TRANSVERSE MODE-COUPLING INSTABILITY IN THE CERN SUPER PROTON SYNCHROTRON

E. Métral and G. Arduini, E. Benedetto, H. Burkhardt, E. Shaposhnikova (CERN), G. Rumolo (GSI)

- **Comparison between**
  - **Theory ⟹ "Several" analytical formalisms for fast instabilities**
  - **Simulations**
    - **MOSES** ⟹ Program computing the coherent modes
    - **HEADTAIL** ⟹ PIC code simulating single-bunch phenomena
- **Measurements of TMCI in the CERN SPS in 2003**
- **SPS impedance estimate and TMCI threshold with MOSES vs. years**

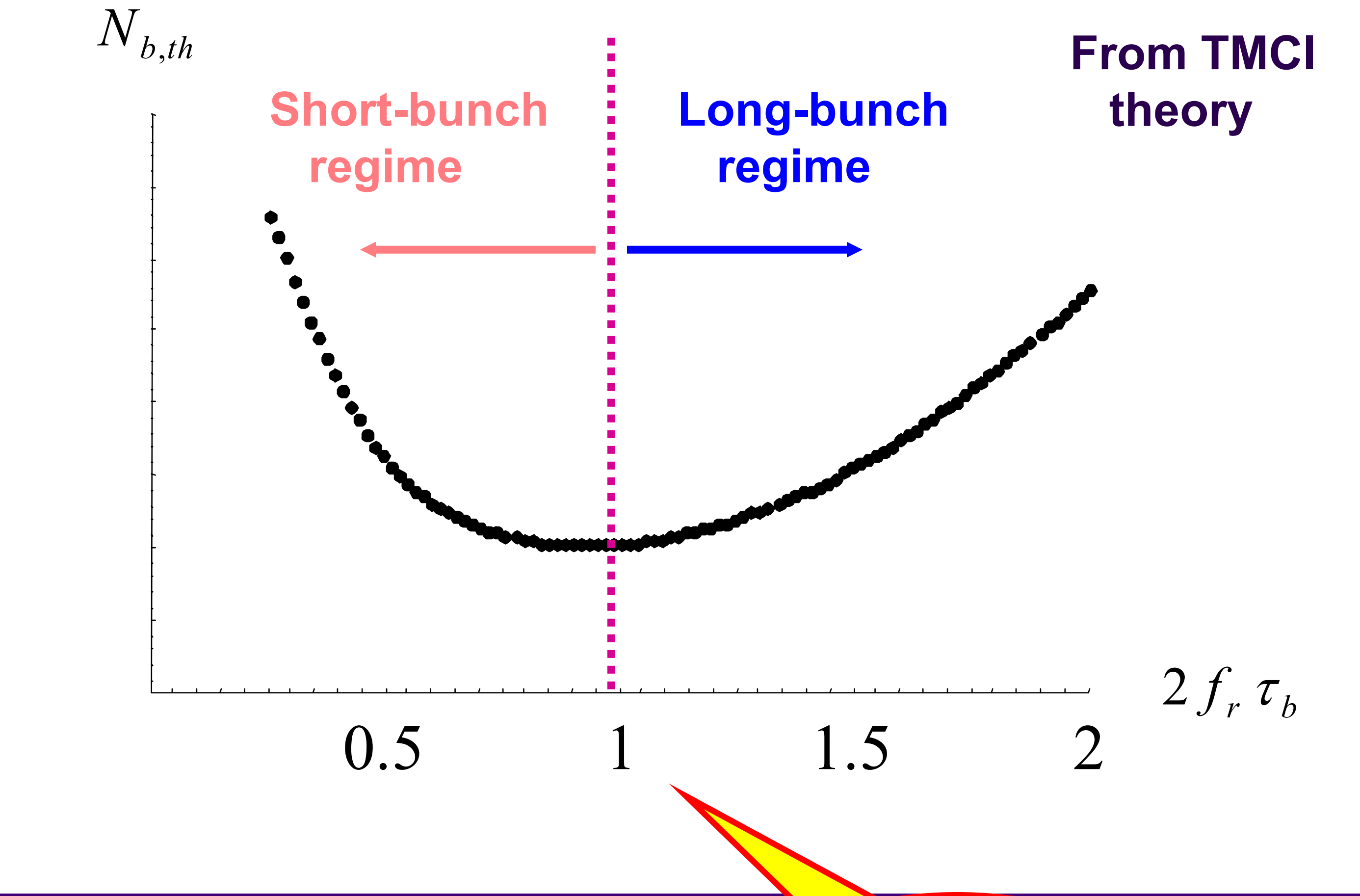
THEORY (1/3)

- **The same formula is obtained (within a factor smaller than 2) from 5 seemingly diverse formalisms for a broad-band resonator impedance (Q = 1) :**
  - **Coasting-beam approach with peak values**
  - **Fast blow-up (Ruth and Wang)**
  - **Beam break-up (Brandt and Gareyte , for 0 chromaticity)**
  - **Post head-tail (Kernel et al.)**
  - **TMCI with 2 modes in the "long-bunch" regime (Zotter, for 0 chromaticity)**

$$N_b \leq \frac{32\sqrt{2}}{3} \times \frac{Q_y \left| \eta \right| \varepsilon_l \, f_r}{e \, \beta^2 \, c \left| Z_y^{BB} \right|} \times \left(1 + \frac{f_{\xi_y}}{f_r} \right)$$

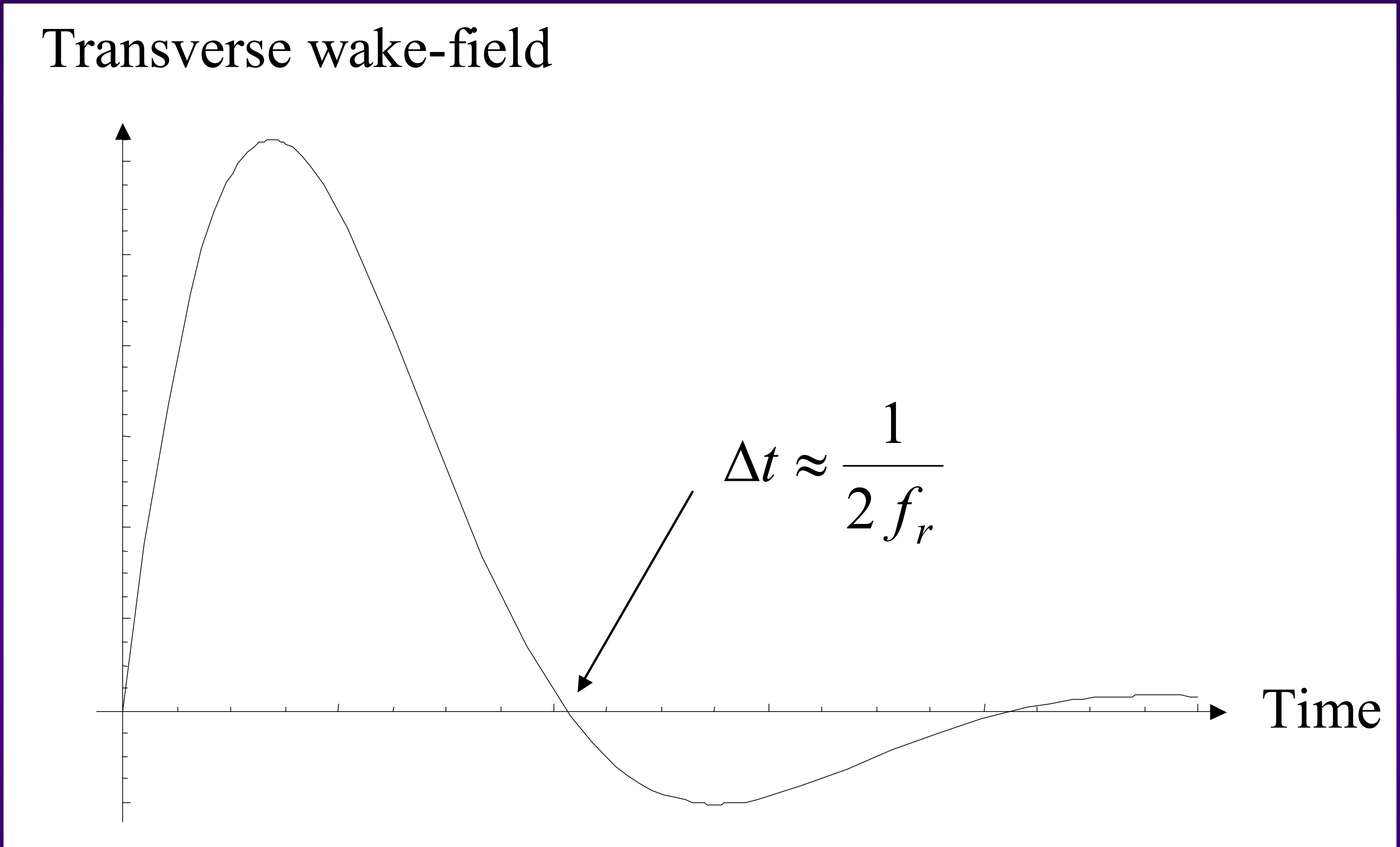
Coasting-beam approach (parabolic bunch)

THEORY (2/3)



$$\tau_b^{min} \approx \frac{1}{2 f_r}$$

THEORY (3/3)



SIMULATIONS (1/4)

- **Broad-band impedance resonator assumed**

f_r $Q_r = 1$

$Z_r = 20\ \mathrm{M\Omega/m}$

- **Numerical values**

$Q_y = 26.13$

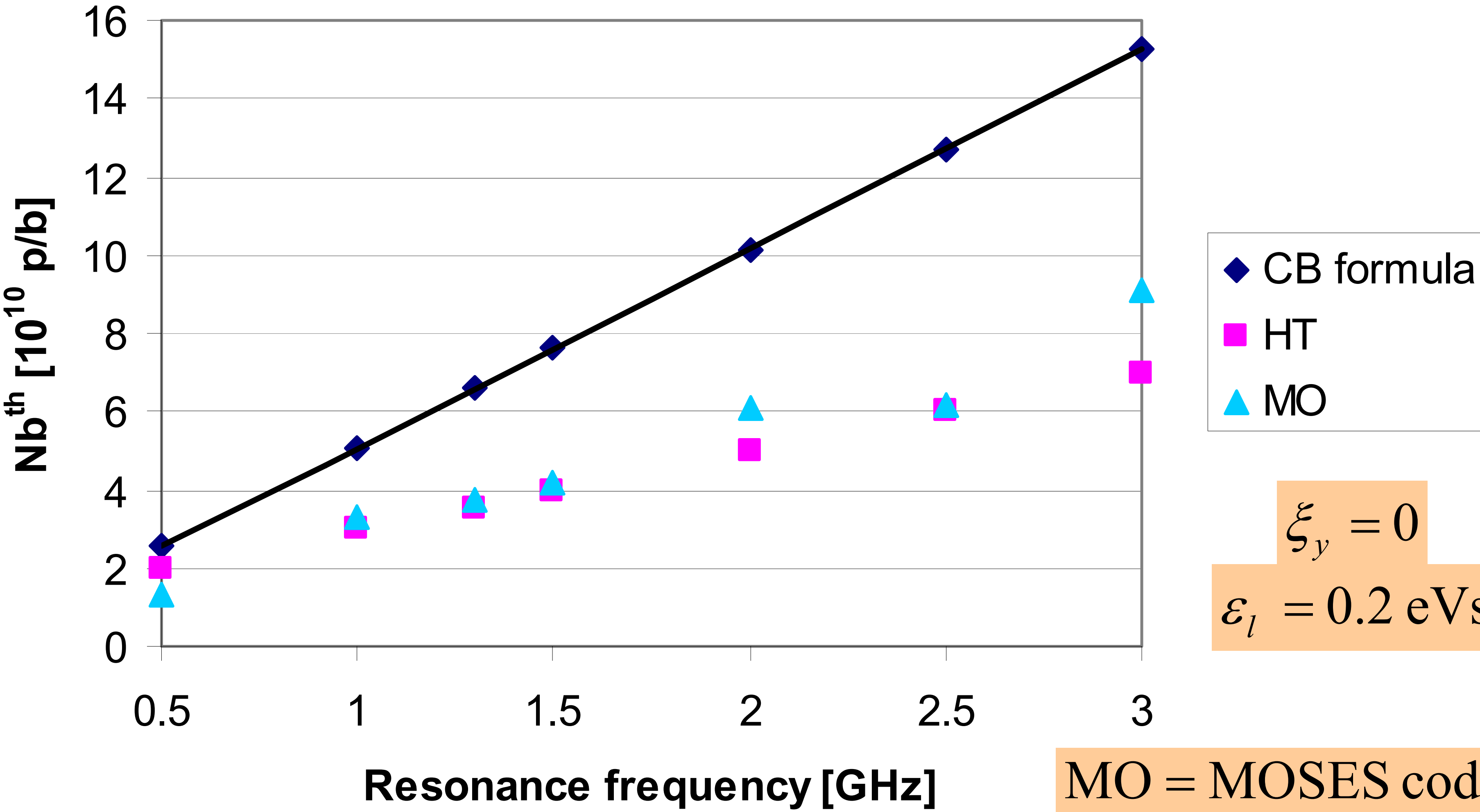
$p = 26\ \mathrm{GeV/c}$

$\eta = 6.1797 \times 10^{-4}$

$f_{rev} = 43347.3\ \mathrm{Hz}$

SIMULATIONS (2/4)

No Space Charge
Round Chamber



$\xi_y = 0$

$\varepsilon_l = 0.2$ eVs

MO = MOSES code

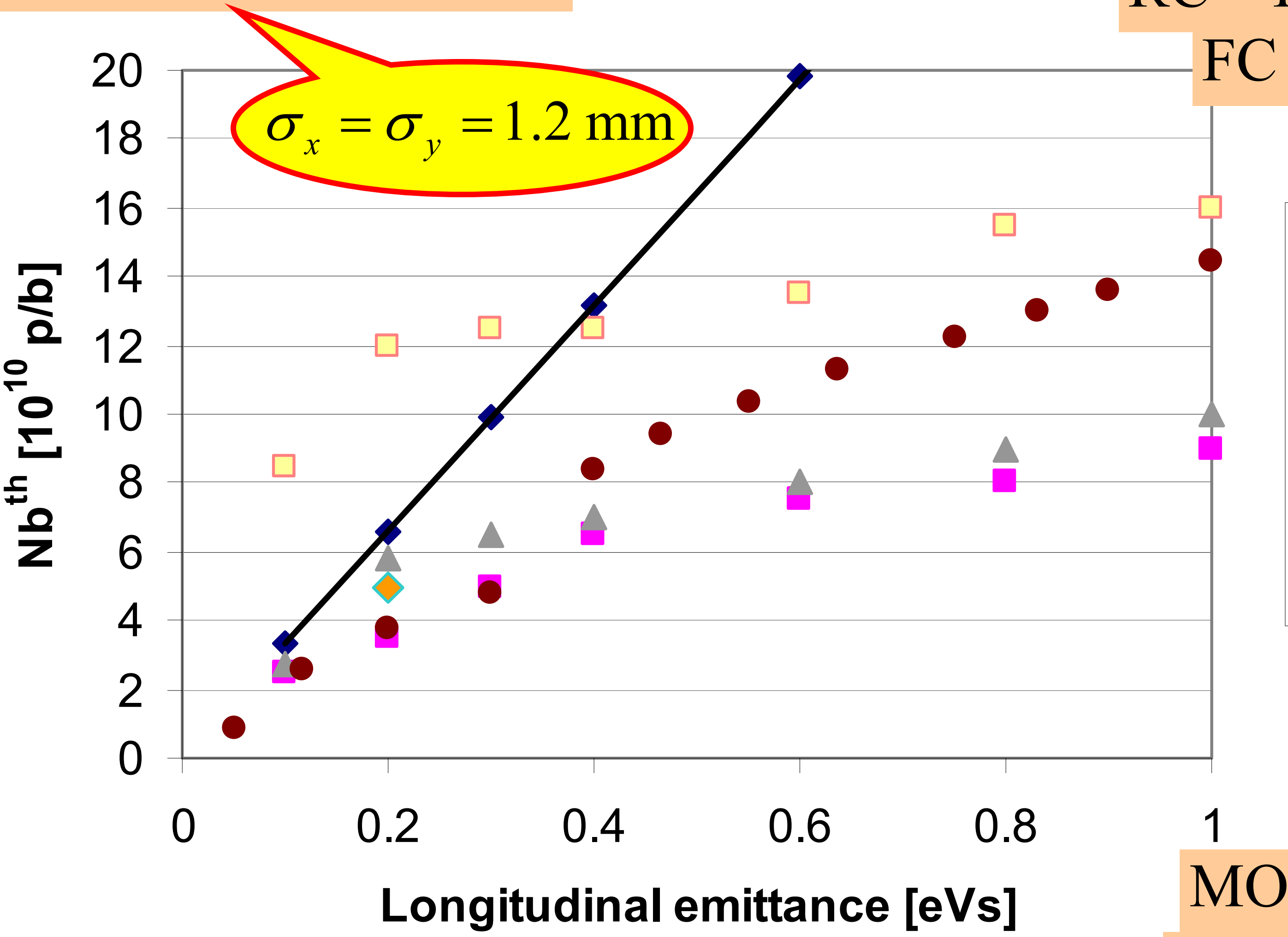
HT = Head Tail code

CB = Coasting Beam

SIMULATIONS (3/4)

SC = with Space Charge

CB = Coasting Beam
RC = Round Chamber
FC = Flat Chamber



$\xi_y = 0$

$f_r = 1.3$ GHz

MO = MOSES code
HT = Head Tail code

SIMULATIONS (4/4)

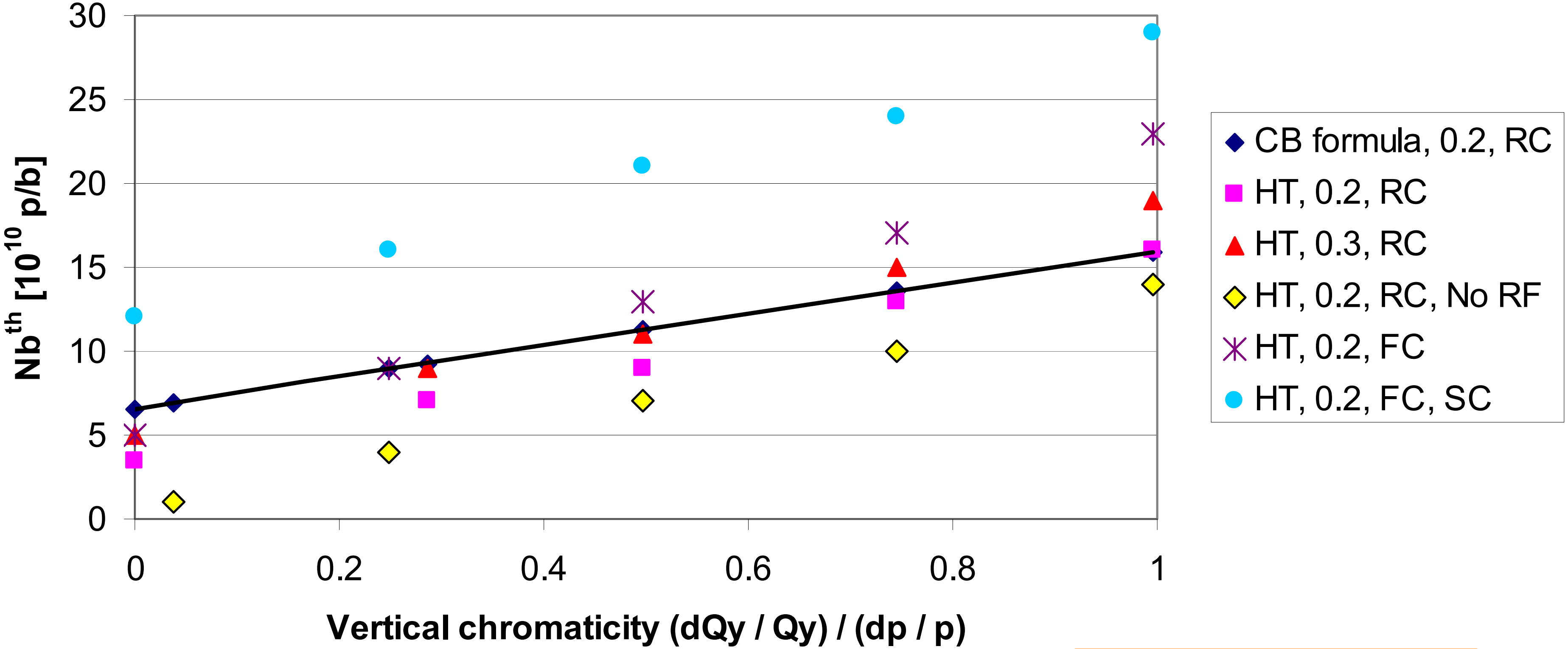
$0.2 \Leftrightarrow \varepsilon_l = 0.2$ eVs

$0.3 \Leftrightarrow \varepsilon_l = 0.3$ eVs

$f_r = 1.3$ GHz

RC = Round Chamber

FC = Flat Chamber



CB = Coasting Beam

SC = with Space Charge

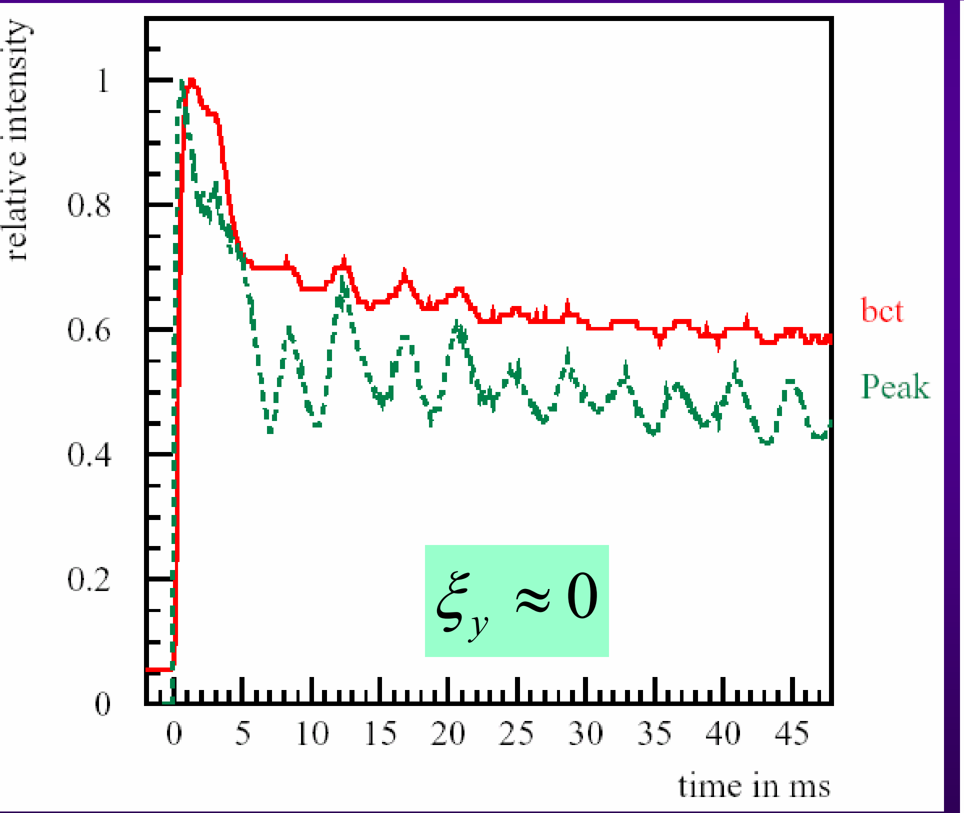
RF = RF Voltage

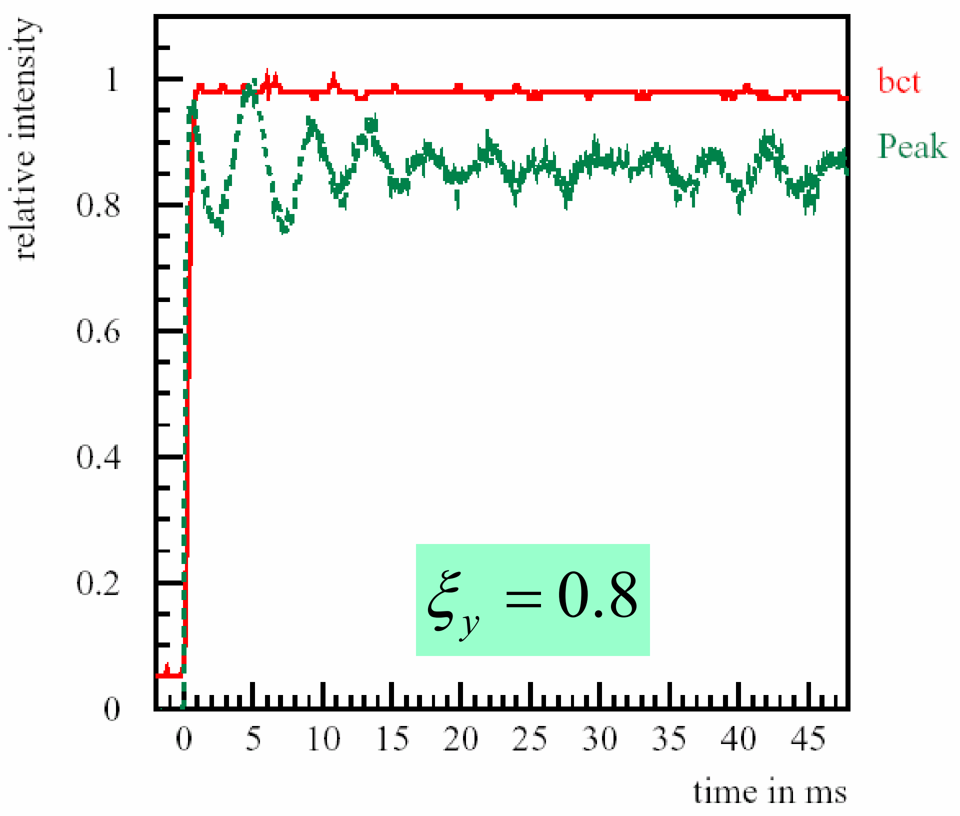
HT = Head Tail code

MEASUREMENTS OF TMCI IN THE CERN SPS IN 2003

$N_b \approx 12 \times 10^{10}$ p/b $p = 26$ GeV/c

$V_{RF} = 0.6$ MV $T_s = 7.1$ ms $\varepsilon_l = 0.2$ eVs

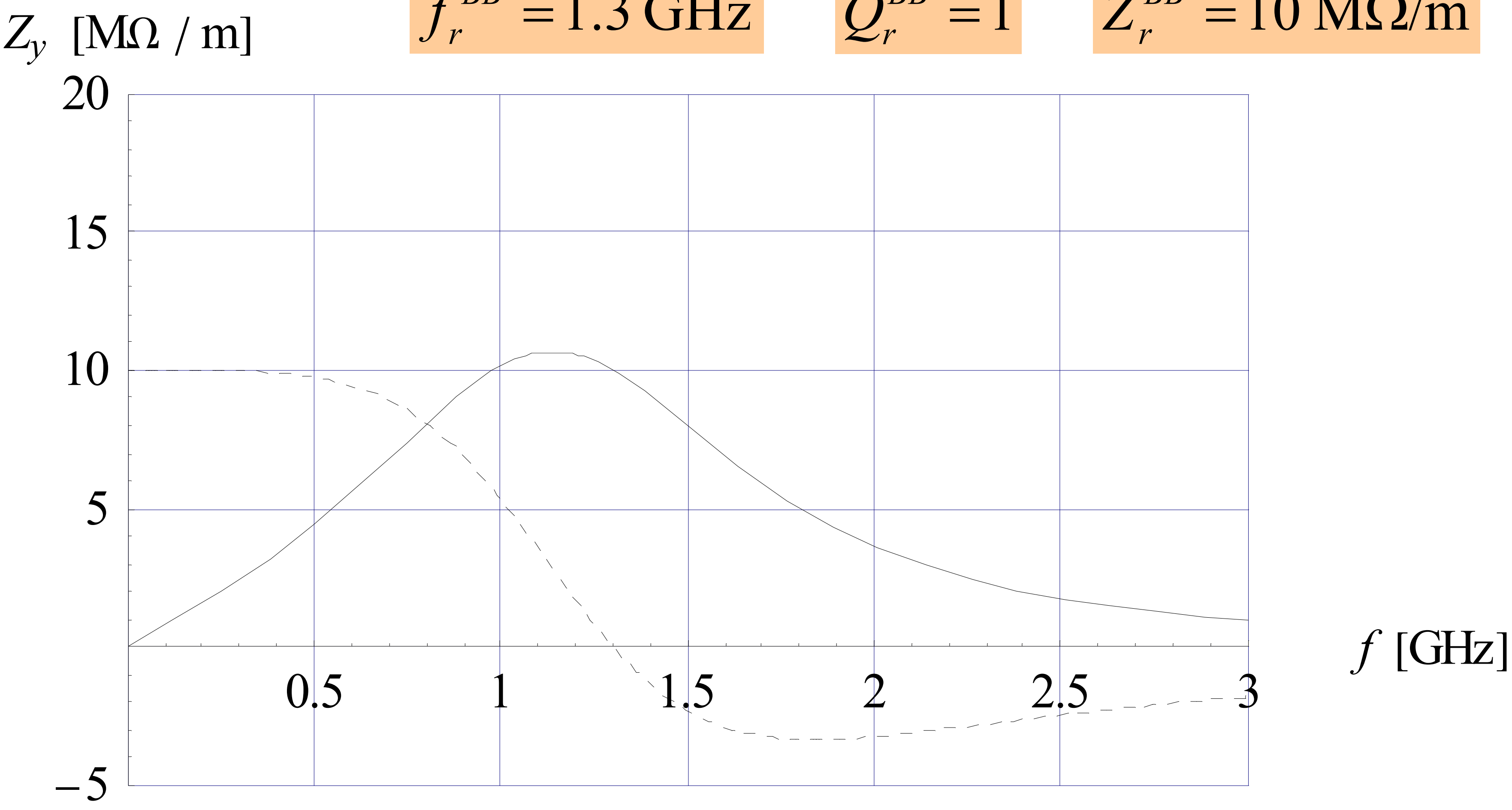




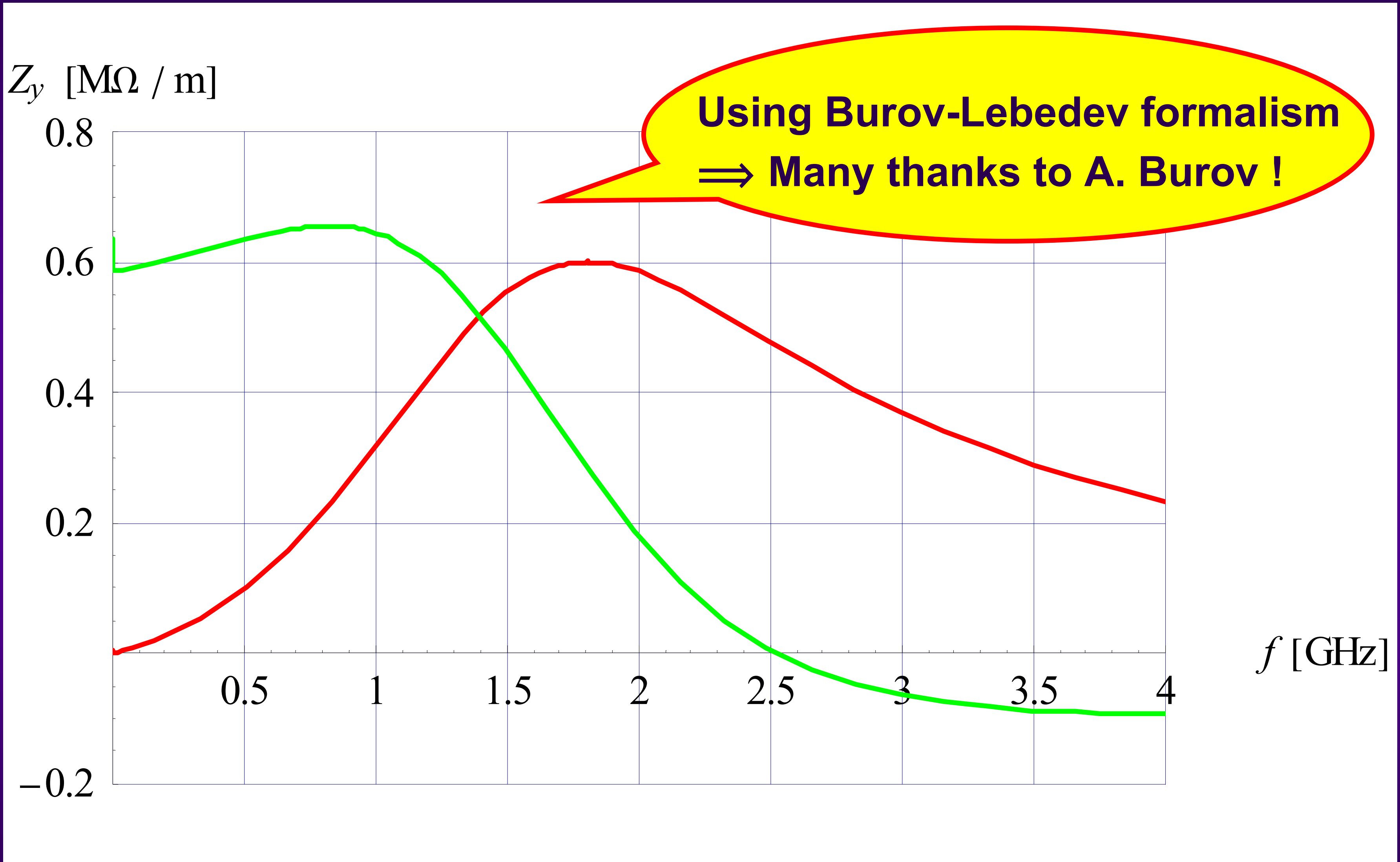
SPS IMPEDANCE ESTIMATE

2002 : Broad-Band (BB) impedance

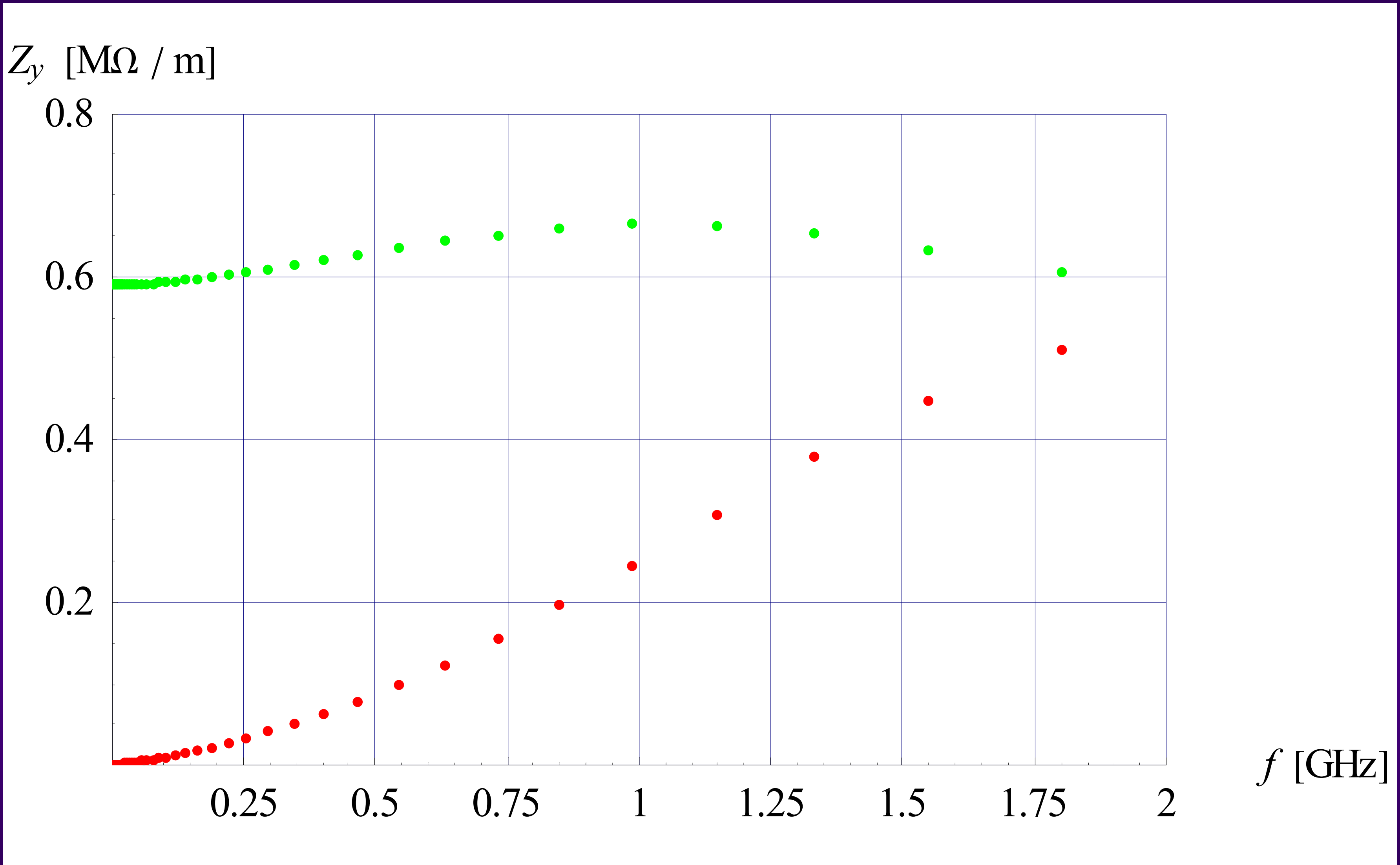
$f_r^{BB} = 1.3$ GHz $Q_r^{BB} = 1$ $Z_r^{BB} = 10$ MΩ/m



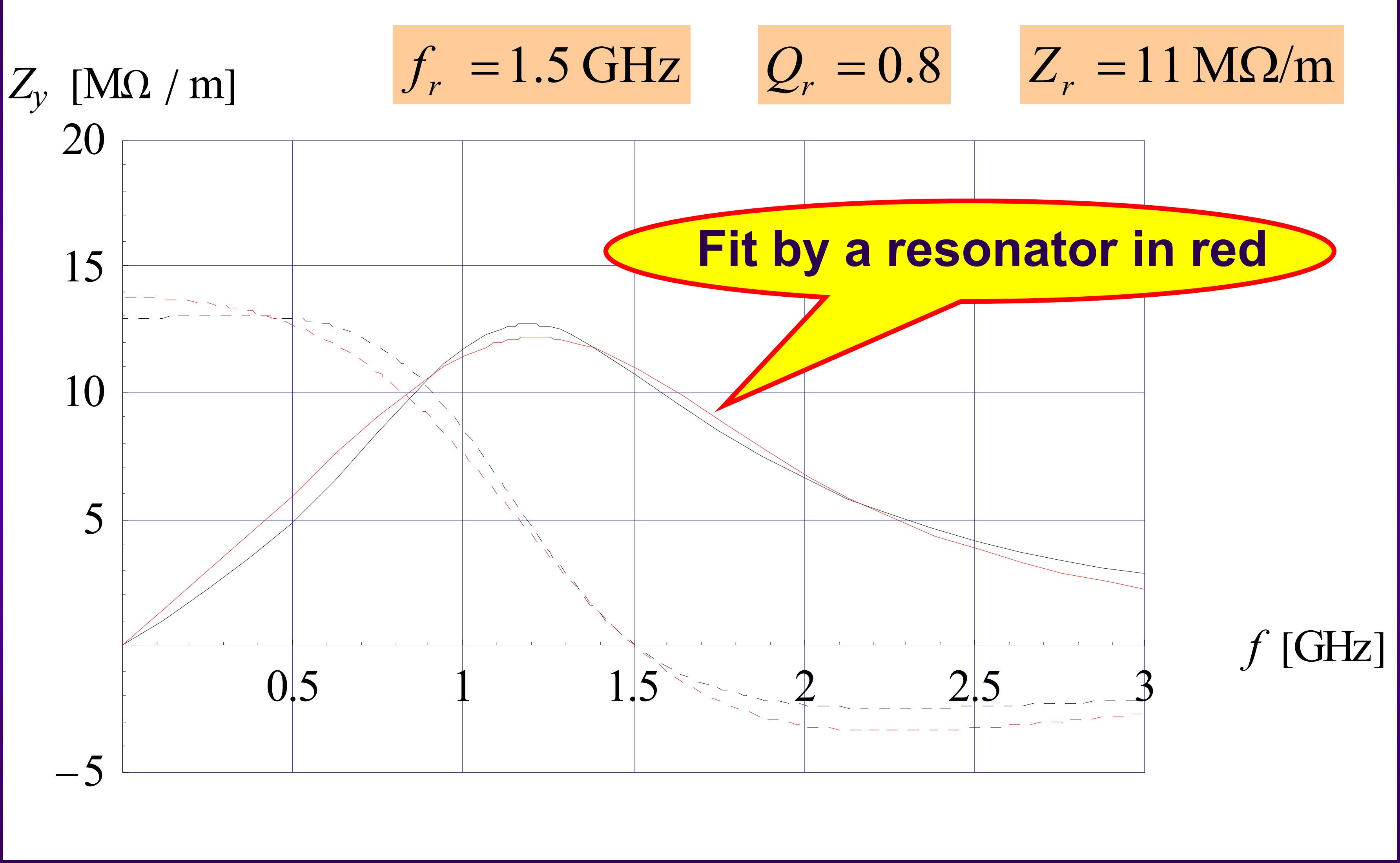
Impedance of 1 MKE kicker (with 4A4 ferrite)



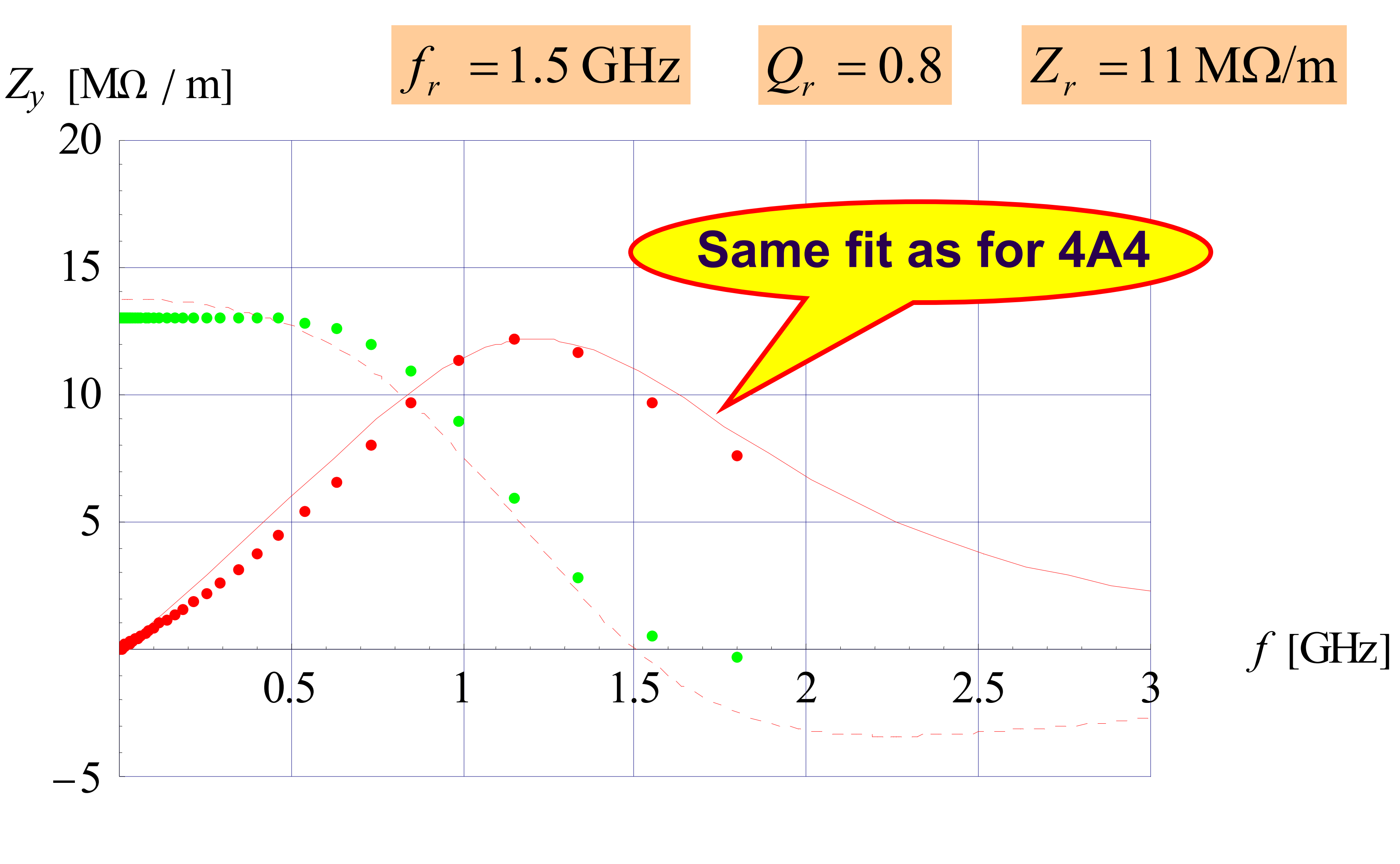
Impedance of 1 MKE kicker (with 8C11 ferrite)



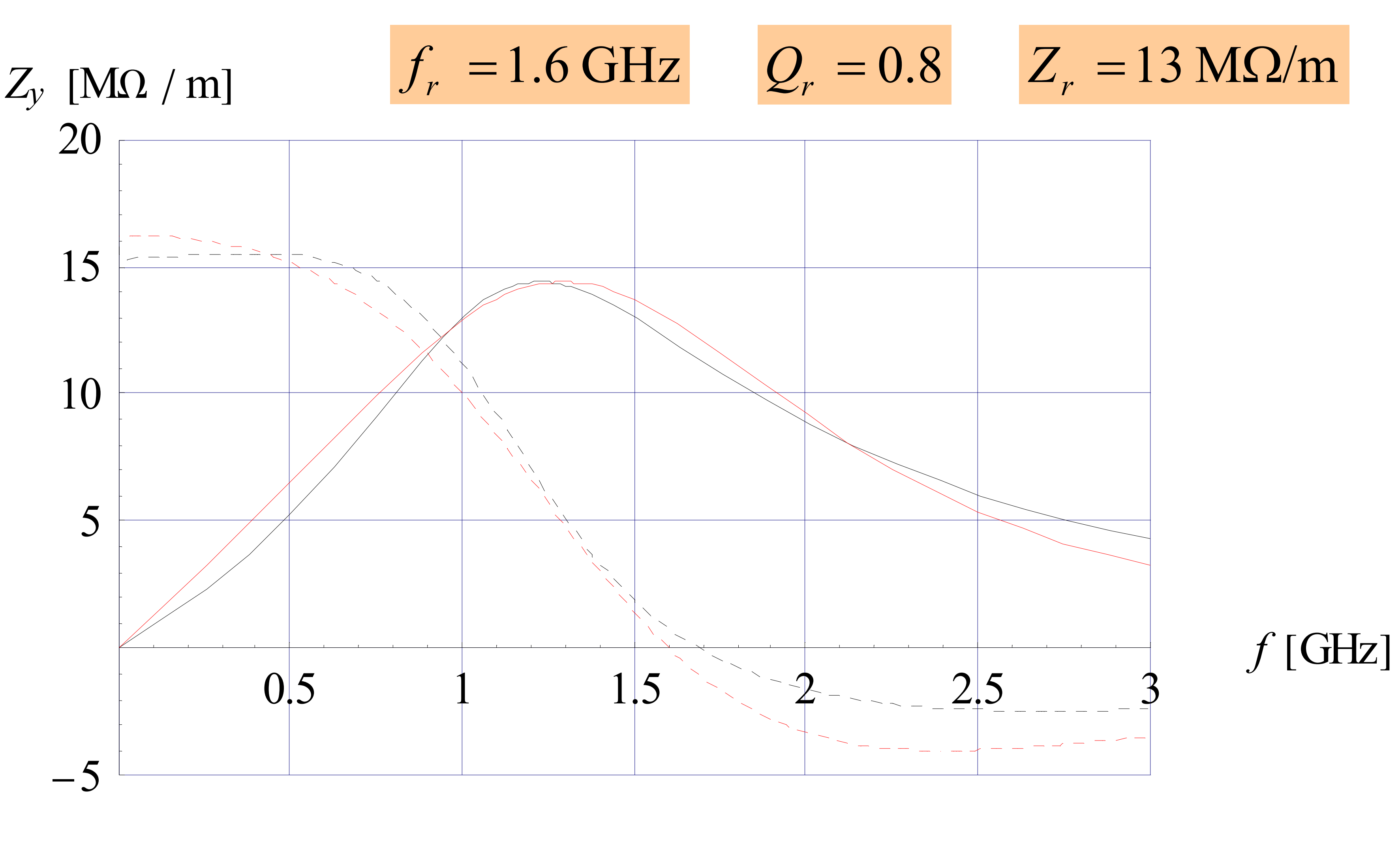
2003 : BB + 5 MKE kickers (with 4A4 ferrite)



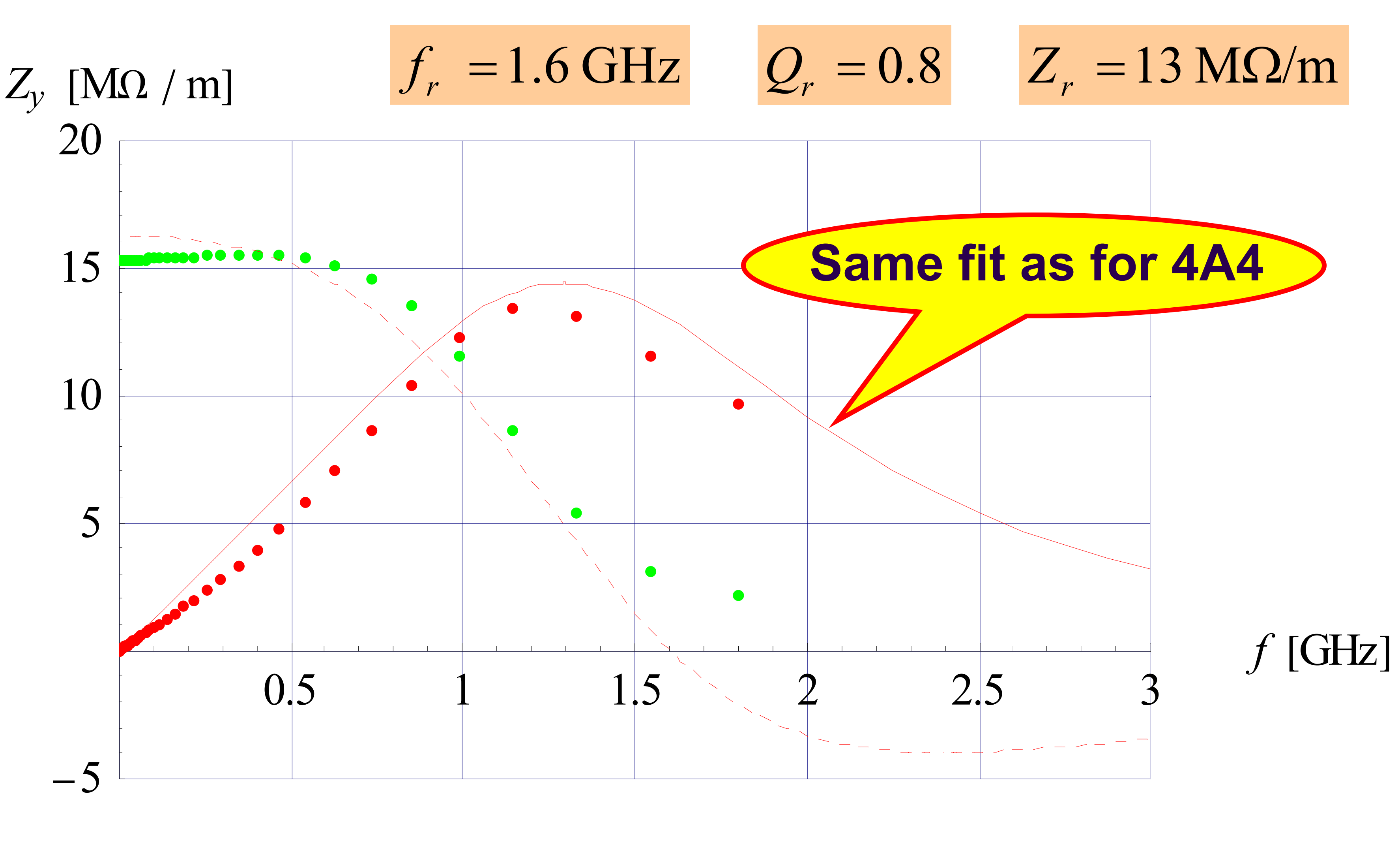
2003 : BB + 5 MKE kickers (with 8C11 ferrite)



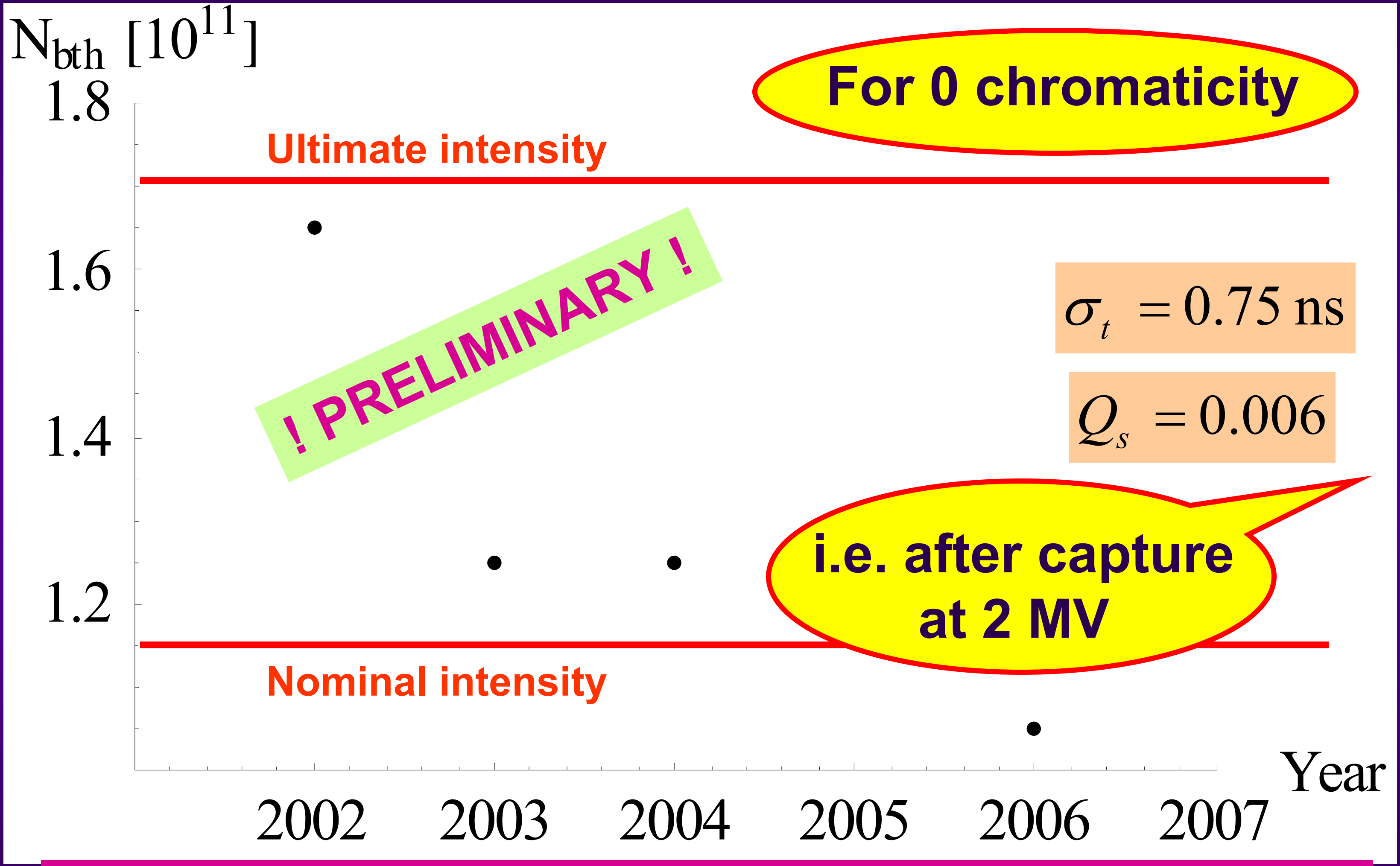
2006 : BB + 9 MKE kickers (with 4A4 ferrite)



2006 : BB + 9 MKE kickers (with 8C11 ferrite)

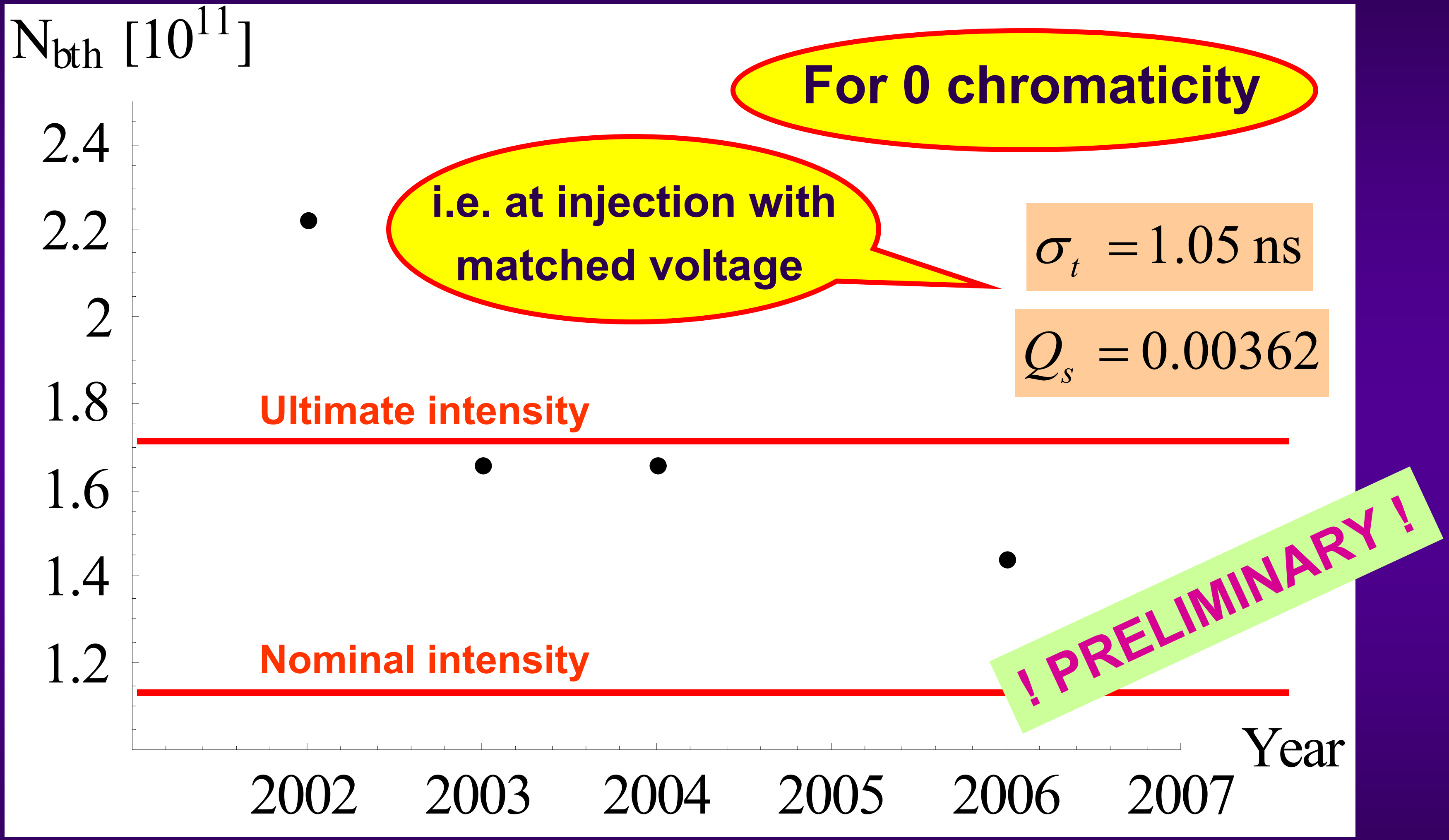


TMCI intensity threshold from MOSES for the LHC beam in the SPS at 26 GeV/c

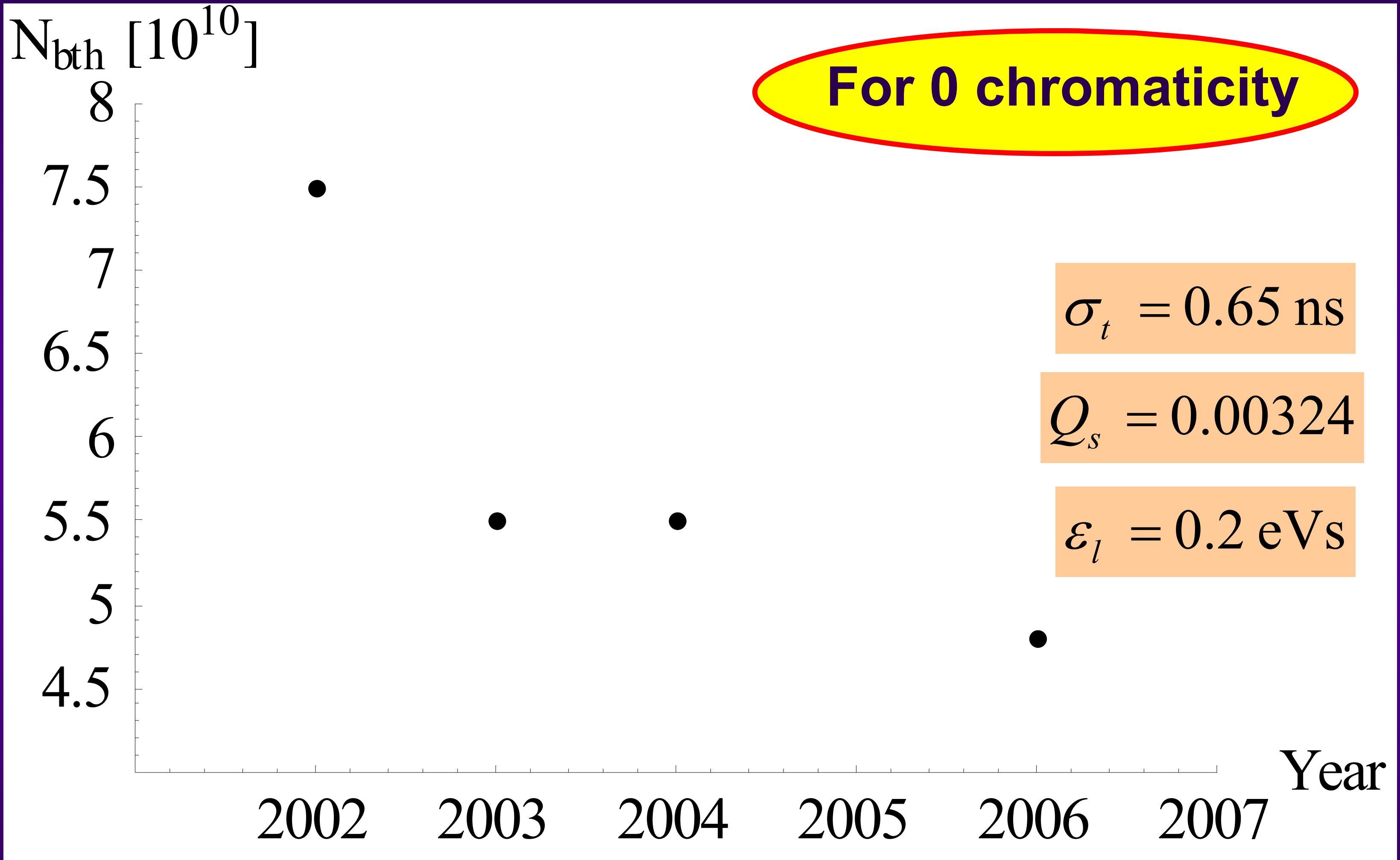


At injection, the matched voltage is V_{RF} = 0.75 MV and σ_t = 1.05 ns

TMCI intensity threshold from MOSES for the LHC beam in the SPS at 26 GeV/c



TMCI intensity threshold from MOSES for the low longitudinal emittance beam in the SPS at 26 GeV/c



In 2003, no losses observed if intensity reduced to ~ $5.5\text{-}6.5 \times 10^{10}$ p/b

TMCI intensity threshold from MOSES for the very low longitudinal emittance beam in the SPS at 26 GeV/c in 2003

$\sigma_t = 0.55 \text{ ns}$ $\quad$ $Q_s = 0.00324$ $\quad$ $\varepsilon_l = 0.15 \text{ eVs}$

- **MOSES** $\Longrightarrow$ $N_{\text{bth}} = 4.5 \times 10^{10} \text{ p/b}$
- **Measurements** $\Longrightarrow$ $N_{\text{bth}} \approx 3 - 4 \times 10^{10} \text{ p/b}$

CONCLUSION

- **The absence of TMCI in hadron machines was generally explained by 3 mechanisms**
  - **The intensity threshold for the longitudinal microwave instability is generally lower than for the TMCI**
  - **Space charge may help**
  - **The intensity threshold increases with bunch length (in the long-bunch regime)**
- **TMCI (= strong head-tail) observed for the 1st time with protons far from transition ?**

FUTURE WORK

- **More realistic model for the transverse SPS impedance**

- **Better evaluate the effect of the 5 SPS MKE kickers installed in 2003 by comparing simulations and measurements done in 2002, when there were no MKE kickers and first signs of TMCI were observed. But the bunch was mismatched in this experiment…**

  Comparison between measurements and simulations in mismatched conditions ?

  - **Analytical predictions and MOSES work for a matched bunch and linear synchrotron oscillations**
  - **$\Longrightarrow$ HEADTAIL code**

APPENDIX

- **MOSES' results for the scan in chromaticity ($\Longrightarrow$ Same parameters as in page 8) for :**

$$\varepsilon_l = 0.2 \text{ eVs}$$

$$f_r = 1.3 \text{ GHz}$$

$$Q_y = 26.13$$

$$\xi_y = 0$$

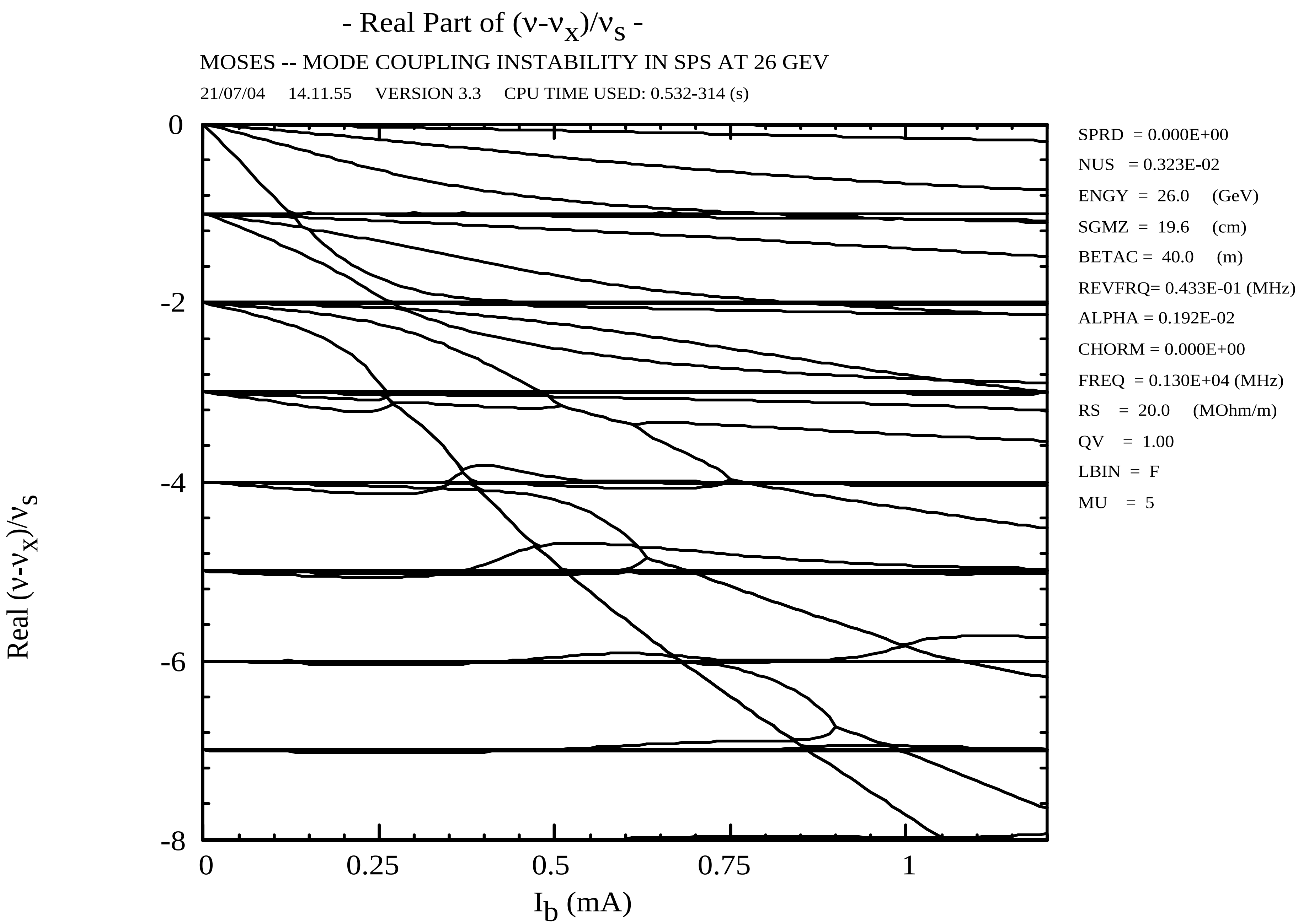
$$\xi_y = 5 / Q_y \approx 0.19$$

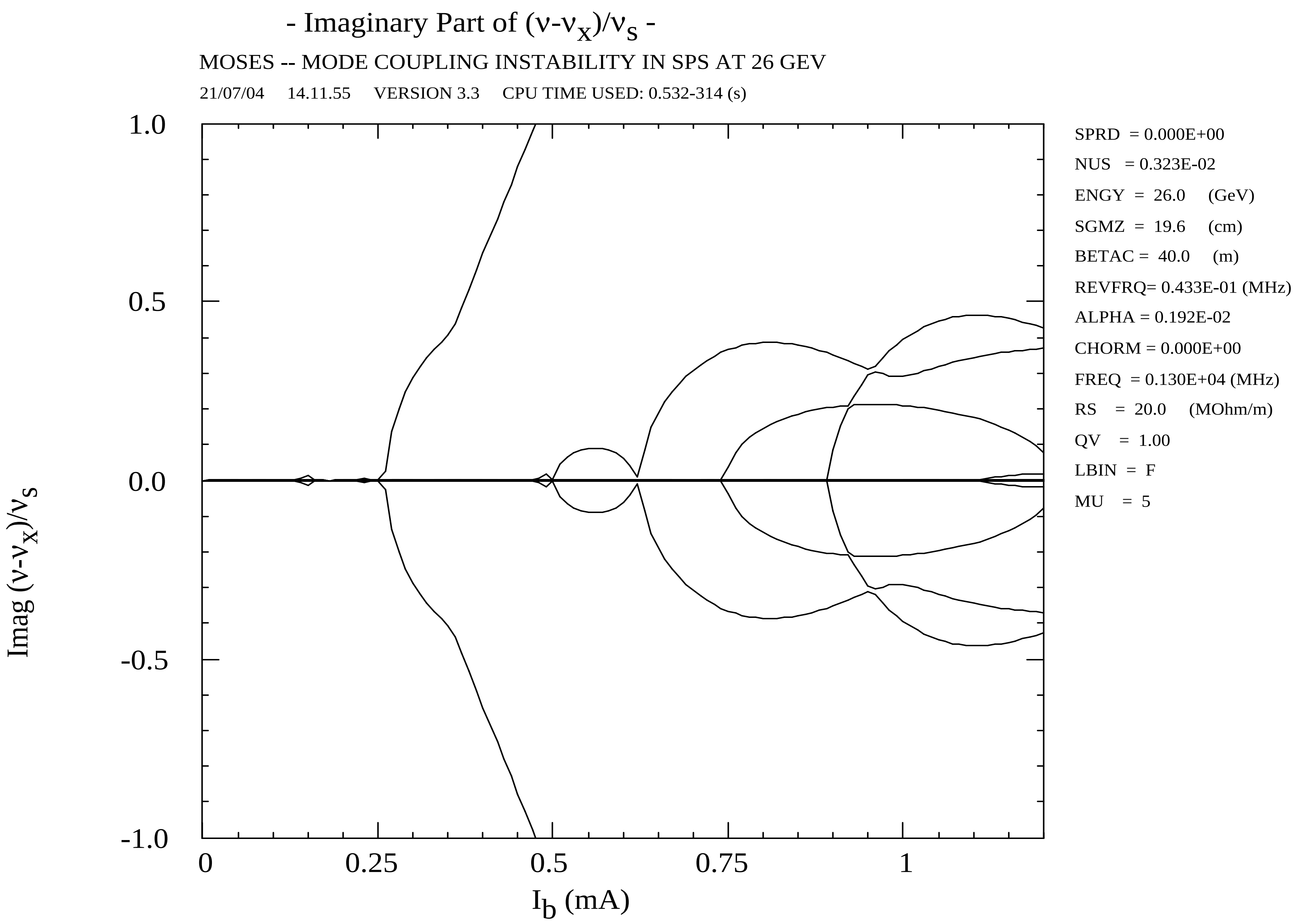
$$\xi_y = 10 / Q_y \approx 0.38$$

$$\xi_y = 15 / Q_y \approx 0.57$$

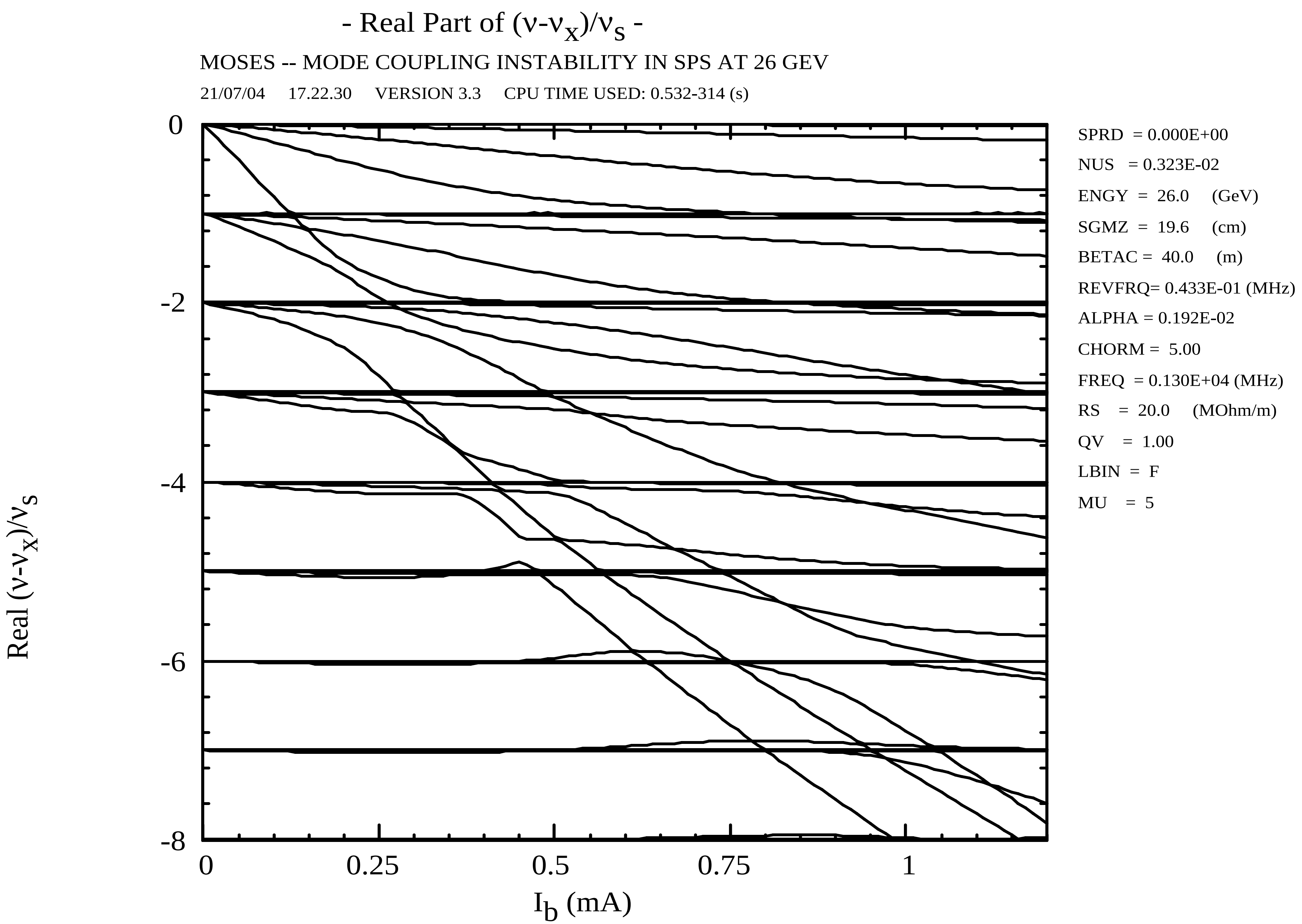
$$\xi_y = 20 / Q_y \approx 0.77$$

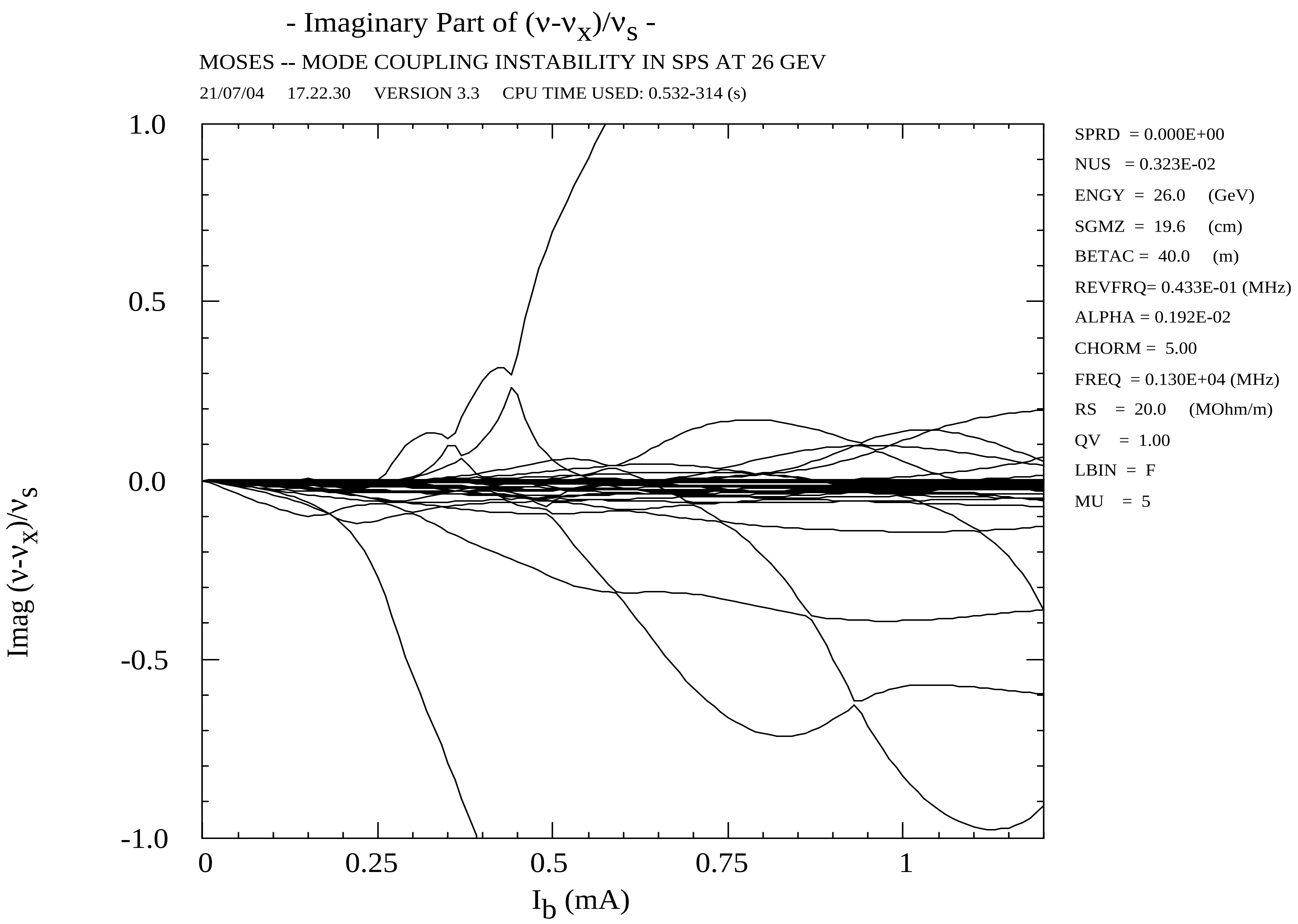
$$\xi_y = 25 / Q_y \approx 0.97$$


- Real Part of $(\nu-\nu_x)/\nu_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 14.11.55 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
I_b (mA)
Real $(\nu-\nu_x)/\nu_s$
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 0.000E+00
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

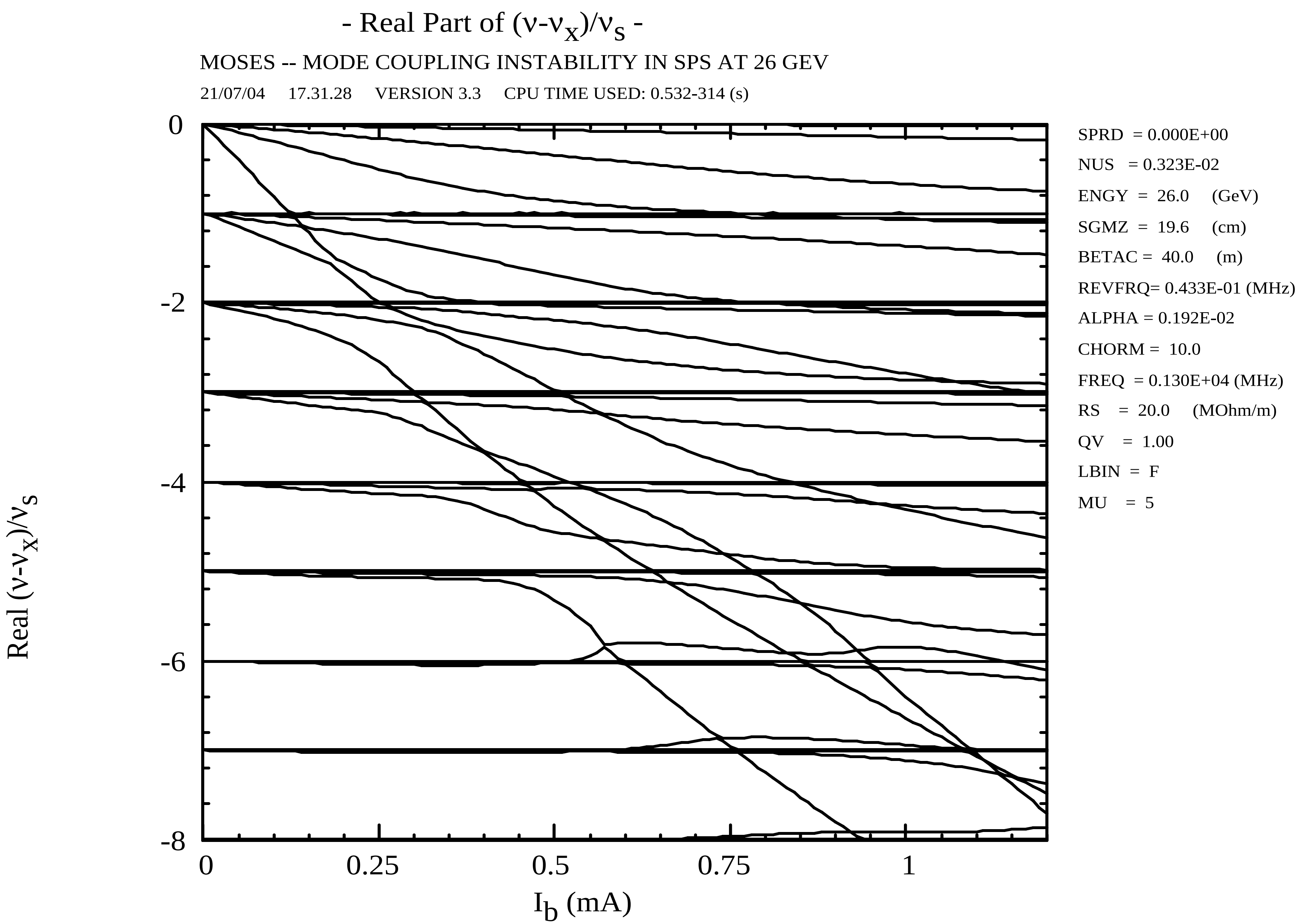


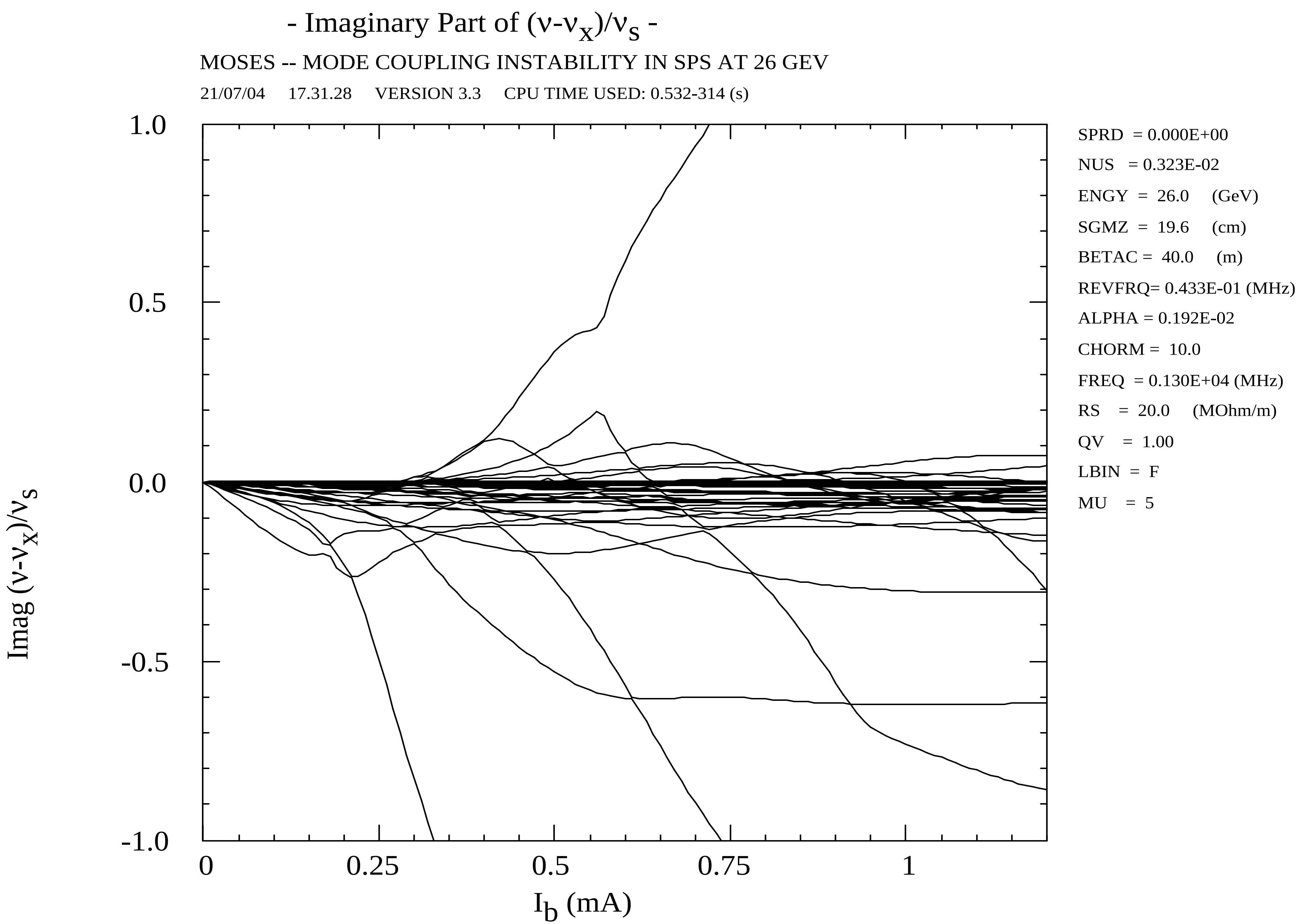
- Imaginary Part of (ν-νx)/νs -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 14.11.55 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
0
0.25
0.5
0.75
1
Ib (mA)
Imag (ν-νx)/νs
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 0.000E+00
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

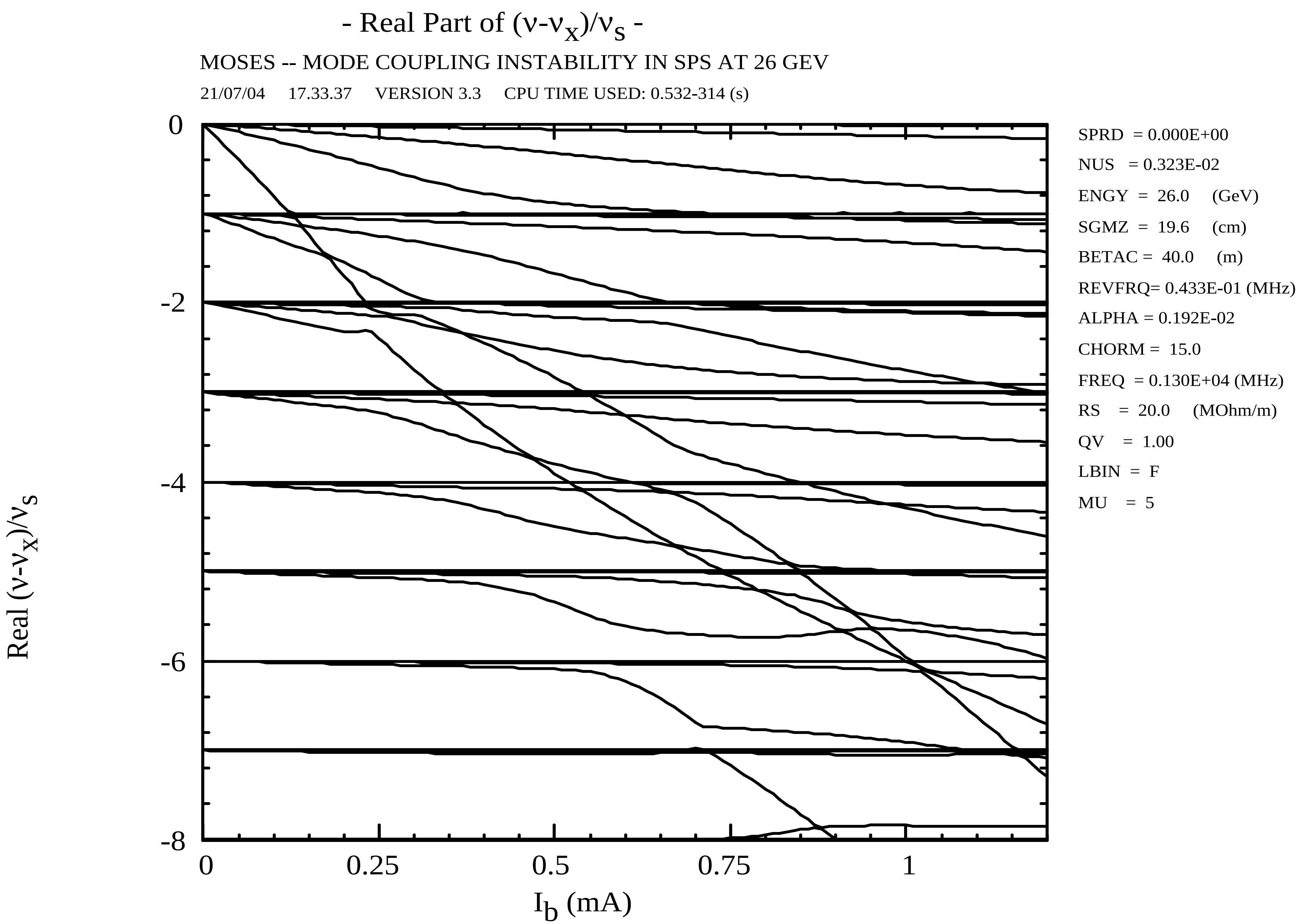

- Real Part of (ν-νx)/νs -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.22.30 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
Real (ν-νx)/νs
Ib (mA)
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 5.00
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

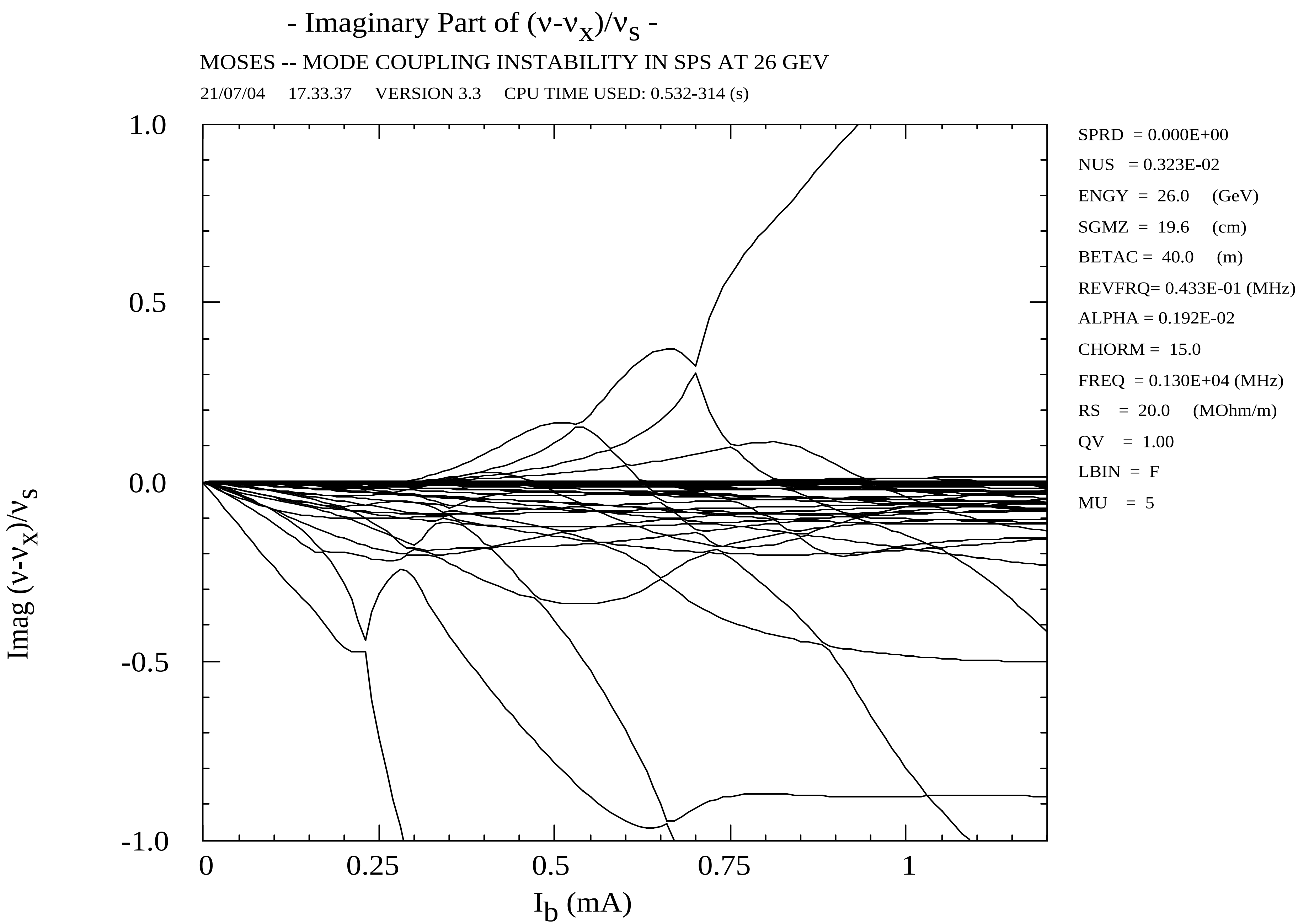


- Imaginary Part of (ν-ν$_x$)/ν$_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.22.30 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
0
0.25
0.5
0.75
1
Imag (ν-ν$_x$)/ν$_s$
I$_b$ (mA)
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 5.00
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

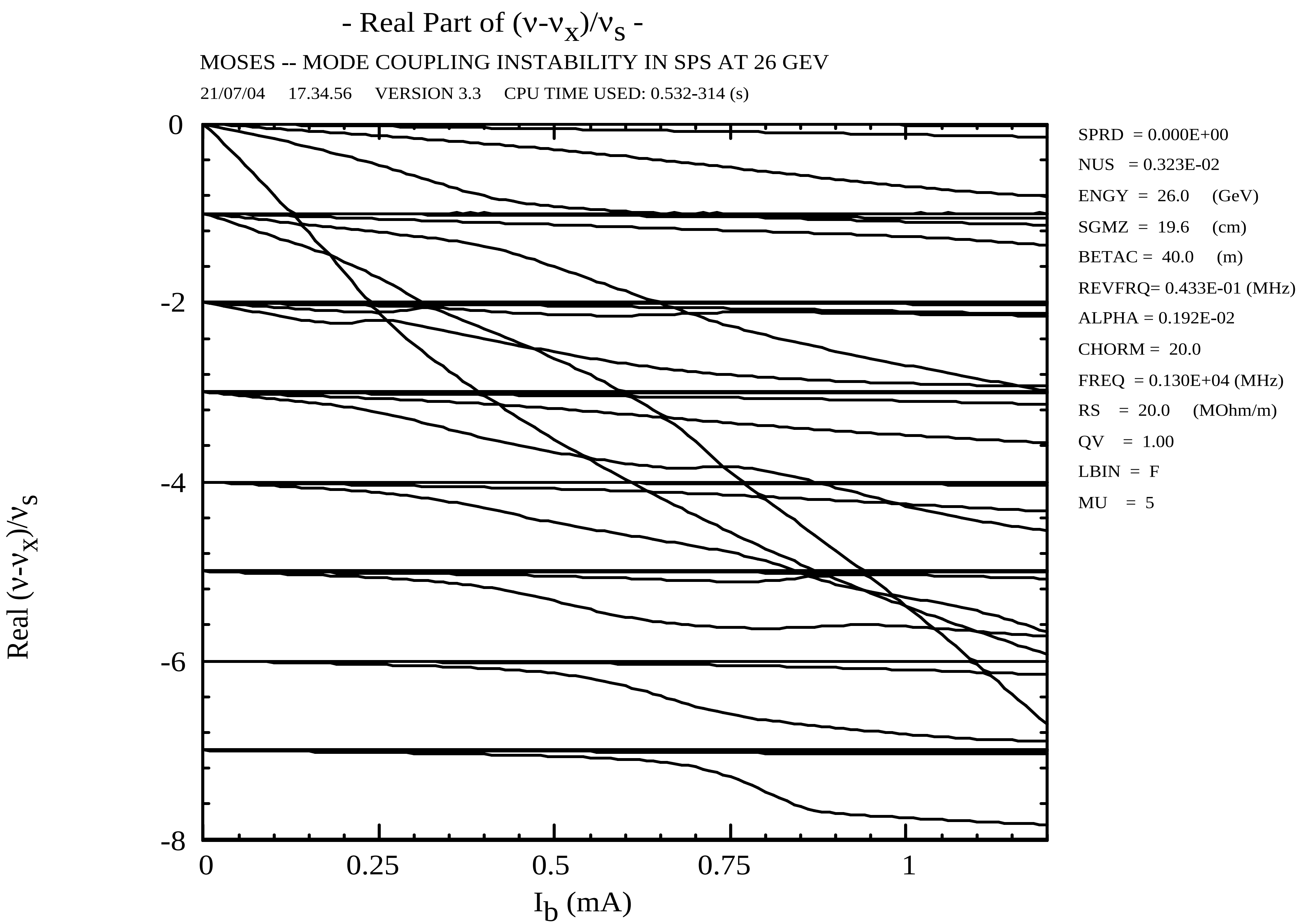

- Real Part of (ν-ν_x)/ν_s -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.31.28 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
I_b (mA)
Real (ν-ν_x)/ν_s
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 10.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

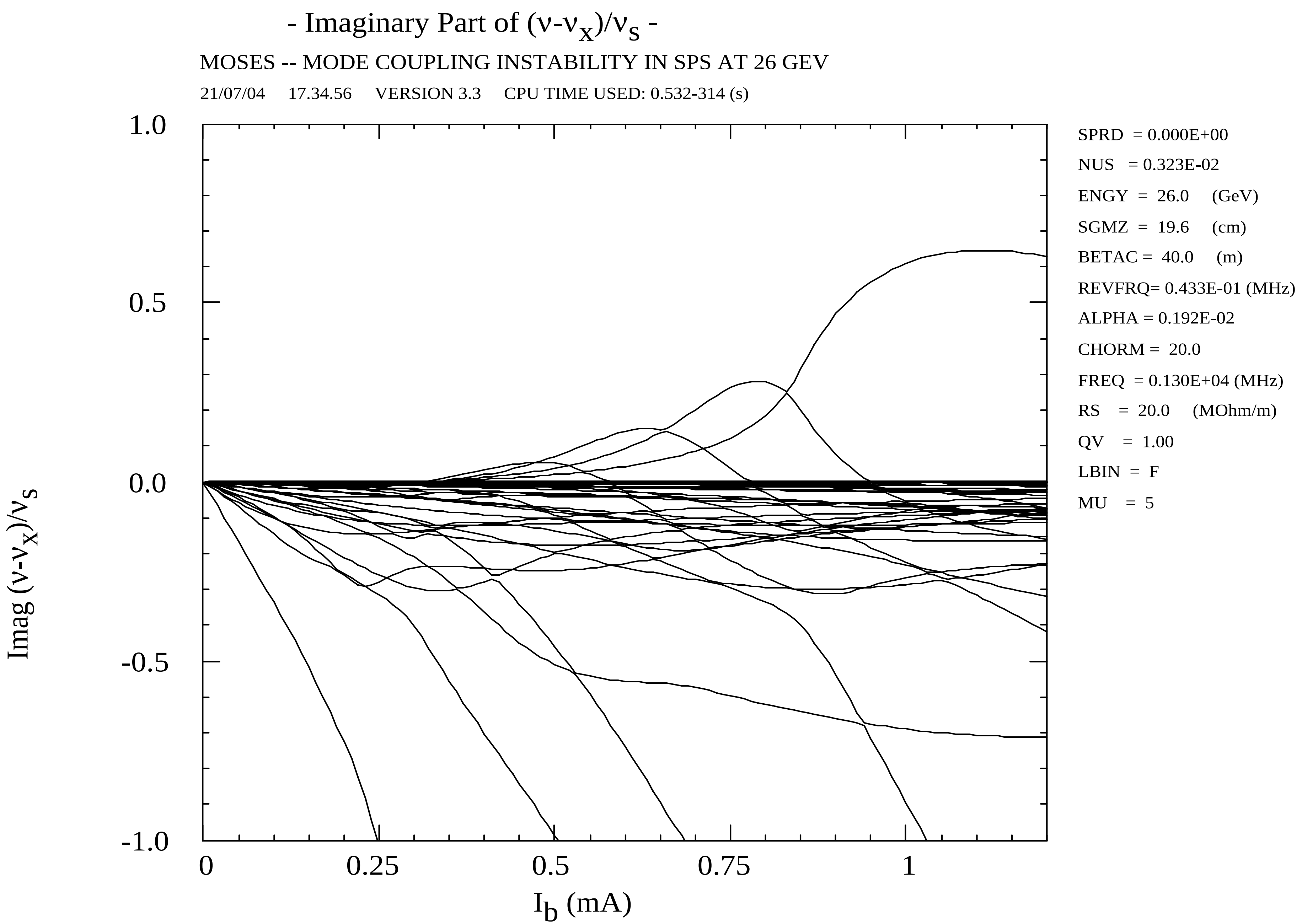

- Imaginary Part of (ν-ν$_x$)/ν$_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.31.28 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
0
0.25
0.5
0.75
1
I$_b$ (mA)
Imag (ν-ν$_x$)/ν$_s$
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 10.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5

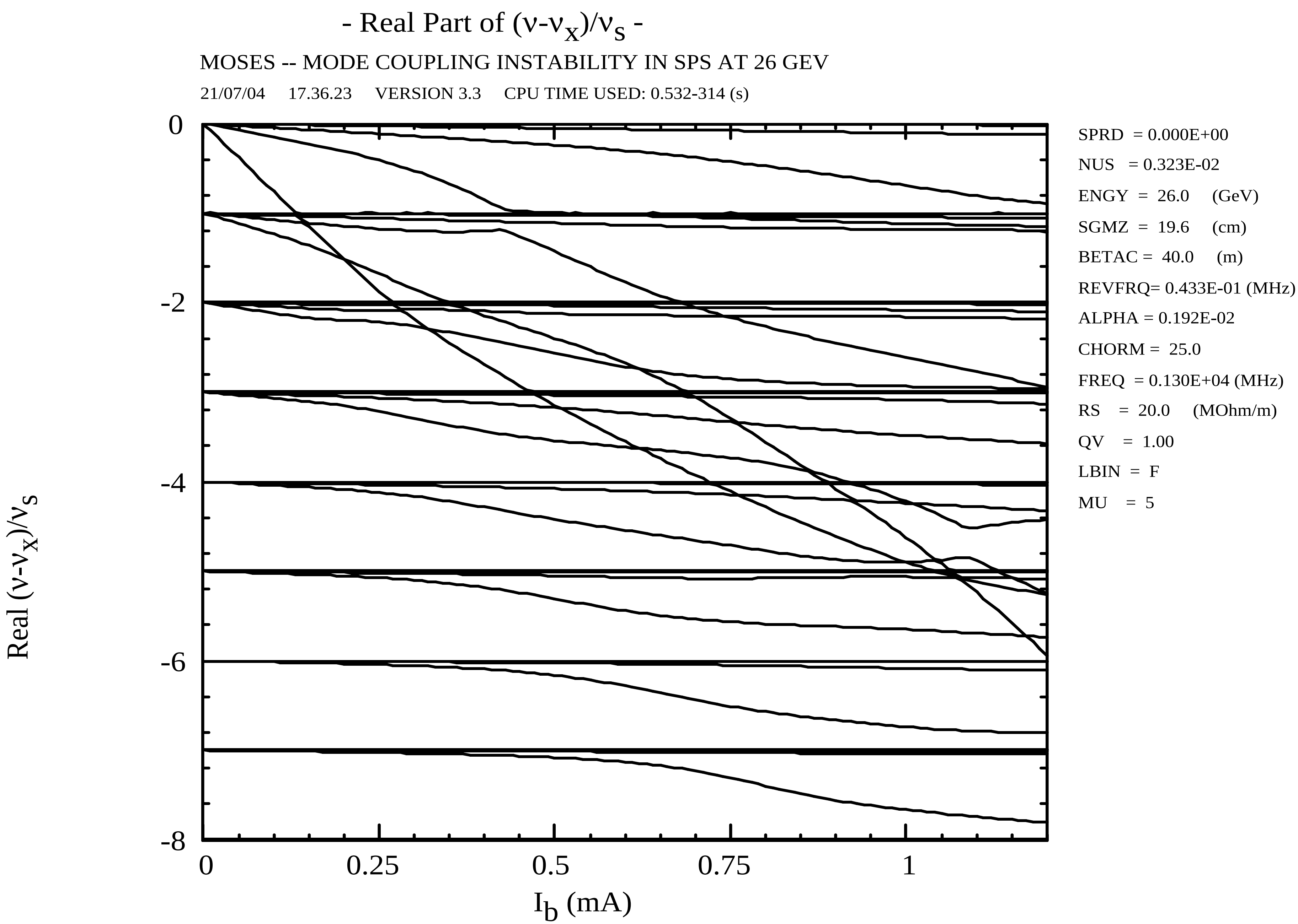

- Real Part of $(\nu-\nu_x)/\nu_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.33.37 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 15.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5
Real $(\nu-\nu_x)/\nu_s$
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
I_b (mA)

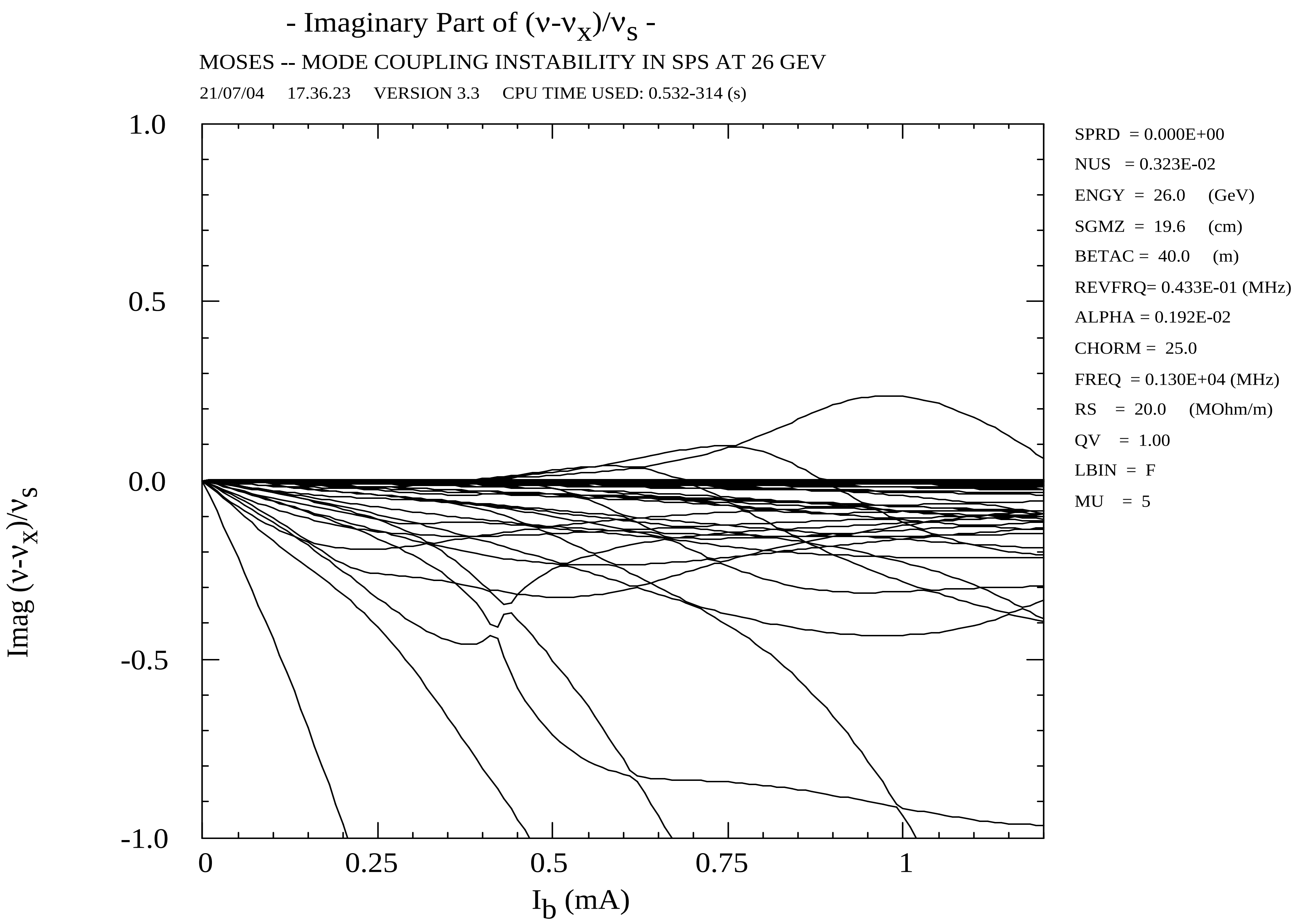


- Imaginary Part of (ν-ν$_x$)/ν$_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.33.37 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
Imag (ν-ν$_x$)/ν$_s$
0
0.25
0.5
0.75
1
I$_b$ (mA)
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 15.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5


- Real Part of $(\nu-\nu_x)/\nu_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.34.56 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
I_b (mA)
Real $(\nu-\nu_x)/\nu_s$
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 20.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5


- Imaginary Part of (ν-ν_x)/ν_s -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.34.56 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
0
0.25
0.5
0.75
1
I_b (mA)
Imag (ν-ν_x)/ν_s
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 20.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5


- Real Part of $(\nu-\nu_x)/\nu_s$ -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.36.23 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
0
-2
-4
-6
-8
0
0.25
0.5
0.75
1
I_b (mA)
Real $(\nu-\nu_x)/\nu_s$
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 25.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5


- Imaginary Part of (ν-νx)/νs -
MOSES -- MODE COUPLING INSTABILITY IN SPS AT 26 GEV
21/07/04 17.36.23 VERSION 3.3 CPU TIME USED: 0.532-314 (s)
1.0
0.5
0.0
-0.5
-1.0
0
0.25
0.5
0.75
1
Ib (mA)
Imag (ν-νx)/νs
SPRD = 0.000E+00
NUS = 0.323E-02
ENGY = 26.0 (GeV)
SGMZ = 19.6 (cm)
BETAC = 40.0 (m)
REVFRQ= 0.433E-01 (MHz)
ALPHA = 0.192E-02
CHORM = 25.0
FREQ = 0.130E+04 (MHz)
RS = 20.0 (MOhm/m)
QV = 1.00
LBIN = F
MU = 5