ERL and Frequency Choice

Rama Calaga, Ed Ciapala, Erk Jensen, Joachim Tückmantel (CERN)

Part 1

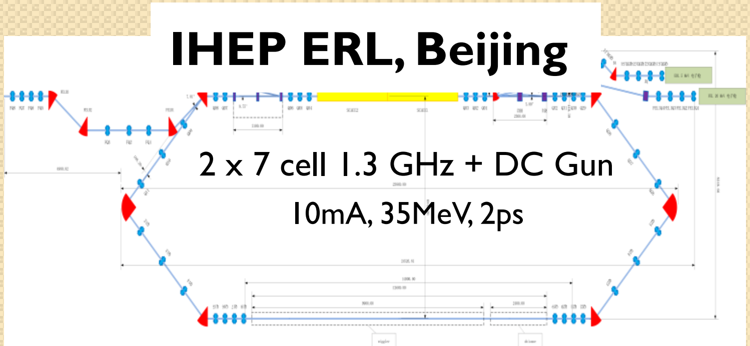
ERL OVERVIEW

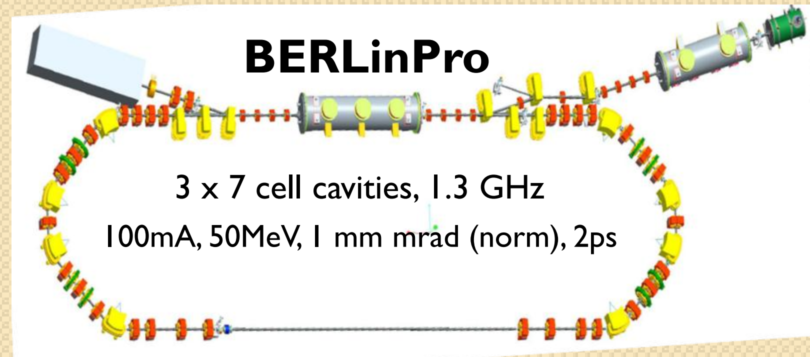
Assumptions for LHeC

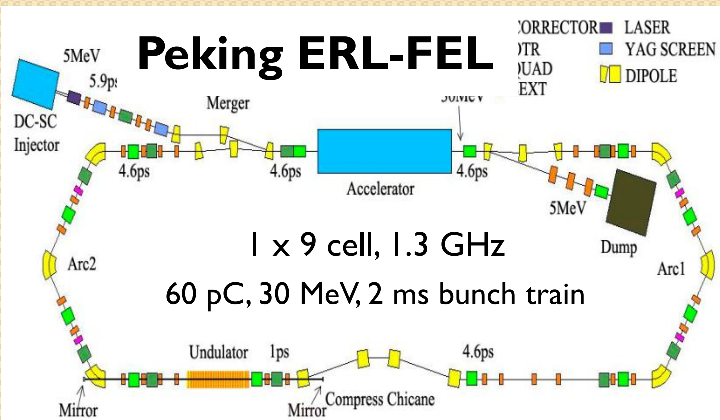
- LHeC with Linac-Ring Option
- Linac with Energy Recovery
- LHeC parameters:

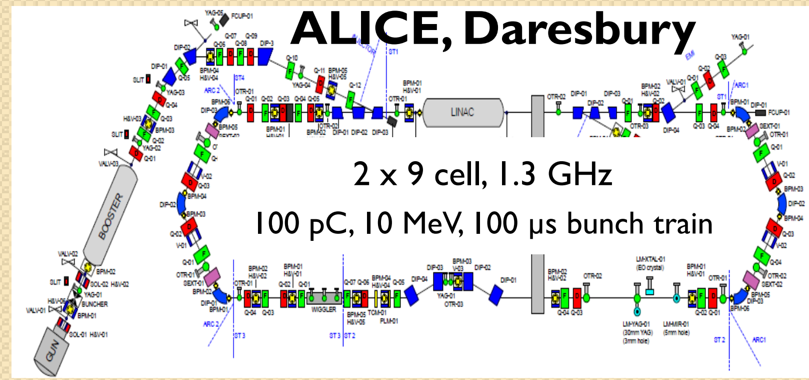
	Units	Protons	RR e-	LR e-
Energy	[GeV]	7000	60	60
Frequency	[MHz]	400.79	**721.42** or	1322.6
Norm. ε	[mm]	3.75	50	50
I_{beam}	[mA]	>500	100	6.6
Bunch spacing	[ns]	25, 50	50	50
Bunch population		$1.7 \cdot 10^{11}$	$3.1 \cdot 10^{10}$	$2.1 \cdot 10^{9}$
Bunch length	[mm]	75.5	0.3	0.3

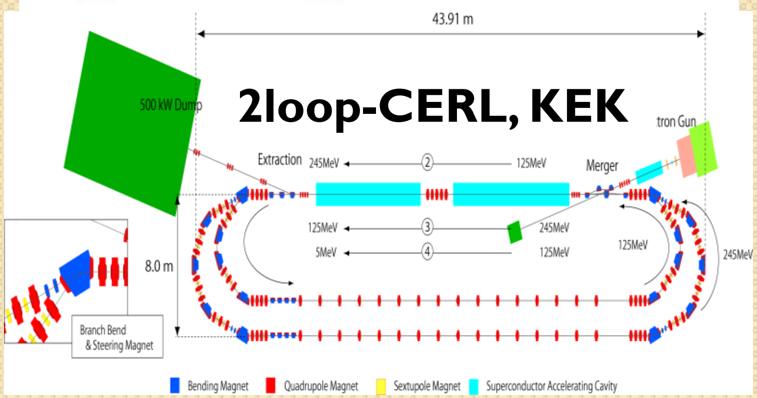
Low Energy ERL's and ERL test facilities





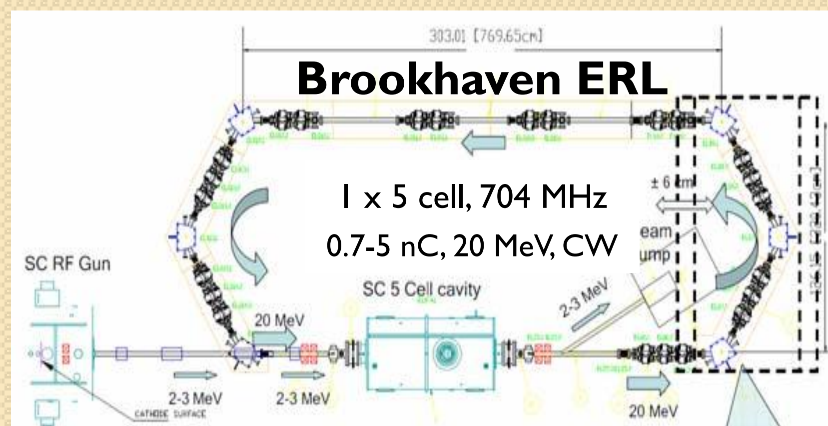




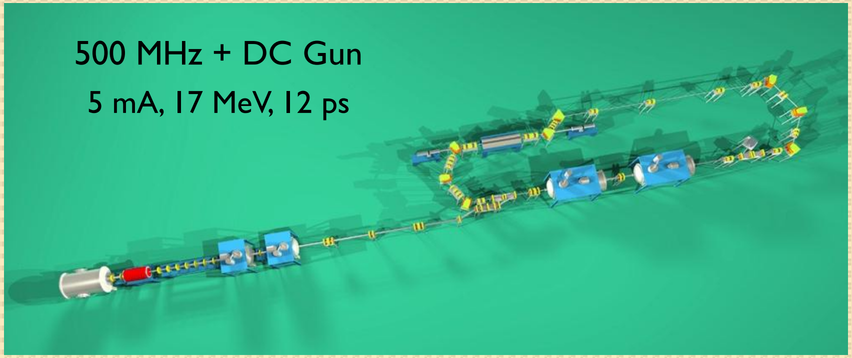


9 cell, 1.3 GHz cavities, 4 modules

77 pC, 245 MeV, 1-3 ps



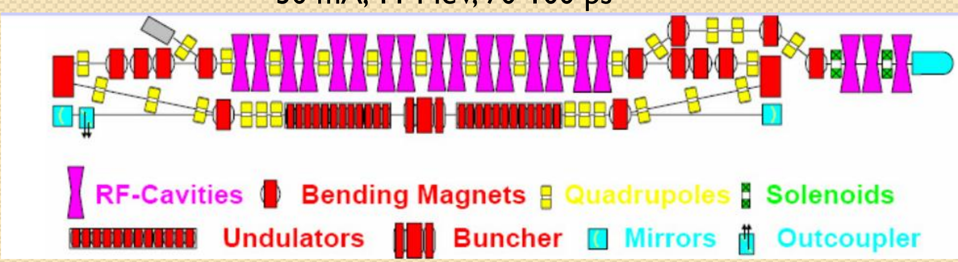
Low Energy ERL's and ERL test facilities (contd.)



JAERI, Tokai

Normal Conducting 180 MHz + DC Gun

30 mA, 11 MeV, 70-100 ps



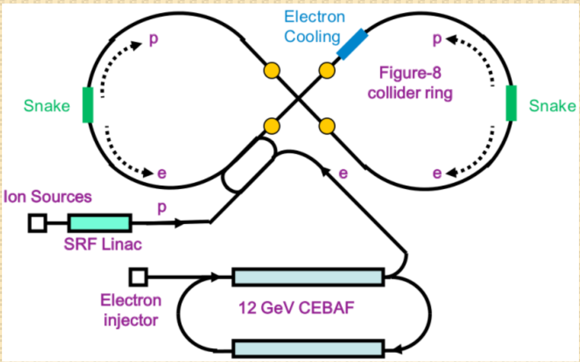
BINP, Novosibirsk

Low Energy ERL's and ERL test facilities (contd.)

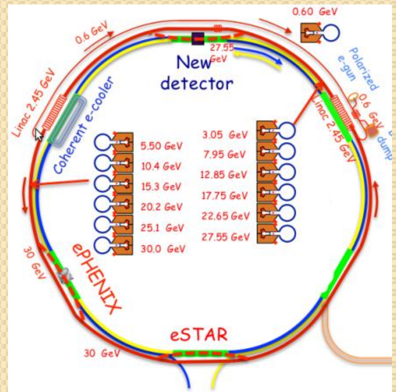
IHEP ERL-TF	HZB BERLinPro	BINP	Peking FEL	BNL ERL-TF	KEK cERL	Daresbury ALICE	JAERI
35 MeV	100 MeV	11-40 MeV	30 MeV	20 MeV	245 MeV	10 MeV	17 MeV
1.3 GHz 9 cell	1.3 GHz	180 MHz	1.3 GHz 9-cell	704 MHz 5-cell	1.3 GHz 9-cell	1.3 GHz 9-cell	500 MHz
10 mA	100 mA	30 mA	50 mA	50-500 mA	10-100 mA	13 μA	5-40 mA
60 pC	10-77 pC	0.9-2.2 nC	60 pC	0.5-5 nC	77 pC	80 pC	400 pC
2-6 ps	2 ps	70-100ps	1-2 ps	18-31 ps	1-3 ps	~10 ps	12 ps
1 pass	1-2 pass	4 passes	1 pass	1 pass	2-passes	1-pass	1-pass
Under construction	Planned / construction	operating		Under construction	Under construction	operating	operating

High Energy ERL's, EIC's (election-ion)

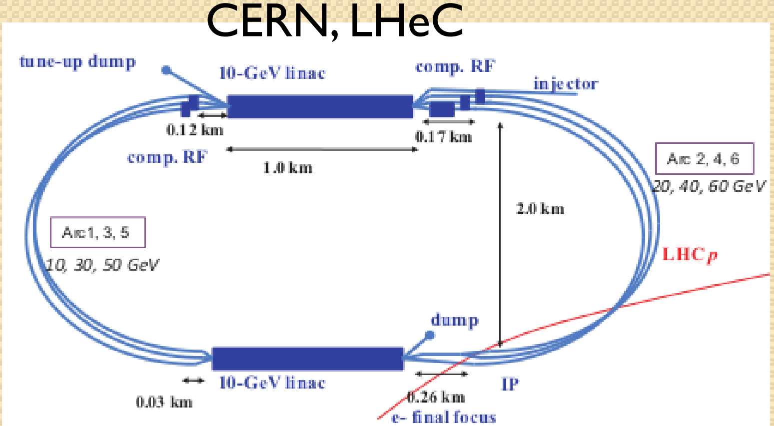
JLAB, MEIC



BNL, eRHIC

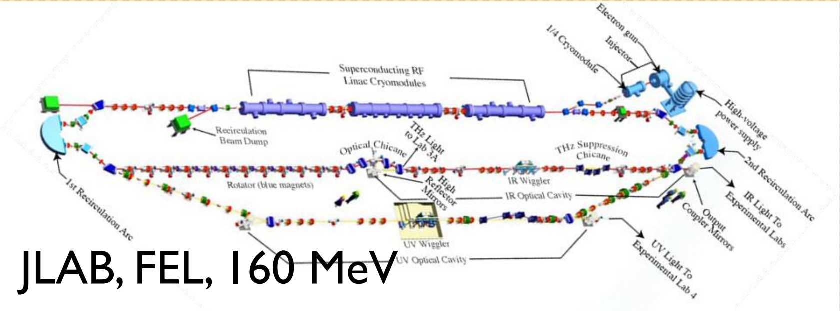


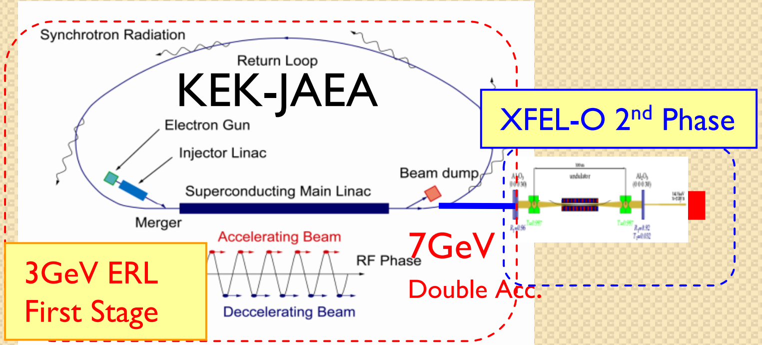
CERN, LHeC



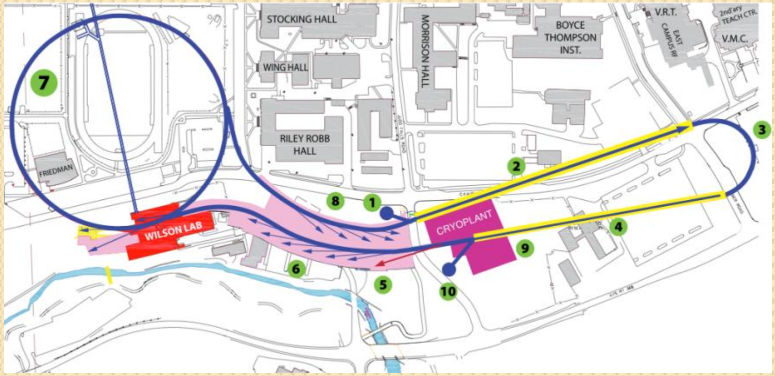
JLab MEIC	BNL eRHIC	CERN LHeC
5-10 GeV	20 GeV	60 GeV
750 MHz ? passes	704 MHz 6 passes	704 MHz 3-passes
3 A	50 mA	6.4 mA
4 nC	3.5 nC	0.3 nC
7.5 mm	2 mm	0.3 mm
Planned	Planned	Planned

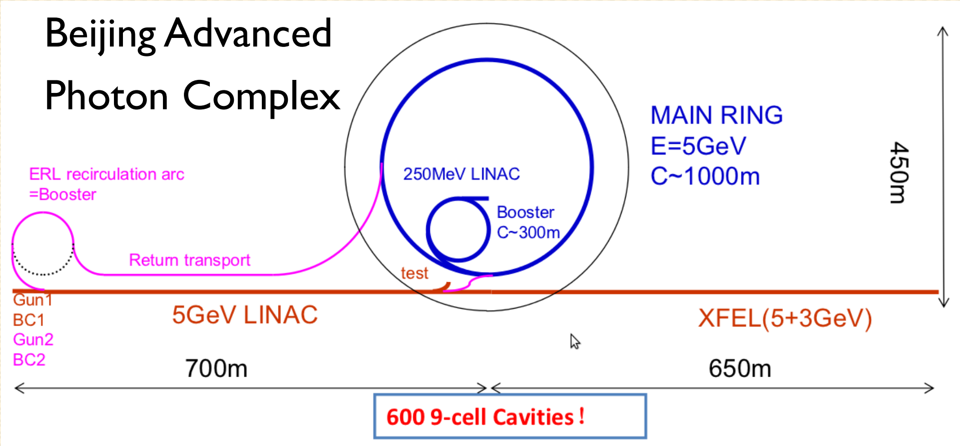
High Energy ERL’s, Light sources, FEL

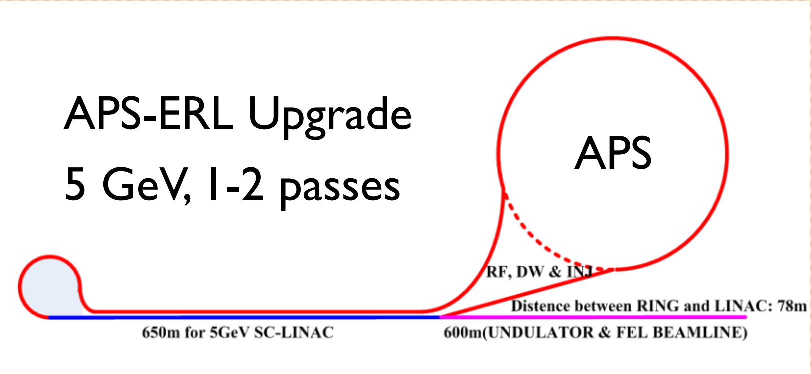




Cornell ERL Light Source, 5 GeV







High Energy ERL's, Light sources, FEL's

JLab FEL (IR, UV)	Argonne Light Source	Cornell Light source	Mainz, MESA ERL	KEK-JAEA Light Source	Beijing Photon Source
160 GeV	7 GeV	5 GeV	100-200 MeV	3 GeV	5 GeV
1.5 GHz	1.4 GHz 1-2 passes	1.3 GHz	? 2 passes	1.3 GHz	1.3 GHz 9 cell
10 mA	25-100 mA	100 mA	0.15-10 mA	0.01-100 mA	10 mA
135 pC	77 pC	77pC	7.7 pC	7.7-77 pC	77 pC
0.045-0.15 mm		0.6 mm	- ps	2 ps	2 ps
Operating	Planned	Planned	?	Planned	Planned

CEBAF not in the list since it is not normally operated in ER mode.
(Is this so? – Please correct me if wrong! – and help fill my other blanks!)

Part 2

CHOICE OF FREQUENCY

Which frequency?
700 MHz vs. 1300 MHz

Advantages 700 MHz

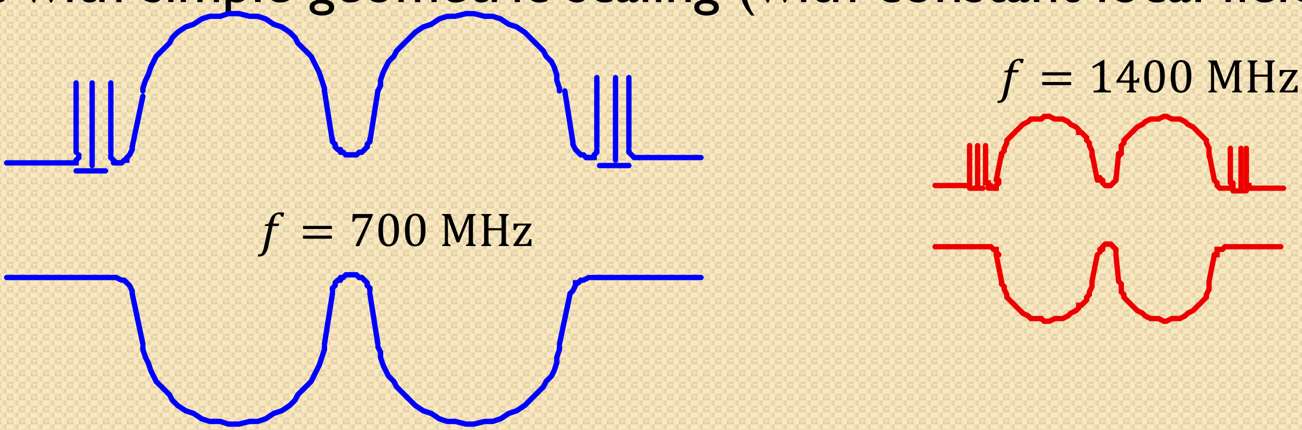
- Synergy SPL, ESS, JLAB, eRHIC
- Smaller BCS resistance
- Less trapped modes
- Smaller HOM power
- Beam stability
- Smaller cryo power
- Power couplers easier

Advantages 1300 MHz

- Synergy ILC, X-FEL
- Cavity smaller
- Larger *R/Q*
- Smaller RF power
  (assuming same Q_{ext})
- Less Nb material needed

Scaling 700 MHz → 1400 MHz
(J. Tückmantel, 2008 for SPL)

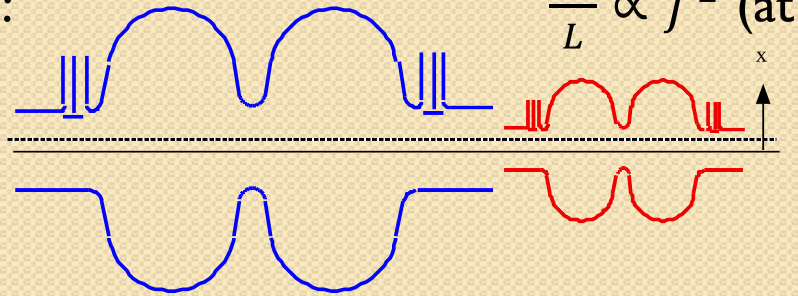
Start with simple geometric scaling (with constant local fields):



- Length, beam pipe diameter: $l, a \propto f^{-1}$
- Surface area(s): $A \propto f^{-2}$
- Volume, stored energy: $W \propto \iiint \vec{E}^2\, dV \propto f^{-3}$
- Voltage: $V \propto \int \vec{E} dl \propto f^{-1}$
- R/Q: $\frac{R}{Q} = \frac{1}{2}\frac{V^2}{\omega W} \propto \frac{f^{-2}}{f f^{-3}} = f^0$
- Loss factor: $k_{loss} = \frac{V^2}{4W} \propto f$

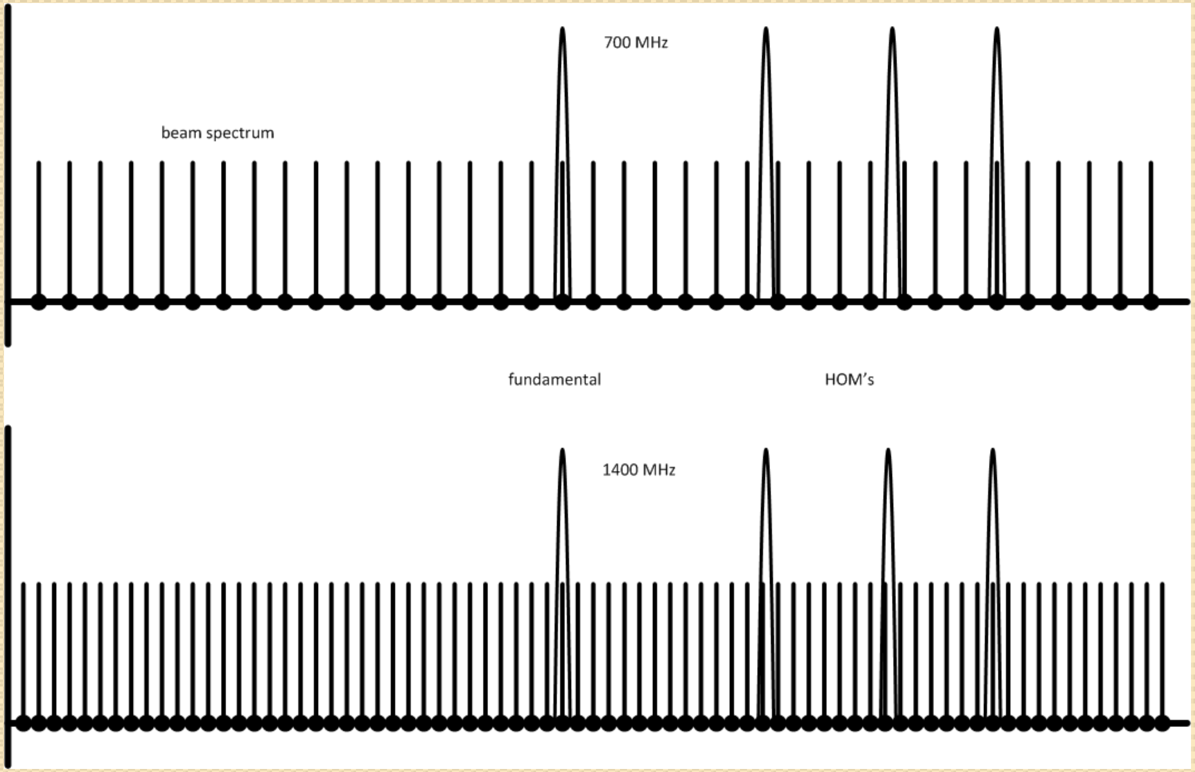
Scaling 700 MHz → 1400 MHz (continued)

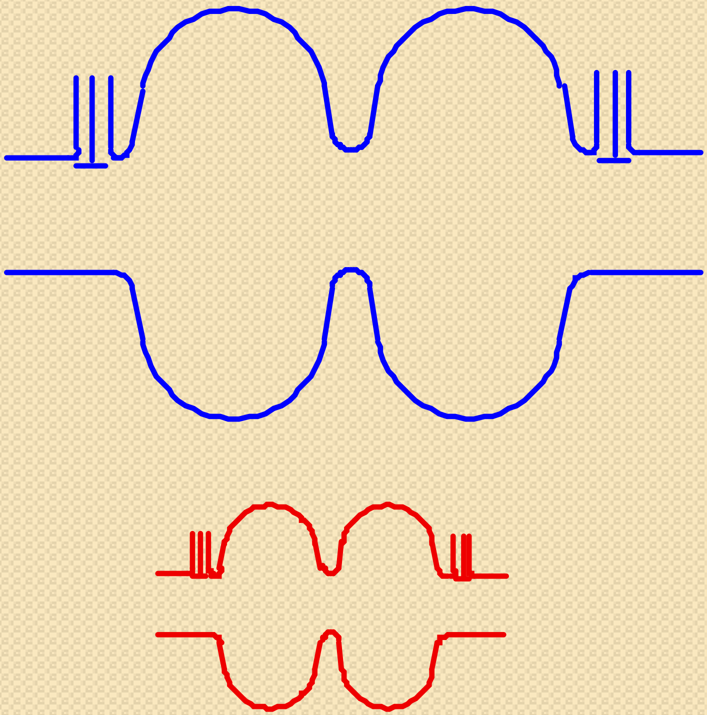
- Power (input, HOM losses, main coupler): all would scale as an area $P \propto f^{-2}$
- How would Q_{ext} scale? $Q_{ext} \propto \frac{\omega W}{P_{ext}} \propto \frac{f f^{-3}}{f^{-2}} = f^0$
  - but please note: Q_{ext} is a choice
- Wakefields:
  - longitudinal short range wakes: $\frac{\Delta V_{induced}}{L} \propto \frac{k_{loss}}{L} \propto f^2$
  - longitudinal impedance: $Z_{\parallel} = \frac{R}{Q} Q_{ext} \propto f^0$
  - longitudinal long range wakes: $\frac{Z_{\parallel}}{L} \propto f$
  - dipole wakes: $\frac{Z_{\perp}}{L} \propto f^2$ (at same offset!)



Scaling 700 MHz → 1400 MHz (continued)

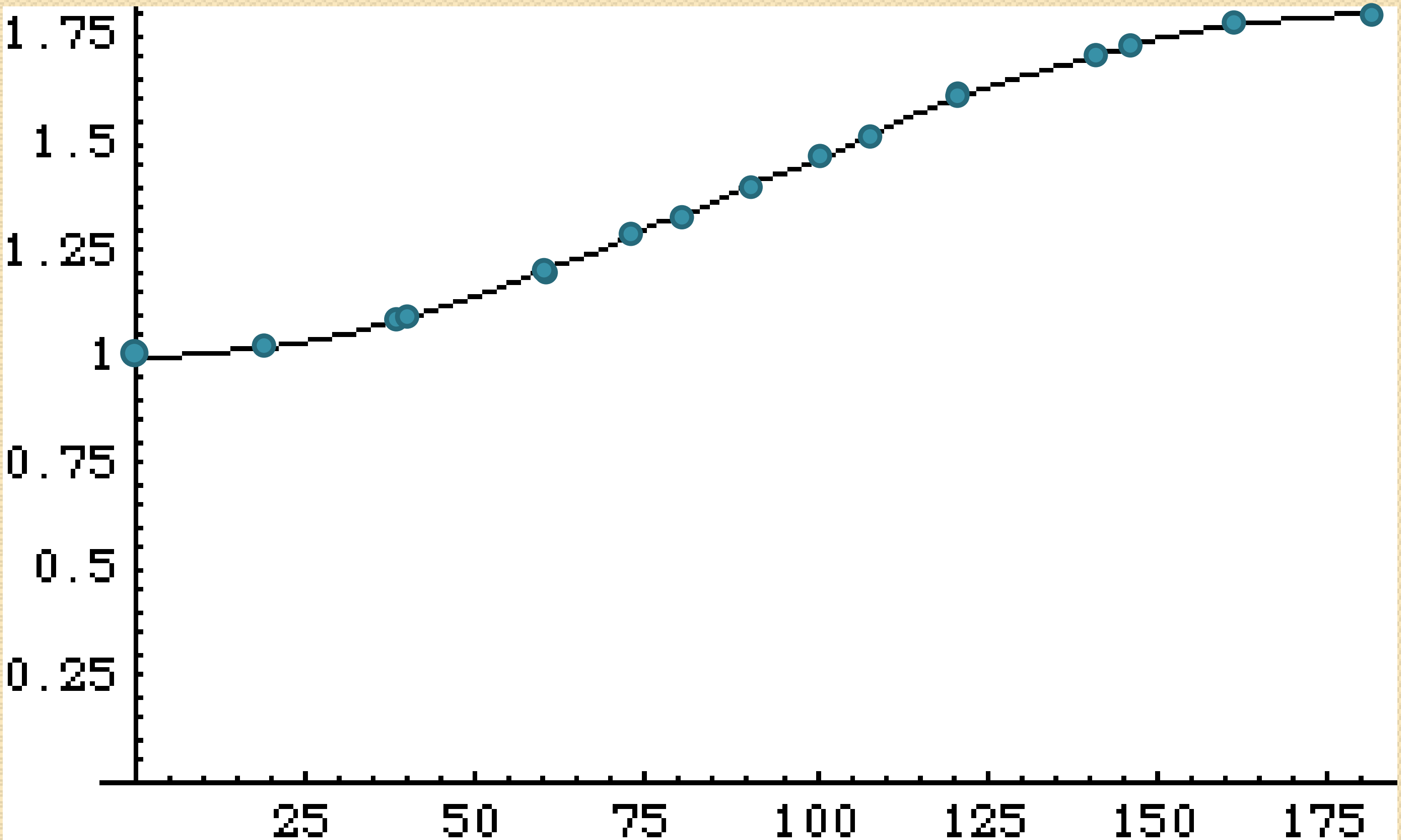
- Meaning of this latter scaling $\frac{Z_\perp}{L} \propto f^2$: the beam break-up threshold scales as f^2!
- Beam spectrum (multiples of 40 MHz, plus betatron and synchrotron sidebands)





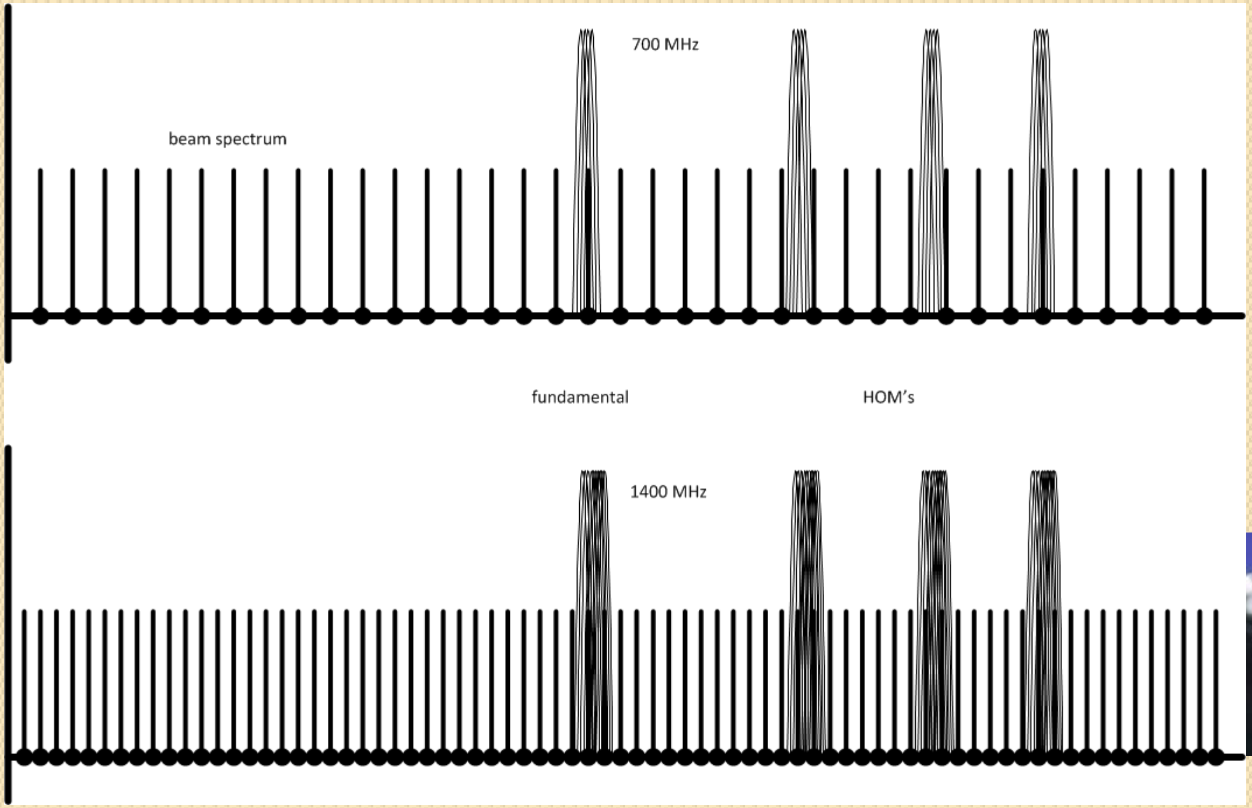
Scaling 700 MHz → 1400 MHz (continued)

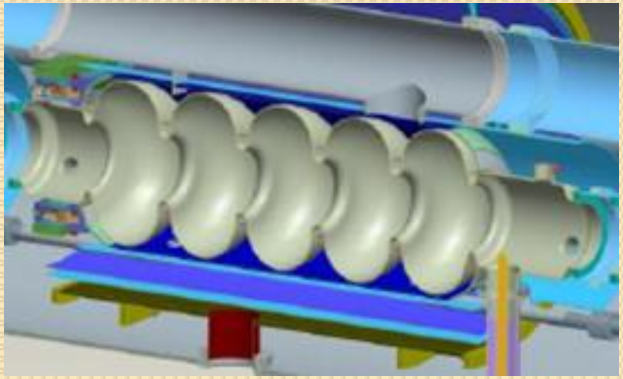
- But at higher *f* you have also to increase the number of cells!
- *n* cells – *n* modes!



1[illegible] cells

Scaling 700 MHz → 1400 MHz (continued)

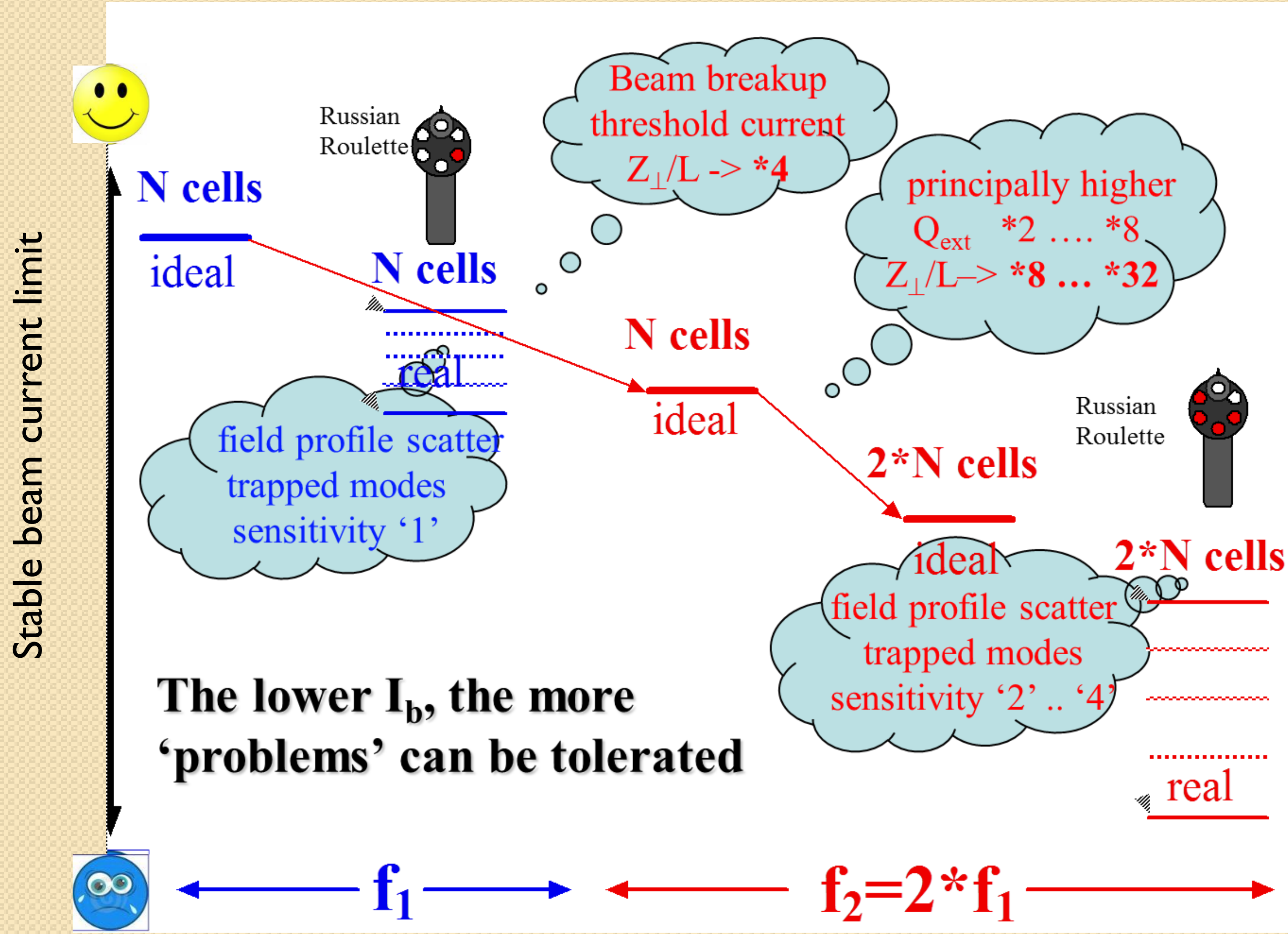




With $\frac{Z_\perp}{L} \propto f^2$ (at same offset!) plus the increased number of cells per cavity:

Beam break-up threshold current decreases with f^{-3}!

Lower *f*, larger currents possible



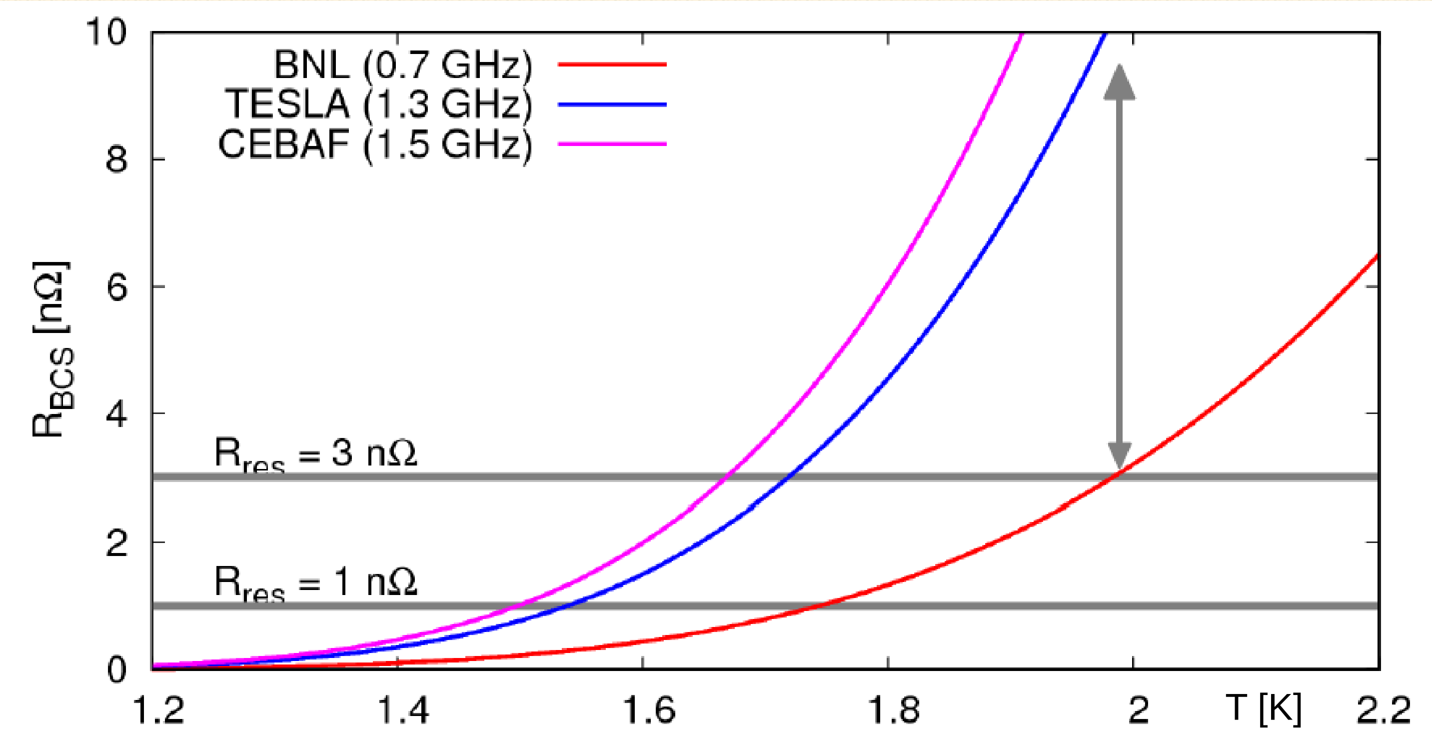
My main message is this:

721 MHz much larger stable beam current limit than 1323 MHz!

… but also:

Dynamic wall losses

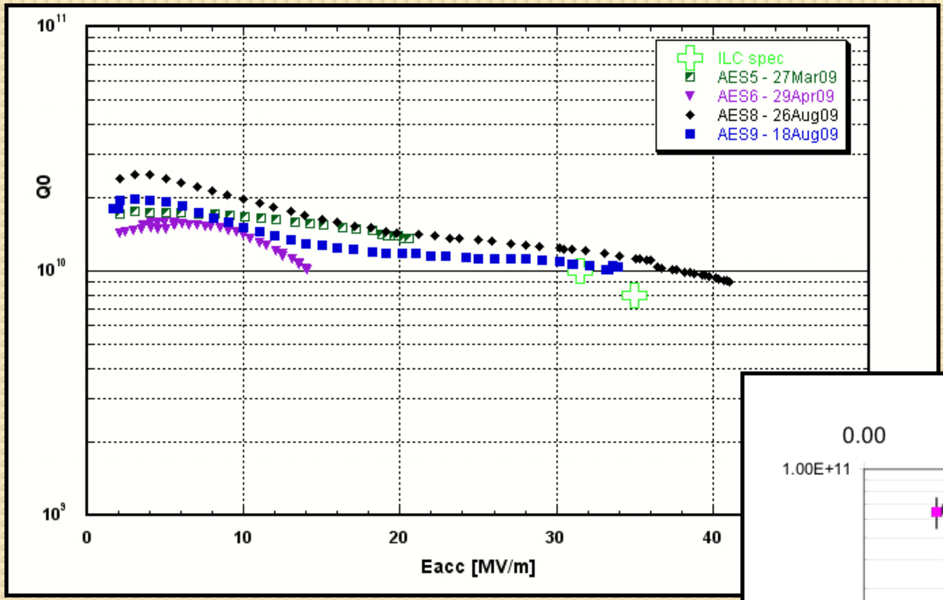
$R_s = R_{BCS} + R_{res}$



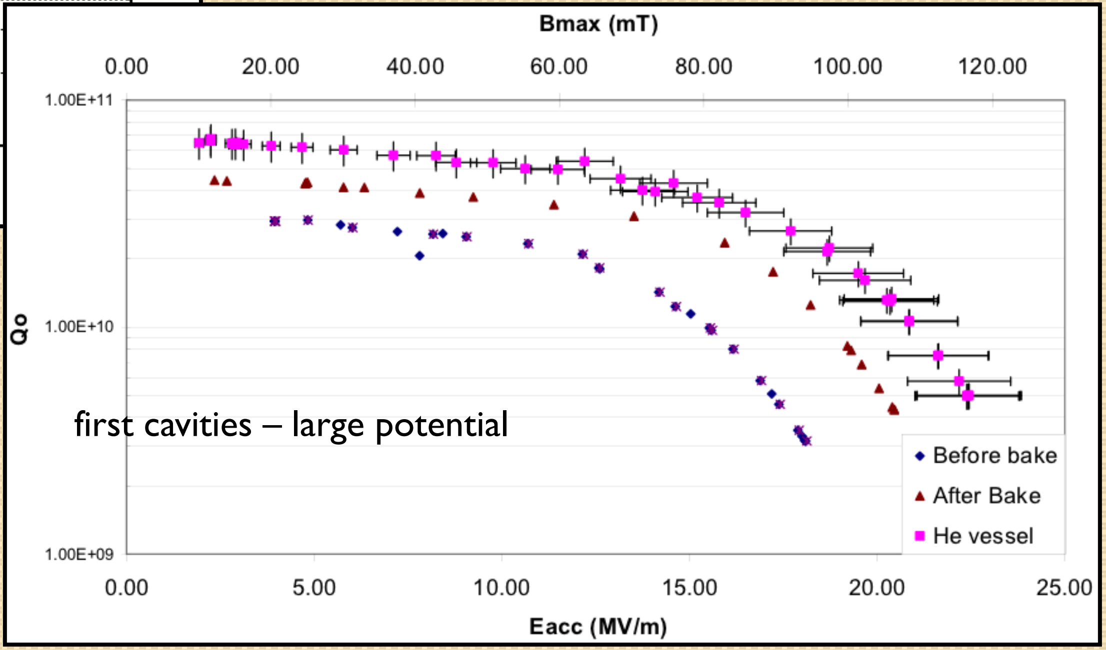
For small R_{res}, this clearly favours smaller f.

One should aim for very large Q_0

ILC Cavities 1.3 GHz, BCP + EP (R. Geng SRF2009)



BNL 704 MHz test cavity, BCP only!
(A. Burill, AP Note 376)



first cavities – large potential

More in Ed Ciapala's talk!

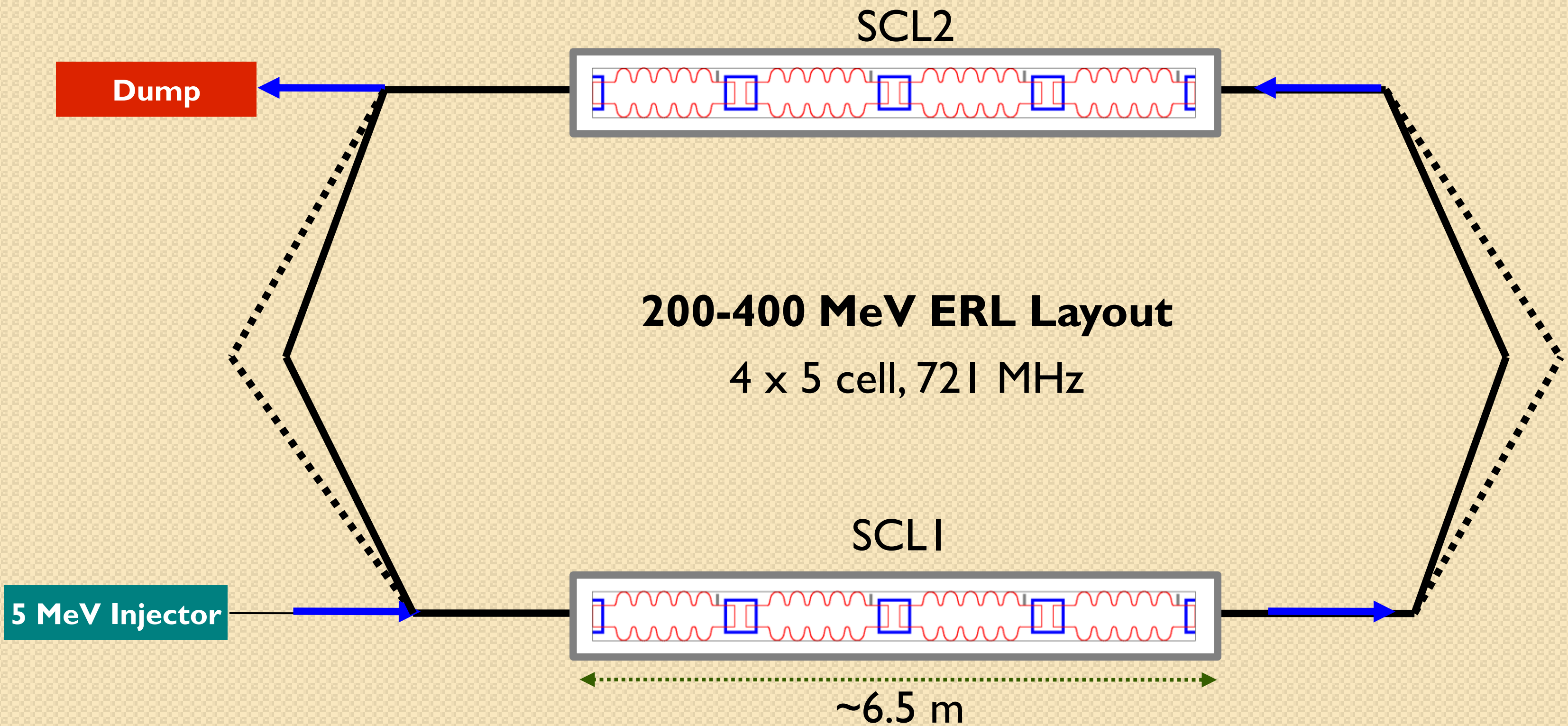
Part 3: - some initial thoughts on

ERL-TF @ CERN

very sketchy and preliminary …

You are invited to contribute!

ERL-TF @ CERN

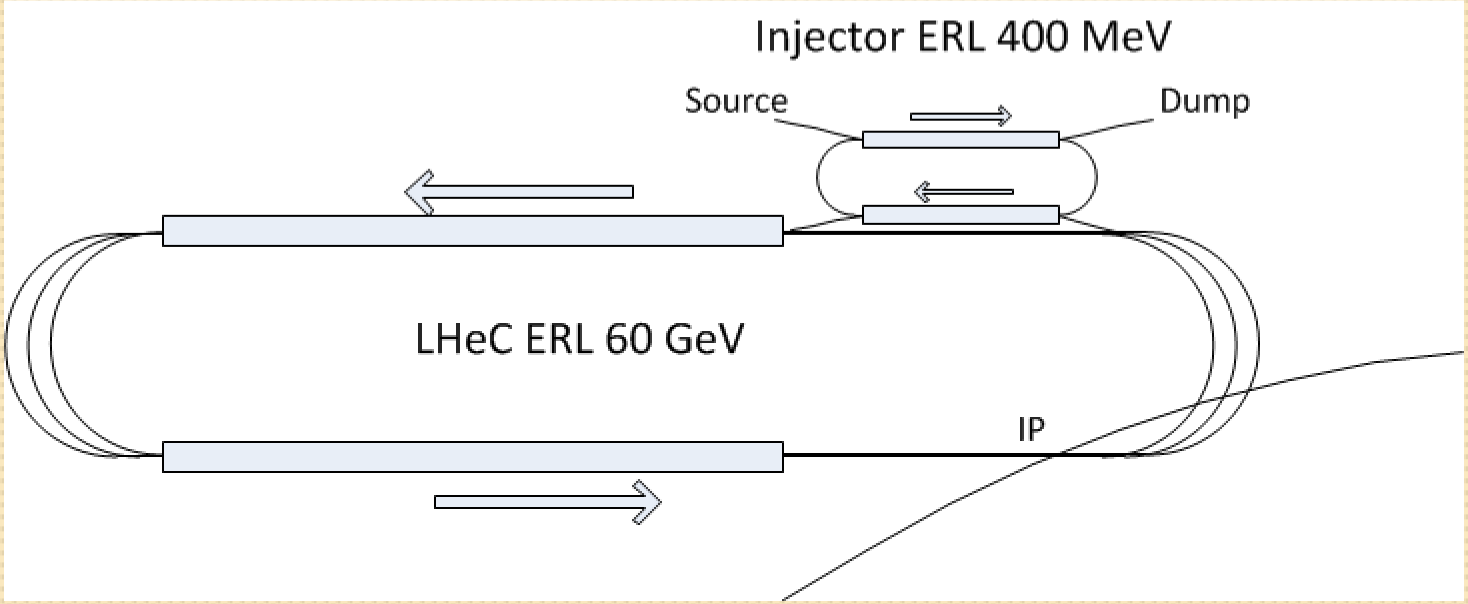


	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep. rate		CW	CW

Why ERL TF @ CERN?

- Physics motivation:
  - ERL demonstration, FEL, γ-ray source, e-cooling demo!
  - Ultra-short electron bunches
- One of the 1^{st} low-frequency, multi-pass SC-ERL
  - synergy with SPL/ESS and BNL activities
- High energies (200 … 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
  - …could test CLIC-type energy recovery from SCL2 → SCL1
- MW class power coupler tests in non-ER mode
- Complete HOM characterization and instability studies
- Cryogenics & instrumentation test bed
- Could this become the LHeC ERL injector (see next page)?
- …

Could the TF later become the LHeC ERL injector ERL?



very preliminary – just an idea by Rama and me yesterday.

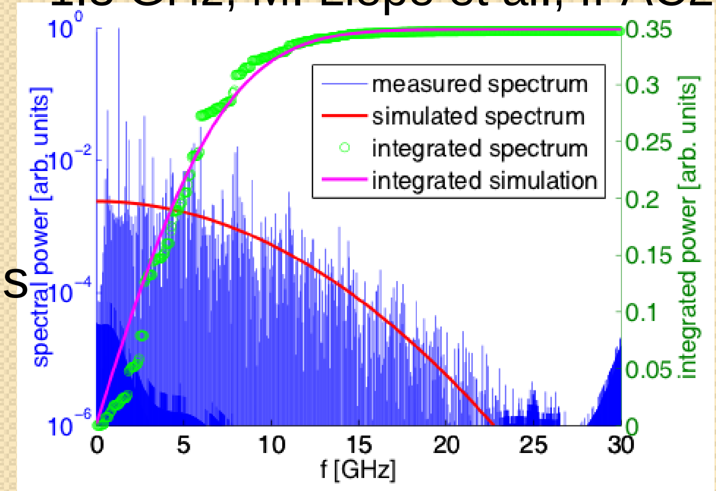
HOM Measurements

Complete characterization of HOM

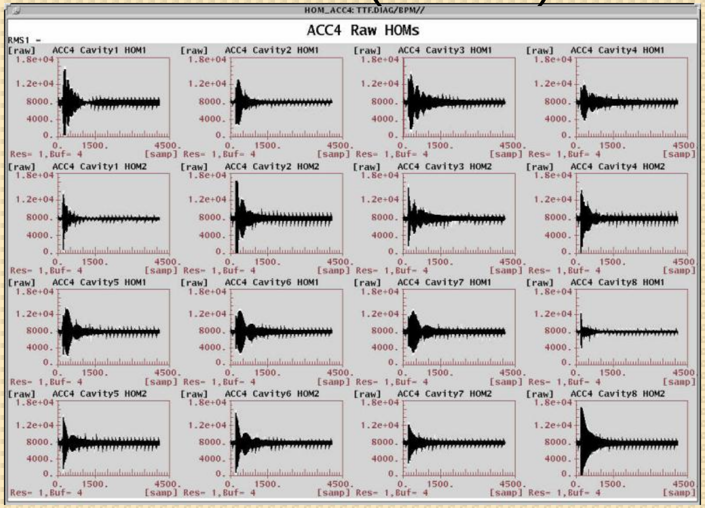
Benchmark simulations

Improvements on damping schemes

1.3 GHz, M. Liepe et al., IPAC2011



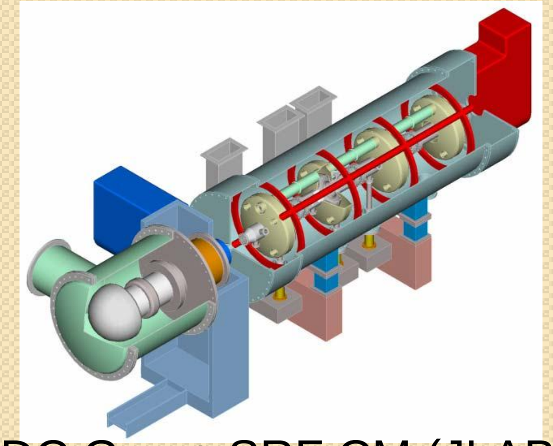
N. Baboi et al. (FLASH)



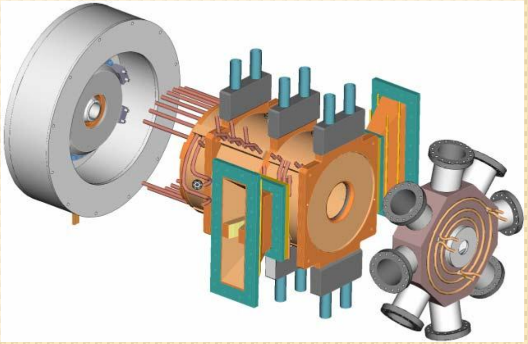
Precision measurement of orbit

Cavity & CM alignment

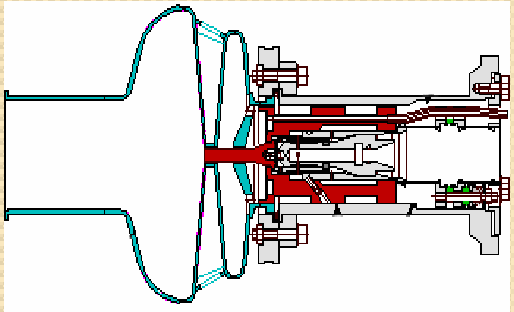
Injector R&D (~700 MHz)



DC Gun + SRF CM (JLAB-AES)

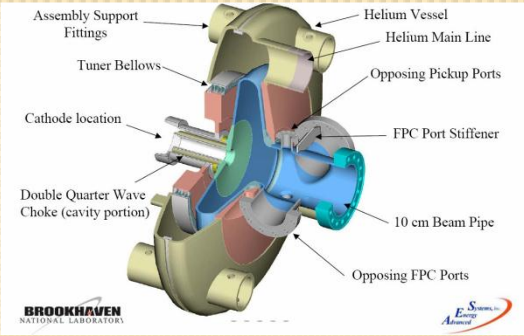


NC Gun (LANL-AES)



SRF Gun (FZR-AES-BNL)

	DC+SRF-CM	NC	SRF
Energy	2-5 MeV	?	2 MeV
Current	100 mA	100 mA	1000 mA
Long. Emit	45 keV-ps	200 keV-ps	-
Trans. Emit	1.2 ❍m	7 ❍m	< 1 ❍m



SRF Gun (BNL-AES)

RF Power

→ 5 MeV injector → P_{beam} ~ 50 kW (10 mA)

Will need higher powers if we go to 100 mA+

Peak detuning

→ Main LINAC (zero beam loading)

$$P_g = \frac{V^2}{R/Q} \cdot \frac{\Delta f}{f} \quad \left\{ Q_{opt} = \frac{1}{2} \cdot \frac{f}{\Delta f} \right\}$$

	721 MHz
Q=1 x 10^6	250 kW
Q=5 x 10^6	50 kW
Q=1 x 10^7	25 kW

Commercial television IOT @700 MHz ←

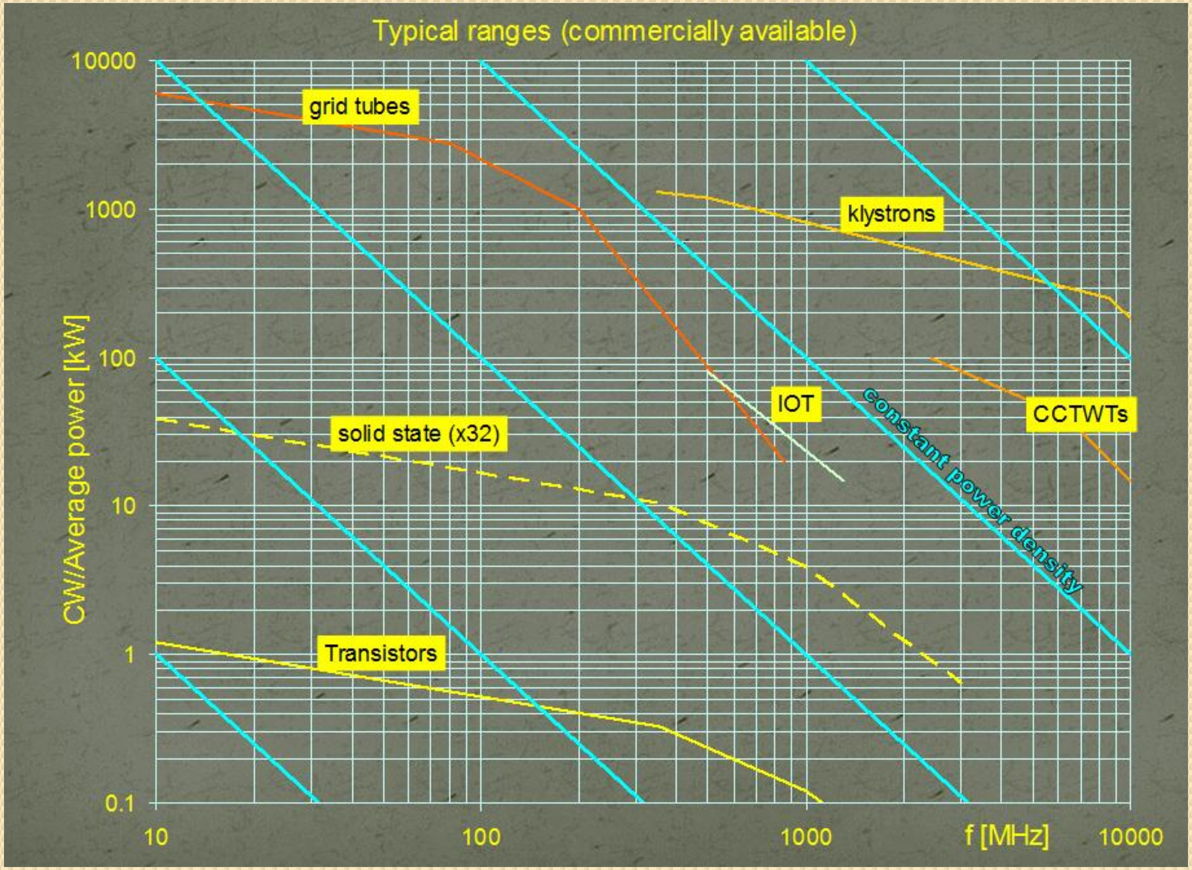
Reach steady state with increasing beam current

RF Power

Use of IOTs ~ 50-100 kW at 700 MHz

High efficiency, low cost

Amplitude and phase stability



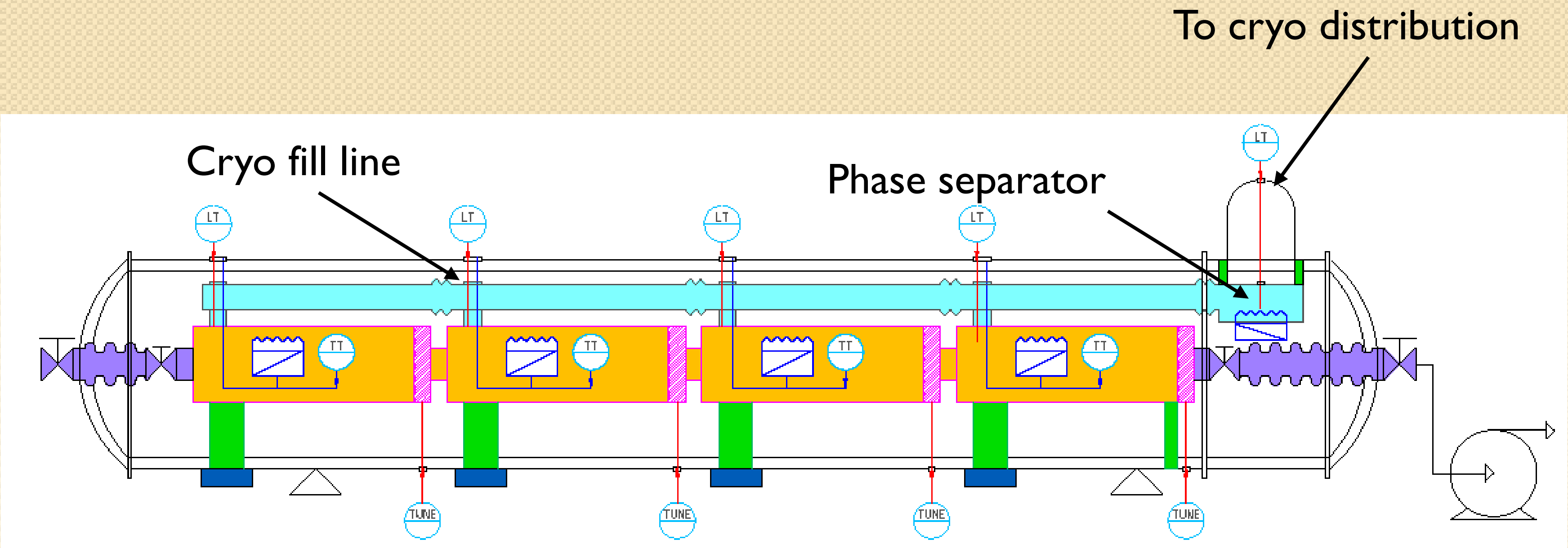
50 kW TV Amplifier, BNL

At 700 MHz

Cryogenic System

Can use the SPL like cryo distribution system

No slope at the C-TF → the distribution line can be in center ?



V. Parma, Design review of short cryomodule

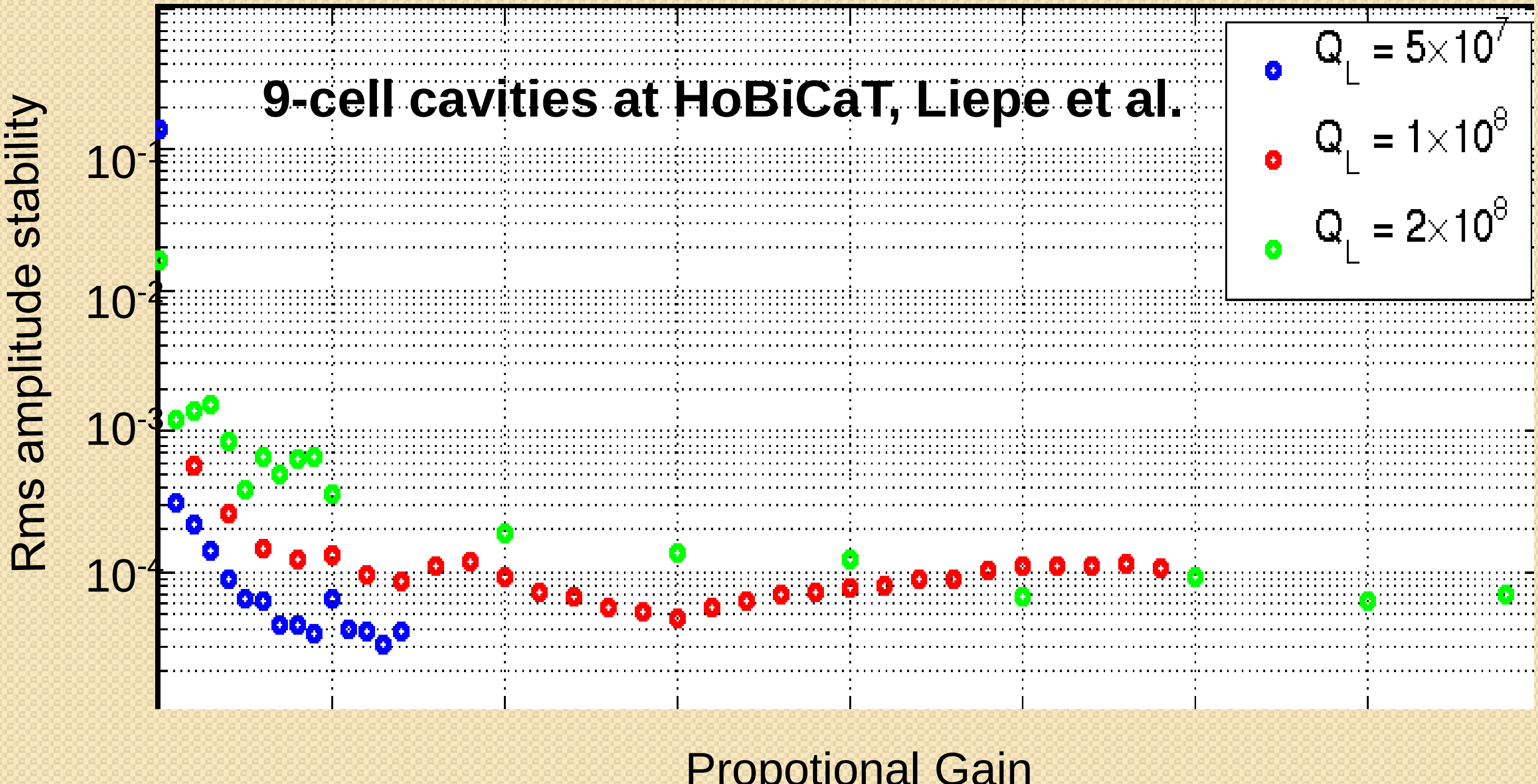
RF Controls

Development of digital LLRF system (Cornell type ?)

Amplitude and phase stability at high Q_0 ~ 1 x 10^8

Reliable operation with high beam currents + piezo tuners

In case of failure scenarios: cavity trips, arcs etc..



RF Failures

Slow failures (for example: power cut)

Q_{ext} is very high → perhaps need to do nothing

Fast failures (coupler arc)

If single cavity → additional RF power maybe ok

Reduce beam currents or cav gradients gradually

If entire LINAC → lot of RF power

Perhaps play with 2-LINAC configuration for safe extraction of high energy beam

Timeline & Costs

If:

SPL R&D CM can be used, then very fast turn-around (cheap option)

Else:

3-4 years of engineering & development (SRF + beam line)

The costs should be directly derived from SPL CM construction (< 5 MCHF ?)

Do we need high power couplers ?

R&D of HOM couplers

Will be needed for probing high current & CW

Key question: where to place the ERL-TF to have maximum flexibility ?

Conclusions

- We are beginners (well, I am) – but there are many ERL's and ERL TF's out there
- … and of course expertise which will help us with the LHeC ERL
- We need you!
- I very strongly recommend the lower frequency (721 MHz) for transverse beam stability!
- There is interesting R&D – synergetic with other activities.
- A dedicated ERL-TF dedicated looks attractive, serves many purposes and is complementary to other facilities.

Thank you very much!