Beam dynamics of the 250 MeV PSI XFEL injector

T. Schietinger, A. Adelmann, R.J. Bakker, C. Kraus, K. Li,
A. Oppelt, B. Oswald, M. Pedrozzi, J.-Y. Raguin, F. Stulle, A.F. Wrulich,
PSI, CH-5232 Villigen, Switzerland

Ji Qiang, LBNL, Berkeley CA 94720, U.S.A.

22nd Particle Accelerator Conference 2007
Albuquerque, NM, 26 June 2007

Contents

- **The project: 250 MeV PSI XFEL injector**
  - Test facility for PSI XFEL, a compact 6-GeV Free-Electron Laser at PSI for the 1-Å wavelength regime.
- **The simulation tool: IMPACT-T**
  - Parallel PIC code developed by J. Qiang (LBNL) and modified by A. Adelmann and C. Kraus (PSI)
  - Also used for ongoing experimental effort (4-MeV test stand)
- **The results:**
  - Projected emittance compensation and conservation
  - Velocity/ballistic compression

A compact XFEL for Switzerland

Target parameters:

photons:

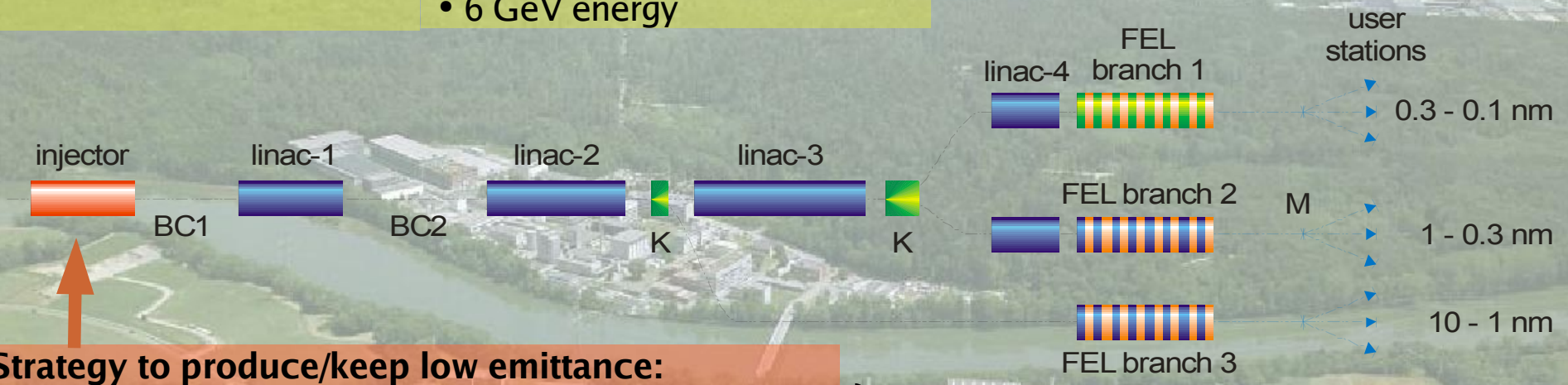
- 1–100 Å
- 10–100 Hz rep. rate
- 0.2–5 × 10^{12} ph./pulse

electron beam at undulator:

- 0.2 nC charge
- 0.1 mm mrad slice emittance
- 1.5 kA peak current
- 6 GeV energy

Time line (tentative):

- Ongoing: gun R&D, 100 kV test stand
- 2007/08: 4 MeV test stand
- 2008–2011: 250 MeV injector
- 2011–2016?: full XFEL



Strategy to produce/keep low emittance:

1) Gun initially based on scaled conventional photocathode, later Field Array Emitter technology
2) Fast acceleration after emission (pulsed diode, 1 MV / 4 mm) to avoid beam blow up
3) Initially low current to reduce space charge effects, increase later by 3-fold bunch compression system

These steps need to be proven!

⇒ Construction of a 250 MeV injector test facility 2008–2011

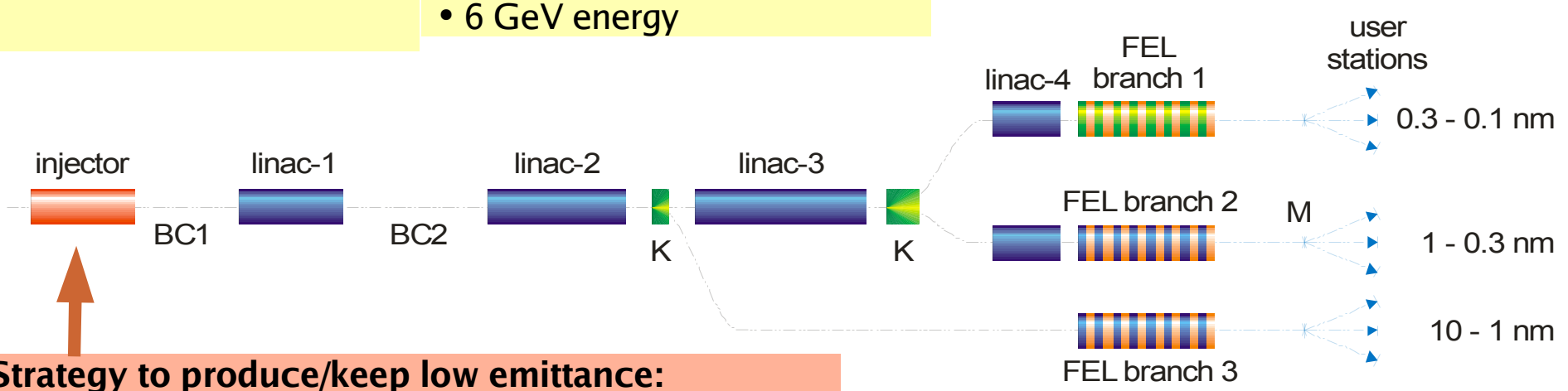
A compact XFEL for Switzerland

Target parameters:

photons:
- 1–100 Å
- 10–100 Hz rep. rate
- 0.2–5 × 10^{12} ph./pulse

electron beam at undulator:
- 0.2 nC charge
- 0.1 mm mrad slice emittance
- 1.5 kA peak current
- 6 GeV energy

Time line (tentative):
- Ongoing: gun R&D, 100 kV test stand
- 2007/08: 4 MeV test stand
- 2008–2011: 250 MeV injector
- 2011–2016?: full XFEL



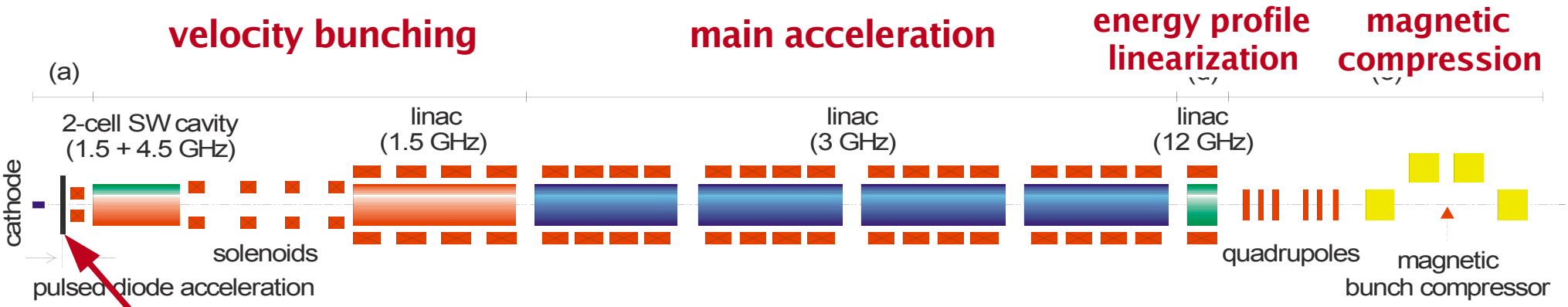
Strategy to produce/keep low emittance:

1) Gun initially based on scaled conventional photocathode, later Field Array Emitter technology
2) Fast acceleration after emission (pulsed diode, 1 MV / 4 mm) to avoid beam blow up
3) Initially low current to reduce space charge effects, increase later by 3-fold bunch compression system

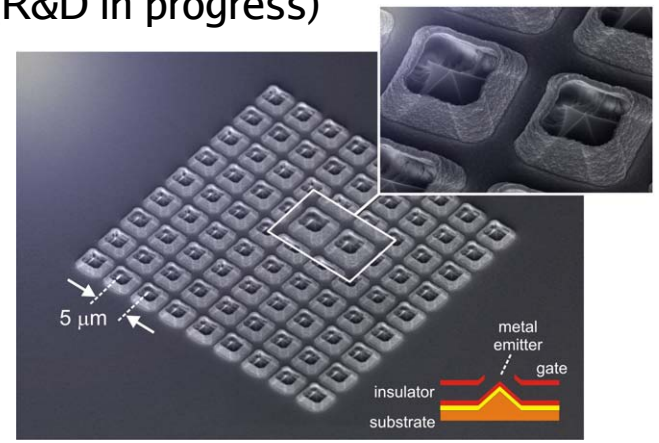
These steps need to be proven!

⇒ Construction of a 250 MeV injector test facility 2008–2011

250-MeV injector facility



Low Emittance Gun: scaled conventional photocathode,
later **Field Emitter Array**
(R&D in progress)



Key requirements:

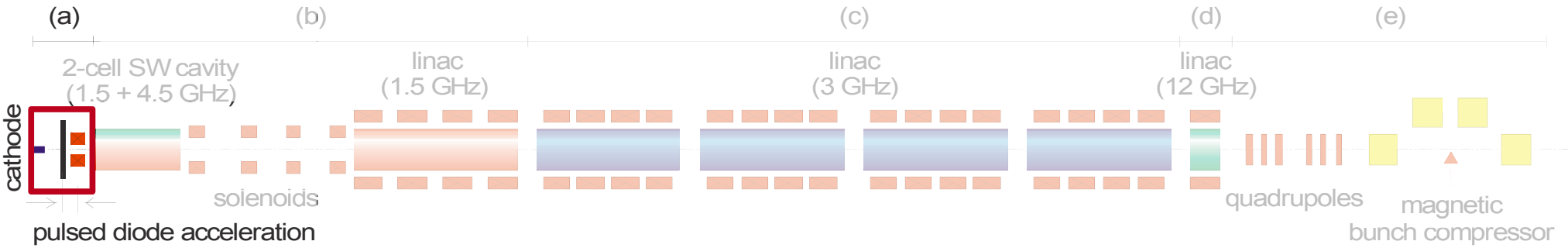
- Accelerate to main linac injection energy while preserving emittance of electron source and increasing brightness
- Shape the electron bunch for optimal X-ray production in undulator

Emittance compensation:

Balance between space-charge forces and natural evolution of emittance

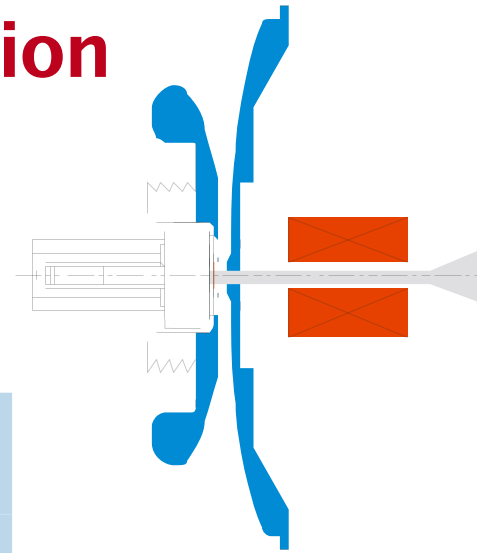
Machine layout

σ_t = 40 ps
I_{peak} = 5.5 A
E = 1 MeV

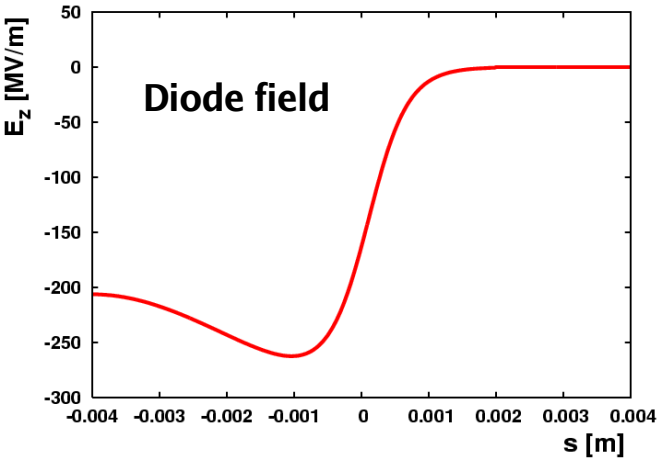


High gradient acceleration

Purpose: inhibit emittance growth from space charge



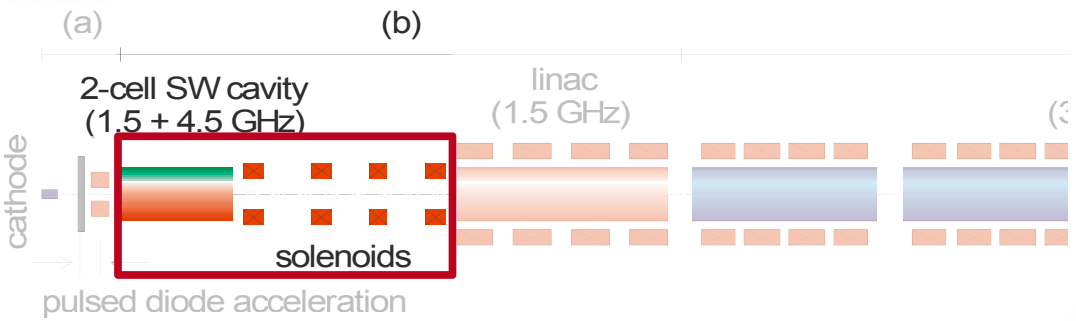
Field modeling:
Poisson Superfish



- Pulsed diode: target gradient 125–250 MV/m across 4 mm gap.
- Pulsed solenoid to focus and match the beam into the first cavity

Machine layout

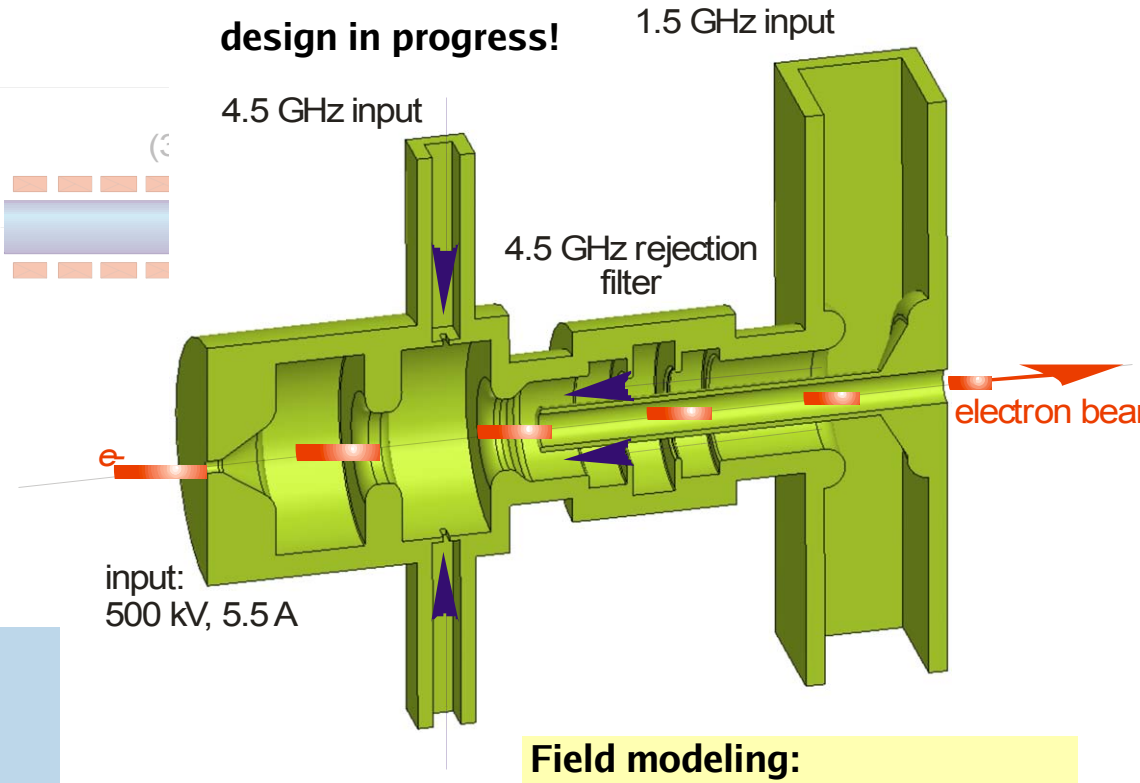
σ_t = 9 ps
I_{peak} = 25 A
E = 3.5 MeV



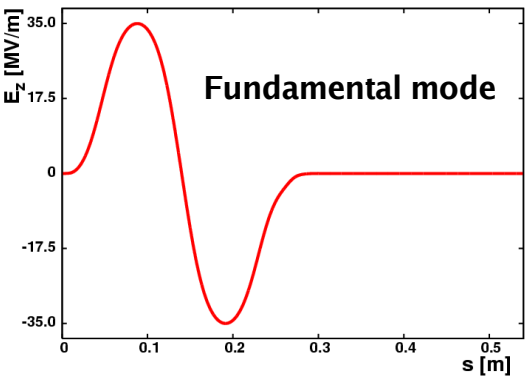
Ballistic compression

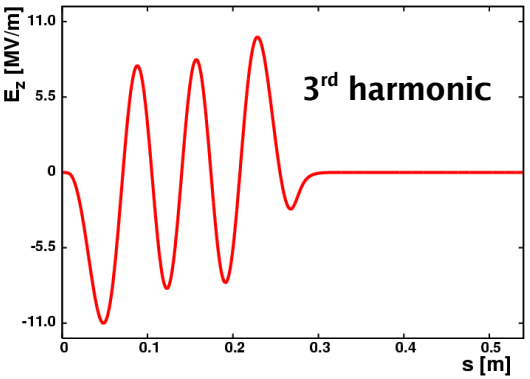
Purpose: reduce bunch length to increase peak current

- 2-cell standing-wave cavity running at two frequencies:
  - 1.5 GHz (fundamental): **acceleration** (4 MeV) with large acceptance, **energy chirp** for ballistic bunching
  - 4.5 GHz (3rd harmonic): **correction of the longitudinal phase space** for optimum bunching.
- Compensation solenoids control transverse bunch dimensions



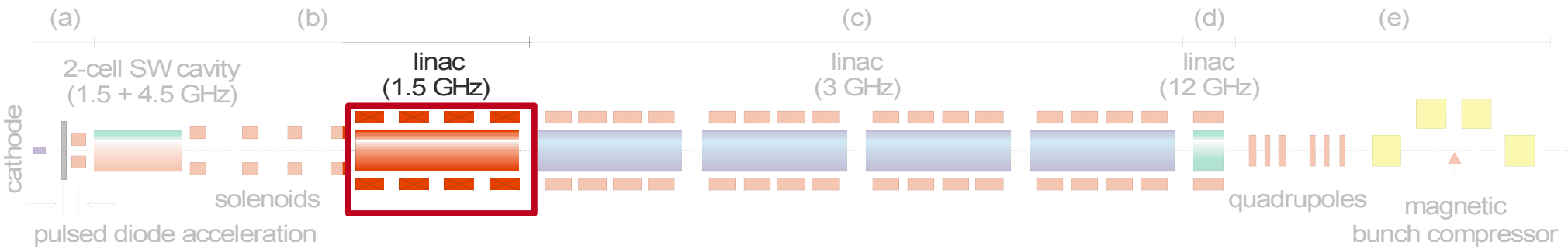
Field modeling:
Poisson Superfish / HFSS





Machine layout

σ_t = 7 ps
I_{peak} = 30 A
E = 30 MeV



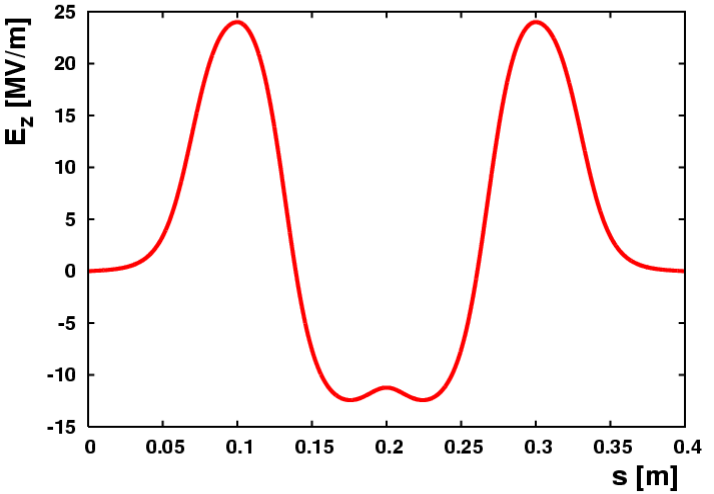
Velocity bunching

Purpose: accelerate, "freeze out" bunch length

- Injector linac: 1.5 GHz (L-band) $2\pi/3$ traveling-wave structure
  - 40 cells
  - Acceleration to 30 MeV (10.6 MV/m), compensate for space charge
  - Scaled SLAC cavity

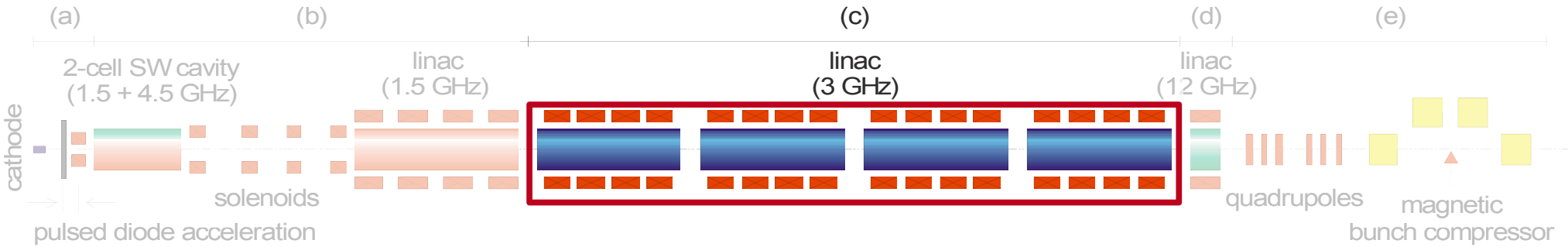
Field modeling:
compute Fourier coefficients of longitudinal electrical field on axis with **Superfish**, derive E and B fields.

G.A. Loew, R.H. Miller, R.A. Early, K.L. Bane:
IEEE Trans. Nuclear Science, NS-29, No. 3 (1979)



Machine layout

σ_t = 7 ps
I_{peak} = 30 A
E = 280 MeV



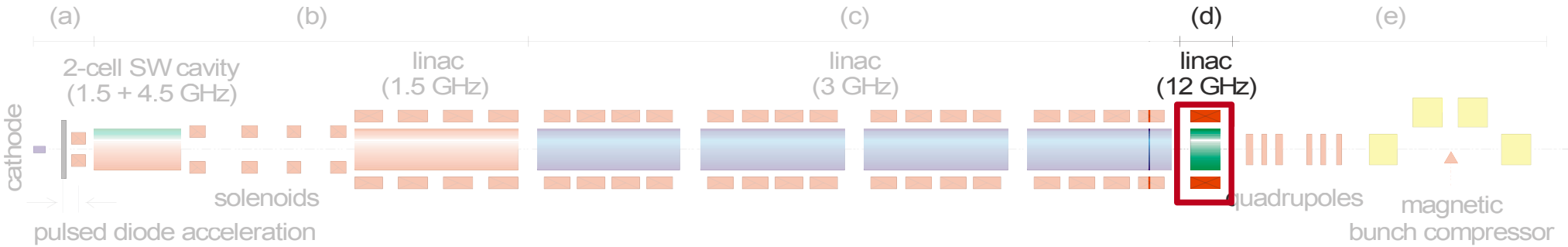
Main acceleration

Purpose: accelerate, tune energy chirp

- Booster linac: 3 GHz (S-band) traveling-wave structure
  - 4 × 120 cells (scaled SLAC cavities)
  - Acceleration to 280 MeV (17.3 MV/m)
- Energy chirp tuning:
  - Controls compression of bunch downstream
  - Compensates wake-field induced energy spread in main accelerator.

Machine layout

σ_t = 7 ps
I_{peak} = 30 A
E = 250 MeV



Energy profile linearization

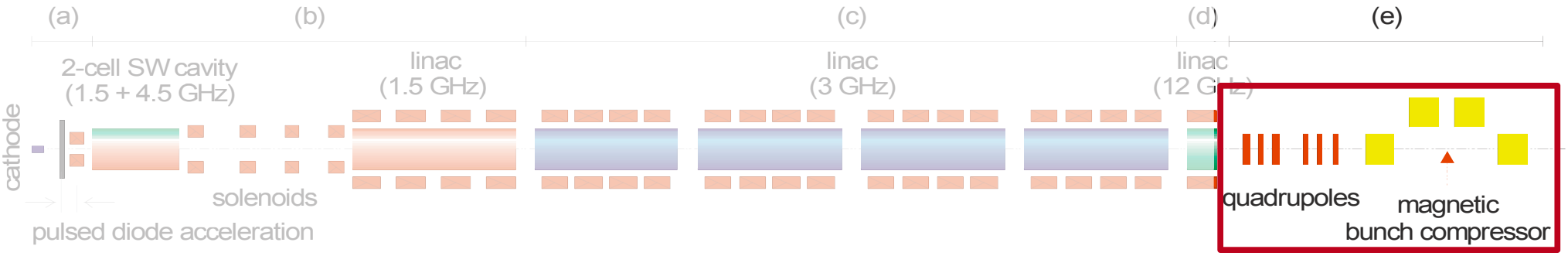
Purpose: compensate non-linearity in energy profile introduced by linac

12 GHz (4th harmonic of S-band) traveling-wave structure:

- 120 cells
- Deceleration to 250 MeV
- International collaboration?

Machine layout

σ_t = 0.63 ps
I_{peak} = 350 A
E = 250 MeV



- Conventional dipole chicane
- Parameters:

Chicane length:	10 m
Dipole length:	0.25 m
Mom. comp. factor R_{56}:	−0.05 m
Compression factor:	11.7
req. E chirp $(1/E_0)dE/ds$:	$-18.25\ m^{-1}$

- Two quadrupole triplets to correct the beam's Twiss parameters (avoid emittance growth from CSR in dipoles)

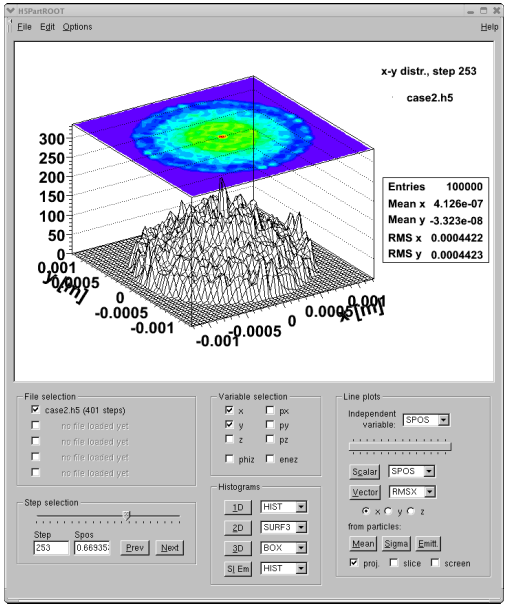
Magnetic compression

Purpose: compress bunch to reach peak current of 350 A

Simulation tool: IMPACT-T

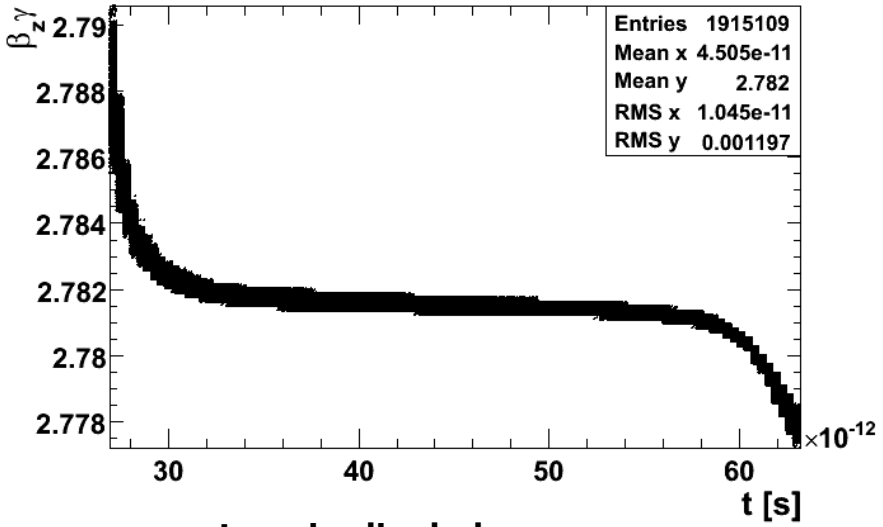
- First order design with **beam envelope tracker (BET)** similar to **HOMDYN**
- But significance of space charge effects calls for validation with **fully 3D code** that tracks **individual particles**
- Large statistics needed, in particular for slice emittance studies
- Our choice: **IMPACT-T**
  - Time-dependent, parallel, particle-in-cell code
  - Integrates 3D trajectories of macro-particles in electrostatic approximation
  - Fields are read in as 3D fieldmaps
  - Fortran-90, "object-oriented"
  - Developed by J. Qiang et al. (LBNL), modified by A. Adelmann and C. Kraus (PSI)
- Feed BET/HOMDYN design parameters into IMPACT-T, readjust optics to match the beam size.
- Post-processing and visualization: **H5Part** (PSI/LBNL) + **ROOT** (CERN), see Poster presentation THPAN076!

J. Qiang, S. Lidia, R.D. Ryne, C. Limborg-Deprey: *Three-dimensional quasistatic model for high brightness beam dynamics simulation,* Phys. Rev. ST Accel. Beams 9 (2006) 044204

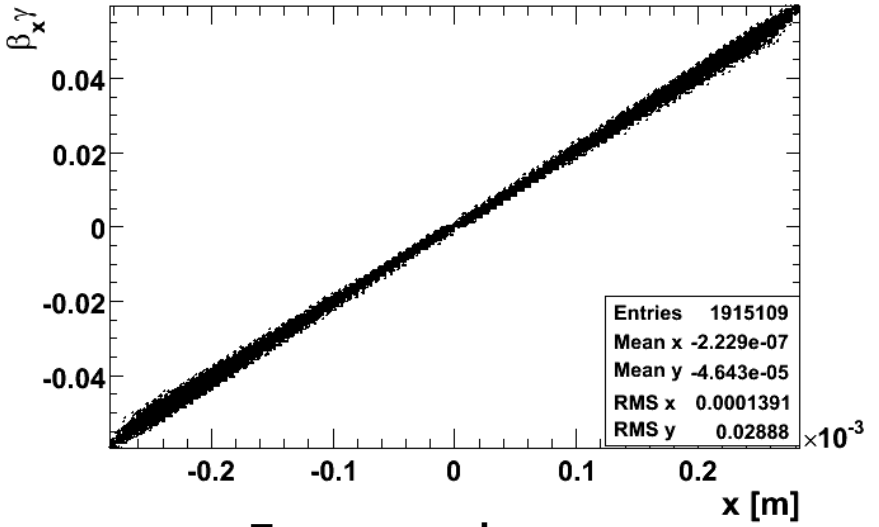


Gun simulation

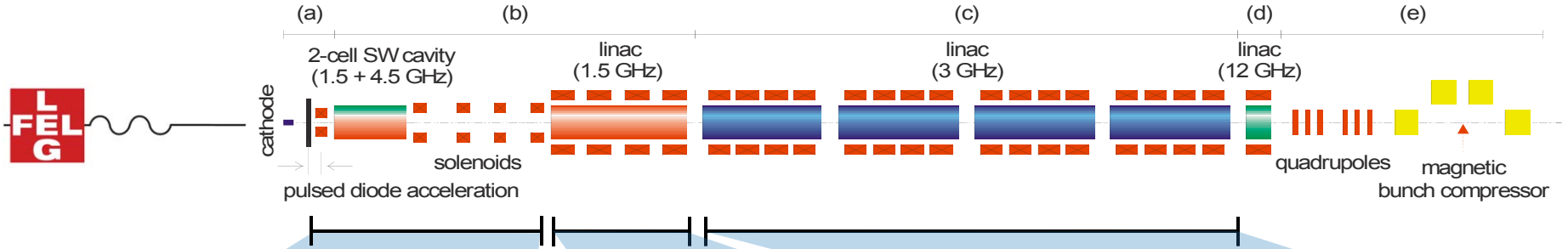
- Long bunch-length (40 ps) and high-gradient acceleration (250 MV/m) at the beginning pose a computational challenge (no common rest-frame for computation of self-fields)
- Solution/approximation: divide bunch into energy bins!
- Emit 0.2 nC in 40 ps in 380 uniform slices at 1 eV energy, then regroup, at each time step, into 32 energy bins for computation of self fields.
- Good agreement with MAFIA simulation



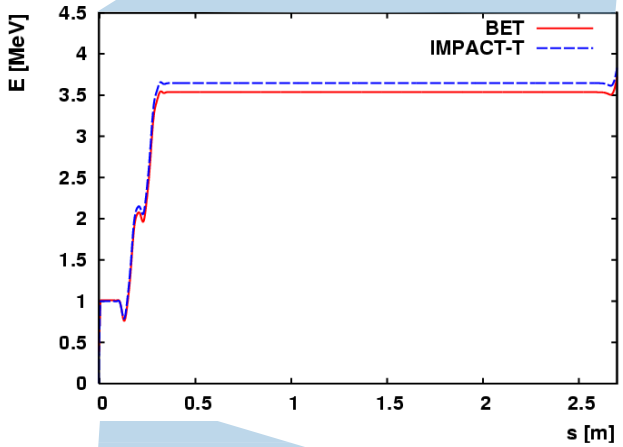
Longitudinal phase space



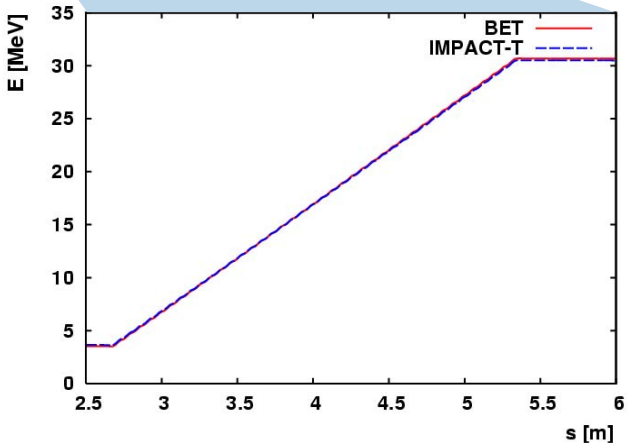
Transverse phase space



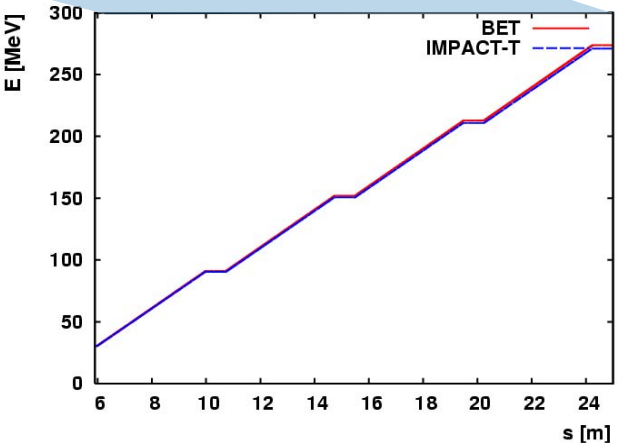
ballistic compression



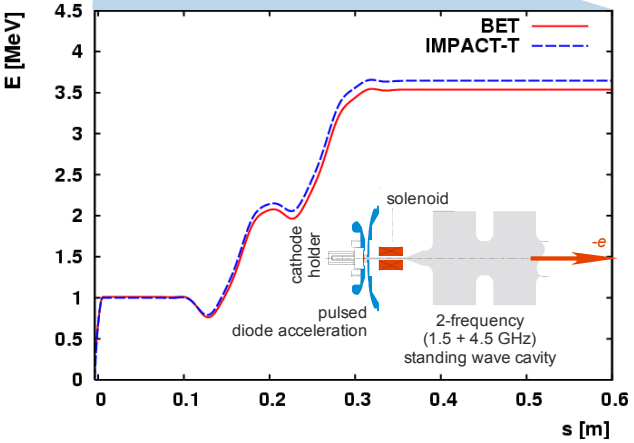
velocity bunching



main acceleration

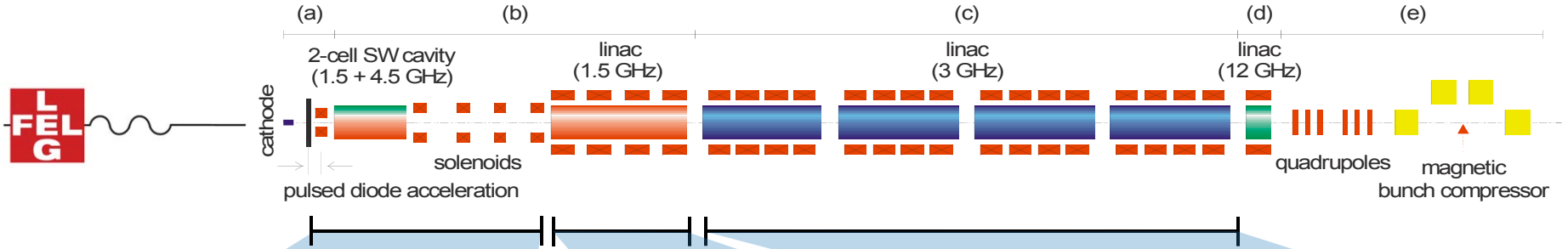


capture cavity

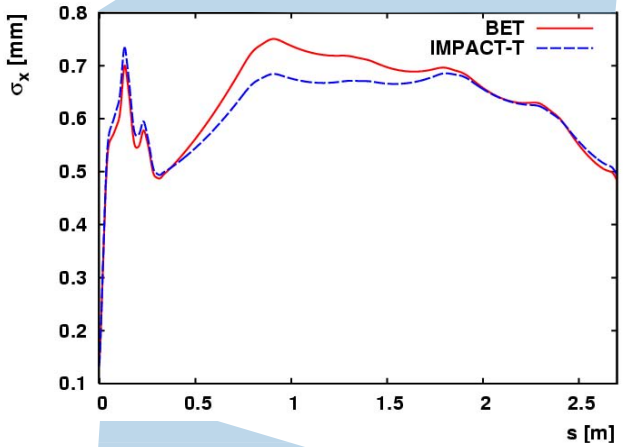


Results (1): energy profile

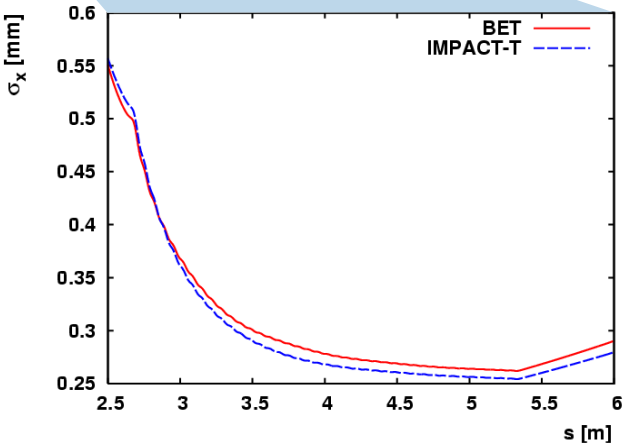
PAUL SCHERRER INSTITUT



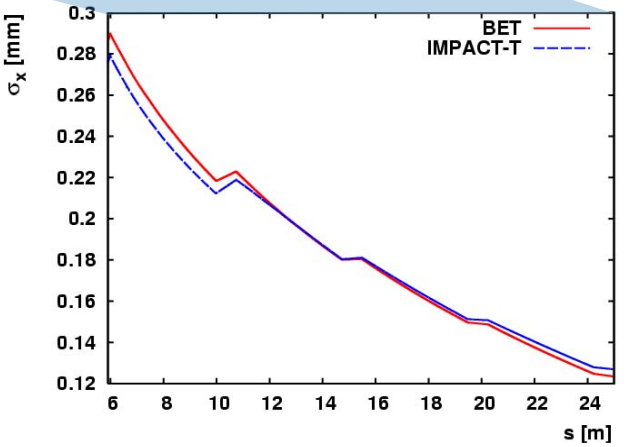
ballistic compression



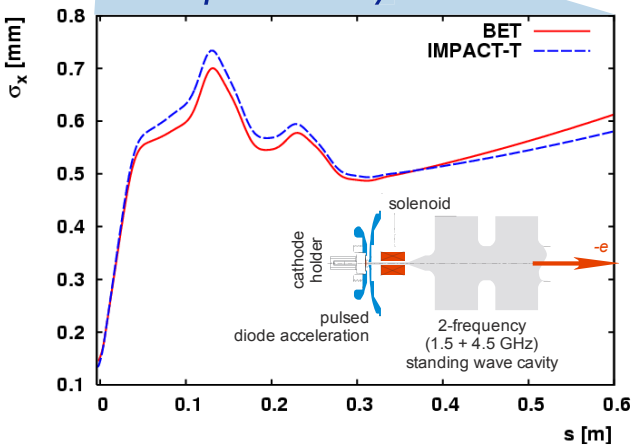
velocity bunching



main acceleration



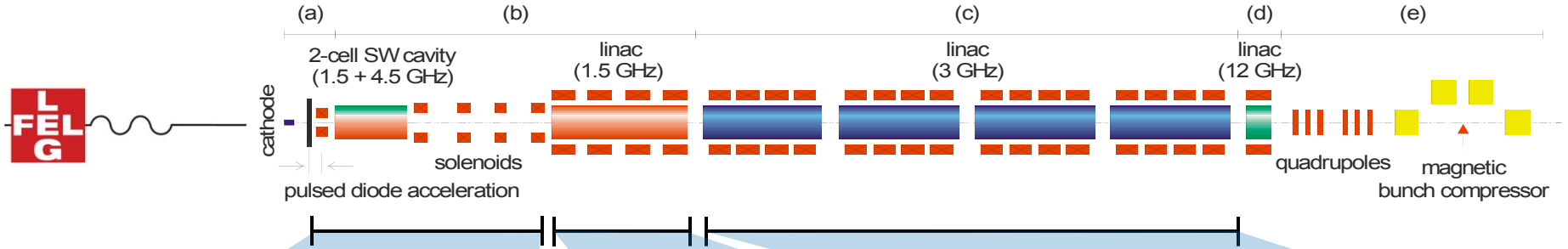
capture cavity



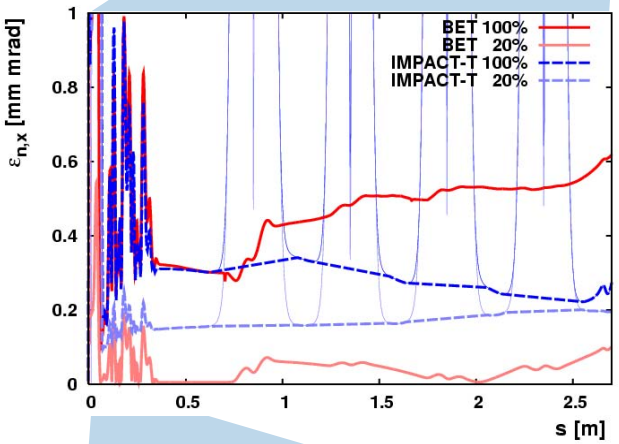
Results (2): beam size

Beam optics readjusted after every component to match beam size – important to ensure that space charge effects remain comparable.

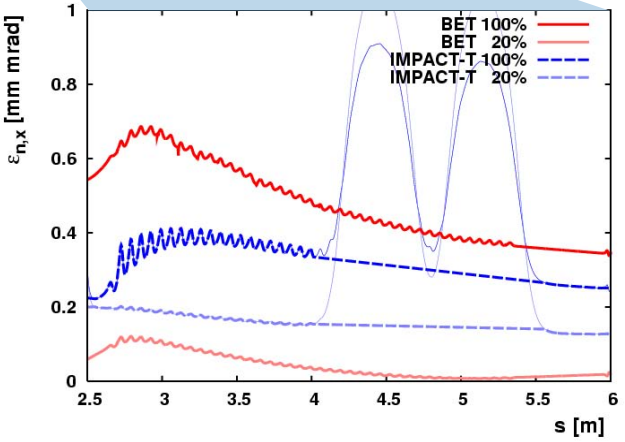
PAUL SCHERRER INSTITUT



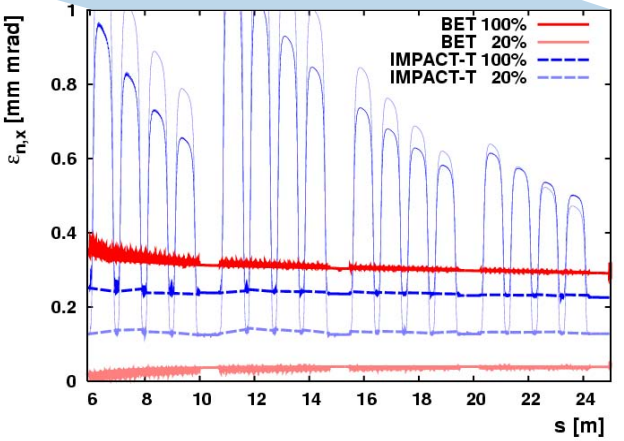
ballistic compression



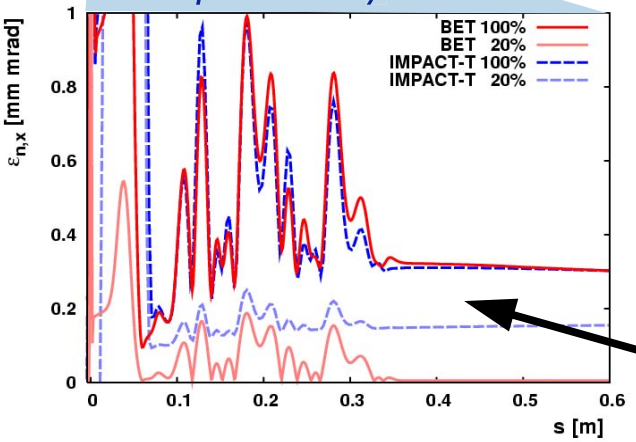
velocity bunching



main acceleration



capture cavity



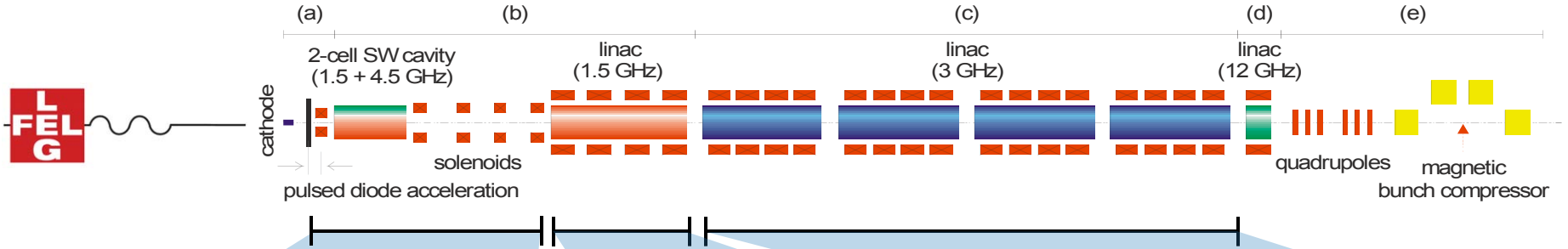
Results (3): emittance

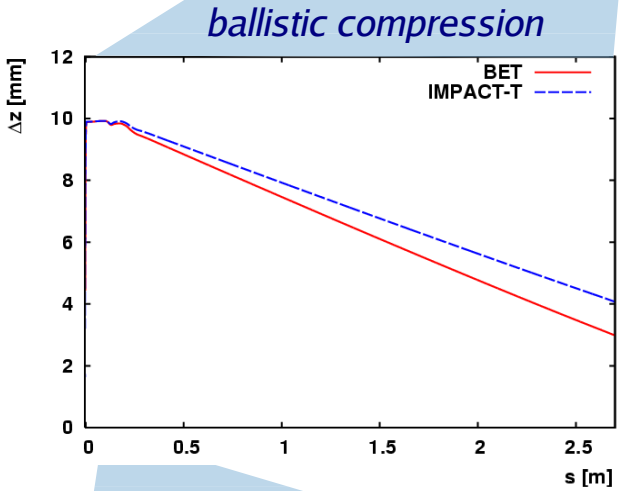
Emittance blow-up in solenoids in 3D code due to electrons spiraling in B-field (Busch theorem)

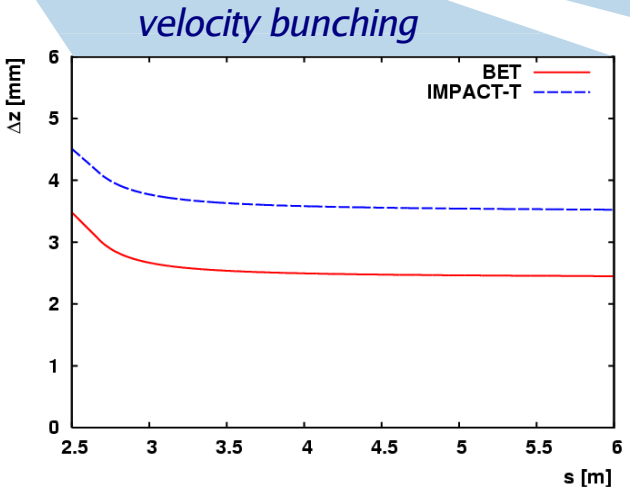
Slice emittances are central 20%

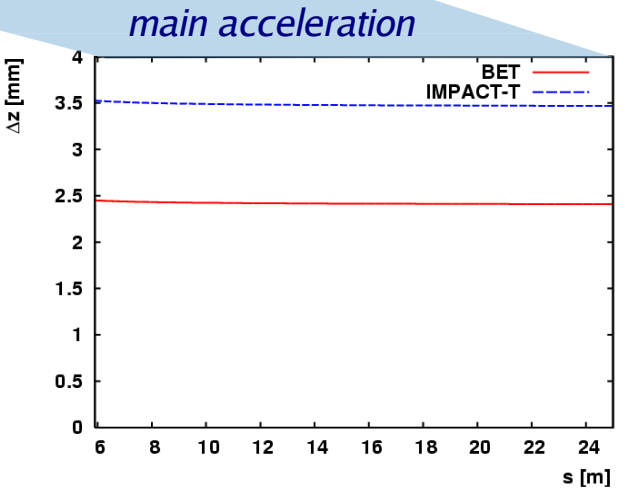
Very good agreement in two-cell capture cavity!

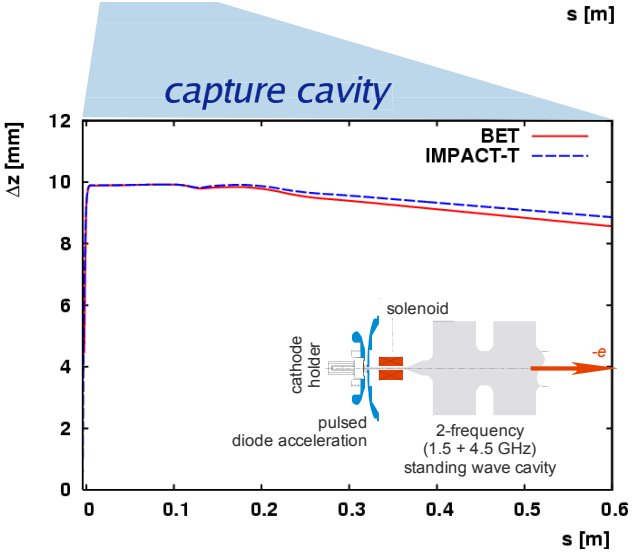
PAUL SCHERRER INSTITUT











Results (4): bunch length

Less ballistic compression in 3D code:

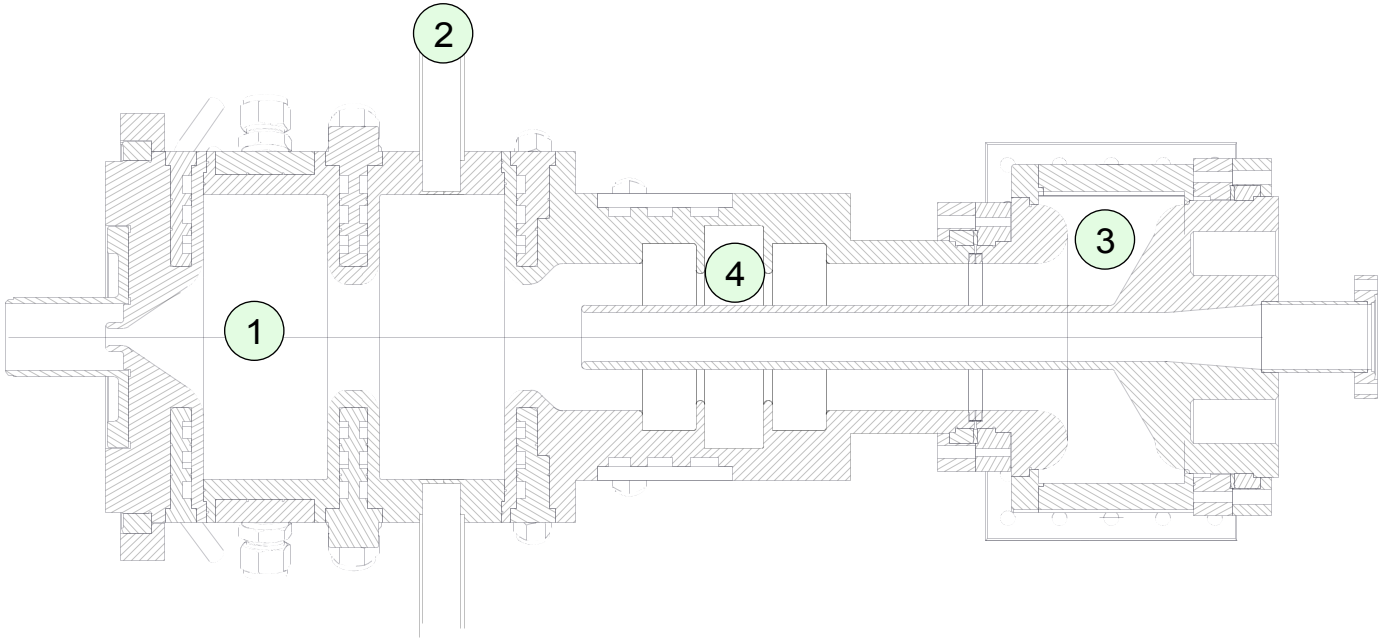
- probably due to small mismatch in phase in 2-cell cavity
- work in progress...

PAUL SCHERRER INSTITUT

Summary

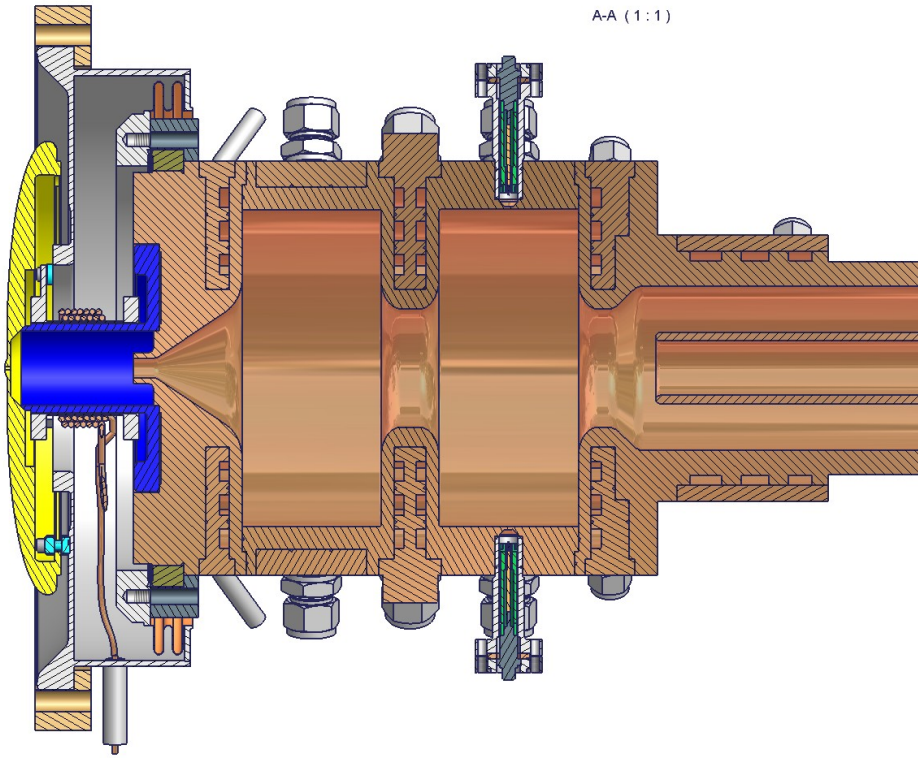
- First **full 3D simulation** of PSI XFEL injector... almost finished!
- In general validates **emittance conservation** and **bunch compression** strategy.
- Next steps:
  - Improve matching between the two codes
  - Error studies (component misalignment, field tolerances, etc.)
  - Utilize experimental input from 4-MeV test stand to refine simulation.
  - **Start construction in 2008!**

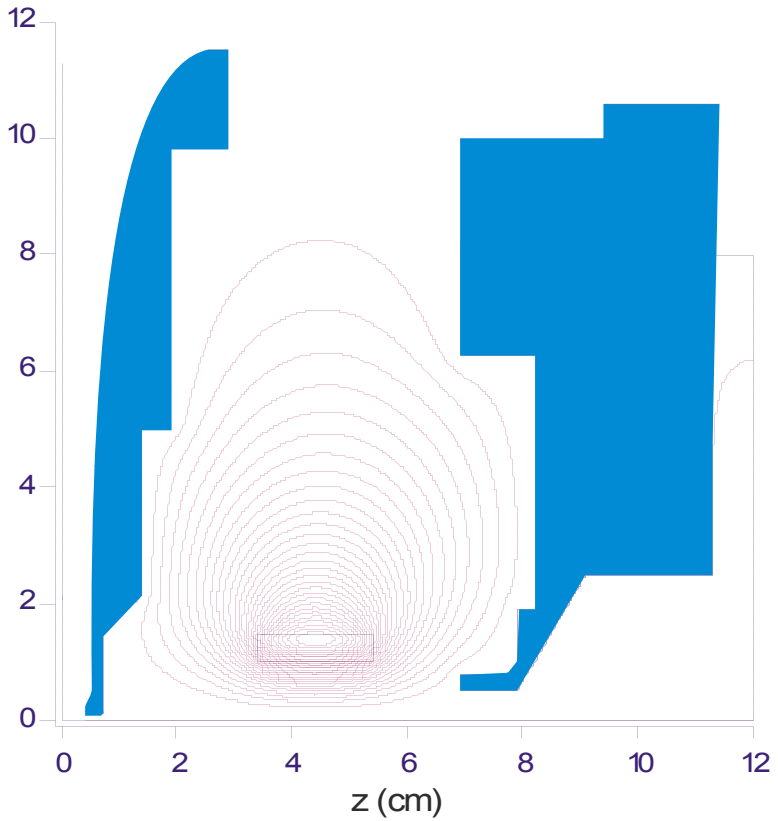
Two-cell capture cavity



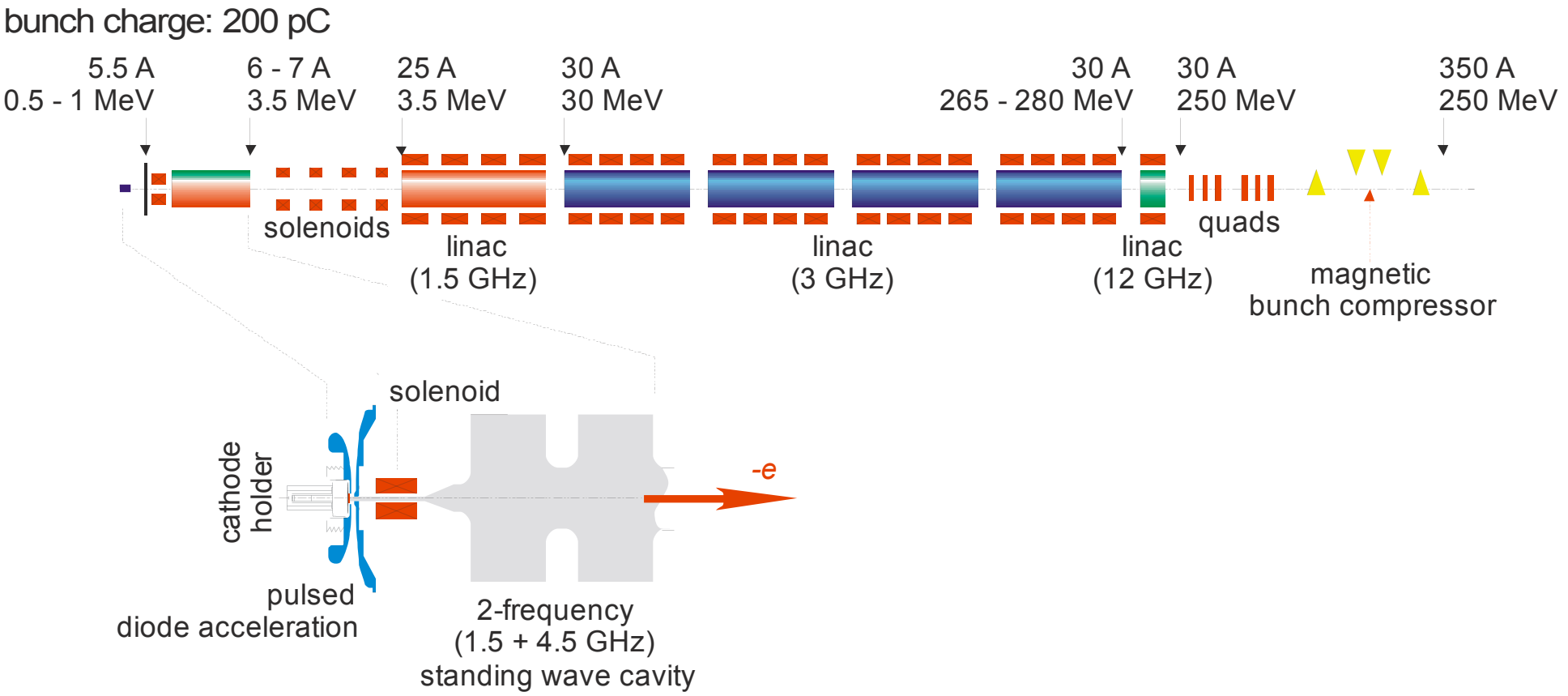
1) Two-cell cavity
2) 3rd harmonic double feed side coupling
3) Fundamental double-feed doorknob coupler
4) 3rd harmonic rejection filter

Diode / capture cavity configuration



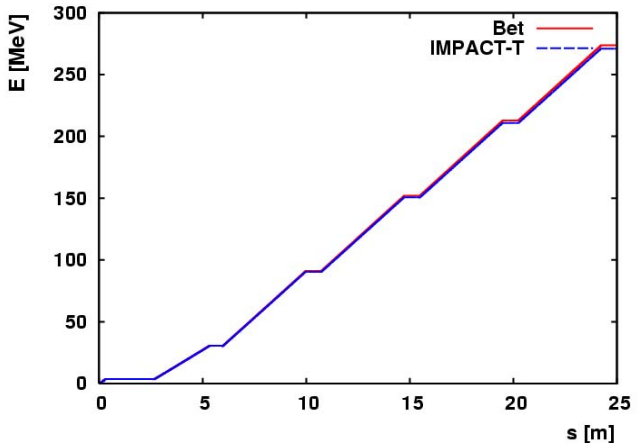


PSI XFEL Injector (schematic)

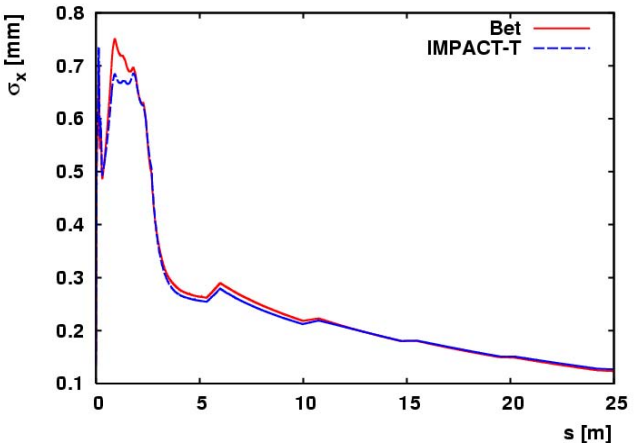


Plots for total length

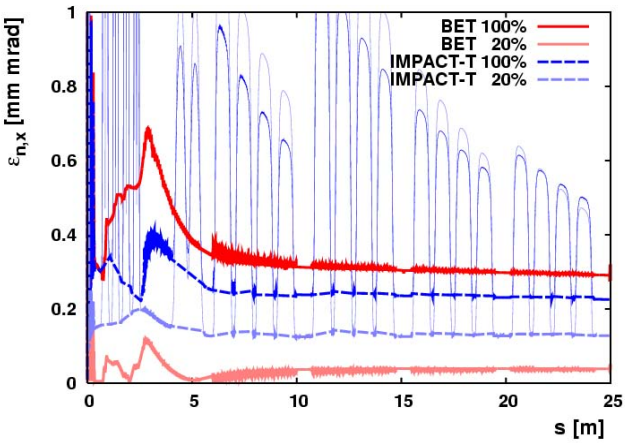
Energy profile



Beam size



Emittance



Bunch length