Short Wavelength Free Electron Lasers at DESY

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MAMI, 27.01.05

Überblick:

- Warum das Ganze ?
- Was ist ein Free-Electron-Laser?
- Supraleitenden Beschleunigertechnologie @ DESY
- TTF/VUV-FEL
- Das Europäische X-FEL Projekt
- Recent Results

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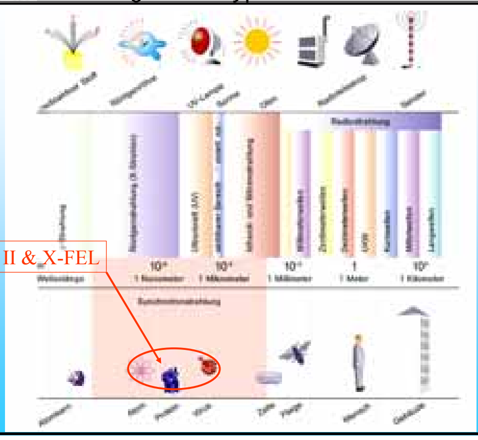
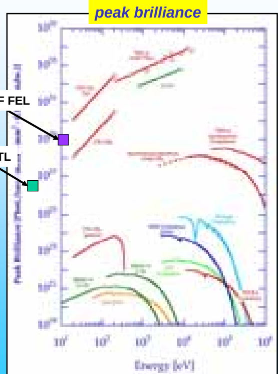
Warum das Ganze?

- Strahlung ist ein wichtiges Werkzeug zur Beobachtung der Natur.
- Immer kleinere Strukturen benötigen immer kürzere Wellenlängen.
- Hohe Intensitäten erlauben die Beobachtung „extremer“ Vorgänge.
- Kohärenz: Holographische Bilder, räumliche Auflösung
- Kurze Pulse: Stroboskopische Beobachtung schneller Abläufe

Wellenlängen und typische Strukturen



X-FEL Goals



- Increase Peak Brilliance by about 10^9 (compared to state of the art 3rd generation sources)
  - FEL Gain gives 10^6
  - Pulse Compression 10^3
- Access the Structure of Matter
  - Energy high enough to access Core Electrons
  - Intensity high enough to use Samples in natural Environment
  - Create „Strange States“ of Matter
- Short Pulses
  - Allow to study Dynamics of biological/chemical Reactions

Dream of the Users:
- 100 keV
- Full transverse and longitudinal Coherence
- Single Attosecond Spikes
- With high Stability and Reproducibility in
  - Intensity
  - Wavelength
  - Timing

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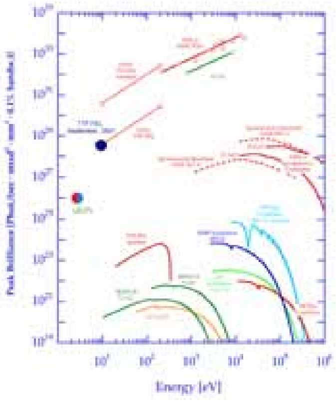
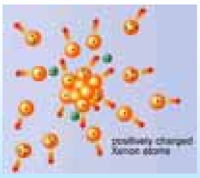
Intensität





Vielphotonenprozesse in Clustern @ TTF:
T. Möller et al. in Nature

SASE FELs sind mehr als 10^9 x „so hell“ wie Speicherringe (im Peak)

- 10^3 durch kürzere Pulse (< 100 fs)
- 10^6 die kohärente Wechselwirkung

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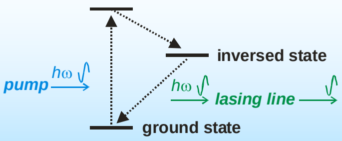
„Klassischer“ Laser & FEL

LASER: e⁻ in festen Zuständen gebunden

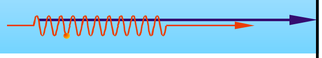


Lasereigenschaften:
- Wellenlänge
- Übergangswahrscheinlichkeiten
- Linenbreite
- Pulslänge

hängen vom Material ab.

Free Electron Laser: **Freie Elektronen im Vakuum,**

die durch externe Beschleunigung zum Strahlen „gezwungen“ werden.



Strahlungseigenschaften werden nur noch durch die e⁻ und die externen Kräfte bestimmt
⇒ Es gibt keine prinzipielle Beschränkung des Spektralbereichs.

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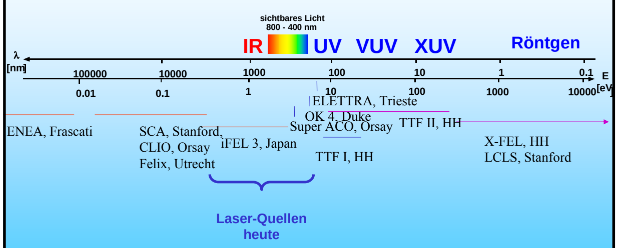
Spektrum und Laser Quellen



Eine Auswahl von FEL Facilities!

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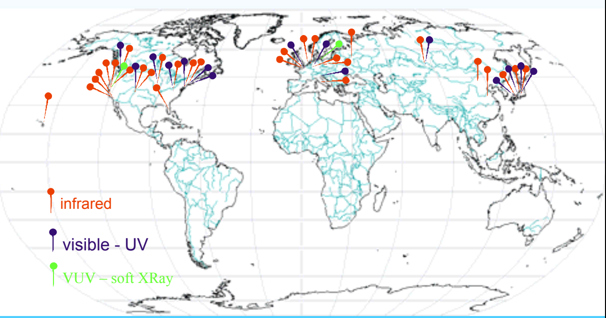
FELs Weltweit



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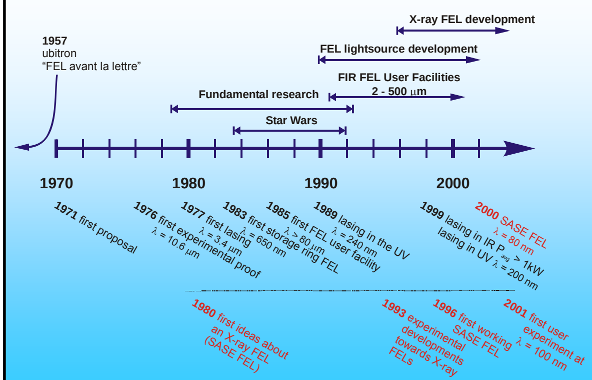
Zeitl. Entwicklung der FEL Technologie



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Funktionsweise eines FEL (I)

Energieaustausch: $mc^2 \frac{d\gamma}{dt} = -e \cdot \vec{v} \cdot \vec{E}$

Ziel: Transfer von Energie aus einem Elektronen- in einen Laserstrahl

Problem: elm. Strahlung ist transversal polarisiert
⇒ das E-Feld steht senkrecht zur Flugrichtung der „mitfliegenden" Elektronen
⇒ Energieübertrag eigentlich unmöglich!

Lösung: transversaler Geschwindigkeitskomponenten in einem Magnetfeld!

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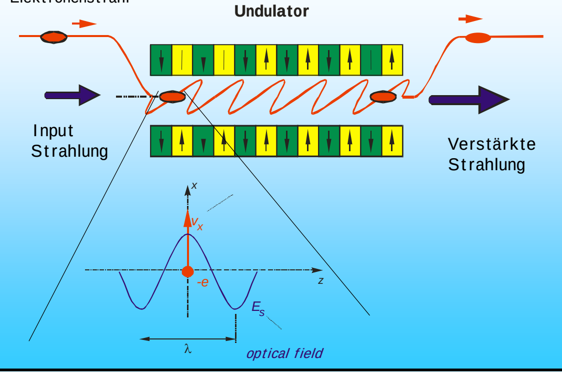
Funktionsweise eines FEL (II)



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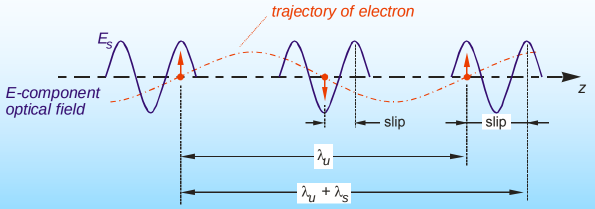
Funktionsweise eines FEL (III)

Resonance condition



$$\frac{\lambda_u + \lambda_s}{c} = \frac{\lambda_u}{v_z} \iff \lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

Energieaustausch: $mc^2 \frac{d\gamma}{dt} \approx -e \cdot \frac{B_0 \cdot E_0}{\gamma} \sin(\phi_0)$

Aber: ϕ_0 ist eine „zufällige" Phase ⇒ Energie wird nur moduliert!

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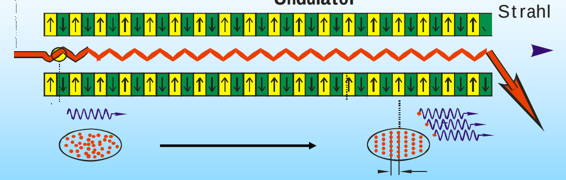
Funktionsweise eines FEL (IV)



Energie Modulation

Dispersion im Magnetfeld
Energiemodulation
⇒ Geschw. Modulation

Bunching
⇒„Phasendichte"-Modulation
⇒ Energieaustausch
⇒ FEL Verstärkung

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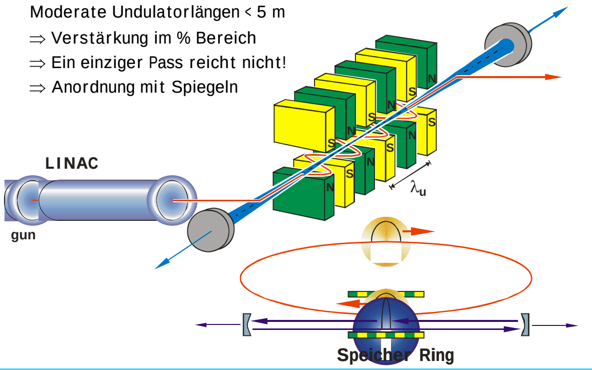
Oszillator FEL

Moderate Undulatorlängen < 5 m
⇒ Verstärkung im % Bereich
⇒ Ein einziger Pass reicht nicht!
⇒ Anordnung mit Spiegeln



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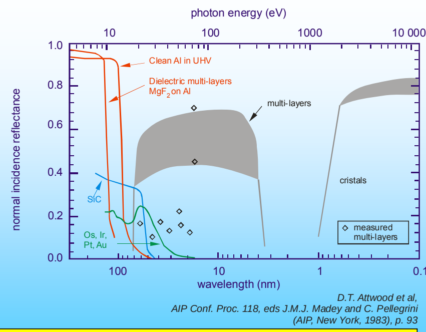
Spiegelproblematik

Wir brauchen:
- etwas ohne Spiegel
- etwas ohne einen Input Laser



D.T. Attwood et al, AIP Conf. Proc. 118, eds J.M.J. Madey and C. Pellegrini (AIP, New York, 1983), p. 93

⇒ Nutze die spontane Synchrotronstrahlung des Undulators
⇒ Verstärke sie in einem einzigen Durchgang
⇒ SASE (Self Amplifying Spontaneous Emission)

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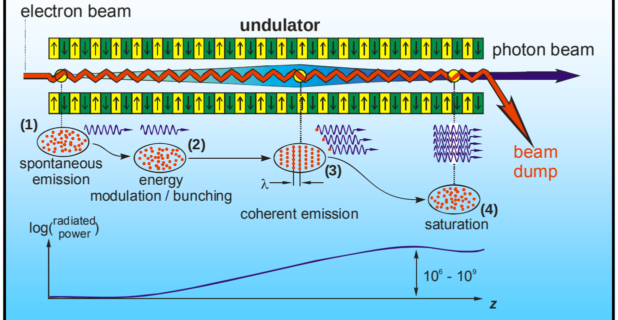
Das SASE FEL Prinzip



Reminder: Movie Zeigen!

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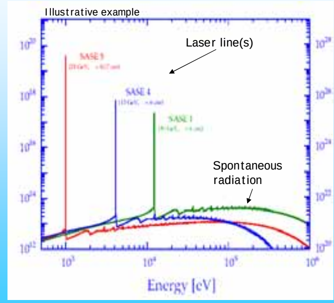
Spectral Characteristics of Radiation



Radiation properties:

- narrow bandwidth
- fully polarized
- transversely coherent

Gain factors:
(compared to 3rd generation sources)

- peak brilliance 10^9 SASE, 10^4 spontaneous
- average brilliance 10^4 SASE
- coherence 10^9 SASE (# photons/mode)

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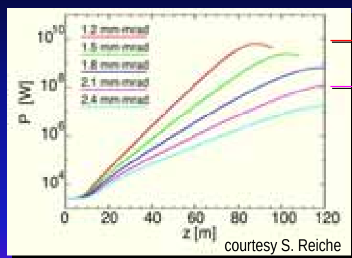
SASE: extreme Anforderungen an den Elektronenstrahl

- Strahlqualität
  - Spitzenstrom (O(kA))
  - Extrem kurze Bunche (O(100fs))
  - Emittanz: $\varepsilon\gamma$ < 2 mm mrad
  - Energiebreite (O(10^{-4}))
- Stabilität
  - Energie bzw. Laserwellenlänge ($\frac{\Delta\lambda}{\lambda} = -2\frac{\Delta E}{E}$)
  - Strahllage (FEL-Prozess, Laserstrahltransport)

Beim LINAC werden die Grundlagen für die Strahlqualität am Anfang gelegt. Danach kann man alles nur noch schlechter machen!

Final Comment (copied from J. Hastings)

For *LCLS*, slice emittance >1.8 μm will not saturate



$\varepsilon_N = 1.2\ \mu m$ → $P = P_0$

$\varepsilon_N = 2.0\ \mu m$ → $P = P_0/100$

Similar of course for XFEL, VUV-FEL, ...

SASE FEL is not forgiving — instead of mild brightness loss, power nearly switches OFF

electron beam *must* meet brightness requirements

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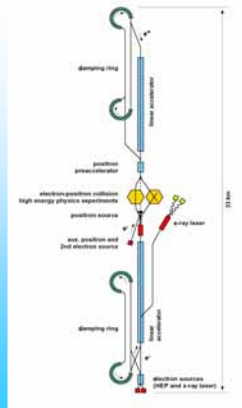

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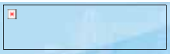
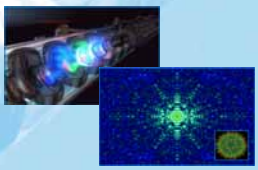


TESLA XFEL

First Stage of the X-Ray Laser Laboratory

Technical Design Report

Supplement



October 2002

TDR update 2002:

Separate **linac for XFEL**

(maintain common site & same s.c. linac technology)

→

- **De-coupling from LC regarding construction & operation (and: *approval*)**
- **Gain in operational flexibility**

Decision by German Government Feb. 2003:

Go ahead with XFEL as European Project, commitment for funding 50% of estimated 684 M€ (year 2000 price basis, *escalation → y2012: 908M€*)

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Superconducting Accelerating Structures for TESLA

Goal during past decade

- Increase gradients from 5 to 25 MV/m
- Reduce costs by a comparable factor

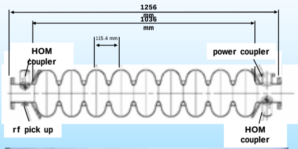
Common effort of almost all laboratories using s.c. accelerating cavities, e.g.

- (CERN), Cornell, DESY, INFN, (KEK), Saclay, TJNL
- 

Improved material quality check

New cavity preparation procedures

- 1400 ºC annealing with a titanium getter
- ultra-pure, high pressure water rinsing
- high peak power processing



One standard 9-cell TESLA accelerating structure operated as a π-mode standing-wave cavity. One 230 kW rf input coupler, an rf pick up antenna and two Higher Order Mode antennas are assembled to each cavity.

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Preparation of TESLA Cavities

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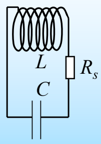
TESLA Cavities

$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

frequency

$$Q_o = \frac{f}{\Delta f} = \frac{G}{R_s}$$

quality factor



Made with solid, pure (RRR >300, high thermal cond.) Niobium

Nb sheets are deep-drawn to make cups (≈100 µm tolerances), which are electron beam welded to form structures.

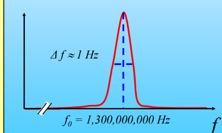
Fill time 420 µs, i.e. $Q_{ext} = Q_{beam} \approx 3 \times 10^6$, $\Delta f \approx 400$ Hz

RF pulse length (400 µs filling + 920 µs flat top) = 1320 µs.

Operated at 2 K in superfluid Helium bath.

RF losses approx. 1 W/m.

RF amplitude and phase adjusted during filling and flat top to compensate beam loading. In steady state **essentially 100% rf input power goes into the beam.**



$Q_0 \approx 10^9 - 10^{10}$

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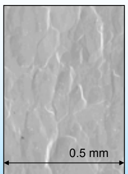
35 MV/m for 800 GeV Option

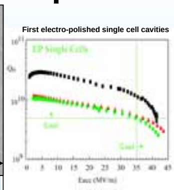


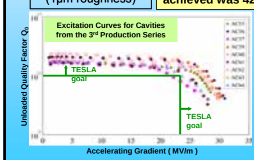
BCP Surface (1µm roughness)

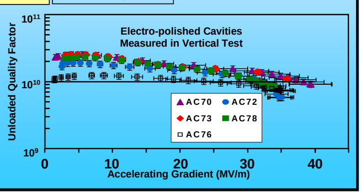
Electro-polishing (EP) instead of the standard chemical polishing (BCP) eliminates grain boundary steps.

Gradients of 40 MV/m at Q values above 10^{10} are now reliably achieved in single cells at KEK, DESY/CERN and TJNAF.
The highest gradient achieved was 42 MV/m.

EP Surface (0.1µm roughness)







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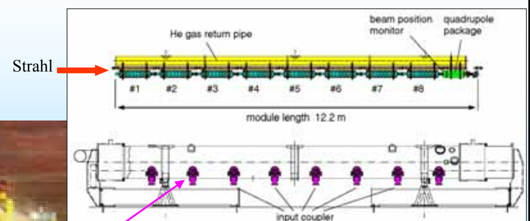
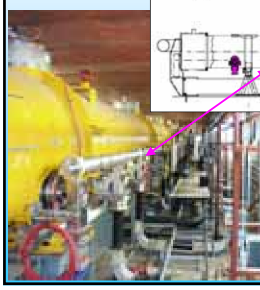
TESLA Module





supraleitende Resonatoren aus Niobium (Temp = 2 K)

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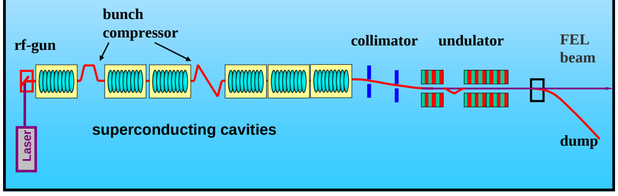
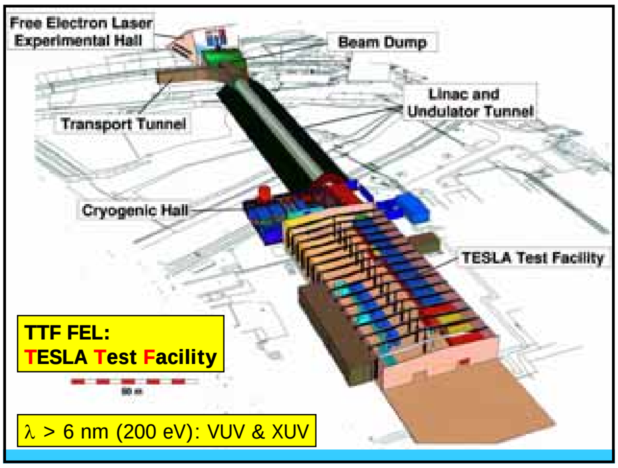
TTF/VUV FEL @DESY:

- Supraleitender 1 GeV LINAC, ca. 260 m lang
- Ladungen zwischen 0.1 and 4 nC
- Normalisierte Emittanz < 2 π mm mrad
- Bunchlängen von ca. ≈ 50-150 µm
- Bis zu 7200 Bunches mit 110 ns Abstand
- 10 Hz Betrieb
- VUV - Soft X-Ray FEL User Facility (bis ≈ 6 nm)





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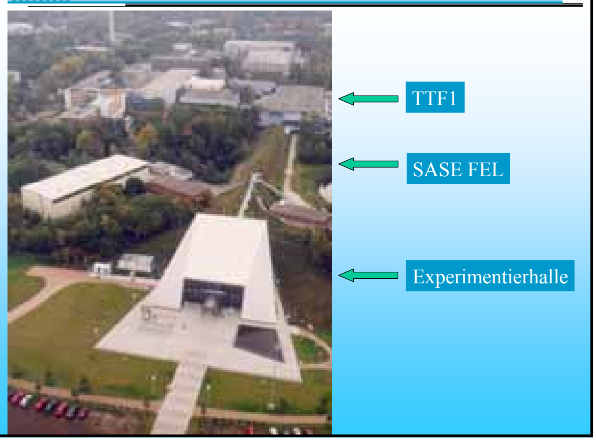

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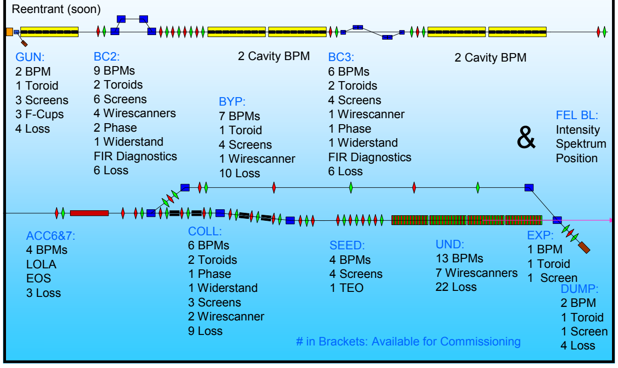
TTF Diagnostic System

TTF has (almost) all, what XFEL needs!
Only the density of devices is much higher!



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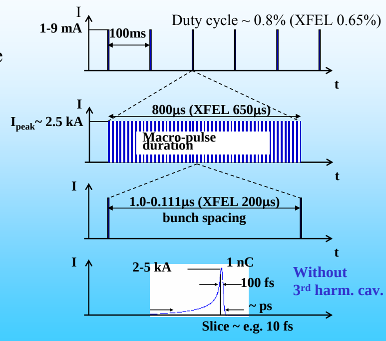
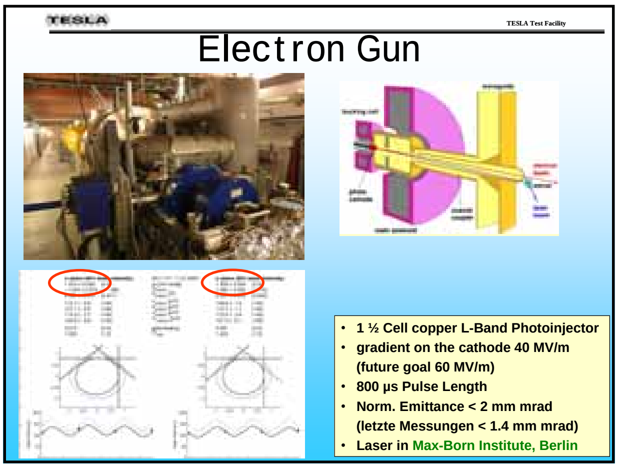
TTF2, XFEL, Superconducting Linac- Time Structure

- Repetition rate
- Macro-pulse
- Bunch
- Slice

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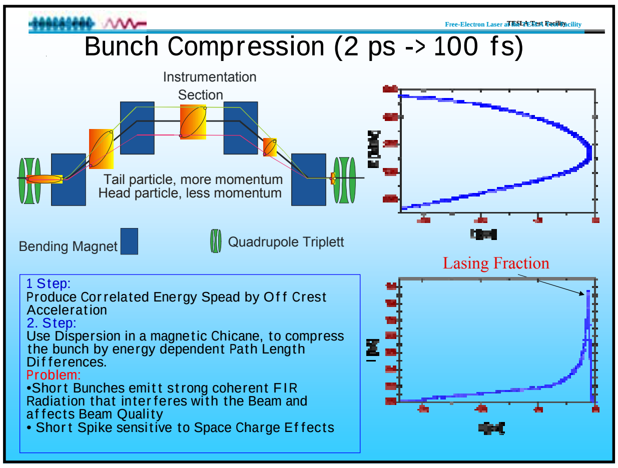
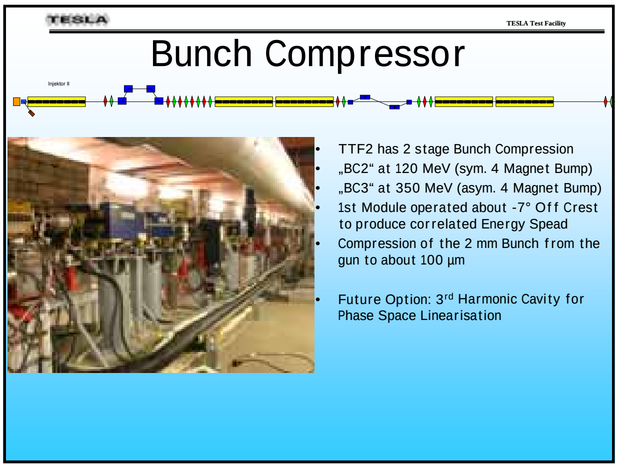
Electron Gun
1 ½ Cell copper L-Band Photoinjector
gradient on the cathode 40 MV/m
(future goal 60 MV/m)
800 µs Pulse Length
Norm. Emittance < 2 mm mrad
(letzte Messungen < 1.4 mm mrad)
Laser in Max-Born Institute, Berlin


Bunch Compression (2 ps -> 100 fs)
Instrumentation
Section
Tail particle, more momentum
Head particle, less momentum
Bending Magnet
Quadrupole Triplett
Lasing Fraction
1 Step:
Produce Correlated Energy Spread by Off Crest Acceleration
2. Step:
Use Dispersion in a magnetic Chicane, to compress the bunch by energy dependent Path Length Differences.
Problem:
•Short Bunches emitt strong coherent FIR Radiation that interferes with the Beam and affects Beam Quality
• Short Spike sensitive to Space Charge Effects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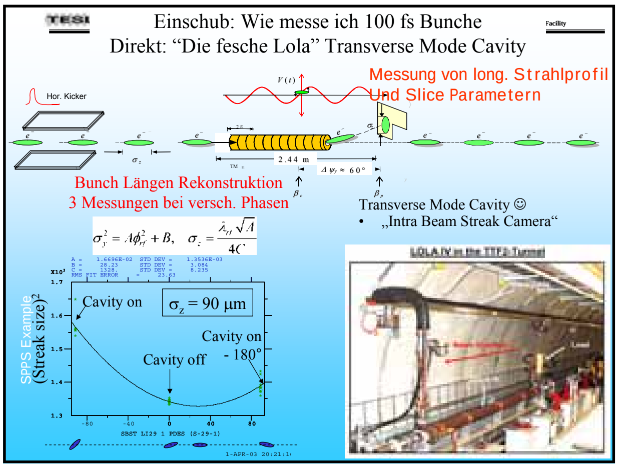
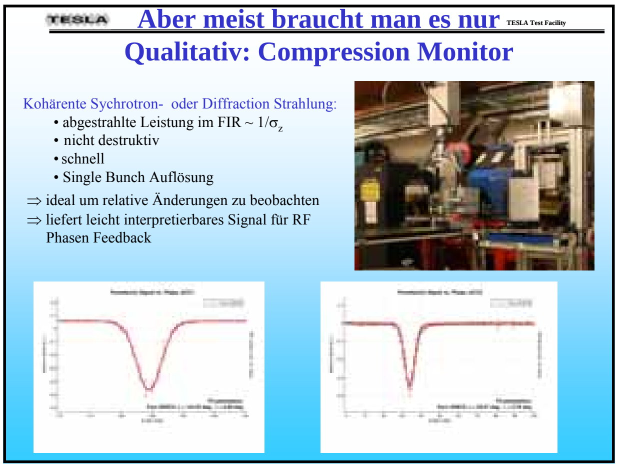
Bunch Compressor
TTF2 has 2 stage Bunch Compression
„BC2“ at 120 MeV (sym. 4 Magnet Bump)
„BC3“ at 350 MeV (asym. 4 Magnet Bump)
1st Module operated about -7° Off Crest to produce correlated Energy Spead
Compression of the 2 mm Bunch from the gun to about 100 µm
Future Option: 3rd Harmonic Cavity for Phase Space Linearisation


Einschub: Wie messe ich 100 fs Bunche
Direkt: “Die fesche Lola” Transverse Mode Cavity
Messung von long. Strahlprofil
Und Slice Parametern
Hor. Kicker
2.44 m
Bunch Längen Rekonstruktion
3 Messungen bei versch. Phasen
Transverse Mode Cavity ☺
„Intra Beam Streak Camera“
$\sigma_y^2 = A\phi_{rf}^2 + B, \quad \sigma_z = \frac{\lambda_{rf}\sqrt{A}}{4C}$
LOLA IV in the TTF2-Tunnel
SPPS Example
(Streak size)²
Cavity on
$\sigma_z = 90$ µm
Cavity on
- 180°
Cavity off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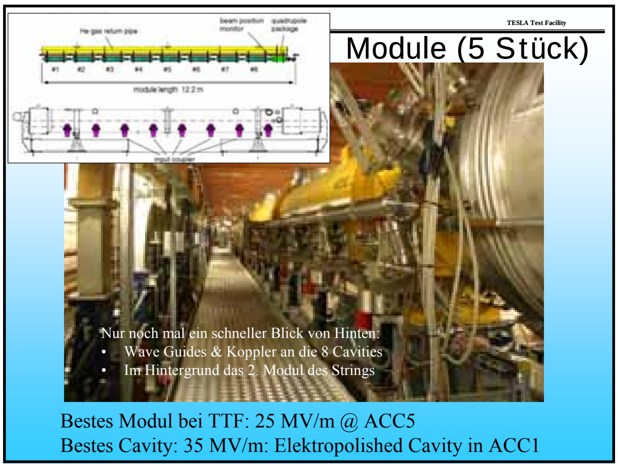
Aber meist braucht man es nur
Qualitativ: Compression Monitor
Kohärente Sychrotron- oder Diffraction Strahlung:
• abgestrahlte Leistung im FIR ~ 1/σz
• nicht destruktiv
• schnell
• Single Bunch Auflösung
⇒ ideal um relative Änderungen zu beobachten
⇒ liefert leicht interpretierbares Signal für RF Phasen Feedback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Module (5 Stück)
module length 12.2 m
input coupler
Nur noch mal ein schneller Blick von Hinten:
• Wave Guides & Koppler an die 8 Cavities
• Im Hintergrund das 2. Modul des Strings
Bestes Modul bei TTF: 25 MV/m @ ACC5
Bestes Cavity: 35 MV/m: Elektropolished Cavity in ACC1

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Kollimator

Warum Kollimatoren?

- Im Linac wird
  - Beam Halo
  - Dunkelstrom der Gun und der Module

  transportiert
- Der Undulator ist sehr empfindlich gegen Strahlungsschäden
  - Bereinigung des Strahls vor dem Undulator
    - Transversal
    - Longitudinal

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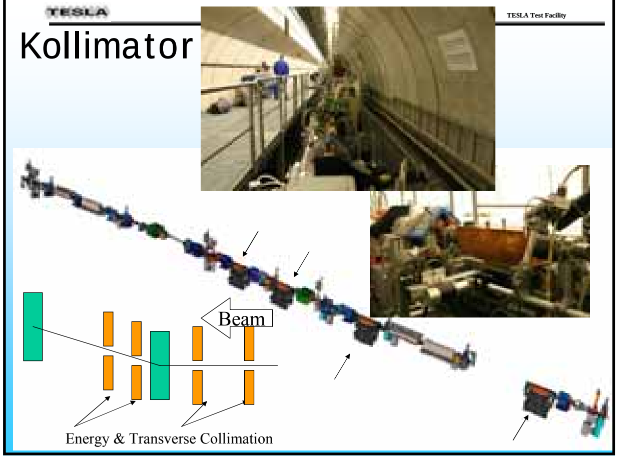
Kollimator



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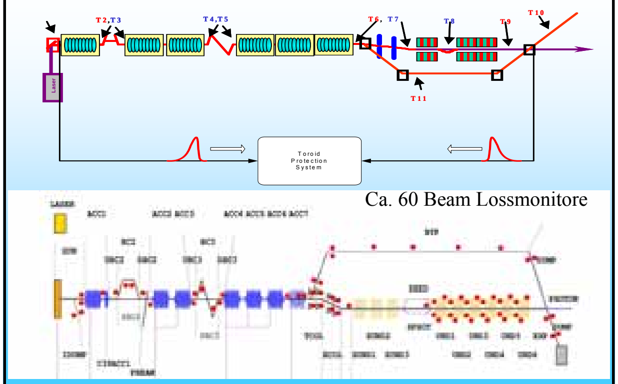
Passive System reichen nicht!



Ca. 60 Beam Lossmonitore

(plus permenente Dosisüberwachung)

Reaktionszeiten ca. 3 µs

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Undulator

- Segmentierter fixed Gap Permanentmagnet Undulator
- 6 Sektionen
- externe Quadrupole in FoDo Lattice
- Gesamtlänge ca. 30 m

- Gap 12 mm (Kammer 10 mm)
- Periodenlänge: 27,3 mm
- K-Wert: 1,22 (Bpeak= 0.4859 T)

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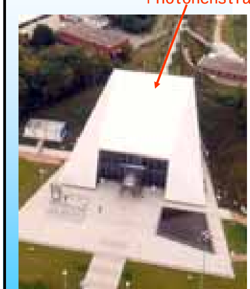
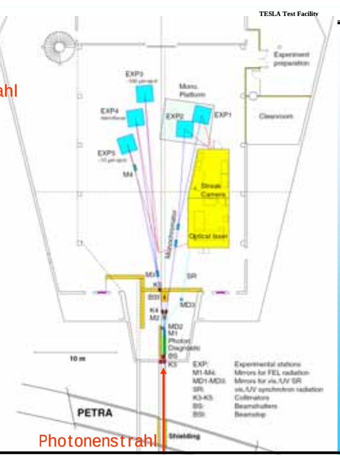
Experimentierhalle

Photonenstrahl





Photonenstrahl

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Überblick:

- Warum das Ganze ?
- Was ist ein Free-Electron-Laser?
- Supraleitenden Beschleunigertechnologie @ DESY
- TTF/VUV-FEL
- **The European X-FEL Project**
- Recent Results

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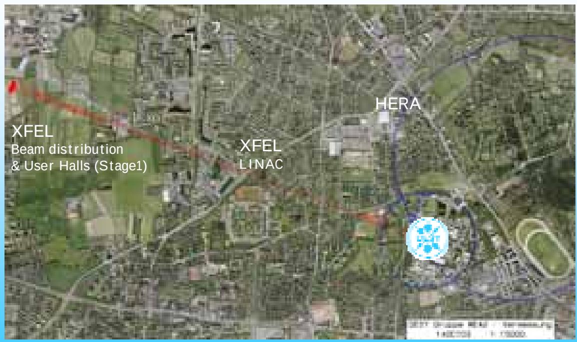
Planned XFEL Site



Planned XFEL Site

- Use existing infrastructure on DESY site
- Acc subsystems (injector, cryogenics, modulators,…) on DESY site
- Linac tunnel 15 – 30m deep in underground of urban area
- User facility in rural area, place for possible extension
- Legal procedure for construction *(Planfeststellung)* in preparation → permission by end of 2005

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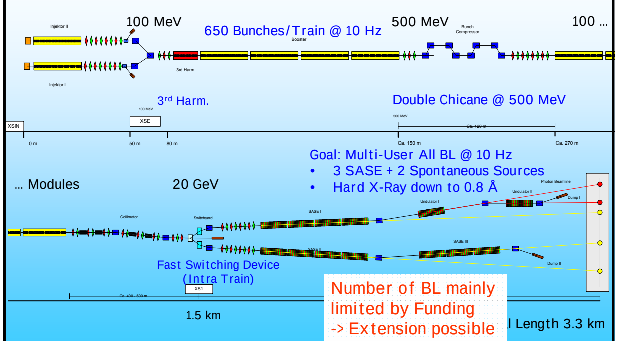
European X-FEL Project

Based on TESLA Technology; Build in European Collaboration @DESY



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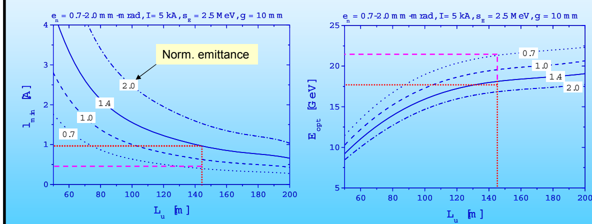
Parameter considerations - Choice of beam energy

Conservative assumption on slice energy spread: 2.5 MeV *(expect ~1MeV including incoherent SR)*



→ 17.5 GeV for 1Å

Improved Emittance: 25 GeV for 0.5 Å

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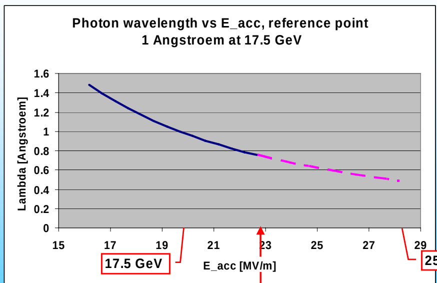
Wavelength vs. acc gradient



Nominal linac energy 20 GeV, includes ^{57}Fe line @ 0.8Å

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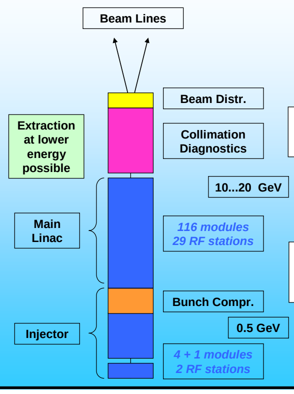
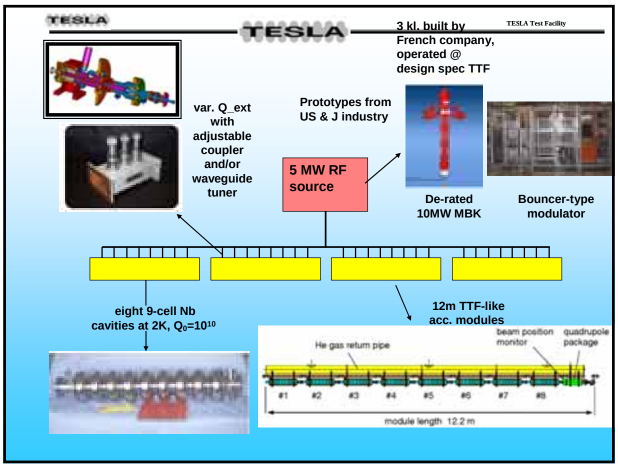
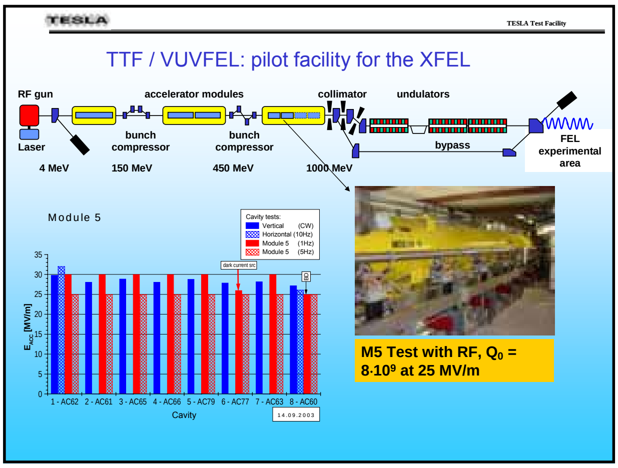
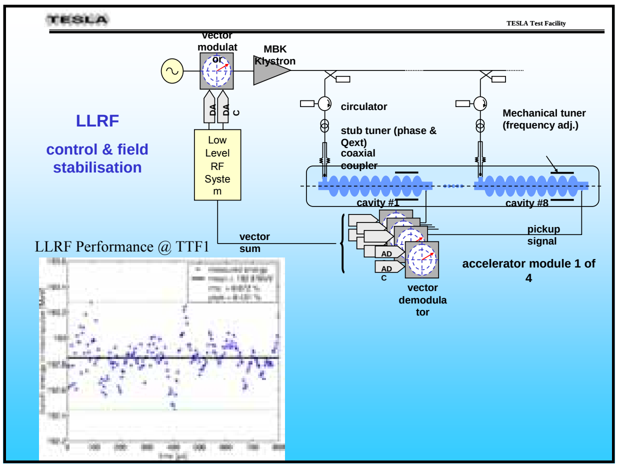
Basic Accelerator Layout



Main linac	
Beam energy	20 GeV
acc gradient	22.9 MV/m
Bunch spacing	200 ns
beam current	5 mA
power→beam p. klystron	3.8 MW
incl. 10% + 15% overhead	4.8 MW
matched Q_{ext}	$4.6 \cdot 10^6$
RF pulse	1.37 ms
Beam pulse	0.65 ms
# bunches p. pulse	3250
Rep. rate	10 Hz
Av. Beam power	650 kW







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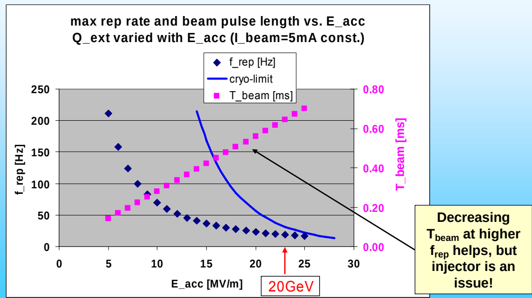
Operational flexibility – duty cycle



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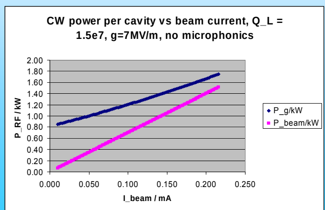
Sketch of possible future CW operation mode

If Å FEL radiation at lower beam energy comes in reach (better injector/beam quality, advanced FEL concepts, …) → high duty cycle, up to CW, can become an attractive option

Linac layout & cryogenics consistent with this option (at E_{acc} = 7…8 MV/m), different RF system has to be added

Maintain good RF → beam efficiency with moderate over-coupling (87 Hz bandwidth, expect <10 Hz rms microphonics)



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Sketch of future CW operation mode cont'd

Beam energy [GeV]	6.5
Acc gradient [MV/m]	7
Beam current$ [mA]	0.18
Bunch spacing [µs]	5.5
RF power / module [kW] (incl. overhead)	~20
Dynamic cryo load 2K [kW]	~2.4

$: total beam power of 1.2 MW sufficient to operate simultaneously 4 undulator beam lines at beam dump limit of 300kW

If user demand for very high average power, ERL option is conceivable

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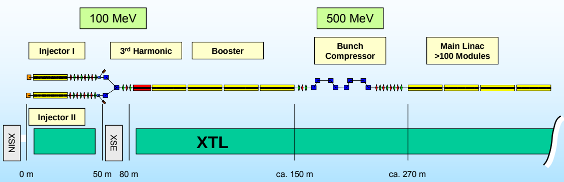
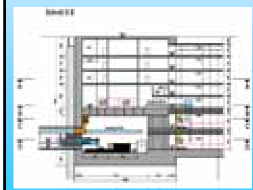
Injector & bunch compressor





Start-to-end beam simulations:

ASTRA (DESY) - space charge dominated e-beams
TraFiC4/CSRtrack(DESY) - self-consistent CSR effects
MAFIA (TUD/CST) - general e.m. field solver for wakefields etc.
elegant (Argonne Natl. Lab.) - e-beam tracking with wakefields
GENESIS1.3 (DESY) - 3D SASE FEL code
FAST (DESY/JINR) - fast SASE FEL code for parameter optimization

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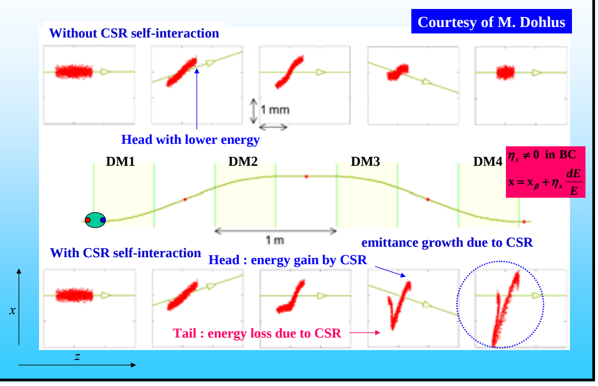
Coherent Synchrotron Radiation (CSR) in BC



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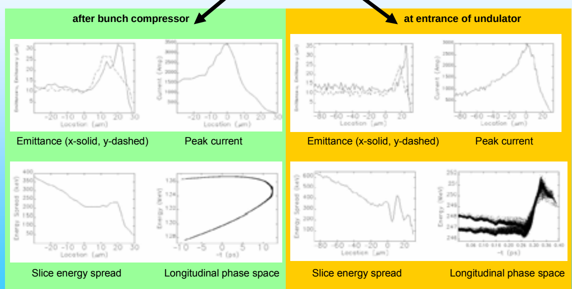
Example of start-to-end analysis: TTF1 FEL



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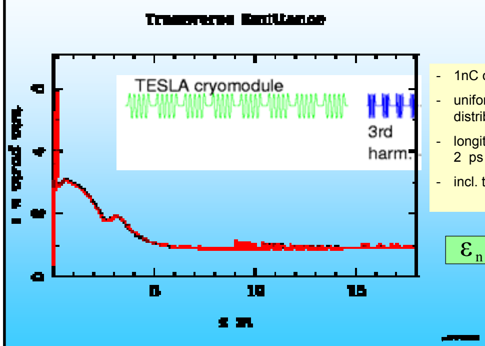
Emittance from photocathode RF gun injector



- 1nC charge
- uniform transverse distribution
- longitudinal flat-top with 2 ps rise time
- incl. thermal emittance

$\varepsilon_n = 0.9\ \mu m$

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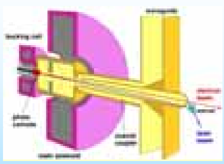
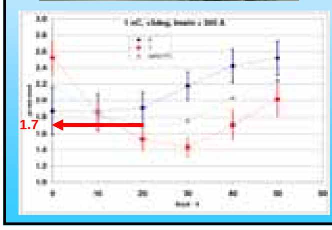
RF gun development at PITZ, DESY-Zeuthen





On-going programme:

- increase the gradient on the cathode from 40 MV/m to 60 MV/m
- further improve the transverse and longitudinal laser profile (collab. Max-Born Institute, Berlin)
- PITZ gun now part of TTF-II/VUVFEL injector (commissioning started, not yet flat long. laser profile)

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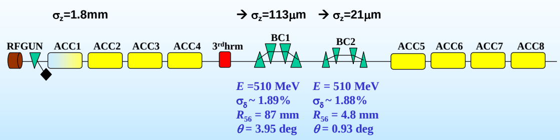
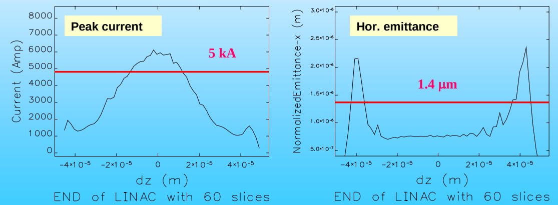
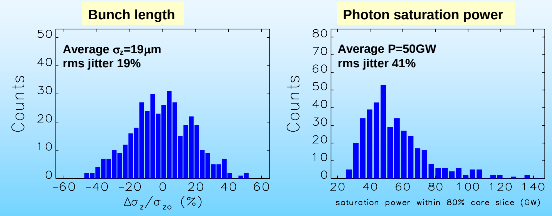
Bunch compressor – single stage/double chicane





Estimate of beam jitter at undulator – challenging stabilization issues

Model calculation: RF phase/amplitude jitter 0.05°/0.02%, laser timing 0.1ps,…

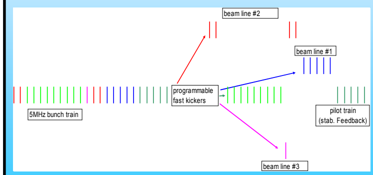


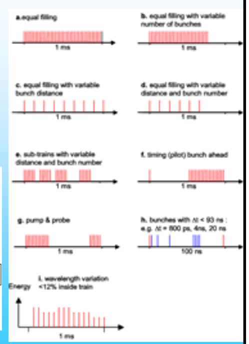
Possibility of intra-pulse RF feedback with SRF helpful

Advantage of 2nd stage compressor at higher energy under study
→ reduction of space charge effects in diagnostics section downstream, additional room for parameter optimization

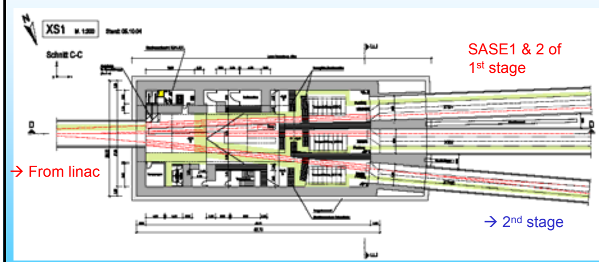
Bunch patterns / beam distribution

Generation of bunch train patterns:
- At the source
  varying transient effects in the entire accelerator (handled e.g. by the LLRF system)
- At the beam delivery / distribution system
  more challenging kicker devices





included in the detailed layout: Kicker/septum concept, extension for 2nd stage ***and*** accessability of tunnels for installation etc., while others are in operation with beam



The European XFEL

- **The 20 GeV s.c. linac based on the technology developed by the TESLA collaboration and successfully demonstrated at TTF is an ideal driver for the Free Electron Laser facility, offering a broad range of operating parameters in its baseline design and with future upgrade options.**
- **With the R&D work towards industrial production of major components, the preparations for the site at DESY and the European project organisation under way, we should be ready to go into construction phase in mid – end 2006.**

Überblick:

- Warum das Ganze ?
- Was ist ein Free-Electron-Laser?
- Supraleitenden Beschleunigertechnologie @ DESY
- TTF/VUV-FEL
- The European X-FEL Project
- Recent Results

Recent Results from TTF

- Oktober 2004: Start des Commissioning
- Vor Weihnachten: Erster Strahl durch den Undulator
- 2KW 2005: Start aus der Weihnachtspause
- 14.01.2005: First Lasing bei 32 nm
- Seitdem: Optimierung des SASE Signals
- Frühjahr 2005: Erste User Experimente

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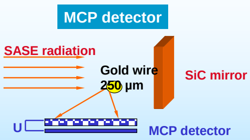
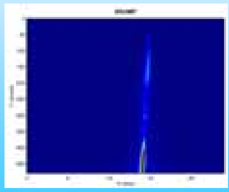
SASE Detection: MCP Detektor





- Messung des SASE Signal
- Strahlung wird an einem dünnen Golddraht gestreut.
- Die Streustrahlung fällt auf einen MCP Detektor, erzeugt Photoelektronen die verstärkt werden.
- Detektor nutzbar für Intensitäten von der Spontanen Strahlung bis zur Sättigung

Fragmentierung auf dem Dump Screen: SASE ist Nahe!

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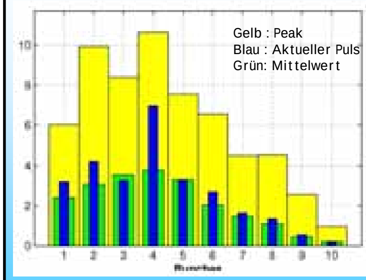
SASE Statistics

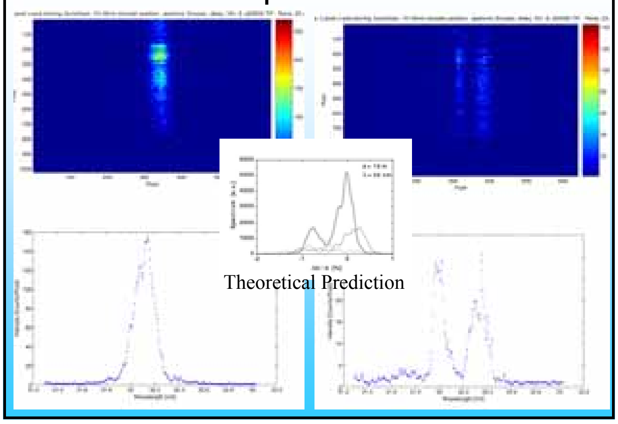


Pulsenergien:

Peak	:	10 µJ
Mittel	:	5 µJ
PeakPower	:	O(1 GW)
Verstärkung	:	10^5
Strahlenergie:		450 MeV
Wellenlänge	:	32 nm
Pulslänge	:	10-20 fs

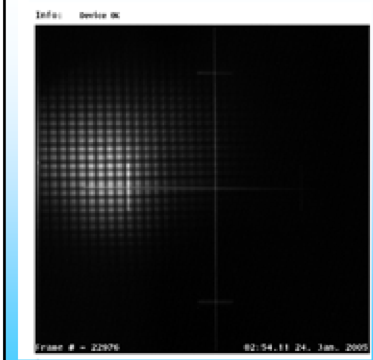
SASE ist ein statistischer Prozess
40% Fluktuationen sind theoretisch vorhergesagt
Alle Messungen in Übereinstimmung zur theoretischen Erwartung!

Spectrum



Theoretical Prediction

Strahlgrösse



FEL Spot auf einem Floureszenskristall

Strukturen: Schatten des MCP Meshes (250 µm)

Spotsize ca. 3 mm, konform zur Theorie

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Danke,
für das Interesse und die Aufmerksamkeit.

Dank auch den vielen Kollegen, die mir Grafiken und Folien zur Verfügung gestellt haben!