CSR-Driven Longitudinal Single Bunch Instability Thresholds

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IPAC’13, Shanghai, China

I. Theoretical Predictions
- I.1 Vlasov-Fokker-Planck Equation
- I.2 Instability Driven by Resistive Impedance
- I.2 Instability Driven by Broad-Band-Resonator
- I.3 CSR-Driven Instability

II. Experimental Observations

Comparison of Threshold Currents:
- II.1 MLS
- II.2 Similarity Between Resistive and CSR-wake
- II.3 Threshold Determination
- II.4 BESSY II

III. Summary

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N>10^9 electrons per bunch → smooth distribution in phase space
→ distribution function:

$$f(q, p, \tau)$$

$$q = z / \sigma_z$$

$$p = -\Delta E / \sigma_E$$

$$\tau = \omega_s t$$

$$\frac{\partial f}{\partial \tau} + p \frac{\partial f}{\partial q} - [q + F_c(q, \tau, f)] \frac{\partial f}{\partial p} = \frac{2}{\omega_s t_l} \frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p} \right)$$

(M. Venturini)

RF focusing — Collective Force — Damping — Quantum Excitation

→ Numerical solution based on
M. Venturini, et al., Phys. Rev. ST-AB 8, 014202 (2005)
Other numerical solutions:
R.L. Warnock, J.A. Ellison, SLAC-PUB-8404, March 2000
S. Novokhatski, EPAC 2000 and SLAC-PUB-11251, May 2005

original VFP-equation:

$$\frac{\partial f}{\partial \tau} + p\frac{\partial f}{\partial q} - \left[q + F_c(q,\tau,f)\right]\frac{\partial f}{\partial p} = \frac{2}{\omega_s t_l}\frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p}\right)$$

Ansatz – “wave function” approach: Distribution function, f, expressed as product of amplitude function, g:

$$f = g \cdot g$$

$$\frac{\partial g}{\partial \tau} + p\frac{\partial g}{\partial q} - \left[q + F_c(q,\tau,g^2)\right]\frac{\partial g}{\partial p} =$$

$$\frac{2}{\omega_s t_l}\left(\frac{g}{2} + p\frac{\partial g}{\partial p} + \frac{1}{g}\left(\frac{\partial g}{\partial p}\right)^2 + \frac{\partial^2 g}{\partial p^2}\right)$$

f >= 0 and solutions numerically more stable

Details on the simulations in my ICAP ‘12 contribution

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Simulations for 6 – 10 damping times, step size $\Delta=\sigma/20 \ldots \sigma/10$, time step ~ $2\pi/1024$. Over last 64 periods the line density is stored 64 times per period for analysis: FFT gives CSR-spectrum, and integrated spectral power is proportional to instantaneous CSR signal. FFT of this signal corresponds to observed signal.

Parameter	BESSY II	MLS
Energy, $\mathbf{E_0}$/**MeV**	1700	629
Bending radius, **ρ/m**	4.35	1.528
Momentum compaction, **α**	$7.3\ 10^{-4}$	$1.3\ 10^{-4}$
Cavity voltage, $\mathbf{V_{rf}}$/**kV**	1400	330
Accelerating frequency, $\boldsymbol{\omega_{rf}}$/**MHz**	2π 500	2π 500
Revolution time, $\mathbf{T_0}$/**ns**	800	160
Natural energy spread, $\boldsymbol{\sigma_E}$	$7.0\ 10^{-4}$	$4.36\ 10^{-4}$
Zero current bunch length, $\boldsymbol{\sigma_{0/}}$**ps**	10.53	1.549
Longitudinal damping time, $\boldsymbol{\tau_l}$/**ms**	8.0	11.1
Synchrotron frequency, $\boldsymbol{\omega_s}$/**kHz**	2π 7.7	2π 5.82
Height of the dipole chamber, ***2h/cm***	3.5	4.2

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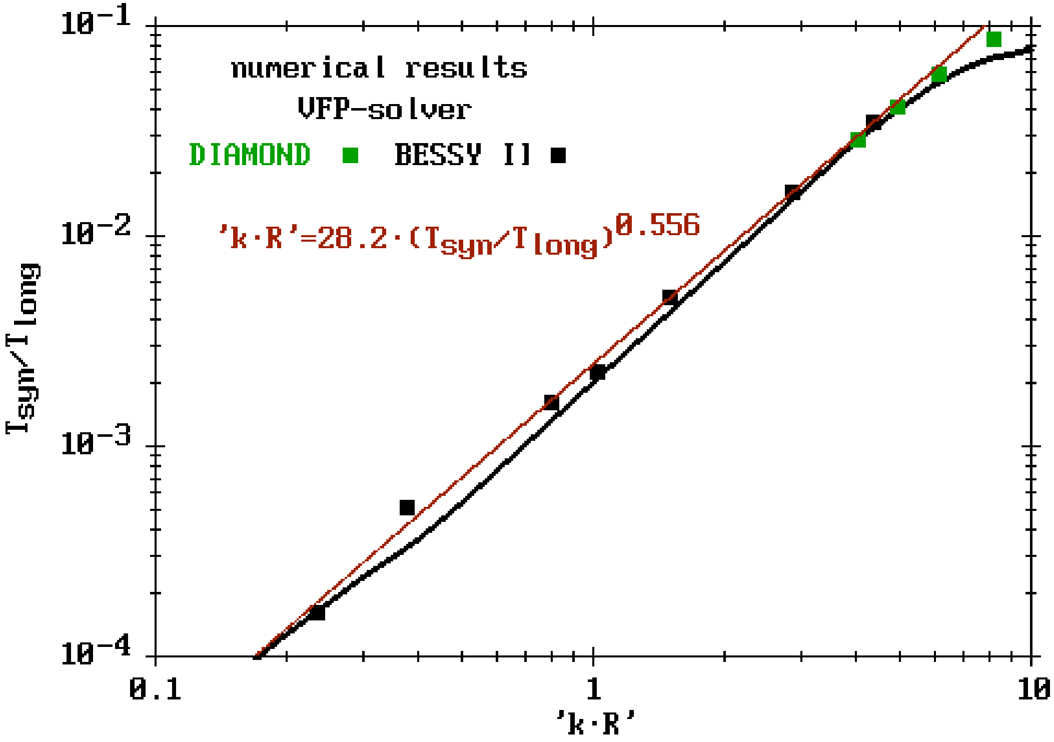
Weak instability theory by K. Oide, Part. Accel. **51**, 43 (1995) - black solid line
Numerical results for the Diamond Light Source (DLS) and BESSY II



DLS: V_{rf}=2, 4, 8, and 16 MV
BESSY II: V_{rf}=0.7, ... 14000 MV.

Oide's dimensionless parameter:

$$'k \cdot R' = \frac{I_{threshold}[A] \cdot R[\Omega] \cdot T_0[s]}{dV_{rf}/dt[V/s] \cdot \sigma_0^2[s]}$$

weak instability –
damping time matters

$$I_{threshold}(\sigma_0 = const) \propto \sqrt{dV_{rf}/dt}$$

I.3 Results for BBR-Wake

$$S_{BBR} = \frac{2Nr_e}{\gamma c Z_0 \nu_s \sigma_\varepsilon} \cdot \frac{2\pi F_{res} R_s}{Q}$$

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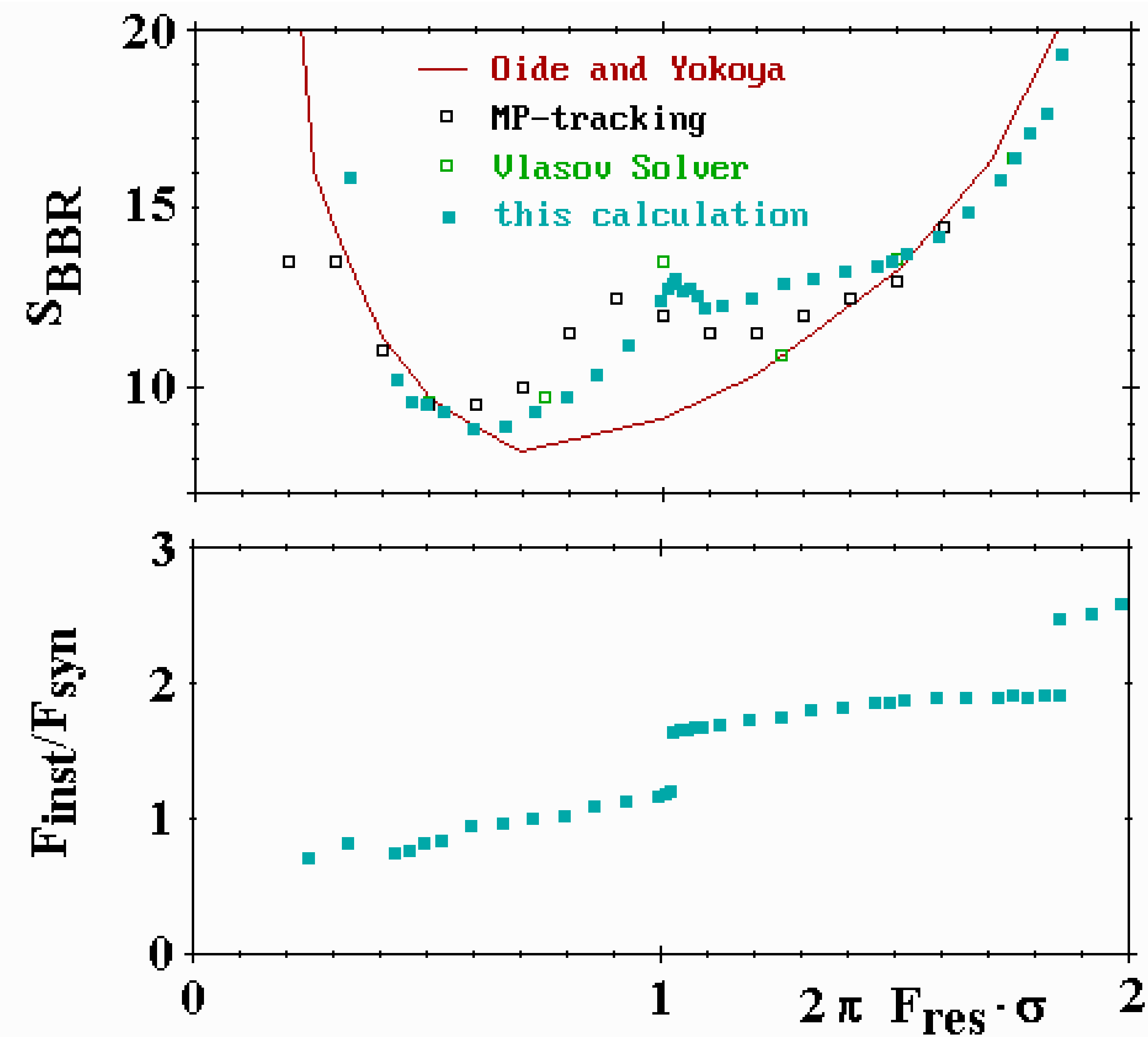

K. Oide, K. Yokoya, „Longitudinal Single-Bunch Instability in Electron Storage Rings“, KEK Preprint 90-10, April 1990

K.L.F. Bane, et al., „Comparison of Simulation Codes for Microwave Instability in Bunched Beams“, IPAC'10, Kyoto, Japan and references there in

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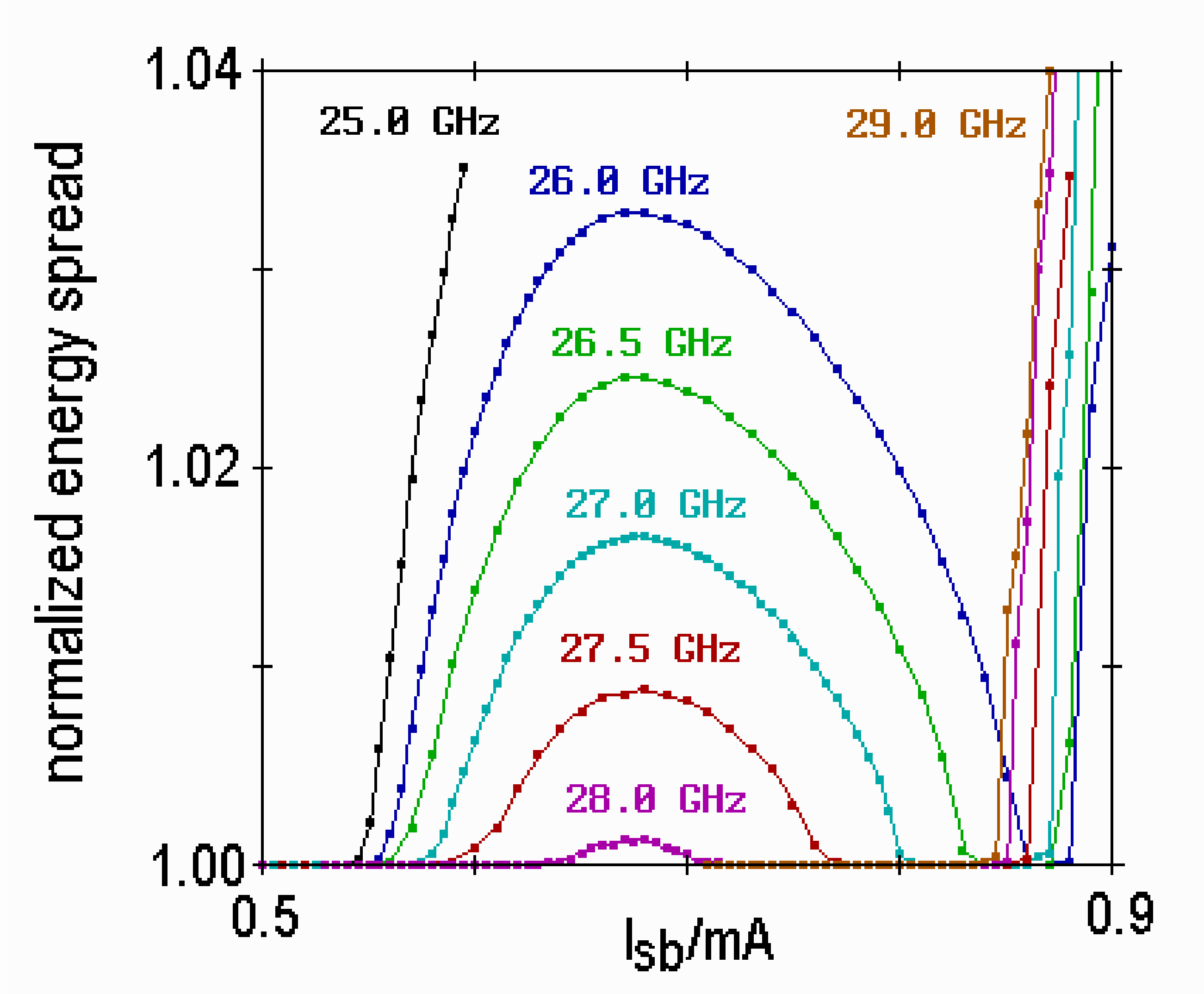

$2\pi \cdot 27\ \mathrm{GHz} \cdot \sigma_0 \sim 1.8$

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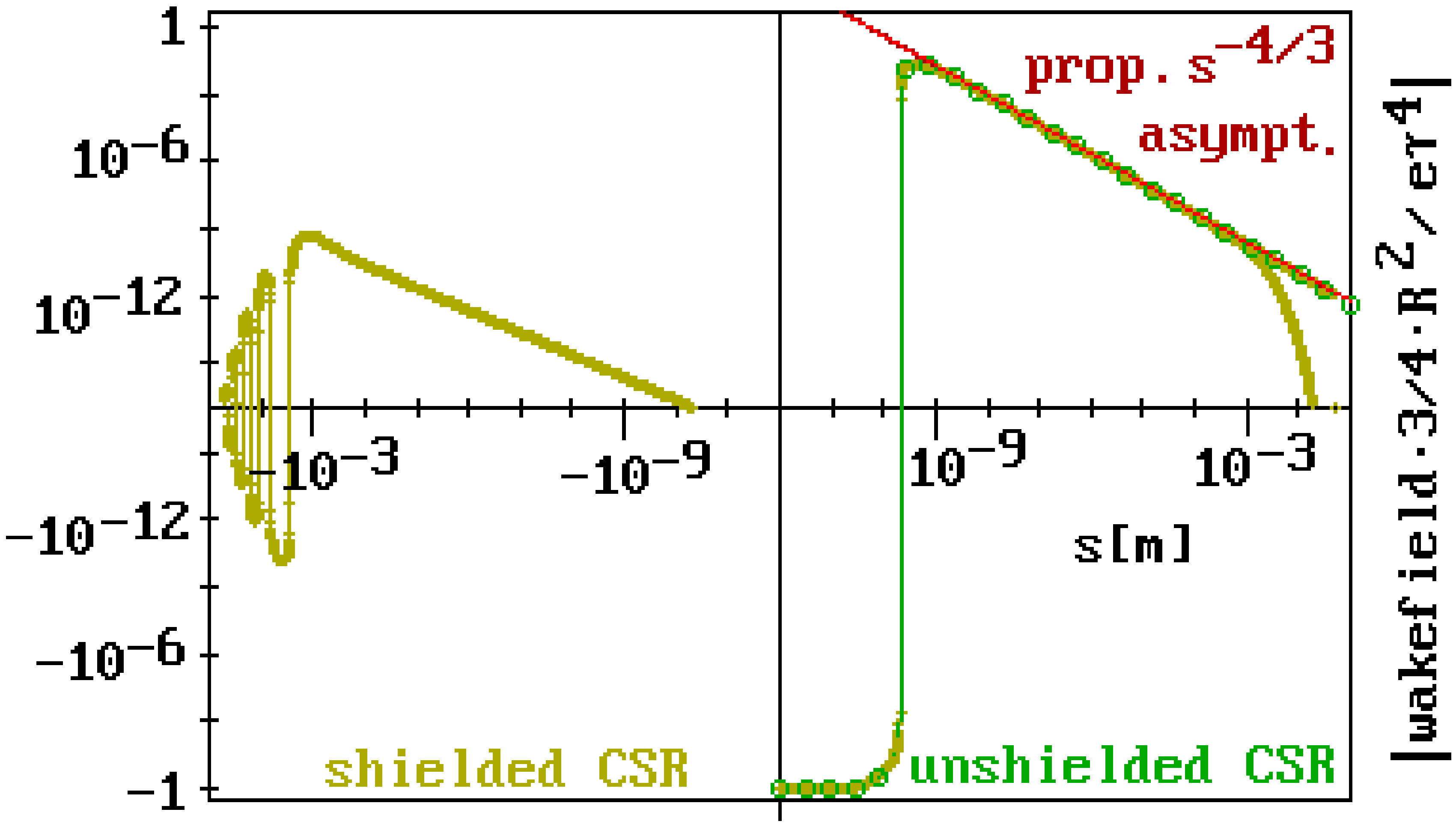
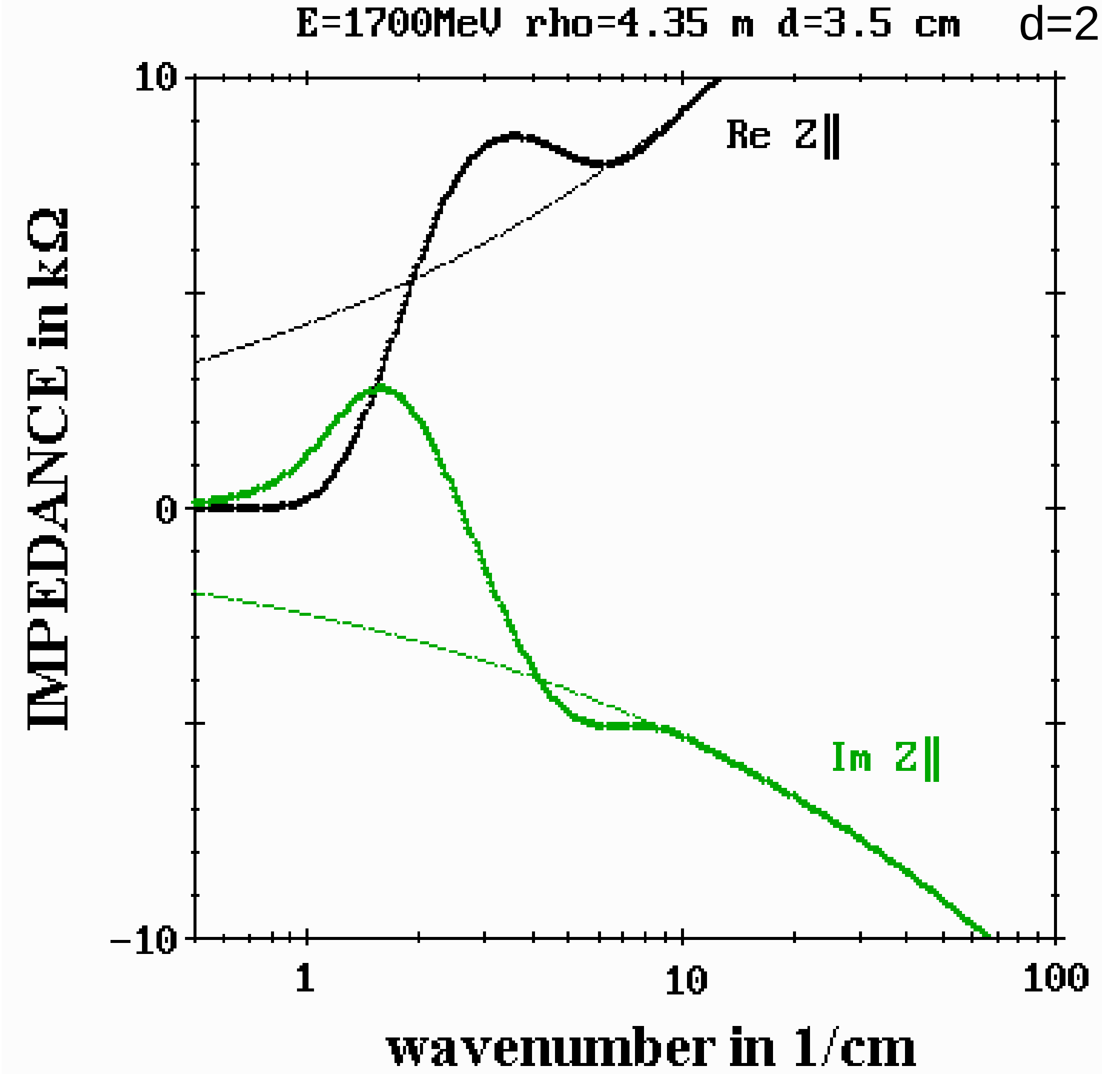
J. B. Murphy, et al., Part. Acc. 1997, Vol. 57, pp 9-64



tail head



d=2h, plate separation

Broad band resonator with low Q:

$$F_{res} = c\sqrt{\pi / 24}\,\rho^{1/2} h^{-3/2}$$

BESSY II: F_{res} ~ 100 GHz

MLS: F_{res} ~ 44 GHz

R.L. Warnock, PAC'91, PAC1991_1824, http://www.JACoW.org

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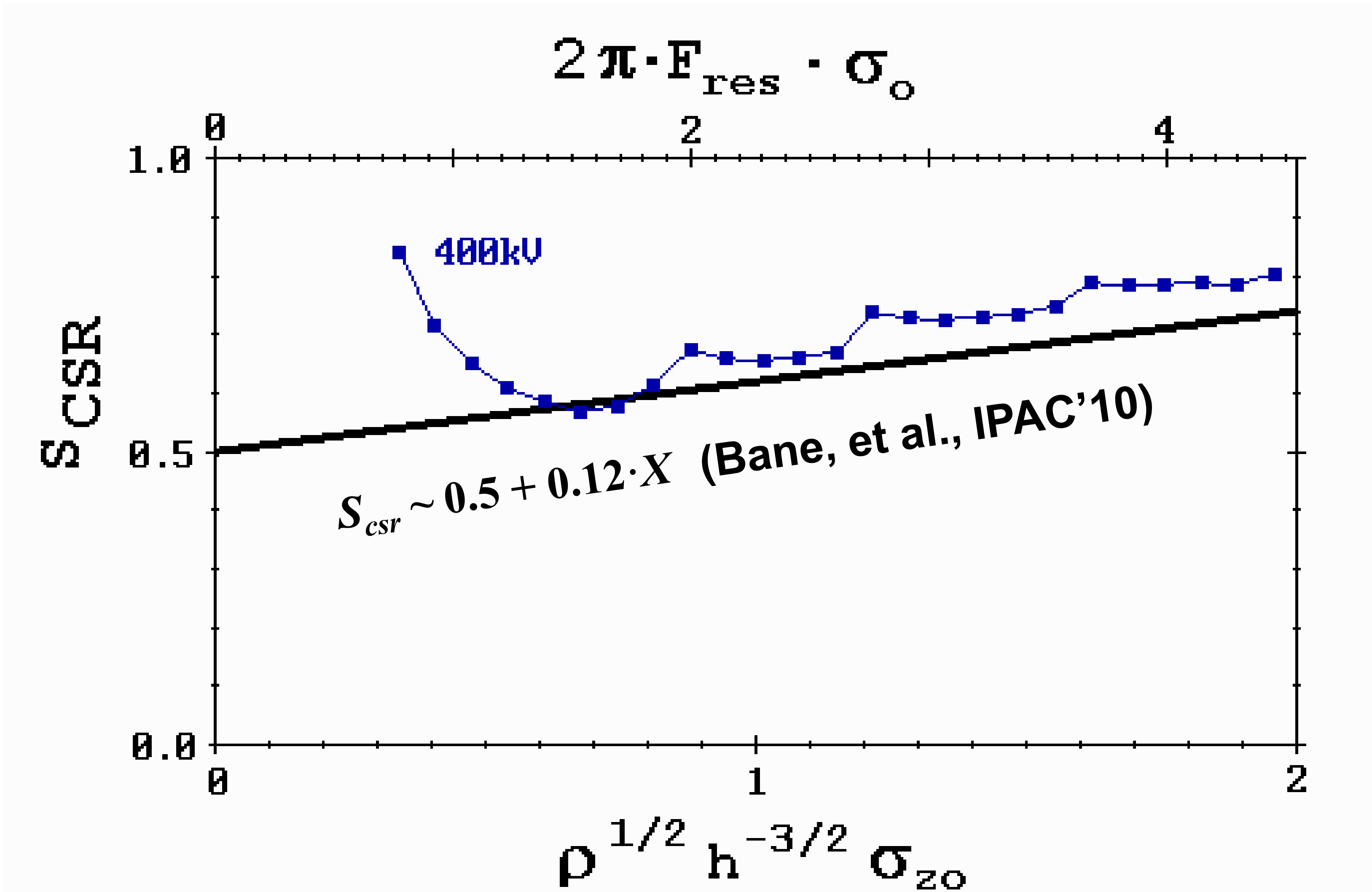
$$S_{csr} = \frac{Nr_e}{2\pi\nu_s\gamma\sigma_\varepsilon}\cdot\rho^{1/3}(c\sigma_0)^{-4/3} \qquad F_{res} = c\sqrt{\pi/24}\,\rho^{1/2}h^{-3/2}$$



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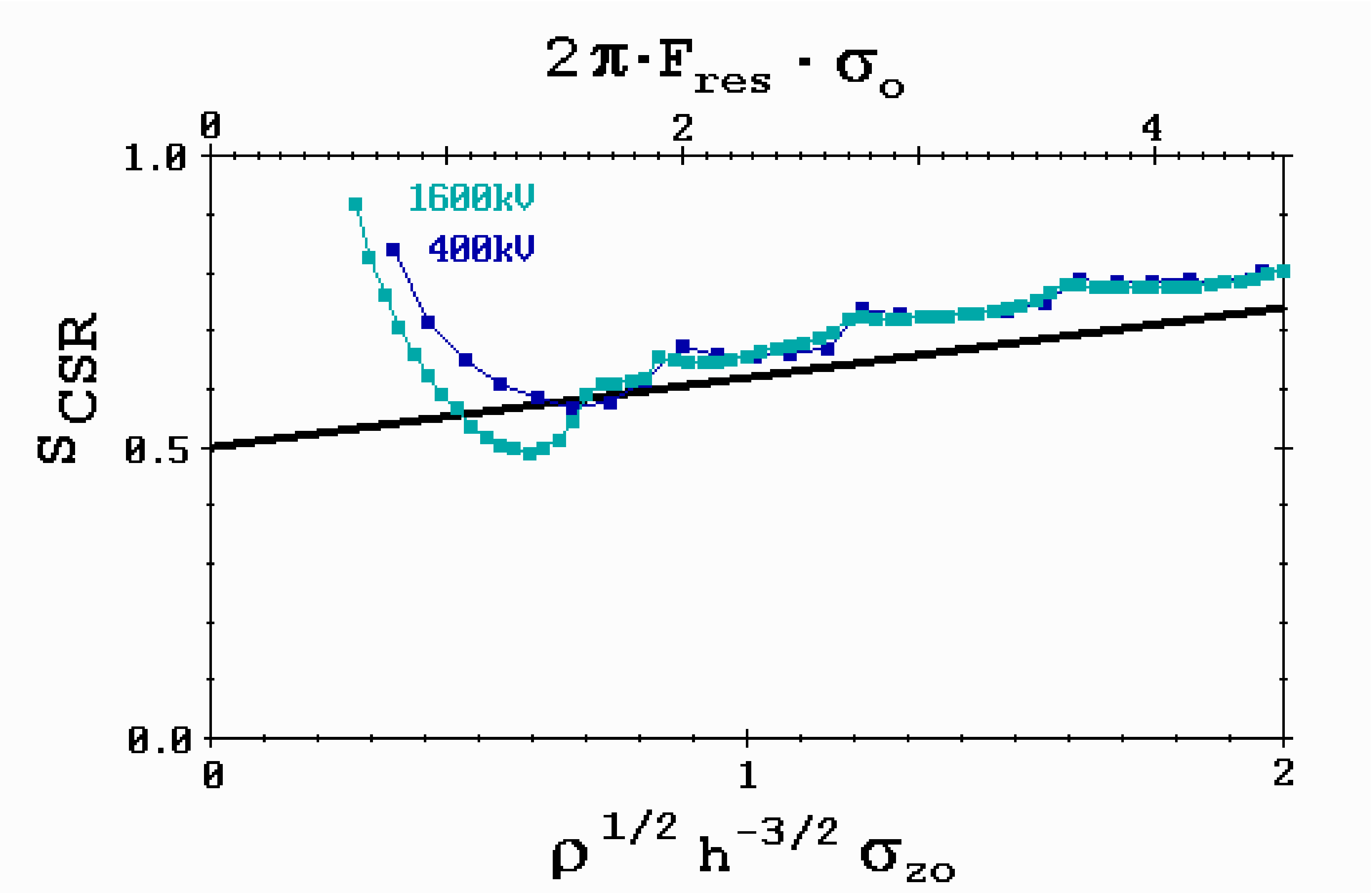

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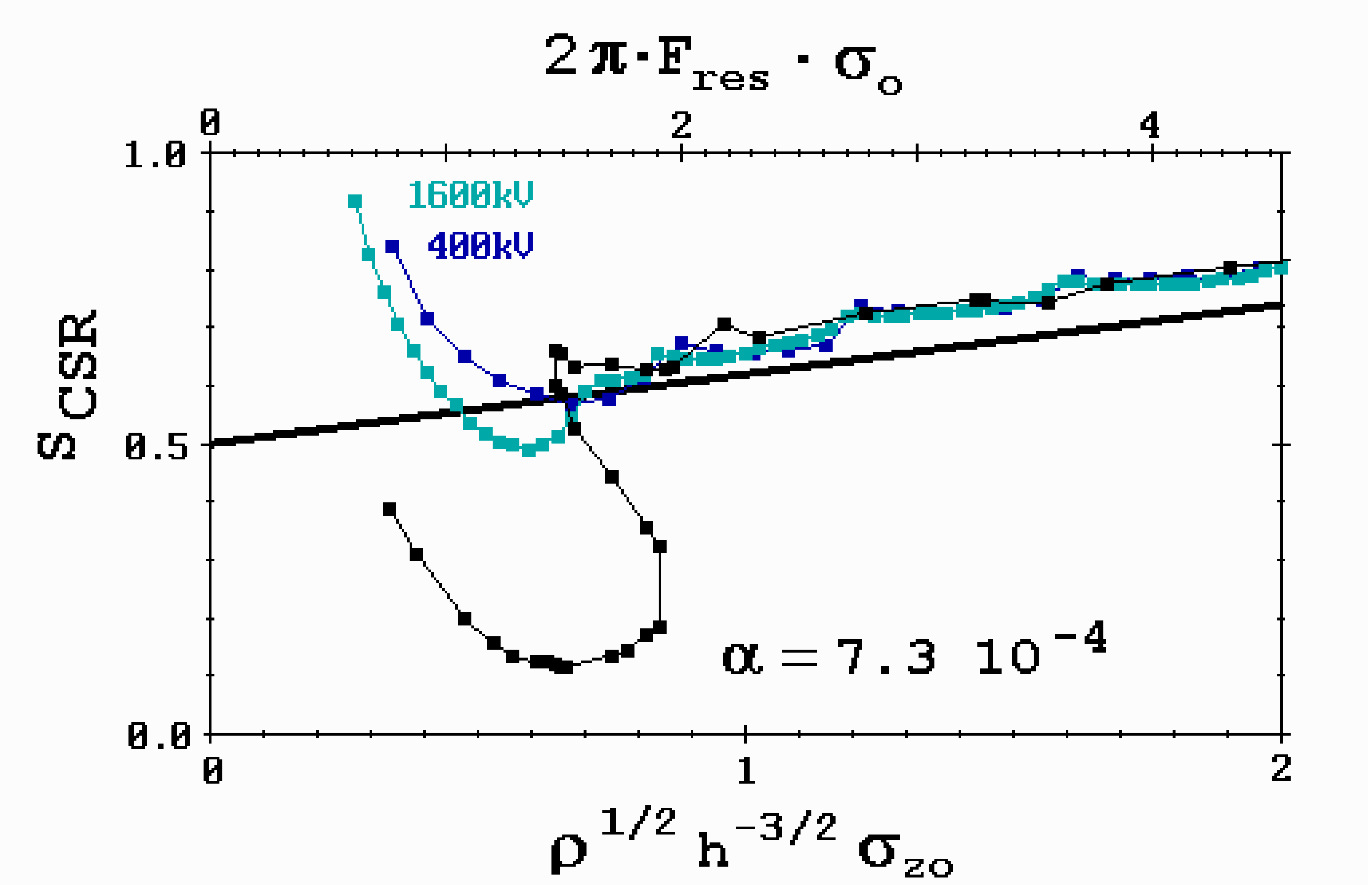

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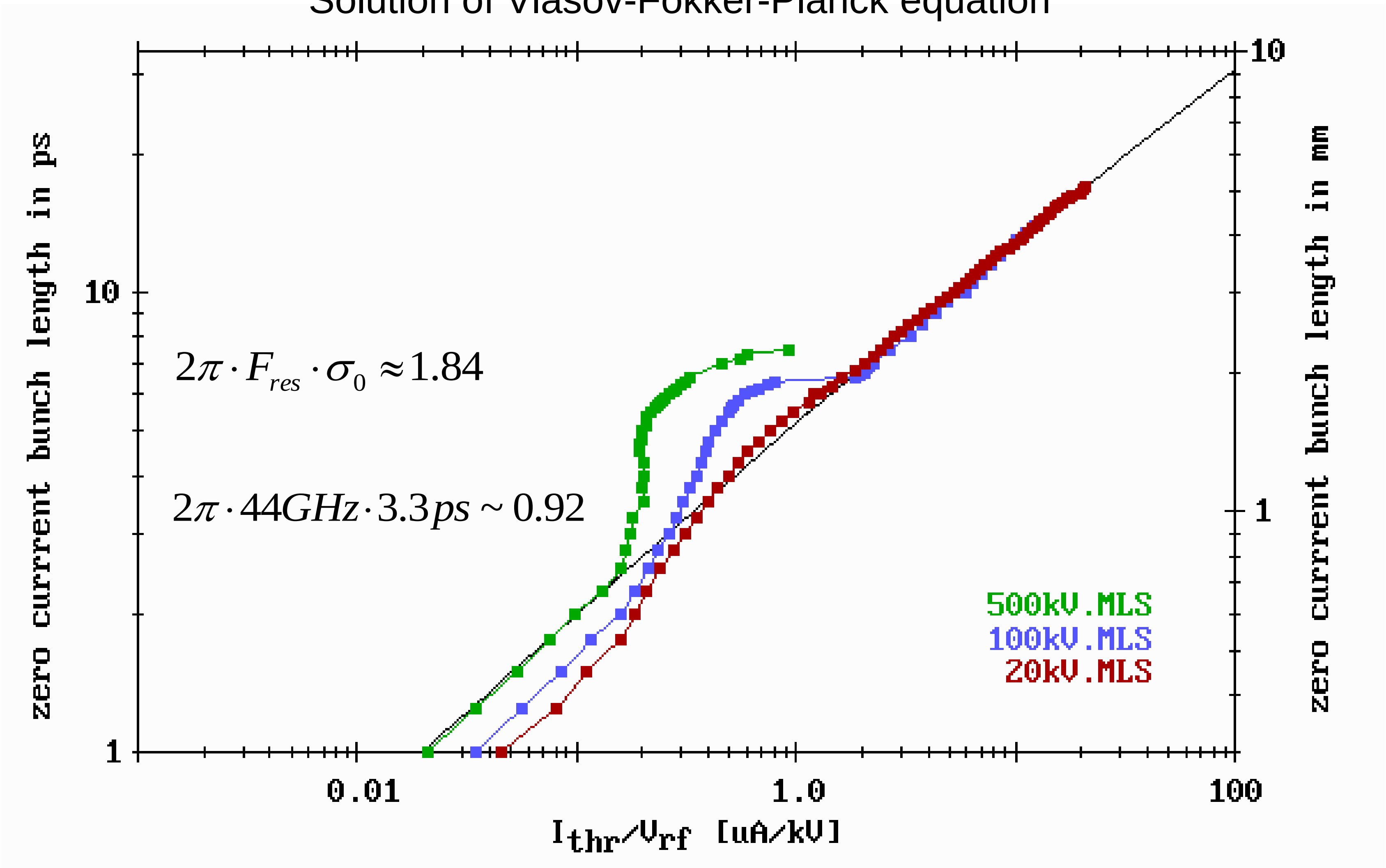
Solution of Vlasov-Fokker-Planck equation



Solid black line: K.L. Bane, et al., Phys. Rev. ST-AB **13**, 104402 (2010)

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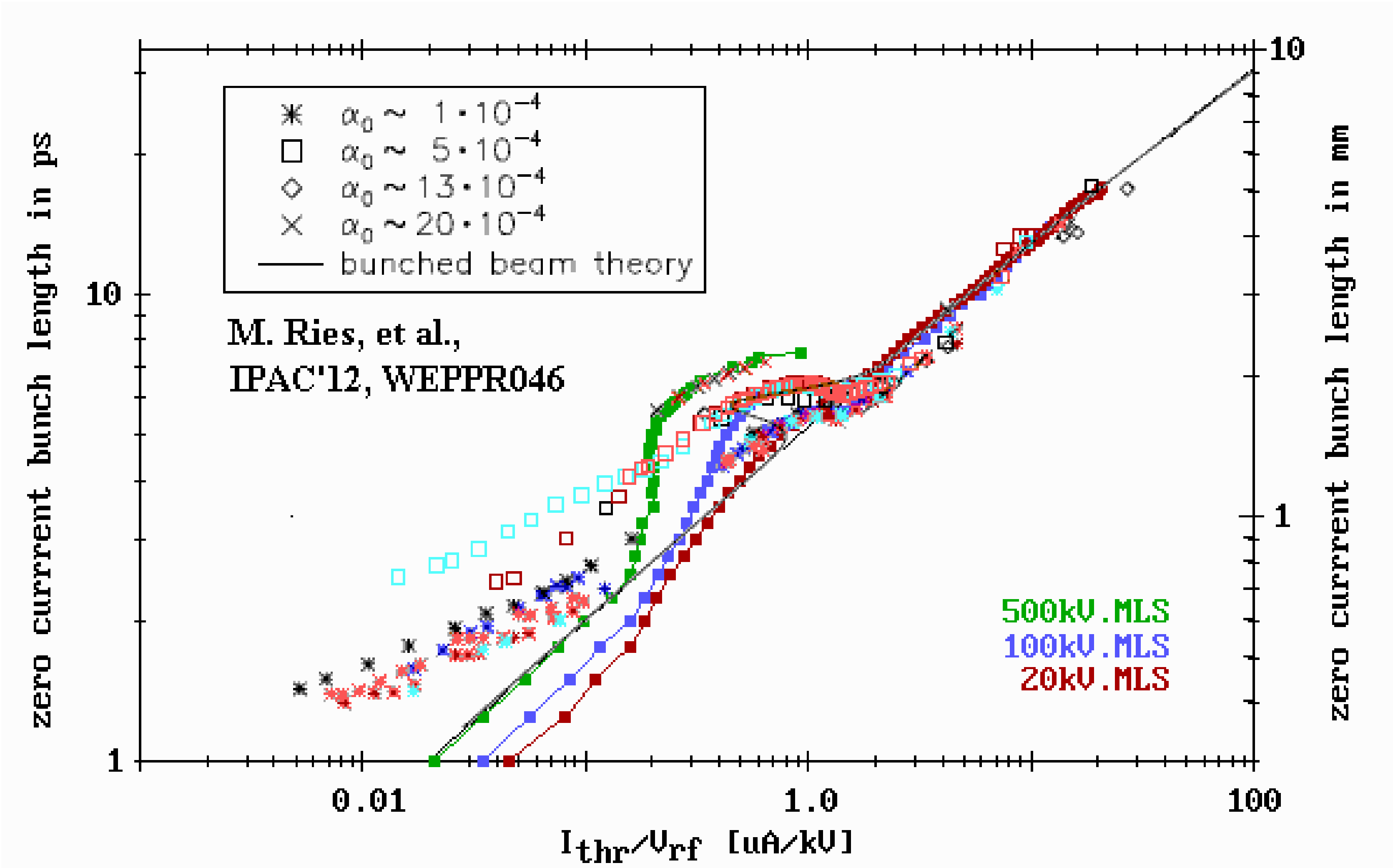

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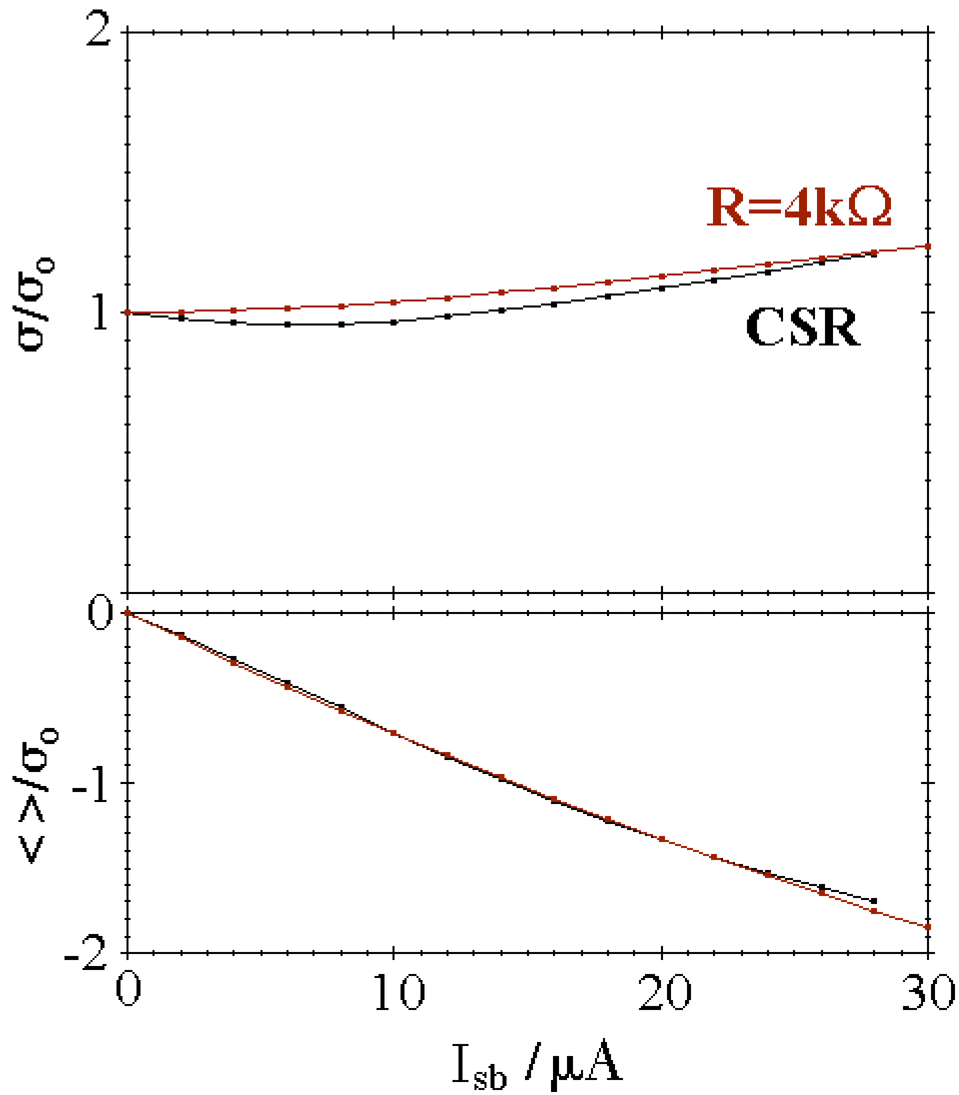
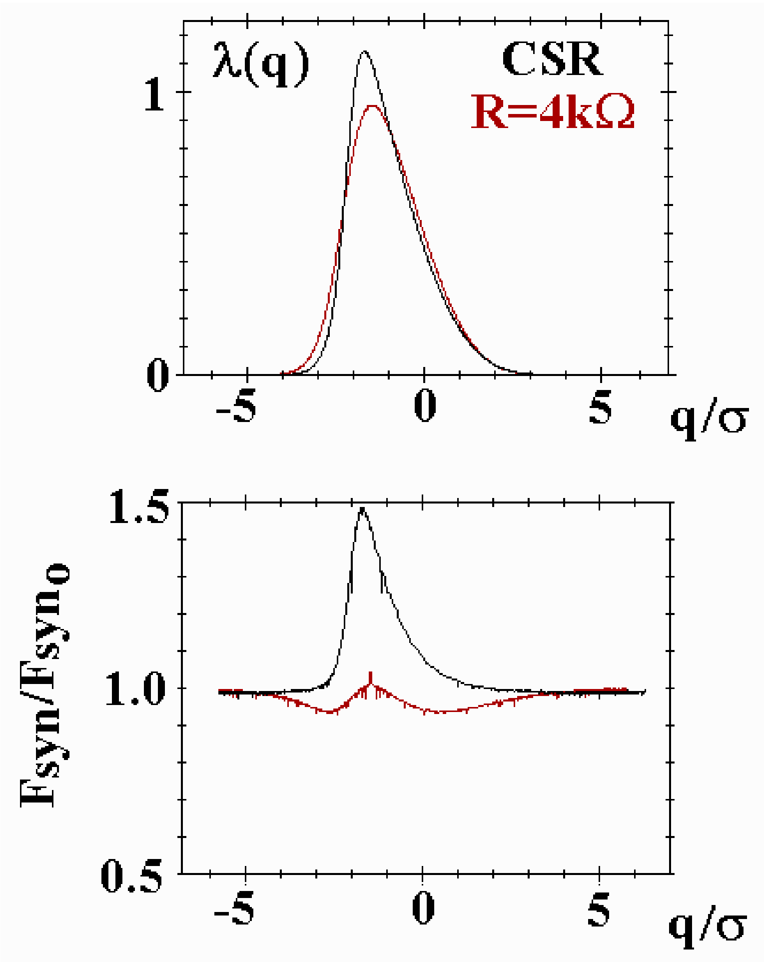
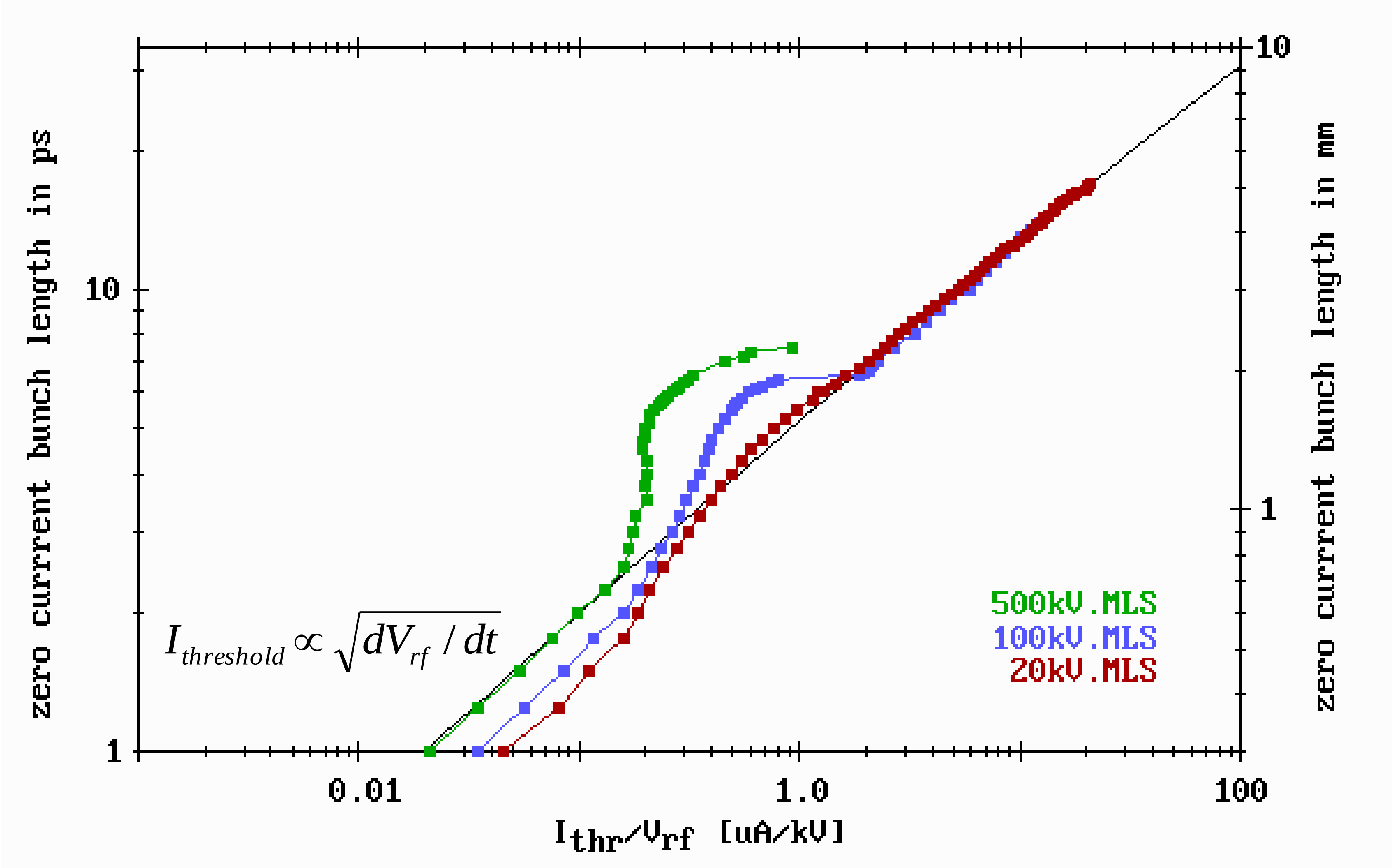
MLS: Vrf=330kV, $\alpha = 1.3\ 10^{-4}$, σ_0=1.55ps







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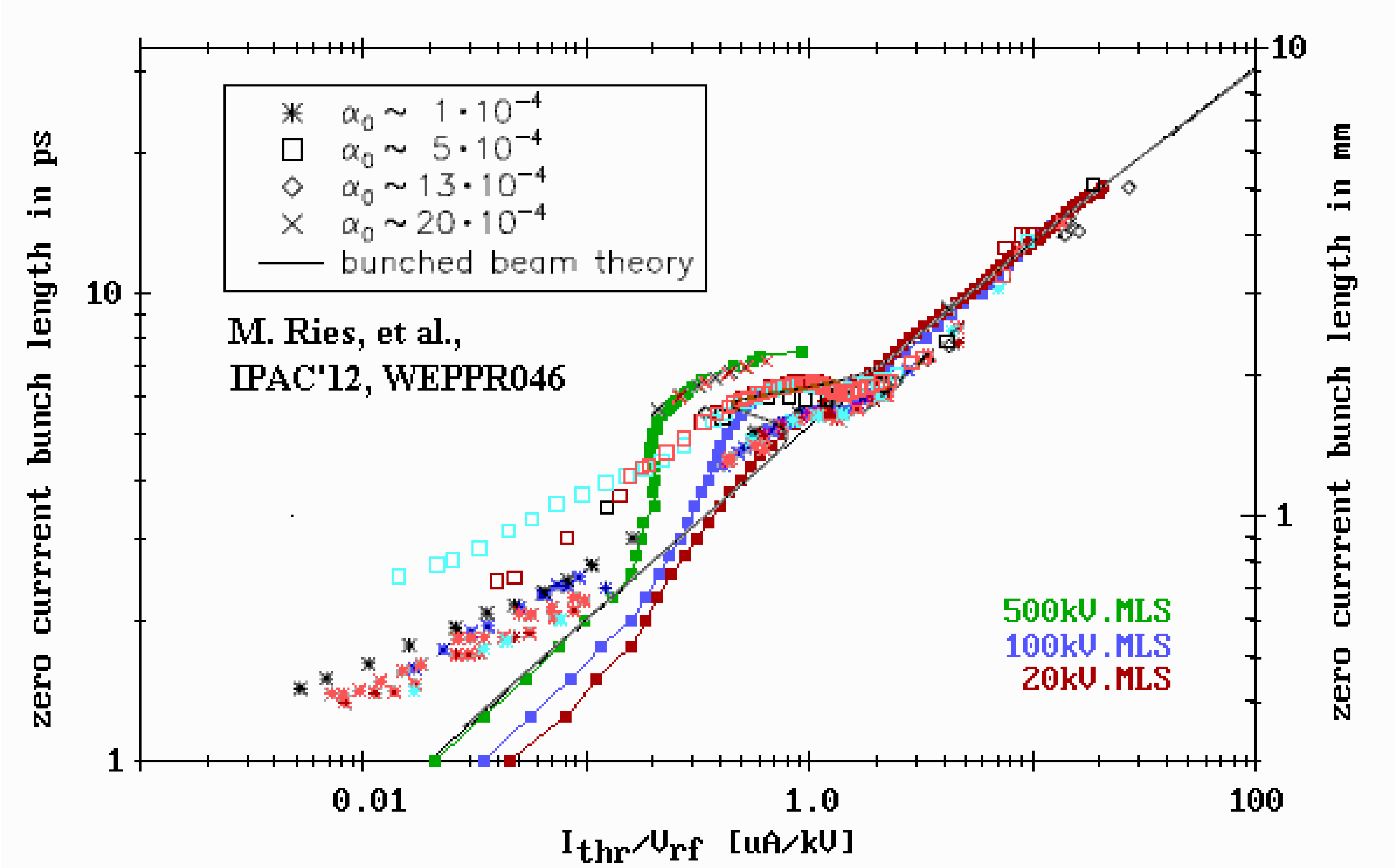

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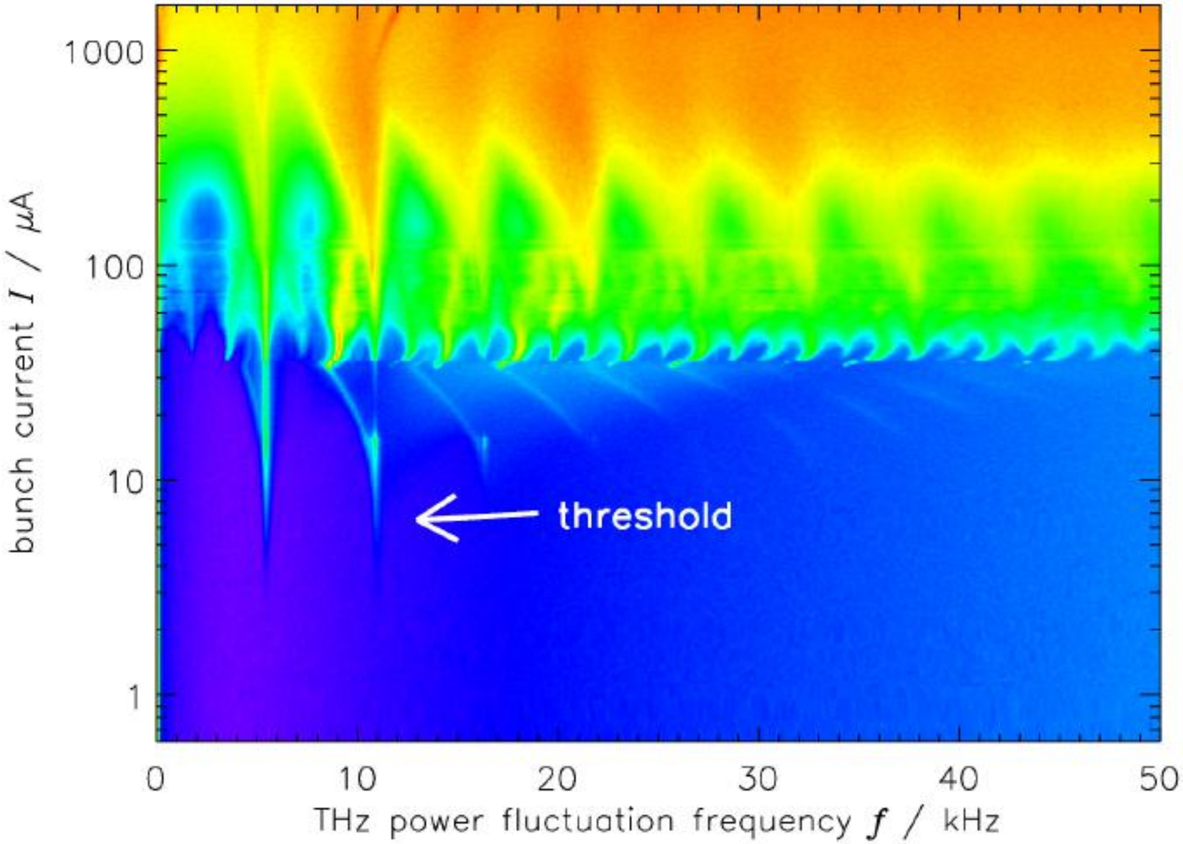

Figure 1: Temporal fluctuation of the THz power as a function of the single bunch current plotted in the frequency domain. The measurement was performed using an InSb hot electron bolometer at a the storage ring parameters $\alpha_0 = 1.3 \cdot 10^{-4}$ and $V = 330$ kV.

M. Ries, et al., IPAC'12, WEPPR046

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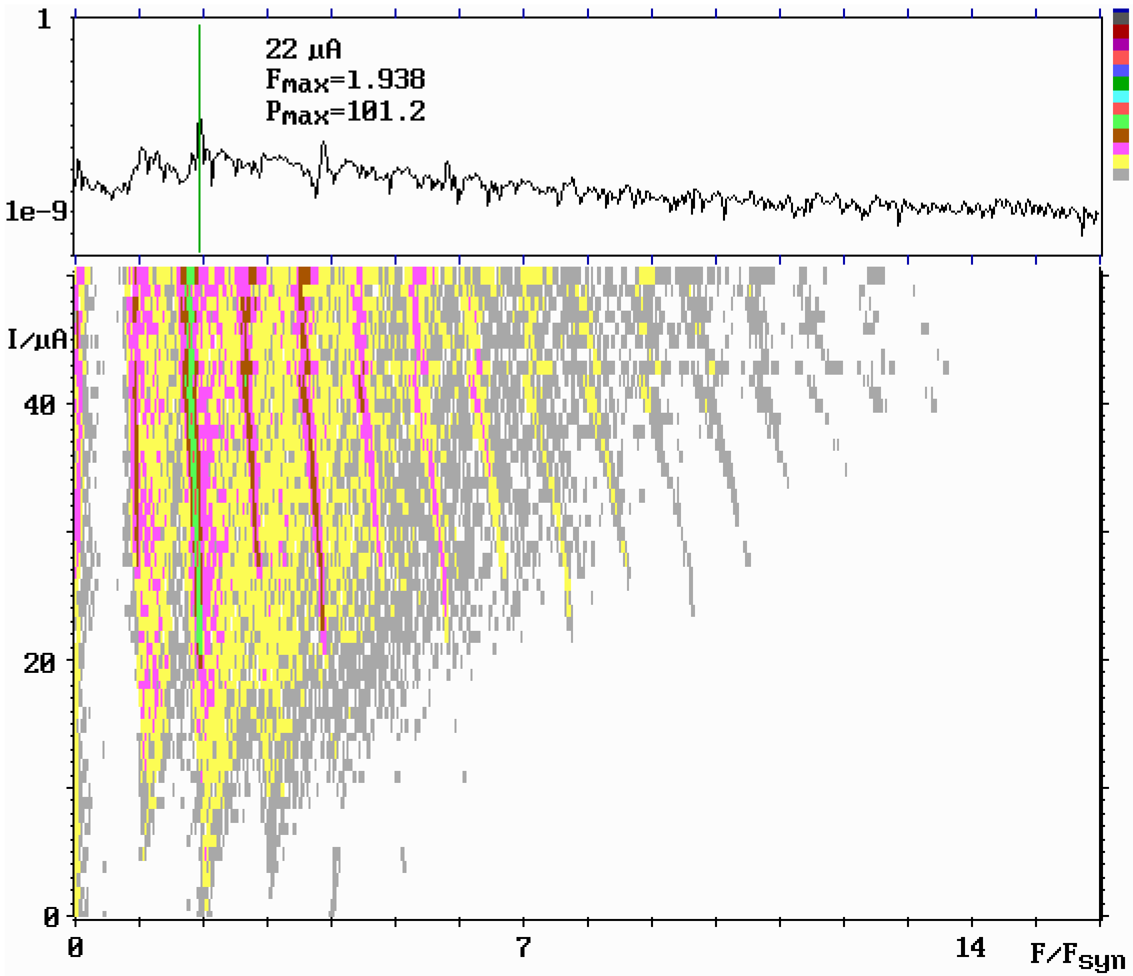
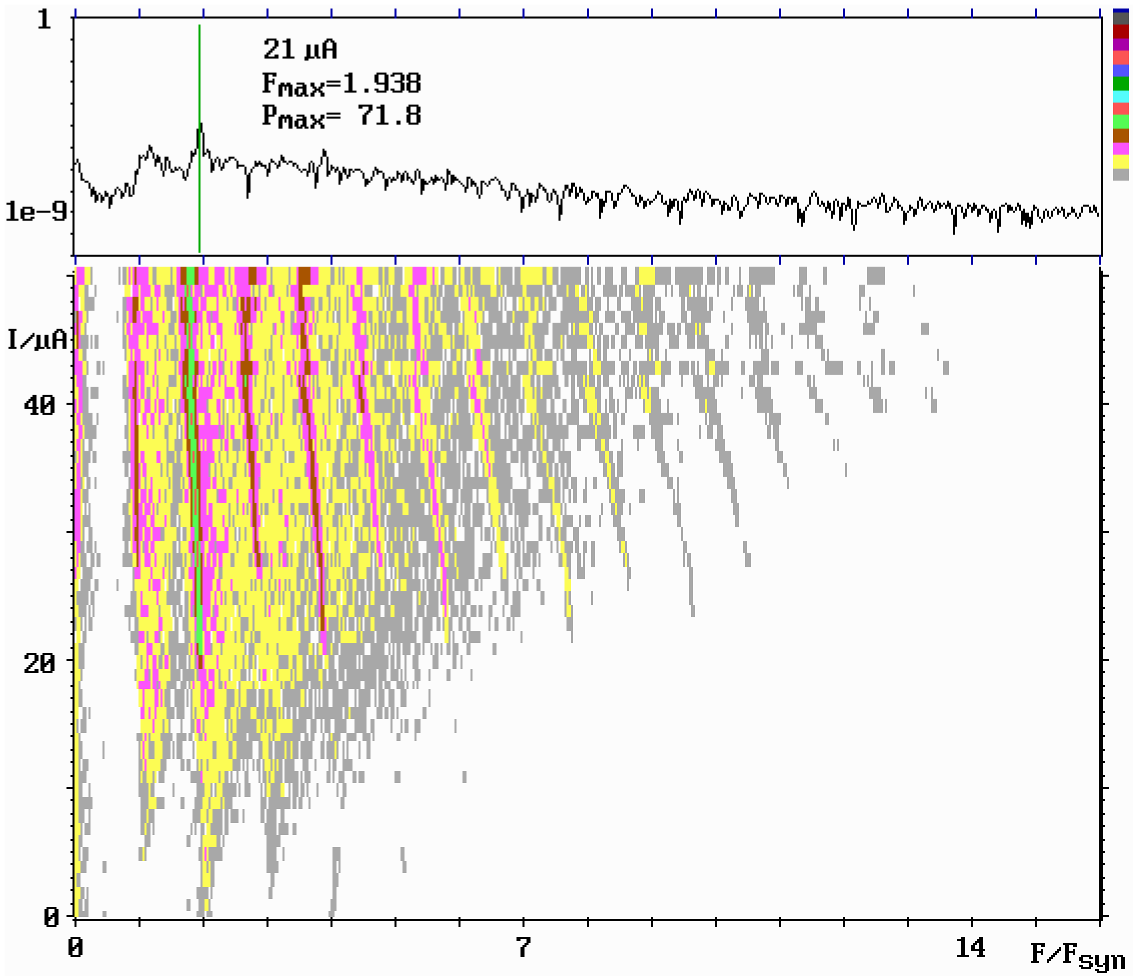


Simulated temporal CSR spectra – multi particle tracking with CSR-wake, 1 Mio. particles, α_o=1.3·10^{-4} and Vrf=330 kV



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MLS – Theoretical Result

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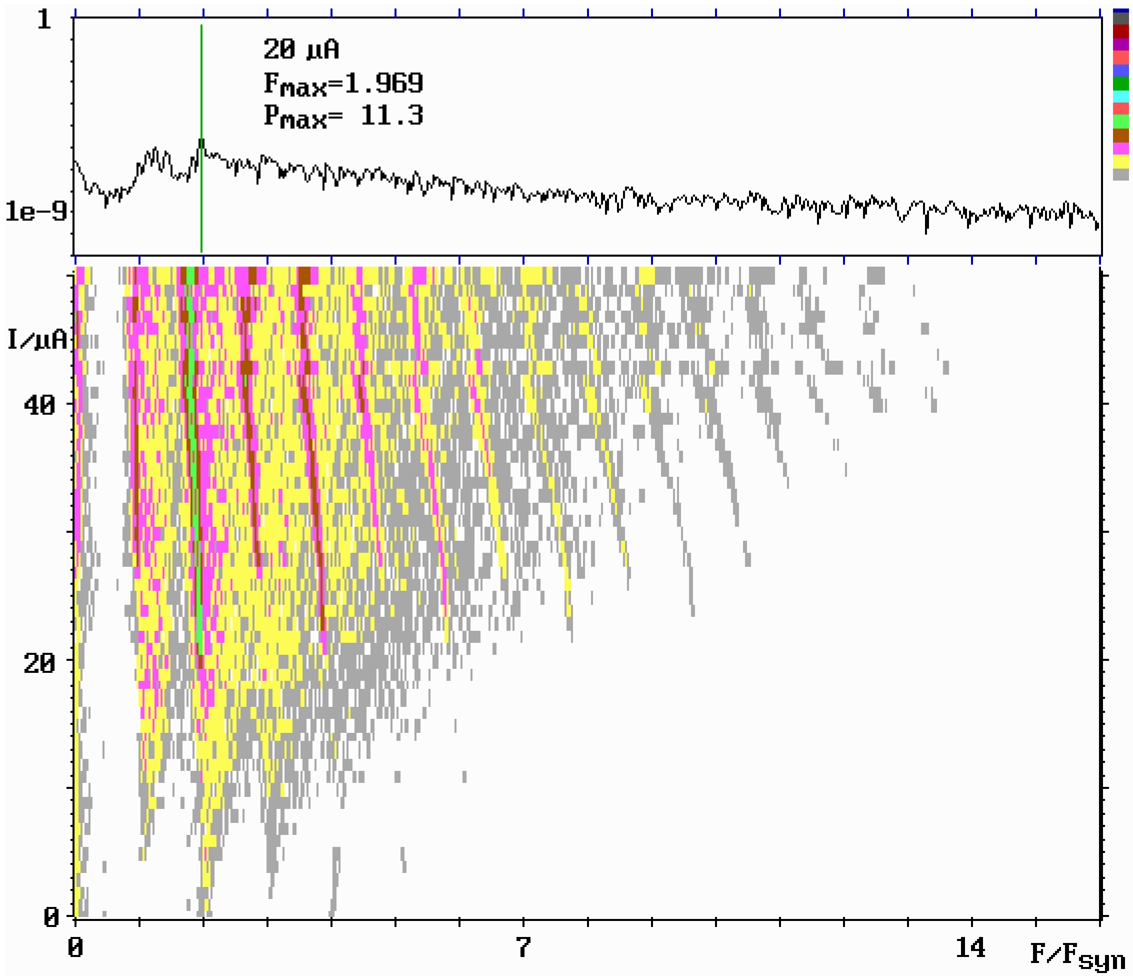

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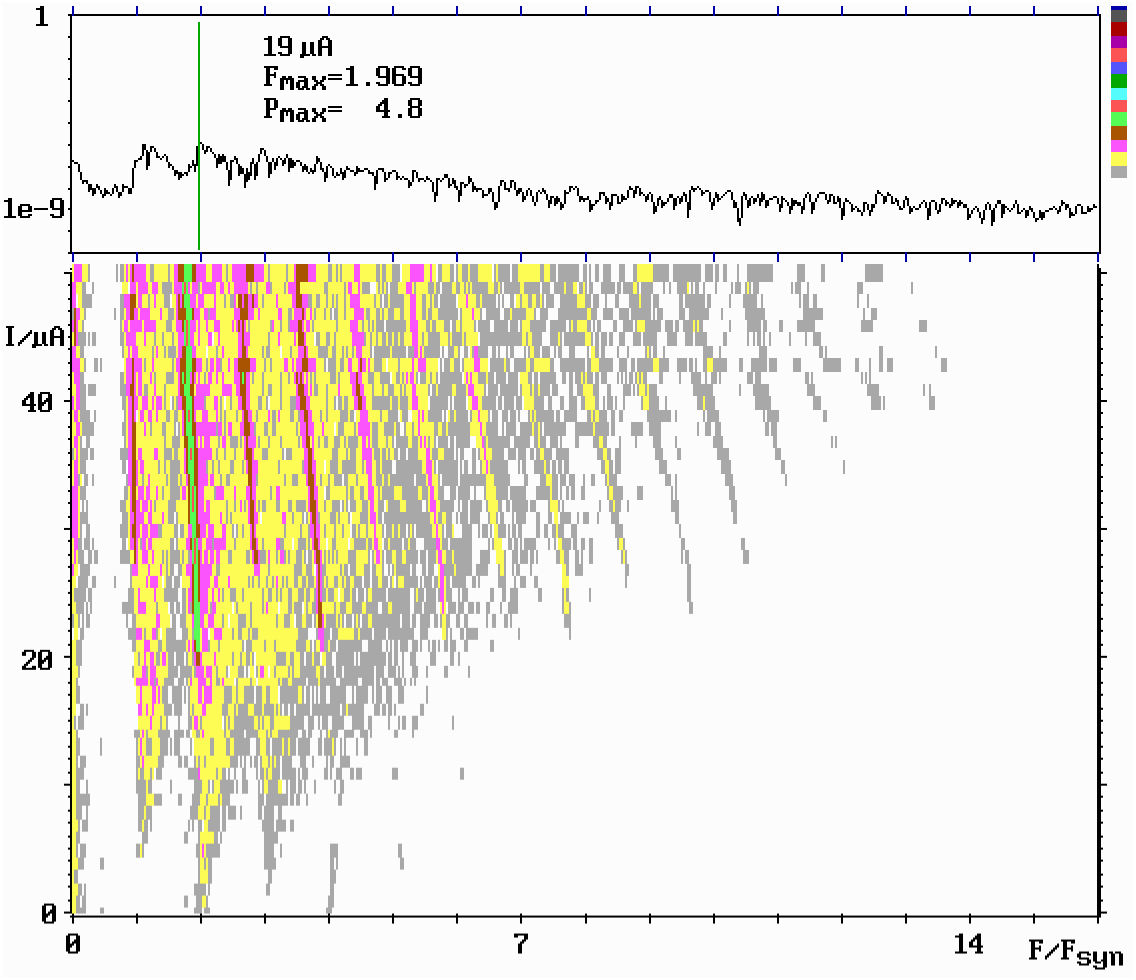

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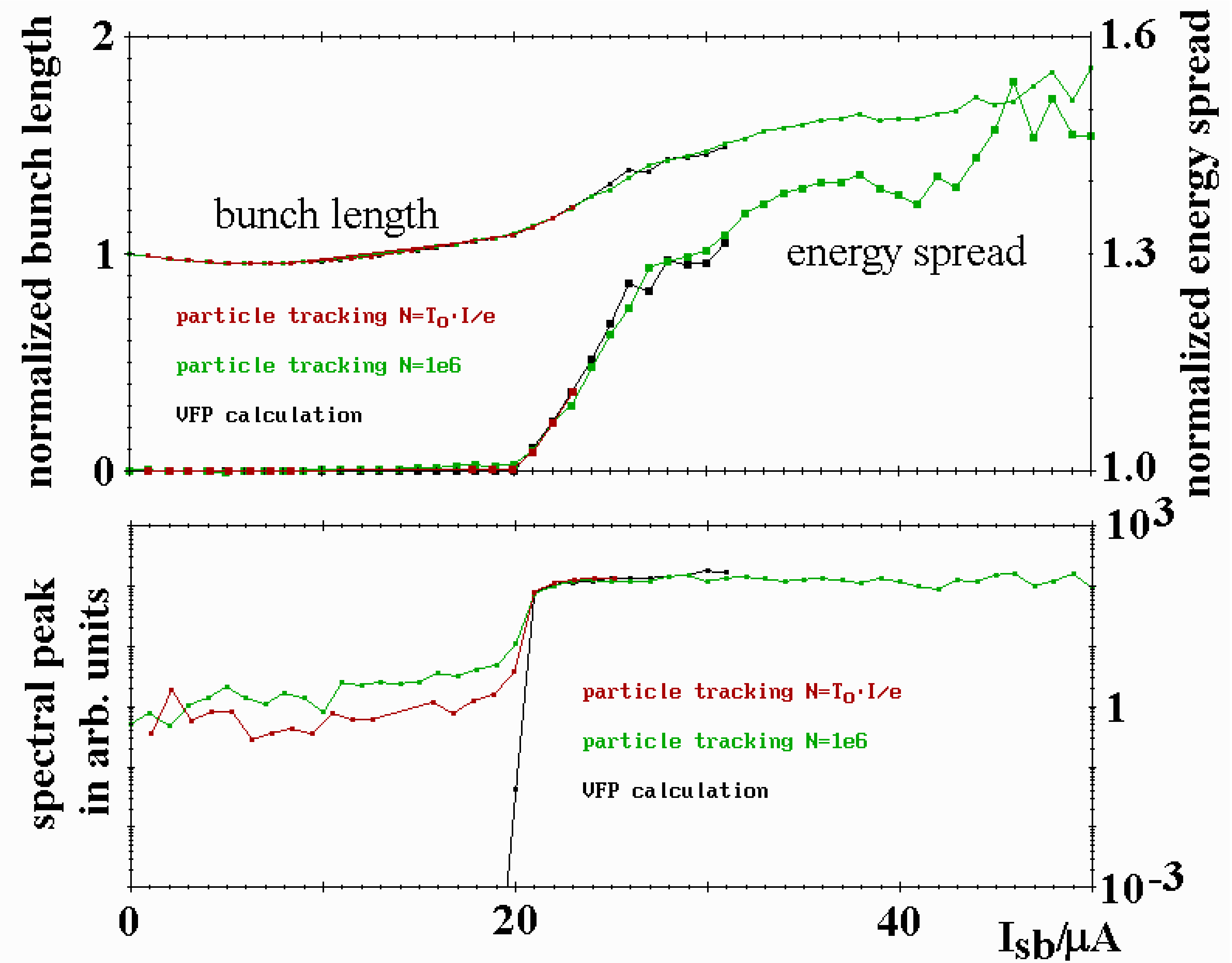
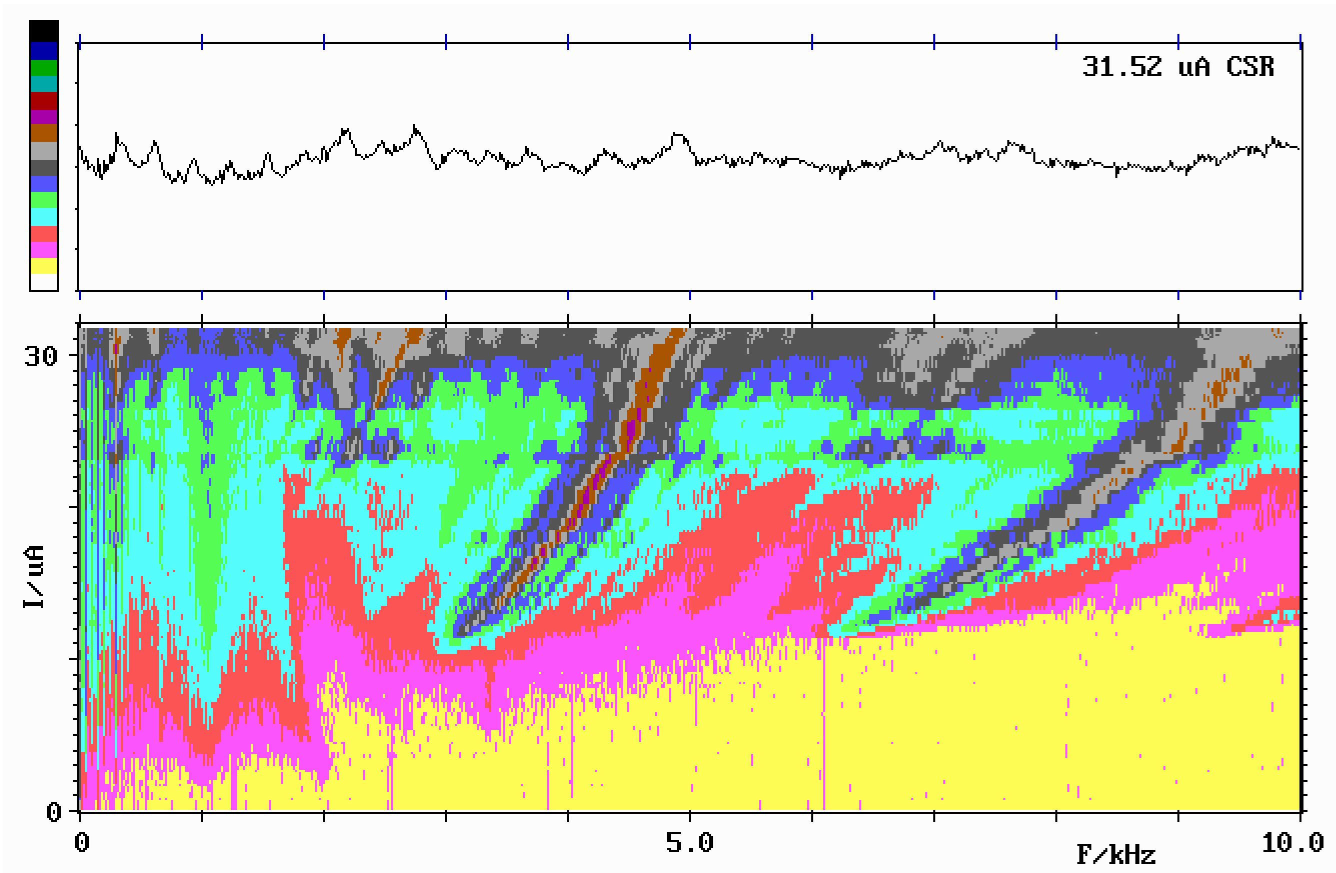
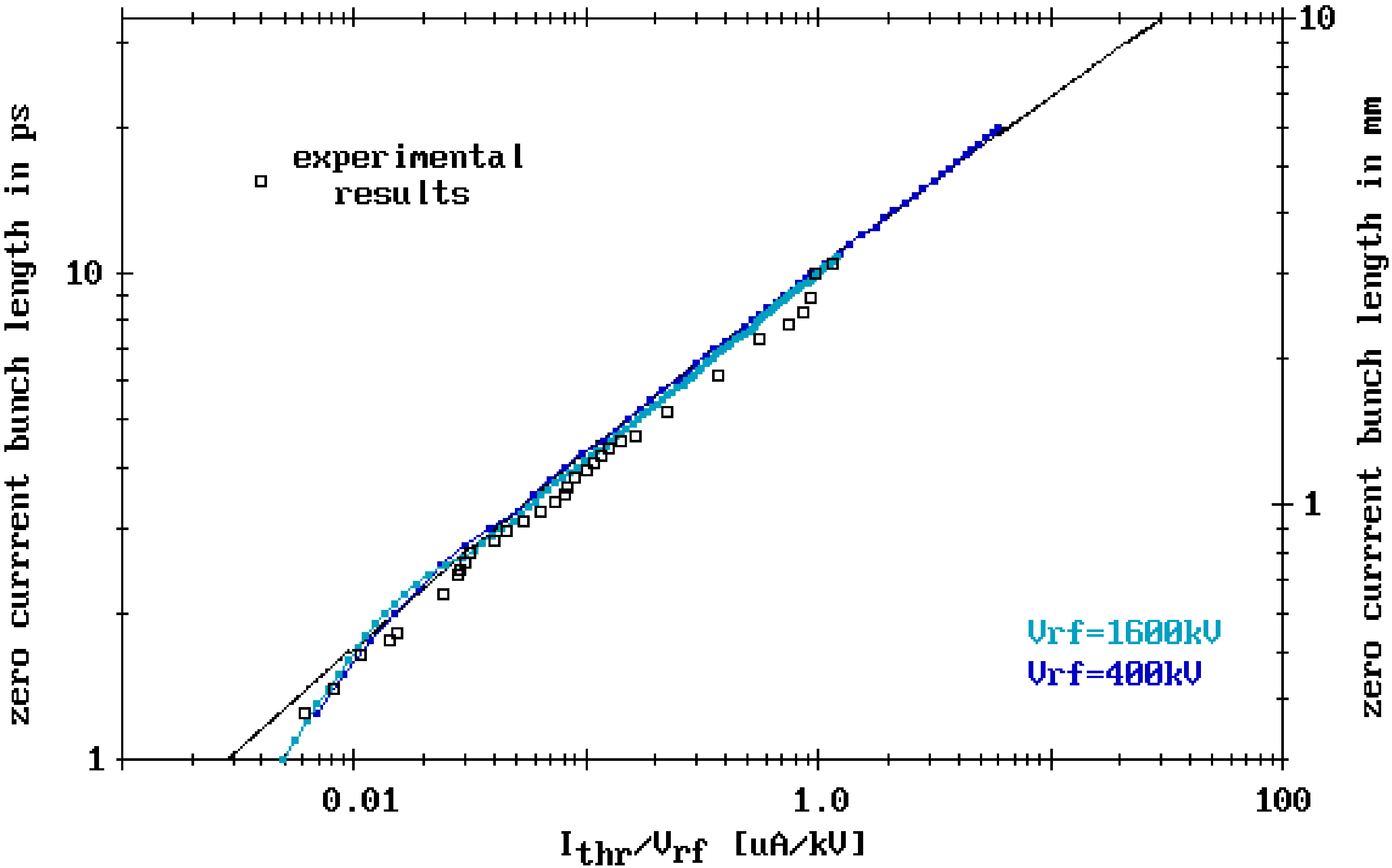

normalized bunch length
2
1
0
bunch length
energy spread
particle tracking N=T0·I/e
particle tracking N=1e6
VFP calculation
1.6
1.3
1.0
normalized energy spread
spectral peak
in arb. units
10^3
1
10^-3
particle tracking N=T0·I/e
particle tracking N=1e6
VFP calculation
0
20
40
Isb/µA

BESSY II, F_{syn_o}=1 kHz, σ_o~1.5 ps



Many modes visible in the Fourier transformed CSR –
Equilibrium fluctuations due to finite number of particle –
Schottky noise effect, longitudinal beam diagnostics

In fair agreement with predictions – bunch lengthening explains shift



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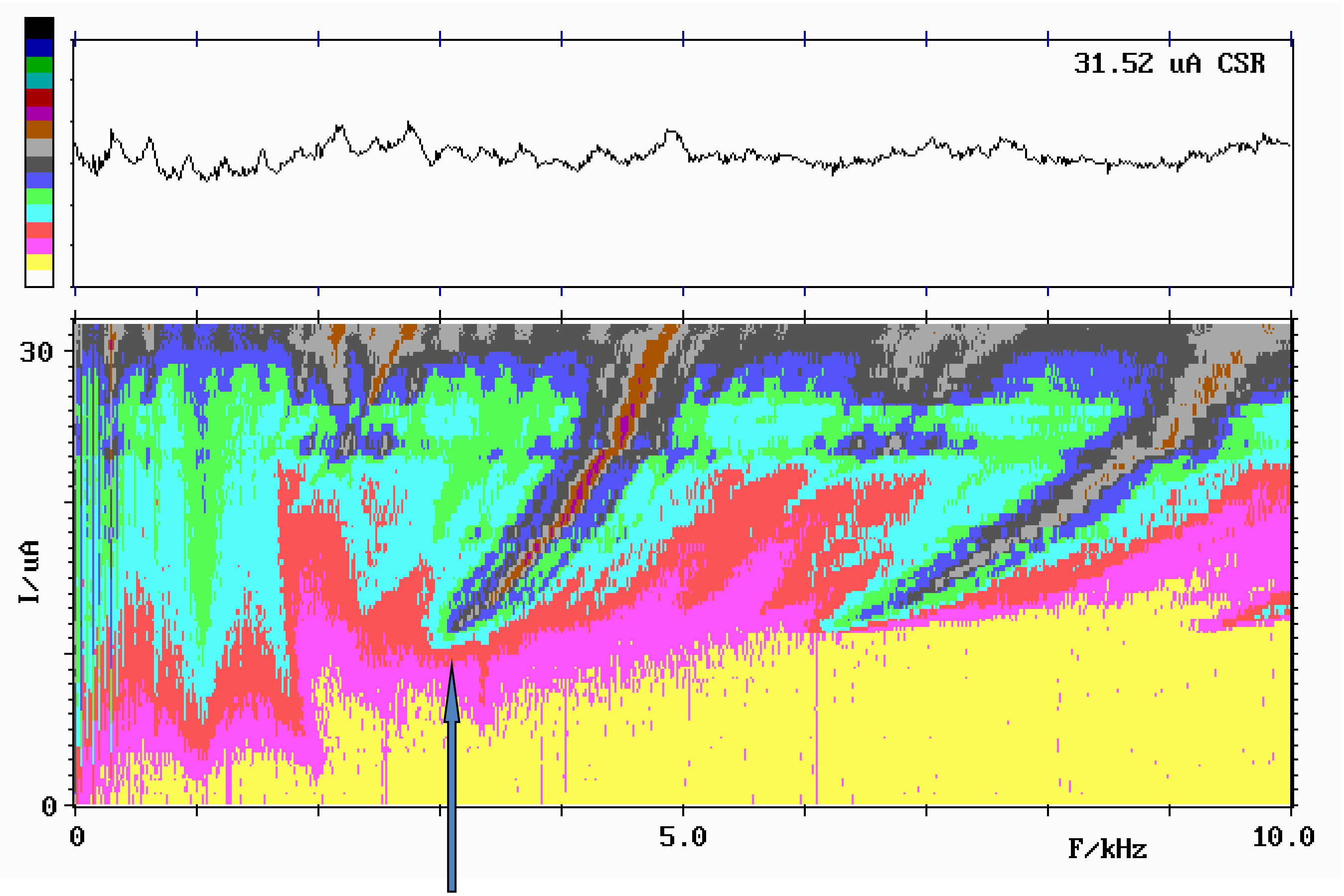
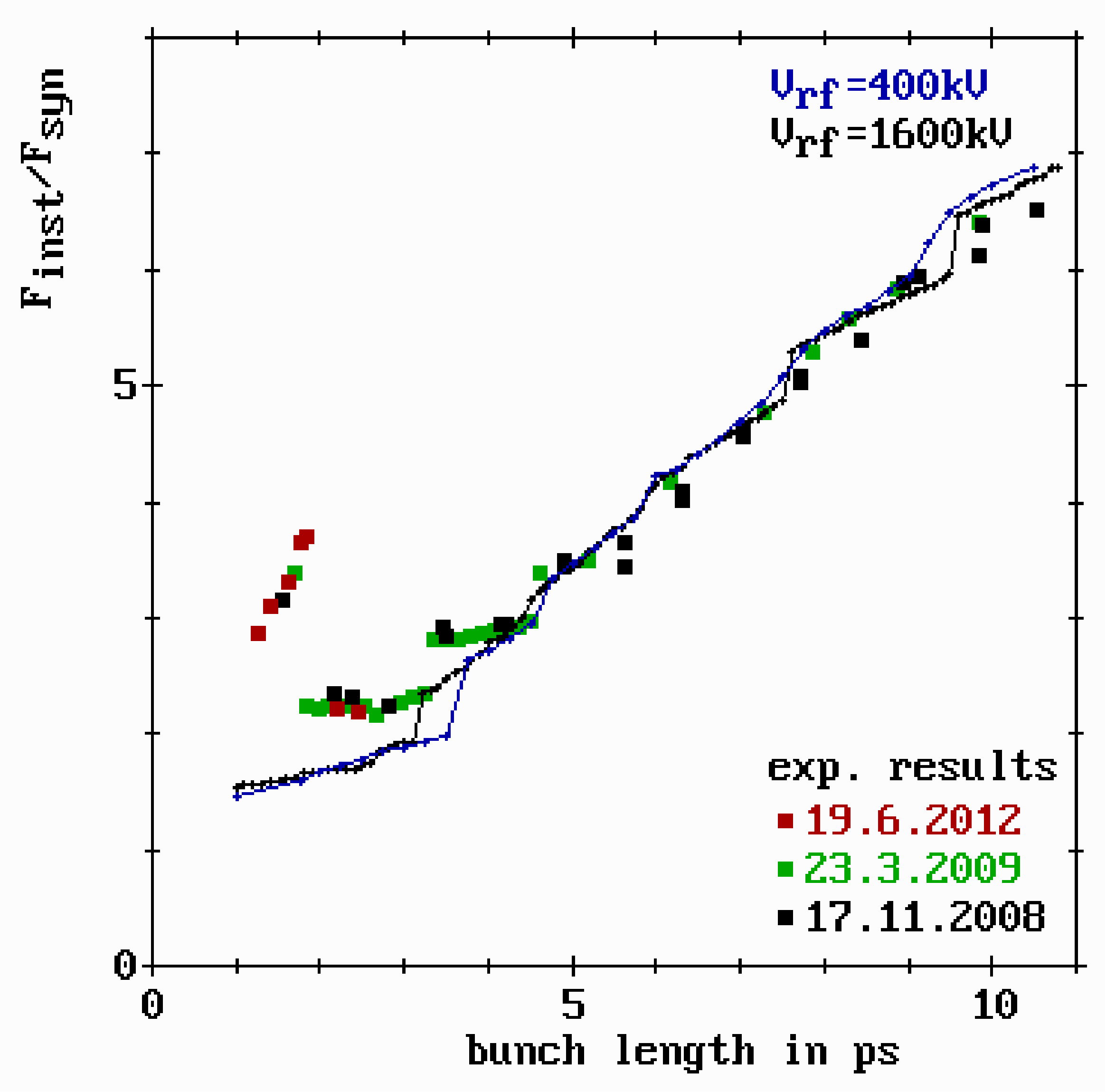
BESSY II, F_{syn_o}=1 kHz, σ_o~1.5 ps



F_{inst}/F_{syn} ~ 3.1 instability mode number



Slope agrees with resonance F_{res}~100 GHz

III. Summary

- Predictions using the shielded CSR-wake are in surprisingly good agreement with measurements at BESSY II and the MLS.
- The observed resonance-like features show the importance of the vertical gap of the dipole vacuum chamber.
- Simulations demonstrate the weak nature of the CSR driven instability - also in the region of very short bunches where shielding is less important.
- Below the instability threshold multi-particle-tracking in better agreement with observations than “noise free” VFP-solutions.
- Equilibrium fluctuations due to finite number of particle and very sensitive THZ-detectors useful for longitudinal bunch diagnostics.
- Experimental determination and scaling of threshold currents requires attention – region of weak instability, low mode numbers.
- Results for very high RF-gradients (higher harmonic, double RF-system) have shown not quite the expected increase of instability thresholds.

- The support of Karsten Holldack, Jens Kuszynski, Fjodor Falkenstern and Dennis Engel is acknowledged.