RF for RF separated beams

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First thoughts for Amber workshop in September

Starting from 3.9 GHz..

f	3 - 5 GHz
deflection per station	15 MV
spill length	~5 s
aperture	?

- 3.9 GHz has been used for ILC crab cavities [1], XFEL [2], LCLS-II harmonic cavities [3], and for the FNAL Kaon beam separator [4] (basis for ILC crabs).
- Good basis for an AMBER design.

[1] C. Adolphsen et al, Design of the ILC Crab Cavity System, EUROTeV-Report-2007-010

[2] P. Pierini et al, European XFEL 3.9 GHz System, SRF 2013.

[3] N. Solyak, 3.9 GHz components design, 3.9 GHz review, FNAL, May 26, 2016.

[4] M. McAshan, R. Wanzenberg, Design of a Transverse Mode Cavity for Kaon Separation, FERMILAB-TM-2144.

ILC Crab Cavities

	ILC values
f	3.9 GHz
cells	9
R/Q	235 Ohm
Q_0 (1.8 K)	3 x 10^9
Active length /cavity	0.34 m
aperture radius	15 mm
deflection/cavity	~2.05 MV
Peak deflection	~6 MV/m
Q_L (determined by beam loading	3 x 10^6

	AMBER extrapolation
cavities/station	8
cryomodules/station	1
CM length	~6 m
deflection/cavity	1.875 MV
peak deflection	5.5 MV/m
Q_L	~1 x 10^7

- Conservative deflecting voltage.
- Synergies with ILC, XFEL and LCSL-II.

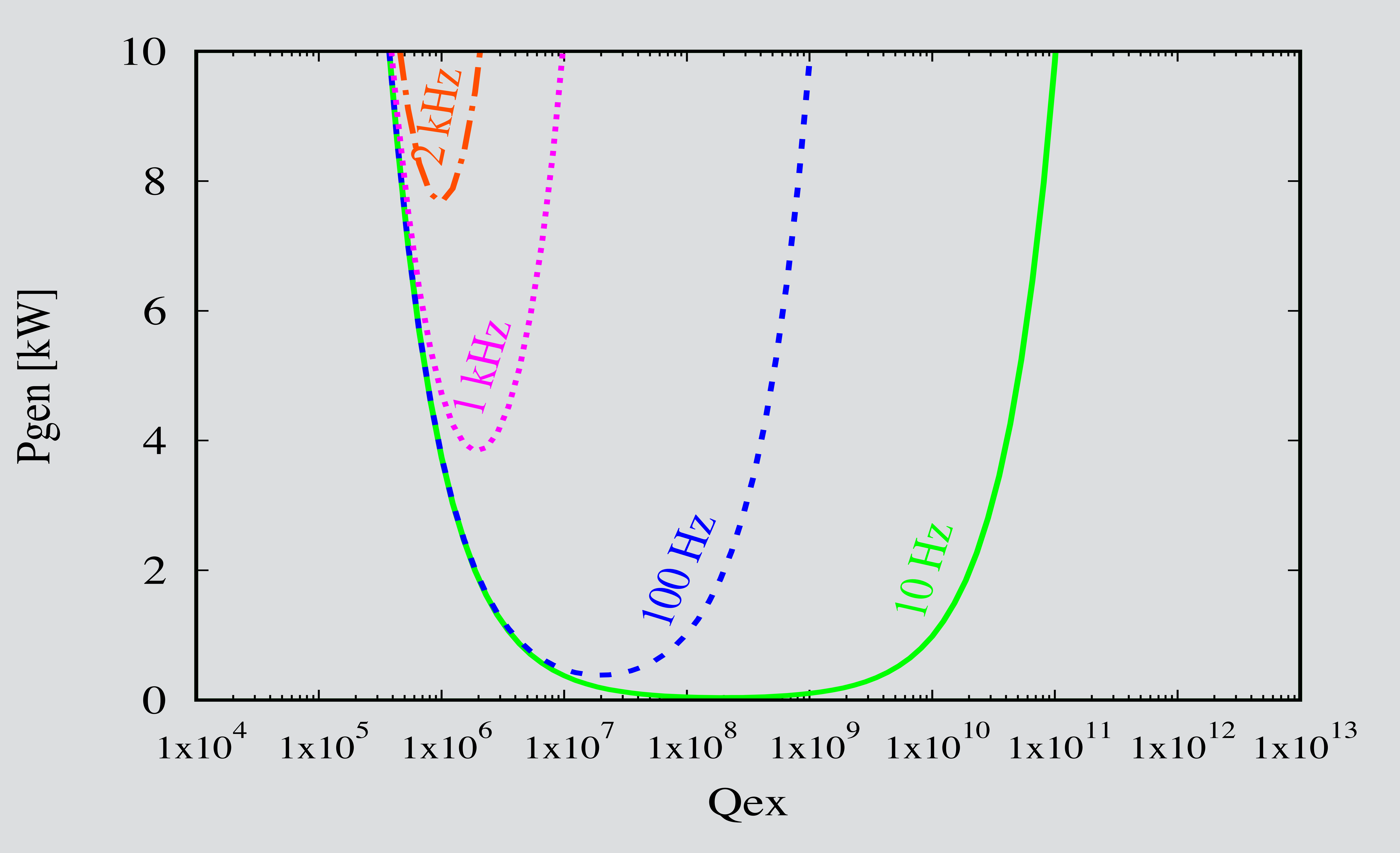
Power and loaded Q

- Dissipated power is negligible (5 W at 1.8 K, higher temperatures would be ok).
- Power given to the beam is also negligible (femto Ohms..)
- Q_L is usually determined by beam loading but with zero beam it will be defined by the need to stabilise phase and amplitude. Microphonics is most likely the major disturbance that needs to be controlled.
- With zero beam and no bunch structure, Lower Order Modes or Higher Order Modes should not be a concern. Passband modes need to be studied.
- Maximum Q_L used in operating machines:
  - 1.2 x 10^7 (HIE-ISOLDE, 100 MHz)
  - 1 x 10^7 (PIP-II 650 MHz)
  - 4 x 10^7 (LCLS-II, 1.3 GHz)

A Q_L of ~10^7 at several GHz is challenging but seems feasible, especially if a Ferro Electric Fast Reactive Tuner (FE-FRT) is employed (prototyped at CERN).

$$P_{diss} = \frac{V^2}{(R/Q)Q_0} \qquad P_g = \frac{V_\perp^2}{4(R/Q)_\perp Q_{ex}} \left(1 + \left(2Q_{ex}\frac{\overset{\substack{\text{max. detuning}\\ \downarrow}}{\Delta\omega}}{\omega}\right)^2\right)$$

Generator power vs Q_{ex}



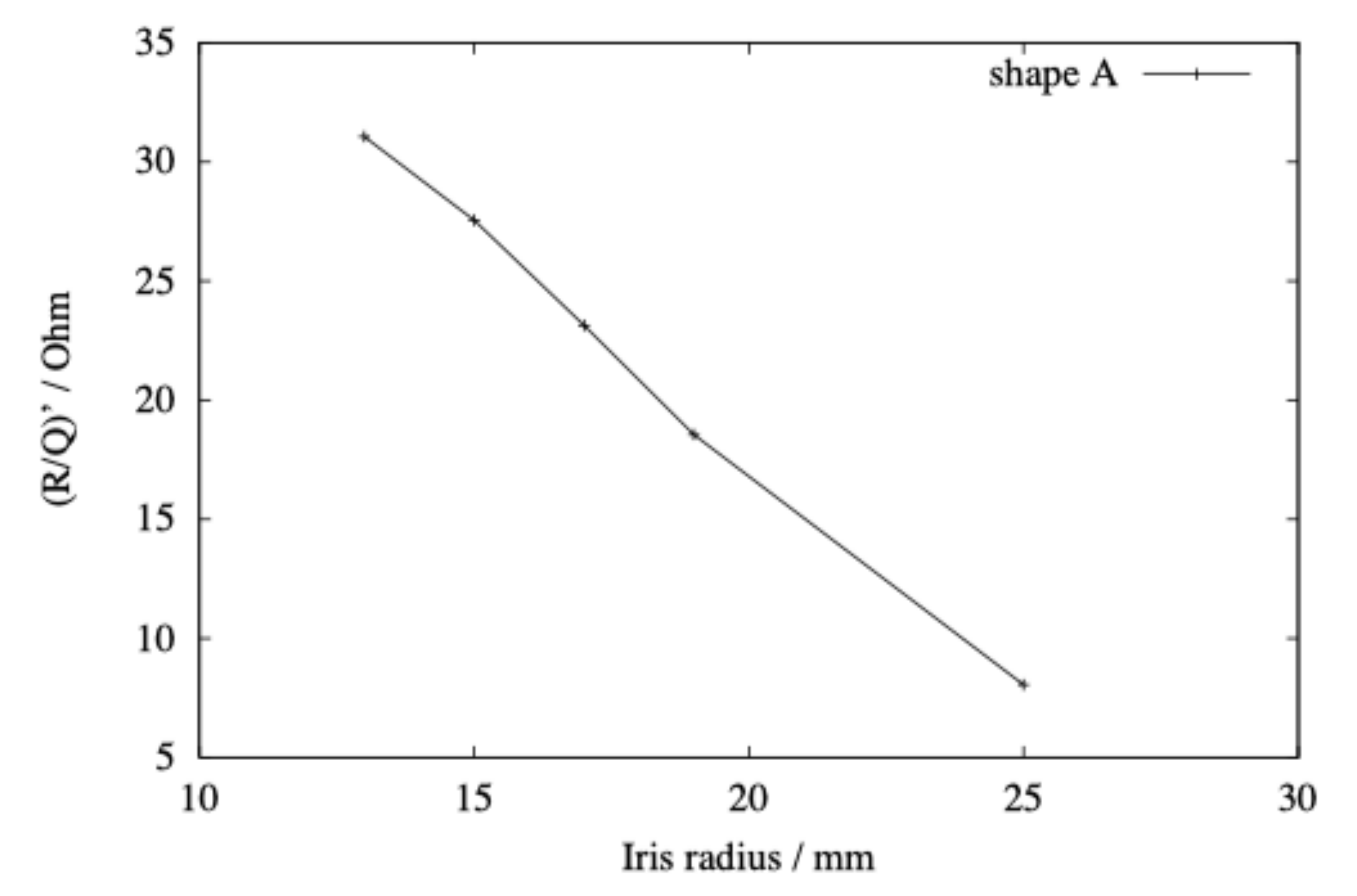
- For ILC type deflecting cavities, the frequency needs to be stabilised to a few 100 Hz to keep the RF power in the kW range.
- Seems feasible but may need a FE-FRT.
- What is needed for the RF separation?

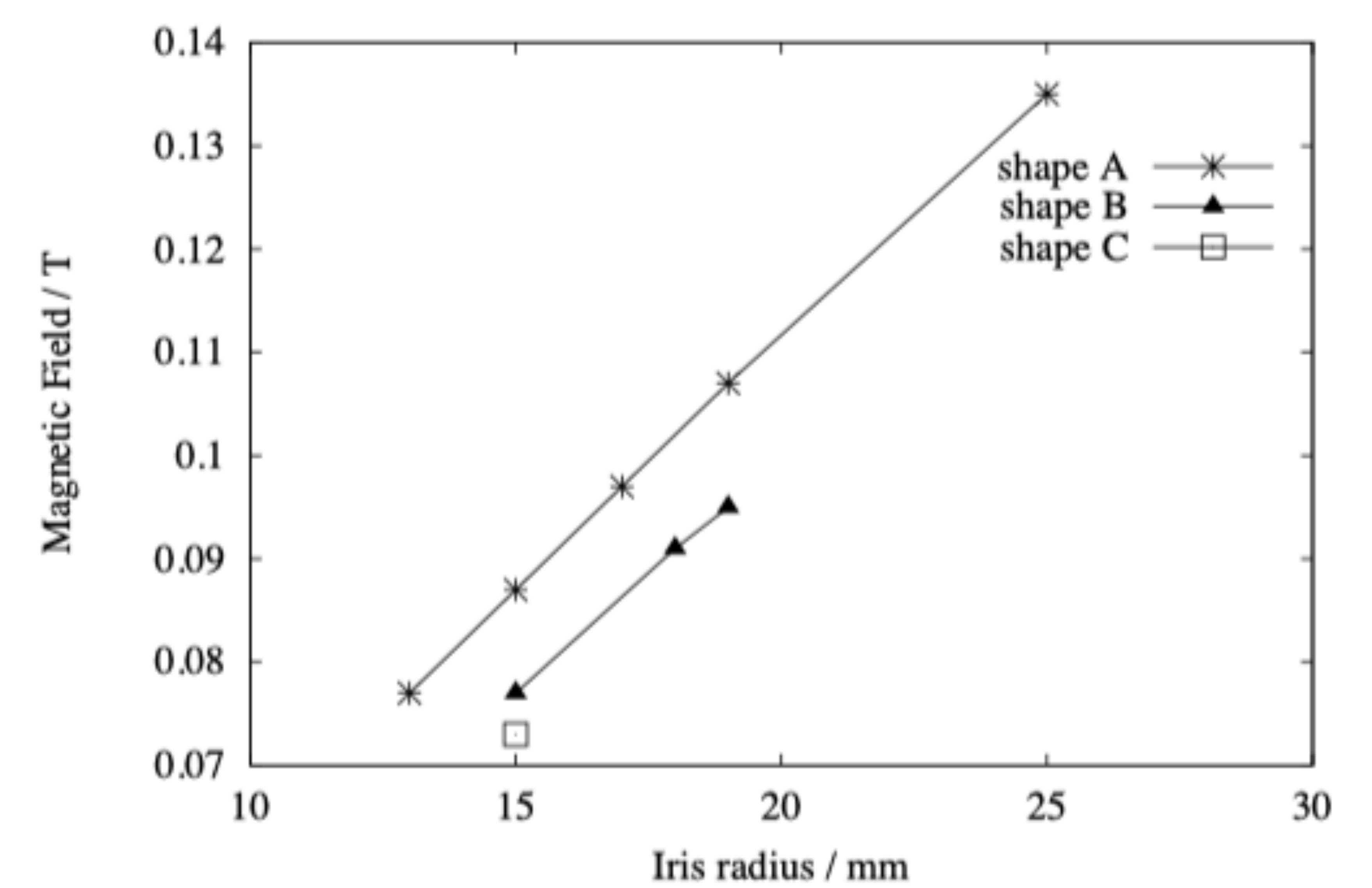
Cryomodules

- A new cryomodule development is costly. The first prototype/pre-series module typically is twice as expensive as a series module (for small series of 10 - 50 modules).
- Re-using existing designs can significantly reduce the development cost for the first module.
- XFEL and LCLS-II have 8-cavity 3.9 GHz modules (harmonic cavities, not deflecting ones), which could be adapted.
- With 2 modules of 8 cavities, it is recommended to have 1 spare (e.g. the prototype/pre-series module). In case an intervention on the cavities is needed it will take at least 1 year for disassembly, cavity cleaning, cavity testing, re-assembly, module re-testing.

scaling with aperture

- The aperture can be increased but at the cost of lowering R/Q (higher power requirements) and higher magnetic surface fields (lowering the electric field level at which the cavity quenches).
- Aperture scaling with frequency: ~1/f (maintaining deflecting voltage and peak surface fields)





Example for 3.9 GHz 9-cell ILC crab cavity from: C. Adolphsen et al, Design of the ILC Crab Cavity System, EUROTeV-Report-2007-010

RF sources

- **Today the f**requency is too high for solid state and other types of tubes. This leaves klystrons as RF source of choice.
- However, given the relatively low power level Silicon Carbide transistor amplifiers may be possible (inquiry with companies started).
- For the time being it is highly recommended to base the frequency on existing klystrons. New developments will be very expensive for a small number of tubes.

Available klystrons

- Highly recommended to base the frequency on existing klystrons. New developments will be very expensive for a small number of tubes.

Manufacturer	type	frequency	average power	comment
Canon	?	5 GHz	500 kW	under development
Canon	E3739B	2.45 GHz	30 kW	
CPI	VKS-7960M - VKS-8269	2.45 GHz	50 - 500 kW	
CPI	VKC-7819B/U	4.4 - 5 GHz	2.6 kW	
CPI	VKC-7810F	3.9 GHz	3 kW	
Thales	?	3.7 GHz	500 kW	used in Fusion reactors
Thales	?	4.6 GHz	60 kW	production would need to be re-started

Outlook

- Need to set limits on aperture, frequency, and max. phase/frequency deviation.
- Stabilisation to a few hundred Hertz is probably ok. In HIE-ISOLDE at 100 MHz we have < 10 Hz during operation).
- Amplifiers will have to provide some kW/cavity (max.), depending on achieve stabilisation with FE-FRT.
- 3.9 and ~4.6 GHz seem manageable.
- The 3.9 GHz version will be cheaper because:
  - one can start from existing 3.9 GHz 8 cavity modules
  - 4.6 GHz will need more cavities to get to the same “active length”
  - maintaining a “large” aperture at 4.6 GHz means higher peak fields and increased RF power.

References

- N. Shipman et al., Ferroelectric Fast Reactive Tuner Applications For SRF Cavities, IPAC2021.
- J. Tückmantel, Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, CERN-ATS-Note-2011-002 TECH.