SPL possible RF power sources

Klystrons / IOTs / SSA

Warmest thanks

- Suppliers:

CPI e2v L3 communications THALES

All given numbers are preliminary rough estimates

- Colleagues:

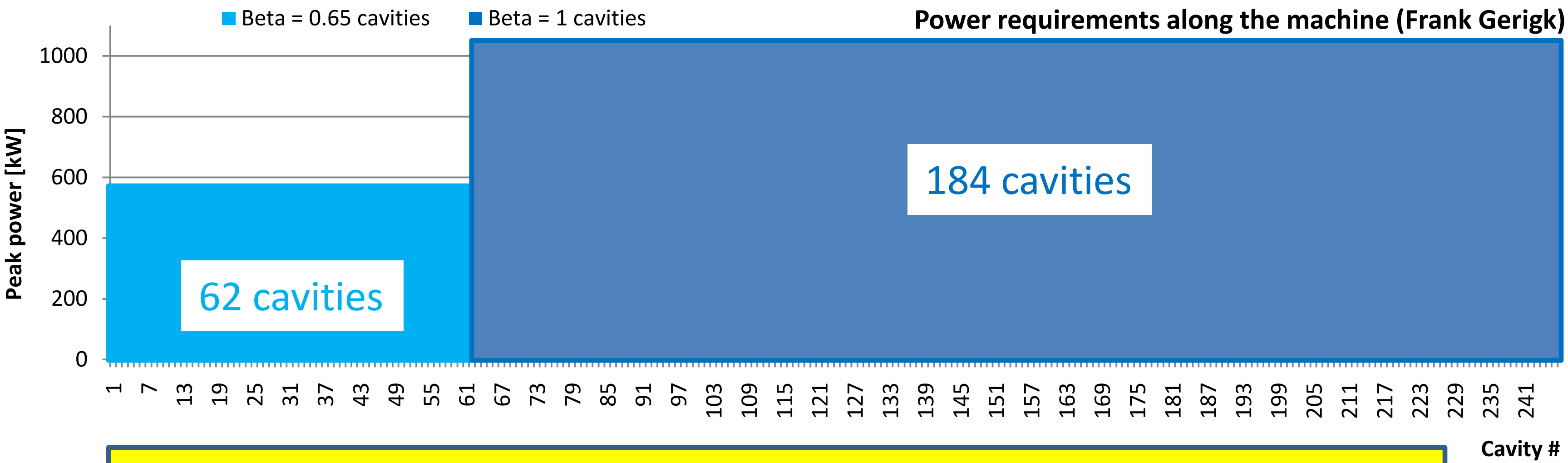
Patrick Marchand, Jörn Jacob, Michel Langlois
John Lyles, Dan Rees
Edmond Ciapala, Erk Jensen, Wolfgang Hofle
Frank Gerigk, Olivier Brunner, Mauro Paulozzi
David Nisbet, Freddy Brodry, François Duval,
Sylvain Weisz

sLHC

RF power requirements along the SPL

CERN
Beams department
RF group

Power requirements along the machine (Frank Gerigk)



HP-SPL 40 mA : 0.78 ms / 50 Hz

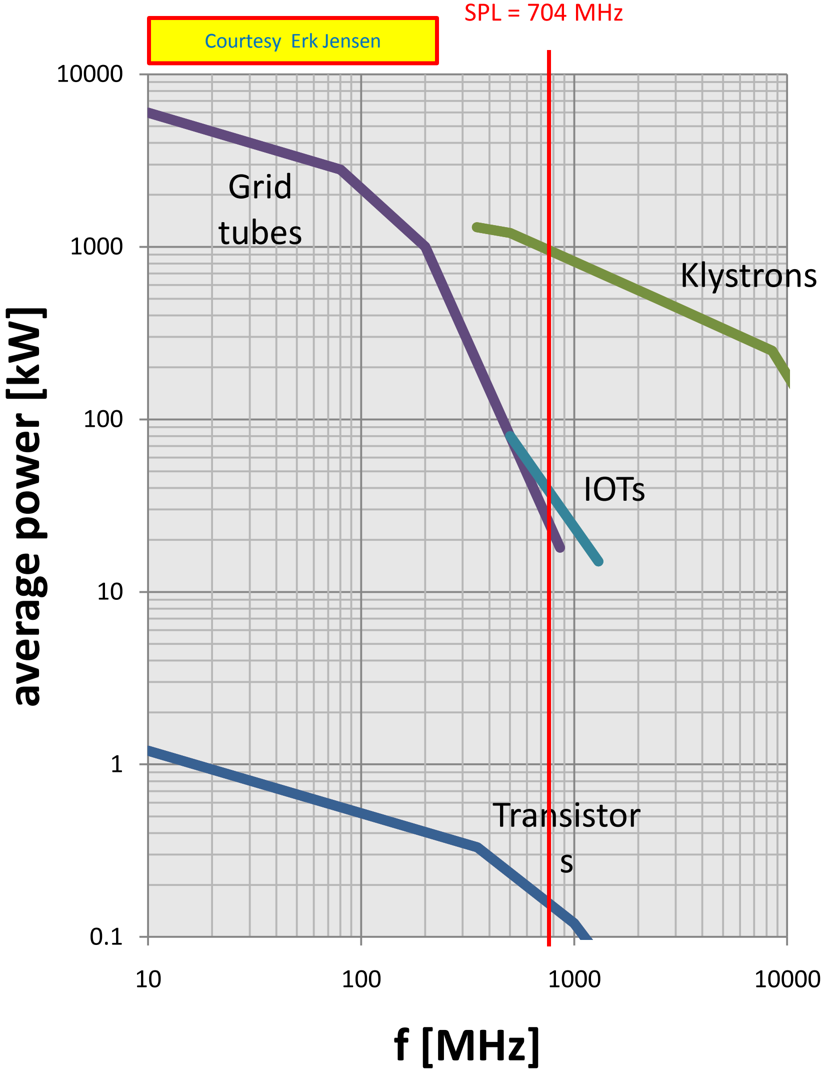
https://twiki.cern.ch/twiki/bin/view/SPL/SPLparameterList#OperationalParameters (Frank Gerigk)

62 'Low Power' cavities	
Maximum power to cavity input (cav #25)	565 kW
Margin for operation : reactive beam loading reserve, detuning resonance (Lorentz Force + micro phonic), variation in Q_L, variation in cavity parameters, beam current fluctuations	35 kW
Maximum total power per cavity input	**600 kW**

184 'High Power' cavities	
Maximum power to cavity input (cav #246)	1'020 kW
Margin for operation : reactive beam loading reserve, detuning resonance (Lorentz Force + micro phonic), variation in Q_L, variation in cavity parameters, beam current fluctuations	80 kW
Maximum total power per cavity input	**1'100 kW**

Proposed solutions

- Klystrons:
  - One klystron per two cavities
  - One klystron per cavity
- IOTs:
  - One IOT per cavity
  - Multiple IOTs combined per cavity
- Solid State Amplifiers (SSA)
- Magnetron

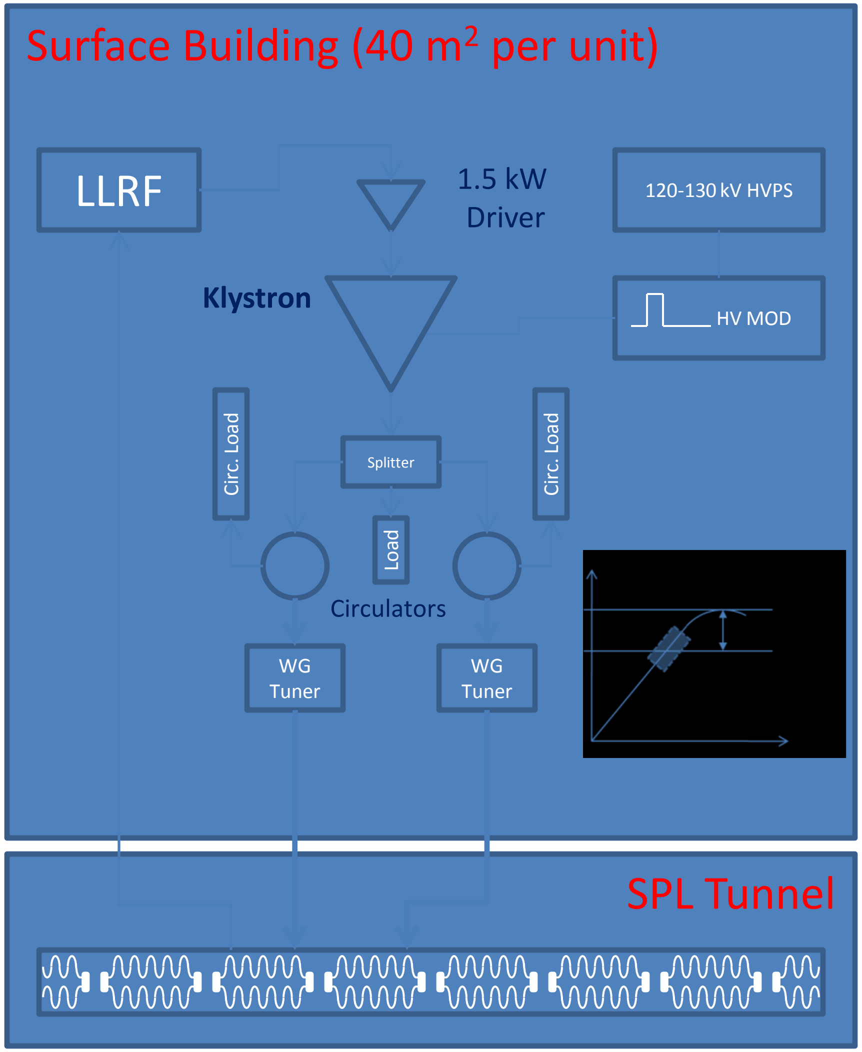


Criteria of comparison

- Power distribution scheme
- Lifetime
- Efficiency
- Availability or possible new study
- Infrastructure size
- Costs

- Not the purpose of this talk : Power converters comparison -> however this could have a deep impact on infrastructure, costs, and overall reliability

One klystron per two cavities



- ↗ High power output
- ↗ fewer items to operate and maintain

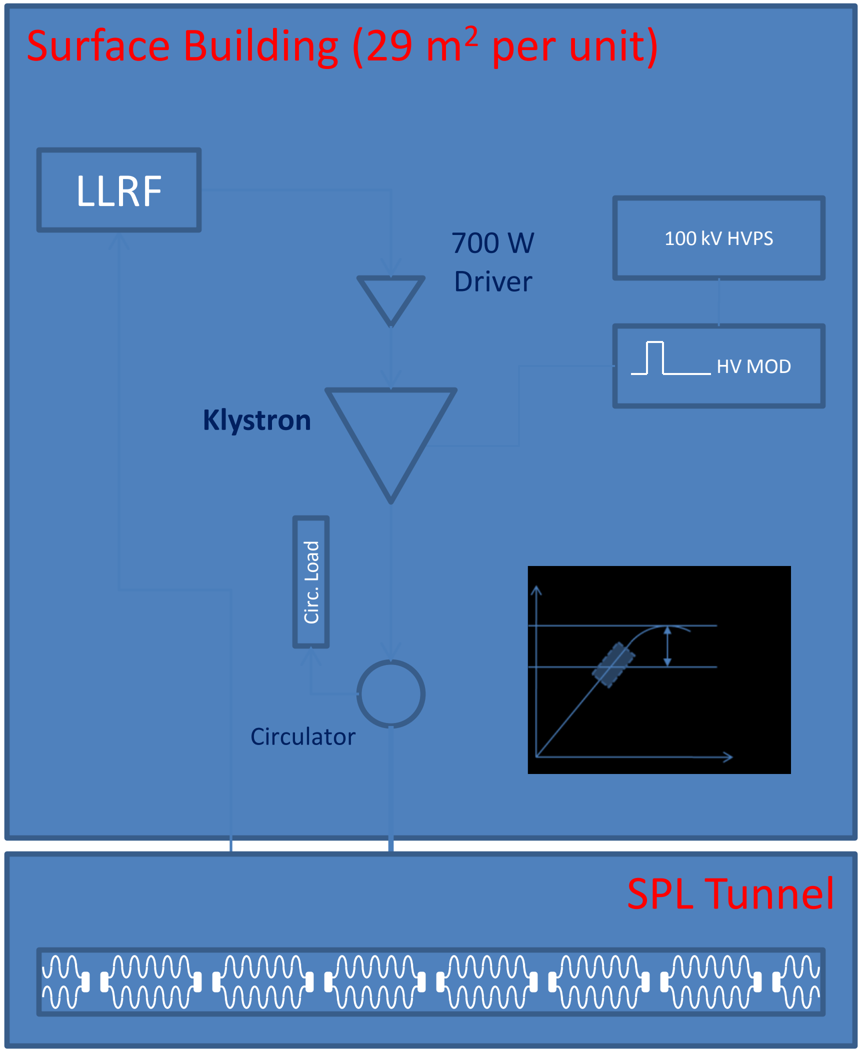
- ↘ Saturation curve + 1.5 dB margin
- ↘ Higher HV -> ~ 120 to 130 kV
- ↘ WG tuner to compensate differences (cavity parameters, Q_L variation, …) -> more losses

Total power from Klystron, $\eta_{RF\ dist.}$ = 91 %		3’400 kW
Operating point below saturation	- 1.5 dB	3’400 kW
Splitting	- 3.1 dB	
Circulator	- 0.1 dB	1’175 kW
Waveguide Tune	- 0.2 dB	1’150 kW
Power to Cavity Input		**1’100 kW**

Operating power

Total power from Klystron, $\eta_{RF\ dist.}$ = 91 %		1’850 kW
Operating point below saturation	- 1.5 dB	1’850 kW
Splitting	- 3.1 dB	
Circulator	- 0.1 dB	640 kW
Waveguide Tuner	- 0.2 dB	630 kW
Power to Cavity Input		**600 kW**

One klystron per cavity



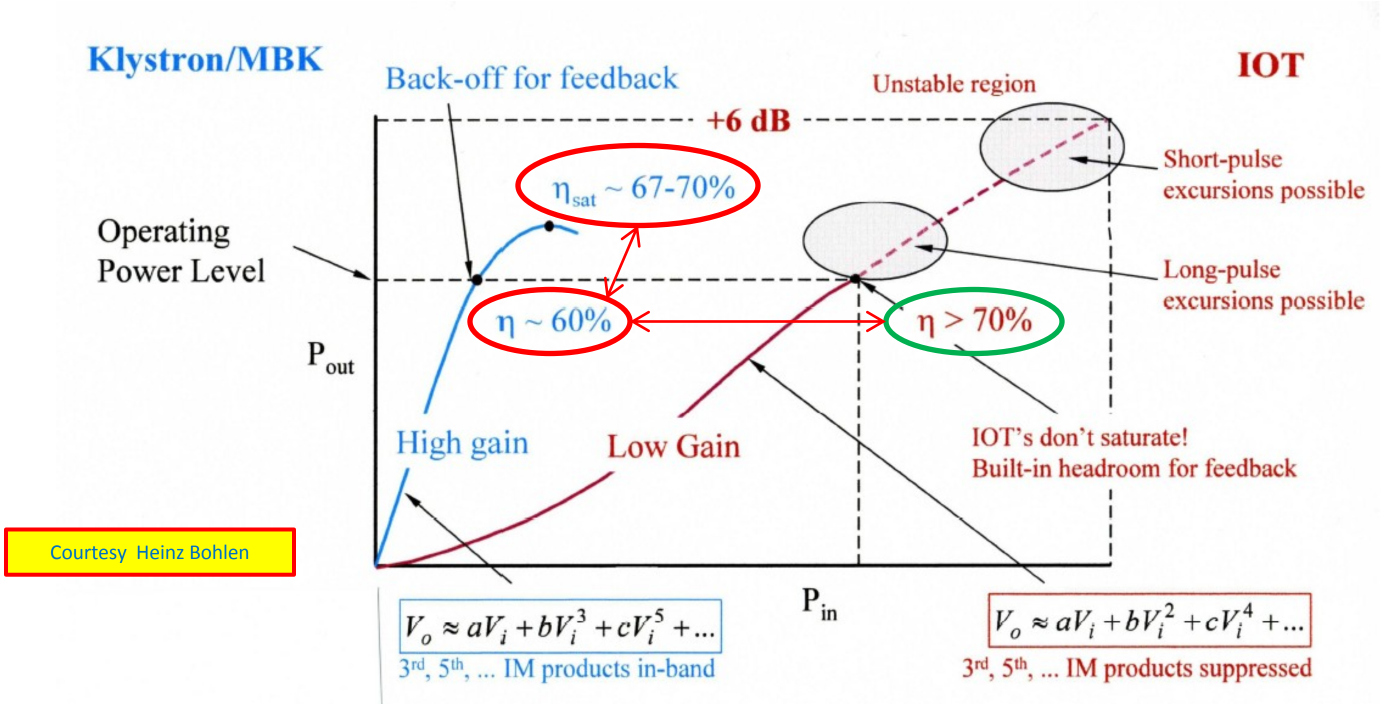
- ↗ Easiest for control, individual LLRF per cavity
- ↗ Easier HV -> ~ 100 kV
- ↗ Less RF distribution -> less losses

- ↘ Saturation curve + 1.5 dB margin
- ↘ Twice the number of klystrons

Total power from Klystron, $\eta_{RF\ dist.}$ = 98 %		**1’600 kW**
Operating point below saturation	- 1.5 dB	1’590 kW
Circulator	- 0.1 dB	
Power to Cavity		**1’100 kW**
Total power fron		**870 kW**
Operating point below saturation	- 1.5 dB	870 kW
Circulator	- 0.1 dB	
Power to Cavity Input		**600 kW**

Operating power

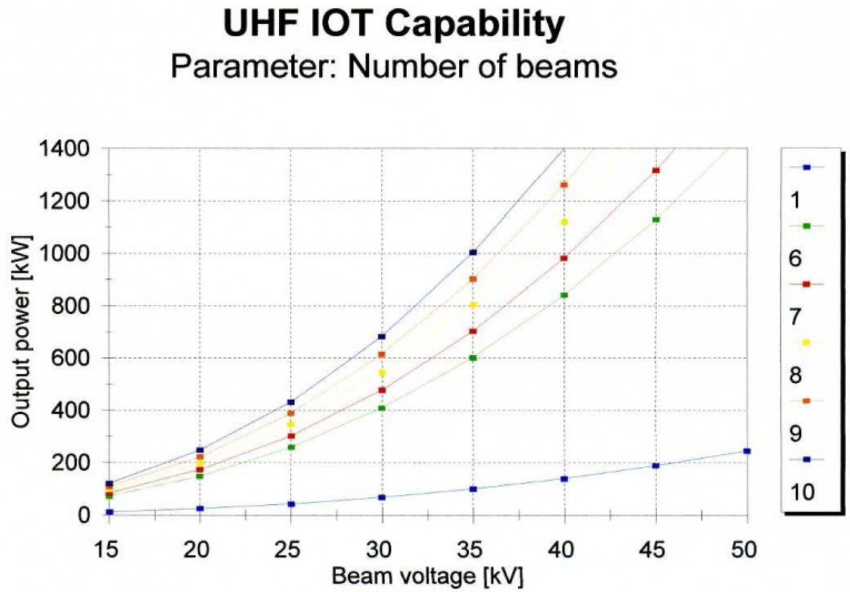
Alternative : IOTs



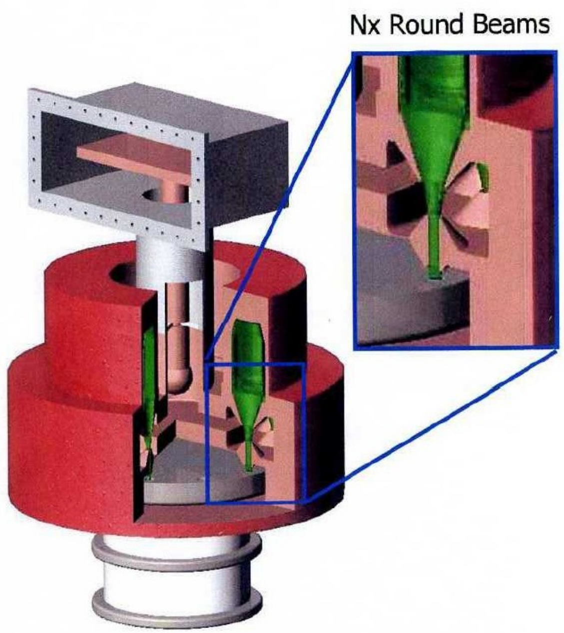
- ↗ IOTs do NOT saturate -> margin for LLRF already included !
- ↗ No pulsed modulator needed -> pulses via RF drive
- ↗ pulse excursions possible
- ↗ Better efficiency than klystron at operating point

- ↘ Less gain
- ↘ Lower peak power

MB-IOT

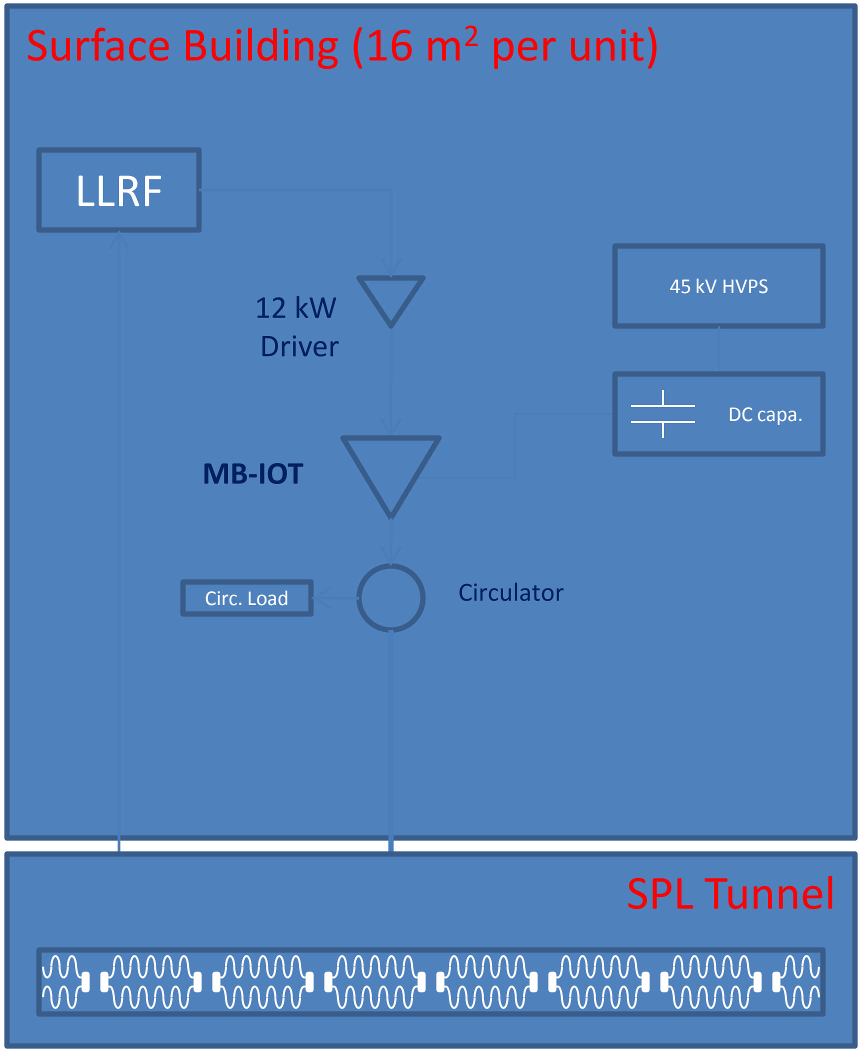


- It is obvious that a single-beam IOT cannot produce the desired output power levels
- Only multi-beam IOTs could cover the power range that is requested
- Already a 6-beam IOT would be able to provide the requested power



Courtesy Heinz Bohlen

One MB-IOT per cavity

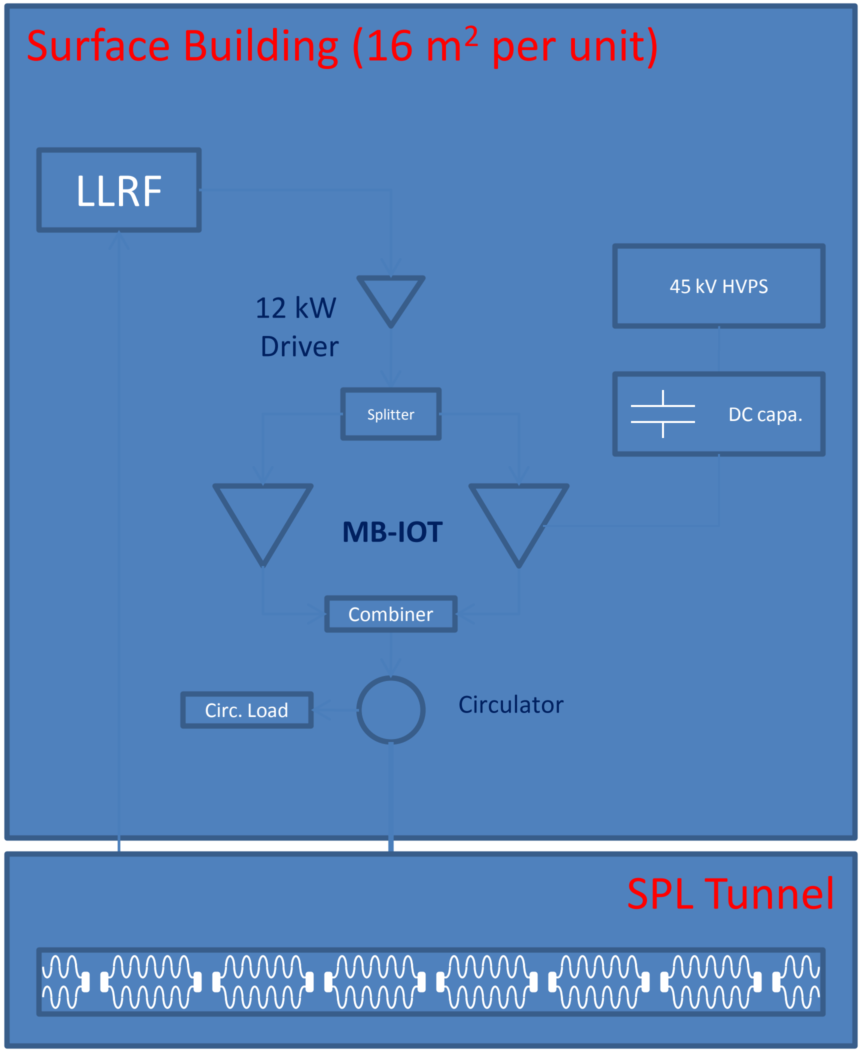


- ↗ Typical DC voltage range 45 kV
- ↗ Pulses via RF drive
- ↗ Easiest for control, individual LLRF per cavity
- ↗ Compact

- ↘ Gain 20 dB -> need a 12 kW driver
- ↘ Very high power level for a single IOT
- ↘ Some suppliers feel it impossible to achieve, the others estimate the risk to fail very high !

Total power from HOM-IOT, $\eta_{RF\ dist.}$ = 98 %		**1’125 kW**
Circulator	- 0.1 dB	1’125 kW
Power to Cavity Input		**1’100 kW**
Total power from HOM-IOT, $\eta_{RF\ dist.}$ = 98 %		**615 kW**
Circulator	- 0.1 dB	615 kW
Power to Cavity Input		**600 kW**

Two MB-IOT per cavity



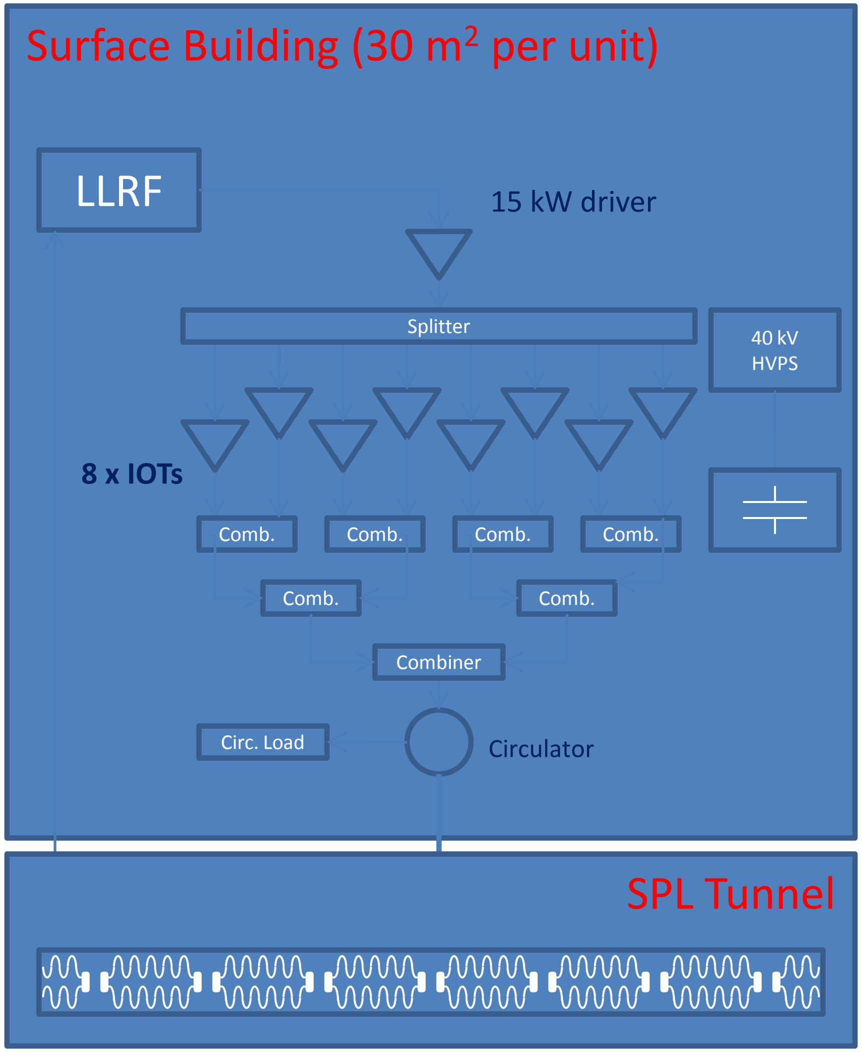
- ↗ Typical DC voltage range 45 kV
- ↗ Pulses via RF drive
- ↗ Easiest for control, individual LLRF per cavity
- ↗ Compact

- ↘ Gain 20 dB -> need a 12 kW driver
- ↘ Still very high power level for a single IOT

Total power from HOM-IOT, $\eta_{RF\ dist.}$ = 95 %		**600 kW**
Combiner	+2.9 dB	580 kW
Circulator	- 0.1 dB	1’125 kW
Power to Cavity Input		**1’100 kW**

Total power from HOM-IOT, $\eta_{RF\ dist.}$ = 95 %		**315 kW**
Combiner	+2.9 dB	315 kW
Circulator	- 0.1 dB	615 kW
Power to Cavity Input		**600 kW**

8 x single beam IOTs



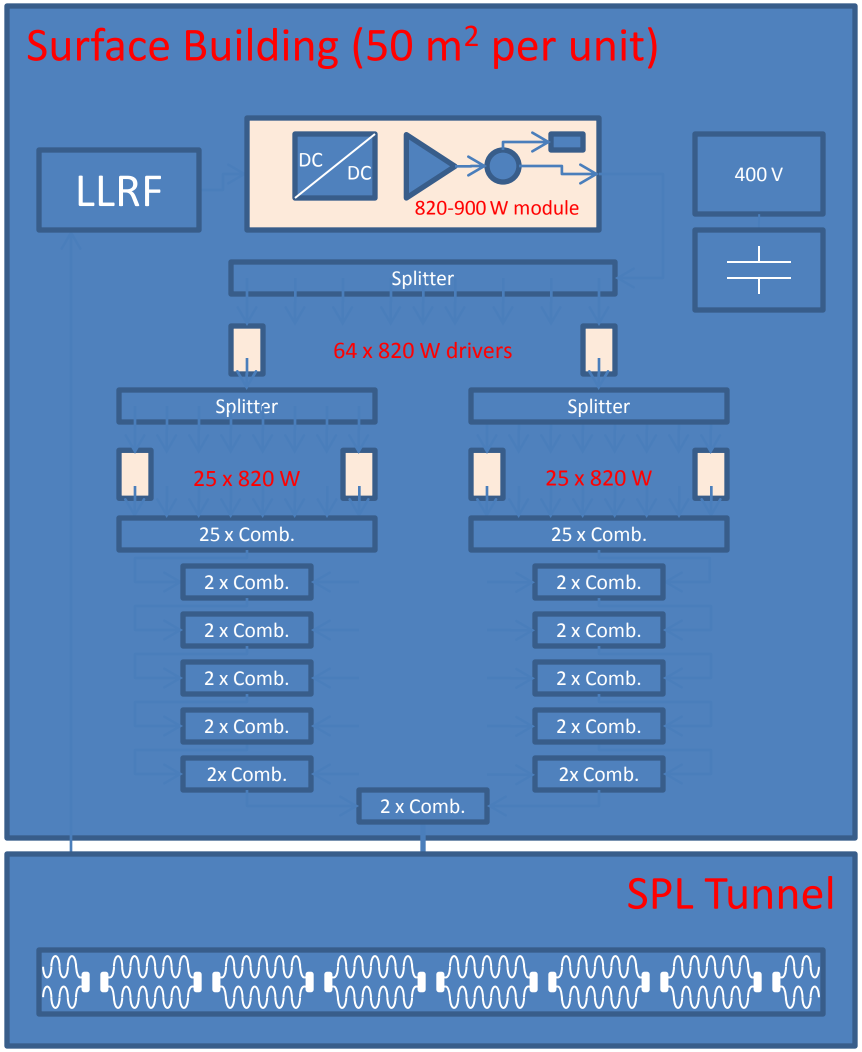
- Quasi 'off the shelf' IOT products
- Typical DC voltage range 40 kV
- Pulses via RF drive
- Easiest for control, individual LLRF per cavity

- 8 x 184 + 4 x 62 = 1720 IOTs
- Production capability of such an item would be of ~ 150 per year per supplier
- It would then required ~ 12 years production, even with three suppliers -> 4 years full production !

Total power from IOT, $\eta_{RF\ dist.}$ = 91 %		**160 kW**
Combiners	+8.7 dB	155 kW
Circulator	- 0.1 dB	1'125 kW
Power to Cavity Input		**1'100 kW**

Total power from IOT, $\eta_{RF\ dist.}$ = 93 %		**160 kW**
Combiners	+5.8 dB	160 kW
Circulator	-0.1 dB	615 kW
Power to Cavity Input		**600 kW**

Solid State Amplifier (SSA)



- ➢ Mandatory principle for reliability, module with:
  - ➢ Individual circulator
  - ➢ Individual DC/DC converter
  - ➢ Long life DC capacitors
- ➢ Foreseen reliable power unit = 1 kW
  - ➢ (perhaps 2 kW within coming years ?)
- ➢ 1665 x 184 + 833 x 62 = 358’006 single modules

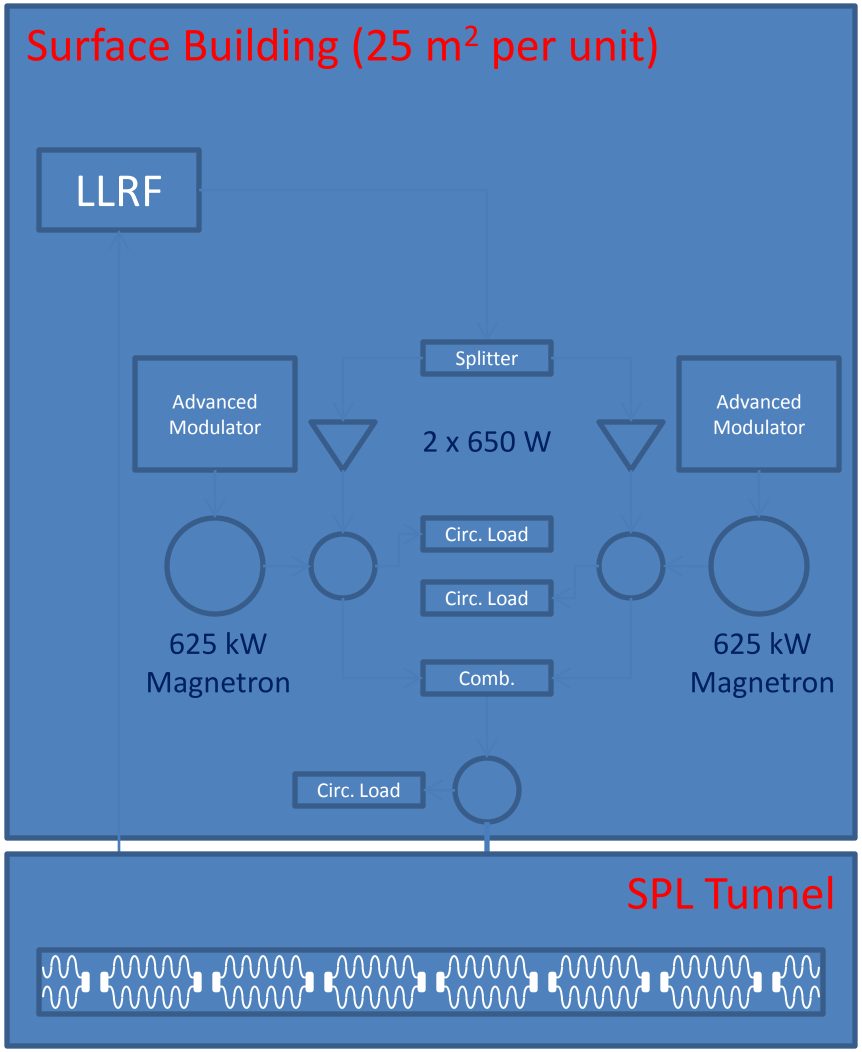
- ↗ Lifetime > 20 years with less than 1% faulty module per year:
  - ↗↘ turnover of ~ 3’500 modules per year
- ↗ No HV needed (↘ but high current !)
- ↗ Gain = 20 dB
- ↗ Single low level per cavity

- ↘ Total surface needs: ~ 11’000 m²

Total power from SSA (x 1600), $\eta_{RF\ dist.}$ = 85 %		**820 W**
Combiners	+31.3 dB	815 W
Power to Cavity Input		**1’100 kW**

Total power from SSA (x 800), $\eta_{RF\ dist.}$ = 87 %		**900 W**
Combiners	+28.4 dB	870 W
Power to Cavity Input		**600 kW**

Magnetrons

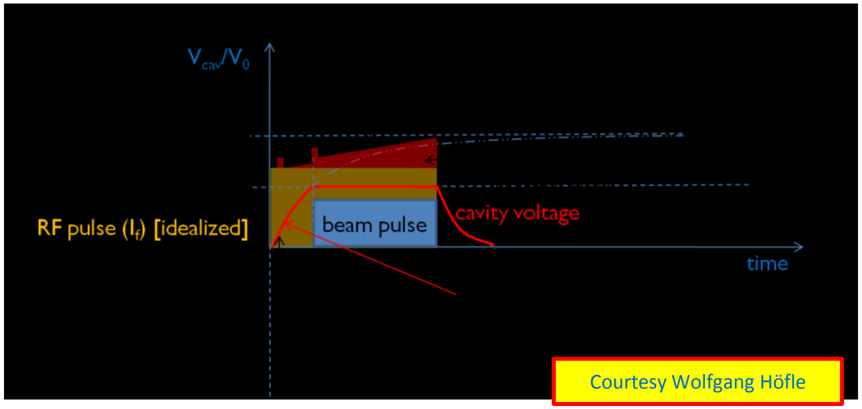


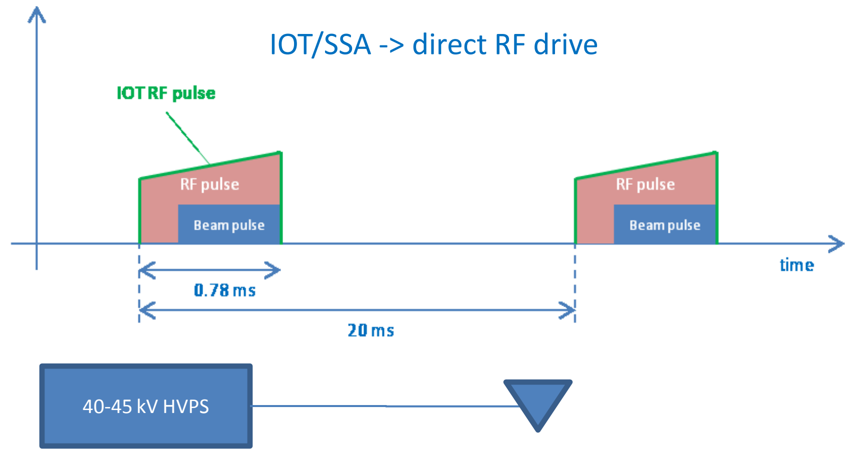
- Not an amplifier, but injection-locked oscillator
- Design presented last year by Amos Dexter (http://indico.cern.ch/materialDisplay.py?contribId=73&sessionId=1&materialId=0&confId=63935)
- Not a lot of information from tube suppliers

Total power per Magnetron		**620 kW**
Margin for locking	- 0.2 dB	620 kW
Circulator	- 0.1 dB	690 kW
Combiner	+2.9 dB	580 kW
Circulator	- 0.1 dB	1’125 kW
Power to Cavity Input		**1’100 kW**

Total power per Magnetrons		**330 kW**
Margin for locking	- 0.2 dB	330 kW
Circulator	- 0.1 dB	325 kW
Combiners	+2.9 dB	315 kW
Circulator	- 0.1 dB	615 kW
Power to Cavity Input		**600 kW**

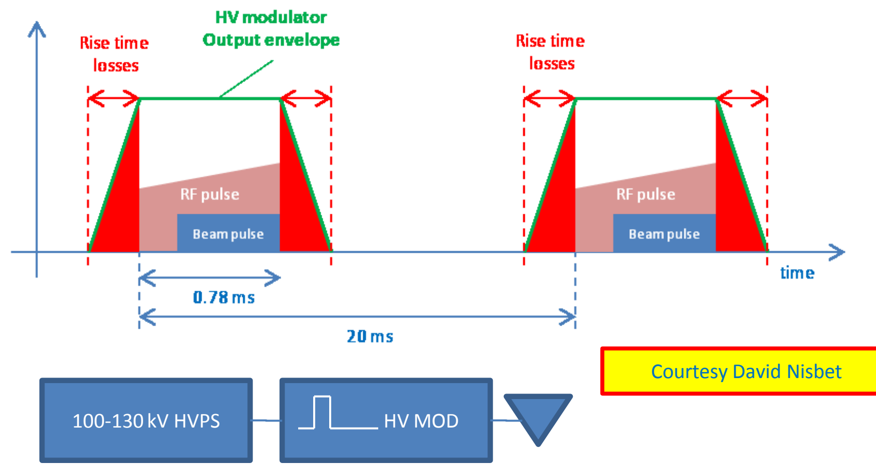
Efficiency





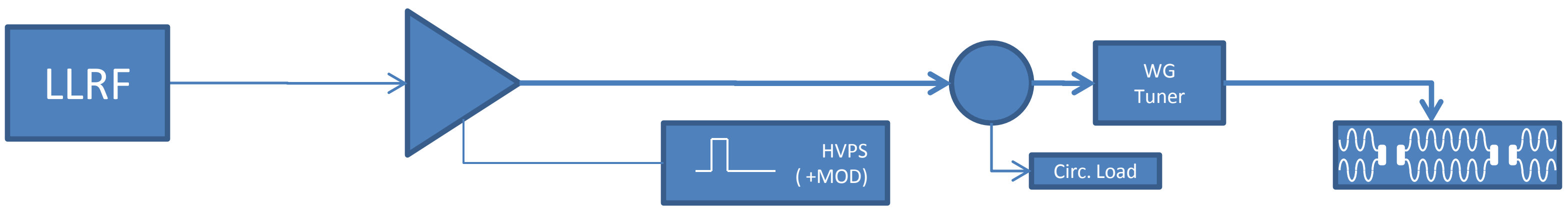
- With MB-IOT, IOTs, SSA:
  - pulse via RF drive!
  - No additional HV pulse modulator necessary
- this would reduce wall plug power quite significantly!

- For klystron, need to pulse HV:
  - HV must be ready before RF pulse
  - Additional losses



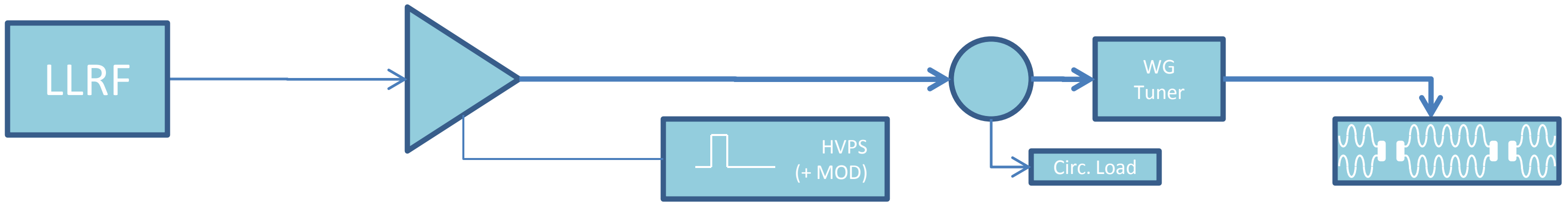
HVPS Modulator for klystron -> additional overall losses

'High Power amplifiers' Efficiency



	$\eta_{RF\ source}$ [%]	η_{HVPS} [%]	$\eta_{RF\ dist.}$ [%]	$\eta_{RF\ tot}$ [%]
½ 3.4 MW Klystron	52	85	91	40
1.6 MW Klystron	57	85	98	47
1.125 MW MB-IOT	65	90	98	57
2 x 600 kW MB-IOT	65	90	95	56
8 x 160 kW IOTs	65	90	91	53
1665 x 820 W SSA	55	90	85	42

'Low power amplifiers' Efficiency



	ηRF source [%]	ηHVPS [%]	ηRF dist. [%]	η RF tot [%]
½ 1.85 MW Klystron	56	85	91	43
870 kW Klystron	60	85	98	50
615 kW MB-IOT	65	90	98	57
2 x 315 kW MB-IOT	65	90	95	56
4 x 160 kW IOTs	65	90	93	54
833 x 900 W SSA	55	90	87	43

sLHC

'High Power amplifiers' Costs over 20 years

CERN
Beams department
RF group

Tentative data

HP-SPL 40 mA : 0.78 ms / 50 Hz (cav #246 : 1.1 MW max)	½ 3.4 MW Klystron	1.6 MW klystron	1.125 MW MB-IOT	2 x 600 kW MB IOTs	8 x 160 kW IOT	1665 x 820 W SSA
Circulator load [kCHF]	250	100	100	100	100	0
RF lines [kCHF]	200	60	60	7[illegible]	1[illegible]	60
Driver [kCHF]	5	5	35	40	45	0
LLRF, Control [kCHF]	150	75	[illegible]5	[illegible]	100	100
Inst. & cabling [kCHF]	275	[illegible]0	20[illegible]	225	250	275
HVPS [kCHF]	900	[illegible]	300	360	560	0
Lifetime [h]	>50'000	>50'000	>50'0[illegible]0	[illegible]0'0[illegible]0	[illegible]'000	>150'000
Tubes [kCHF]	280	140	[illegible]0	[illegible]0	70	3200
Total # tubes	3	3	3	6	24	1.1
# power stations	92	184	184	184	184	184
Amplifier Total [MCHF]	**277**	**272**	**277**	**363**	**607**	**837**
RF efficiency [%]	39	46	57	56	53	42
Wallplug [GVA]	2691	2271	1815	1873	1955	2473
Wall plug [MCHF]	**269**	**227**	**182**	**187**	**195**	**247**
Total	**546**	**499**	**459**	**550**	**803**	**1084**
Risk to fail	**Medium**	**Low**	**High**	**High**	**Low**	**Low**

RF components [kCHF per unit]			
Circulator	50	Driver	3/kW
Load	50	LLRF	50
Waveguide	60	Control	25
WG tuner	30	Infrastructure	75
Splitter	20	Cooling	50
Combiner	20	Cabling	75

- Operation = 20 years x 10/12 months (300 days) x 24 hours = 150'000 hours
- Total # tube = 150'000 / lifetime
- Amplifier total = # power amplifiers x [RF components + HVPS + Tubes]
- Total RF power scaled along 'high power' cavities = 185 MW
- Wall plug [GVAh]= 185 MW x 3.9 % duty cycle * 150000 hours / RF efficiency
- Wall plug [MCHF] = Wall plug [GVAh] [CHF/kVAh]

Today Wall Plug amounts all inclusive = 0.07 [CHF/kWh], but from 2015, will be 0.1 [CHF/kWh]

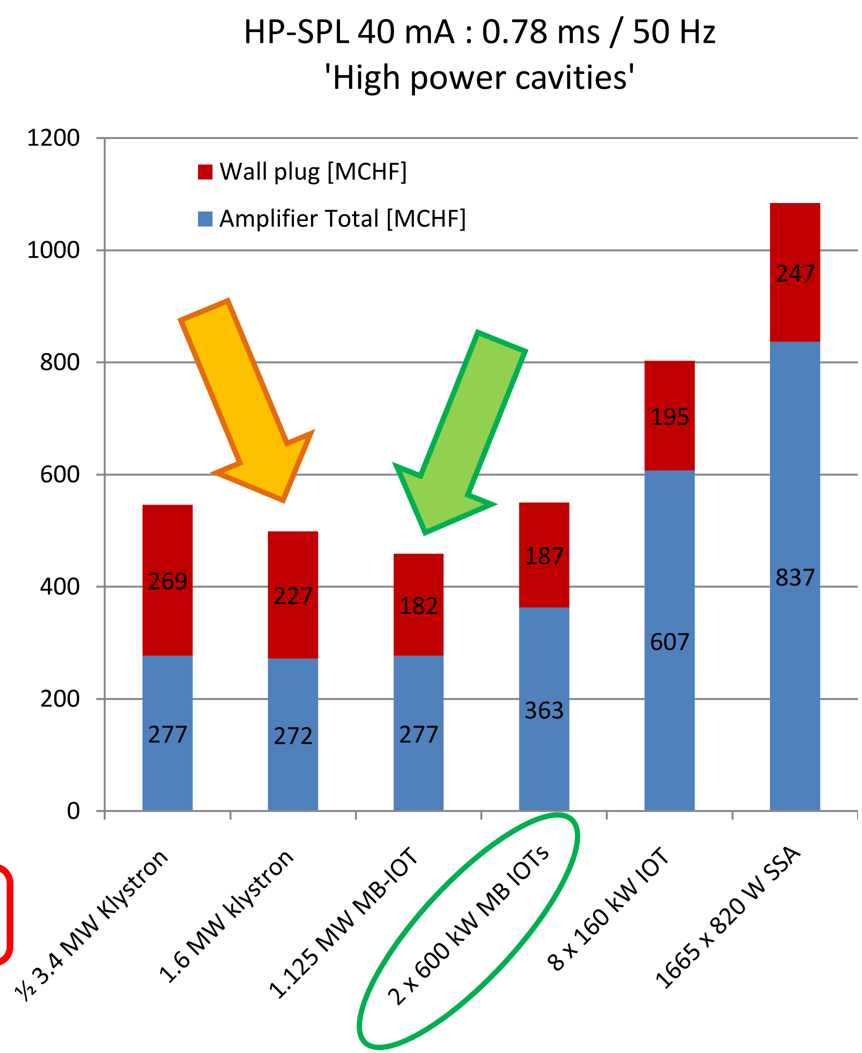
Fredry Brodry, François Duval

sLHC ‘High Power amplifiers’ Costs over 20 years

CERN
Beams department
RF group

HP-SPL 40 mA : 0.78 ms / 50 Hz (cav #246 : 1.1 MW max)	½ 3.4 MW Klystron	1.6 MW klystron	1.125 MW MB-IOT	2 x 600 kW MB IOTs	8 x 160 kW IOT	1665 x 820 W SSA
Circulator load [kCHF]	250	100	100	100	100	0
RF lines [kCHF]	200	60	60	[illegible]	[illegible]	60
Driver [kCHF]	5	5	35	40	45	0
LLRF, Control [kCHF]	150	75	[illegible]	[illegible]	100	100
Inst. & cabling [kCHF]	275	[illegible]	[illegible]	225	250	275
HVPS [kCHF]	900	[illegible]	300	360	560	0
Lifetime [h]	>50’000	>50’000	[illegible]	[illegible]	[illegible]	>150’000
Tubes [kCHF]	280	140	[illegible]	[illegible]	70	3200
Total # tubes	3	3	3	6	24	1.1
# power stations	92	184	184	184	184	184
Amplifier Total [MCHF]	277	272	277	363	607	837
RF efficiency [%]	39	46	57	56	53	42
Wallplug [GVA]	2691	2271	1815	1873	1955	2473
Wall plug [MCHF]	269	227	182	187	195	247
Total	546	499	459	550	803	1084
Risk to fail	Medium	Low	High	High	Low	Low

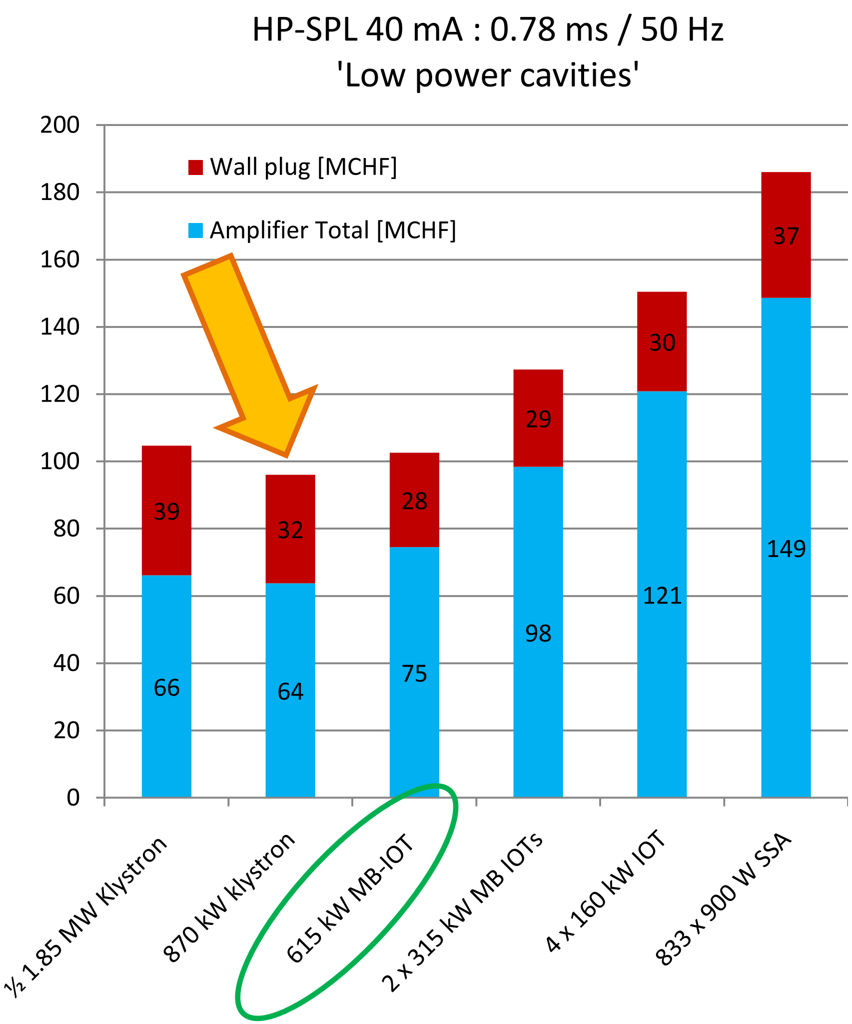
Tentative data



‘Low Power Amplifiers’ Costs over 20 years

HP-SPL 40 mA : 0.78 ms / 50 Hz (cav #26: 600 kW max)	½ 1.85 MW Klystron	870 kW klystron	615 kW MB-IOT	2 x 315 kW MB IOTs	4 x 160 kW IOT	833 x 900 W SSA
Circulator load [kCHF]	200	80	80	80	80	0
RF lines [kCHF]	200	60	60	[illegible]	[illegible]	60
Driver [kCHF]	5	5	30	35	40	0
LLRF, Control [kCHF]	150	75	[illegible]	[illegible]	100	100
Inst. & cabling [kCHF]	275	[illegible]	[illegible]	225	250	275
HVPS [kCHF]	500	[illegible]	180	200	280	0
Lifetime [h]	>50’000	>50’000	[illegible]	[illegible]	[illegible]	>150’000
Tubes [kCHF]	175	85	[illegible]	[illegible]	70	1500
Total # tubes	3	3	3	6	12	1.1
# power stations	31	62	62	62	62	62
Amplifier Total [MCHF]	66	64	75	98	121	149
RF efficiency [%]	42	50	57	56	54	43
Wallplug [GVA]	385	322	281	289	296	374
Wall plug [MCHF]	39	32	28	29	30	37
Total	105	96	103	127	150	186
Risk to fail	Low	Low	High	High	Low	Low

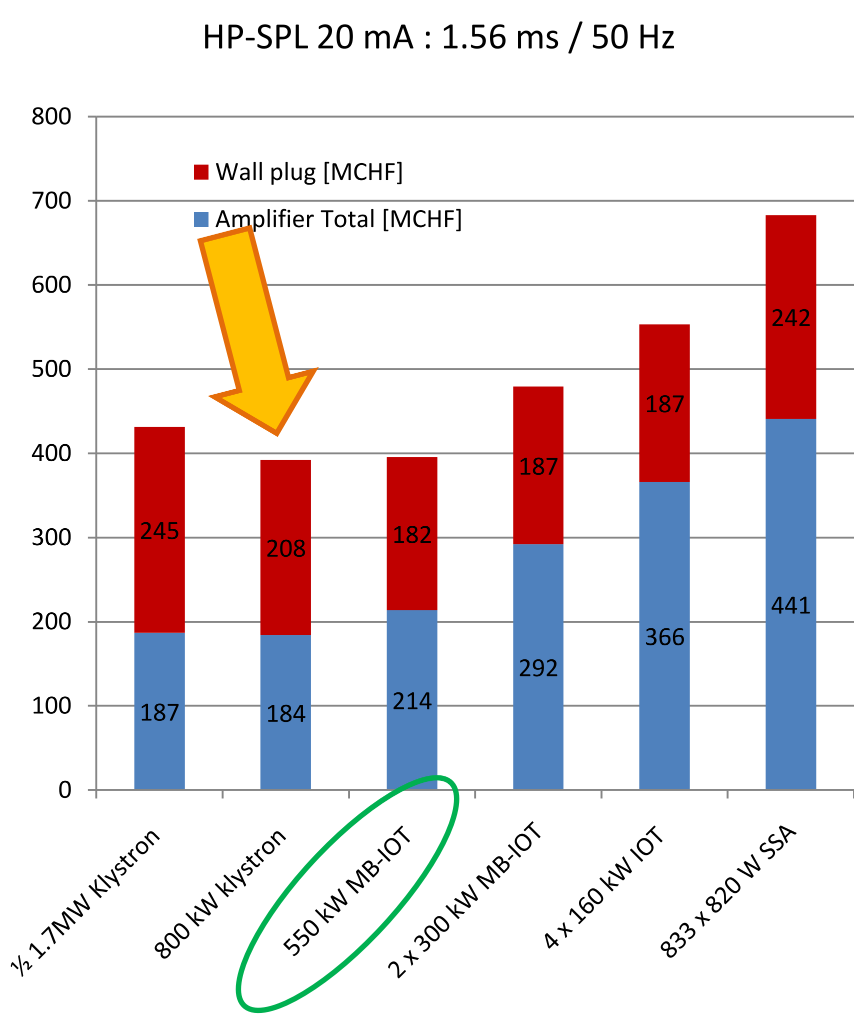
Tentative data



HP-SPL 20 mA : 1.56 ms / 50 Hz

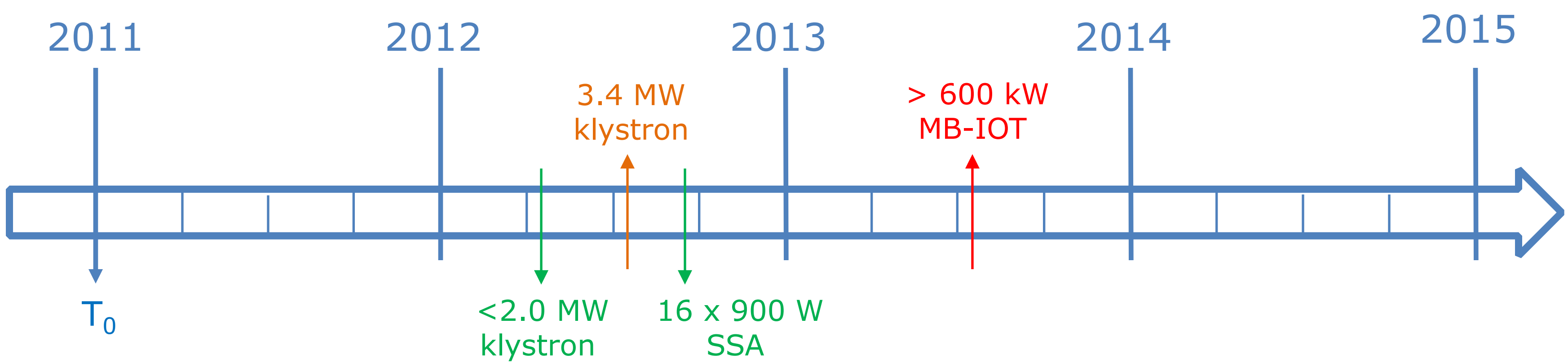
HP-SPL 20 mA : 1.56 ms / 50 Hz (cav #246 : 550 kW max)	½ 1.7MW Klystron	800 kW klystron	550 kW MB-IOT	2 x 300 kW MB-IOT	4 x 160 kW IOT	833 x 820 W SSA
Circulator load [kCHF]	225	90	70	80	80	0
RF lines [kCHF]	200	60	60	75	[illegible]	60
Driver [kCHF]	5	5	25	35	45	0
LLRF, Control [kCHF]	150	75	75	75	100	100
Inst. & cabling [kCHF]	275	200	[illegible]	225	250	275
HVPS [kCHF]	475	200	175	200	280	0
Lifetime [h]	>50'000	>50'000	>50'000	[illegible]	[illegible]	>150'000
Tubes [kCHF]	145	80	[illegible]	[illegible]	70	1500
Total # tubes	3	3	3	6	12	1.1
# power stations	92	184	184	184	184	184
Amplifier Total [MCHF]	**187**	**184**	**214**	**292**	**366**	**441**
RF efficiency [%]	43	50	57	56	56	43
Wallplug [GVA]	2446	2082	1815	1873	1873	2417
Wall plug [MCHF]	**245**	**208**	**182**	**187**	**187**	**242**
Total	**431**	**392**	**395**	**479**	**553**	**683**
Risk	Low	Low	High	Medium	Low	Low

Tentative data



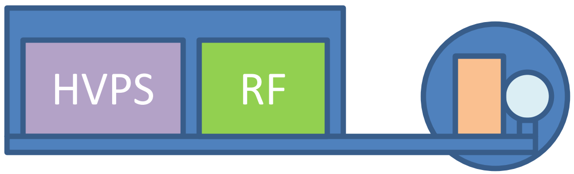
Prototypes

	Month	Design [kCHF]	HVPS [kCHF]	RF dist. [kCHF]	Risk (suppliers)	Proto [kCHF]	HP 40 mA	HP 40 mA	HP 20 mA
3.4 MW Klystron	18	1500	1200	100	Moderate	2800	1/2		
1.9 MW Klystron	15	1000	550	50	Low	1600	1	1/2	1/2
870 kW klystron	15	700	300	50	Low	1050		1	1
1.2 MW MB-IOT	30	2000	400	50	High	2450	1	1/2	1/2



All numbers are preliminary rough estimates !

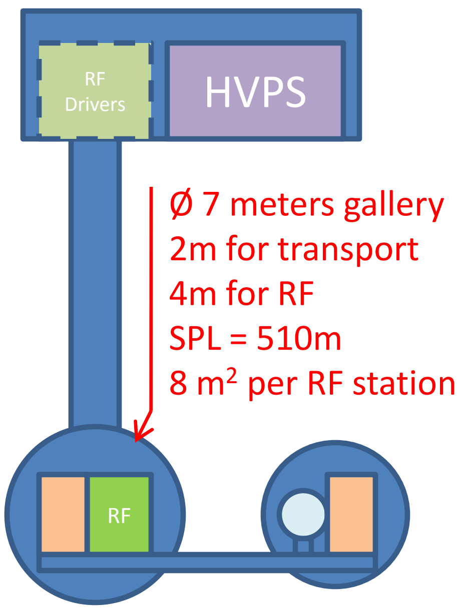
Infrastructure



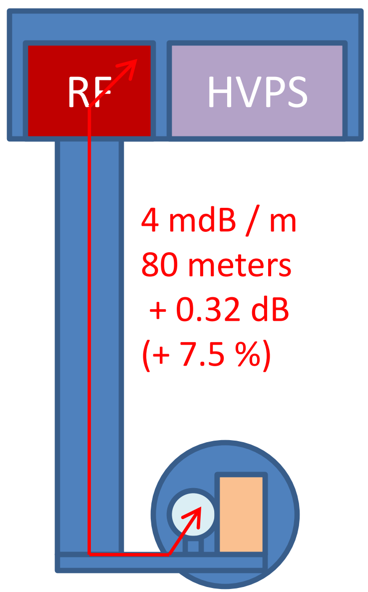
Galleries only

	1 Klysrton 2 cavities	1 klystron 1 cavity	1 MB-IOT 1 cavity	2 MB-IOT 1 cavity	8 x IOTs 1 cavity	4 x IOTs 1 cavity	1617 SSA 1 cavity	808 x SSA 1 cavity
RF m^2 / cavity	8	9	6	9	20	14	40	20
PS m^2 / cavity	12	20	10	15	10	5	10	5

Surface + Galleries



Surface only



- Can we build a whole RF hall within the same floor as the cavities ?
- OR, can we have the power source compact enough such located in a service gallery of a restricted size ?
- Or do we need to have all equipments located in a surface building ?
  (-> Need more powerful sources and more waveguides):
  - 80 m distribution waveguide -> 80 x .004 = 0.32 dB
  - Scaled to all cavities -> additional 16 MW additional RF losses
  - Duty cycle x 10/12 months x efficiency ~ 55 % -> additional 800 kCHF/ year wall plug bill !

Conclusion

- Multi 'TV-IOTs' and SSA seem very expensive…
- Single klystron seems the best solution
- Not enough data to include Magnetron into comparison
- Rough estimates have been presented, consistent with previous studies, a lot of important details are missing :
  - All subsystems (cooling, building,…)
  - Accurate power distribution along the machine,…
  - HVPS
- 600 kW MB-IOT is a very interesting option to study:
  - Series tube price, life time and effective efficiency ???
  - Even if very risky, building a new IOT prototype could help to improve IOT technology and reduce (?) final total cost, and be useful for other projects

Thank you for your attention