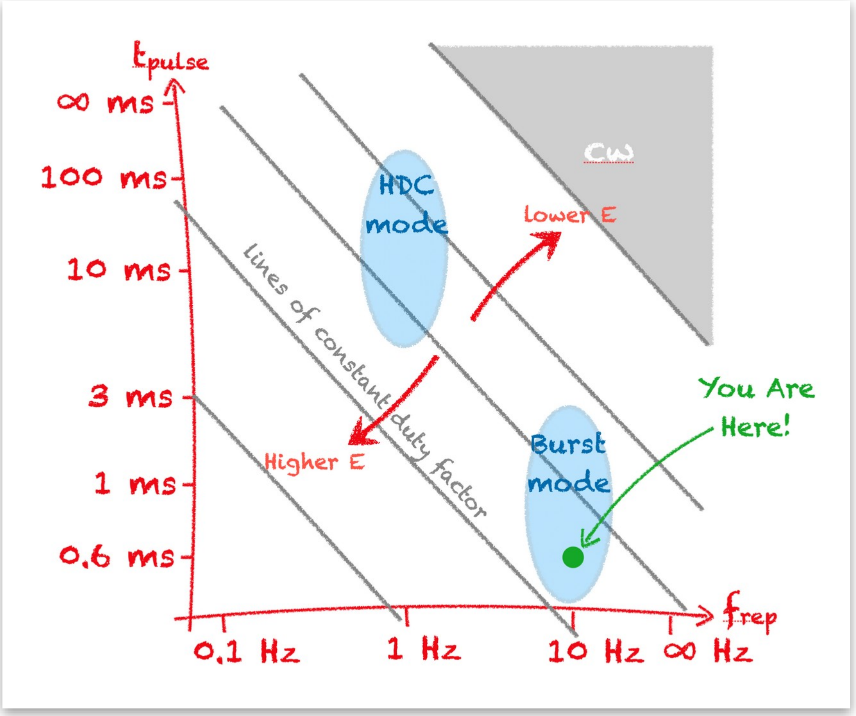
Linear accelerator parameters and scalings: what limits, what not

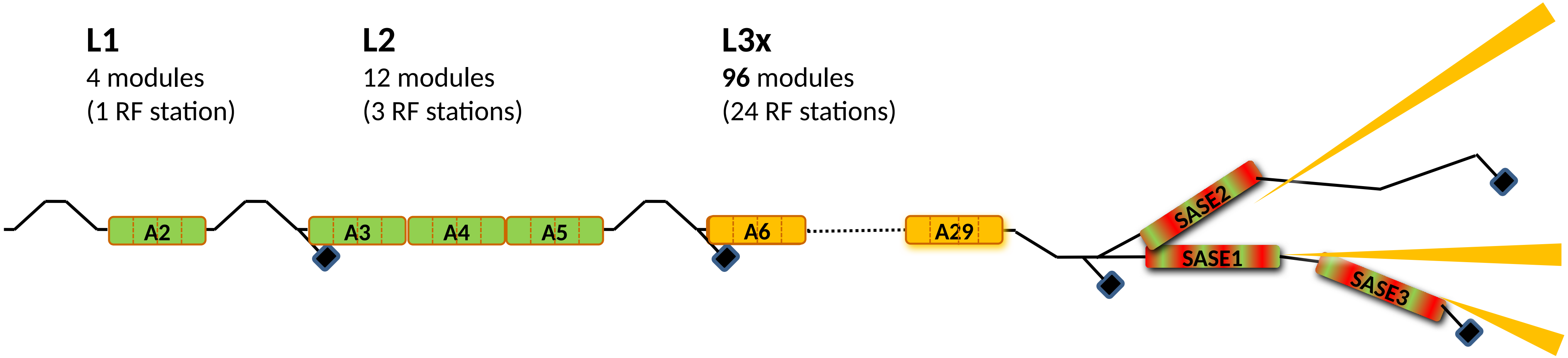
Nick Walker
on behalf of the XFEL HDC Team



HDC Colloquium 2nd June 2026

One man's Limit is
another man's R&D challenge!

L1/L2 energy is fixed by the bunch compressor dynamics; L3x energy gain can vary

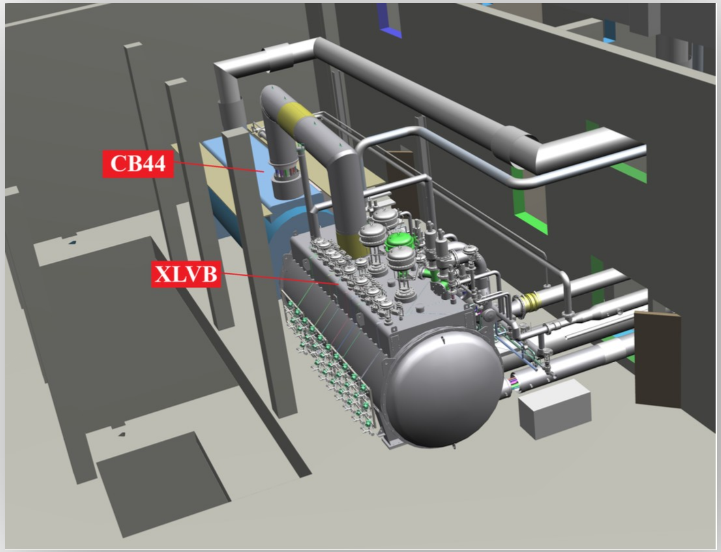


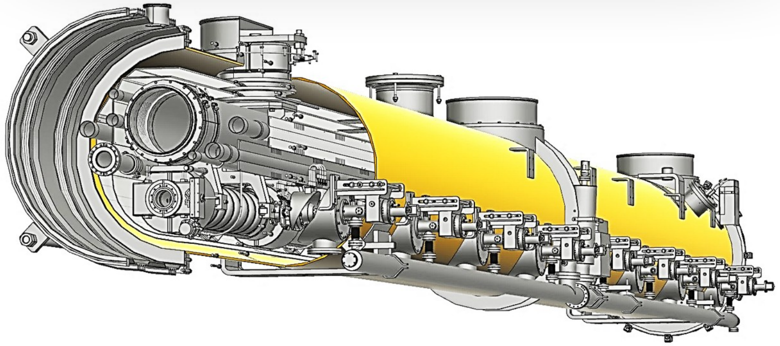
L1/L2
16 new cryomodules
Fixed energy: 2 GeV
($E_{acc} \approx 20$ MV/m)

L3x
96 existing cryomodules
Variable energy: ≤ 16 GeV
($E_{acc} \leq 7.5 - 17.6$ MV/m)

Different issues → different solutions

Limiting factor 1: CRYOGENICS



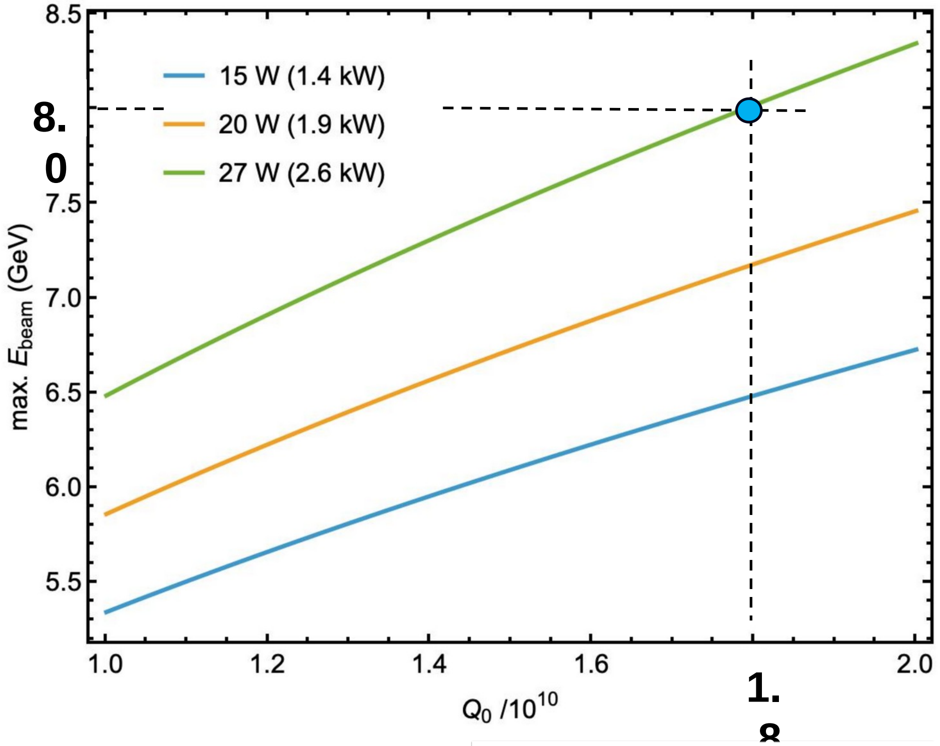


Or more specifically 2K Dynamic Heal Load (DHL)

Cryogenic limit in L3x: 27 W Dynamic Heat Load (DHL) per cryomodule should achieve design goal of 8 GeV CW

With possibly some in situ modifications to the existing cryostrings → R&D

RF cavity gradient	7.5 MV/m	*for 8 GeV*
2K Dyn. HL/module	27 W	*limit*
Q_0	**1.8×10^{10}**	***derived requirement***
Static HL/module	5 W	
Total HL/module	32 W	
Total 2K HL L3x	3.2 kW	← *new cryoplant!*



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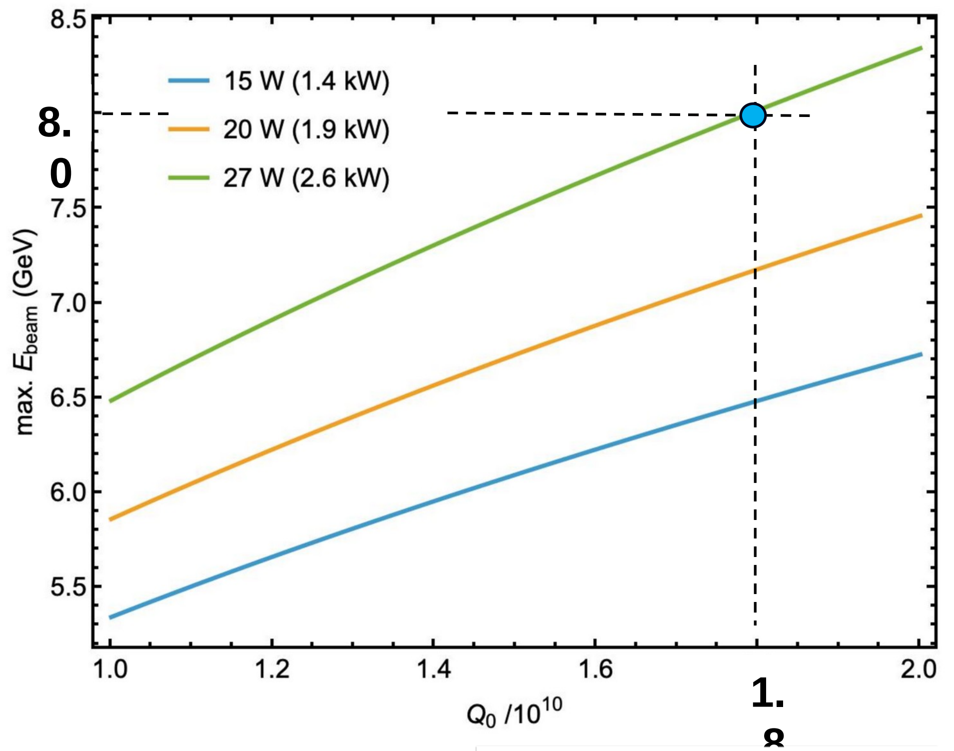
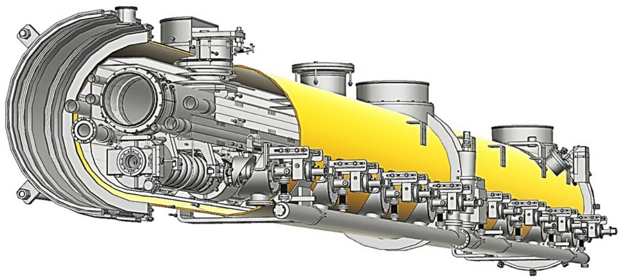


$$8\frac{E_{cav}^2}{Q_0\left(\frac{r}{Q}\right)} \leq P_{2K,max}$$

Challenges:
- Experimental validation 27 W limit cryo solution
- Measuring effective average Q_0 at 7.5 MV/m in L3

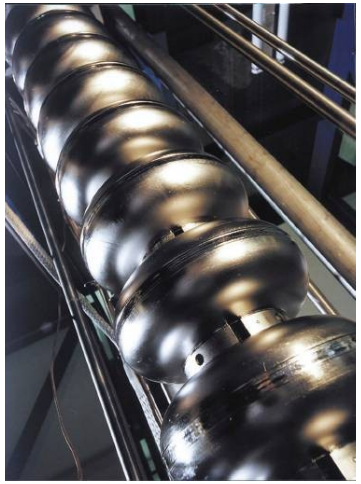
L1/L2 requires high-gradient (20 MV/m) high-Q_0 CW-optimised cryomodules similar to LCLS-II-HE



Major on-going R&D programme (already quite advanced)

Requirements:

RF cavity gradient	20 MV/m	*fixed by 2 GeV (constant) beam energy*
2K Dyn. HL/module	114 W	*derived*
Q_0	**3×10^{10}**	*specified design goal*
Static HL/module	10 W	
Total HL/module	124 W	
Total 2K HL L1/L2	2 kW	← *existing cryoplant (with some modifications)*



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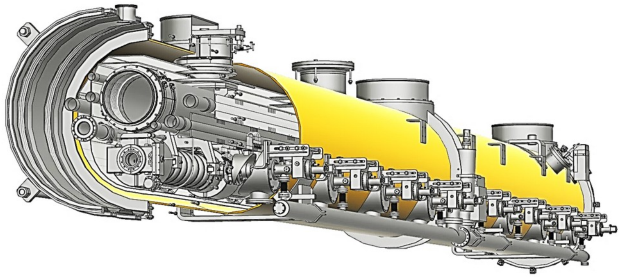
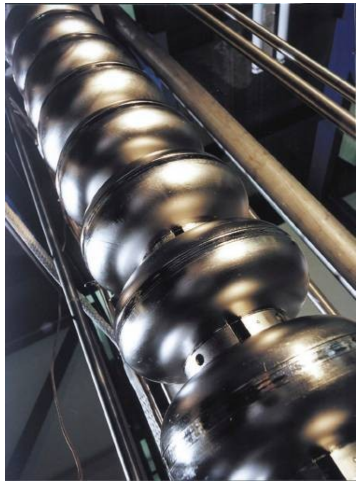
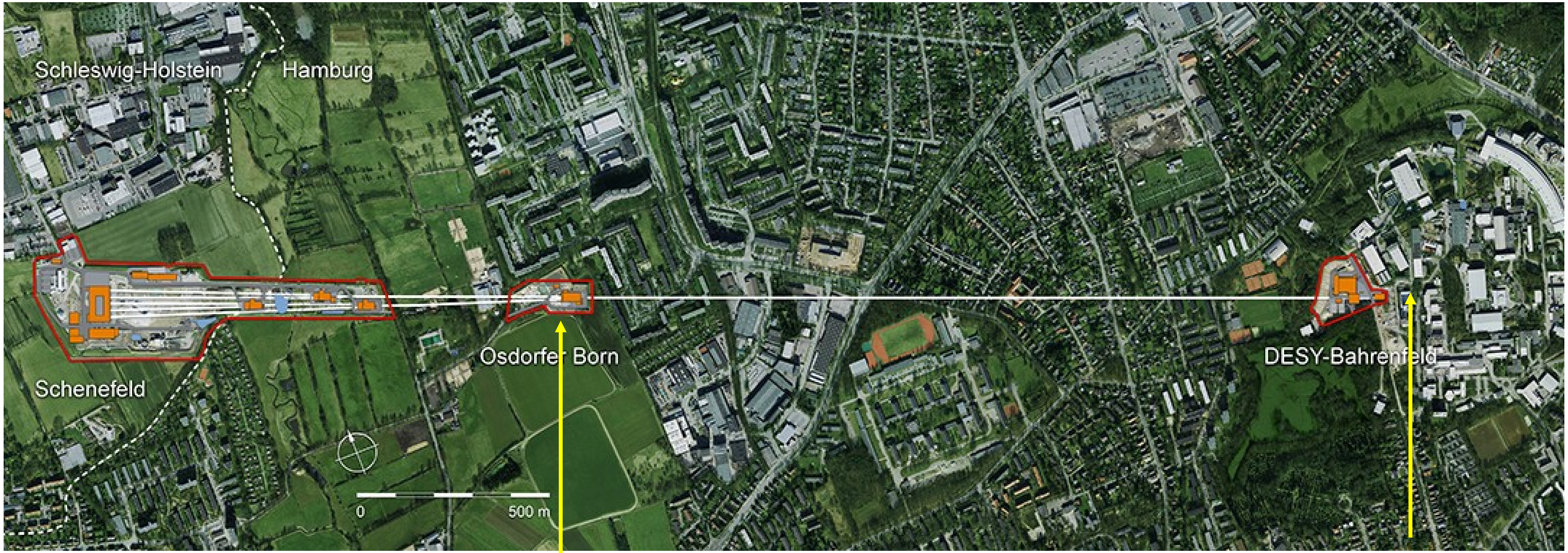


Challenges:

- New surface recipe for high E_{cav} / high Q_0 for nine-cell cavities
- Understanding impact of magnetic flux sensitivity
- Mitigating Field Emission in string assembly
- Consolidating final design modifications for cryomodule
- Modified Fundamental Power Coupler



New HDC cryoplant: options conceptually studied



Option 2:
Located in
Osdorfer Bonn

Option 1:
Located on
DESY campus

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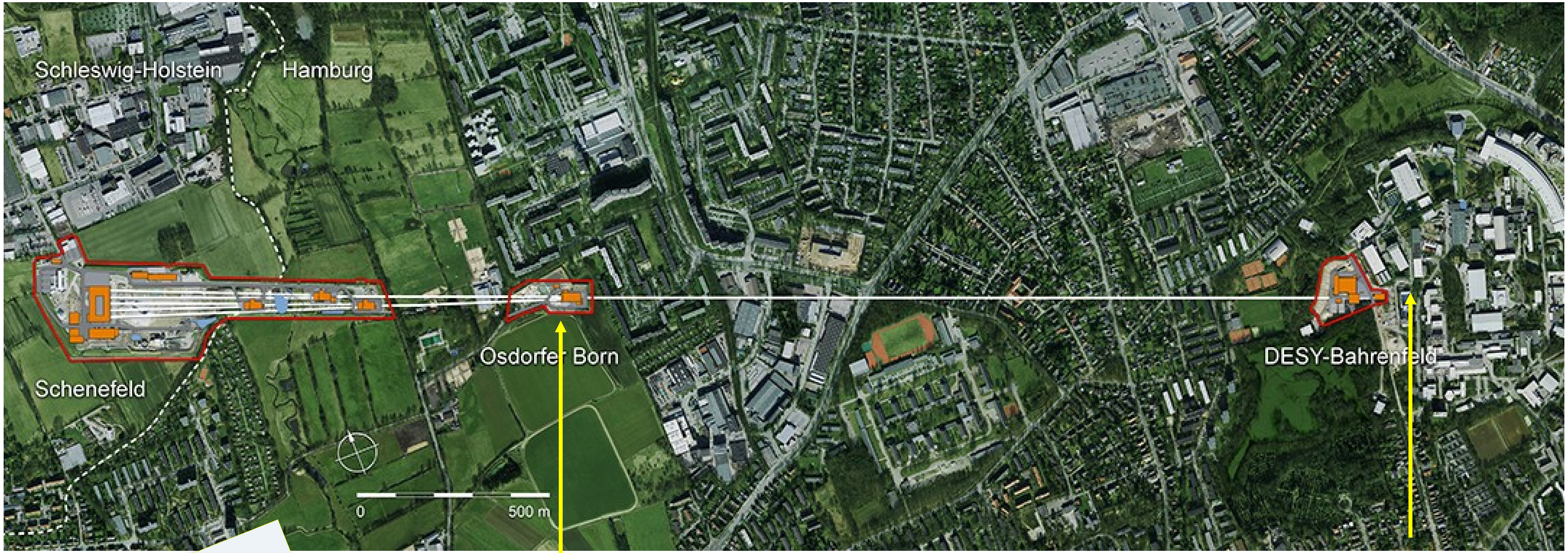

lower cryo tech risk

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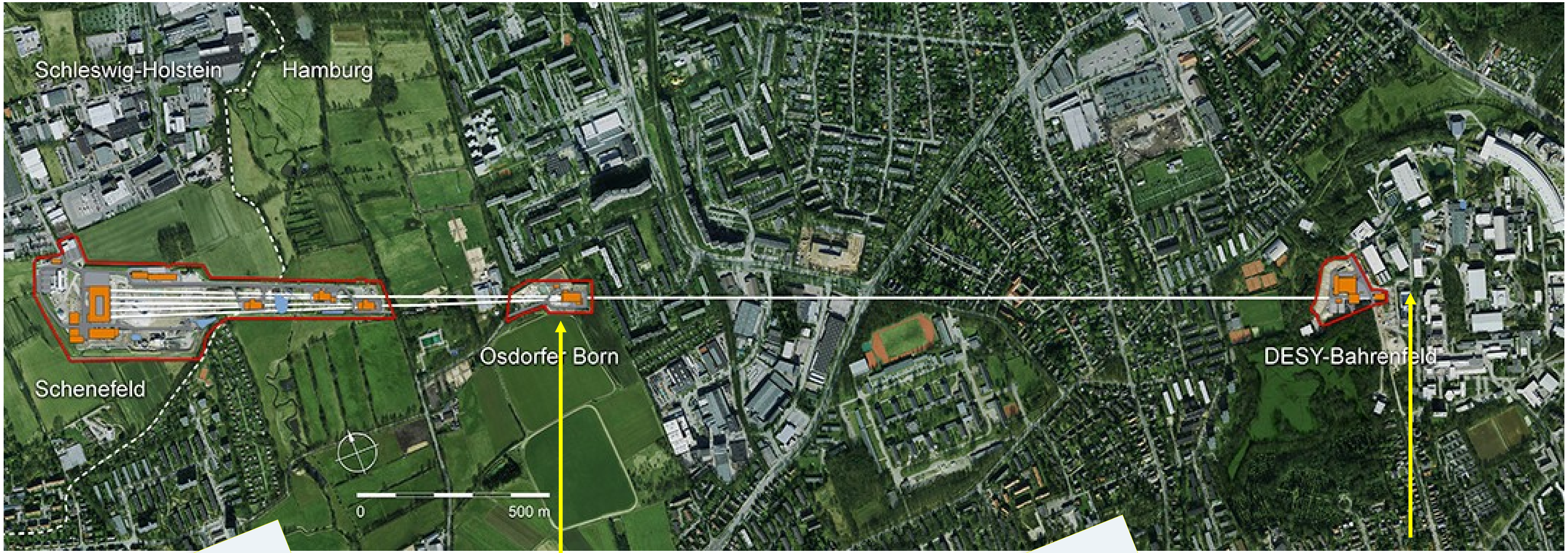


lower cryo tech risk

Option 2:
Located in
Osdorfer Bonn

likely more practical

Option 1:
Located on
DESY campus

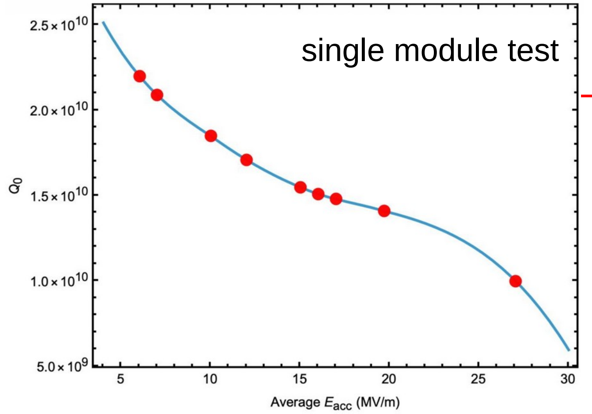
Long-Pulse (LP) operation: with fixed DHL (27 W/module), a beam duty cycle of 10% should be achievable at 16 GeV

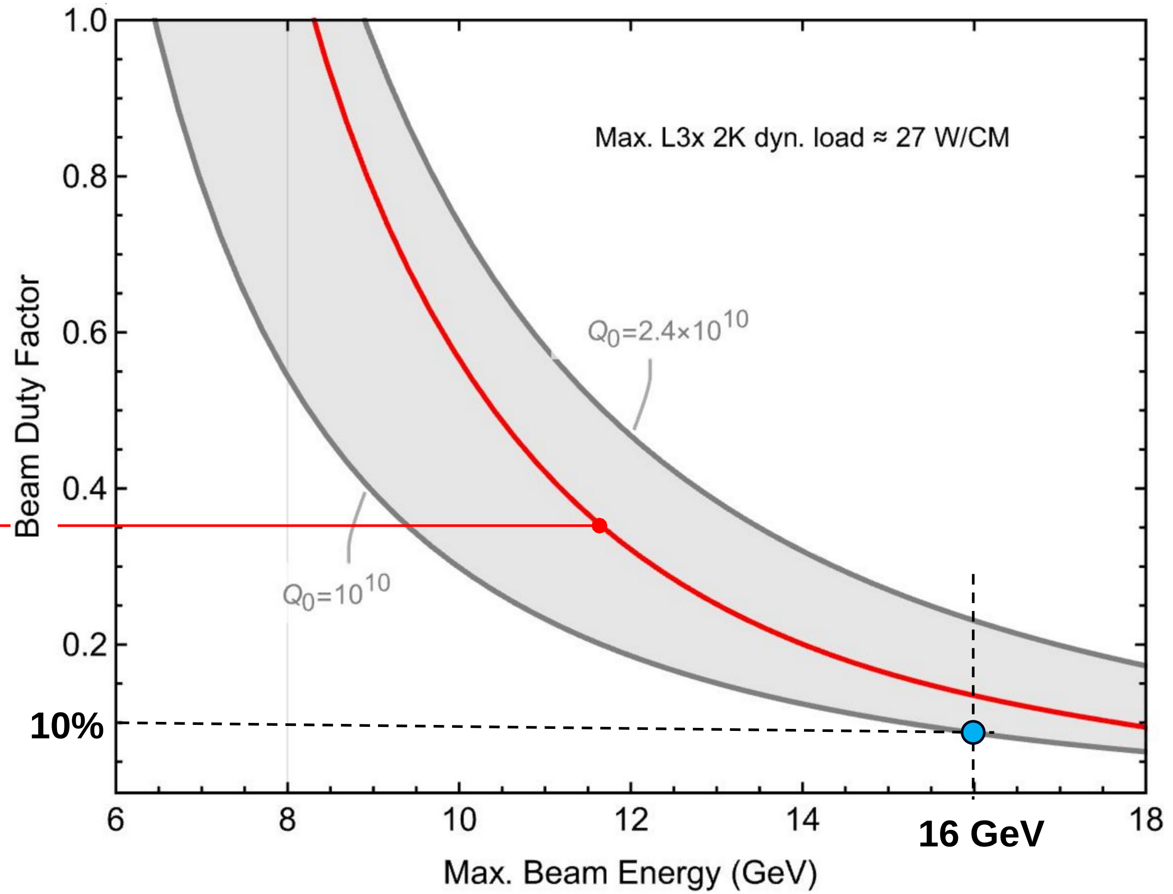
Assuming Q_0 drops to 1×10^{10} at E_{cav} = 17.6 MV/m

Assumption: Only ***average* DHL matters**

Scale duty cycle with beam energy:

$$D_{\mathrm{cryo}} \propto \frac{E_{\mathrm{cav}}^2}{Q_0(E_{\mathrm{cav}})}$$

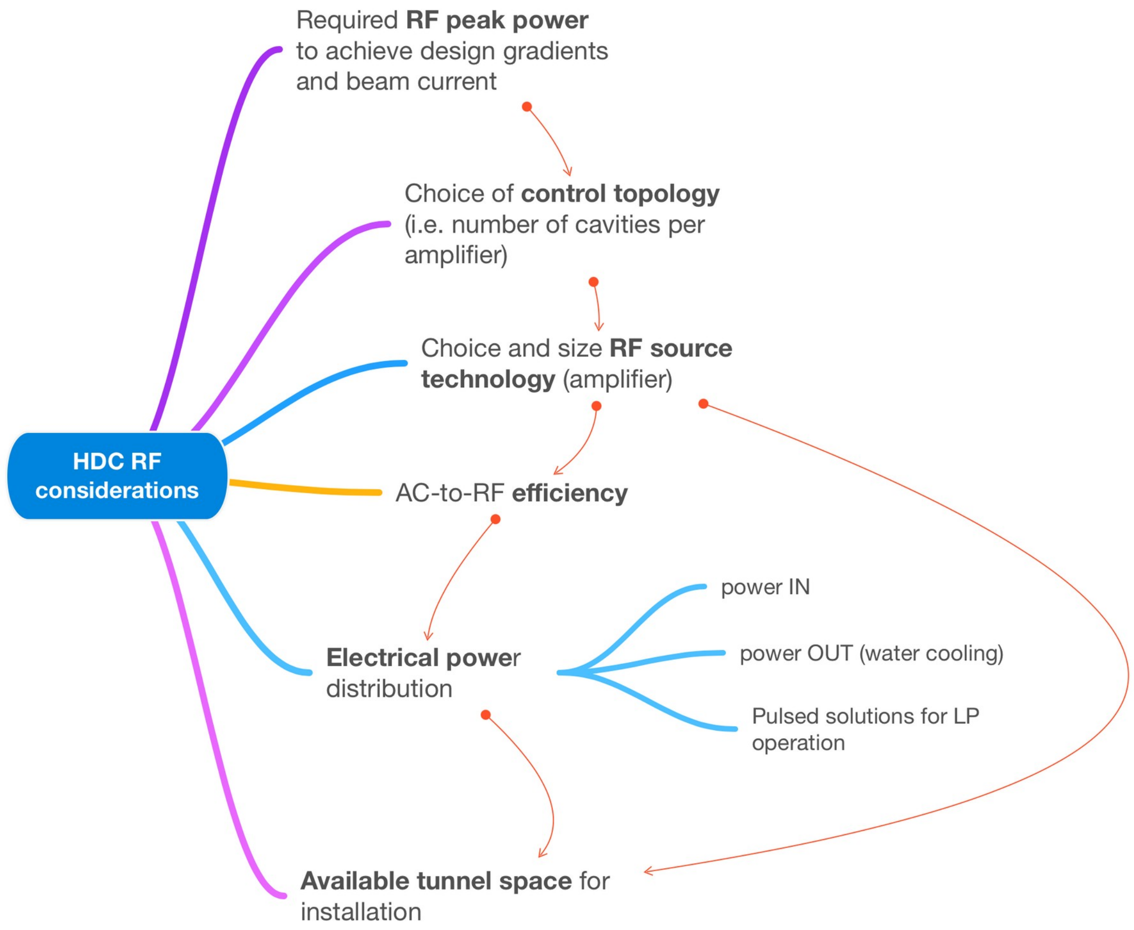




Limiting factor 2: RF power

And RF control; and ultimately AC power consumption

The same basic scaling arguments apply to RF power as for 2K DHL, but the ‘limits’ are arguably more complex.



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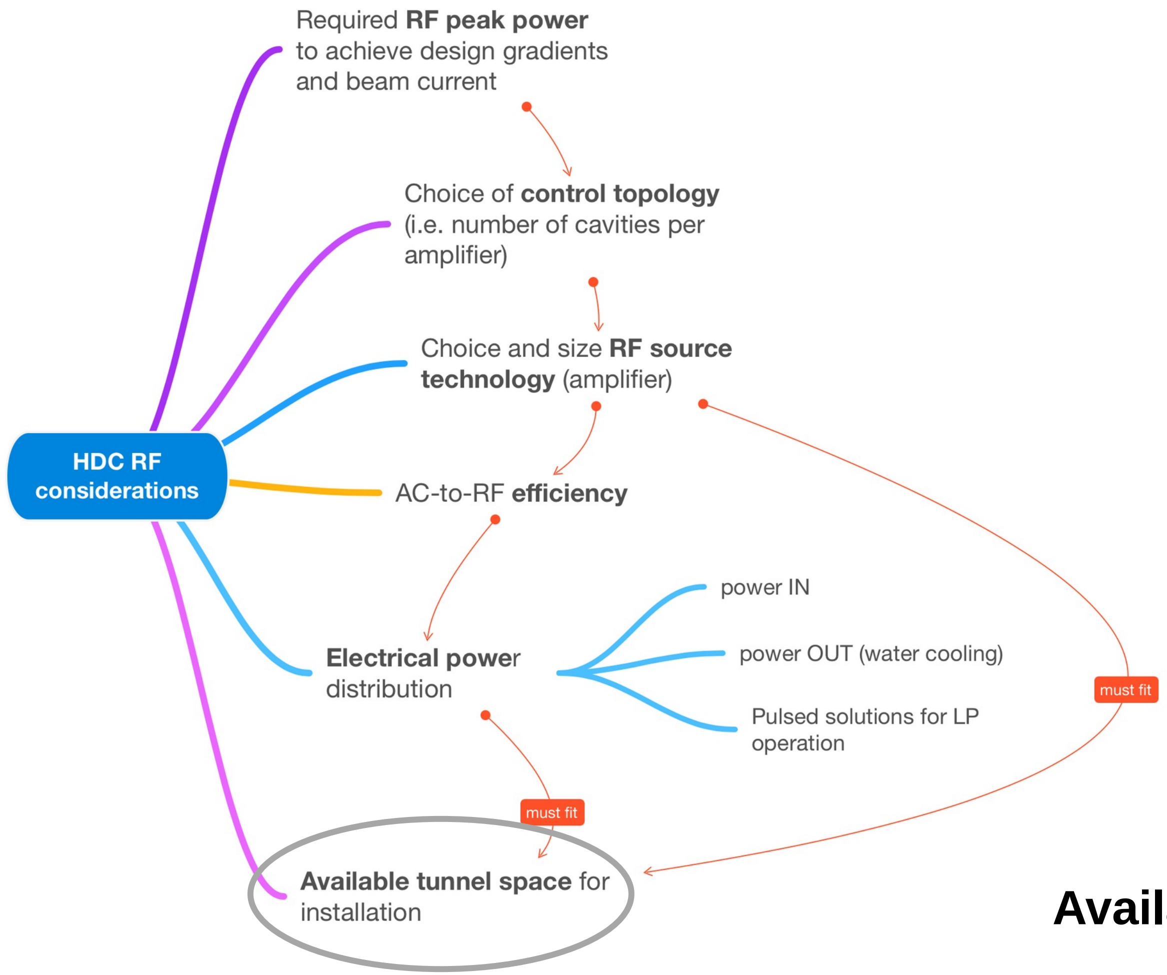

Available Tunnel Space is a hard limit!

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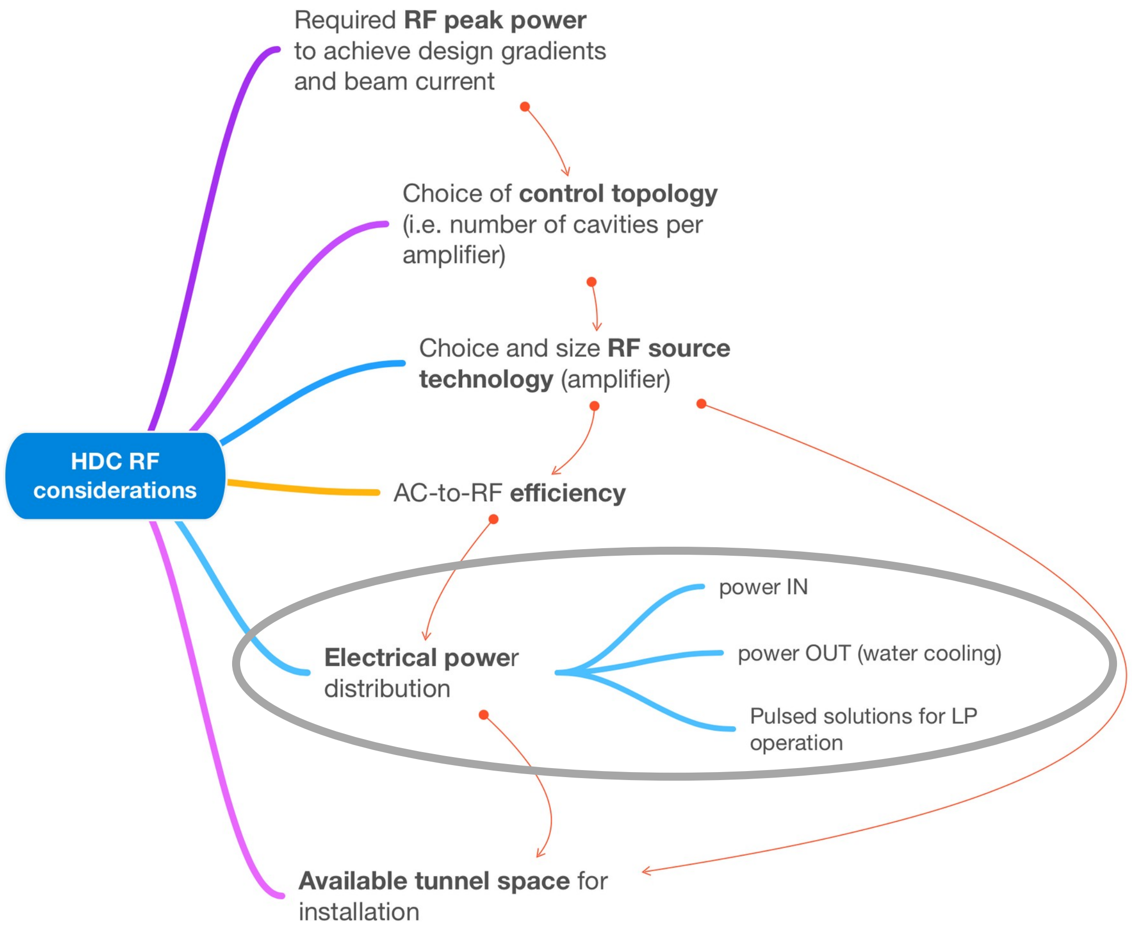


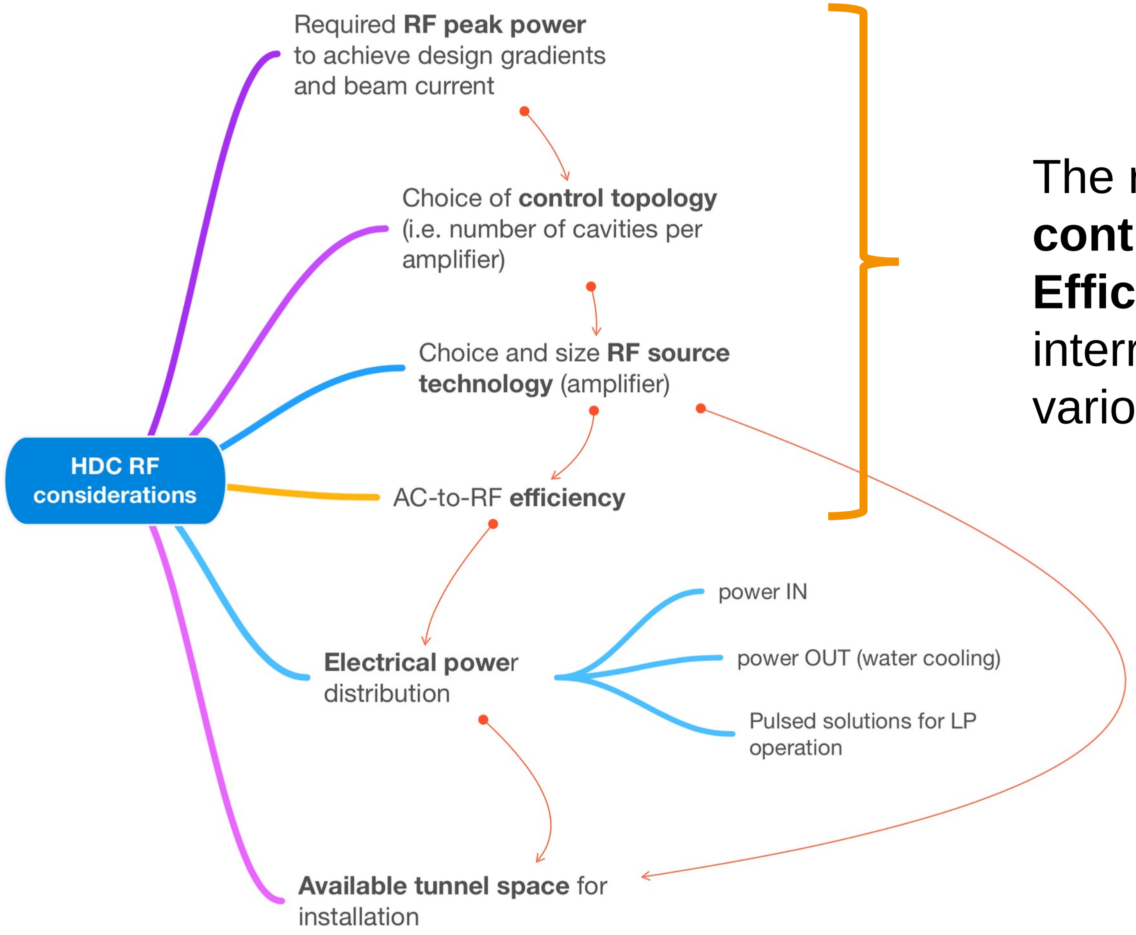
Keeping **Electrical Power** as low as possible is highly desirable but is there a limit?

Burst mode typically 3—5 MW

Current water cooling installed for ~7 MW (but this is not a fundamental limit)

Approach: keep as low as possible

The same basic scaling arguments apply to RF power as for 2K DHL, but the ‘limits’ are arguably more complex.



The remainder (cavity **RF power, control topology, RF amplifier, Efficiency**) are fundamental interrelated design decisions with various trade offs, pros and cons.

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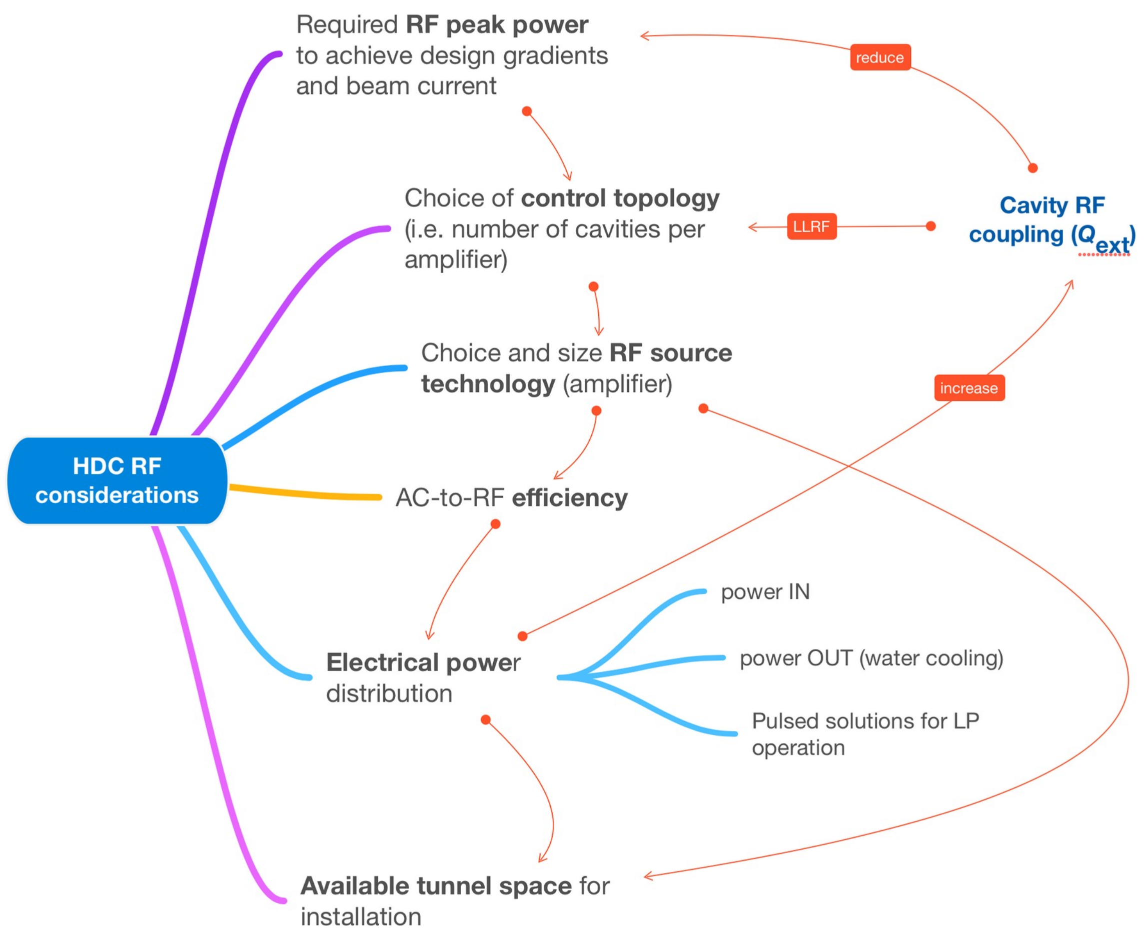


Focus first on **reducing the RF power**

→ **importance of the cavity *Q*ext**

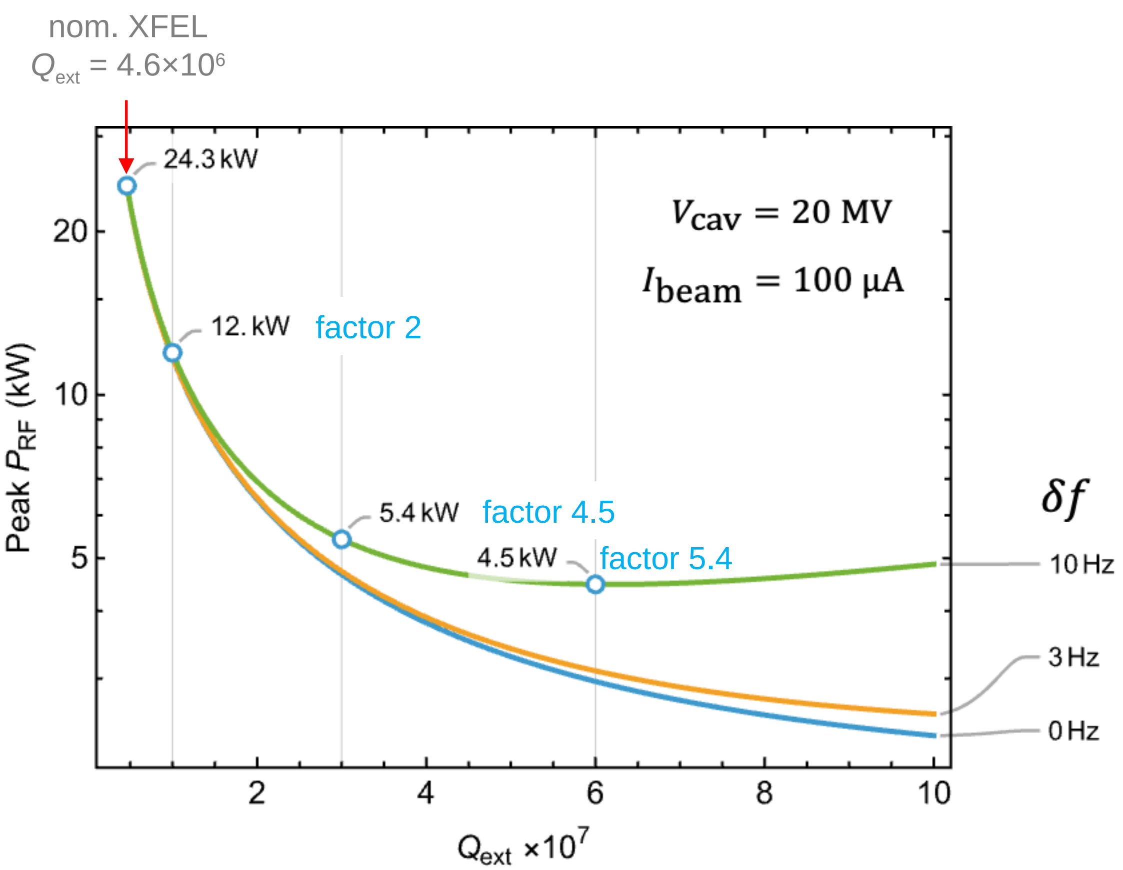
Fundamental Power Coupler (FPC): Increasing the loaded shunt impedance $R_L \propto Q_{ext}$

cavity voltage | beam loading | resonance control

$$P_{RF} = \frac{V_{cav}^2}{4R_L}\left[\left(1 + \frac{I_{beam}R_L}{V_{cav}}\right)^2 + \left(\frac{\delta f}{f_{1/2}}\right)^2\right]$$

for on-crest acceleration

$$R_L \approx \left(\frac{r}{Q}\right)Q_{ext}, \quad f_{1/2} \approx \frac{Q_{ext}}{2f_0}$$



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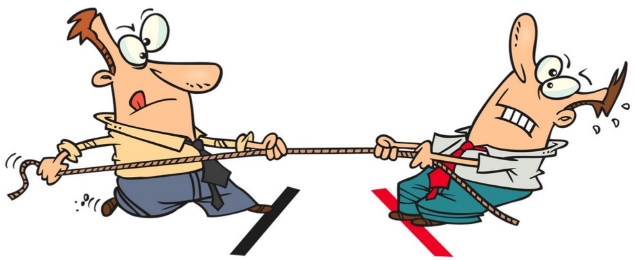
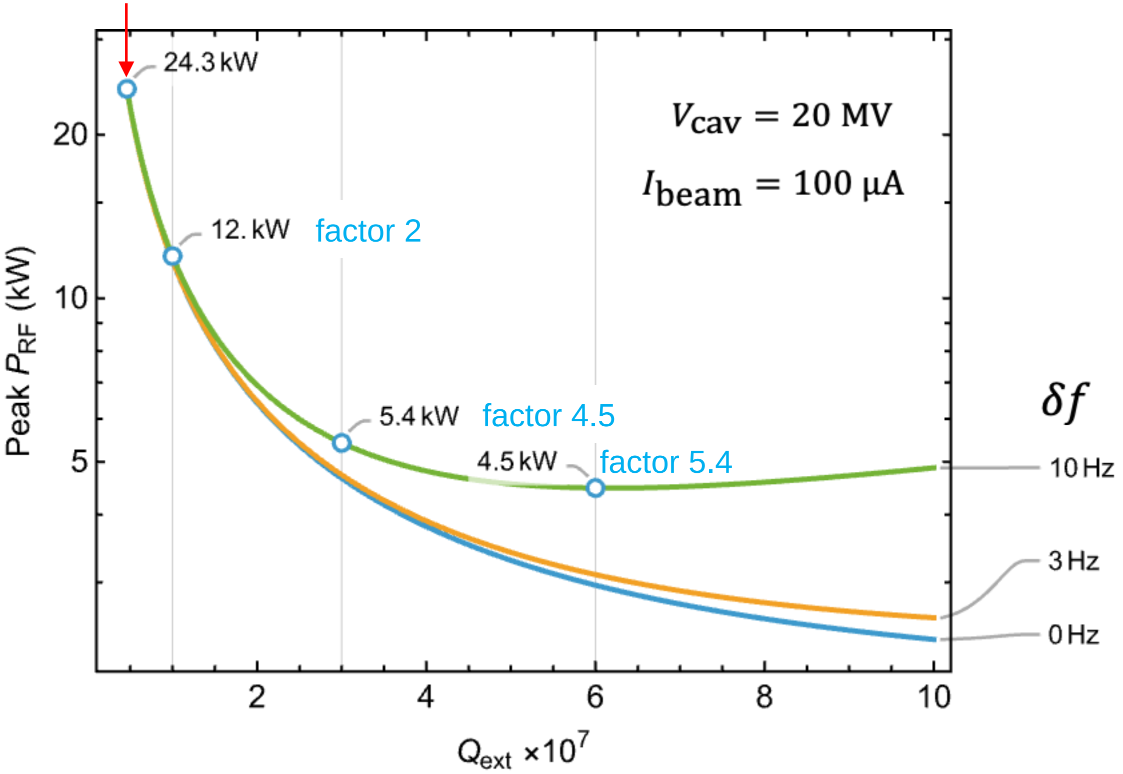


The need to: *reducing RF power* *staying on resonance*



For L1/L2 increase Q_{ext} to 6×10^7 to reduce the RF power by a factor of >5

CW-optimised coupler (modified XFEL) with shorter antenna giving **Q_{ext} range $(1—8)\times10^7$**

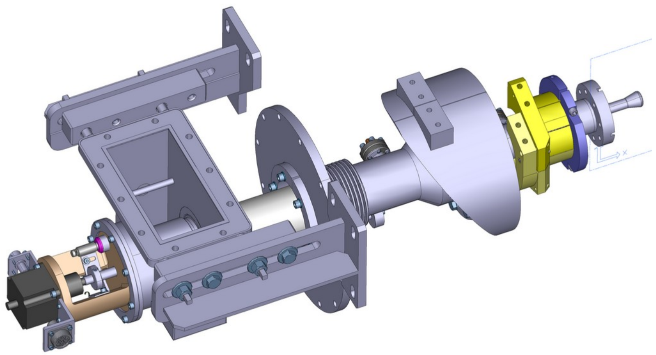
RF gradient	20 MV/m
Qext	**6×10^7**
Ibeam	100 μA
δf	<10 Hz
ϕ_{beam}	≤40°
P_{RF}	4.8 kW
PAC*	1.2 MW

*not including margin/overhead. Assuming 50% AC-RF efficiency!

Compared to nom. XFEL $Q_{ext} = 4.6\times10^6$

factor 13 in bandwidth (282 Hz → 22 Hz)

factor >5 in RF power (24.1 kW → 4.8 kW)



Choice of Q_{ext} in L3x is more constrained: limited by existing coupler

XFEL design range (1—10)×106

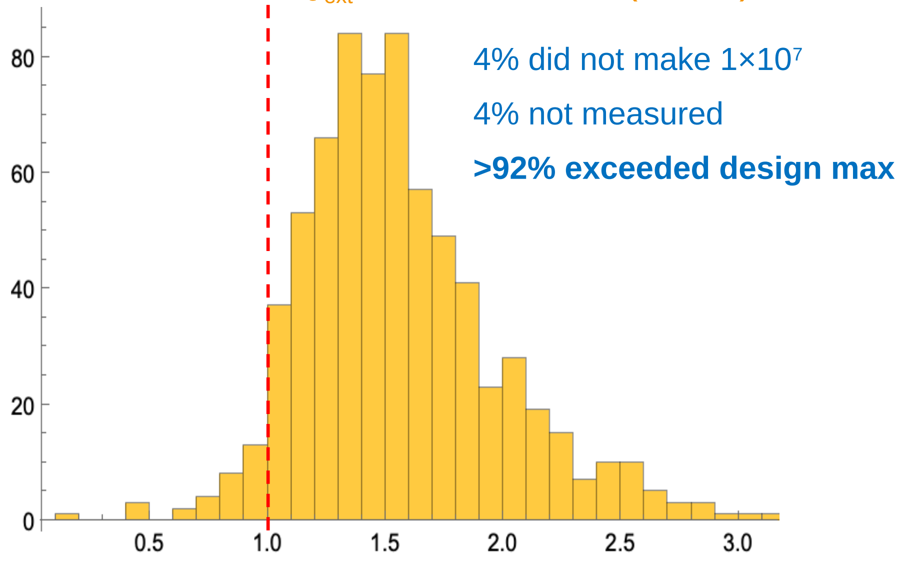
Lowest-risk 'baseline' assumes $Q_{ext} = 1\times10^7$

	8 GeV CW	16 GeV 10%
Gradient	7.5 MV/m	17.6 MV/m
Qext	**1×10^7**	**1×10^7**
Ibeam	100 µA	100 µA
df	<10 Hz	<10 Hz
P_{RF}	**2 kW**	**9.3 kW**
<PRF>	2 kW	1.1 kW
P_{AC}*	**3 MW**	**1.7 MW**

*not including margin/overhead and taking a constant 50% AC-RF efficiency

- 16 GeV 10% has **highest peak RF power**
- 8 GeV CW has **highest average RF power**

Max. achieved Q_{ext} in module tests (AMTF)



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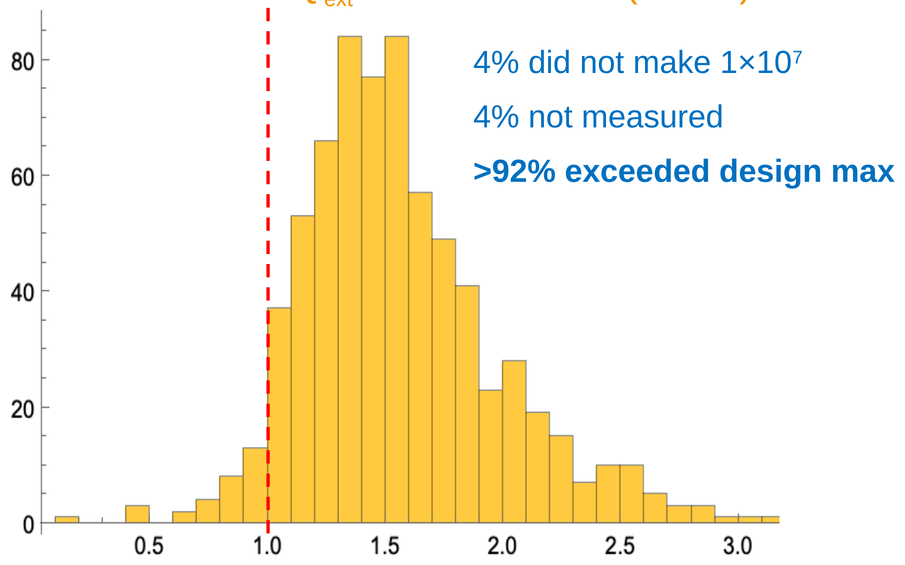
Note: Achieving $Q_{ext} = 3\times10^7$ buys a factor of 2! (→ ongoing R&D)

Max. achieved Q_{ext} in module tests (AMTF)



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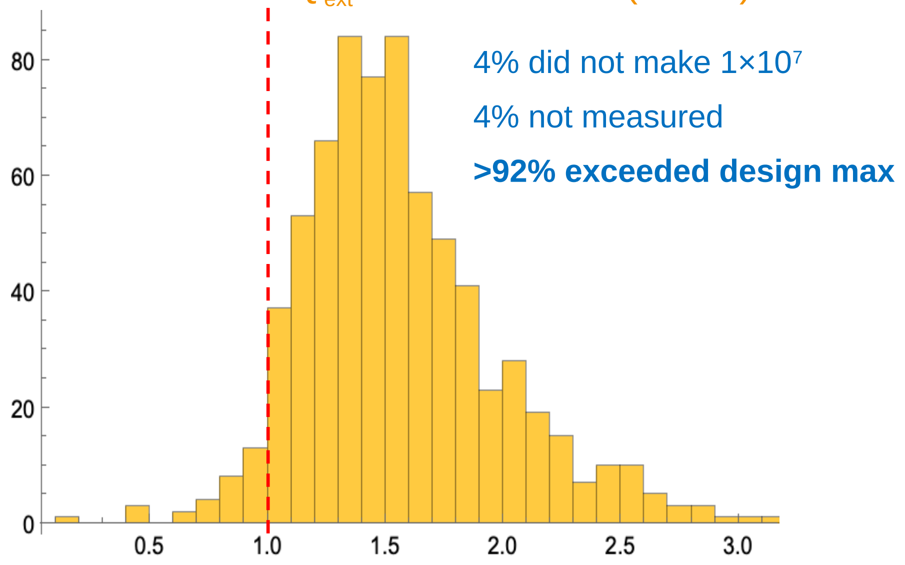
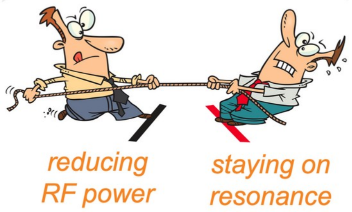
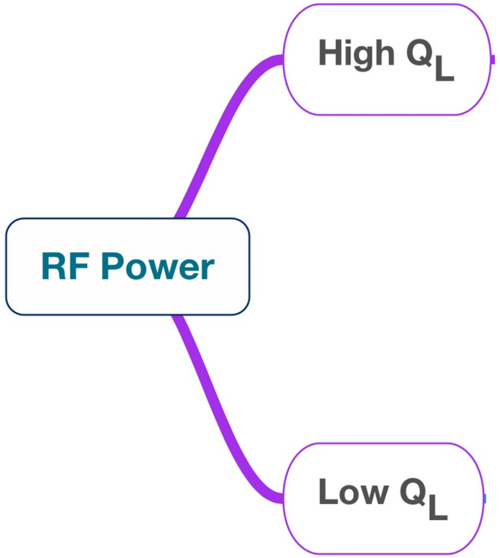


$Q_{ext}\ \times10^7$

Coupler heating remains a concern

RF Amplifiers and LLRF control: choice of Q_L is critical





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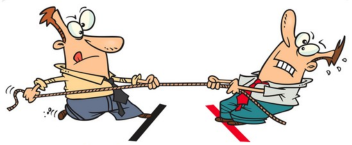
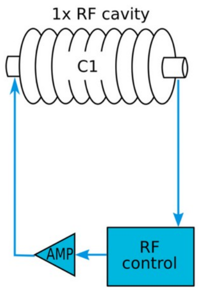


RF Power

- High Q_L
  - 👍 Lower P_{RF} per cavity — allows → Single cavity / amplifier (SCAV)
  - 👎 Harder resonance control — requires → Single cavity / amplifier (SCAV)
- Low Q_L

Single cavity / amplifier (SCAV)



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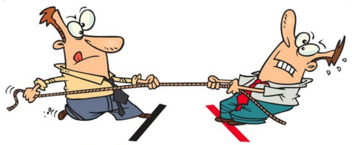

reducing RF power · *staying on resonance*

RF Power

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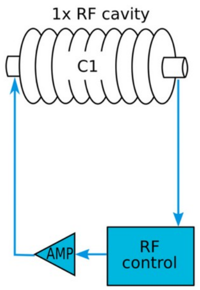
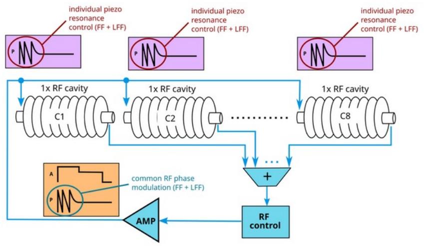
- **Low Q_L**
  - 👎 Higher P_{RF} per cavity — *requires* → **Multiple cavity / amplifier (MCAV)**
  - 👍 Easier resonance control — *allows* → **Multiple cavity / amplifier (MCAV)**





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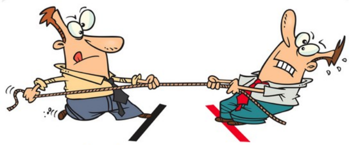

reducing RF power

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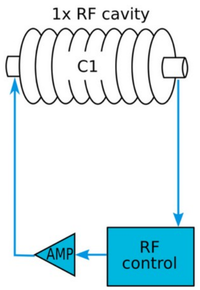
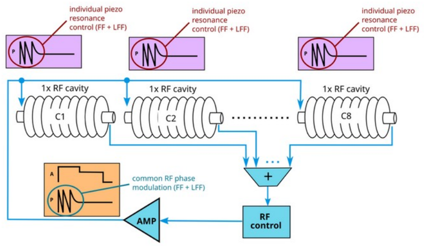


L1/L2
128× ~7 kW
compact
amplifiers
~1 amp per metre



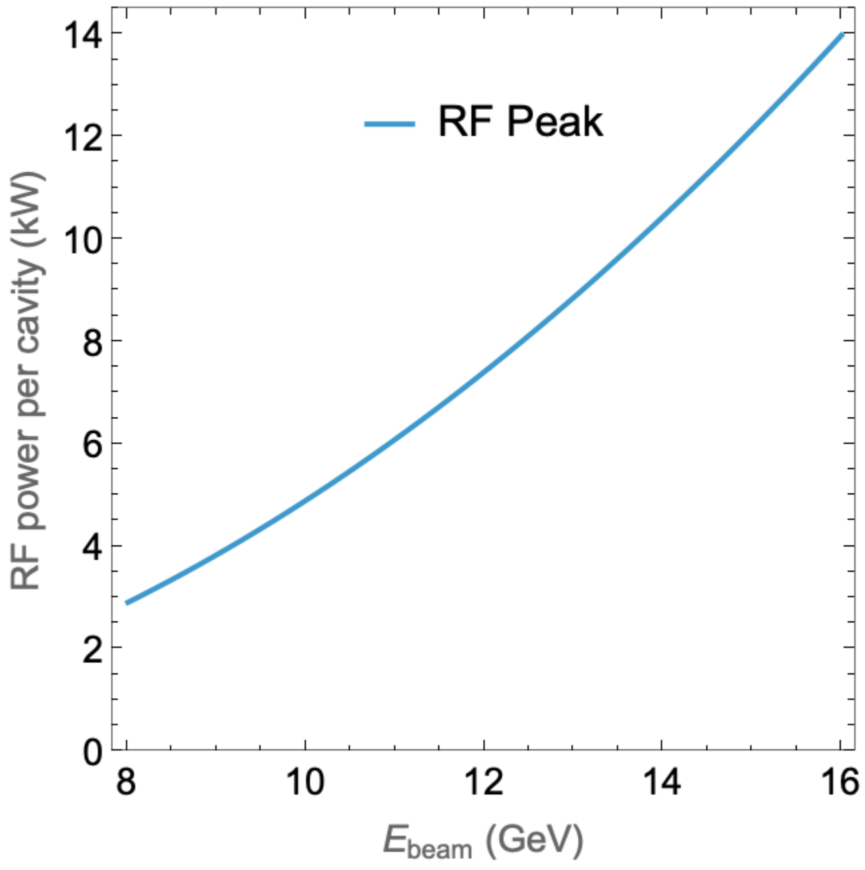
L3x
96× ~112 kW
amplifiers
8 cavities per amplifier
1 amp per ~12 metres

Both solutions are challenging for different reasons
Both need significant R&D

Amplifier Efficiency and AC Power: The large dynamic range in RF output power for L3x adds demanding requirements to the RF sources (amplifiers)

We have already seen that 16 GeV 10% LP defines the peak RF power requirement

- size of amplifiers
- Factor ~14/3 ~ 4.7 in output power



Now includes 50% margin / overhead

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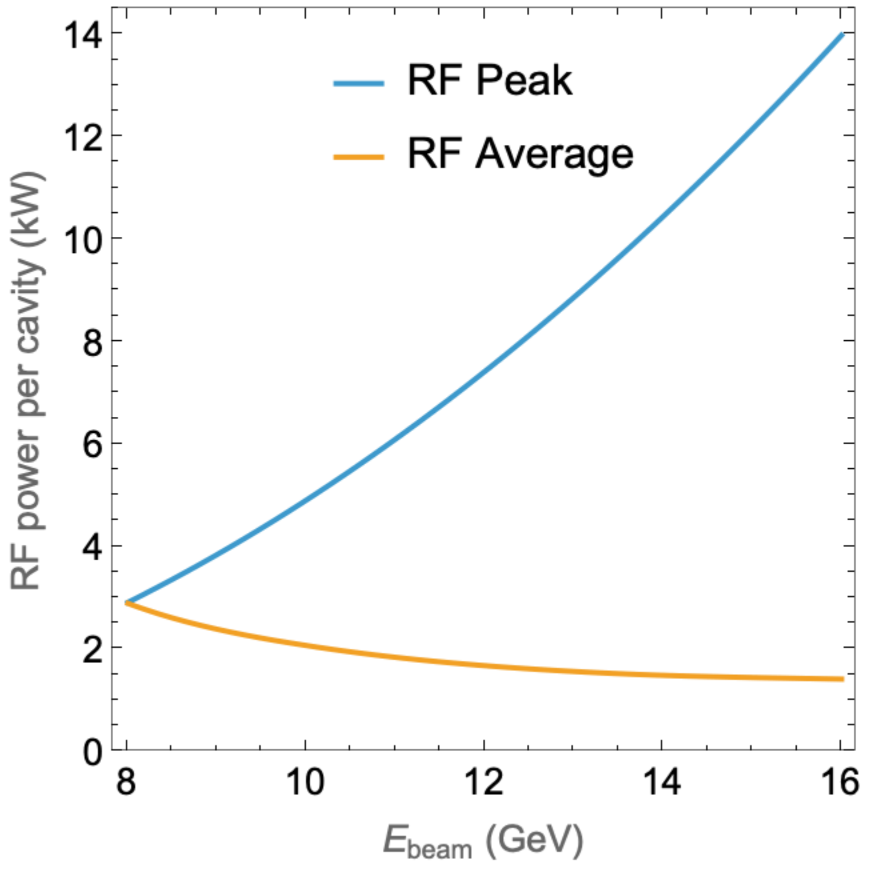
- size of amplifiers
- Factor ~14/3 ~ 4.7 in output power

The **average RF power** is scaled by the duty factor (constrained by the cryogenic 2K DHL)

Max is defined by 8 GeV CW



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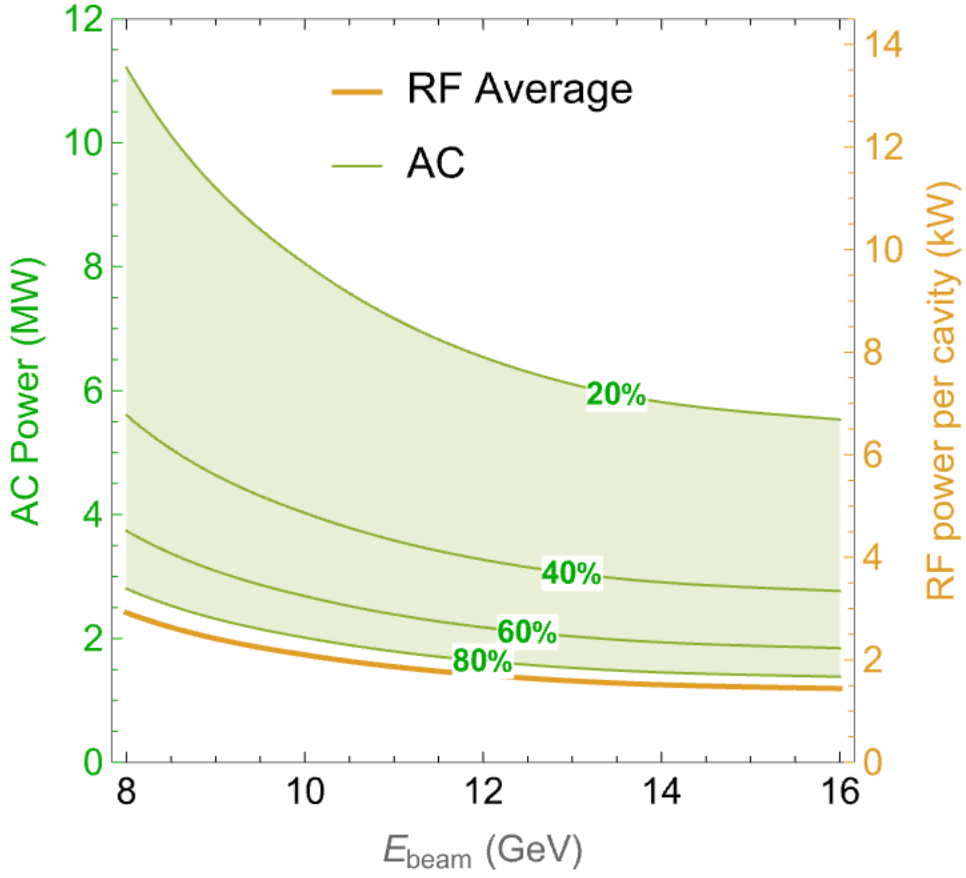
Amplifier Efficiency and AC Power: The large dynamic range in RF output power for L3x adds demanding requirements to the RF sources (amplifiers)

To convert to AC power, we divide the average RF power by the **AC-to-RF efficiency**

(Note have take 50% on previous slides as example.)

Amplifiers are designed for **High Efficiency at the Max RF Output Power**. But efficiency reduces with lower output.



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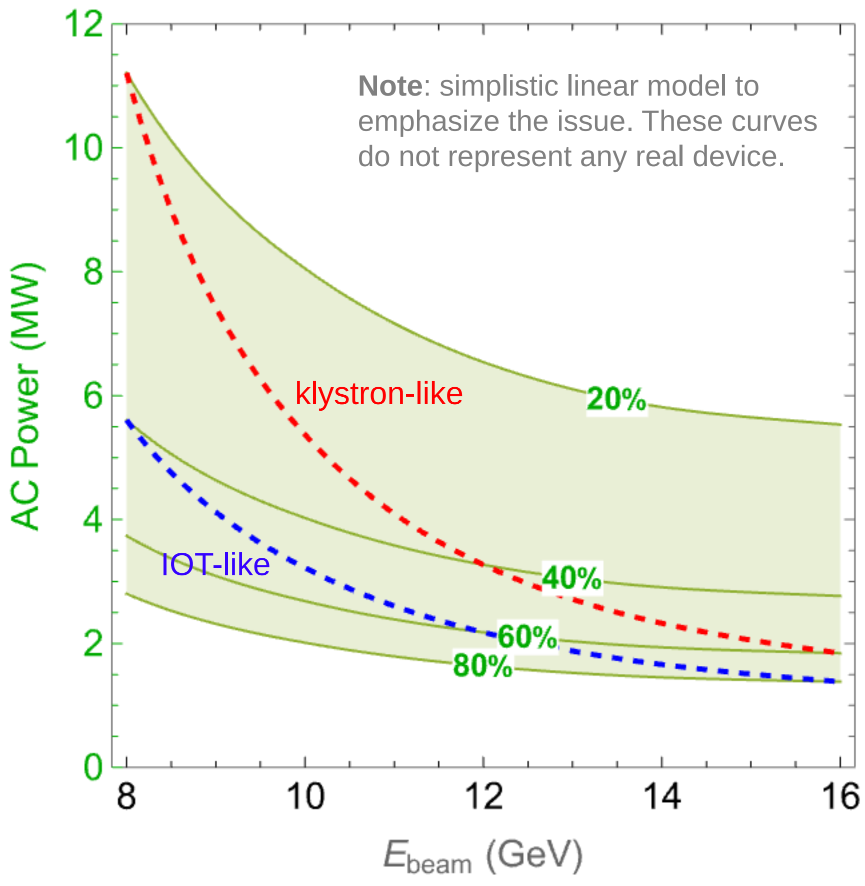

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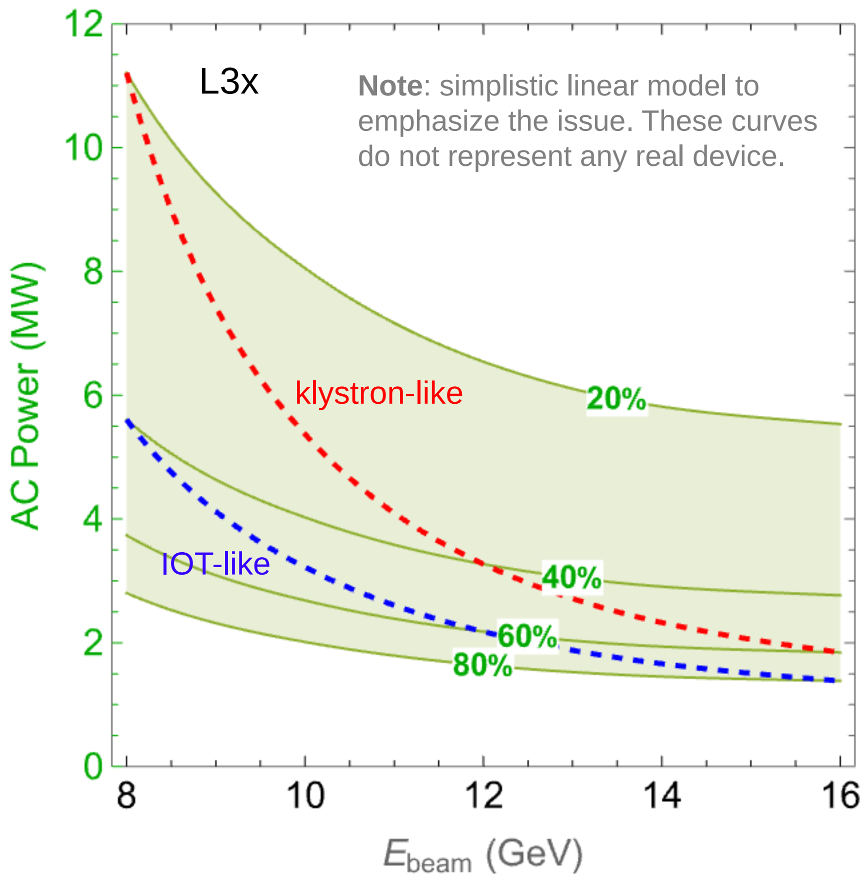
The RF amplifier challenge: In summary

For L3x:

Develop an amplifier which can provide:

- factor of ~5 in RF power up to 112 kW
- Works in CW and pulsed operation
- Maintains high efficiency across entire operational range



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- Works in CW and pulsed operation
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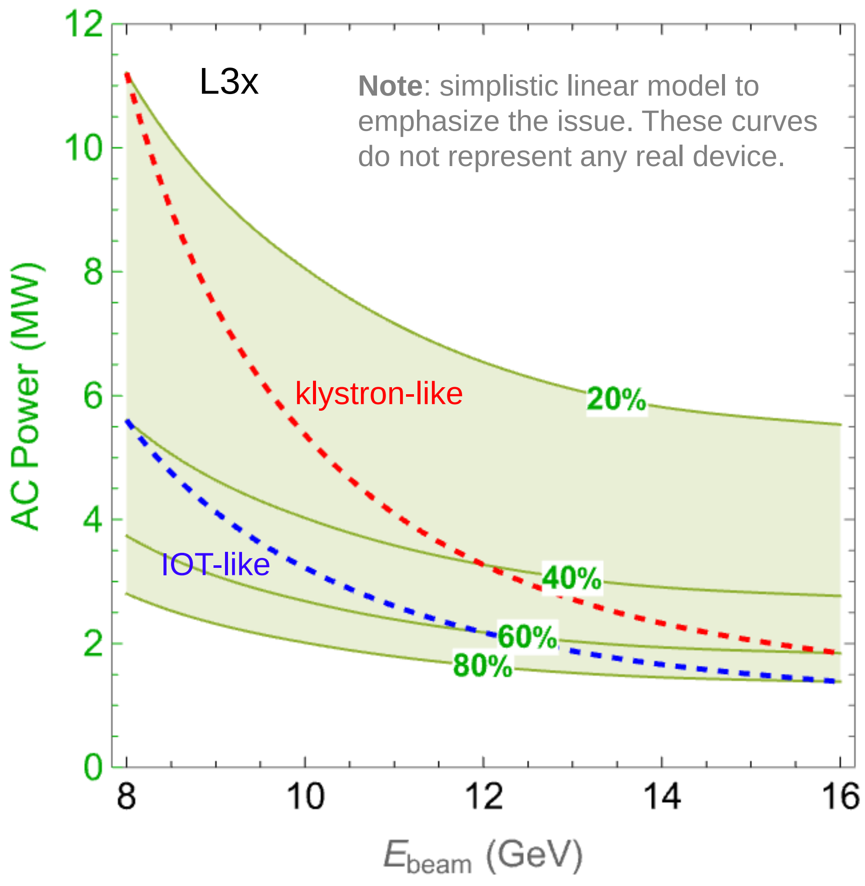
For L1/L2:

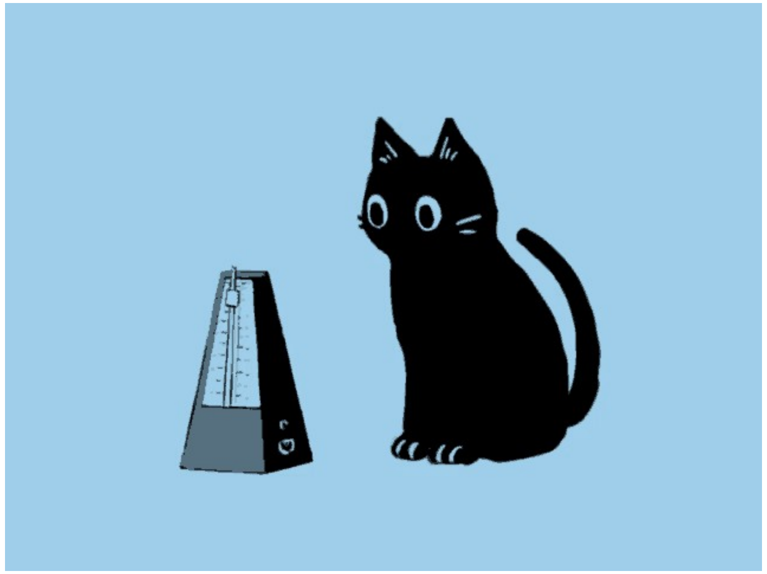
Develop a compact ~7 kW CW amplifier with high efficiency

- Remember: peak RF power remains constant for L1/L2
- ideally should also support pulsed operation



Now includes 50% margin / overhead

What about pulse rep rate?



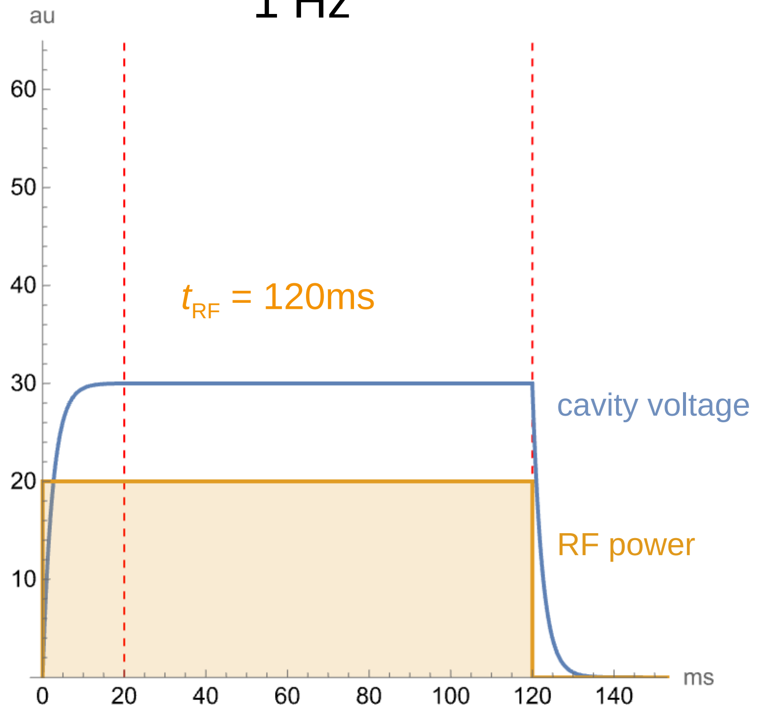
We have only discussed **duty cycle factor** so far

FOS Report **assumes 1 Hz repetition rate**

i.e. 10% is a **100 ms beam pulse at 16 GeV**

Because of the long cavity fill time associated with high Q_{ext}, 100 ms at 1 Hz is not the same as 10 ms @ 10 Hz.

1 Hz

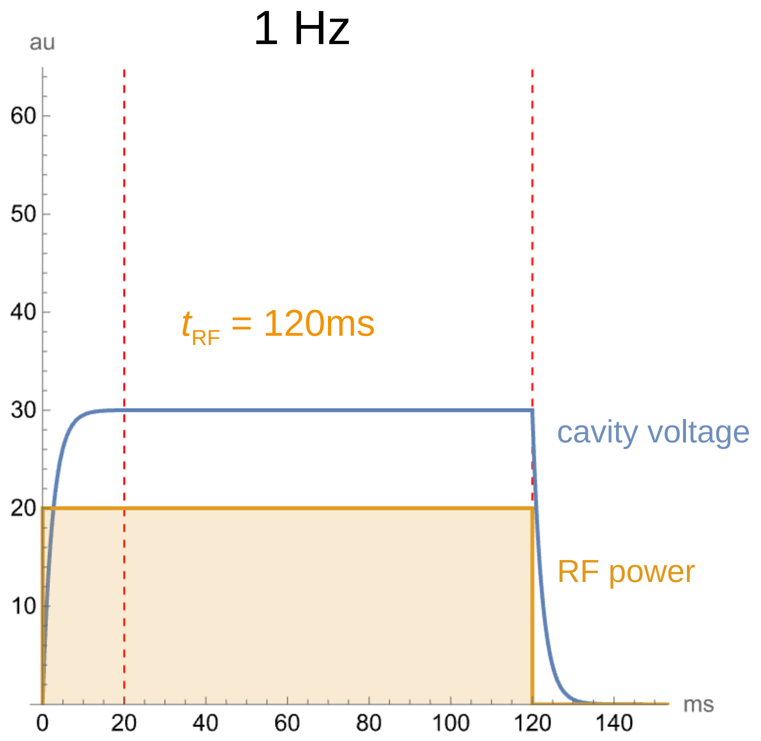


t_{fill} = 20ms t_{beam} = 100ms

RF duty cycle = 12%

constrained by 2K DHL

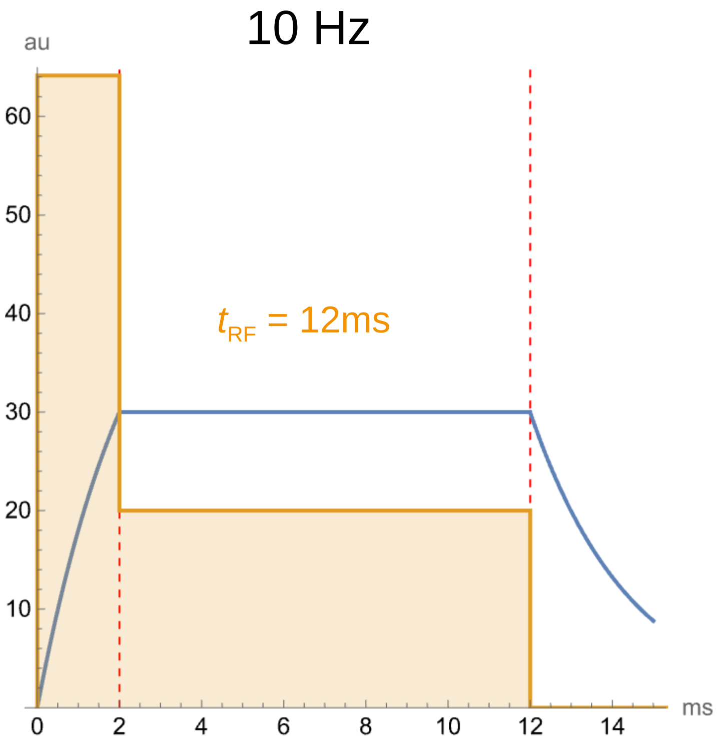
Because of the long cavity fill time associated with high Q_{ext}, 100 ms at 1 Hz is not the same as 10 ms @ 10 Hz.



t_{fill} = 20ms t_{beam} = 100ms

RF duty cycle = 12%

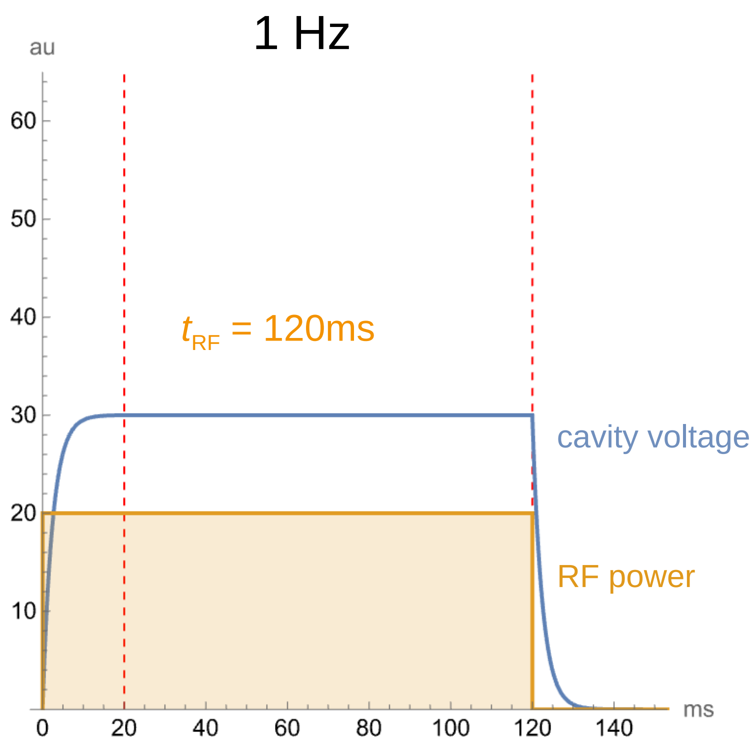
constrained by 2K DHL



t_{fill} = 2 ms t_{beam} = 10ms

RF duty cycle = 12%

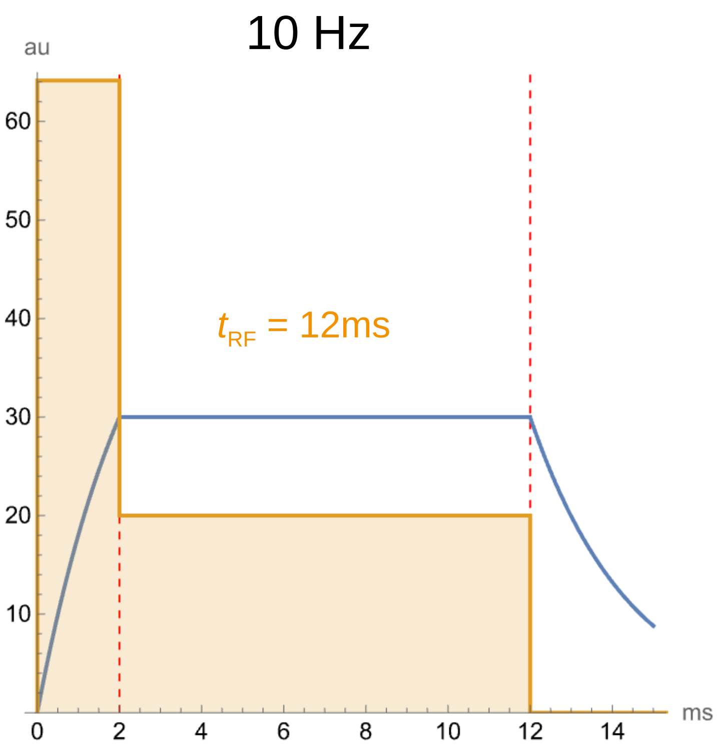
Because of the long cavity fill time associated with high Q_{ext}, 100 ms at 1 Hz is not the same as 10 ms @ 10 Hz.



t_{fill} = 20ms t_{beam} = 100ms

RF duty cycle = 12%

constrained by 2K DHL



t_{fill} = 2 ms t_{beam} = 10ms

RF duty cycle = 12%

Increased peak P_{RF} by ~×3

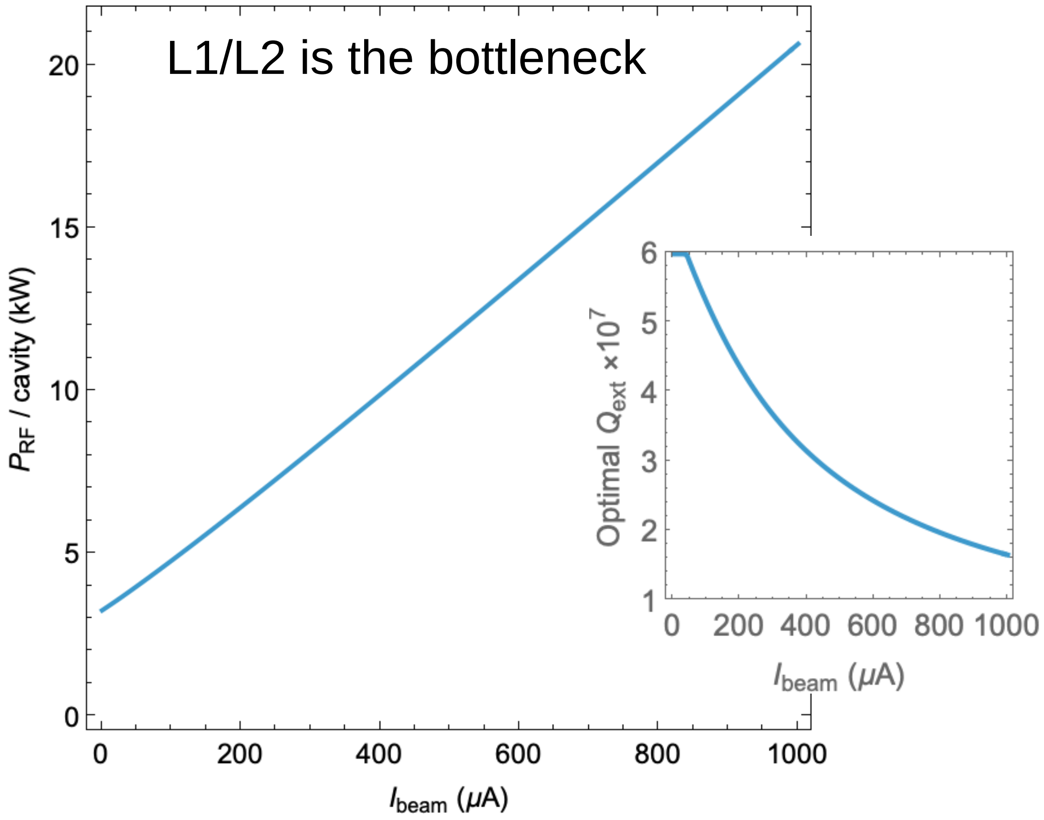
- Larger amplifiers
- Increased AC power
- More demanding LLRF control during *t*fill

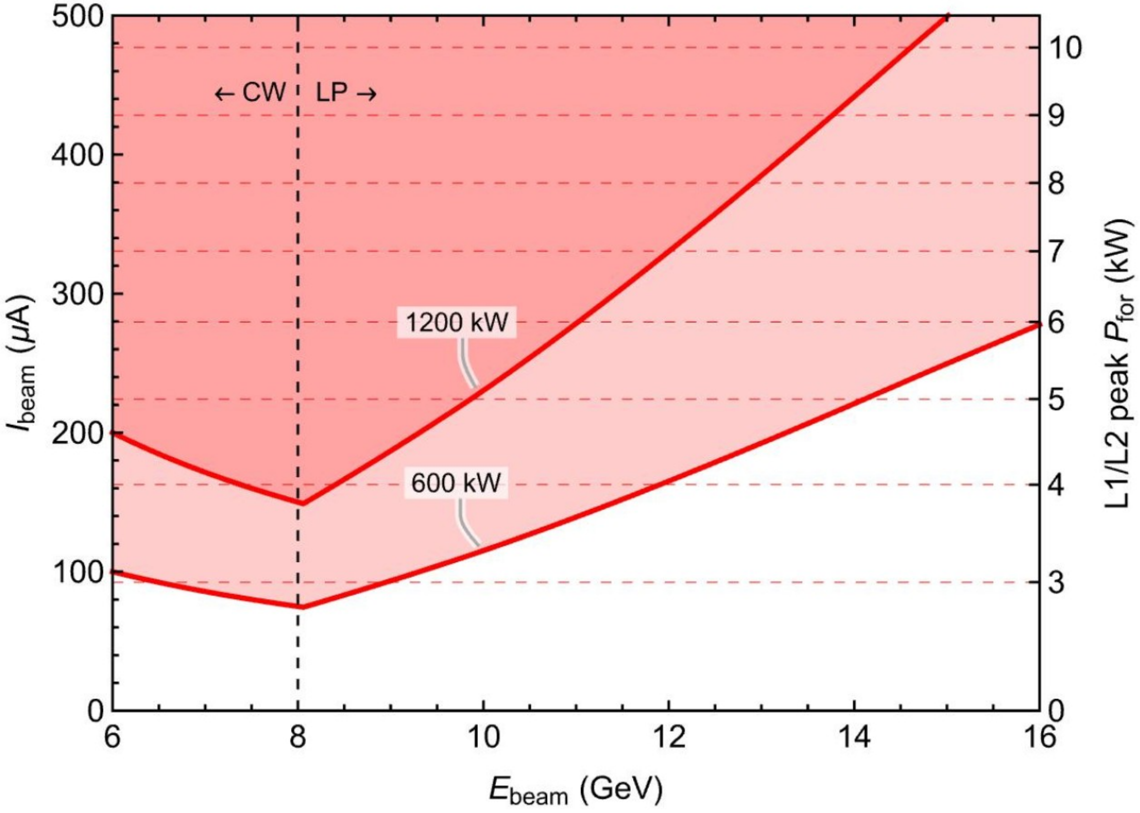
f_{rep}	Hz	1	5	10
t_{fill}	ms	20	4	2
t_{beam}	ms	100	20	10
peak P_{RF}	kW	13.7	19.0	39.5
est. P_{AC}	MW	2.1	2.9	6.1

Beam current

bunch charge × beam repetition rage

FOS beam parameters are 100 pC at 1 MHz = 100uA beam current. For the LINAC it is basically only average current that counts. Limited by RF power (and to a lesser extent beam dumps)





Higher CW currents puts greater demand on Photoinjector (laser power!)

The (current) HDC Parameters

- The HDC parameters published in the FOS Report are a consistent set based on the previous arguments
  - But they remain just one example in a complex parameter space
- They contain risk
  - Cryogenic plant / 2K DHL in L3x
  - Challenging RF Amplifier spec. (efficiency / margin)
  - CW module performance
  - (Photoinjector performance –not discussed here)
  - CW 8 GeV AC power (RF+Cryo ~12 MW)
- Going forward, we have a draft R&D plan to assess these risks

Beam parameters				
Beam energy	GeV		8	16
Beam duty factor			100 %	10 %
Average bunch rate	/s		10^6	10^5
Bunch repetition rate	MHz		1	1
Pulse repetition rate	Hz			1
Beam pulse length	ms			100
Bunch charge	pC		100	100
Beam current	μA		100	100
LINAC parameters		L1/L2 (CW)	L3x (CW)	L3x (LP)
Beam energy	GeV	2	8	16
Gradient	MV/m	20	7.5	17.6
Max. off-crest phase (1)		40°		
RF duty factor		100 %	100 %	12 % (2)
Cryogenic				
Cavity Q_0 (3)		3×10^{10}	1.8×10^{10}	1.14×10^{10}
Cryo 2 K dyn. load / module	W	114	27	27
Cryo total 2 K dyn. load	W	1820	2590	2590
RF parameters				
Q_{ext}		6×10^7	1×10^7	1×10^7
Max. detuning ($\pm\Delta f$) (4)	Hz	10	10	10
Max. P_{for} per cavity	kW	4.8	2.0	9.3
Cavities per amplifier		1	8	8
Number of amplifiers		128	96	96
Max. P_{for} per amp. (5)	kW	7.3	23.5	112.1
AC-RF efficiency		≥60 %	≥40 %	≥60 %
RF AC power / amplifier	kW	12.1	58.8	22.4
Total RF AC power	MW	1.6	5.6	2.2

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