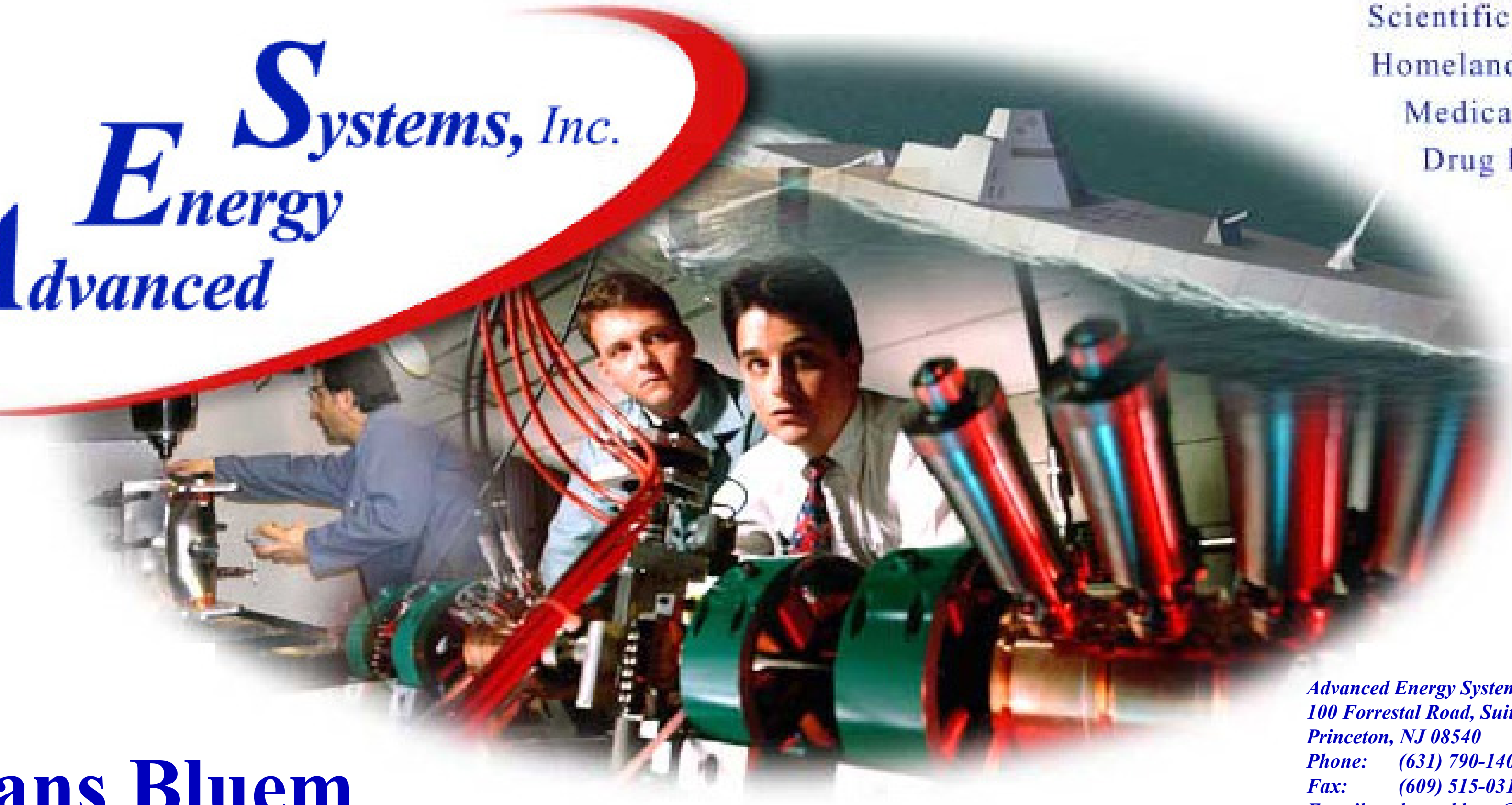
Accelerator Beamline Performance for the IR FEL at the Fritz-Haber-Institut, Berlin

FEL 2012 Nara, Japan, August 2012

Advanced Energy Systems, Inc.



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Homeland Security
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Hans Bluem

Advanced Energy Systems Inc.
100 Forrestal Road, Suite E
Princeton, NJ 08540
Phone: (631) 790-1405
Fax: (609) 515-0318
E-mail: hans_bluem@mail.aesys.net

Putting Accelerator Technology to Work

Abstract

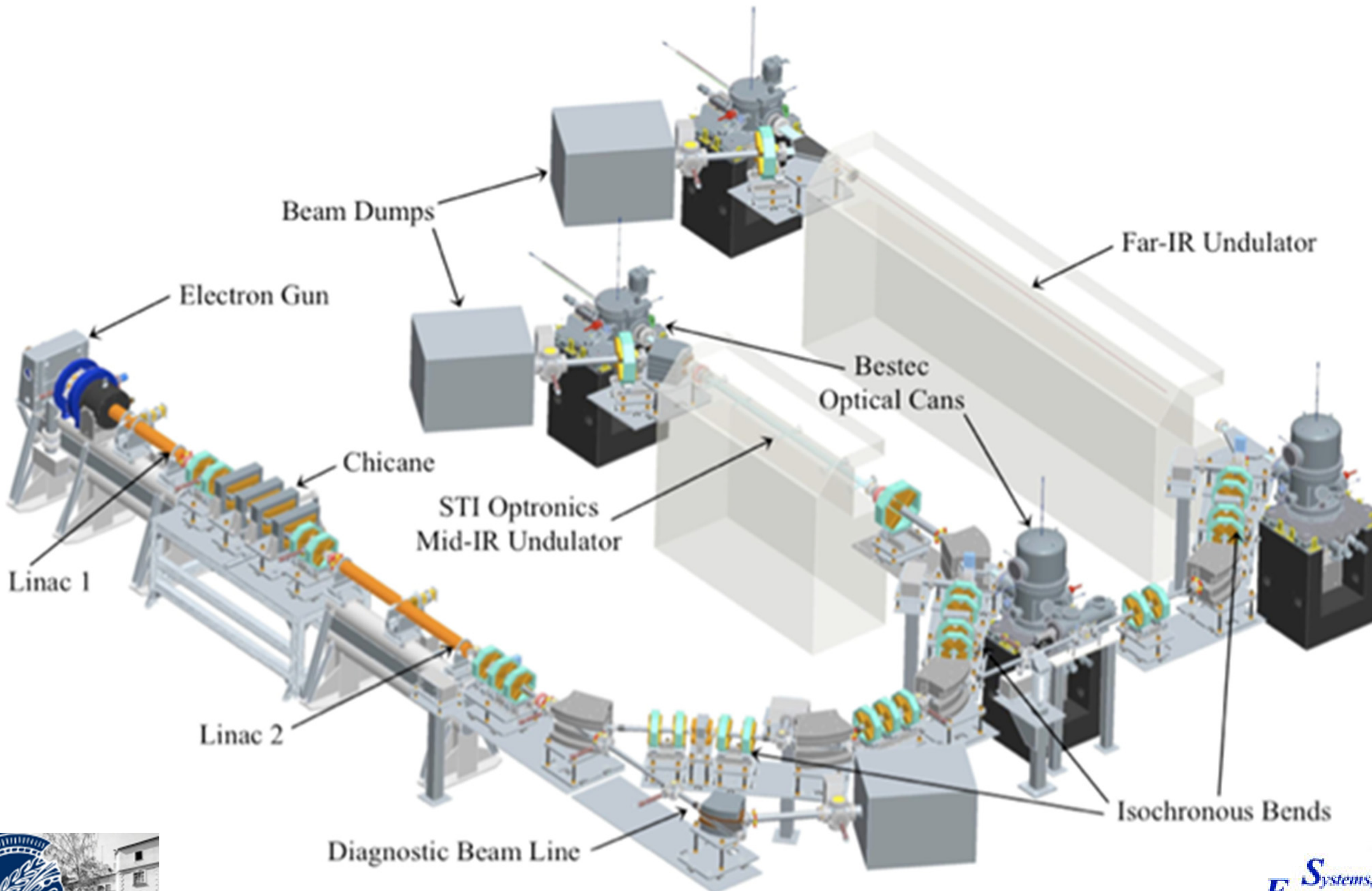
H. P. Bluem, J. Ditta, D. Dowell*, H. Loos*, J. Park,
A. M. M. Todd and L. M. Young*
Advanced Energy Systems, Medford, NY, USA.

S. Gewinner and W. Schöllkopf, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany

An electron accelerator and beamline for an IR and THz FEL with a design wavelength range from 4 to 500 μm has been commissioned by Advanced Energy Systems at the Fritz-Haber-Institut (FHI) [1] in Berlin, Germany, for applications in molecular and cluster spectroscopy as well as surface science. The linac comprises two S-band standing-wave copper structures and was designed to meet challenging specifications, including a final energy adjustable in the range of 15 to 50 MeV, low longitudinal emittance (< 50 keV-psec) and transverse emittance (< 20 π mm-mrad), at more than 200 pC bunch charge with a micro pulse repetition rate of 1 GHz. First lasing was achieved February 2012.

* Consultants to AES

FEL Layout



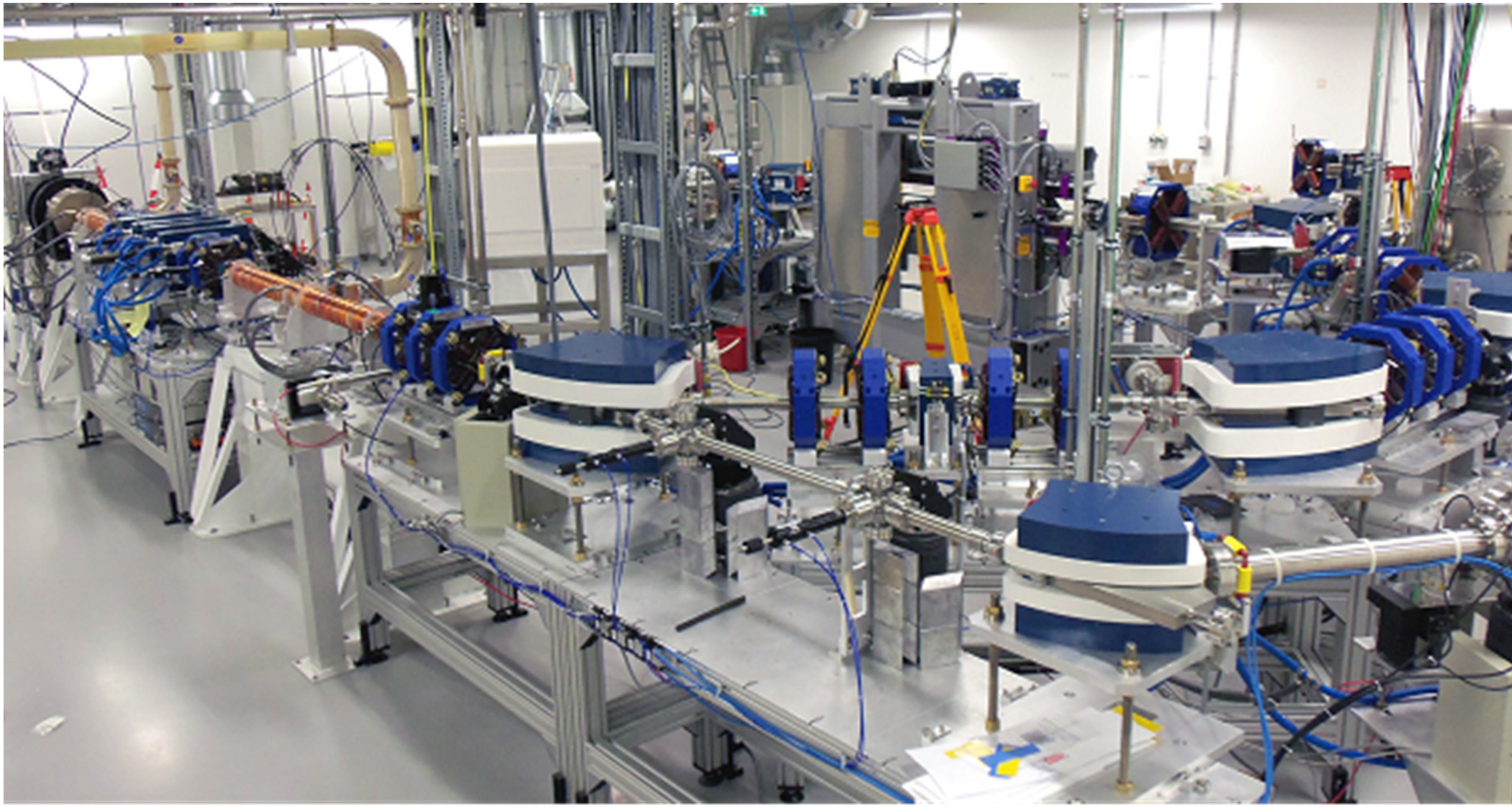
Beam Dumps
Far-IR Undulator
Electron Gun
Bestec
Optical Cans
Chicane
STI Optronics
Mid-IR Undulator
Linac 1
Linac 2
Isochronous Bends
Diagnostic Beam Line

Oscillator and Electron Beam Properties

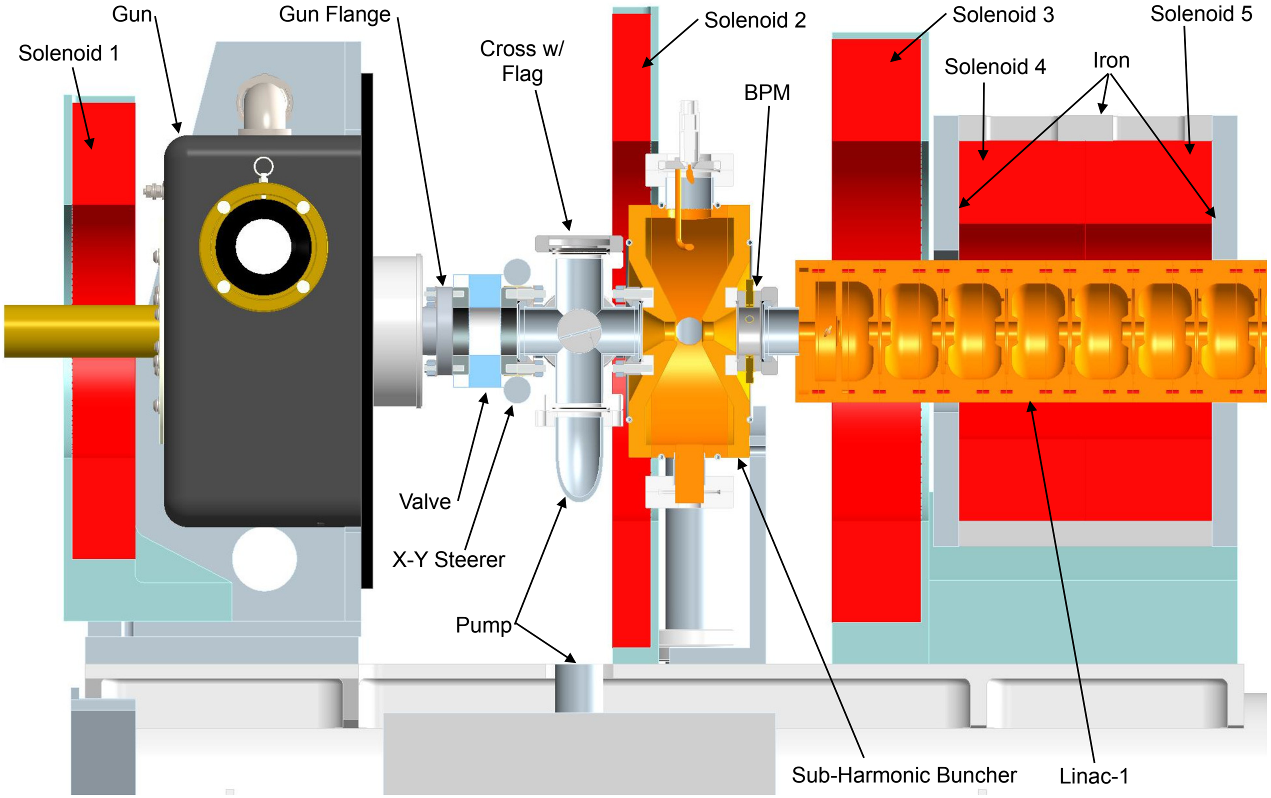
Undulator	MIR	FIR
Type	Planar hybrid	Planar hybrid or PPM
Material	NdFeB	NdFeB or SmCo
Period (mm)	40	110
No. of periods	50	40
Length (m)	2.0	4.4
K_{rms}	0.5 – 1.6	1.0 – 3.0
IR-cavity	**MIR**	**FIR**
Length (m)	5.4	7.2
Waveguide	none	1-D 10 mm high
Wavelength	4 – 50 μ	> 40 μ

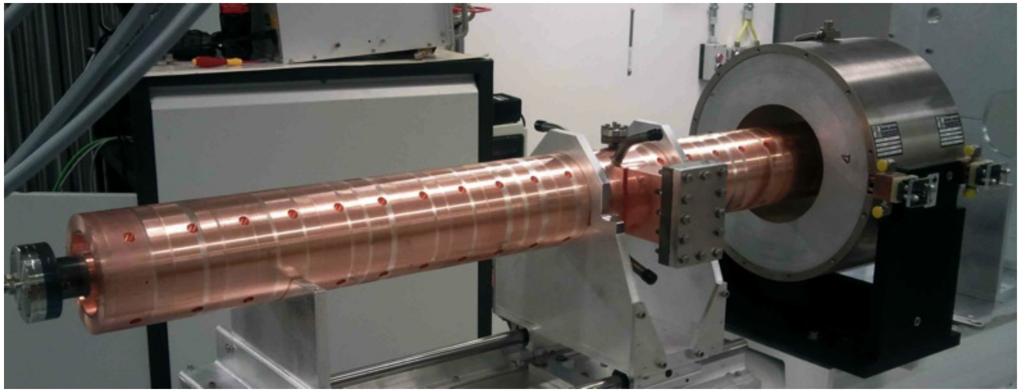
Parameter	**Unit**	**Specification**	**Achieved**
Electron Energy	MeV	(15) 20 - 50	20 - 50
Energy Spread	keV	(<) 50	50
Energy Drift per Hour	%	(<) 0.1	TBD
Bunch Charge	pC	(>) 200	215
Micropulse Length	psec	1 - 5 (10)	2 - 5
Micropulse Repetition Rate	GHz	1	1
Micropulse Jitter	psec	0.5 (0.1)	TBD
Macropulse Length	μsec	1 - 8 (15)	1 - 8
Macropulse Repetition Rate	Hz	10 (20)	1
Transverse RMS Emittance	π mm-mrad	20	13.1

Photo of Installed System

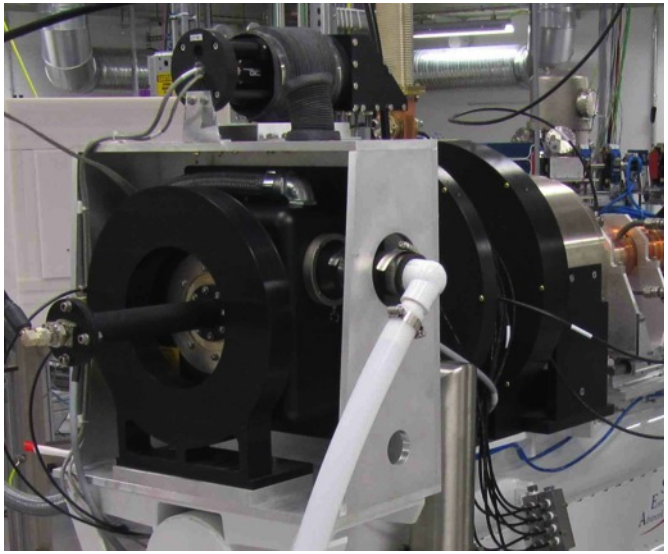


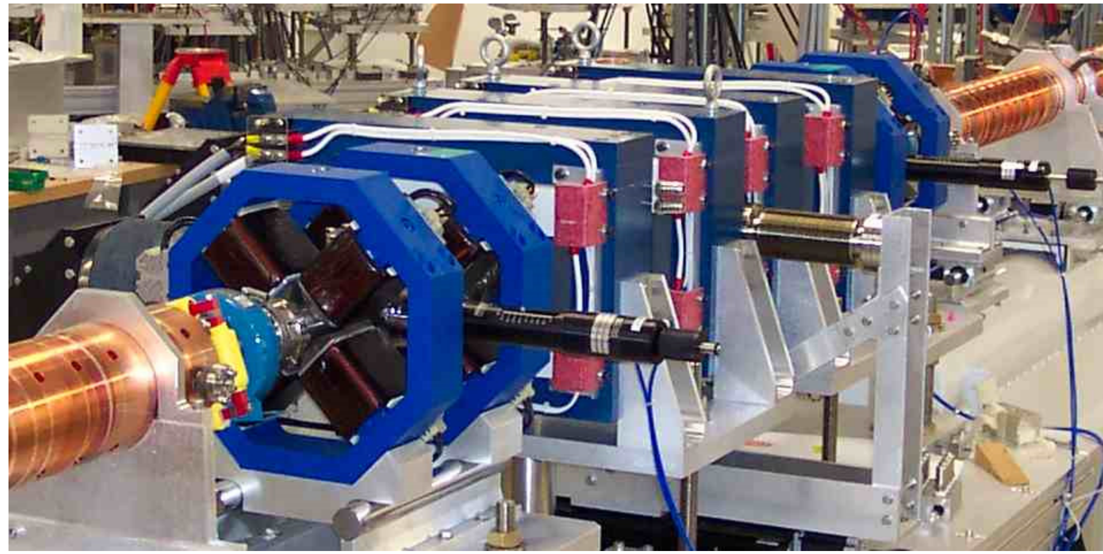
Front End & Linacs



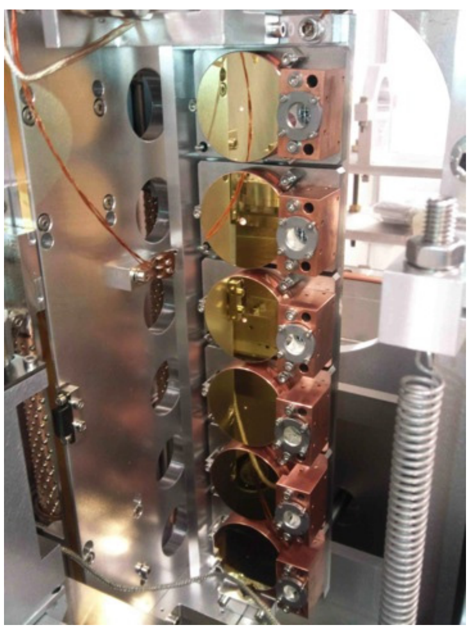


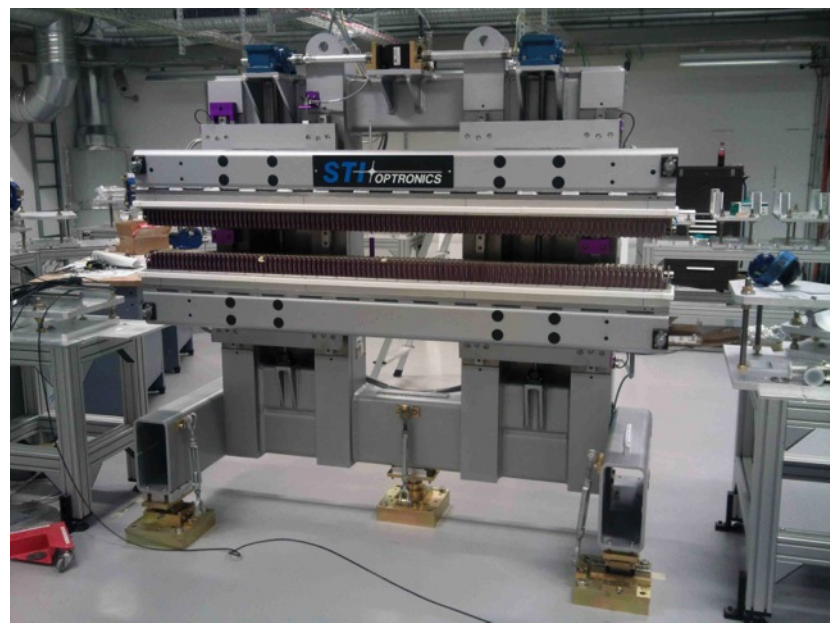
Gun, Chicane, Mirrors & Undulator





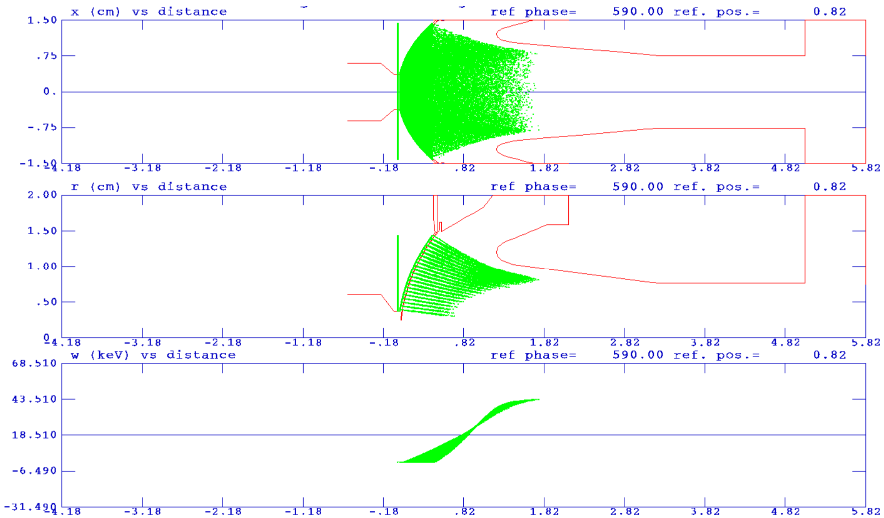
Bestec GmbH

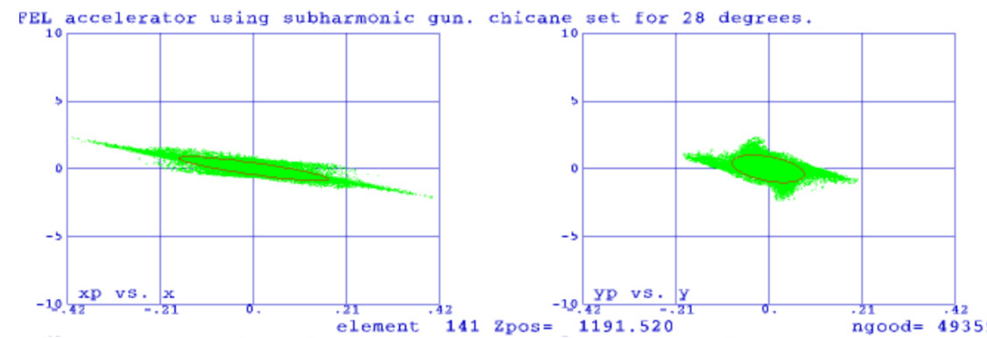


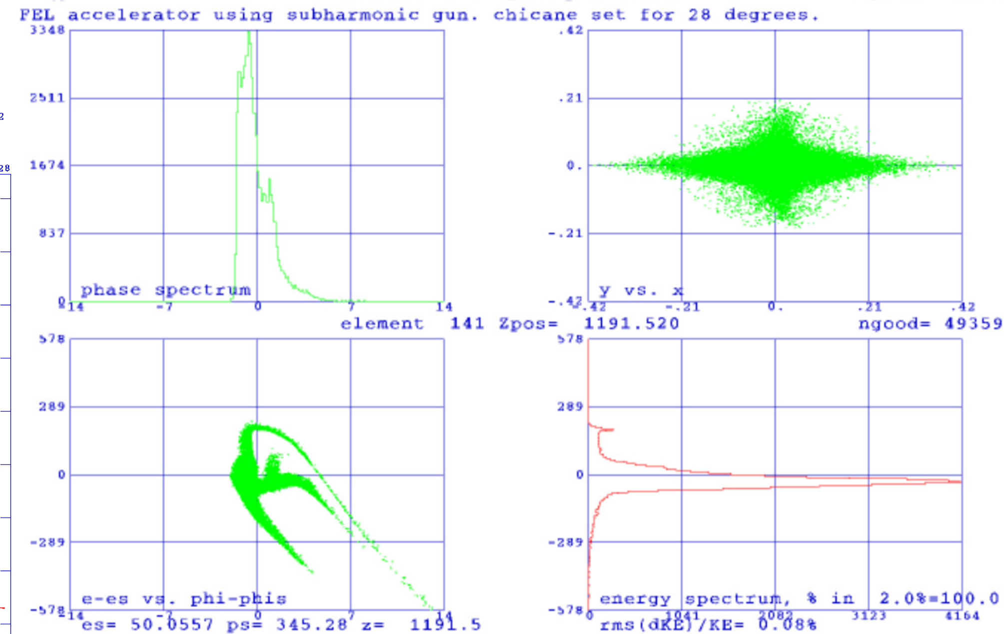


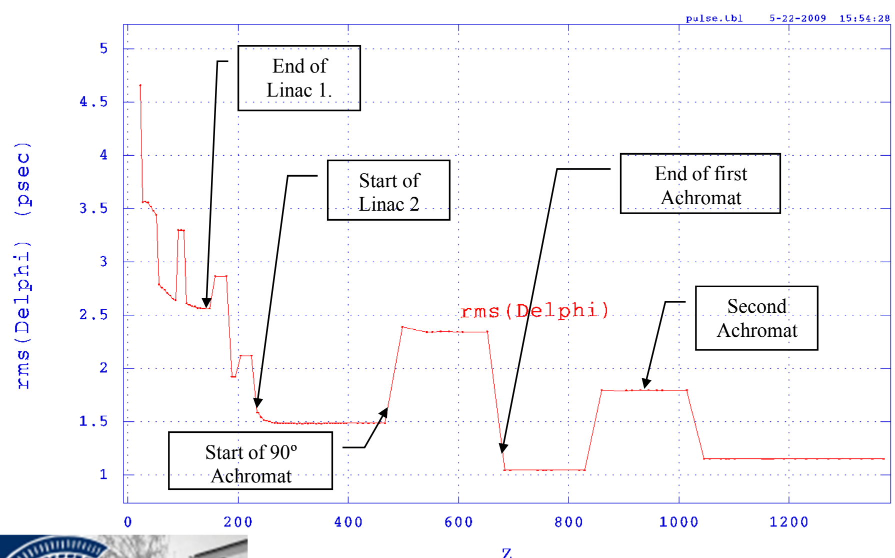
STI Optronics

50 MeV Design Point Beam Dynamics Simulations

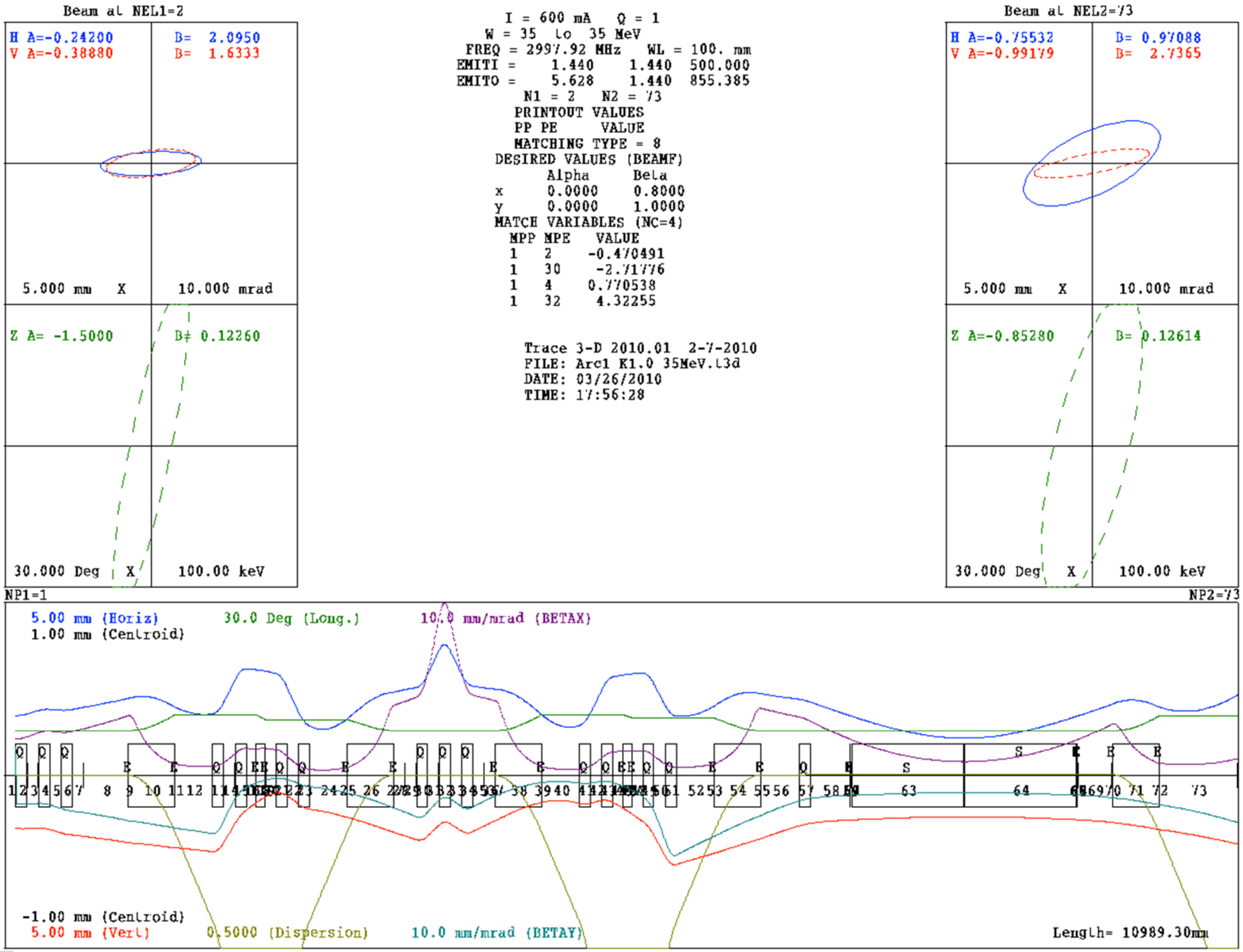






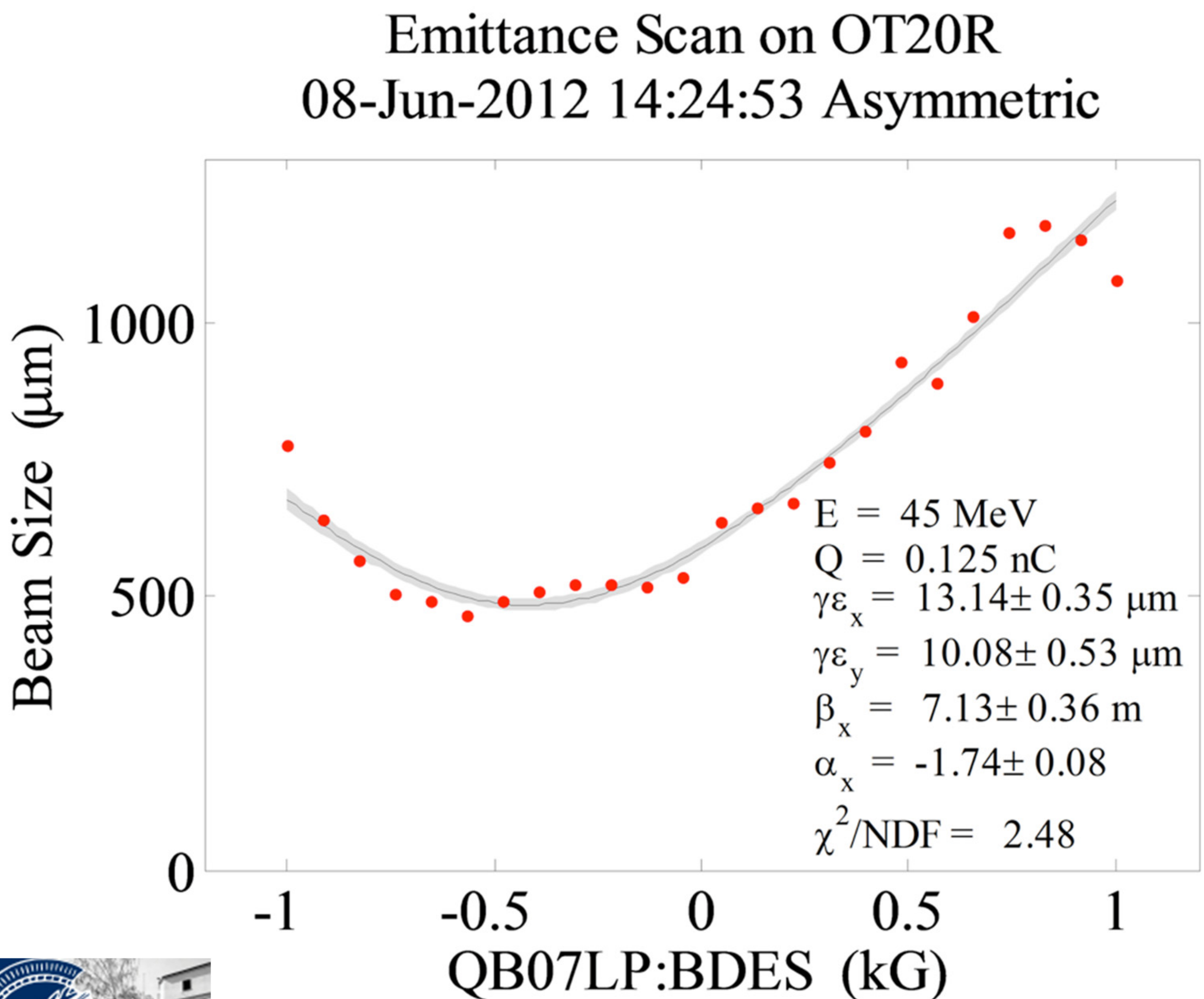


35 MeV, K = 1.0 Beam Envelope Undulator Simulation



Putting Accelerator Technology to Work

Emittance Measurement @ 125 pC & 45 MeV



13.14 ± 0.35 (H)
10.08 ± 0.53 (V)
π mm-mrad

< ± 3% measurement statistical error implies good shot-to-shot stability.

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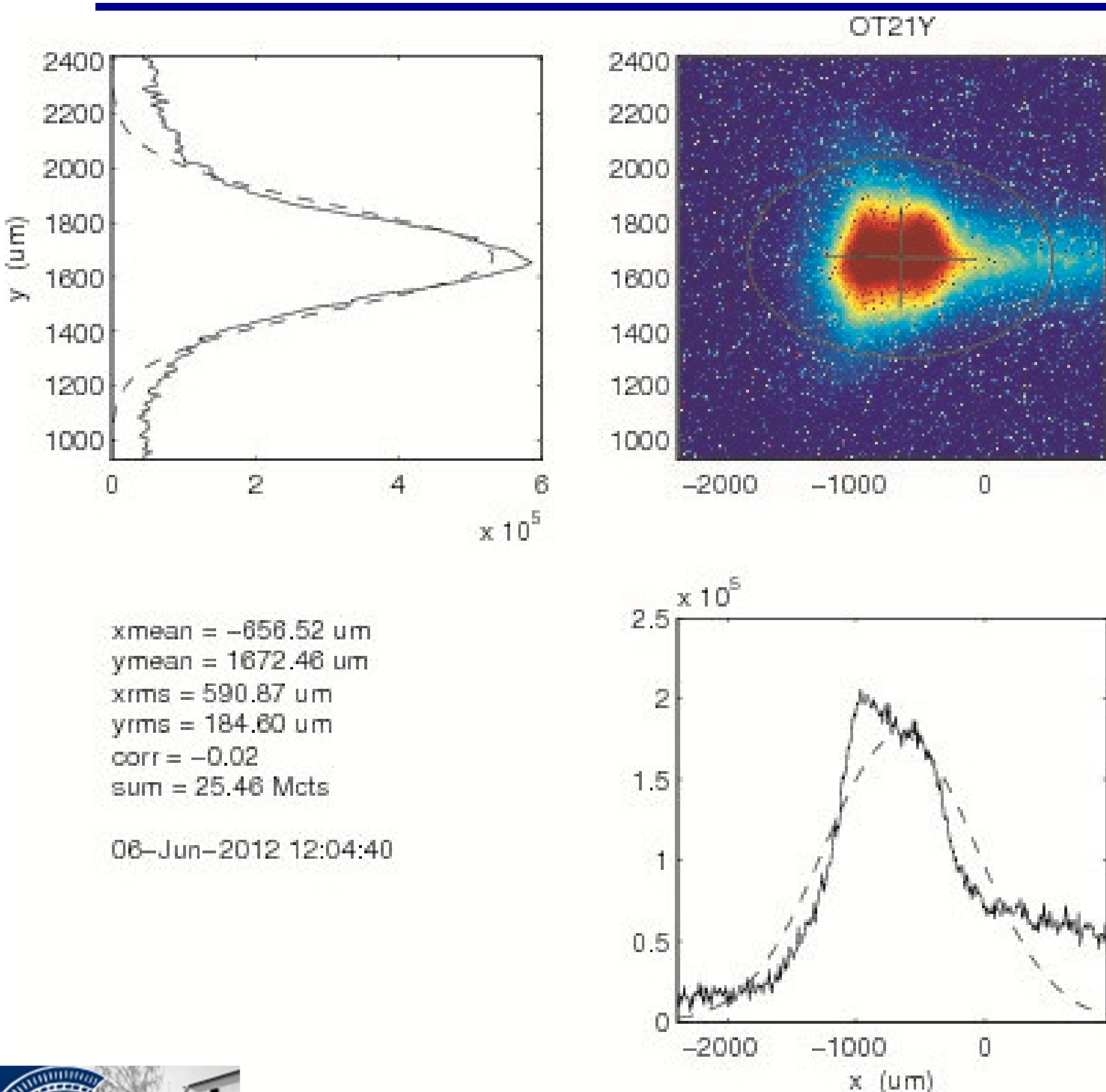
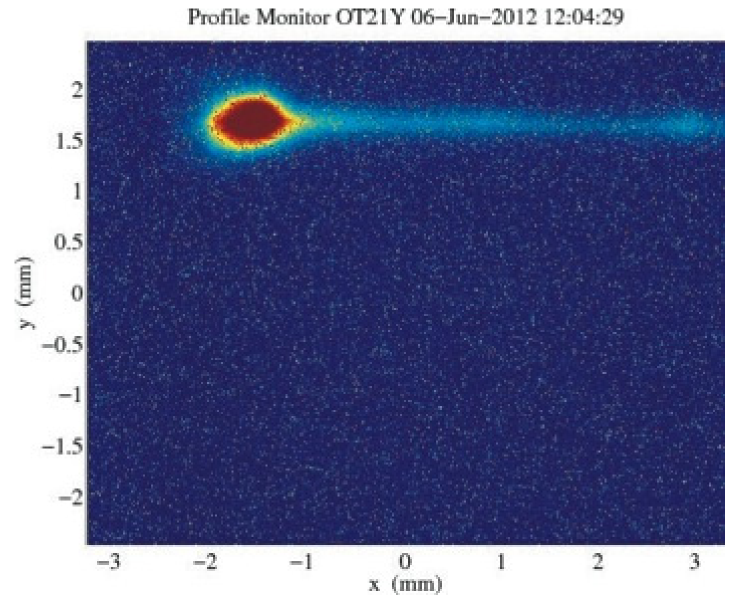
Energy Spread Measurement @ 45 MeV





Beam image from YAG screen in diagnostic beamline

~ 50 keV energy spread measured at 25 MeV and 45 MeV

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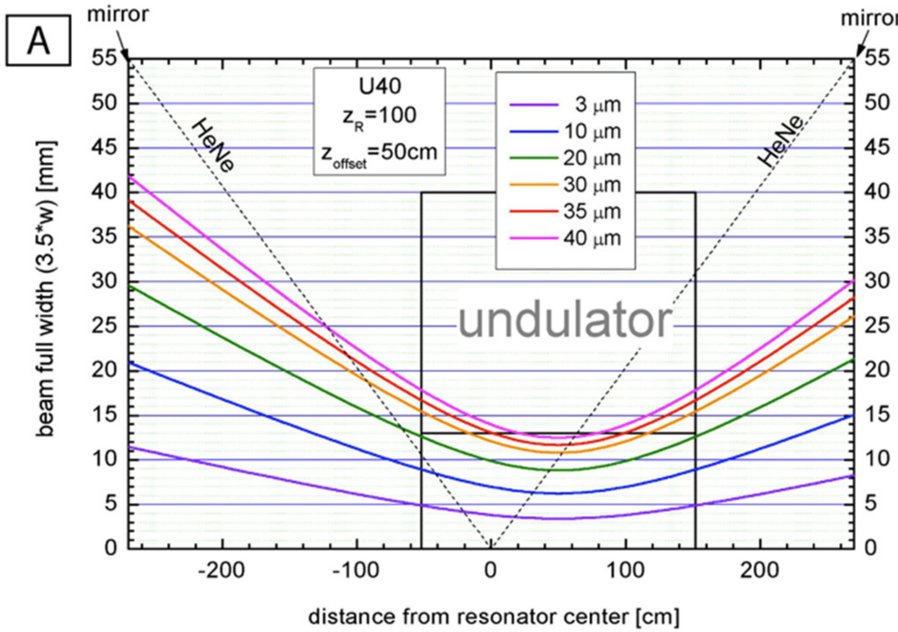
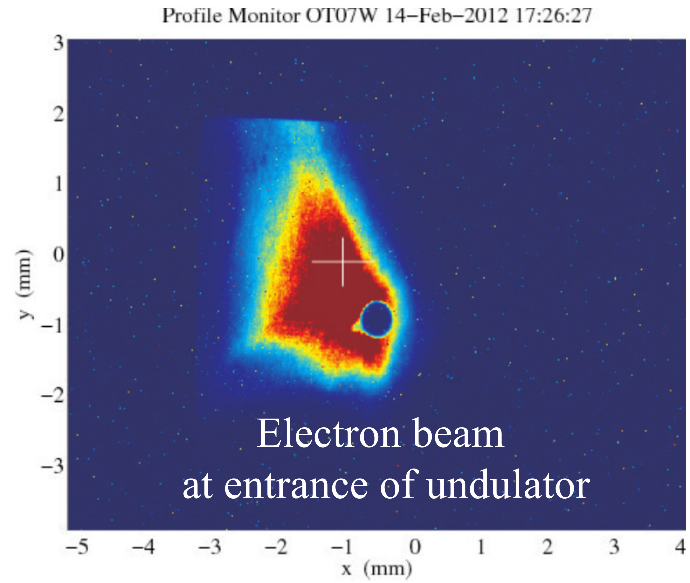
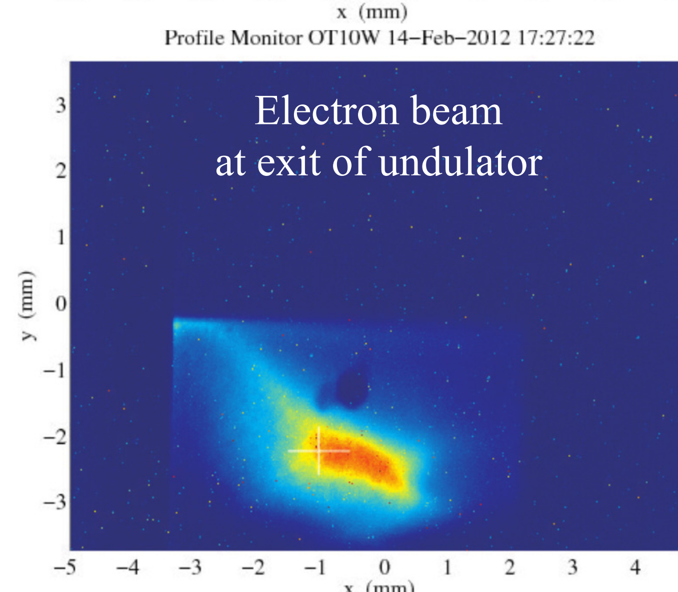
Bunch Length Measurement

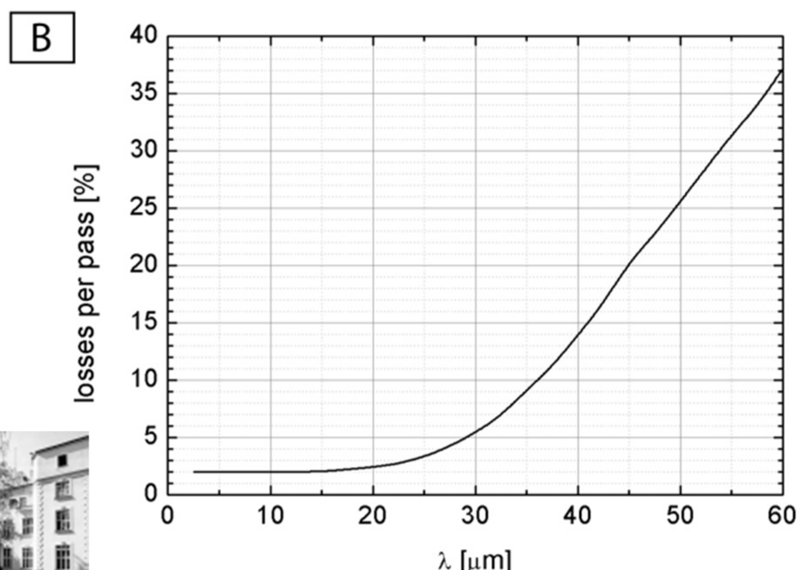
- Bunch length is set by the end of the chicane (20 MeV) and does not change significantly in the downstream beamline
- Set Linac 2 to compensate for beam loading and to deliver zero energy gain
- Use the zero-crossing technique to correlate the bunch length with energy spread (Graves at SDL)
- Phase scan of Linac 2 with measurement of the energy spread gives an estimate the longitudinal phase space (SLAC et al.)
- Bunch length with chicane on/off estimated to be 2/5 psec

Optical and Electron Beams Through Undulator

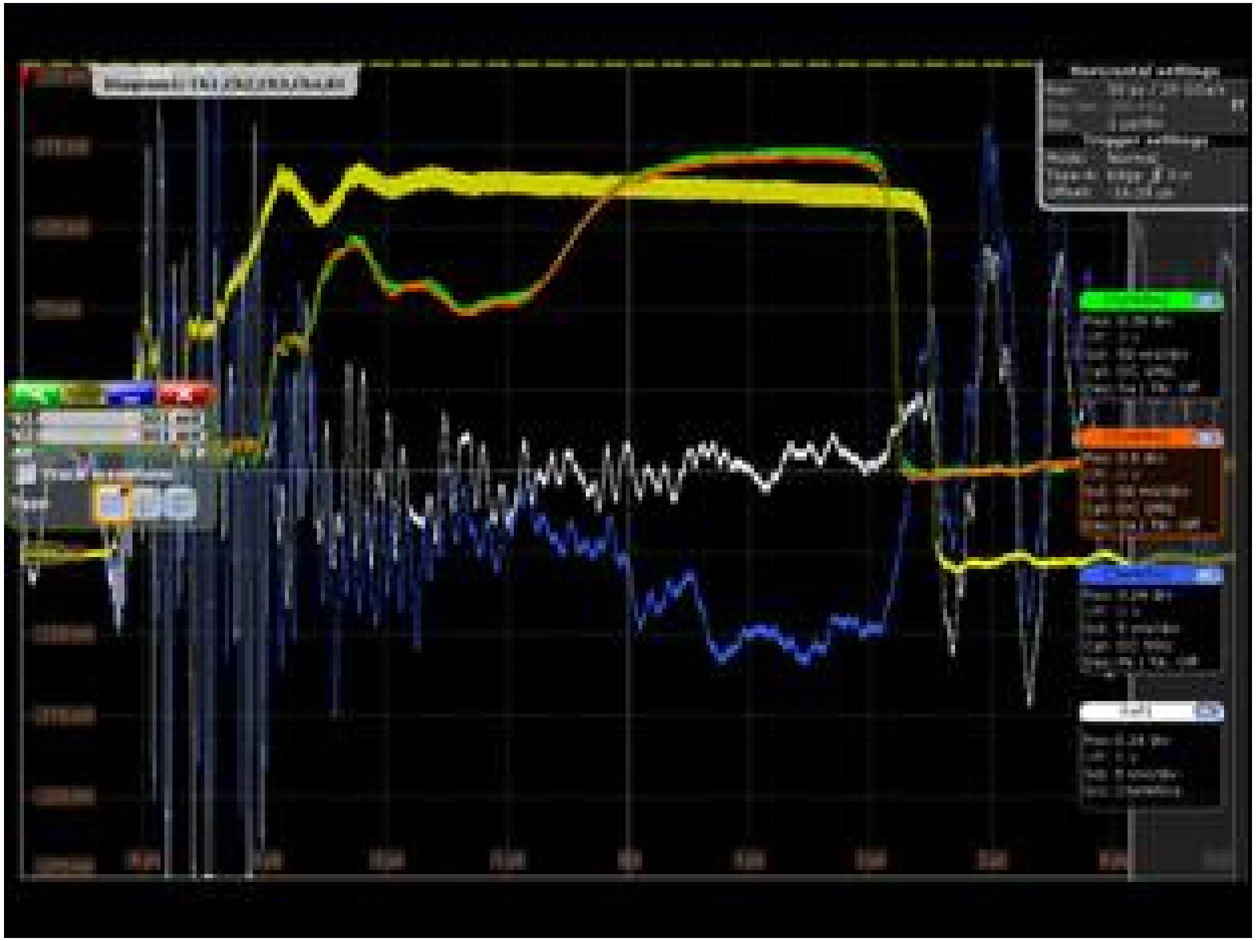






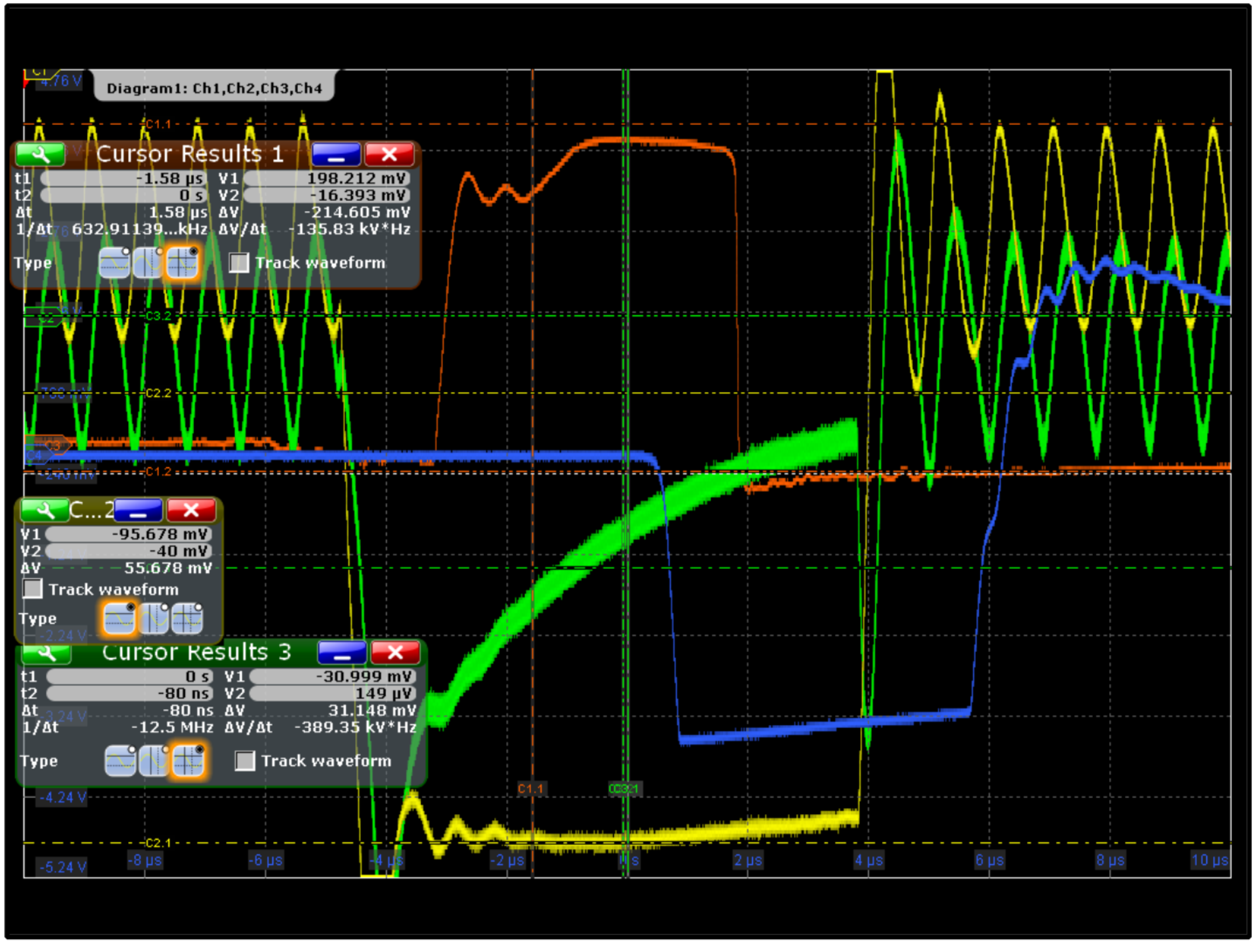


Spontaneous Emission @ 28 MeV & K_{rms} = 1.22



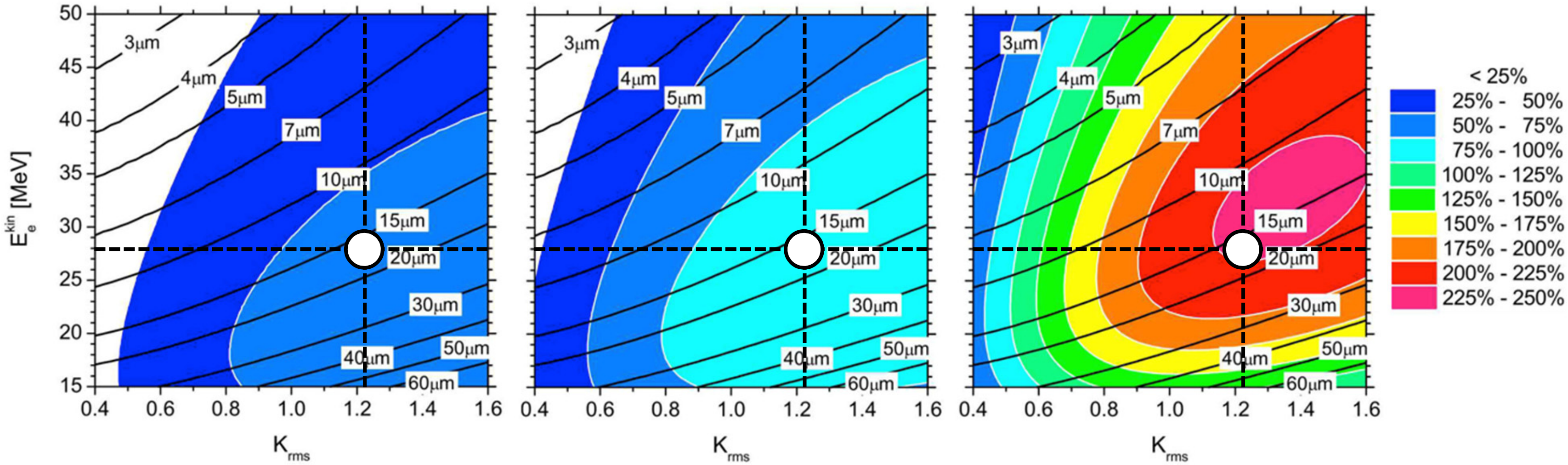
- Current transformers at undulator entrance and exit (Red and Green respectively)
  - Initial 3 μsec has significant spread in energy => isochronous bend loss
  - Final 2 μsec shows near 100% transmission through undulator
- Baseline MCT signal without beam (White)
- Spontaneous emission (Blue)
- Electron beam current signal > 200 mA or 210 pC (Yellow)

First Light @ 16 microns



- 28 MeV with K_{rms} = 1.22 (20 mm gap)
- Saturated MCT signal (Blue)
- Electron beam current signal > 200 mA or 210 pC (Red)
- Subharmonic buncher I & Q signal (Yellow and Green respectively)
  - Green curve indicates large phase slew and shot-to-shot variation (now fixed)

Gain Contours



5 ps bunch length   3 ps bunch length   1 ps bunch length

- Contours assume 200 pC bunch charge, 50 keV energy spread, 20 µ transverse emittance => estimated gain ~ 60%
- First light: 210 pC and estimated ~ 50 keV energy spread (50 keV @ 25 and 45 MeV), ~ 20 µ transverse emittance (13.1 µ measured @ 45 MeV and 125 pC) with microbunch length assumed ~ 5 psec (measured with chicane off)

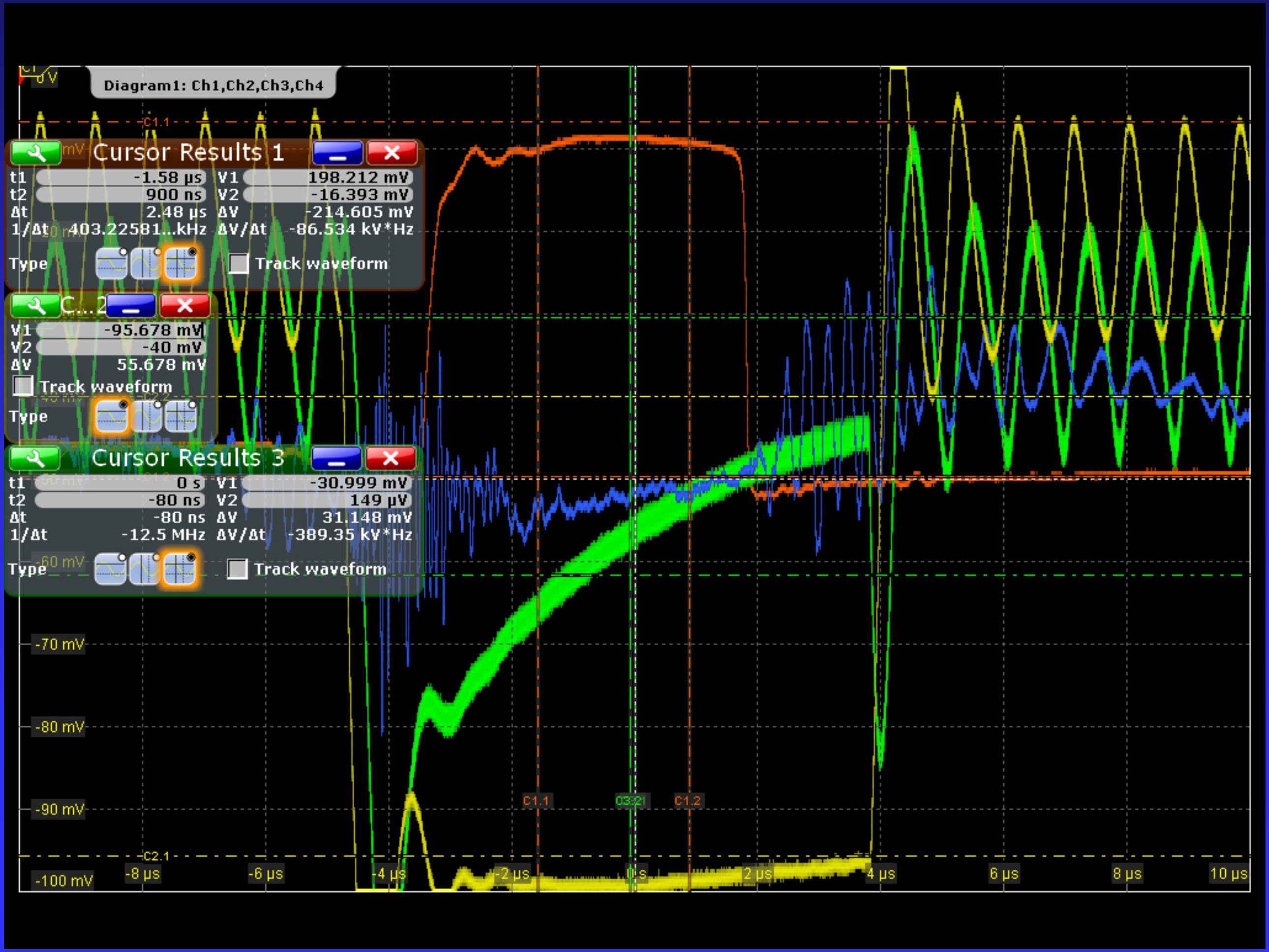
* Gain curves courtesy Rudi Wünsch, HZDR, Dresden

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown trace: electron bunch current

Green trace: SHB phase, Yellow trace: SHB amplitude

Cavity length L detuned; No lasing



E_{El} = 28 MeV

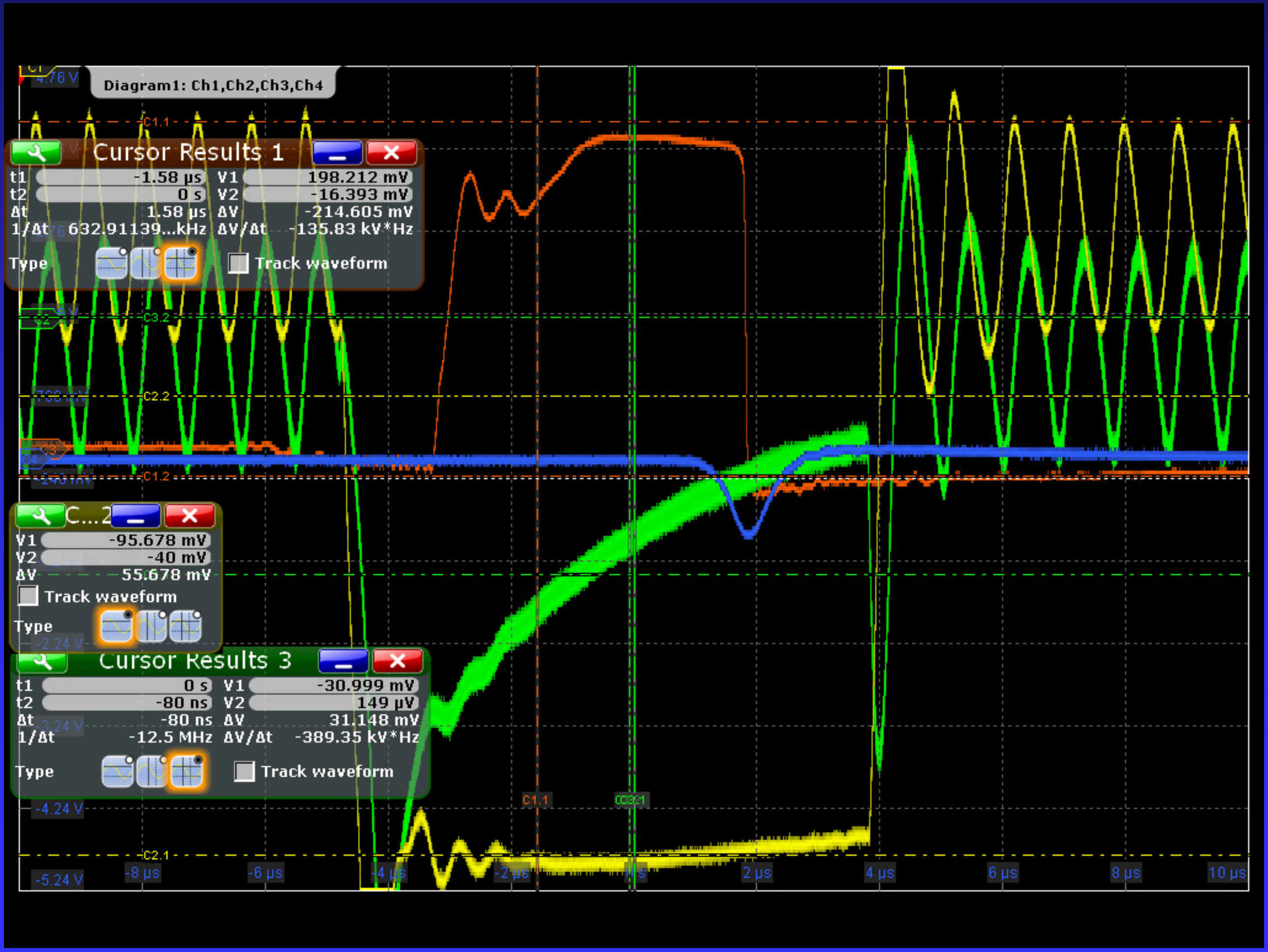
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

L=L_0



E_{El} = 28 MeV

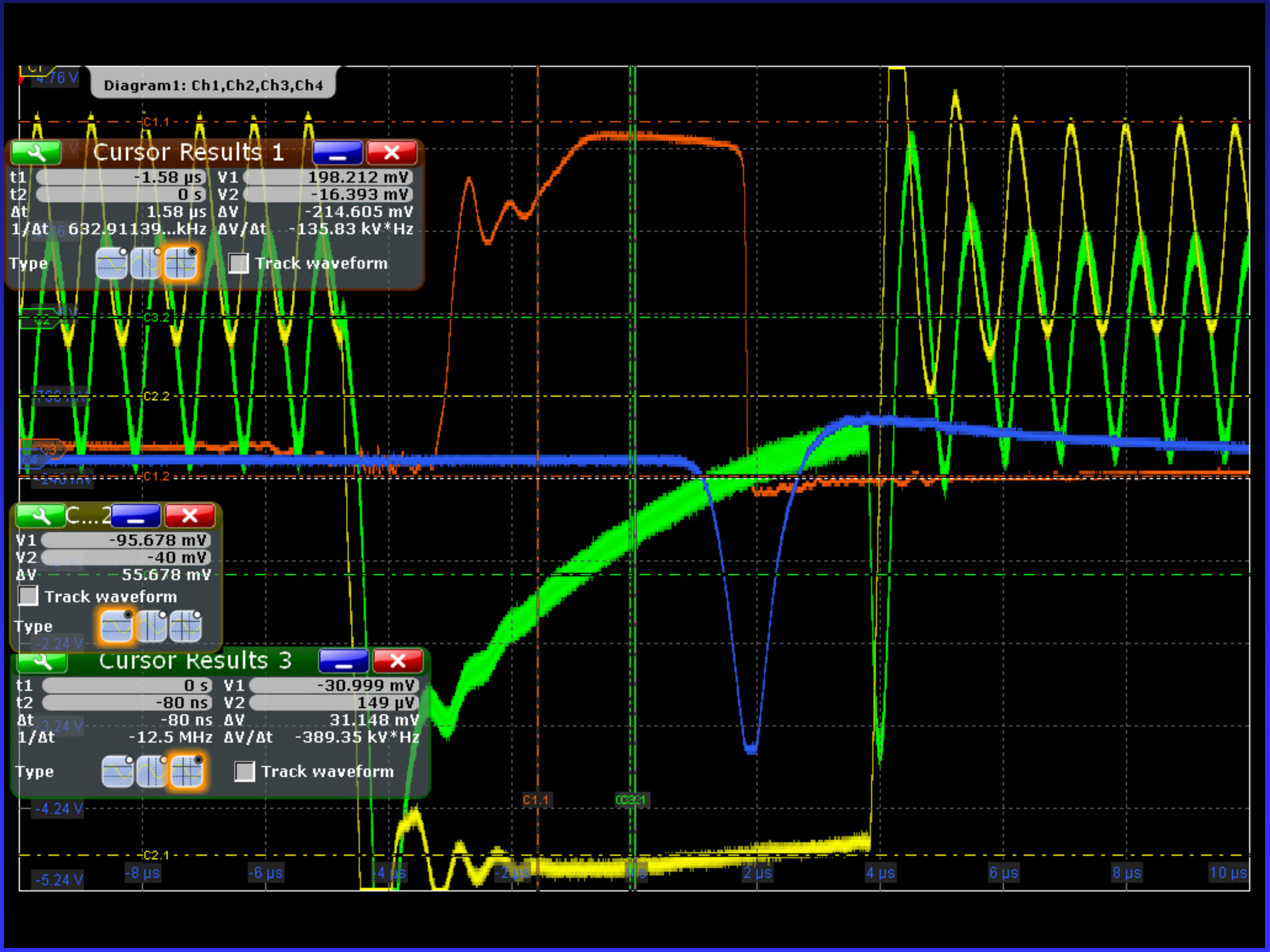
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

ΔL = 10 µm



E_{El} = 28 MeV

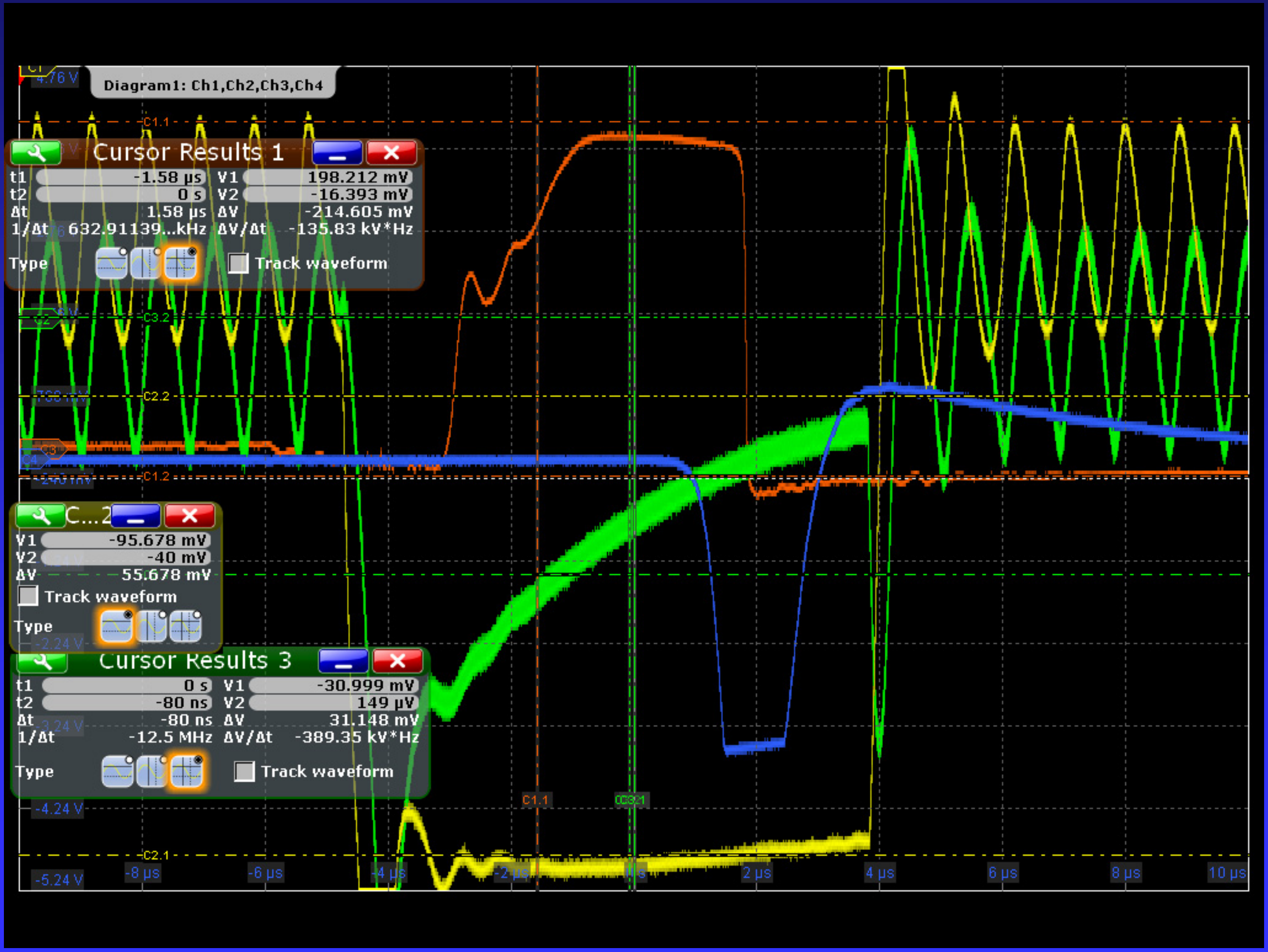
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal,   Brown signal: electron bunch current

Cavity length L:

ΔL = 20 µm



E_{El} = 28 MeV

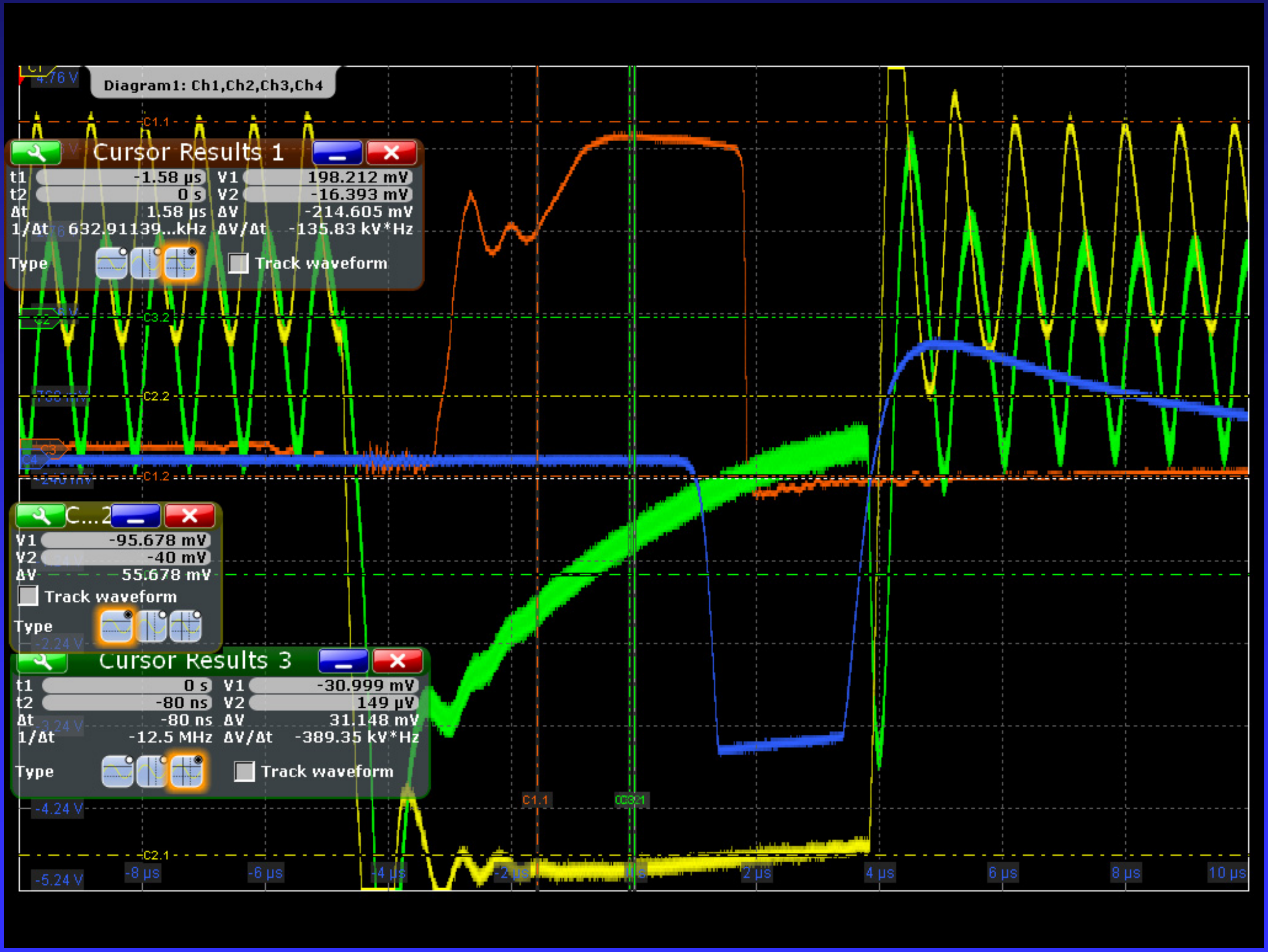
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

ΔL = 30 µm



E_{El} = 28 MeV

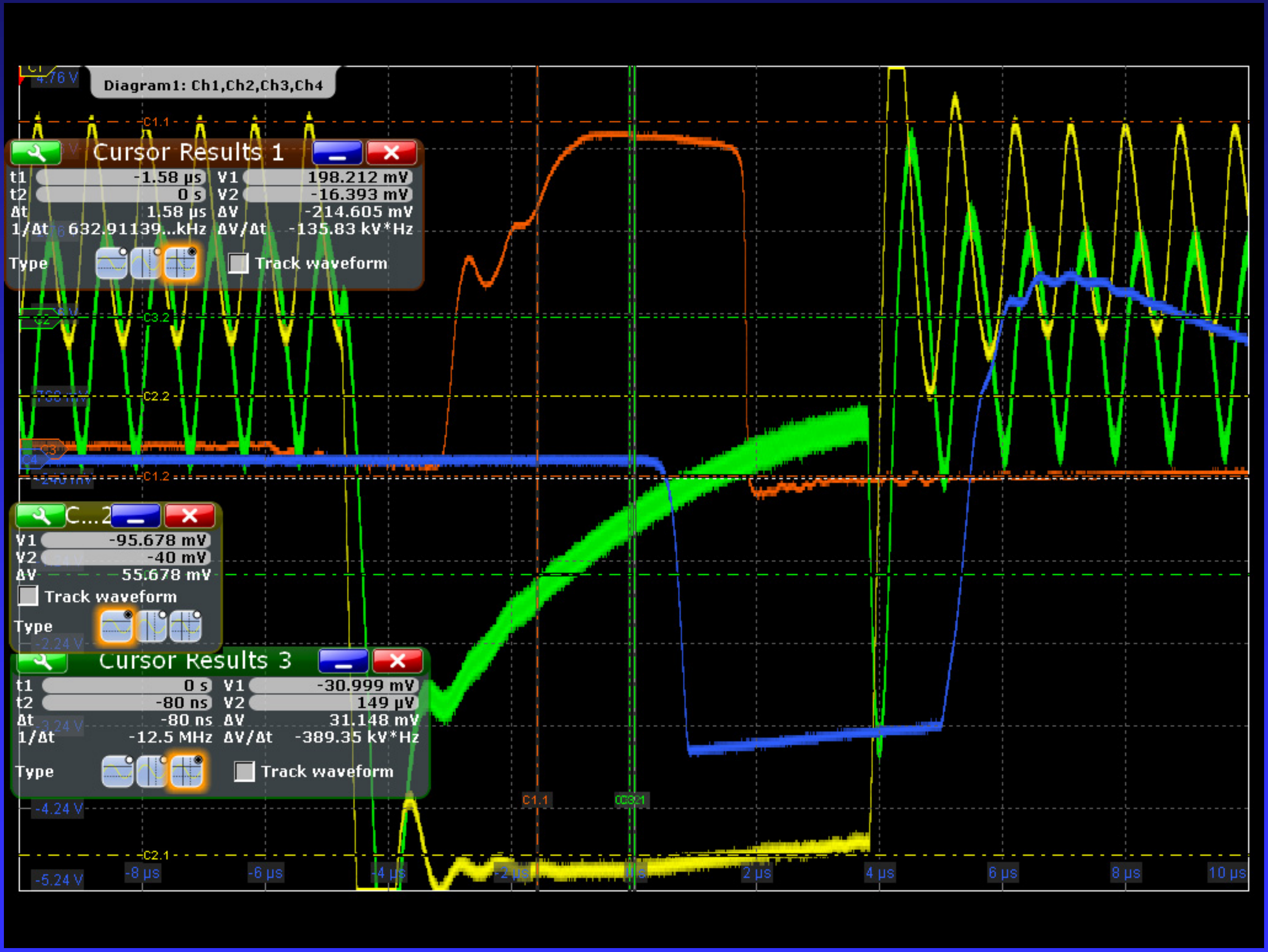
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

ΔL = 40 µm



E_{El} = 28 MeV

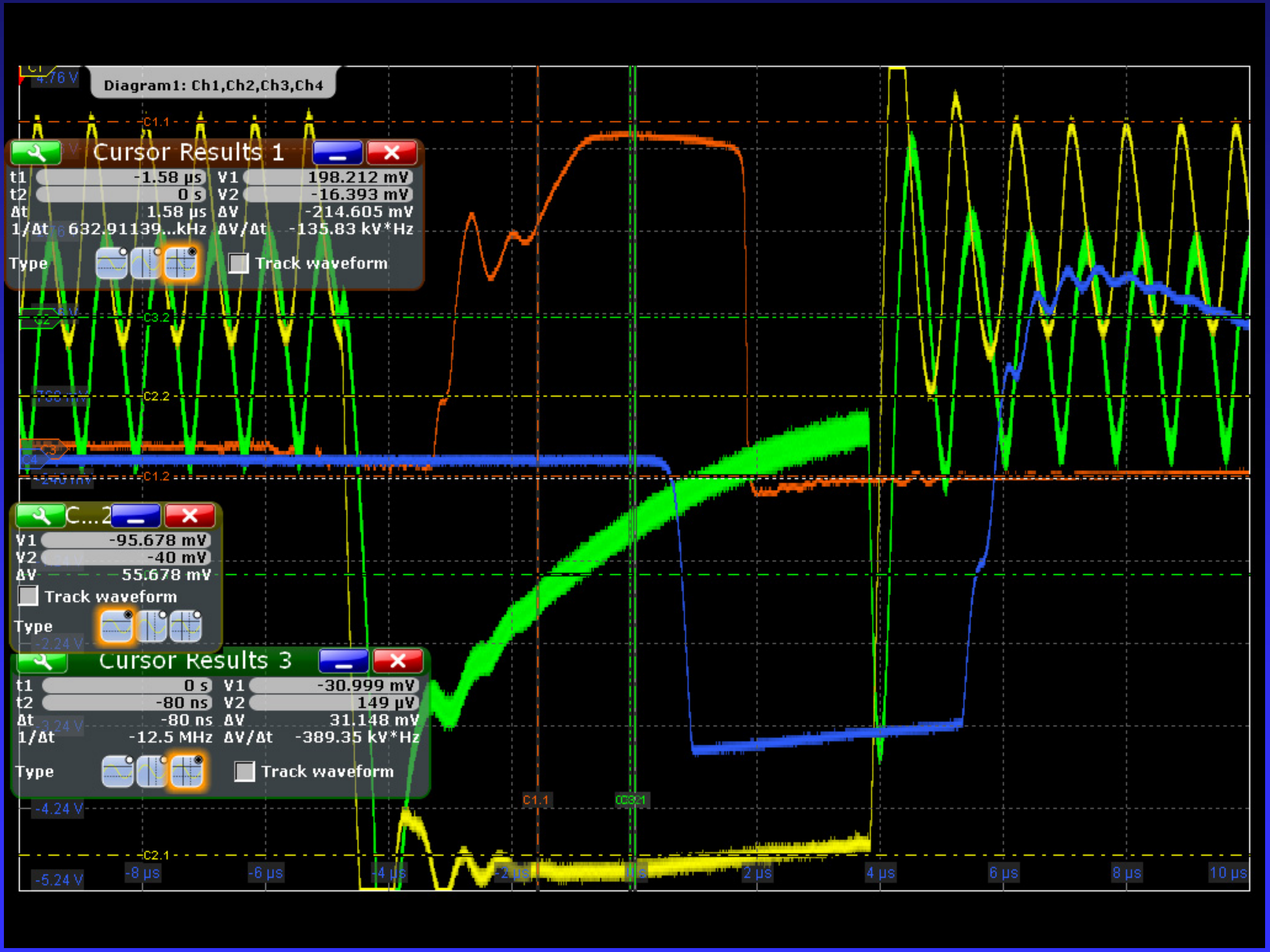
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal,   Brown signal: electron bunch current

Cavity length L:

ΔL = 50 µm



E_{El} = 28 MeV

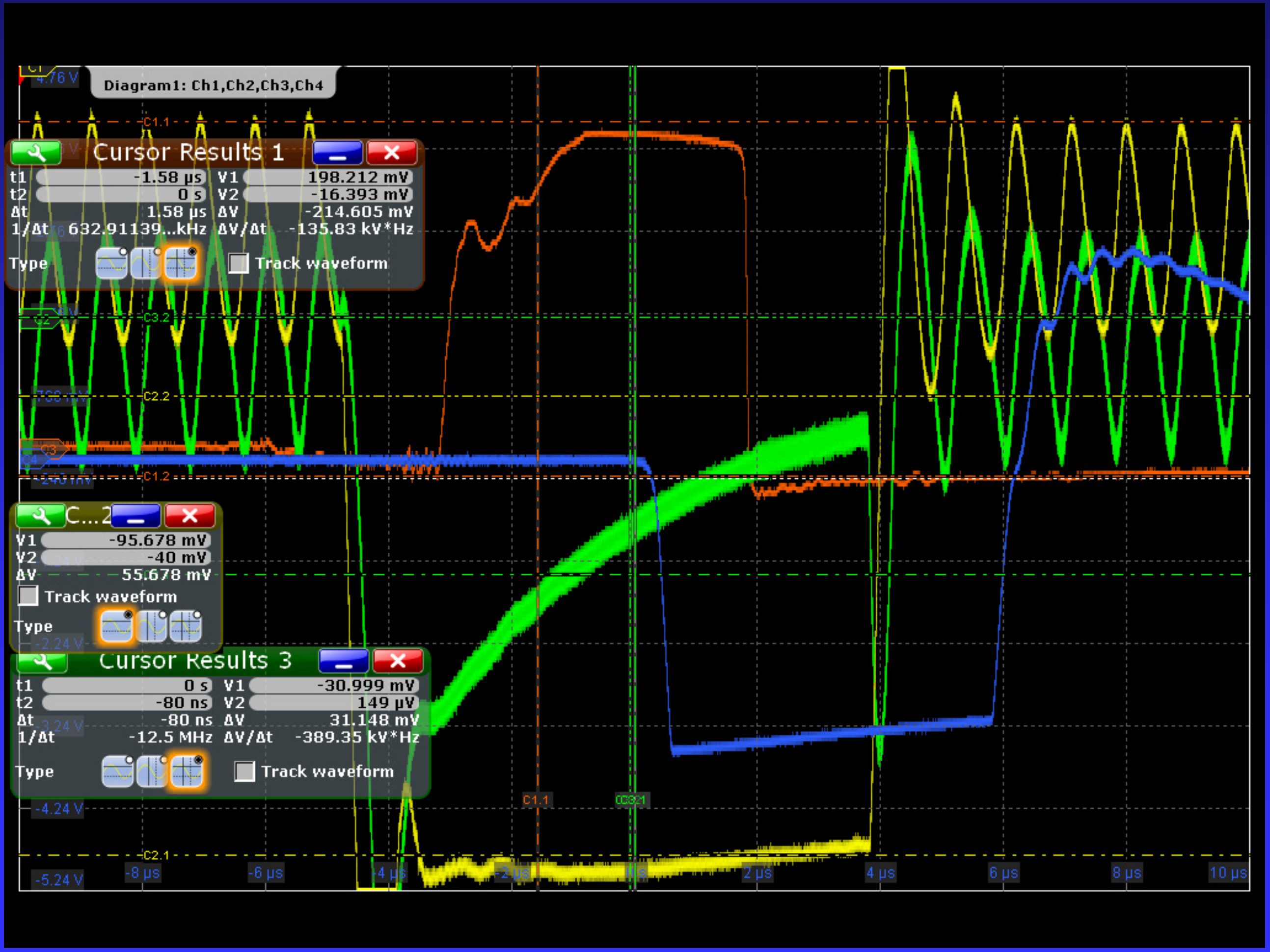
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal,   Brown signal: electron bunch current

Cavity length L:

ΔL = 60 µm



E_{El} = 28 MeV

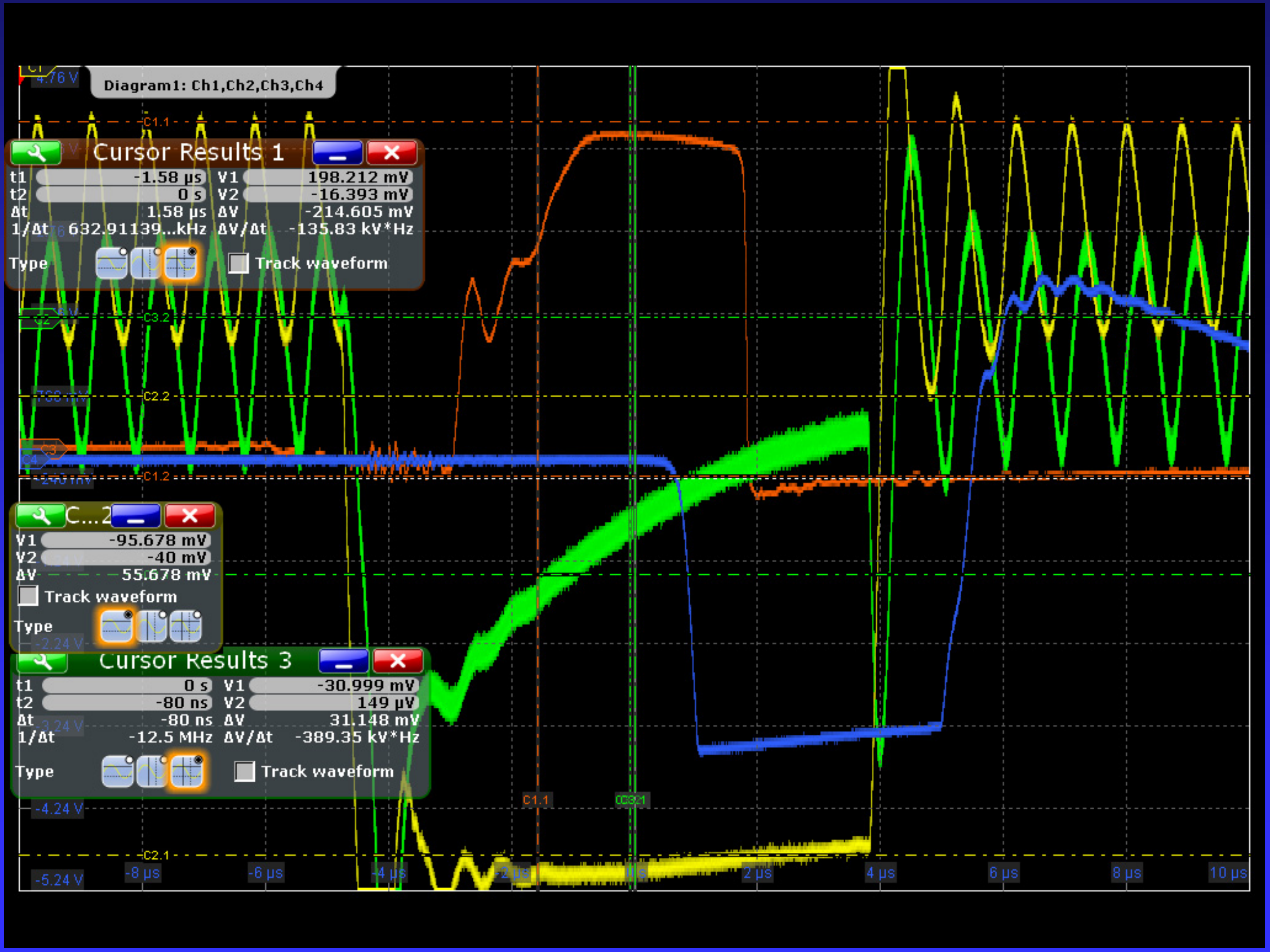
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

ΔL = 70 µm



E_{El} = 28 MeV

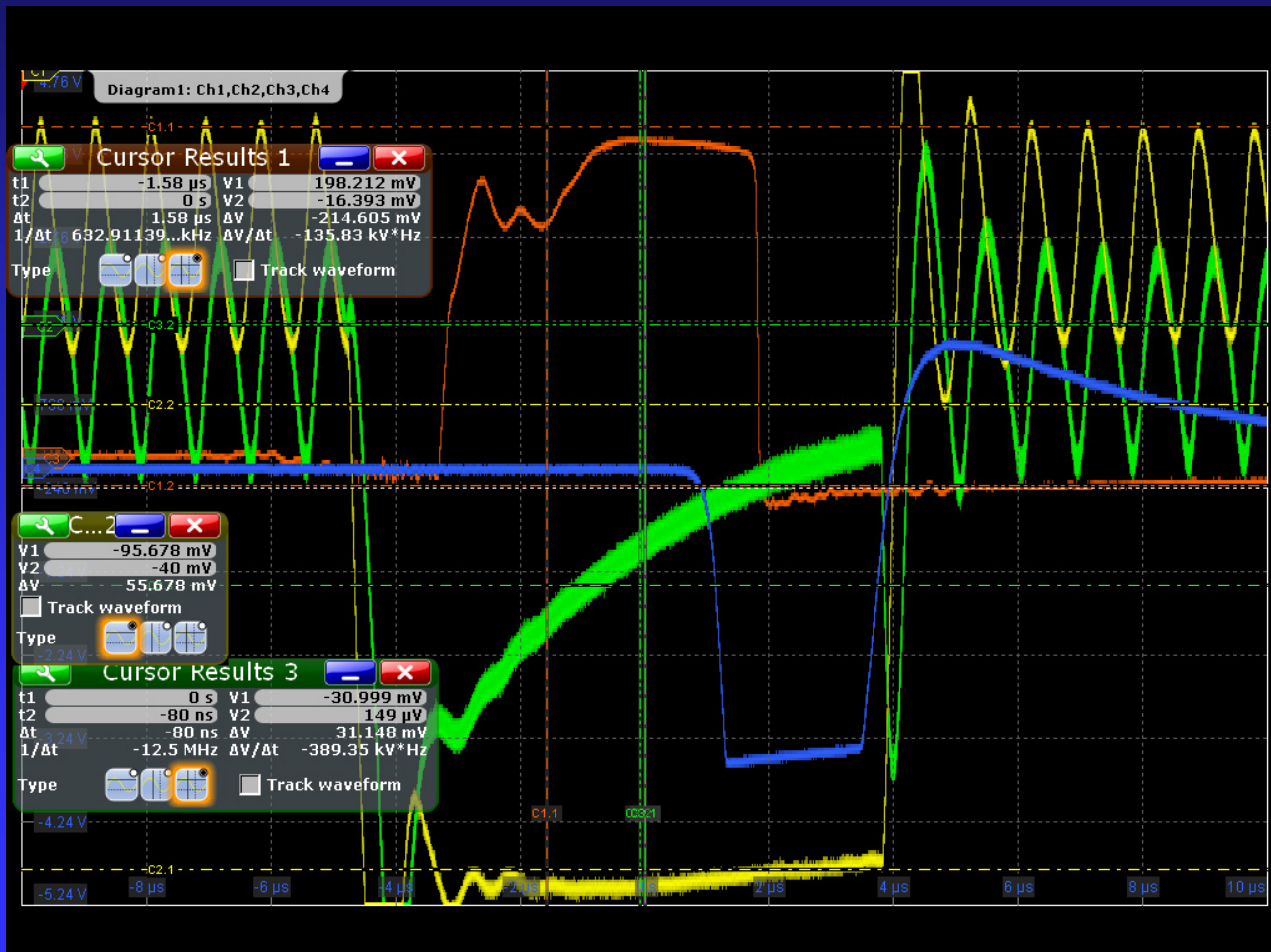
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

$\Delta L =$ 80 µm



$E_{El} =$ 28 MeV

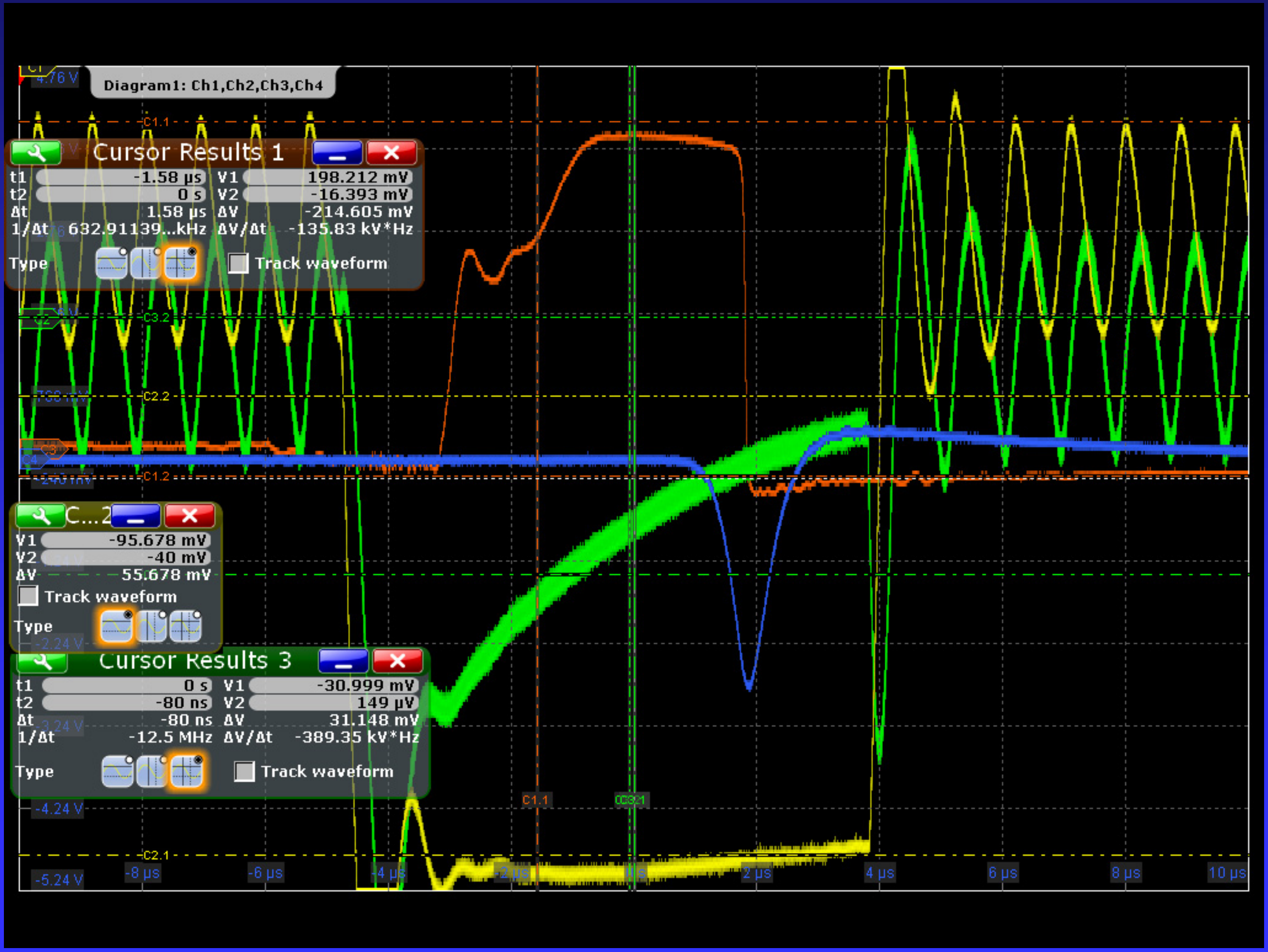
$\lambda_{IR} =$ 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

ΔL = 90 µm



E_{El} = 28 MeV

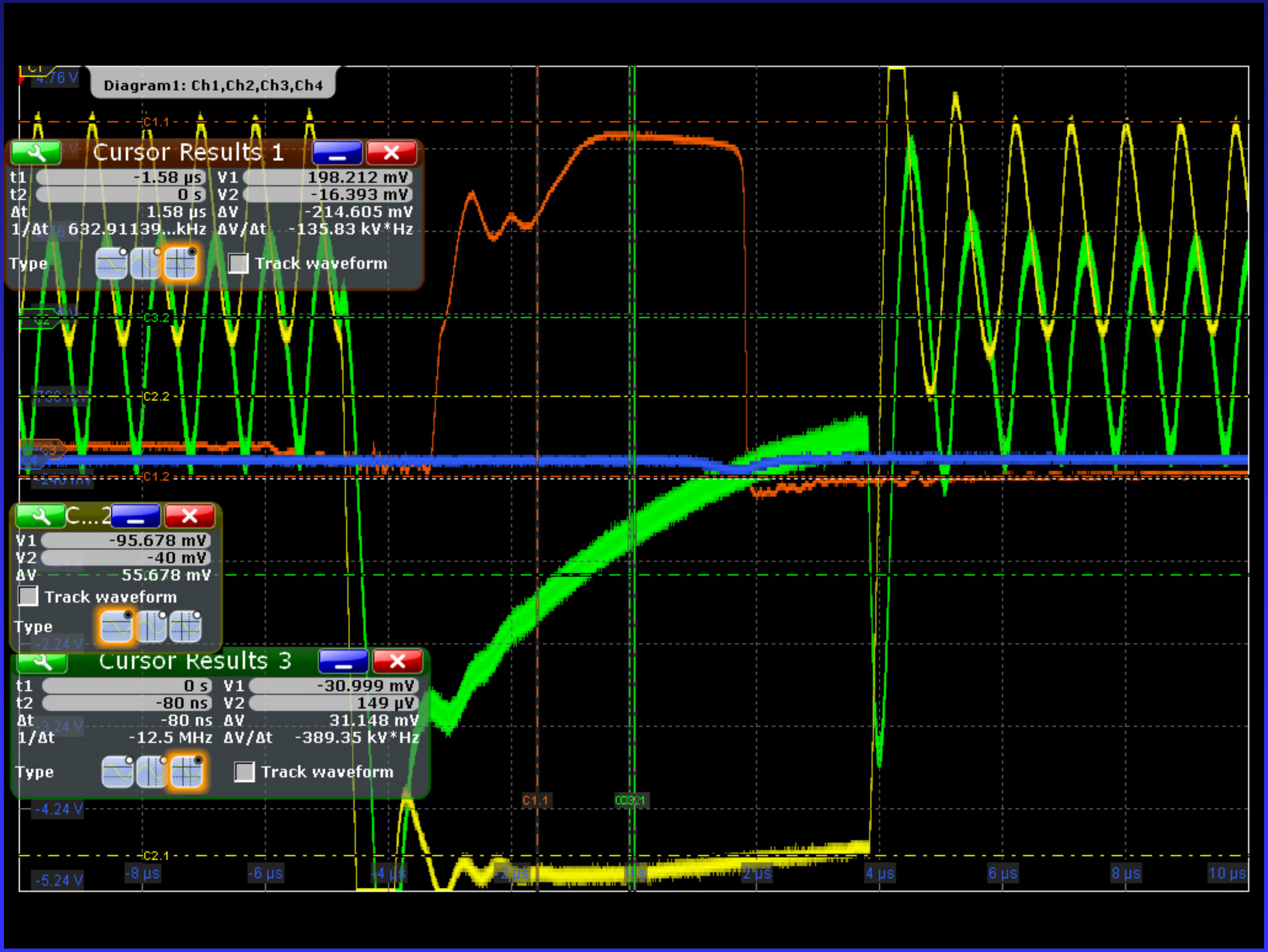
λ_{IR} = 16 µm

First Lasing 14.2.2012

Blue trace: IR detector signal, Brown signal: electron bunch current

Cavity length L:

$\Delta L =$ 100 µm



$E_{El} =$ 28 MeV

$\lambda_{IR} =$ 16 µm

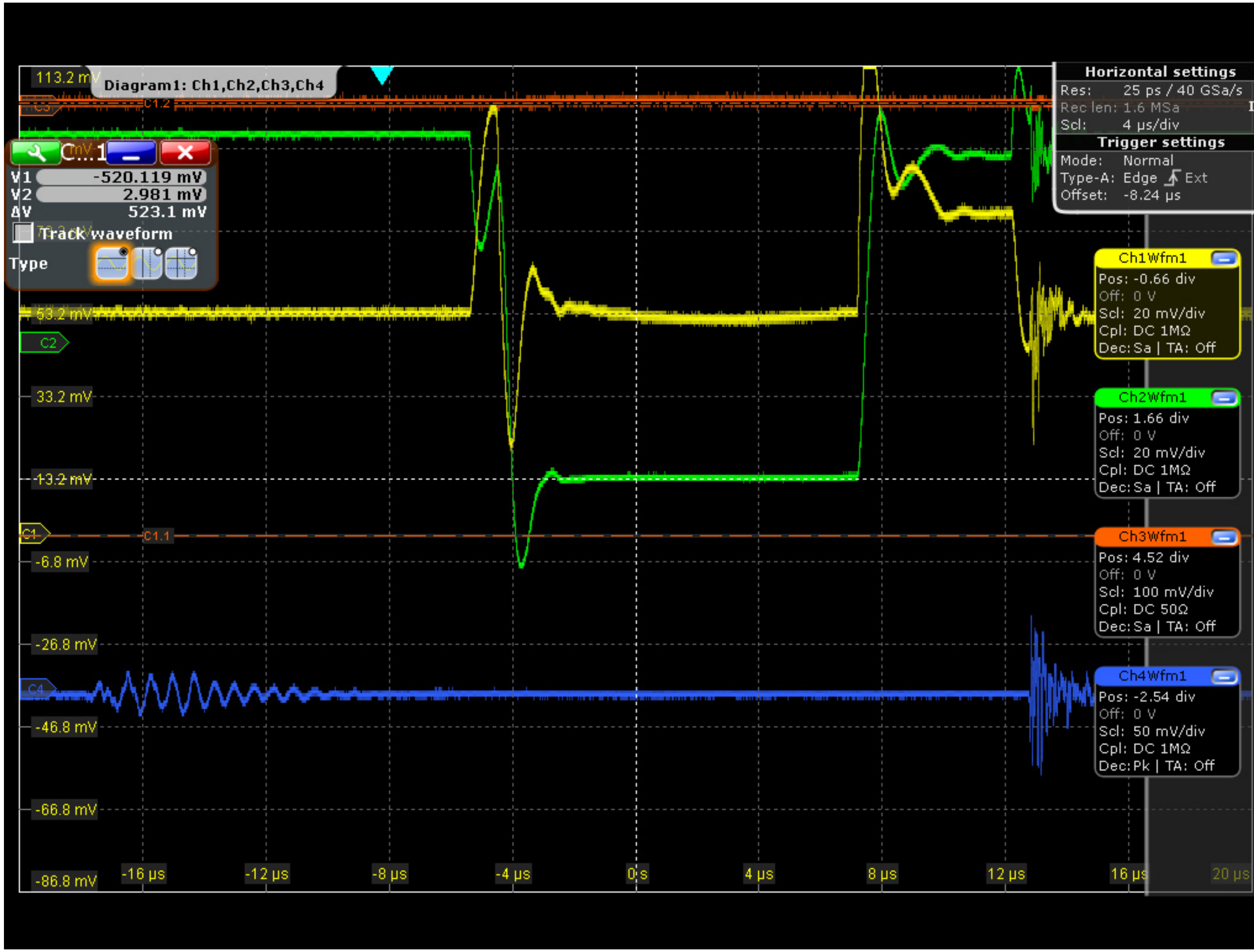
Improved SHB Signal (Beam Loaded)

SHB Q

SHB I

N/A

N/A



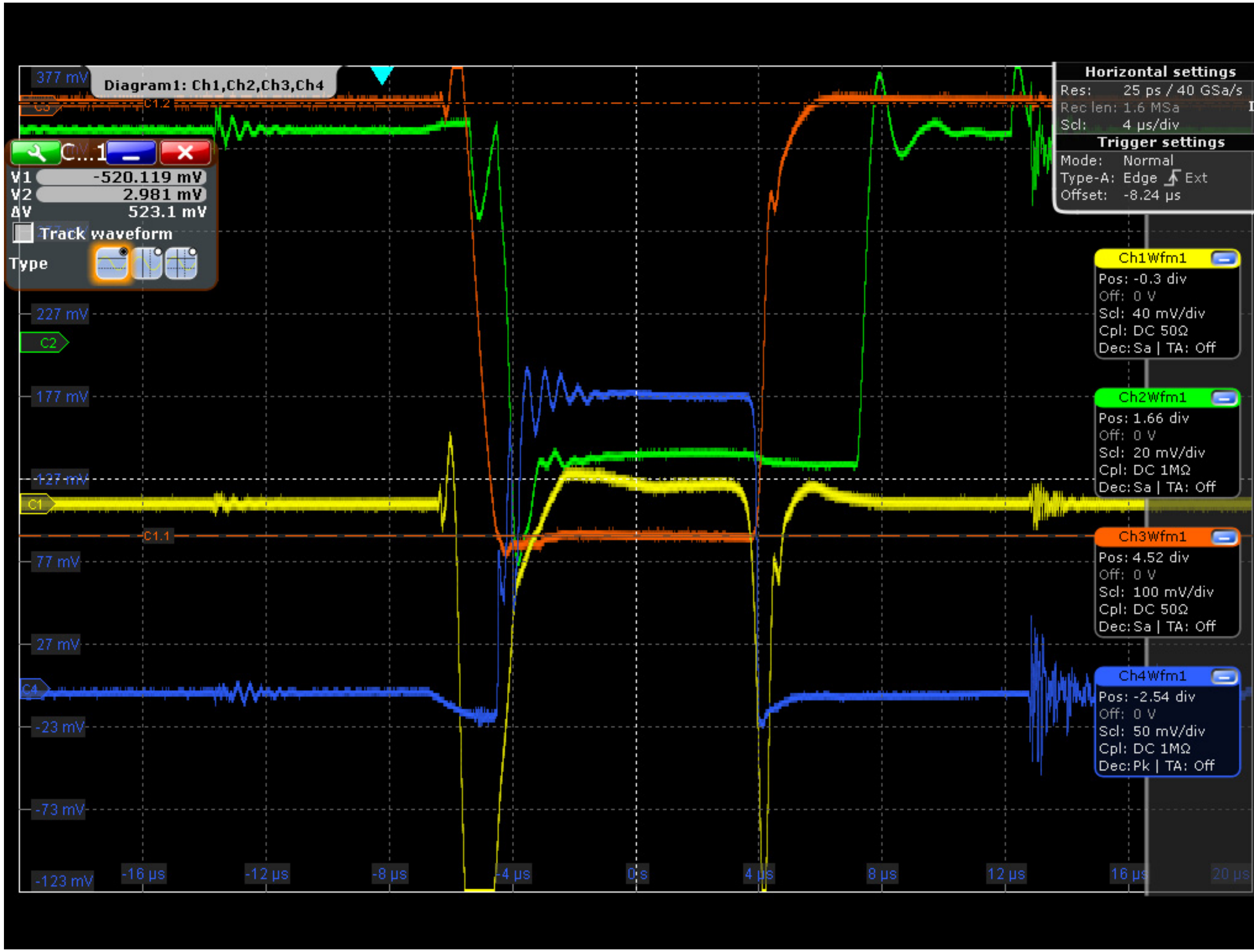
Flattened Linac 1 Signal with Beam Pulse

SHB Q

Linac 1 I

Linac 1 Q

CT

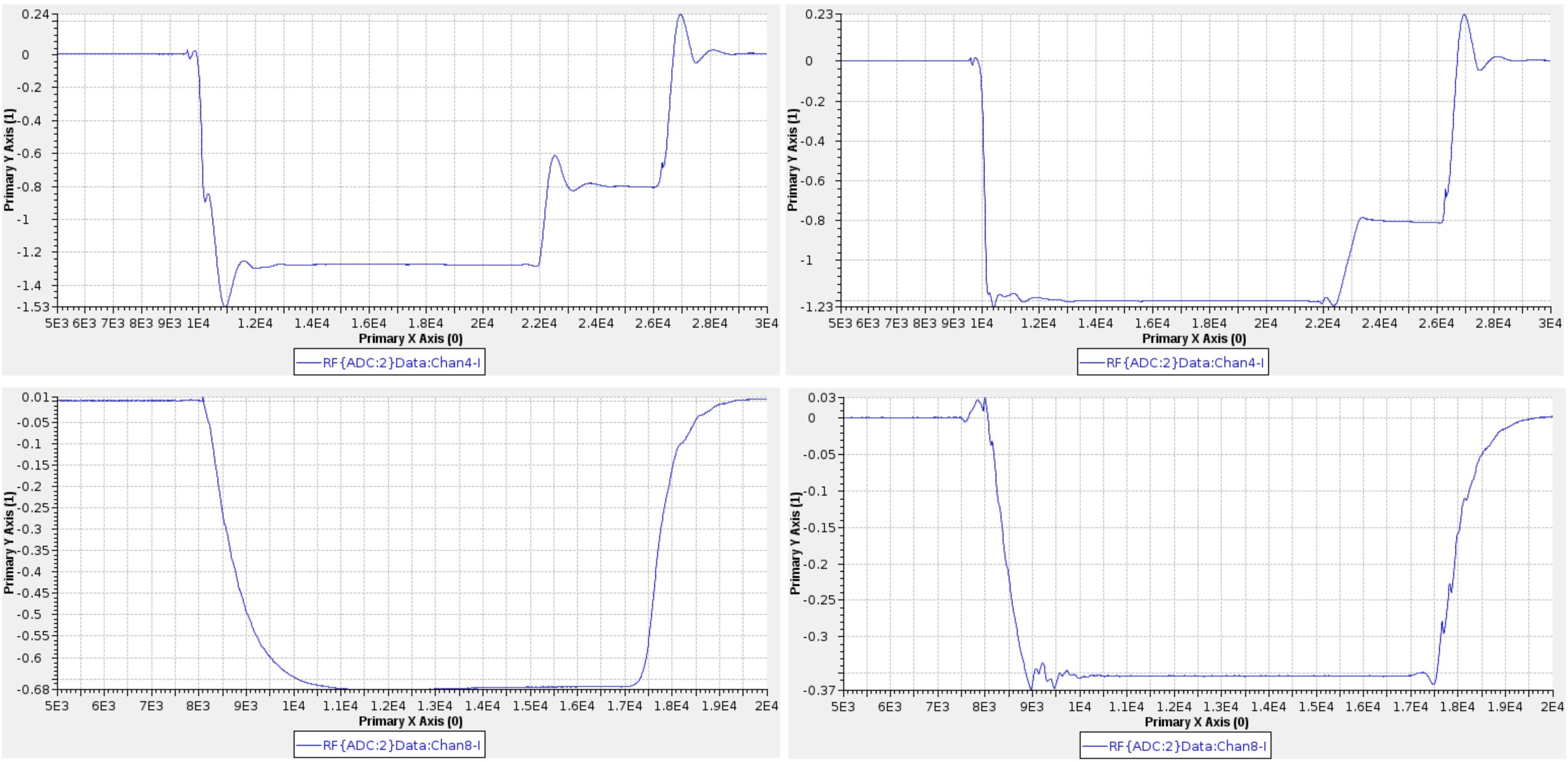


Effect of LLRF Feedforward

Q Without LLRF Feedforward | Q With LLRF Feedforward

Subharmonic Buncher

Linac 2



Issues & Plans

- 20 – 50 MeV achieved but decelerating mode for energies < 20 MeV must be demonstrated with second accelerator
- Confirm 50 keV energy spread requirement across the full energy range
- Verify transverse emittance < 20 π mm-mrad at full current
- Verify bunch length measurements and demonstrate ~ 1 psec with chicane
- Increase the macropulse length to > 8 μsec
- Approval to increase the PRF to 20 Hz is anticipated shortly
- Complete residual punch list
- Provide method for reduced micropulse repetition rate operation
- Complete and test final gun HVPS (temporary system has stability issues)
- One klystron requires refurbishment to reach the desired power level (FHI is also purchasing a spare)
- Acceptance testing will be completed shortly

Summary

- FHI FEL MIR beamline is being commissioning:
  - Beam first delivered to MIR beam dump in mid October 2011
  - First light at ~ 16 microns was achieved on February 14, 2012
- Demonstrated performance includes:
  - 20 – 50 MeV (15 – 50 MeV)
  - 215 pC current @ 1 GHz (> 200 pC)
  - 50 keV energy spread at 25 MeV and 45 MeV (0.1% @ 50 MeV => 50 keV)
  - 13.1 (H) / 10.1 (V) π mm-mrad @ 125 pC and 45 MeV (20 π mm-mrad)
  - ± 3% emittance error bar implies good energy stability
  - 2 / 5 psec bunch length estimated with chicane on / off (1 – 10 psec)
- Acceptance testing planned for Fall when new gun HVPS is commissioned

Acknowledgement

- Organizers for the opportunity to present this work at FEL 2012
- Max-Planck-Gesellschaft for the opportunity to design and build their challenging FEL
- The FEL crew at FHI (Wieland Schöllkopf, Sandy Gewinner, Gert von Helden, Heinz Junkes, Weiqing Zhang, Gerard Meijer, Wolfgang Erlebach, Andreas Liedke) and HZDR (Ulf Lehnert, Wolfgang Seidel, Rudi Wünsch and Peter Michel) for their support
- Lex van der Meer for his interest and invaluable suggestions
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- Dave Dowell, Lloyd Young, Ralph Lange, Henrik Loos, Kevin Jordan, Bob Dalesio, Michael Davidsaver and Dave Douglas for their varied and irreplaceable contributions
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