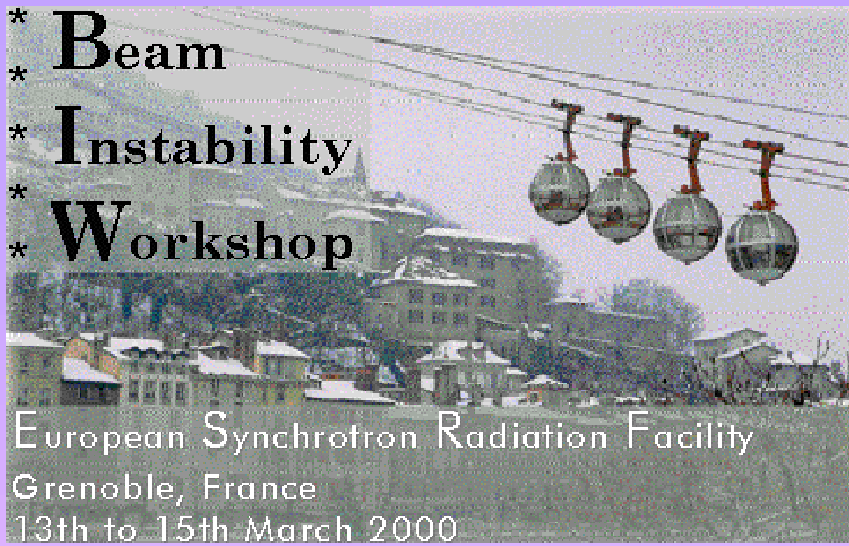


Harmonic Cavities:the Pros & Cons

Jörn Jacob

Content

- *Main motivation for harmonic cavities:* $t_{Touschek}$
- *Harmonic cavities on existing light sources / achievements, problems*
  - *NC passive cavities*
  - *NC active cavities*
- *Projects for SC harmonic cavities*
- *Harmonic cavities for the ESRF ?*
- *Pros & Cons*
- *Conclusions*

Motivation for harmonic cavities

Penalizes few bunch operation

$$\frac{1}{\tau_{Touschek}} \propto \frac{I\,/\,bunch}{\sigma_x \sigma_z \sigma_s\, \gamma^2 (\Delta E / E)^3} \times D(\nu)$$

$$\nu = \frac{(\Delta E / E)^2 \beta_x^2}{\gamma^2 \sigma_x^2}$$

Exponential increase of $\tau_{Touschek}$ with ν if σ_x very small: ⟶ future sources?

Optimized brilliance for 3rd generation sources:
=> lower $\tau_{Touschek}$

Bunch lengthening:
=> increases $\tau_{Touschek}$

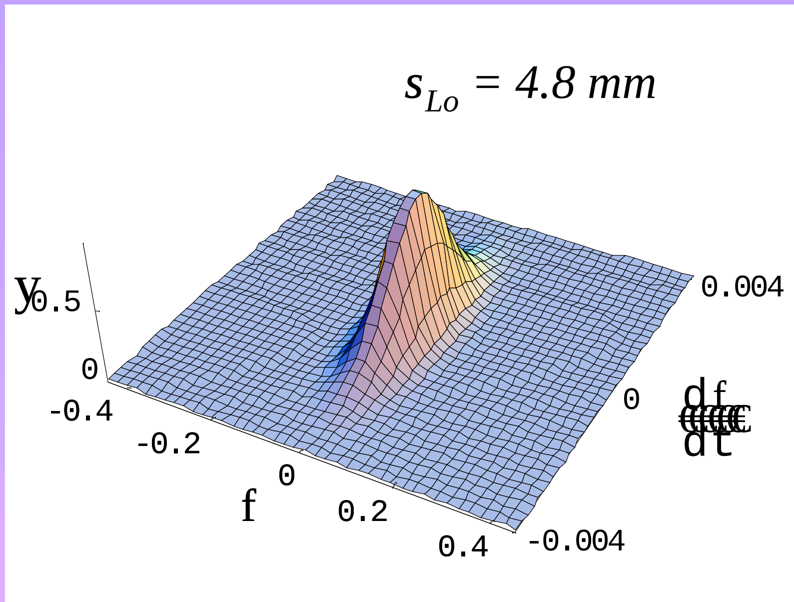
RF or dynamic acceptance:
=> limits $\tau_{Touschek}$

Low energy machines:
=> lower $\tau_{Touschek}$

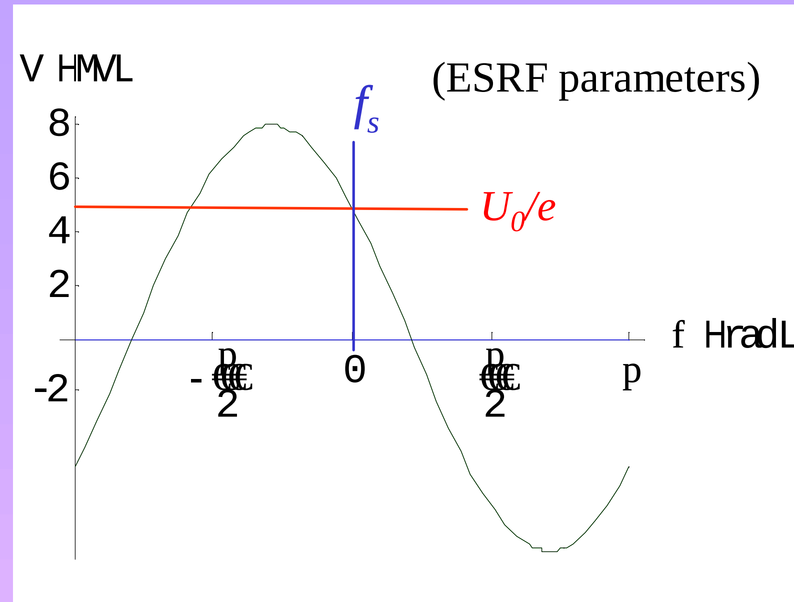
Harmonic Cavities for bunch lengthening

- Cavity at $f_{harm}=n\,f_{RF}$ (often $n=3$)
- Passive / active
- Normal/Super-conducting (NC/SC)
- Maximum bunchlength for:

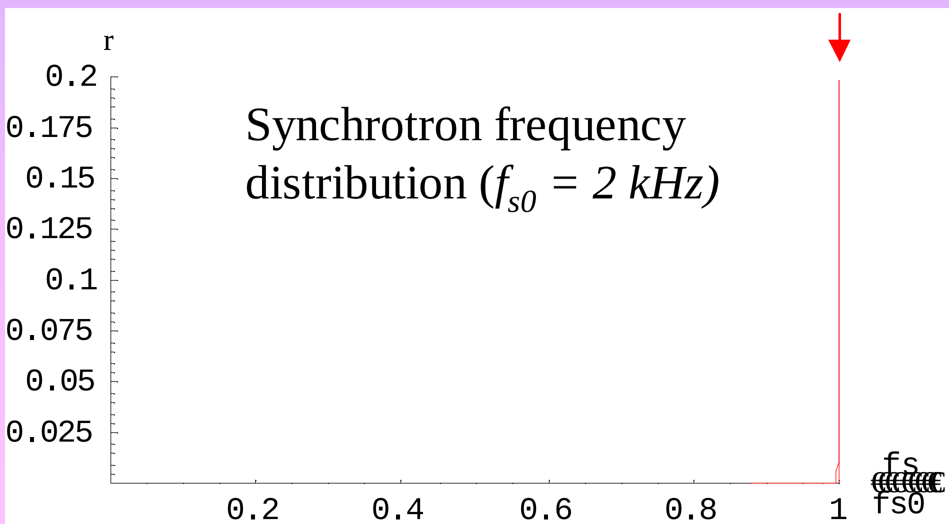
$$\begin{cases} V_{harm} = V_{opt} \\ f_{harm} = f_{opt} \end{cases}$$



σ_{Lo} = 4.8 mm
0.5
0
-0.4
-0.2
0
0.2
0.4
0.004
0
-0.004

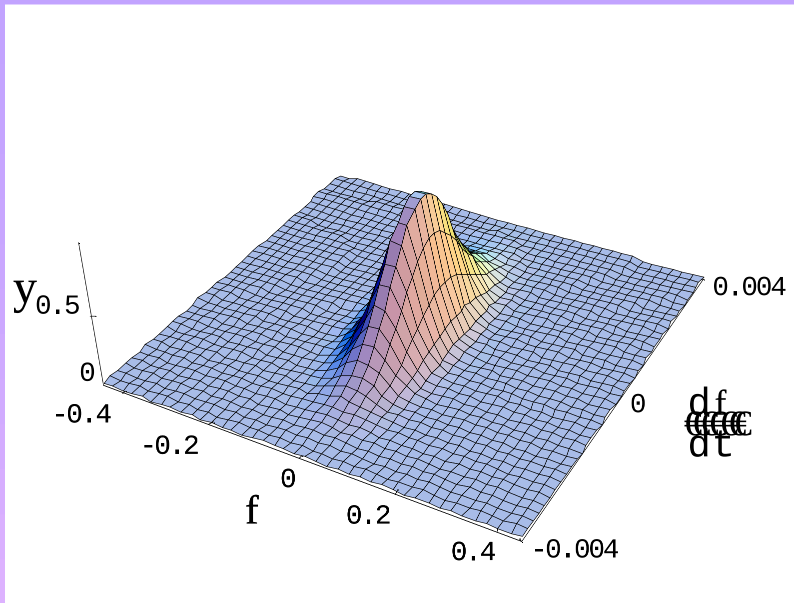


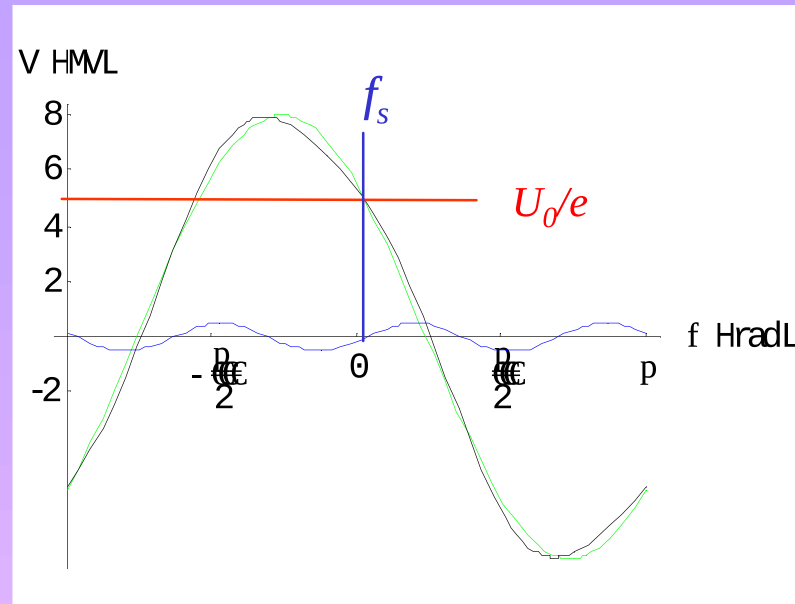
(ESRF parameters)
8
6
4
2
-2
0
f_s
U_0/e

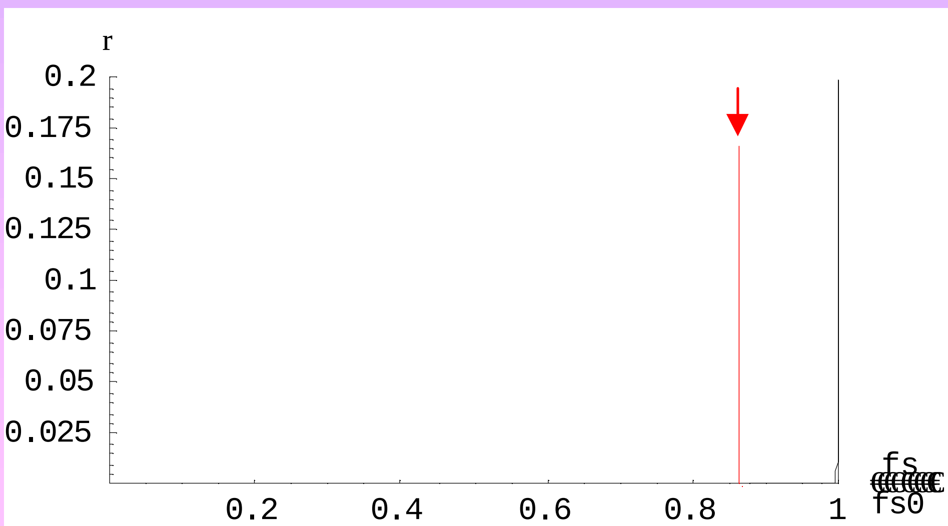


Synchrotron frequency distribution (f_{s0} = 2 kHz)
0.2
0.175
0.15
0.125
0.1
0.075
0.05
0.025
0.2
0.4
0.6
0.8
1
fs
fs0

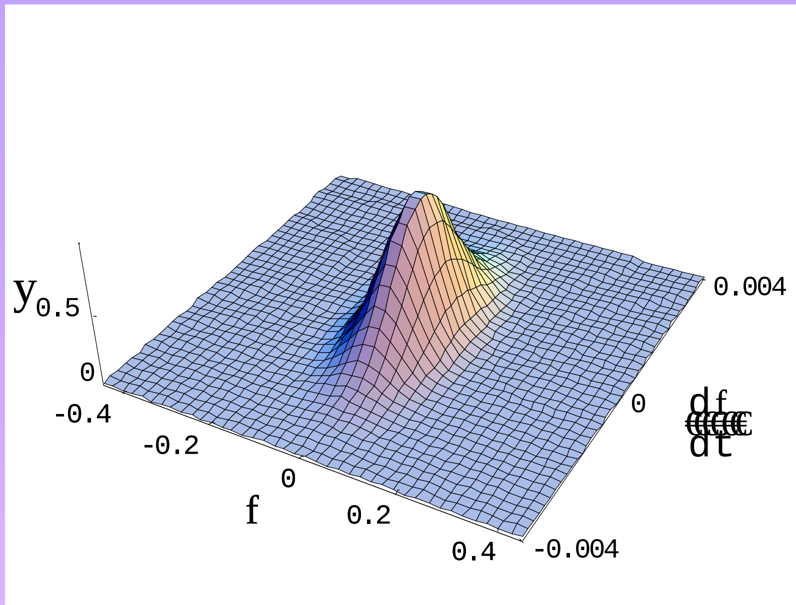
$V_{harm}/V_{opt} = 0$

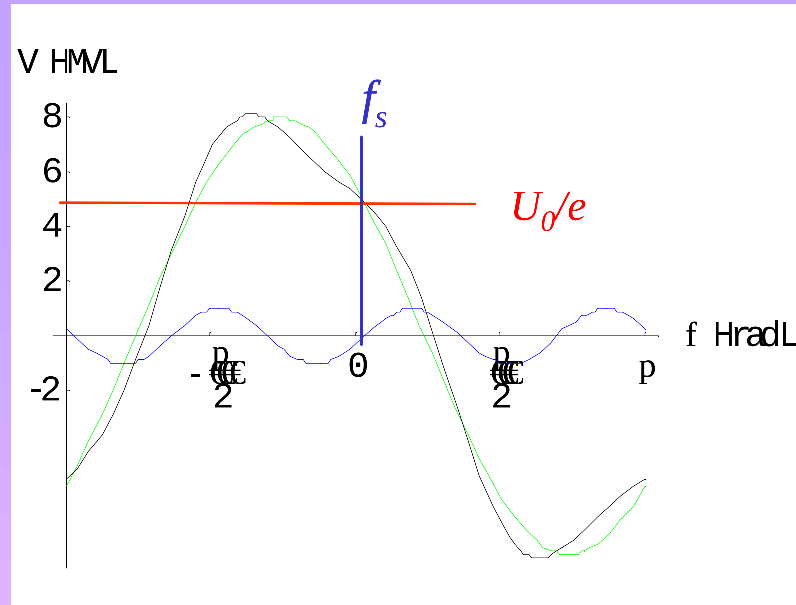


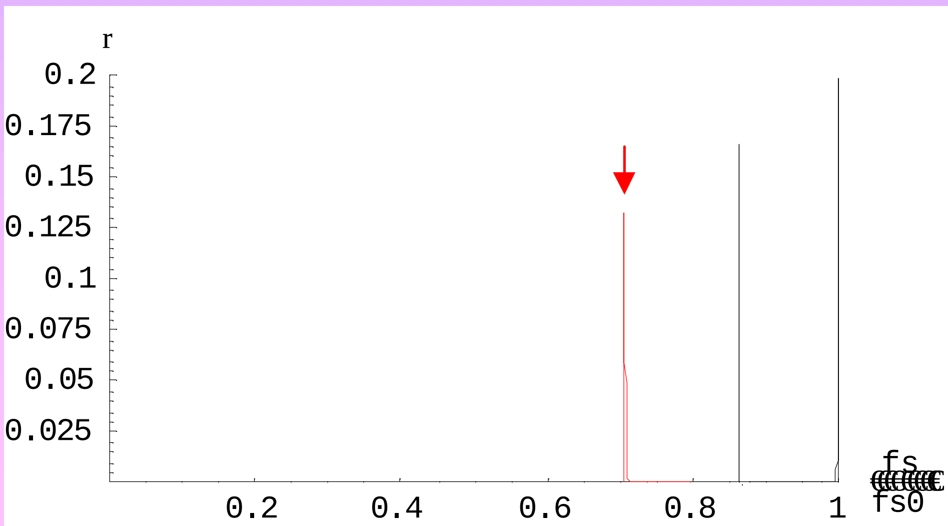




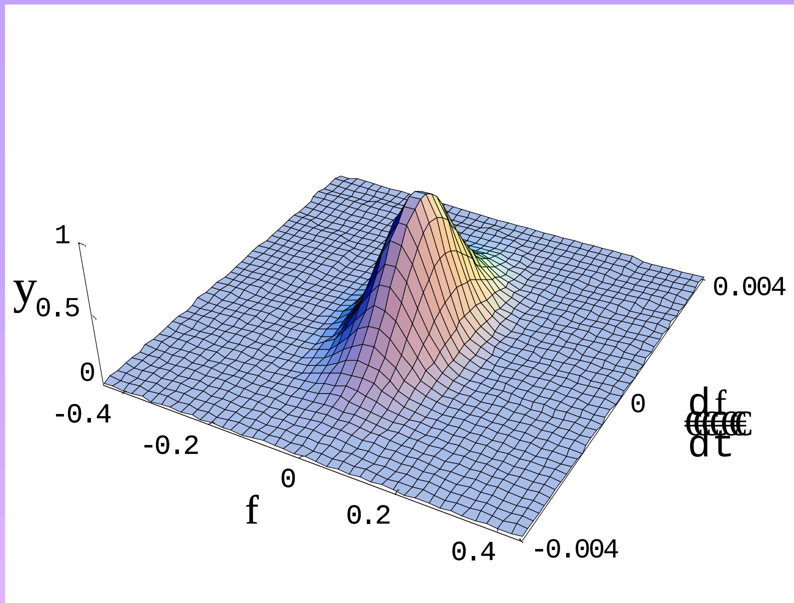
$V_{harm}/V_{opt} = 0.25$

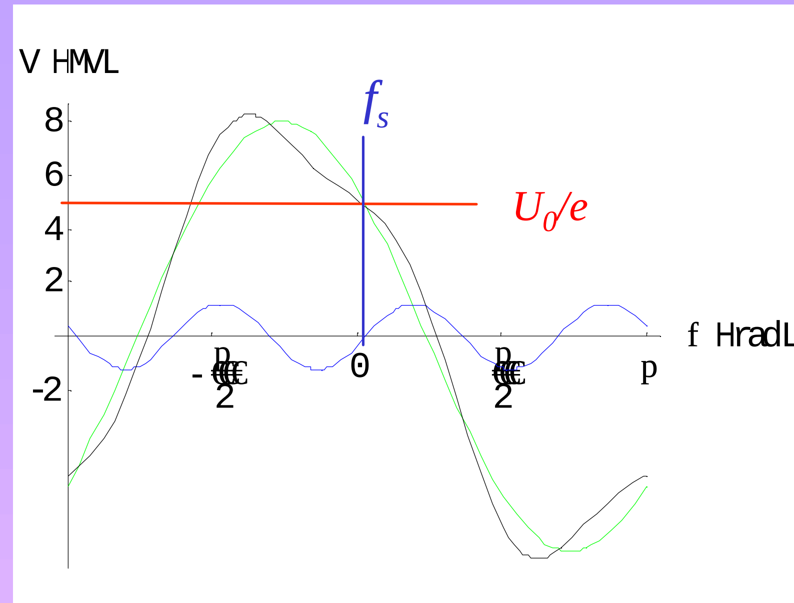


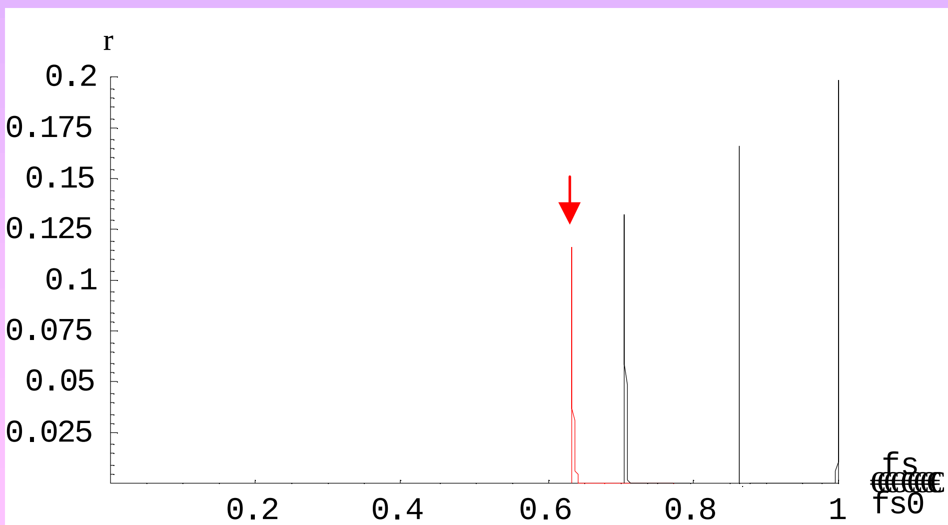




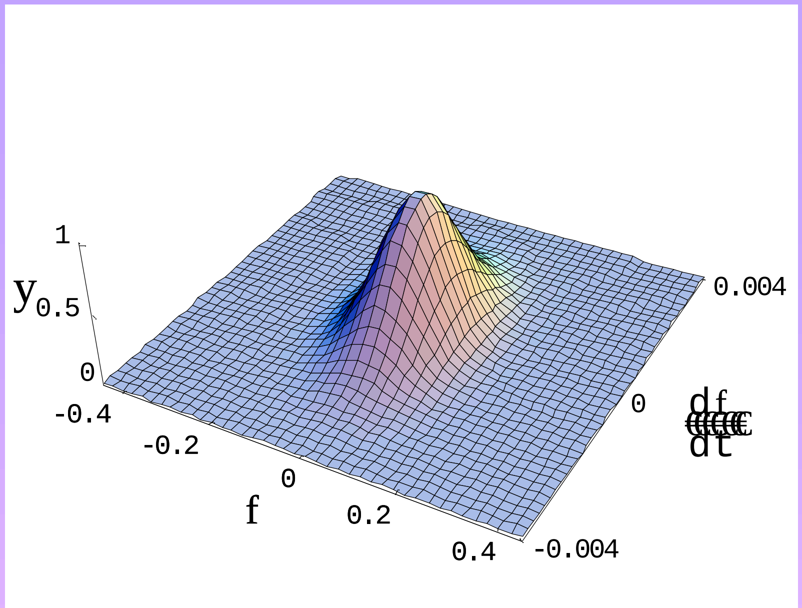
$V_{harm}/V_{opt} = 0.5$

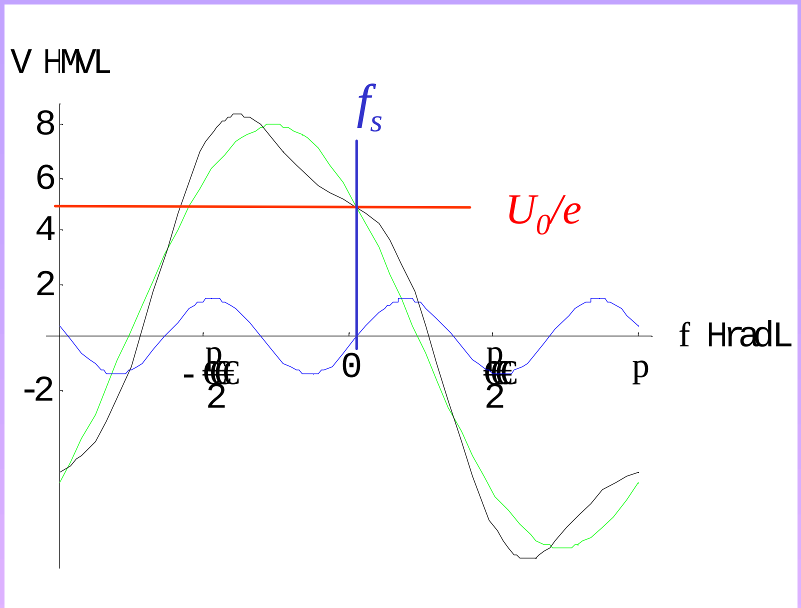


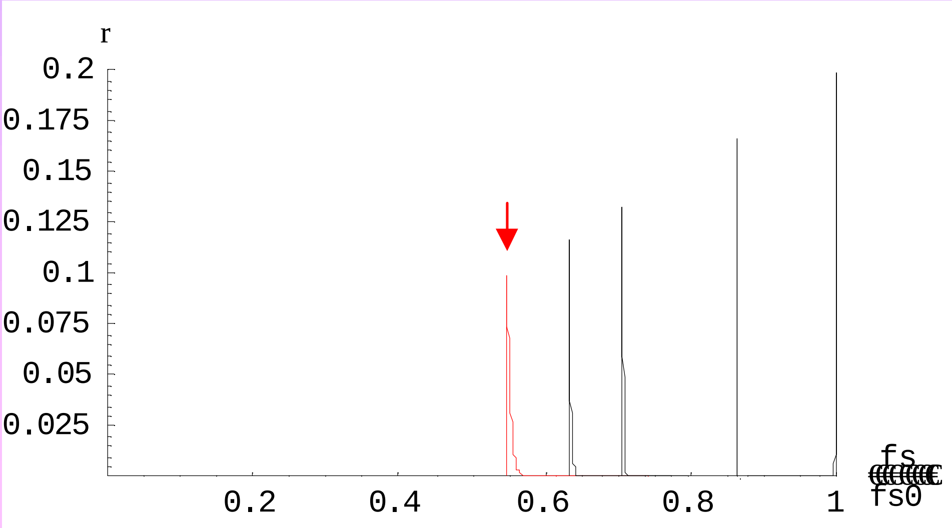




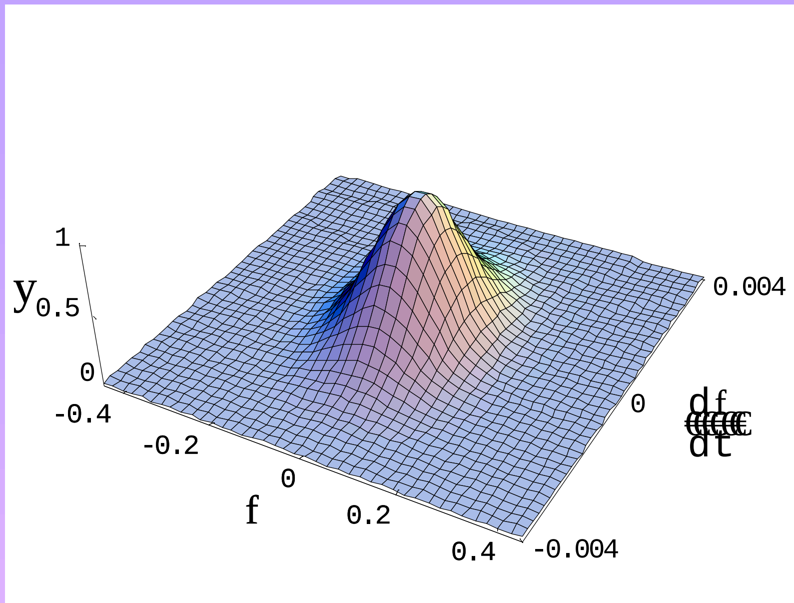
$V_{harm}/V_{opt} = 0.6$

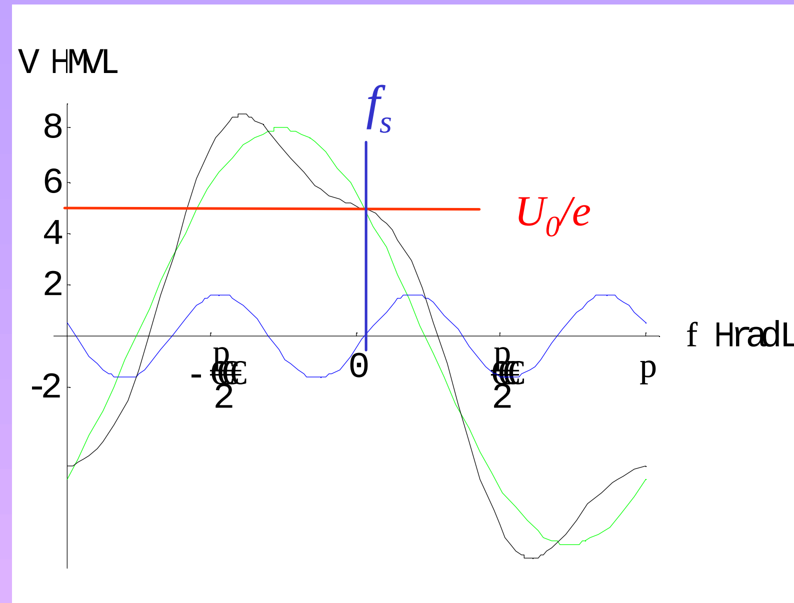


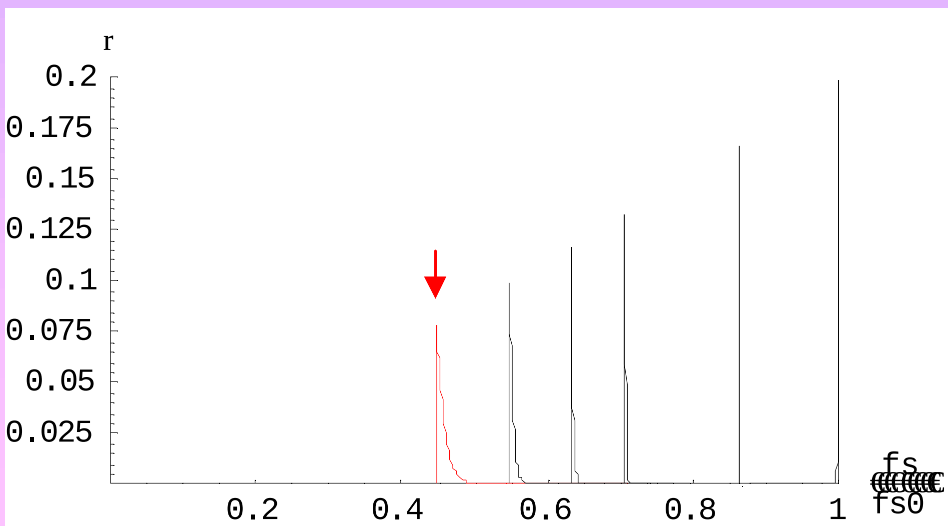




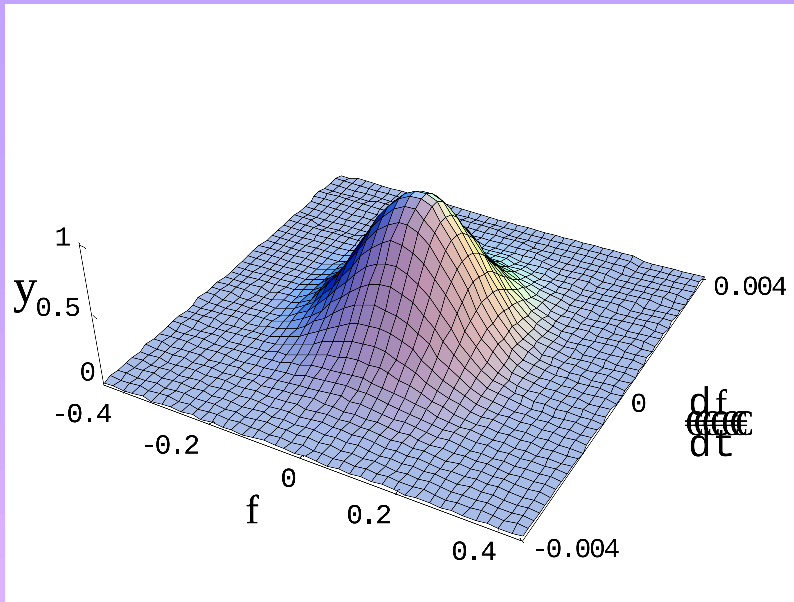
$V_{harm}/V_{opt} = 0.7$

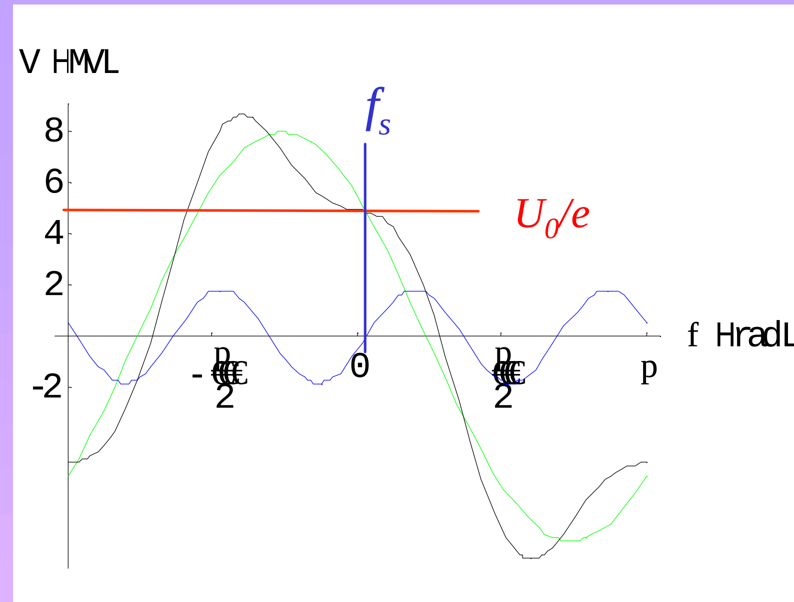


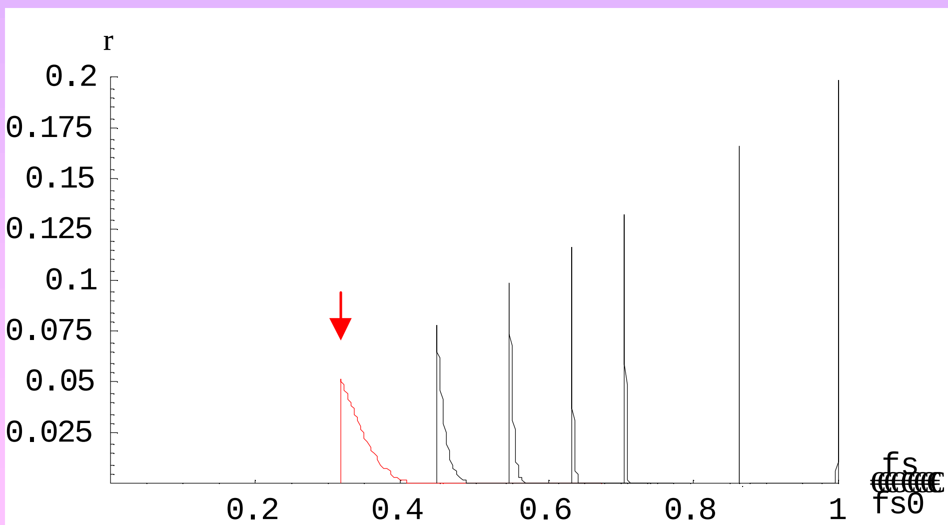




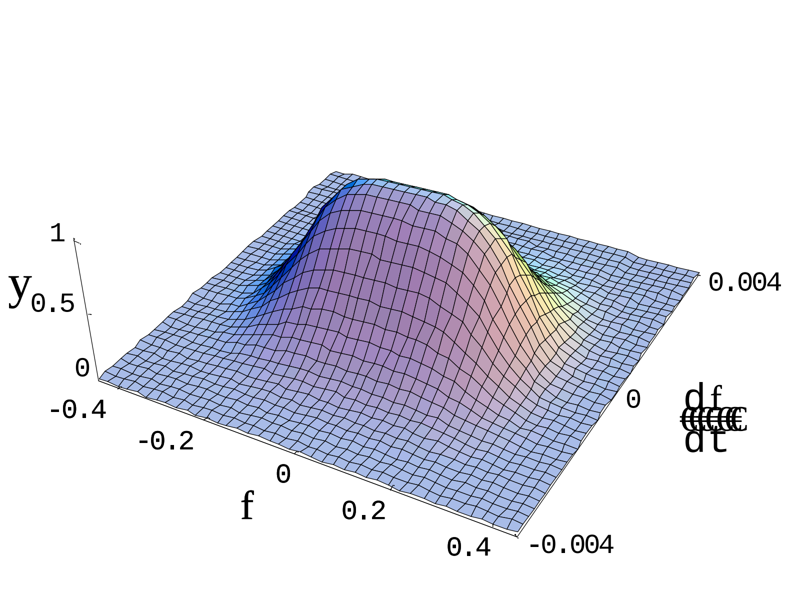
$V_{harm}/V_{opt} = 0.8$

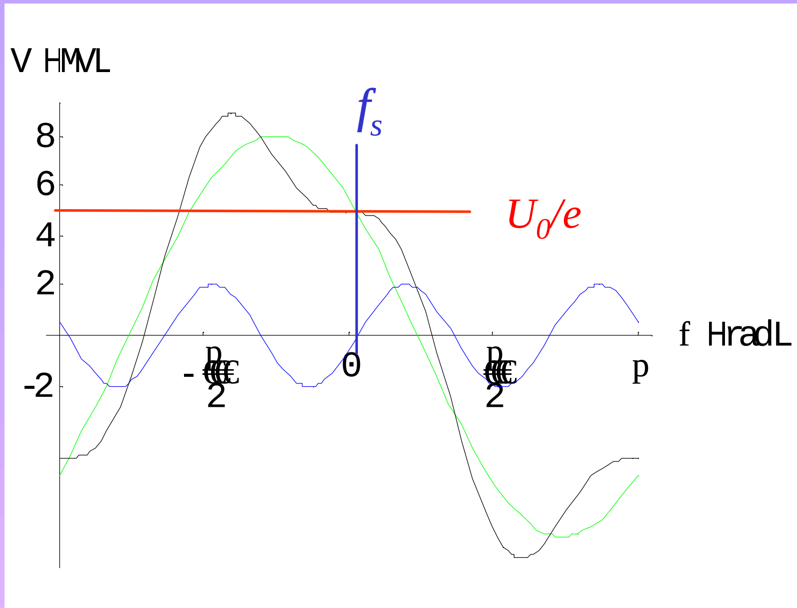


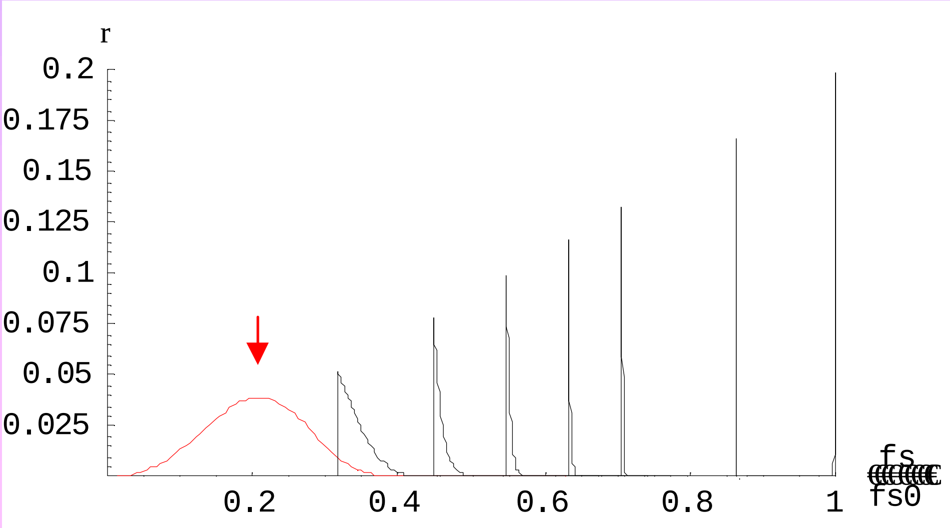




$V_{harm}/V_{opt} = 0.9$

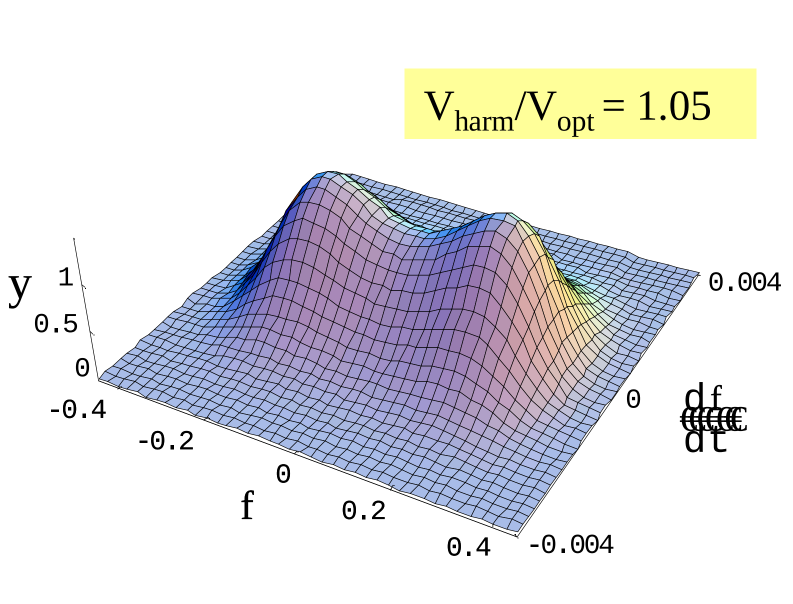


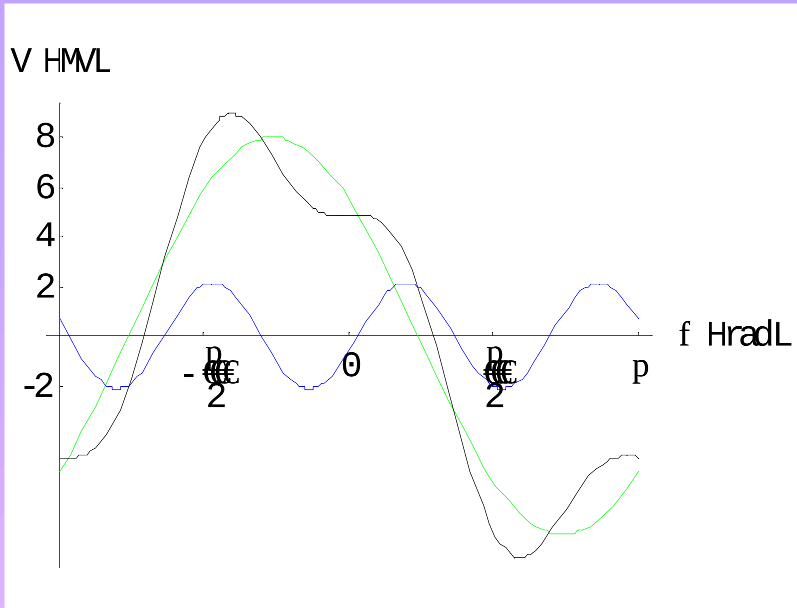




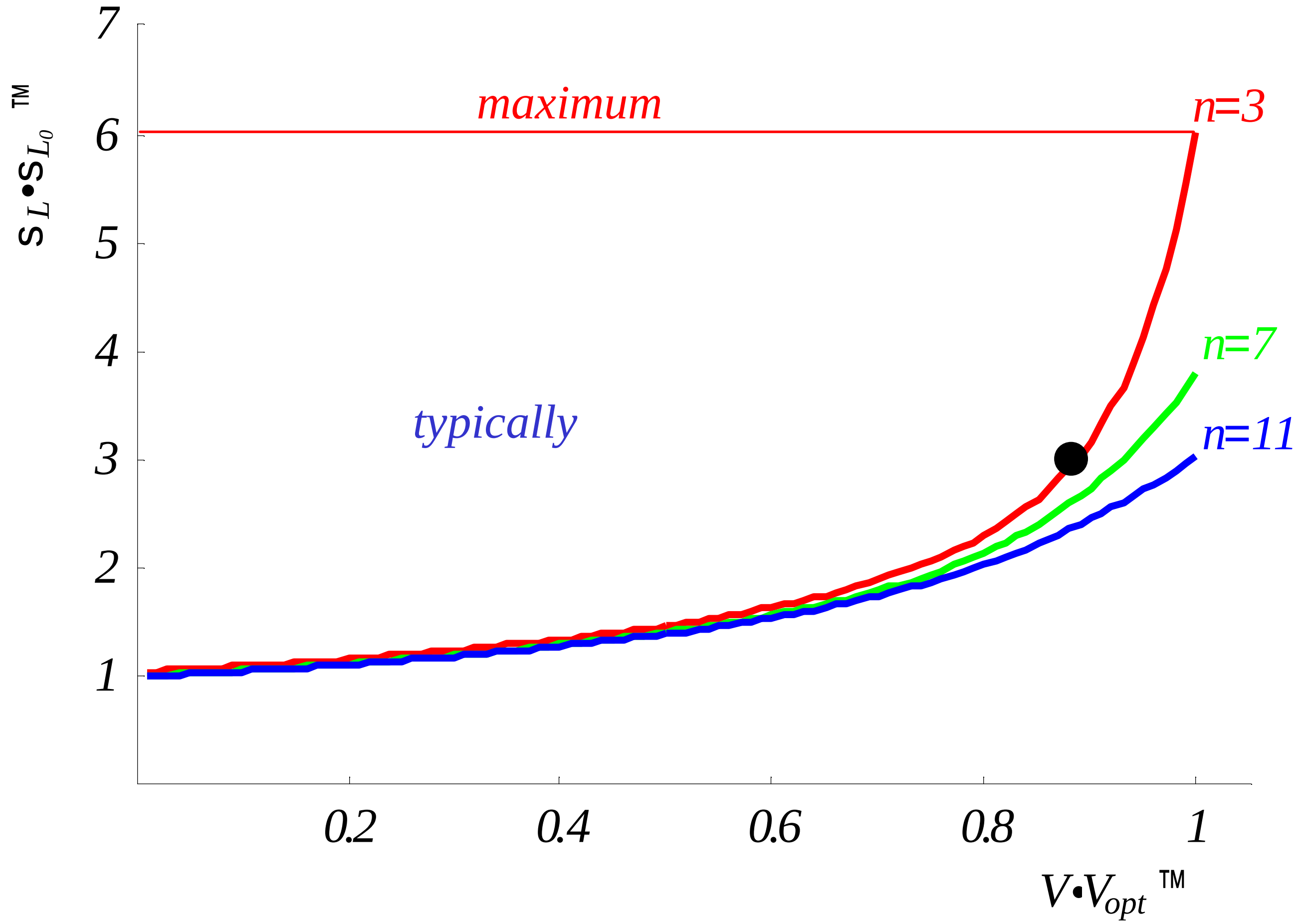
$V_{harm}/V_{opt} = 1$

[A. Hofmann & S. Myers]





Over stretching => formation of two bunches



7
6
5
4
3
2
1
maximum
n=3
n=7
n=11
typically
0.2
0.4
0.6
0.8
1

NC passive harmonic cavities

- The beam drives V_{harm}

  => multibunch operation ($I_{beam} > I_{minimum}$)

  => V_{harm} controlled by Cavity tuning (*typ.:* $f_{harm} » n\, f_{RF} + f_0/3$)

  => $f_{harm} = f_{opt}$ only possible at one current

- MAX II: E_{max} = 1.5 GeV, I_{beam} = 250 mA ->100 … 70 mA

  f_{RF} = 500 MHz 4 copper pillbox HC's, $f_{harm} = 3\, f_{RF}$, 2 tuners

  Achievements:

  œ t_{Life} doubled (I x t_{Life}: 3 Ah ® 5…6 Ah)

  œ Landau damping of multibunch instabilities (not fully stable):

  œ *Energy spread:* 0.7 x 10^{-3} for $I_{beam} = 0$

  4…5 x 10^{-3} at nominal Ibeam for $V_{harm} = 0$

  1.1 x 10^{-3} with Landau damping

[Å. Andersson, M. Georgsson et al.]

NC passive harmonic cavities *(continued)*

- ALS: E_{max} *= 1.9 GeV,* I_{beam} *= 400 mA ® 200 mA, LFB & TFB*

f_{RF} *= 500 MHz* 5 Cu reentrant HC's, f_{harm} = 3 f_{RF} / 2 tuners, HOM absorber

Achievements:

œ in experiment: t_{Life} increase by factor *2.5* (t_{Life}*: 4 h ® 10 h)*

t_{Length}*: 55 ® 120 ps,* f_s*: 11.5 ® 5 kHz*

→ LFB f_s filter (now *4 kHz)* limits $Dt_{Length\text{-}max}$

œ in operation: *50%* increase in t_{Life}*® 6 h (2 cavities tuned in)*

œ no energy spread => detuning of HC-HOM *(TM011 at ALS)*

Problems:

œ Users require 20 % gap in filling → transient beam loading

→ strong beam and Voltage *f* modulation

→ less average bunch lengthening

→ TFB: heterodyne → homodyne receiver: solved the problem

→ LFB: f_s modulation → factor 6 at 3 GHz detection frequency

→ feedback saturates if $|D\, f_s|$ >15° *[J. Byrd et al.]*

NC passive harmonic cavities *(continued)*

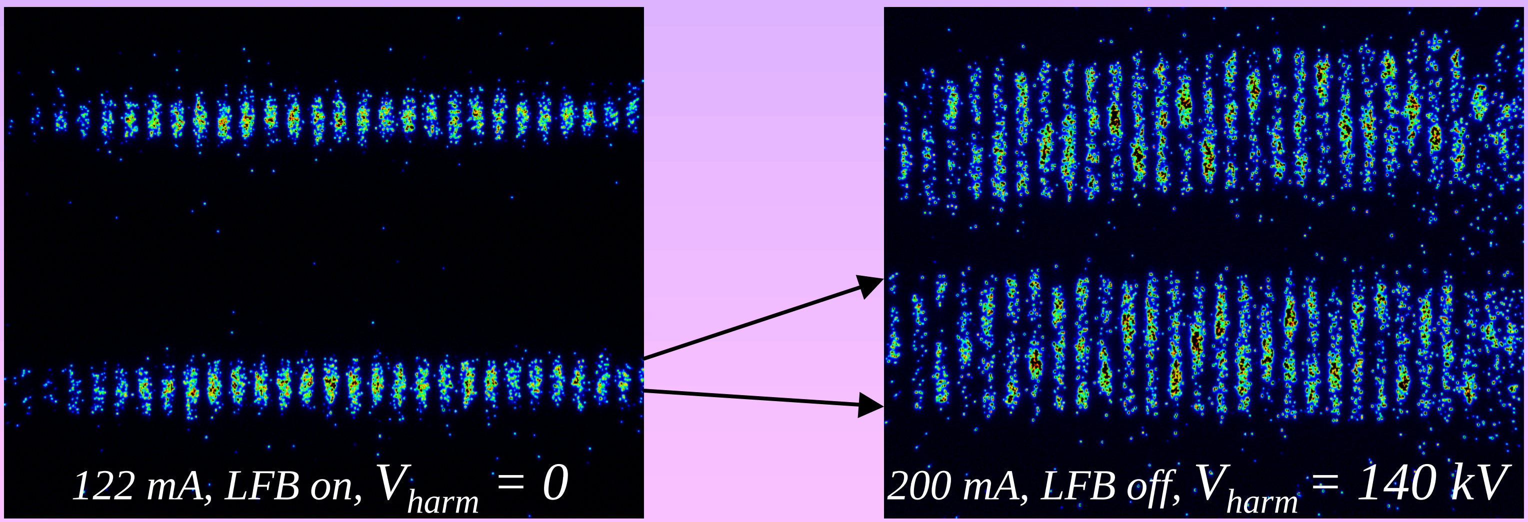
- BESSY II: E_{max} = 1.9 GeV, I_{beam} = 220 mA, LFB & TFB

  f_{RF} = 500 MHz — 4 Cu Pillbox HC's, f_{harm}= 3 f_{RF} / 2 tuners

  Achievements (still in commissioning):

  œ t_{Life}: 3.2 h ® 5.2 h at 200 mA

  œ t_{Length}: increase by factor 2.5 to 3

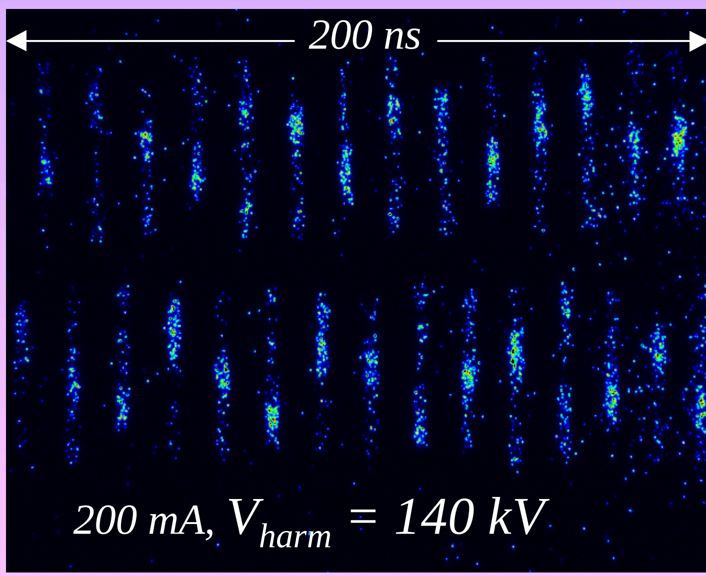


Streak Camera: same time scale, V_{acc} = 1 MV

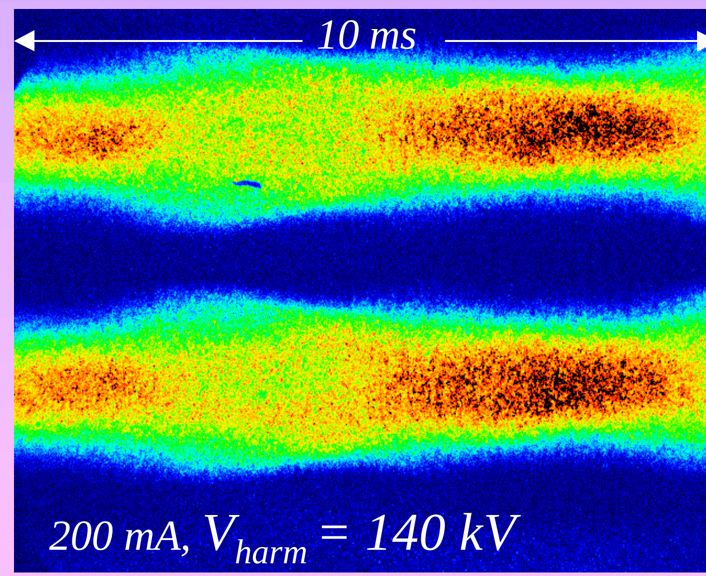
[W. Anders et al.]

NC passive harmonic cavities *(continued)*

- BESSY II:
  - œ TFB: operational
  - œ LFB: not yet compatible (filter bandwidth)
  - œ Phase transients with gap: max 50°
  - œ HOM problems still present:



Coupled bunch mode
with some bunch shape oscillation

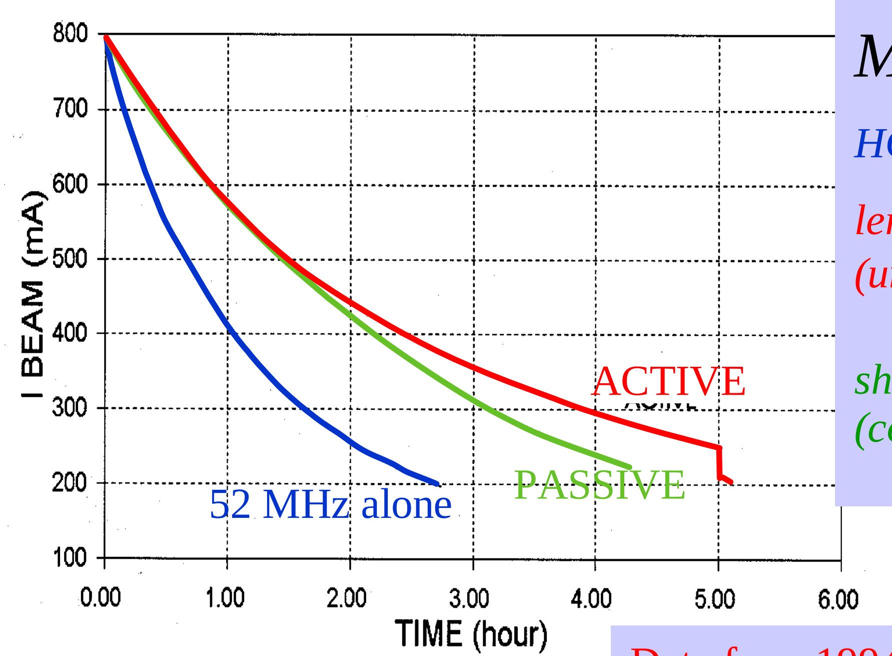


Relaxation effect, Period = *6 ms*

[W. Anders et al.]

NC active harmonic cavities

- NSLS VUV: $E = 0.8\ GeV$ $f_{RF} = 52.9\ MHz$, $f_{harm} = 4\ f_{RF}$
  - œ Operation alternatively in bunch *lengthening* or *shortening* mode
  - œ Powered cavities allow operation near V_{opt}, f_{opt} for any I_{beam}
  - œ No Beam power



Data from 1994

Latest Figures:

Mode	I_{beam}	t_{Length}	t_{Life}
HC detuned	*700 mA*	*0.9 ns*	*2.5 h*
lengthened	*700 mA*	*1.7 …2 ns*	*4 h*
(unstable above 700 mA ® nominal 1 A)			
shortened	*600 mA*	*0.48 ns*	*2 h*
(constant length)			

[S. L. Kramer, N. Towne et al.]

NC active harmonic cavities *(continued)*

- NSLS VUV / Slow tuning, amplitude and phase feedback

Principle using a *Complex Phasor Modulator:*

œ Voltage error signal ® *real part a_r regulated to "zero" by tuning*

=> f_{harm} = -90° (and not f_{opt} » -93°)

œ In *lengthening*, phase error signal from beam PU ® *imaginary part a_i*

(at f_{harm} » f_{opt} , due to flat RF potential® GAIN f_{beam}/ f_{Vcav} » -4.5)

œ In *shortening*, phase error signal from cavity ® *imaginary part a_i*

a_r + j a_i amplified and fed to the cavity

œ System can be switched to standard tuning for *passive* operation

œ Stable operation in *shortening* mode difficult (high beam loading)

® *constant bunch length, but limited to 600 mA*

[S. L. Kramer, N. Towne et al.]

NC active harmonic cavities *(continued)*

- NSLS VUV / Observed related instabilities:

œ *Lengthening* mode: Landau Damping of coupled bunch instabilities

œ Injection: partially stretched mode => needs LFB

œ Occurrence of *non-rigid bunch instabilities* in particular if over-stretched:

® *chaotic appearance of broad, strong sidebands*

® *beam lost if high I_{beam}*

œ For nearly *optimum lengthening*: peak beam response at *1.1* f_{s0} to *1.4* f_{s0}

® *insensitive to Ibeam, Cavity tuning*

® *sensitive to V_{harm}*

[S. L. Kramer, N. Towne et al.]

NC active harmonic cavities *(continued)*

- NSLS VUV: Stretched bunch shapes = *f(small variations of RF potential)*

3 Reasons:

œ Shape very sensitive to ϕ_{harm} near V_{opt}, f_{opt}

œ Gap in filling against ion trapping:

® *Phase transients*

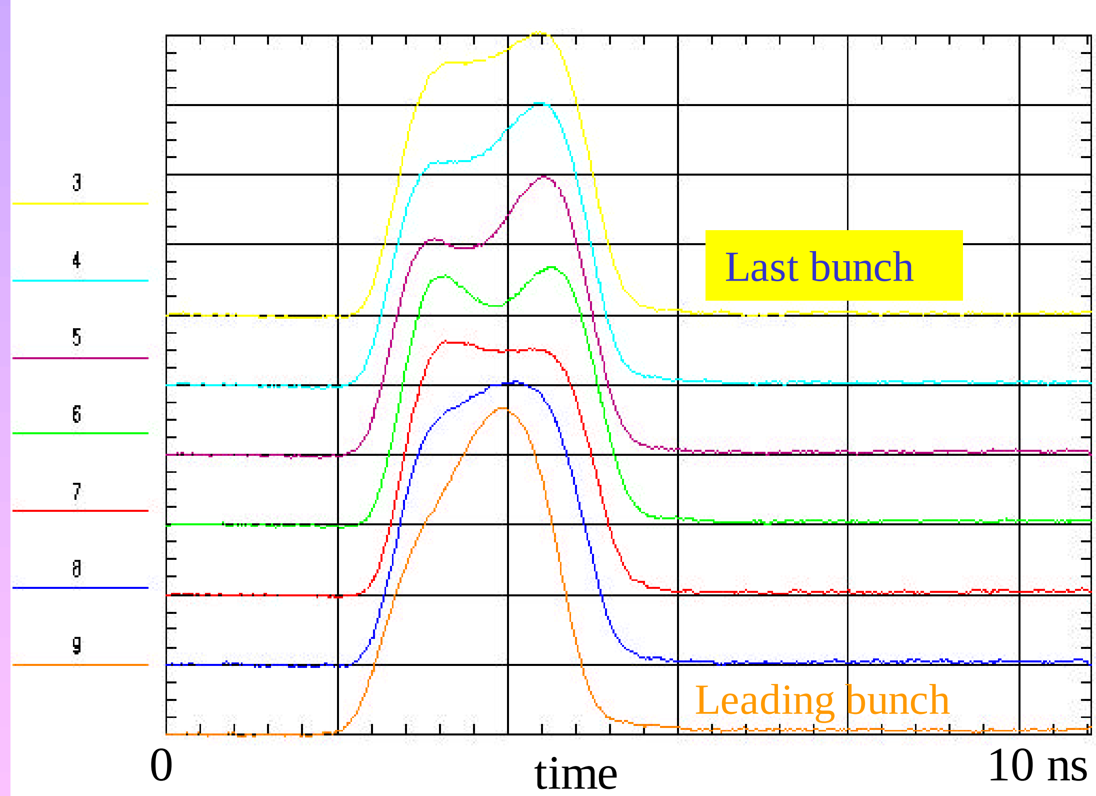
œ Gap in filling:

® additional revolution harmonics

® excite HOMs

® *different potential distortion for different bunches*

7 / 9 bunches filled, I_{beam} = 1000 mA



[N. Towne]

NC active harmonic cavities *(continued)*

- Super ACO: *$E = 0.8$ GeV* $f_{RF} = 100$ *MHz,* $f_{harm} = 5 f_{RF}$

Bunch shortening for FEL operation and time resolved experiments

œ Shortening by a factor *up to 3.5* achieved *(f_s: 14 ® 40 kHz)*

New types of instabilities observed:

œ Vertical single bunch instability at *10 mA/bunch:* no sensitivity to n_z , x_z , V_{harm}

œ Vertical TMCI starting at *30 mA, m=0* and *-1* modes merging at 40 mA: cured by high x_z: +2.5 ® 4

œ Interference between 2 longitudinal single bunch oscillations

– Low frequency sawtooth oscillations (< 300 Hz), at any current

– High frequency oscillations at mainly f_s and 2 f_s , only between 2 and 8 mA/bunch

[G. Flynn et al.]

Bunch lengthening mode:

® Landau damping of LCBI

® expected Robinson^{II} instability ?

[M.P. Level, M. Georgsson, et al.]

SC passive cavities

- Elettra, SLS, ... collaboration project with CEA-Saclay
  (2 GeV) (2.4 GeV) *f_{RF} = 500 MHz, f_{harm} = 1500 MHz*
  - ® HOM free harmonic cavities = scaling of 352.2 MHz SOLEIL cavities (pair of cavities within a single cryostat)
  - ® Tuning angle *y* » *90°* => *P_{beam}* » *0*, and as for NSLS: *f_{harm}* » *90°*
  - ® Simple amplitude control by frequency tuning such as:

$$V_{harm} \text{ » } I_{beam} \text{ (R/Q) } f_{harm} / \text{ đ}f_{harm}$$

  - ® Expected *Bunch lengthening* by a *factor 4* ($V_{harm} < V_{opt}$)
  - ® Passive operation down to very low currents,
  - ® However, possible Robinson instability on *m f_s* for low đf_{harm} at low I_{beam}
  - ® Phase transients also expected with SC cavities

[P. Marchand, M. Svandrlik, A. Mosnier et al.]

® *[J. Byrd]*

- SRRC: abandon NC harmonic cavities ® required space, HOMs,…
  - ® Feasibility study for SC harmonic cavities

[K.T. Hsu]

Harmonic Cavity for the ESRF ?

f_{RF} = 352.2 MHz, Example: $f_{harm} = 3\, f_{RF}$

Reason for an HC ?

Operation modes:

- Multibunch at *200 mA,* x_v = *0.4 to 0.5* t_{Life} = *60 ... 70 h* => *NO*
- 16 bunch at 90 mA (5.5 mA/b): x_v = *0.6* t_{Life} = *12 h* => *yes*
- Single bunch at 15 mA: x_v = *0.9* t_{Life} = *4 h* => *yes*

- Optimistic assumption *Lengthening factor 6:*

Current per bunch	10 mA	15 mA	25 mA
Lengthening factor from BBR only	3.6	4.2	5.4
Lengthening factor from BBR and 3rd harmonic cavity	6.2	6.6	7.6
Net gain in bunch length with a harmonic cavity	+ 72 %	+ 57 %	+ 41 %

Longer bunches

↓

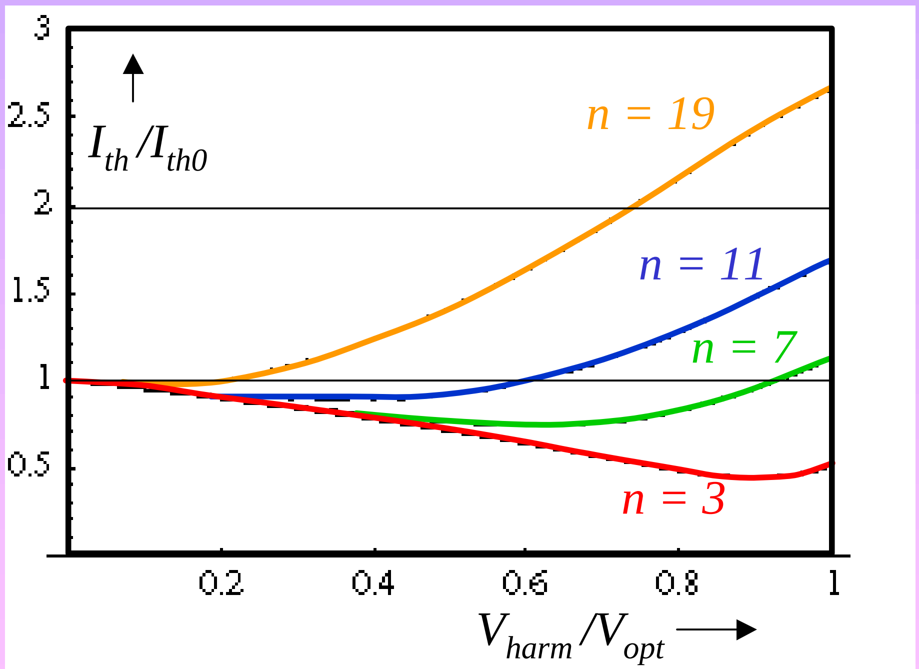
lower *x*

↓

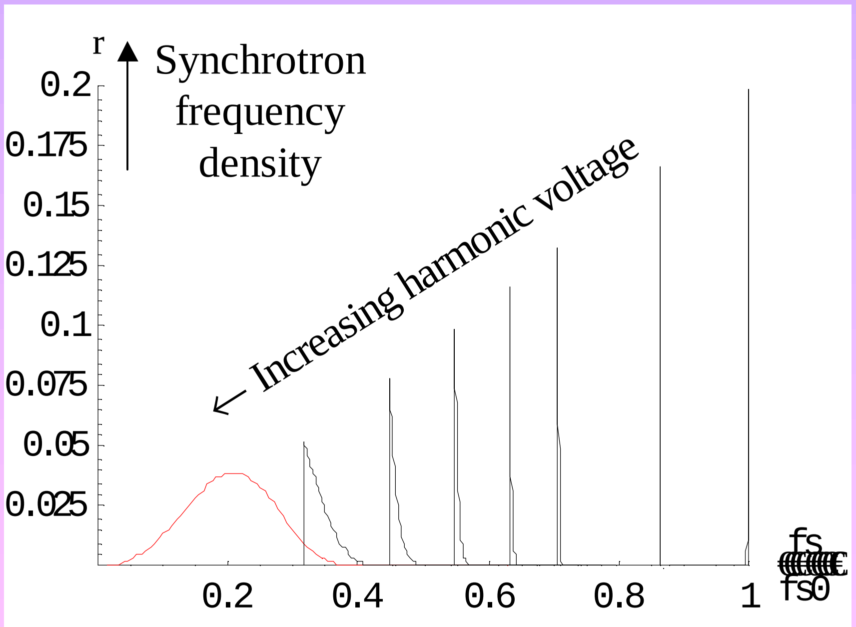
more gain in t_{Life} *than from* Dt_{Length}

Harmonic Cavity for the ESRF ? *(continued)*

- Tracking simulations® unchanged energy spread with HC / µ-wave instability
- More sensitive to HOM driven Longitudinal Coupled Bunch Instabilities:



LCBI threshold with a harmonic cavity



Harmonic cavities: Pros & cons

Points of debate for the subsequent working group discussions

Effects in bunch lengthening:	*Consequences:*	*Pros / Cons*
• Longer bunches: $\Delta\tau_{Length}$	® Especially low energy machines or high I/bunch: gain in Lifetime	+
• Less spectral width of beam signals	® Probing less of the BBR: Þ Less prone to transverse single bunch head tail instability ?	+
	® Less HOM losses: Þ Reduced heating in few bunch operation	+
• RF slope ® zero: Phase sensitivity	® Gap induced Phase transients NC & SC (increased by HOMs) ⇒ Reduced gain in Lifetime	-
	® TFB must be adapted	o
	® LFB saturation	-

Harmonic cavities: Pros & cons, *(continued)*

Effects in bunch lengthening:	*Consequences:*	*Pro / Con*
• Difficult to control V_{opt}, f_{opt}	® limited bunch lengthening	-
	® Over-stretching Þ non rigid bunch instability (NSLS)	-
• RF slope ® zero: Smaller f_s	® Single bunch fast head tail (TMCI) : lower threshold ? [S.Myers, Y.C. Chin, CERN]	-
	® LCBI: lower thresholds	-
	® More sensitivity to low frequency noise / power supplies	-
• Distorted RF potential: Spread of f_s	® Landau damping for: LCBI, TMCI ?, transverse instabilities with m ≠ 0 ?	+
• More impedance (BBR, HOM)	® Bad for all kind of instabilities	-
	® Robinson stability to be checked	o

Harmonic cavities: Pros & cons, *(continued)*

Resistive wall instability:

œ Smaller spectral width ® less chromaticity needed to shift the modes | +

or

œ Less overlap with BBR ® *less damping ?* | -

Operation in bunch shortening:

œ NSLS: current limited by slow RF feedback stability

œ Super ACO: new types of instabilities ® deserve further investigations

œ No experience from low emittance machines

Conclusion

NC passive harmonic cavities:

- œ sufficient voltage for low or medium energy machines /multibunch operation
- œ tuning not easy to handle for simultaneous *Voltage* and *HOM* control
- œ operate mostly *below* V_{opt}
- œ Gain in *Lifetime* by typically a *factor 2 to 2.5* => good for these machines !

NC active harmonic cavities:

- œ allow operation at low current (e.g. single bunch operation)
- œ operation in bunch shortening demonstrated

SC HOM free harmonic cavities:

- œ only way for high energy machines , where interest is mainly for high I/bunch
- œ no major problems with HC HOMs, Robinson, …
- œ tuning should be easier
- œ still needs R&D to check performance, reliability and operational costs

Transient beam loading and Beam instability issues with Harmonic cavities:
® good candidates for extensive discussions in this workshop