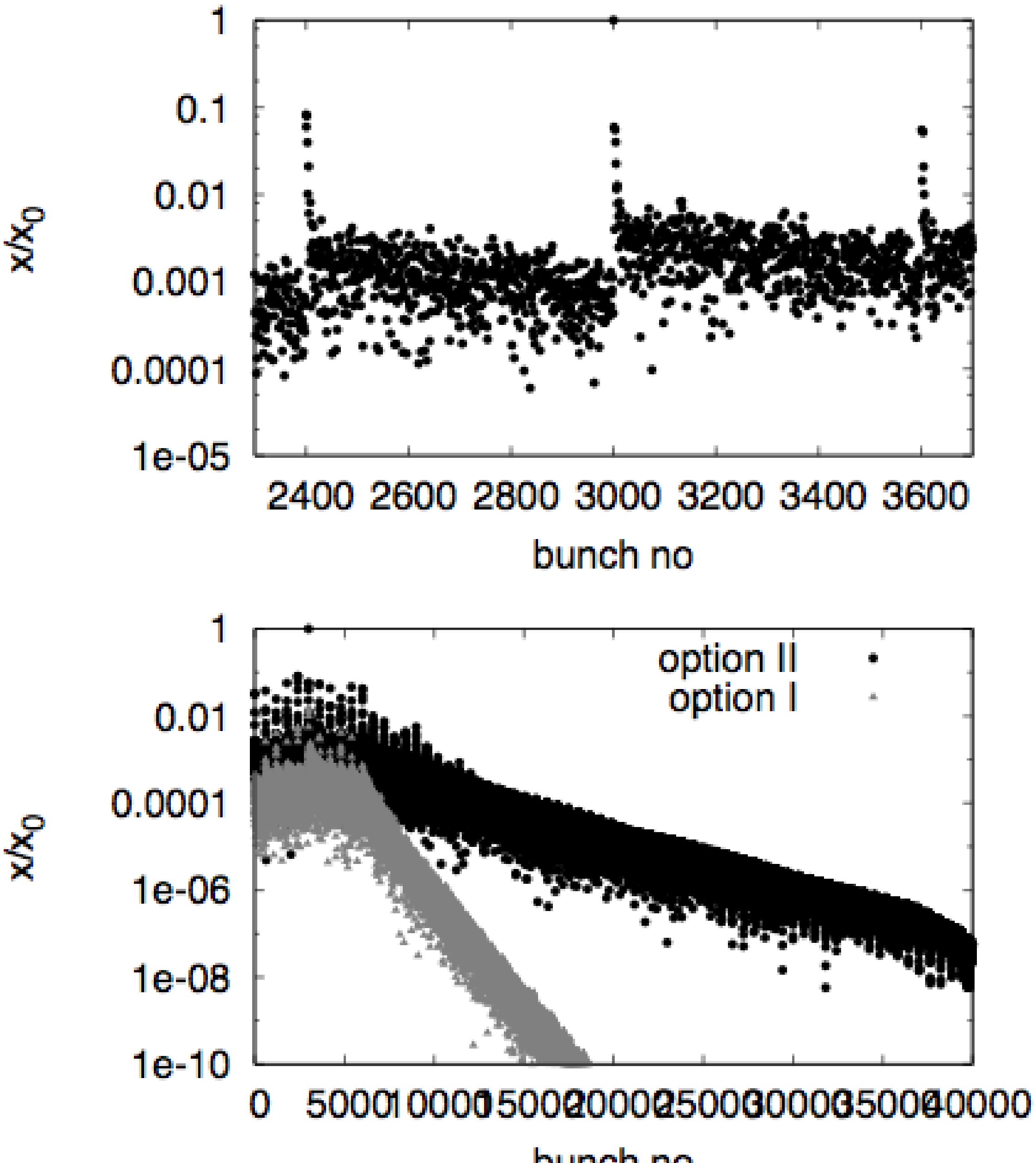
$$\int_0^L \frac{\beta(s)}{E(s)}ds$$

This minimises wakefield effects

Multi-bunch Wakefield Effects

Single bunch is also OK

- Simulation procedure
  - offset one bunch by one unit
  - track the beam
  - use the final RMS amplitudes as measure of wakefield effect
  - all done in normalised phase space
- Upper plot: ILC/TESLA wakefields, lower plot: SPL wakefields
- RMS amplitude jitter amplification
  - 0.12% with quadrupoles
  - 7% with no quadrupoles

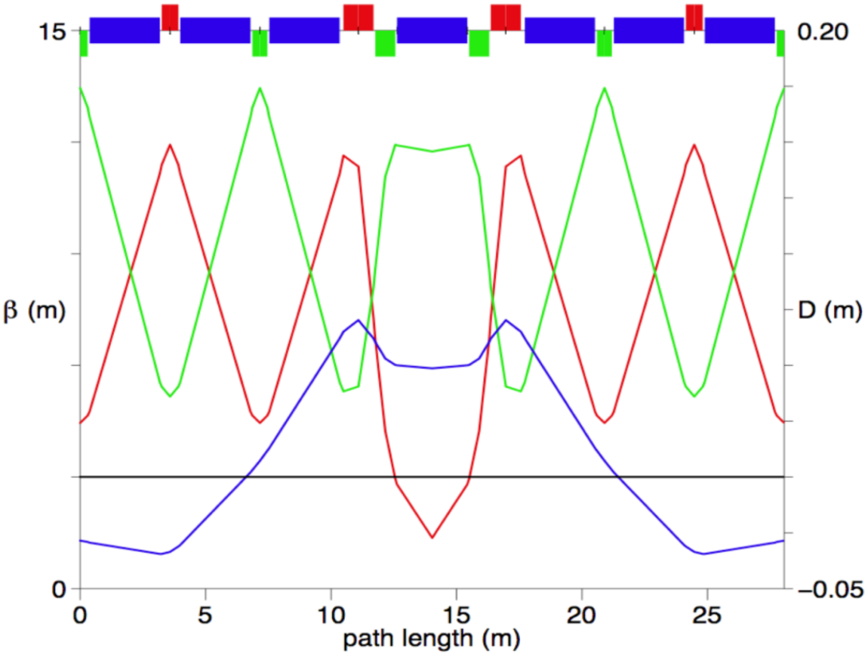


Arc's lattice

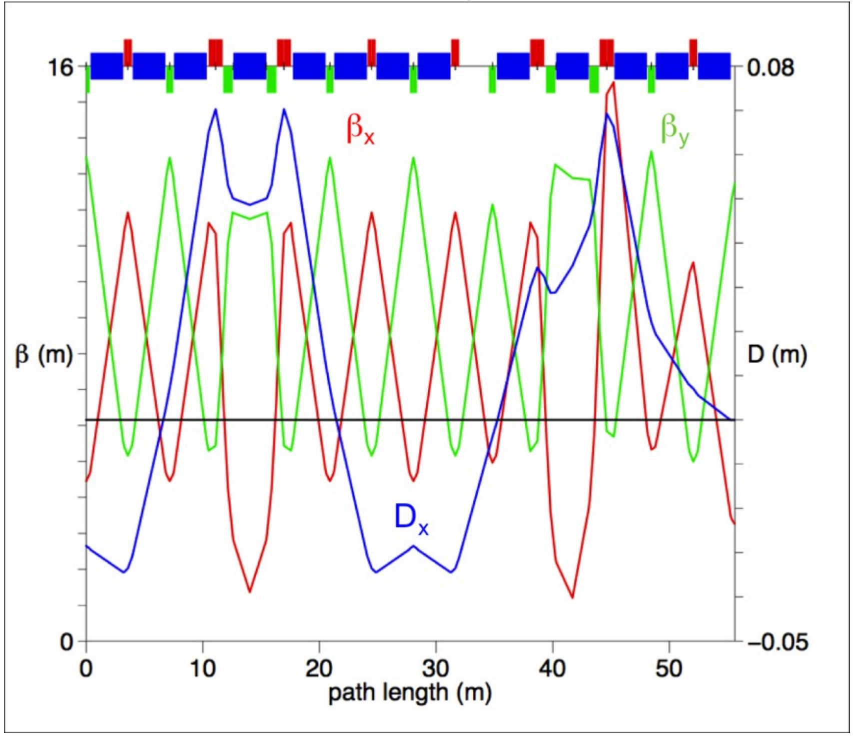
© D.Trbojevic

- Regular isochronous lattice of ERL's arcs. Length of cell is 27.8017 m. Red line – horizontal β-function, green - vertical β-function, blue – dispersion.

- The regular and the end of the arc cell lattice.

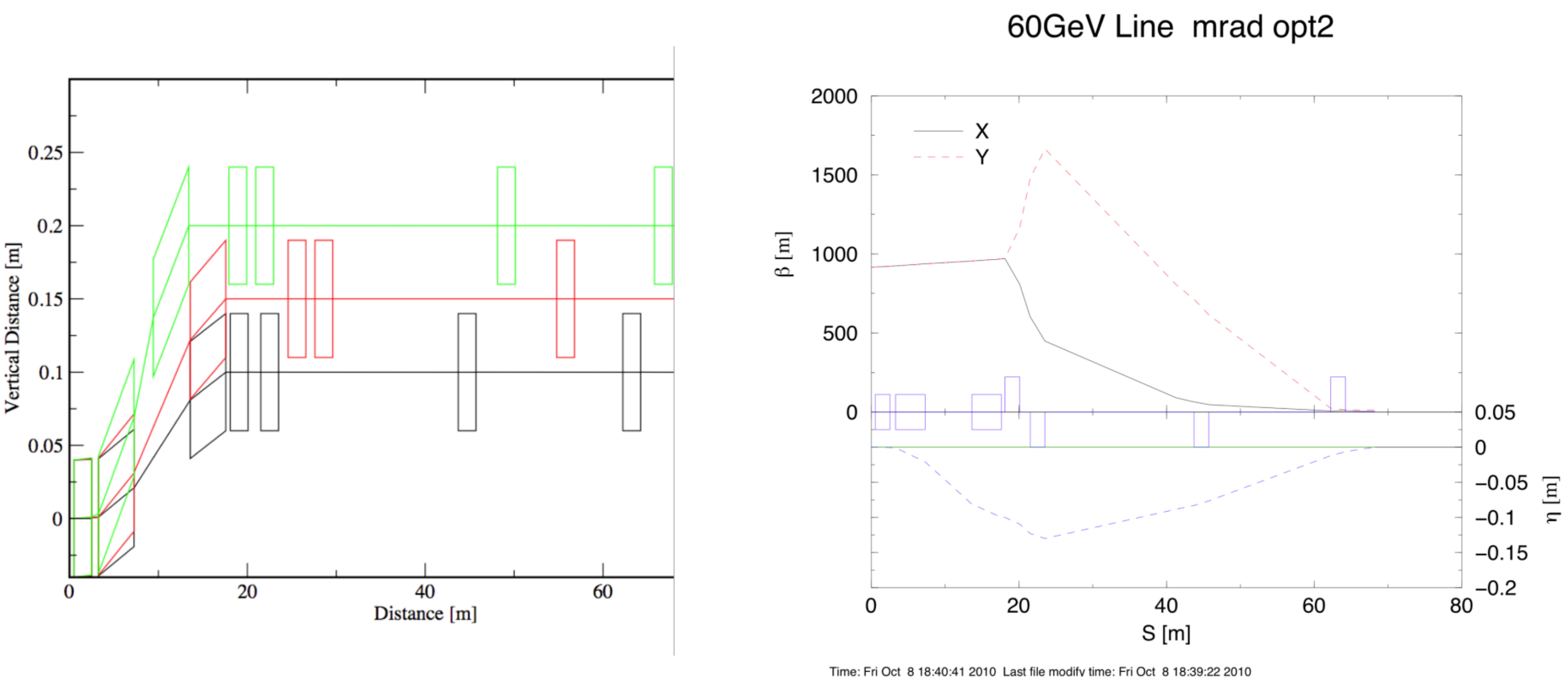


Emittance growth is OK



Another design exists from A. Bogacz

Splitters/combiners + matching



60GeV Line mrad opt2

Time: Fri Oct 8 18:40:41 2010 Last file modify time: Fri Oct 8 18:39:22 2010

Optics functions of splitter for 20, 40 and 60 GeV beams and matching with the arc.

© N.Tsoupas

Clearing Gap

- Clearing gap can remove ions
  - use $10\,\mu s$ gap (and $20\,\mu s$ train)

  ⇒ to be optimised

⇒ Ions are trapped only at a small number of short locations

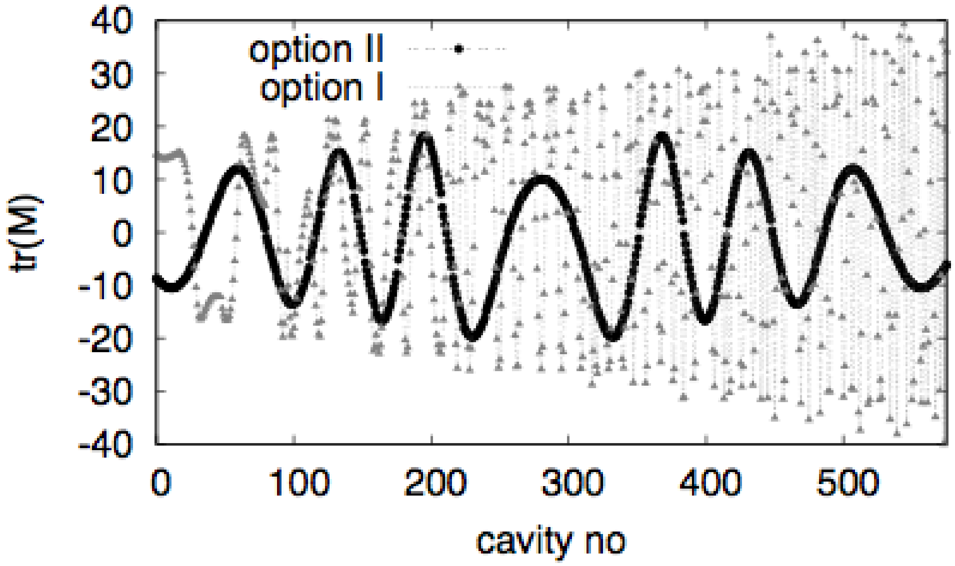
⇒ Detailed study of the fast beam-ion instability is mandatory

- Clearing gaps will reduce luminosity and power consumption

  ⇒ should we increase bunch charge to recover?

- Gradient variation due to gap is $\approx 1\%$

trapped ions can render beam unstable



Thick lens model for the bunch train and the gap leads to instability requirement

$$\left|2\cos(\sqrt{k}L_{train}) - \sqrt{k}L_{gap}\sin(\sqrt{k}L_{train})\right| \geq 2$$

- agrees well with more detailed simulations

⇒ more detail to be done later

Preliminary results are OK for good vacuum

Vacuum

J.M. Jimenez

- Many challenges
  - Very good vacuum required (currently 10^{-11}hPa cold, 10^{-9}hPa warm)
  - Strong synchrotron radiation in arcs
  - Warm cold transitions
  - Space contraints for vacuum equipment
    - backeout
- But not shocked at requirements
  - NEG coating
  - Ion pumps
  - Experience from light sources

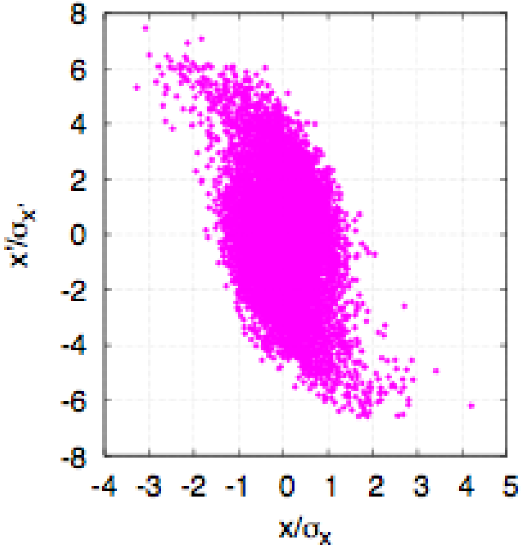
IP parameters (ERL option)

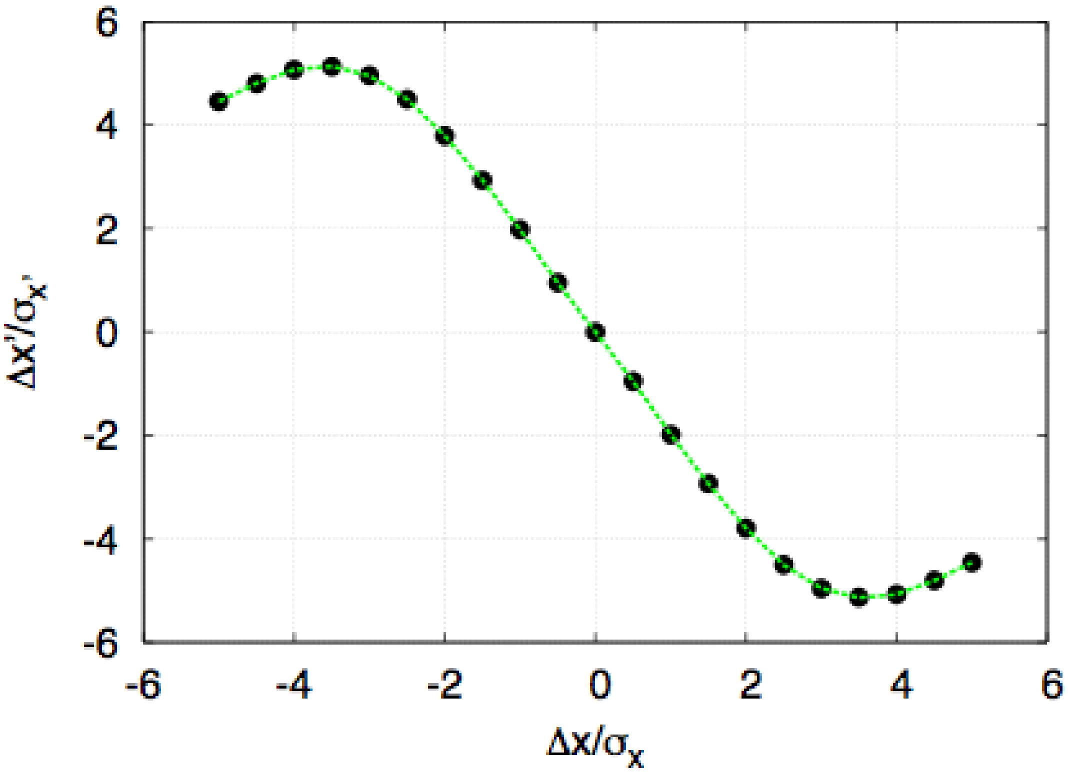
	protons	**electrons**
beam energy [GeV]	7000	60
Lorentz factor γ	7460	117400
normalized emittance $\gamma\varepsilon_{x,y}$ [μm]	3.75	50
geometric emittance $\varepsilon_{x,y}$ [nm]	0.50	0.43
IP beta function $\beta^*_{x,y}$ [m]	0.10	0.12
rms IP beam size $\sigma^*_{x,y}$ [μm]	7	7
rms IP divergence $\sigma'_{x,y}$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

Beam-beam Effects

700W beamstrahlung

E_γ=Q(1.4GeV)





- For electrons $D_{x,y} \approx 6$
- Head-on collisions
  - $\mathcal{L} \approx 1.35 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - $\Delta\epsilon \approx 14$–$20\%$
  - should use $\beta \approx 3\,\mathrm{cm}$ for extraction

$|x'| \leq 4\sigma_{x,extr}$

$|x'| \leq 8\sigma_x$

- GUINEA-PIG simulations

- Deflection is

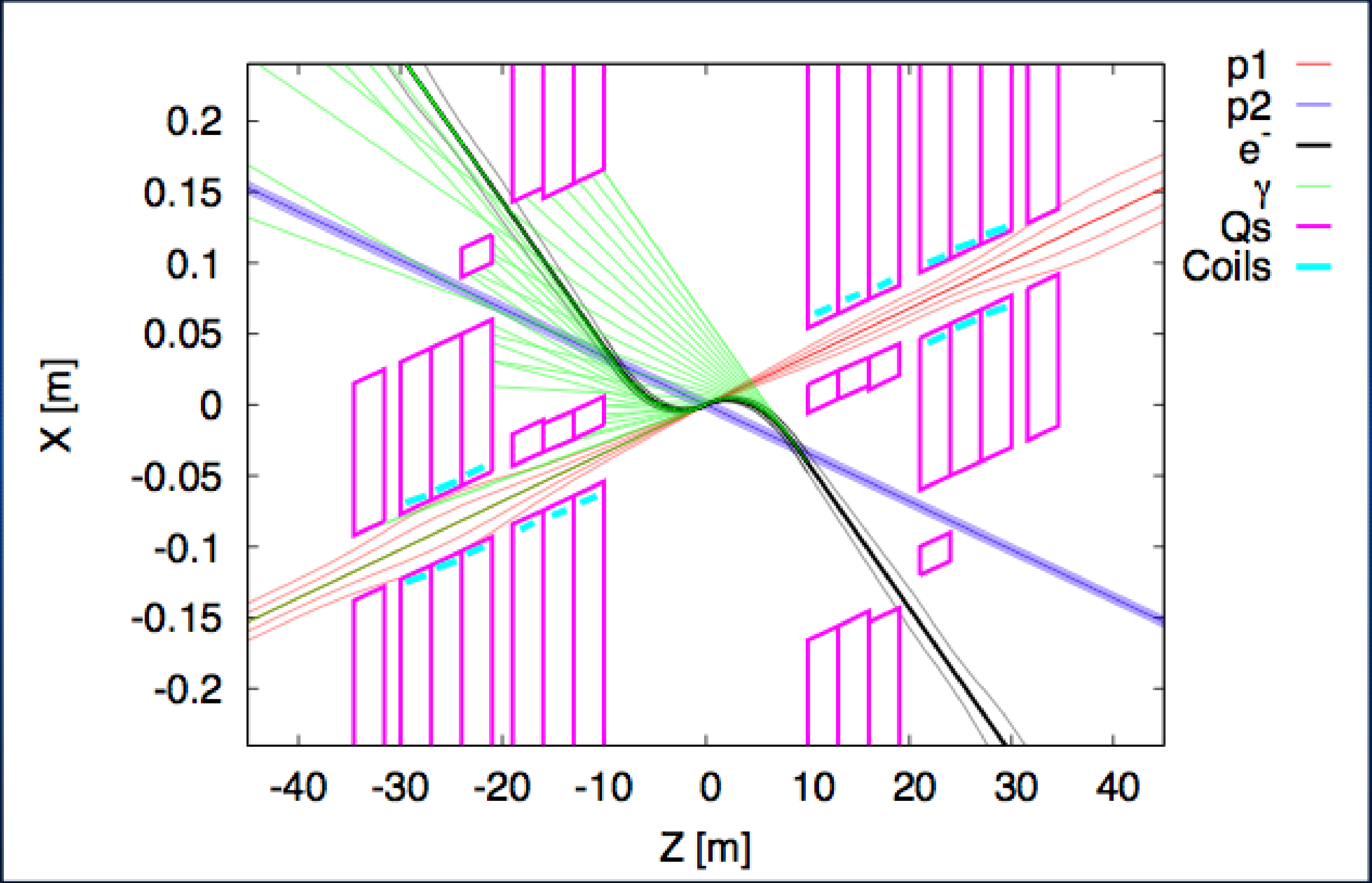
$$\Delta x' \approx -2\sigma_x \frac{x}{\sigma_x}$$

$$\Delta x' \approx -1\sigma_{x,extr} \frac{x}{\sigma_x}$$

To be checke
if OK for LHC

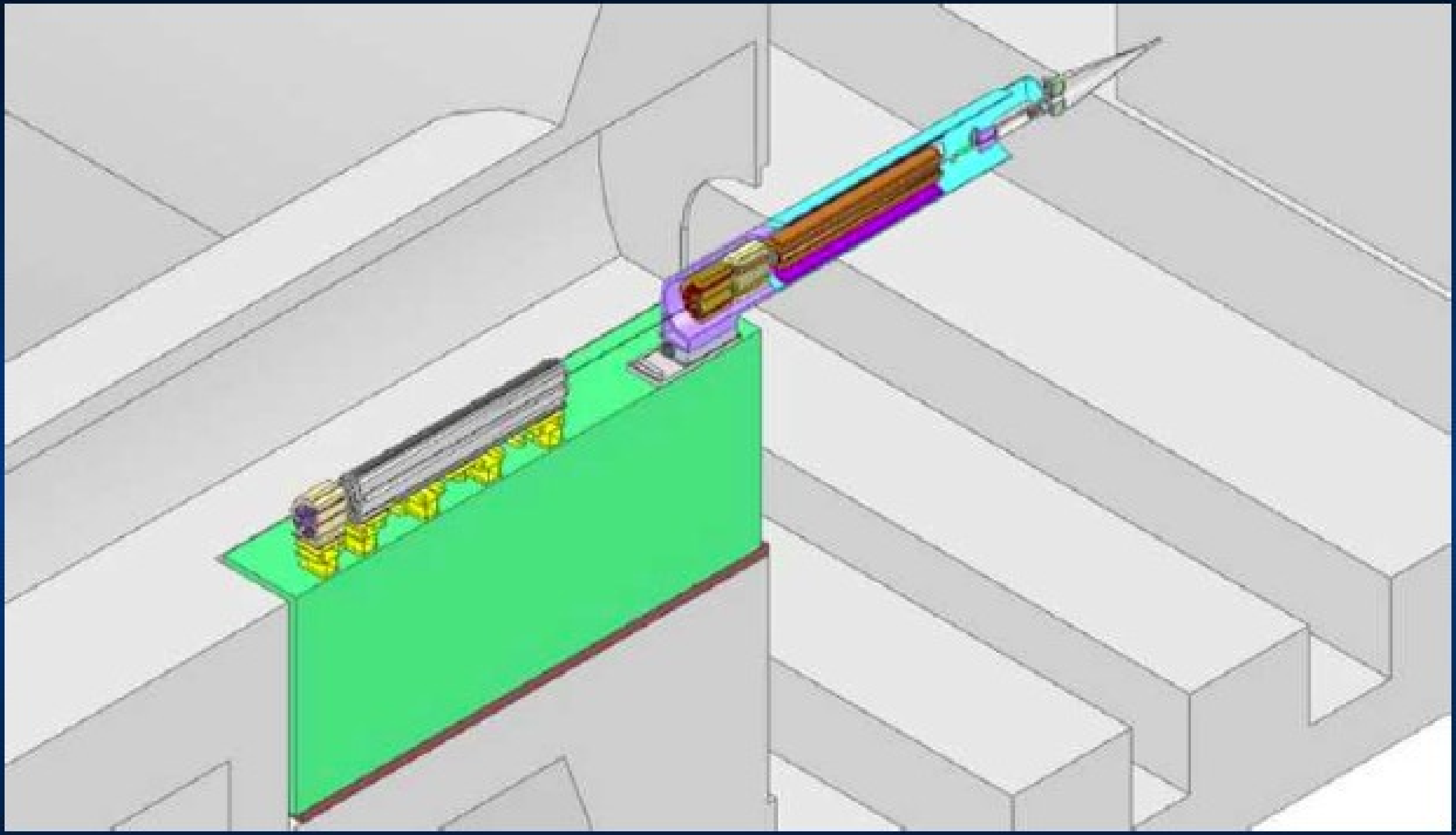
- Maximum mean deflection $5\sigma_x$ $2.5\sigma_{x,extr}$
- Maximum mean deflection for protons $\approx 0.03\,\mu$radian

The IR



Radiated power = 48 kW, Ec= 720 keV

How to get to L*=10 m?



CLIC QD0 ground preisolation and canteliver.

Is e-/p chromaticity correction an obstacle?

- Most likely not. There are various approaches for chromaticity correction in the LHC:
  - ⋆ In the matching section, C.J. Johnstone.
  - ⋆ IR-to-IR phase and arc cell phase optimization, S. Fartoukh.
  - ⋆ Beta wave in the arcs, S. Fartoukh.
- Similarly for the e^-:
  - ⋆ FFTB approach
  - ⋆ Local chromaticity correction, P. Raimondi and A. Seryi

Linac-Ring Final Quadrupoles

S. Russenschuck

23 mm Aperture, 300 T/m, small septum

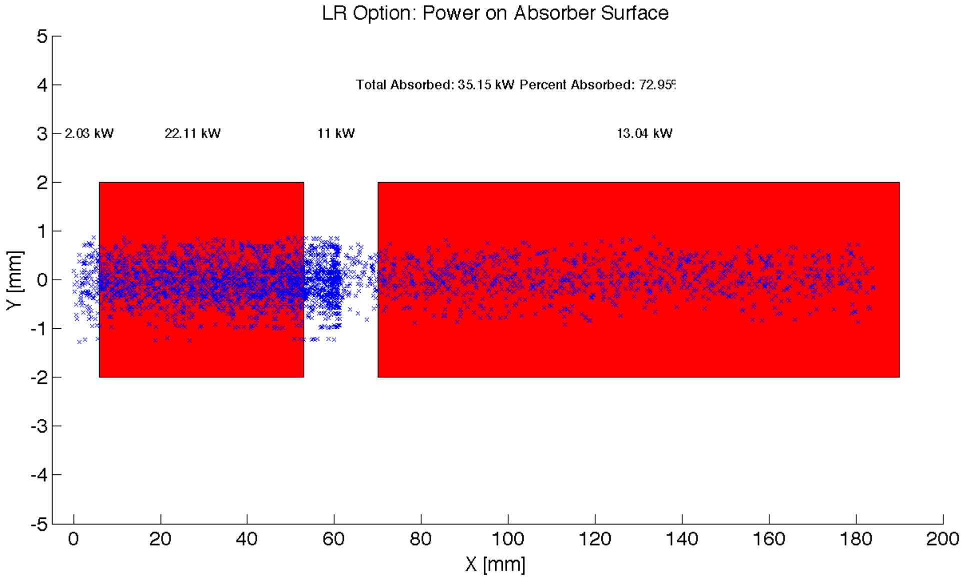
Study limitations in magnet design for Nb-Ti and Nb3Sn technology

Nb-Ti LHC main dipole cable parameter, 250 T/m instead of 300 T/m

Nb3Sn in accordance with measurements on single strands for CLIC wiggler development (HFM46) and goals for the development of cables for HE-LHC, Inner-triplet upgrade, 11 T dipoles etc.
(2500 A/mm^2) at 12 T and 4.2 K and operation at about 80% on the load-line.

But:
Mechanical structure far from trivial
Setting errors (large persistent current)

Power on Absorber

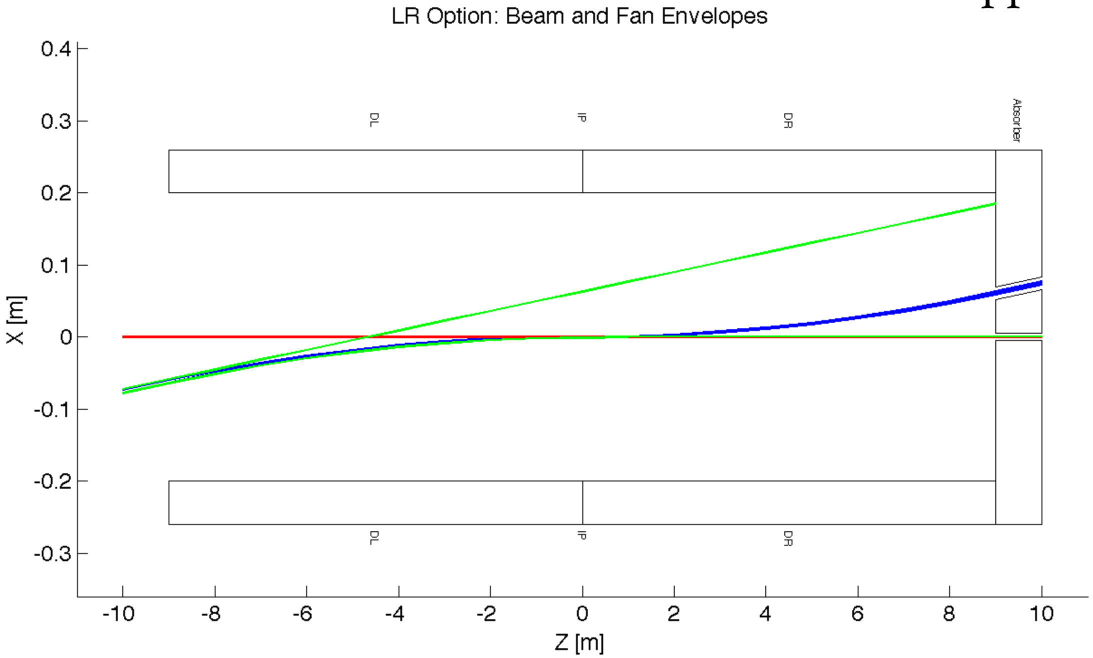


- 35.15 kW or 72.95% will hit the absorber surface.
- Backscattering hasn’t been taken into account.
- 13.03 kW will continue into the proton triplet.

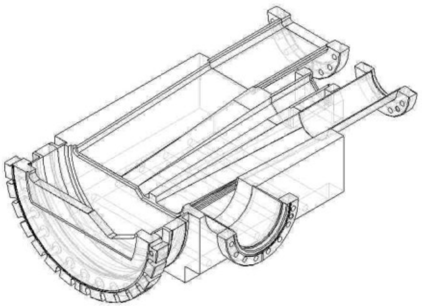
Nathan Bernard
Robert Appleby

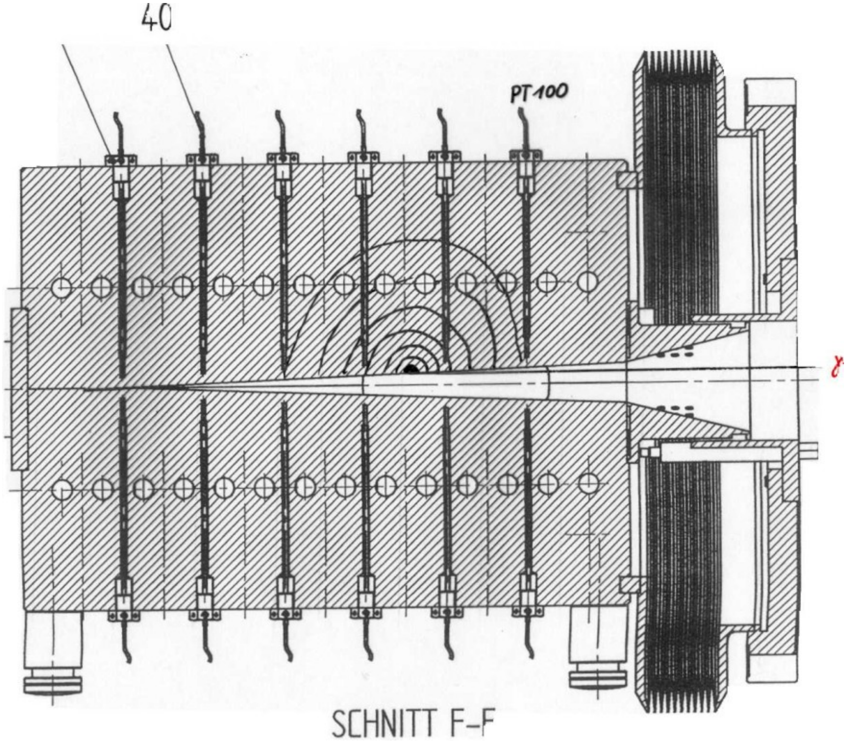
Fan Growth in Z

- The fan envelope will require unique beam pipe shape for optimization.
- LR option requires the largest beampipe width inside the detector.



Absorber/Masks*





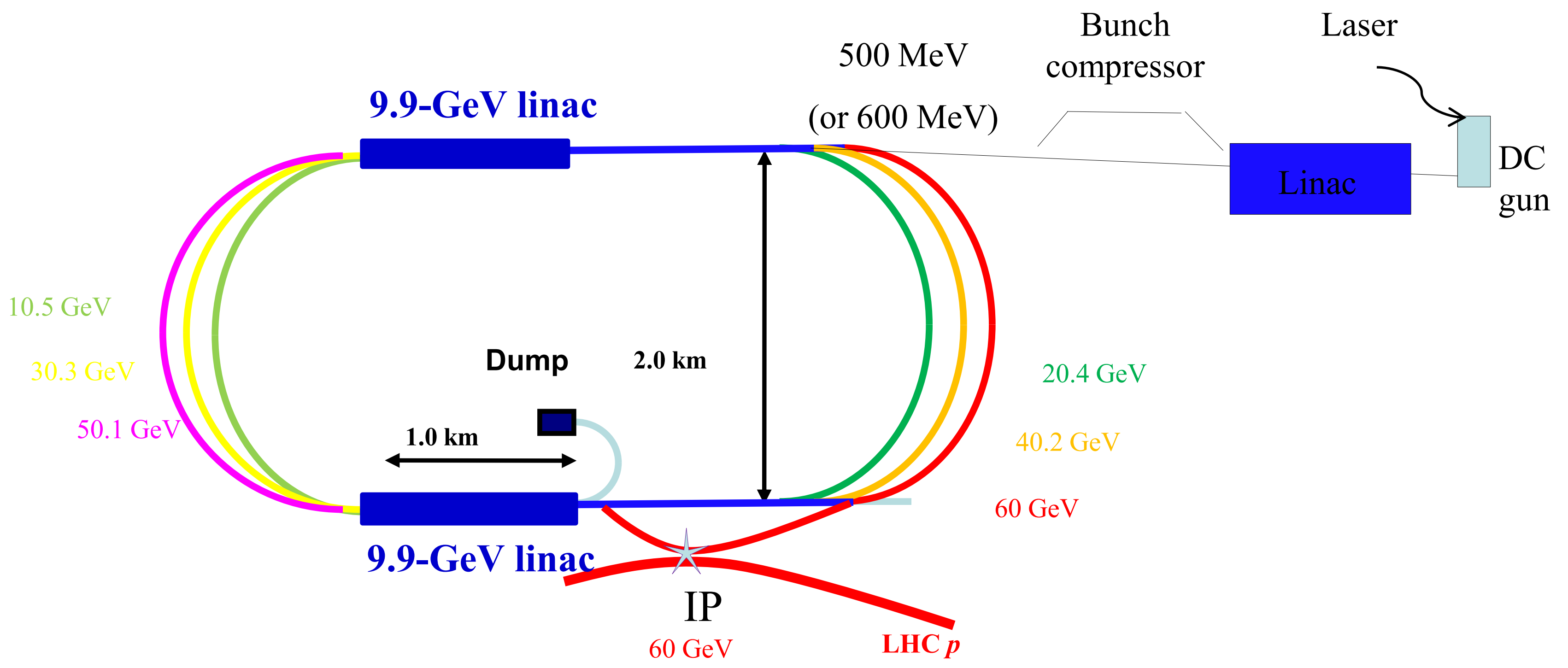
- I have written a program in Geant4 to simulate backscattering off an absorber.
- We will model the absorber after the cone shaped absorber from HERA.
- Once the backscattering has been minimized beam pipe masks will be simulated to limit the SR entering the detector.

Nathan
Bernard
Robert Appleby

*Drawings are from the Hera absorber

(Polarised) Electrons

L. Rinolfi



Requirements stretch what has been done

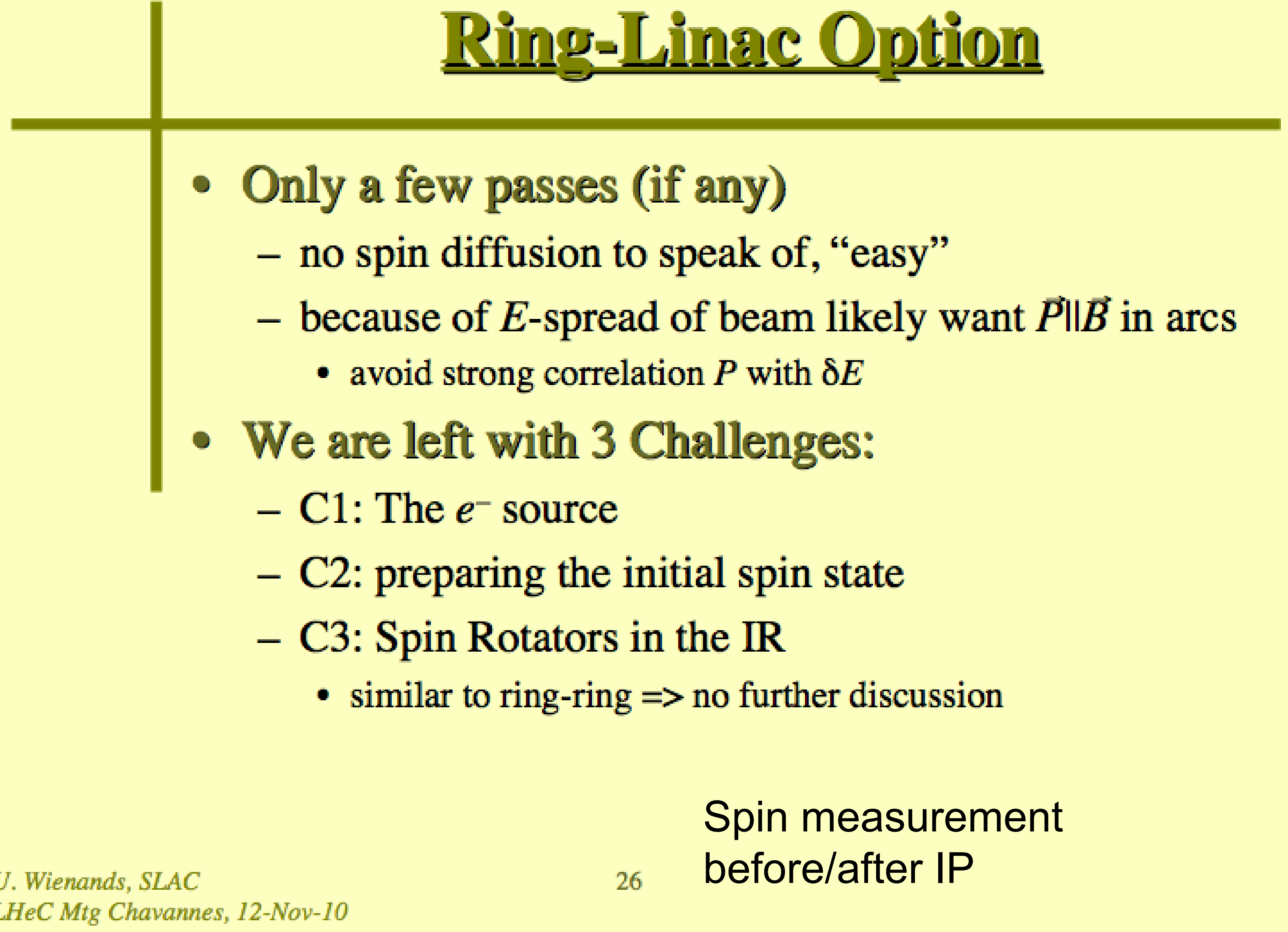
But with R&D should be within reach

90% polarisation

Positrons

- Louis presented some ideas
  - But need O(100) more positrons than ILC
- One may always hope to find a solution
  - There are always ideas
- But I would not bet on it
  - Regard positrons as an upgrade that might be feasible or not

Polarisation



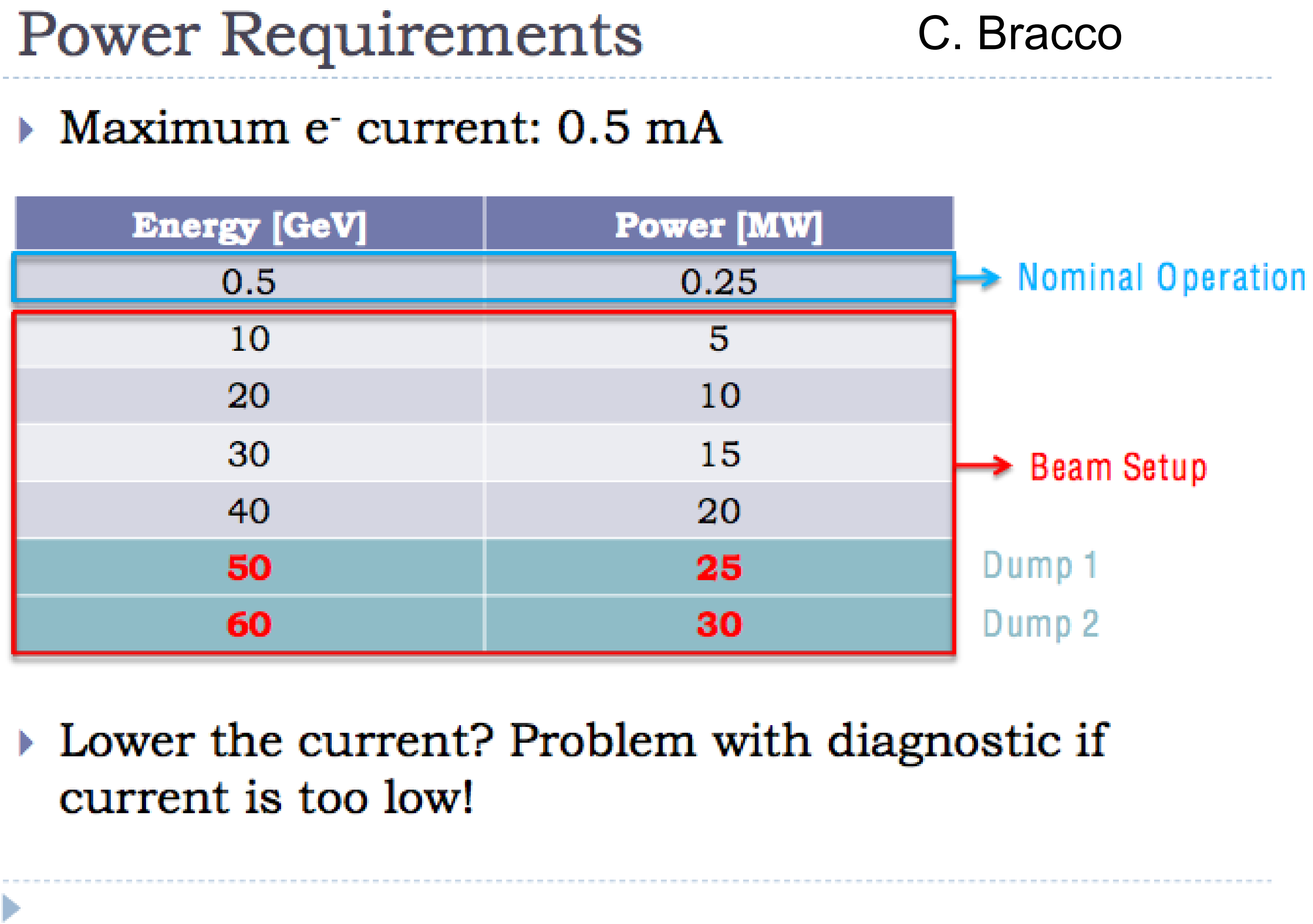
Ring-Linac Option

- Only a few passes (if any)
  - no spin diffusion to speak of, “easy”
  - because of *E*-spread of beam likely want $\vec{P} \| \vec{B}$ in arcs
    - avoid strong correlation *P* with δE
- We are left with 3 Challenges:
  - C1: The e^- source
  - C2: preparing the initial spin state
  - C3: Spin Rotators in the IR
    - similar to ring-ring => no further discussion

Spin measurement
before/after IP

Beam Dump

C. Bracco



Power Requirements

- Maximum e^- current: 0.5 mA

Energy [GeV]	Power [MW]
0.5	0.25
10	5
20	10
30	15
40	20
50	**25**
60	**30**

→ Nominal Operation

→ Beam Setup

Dump 1

Dump 2

- Lower the current? Problem with diagnostic if current is too low!

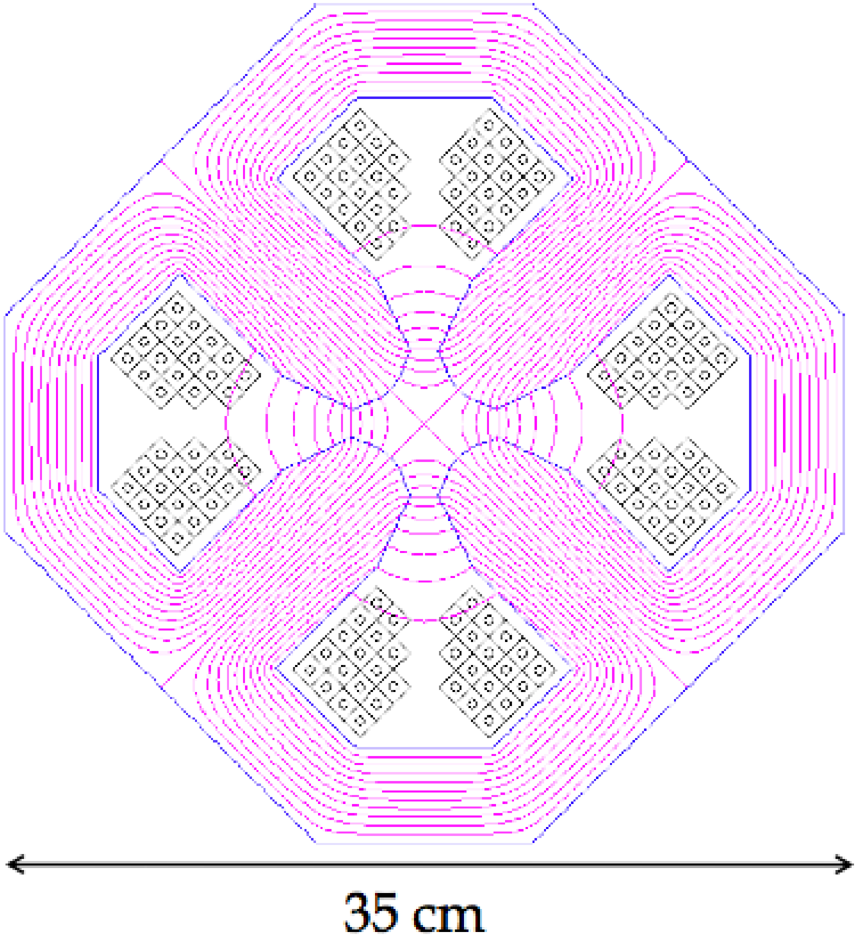
Magnets

Davide Tommasini

- Have design for the linac and arc magnets
- Magnets are not difficult
- But we need many
  - 3600 bends
  - 1500 quadrupoles
- Power consumption of the order of 2MW

Quadrupoles for 60 GeV Recirculator

Parameters for Quadrupoles	
Number of magnets	1440
Aperture radius [mm]	20
Field gradient [T/m]	41
Magnetic Length [mm]	900-1200
Weight [kg]	550-750
Number of turns/pole	17
Current [A]	410
Conductor material	Copper
Current density [A/mm^2]	5
Resistance [m]	30-40
Power [kW]	5-7
Inductance [mH]	15-20
Cooling	water



Main Magnet System

O. Brüning

Based on input from V. Mertens, B. Godard, D. Tommasini, M. Fitterer

🟩 Magnet design and prototyping:

Conventional magnet technology – industrial experience:

→ 2-3 years for generating specification for magnet production

🟩 Production time:

-Ring-Ring: ca. 4000 magnets (3000 dipole & 1000 quadrupoles)

-Linac-Ring: ca. the same number of magnets for ER option!

→ LHC transfer lines (ca. 6km); 350 warm magnets in 3 years (10/month)

→ LHeC magnet production requires industrial production

→ requires several contractors and production lines: pre-series and QA!

→ 1-2 years of pre-series production.

→ assume 80 magnets / month (8 * TL) → 5 years of production

Total of ca. 10 years for magnet production time?

ERL RF system at 721 MHz

Energy = 3 * 20 GeV, 721 MHz RF, to allow by 25 nS bunch spacing
CW 6.6 mA produced, 20 mA in linacs

E. Ciapala

20 MV/m (SPL) (More conservative than p-60)

- 1.06 m/cavity => 21.2 MV/cav => 944 cavities total (!)
- Ipk = Iav = 20 mA
- Ptot = 22 MW (losses in arcs ?) => 23 kW per cavity - very low
- No challenge for power couplers, power sources
- Again, 8 cavities in a 15 m cryomodule Total length = 2x1 km + 20%
- A very impressive linac, but a less impressive power system for each cavity,

  Power amplifiers could be solid state.

- Can be easily housed in 4-5 m diameter RF gallery adjacent to the linac sections

RF Conclusions

E. Ciapala

Linacs

- p-60 needs a lot of hardware, cavities, klystrons, power modulators

  Better to stay with 25 MV/m in estimates

- ERL … looks attractive, but:

Issues with energy loss in arcs, also operationally critical.

'Weak' RF system. Cavity mechanical resonances, ponderomotive effects, tuning errors, phase errors, noise, could all easily seriously upset operation

Detailed fundamental study of all these issues needed

Verification of Q_0 value is important (heat load)

Cavity Development & Production

Based on input from Edmond Ciapala

O. Brüning

- Cavity design and prototyping:

  ➔ 2-3 years for prototype development and testing?

- Test stand operation:

  ➔ 4-5 years from LEP and LHC experience?

- Production time:

  -LEP: 8 years from proto type to final installation of 73 4-cavity modules
  -LHC: ca. 6 years from proto type to final installation of 4 modules
  -LHeC ER linac requires ca. 2*80 modules of 6 700 MHz 5-cell structures
  ➔ ca. 1000 structures; ca. 13 times the number of LEP structures

  ➔ LHeC RF production requires industrial production: pre-series and QA!
  ➔ requires several contractors and production lines: pre-series and QA!
  Ca. 6 to 10 years for cavity production!!!

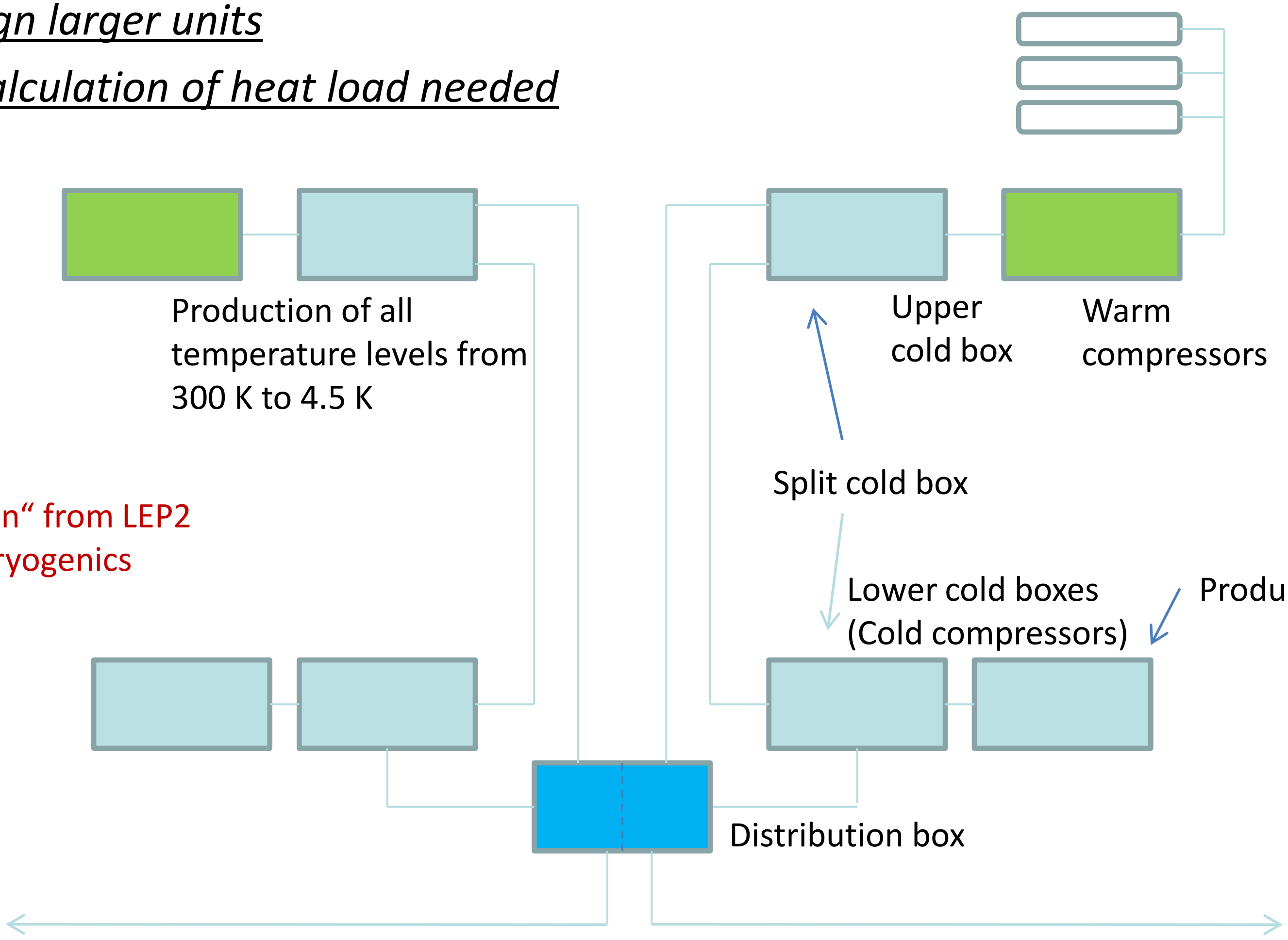
Basic refrigerator lay-out (simplified)

F. Haug

LHC „standard“ Refrigerator units yields 2.4 kW @ 1.8 K.

Could design larger units

Detailed calculation of heat load needed



He Storage

On surface

Production of all temperature levels from 300 K to 4.5 K

Upper cold box

Warm compressors

Split cold box

„inspiration“ from LEP2 and LHC cryogenics

Lower cold boxes (Cold compressors)

Production of 2 K

underground

Distribution box

Supply to string of cryomodules

Civil Engineering Requirements

Numbers based on input from John Osborne O. Brüning

- Energy recovery linac option for linac-ring design:

  total tunnel length of ca. 14km (similar to 500 GeV CLIC option):

  ➔ 4 years for civil engineering

  ➔ 2 years of service installation (piping, cabling, EL general services)

  ➔ 2 years of actual machine installation

  ➔ Total of 6 years with partial overlap of some of these activities

- Bypass for ring-ring option:

  Total tunnel length of ca. 2km (ca. 500 on either side of experiment)

  But also requires two access shafts (safety)

  Requires dedicated alcoves for Klystrons and RF system

  ➔ perhaps slightly shorter intervention time as for Linac-Ring options

  ➔ Total of 5 years with partial overall of some of these activities

  (Civil engineering for injector complex not considered here)

LHeC Requirements

O. Brüning

- LHeC installation should be compatible with 5-10 years operation:
  - ➔ assume LHC end of lifetime reached in 2030-2035 (radiation damage)
  - ➔ LHeC operation start required by 2025 (at latest)
  - ➔ start production of key components (magnets & RF) by 2015
  - ➔ prototype development (magnets & RF) launched by 2013 ± 1

- LHeC installation time:
  - ➔ Magnet installation for Ring-Ring option only possible during long LHC shutdown ➔ 2016, 2020, (2025?)
    LEP installation into empty tunnel took ca. 1 year!
  - ➔ Only one scheduled long shutdown if LHeC can not profit from 2016 shutdown

Conclusion

O. Brüning

- Keeping an LHeC option open for the LHC requires:
  - ➔ launch of R&D and design activities for key components (magnets, RF) needs to start very soon
  - ➔ planning the installation of the ring-ring option requires careful synchronization with LHC operation schedule (assume minimum of two long shut downs for installation)
  - ➔ Civil engineering must start before 2018
- Requirements:
  - ➔ The above work can not be done with the current arrangement and requires a focused team and sufficient resources
- Conclusion:
  - ➔ Decision on LHeC option should be taken by 2012

Conclusion

- Overall design has strongly progressed
  - Not everything is designed
  - But things move forward
- Conceptual design seems a bold name for the report
  - But good design study
- Need to define R&D programme for the next phase
  - In my mind part of the report

Many thanks to all the speakers and participants of our session