Gyrotrons from magnetic fusion to THz applications

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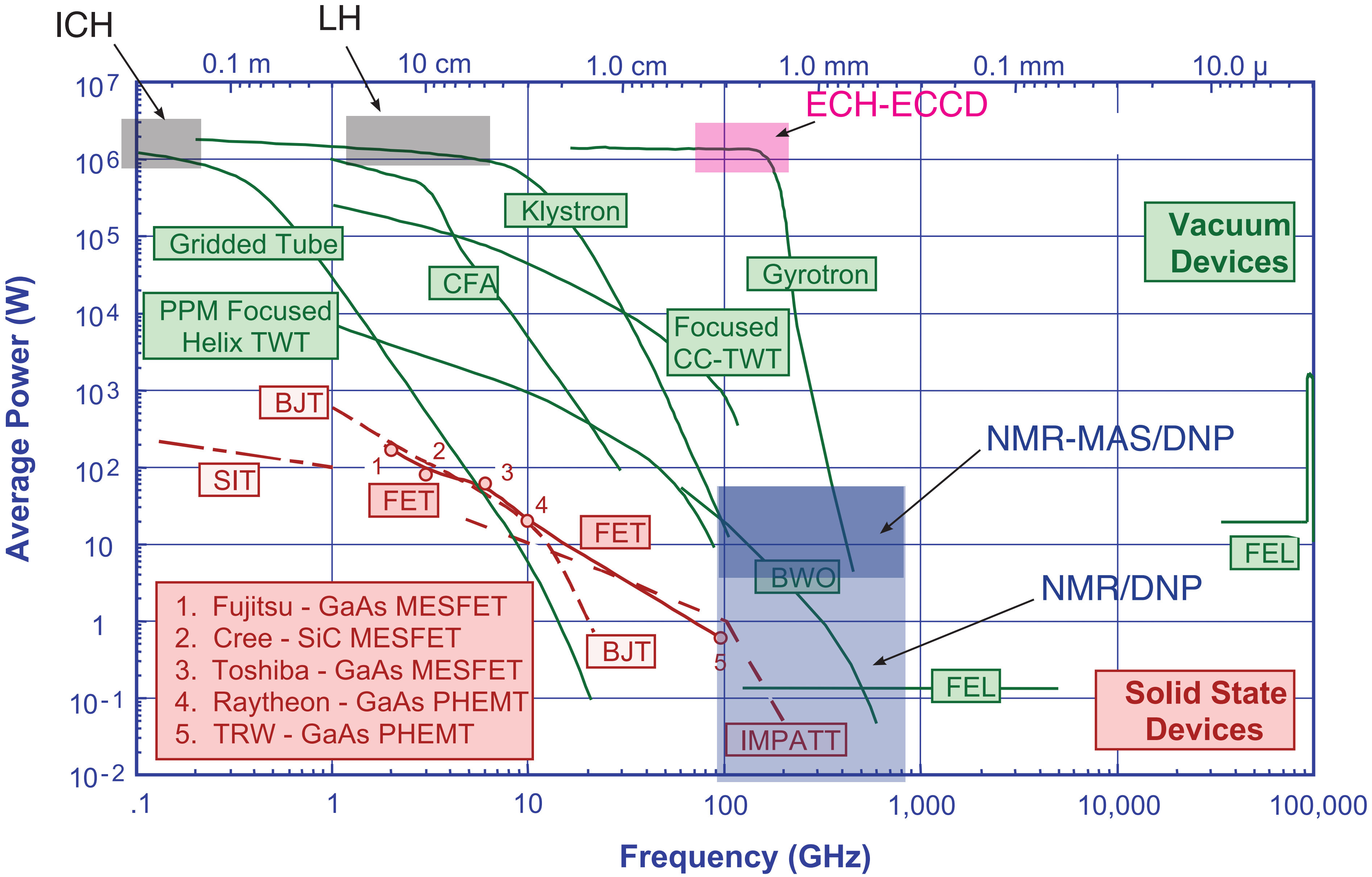
Acknowledgements

- The material presented in this course is the result of a longstanding collaborative effort within the European gyrotron development activity which includes a variety of European research institutes (CRPP, EPFL, KIT, HELLAS, CEA, TEKES), Swiss and European agencies (SNSF, EFDA, F4E) and an industrial partner (THALES Electron Devices).

OUTLINE

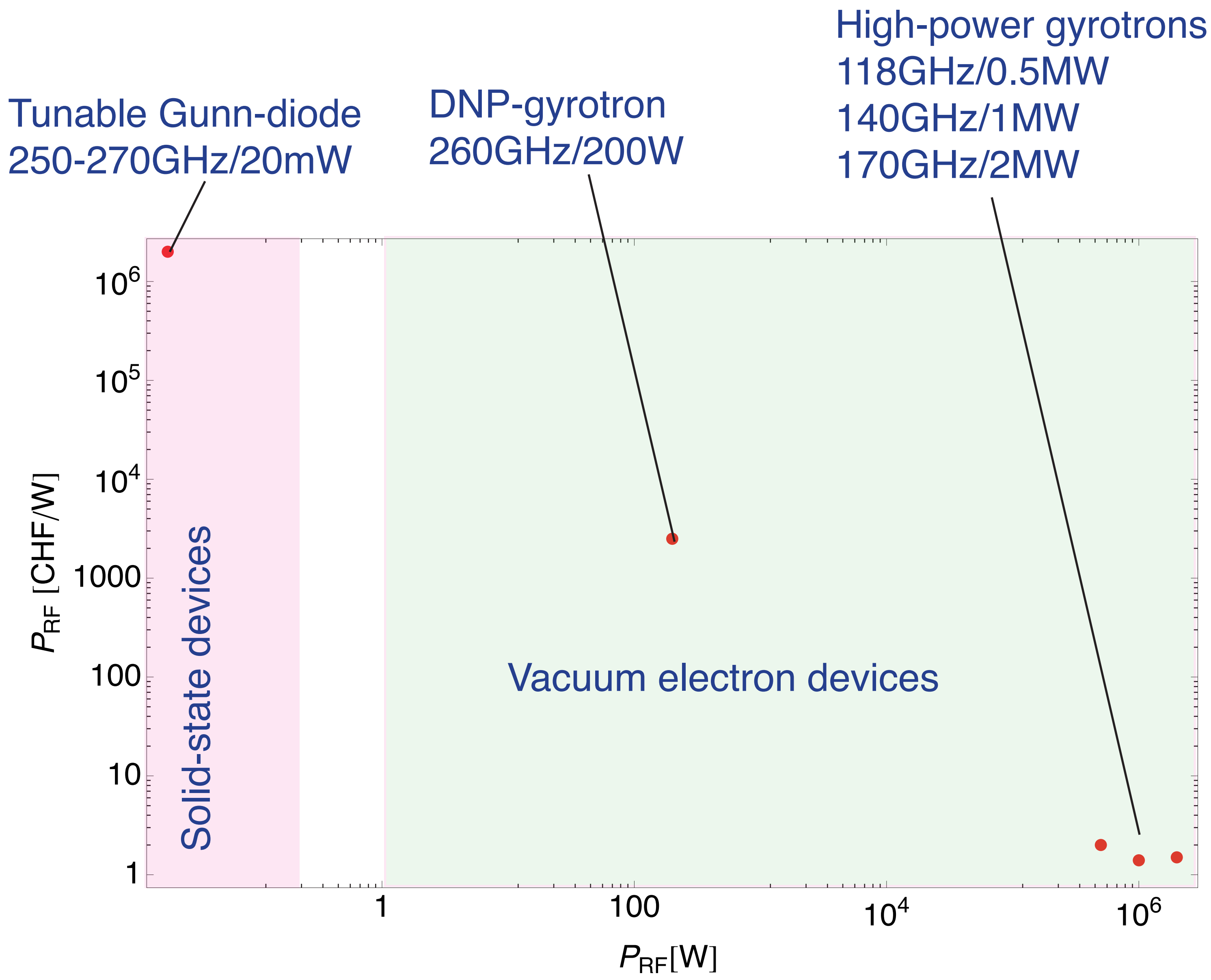
- Gyrotron as a coherent THz source based on electron beams
- Electron Cyclotron Maser, basic concepts
- Gyrotron modeling capabilities
- Layout of DNP/NMR experiment
- Experimental results of frequency-tunable gyrotron
- From linear to chaotic regimes
- Future prospects
- Conclusions

Gyrotron among mm-wave sources



R. Temkin (MIT), Dynamic Nuclear Polarization Symposium, Nottingham, August 2007

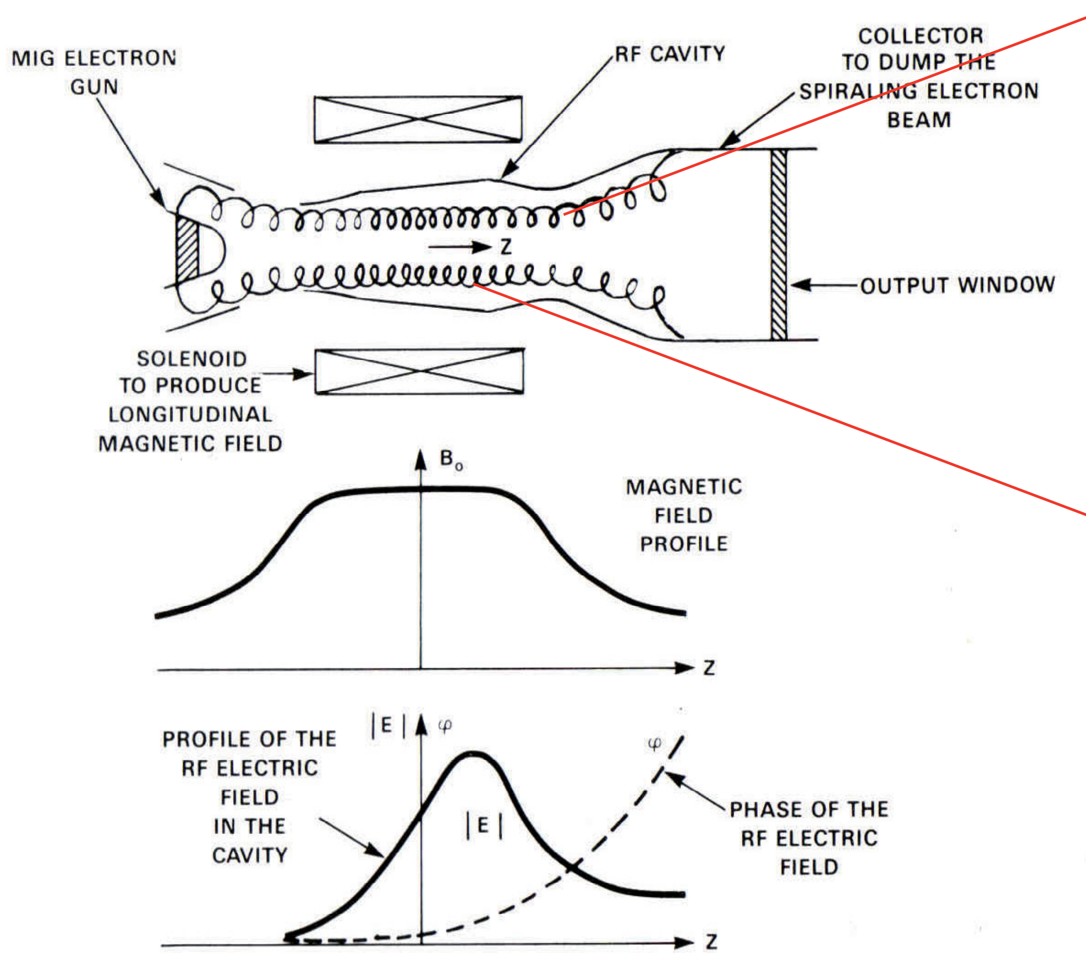
THz CW/RF source: cost per unit power



Worldwide R&D of «commercial» gyrotrons

	Fusion	DNP-NMR
Europe	EGYC/F4E/THALES	CRPP/EPFL/THALES
Russia	IAP/GYCOM	IAP/GYCOM
US	CPI/MIT	CPI/MIT
Japan	Toshiba/Jaeri	Fukui University

The Gyrotron: Cyclotron Resonance Maser (CRM)



- Magnetized weakly-relativistic electron beam (non-neutral plasma)

- Electron cyclotron frequency:

$$\Omega_c = -eB_0/m_0\gamma_0; \qquad \gamma_0 = 1+E_0/m_0c^2$$

- Electron-beam distribution function

$$f_0(p_\perp, p_\parallel) = \frac{1}{2\pi p_{\perp 0}}\delta(p_\perp - p_{\perp 0})\delta(p_\parallel - p_{\parallel 0})$$

f_0 is CRM unstable

- EM cavity resonant at frequency ω_{THz}

- Resonance condition:

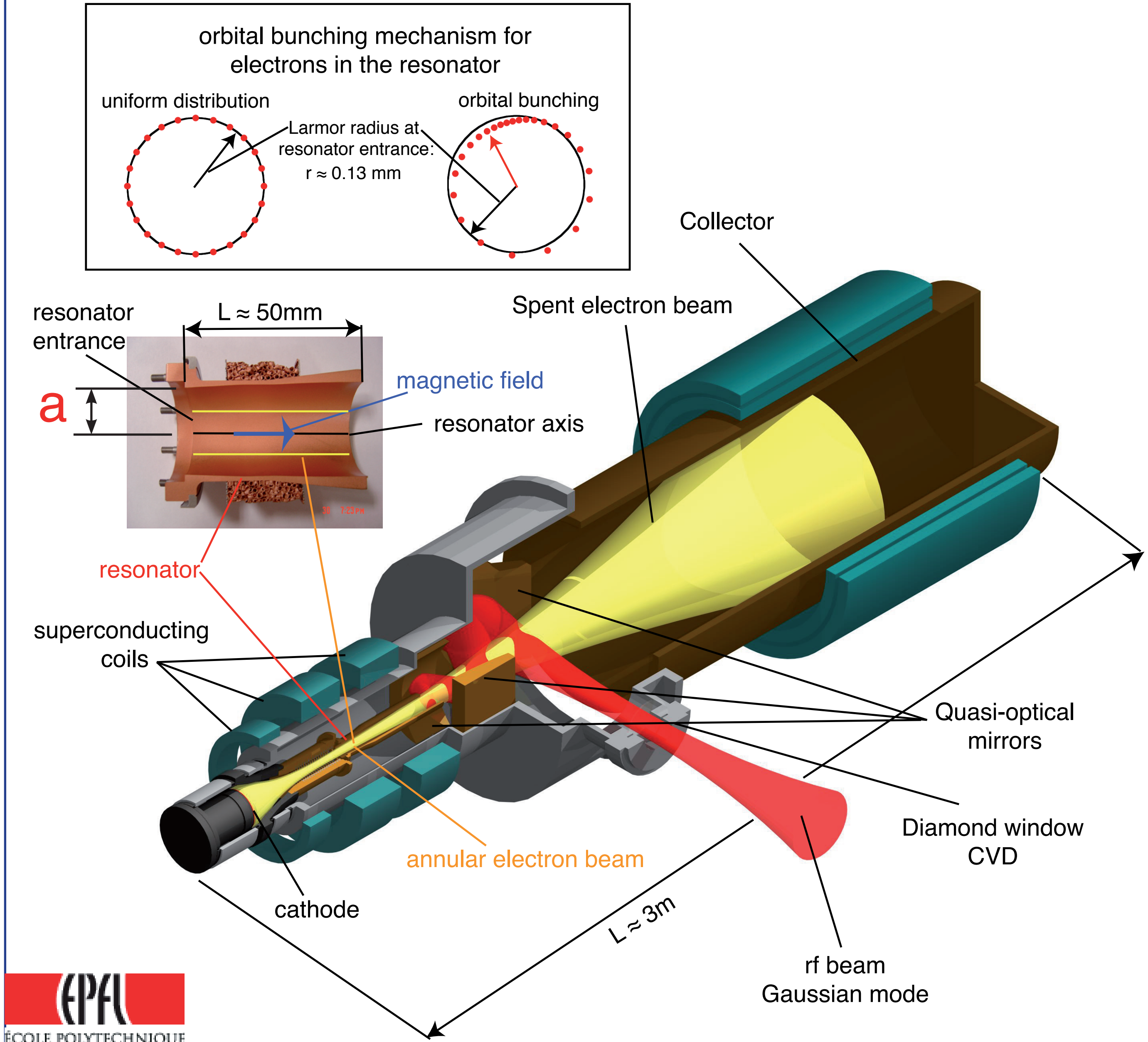
$$s\ \Omega_c \approx \omega_{THz}$$

(s,harmonic number)

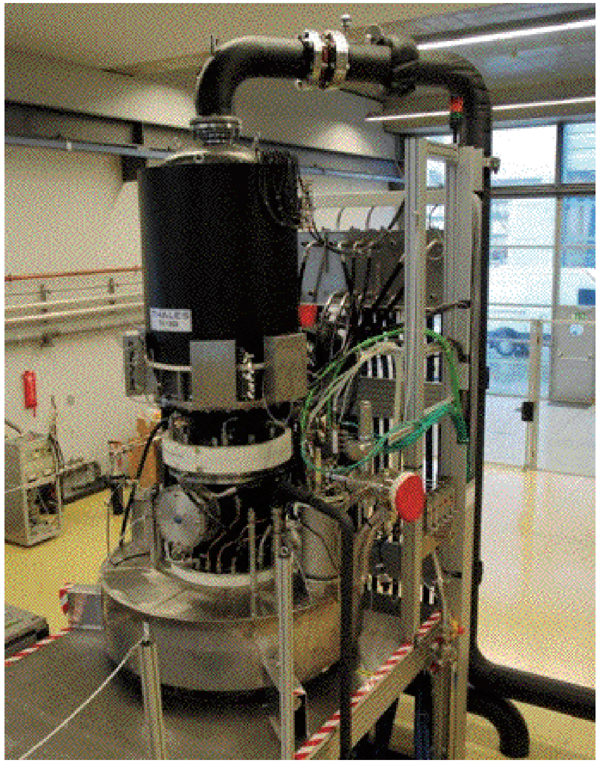
$f_{THz} = s/\gamma_0\ B\ 28\text{GHz/T}$ ($\gamma_0 = 1.02\text{-}1.04$)
($E_0 = 10\text{-}20$ keV)

- Kinetic rotational (perpendicular) energy efficiently converted into EM waves (max $\eta_{perp} = P_{EM}/P_{rot} = 70\%$)

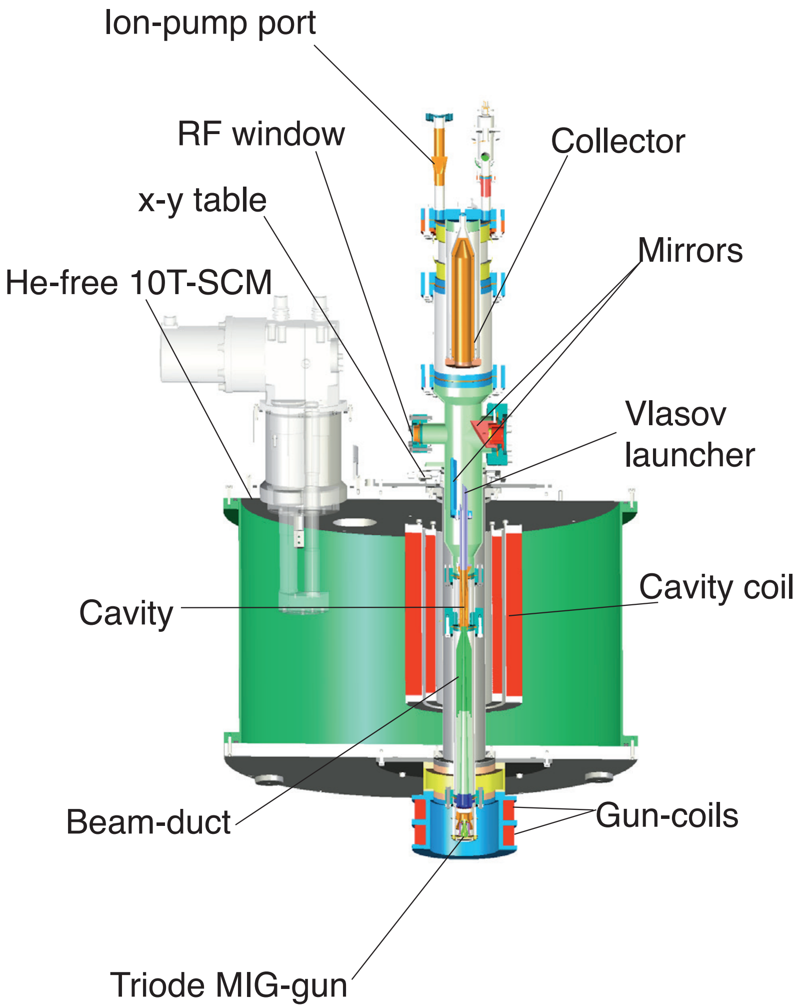
Gyrotron for magnetic fusion application: $a/\lambda \approx 10\text{-}15$



2MW 170GHz Coaxial Gyrotron



Gyrotron for DNP/NMR application: $a/\lambda \approx 2\text{-}3$



Gyrotron: wave-particle interaction

$$\mathbf{E}(\mathbf{x},t) = \mathbf{E}_0 \exp(i\mathbf{k}\cdot\mathbf{x} - i\omega t)$$

EM wave: plane wave approximation
valid in free space
(in a gyrotron cavity **E**(**x**,t) has to satisfy boundary conditions -> eigenmodes, TE (TM) modes

$$x_\parallel = v_\parallel t + x_0$$

$$\mathbf{x}_\perp = Re[r_L(\mathbf{e}_x + i\mathbf{e}_y)\exp[i(\Omega_c t + \phi_0)]$$

electron: unperturbed trajectory

electron-wave interaction

$$\frac{dW}{dt} = -e\mathbf{v}\cdot\mathbf{E} = \frac{e}{2}Re\sum_{s=-\infty}^{s=+\infty}\{[(v_\perp(J_{s-1}(\chi)E_{(+)}+J_{s+1}(\chi)E_{(-)})+v_\parallel J_s(\chi)E_\parallel]\exp\{i[\psi(t)]\}$$

Circularly polarized component co-rotating with electrons

$$\chi = k_\perp r_L$$

resonant interaction if ψ(t) ~ constant:

$$\psi(t) = \psi_0 + \omega t - k_\parallel v_\parallel t - s\Omega_c t$$

$$\boxed{\omega = k_\parallel v_\parallel + s\Omega_c}$$

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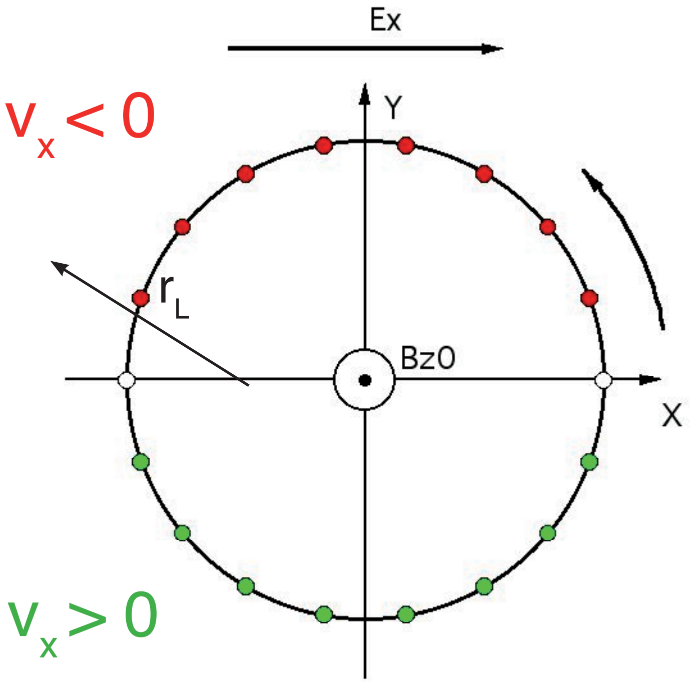
CRPP

Negative mass instability

Fast-wave device: phase velocity: $\omega/k_{||} > c$

- CRM mechanism: $k_{||} \approx 0$
  Cyclotron frequency depends on energy

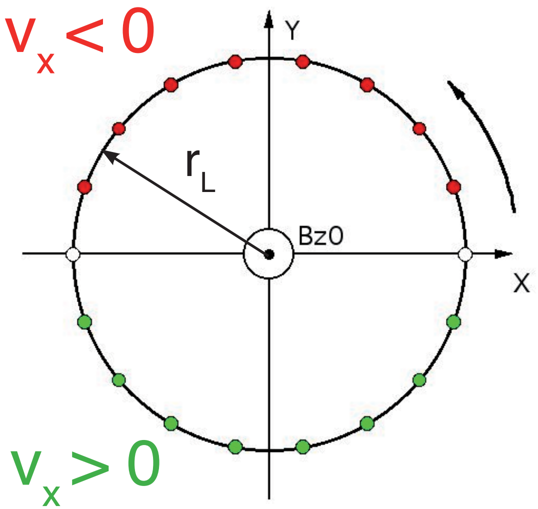
$$\Omega_c = \frac{eB_{z0}}{\gamma m_0} \quad \Leftrightarrow \quad \begin{cases} \text{if } \gamma \uparrow & \Rightarrow \quad \Omega_c \downarrow \\ \text{if } \gamma \downarrow & \Rightarrow \quad \Omega_c \uparrow \end{cases}$$



Take an electron set and make 'snapshots' at every wave period

$$\tau_i = i\frac{2\pi}{\omega}$$

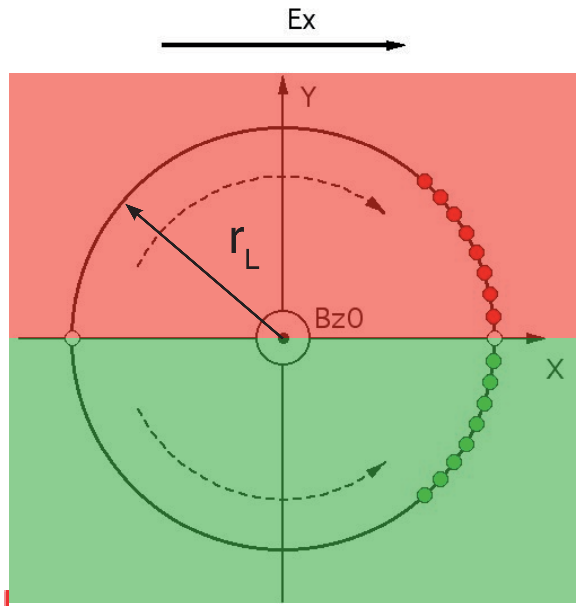
Negative mass instability



Case A: $E_x = 0, \omega = \Omega_c$

Nothing happens

$dW/dt = - e\ v_x\ E_x$



Case B: $E_x > 0, \omega = \Omega_c$

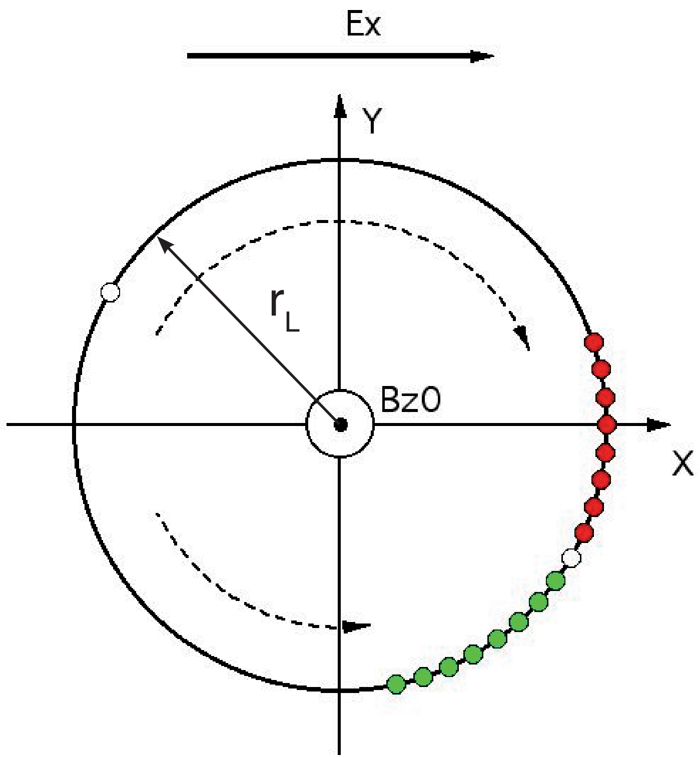
Red electrons gain energy, rotate slower and accumulate (bunch), at $X=r_L$

Green electrons loose energy, rotate faster and accumulate at $X=r_L$ too

bunching

But no net energy exchange

Negative-mass instability



Case C: $E_x > 0, \omega > \Omega_c$

In addition to bunching, all the picture is rotated clockwise

Bunching takes places in a region where the electrons are loosing energy.

Net energy loss from electrons.

Energy conservation <=> Electric field increases

The negative-mass instability (Cyclotron Maser Instability) is a relativistic instability.

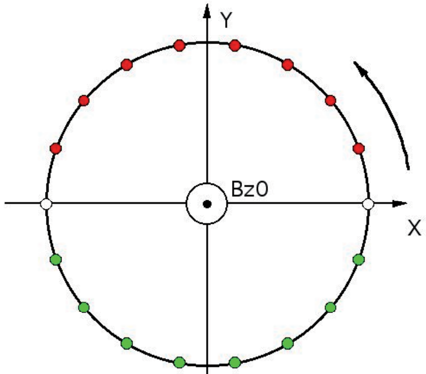
If $\omega > \Omega_c$ the EM energy increases exponentially in the linear regime

Classical analogies between ECR and ESR

Gyrotron

Magnetized free electron:

$$d\mathbf{v}/dt = \mathbf{v} \wedge \Omega_c$$



electron rotation

Electron Cyclotron frequency

$$\Omega_c = -(e/m_0\gamma_0)\,\mathbf{B}$$

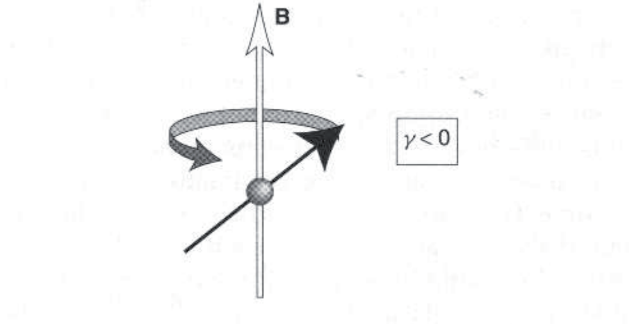
Wave-particle interaction

$$\mathbf{E}_{THz}(\mathbf{r},t) = E_{THz}(\mathbf{r})\exp(i\,\omega_{THz}\,t)$$

DNP/NMR sample

Magnetized free electron spin:

$$d\mu_S/dt = \mu_S \wedge \omega_S$$



Spin precession

Larmor frequency

$$\omega_S = -g_s\,(e/2m_e)\,\mathbf{B} = \gamma_S\,\mathbf{B}$$

$$g_s = 2.0024$$

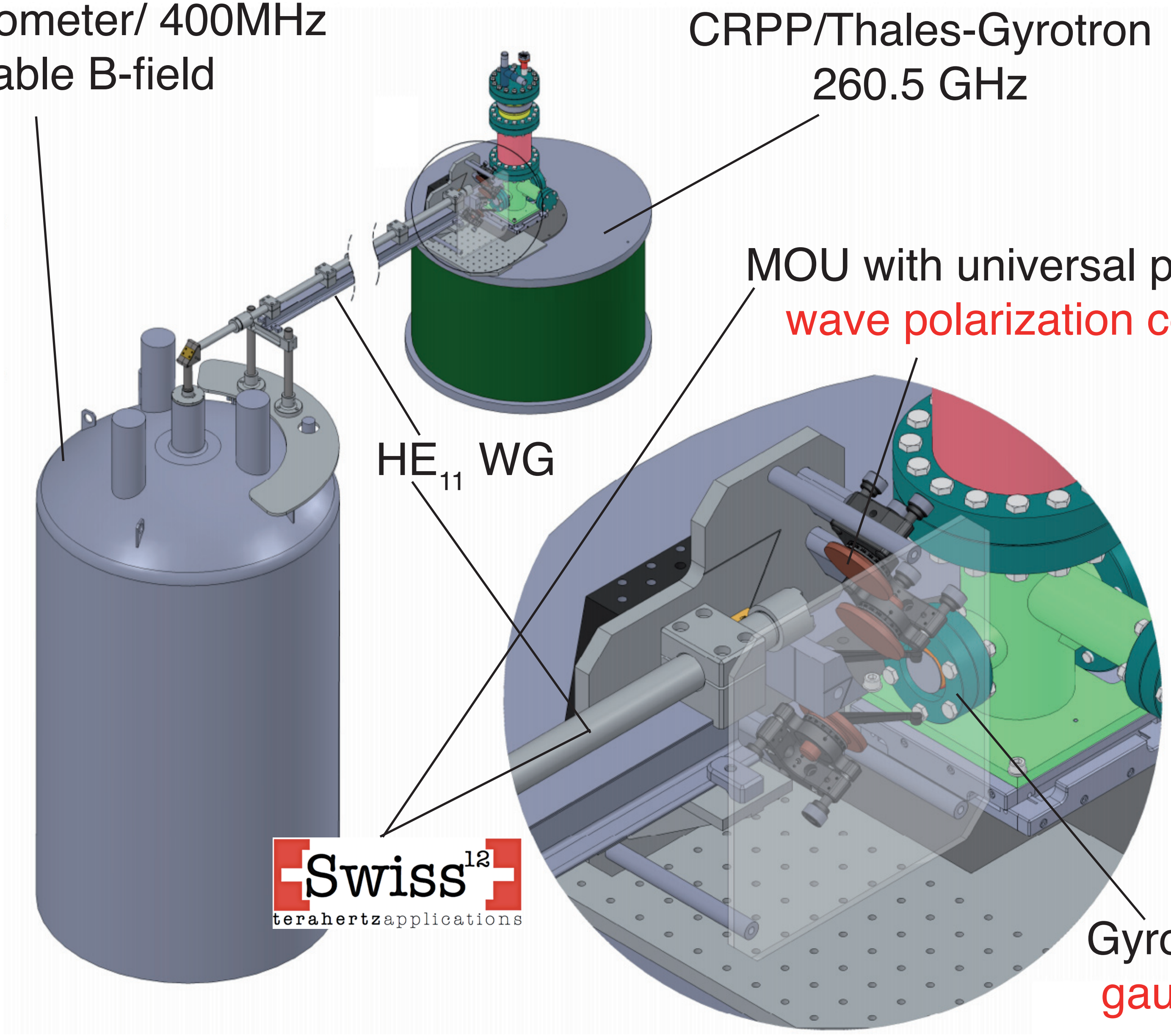
Wave-particle interaction

$$\mathbf{B}_{THz}(\mathbf{r},t) = B_{THz}(\mathbf{r})\exp(i\,\omega_{THz}\,t)$$

$$\Omega_c \approx \omega_{THz} \approx \omega_S$$

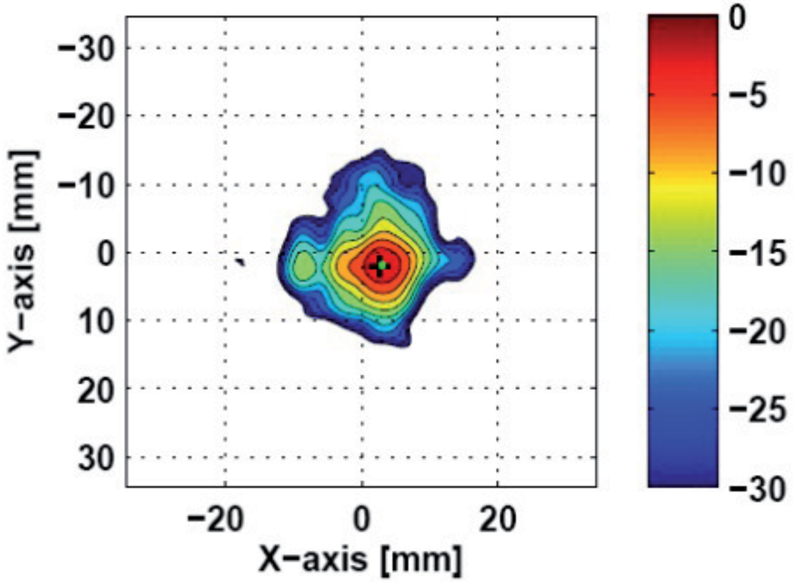
Figures from: M. Levitt, Spin dynamics, Wiley, (2002)

Frequency-tunable DNP/NMR (263GHz/400MHz) @ EPFL/LPMN

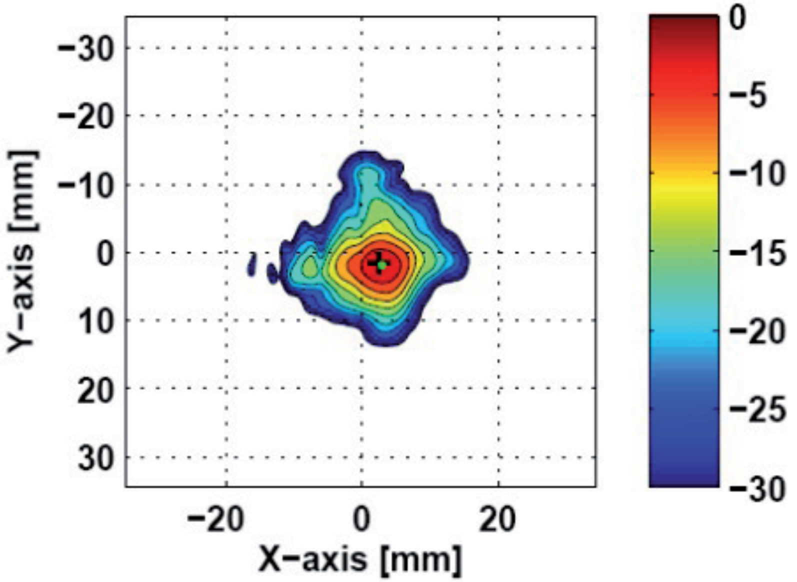


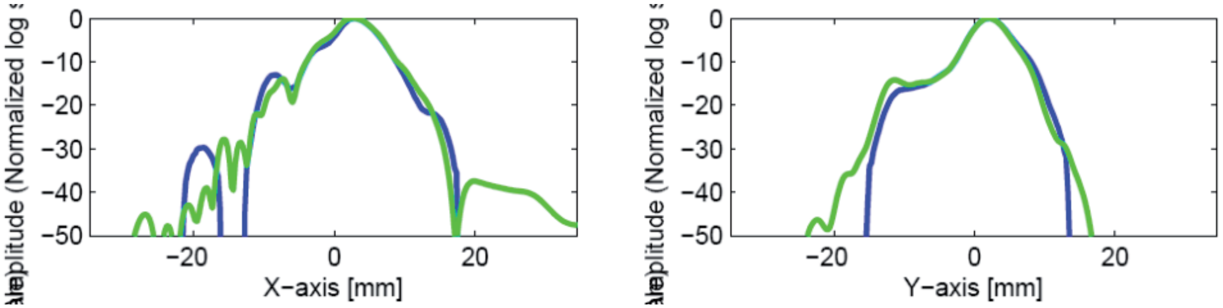
THz waves: quasi-optical propagation

Measured amplitude



Reconstructed amplitude

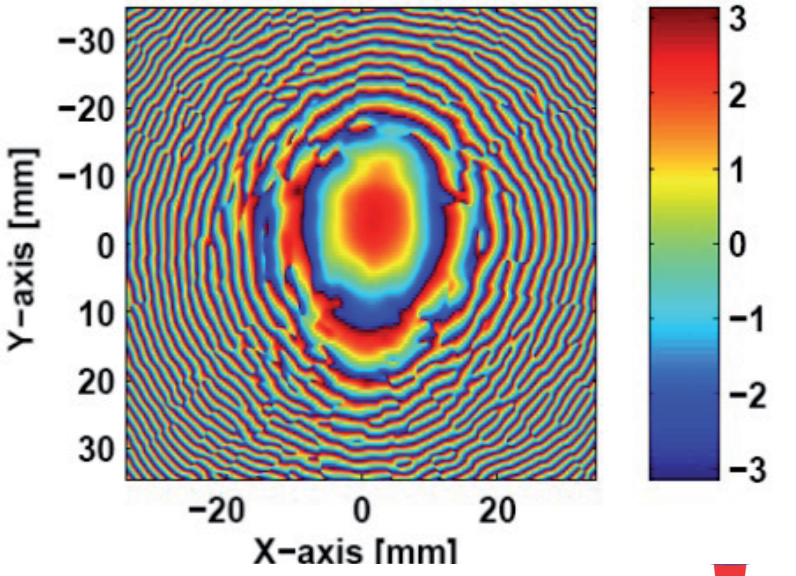




«Gaussian» beam with simple-astigmatism

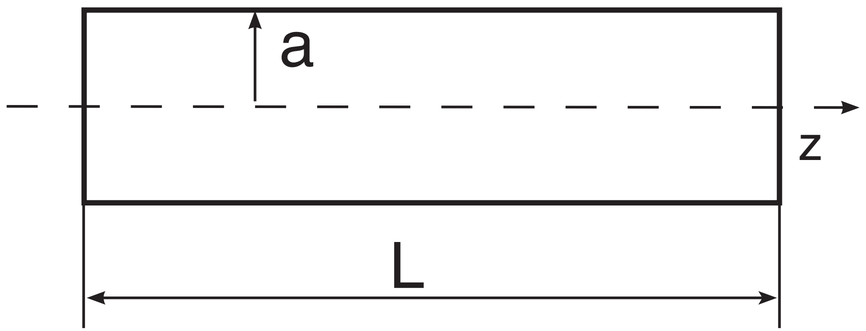
Phase reconstruction based on a diffraction-optics inverse problem

Reconstructed phase



TE mode in cylindrical closed cavity

Closed cylindrical cavity w/o losses



TE mode: $E_z = 0$

EM wave dispersion relation:

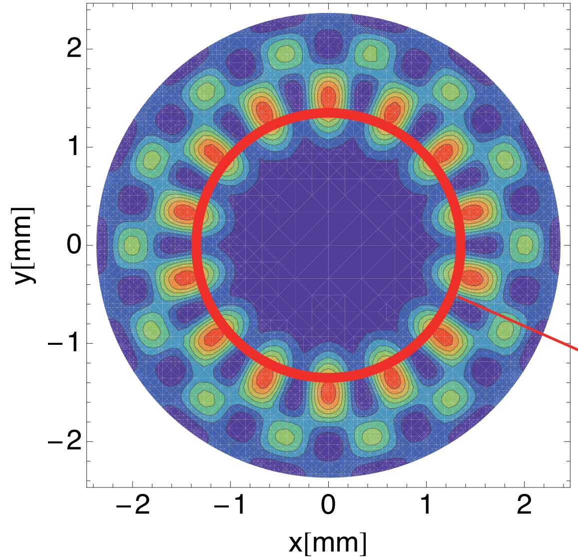
$$\omega = c\sqrt{k_\perp^2 + k_\parallel^2} \simeq ck_\perp$$

$$k_\perp = \frac{\nu_{nm}}{a}; \quad \mathbf{k}_\parallel = \frac{q\pi}{L}; \quad k_\perp \gg k_\parallel$$

$TE_{7,2}$

a = 2.693mm; L = 22mm

freq = 263GHz



annular electron beam

$$E_\theta(r,\theta,z) = E_0 \underbrace{J'_m(k_\perp r)\cos(m\theta)}_{\text{transverse eigenmode}} \underbrace{\sin(\frac{q\pi z}{L})}_{\substack{f_q(z) \\ \text{longitudinal eigenmode}}}$$

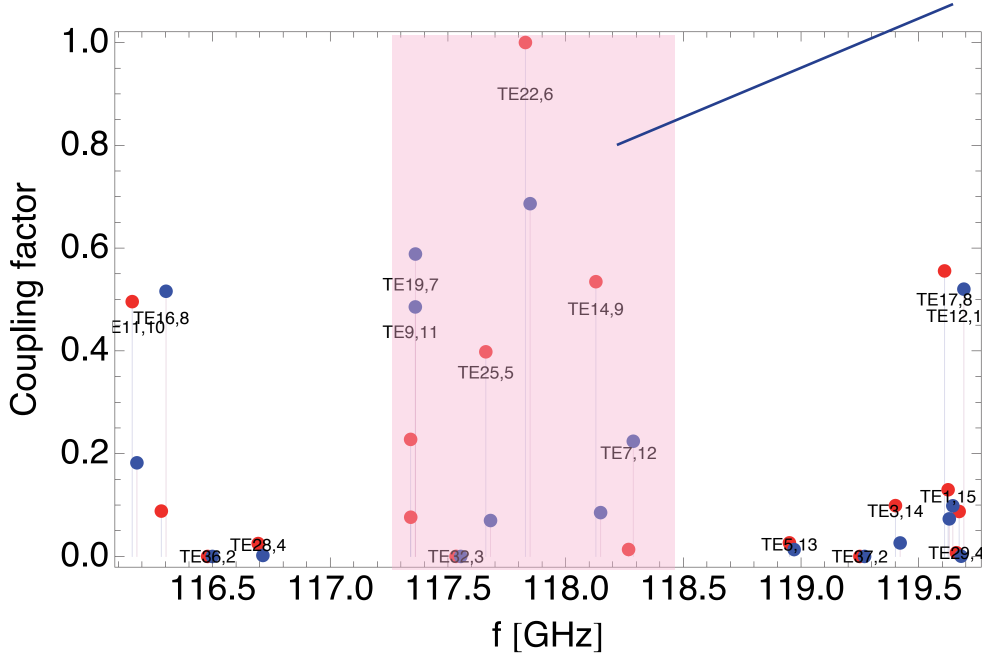
- For a given $TE_{m,n,q}$ mode, the frequency is essentially determined by the resonator radius, a

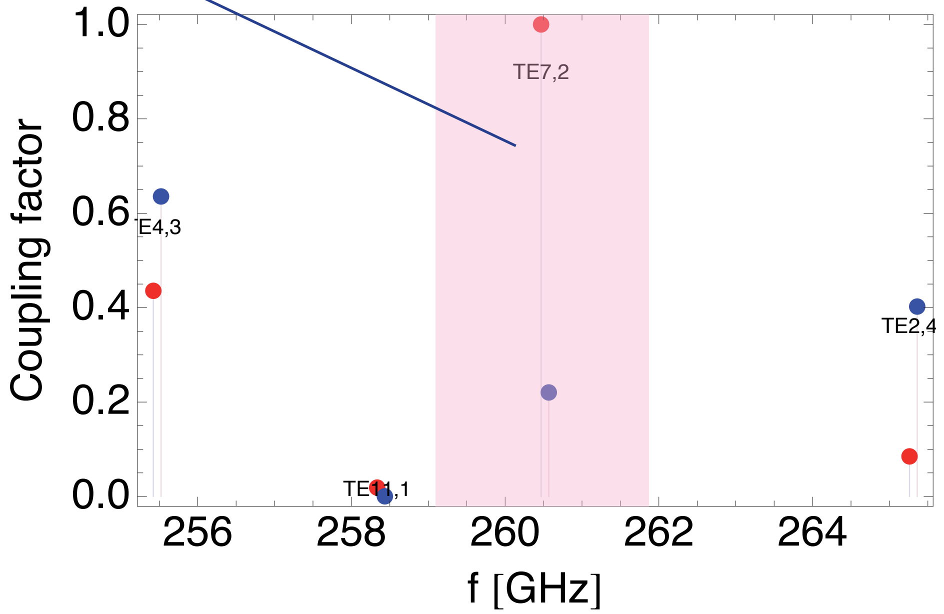
Density of transverse mode

High-Power gyrotron for fusion applications
$a/\lambda \approx 10\text{-}15$

DNP gyrotron
$a/\lambda \approx 2\text{-}3$

Instability bandwith $df/f \approx 1\%$





Multimode
dynamics dominated by
transverse mode competition $TE_{m,n}$

Single transverse mode (monomode)
dynamics dominated by
longitudinal mode competition $TE_{7,2,q}$

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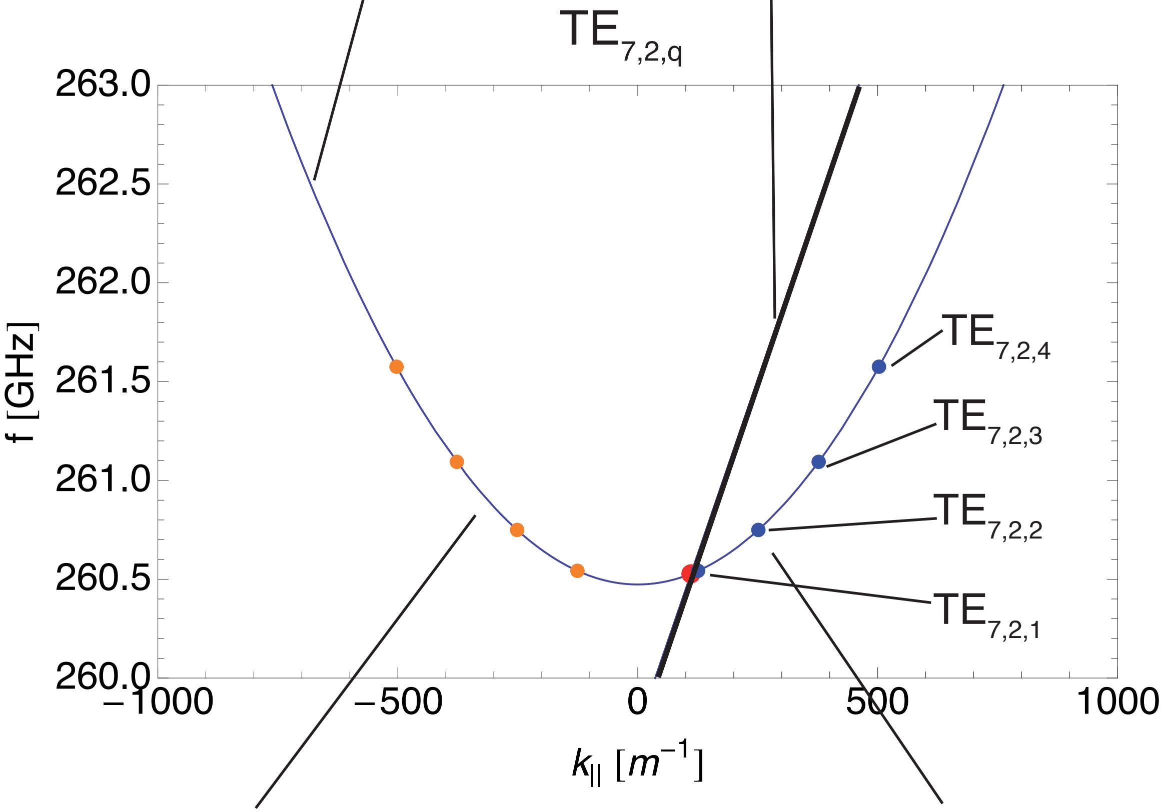
DNP Gyrotron: longitudinal mode competition

EM mode

beam mode

$$[\omega^2 - c^2(k_{\perp(m,n)}^2 + k_\parallel^2)][\omega - k_\parallel v_\parallel - s\Omega_c]^2 = 0$$

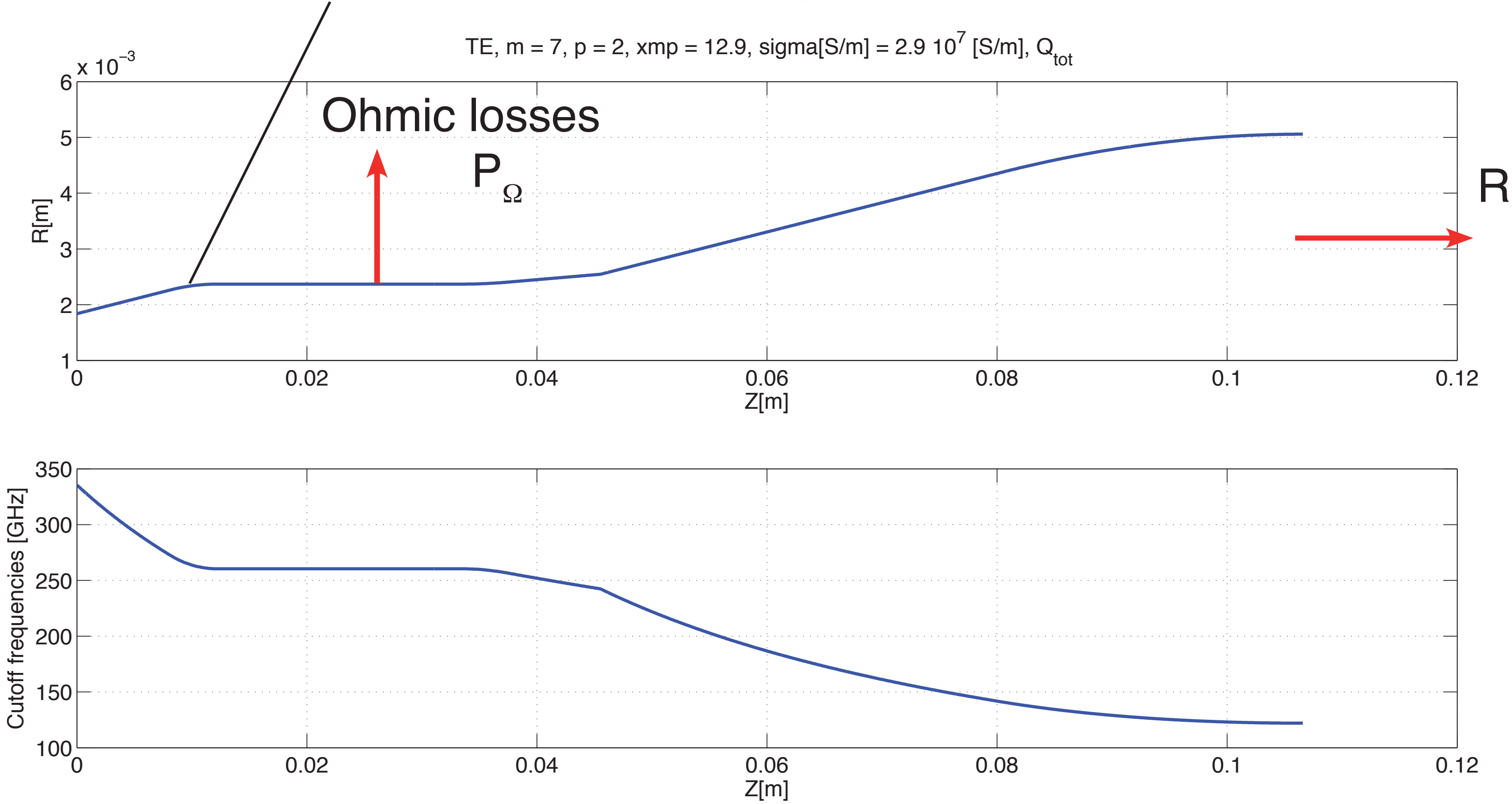


$k_\parallel < 0$, backward-wave
Gyro-BWO

$k_\parallel > 0$, forward-wave
Gyro-TWT

Open gyrotron resonator with radiation & ohmic losses

cavity radius:a = a(z) => finite & inhomogeneous system, finite conductivity σ



Ohmic losses

P_Ω

Radiation losses

$P_{RF} = P_{rad}$

DNP-gyrotron

$P_\Omega \approx P_{rad}$

Longitudinal profile f(z) of EM field solution of eigenvalue problem:

$$dW_{EM}/dt + (\omega/Q)\, W_{EM} = 0$$

$$W_{EM}(t) = W_{EM}(0)\exp(-t/\tau_c)$$

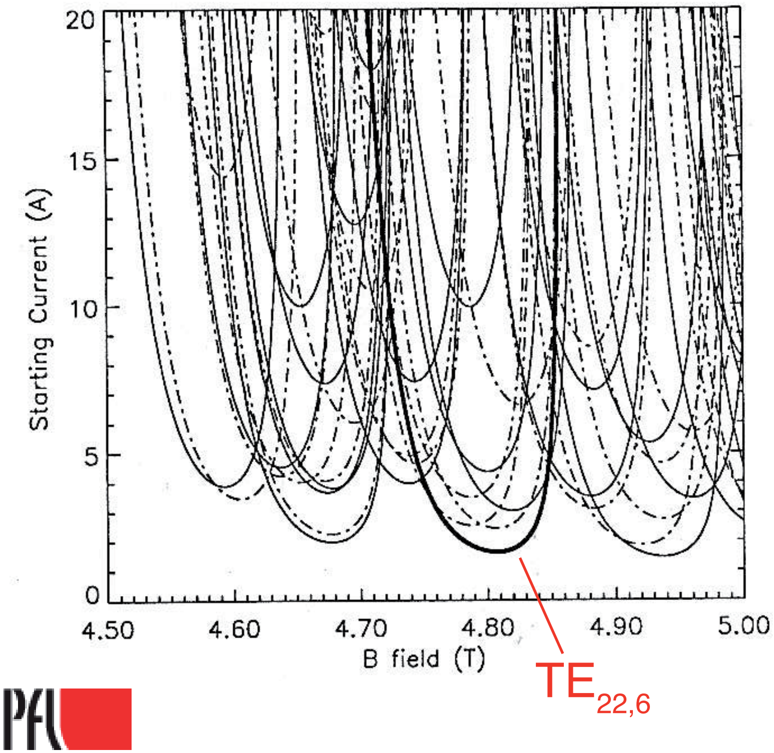
Linear regime: starting current

Gain has to overcome losses

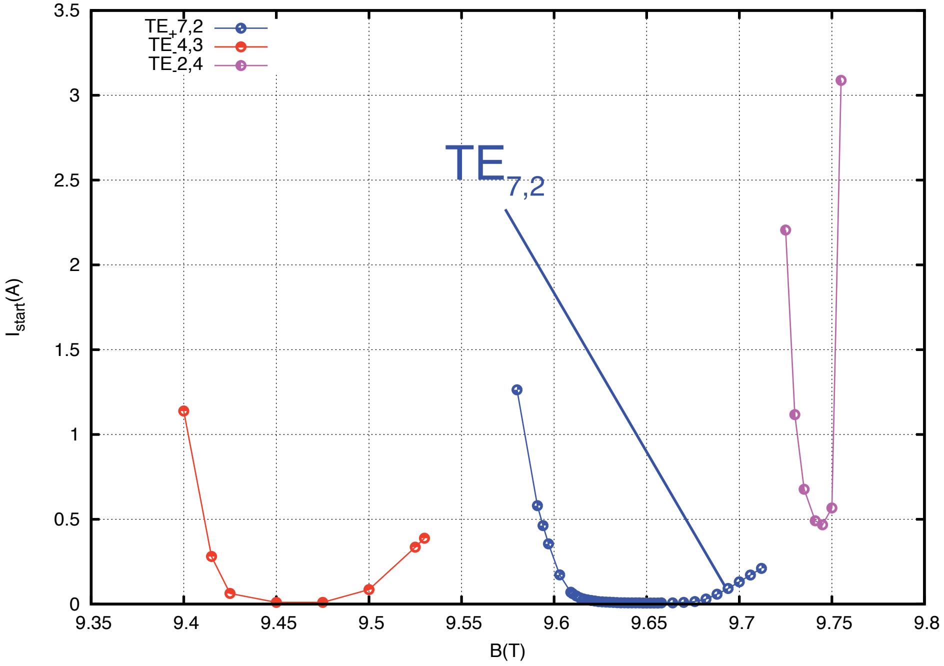
$$dW_{EM}/dt + (\omega/Q)\, W_{EM} = \mathrm{Gain}(I_b)\, W_{EM}$$

Starting current curves $I_{st}(B)$ (fixed $L, \gamma_0, \ldots$)

High-power gyrotron



DNP/NMR Gyrotron



Time scales in THz-gyrotron dynamics

- Electron cyclotron period

  $\tau_{cycl} = 2\pi\, m_0\gamma/eB_0 \approx 1\text{-}10\,\mathrm{ps}$

- Non-linear longitudinal mode competition

  $\tau_{non\text{-}lin} = 2\tau_w \approx 1\text{-}5\,\mathrm{ns}$

- Linear instability growth time

  $\tau_{lin} = Q/\omega/(I_b/I_{st} - 1) \approx 10\text{-}100\,\mathrm{ns}$

- Start-up conditions and ext. parameters control

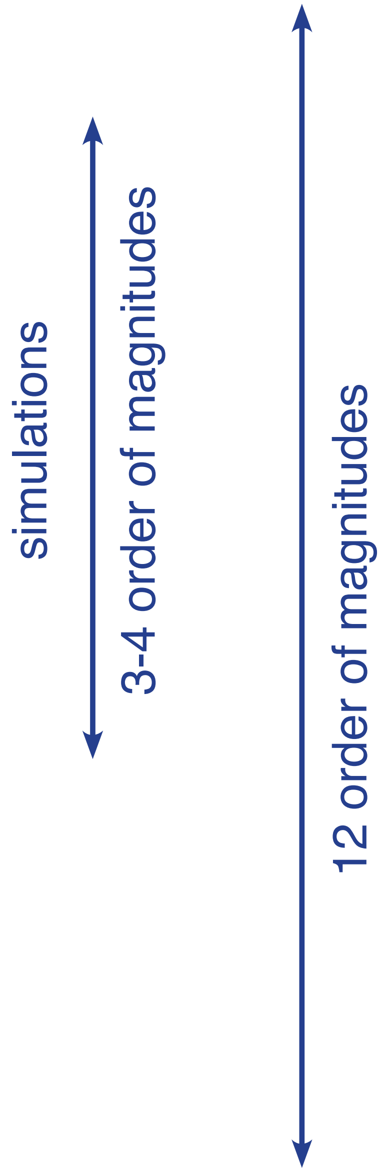
  $\tau_{ext} \approx 1\,\mu\mathrm{s}\text{-}1\,\mathrm{ms}$

- Electron-beam space-charge neutralization

  $\tau_{sc} = 1/n_n\sigma v_b \approx 10\text{-}100\,\mathrm{ms}$

- Cavity thermo-mechanical effects

  $\tau_{thermal} \approx 100\text{-}500\,\mathrm{ms}$



simulations

3-4 order of magnitudes

12 order of magnitudes

Gyrotron modeling

- General comment: in gyrotrons we are dealing with strongly overmoded electromagnetic structures ($\lambda << a$). This implies that commercially available finite-elements and/or PIC codes are practically unusable.

- 2.5D/3D Electron beam optics codes.

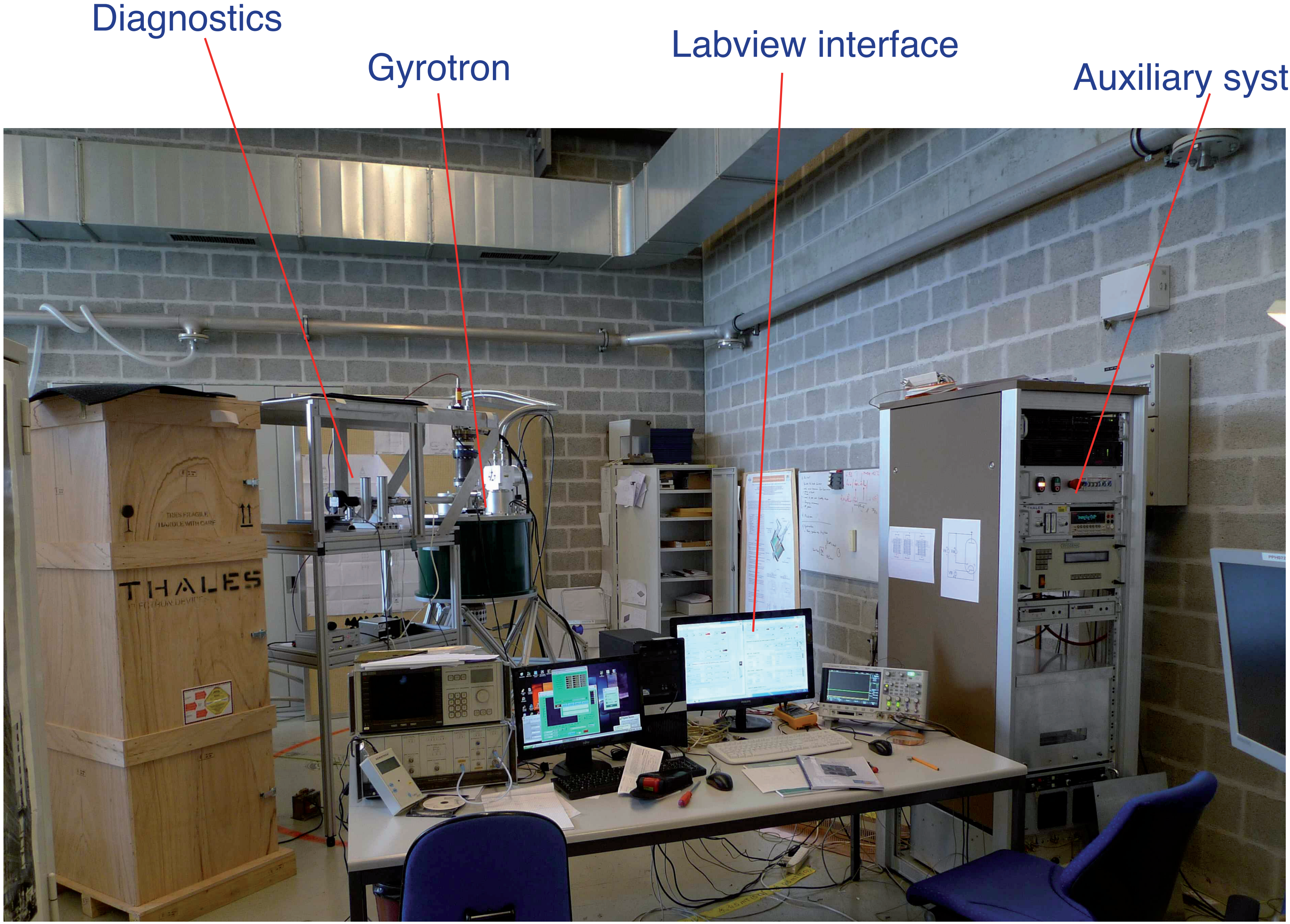
Electrostatic space-charge effects are essential for characterizing the e-beam properties in the cavity.

- Cyclotron-wave interaction.
  - -Self-consistent monomode interaction codes.
  - -Self-consistent multimode interaction codes.
  - -Specific models for studying spurious oscillations.

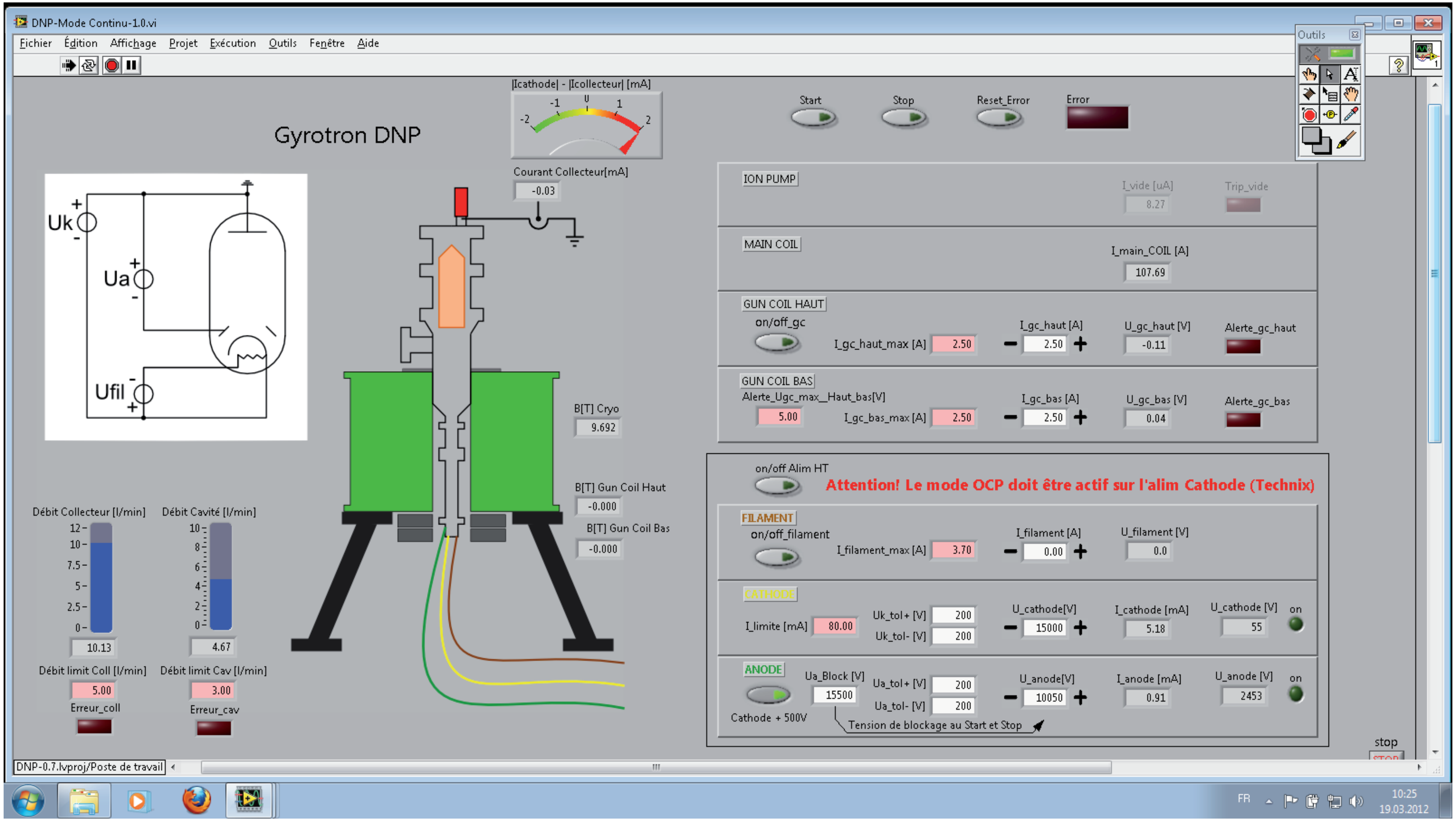
- Quasi-optical converter.

Efficient conversion of a cavity TE-eigenmode to the fundamental eigenmode in free-space propagation (gaussian beam). Diffraction-optics models.

System integration



LabView Control and protection system



Courant Collecteur[mA] -0.03

B[T] Cryo 9.692

B[T] Gun Coil Haut -0.000

B[T] Gun Coil Bas -0.000

Débit Collecteur [l/min] 10.13

Débit Cavité [l/min] 4.67

Débit limit Coll [l/min] 5.00

Débit limit Cav [l/min] 3.00

I_vide [uA] 8.27

I_main_COIL [A] 107.69

I_gc_haut_max [A] 2.50

I_gc_haut [A] 2.50

U_gc_haut [V] -0.11

Alerte_Ugc_max__Haut_bas[V] 5.00

I_gc_bas_max [A] 2.50

I_gc_bas [A] 2.50

U_gc_bas [V] 0.04

Attention! Le mode OCP doit être actif sur l'alim Cathode (Technix)

I_filament_max [A] 3.70

I_filament [A] 0.00

U_filament [V] 0.0

I_limite [mA] 80.00

Uk_tol+ [V] 200

Uk_tol- [V] 200

U_cathode[V] 15000

I_cathode [mA] 5.18

U_cathode [V] 55

Ua_Block [V] 15500

Ua_tol+ [V] 200

Ua_tol- [V] 200

U_anode[V] 10050

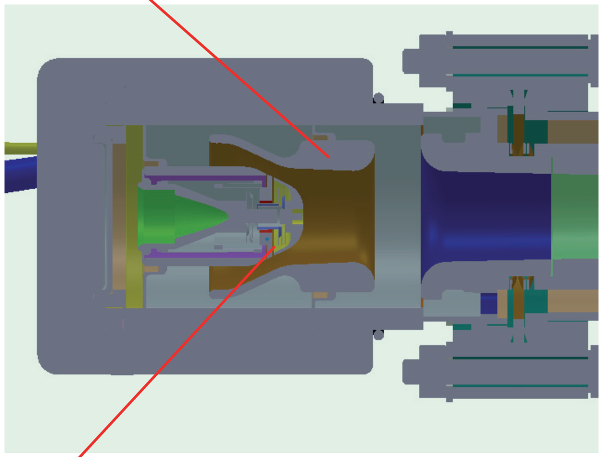
I_anode [mA] 0.91

U_anode [V] 2453

Control parameters

Triode MIG-gun

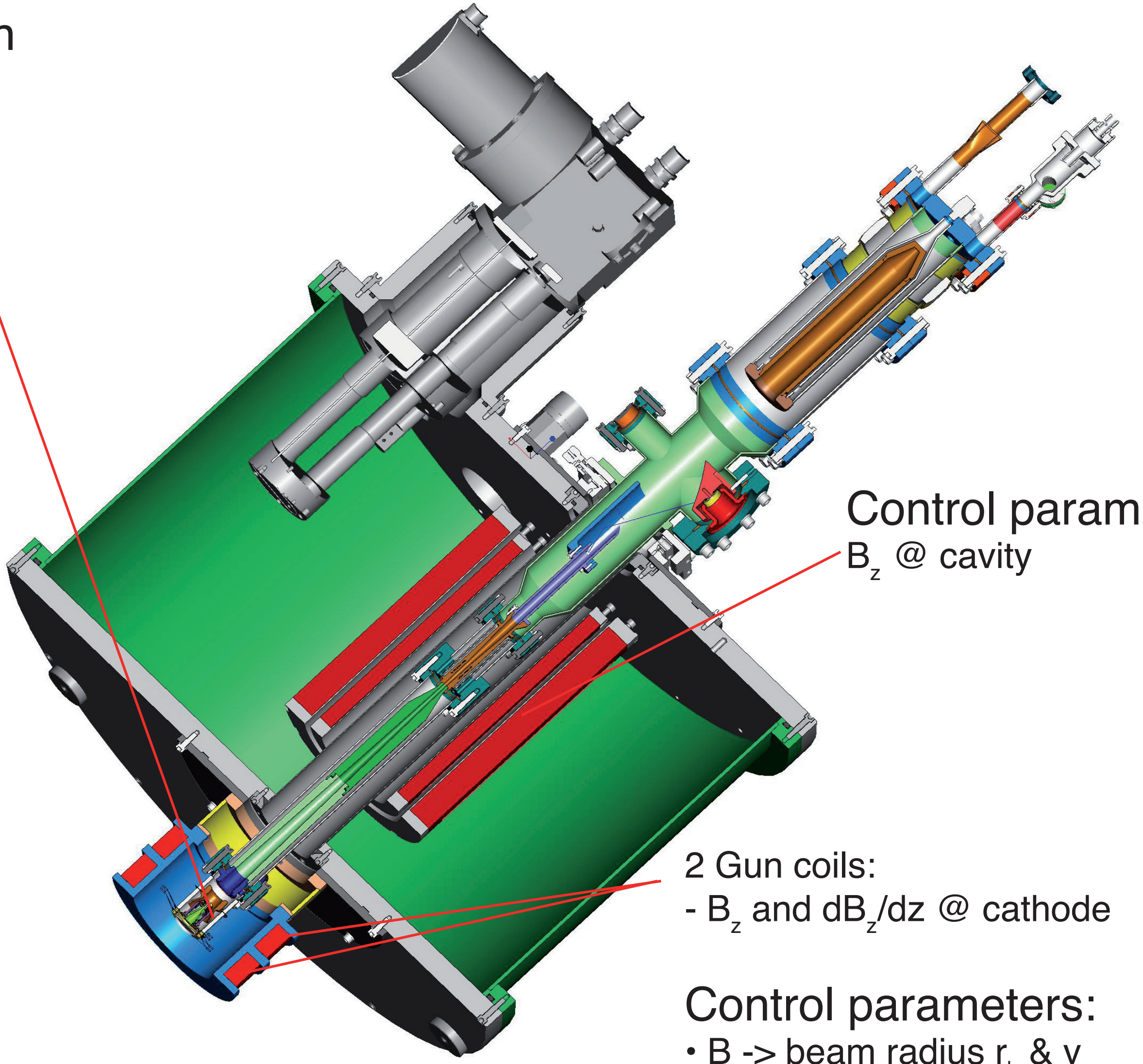
Anode:
- anode voltage, V_a



Cathode:
- cathode temperature T_{cath}
- cathode voltage, V_b
- anode voltage, V_a

Control parameters:

- T_{cath} -> beam current I_b
- V_b -> beam energy, γ
- V_a -> pitch angle, $\alpha = v_\perp / v_{\parallel}$



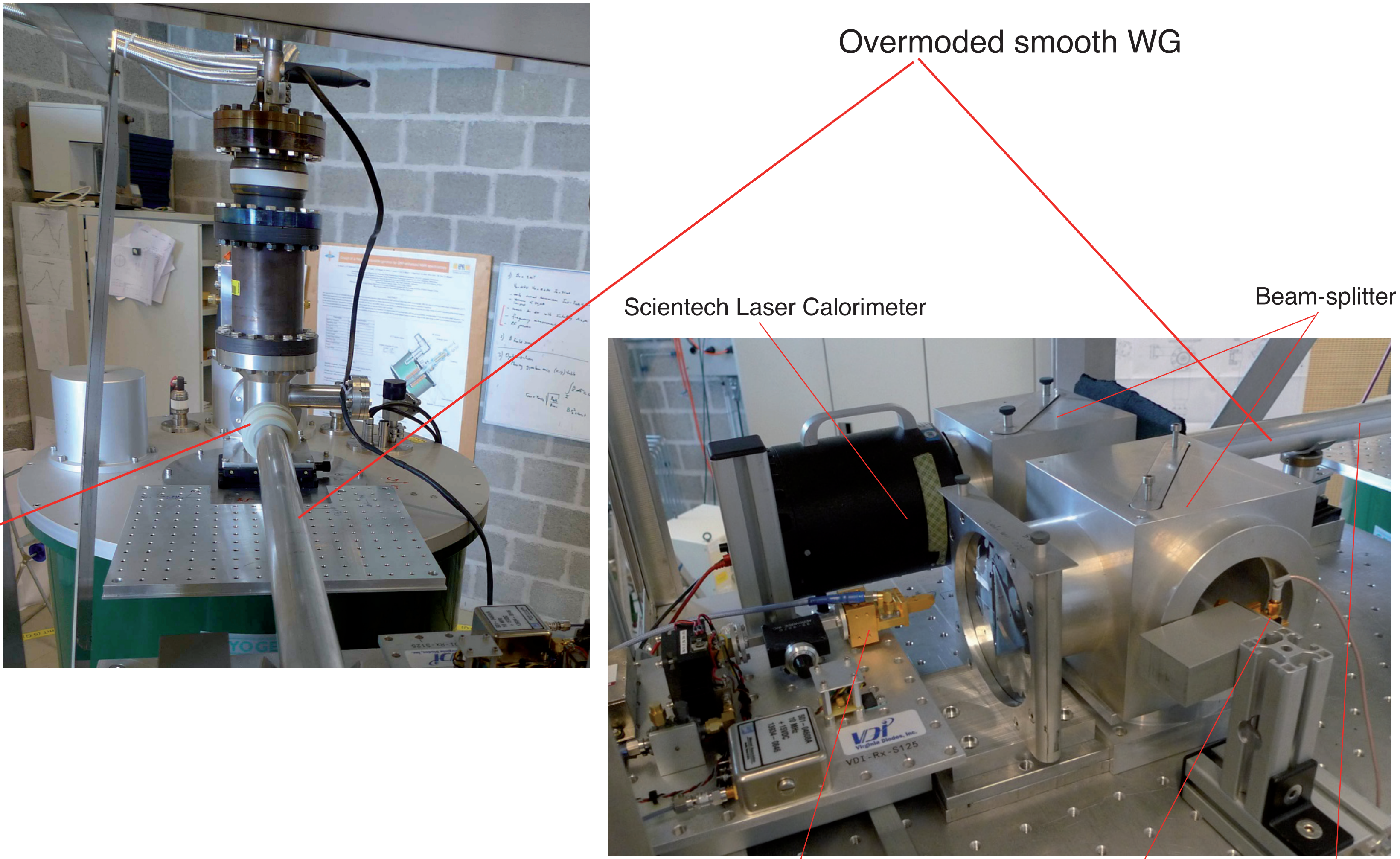
Control parameter:
B_z @ cavity

2 Gun coils:
- B_z and dB_z/dz @ cathode

Control parameters:

- B_z -> beam radius r_b & v_{perp}
- dB_z/dz -> T_{perp} (spread)

DNP-gyrotron Diagnostics



Overmoded smooth WG

gyrotron window

Scientech Laser Calorimeter

Beam-splitter

VDI heterodyne receiver

VDI Schottky diode

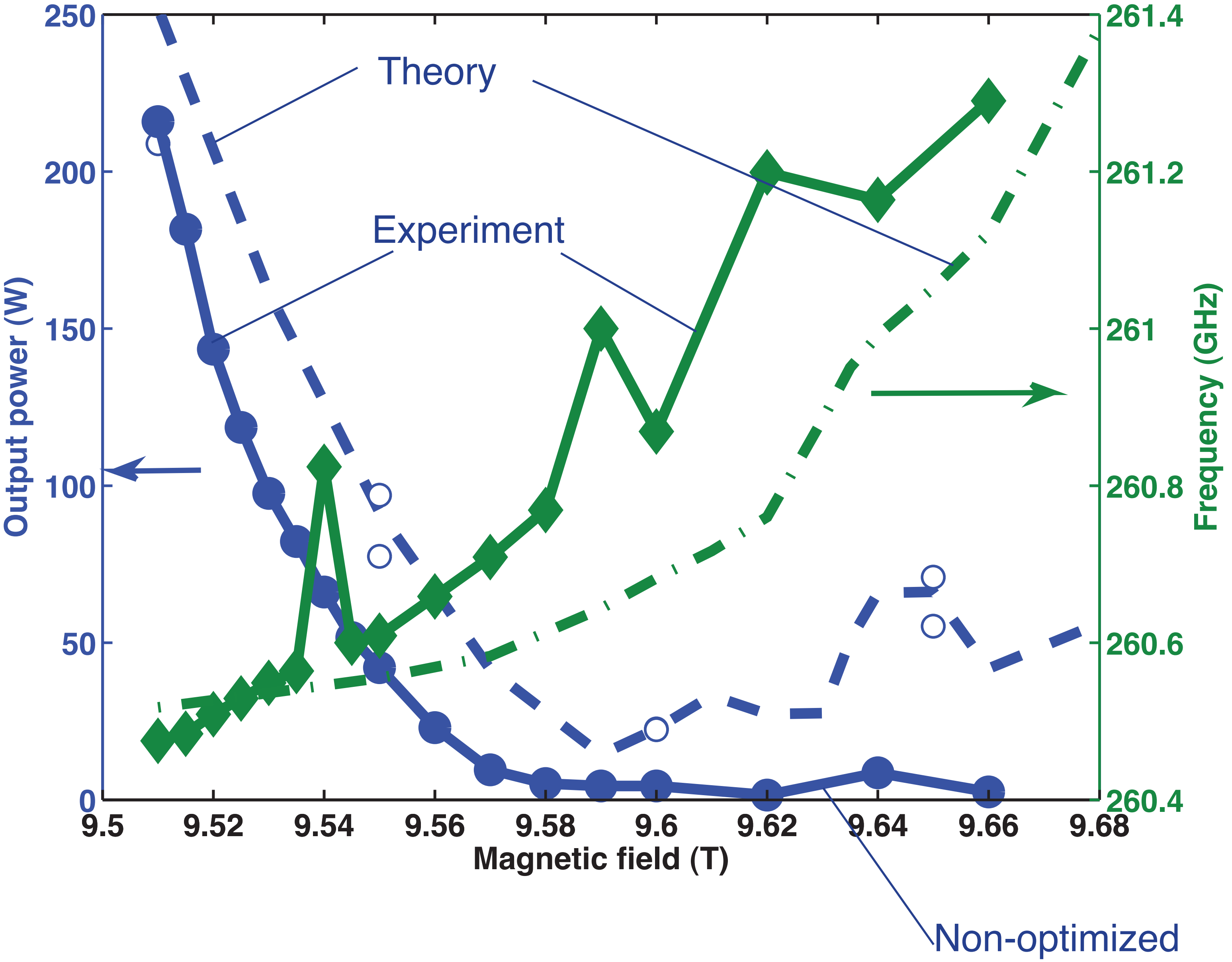
Overmoded WG

Bandwidth: DC-20GHz

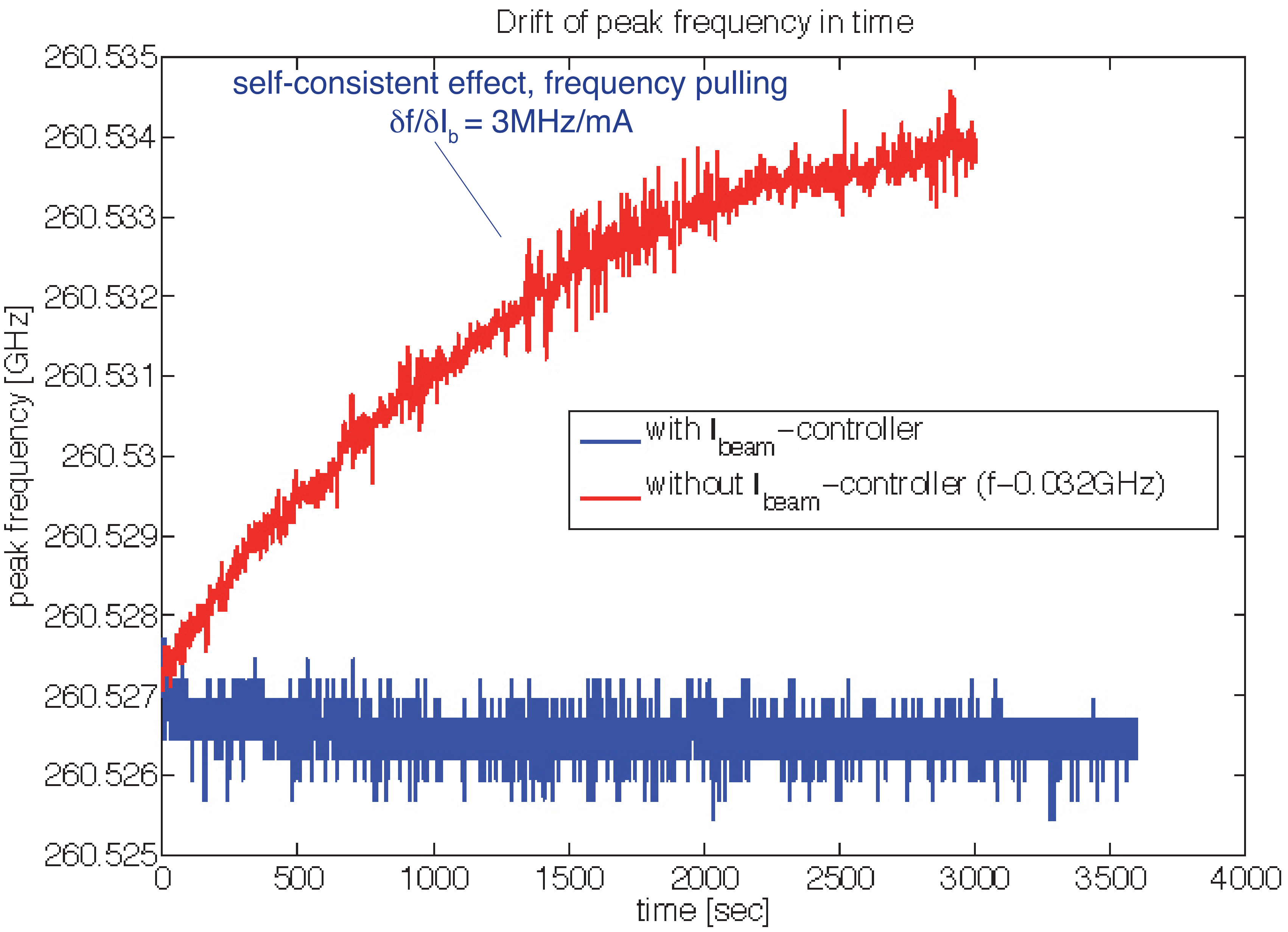
Technology of low-power high-frequency CW gyrotron

- First prototype designed by CRPP and manufactured by Thales
- After installation, t_0, first electron beam obtained after ~ t_0 + 4h
- First RF obtained after ~ t_0 + 6h
- Conditioning to CW operation ~ t_0 + 36h
- CW operation (>1h) routinely obtained with nearly no outgassing (2μA cathode heating, 0.3-0.5μA in CW at nominal parameters)
- Arcing events practically inexistent and the gyrotron CW and/or pulsed operation is extremely easy and reliable

RF power & frequency versus versus cavity B field

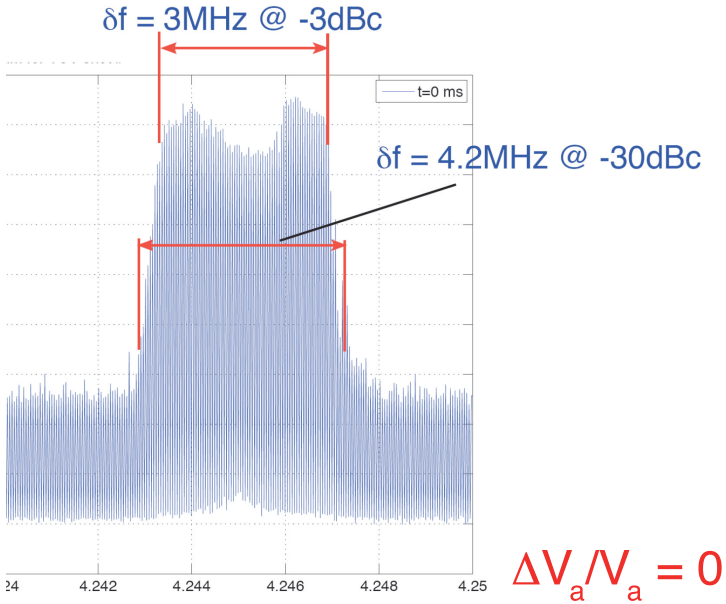


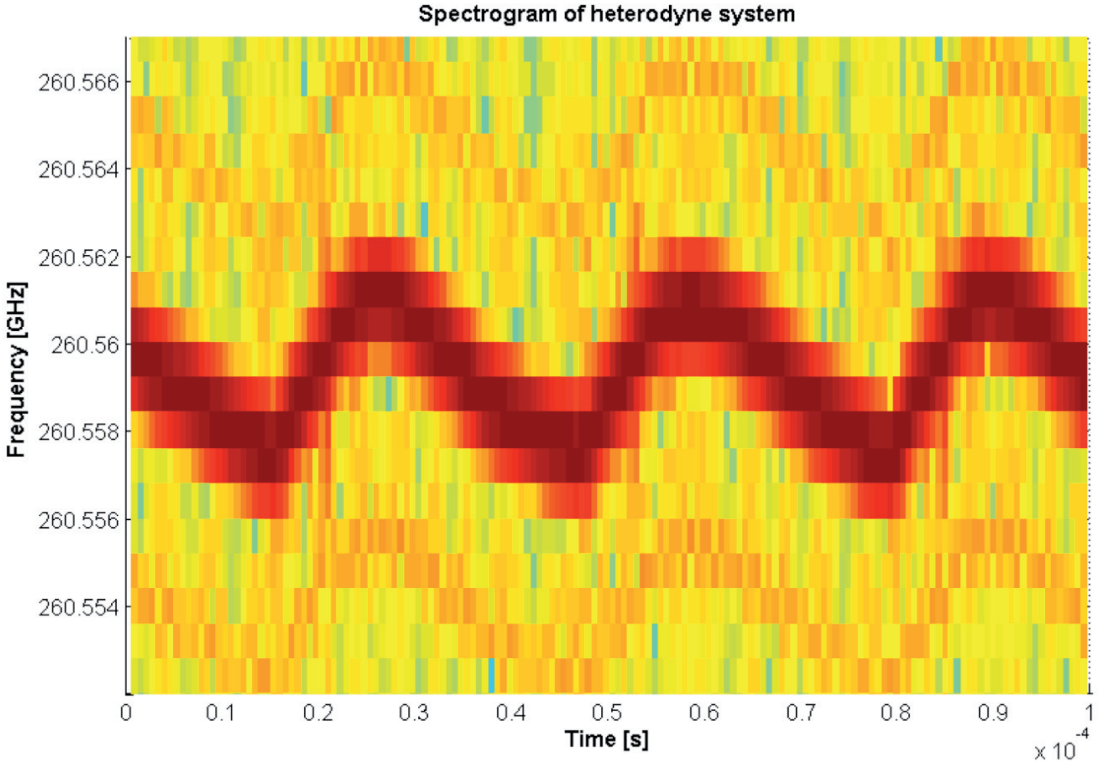
Stabilized frequency with PI controller on beam current

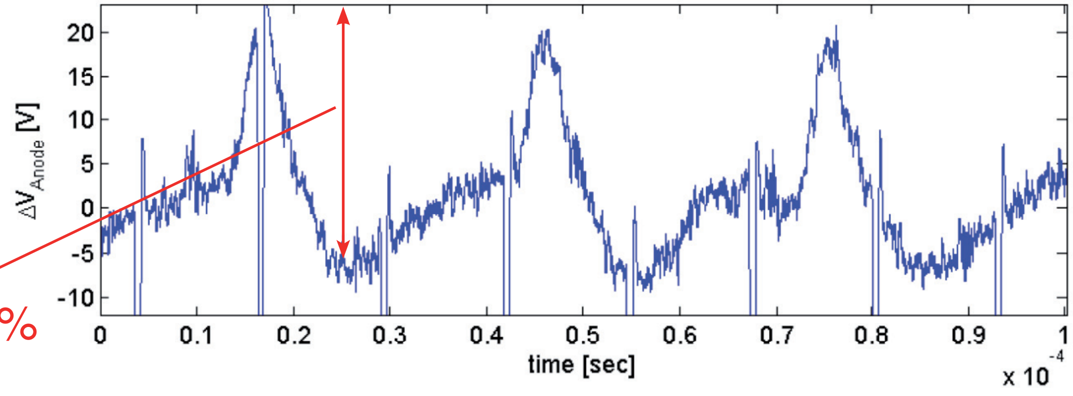


Radiation Spectral properties

- Time-averaging in spectrum analyzer over fluctuating frequency
- Fluctuation of anode-voltage causes ‘frequency-pulling’ (synchronous)

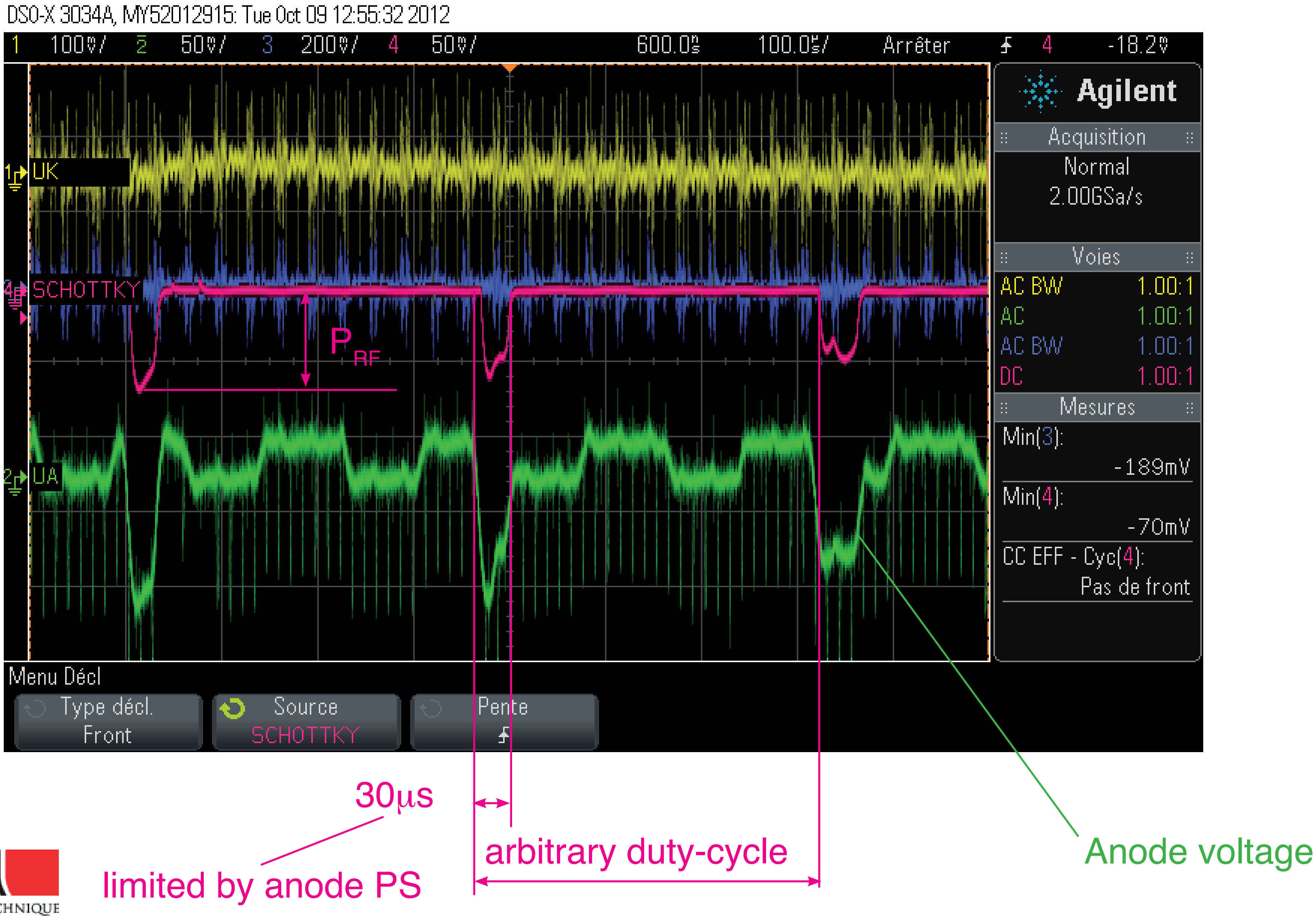






$\Delta V_a / V_a = 0.3\%$

Pulsed mode with anode control: 30μs to DC



DSO-X 3034A, MY52012915: Tue Oct 09 12:55:32 2012

1 100mV/ 2 50mV/ 3 200mV/ 4 50mV/ 600.0us 100.0us/ Arrêter 4 -18.2mV

Acquisition
Normal
2.00GSa/s

Voies
AC BW 1.00:1
AC 1.00:1
AC BW 1.00:1
DC 1.00:1

Mesures
Min(3): -189mV
Min(4): -70mV
CC EFF - Cyc(4): Pas de front

Menu Décl
Type décl. Front
Source SCHOTTKY
Pente

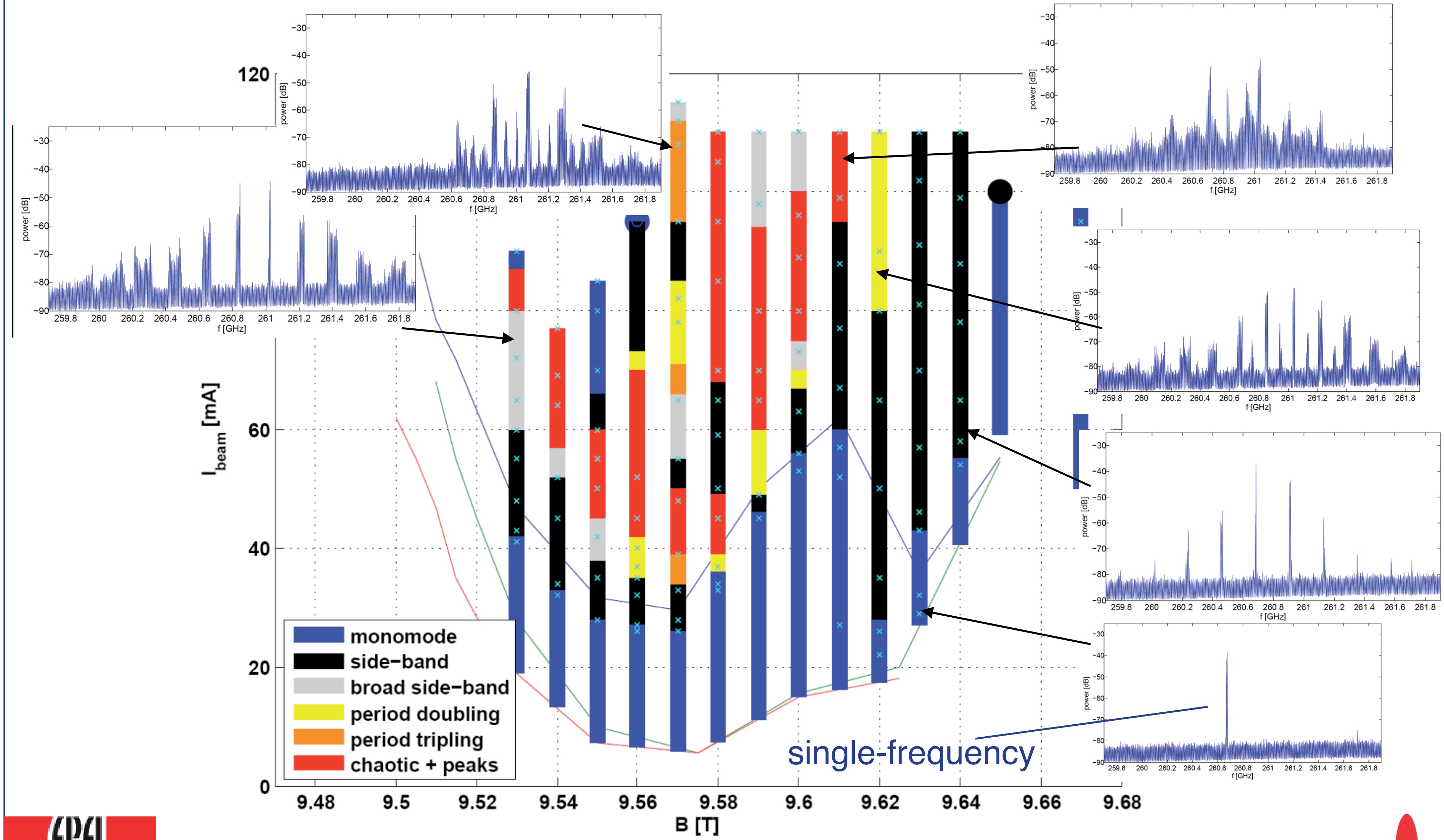
30μs

limited by anode PS

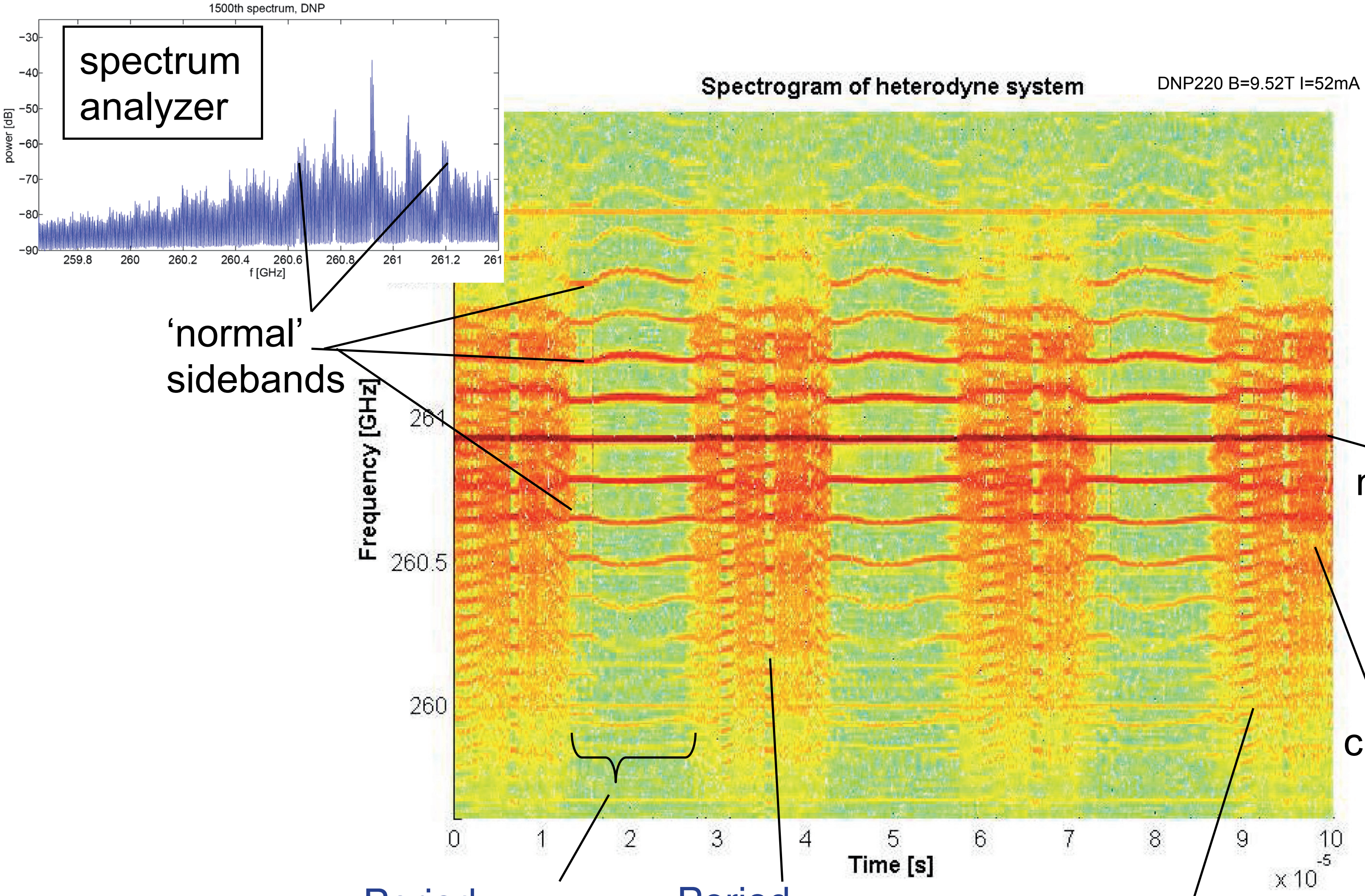
arbitrary duty-cycle

Anode voltage

From linear to chaotic regimes



Chaos via period doubling cascade



‘normal’ sidebands

main peak

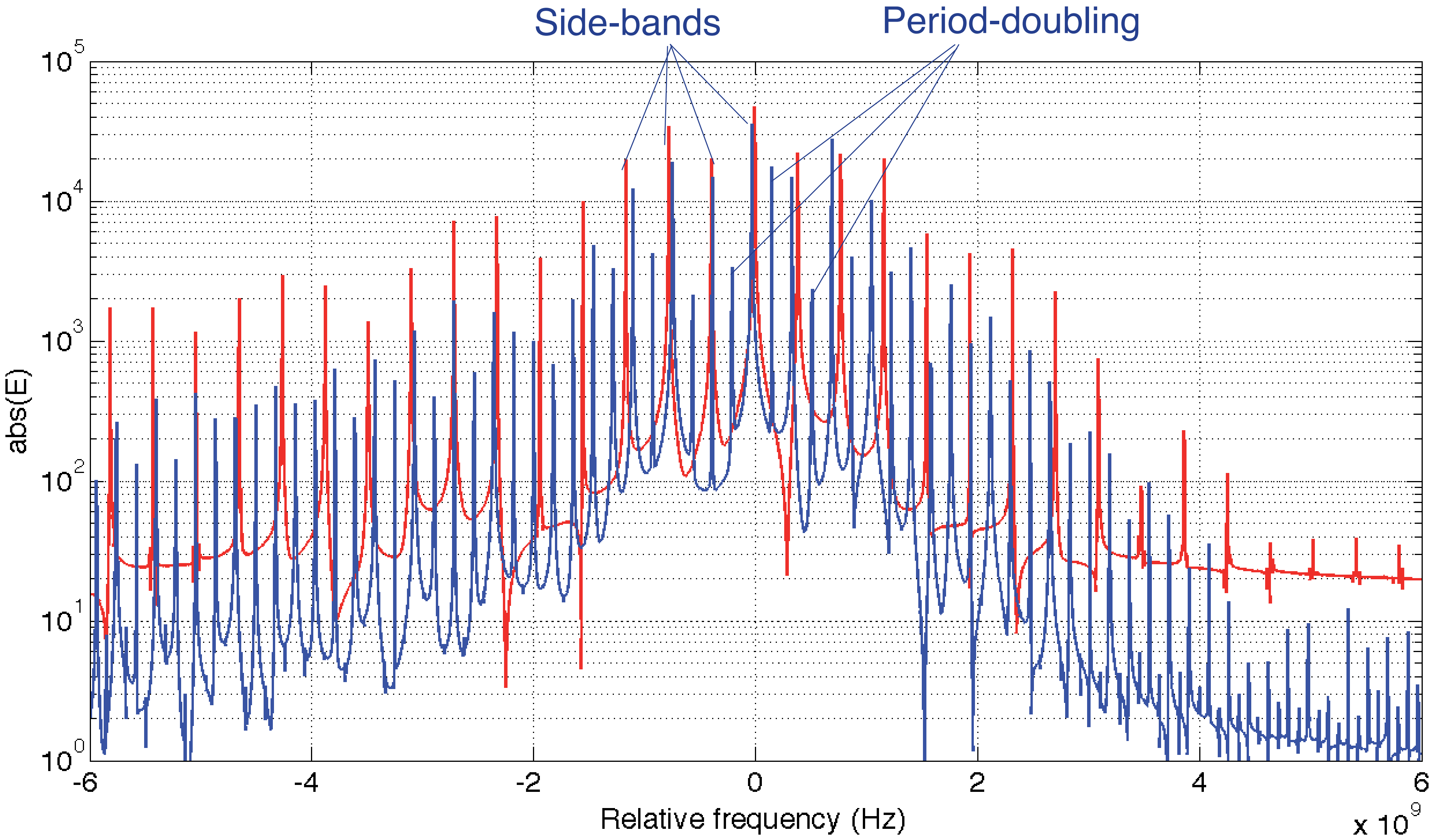
chaotic

Period doubling

Period tripling

Period quintupling

Numerical simulations with TWANG



Future prospects

- Short-pulse regime (< 1ns) will be investigated both experimentally and theoretically.
- Phase locking with priming will be investigated
- The DNP-gyrotron will be integrated in the NMR spectrometer at LPMN in the next months.
- The modular design concept eventually allows to study different cavity concepts at the fundamental (263GHz) or 2nd cyclotron (526GHz) harmonics.

Conclusions

- For DNP/NMR experiments on a variable field NMR system the present gyrotron fulfills the requirements.
- Novel operational regimes intrisically related to the strongly non-linear dynamics have been experimental investigated.
- Advanced modeling of the non-linear dynamics has been extensively validated
- Novel operational regimes with side-bands may open up new applications for gyrotrons.