Attosecond Diagnostics of Muti-GeV Electron Beams Using W-Band Deflectors

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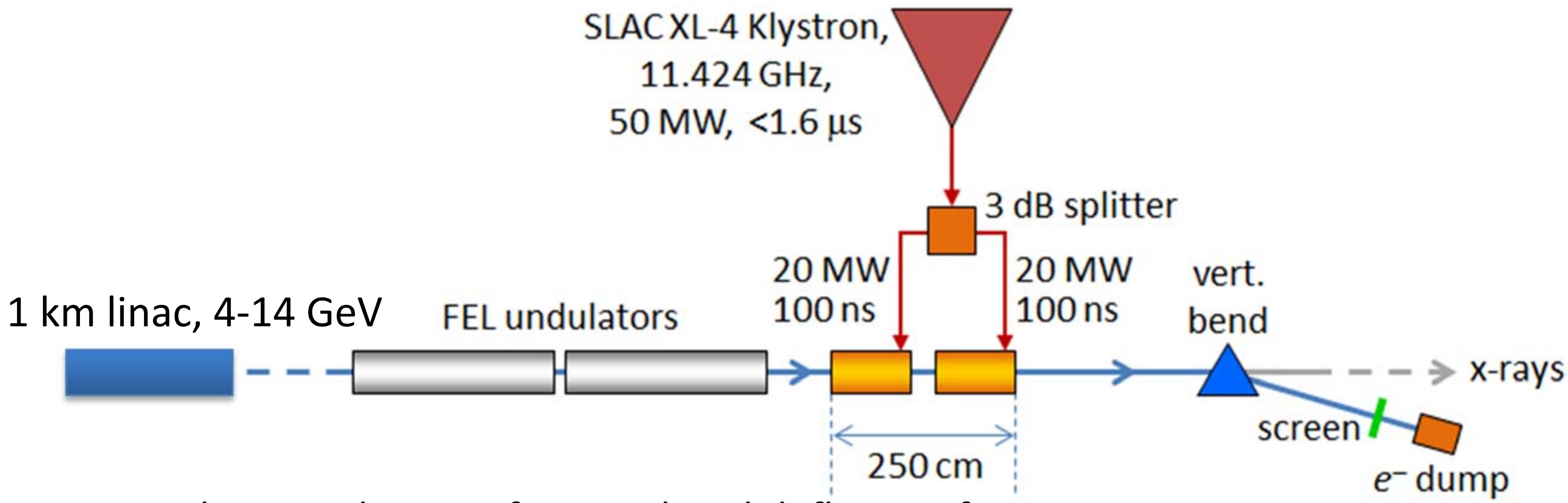
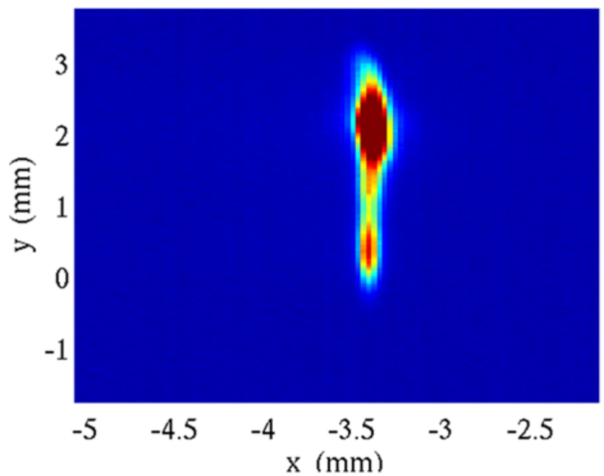
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

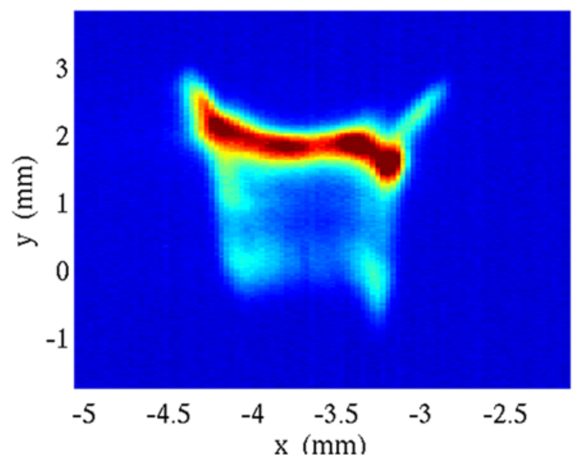
Measurement of 4…14 GeV LCLS bunch



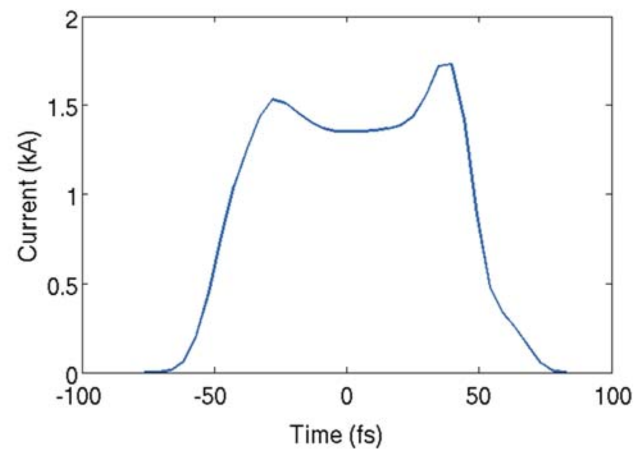
Schematic layout of LCLS X-band deflector rf system



Deflector off



Deflector on



Beam profile with absolute units after applying the measured calibration factor.

V.A. Dolgashev *et al.*, Phys. Rev. ST Accel. Beams **17**, 102801,2014

C .Behrens, *et al.,* Nat. Commun. 5, 3762 (2014).

Outline

- MeV scale X-band deflectors at SLAC
- 100 GHz Accelerating structures
- W-band deflectors
  - Kick with external rf source
  - Kick with bunch short range wake-field

Motivation

- Performance of the LCLS and LCLS-II is determined by the properties of the extremely short electron bunch. Multi-GeV electron bunches in LCLS are less than 100 fs long. Optimization of beam properties and understanding of free-electron laser operation requires electron beam diagnostics with time resolution of less than 10 fs. These were achieved with the X-band RF deflector.
- We propose the next generation of this time-resolved beam diagnostic with improvements in resolution by an order of magnitude, possibly resolving to a few hundred attoseconds at 15 GeV. We expect that, as with the current X-band deflector, it will allow smooth commissioning, operation and further improvement of LCLS-II performance.
- This 8-fold increase of the timing resolution could, in principal, be achieved by scaling the existing X-band system, which would be ~16 meter long and powered by 8 SLAC 50 MW XL-4 X-band klystrons. We see this as an impractical solution and instead propose to increase the operating frequency of the deflector from 11 GHz to 90 GHz. Two 1-meter long deflectors might be located about 10 meters after the FEL undulator for diagnostics for the electron bunch and the FEL x-ray pulse, but providing 8-times better temporal resolution down to about 0.5 fs, and less.

RF deflector resolution – the higher frequency the better

$$\sigma_z \gtrsim \frac{\lambda}{\pi e V_0} \frac{m_0 c^2}{\sin \Delta\psi} \sqrt{\frac{\gamma \varepsilon_n}{\beta_d}}$$

λ - rf wavelength

V_0 - peak deflecting voltage a crest phase

ε_n - normalized emittance of the beam

β_d - beta function at the deflector

$\Delta\psi$ - betatron phase advance from deflector to screen

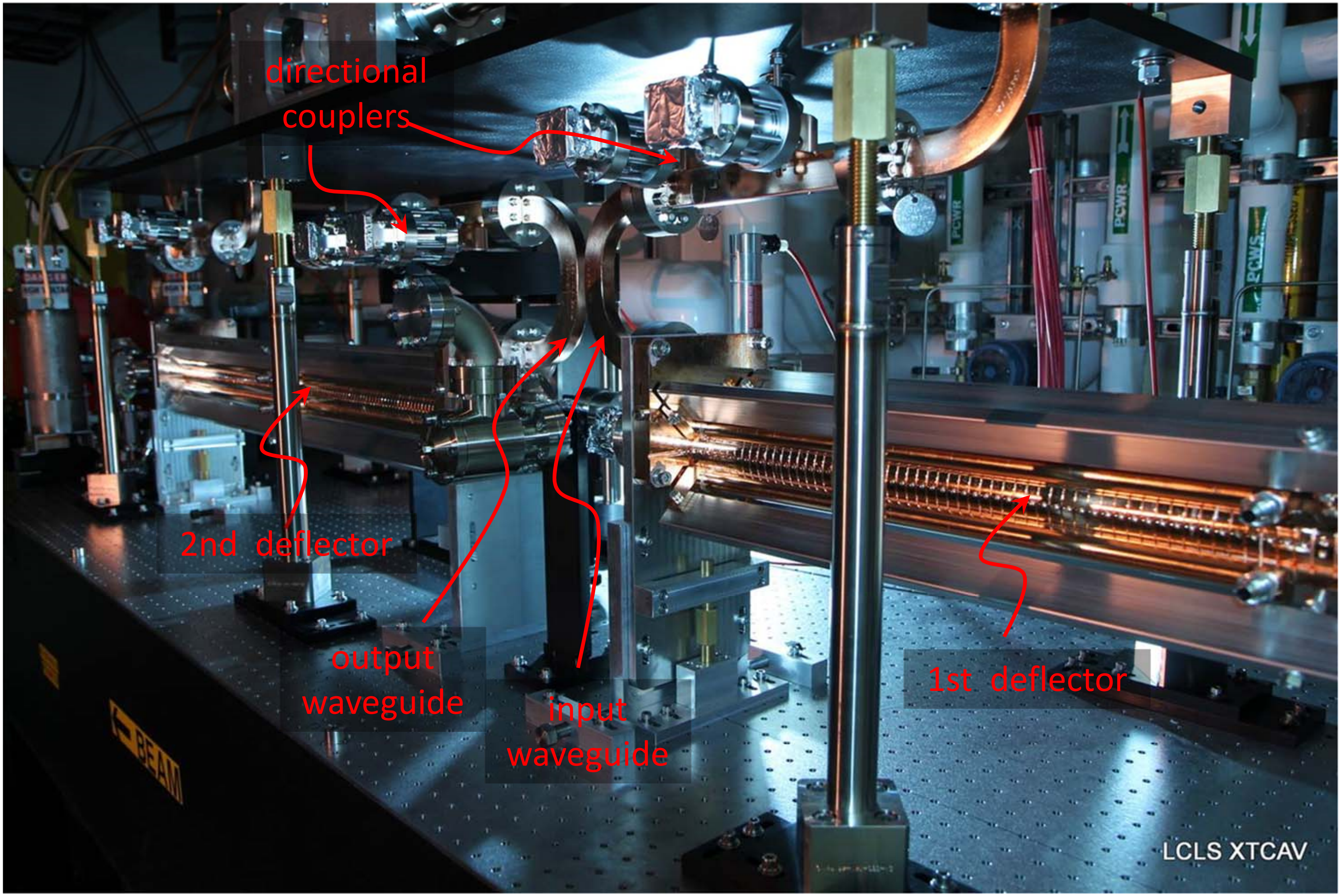
γ - relativistic factor of the beam

SLAC X-band deflectors

LCLS – Linac Coherent Light Source - X-ray Free Electron Laser, uses 14 GeV SLAC Linac
FACET – Facility for Advanced Accelerator Experimental Tests, use 20 GeV SLAC Linac
NLCTA – Next-Linear-Collider Test Accelerator – X-band linac with S-band photo gun, 120 MeV
XTA - X-Band Test Area, compact X-band linac with X-band photo gun, 75 MeV

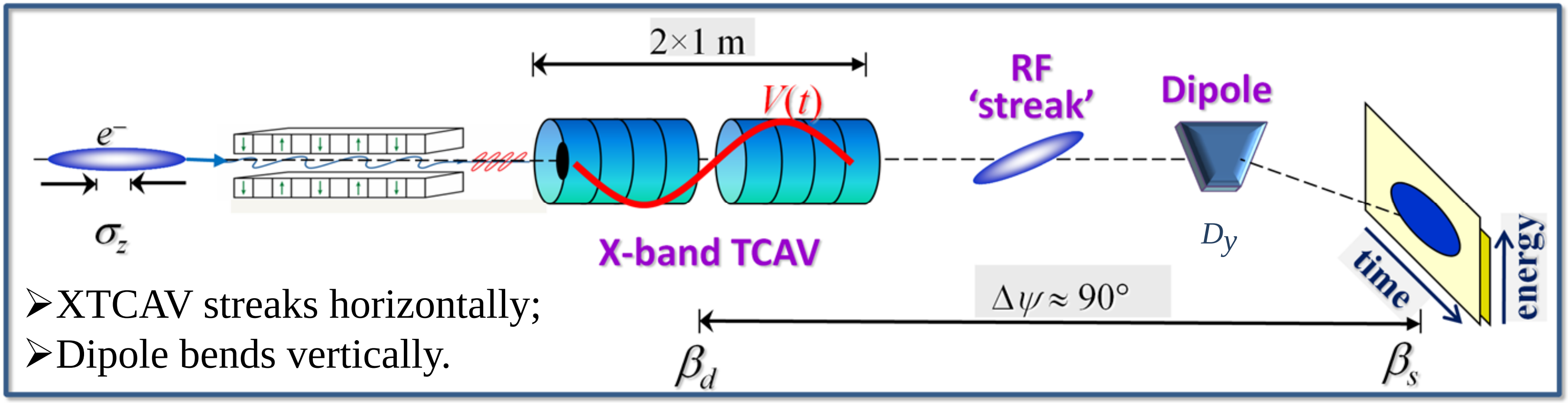
Parameter	LCLS	FACET	NLCTA	XTA	Unit
Beam Energy	**4,000-14,000**	**20,000**	**120**	**75**	**MeV**
Beam emittance	0.5	40	2	0.55	um
Structure length (with beam pipes)	2*1.185	1.185	0.432	0.293	m
Number of regular cells (including joining ring)	2*113	113	27	11	
Input power	17.5+17.5	35	20	2	MW
On-crest deflecting voltage	**45**	**30**	**6**	**0.9**	**MeV**
Resolution achieved	**1-4**	**70**	**30**	**30**	**rms fs**
Distance deflector-screen	32	14.75	3	2.5	m
Beta functions at RF deflector	120@14 GeV	150	5	11	m
Beta functions at the screen	22@14 GeV	0.41	8	2	m
Quadrupole focusing after deflectors	Yes	Yes	Yes	Yes	
Dipoles after deflectors	Yes	Yes	No	No	

X-band RF deflector system installed at the LCLS undulator beamline



P. Krejcik *et al.*, SLAC

XTCAV: x-ray beams temporal diagnostics

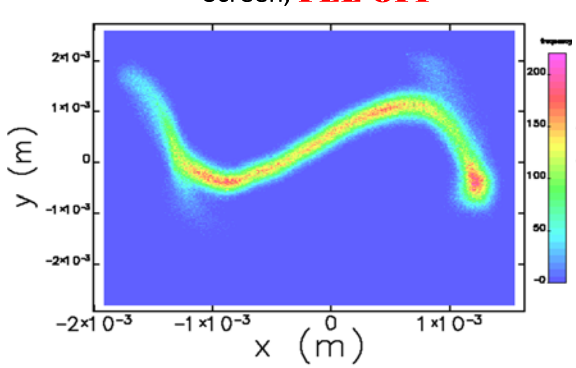


- ➢XTCAV streaks horizontally;
- ➢Dipole bends vertically.

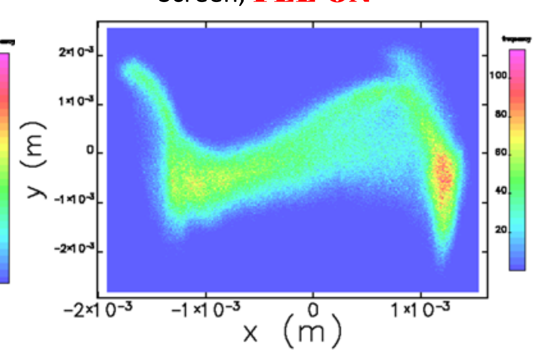
XTCAV for x-ray temporal diagnostics:

- ✓ High resolution, ~ few fs;
- ✓ Applicable in all FEL wavelength;
- ✓ Wide range, ~ 1 fs to ~100s fs;
- ✓ Beam profiles, single shot;
- ✓ No interruption with operation;
- ✓ Both e-beam and x-ray profiles.

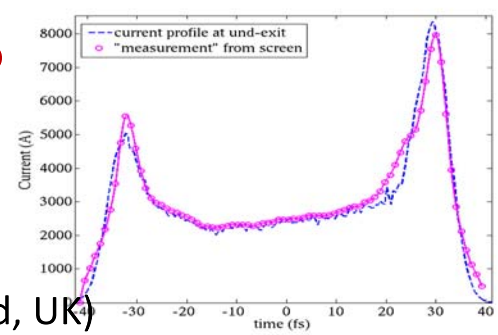
Screen, **FEL OFF**



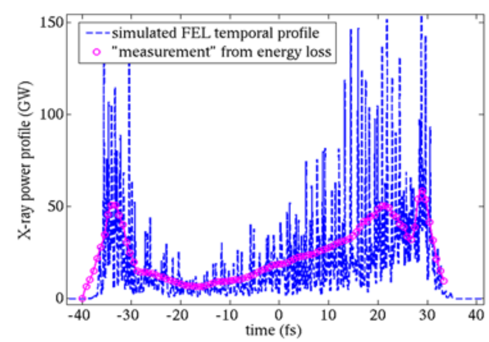
Screen, **FEL ON**



Reconstruction e-beam profile



Reconstruction x-ray profile



Project started in 2011, and took about two years to complete, total cost ~$5M, and now routine diagnostics

Y. Ding *et al.,* Phys. Rev. STAB.**14**.120701 (2011)

P. Krejcik *et al.,* in *Proceedings of IBIC2013* (Oxford, UK)

SLAC X-band deflectors

- As for now, LCLS 2-m X-band deflector has unprecedented performance. Planned upgrade with rf pulse compressor will improve the resolution more.
- It is instrumental in advancing physics of FELS, see for example:

D. Ratner et al., *Time-resolved imaging of the microbunching instability and energy spread at the Linac Coherent Light Source,* Phys. Rev. ST Accel. Beams 18, 2015

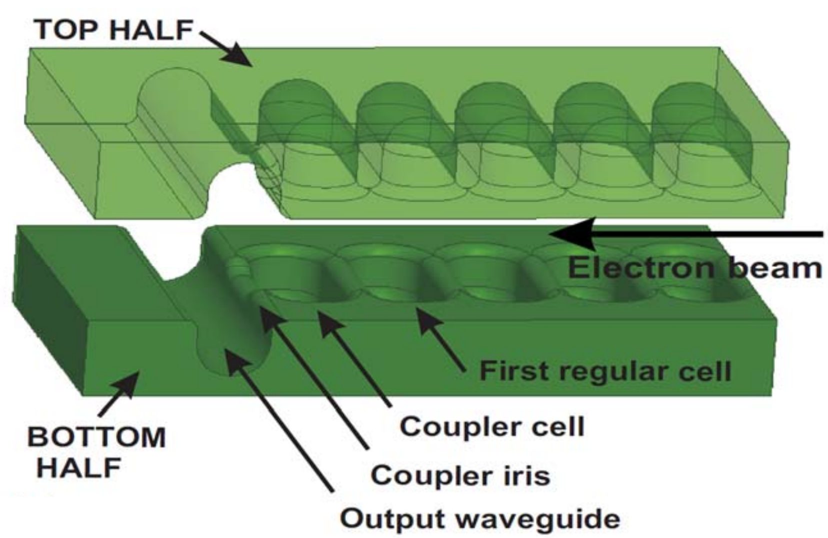
A. Marinelli et al., *High-intensity double-pulse X-ray free-electron laser,* Nature Communications 6, 6369, March 2015

…

Toward W-band deflectors: 100 GHz traveling wave accelerating structures

Questions:

- Can we build practical ~100 MV/m W-band structures?
- At what field gradients and pulse length W-band structures could operate without faults?



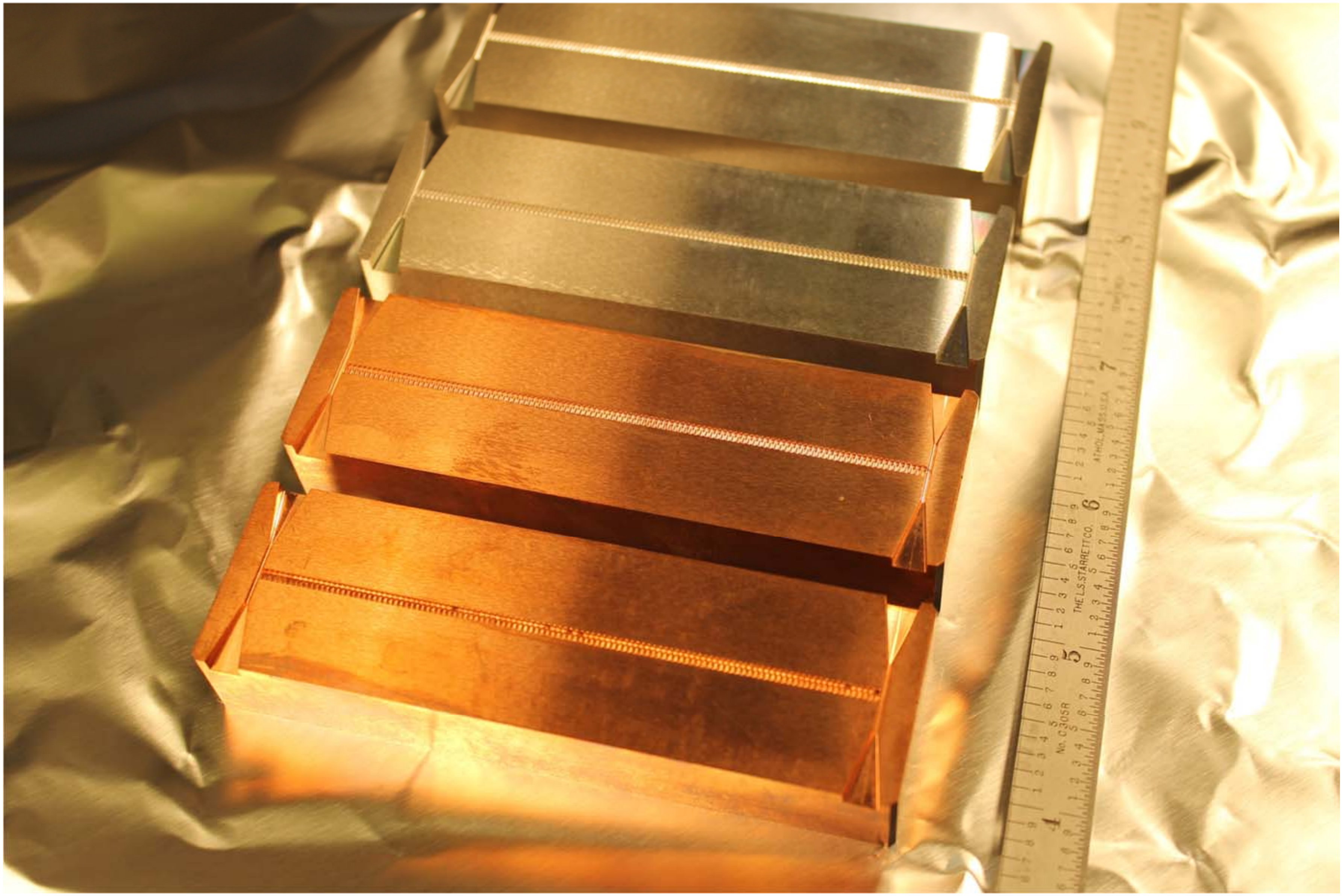
Goals of the E204 experiment

- Determine *statistical properties of rf breakdown* in metal structures *vs.* structure geometry, accelerating gradient and pulse length at 100 GHz frequencies
- Material test: find difference of performance between copper and stainless steel.

Method:

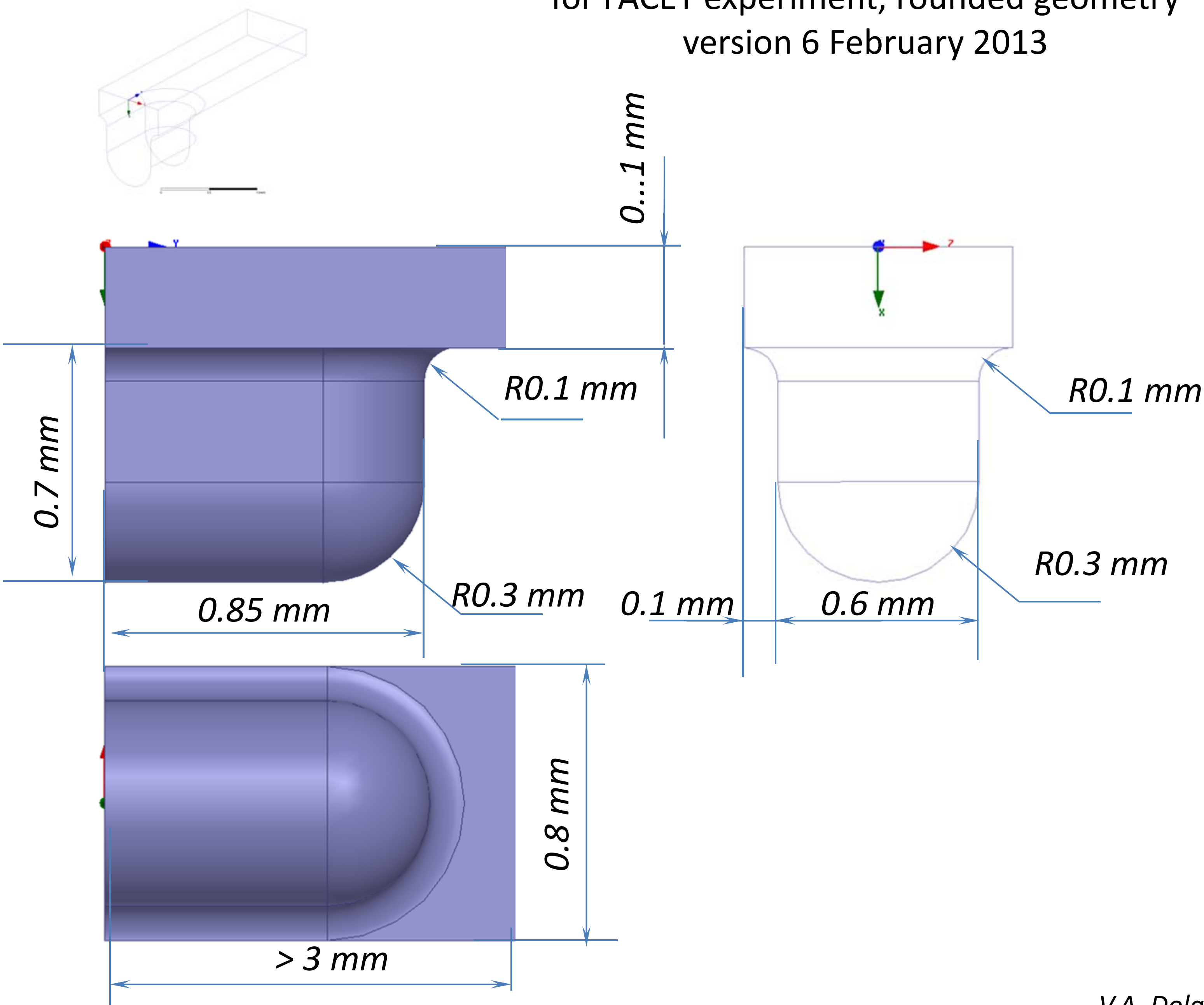
We use open traveling wave structures excited by the few nC 20 GeV FACET beam.

100 GHz copper and stainless steel traveling wave accelerating structures, as received from vendor



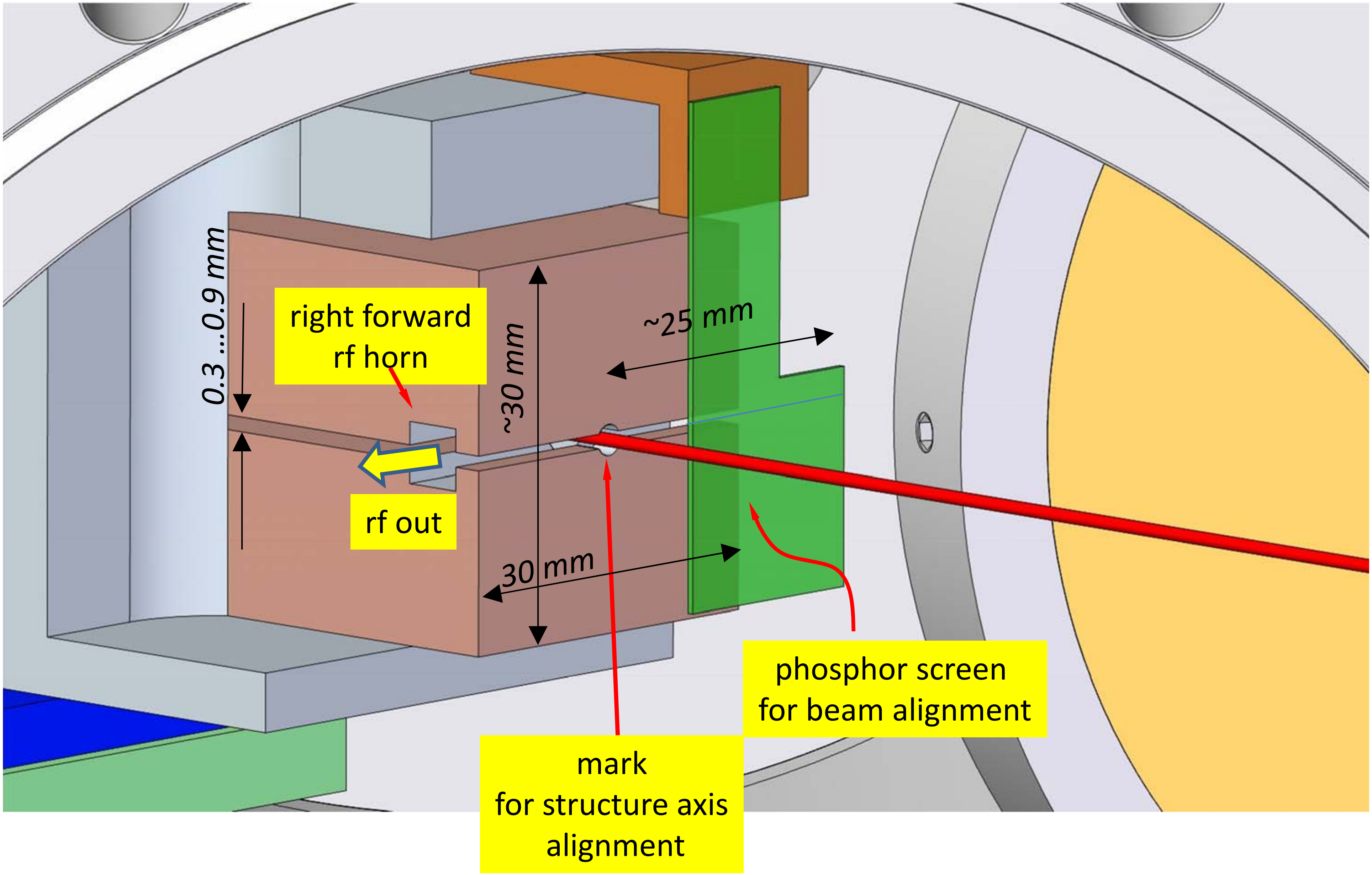
Manufacturing: EDM Department Inc.

Geometry of one quarter of one period of metallic THz structure for FACET experiment, rounded geometry version 6 February 2013

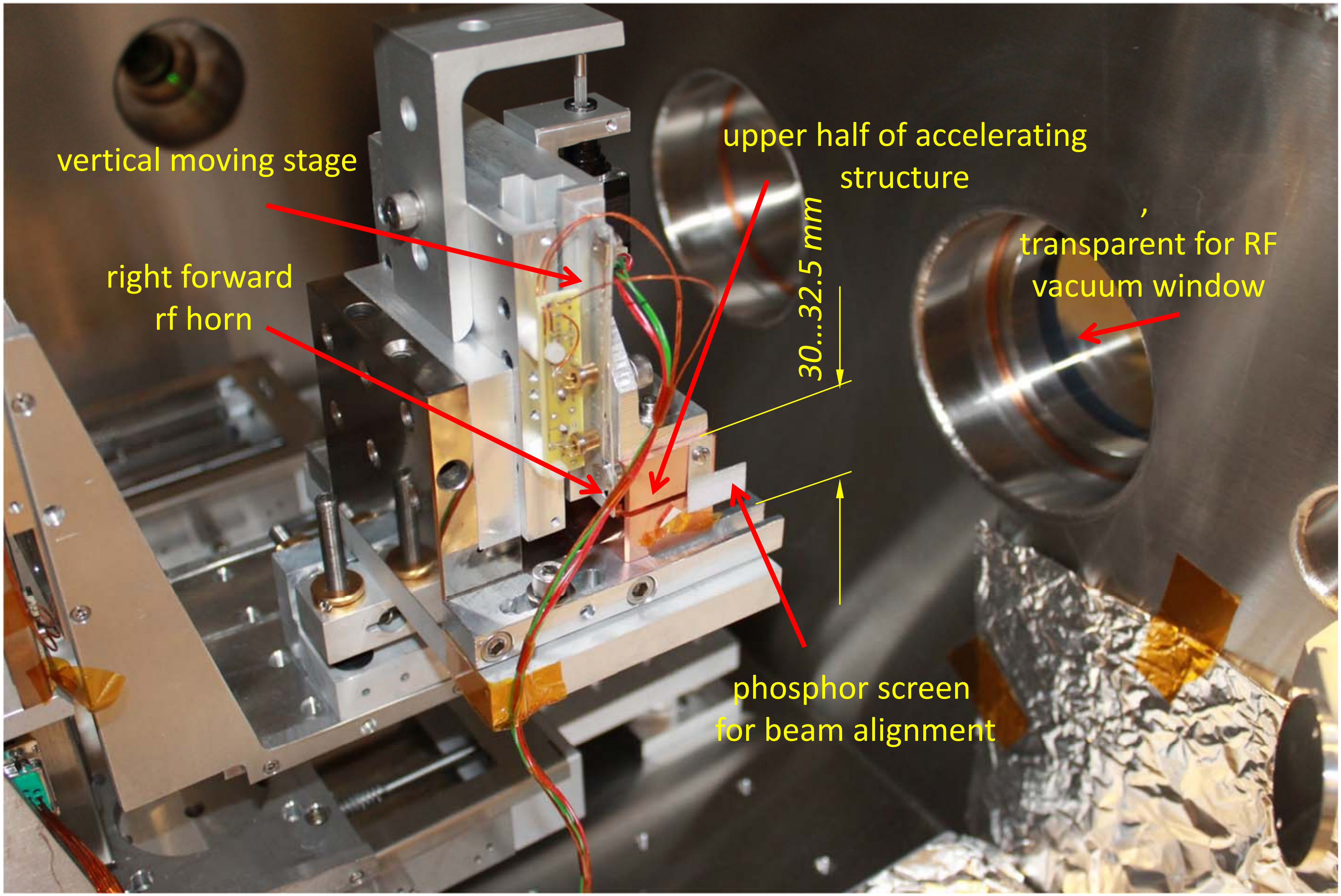


V.A. Dolgashev, 13 March 2012

First experiment: alignment camera view



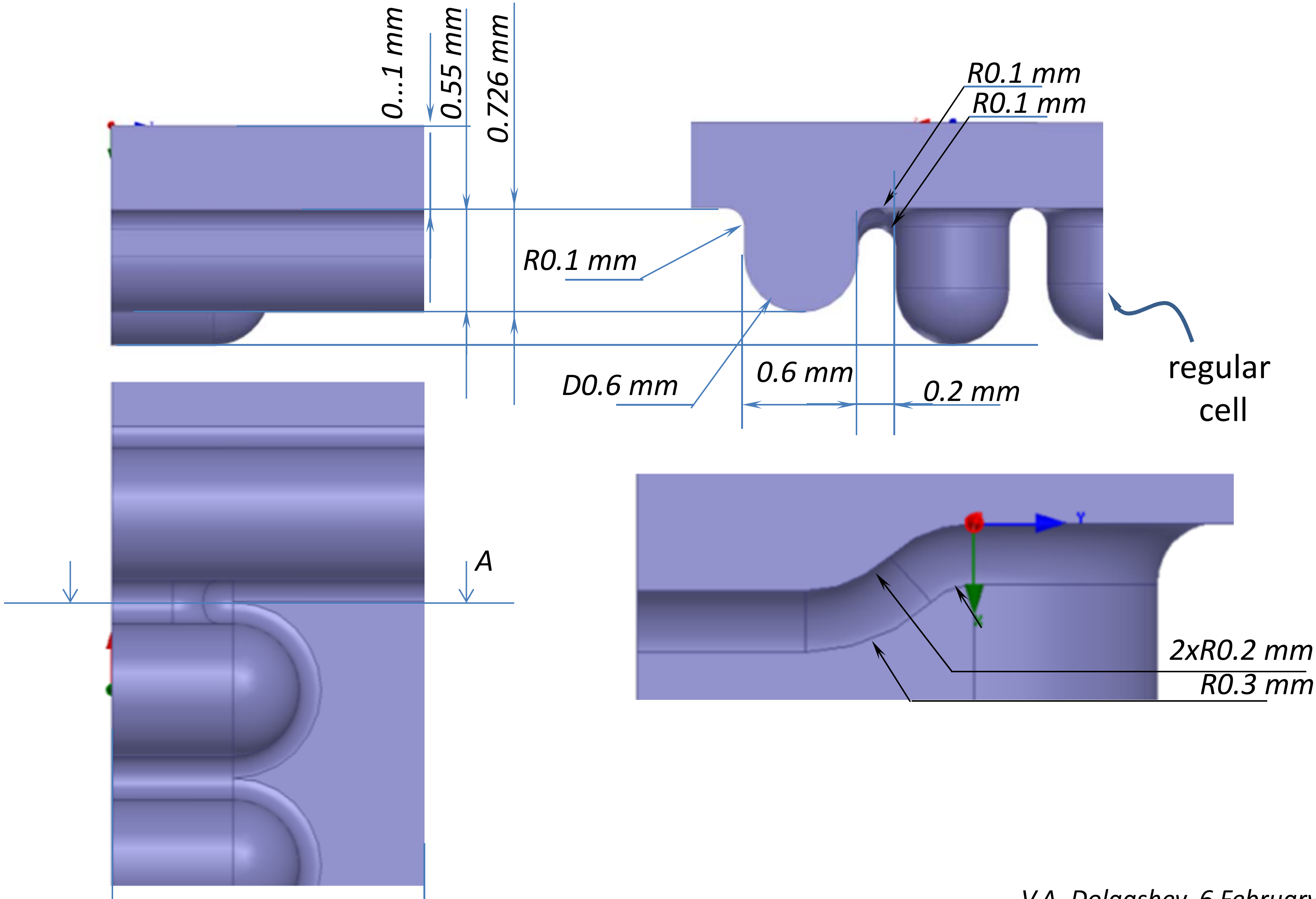
FACET experiment with *copper structure* in vacuum chamber



100 GHz Traveling Wave Accelerating Structure

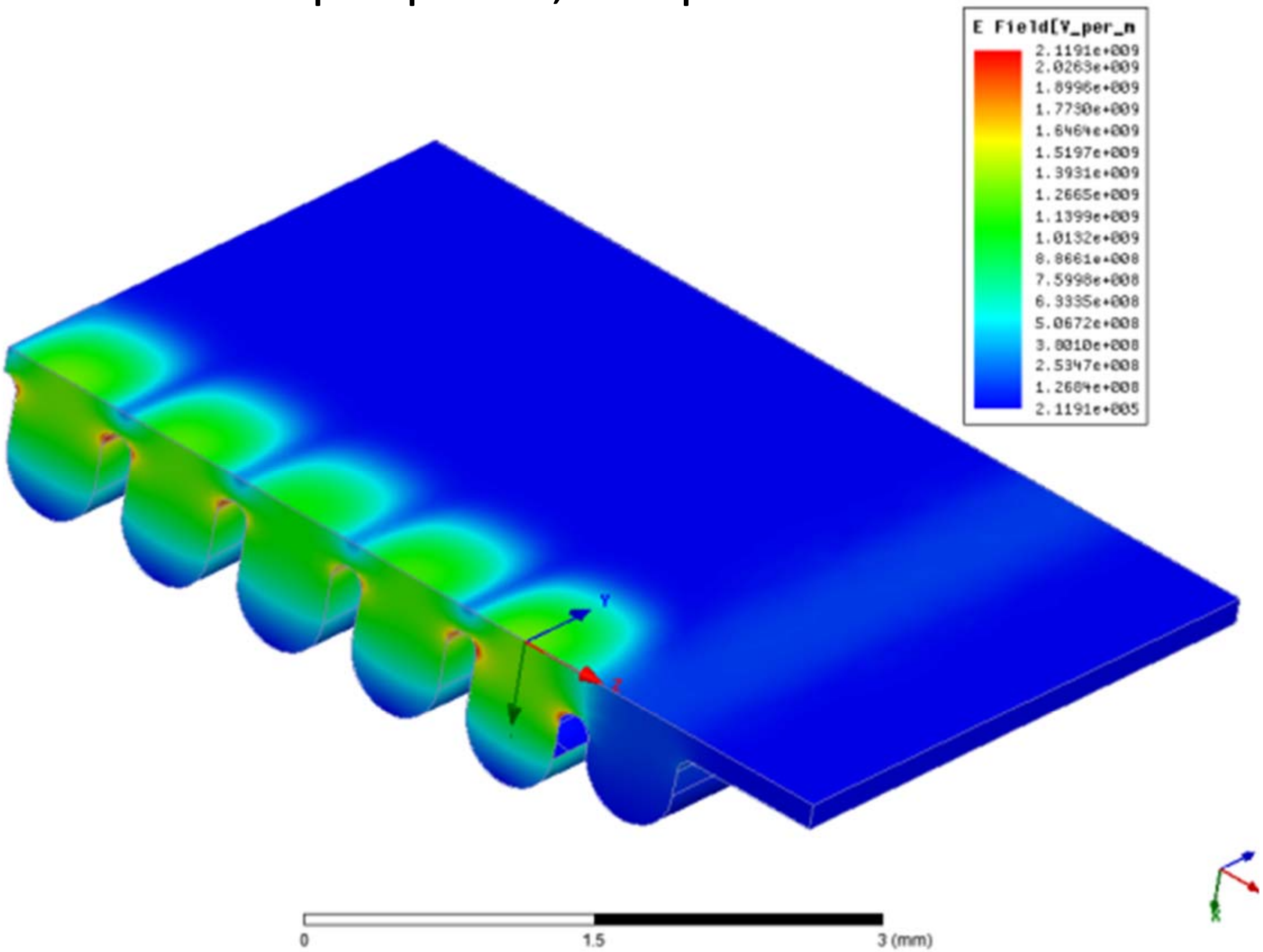
- RF output coupler matched at gap=0.3 mm and with more than 80% power transmission at other apertures

Matched coupler



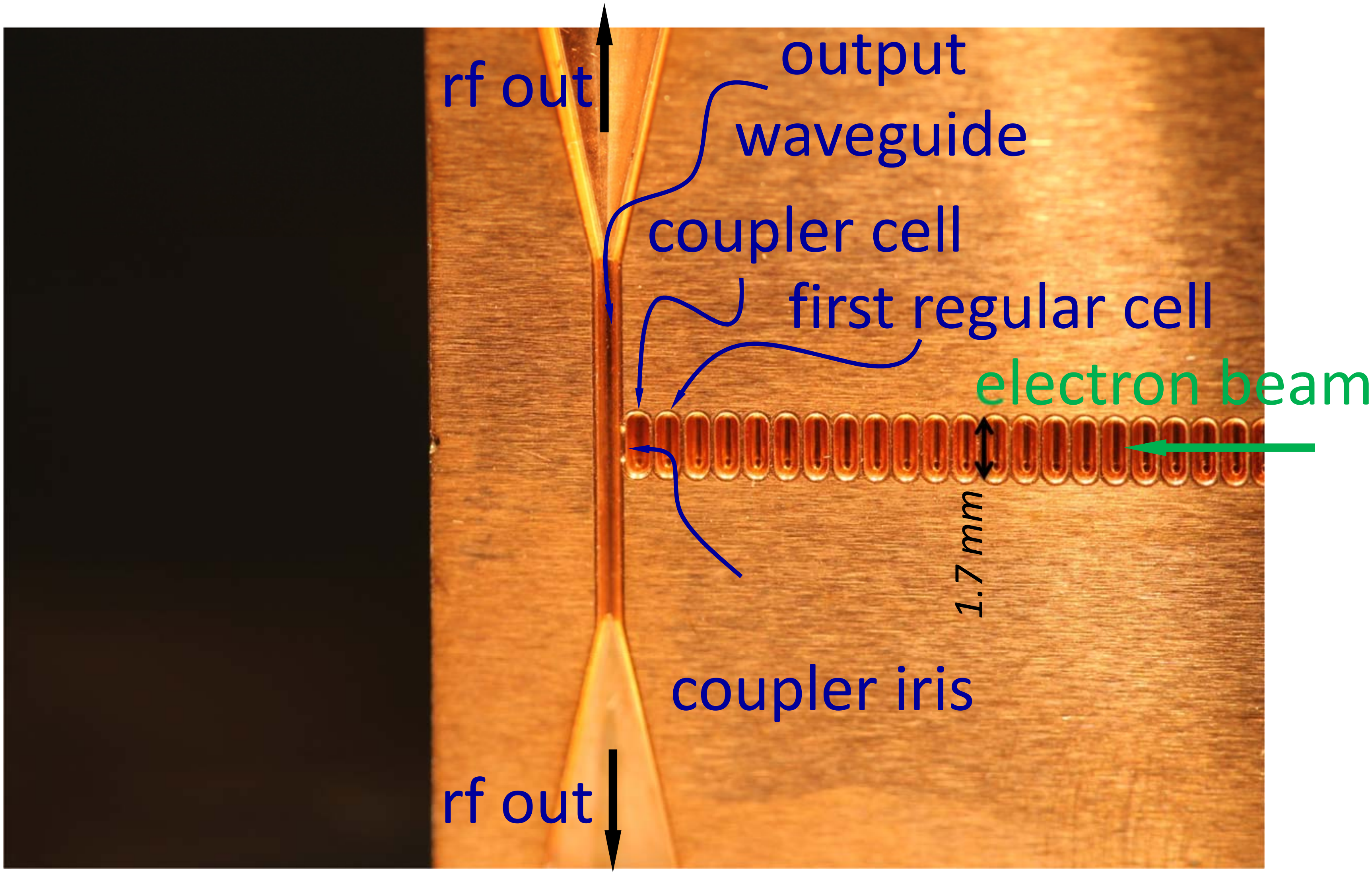
V.A. Dolgashev, 6 February 2013

Output coupler of traveling wave accelerating structure, aperture 2a = 0.3 mm, synchronous frequency 136 GHz, fields normalized to 10 MW of input power, coupler reflection R=0.09

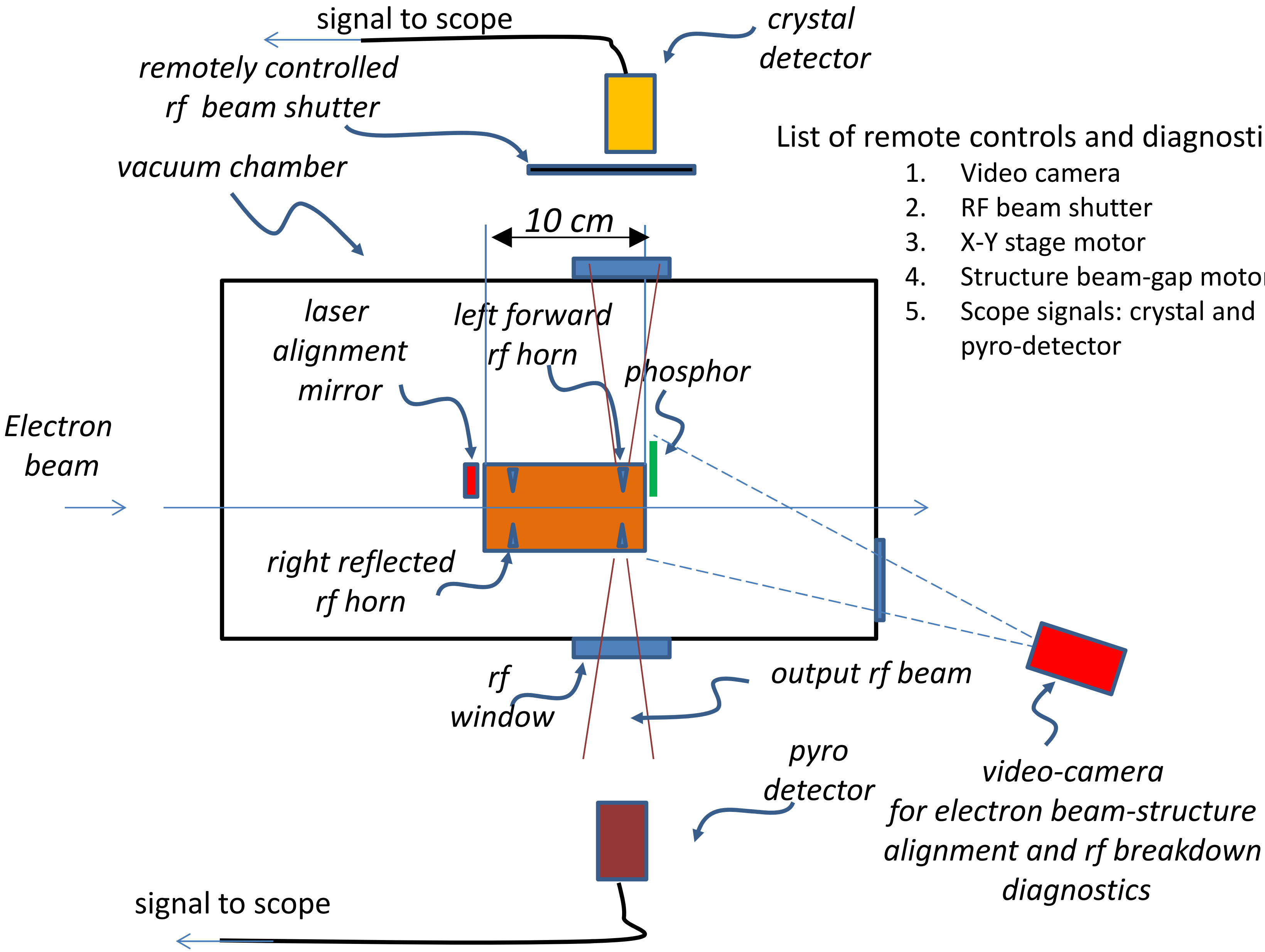


V.A. Dolgashev, SLAC, 7 January 2013

Power coupler of the 100 GHz structure



Schematic layout of 100 GHz TW structure test

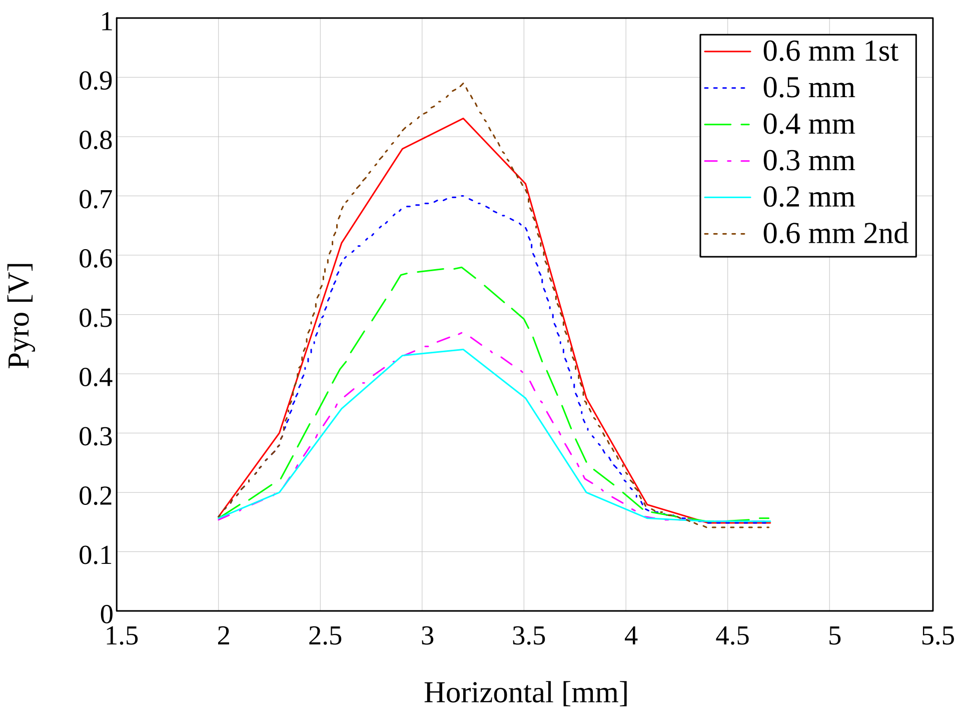


List of remote controls and diagnostics:

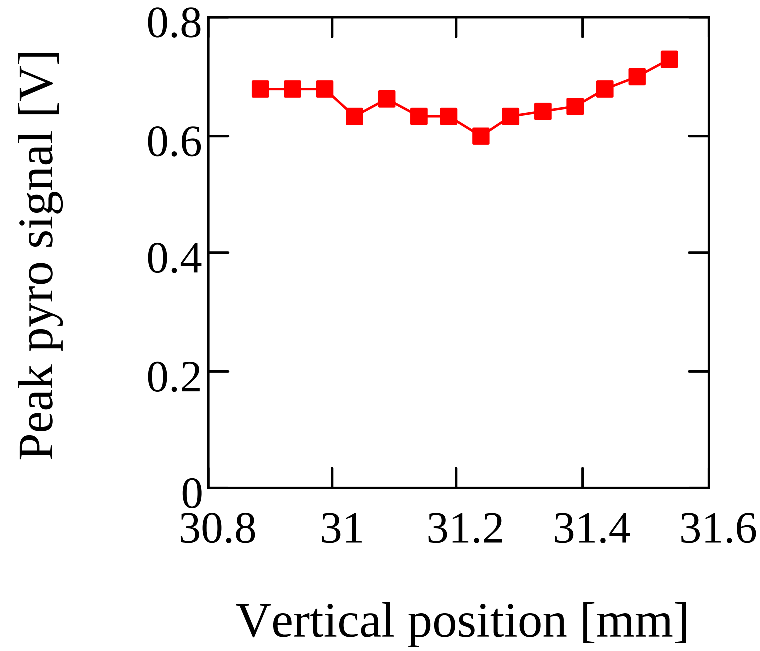
1. Video camera
2. RF beam shutter
3. X-Y stage motor
4. Structure beam-gap motor
5. Scope signals: crystal and pyro-detector

V.A. Dolgashev, SLAC, 31 March 2014

100 GHz signals

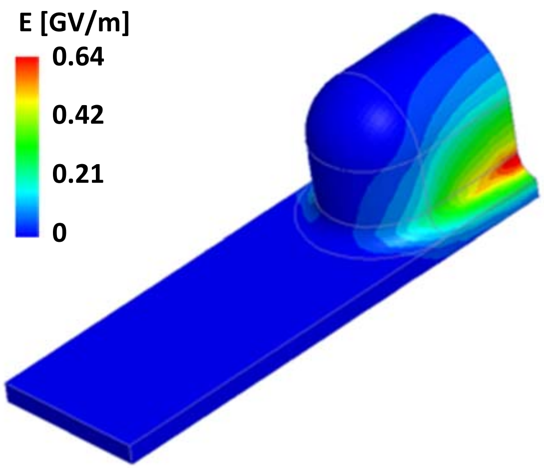


Pyro signal vs. horizontal structure position for different gaps

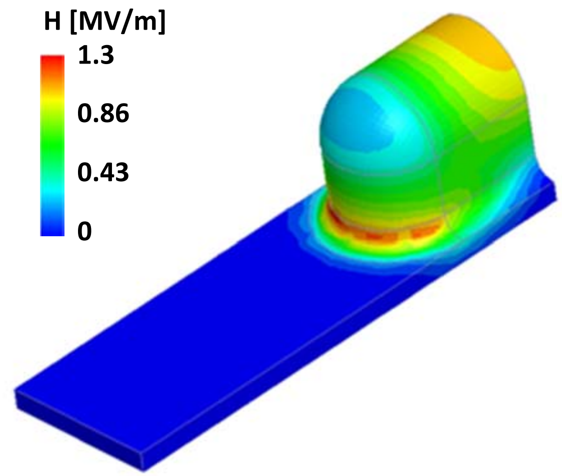


Peak pyro signal (@3.2mm horizontal position) vs. Vertical structure position

Fields in copper traveling wave structure at 140 GHz, excited by **3.2 nC bunch**



Surface electric fields with E_{max} = 0.64 GV/m



Surface magnetic fields with H_{max} = 1.3 MA/m

Parameter	Value
Gap (2a)	0.2 mm
Synchronous frequency	140.29 GHz
Phase-per-cell	133.46 deg
RF Power @ 3.2 nC	0.3 MW
Acc. Gradient @ 3.2 nC	**0.3 GV/m**
E_{max} @ 3.2 nC	**0.64 GV/m**
H_{max} @ 3.2 nC	1.3 MA/m
v_g/c	0.22%
Att. Length	1.56 mm
Att. Length/v_g	**2.3 ns**
L/v_g (20 cells)	24 ns

Current status

- At FACET, we have tested tree 100 GHz traveling wave metal accelerating structures: two copper and one stainless steel.
- From SEM inspection, we estimate following “no damage” pulse parameters

Parameter	Traveling Wave, Copper
Acc. Gradient	0.3 GV/m
E_{max}	0.64 GV/m
Pulse length	~2.3 ns

With these experiments we are developing understanding, tools, techniques, diagnostics, etc. which we can use for W-band deflector

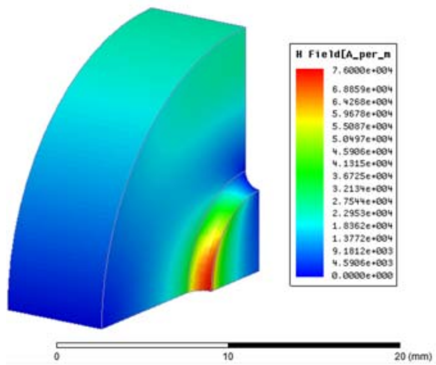
W-band deflectors powered by rf source

http://www.calcreek.com/hardware.html:

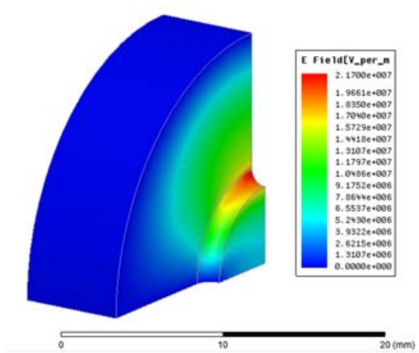
Calabazas Creek Research, Inc., in association with the University of Maryland, developed a **10 MW** gyroklystron **at 91.392 GHz** for W-Band accelerator research. The device is designed to produce **1 microsecond pulses at 120 Hz** with an efficiency of approximately 40% and a gain of 55 dB. A magnetron injection gun produces a high-quality, 55 A beam at 500 kV that interacts with a six cavity, frequency doubling microwave circuit. A super conducting magnet produces a 28 kG magnetic field in the gun region with a separate coil for controlling the field in the gun region.

Scaling of X-band deflector to W-band

11.424 GHz



Hpeak: 76 kA/m

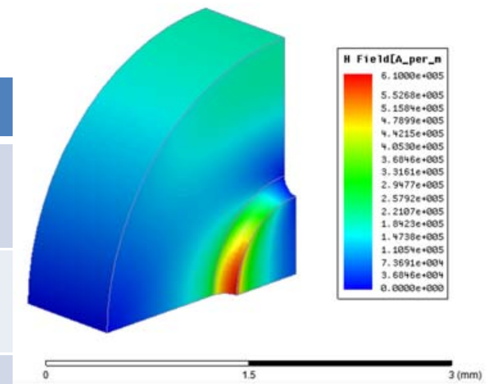


Epeak: 21.7 MV/m

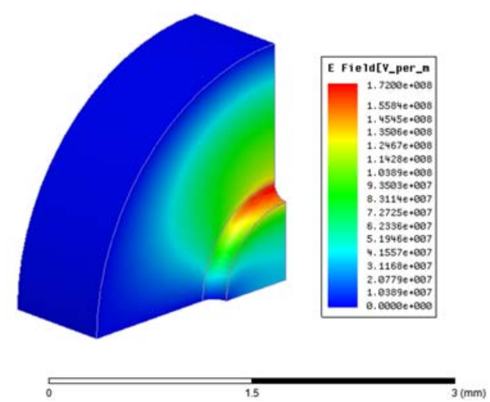
Cell of X-band deflector, fields normalized to 1 MW of transmitted power

	X-band	W-band
aperture diameter	10 mm	1.25 mm
Kick@1MW	7.07 MV/m	**56.5 MV/m**
Q0	6296	2226
Epeak @1MW	21.7 MV/m	172 MV/m
Hpeak@1MW	76 kA/m	610 kA/m
Att. Length	84 cm	**3.7cm**
Group velocity/c	3.2%	3.2%

91.329 GHz



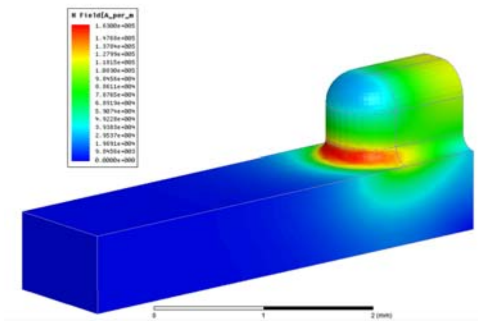
Hpeak: 610 kA/m



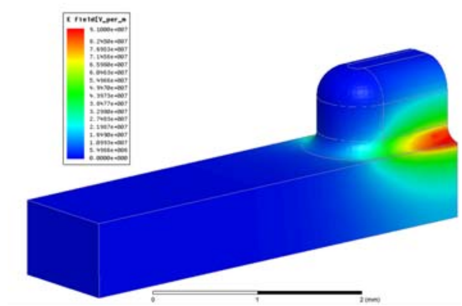
Epeak: 172 MV/m

Cell of W-band deflector, fields normalized to 1 MW of transmitted power

Open W-band accelerator as deflector

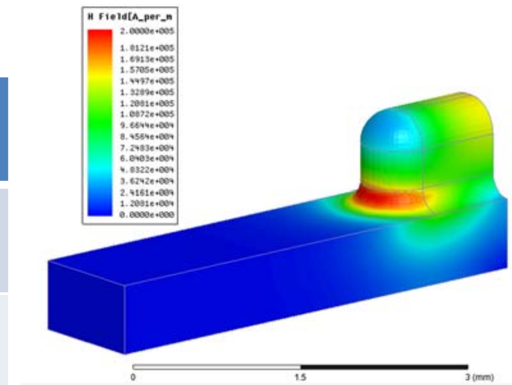


Hpeak: 163 kA/m

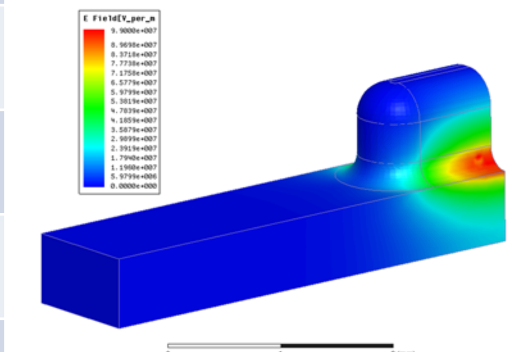


Epeak: 91 MV/m

	Nominal aperture	**Reduced aperture**
aperture diameter	1.5 mm	1.3 mm
Kick@1MW	**7.8 MV/m**	**11.1 MV/m**
Q0	2480	2285
Epeak @1MW	91 MV/m	99 MV/m
Hpeak@1MW	163 kA/m	200 kA/m
Att. Length	**25 cm**	**16 cm**
Group velocity/c	19.4%	13.4%



Hpeak: 200 kA/m

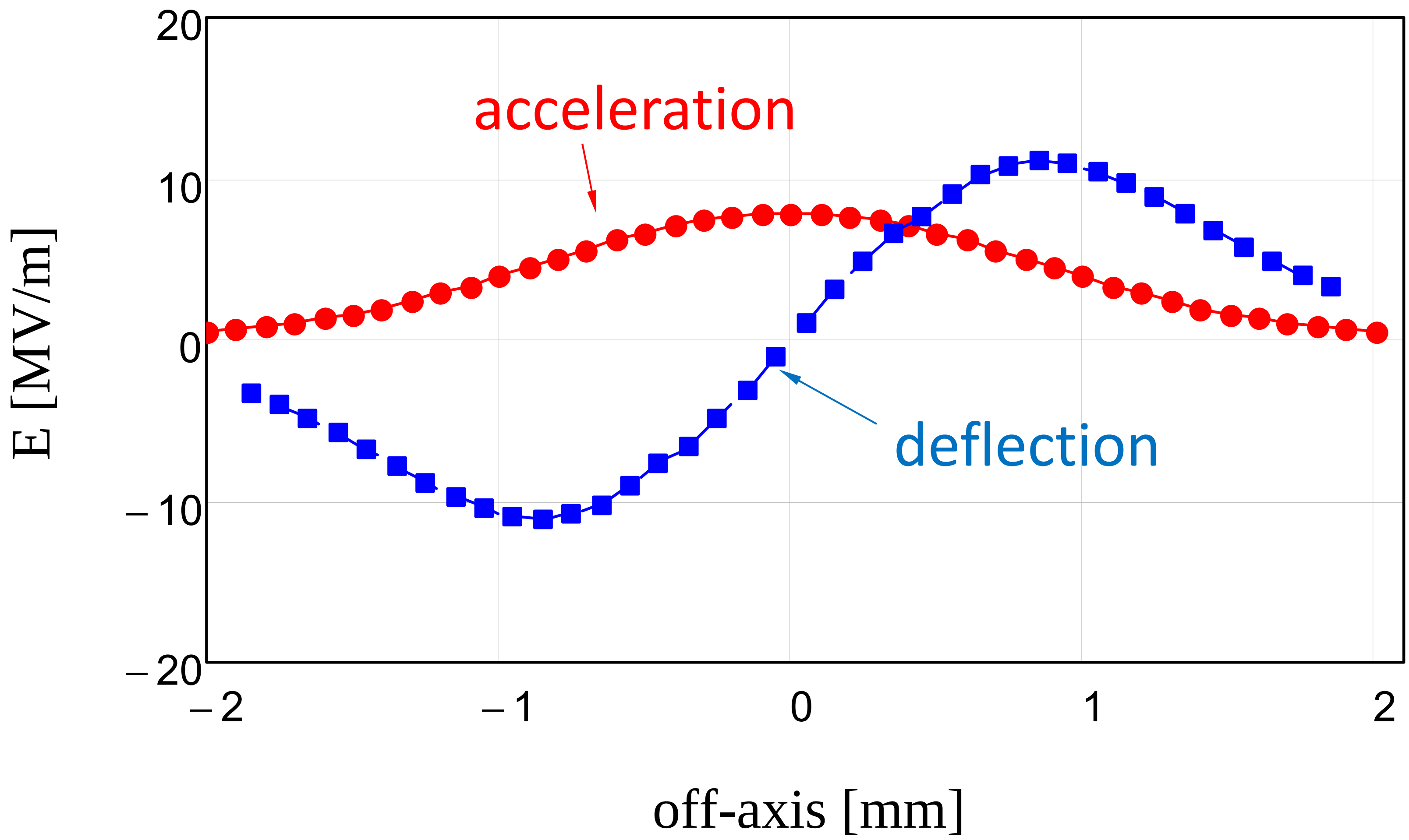


Epeak: 99 MV/m

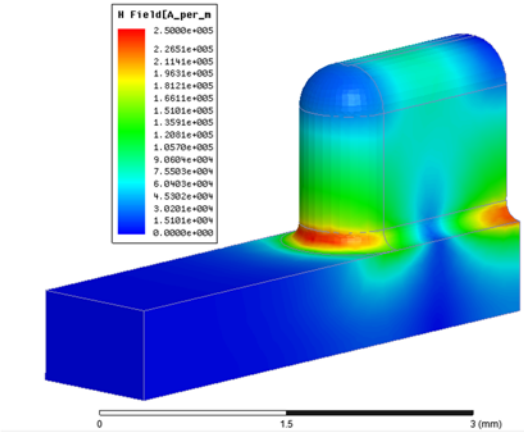
W-band acclerator, aperture 1.5mm,
fields normalized to 1 MW
of transmitted power

W-band acclerator, aperture 1.3 mm,
fields normalized to 1 MW
of transmitted power

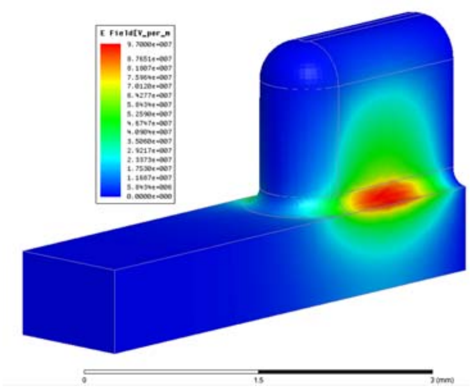
Deflection in open accelerating structure: moving beam off axis



Open W-band deflectors



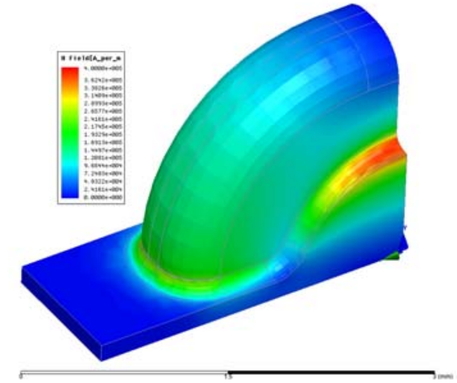
Hpeak: 250 kA/m



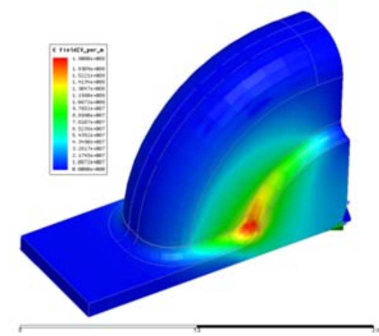
Epeak: 97 MV/m

W-band deflector, aperture 1.5mm, fields normalized to 1 MW of transmitted power

	Nominal aperture	Reduced aperture
aperture diameter	1.5 mm	1.84 mm
Kick@1MW	**10.83 MV/m**	**31 MV/m**
Q0	2520	2230
Epeak @1MW	97 MV/m	180 MV/m
Hpeak@1MW	250 kA/m	400 kA/m
Att. Length	10 cm	5 cm
Group velocity/c	7.7 %	4.6%



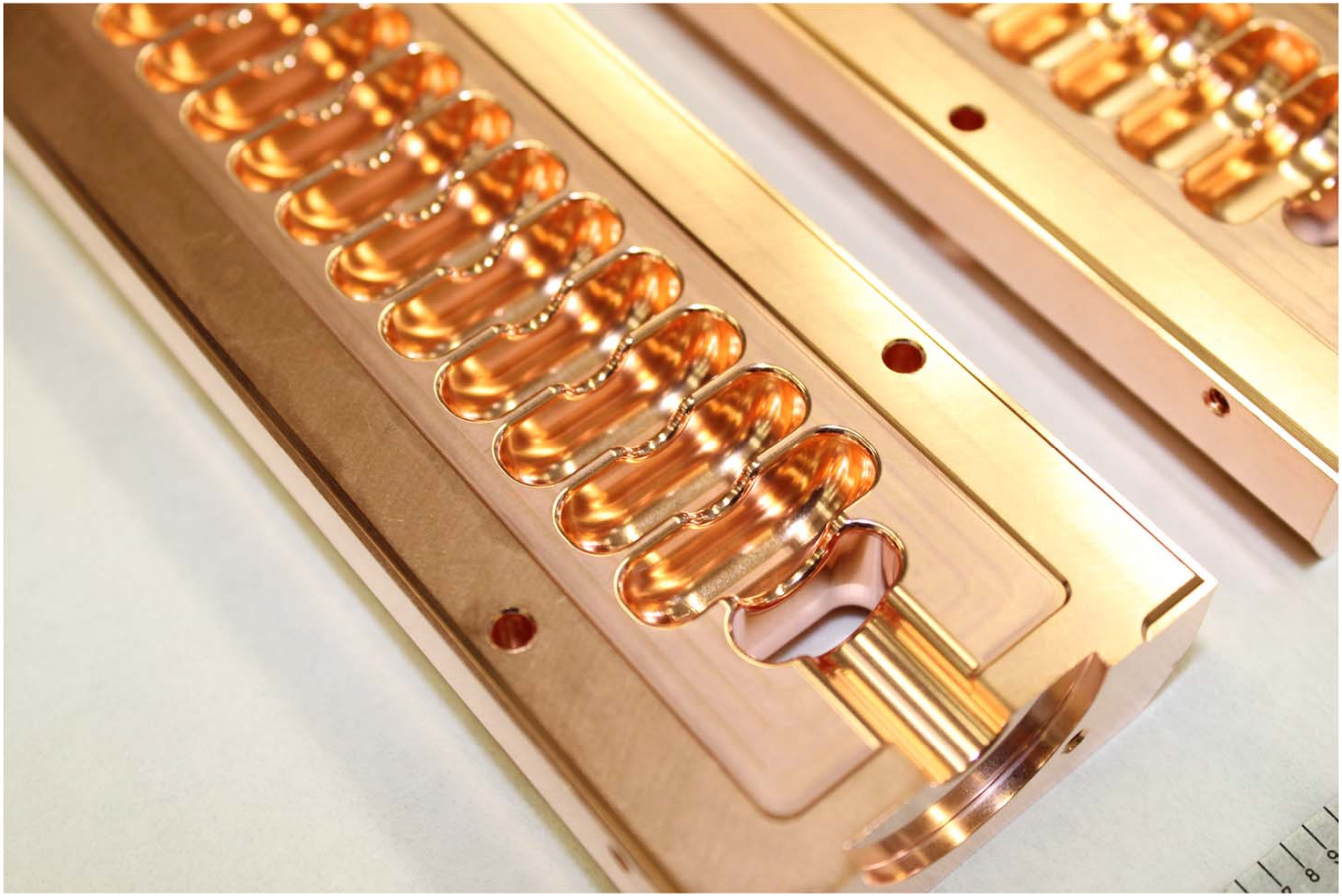
Hpeak: 400 kA/m



Epeak: 180 MV/m

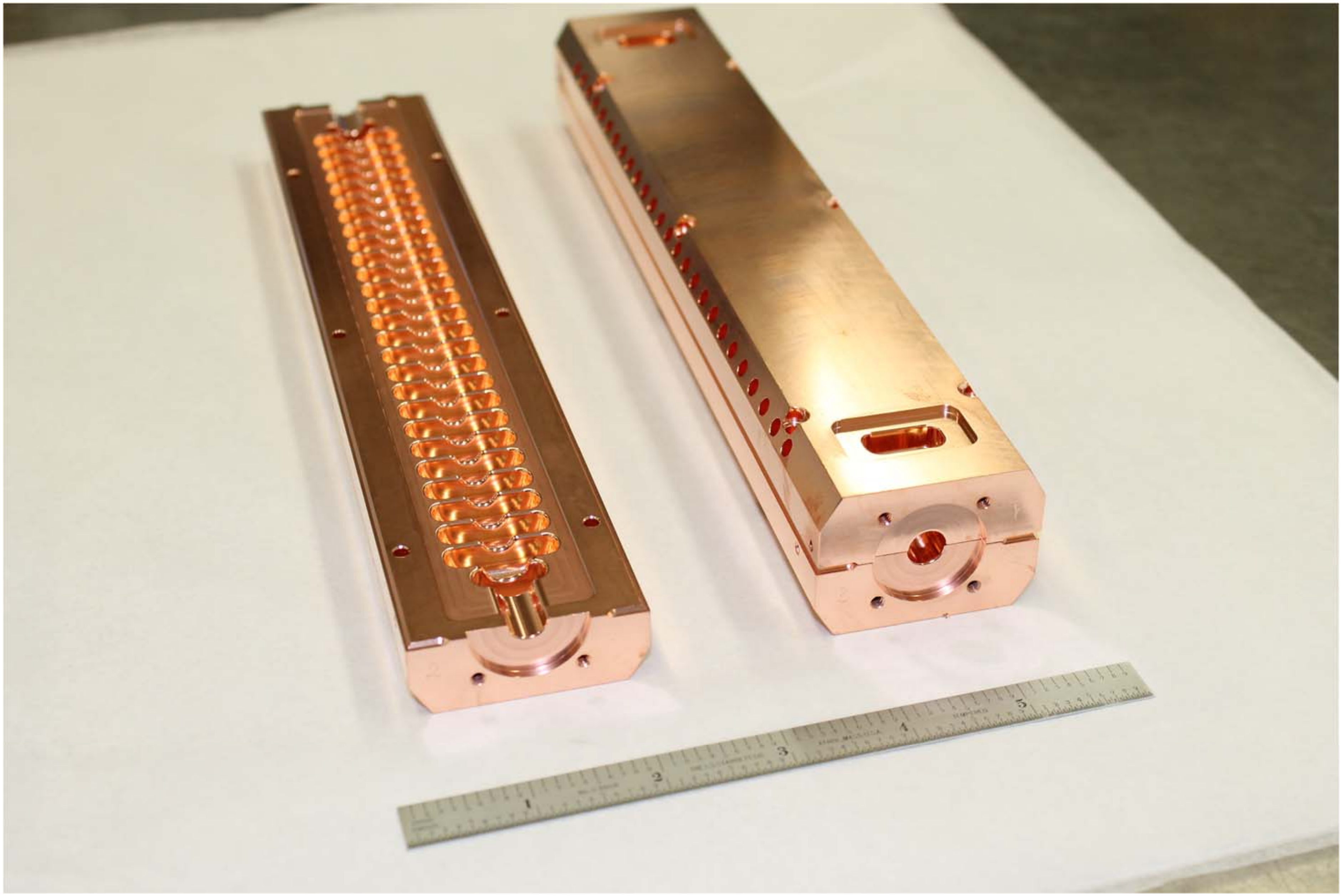
W-band deflector, aperture 1.84 mm, fields normalized to 1 MW of transmitted power

Example of open 12 GHz traveling wave accelerating structure, CLIC-G-OPEN



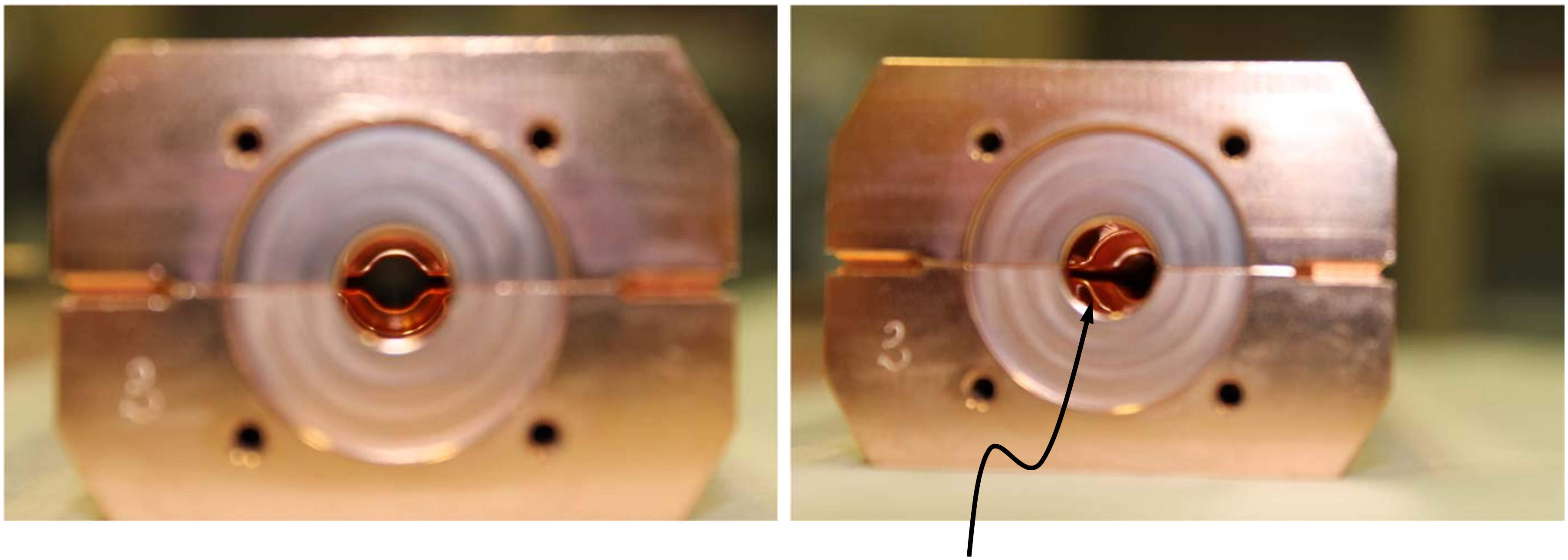
Half-Structure

Example of open traveling wave 12 GHz accelerating structure, CLIC-G-OPEN



Half structure and full-structure assembly

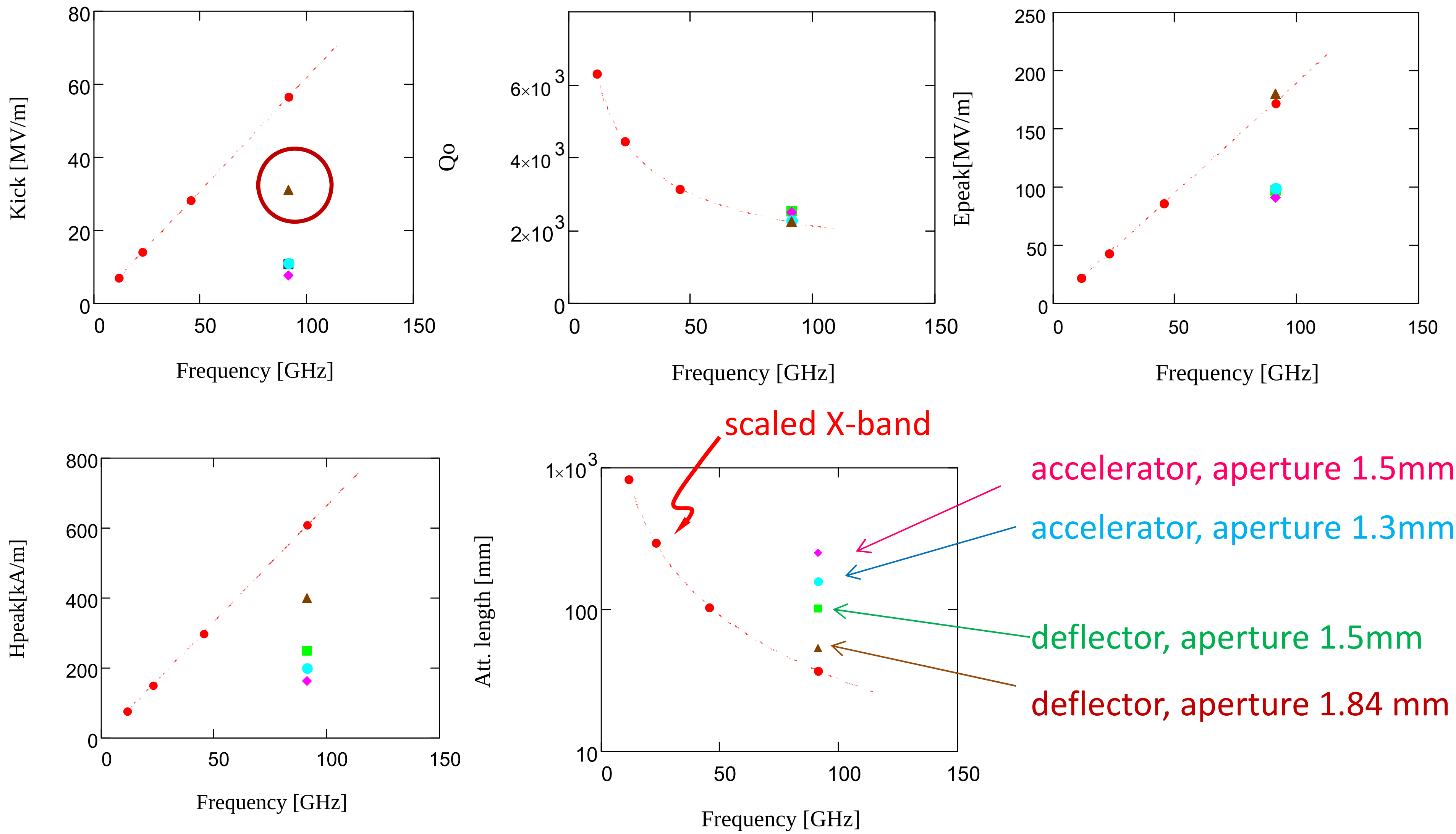
Example of open traveling wave 12 GHz accelerating structure, CLIC-G-OPEN



1 mm gap

View from beam pipe

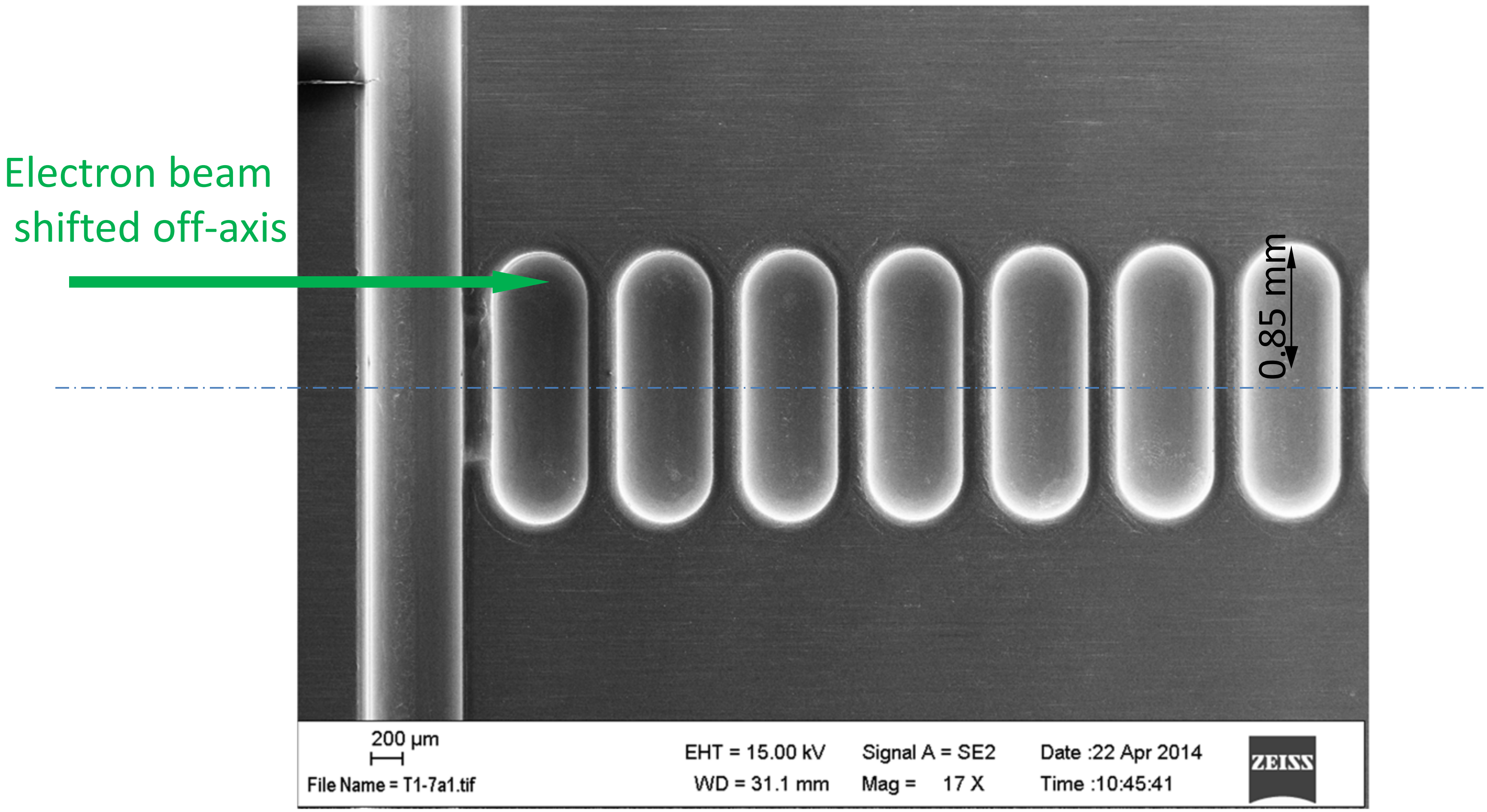
Now compare scaled X-band deflector and open W-band deflectors, field normalized to 1 MW of power flow



Summary for rf source powered deflector

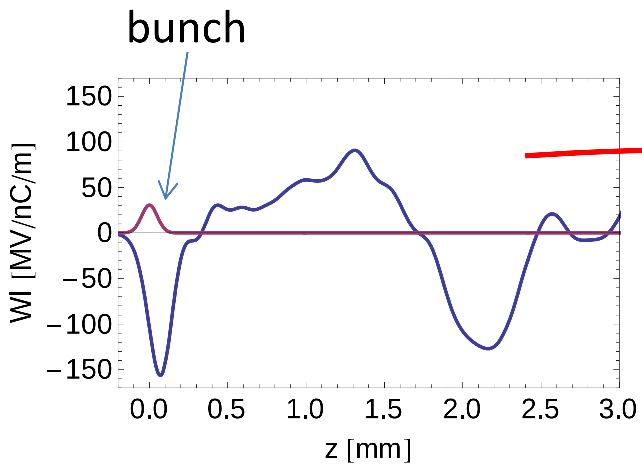
- One module, or 1-m long deflector powered by 10 MW will produce total kick of about 23 MV (for deflector with 1.84 mm aperture), other structures have total kick between 11 and 14 MV/m.
- We will need two modules to get 46 MV deflection for ~500 attosecond resolution at 14 GeV and ~120 attosecond at 4 GeV.

Wakefield-powered deflector

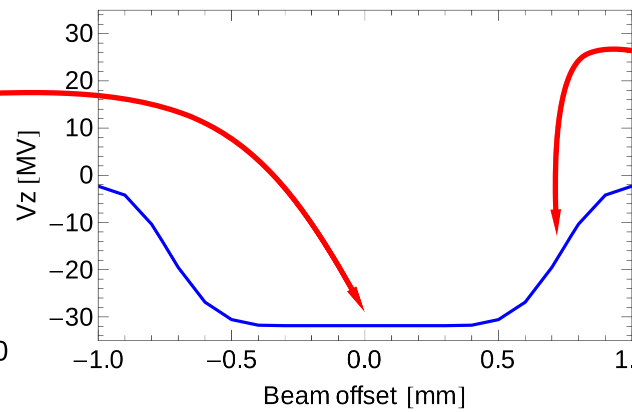


100 GHz traveling wave accelerating structure

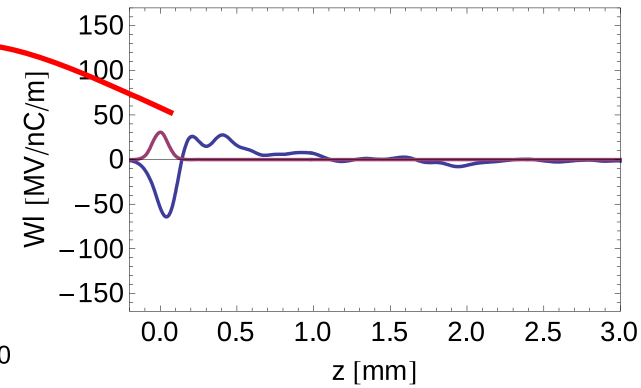
Short range wakefields in 100 GHz accelerating structure, gap 0.3 mm, bunch length 50 µm



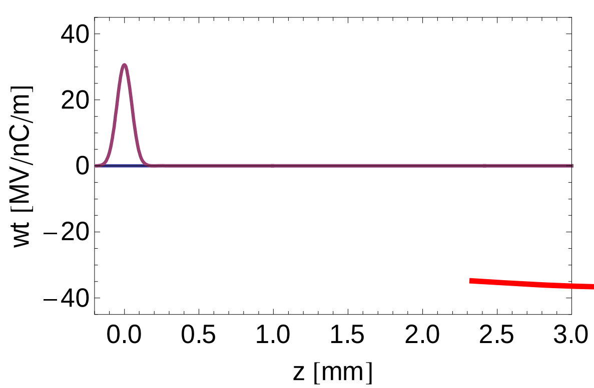
Longitudinal wake,
offset 0 mm



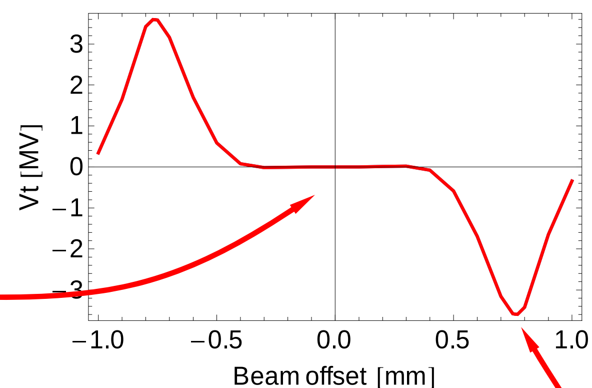
Loss factor



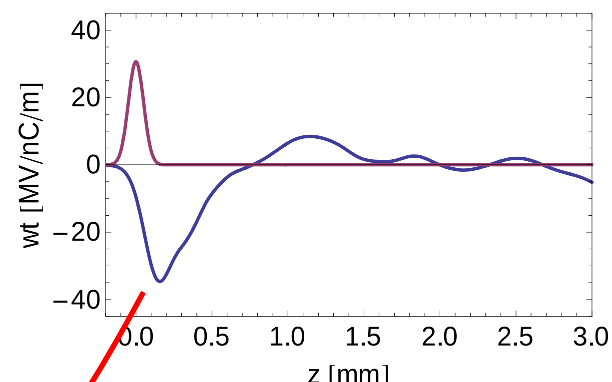
Longitudinal wake,
offset 0.75 mm



Transverse wake,
offset 0 mm

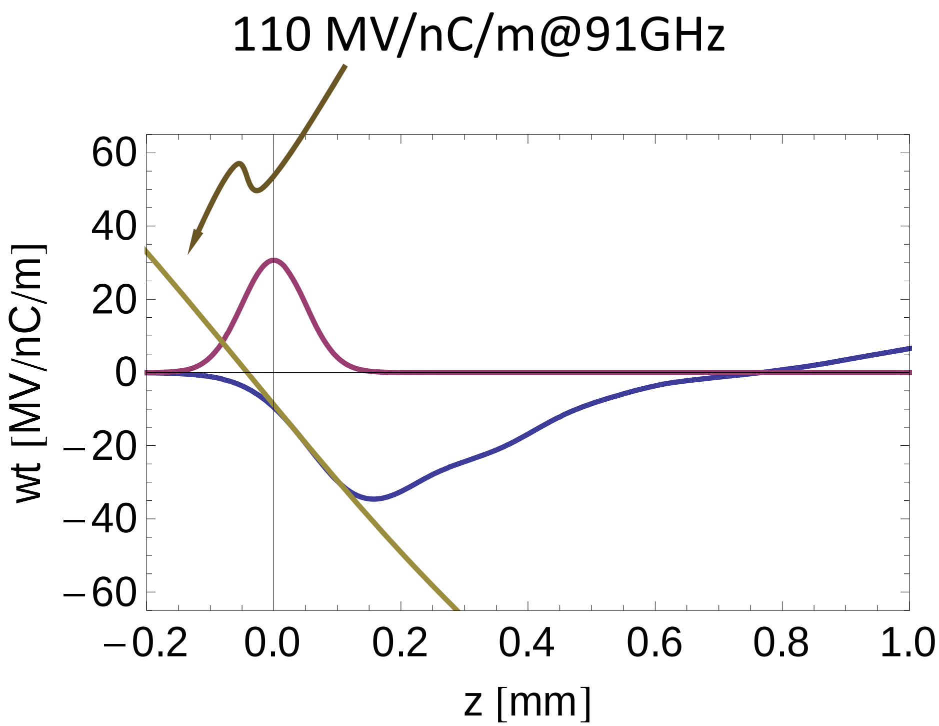


Kick factor

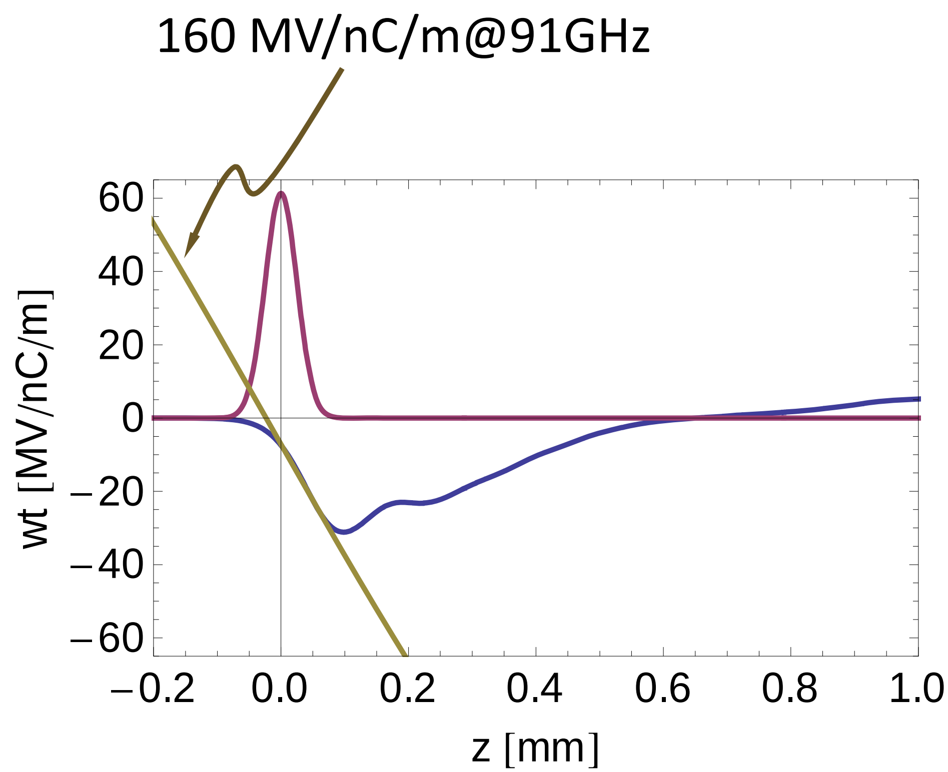


Transverse wake,
offset 0.75 mm

Short range transverse wakefield, 100 GHz accelerating structure, gap 0.3 mm

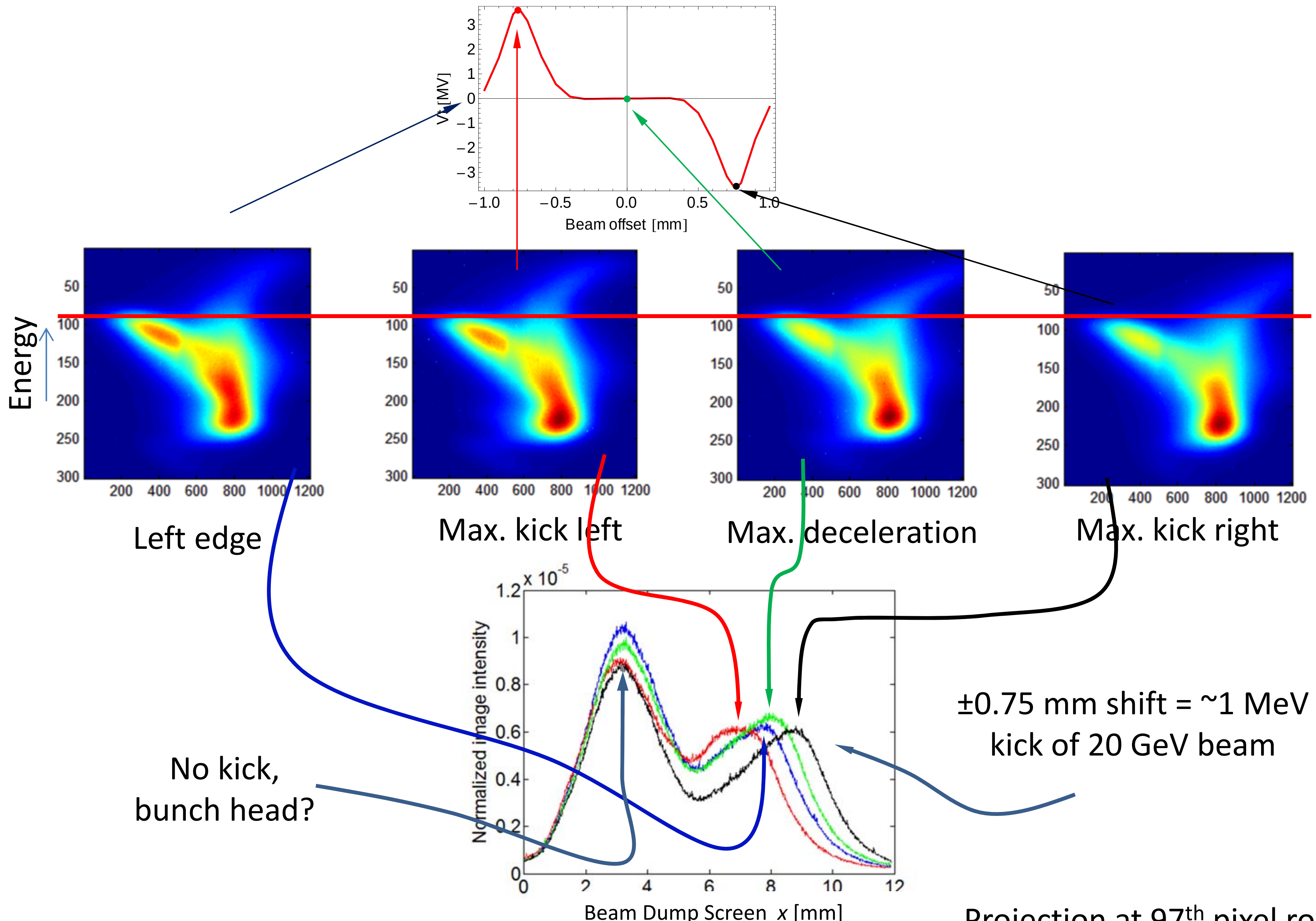


Offset 0.8 mm, bunch length 50 µm



Offset 0.76 mm, bunch length 25 µm

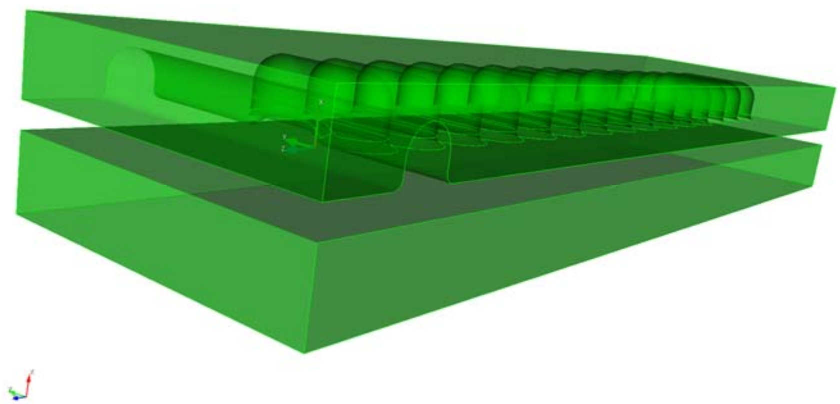
100 GHz accelerating structure, gap 0.9 mm, FACET shift 4 April 2015



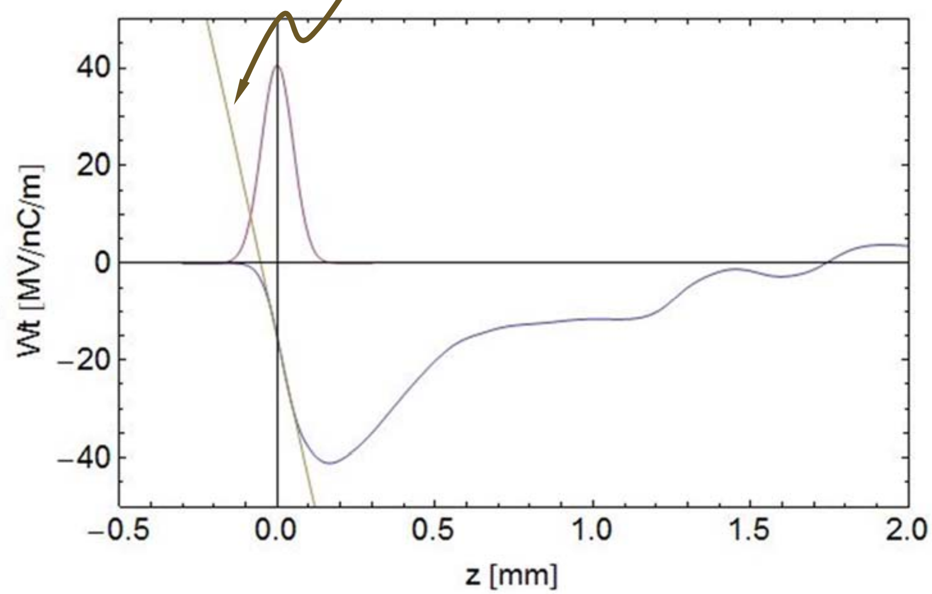
Projection at 97th pixel row

Asymmetric geometry, gap 0.3 mm

155 MV/nC/m@91GHz



Half geometry, no cavities on bottom



On-axis bunch,
bunch length 50 µm

Summary for wakefield driven deflector

- With practical structures we should be able to produce chirp of transvers kick needed for few hundred attosecond timing resolution of ~200 pC bunch.
- We can clearly see the kick on 20 GeV FACET beam.
- Absolute calibration would be difficult.
- Head of the bunch is not kicked, so we need to understand how useful the diagnostics with this limitation.