



Energy Recovery Linacs

Virtual beam power for a multitude of applications

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The CERN Accelerator School
Advanced Accelerator Physics Course
Warsaw, 03.10.2015

Content

Energy Recovery Linacs – Why and How ?

storage ring versus linac (real ↔ virtual power, equilibrium ↔ control)
the ERL principle and its promises

History

first idea, first tests, first projects

Applications

multi-user light sources, collider, cooler, compact sources

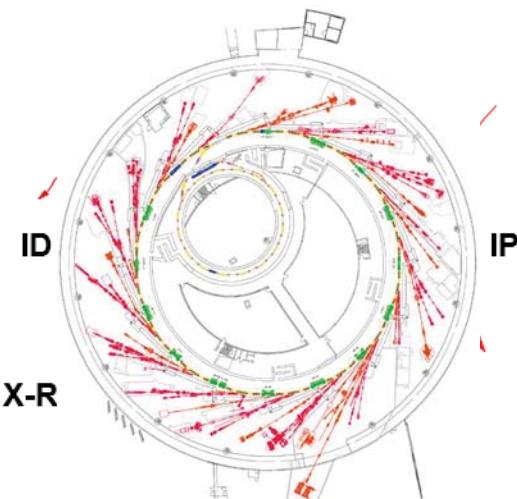
Challenges

electron source, beam optics, beam break up, collective effects, unwanted beam
at the example of the Berlin Energy Recovery Linac Project bERLinPro

more details on many aspects:
<https://www.bnl.gov/erl2015/>

ERL2015, ICFA Workshop
Stony Brook University

Storage ring ↔ linac – virtual ↔ real power



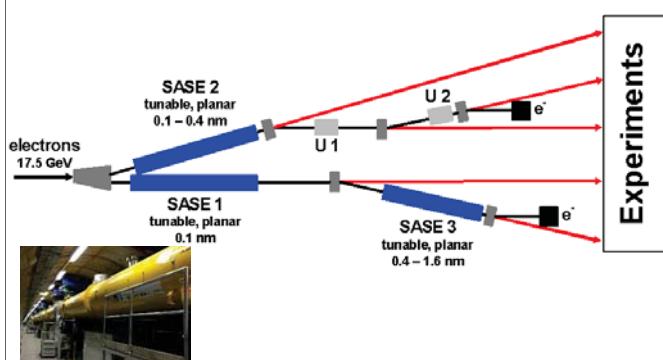
synchrotron radiation source, collider

$$P_{\text{virtual}}[\text{W}] = E[\text{eV}] \cdot I[\text{A}]$$

$$E_{\text{stored}}[\text{J}] = E[\text{eV}] \cdot I[\text{A}] \cdot T_{\text{rev}}[\text{s}]$$

e.g. BESSY II, 3rd generation light source

1.7 GeV, 300 mA = 510 MW virtual beam power,
thereof ca. 90 kW synchrotron radiation power
(and only 408 J stored energy)



free electron laser, collider, fixed target

$$P_{\text{real}}[\text{W}] = E[\text{eV}] \cdot I[\text{A}]$$

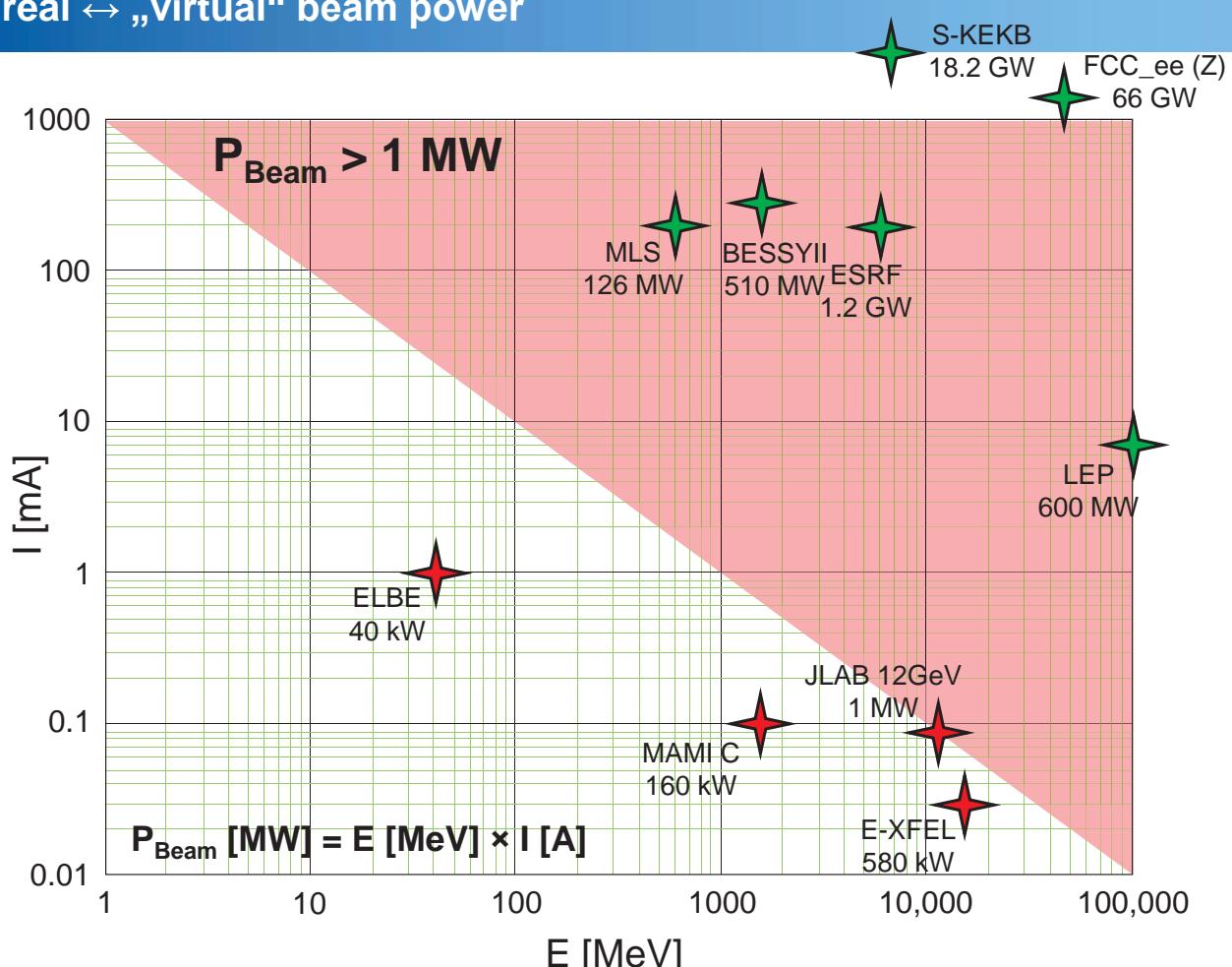
e.g. European XFEL, 1 Å hard X-ray source

17.5 GeV, 0.033 mA = 580 kW real beam power,
ca. 100 GW peak power in 100 fs, 10 x 2700 pps,
ca. 500 W

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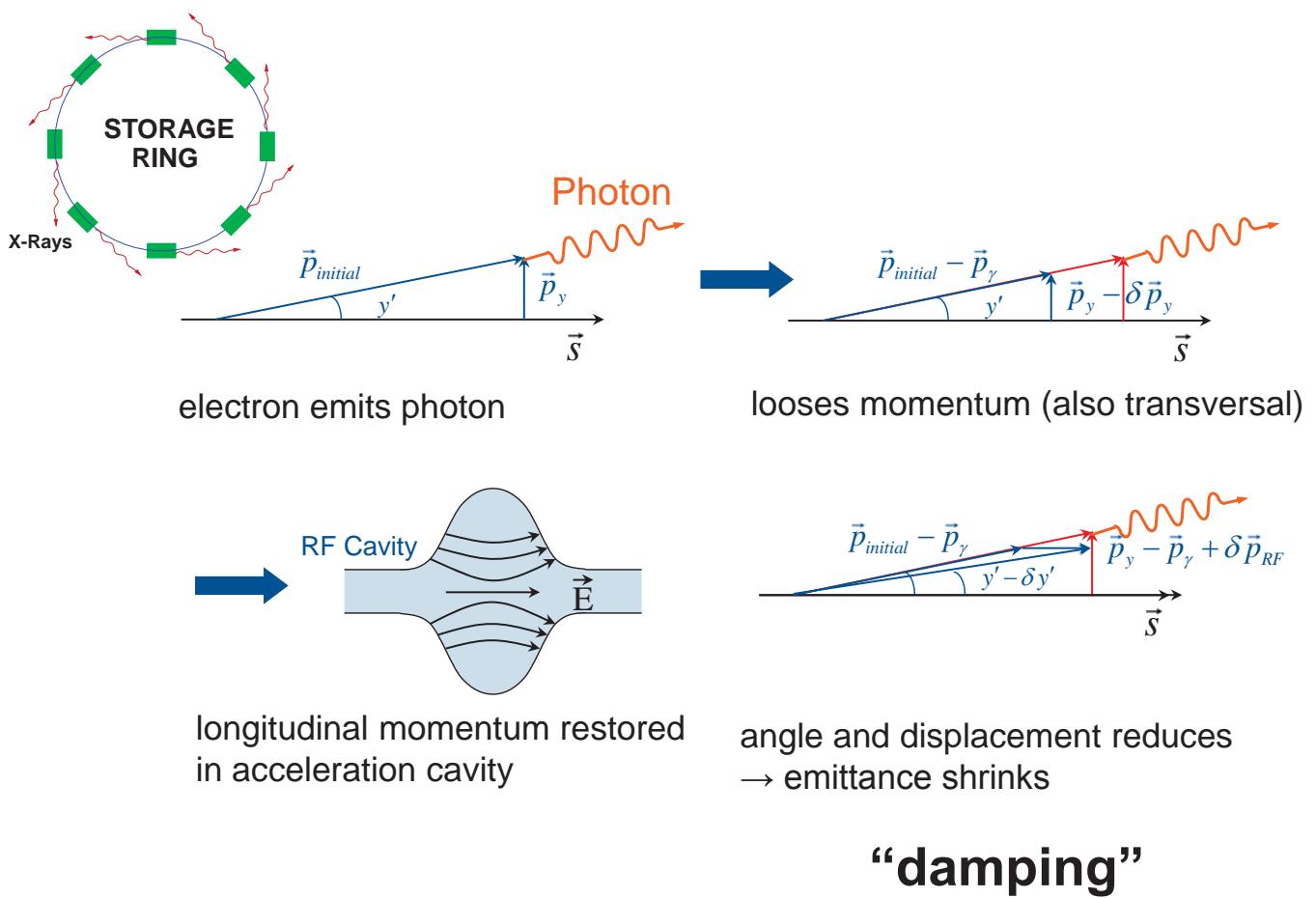
real ↔ „virtual“ beam power



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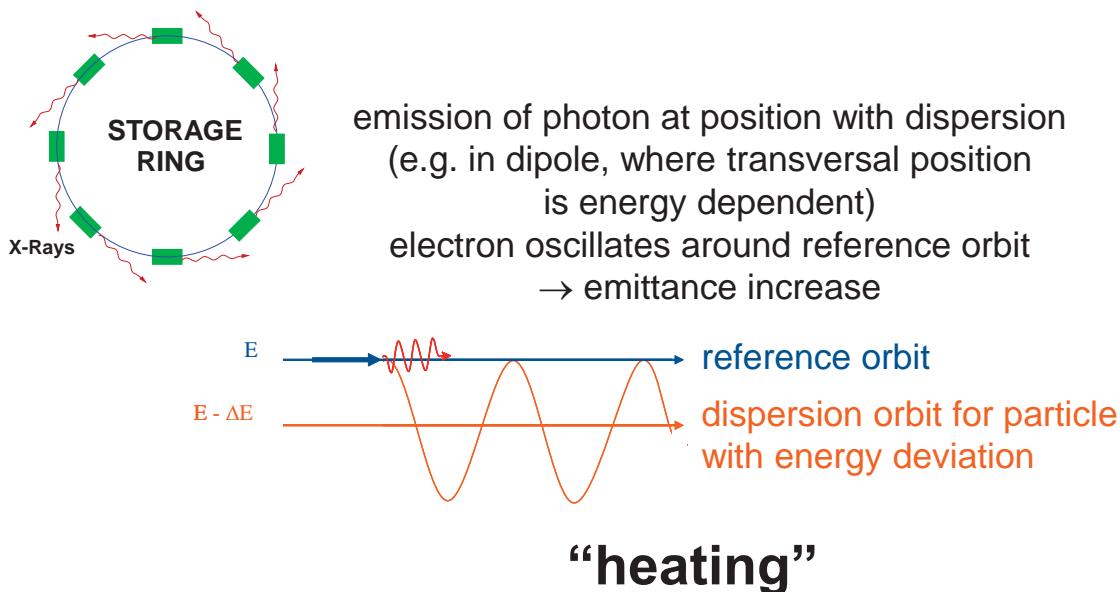
Storage ring – governed by equilibrium processes



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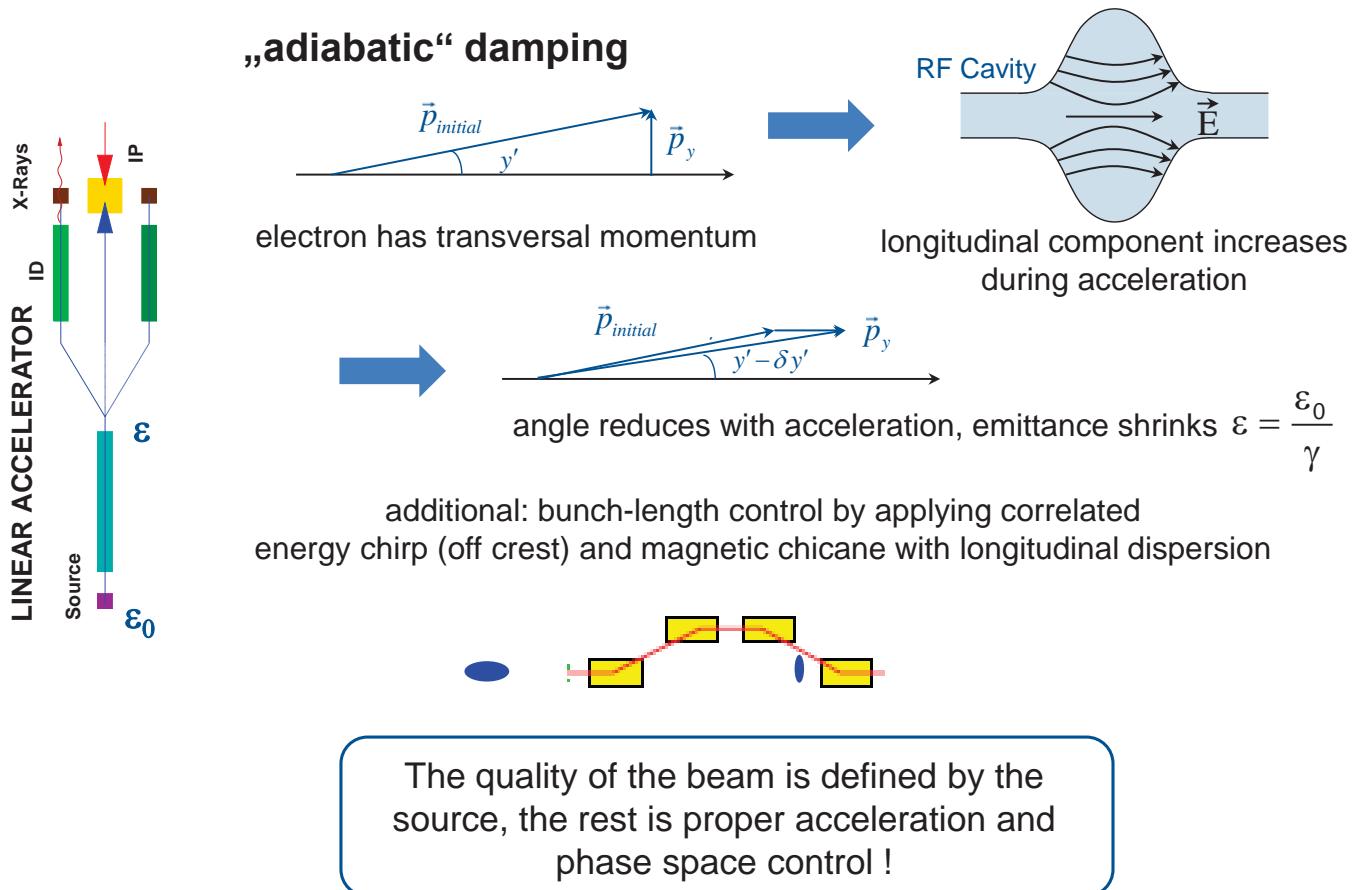
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Storage ring – governed by equilibrium processes



emittance is defined by an equilibrium between these two processes (damping and heating)
typical order: some nm rad horizontal (1/100 vertical)
similar process defined energy-spread and pulse length

Linac – governed by adiabatic damping and control



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Storage ring versus Linac

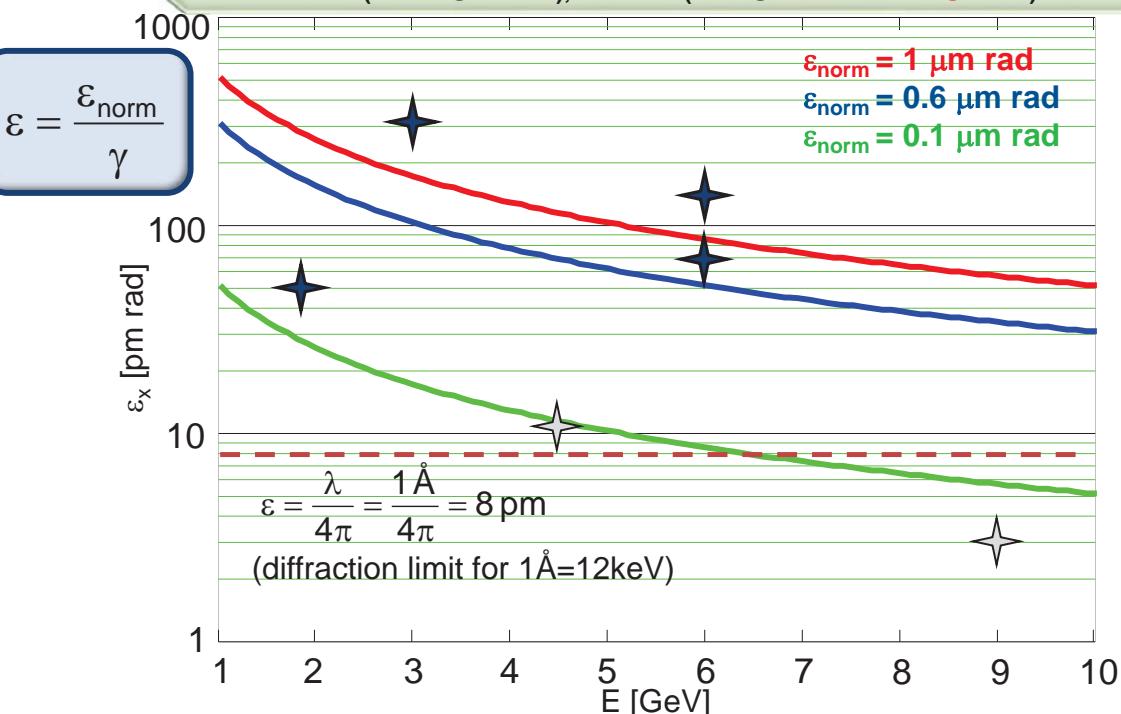
equilibrium beam dimensions	adiabatic damping + control
$\epsilon_x = C_\gamma \cdot \frac{\gamma^2}{J_x} \cdot \frac{\left\langle \frac{1}{R^3} H(s) \right\rangle}{\left\langle \frac{1}{R^2} \right\rangle} \sim \frac{\gamma^2}{N^3}, \epsilon_y = \kappa \cdot \epsilon_x$	$\epsilon_{x,y} = \frac{\epsilon_0}{\gamma}$
$\frac{\sigma_E}{E} \sim \frac{\gamma}{\sqrt{\rho}}$	$\left(\frac{\sigma_E}{E} \right)_0 \sim \frac{1}{\gamma}$
$\sigma_s \sim \sqrt{\frac{\alpha}{V'}} \cdot \sigma_E$	$\sigma_s = f(\sigma_0)$ plus bunch manipulation

“virtual (internal) power”

real (external) power

Beam emittance – single pass machine ↔ storage ring

3rd generation light sources in operation (selection):
 ALBA (5 nm@3 GeV), SOLEIL (4 nm@2.7 GeV), DIAMOND (3 nm@3 GeV),
 ESRF (4 nm@6 GeV), APS (3 nm@7 GeV), SPring8 (3nm@8 GeV)
 ALS (2.2 nm@1.9 GeV), PETRAIII (1 nm@6 GeV / **0.16nm@3GeV**)



- MBA ultra low emit. lattices:
 - 320 pm, MAX IV (commissioning)
 - 147 pm, ESRF II (2020 back in op.)
 - 65 pm, APS (design phase)
 - ~50 pm, ALS-U (design phase)
- 11 pm, PEPX (design study)
- 3 pm, tUSR (design study)

Storage rings: low emittance goes hand in hand with necessity to operate with long bunches (50 ps – 200 ps) to reduce Touschek and IBS scattering!

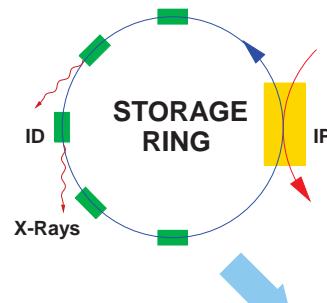
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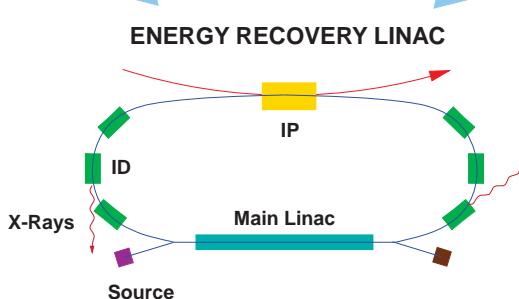
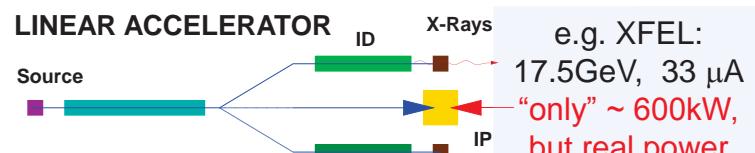
Energy Recovery Linacs – The idea

- high average („virtual“) beam power (up to A, many GeV)
- many user stations
- beam parameter defined by equilibrium
- typical long bunches (20 ps – 200 ps)

e.g. ESRF:
 6 GeV, 200 mA
1.2 GW
 virtual power,
 stored energy
 only 3380 J



- outstanding beam parameter
- single pass experiments
- high flexibility, short bunches (~ 10 fs)
- low number of user stations
- limited average beam power (<<mA)



$$\epsilon \sim \frac{1}{\gamma} \cdot \epsilon_{\text{source}}$$

intrinsic short bunches, high current

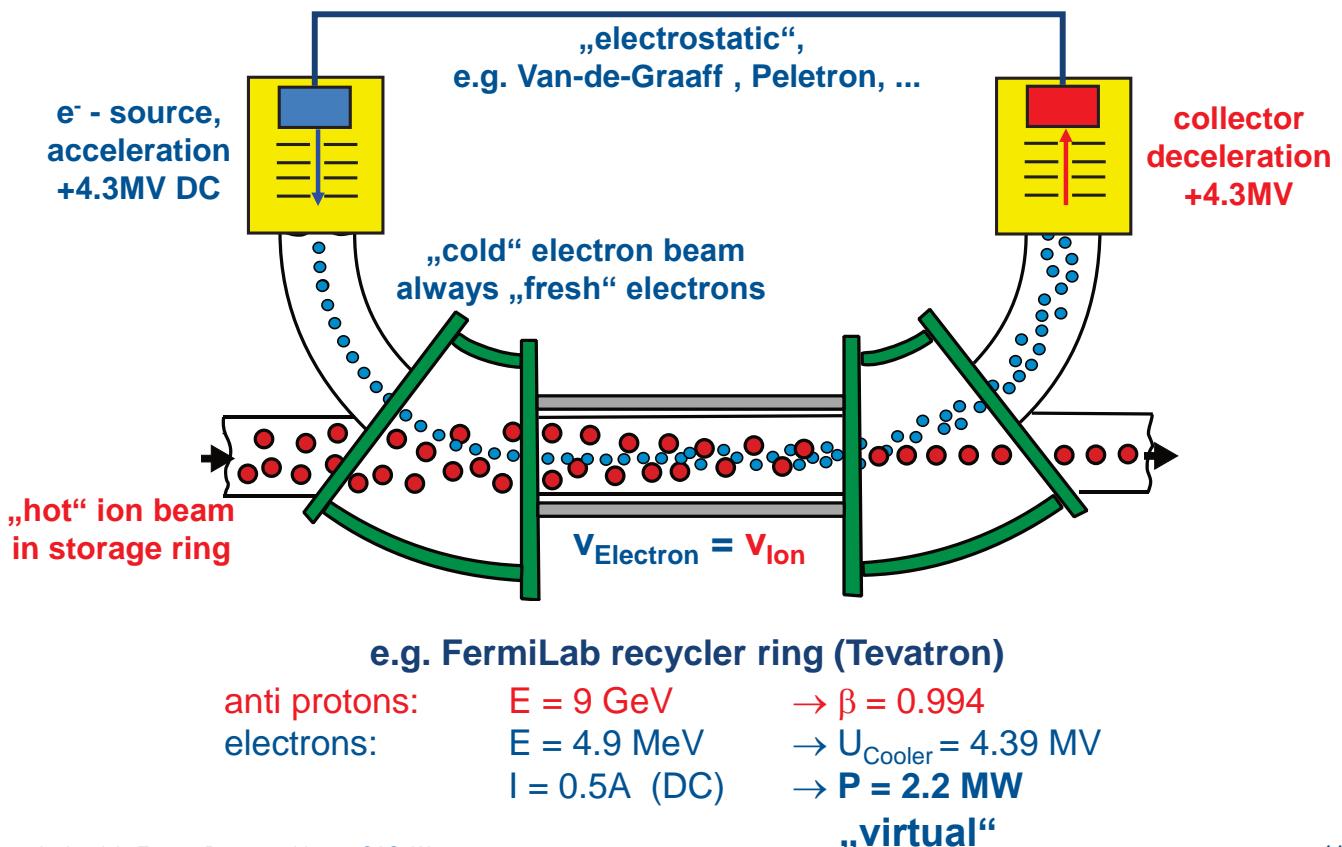
high average beam power (multi GeV @ some 100 mA) for single pass experiments, excellent beam parameters, high flexibility, multi user facility

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Energy recovery (nothing spooky)

e.g. „electron cooler“ for ion beams, first devices in the 70ies

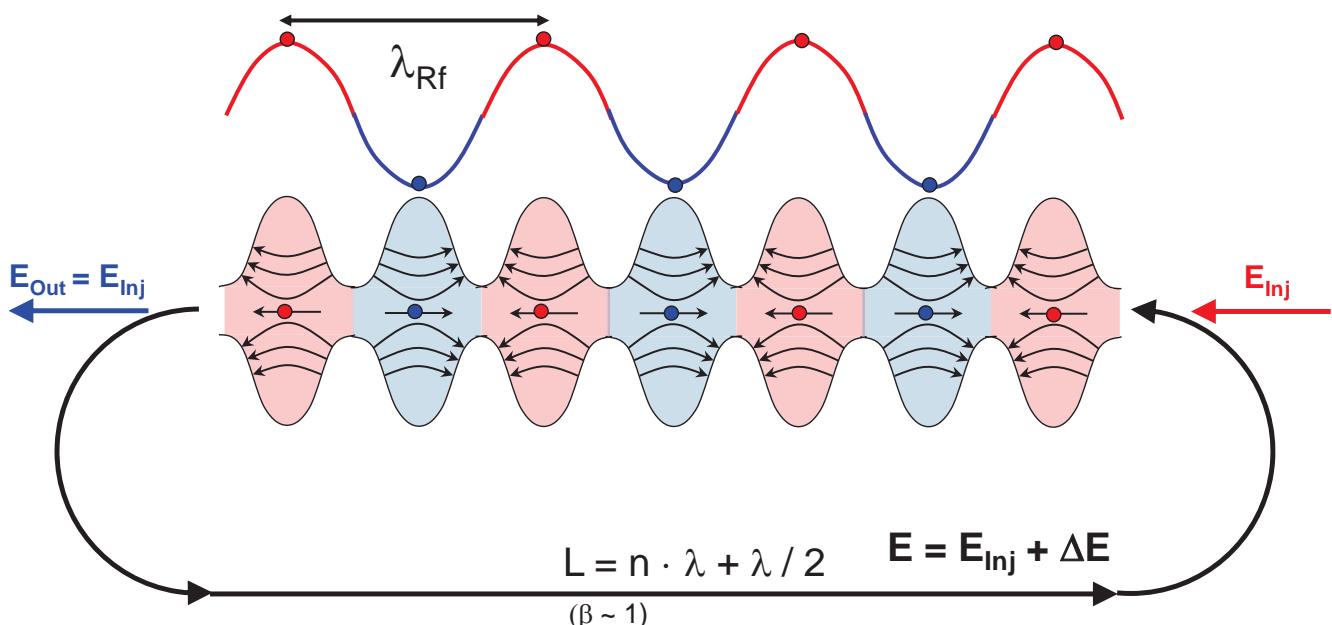


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Energy recovery in RF-fields – braking the DC limit

RF linear accelerator



Energy supply = acceleration

→ „loss free“ energy storage (in the beam)

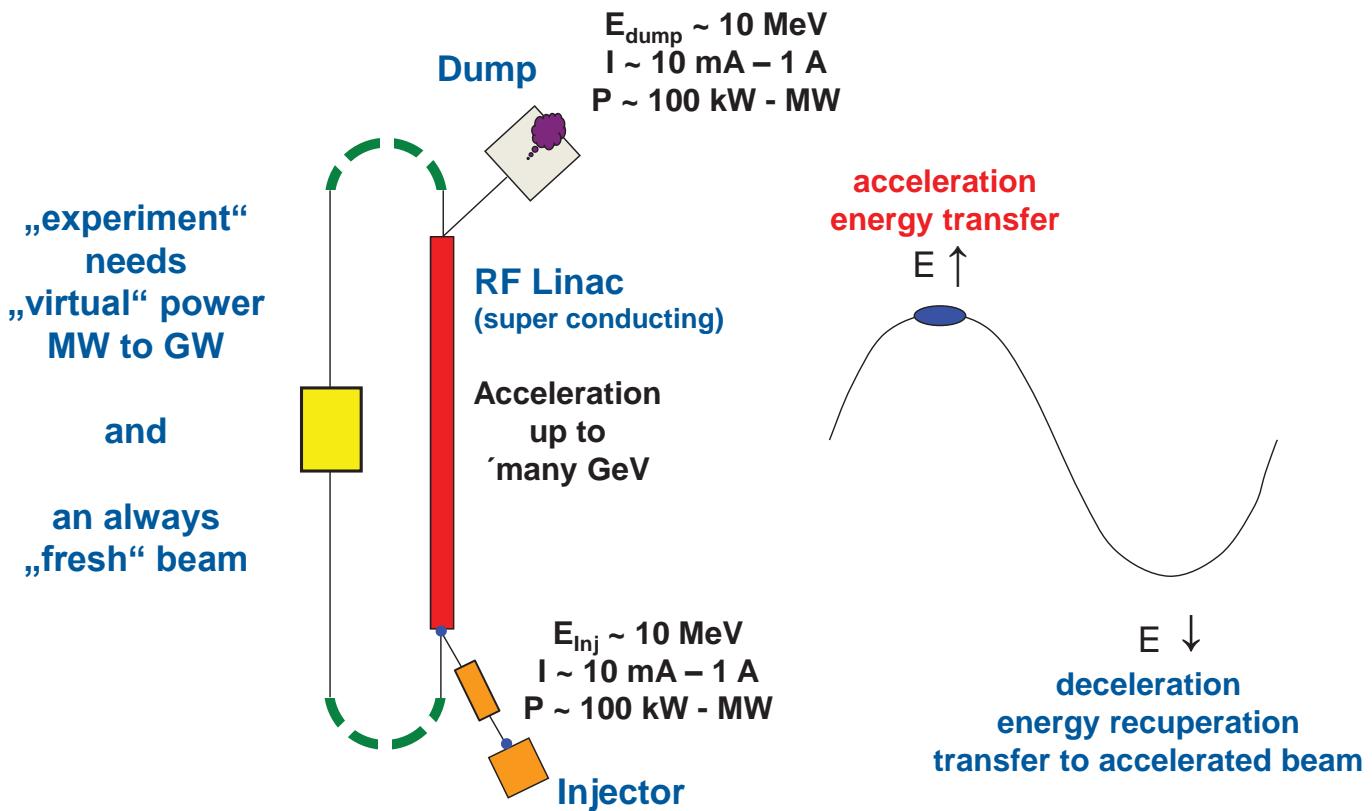
→ Energy recovery = deceleration

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The Energy Recovery Linac Principle



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ERLs are in favor of superconducting RF

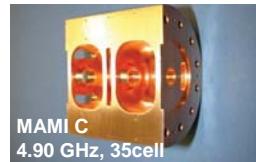
normal conducting (Cu) RF

(typical S/C-Band, ~2 – 6 GHz)

$$\Delta E \sim 1 \text{ MV/m} / P_{\text{RF}} \sim 15 \text{ kW/m (CW)}$$

(in short structures 210 kW/m reached = 3.8 MV/m)

pulsed operation allows ~ 50 MV/m, but duty cycle reduced by min $1/50^2 = 0.4 \%$



cw high current operation hampered by limited HOM damping capabilities

(efficiency needs long structures with many cells, apertures typical only 10-20mm)

super conducting (Nb) RF

(L-Band, ~ 1 – 2 GHz)

$$\Delta E \sim 20 \text{ MV/m} / P_{\text{RF}} \sim 20 \text{ W/m (CW)}$$

(JLAB upgrade: 19.2 MV/m)

large apertures (70mm+) and low number of cells allows efficient HOM damping



SC RF allows to built an ERL “compact” (high gradient) for high current cw operation (large apertures, strong HOM damping)

Wall plug power consumption shifts from RF to Cryo (2K efficiency ~ 1/1000)
ERL is not necessarily a “green machine”



History – First idea

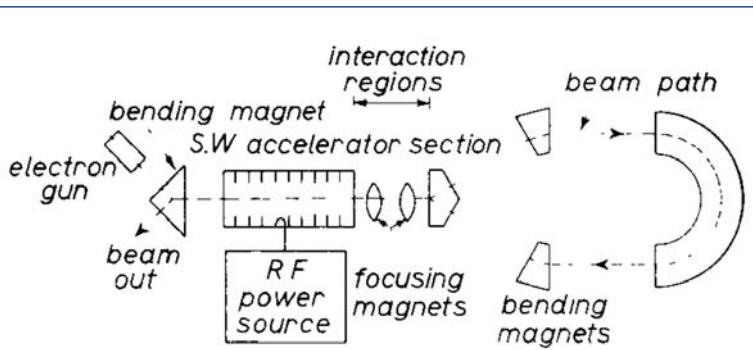
First idea: M. Tigner, Nuovo Cimento 37 (1965) 1228

A Possible Apparatus for Electron Clashing-Beam Experiments (*).

M. TIGNER

Laboratory of Nuclear Studies, Cornell University - Ithaca, N. Y.

(ricevuto il 2 Febbraio 1965)



- stability issues (charge) solved
- one linac only

Maybe first realisation
(1977, without taking attention to it):
Reflexotron (two pass linac) for
medical application
(Chalk River, Canada)

S.O. Schreiber, IEEE NS-22 (1975) (3) 1060-1064

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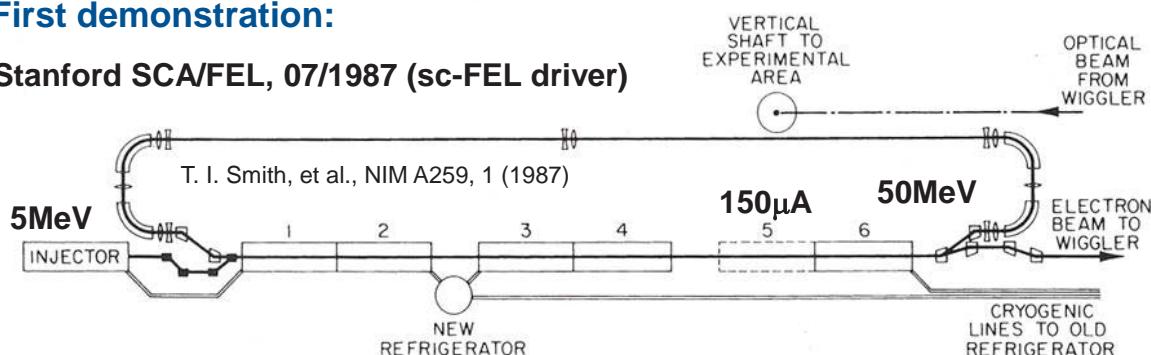
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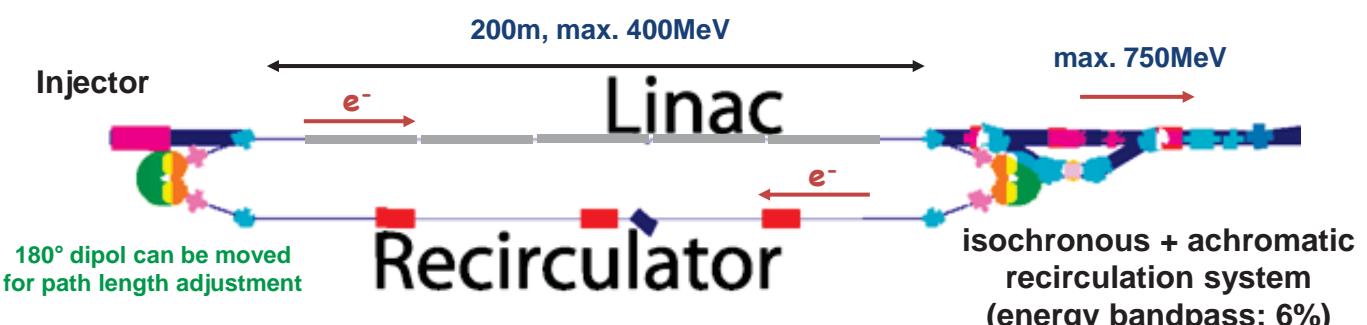
History – First demonstration

First demonstration:

Stanford SCA/FEL, 07/1987 (sc-FEL driver)



MIT Bates Recirculated Linac (2.857GHz, nc, pulsed), 1985



J.B. Flanz et al., IEEE Trans. Nucl. Sci., NS-32, No.5, p.3213 (1985)

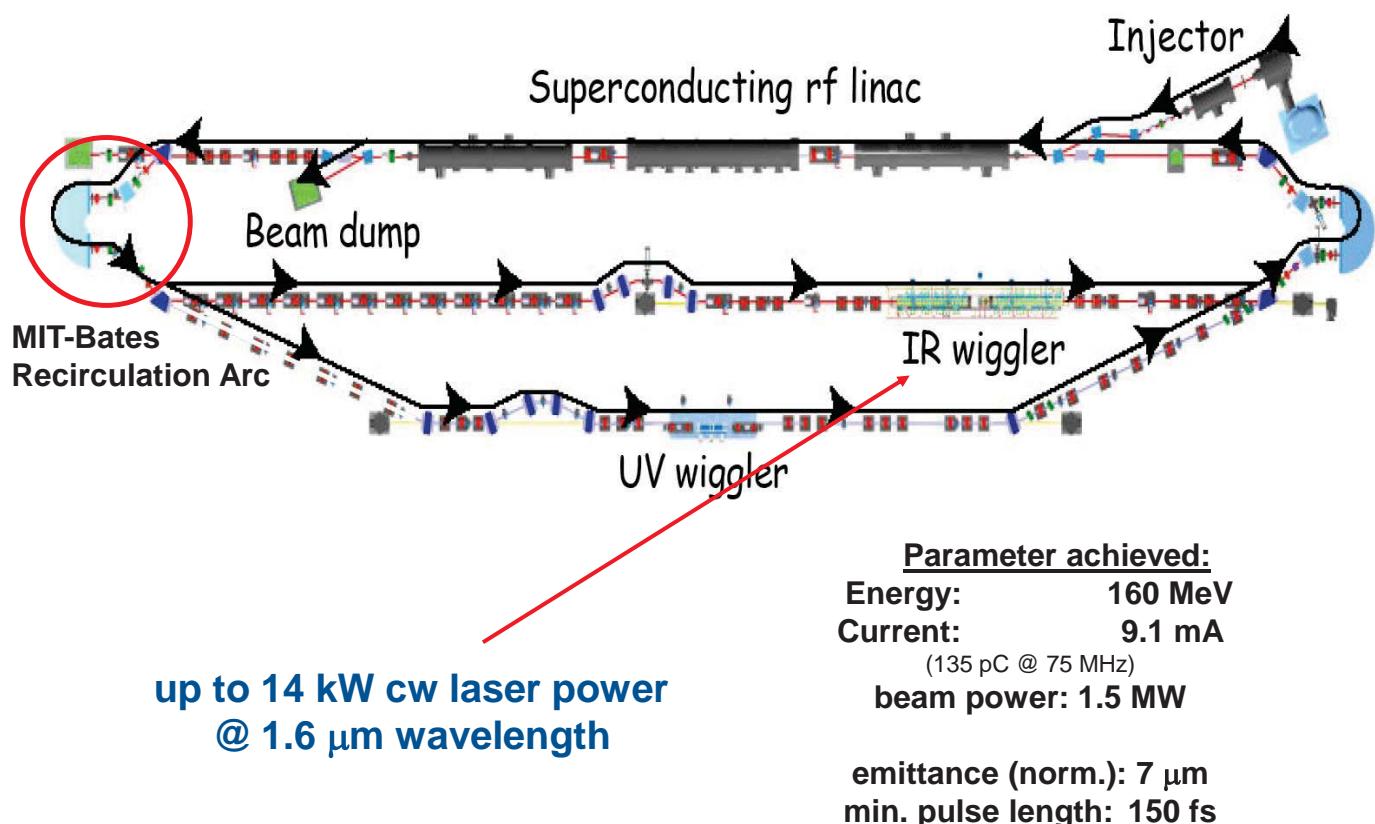
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First facilities – JLAB FEL

G.R. Neil, et al., Nucl. Instr. & Methods A557 (2006) 9.



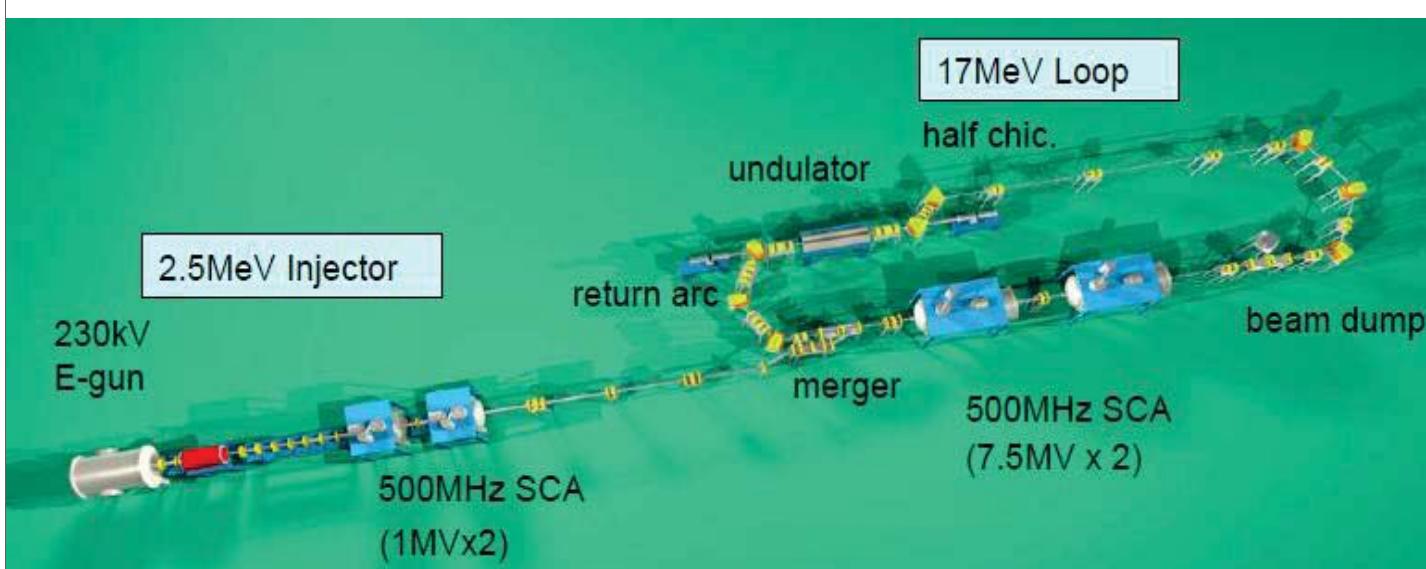
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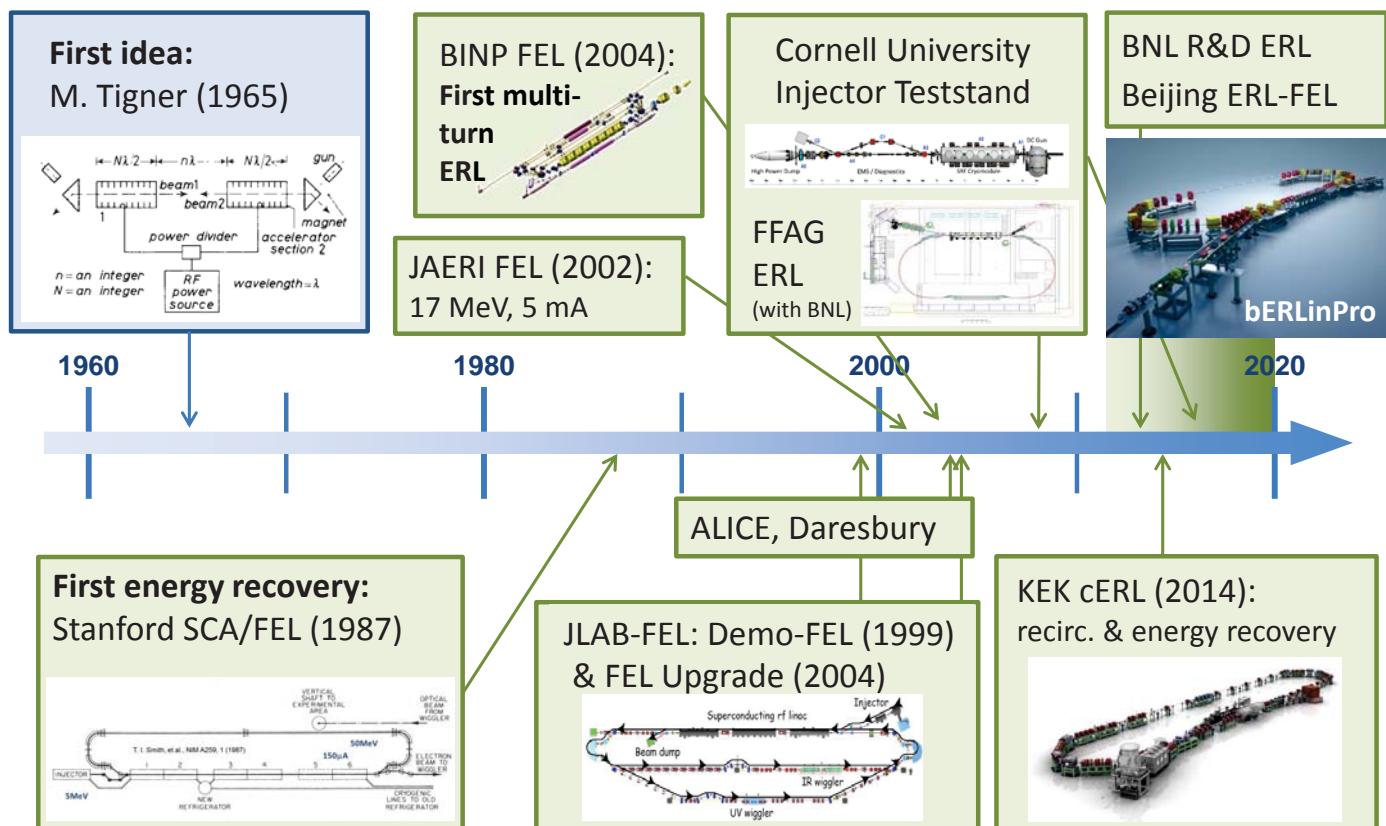
First facilities – KEK / JAEA ERL FEL

JAEA IR-FEL (starts 1987, JAERI):
500 MHz sc cavities, 15 – 20 MeV, 8 mA → 2 kW cw laser power @ 22 μm
at the beginning single pass → 2002 upgrade to energy recovery setup



**Around 2005: KEK and JAEA proposes ERL based light sources (5 GeV)
Decision to built in an common effort: Compact ERL !**

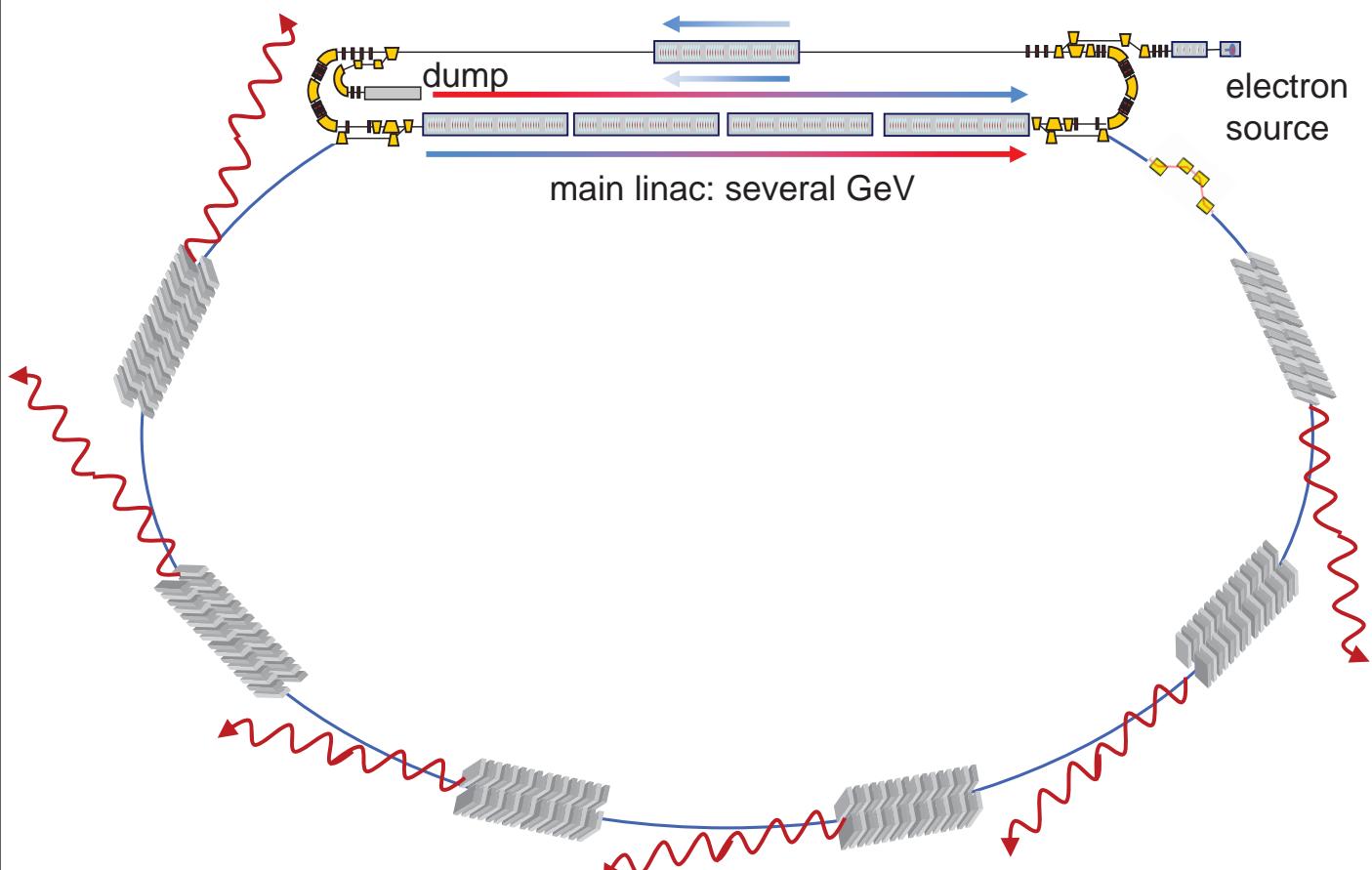
Overview on projects and facilities



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ERL as next Generation Multi-GeV, Multi-User SR-Source



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ERL as next Generation Multi-GeV, Multi-User SR-Source

Combines the two worlds of storage rings and linacs

- with energy recovery: some 100mA @ many GeV possible
- always “fresh” electrons (no equilibrium)
 - small emittanz ($\sim 0.1 \mu\text{m rad}$ norm. = 10 pm rad @ 6GeV)
 - high brilliance ($\times 100 - 1000$ compared to SR)
 - short pulses (ps down to 10 – 100 fs)
- free choice of polarisation
- 100% coherence up to hard X-rays
- real multi-user operation at many beam lines
- tailored optics at each ID

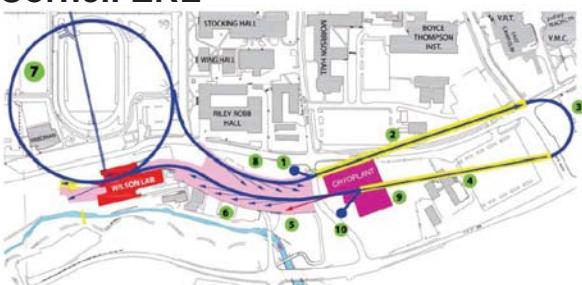
**Flexible modes of operation (high brilliance, short pulse, different pulse patterns)
adaptable to user requirements!**

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ERL light source design studies

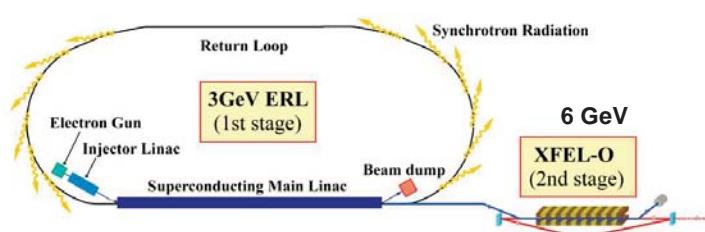
Cornell ERL



5 GeV, 100mA, $\epsilon = 8 \text{ pm rad}$

($\epsilon_{\text{norm}} = 0.08 \mu\text{m}$ (@77pC), 2ps)

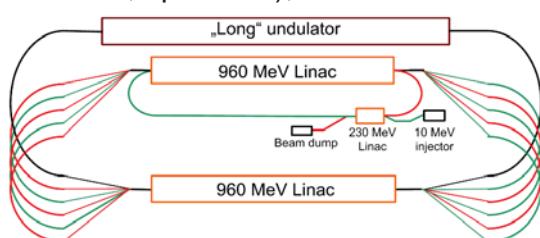
KEK ERL



3 GeV, 100mA, $\epsilon = 17 \text{ pm rad}$

($\epsilon_{\text{norm}} = 0.1 \mu\text{m}$ (@77pC), 2ps)

Femto Science Facility (FSF) (multi turn, split linac), A. Matveenko et al.



6 GeV, 20/5 mA, $\epsilon = 8/40 \text{ pm rad}$

($\epsilon_{\text{norm}} = 0.1/0.5 \mu\text{m}$ (@15/4 pC), < 1 ps / 10 fs)

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ELR as electron part of Electron Ion Collider

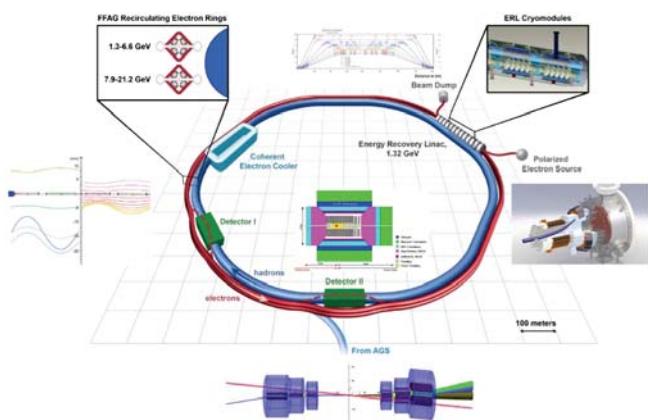
e.g. eRHIC: addition of a ERL to RHIC / BNL = Electron Ion Collider

250 GeV polarised protons \leftrightarrow 20GeV polarised electrons, $L=10^{33-34} \text{ cm}^{-2} \text{ s}^{-1}$

(415 mA)

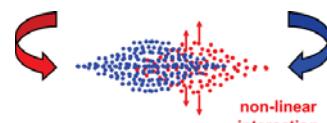
(10 mA)

($\beta^*=5\text{cm}$, $6\mu\text{m}$ spot size @ IP)



ERL compared to storage ring

- electron beam needs to pass the interaction zone only once
- disturbance of electron beam by proton beam can be up to 20x stronger
- higher number of protons with high density possible
→ drastic increase in luminosity
- higher flexibility in interaction region design
- spin transparency (free choice to arrange spin orientation at IP)



Why ERL and not storage ring?

Luminosity

$$L = f_{\text{coll}} \cdot \frac{n_{\text{ion}} \cdot n_e}{4 \cdot \pi \cdot \varepsilon \cdot \beta} \cdot F_{\text{HGR}}$$

Limit: beam-beam parameter electrons (!)

$$\xi_e = \frac{r_{0,e}}{4\pi} \cdot \frac{n_{\text{ion}}}{\gamma_e} \cdot \frac{\beta_e^*}{\varepsilon_{\text{ion}} \cdot \beta_{\text{ion}}^*} < 0.1$$

non-linear
interaction

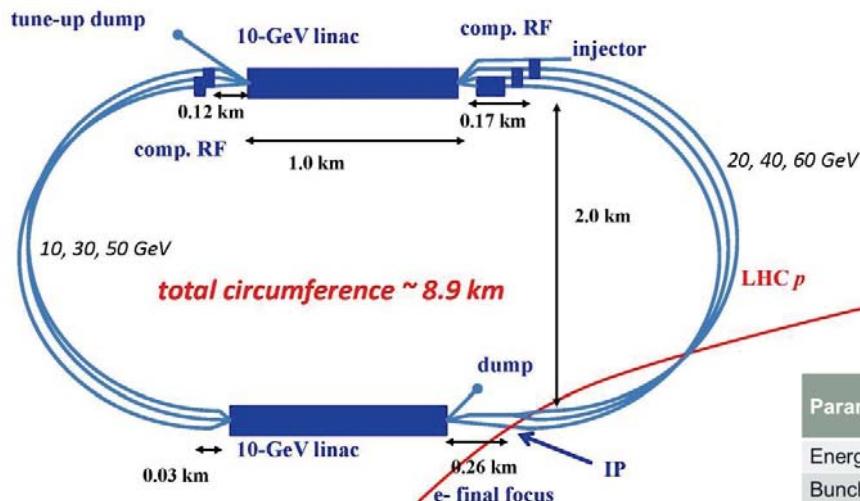
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ELR as electron part of Electron Ion Collider

60 GeV (e) \times 7 TeV (p)

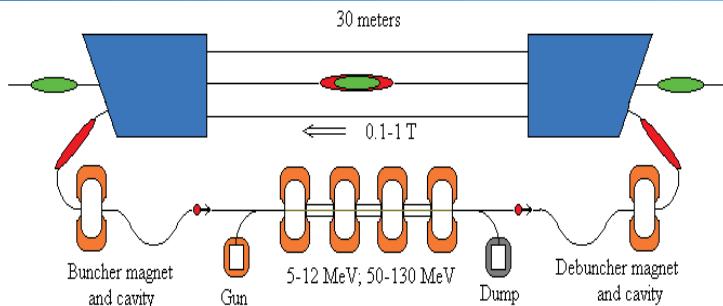
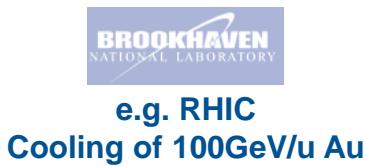


Parameters	LHeC	
	e	p
Energy (GeV)	60	7000
Bunch spacing (ns)		25
Intensity, 10^{11}	0.01	1.7
Current (mA)	6.4	860
rms norm. emit. (mm-mrad)	50	3.75
β_{xy}^* (cm)	12	10
rms bunch length (cm)	0.06	7.6
IP rms spot size (μm)		7.2
Beam-beam parameter		0.0001
Disruption parameter		6
Polarization, %	90	None
Luminosity, $10^{33}\text{cm}^{-2}\text{s}^{-1}$		1.3

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ELR as electron cooler



Efficient cooling needs

- $\gamma_{\text{ion}} = \gamma_{\text{electron}}$, e.g. 100 GeV protons needs 54.5 MeV electrons
- low emittance of electron beam ($\epsilon_{\text{norm}} \sim \mu\text{m rad}$)
- low energy spread of electron beam ($\delta_{E,\text{rel}} \sim 0.05\%$)
- high electron beam current

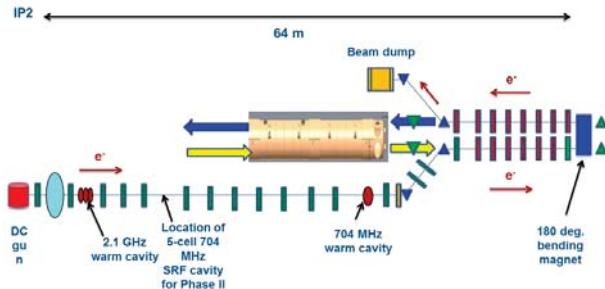
54.5 MV and A class currents not feasible with electrostatic accelerators

ERL cooler needs overlap of (many “short”) electron bunches with (“long”) ion bunches
(LEReC Phase-I project@BNL,
up to 2 MeV, gun2dump approved)

for ultra high ion energies

Coherent Electron Cooling (“stochastic cooling”)

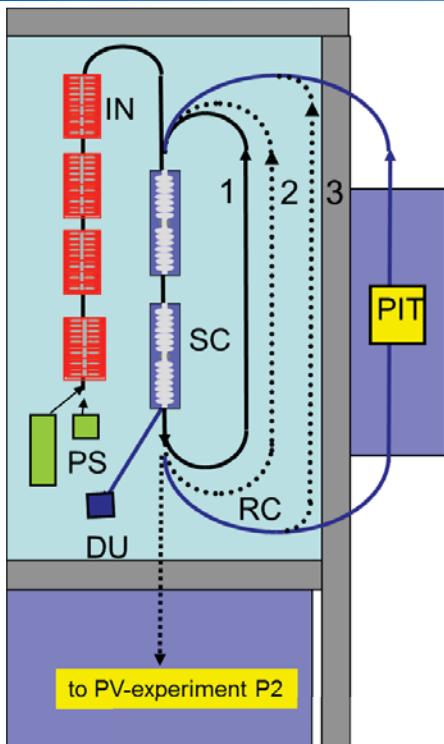
- ion beam imprints modulation on electron beam
- modulation on electron beam amplified by FEL
- electron beam acts back on ion beam



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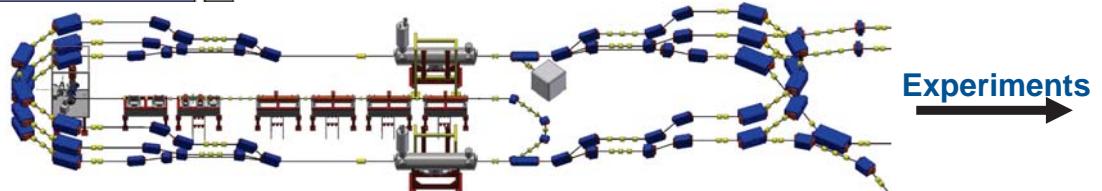
Compact ERL for high luminosity, low energy internal targets



MESA @ Mainz University

Multi turn ERL for

- External beams for precision measurements (weak mixing angle)
 $E=155 \text{ MeV} @ 150 \mu\text{A}$, polarized e^- , $L=10^{39} \text{ cm}^{-2} \text{ s}^{-1}$
- Pseudo Internal Target (PIT) experiments in Energy Recovery mode (dark photon search)
 $E=105 \text{ MeV} @ 10 \text{ mA}$, $L=10^{35} \text{ cm}^{-2} \text{ s}^{-1}$



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Challenges to be solved

Electron source:

high current, low emittance ($100 \text{ mA} - \text{A}$ cw with $\varepsilon_{\text{norm}} < \mu\text{m rad}$) not yet demonstrated
(big step forward: Cornell's 80 mA)

Injector/Booster:

$100 \text{ mA} @ 5 - 15 \text{ MeV} = 500 - 1500 \text{ kW}$ beam loading (coupler, HOM damper, beam dump)

Main-Linac:

100 mA recirculating beam \rightarrow beam break up (BBU), higher order modes (HOM), highest cw-gradients ($> 15 \text{ MV/m}$) with quality factor $> 10^{10} \rightarrow$ reduce cryo costs

Beam dynamics / optics:

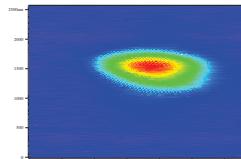
recirculation, flexible optics, bunch compression schemes = flexibility

Control of beam loss

unwanted beam = dark current from cathode, gun, cavities due to field emission, stray light laser beam halo, collimation schemes !?

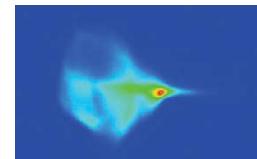
Storage ring:

nearly Gaussian
~ pA losses typical
~ 10 nA maximum



ERL:

no dead mathematician
~ $100 \mu\text{A}$ losses possible



The "hummingbird"
P. Evtushenko, JLAB

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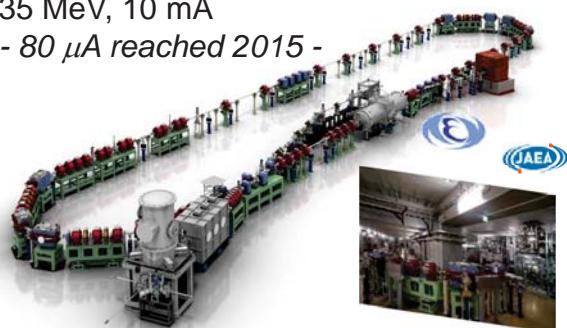
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demonstrator projects world-wide

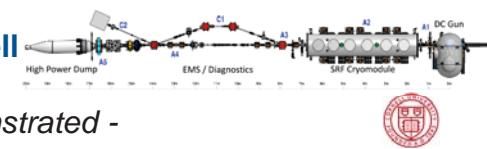
cERL, KEK + JAEA

35 MeV, 10 mA
- $80 \mu\text{A}$ reached 2015 -



ERL Injector, Cornell

5 – 15 MeV, 100 mA
- 80 mA max. demonstrated -



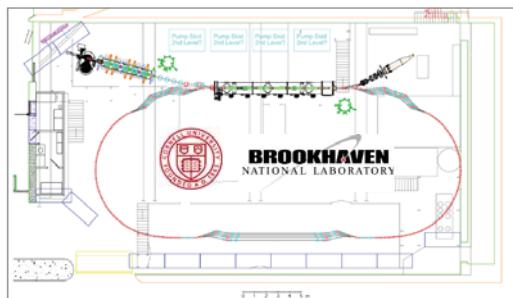
BNL ERL

20 MeV, 30 mA
- first electrons from gun 2014 -



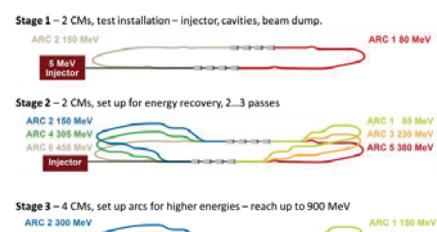
FFAG ERL, Cornell/BNL

286 MeV (4 turns), 40 mA
- "white paper" issued, to be approved -



CERN ERL

max. 900 MeV
staged
- study -



all based on DC photo electron sources

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bERLinPro – Berlin Energy Recovery Linac Project

bERLinPro = Berlin Energy Recovery Linac Project

100 mA / low emittance technology demonstrator (covering key aspects of large scale ERL)

bERLinPro
Helmholtz-Zentrum Berlin

test and diagnostic line

(5 mA@10 MeV dump,
energy & slice diag.)

**merger
dogleg**

linac module

3 x 7 cell srf cavities
44 MeV

beam dump

6.5 MeV, 100 mA
= 650 kW

modified Cornell booster

3 x 2 cell srf cavities
4.5 MeV

srf-photo gun

1.5-2.3 MeV,
single solenoid,

project started 2011, fully funded

building ready 2016

first electrons 2018

recirculation 2019

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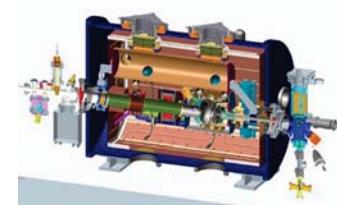
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	Basic Parameter
max. beam energy	50 MeV
max. current	100 mA (77 pC/bunch)
normalized emittance	1 μm (0.5 μm)
bunch length (straight)	2 ps or smaller (100 fs)
rep. rate	1.3 GHz
losses	< 10^{-5}

bERLinPro – Technological challenges I

High current, GeV range ERLs

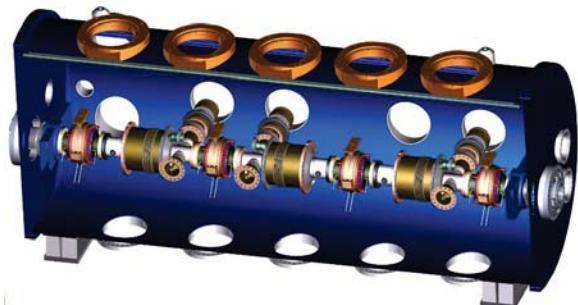
- massive virtual (x 100 MW) and real (x 100 kW) power
 - RF generator & amplifier, RF control: transient beam loading
- high current source
 - nc (Cornell: 80 mA DC-gun (2014)) vs. sc (Elbe/HZDR, bERLinPro/HZB)
 - cathode: material, handling & insertion, QE, lifetime, ...
 - laser: power, wavelength, pattern, ...
- sc technology
 - high fields / gradients, high Q(uality)
 - fieldemission (dark current), multipacting
 - cavity treatment (forming & welding, HPR, ECP, BCP, ..), module assembly (clean room, ...)
 - high power coupler
- radiation & machine safety
 - fast MPS
 - high power beam dump



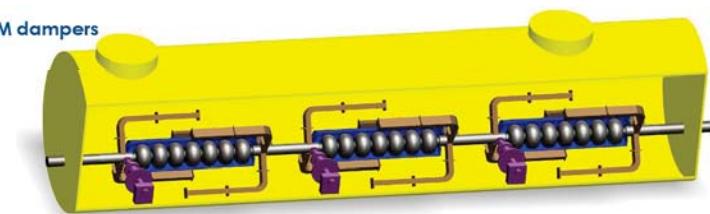
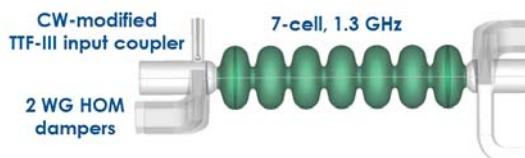


bERLinPro – Technological challenges II

Booster cavities and module are based on the Cornell design
 (3 x 2 cell, 1.8 K, 4 MeV@100 mA = 400 kW real beam power, 2 x 230 kW klystron)



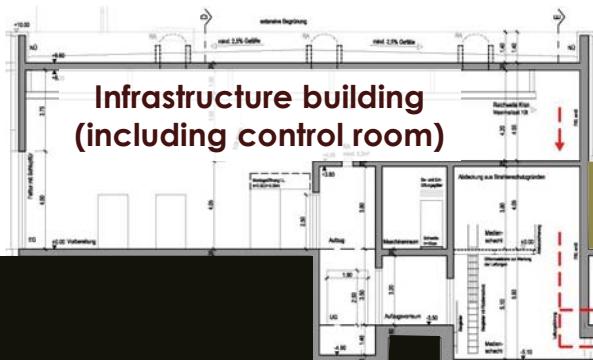
Linac cavities and module (HZB design)
 (3 x 7 cell, 1.8 K, 44 MeV@2x100 mA, zero net beam-loading, 3 x 10 kW SSA)



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Radiation protection for ERL – shielding neutrons



bERLinPro building

Ca. 3 m sand

Accelerator

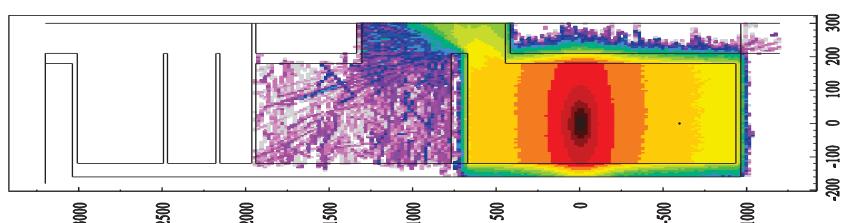
16 m

Partially shielded ante-room for equipment close to the accelerator (klystron, cold-compressor for cryogenics)

Fluka calculations
(K. Ott, HZB)



50 MeV, 100 mA = 5 MW
 → kW losses easily possible



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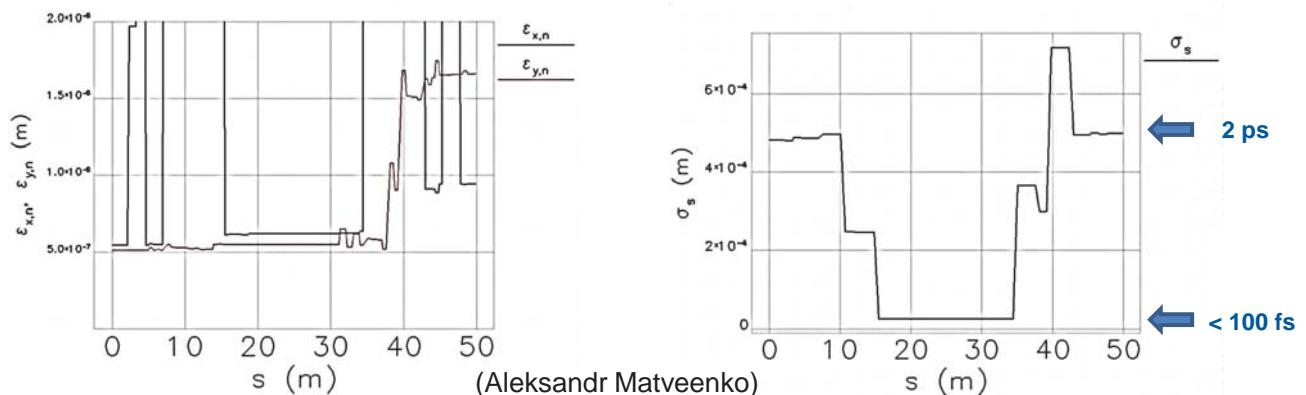
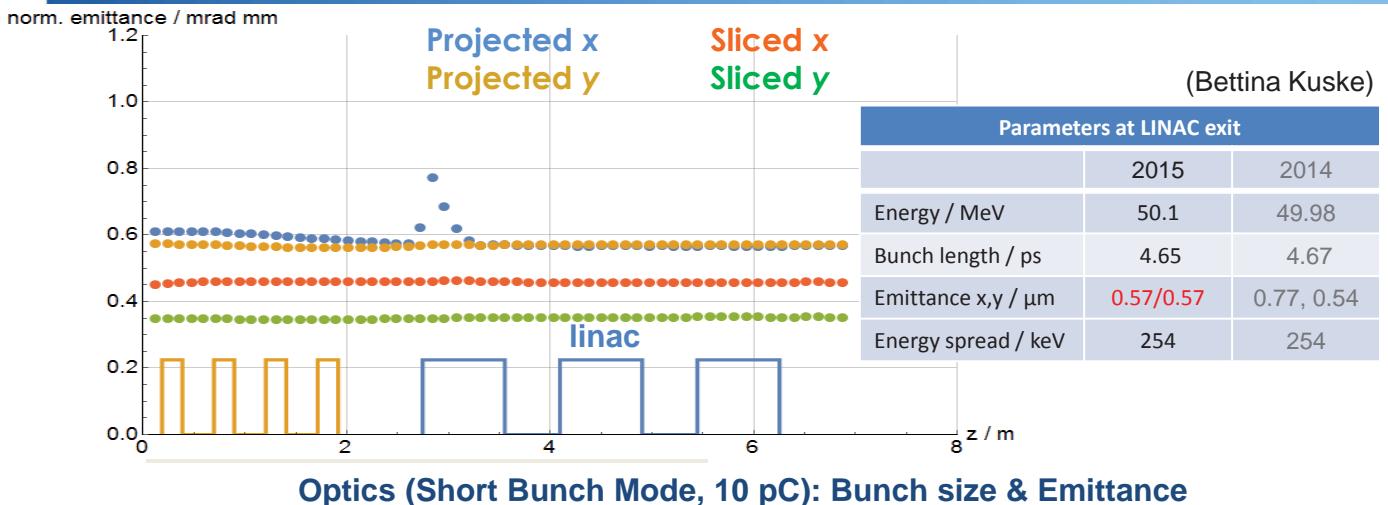


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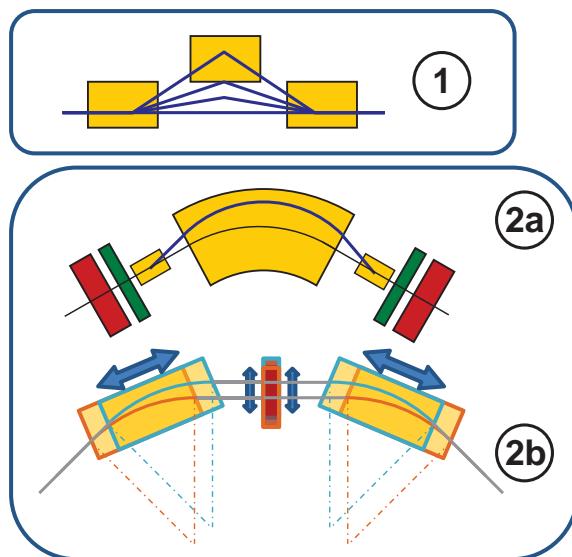
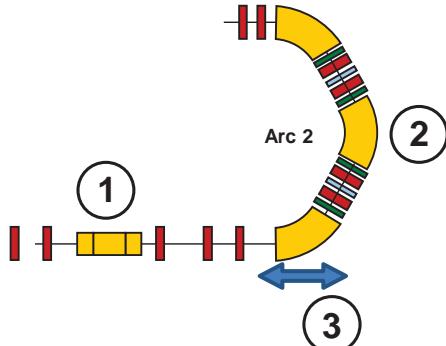
bERLinPro – performance parameter (simulations)





ERL Beam Dynamics – path length adjustment

- options:
- extra chicane **1**
 - inside arc **2**
 - moveable arc **3**



$$\text{recirculator path length: } L_{\text{Rec}} / (\beta c) = (n + 1/2) T_{\text{rf}} \rightarrow 180^\circ \text{ rf phase advance}$$

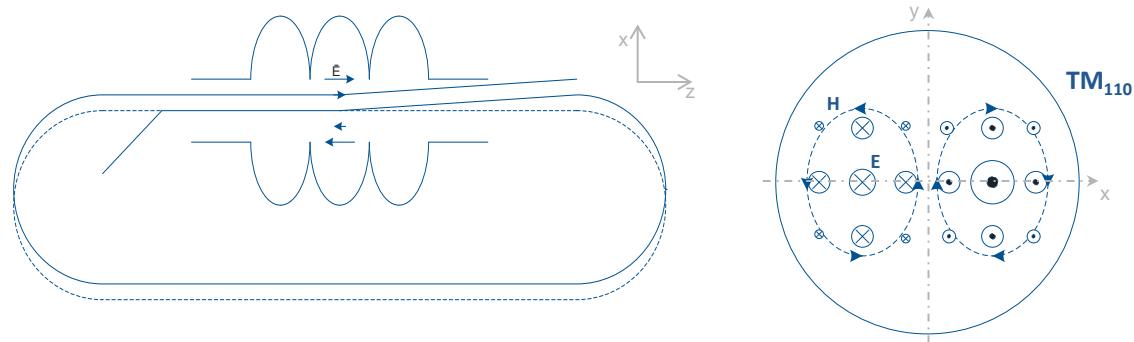
path length may change: $v = f(E)$, misalignments & field offsets \rightarrow orbit oscillations
 → adjust recirculation length
 → adjust f_{rf} : ☺



ERL Beam Dynamics – Beam Break Up

Beam Break Up: resonant interaction of short & long range cavity wake fields with the generating bunch or subsequent bunches \rightarrow **instability & beam loss**

e.g. **Multibunch BBU:** many flavours: cumulative / regenerative, transverse / longitudinal, single-/multi-cavity, single-/multiple-turn



regenerative transverse BBU (single cavity, single turn, one mode):

1. bunch passes cavity "off axis" during accelerating passage \rightarrow induce HOM voltage & transverse kick due to HOM
2. after recirculation kick transforms to an offset & HOM damp according to its Q
3. bunch passes cavity with varied offset on decelerating passage \rightarrow induce HOM voltage & transverse kick due to HOM

BBU: HOM excitation exceeds HOM damping \rightarrow kick strength growth up to loss



$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

BBU threshold current

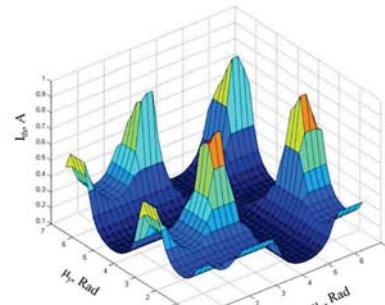
Countermeasures

1. cavity design:

- HOMs: small R/Q, varying ω_λ at fixed $\omega_0 \rightarrow$ multi cavity BBU thresholds increase
- no HOM on a fundamental's harmonics: $\omega_\lambda \neq n^* \omega_{rf}$
- low Q for HOM \rightarrow HOM dampers (ferrites, waveguides, ...)

2. recirculator beam optics:

- for $\alpha=0$ & uncoupled beam transport $\rightarrow m^* = m_{12} = (\beta_1 \beta_2)^{1/2} \sin(\Delta\phi_x)$
 \rightarrow stable for $\Delta\phi = n\pi$
- adjust $\sin(\omega_\lambda T_{rec}) = 0$ for worst HOM
large path length change \rightarrow impractical ☹



Y. Peteney

E. Pozdeyev et al.: Multipass beam breakup in energy recovery linacs, NIM-A 557 (2006) 176–188

G. Hoffstaetter et al.: Beam-breakup instability theory for energy recovery linacs, PRST-AB 7, 054401 (2004)

G. Hoffstaetter et al.: Recirculating beam-breakup thresholds for polarized higher-order modes with optical coupling, PRST-AB 10, 044401 (2007)

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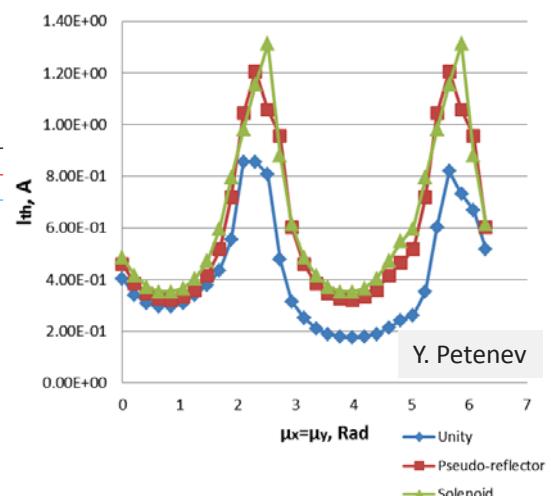
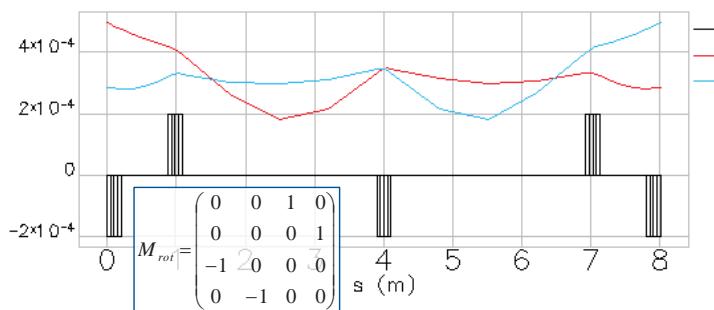
$$I_{th} = -\frac{2pc^2}{e\omega_\lambda \left(\frac{R}{Q}\right)_\lambda Q_\lambda m^* \sin(\omega_\lambda T_{rec})}$$

BBU threshold current

Countermeasures

2. recirculator beam optics (continued):

- coupled beam transport: switching of planes $M=((M_x, 0), (0, M_y)) \rightarrow M=((0, M_{yx}), (0, M_{xy}))$
 $m_{12}=0 \rightarrow$ horizontal HOM kick transforms to vertical offset \rightarrow HOM not further excited by the oscillatory part of x_2
 \rightarrow two options: solenoid (low energy), rotator



Y. Peteney



Unwanted Beam

Halo

generated by / together with wanted beam

- scattered particles (residual gas, IBS)
- laser stray light on cathode
- laser: limited extinction ratio
- ... (?)

moving together with wanted beam at design rf phases → same energy, no dispersive separation

Dark Current

generated independently of wanted beam (laser off)

- field emission in rf cavities
- ghost pulses from laser
- ... (?)

beside Dark Current from the gun → lower energy than wanted beam → lost in dispersive regions

UBW 2012: <https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2>



Unwanted Beam

Amount:

- not reliably predictable for most sources

Loss positions:

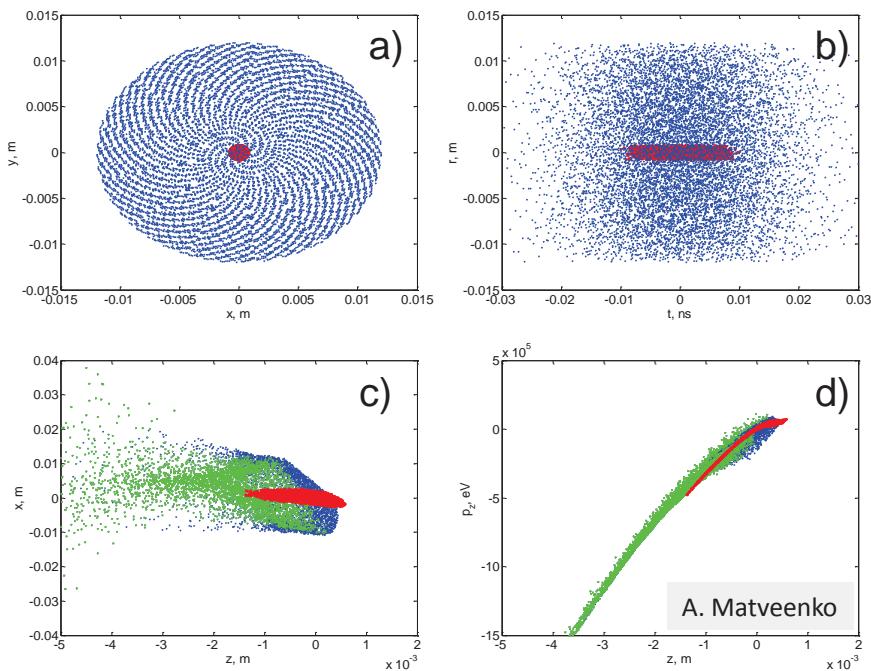
- with initial beam parameter (place of origin, momenta) loss position along the machine can be calculated for the various generation processes → loss probability (to be weighted with unknown loss current ☺)

source	generating process	loss positions	amount
Halo	scattered Particles		
	stray light – laser halo		
Dark Current	field emission gun cath & plug		
	field emission booster & linac		

UBW 2012: <https://indico.helmholtz-berlin.de/conferenceDisplay.py?confId=2>



- Halo:**
1. residual gas scattering
 2. intra beam scattering → Touschek losses
 3. laser stray light from cathode



Beam halo modeling:

particle distribution from ASTRA.
red – active beam particles,
blue – passive halo particles,
green – particles lost in collimators.

Initial distribution on the cathode in
a) x-y plane,
b) x-t plane.

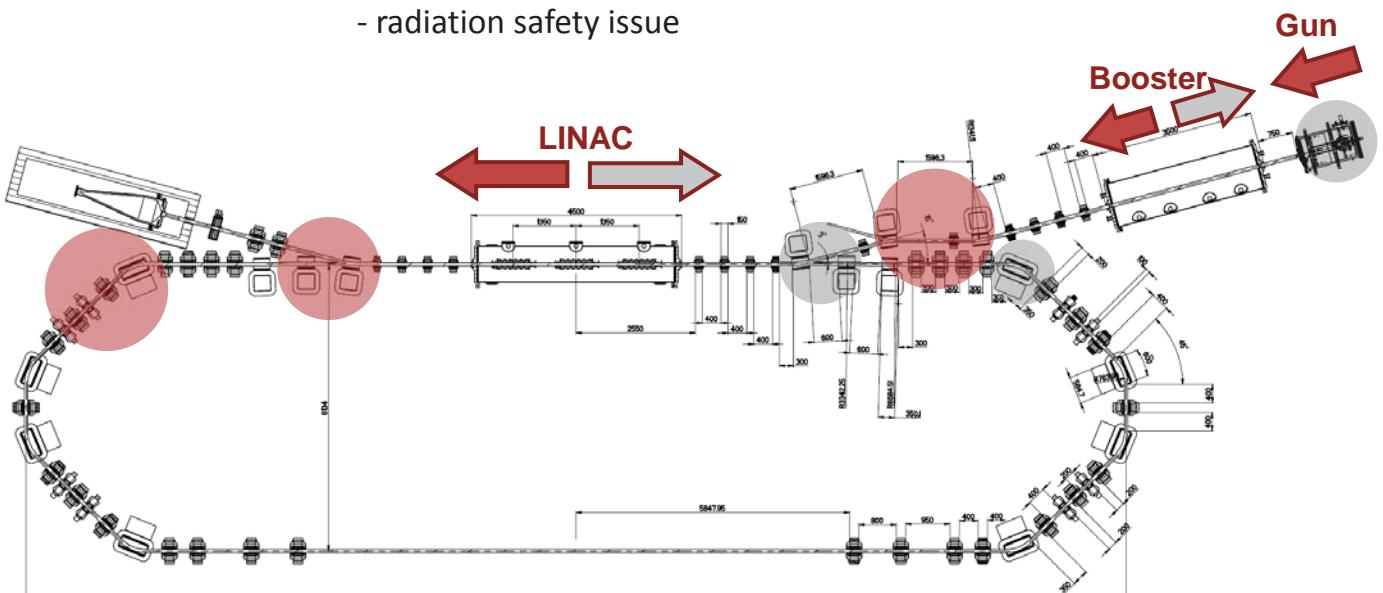
Particle distribution after the merger section in
c) x-z plane,
d) p_z -z plane.

→ Collimation of large fraction of halo particles, but not 100%.

bERLinpro: one testing collimator in the merger section



- Dark Current:**
- consuming rf power (linac)
 - MPS relevant: μA @ tens of MeV $\rightarrow 10^2 \dots 10^3 \text{ W}/??$
 - radiation safety issue



- dark current from booster ($E_{\max} = 4.5 \text{ MeV} \rightarrow \Delta E > 30\%$) will be lost in merger
- dark current from linac ($E_{\max} = 44 \text{ MeV} \rightarrow \Delta E > 13\%$) will be lost in the 1st arc bend

Only dark current from gun will potentially reach the recirculator!



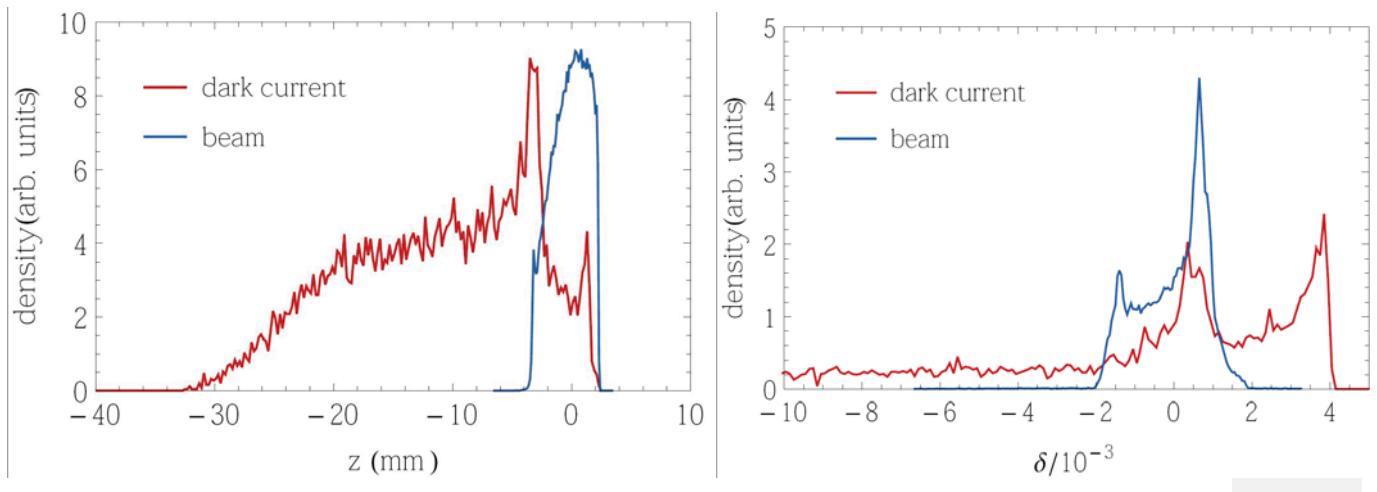
Dark Current: field emission from gun cathode

Field Emission from gun cathode

- Fowler Nordheim: $\varphi = 1.9$ eV, $\beta = 200$, $E_{\max} = 30$ MV/m
- tracking through merger incl. SC of reference bunch
- x-y apertures in booster & merger \rightarrow loss distribution

$$j(E) = \frac{A_{FN}(\beta_{FN}E)^2}{\varphi} \exp\left(-\frac{B_{FN}\varphi^2}{\beta_{FN}E}\right)$$

E – electric field, φ – work function



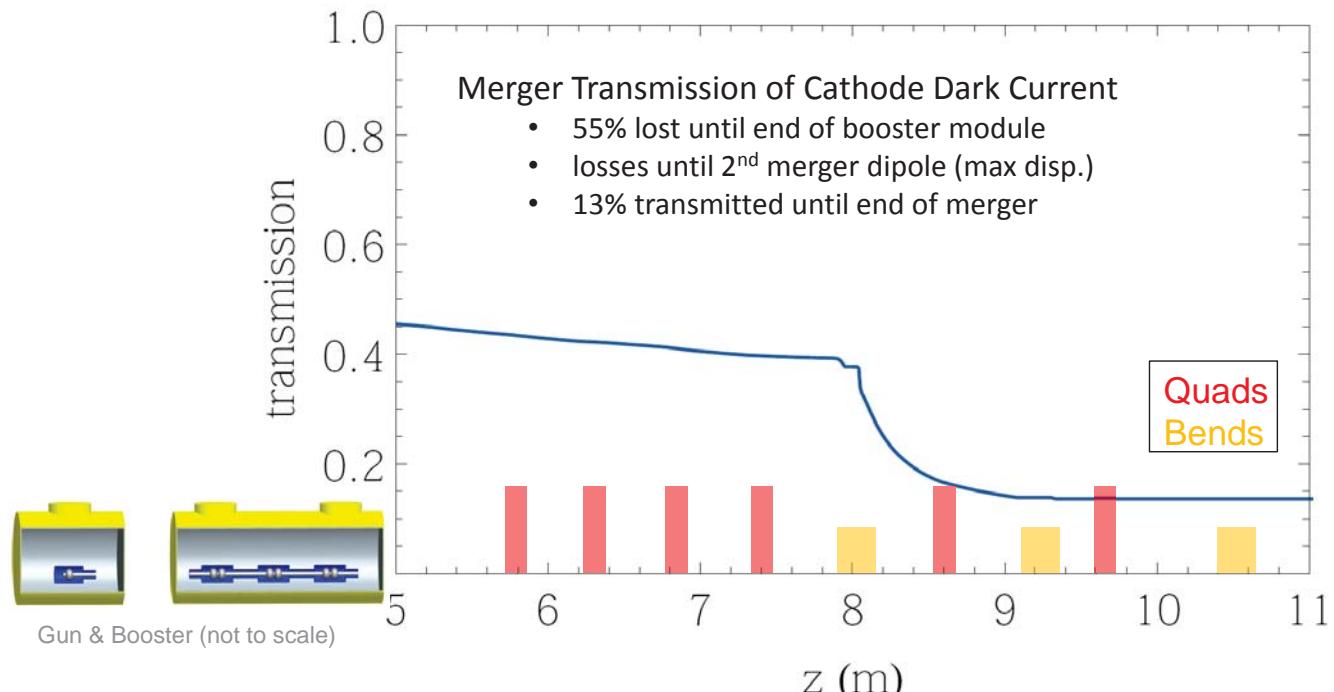
S. Wesch

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Dark Current: field emission from gun cathode



S. Wesch

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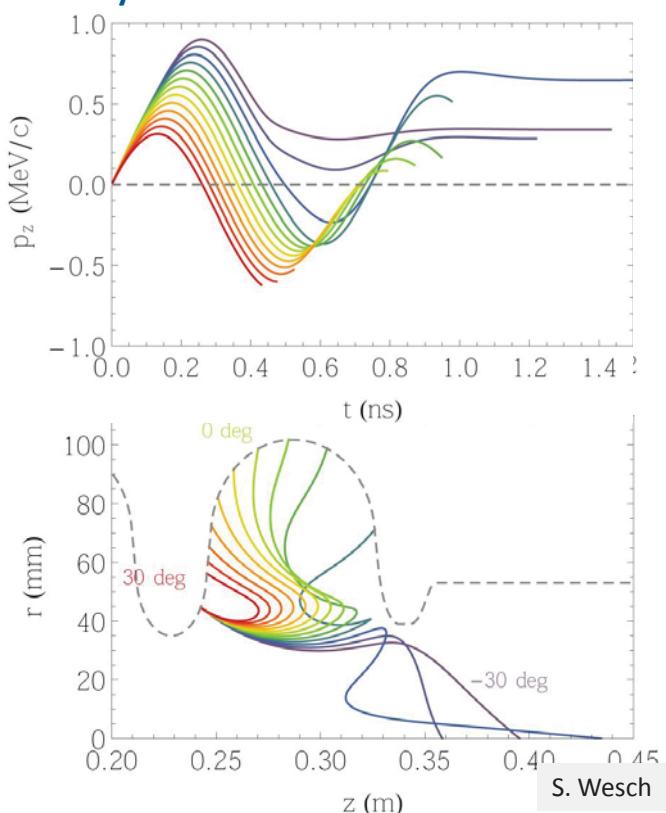


Dark Current: field emission from booster cavity

Dark current simulations booster cavity:

- calculate trajectories of field emitted electrons inside cavity (2D – cylinder symmetry assumed)
- current weighting according to Fowler-Nordheim:
 $I=f(|E|(t), \Phi, \beta, A)$

Simulation: - $|E|_{\max} = E_{\max, \text{on_axis}} = 20 \text{ MV/m}$
- FN parameter: $\beta=100$, $\Phi_{\text{Nb}} = 4.3 \text{ eV}$
- emission phase: $-30 \dots +30$ degree
- emission point: max. cavity wall field



Extended Simulations:

- emission from various points on the cavity wall & collect parameters of escaping electrons to track them downstream the machine
- equivalent study for gun cavity

[L.Fröhlich: Machine Protection for FLASH and the European XFEL](#)

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Summary

Energy Recovery Linacs can provide high current, high quality beams for single pass experiments in flexible setups
multi user light sources, collider, cooler, compact sources, ...

cw superconducting RF is the enabling technology
high gradient, large apertures

many challenges to be addressed

low emittance/high current sources, HOM damped cavities (BBU),
flexible bunch compression, control of unwanted beam, optimising
SRF efficiency (high gradient, high Q_0)

ongoing, worldwide effort to push ERL technology

bERLinPro, cERL, BNL ERL, Cornell Injector + FFAG ERL,
CERN Test ERL, JLAB ERL-FEL, Beijing University & IHEP, ALICE,
NovoERL, MESA, S-DALINAC

Thanks to many of my colleagues providing me data and information and to Michael Abo-Bakr for transparencies on bERLinPro beam dynamic issues.