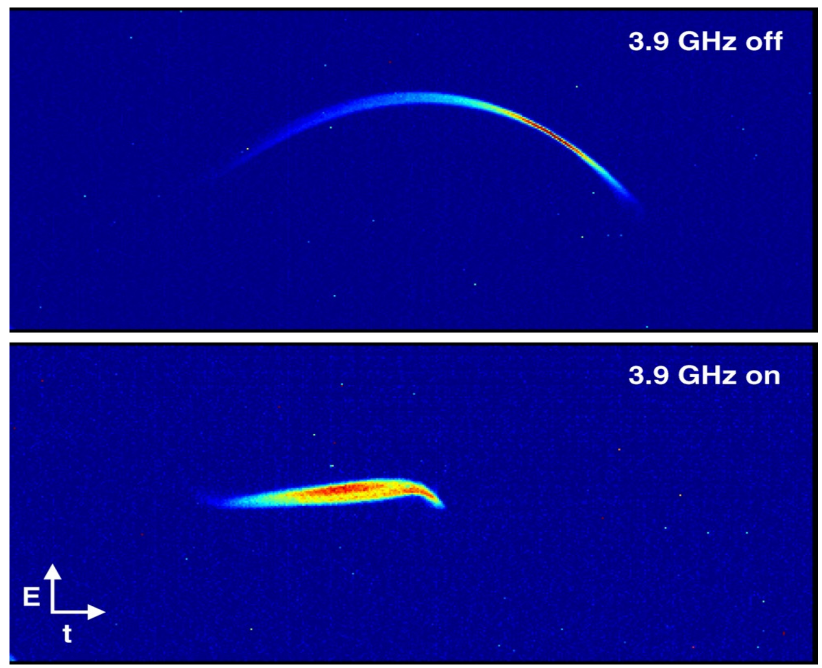
Beam Diagnostics using RF Deflectors

The ultimate time-resolved Beam Characterization



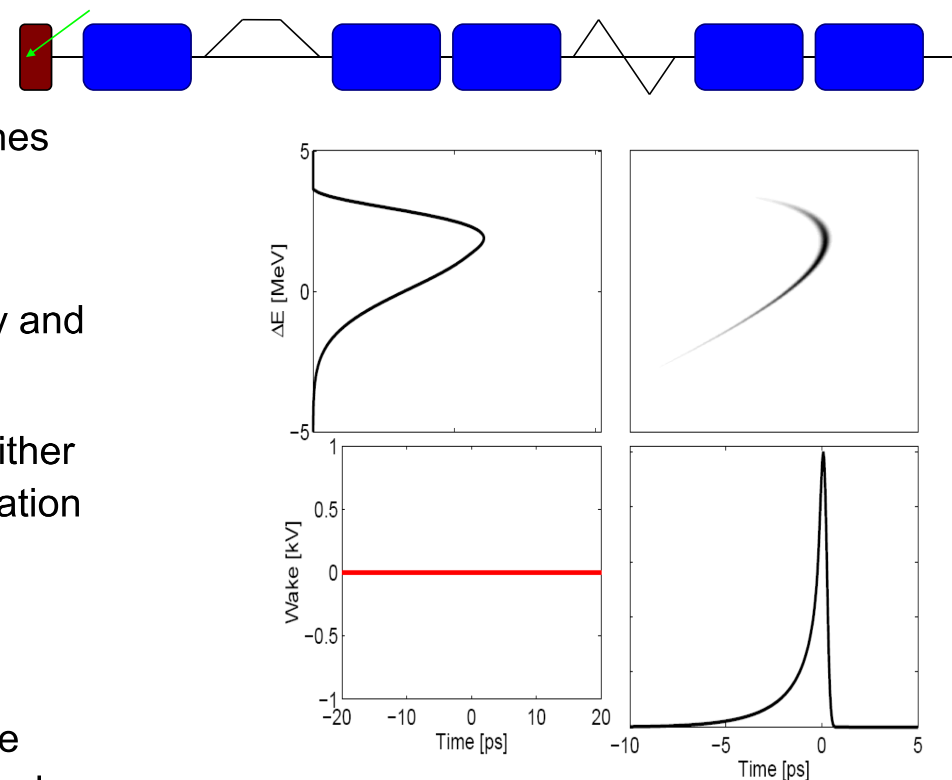
Markus Hüning

Bejing, September 21st, 2018

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Background

- Many Electron Linacs – especially those used as FEL drivers – are operated with very short bunches (σ_τ<<1ps)
- Even the most basic phase-space manipulations (bunch compressors) involve non-linear effects both longitudinally and transversally
- Beam diagnostics that deliver projections or moments – either transversally or longitudinally – do deliver valuable information but leave substantial gaps
- For optimum control of the phase-space manipulations a measurement technique is required that not only delivers longitudinal profiles with femtosecond resolution but at the same time offers the possibility for time-resolved transversal measurements



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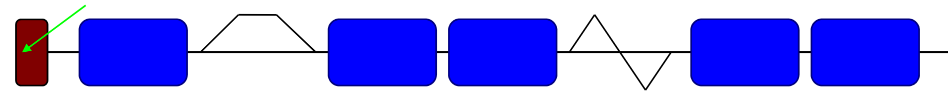
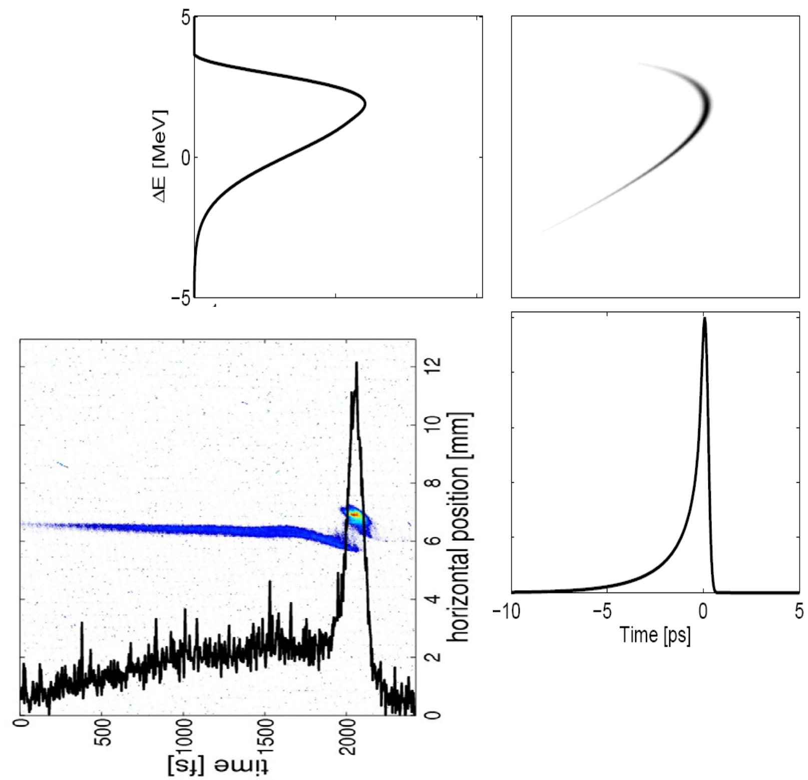
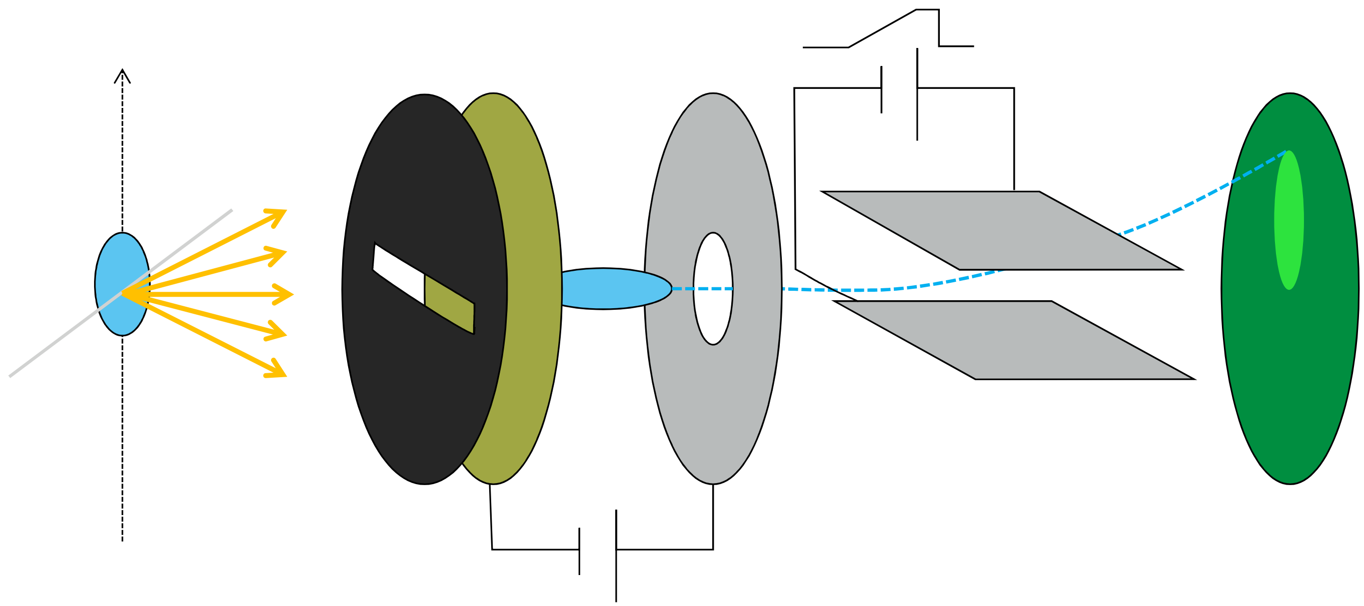




Streak Camera

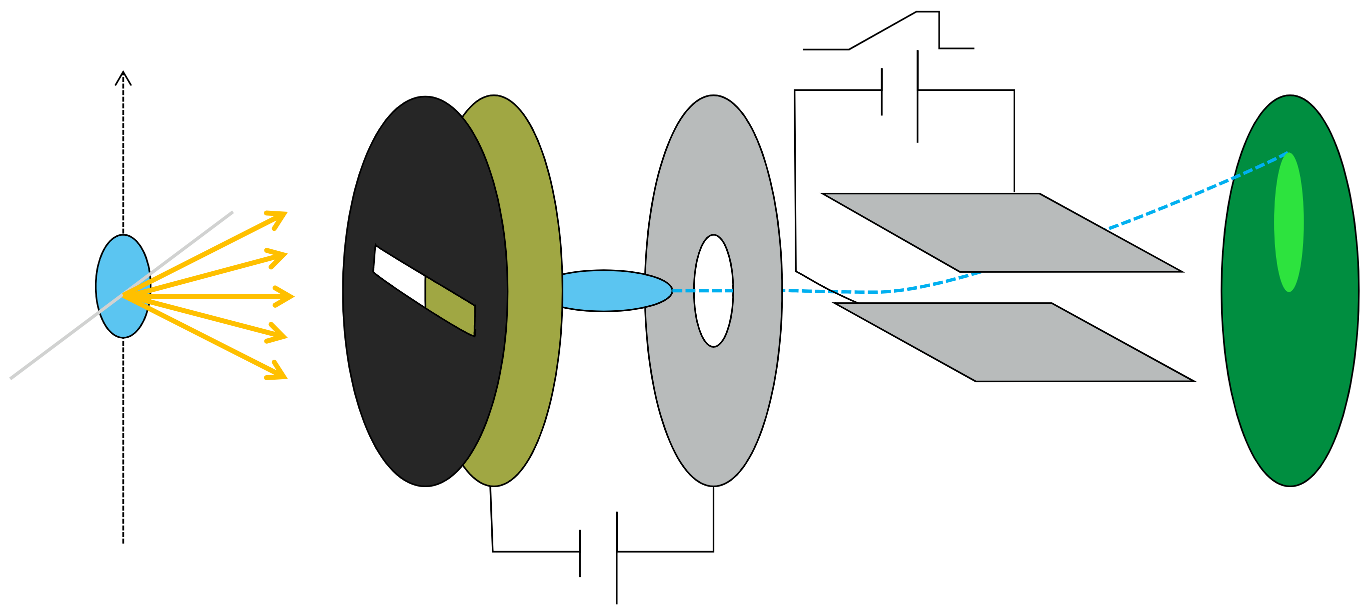
Method of Choice for Picosecond Measurements



- Reproduce the electron bunch in a light pulse (E.G. OTR)
- With a photo cathode produce electrons proportional to and in time with the light (slit to reduce size in direction of streak)
- Accelerate the electrons and deflect with a ramped field
- Image on scintillator screen shows intensity vs time

Entrance: RF Deflector

Overcoming the Space-Charge Limit



- Avoid space charge limit at cathode
- High frequency deflection for fast streak
- Time resolution determined by ratio of deflector strength and beam energy

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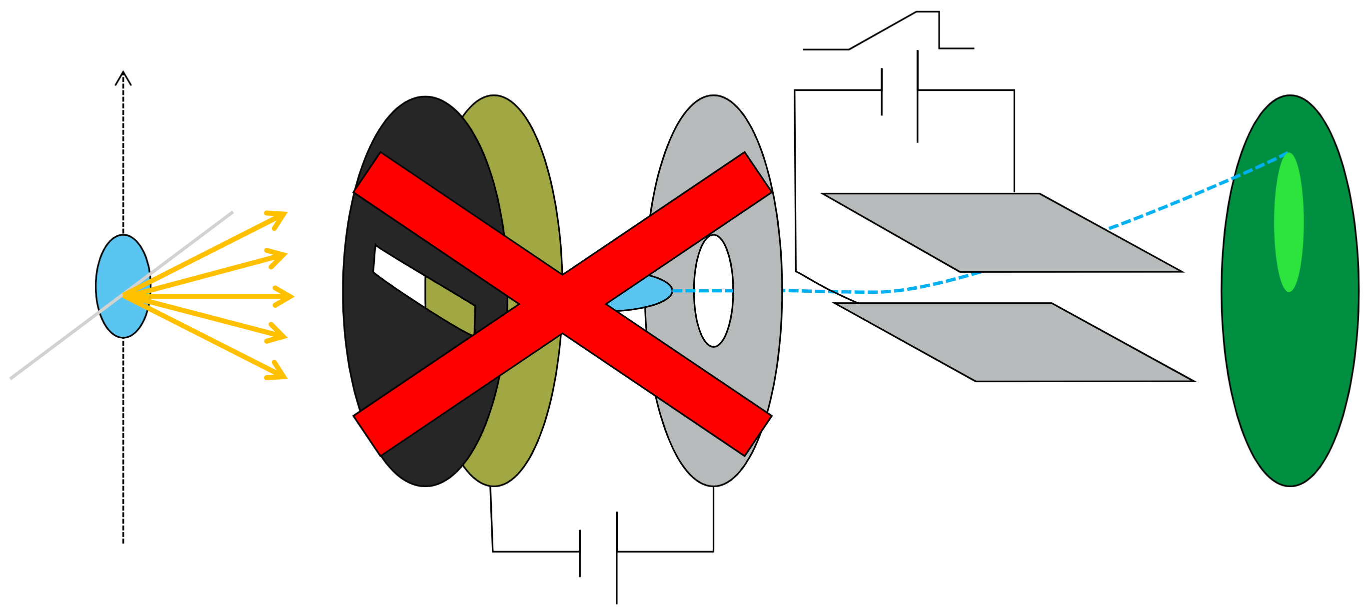

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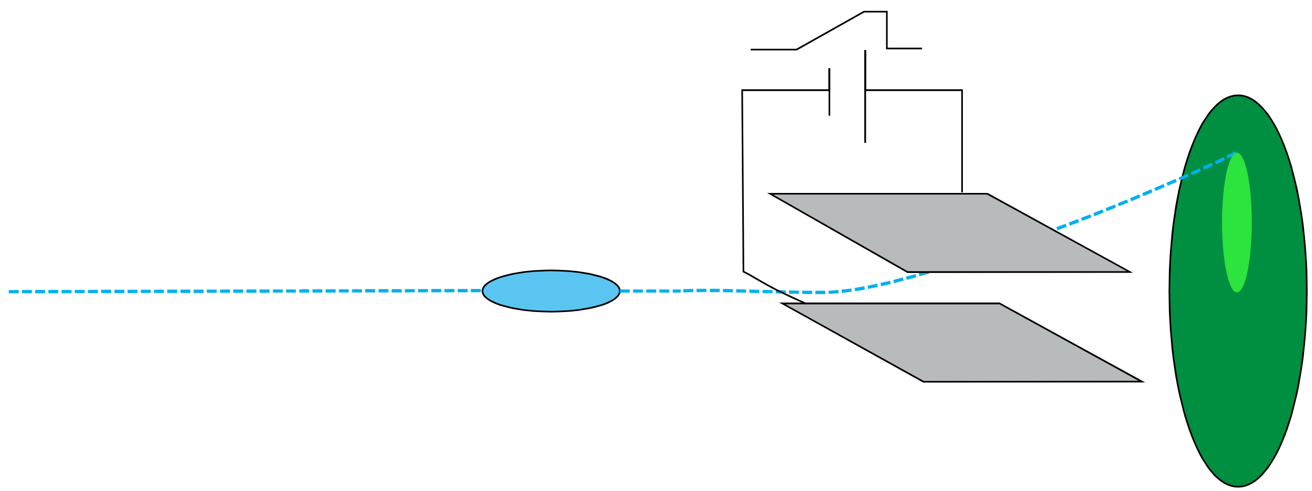

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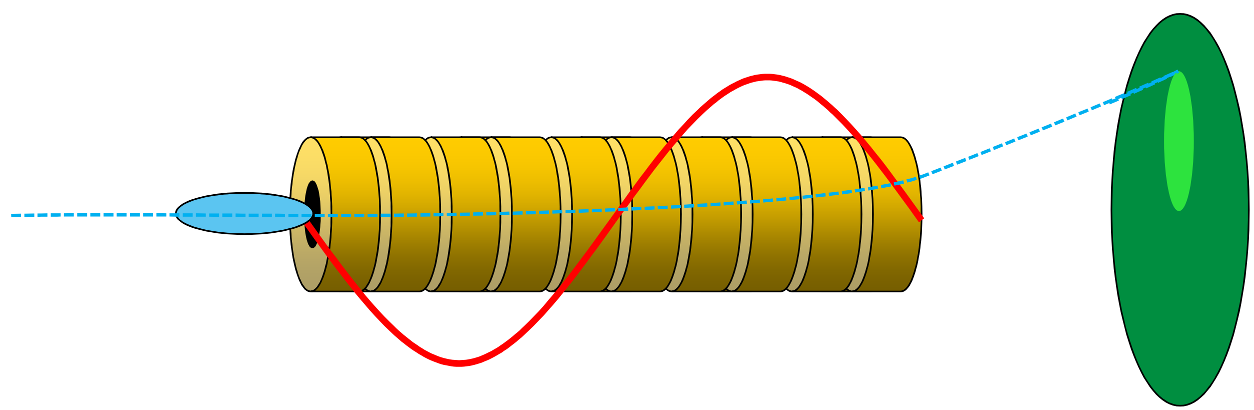

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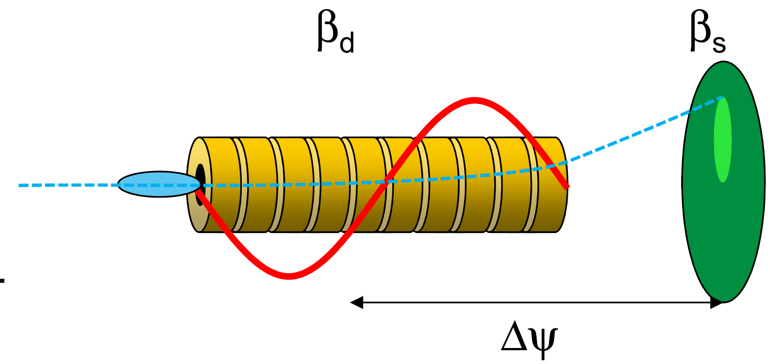
Resolution of Measurement



Size of streaked bunch on screen

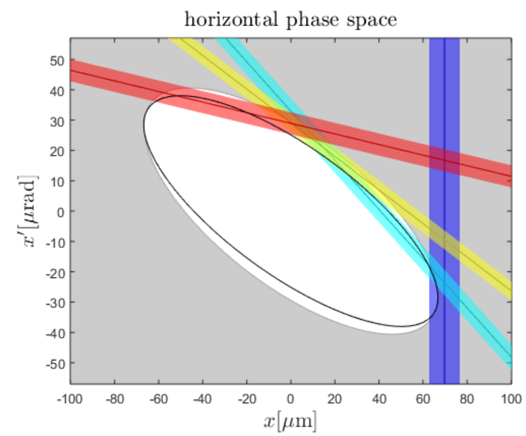
$$\sigma_y = \sqrt{\sigma_{y0}^2 + \sigma_{ys}^2}$$

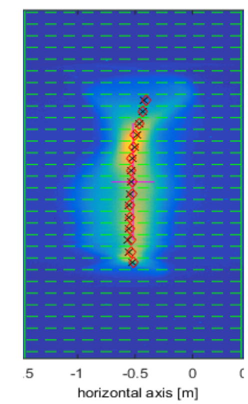
$$\sigma_{ys} = \omega\sigma_t \frac{eV_0}{E_0} \cos\varphi \sqrt{\beta_d \beta_s} \sin\Delta\psi$$

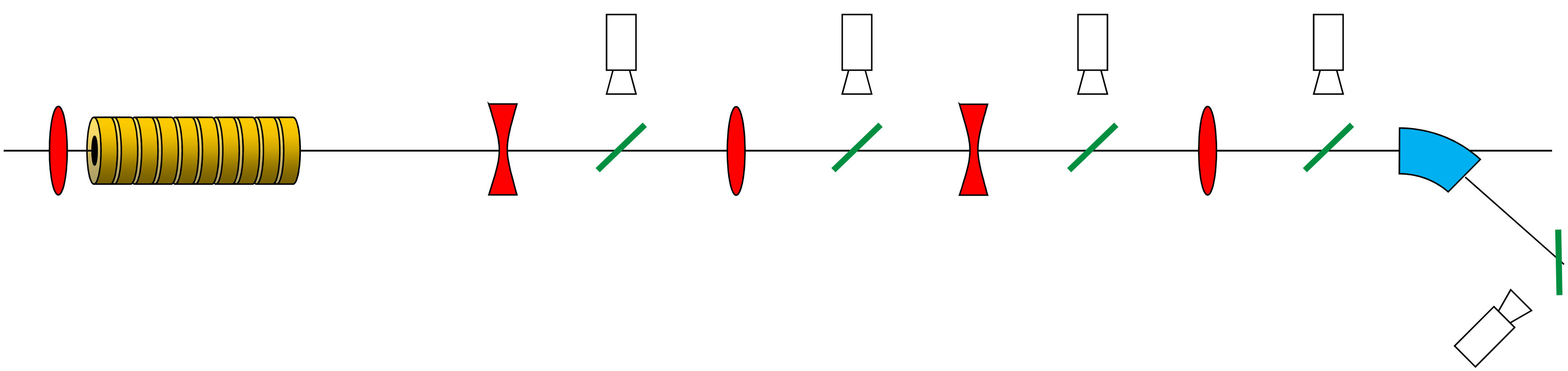
$$\frac{1}{\sigma_{t0}} = \underbrace{\omega \frac{eV_0}{E_0} \cos\varphi}_{\text{RF/Structure}} \underbrace{\sqrt{\beta_d / \varepsilon} \sin\Delta\psi}_{\text{Beam Optics}}$$

Measurement Setup

- In the simplest setup pure drift between TDS and screen
- A dipole (deflection orthogonal to RF deflection) allows for images of the longitudinal phase-space (conflict of temporal vs. energy resolution)
- A FODO channel with four screens allows for quick measurements of slice emittance (losing temporal resolution)







The Deflecting Mode

Some Basics

- For ultrarelativistic particles and matched fields the deflecting force is

$$\vec{F}_\perp = \frac{e}{k}\vec{\nabla}_\perp E_z$$

  Therefore TE-modes are not suitable for RF deflectors

- The mode of choice is TM_{11}
  (or rather HEM_{11} or TM_{11}-like)

- Apply means to avoid mode rotation

- Due to strong magnetic coupling the group velocity is negative

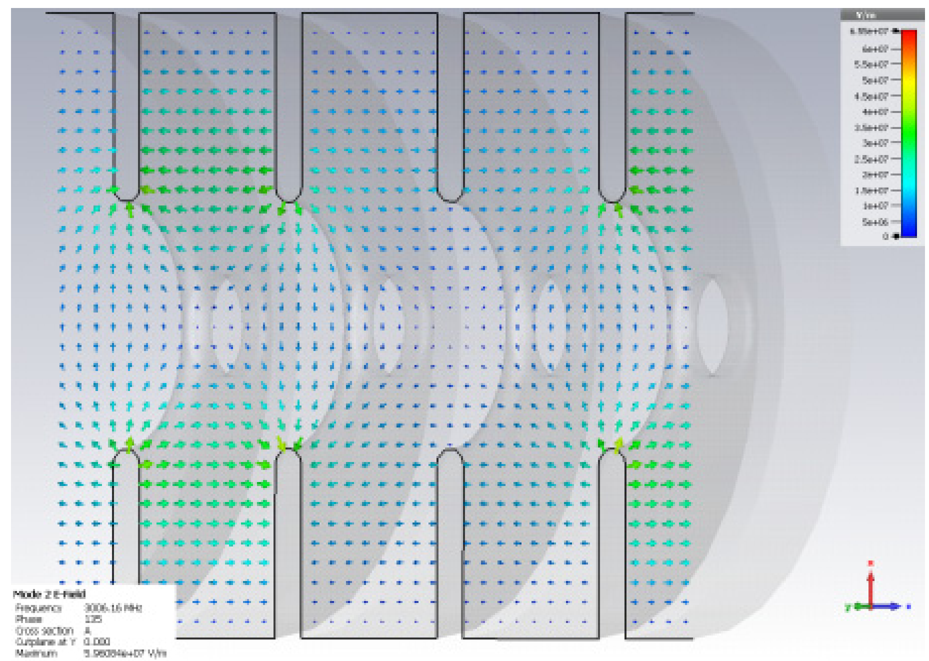
- To first order the deflection is independent of offset,

- However off-axis paticles are actually accelerated

$$V_z(y) = kyV_0$$

- This results in a relation of time and energy resolution

$$\frac{\sigma_E}{E}\sigma_t = \frac{\varepsilon}{c}$$



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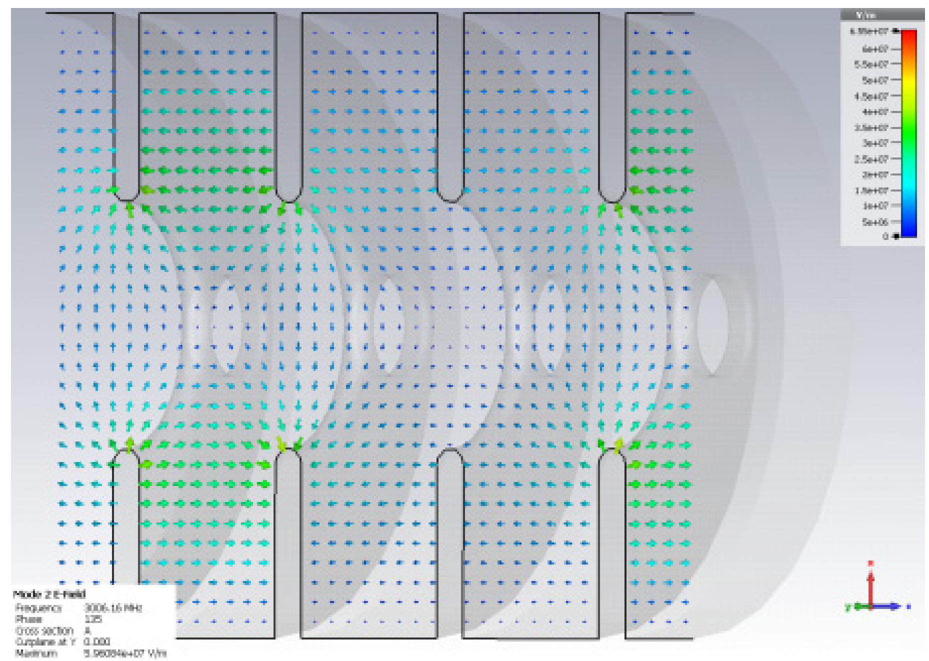
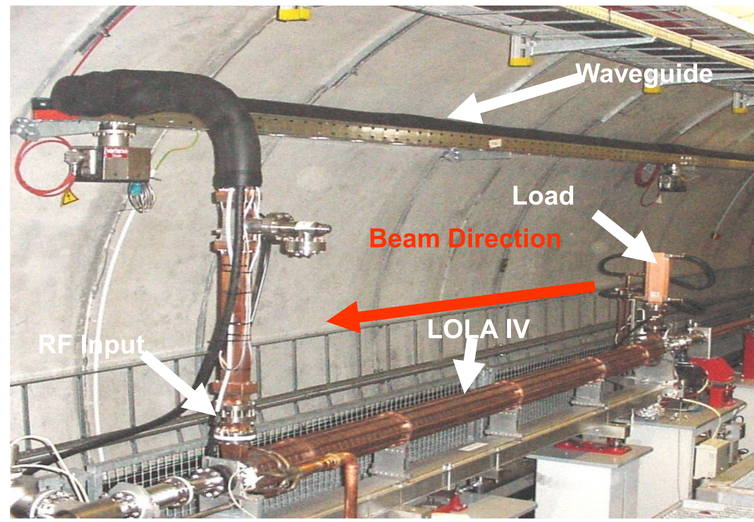
$$\delta_E \sigma_z = \varepsilon$$

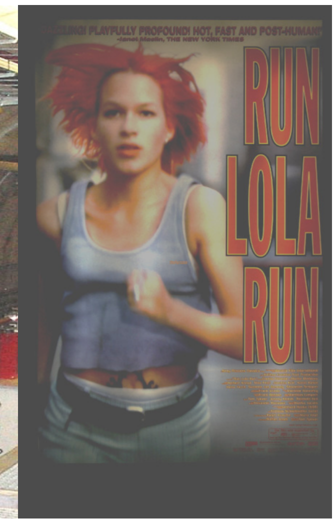


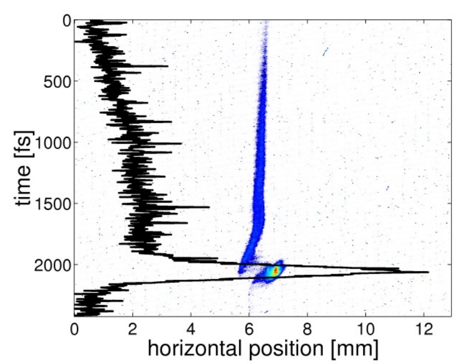
LOLA IV

An old RF Separator used for Beam Diagnostics

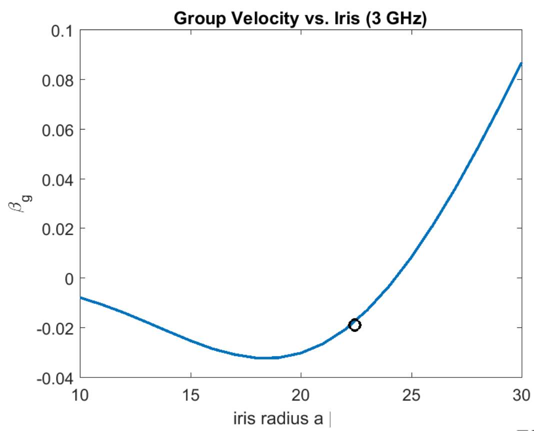
- Designed in the late 60‘ies as a separator in a secondary beam at SLAC
- S-Band (2.856 GHz),
  - deflecting voltage 26MV@20MW
  - Fill-time 645 ns, β_g -0.0189
  - Length 3.64 m
  - Iris 44.88 mm
- Put back to use in preparation for LCLS
- Permanent loan to DESY being used at FLASH

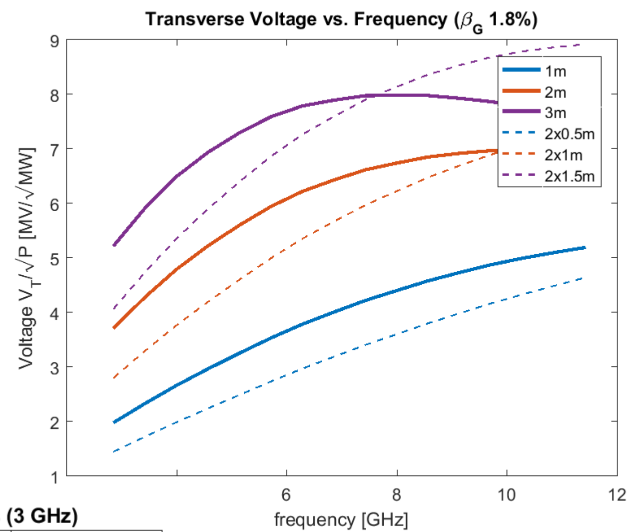


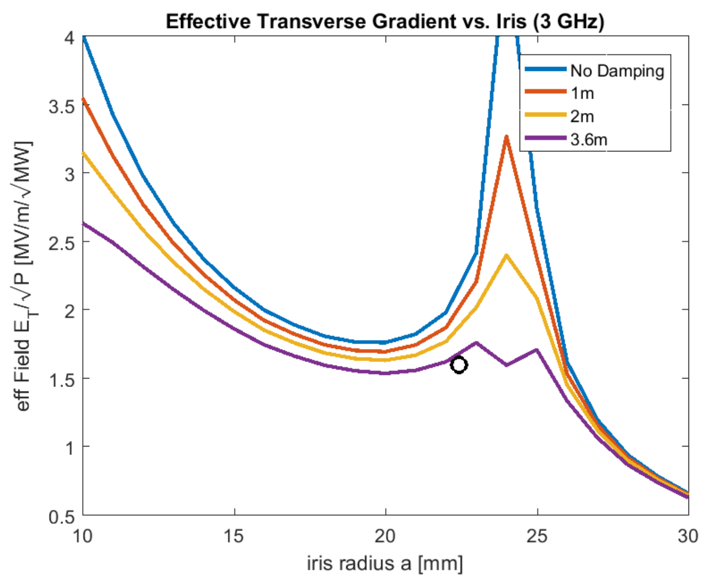


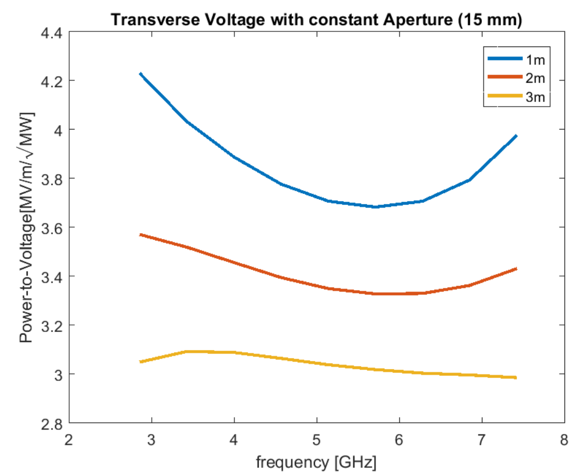


Some Scaling

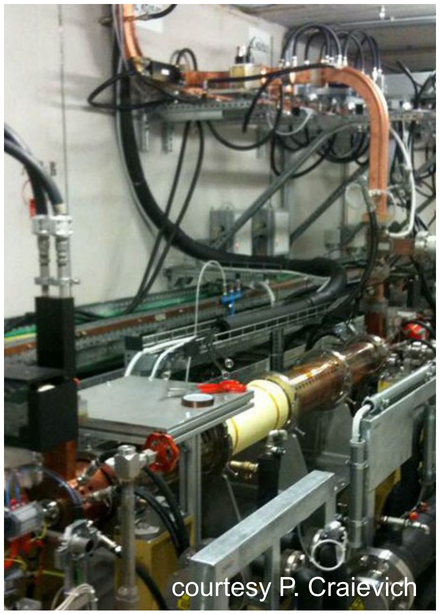




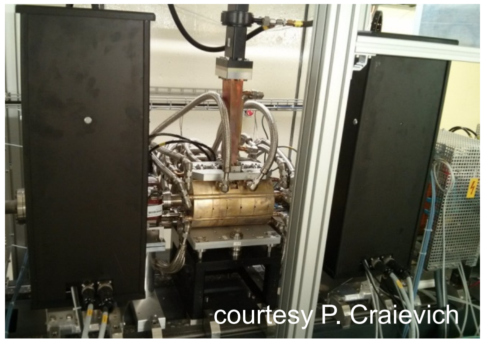




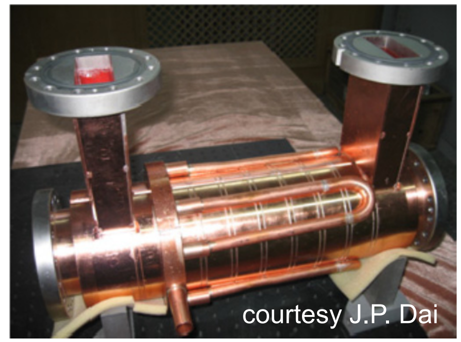
Other Examples at 3 GHz



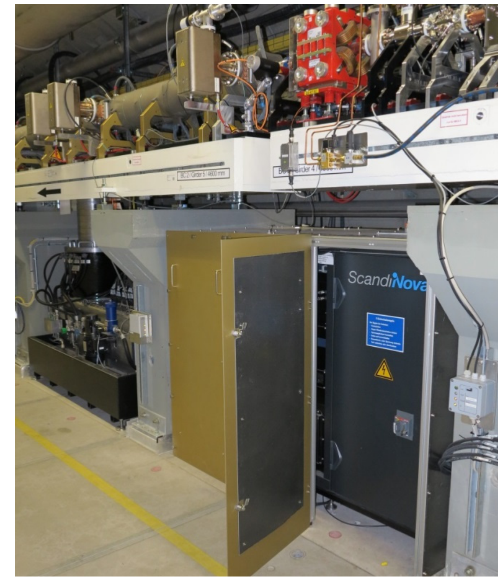
FERMI@Elettra (hor/ver)	
L(active)	2.466 m
Fill-Time	500 ns
β_g	-0.0157
Iris	25 mm
Voltage	23 MV@15MW
Pwr to Vltg	2.4 MV/m/√MW
Energy	1200 MeV



SPARC/FERMI/SwissFEL	
L(active)	0.25 m
Fill-Time	800 ns
Standing Wave	
Iris	36 mm
Voltage	4.9 MV@5MW
Pwr to Vltg	8.8 MV/m/√MW
Energy	150 MeV



Shanghai DUV-FEL	
L(active)	0.35 m
Fill-Time	62 ns
β_g	-0.0189
Iris	44.88 mm
Voltage	0.56 MV@1MW
Pwr to Vltg	1.6 MV/m/√MW
Energy	5 MeV



EuropeanXFEL (by INR)	
L(active)	2×1.5 m
Fill-Time	2×333 ns
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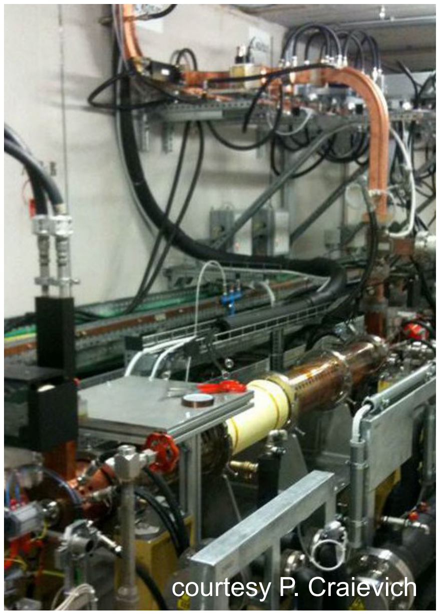

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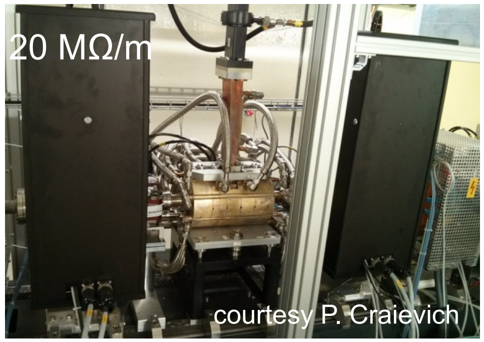

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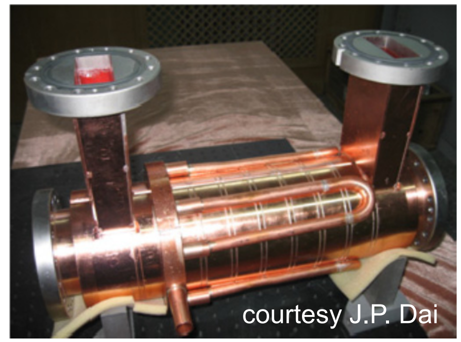

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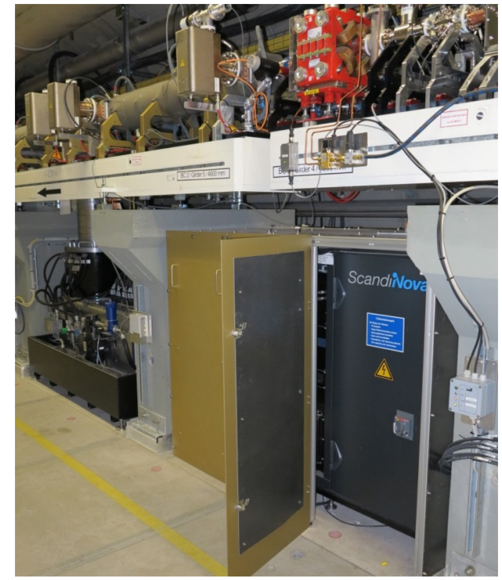

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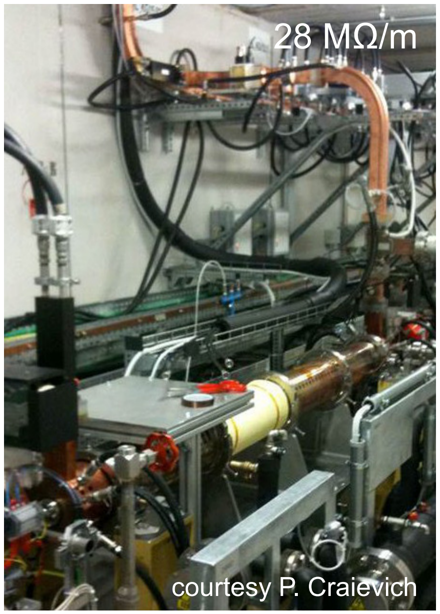

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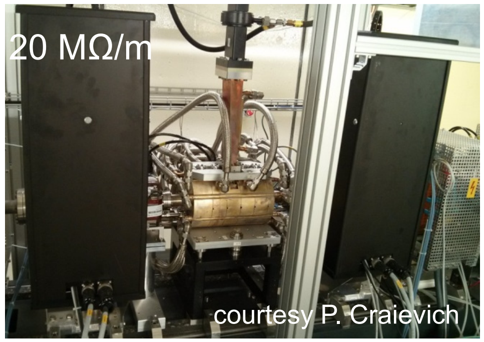

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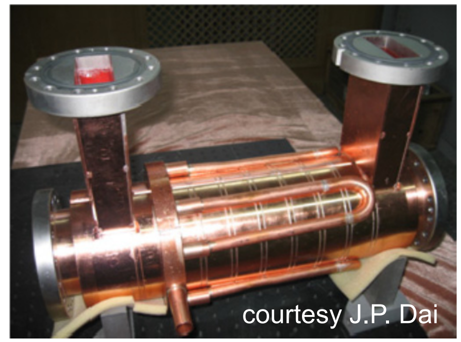

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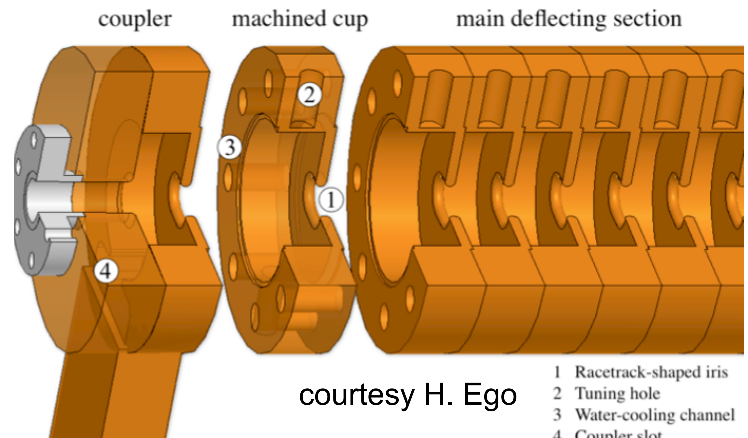
Moving on to C-Band

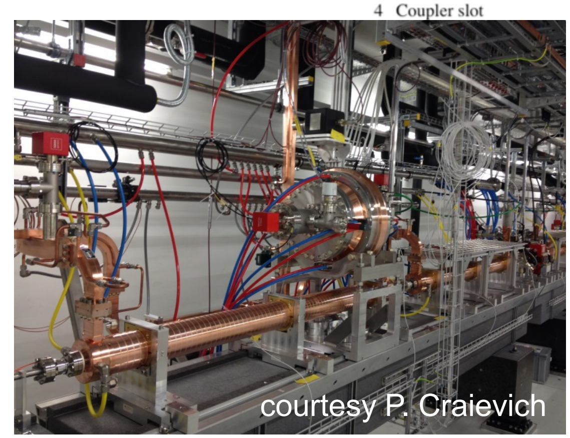
- At the SACLA XFEL an RF-Deflector was developed which operates in C-Band (5.712 GHz, like the Linac)

L(active)	2×1.7 m
Fill-Time	2×269 ns
β_g	-0.0214
Iris	12×20 mm (racetrack)
Voltage	60 MV@40MW
Pwr to Vltg	4 MV/m/√MW
Energy	1450 MeV

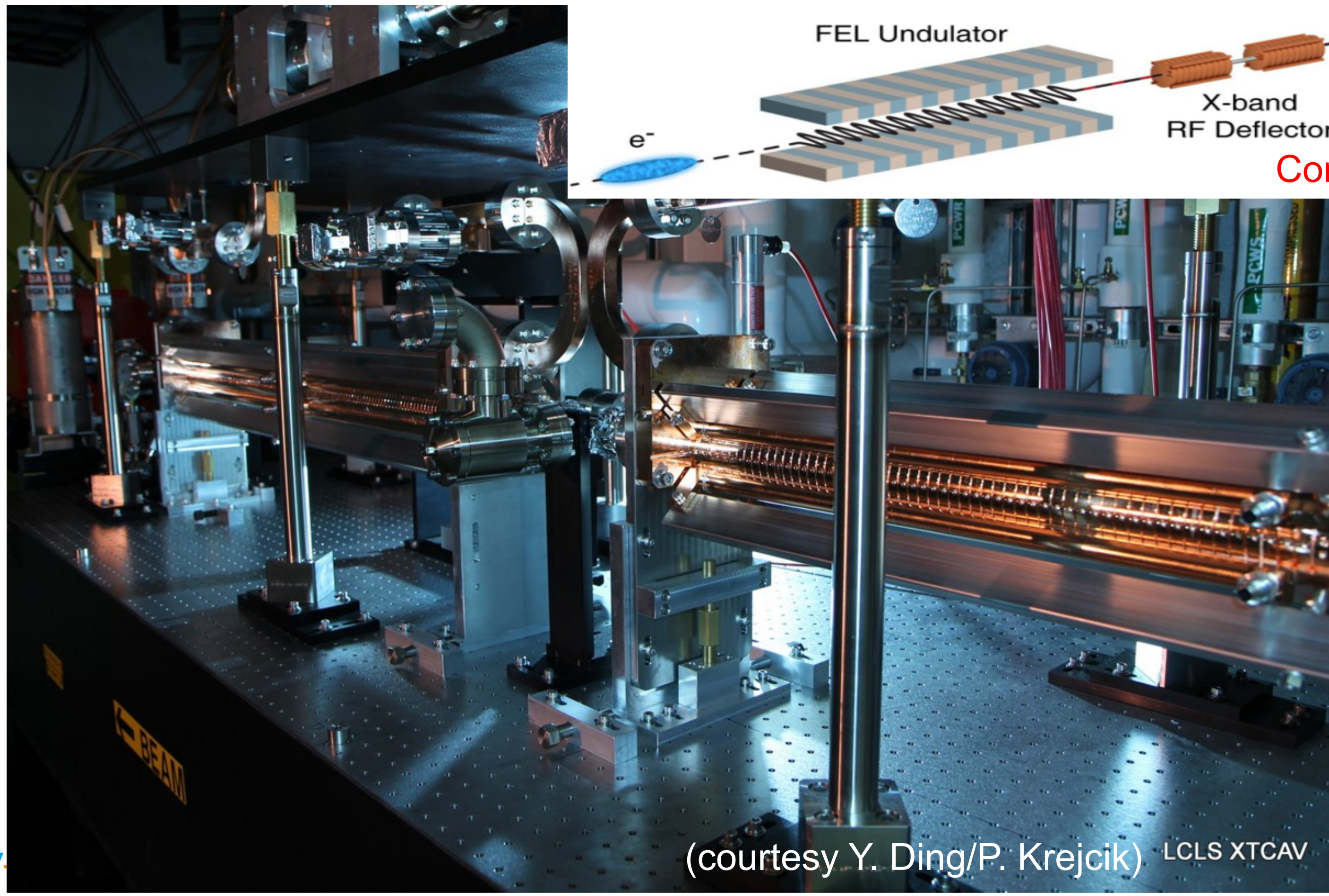
- Compared to S-Band **gain of 1.7 in voltage and 3 in streak**
- For their high energy deflector SwissFEL decided to adopt this design (bought at Mitsubishi Heavy Industries)
- Routinely used with pulse compressor at 80 MV

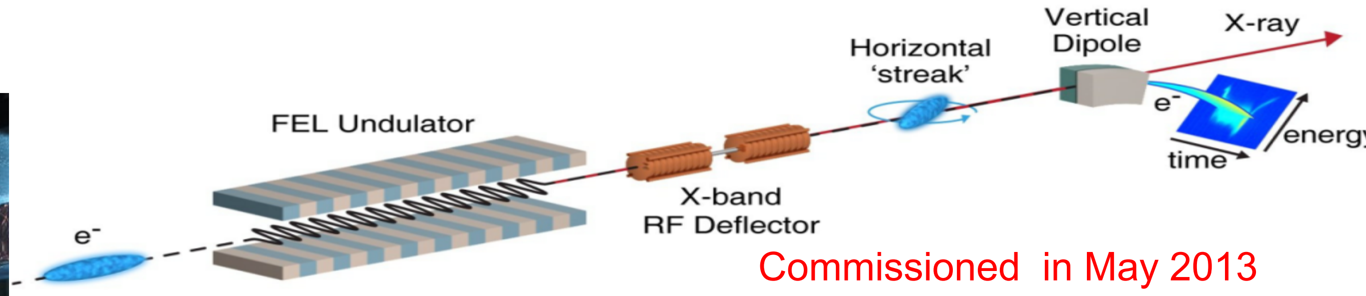


courtesy H. Ego



Yet another Step to X-Band





Commissioned in May 2013

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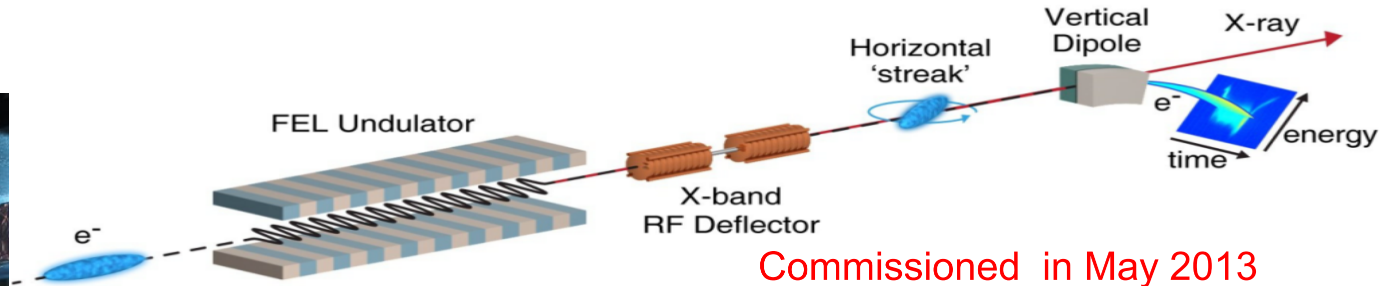

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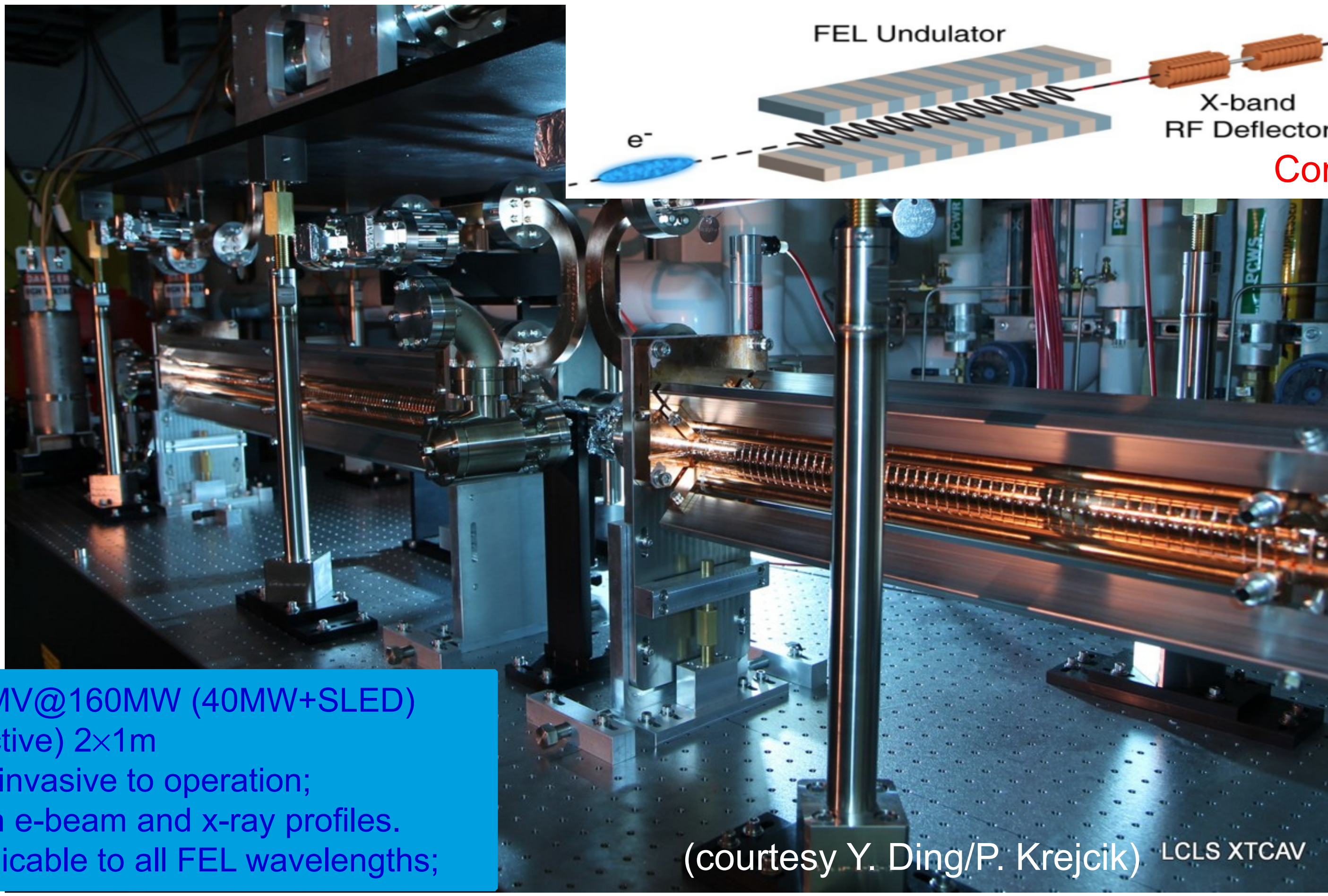
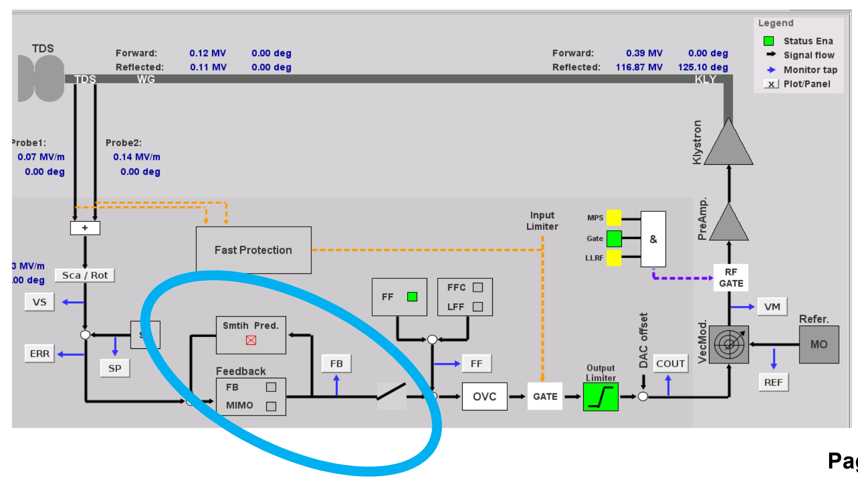


- ✓ 85 MV@160MW (40MW+SLED)
- ✓ L(active) 2×1m
- ✓ Noninvasive to operation;
- ✓ Both e-beam and x-ray profiles.
- ✓ Applicable to all FEL wavelengths;

RF Drive

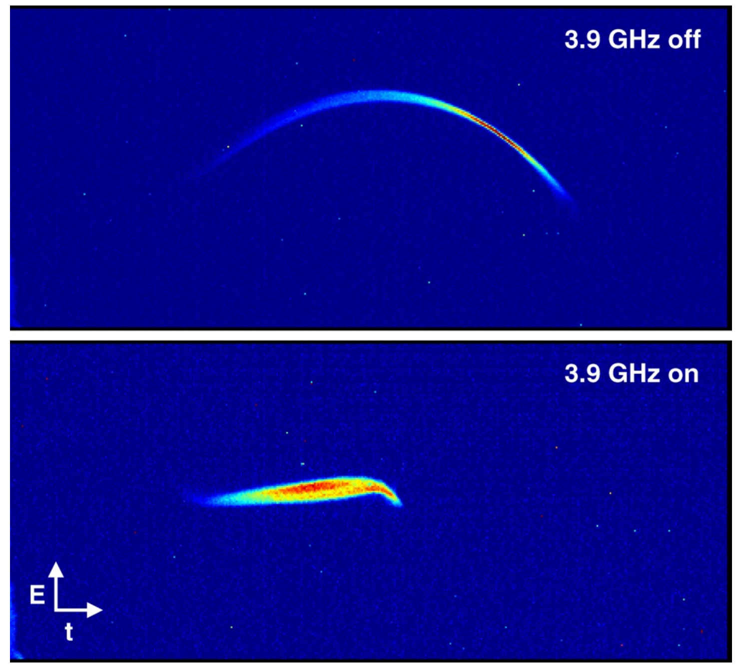
- The fast streak that is applied necessitates a stable RF phase
- Consider an X-Band structure at 12GHz with a filling time of 100ns
- A phase change of 0.2° corresponds to 50fs time difference, which at 200fs total streak is already ¼
  - For the above structure this means a temperature stability of <50mK
  - A SLED with QL=20000 requires temperature stability of 10mK
- For temperature drifts surely a slow feedback suffices
- Fast jitter from klystron is reduced by modern semiconductor modulators (voltage stability 10ppm → 3fs timing jitter (6MW klystron))

- Phase accuracy (esp. 180°) and low coupling between amplitude and phase for precise calibration
- Fast feedback loop often not possible because of short pulses
- Short loop delay, appropriate filtering and correspondingly longer pulses may help
- Slow loop on local computer



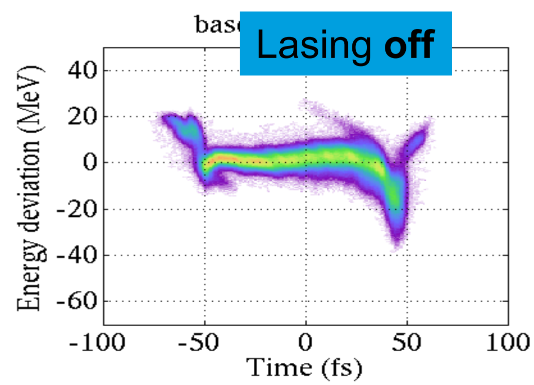
Example: Longitudinal Phase-Space

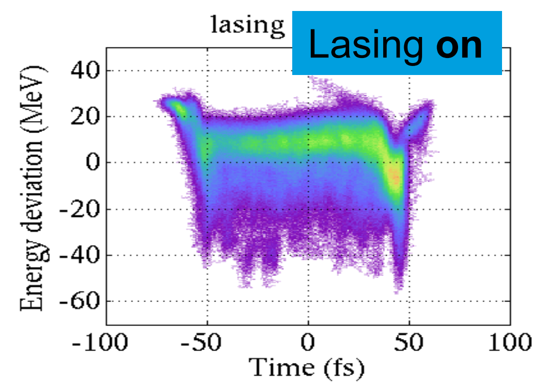
- The pictures on the right were taken at FLASH while commissioning the 3rd harmonic system
- The time axis was obtained by streaking the bunches with LOLA
- The energy axis by deflecting with a dipole
- The streak was not paticularly strong (several ps on screen)



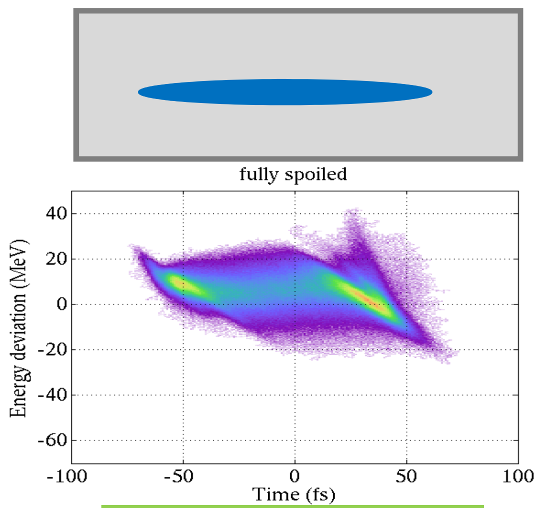
Example: Phase-Space Behind the Undulator

Regular SASE,
Without foil

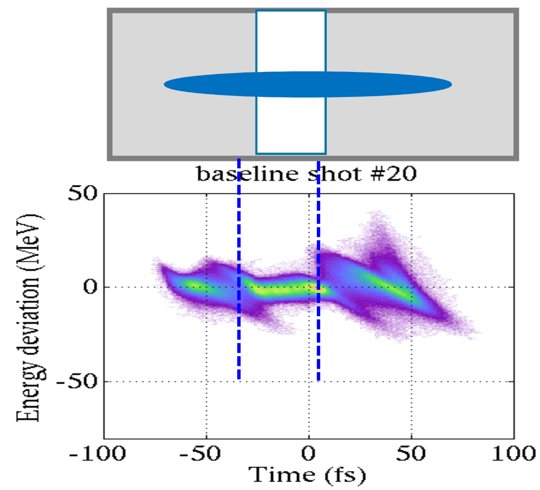




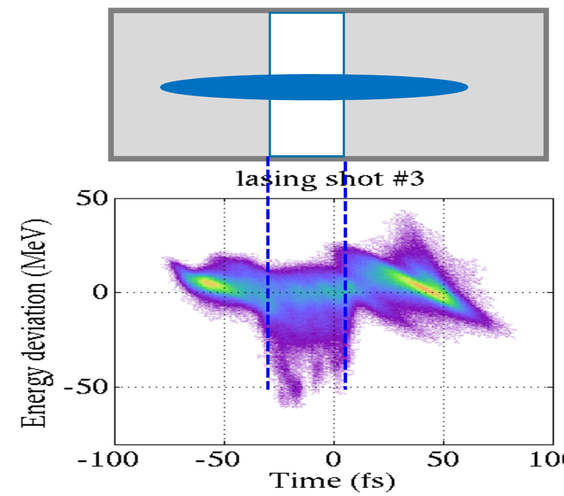
With foil



fully spoiled, no slot



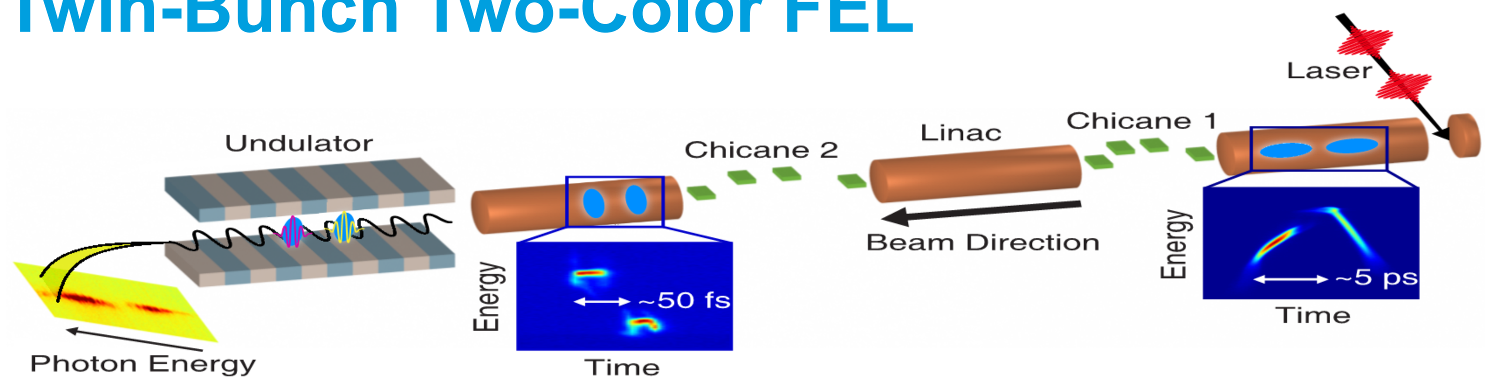
Lasing **off**, single slot

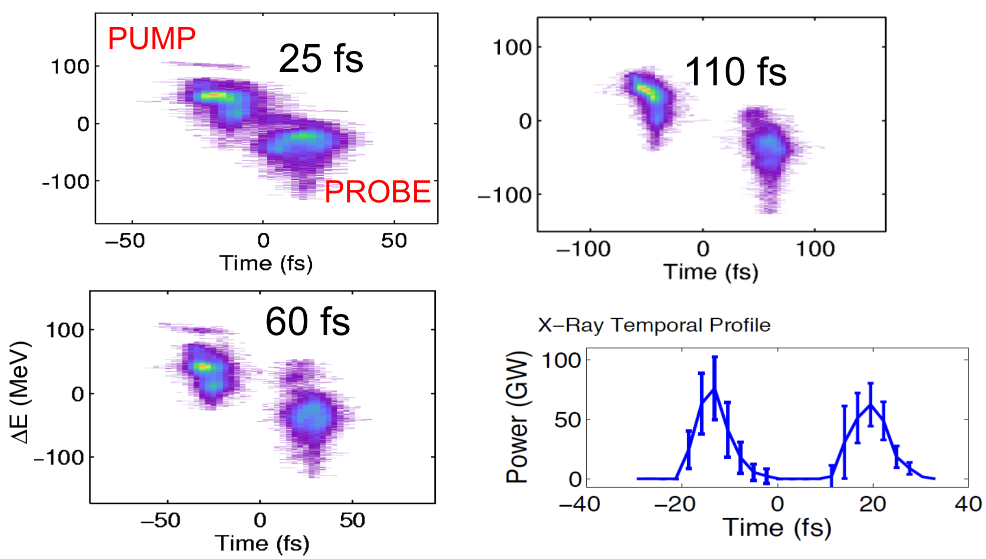


Lasing **on**, single slot

Y. Ding et al., APL 107, 191104 (2015)

Example: Twin-Bunch Two-Color FEL





Twin-bunch takes full advantage of the XTCAV capability.

- Improve the peak power of 2-color SASE by a factor 20 at hard x-rays

- Allow 2 color self-seeding with large separation

- Allow x-ray pump/x-ray probe at high intensities

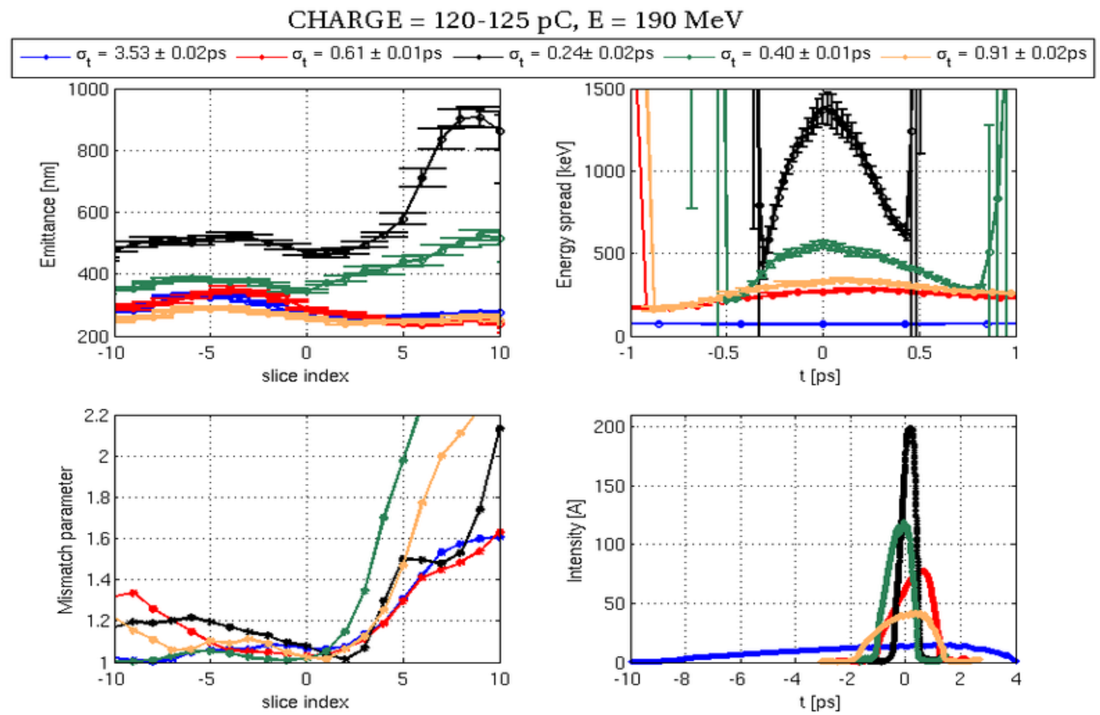
✓ **~10 fs pulse duration, over 1mJ pulse energy, pulse delay up to 150 fs.**

✓ **Up to 1% energy separation at HXR.**

(A. Marinelli et al., Nature Commun. 6, 6369, 2015)

Example: Slice Emittance

- Measurement taken at the SwissFEL injector during early commissioning
- At the time they were looking for some problem with emittance increase which is meanwhile solved

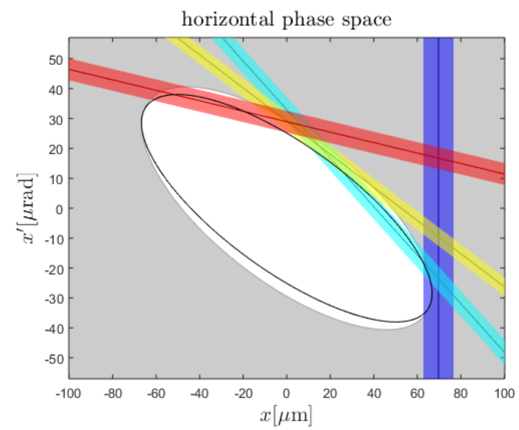


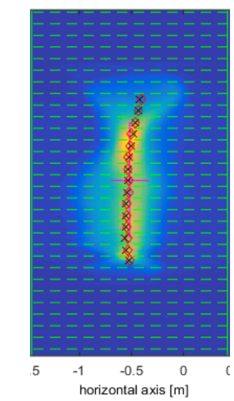
Courtecy B. Beutner

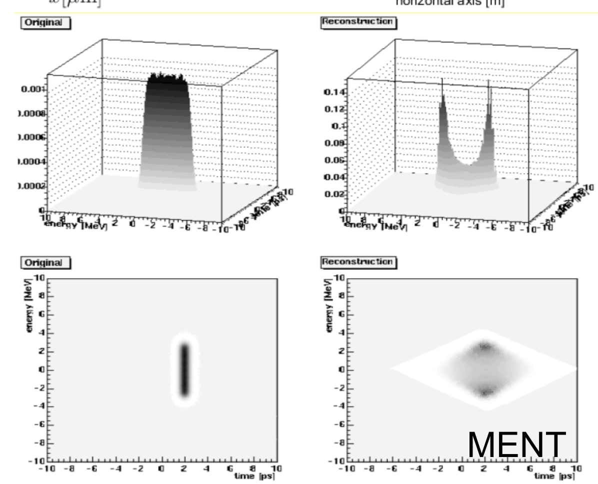
PAUL SCHERRER INSTITUT

Limits of Slice Emittance Measurements

- Along the streak longitudinal and transversal distributions are mixed
- Transversal slice emittance measurements are possible only orthogonal to streaking direction
- To overcome this limit one can install two structures orthogonally (E.G. FERMI@Elettra)
- One might try Tomography but will never reach full resolution (in beam size)

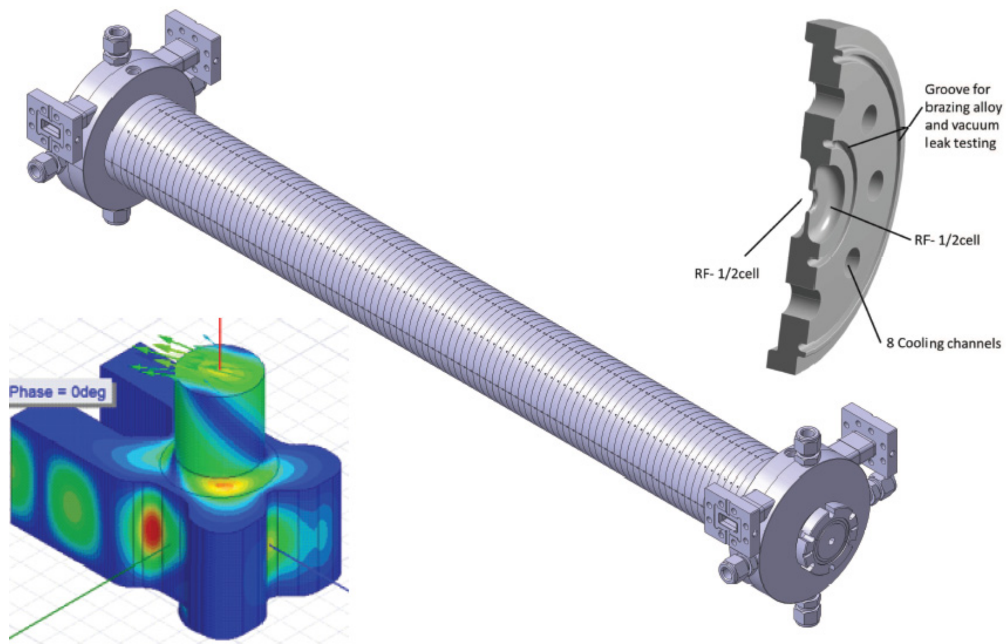






PolariX: TDS with variable Polarization

- Collaboration between CERN/PSI/DESY
- Input coupler on axis with variable polarization, adjusted by phase between input arms, strictly rotational symmetric (axial coupler, no tuning, no field probes)
- Frequency 11.995 GHz
- Active length 800/1000 mm
- Filling time 105/130 ns
- Power-to-Voltage 6.12 MV/m/√MW
- Design finished, prototype being manufactured
- First high power tests in spring

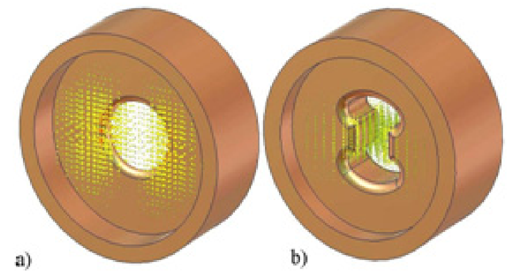


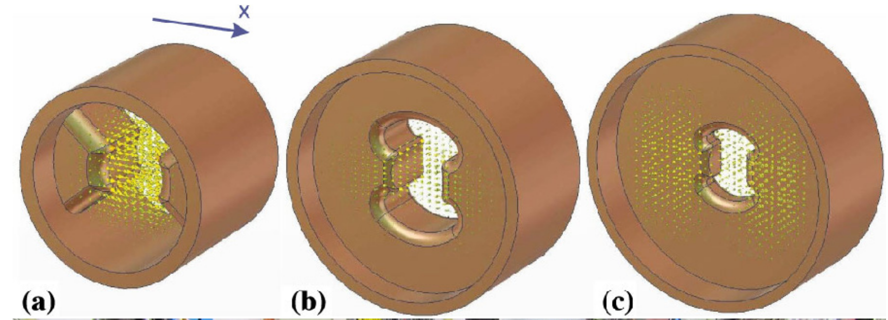
TE Mode Deflector

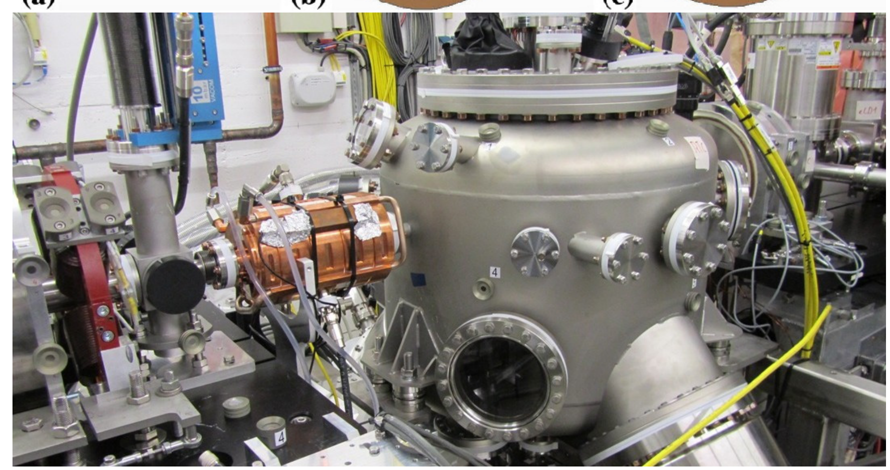
- Decoupled structure proposed at INR to optimize E-Field and H-Field independently
- Allows for very high efficiency design

AND/OR

- Very low nonlinear fields
  - High precision emittance measurements
  - Emittance preservation at phase space manipulations
- Prototype built, installed at REGAE, first beam tests soon, 43.2 MΩ/m







Thank you