BESSY

Berliner Elektronenspeicherring-Gesellschaft
für Synchrotronstrahlung m.b.H.

Review of SRF Linac-Based FELs

(Current and Future)

J. Knobloch, BESSY

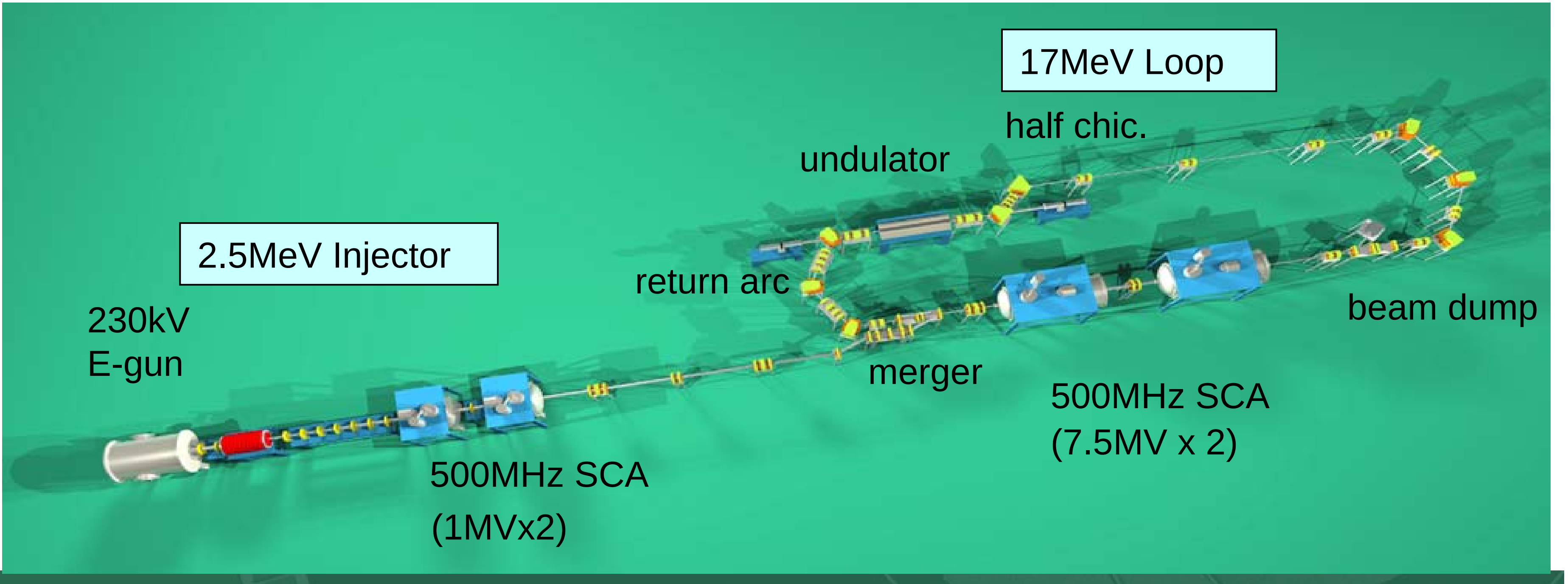
Leibniz
Gemeinschaft

Some existing superconducting FELs

	Frequency (MHz)	Energy (MeV)	Current (mA)	Emittance (mm mrad)	Wavelength (µm)	Type
JAEA-FEL Japan	**500**	**17**	**5.2-40 (pulsed)**	**40**	**22**	**FEL, ERL**
JLAB-FEL USA	**1500**	**120**	**5-10**	**7**	**1-6 + UV(soon)**	**FEL, ERL**
ELBE Germany	**1300**	**12-40**	**1 mA**	**20**	**2-10**	**FEL**
S-DALINAC Germany	**3000**	**130**	**0.06**		**2.5-7**	**FEL, ERL**
SCA, USA	**1300**	**40-50**	**0.15**		**1-2**	**FEL,ERL**
PKU FEL (under constr.)	**1300**	**30**	**1-5**	**< 20**	**5-10**	**FEL**
FLASH Germany	**1300**	**1000**	**mA (pulsed)**	**3 (?)**	**> 6.5 nm so far**	**SASE-FEL**

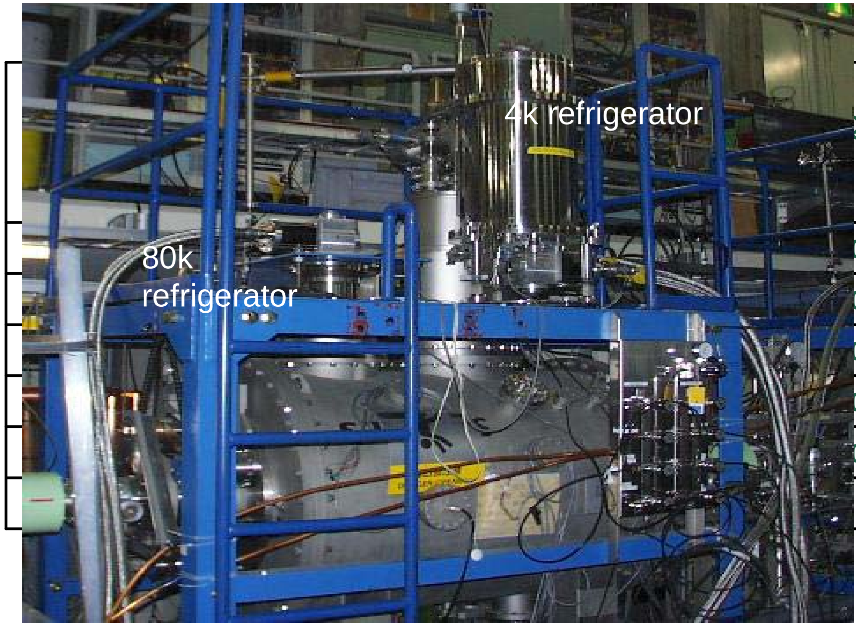
JAEA FEL

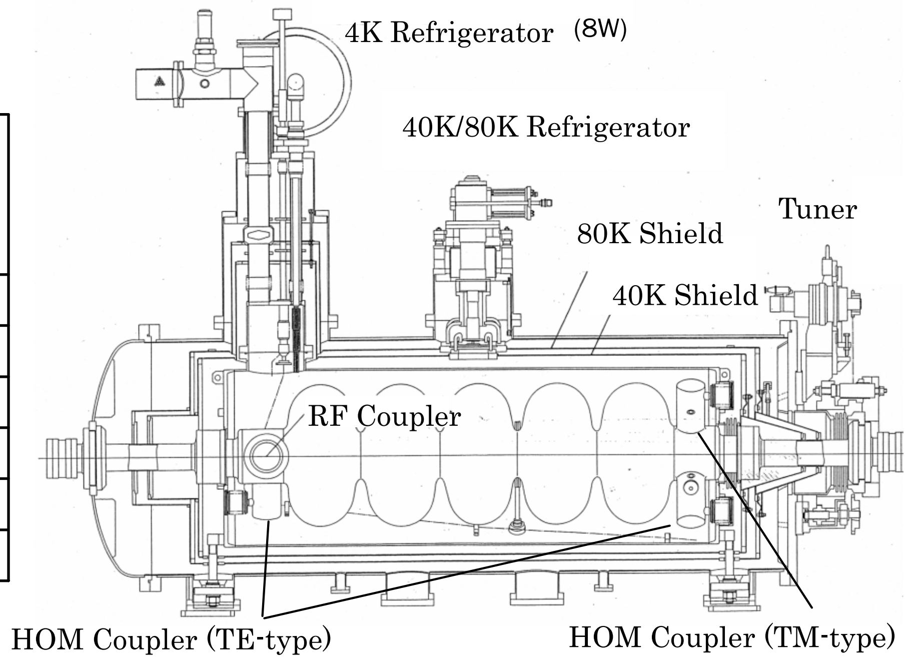
- **Demonstrator IR FEL for industrial material treatment (e.g., against stress corrosion cracking)**
- **Configuration in 2001**
  - Pulsed operation: 1% DF (10 Hz x 1 ms x 10.4 MHz) due to available cryopower & radiation shielding
- **Upgrade JAEA in 2002 for ERL mode**
- **Increased microbunch rep rate to 20.8 MHz (8 mA) + 50 kW IOTs for injector**
- **→FEL efficiency increased to 2.8 %**
- **Beam power = 136 kW → 700 W FEL power (including extraction efficiency)**



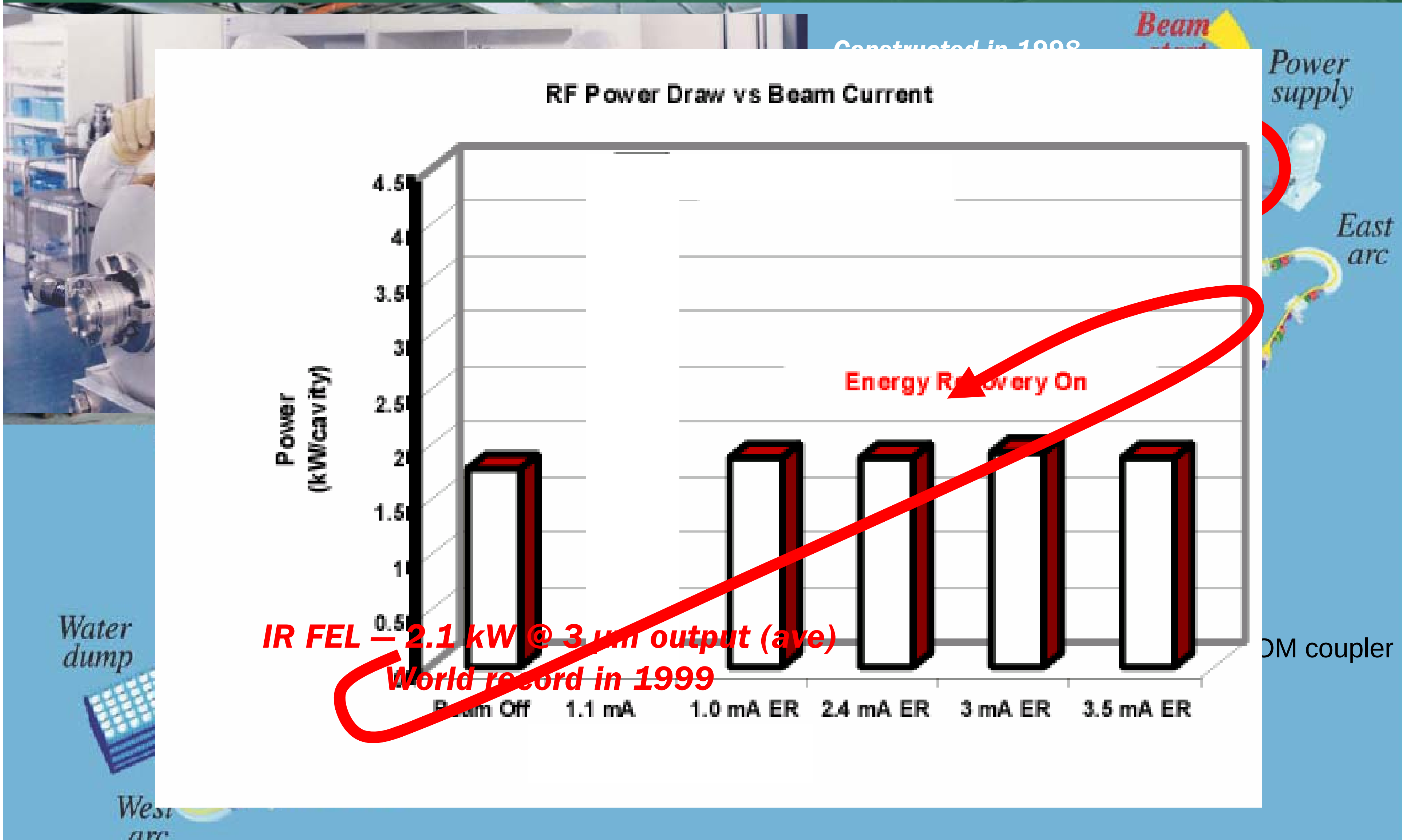
Superconducting Cavities for JAEA-FEL

- Superconducting 500 MHz system operating at 4.2 K
- E_{acc} = 5 MV/m
- Refrigerator is part of the cryostat: Q_0 = 2E9 → CW losses of order 100 Watt
- Variable input coupling, from 10^9 to 10^6 ← CW ERL operation theoretically possible
- Three HOM couplers
- HOM Measurements/calculations + BBU simulations → BBU limit at about 3 A





JLAB IR FEL Demonstrator



G. Neil et al., Jefferson Lab

JLAB ERL-FEL Upgrade

- Facility available for user experiments
- IR, TH
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- Increa
- Beam „man

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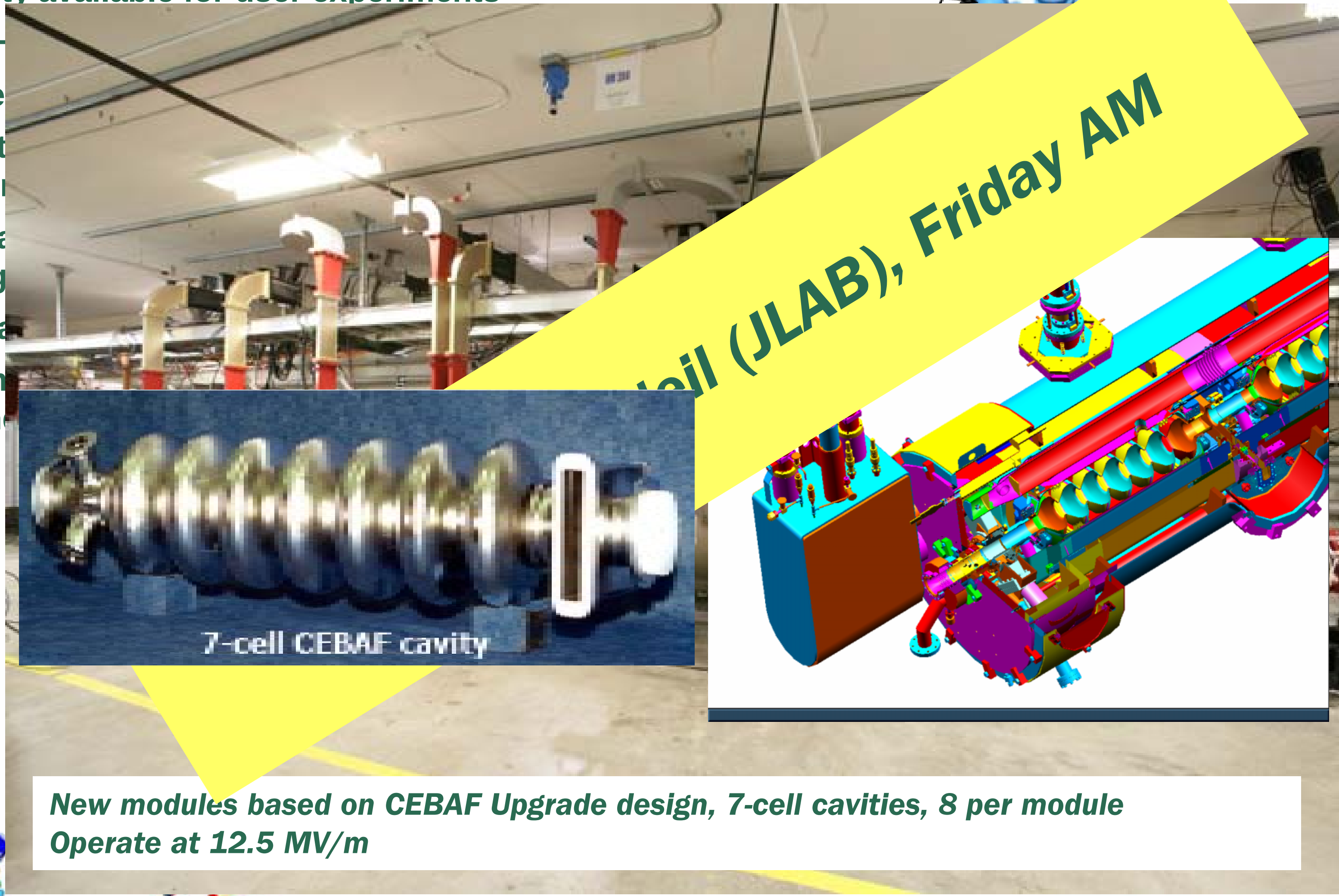
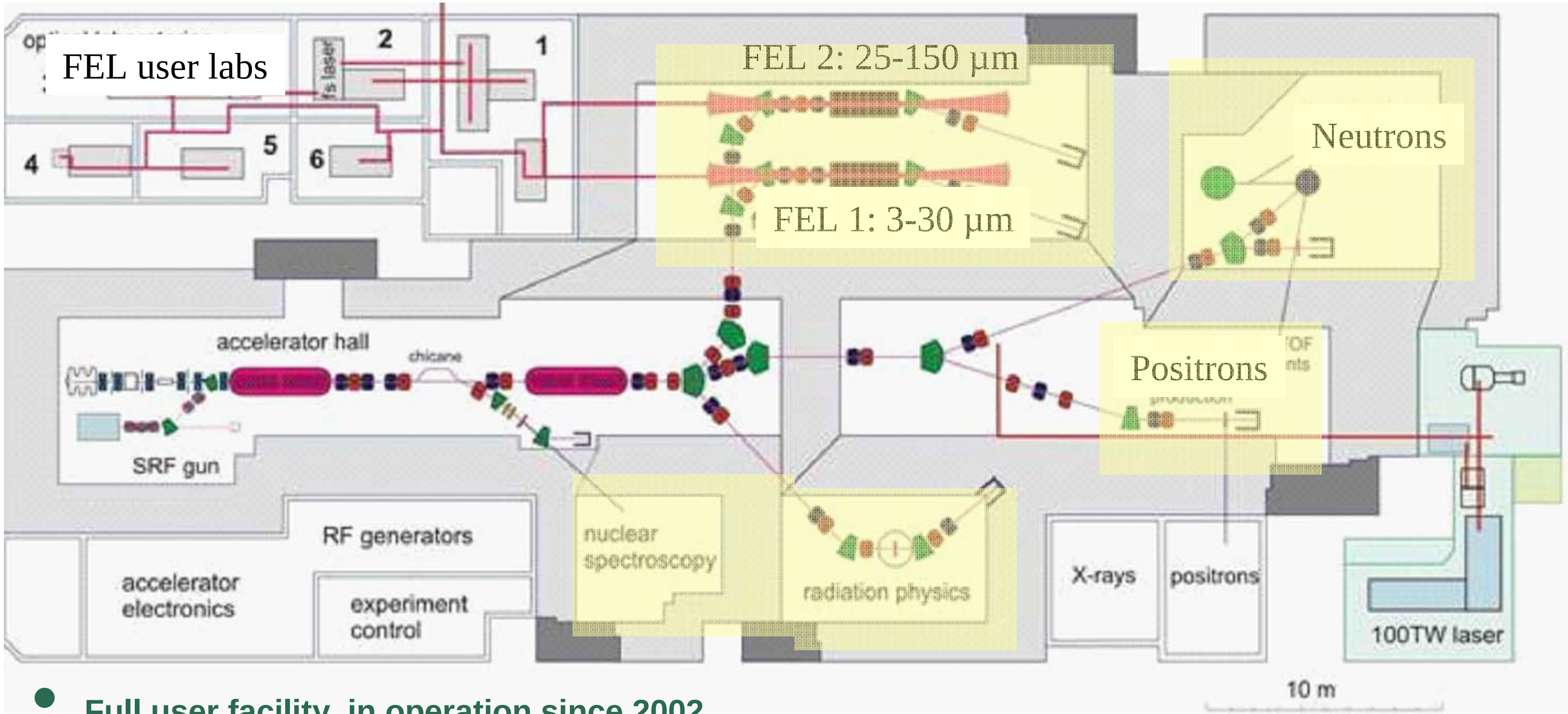
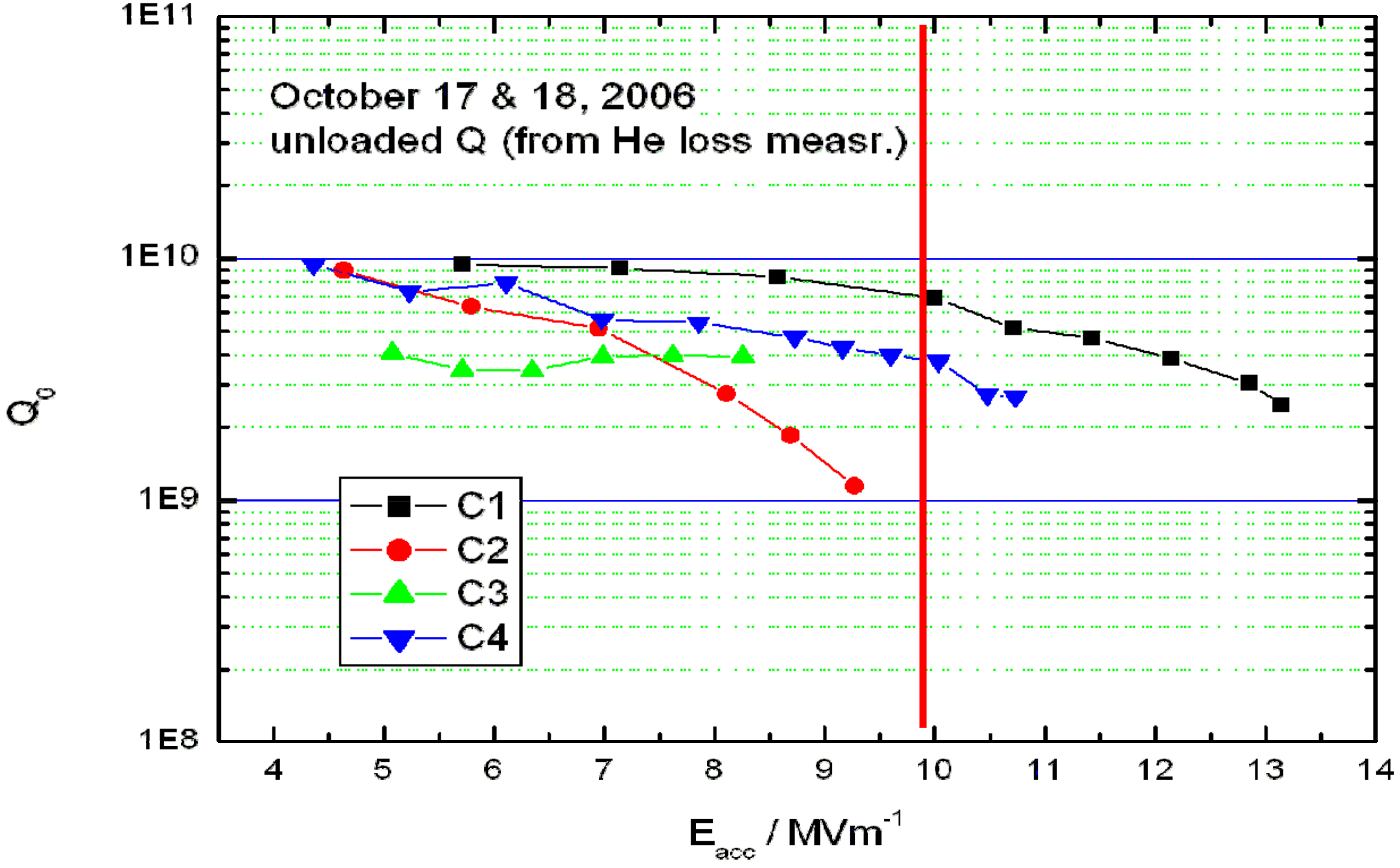


New modules based on CEBAF Upgrade design, 7-cell cavities, 8 per module
Operate at 12.5 MV/m

ELBE @ Forschungszentrum Dresden-Rossendorf



- Full user facility, in operation since 2002
- Operates two FELs in the IR
- Also provide different beams for neutron production, positron production, bremstrahlung and x-radiation.
- For latter need ultra-low emittance beam


October 17 & 18, 2006
unloaded Q (from He loss measr.)
1E11
1E10
1E9
1E8
Q0
4
5
6
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8
9
10
11
12
13
14
Eacc / MVm-1
C1
C2
C3
C4

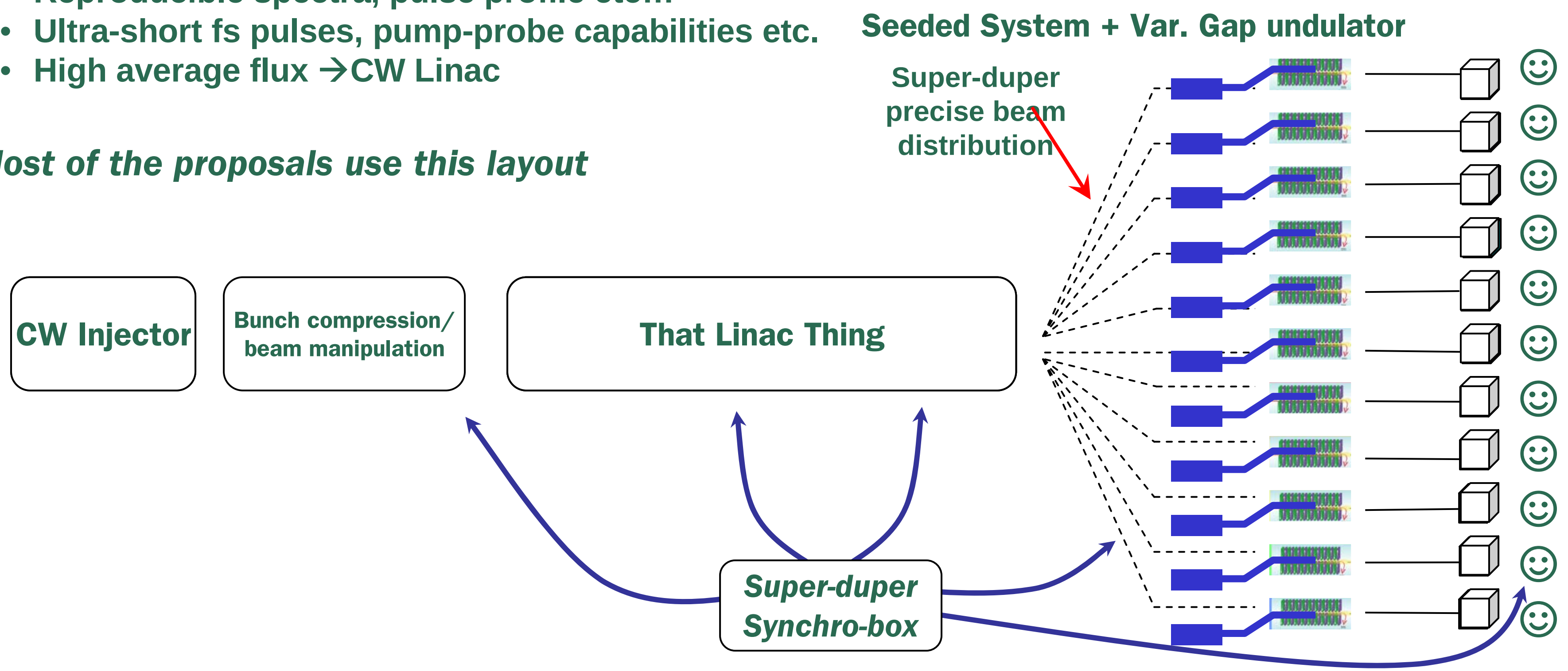
	Frequency (MHz)	Energy (GeV)	Current (mA)	Emittance (mm mrad)	Wavelength	Type
European XFEL Germany	**1300**	**20**	**1-1** **Being Built**		**X ray**	**SASE-FEL**
4GLS UK	**1300 (?)**	**0.6**	**100**	**2 @ 1 nC**	**VUV, Soft X ray**	**ERL, FEL**
BESSY FEL/STARS Germany	**1300**	**2.3**	**0.075**	**1.5 (slice) @ 2.5 nC/1 nC**	**VUV, Soft X ray**	**FEL**
Arc-en-Ciel, France	**1300**	**3**	**1-100**	**1.2 @ 1 nC**	**VUV, Soft X ray**	**ERL, FEL**
Wisconsin FEL, USA	**1300**	**2.2**	**1**	**<1 @ 0.2 pC**	**VUV, Soft X ray**	**FEL**
FLS, LBNL USA	**1500 (1300?)**	**2.5**	**?**	**?**	**VUV, X ray**	**FEL**
POLFEL Poland	**1300**	**0.6**	**White paper**	**C**	**UV**	**SASE-FEL**

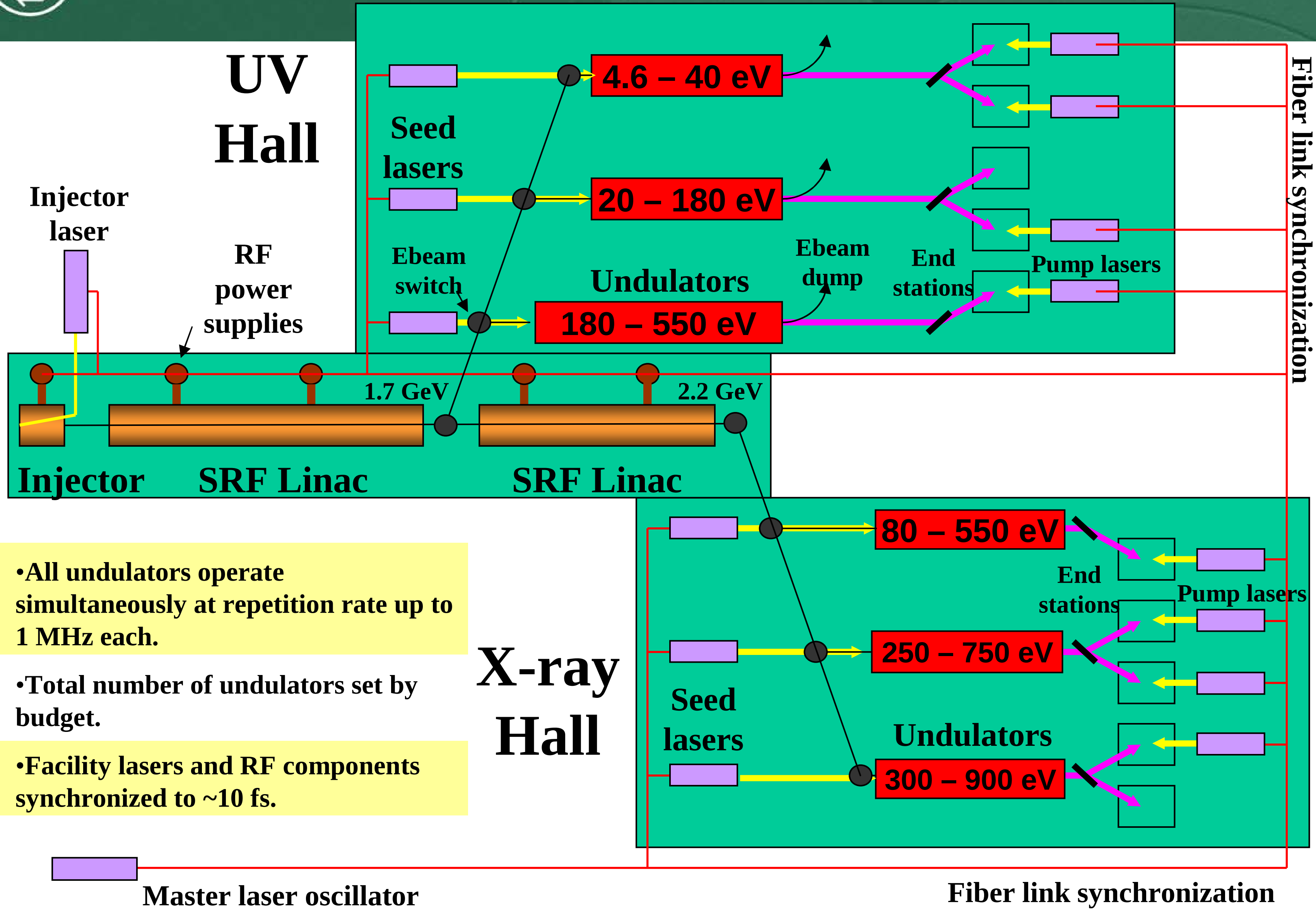
VUV-Soft X-ray FELs: The „egg-laying full-milk woolly sows“

What do these FELs have in common? The are designed to do everything!

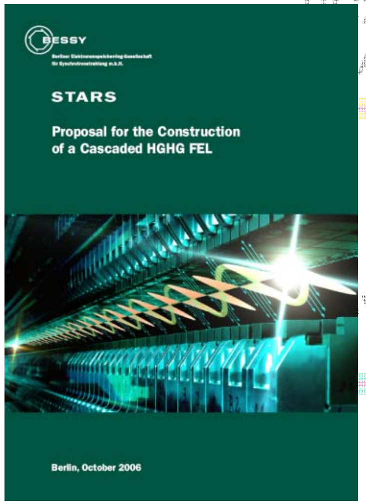
- Many users
- Resonable cost
- Cover UV to X ray range
- Independent control of wavelength
- Independent control of pulse duration, polarization
- Reproducible spectra, pulse profile etc…
- Ultra-short fs pulses, pump-probe capabilities etc.
- High average flux →CW Linac

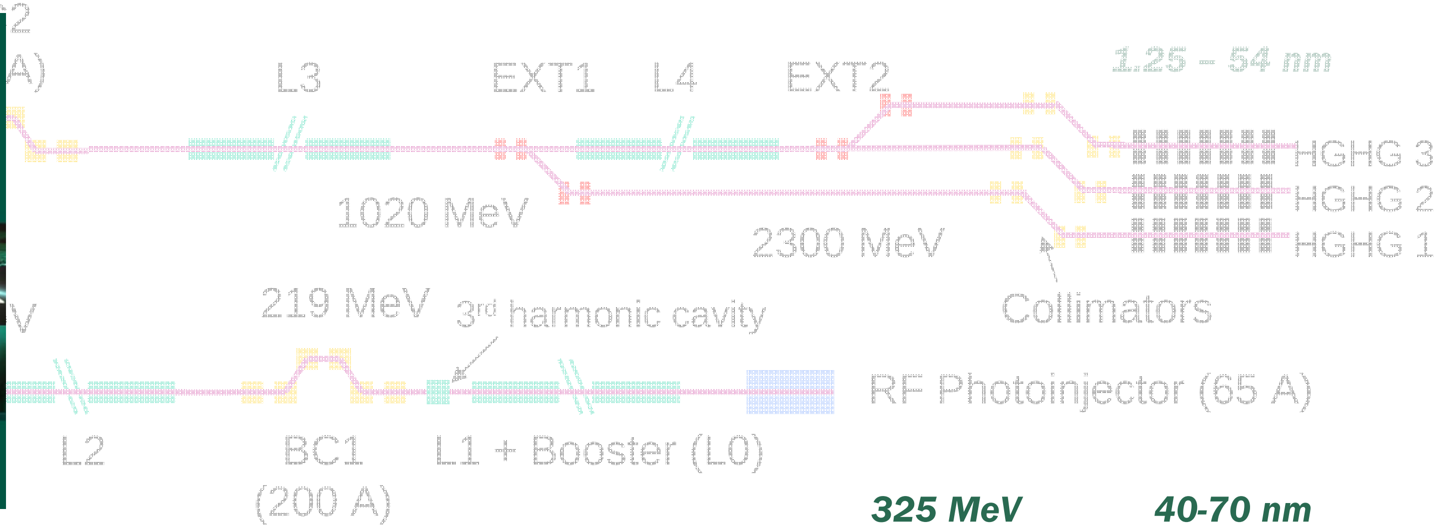
Most of the proposals use this layout

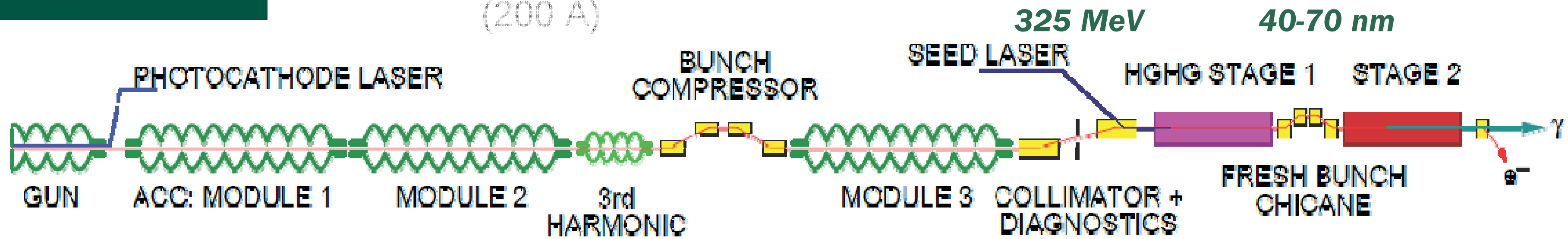




- All undulators operate simultaneously at repetition rate up to 1 MHz each.
- Total number of undulators set by budget.
- Facility lasers and RF components synchronized to ~10 fs.







- **Technical design report completed in 2004**
- **Evaluated by the German Science Council 2006**
  - Recommendation: Realize BESSY FEL under condition that cascaded HGHG be demonstrated
- **2006: Development of an HGHG demonstrator (STARS)**

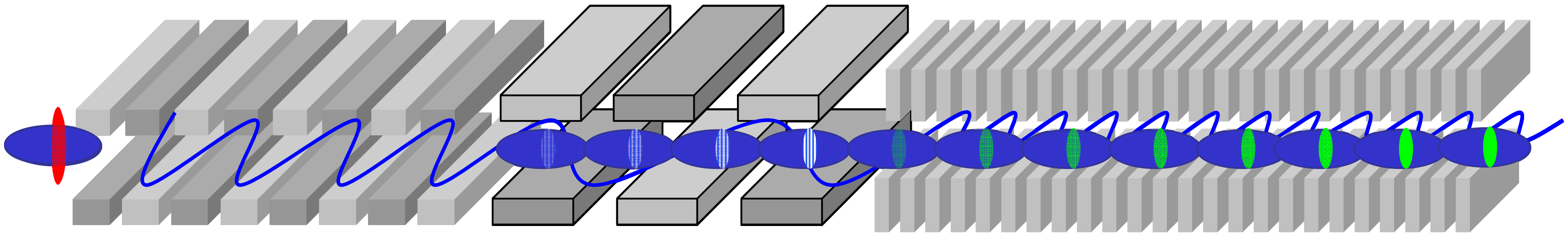
- For UV/X ray lasers cannot use „optical cavity“
- → Seed machines and use relatively long undulators for single-pass amplification
- Seed lasers at the desired wavelength do not exist

  → must „upconvert“

High-Gain-Harmonic Generation (HGHG)

High-Brilliance electron beam (Emittance < 2 μm)

Very short pulse seed laser (< 100 fs), e.g. Ti:Sa or HHG Laser



External seed, ω_0 overlaps the bunch and modulates the energy

Chicane converts the energy modulation into a spatial bunching

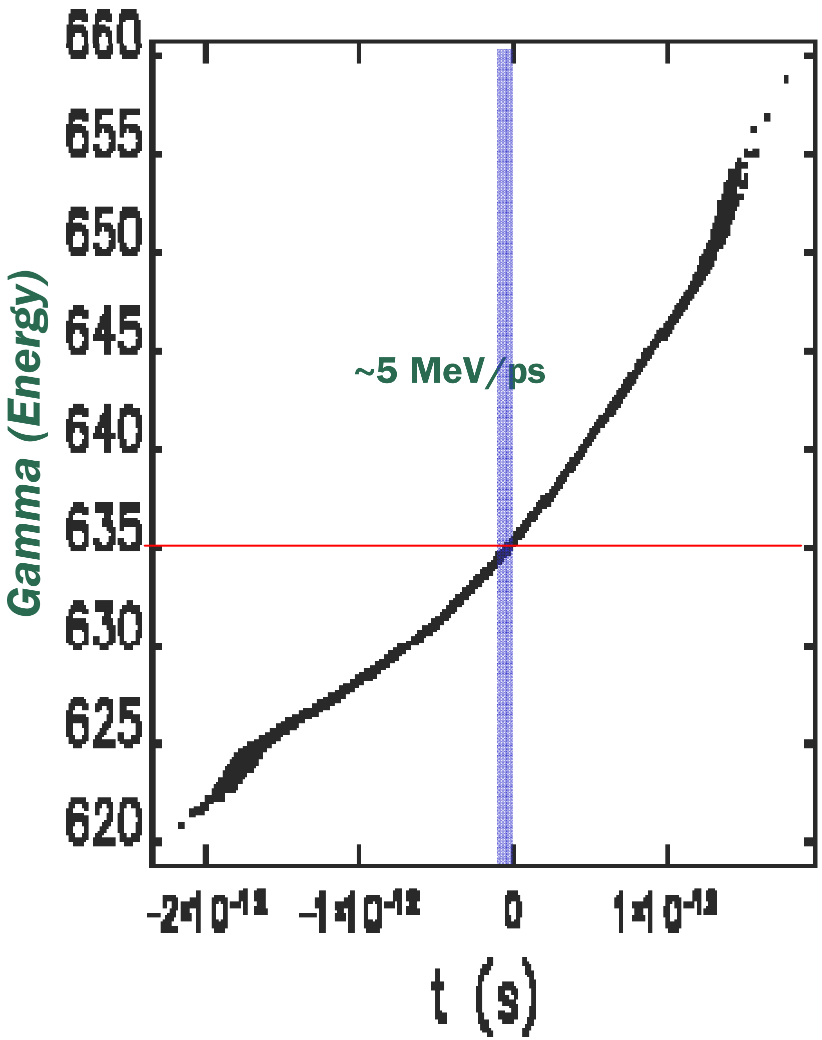
Modulated part of the bunch radiates coherently at a harmonic of the seed laser
Limited to about $n \leq 5$.

Developed by L.-H. Yu et al, Brookhaven

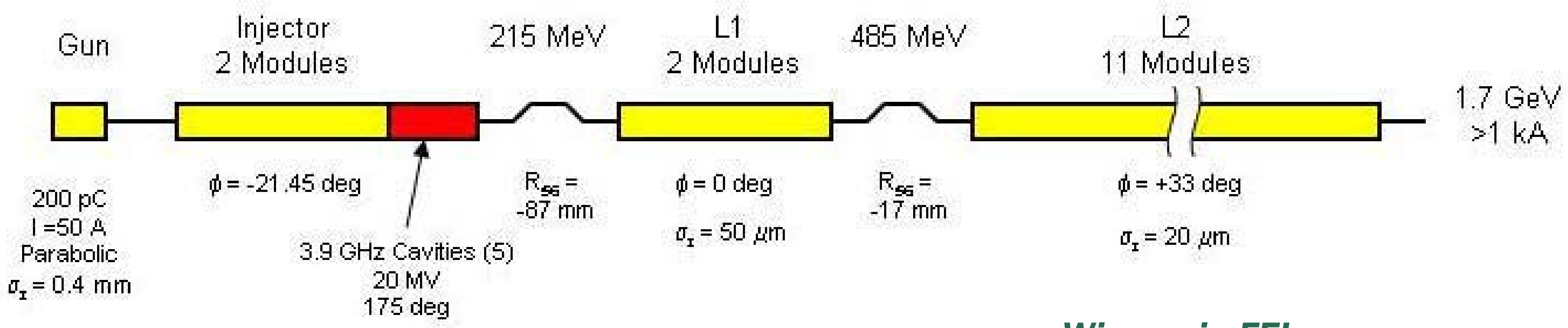
- **Key advantage of seeding: Output-pulse properties determined by seed laser not the electron bunch!**
  - →Spectrum and pulse shape is reproducible (not so with SASE)
  - → Each beamline can be seeded differently = Flexibility!

- **But seeding is challenging!**
  - Very precise beam timing (and position) control is needed, because of chirped beam (< 100fs)
  - Beam „quality" must be constant along the bunch.

- **→ FEL Output critically depends on the performance of the SRF linac**
- **Need a low emittance injector**
- **Need third harmonic cavities to linearize RF**
- **Need very precise RF controls of the cavities**
  - Order 0.02 deg, 0.02%
- **Need very precise timing distribution system**



Linac for VUV-Soft X-ray FELs

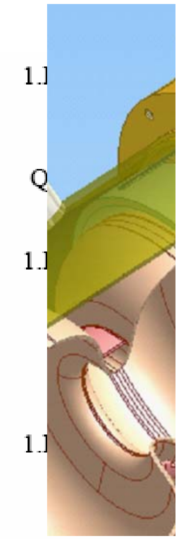


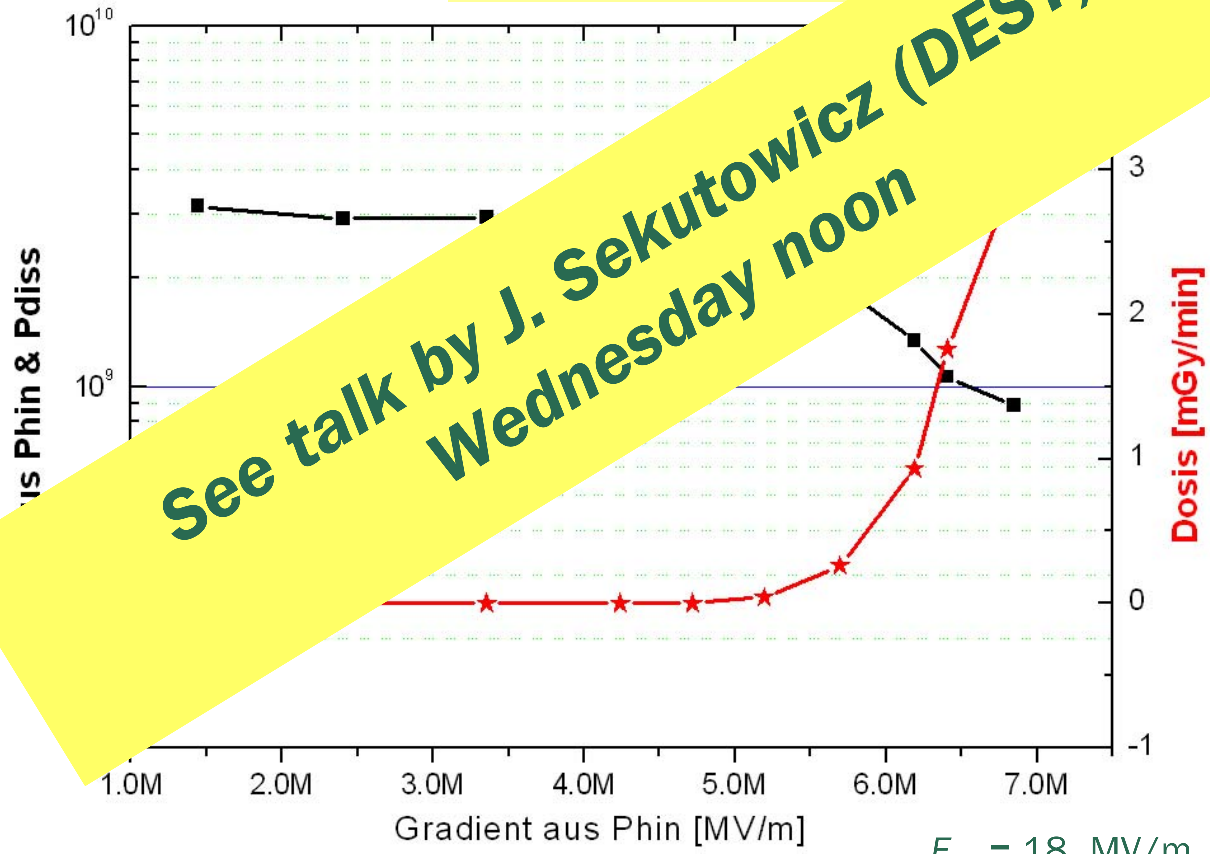
Wisconsin FEL
J. Bisognano, PAC07

- **Development of CW capable low emittance injectors a high priority**
- **SR**
- **Ro**
- **Bu**

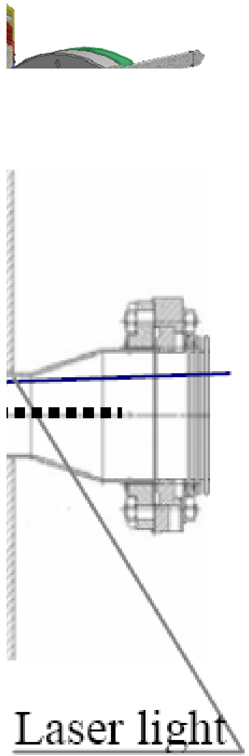
Results from la

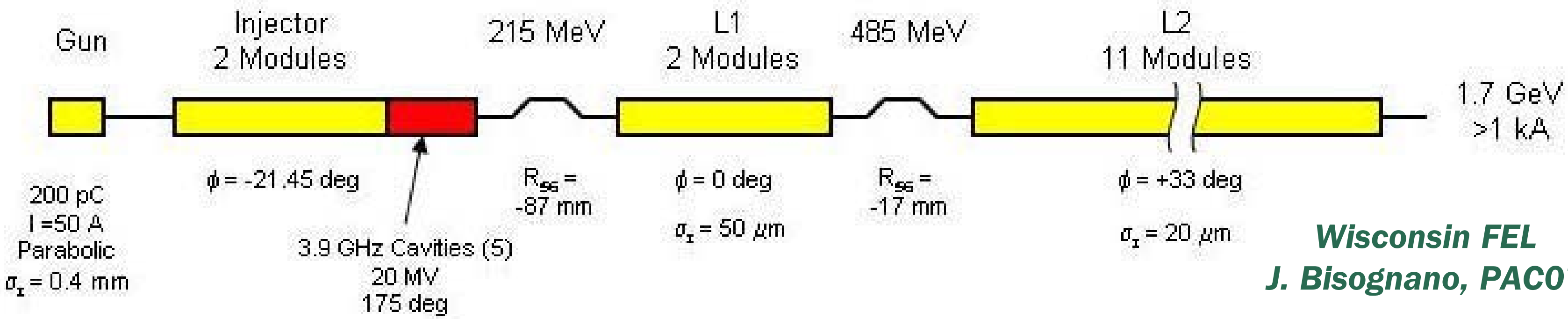
See talk by J. Sekutowicz (DESY) Wednesday noon





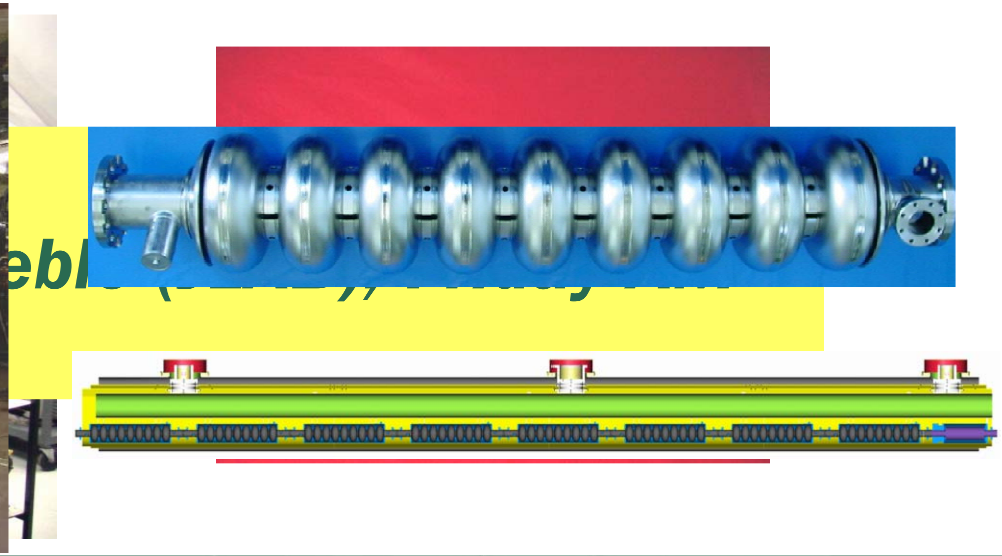
E_{pk} = 18 MV/m





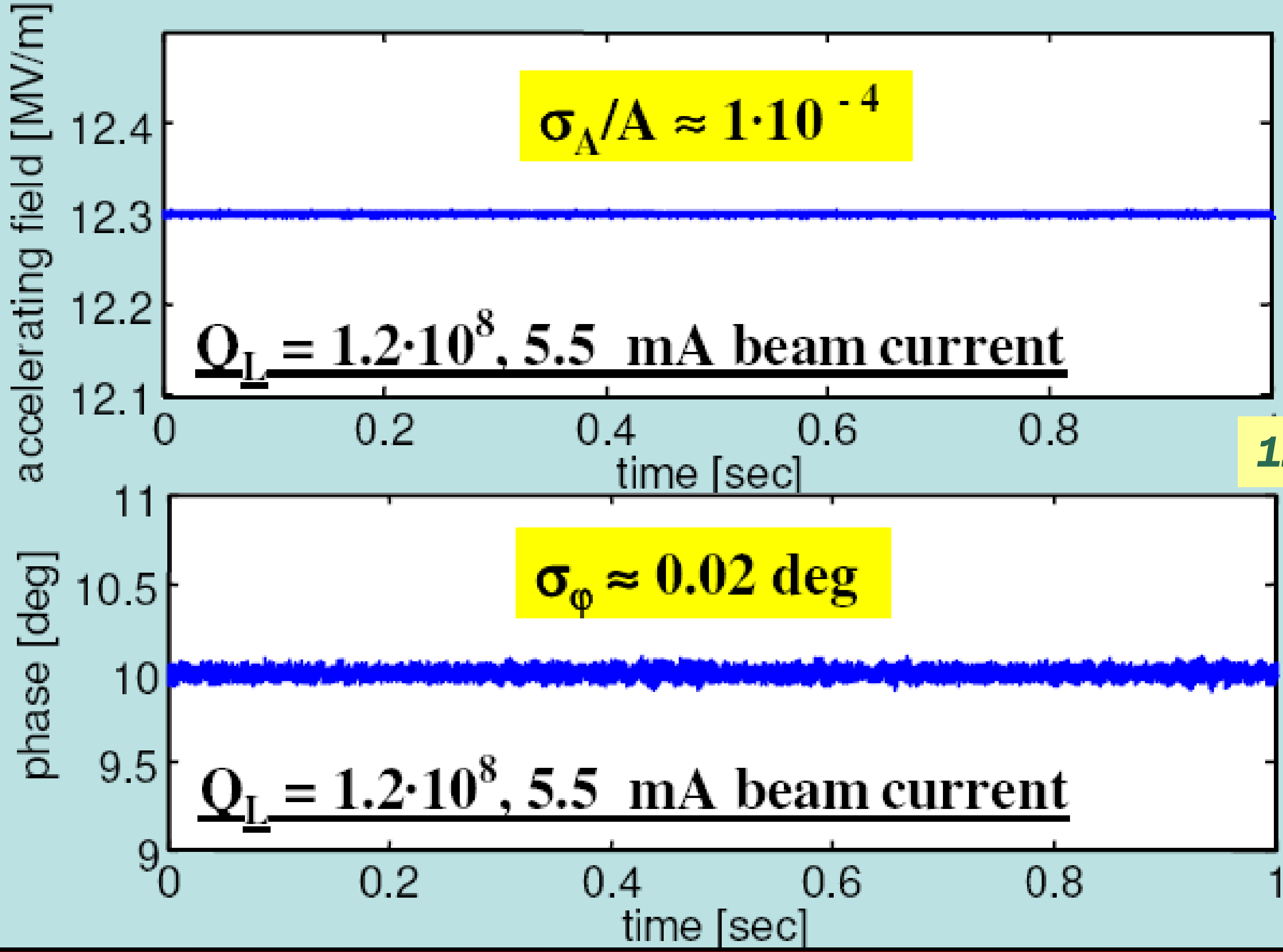
Wisconsin FEL
J. Bisognano, PAC07

- **All proposals discussed here rely on existing SRF technology**
  - Cost: New development prohibitively expensive
  - Experience: Existing technology has already proven its worth



Cornell University

Where are we today?
Cornell RF control test (IV)



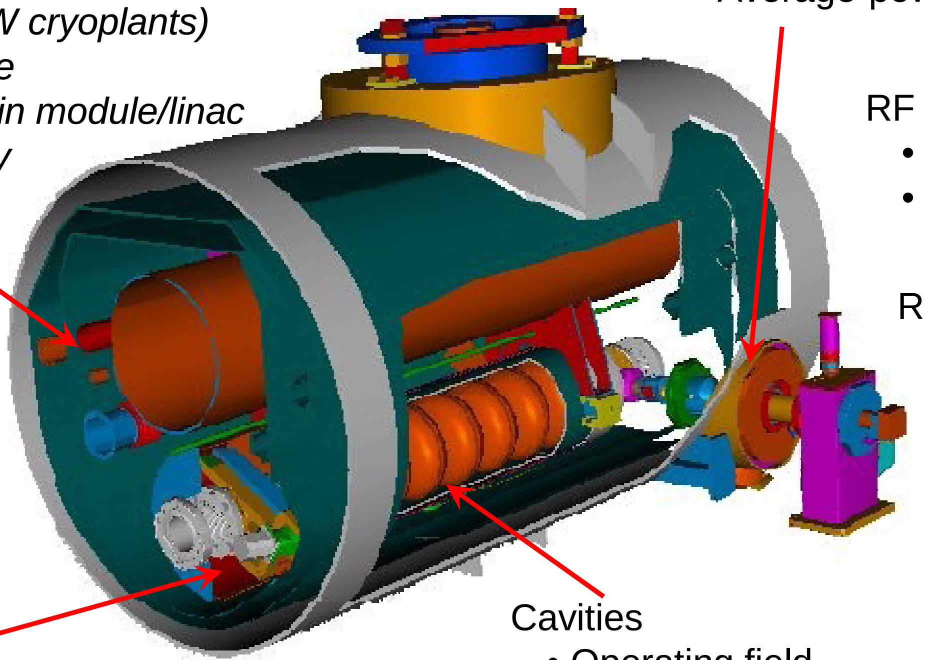
12.5 Hz BW

CW operation issues for TESLA technology

- **TESLA technology: Designed for high-power pulsed operation**
- **Certain changes are required for CW operation**

Input couplers
- Adjustibility?
- Average-power (SW) capability

Cryogenics
- *CW loads!! (4 kW cryoplants)*
- *Bath temperature*
- *LHe distribution in module/linac*
- *Pressure stability*



RF Control
- Exacting amplitude & phase control
- Flexibility and programmability

RF Sources
- Efficient
- Low cost
- Reliable
- Typically in the 20 kW CW range

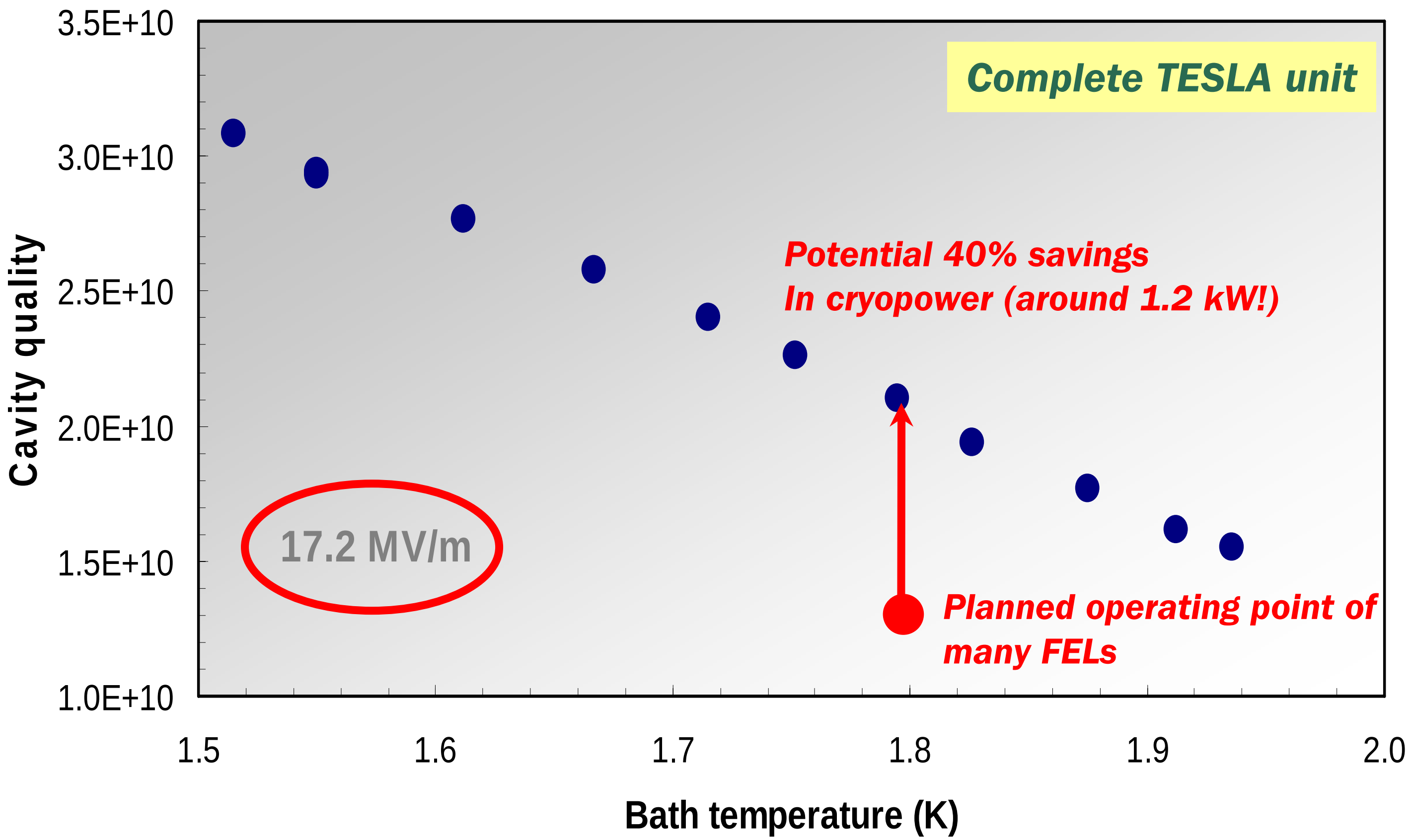
Cavity tuner
- Reliable
- Design to minimize microphonics
- *Active microphonic compensation*

Cavities
- Operating field
- *Maximum quality factor? Improve magnetic shielding?*
- *HOM Dampers – quenches during CW operation*

- HoBiCaT Facility
- Testing of 2 fully equipped TESLA cavities
- 80 W @ 1.8 K cryogenics
- IOT + klystron transmitters for RF source development

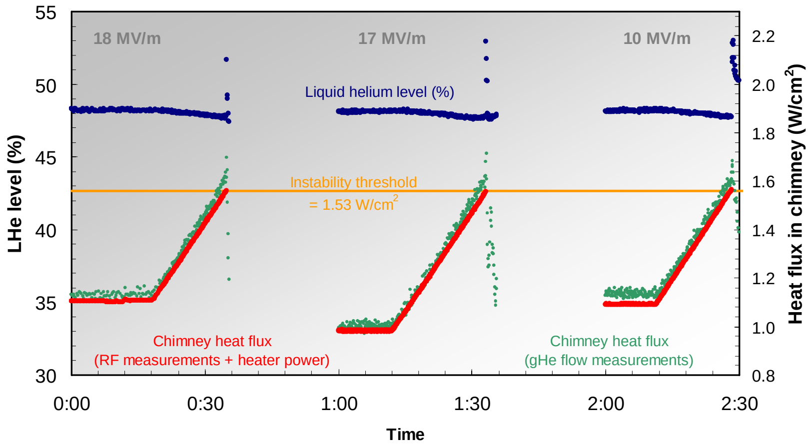
Power dissipation in CW TESLA cavities

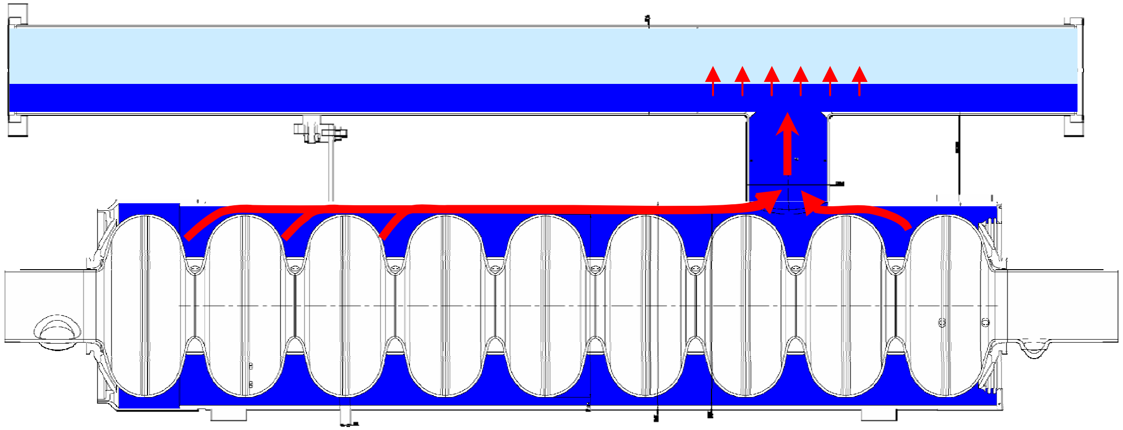
- **Because of CW operation and size of cryogenic installation**
  - *Highest quality factors are critical, not highest gradient*



Power extraction from TESLA cavities

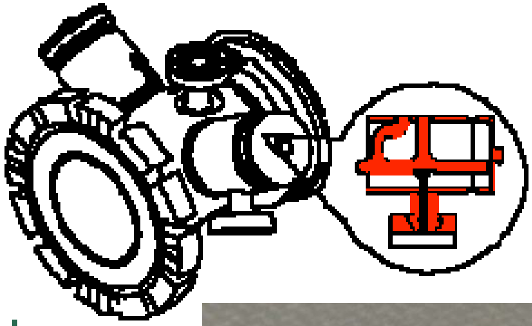
- Large dynamic losses must be extracted from the helium tank
- Theory predicts a „boiling“ limit in the chimney of 1.5 W/cm²
- Measurements confirm this with TESLA cavities:
  - 20 MV/m operation barely possible
- Modified the chimney to accomodate larger losses

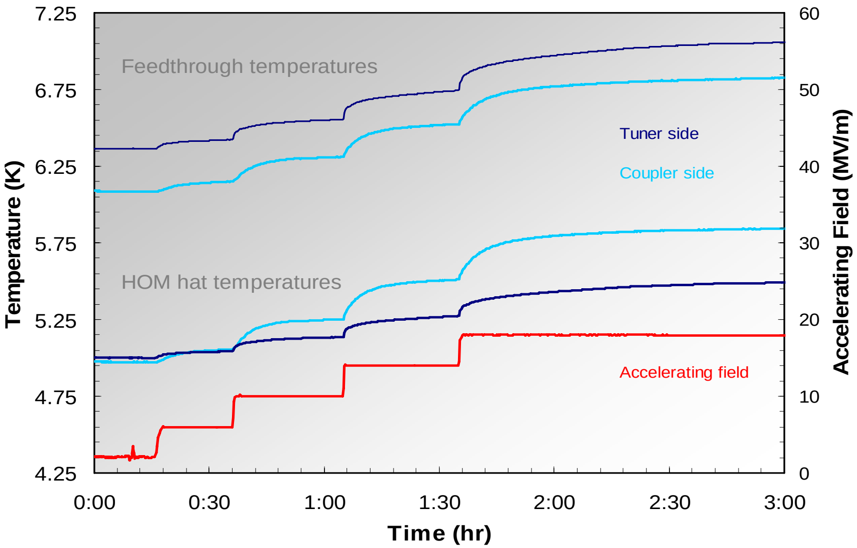




Heating at the HOM pickup

- Reported at last SRF WS:
- HOM pickups problemematic for CW
- Pickup „sees“ small part of accelerating field
  →Tip heats up a little (<< 1 W)
- But: Cooling of tip is only via the ceramic feedthrough
  →Thermal bottleneck can cause thermal runaway
- Solution—improve cooling of inner conductor with sapphire

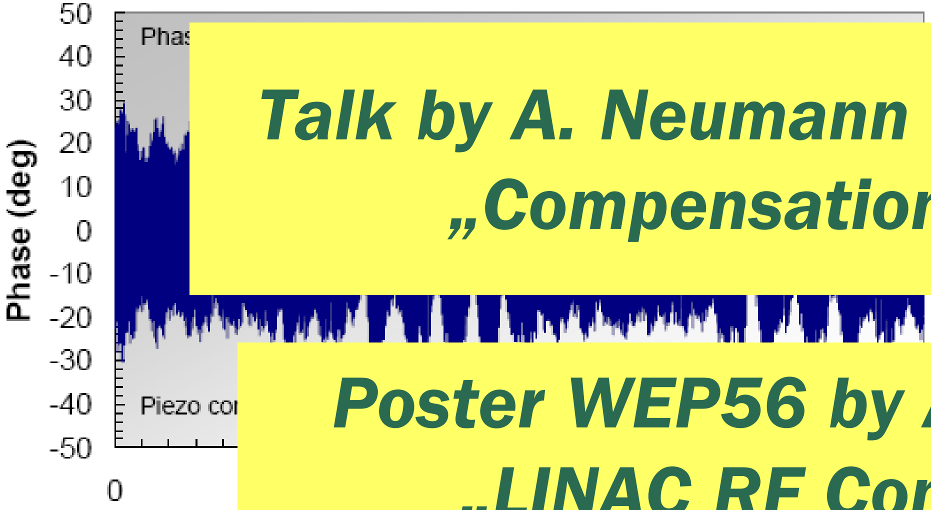


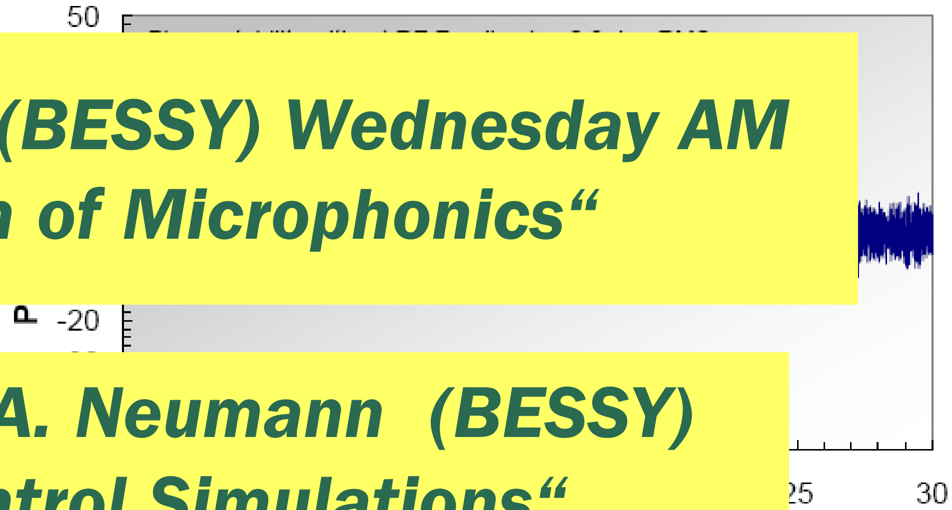


- RF st
  - Ji
  - Jit
- Many potential sources of jitter → analyze these in HoBiCaT
- Micro

Poster TUP40 by Wolfgang Anders (BESSY)
„CW Operation of TESLA Cavities“

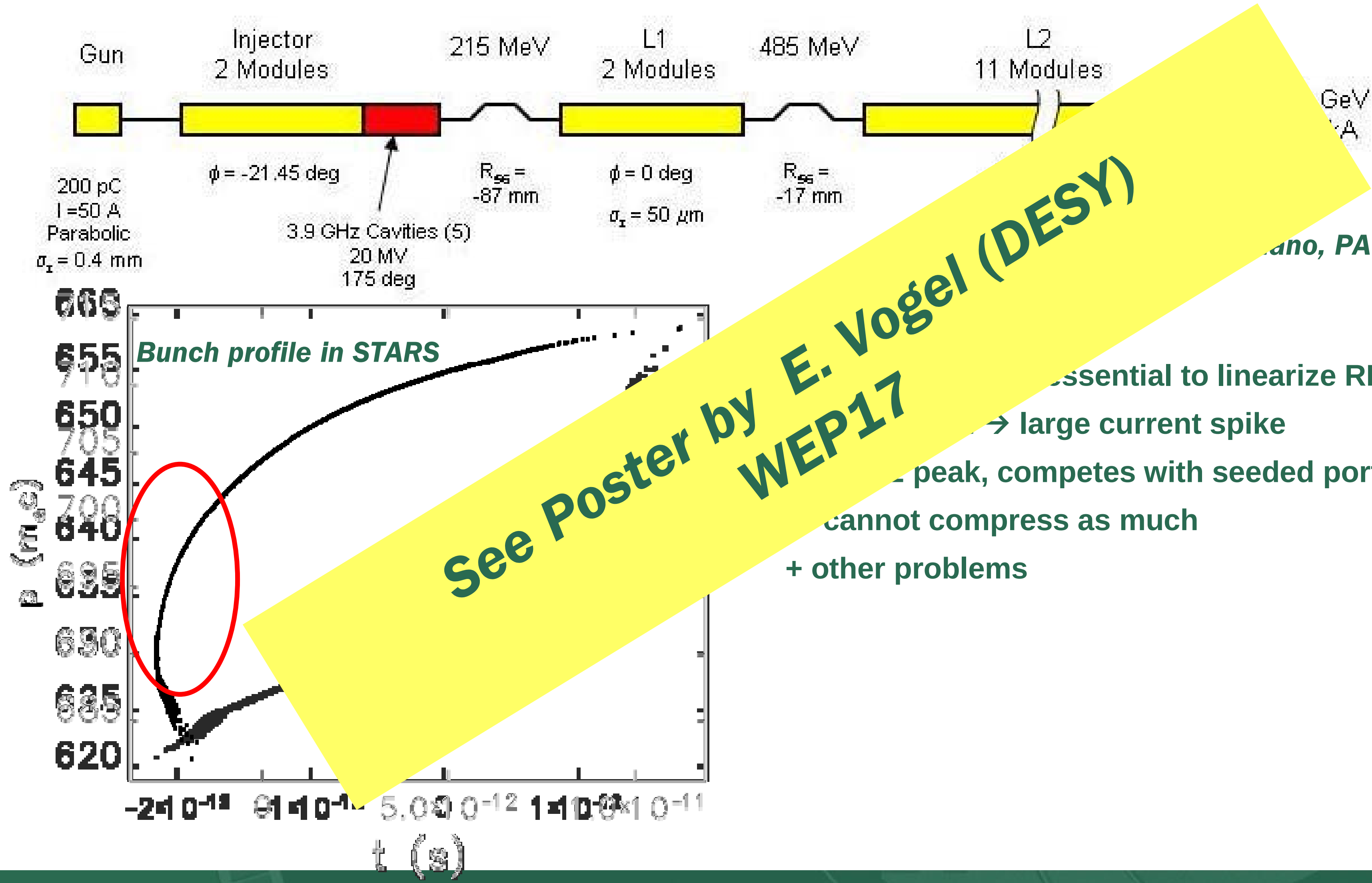
Poster WEP58 by O. Kugeler (BESSY)
„Tuner Characterization“





Talk by A. Neumann (BESSY) Wednesday AM
„Compensation of Microphonics“

Poster WEP56 by A. Neumann (BESSY)
„LINAC RF Control Simulations“



ano, PAC07

...ssential to linearize RF!

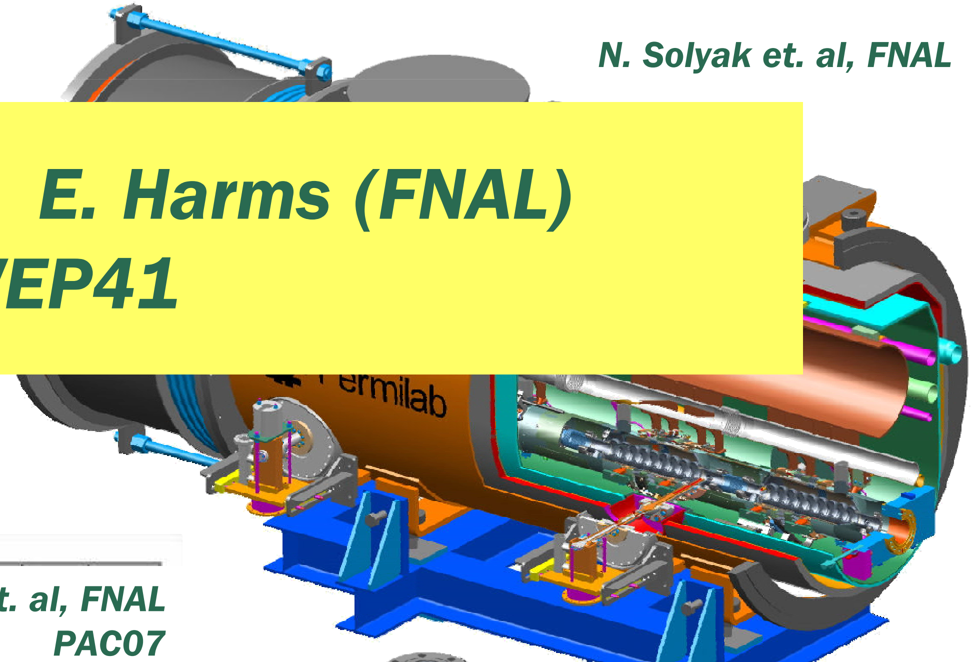
→ large current spike

... peak, competes with seeded portion

... cannot compress as much

+ other problems

N. Solyak et. al, FNAL



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- Many...
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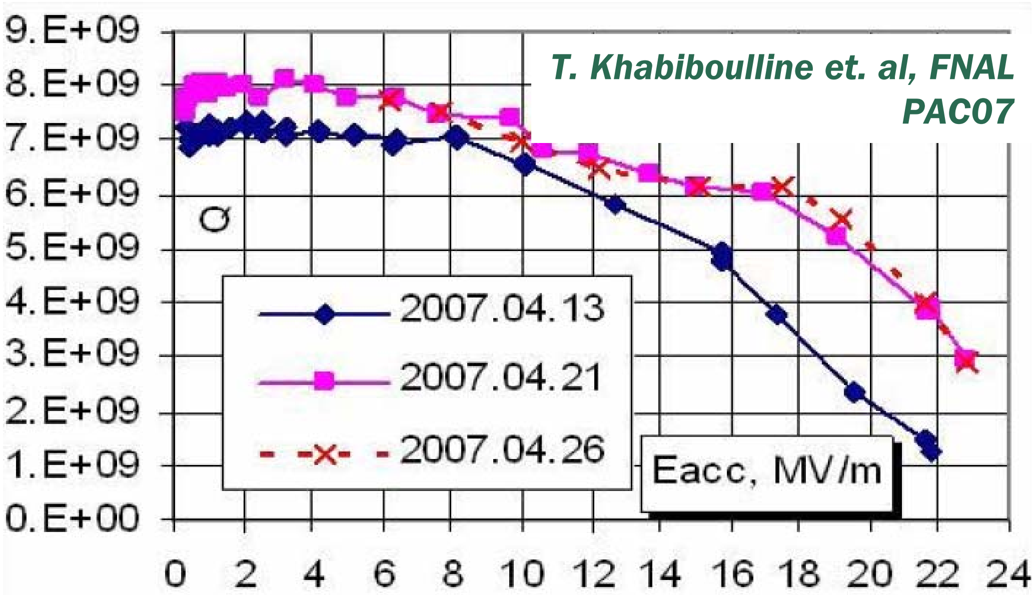
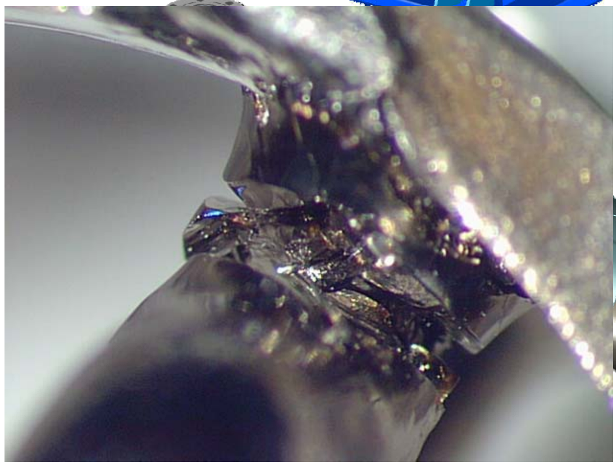
- Insta...

See Poster by E. Harms (FNAL) WEP41

- **CW DEVELOPMENT STILL NEEDED**



T. Khabiboulline et. al, FNAL PAC07

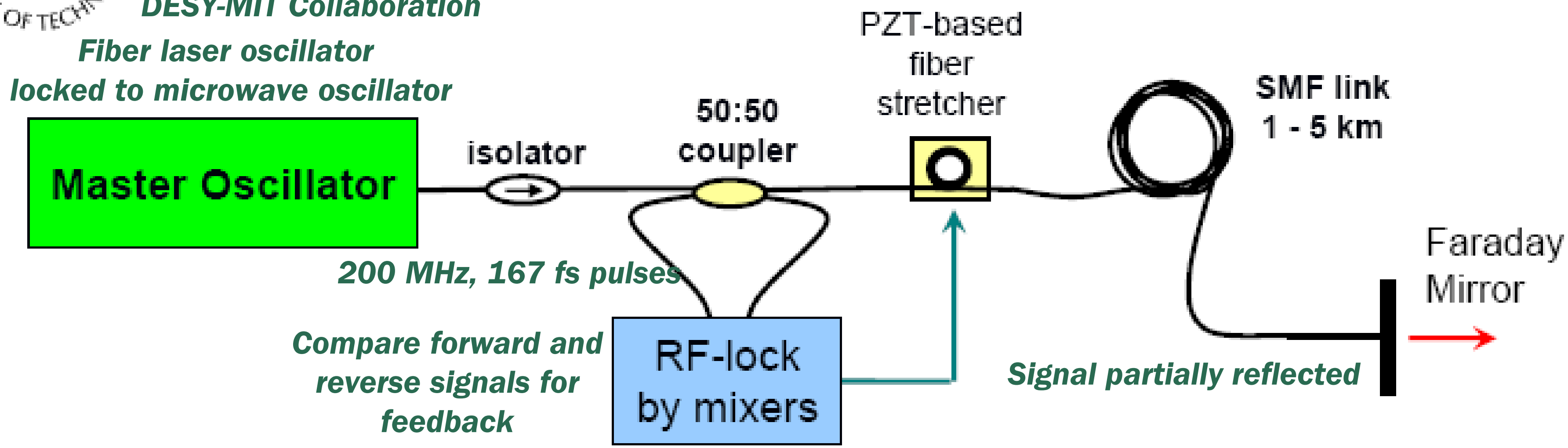


Thank you

- **Thank you to all the people who supplied information**
  - George Neil, JLAB
  - Joe Preble, JLAB
  - Marie-Emanuelle Couprie, Soleil
  - Matthias Liepe, Cornell
  - John Byrd, LBNL
  - P. Michel, FZ Dresden-Rossendorf
  - J. Teichert, FZ Dresden-Rossendorf
  - Joseph Bisognano, U. Wisconsin
  - Nobuyuki Nishimori, JAEA
  - Ralf Eichhorn, TU-Darmstadt

Stable Distribution of Timing Signals

DESY-MIT Collaboration

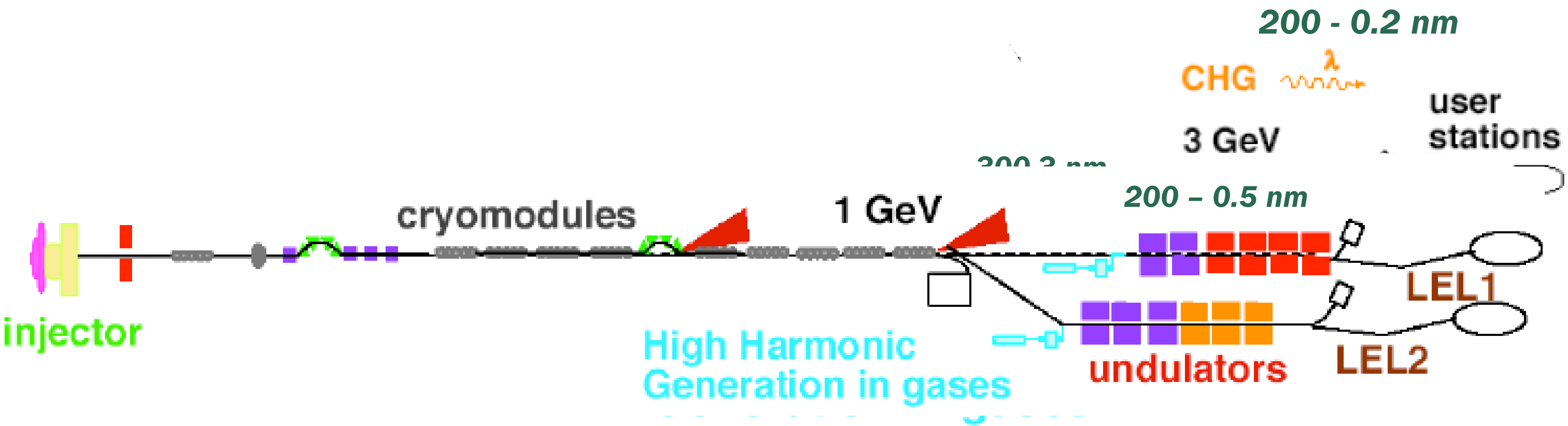


- Test done at accelerator environment (MIT Bates Laboratory)
  - Locked EDFL to Bates master oscillator
  - Transmitted pulses through 400 meters fiber link
  - Close loop on fiber length feedback (12-fs in-loop jitter [0.1Hz,5kHz])

A. Winter et al., Paper FROA002, FEL 2005.

- Test done at the installed fiber underground (NIST/JILA)
  - Transmitted pulse train via a 7-km fiber link between NIST and JILA
  - 19-fs relative jitter between two locations [1 Hz, 46.5MHz]

D. Hudson et al, OL **31**, 1951 (2006).



- **For cost-optimization, use recirculating linac**
  - → Impacts the linac cavities
  - → Consider BBU
  - → Consider HOMs
- **Develop Arc-en-Ciel in Stages**

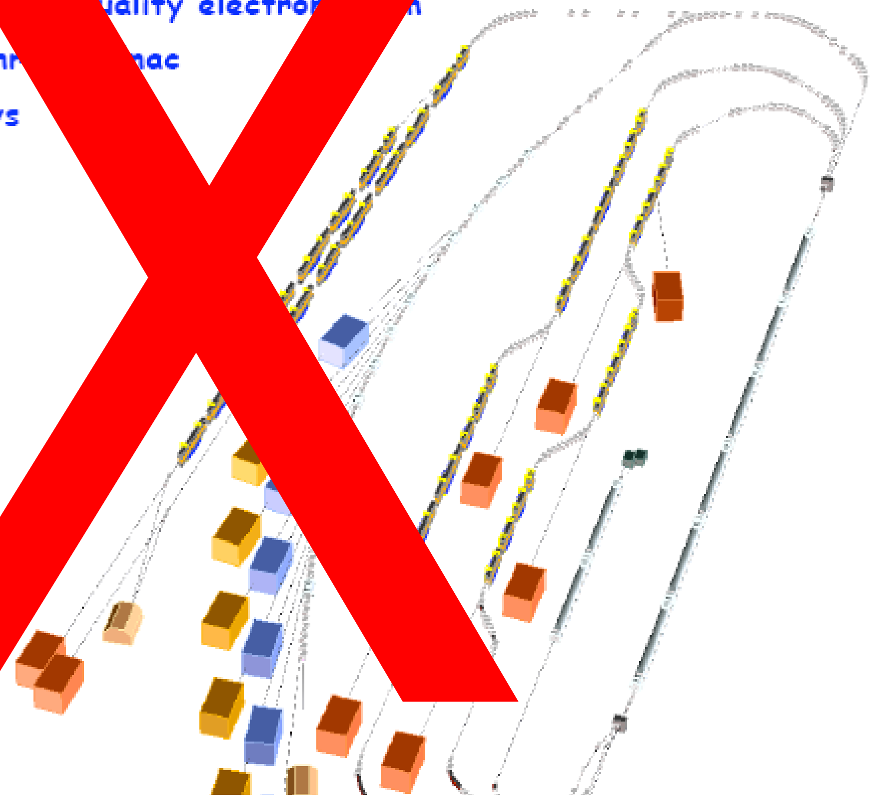
Berkeley Lab

Recirculating linac provides a platform for a refine… …urce of ultr… …ast x-ray pulses

…elength,

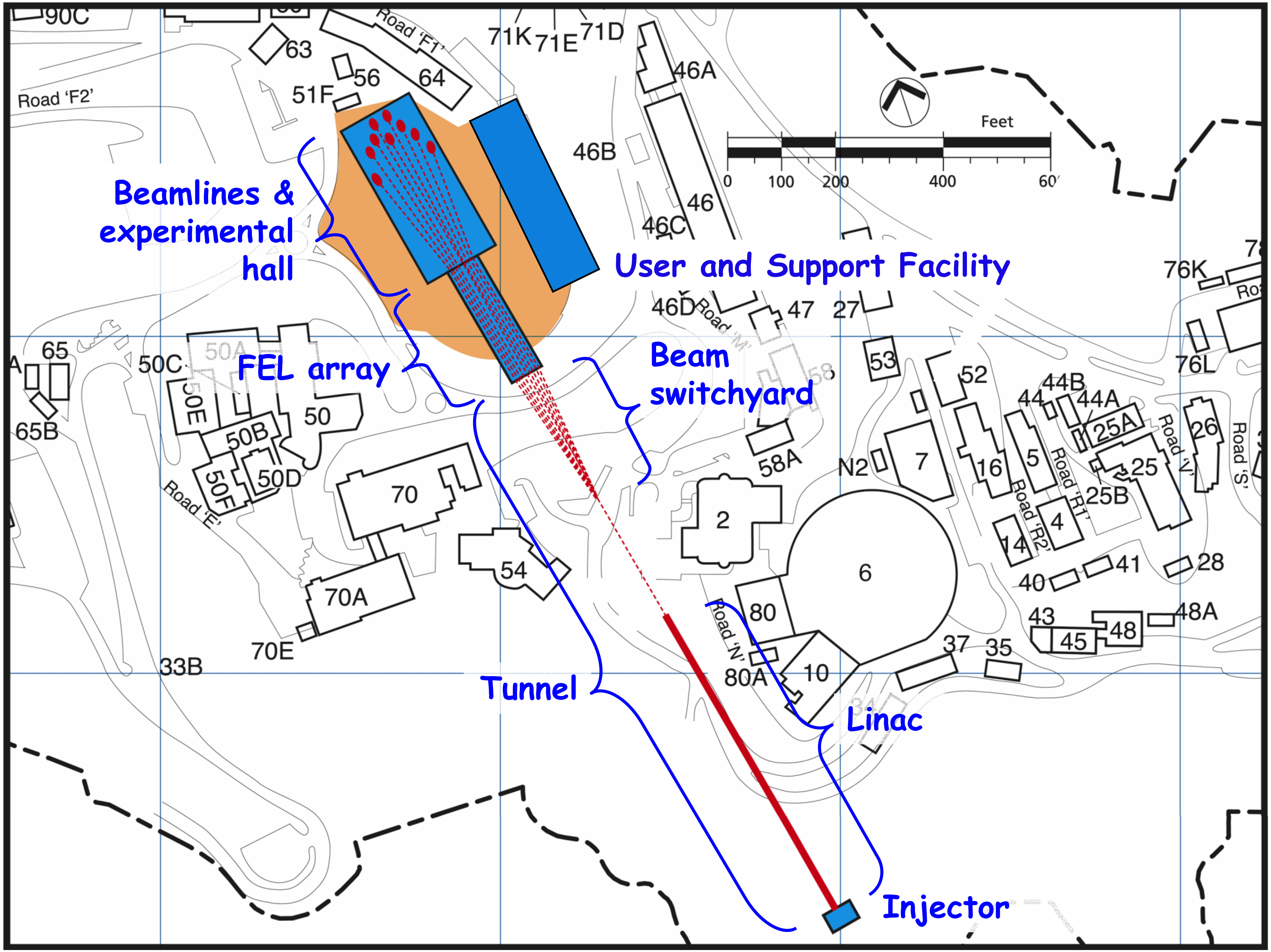
…ded,

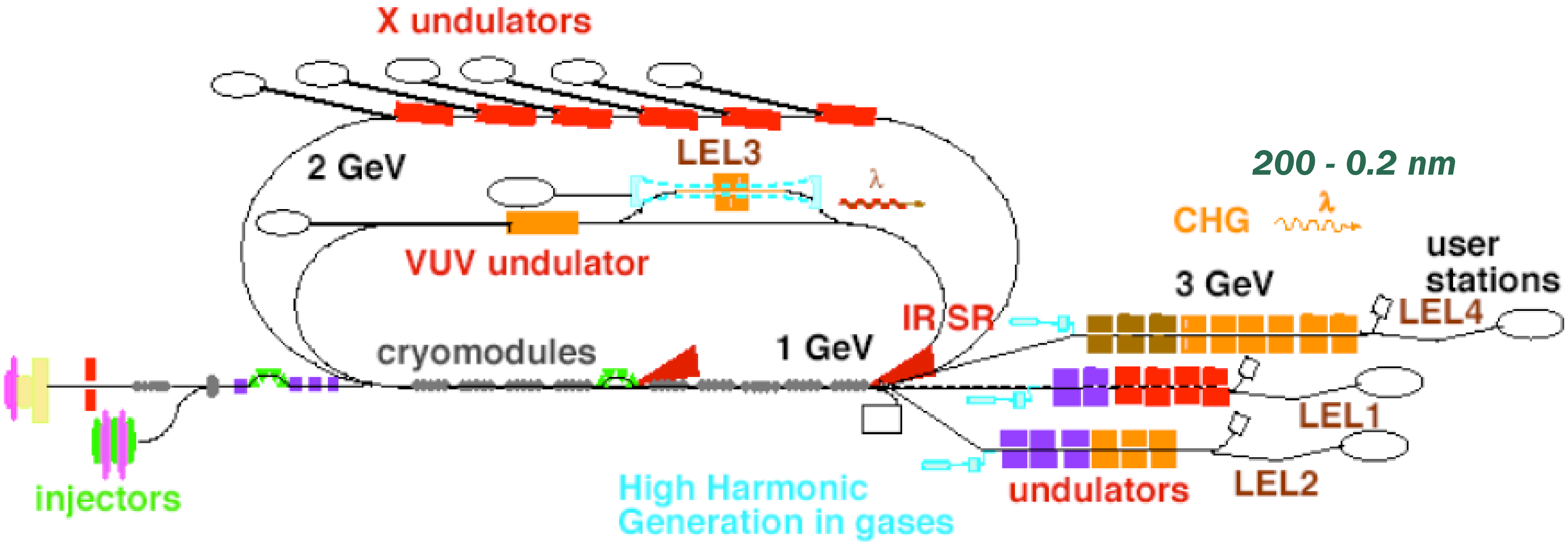
- RF photocathode gun produces … …uality electron… …n
- Accelerate in multiple passes thr… …nac
- 1-3 GeV beam generates x-rays
  - 10-100 fs duration
- Compact (~ 150 x 50 m)
- Flexible configuration
  - Each pass provides opportunities for
    - Manipulation of the electron beam
    - Photon production
  - Variable repetition ra…
  - Energy recovery option



- **Recirculating LINAC for the FEL was apparently not technically convincing**
- **Political issues got in the way**

John Byrd, LBNL, 2004

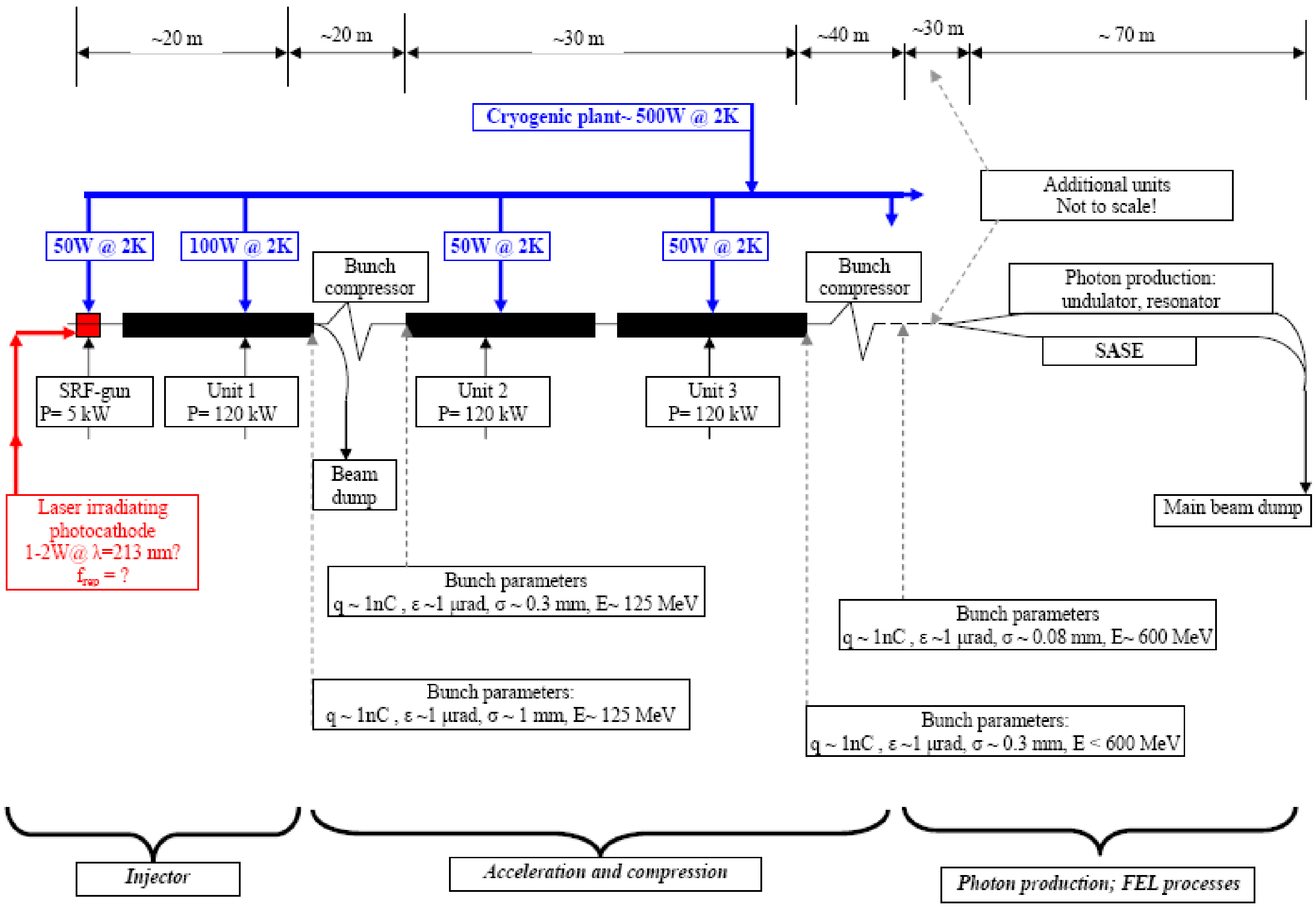

Beamlines & experimental hall
User and Support Facility
FEL array
Beam switchyard
Tunnel
Linac
Injector
Feet
0
100
200
400
600
Road 'F2'
Road 'F1'
Road 'E'
Road 'M'
Road 'N'
Road 'R1'
Road 'R2'
Road 'V'
Road 'S'



- **For cost-optimization, use recirculating linac + ERL option (100 mA)**
  - →Consider HOMs
  - →Consider BBU

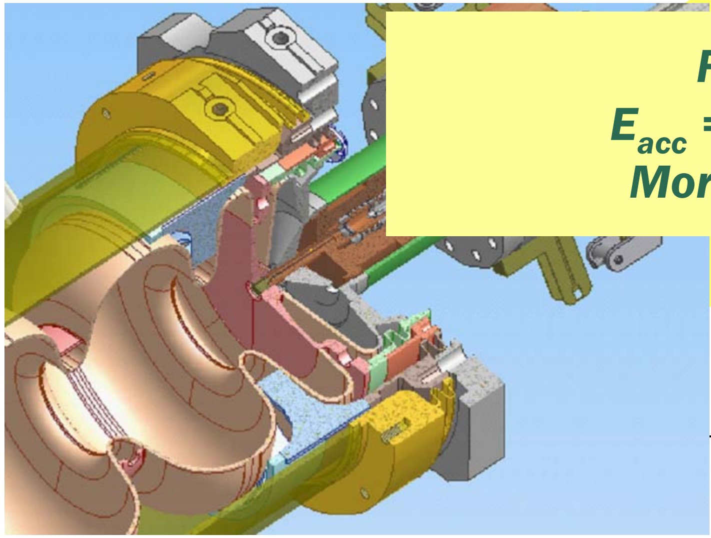
  } **Significant impact on the SRF system**

- **No significant development of the linac/SRF so far**
- **No clear signals on funding/time line**

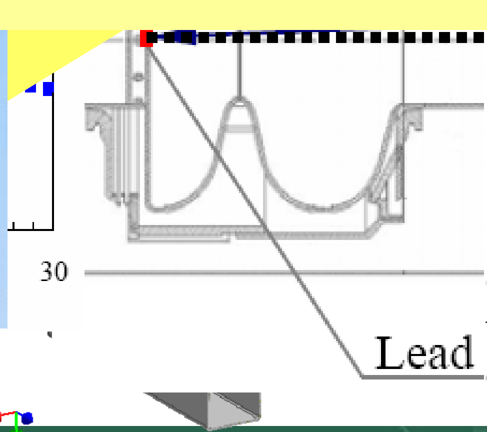

~20 m
~20 m
~30 m
~40 m
~30 m
~ 70 m
Cryogenic plant~ 500W @ 2K
50W @ 2K
100W @ 2K
50W @ 2K
50W @ 2K
Additional units
Not to scale!
Bunch compressor
Bunch compressor
Photon production: undulator, resonator
SASE
SRF-gun P= 5 kW
Unit 1 P= 120 kW
Unit 2 P= 120 kW
Unit 3 P= 120 kW
Beam dump
Main beam dump
Laser irradiating photocathode 1-2W@ λ=213 nm? f_rep = ?
Bunch parameters q ~ 1nC , ε ~1 µrad, σ ~ 0.3 mm, E~ 125 MeV
Bunch parameters q ~ 1nC , ε ~1 µrad, σ ~ 0.08 mm, E~ 600 MeV
Bunch parameters: q ~ 1nC , ε ~1 µrad, σ ~ 1 mm, E~ 125 MeV
Bunch parameters: q ~ 1nC , ε ~1 µrad, σ ~ 0.3 mm, E < 600 MeV
Injector
Acceleration and compression
Photon production; FEL processes

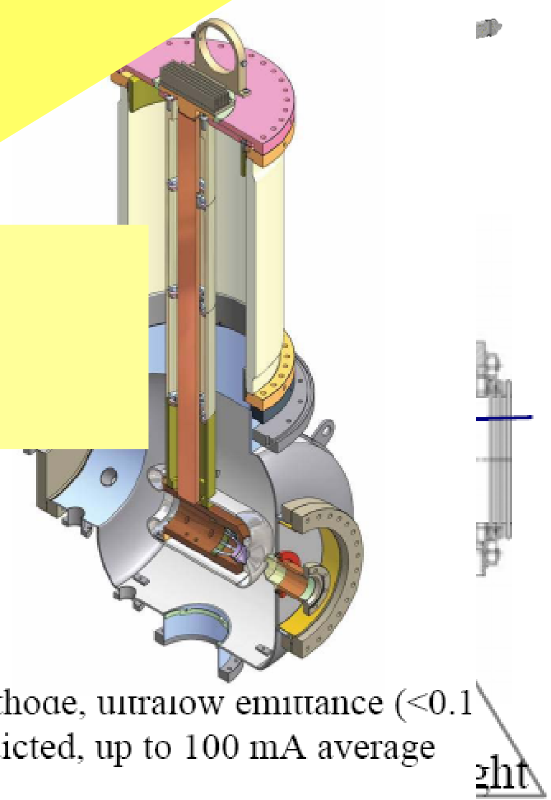
- Development of CW capable <u>low emittance</u> injectors a high priority
- SRF System appears most promising at present
- Rossendorf system in the most advanced stage
- But other systems also being developed
- Even DC systems may be possible, especially f... bunch charge and high-rep rate

M. Liepe, Monday AM
...r by

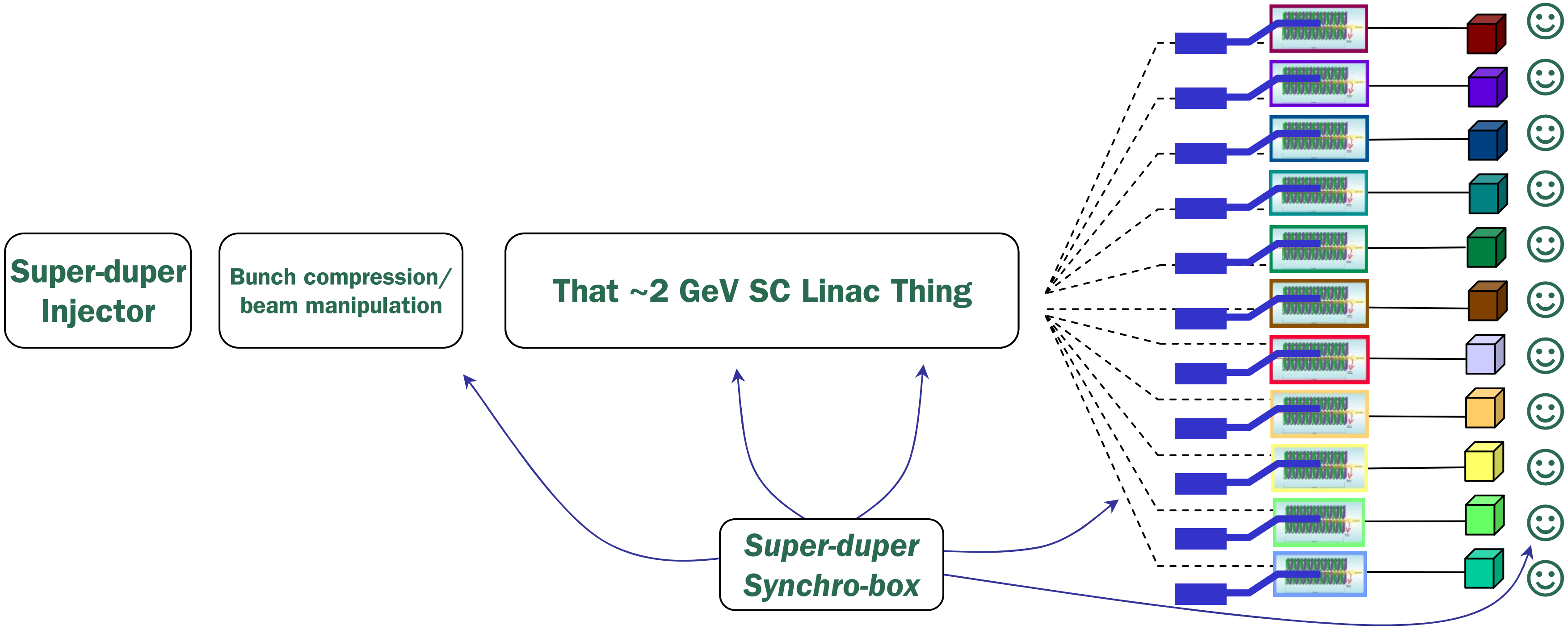


RF applied this month
E_{acc} = 5 MV/m achieved so far
More results and beam soon





Epk = 18 MV/m


Super-duper Injector
Bunch compression/ beam manipulation
That ~2 GeV SC Linac Thing
Super-duper Synchro-box

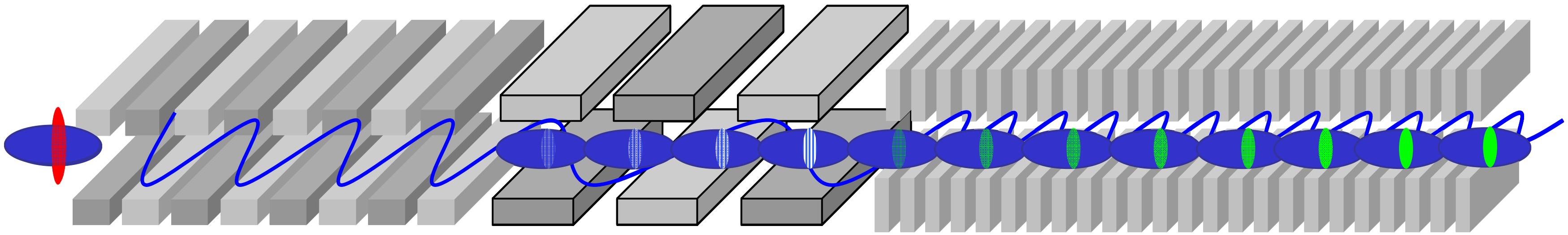
Seeded high-gain harmonic generation

- For UV/X ray lasers cannot use „optical cavity“
- → Seed machines and use relatively long undulators for single-pass amplification
- Seed lasers at the desired wavelength do not exist

  → must „upconvert“

High-Gain-Harmonic Generation (HGHG)

High-Brilliance electron beam (Emittance < 2 µm)
Very short pulse seed laser (< 100 fs), e.g. Ti:Sa or HHG Laser



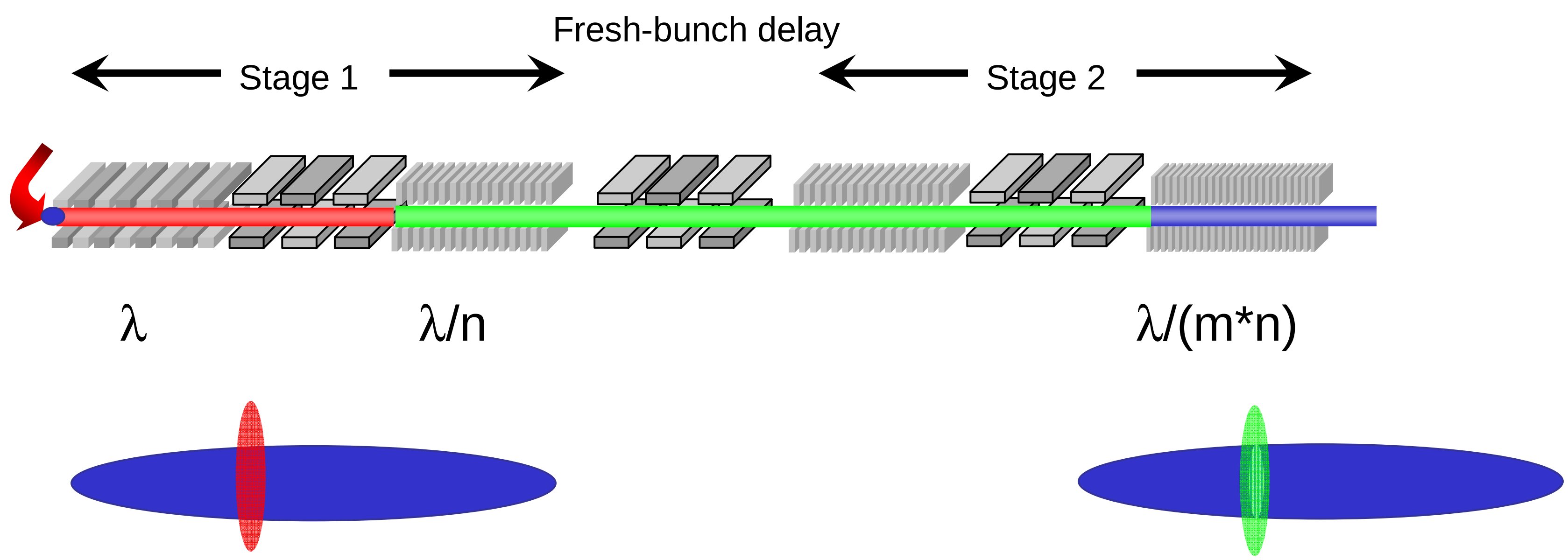
External seed, ω_0 overlaps the bunch and modulates the energy

Chicane converts the energy modulation into a spatial bunching

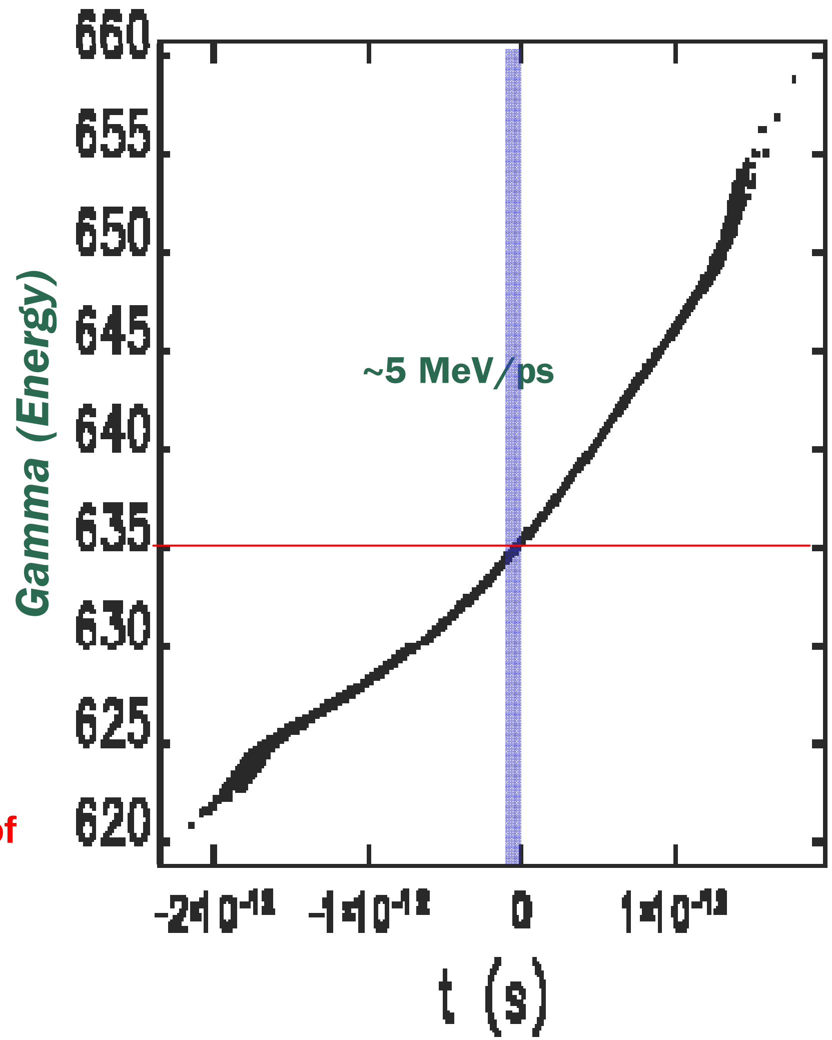
Modulated part of the bunch radiates coherently at a harmonic of the seed laser
Limited to about $n \leq 5$.

Developed by L.-H. Yu et al, Brookhaven

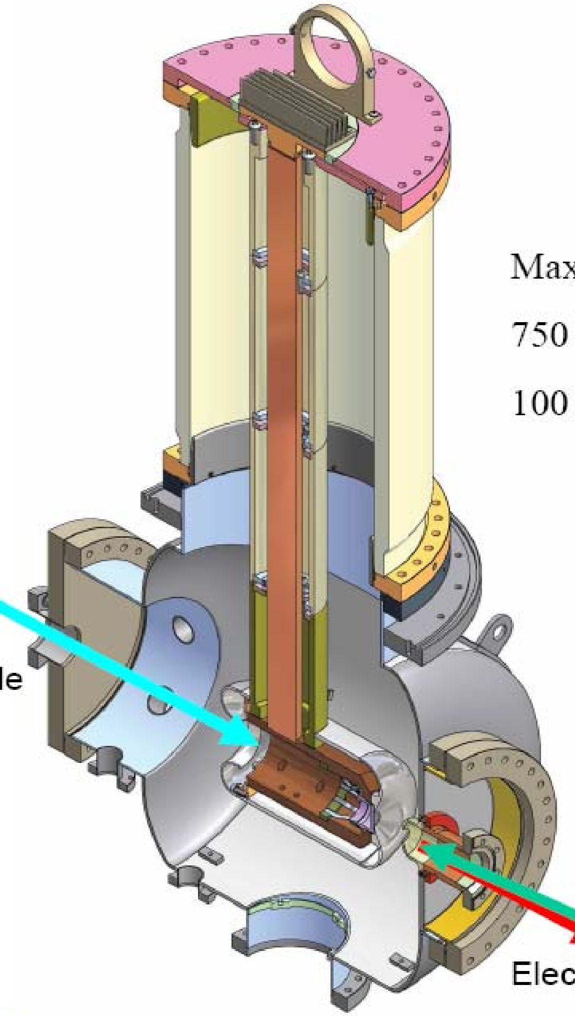
- To reach even shorter wavelengths, can cascade HGHG stages
- Include an additional delay between stages to select a new „fresh“ part of the bunch for subsequent stages
- E.g., to reach 1 nm need about 4 stages



- **Key advantage of seeding: Output-pulse properties determined by seed laser not the electron bunch!**
  - → Spectrum and pulse shape is reproducible (not so with SASE)
  - → Each beamline can be seeded differently = Flexibility!
- **But seeding is challenging!**
  - Very precise beam timing (and position) control is needed, because of chirped beam (< 100fs)
  - Beam „quality" must be constant along the bunch.
- **→ Need third harmonic cavities to linearize RF**
- **→ Need very precise RF controls of the cavities**
  - Order 0.02 deg, 0.02%
- **→ Need very precise timing distribution system**
- **→ FEL Output critically depends on the performance of the SRF linac**



750 kV Gun



Max capabilities:

750 kV

100 mA