RF for the LHeC

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RF design for the ring-ring option

RF design for the linac option

RF design for the ERL option

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RF design for the ring-ring option:

1) RF design

RF Power and Voltage, Margins
Frequency choice,
Cavities, # klystrons

2) Space estimates in the bypasses for cavities

3) Space estimates for RF Power equipment and klystrons

New RF and beam parameters 27.7.2010

LHeC – design parameters

electron beam	RR	LR ERL	LR
e- energy at IP[GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	17	10	0.44
polarization [%]	5 - 40	90	90
bunch population [10^9]	26	2.0	1.6
e- bunch length [mm]	10	0.3	0.3
bunch interval [ns]	25	50	50
transv. emit. $\gamma\varepsilon_{x,y}$ [mm]	0.58, 0.29	0.05	0.1
rms IP beam size $\sigma_{x,y}$ [μm]	30, 16	7	7
e- IP beta funct. $\beta^*_{x,y}$ [m]	0.18, 0.10	0.12	0.14
full crossing angle [mrad]	0.93	0	0
geometric reduction H_{hg}	0.77	0.91	0.94
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]	131	6.6	5.4
tot. wall plug power[MW]	100	100	100

proton beam	RR	LR
bunch pop. [10^{11}]	1.7	1.7
tr.emit.$\gamma\varepsilon_{x,y}$ [μm]	3.75	3.75
spot size $\sigma_{x,y}$ [μm]	30, 16	7
$\beta^*_{x,y}$ [m]	1.8,0.5	0.1$
bunch spacing [ns]	25	25

$ smaller LR *p*-β* value than for nominal LHC (0.55 m):
- reduced *l** (23 → 10 m)
- only one *p* beam squeezed
- new IR quads as for HL-LHC

DRAFT: BH,FZ,MK 29.7.2010

RR= Ring – Ring
LR =Linac –Ring
ERL=energy recovery linac

Energy (RR) = 60 GeV, Idc = 131 mA

Ring RF system from parameters list 27.7.2010

Energy = 60 GeV

- Energy loss / turn @ 60 GeV= 379 MeV
- Beam current I_{dc}= 131 mA
- Beam Power Pb= **50 MW** (Losses due to synchrotron radiation)

(NOTE – At 104 GeV LEP had 'only' **20 MW**...., but LHeC energy below rad damage threshholds)

- Total RF voltage V_{rf}= 430 MV gives Q_L 100 hrs + Some Reserve => 500 MV
- Total RF power needed (margins – WG loss, LLRF, critical coupling, other)

=> **60 MW cw** (t.b.c)

Note 40 % efficiency Wall Plug to RF ... (Factor 2.5 in total power) **150 MW**

(Includes Power Conversion, Cooling, Ventilation but not CRYO)

- # cavities ?
- # klystrons ?
- Choice of frequency ?....

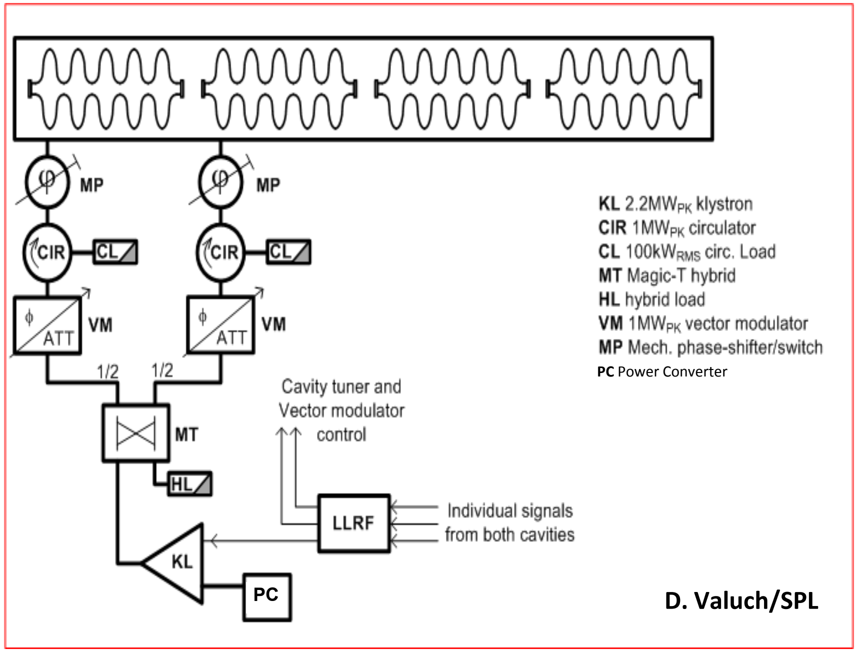
Ring RF system at 400 MHz

Energy = 60 GeV, 400 MHz RF, 500 MV, 60 MW.

Like 400 MHz LHC RF (3 MV/cavity: a maximum – LHC has 2 MV nominal per cavity)
168 cavities, 3MV/cavity => 42 LHC style 4-cav SC modules (8m long) => 168 m + 20%

- 350 kW/cavity, within existing LHC variable power coupler ratings

=> RF Config: 168 klystrons, or 84 700 kW klystrons, each driving 2 cavities



SPL layout example

Bulky cavities & cryostats

- Would use sputtered Nb cavities
- 3 MV/cav = 8 MV/m is just at limit of LHC cavities, may be expensive on cryo (tbc)

Ring RF system at 721.4 MHz.

Energy = 60 GeV, 721.4 MHz RF, 500 MV, 60 MW installed RF.

Use SPL like cavity, but at harmonic that allows 25 ns bunch spacing (40 MHz)
= > slightly smaller than SPL 704 MHz cavity, use similar (but shorter) cryostat, similar tuner, power couplers etc

- Assume 250 kW per coupler, 2 couplers per cavity, => 120 cavities (Reasonable)
- 4.2 MV/cavity only needed, i.e. Use double cell cavity

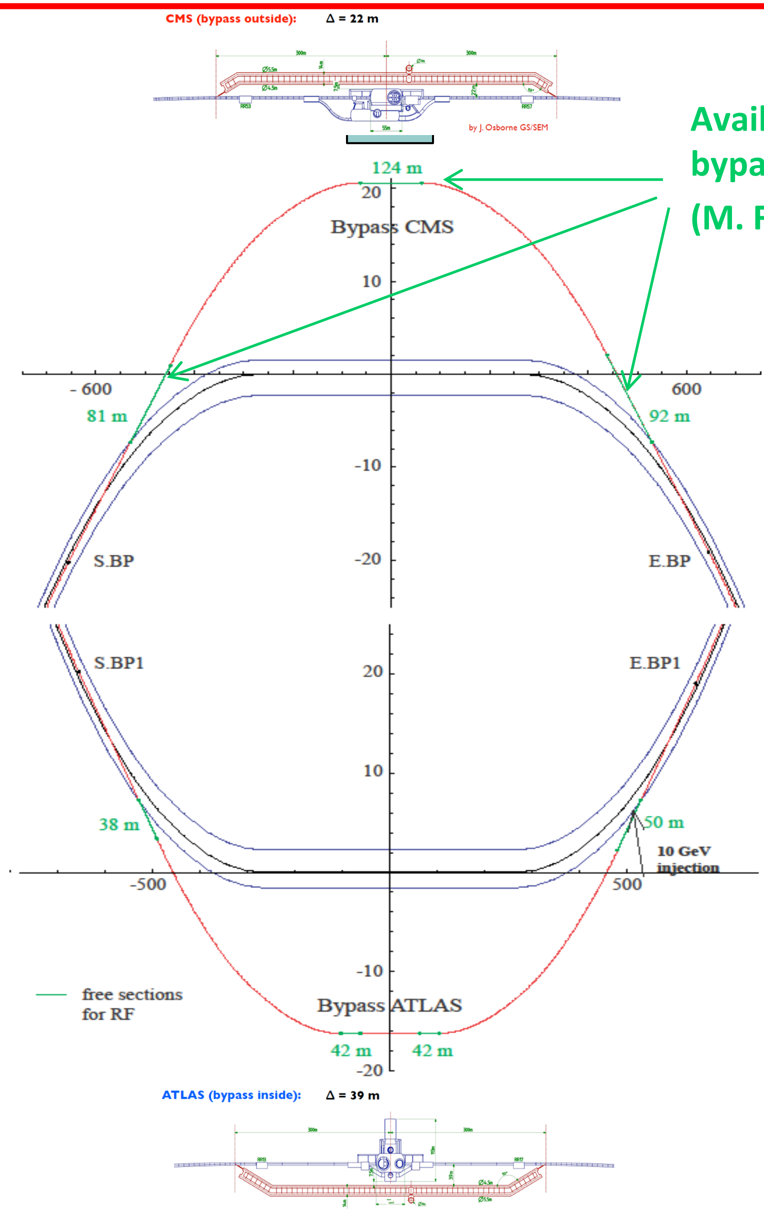
  (SPL spec is 25 MV/m for 1.06 m 5 cell cavity) => 9.8 MV/m (Conservative)
- 8 double cell cavities in 12 m cryomodules, with 15 cryomodules total

  Total Cryomodule length = 15 * 12 = 180 m, + space for Quads, Vacuum, BI
- Feed each cavity with one 500 kW klystron, => 120 klystrons (Safe Option)
- Or - Feed two cavities with one 1 MW Klystron - RF Splitting in machine tunnel

  – (Economical option, less space, "Only" 60 klystrons...)

Large beam current - HOMs & HOM Coupler studies needed.

Layout for Ring-Ring Option



Available space in the bypass tunnels

(M. Fitterer, H. Burkhardt)

Simplest option:

Install only in the IR bypass sections

208 m available

15 x 12m Cryomodules Total

9 at CMS bypass = 108m

2 x 3 at ATLAS bypass = 2 * 36m

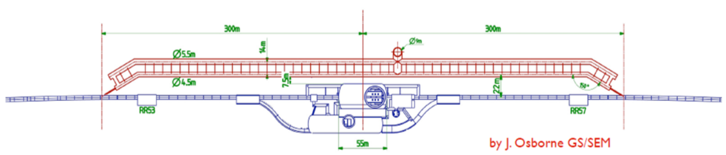
Total 180 m

This layout forces the 60 klystron option

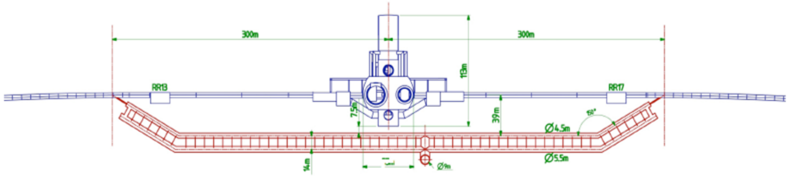
Ring-Ring Option – RF power system layout with 60 Klystrons

Need space in RF galleries for 120 (60) klystrons, circulators, loads
=> CMS bypass: 36 klystrons, ATLAS bypass: 24 klystrons

CMS (bypass outside): Δ = 22 m



ATLAS (bypass inside): Δ = 39 m



Per 8 cavity module -

- 4 x 1 MW klystrons (vertical), + 8 circulators & loads ($4x2 + 8x2\ m^2$)
- HV bunker (crowbar) for 4 klystrons ($9m^2$)
- LLRF & Controls racks (4 racks per klystron) ($16x0.5m^2$)
- Total footprint in RF gallery $41m^2$, => **$100m^2$** floor space needed, factor 2.5 'packing'

Have **14 m** / 12 m module in the RF galleries,
=> 7 m wide gallery full length of SSs (2 tunnels total)

OR 4-5 m both sides of the bypass tunnels (3 tunnels total)
Best options to be seen with CE and Integration experts….

\+ 1 HV Power Converter rated 8 MVA per 4 klystrons on surface..
(15 total) or simply 30 LEP type 4 MVA converters….

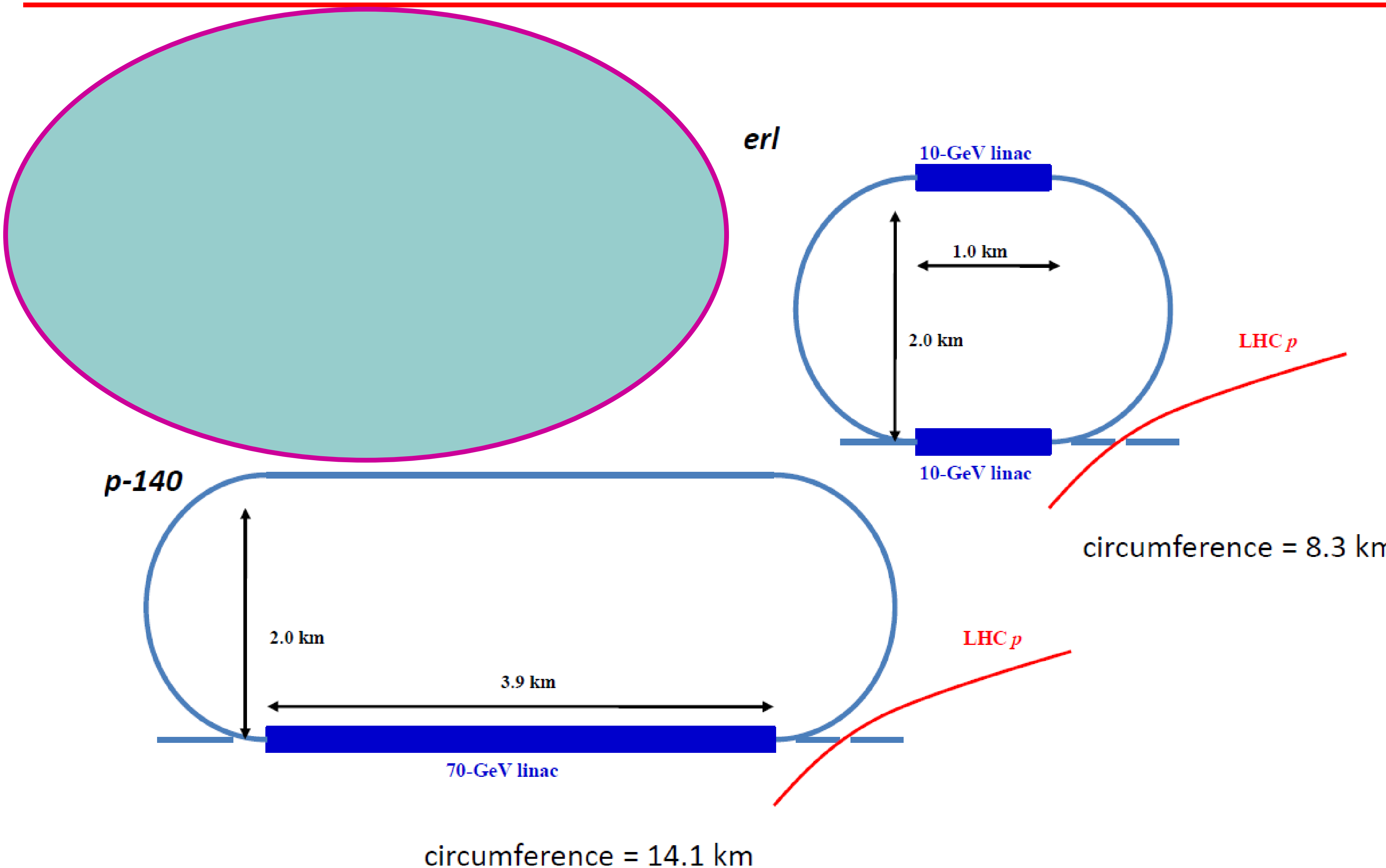
RF design for the Linac options:

RF design

- RF Power and Voltage
- Frequency choice,
- # Cavities # klystrons

Space estimates in the tunnels

RF design for the linacs p-60



Linac p-60 RF system at 721 MHZ

Energy = 2x30 GeV, Again use 721.4 MHz RF, to allow 25 nS bunch spacing
Pulsed 10 Hz 5 ms, Ipk = 2x16 mA, Iav = 0.64 mA

Gradient 25 MV/m (SPL) (Conservative wrt ILC)

- 1.06 m/cavity => 26.5 MV/cav => 1136 cavities (!)
- 8 cavities in a 15 m cryomodule (SPL design) 142 cryomodules
- Total cryostat length = 2.1 km + 20%
- Ipk = 32 mA => Pcav pk = 850 kW per cavity
- Iav = 0.64 mA, Pcav av = 42 kW per cavity (low) – no issue for power couplers

  But 48 MW total average RF power.....
- Take one 2 MW klystron per 2 cavities, not ideal but better for initial cost

  => 568 klystrons
- Klystron modulators => 170 kW av. for 4 cavities = 2 klystrons, 284 needed.

  synergy with SPL, ILC, CLIC. (Although the 5 ms is a longer pulse)
- Quite an impressive linac ....

Layout for Linac Option – RF power System

Need space in the RF galleries for:

800 klystrons, splitters, 1600 circulators with loads and 200 pulsed power klystron modulators. + LLRF and controls racks

Per 8 cavity cryomodule of 15 m length we need:

- 4 klystrons (vertical), + 8 circulators & loads (4x2 + 8x2 m^2)
- 2 Klystron modulators (2x10m^2)
- LLRF & Controls racks (4 racks per klystron) (16x0.5m^2)
- Total footprint in RF gallery = 52m^2, => 120m^2 floor space, factor 2.5 'packing'

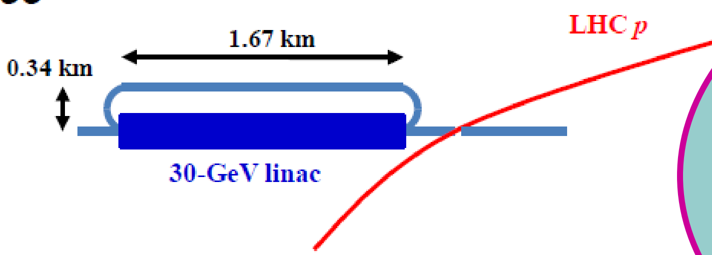
Have **18 m** / 15 m module in the RF galleries, (With 20 % margin)

⇒ 6 m wide gallery full length of SSs

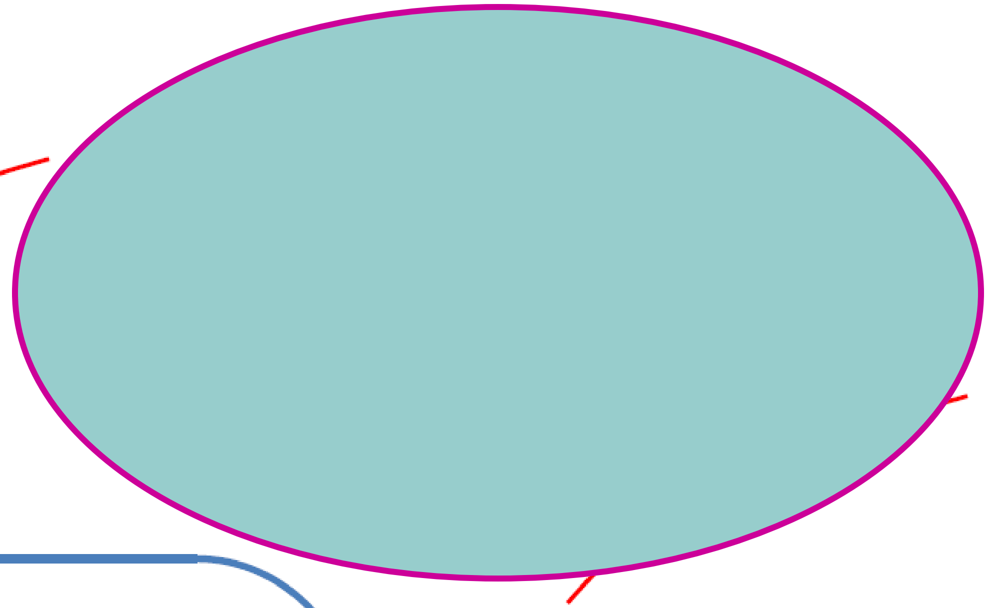
Again to be studied with CE

RF design for the linacs - ERL

p-60

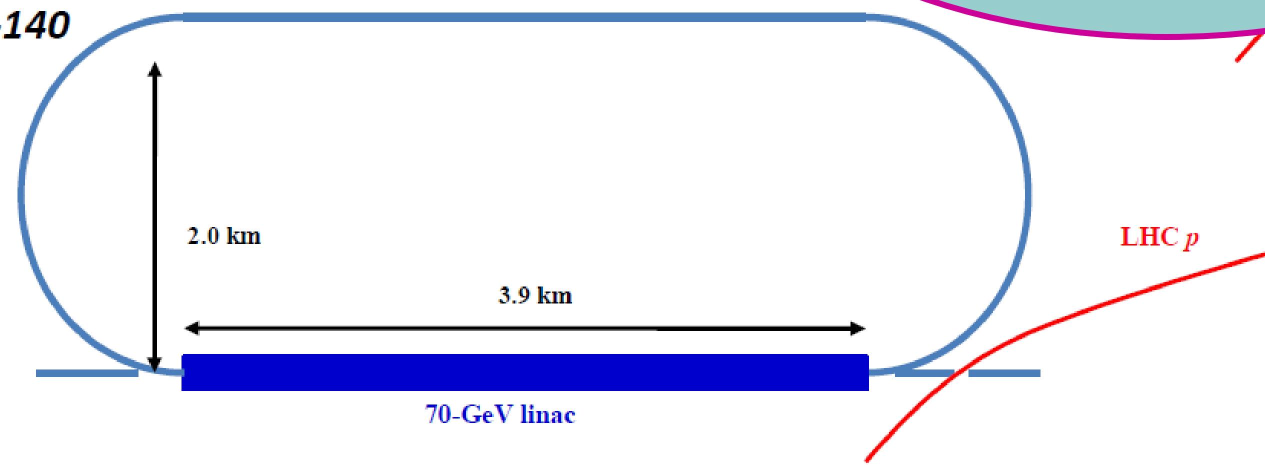


circumference = 4.4 km



circumference = 8.3 km

p-140



circumference = 14.1 km

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

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

Issues on the ERL

Synchrotron radiation losses on arcs cannot be considered as 'small perturbation'

Arc E [GeV]	Loss [MeV]	Passages	total [MeV]
60	570	1	570
50	275	2	550
40	115	2	230
30	35	2	70
20	7	2	14
10	0.4	2	0.8
			1434.8

(arc radius 1 km)

- Total loss of 1.5 GeV : larger than 0.5 GeV injection energy
- Isochronous condition of arcs not possible. for accelerated <u>and</u> decelerated beam (beams too different in energy)

Two possibilities (D. Schulte):

1) Set linac phase angles such that accelerated beam sees <u>more acceleration</u>,
   decelerated beam sees <u>less deceleration</u>
   <u>May be very difficult to manage operationally</u> (To be studied)

2) Add re-accelerating 'mini'-linacs half-way around <u>in each arc</u>:
   Double nominal frequency (1400 MHz): <u>acceleration for both beams</u>

RF systems in the ERL arcs……

570 MeV -> V_{tot}=700 MV @ 1400 MHz, I_b=6.6 mA (single beam, behind IP) 8 MV/cavity -> 90 cavities, 70 m, 53 kW beam power per cavity: about 5 MW beam power (12.5 MW plug + cryo)

275 MeV -> V_{tot}=350 MV @ 1400 MHz, I_b=13.2 mA (double beam, 'accel.' & 'decel.') 8 MV/cavity -> 45 cavities, 35 m, 106 kW beam power per cavity: about 5 MW beam power (12.5 MW plug + cryo)

115 MeV, 35 MeV scaled version of 275 MeV linac (all double beam current)

(7 and 0.4 MeV can probably be omitted, isochronous condition dE/E ≤ 1% (D. Sch.))

Since here synchrotron radiation losses are compensated outside the ERL scheme, efficiency of ERL will be bigger than 94% –> 96 … 97 %:

Conclusions

Ring

- 720 MHz can be just fitted in the two bypasses nearest ATLAS and CMS
- A large power system, integration & CE need study, to optimize tunnel/cavern arrangement.
- Phased installation is an interesting possibility – as LEP
- Don't forget wall plug to RF power efficiency in the estimates

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

Spare Slides

RF design for the linacs I-III

Parameters (Frank)

Table 4: Lepton beam parameters and luminosity.

	p-60	erl	p-140
e^- energy at IP [GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	1.1	10.1	0.4
polarization [%]	90	90	90
bunch population [10^9]	4.5	2.0	1.6
e^- bunch length [μm]	300	300	300
bunch interval [ns]	50	50	50
transv. emit. $\gamma\epsilon_{x,y}$ [μm]	50	50	100
rms IP beam size [μm]	7	7	7
hourglass reduction $H_{\rm hg}$	0.91	0.91	0.94
repetition rate [Hz]	10	CW	10
bunches/pulse [10^5]	1	N/A	1
pulse current [mA]	16	10	6.6
beam pulse length [ms]	5	N/A	5
ER efficiency η	0	94%	0
total wall plug power [MW]	100	100	100

RF design for the linacs I-III – More Parameters

Table 2: SC linac parameters. *RT: room temperature.

	p-60	erl	p-140
RF frequency [MHz]	700	700	700
cavity length [m]	1	1	1
energy gain / cavity	31.5	18	31.5
R/Q [Ω]	403	403	403
Q_0 [10^{10}]	1	2.5	1
power loss, stat [W/cav.]	5	5	5
power loss, RF [W/cav]	12.3	32	12.3
power loss, total [W/cav]	17.3	37.2	17.3
real-est. gradient [MeV/m]	17.8	10.26	17.8
length/GeV [m]	97.5	55.7	97.5
#cavities/(1 GeV)	55.6	31.8	55.6
power loss/GeV (2 K) [kW]	0.55	2.06	0.55
"W per W" (1.8 K to RT*)	600	600	600
power loss/GeV (RT*) [MW]	0.33	1.24	0.3
final energy [GeV]	60	60	140
# passes for acceleration	2	3	2
# passes for deceleration	0	3	0
tot. linac length [km]	1.67	1.95	3.90
tot. cryo power (RT) [MW]	9.9	24.75	23.1
av. beam current [mA]	0.74	6.6	0.27
beam power at IP [MW]	45	396	39
RF power [MW]	89	(22)	75.6
cryo + RF power [MW]	99	(47)	98.4

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	p-60	erl	p-140
e^- energy at IP [GeV]	60	60	140
luminosity [10^{32} cm^{-2}s^{-1}]	1.1	10.1	0.4
polarization [%]	90	90	90
bunch population [10^9]	4.5	2.0	1.6
e^- bunch length [μm]	300	300	300
bunch interval [ns]	50	50	50
transv. emit. $\gamma\epsilon_{x,y}$ [μm]	50	50	100
rms IP beam size [μm]	7	7	7
hourglass reduction H_{hg}	0.91	0.91	0.94
repetition rate [Hz]	10	CW	10
bunches/pulse [10^5]	1	N/A	1
pulse current [mA]	16	10	6.6
beam pulse length [ms]	5	N/A	5
ER efficiency η	0	94%	0
total wall plug power [MW]	100	100	100