INFN ACCELERATORI ERICE Accelerator School

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

TO PAY A PERMANENT TRIBUTE TO ARCHIMEDES AND GALILEO GALILEI, FOUNDERS OF MODERN SCIENCE AND TO ENRICO FERMI, THE "ITALIAN NAVIGATOR", FATHER OF THE WEAK FORCES

TECHNISCHE UNIVERSITÄT DARMSTADT

OVERVIEW OF ERL RESULTS

Acknowledgments:

Georg Hoffstaetter (Cornell), Hiroshi Sakai (KEK), Nikolay A. Vinokurov (BINP), Peter Williams (STFC)

CBETA

Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

Brookhaven National Laboratory

iCASA Innovation Center for Applied Superconducting Accelerators 応用超伝導加速器イノベーションセンター

The Cockcroft Institute of Accelerator Science and Technology

UKRI Science and Technology Facilities Council

Nuclear Photonics

Institut für Kernphysik S-DALINAC Technische Universität Darmstadt

OUTLINE

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OVERVIEW

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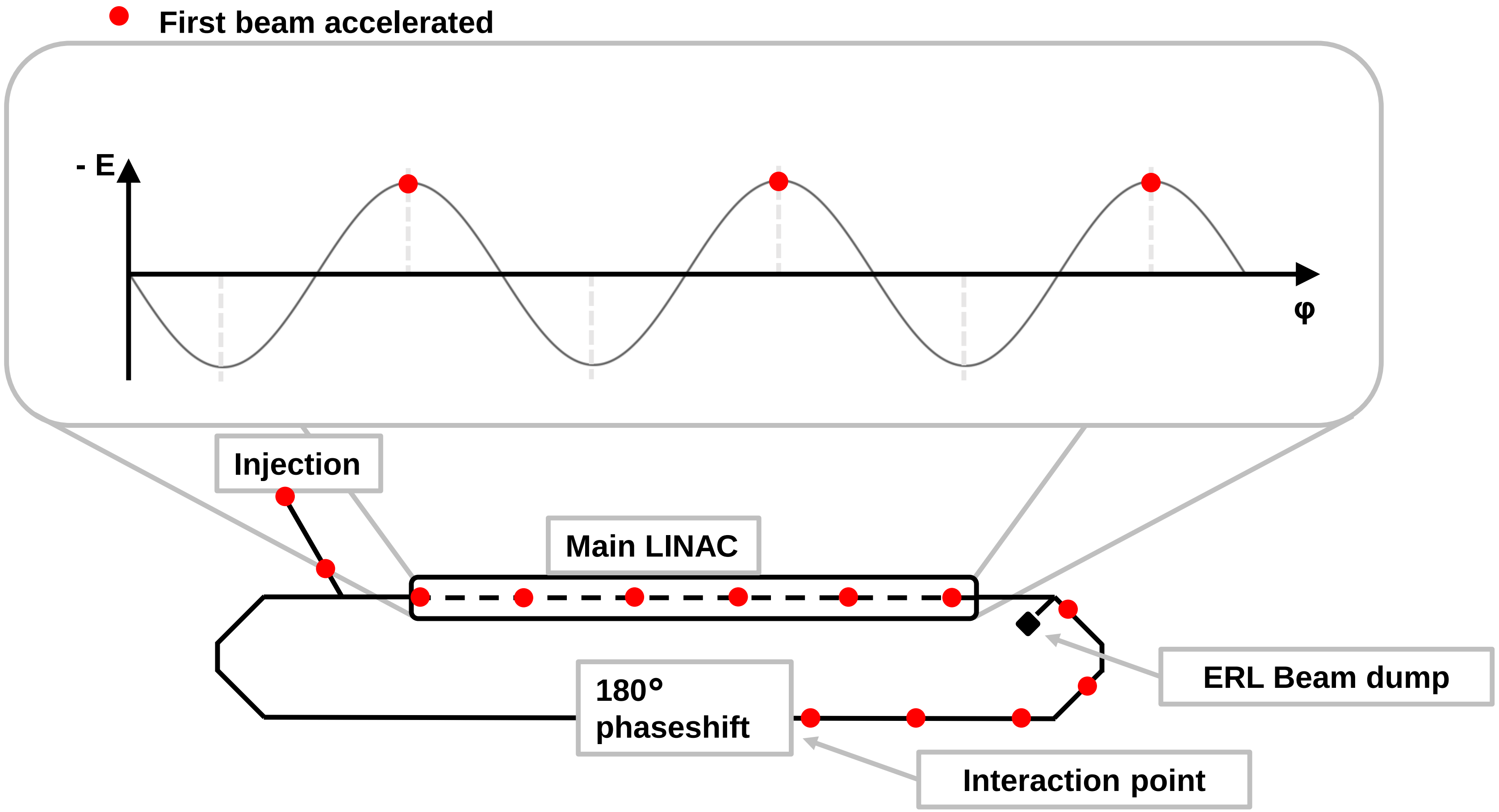
ERL PRINCIPLE



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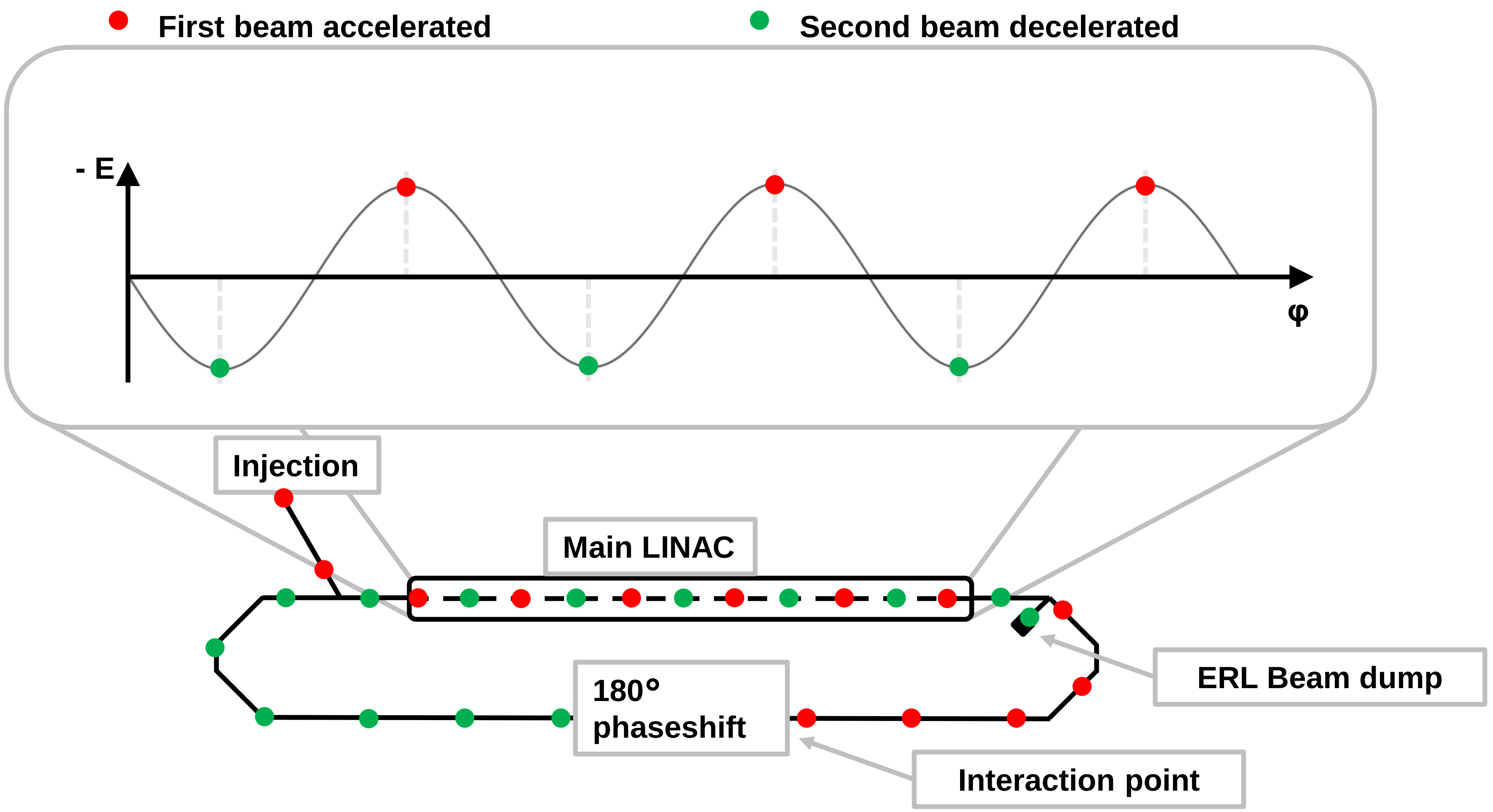
ERL PRINCIPLE



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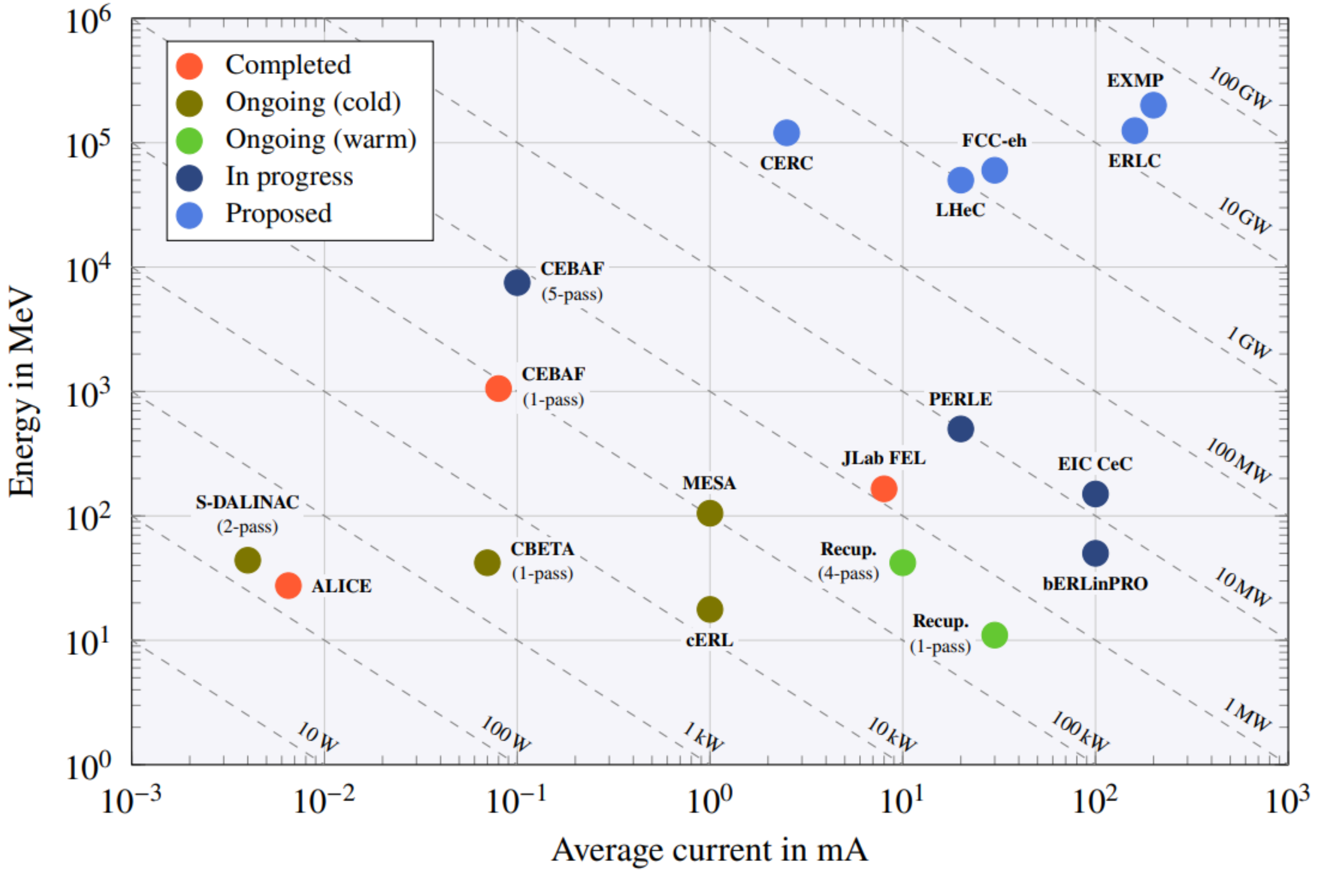
ERLS AROUND THE WORLD



arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

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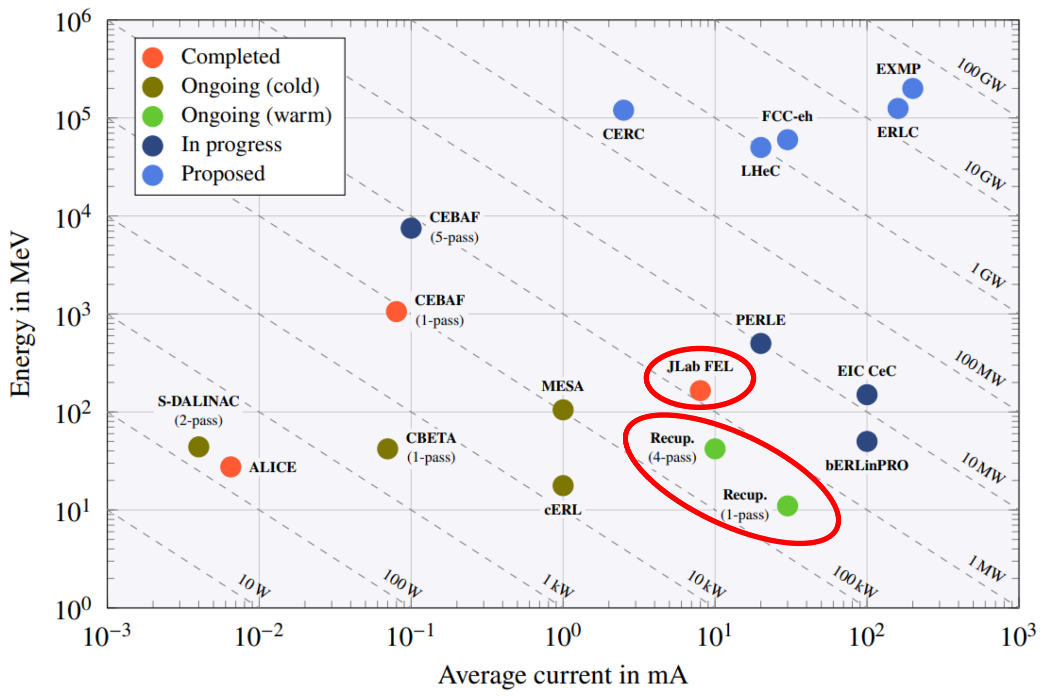
ERLS AROUND THE WORLD



JLabFEL

- First and so far only ERL that operated > 1MW beam power
- Important role in whole ERL development since early 2000

NovoFEL (Recup.)

- NC multi-turn ERL, first multi-turn operation world-wide in 2008
- 3 FELs and many working stations for experiments

arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

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JLAB FEL

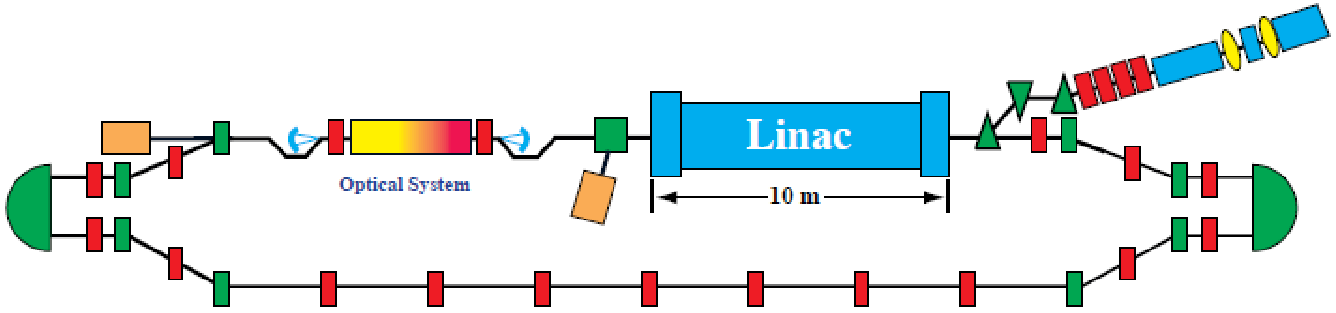

Figure 2.7. IR Demo schematic layout. The photocathode injector is in the upper right. The beam is then merged with the recirculated beam and accelerated to full energy in a single cryomodule. The FEL is between two chicanes that give room for the two cavity mirrors of the resonator. The exhaust beam is transported through two Bates 180° bends and decelerated to the injection energy. It is then dumped in a high-power dump.

- ~ 2000: First successful „same-cell energy recovery" during FEL operation

Table 2.1. Design and As-built parameters for the IR Demo FEL.

Parameter	Design	As built
Energy (MeV)	41	47.3
Current (mA)	5	4.5
Charge (nC)	0.135	0.060
Energy spread	0.2 %	0.15 %
ϵ_x (µm)	8	6
Wavelength (µm)	3.2	3.2
Wiggler K_{rms}	0.7	0.99
Wiggler gap (cm)	1.0	1.0
Number of periods	40	40
Output coupling	10 %	10 %
Laser power (kW)	1.0	2.1

arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

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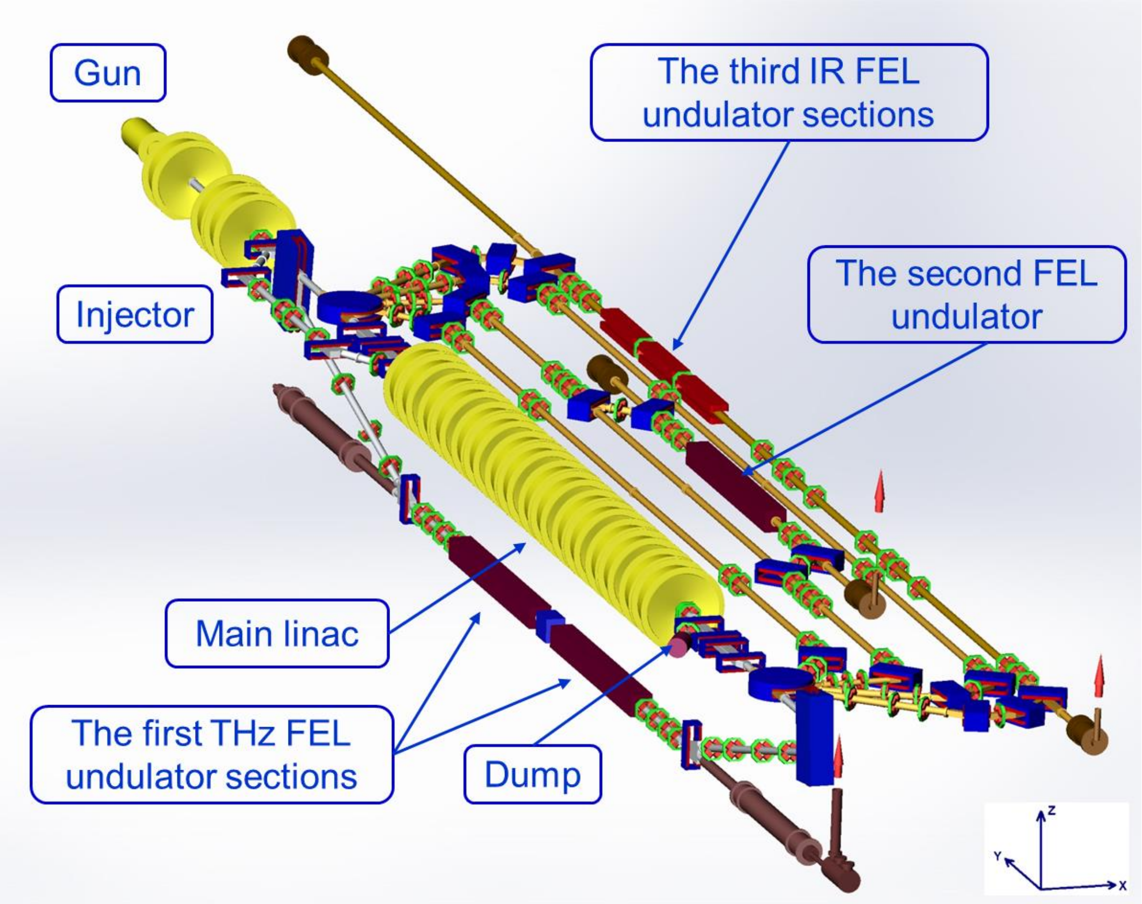
NOVOSIBIRSK FOUR-ORBIT ERL WITH THREE FELS



FEL #	1	2	3
Energy, MeV	12	22	42
Current, mA	30	10	3
Wavelength, μm	90-340	37-80	8-11
Radiation power, kW	0.5	0.5	0.1
Electron efficiency, %	0.6	0.3	0.2

- The Novosibirsk ERL is the first multiturn ERL in the world.
- normal-conductive 180 MHz accelerating system
- DC electron gun with the grid thermionic cathode
- three operation modes of the magnetic systems
- a rather compact (6×40 m2) design.
- The facility has been operating for users of terahertz radiation since 2004.

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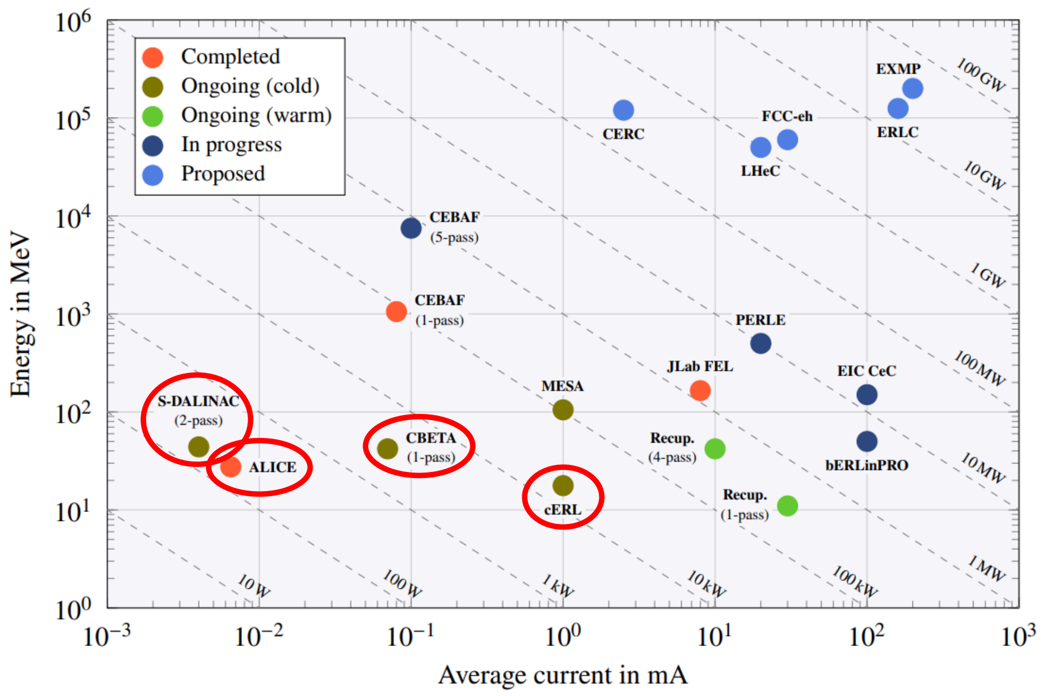
ERLS AROUND THE WORLD



arXiv:2207.02095 [physics.acc-ph]; accepted for publication in JINST

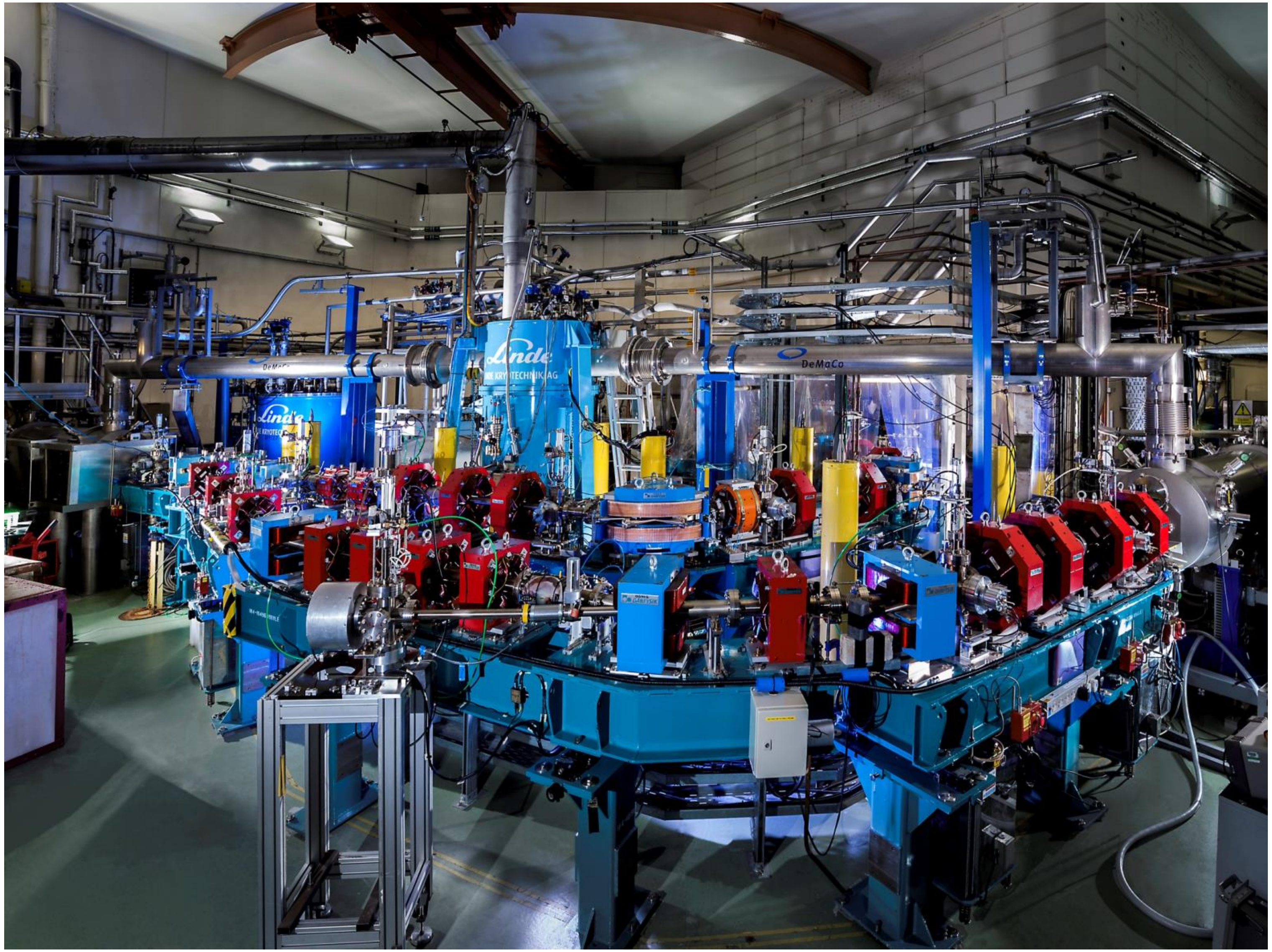
ALICE
- 2003 design, 2008 first ERL run, 2016 shut down
- Various applications (medical and industrial)

cERL
- Start construction 2009, start commissioning 2013
- Many different applications, up to 1mA (cw)

CBETA
- 1-turn ERL: June 2019
- 4-turn ERL: Dec. 2019

S-DALINAC
- No „born-ERL“, ERL mode since upgrade in 2015/2016
- 1-turn ERL: 2017
- 2-turn ERL: 2021

ALICE



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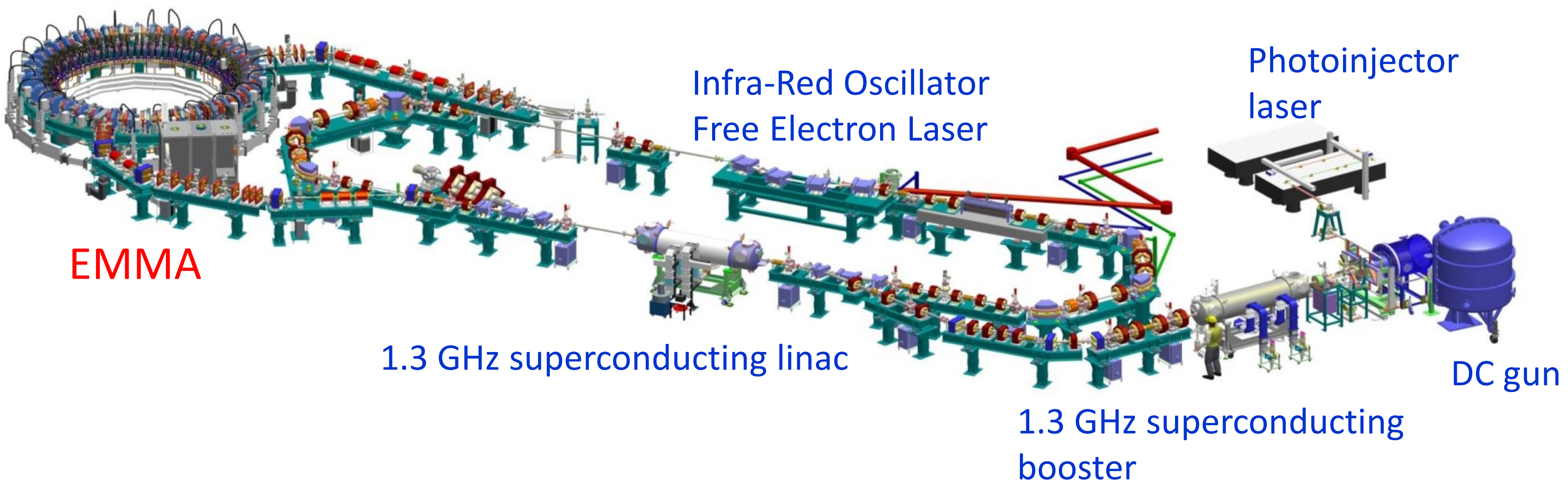
THE ALICE ENERGY RECOVERY LINAC @ DARESBURY

Accelerators and Lasers In Combined Experiments



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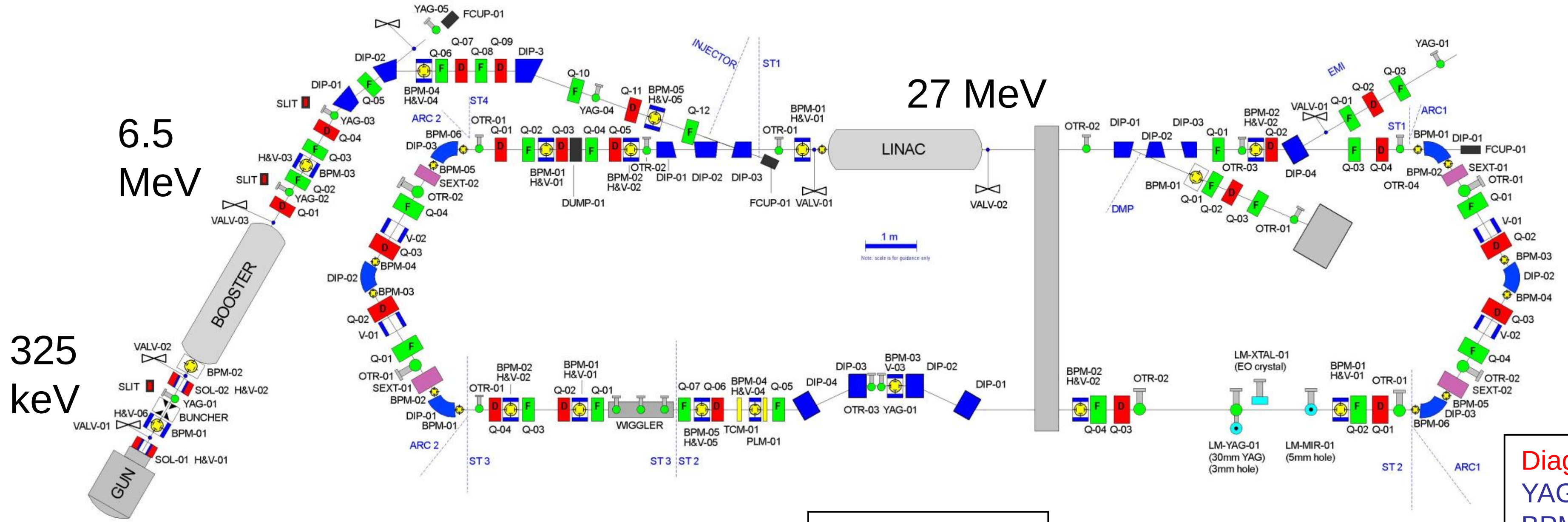
OVERVIEW

RF System
Superconducting booster + linac; 9-cell cavities. 1.3 GHz, ~10 MV/m.
Pulsed up to 10 Hz, 100 μS bunch trains; Cryo capacity 180W @ 2K

Beam transport system.
Outward TBA arc tuned first-order isochronous, second order compensates T566 of chicane

4-dipole bunch compression chicane R_{56} = 28 cm

Return TBA arc decompresses and de-linearises – match to small energy spread at ER dump



The main goal of ALICE was to deliver the bunch as short as possible to IR oscillator FEL and for generation of broadband THz radiation from the bunch compression chicane

DC Gun + Photo Injector Laser
325 kV; Green (532nm) laser; GaAs cathode; QE=2.5-3.0%
Up to 100 pC bunch charge; Up to 81.25 MHz rep rate

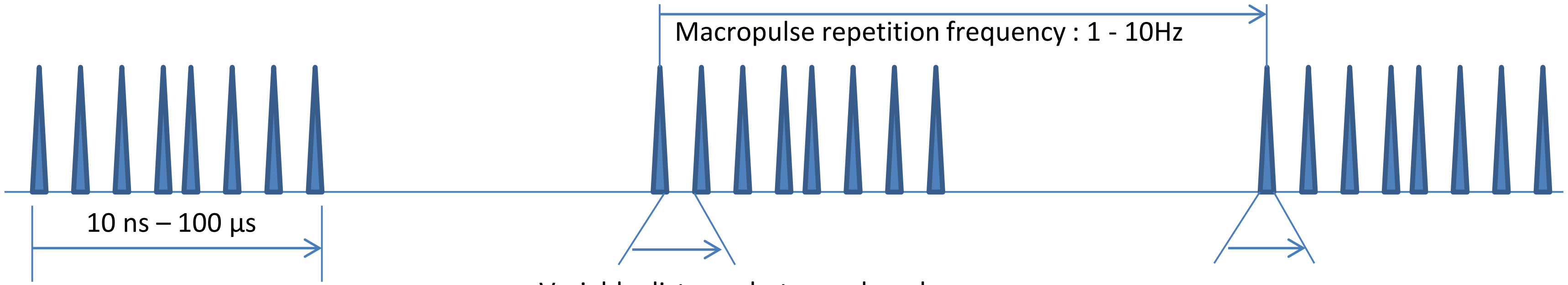
Free-electron laser
Oscillator type
Variable gap wiggler
11m optical cavity

Diagnostics
YAG/OTR screens
BPMs (stripline / button)
Slits
Energy spectrometers
Electro-optic bunch profile monitor

PARAMETERS AND TIMING STRUCTURE

Parameter	Design	Operating	Units
Bunch charge	80	20 - 80	pC
Gun energy	350	230 → 325	kV
Booster energy	8.35	6.5	MeV
Linac energy	35	27	MeV
Repetition rate	81.25	16.25 - 81.25	MHz
Current within macropulse	Up to 6.5	> 6.5	mA

Due to Accel modules not meeting spec



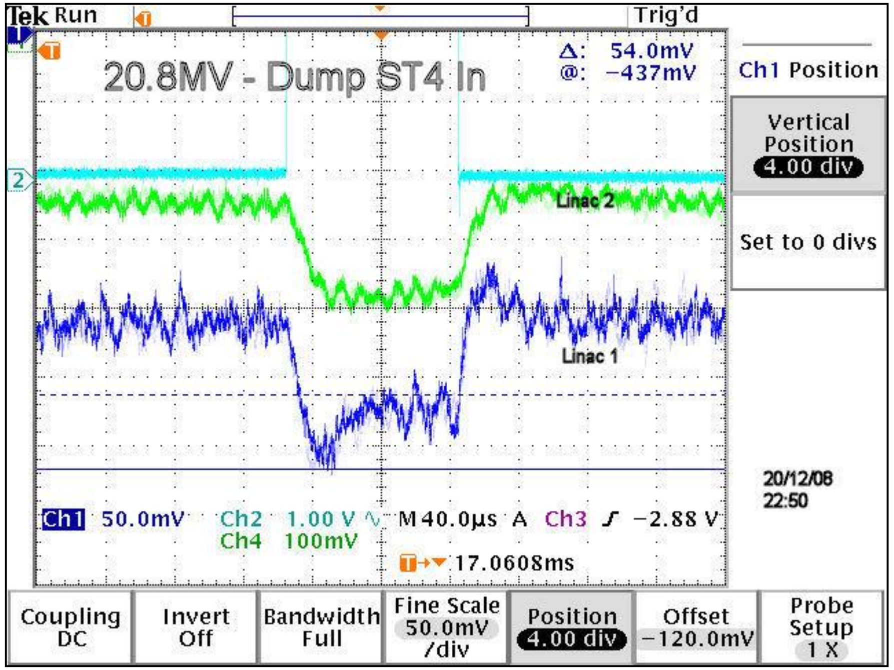
Macropulse train of bunches
Charge / bunch 60 – 80 pC

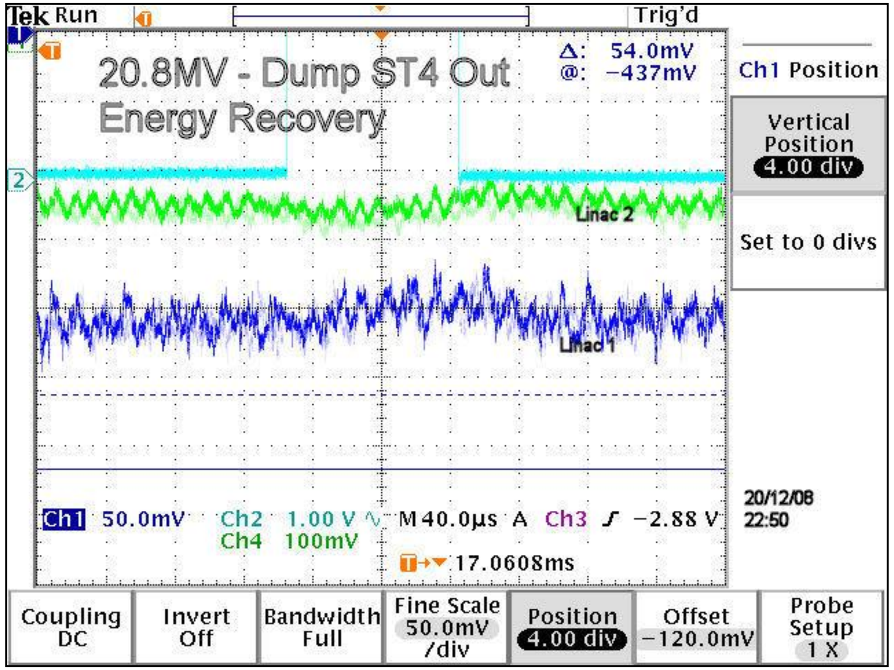
Variable distance between bunches
IR-FEL : 16.26MHz (62 ns spacing)
THz : 40.63MHz & 81.25MHz (25/12.5 ns spacing)

Bunch length
compressed : ~ 1 ps
Uncompressed: ~10 ps

DESIGN AND FIRST ENERGY RECOVERY

- 2003: Design
- 2008: Successful energy recovery: 20.8 MeV, ~ 10 pC; 80 pC early 2009 – ER efficiency > 100% [i.e. possible to dump at less than injection energy]

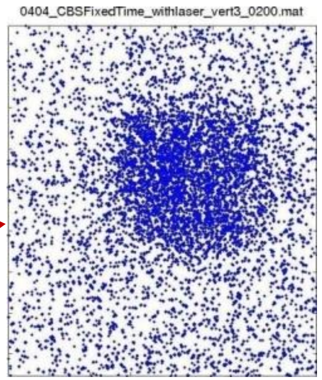


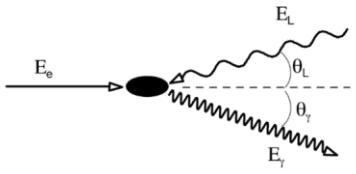


The gradient demand traces from the two linac cavities (original analogue LLRF system) as pop-in dump in return path is retracted

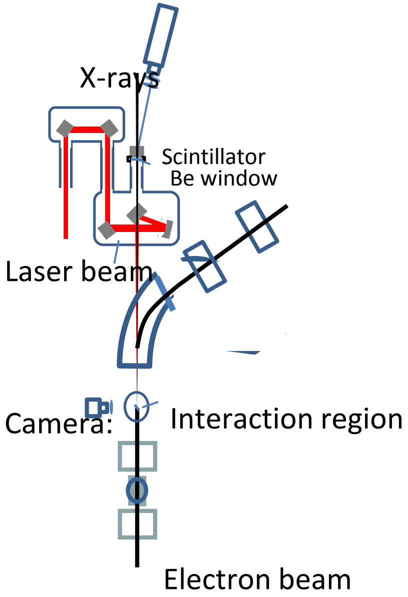
2009: INVERSE COMPTON SCATTERING X-RAY DEMO

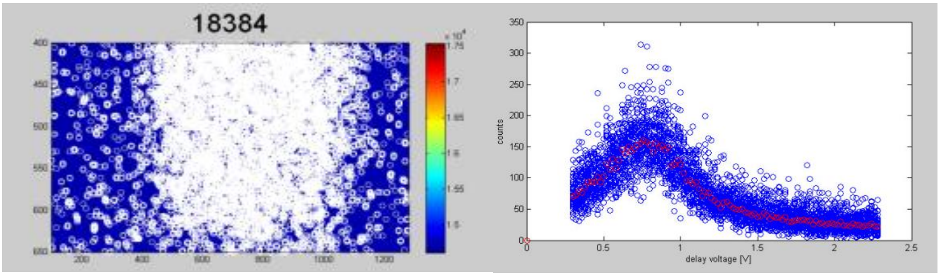
- 10 TW, 800 nm laser produced X-rays in head on configuration at ~30 keV
- Image shows X-rays detected on screen ~10^3 per macropulse
- Plot shows X-ray intensity as laser timing scanned, pulse ~100 fs duration
- This was just a demonstration – remember ALICE was not designed specifically with an optimized Compton interaction region and it was difficult to squeeze the beam (no cw operation, no optical enhancement cavity)





$$E_\gamma \approx 4\gamma^2 E_L$$

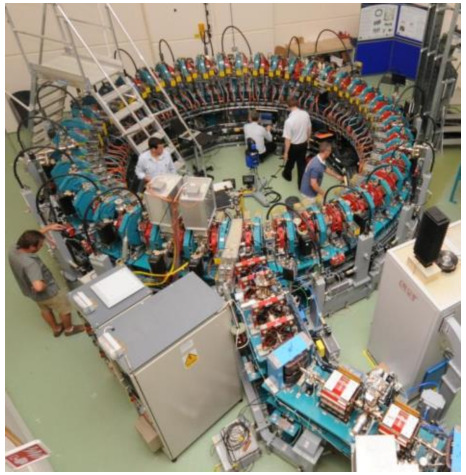


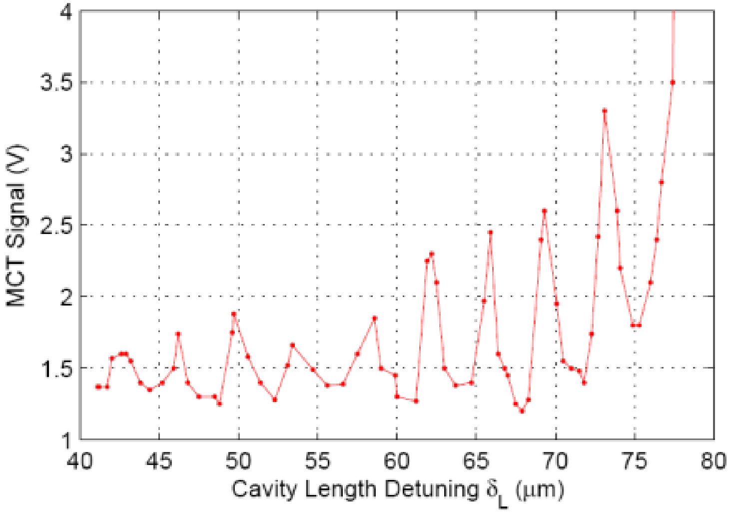


2010: ON THE WAY TO IR-FEL LASING

- **EMMA ring**: ALICE used as an injector for world's first Non-Scaling FFAG and completed many turns – not the subject of this talk

- **FEL preparation**: Cavity mirrors installed and aligned, first observation of spontaneous emission. Radiation was stored in the cavity immediately, indicating the transverse pre-alignment was reasonable. Spectrometer installed and tested. Strong coherent emission seen with dependence on cavity length…





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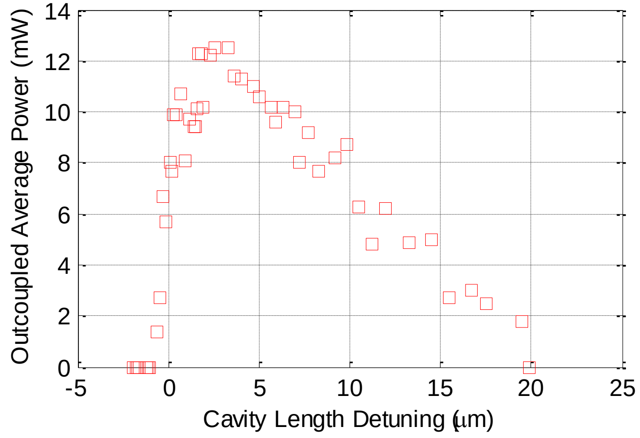
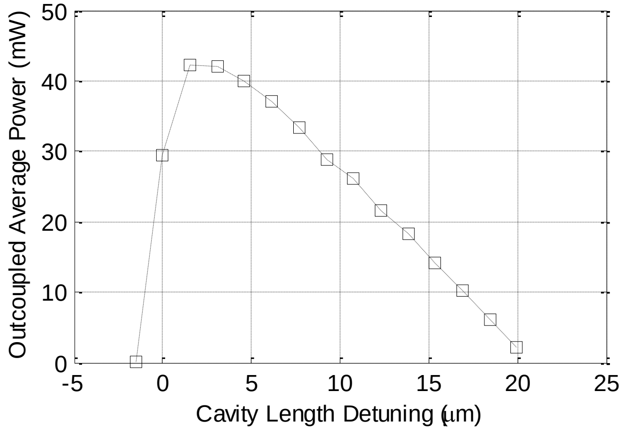
FIRST LASING: 23 OCTOBER 2010

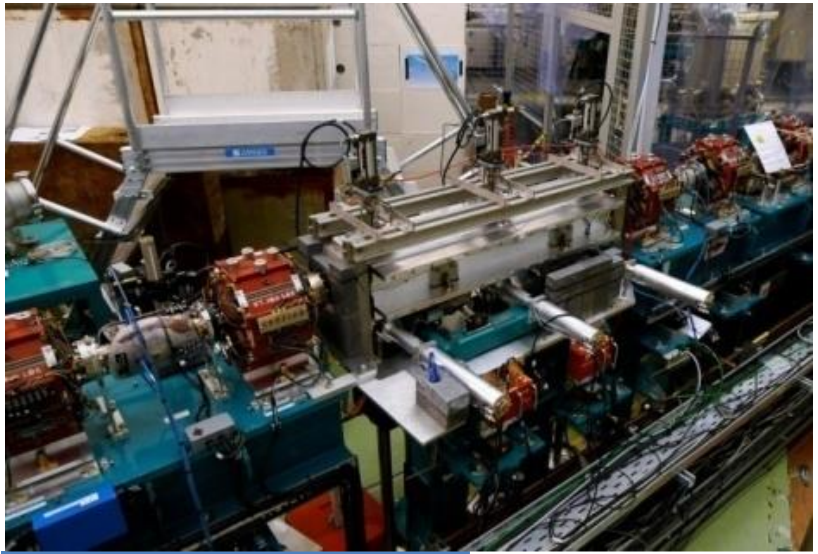
Lasing 100-40 pC @ 16.25 MHz

First Lasing Data: 23/10/10



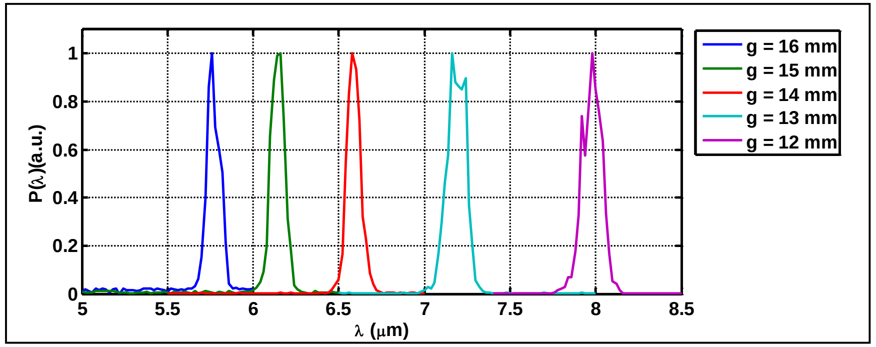
Simulation (FELO code)



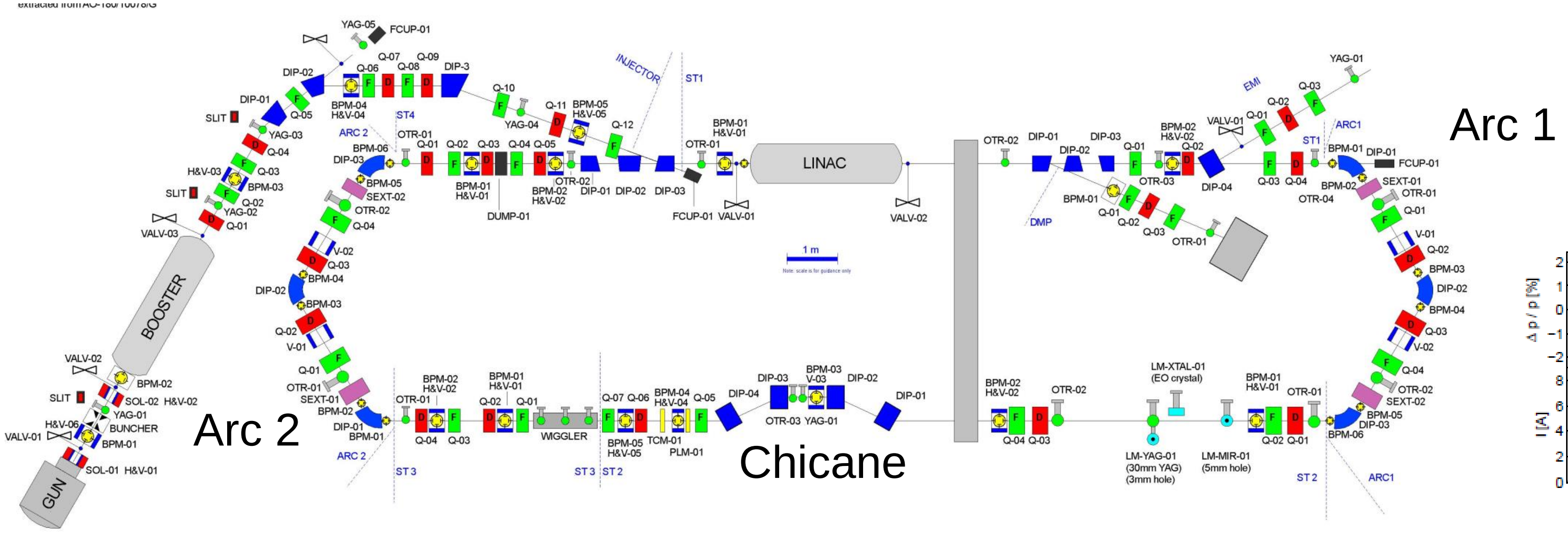


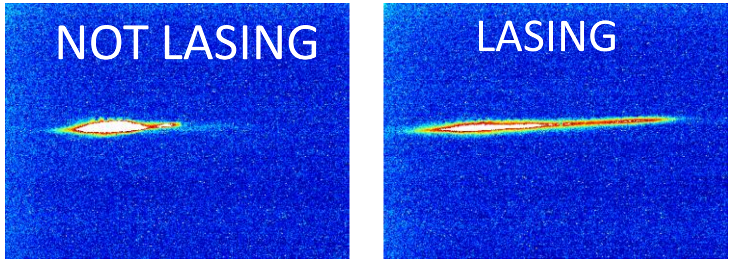
The peak power ~3 MW
Single pass gain ~25 %

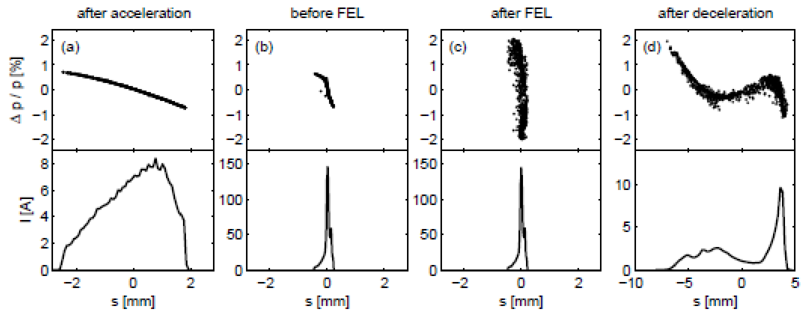
Continuous tuning 5.7-8.0 µm, varying undulator gap



ENERGY RECOVERY TRANSPORT WITH FEL LASING







- Chicane R_{56} = 28 cm → for a flat bunch on linac entrance at 6.5 MeV would need linac phase of +10°
- But need to compensate predominantly space-charge driven energy chirp in the bunch coming from injector from 0 to +5 °; hence overall off-crest phase +15 / +16 °
- Arc 1 nominally achromatic & isochronous at first order, sextupoles in AR1 ensure linearization of curvature (T_{566}~3m)
- Arc 2 R_{56} set to -28 cm and reintroduces curvature to ensure longitudinal match at linac re-entry

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2010 – 2016: TYPICAL OPERATIONAL ERL WITH FEL LASING PARAMETERS

Full Energy (MeV)	24-27
Injector Energy (MeV)	6
Bunch Charge (pC)	60 – 80
Micropulse rep. rate (MHz)	16.25 / 32.5
Macropulse length (µs)	85 + 15 startup
Number of micropulses / macropulse	1400 / 2800
Macropulse rep. rate (Hz)	10
Wavelength range (µm)	5.5 – 11
Micropulse energy at sample (µJ)	2
Peak power at sample (MW)	2
Av. Power within macropulse (W)	20
Av. Power (mW)	40
Linear polarisation	>95%
Power stability	~0.2 – 1 %

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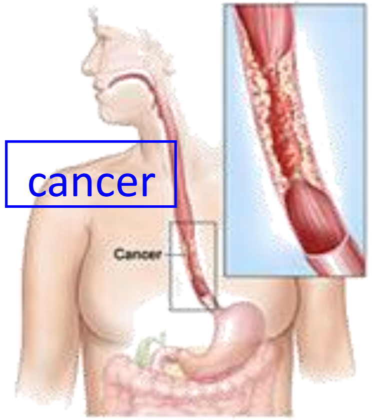
2011: IR-FEL ILLUMINATED NEAR-FIELD MICROSCOPY FOR OESOPHAGEAL CANCER DIAGNOSIS

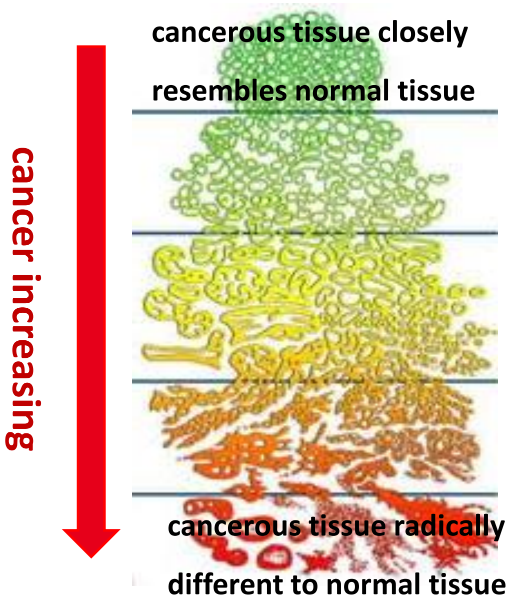
- Motivation:
  - Oesophageal adenocarcinoma is the fastest rising incidence of cancer in the western world and survival rates are very poor
  - Oesophageal adenocarcinoma often progresses from Barrett's oesophagus: lining of the oesophagus is damaged by stomach acid and changed to a lining similar to that of the stomach.
  - The challenge is to identify patients with Barrett’s oesophagus who will develop oesophageal cancer.



- Present method of diagnosis:
  - Subjective
  - Patterns difficult to interpret
  - Biopsy may not be representative

false positive -> patient has unnecessary surgery

false negative -> patient dies



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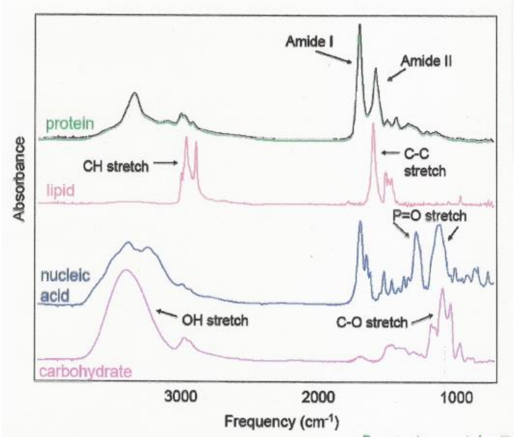
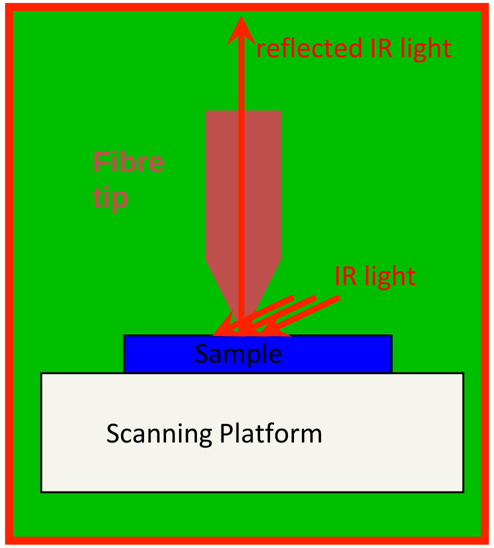
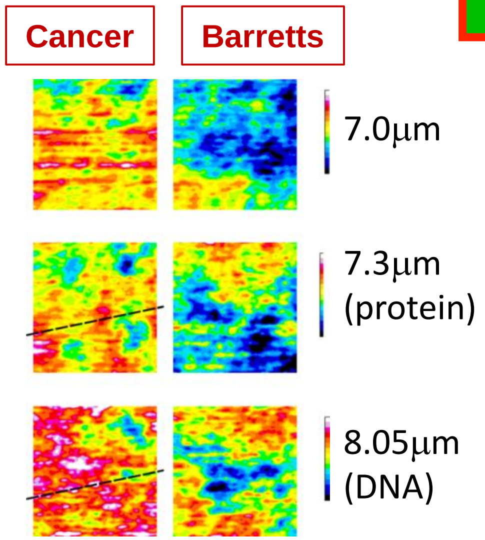
2011: IR-FEL ILLUMINATED NEAR-FIELD MICROSCOPY FOR OESOPHAGEAL CANCER DIAGNOSIS

- Potential solution: Spectroscopy and microscopy in the IR
  - The different components of tissue have different IR spectra
  - Traditionally the weakness has been resolution ~ λ/2 ~ 3-4 µm – but the features are ~ 10 nm
  - The SNOM overcomes this by working in the near field
  - A tapered optical fibre probe is placed within a fraction of a wavelength in close proximity to a sample and scanned
  - The spatial resolution is now given by the tip diameter
  - However, there is strong reduction of the intensity due to the aperture of the fibre
  - So the technique needs a high-intensity tune-able IR source – ALICE FEL
  - Image cluster analysis at 3 wavelengths selected to differentiate the components and quantify the “spreaded-outness” of DNA → diagnosis







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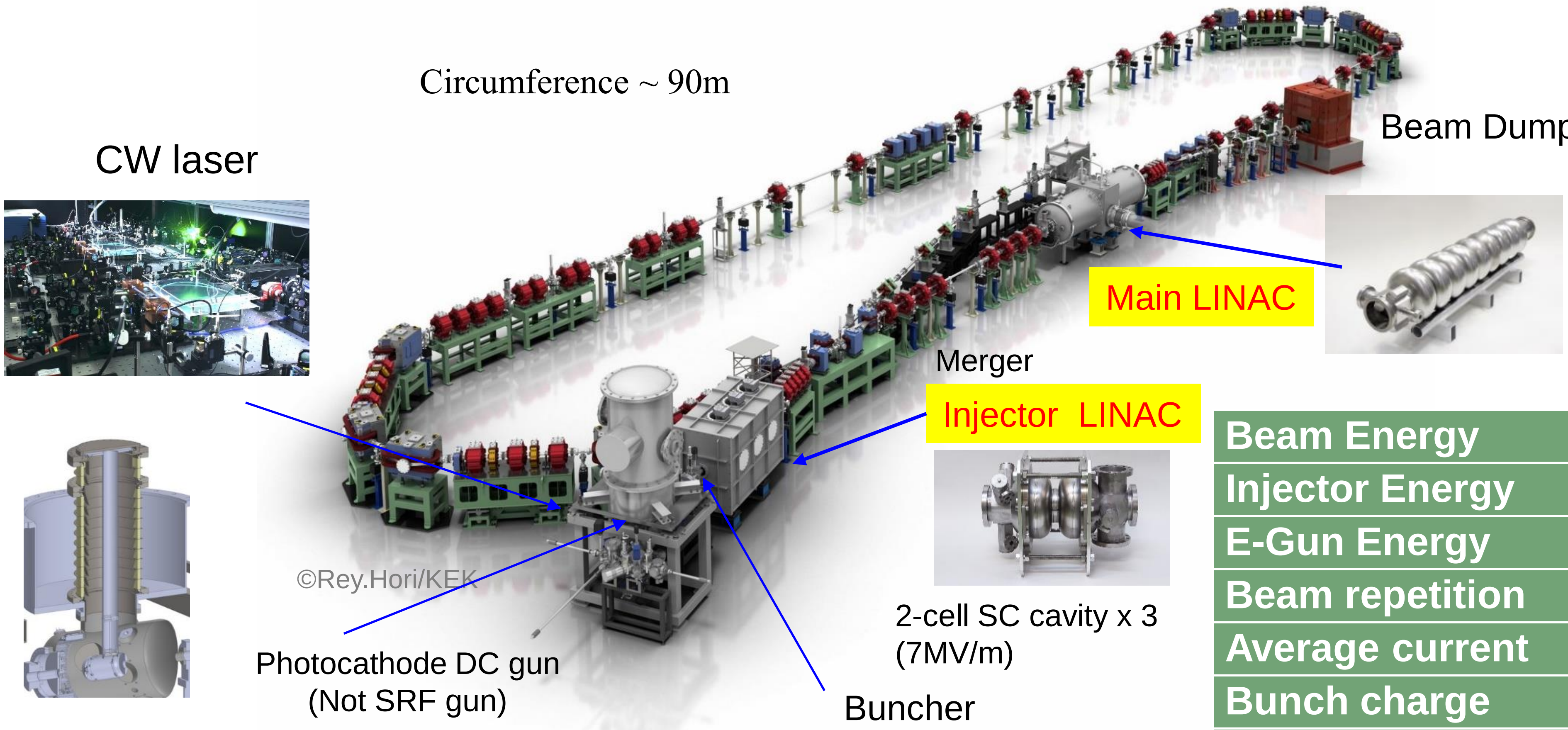
2016: SHUT-DOWN OF ALICE

- ALICE showed potential of ERLs, but ALICE itself had gone as far as it could in terms of accelerator physics
- Successes
  - First SCRF linac operating in the UK
  - First DC photoinjector gun in the UK
  - First ERL in Europe
  - First FEL driven by energy recovery accelerator in Europe
  - First transmission IR-SNOM imaging

  - ALICE was intended as a short lived test-bed and learning tool, but transcended it's original purpose and became a scientific facility in its own right

CERL

COMPACT ERL (CERL) IN KEK



RF frequency= 1.3 GHz

9-cell SC cavity x 2 (8MV/m)

Beam Energy	17.6 MeV
Injector Energy	3.0 – 5.0 MeV
E-Gun Energy	500 keV
Beam repetition	1.3 GHz & 81.25 MHz
Average current	1 mA CW (max)
Bunch charge	60 pC/bunch (max)
Operation mode	CW or Burst

500kV DC Gun (highest DC voltage in the world)

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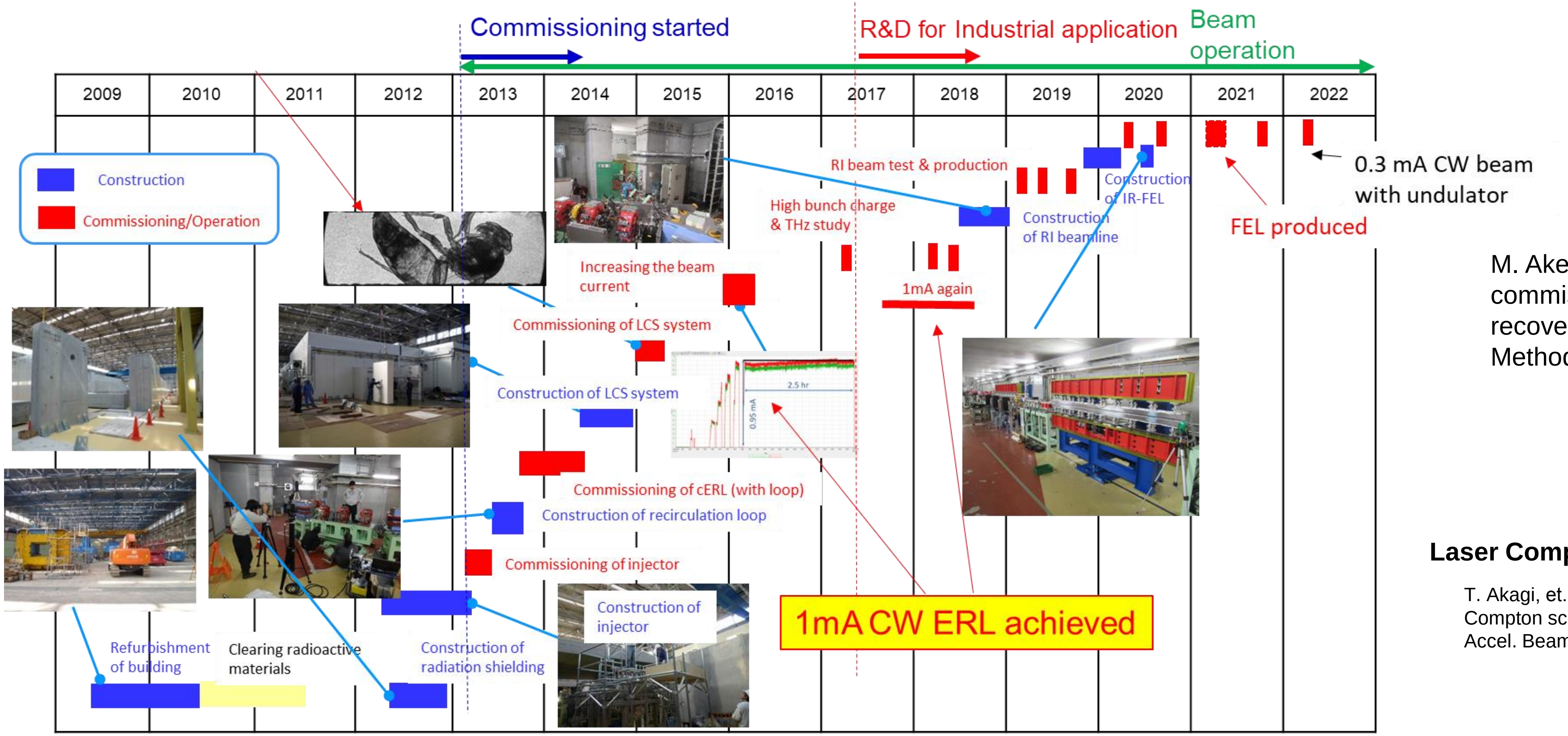
HISTORY

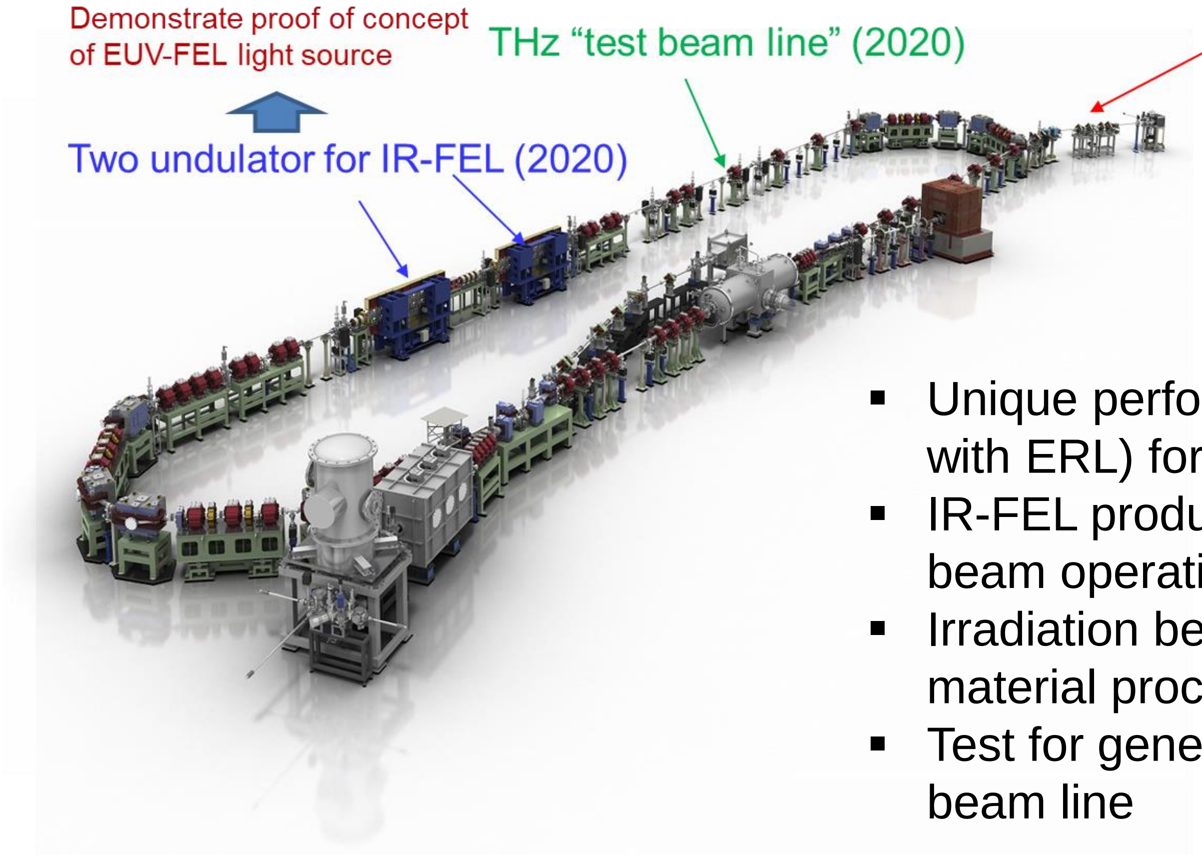


M. Akemoto *et al.*, "Construction and commissioning of the compact energy-recovery linac at KEK" Nucl. Instrum. Method A 877 p.197-219 (2018).

Laser Compton scattering experiment in ERL

T. Akagi, et., al. "Narrow-band photon beam via laser Compton scattering in an energy recovery linac" Phys. Rev. Accel. Beams 19, 114701 (2016)

OPERATION SINCE 2019 - OVERVIEW



Irradiation beam line was constructed (2019)
Max 26 MeV
10μA

- Unique performance (high current, low emittance, short bunch with ERL) for several important industrial applications
- IR-FEL production with continuous CW & high charge ERL beam operation for proof of concept of EUV-FEL
- Irradiation beam line was constructed for RI production, material processing by CW high-intensity beam irradiation
- Test for generation of coherent THz beam, construction of beam line

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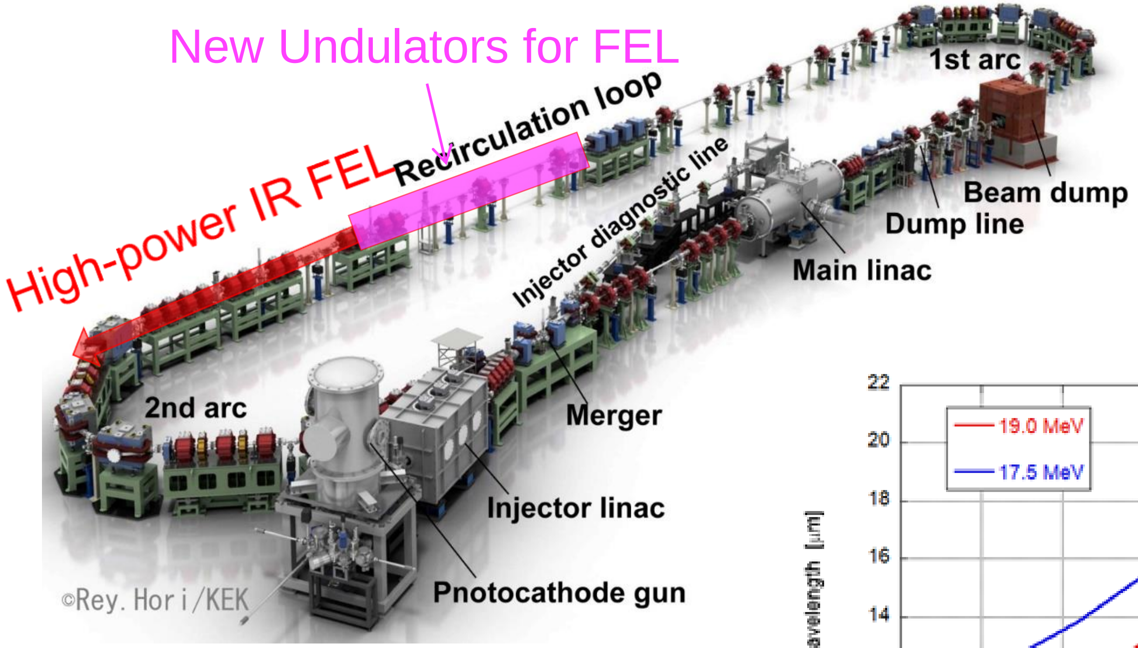
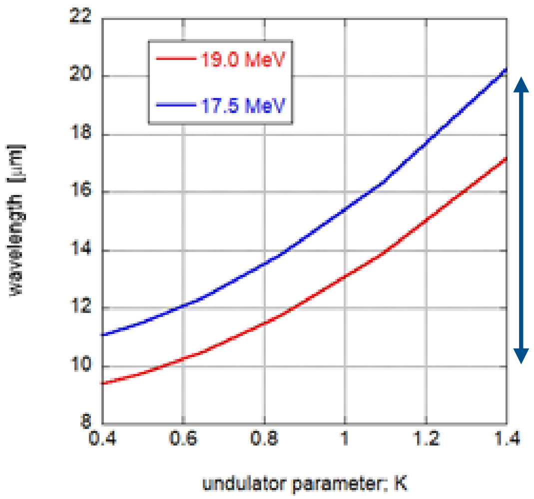
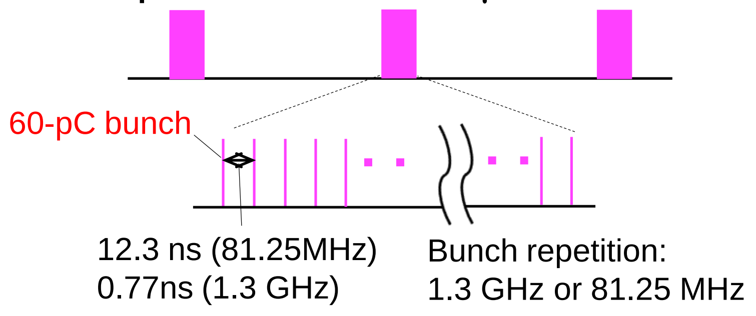
IR-FEL





- Burst mode during FEL optimization

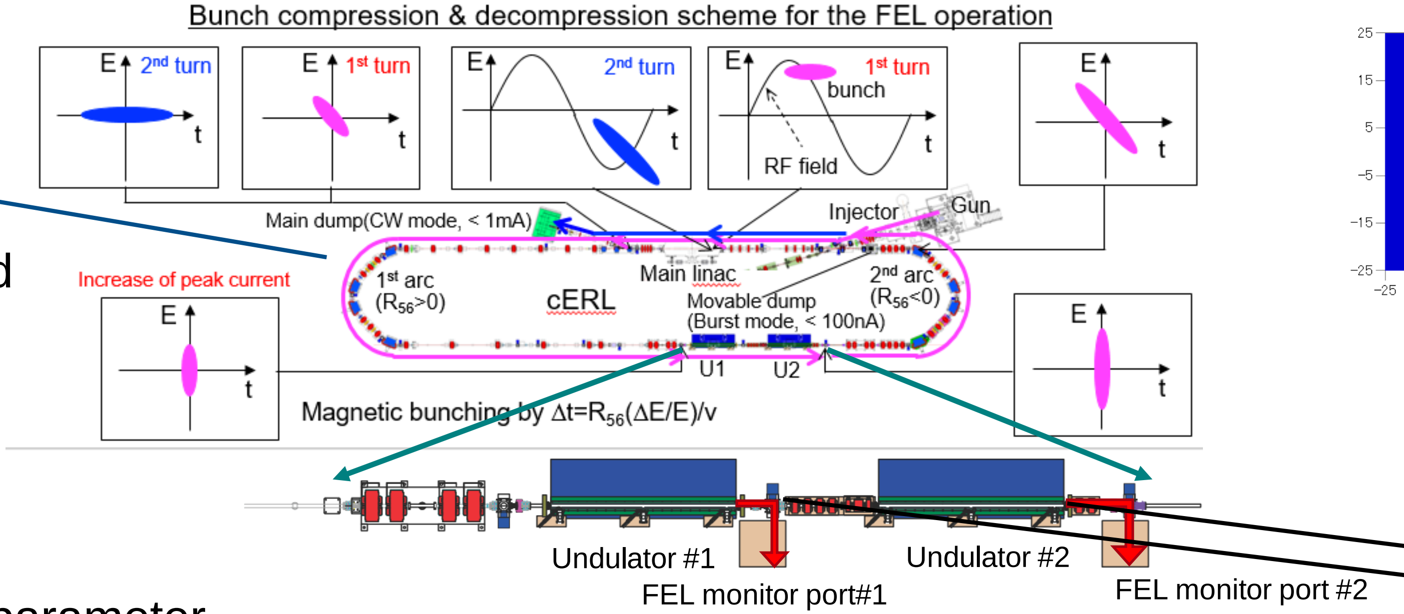
Macro pulse of 0.1 ~1 μs at 1 - 5 Hz

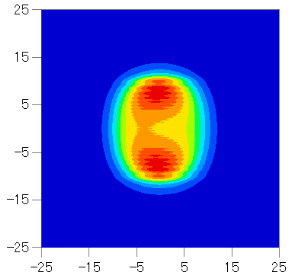


Requirement of the wavelength range of IR-FEL (10～20um)

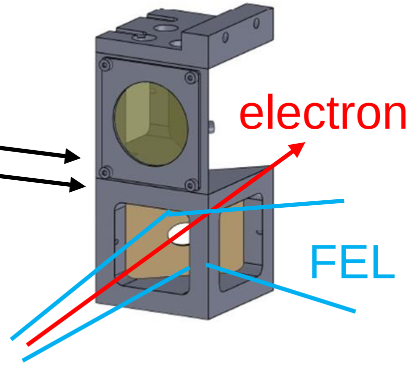
SETUP OF CERL-FEL

Bunch length compressed in this arc section





FEL profile at mirror



Beam parameter

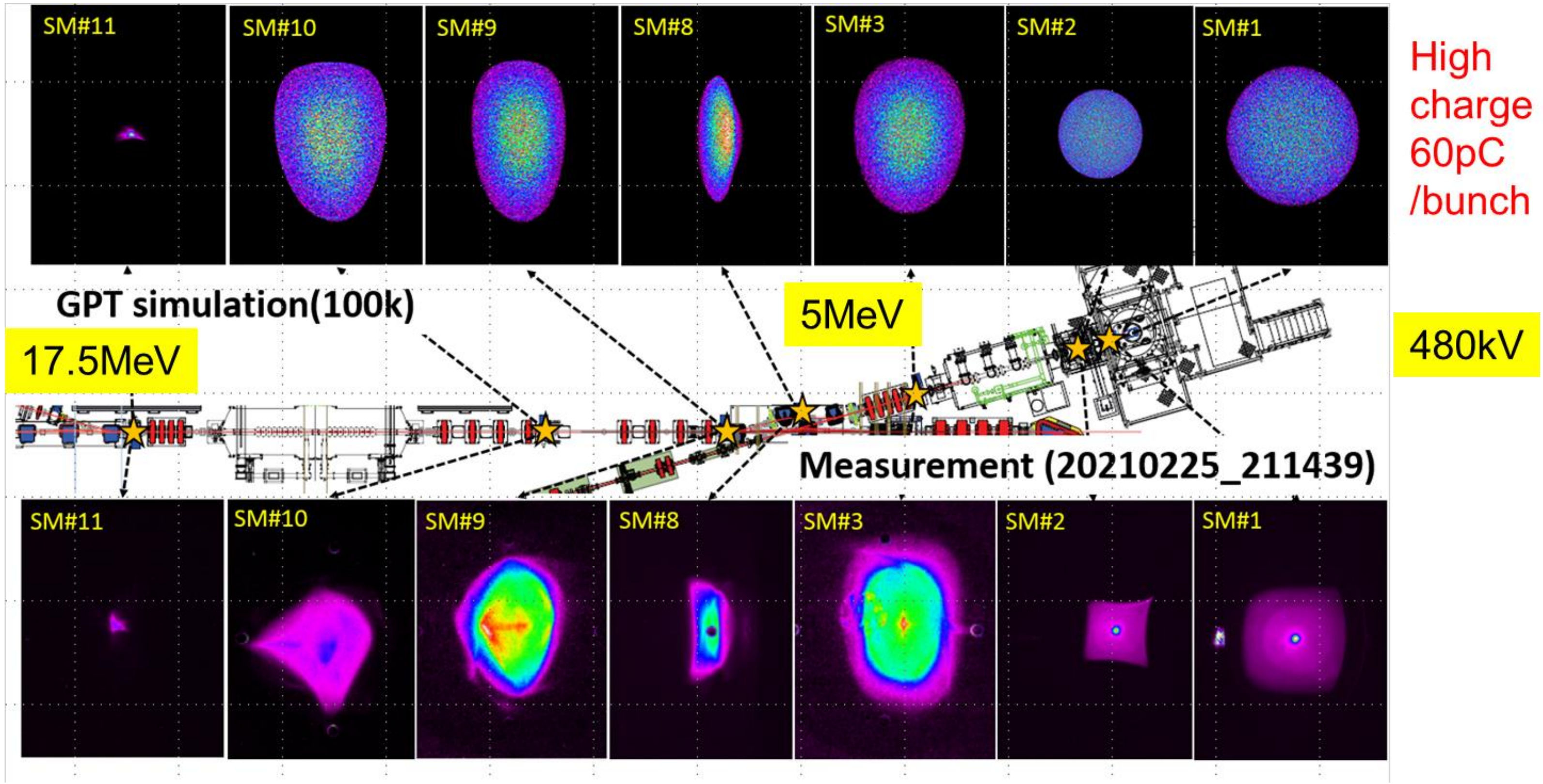
- Energy : 17.5 (– 19.0) MeV
- Bunch charge : 60 pC
- Repetition : 81.25 MHz
- Bunch length : 0.5 – 2 ps (FWHM)
- Energy spread : 0.1%
- Norm. emittance : 3 π mm mrad

Undulator parameter

- Type: APU (Planar)
- Gap: 10 mm (Fixed)
- K: 1.42
- Period λ_u : 24 mm
- Total length : 3 m
- No. of Undulator : 2

Only FEL was reflected and electron went through the hole

OPTICS TUNING OF HIGH CHARGE OPERATION



Meausment results of emittances at the exit of main linac

Design (60pC/bunch):

1.74 π mm mrad (x) /

1.92 π mm mrad (y)

Measurement (60pC/bunch) :

2.87 ± 0.03 π mm mrad (x) /

1.57 ± 0.02 π mm mrad (y)

- Good agreement between simulation and measurement including space charge effect
- Requirements for FEL operation satisfied

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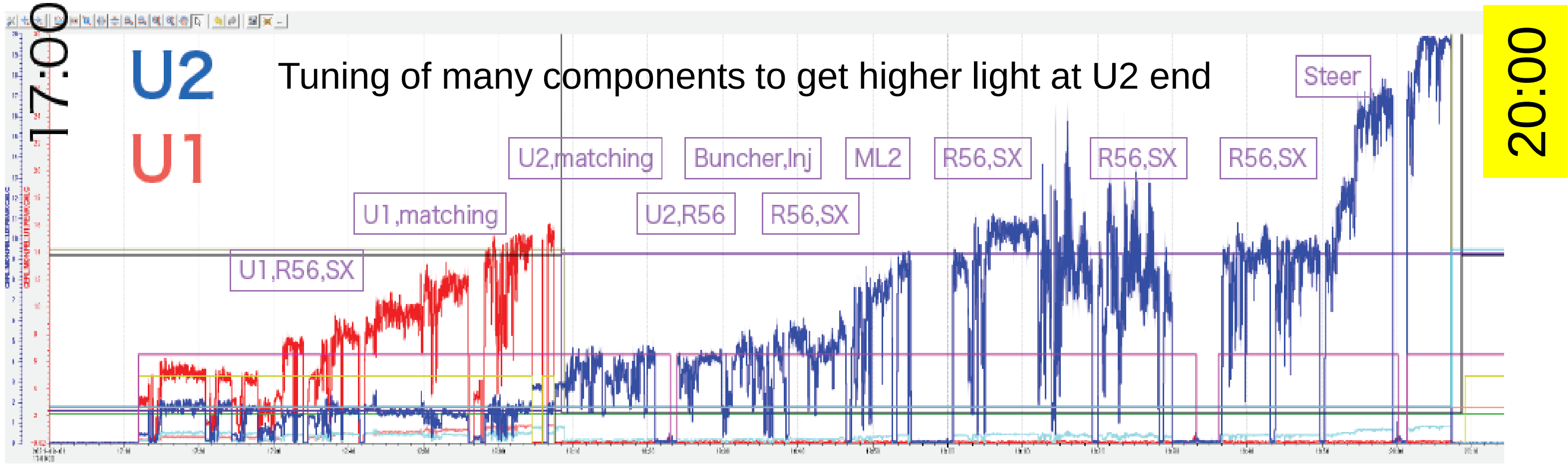
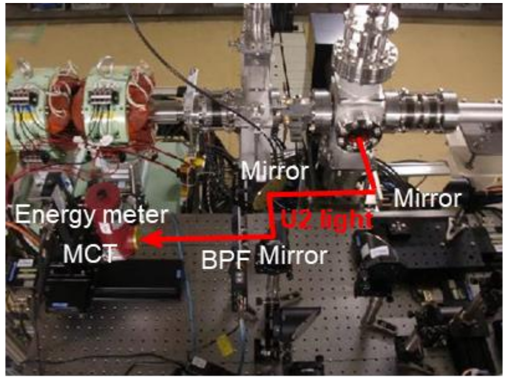
FIRST IR-FEL PRODUCTION





FEL monitor port #2 for the U2 light

Commissioning of MIR FEL

- 5~10 times higher light signal from U2 than that from U1 was achieved by using FEL optimization (AI methods) during stable beam

  → FEL was produced, light intensity almost satisfied requirements

- Next target is CW ERL-SASE-FEL (for proof of concept for EUV-FEL)

Y. Honda et al. *"Construction and Commissioning of Mid-Infrared SASE FEL at cERL"* https://doi.org/10.1063/5.0072511 is published in "Review of Scientific Instruments, (11) Vol.92

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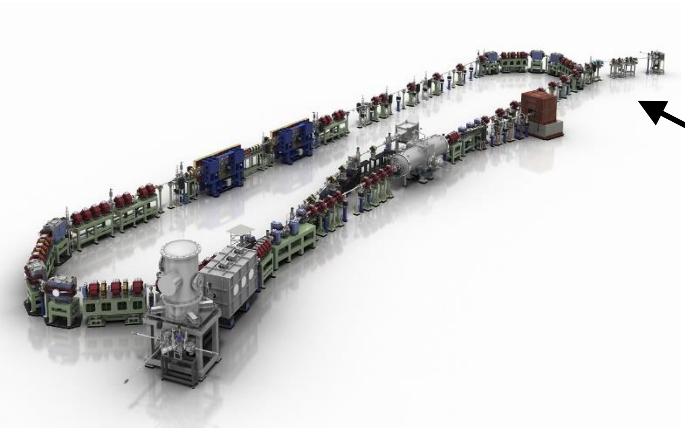
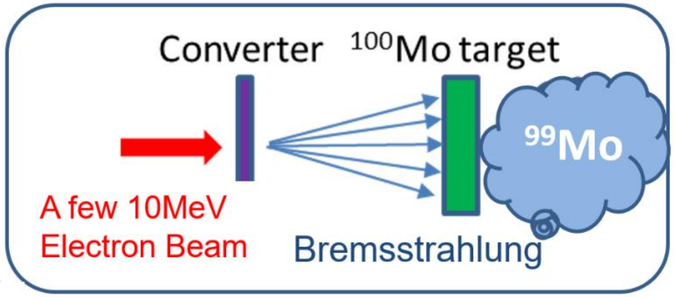
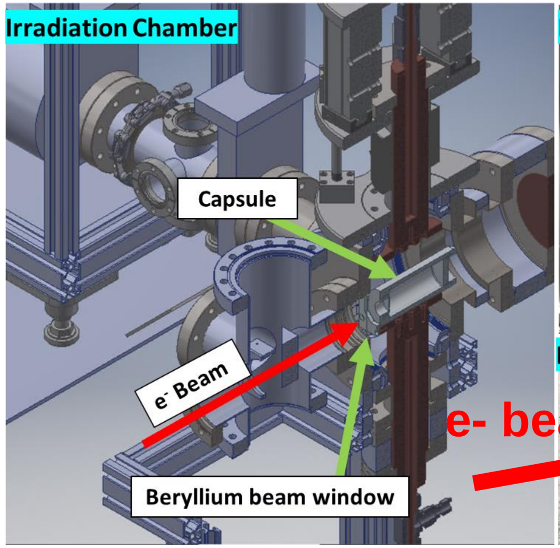
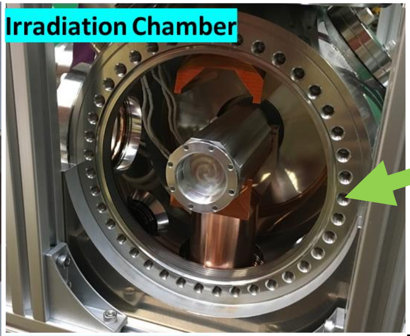
IRRADIATION BEAM LINE



Development of RI manufacturing (^{99} Mo / $^{99\,m}$Tc) by using accelerator for stable supply





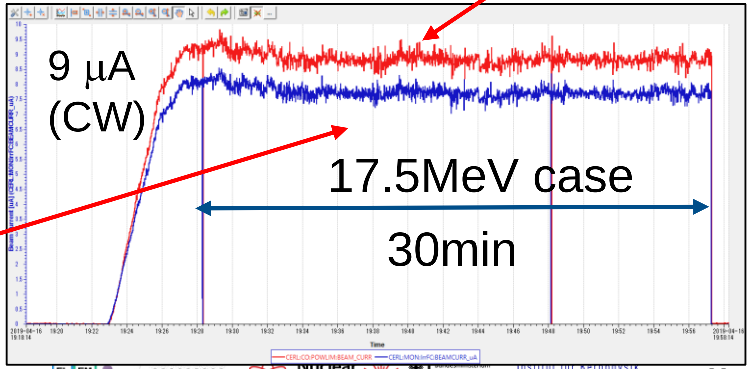


Aluminum capsule target holder

100Mo targets with 1mm disks and 9mm disks in target folder

Beam current is very stable

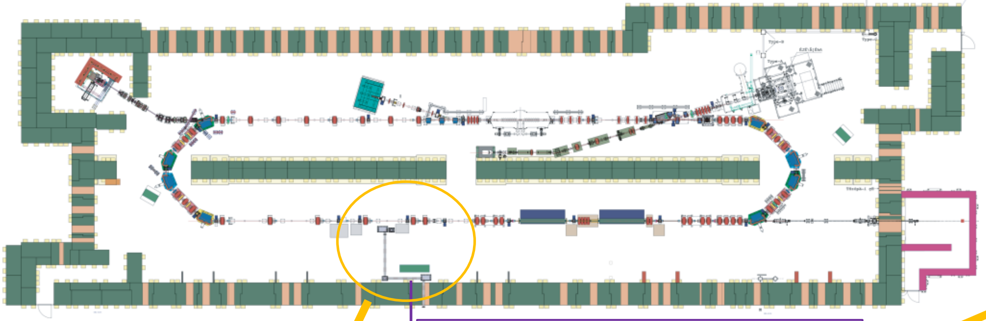
Gun current



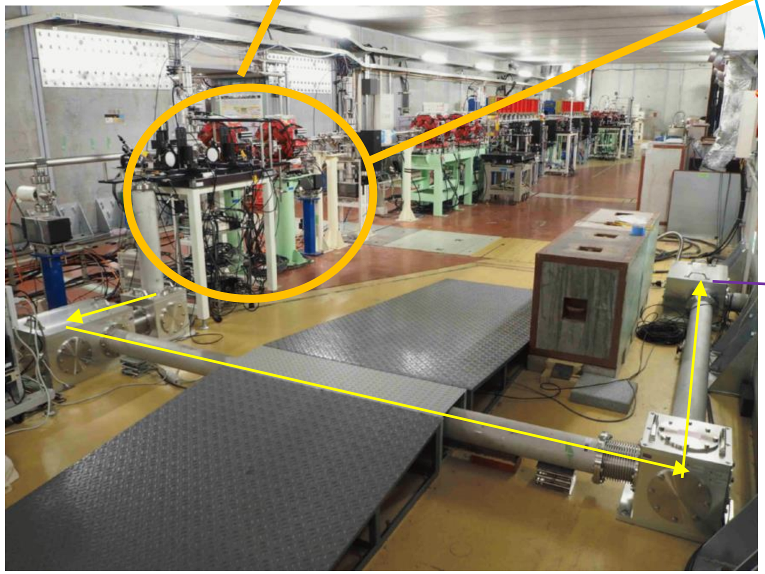
Typical trend of beam current (faraday cup set on the same position of target)

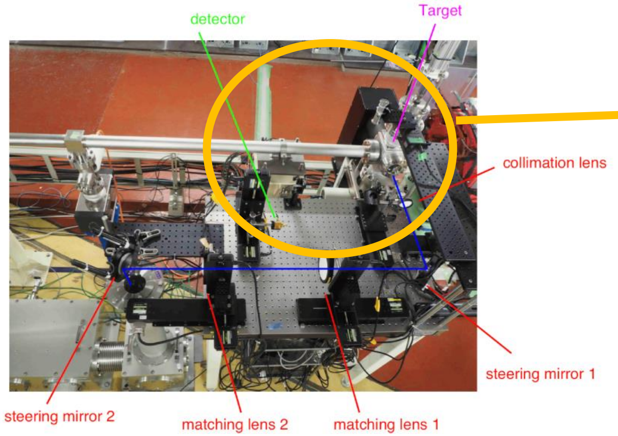
Y. Morikawa, *et al.*, “New Industrial Application Beamline for the cERL in KEK”, Proc. of IPAC2019, (Melbourne, Australia) p3475-3477, (2019)

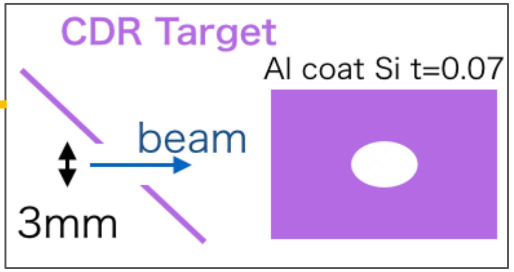
CDR THZ VECTOR BEAM GENERATION AND NEW BEAM LINE



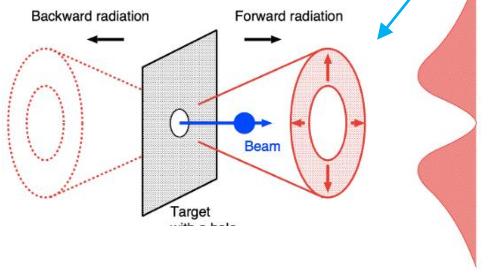
Experimental room



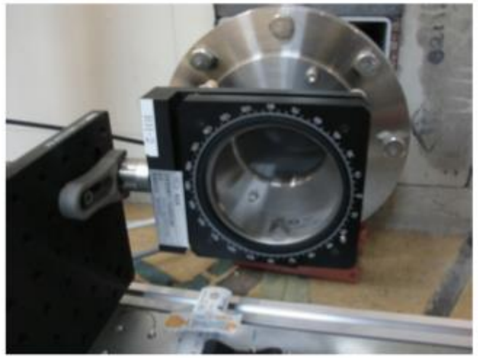




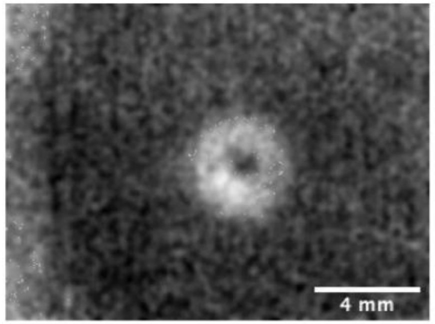
Vector beam



THz camera (TZCam Premium)
Spectrum range (0.1 – 5THz)



CDR

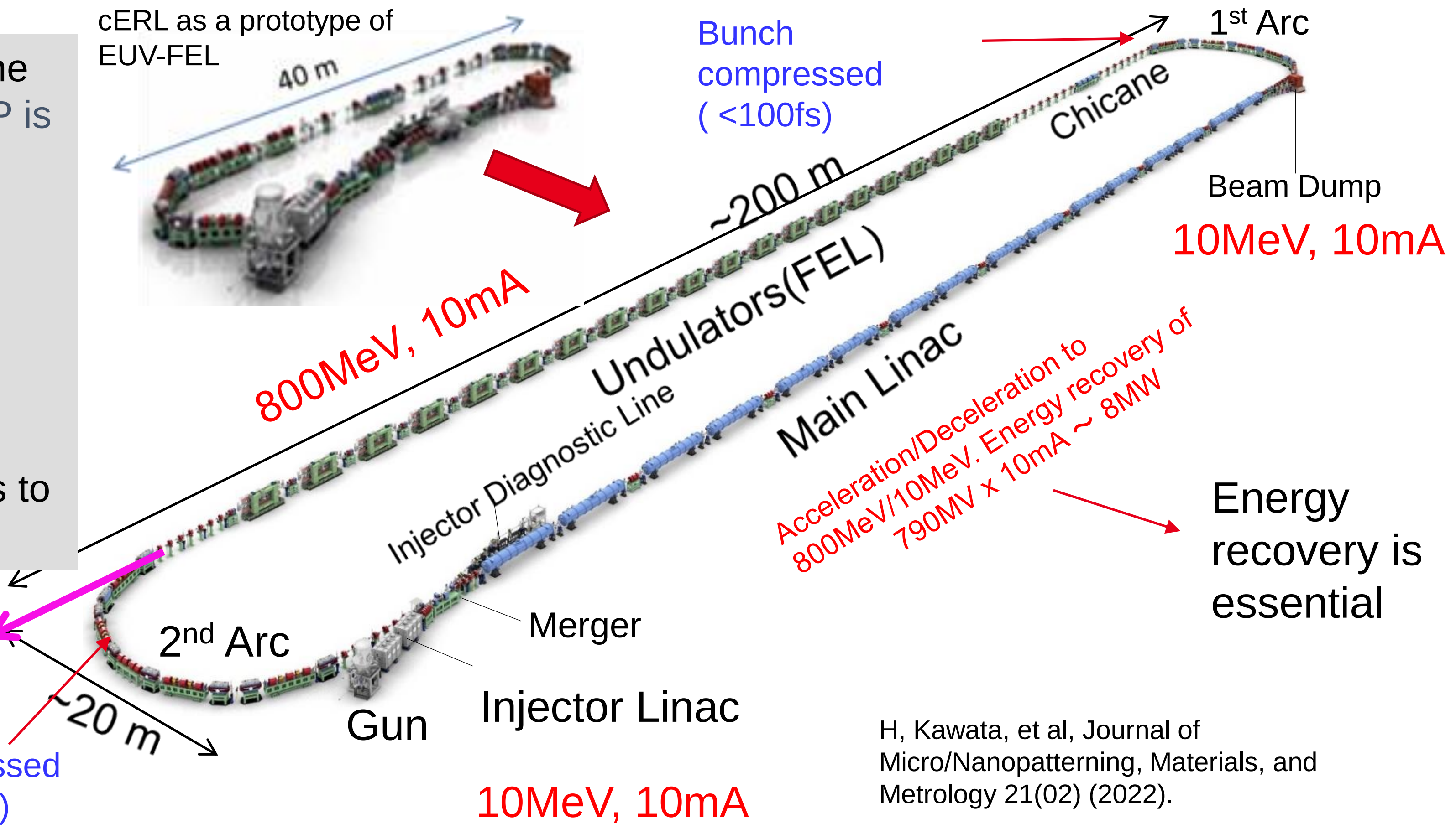


Measured profile by THz camera set at experimental room

Y. Honda, Phys. Rev. Accel. Beams 22, 040703 (2019).

FUTURE PLAN AND DEVELOPMENT

- 10-kW class EUV sources are required in the future for Next Generation Lithography (LPP is 250W) ERL-FEL is the most promising light source
- Features of EUV-FEL
  - High EUV power (> 10 kW)
    10 kW SASE-EUV-FEL is produced by undulator with CW short pulse
  - Low electric power consumption thanks to energy recovery



Parameters	Design
Beam energy	800 MeV
Beam current	10 mA

H, Kawata, et al, Journal of Micro/Nanopatterning, Materials, and Metrology 21(02) (2022).

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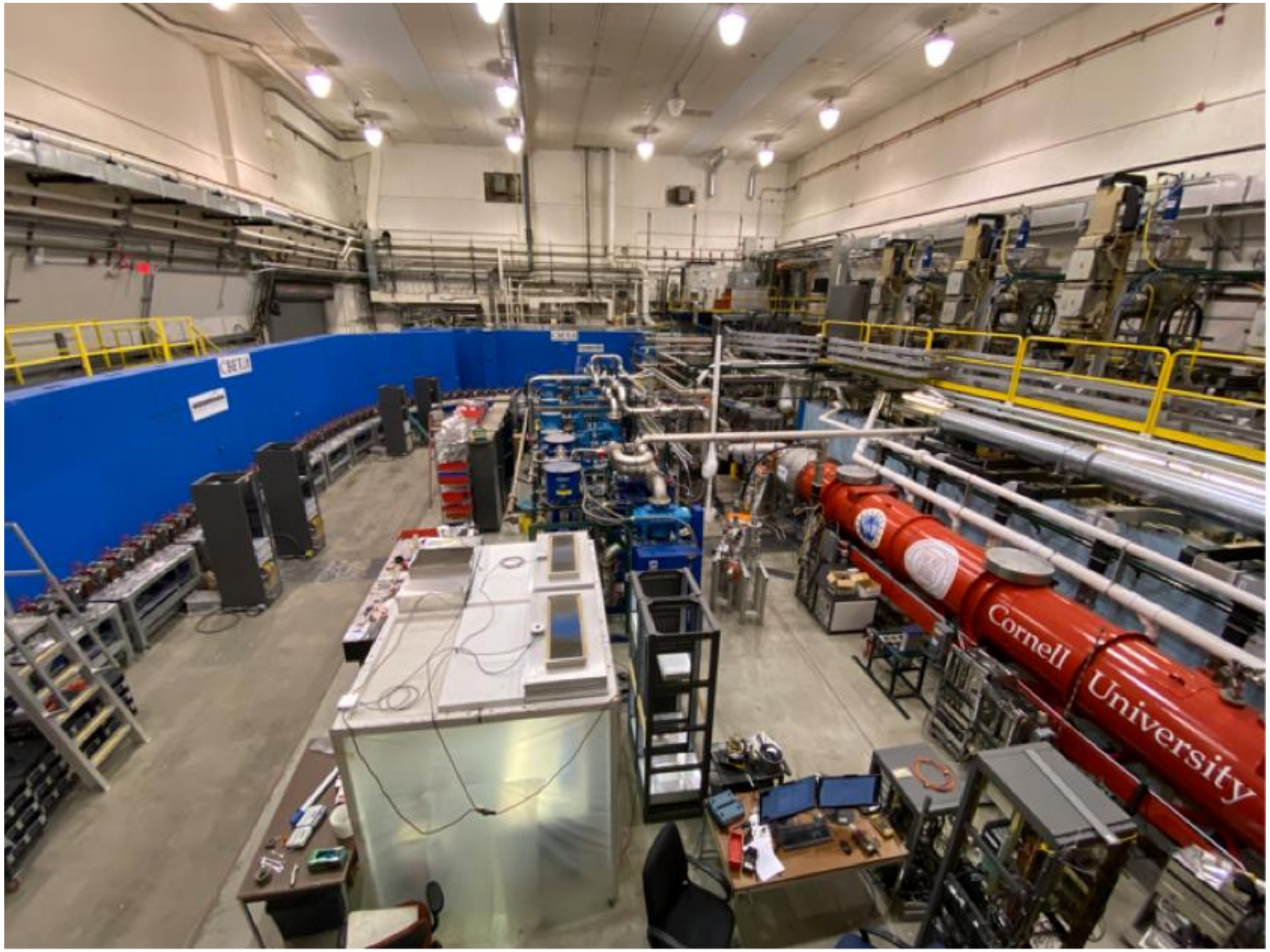
CBETA



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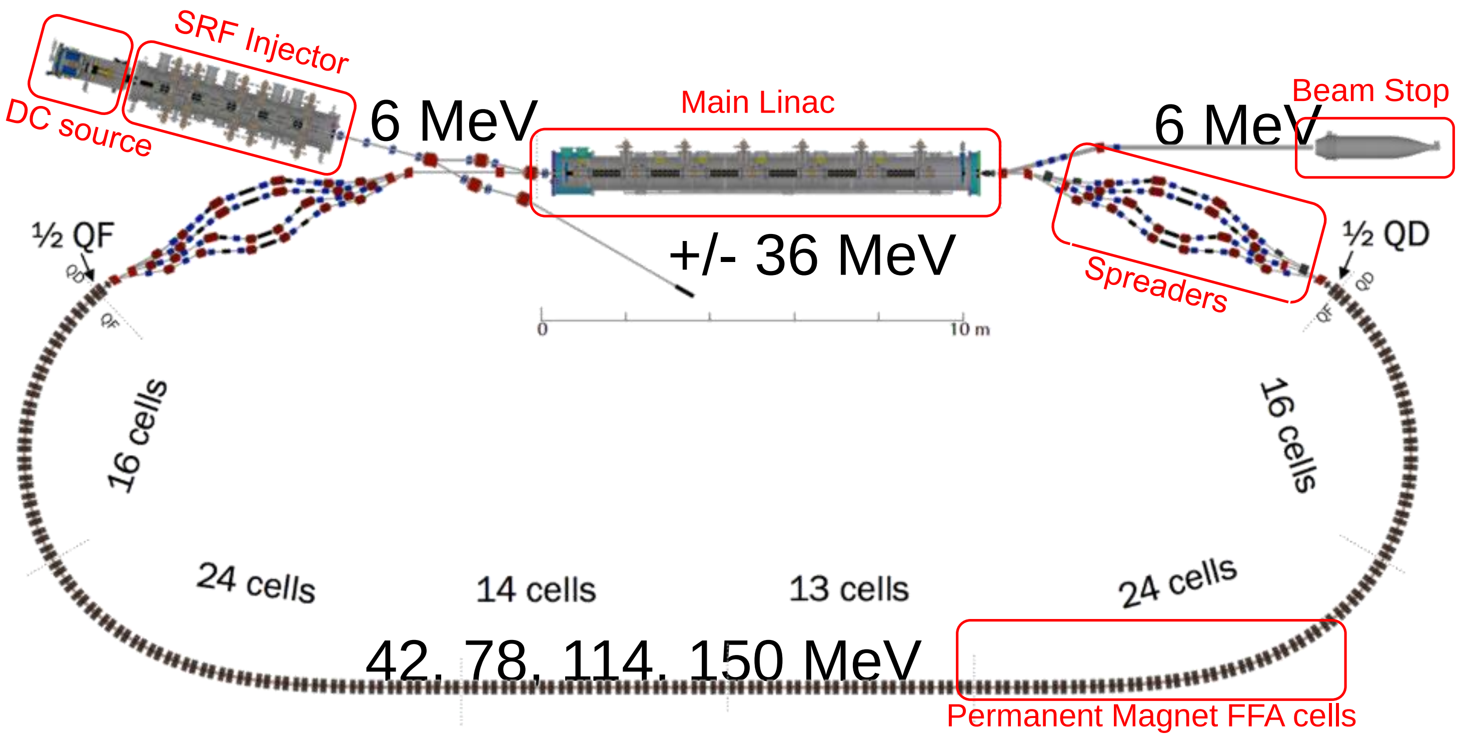
LAYOUT



Radiati
on

- Cornell-BNL Electron Test Accelerator – test facility for EIC
- Cornell DC gun, 2nC peak
- 100mA, 6MeV SRF injector (ICM), 1.3GHz
- 320mA, 6-cavity SRF CW Linac (MLC), 1.3GHz
- 4 Spreaders / Combiners with electro magnets
- FFA cells with permanent magnets, 3.8 energy aperture, 7 beams
- 600kW beam stop

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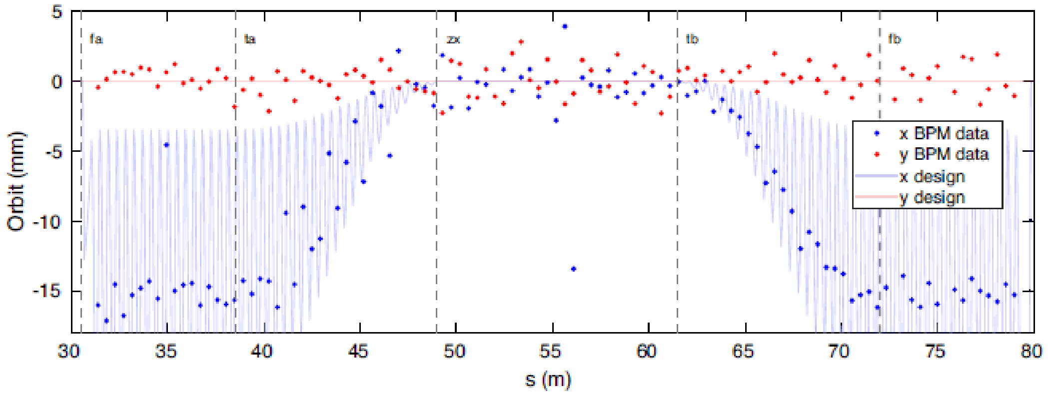
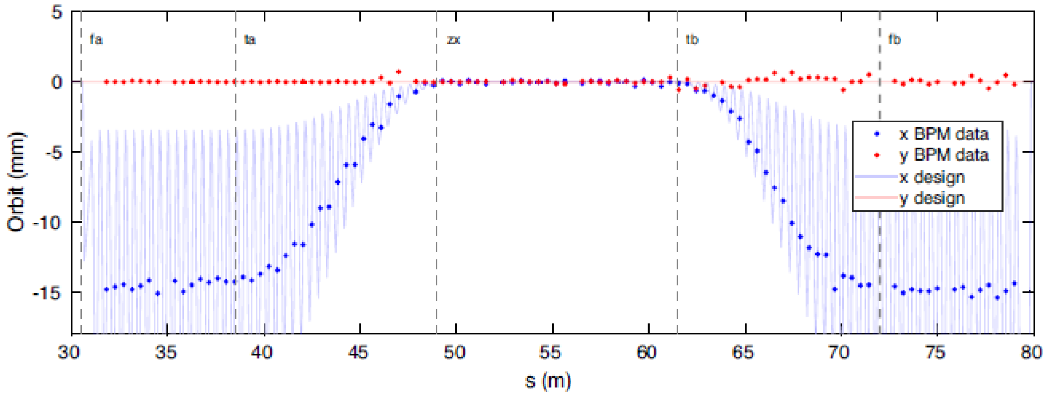
ORBIT CORRECTION



(a) Uncorrected orbit.



(b) Corrected orbit.

- Measured before enery-recovery to verify orbit and linear optics of return loop
- Algorithm using corrector to BPM response matrix (online Bmad model)
- Single pass orbit, tuned by hand (a)
- Algorithmus applied section by section results in (b)

C. Gulliford et al., Phys. Rev. Accel. Beams ***24****, 010101 (2021).*

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1-TURN OPERATION

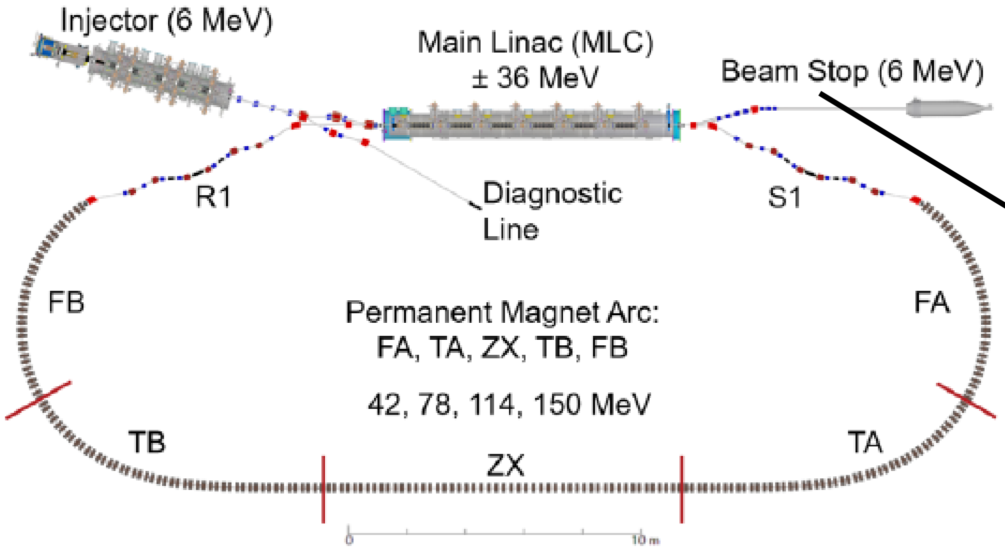
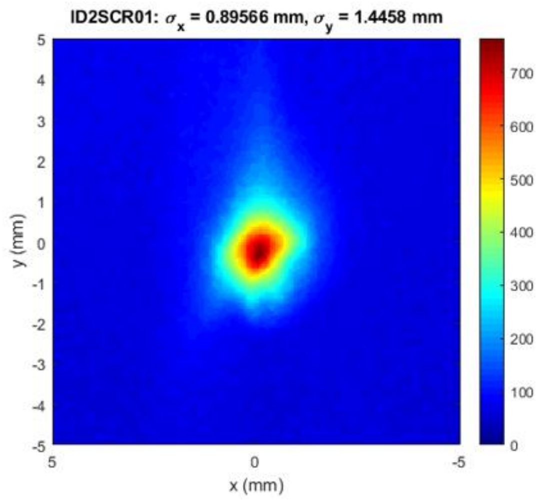


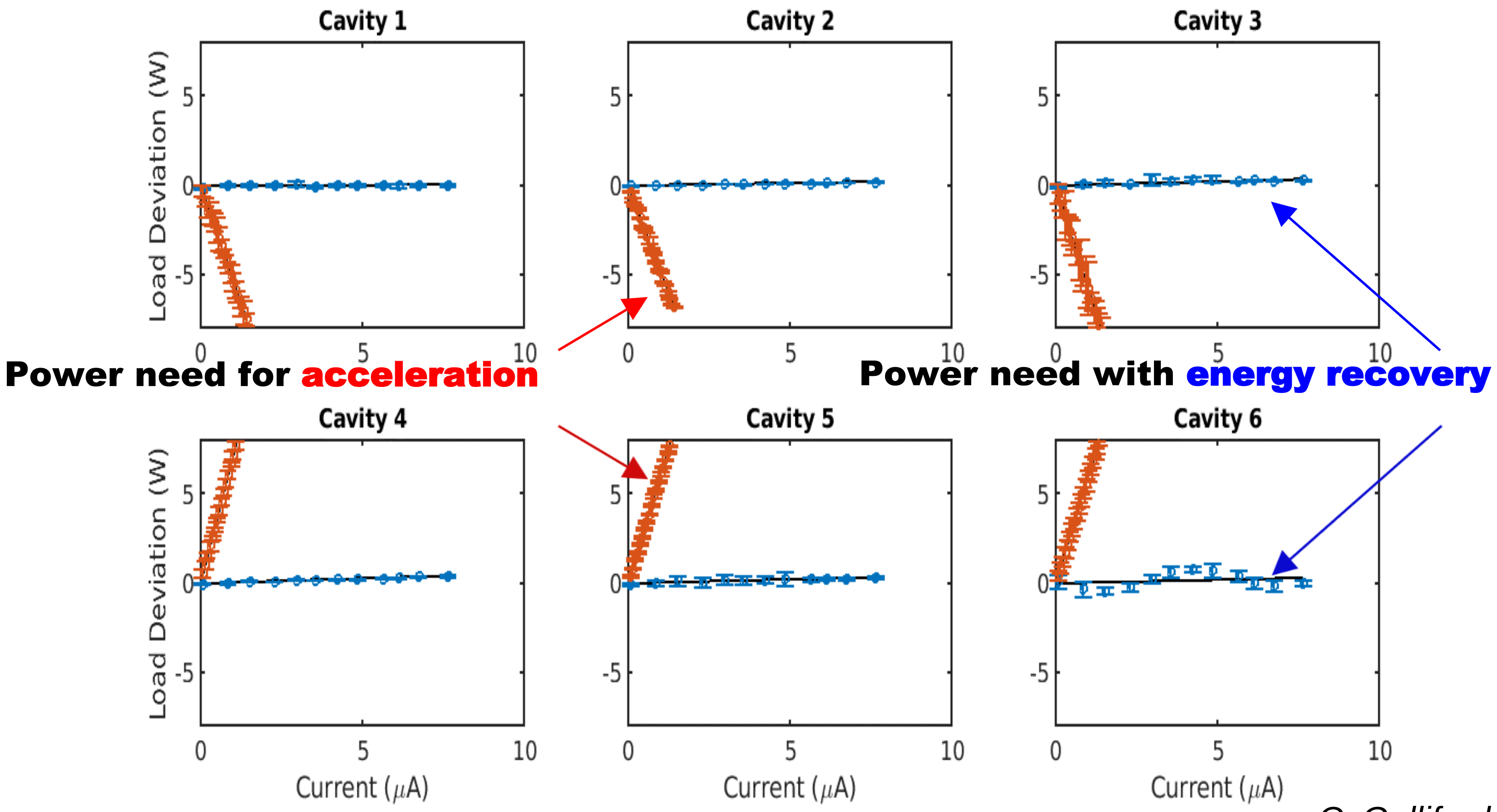
FIG. 1. Layout of CBETA in the one-turn configuration.

- Successful operation, including energy recovery in each cavity (June 24th, 2019)



C. Gulliford et al., Phys. Rev. Accel. Beams ***24****, 010101 (2021).*

ENERGY RECOVERY IN EVERY CAVITY

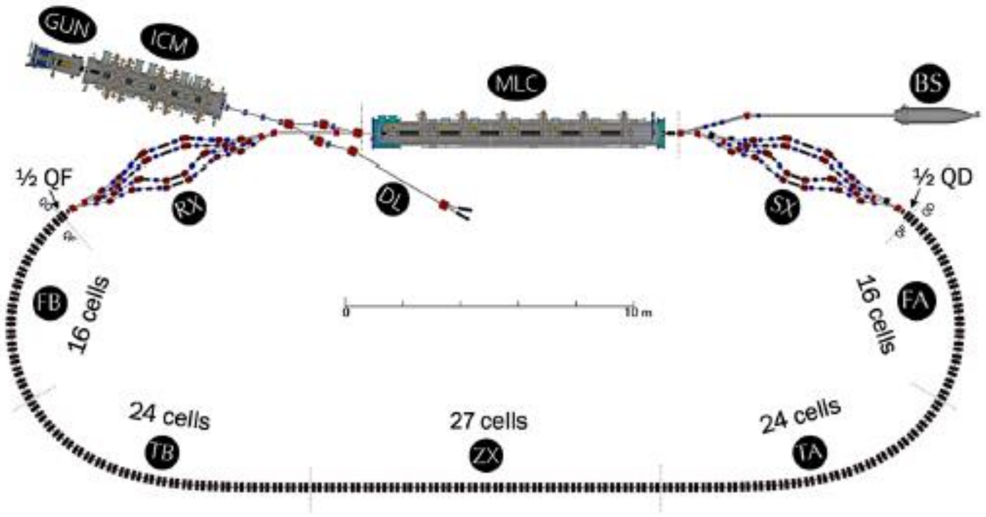


- Transmission 99.6 ± 0.1% ; energy recovery > 99.8%
- Measured up to 8 μA
- Each cavity accelerates beam without receiving external power for it

C. Gulliford et al., Phys. Rev. Accel. Beams ***24****, 010101 (2021).*

4-TURN OPERATION

- 4-turn Layout
- Multi-turn energy recovery achieved on December 24, 2019
- Beam on the first viewscreen in the beam stop line



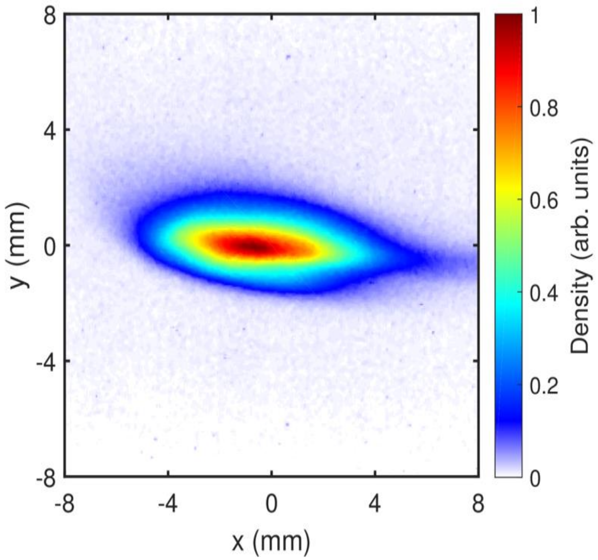


TABLE I. CBETA machine parameters.

Parameter	Value	Units
Bunch charge, design limit	125	pC
Bunch charge, commissioning	5	pC
Bunch rate, design limit	325	MHz
Bunch rate, commissioning	< 1	kHz
Beam current, design limit	40	mA
Beam current, commissioning	1	nA
Beam energy, injector	6	MeV
Beam energy, peak	150	MeV

*A. Bartnik et al, PRL **125**, 044803 (2020).*

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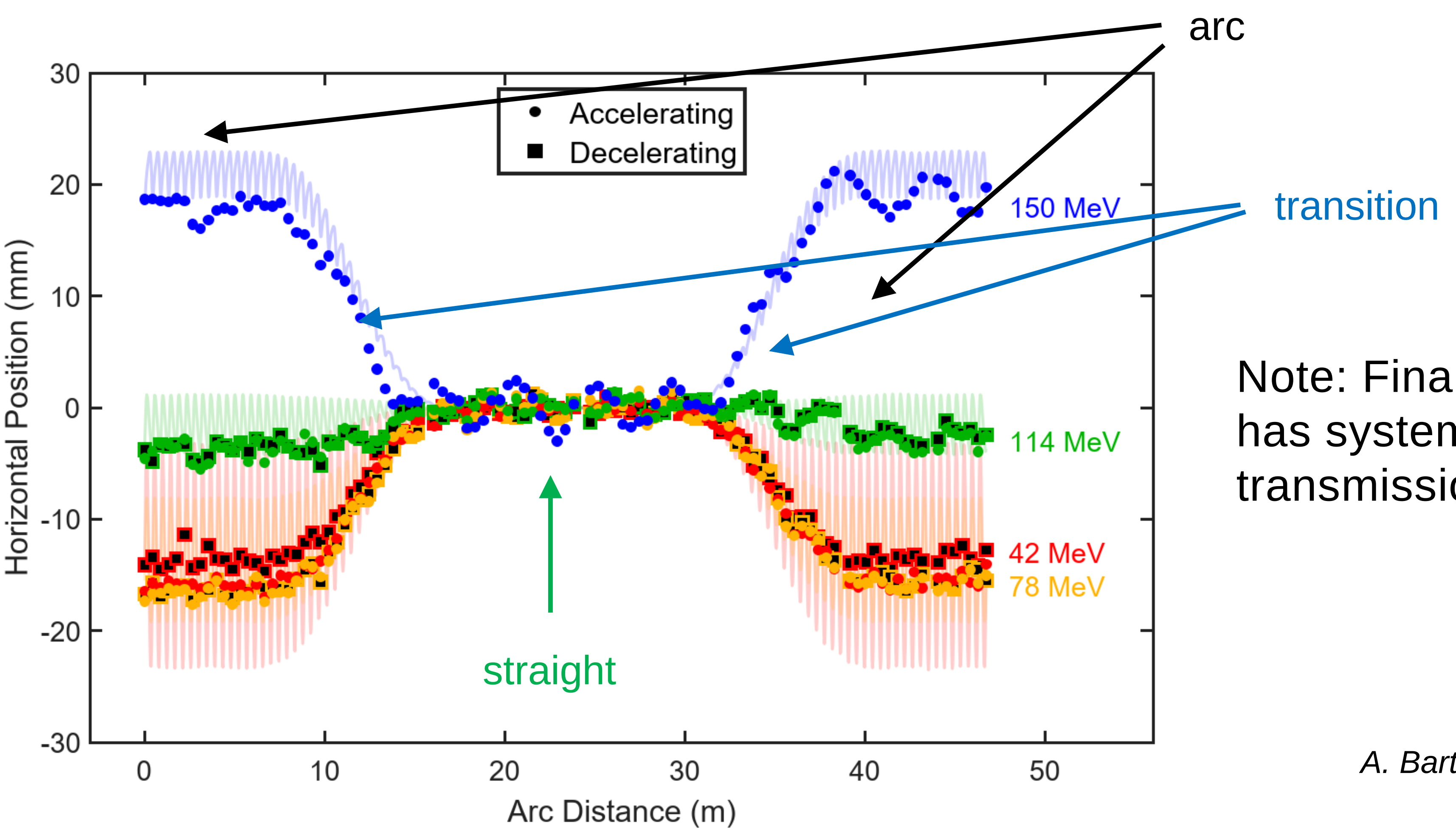
7 HORIZONTAL ORBITS IN THE COMMON FFA LOOP



Note: Final 42 MeV orbit (red) has systematic error due to poor transmission

*A. Bartnik et al, PRL **125**, 044803 (2020).*

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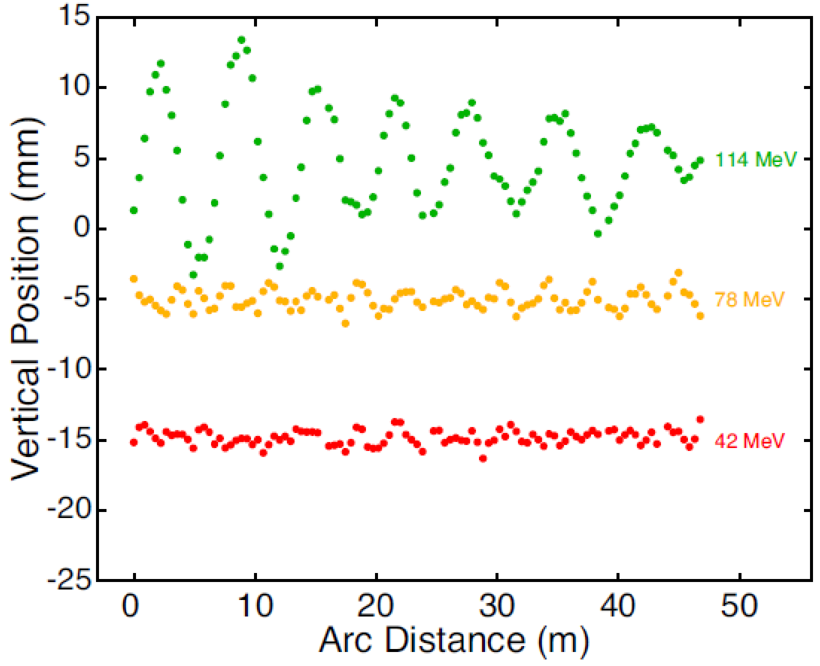
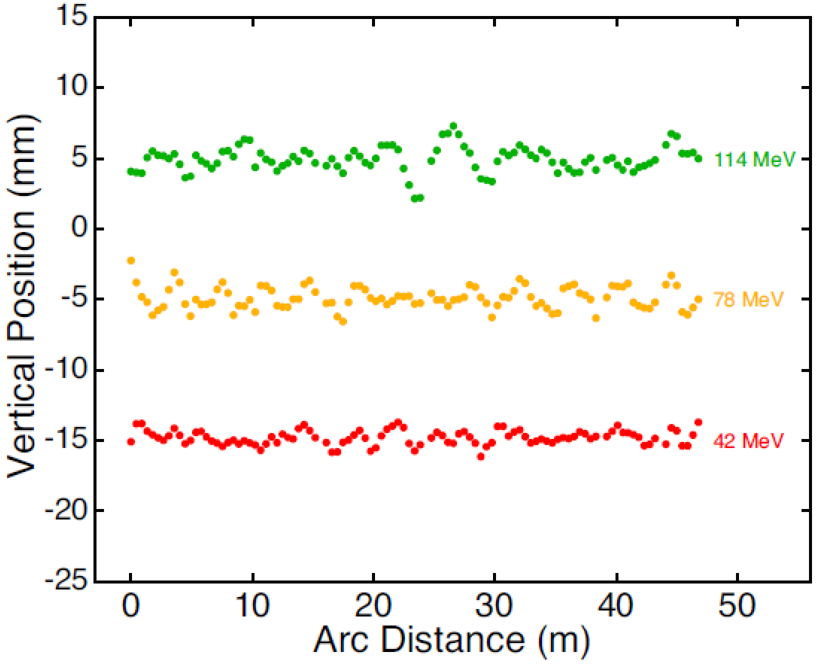
VERTICAL ORBIT CORRECTION



before



after

- First three passes through FFA return loop
- Orbit correction algorithm was applied
- Offset of orbits for clarity

*A. Bartnik et al, PRL **125**, 044803 (2020).*

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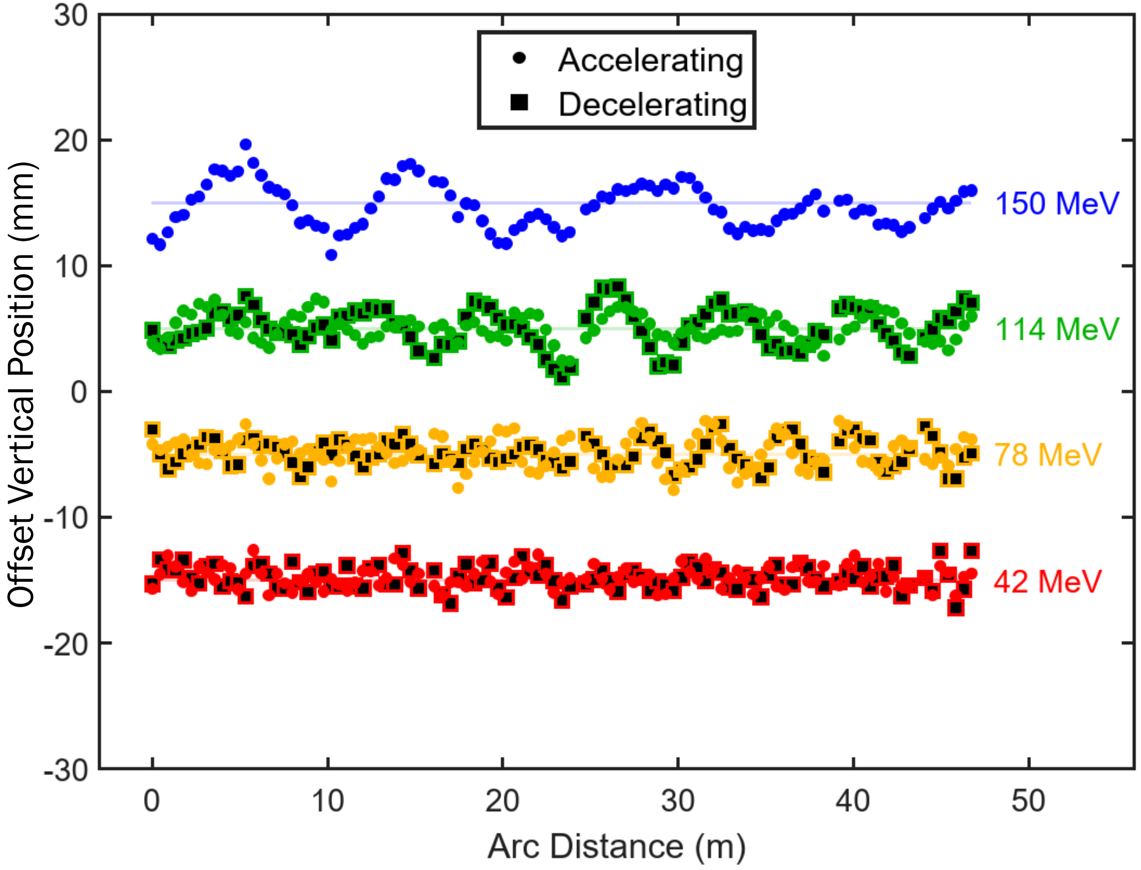
VERTICAL ORBIT CORRECTION



- All seven beams
- Orbit correction algorithm was applied
- Offset of orbits for clarity

*A. Bartnik et al, PRL **125**, 044803 (2020).*

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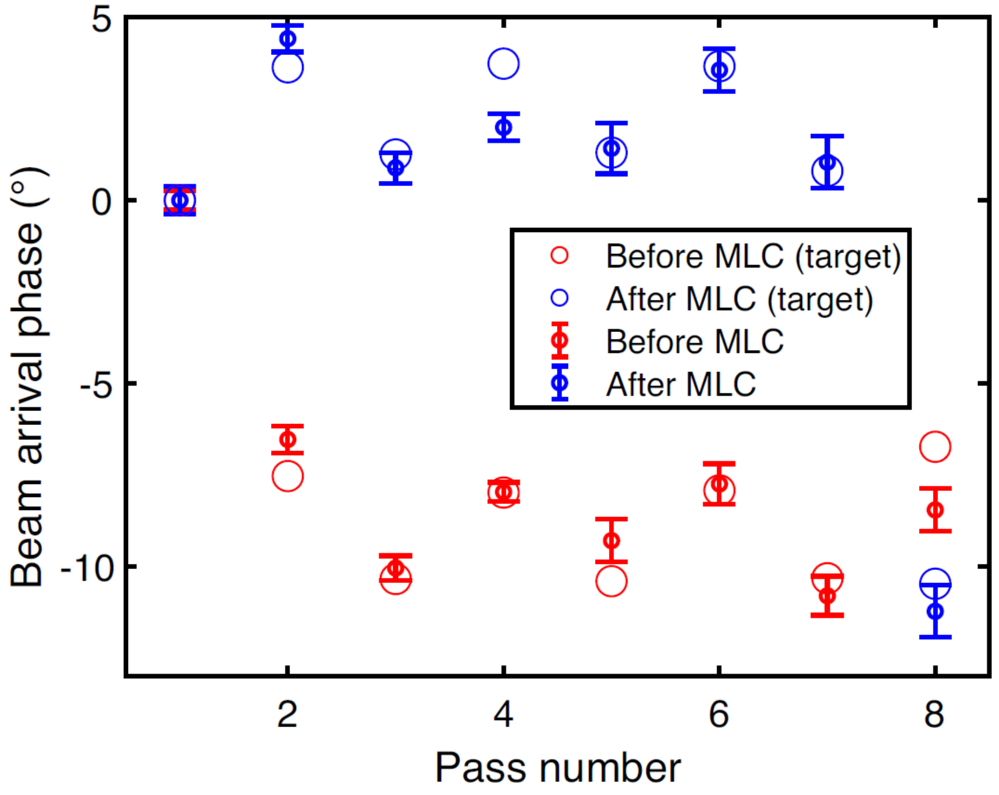
BEAM ARRIVAL PHASES



- Beam arrival phases at entrance and exit of main linac cryomodule (MLC) (measurement vs simulation)
- Phases are shown relative to 1st pass
- Negative phase = later arrival time

A. Bartnik et al, PRL ***125****, 044803 (2020).*

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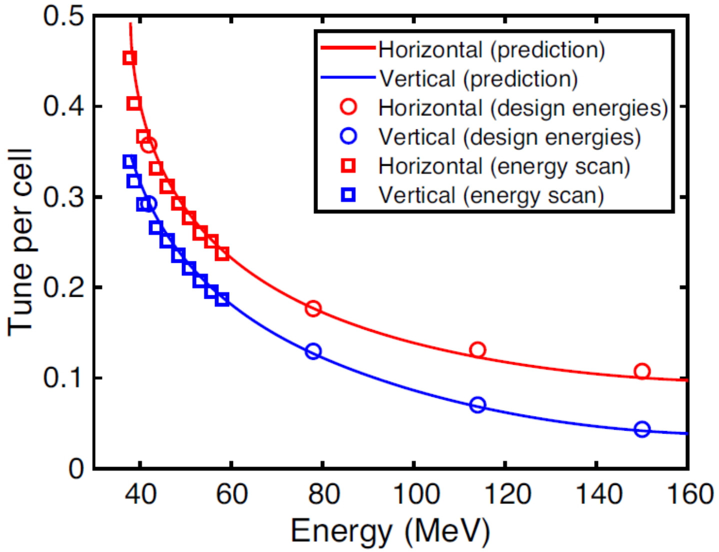
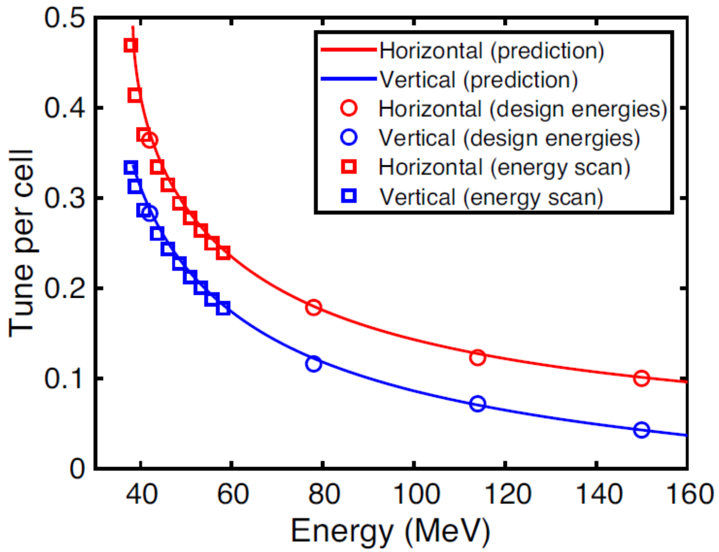
BETATRON TUNES



arc sections



straight section

- Energy scan measured during 1-turn run (39 - 59 MeV)
- Design energies measured during 4-turn run (42, 78, 114, 150 MeV)
- Measurements show a good agreement with the FFA model

*A. Bartnik et al, PRL **125**, 044803 (2020).*

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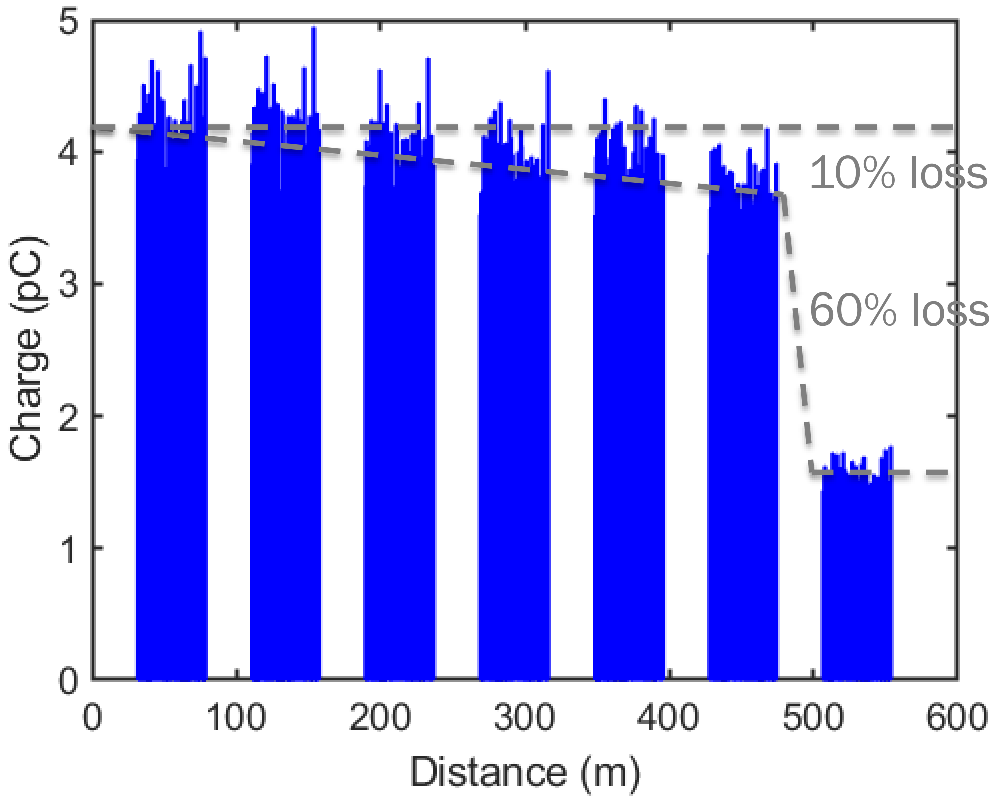
BEAM LOSS THROUGH 7 RETURN LOOPS



*A. Bartnik et al, PRL **125**, 044803 (2020).*

- Beam losses in all 7 passes through the FFA are low.
- Between the FFAs there are 6 passes with gradual 10% losses
- Before the 7th FFA pass there is a 60% loss (in Recombiner-2)
- Source of losses: many small problems in optics settings, nonlinear stray fields, evidence of microbunching, and others (not yet been fully investigated)
- Percentages improve with lower initial charge (not shown)

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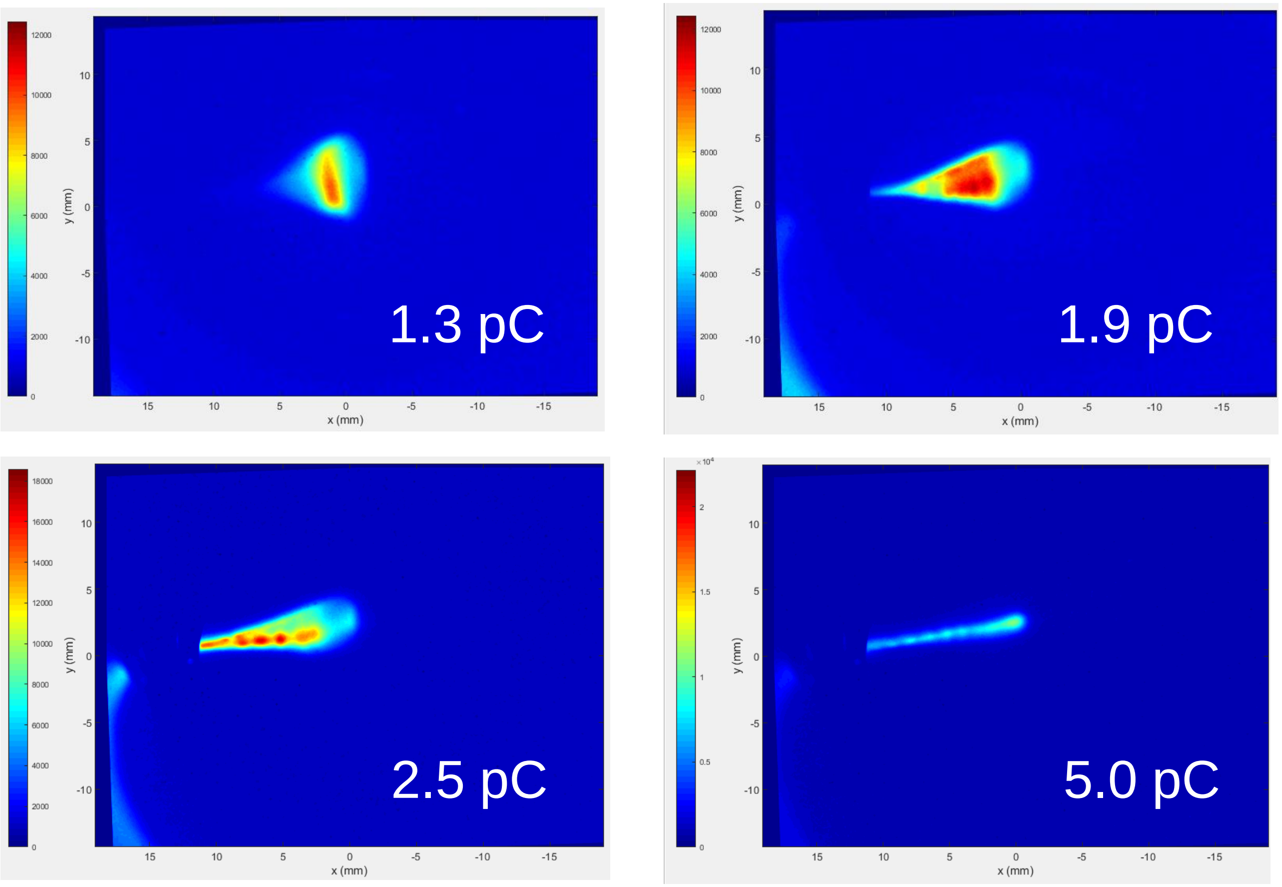
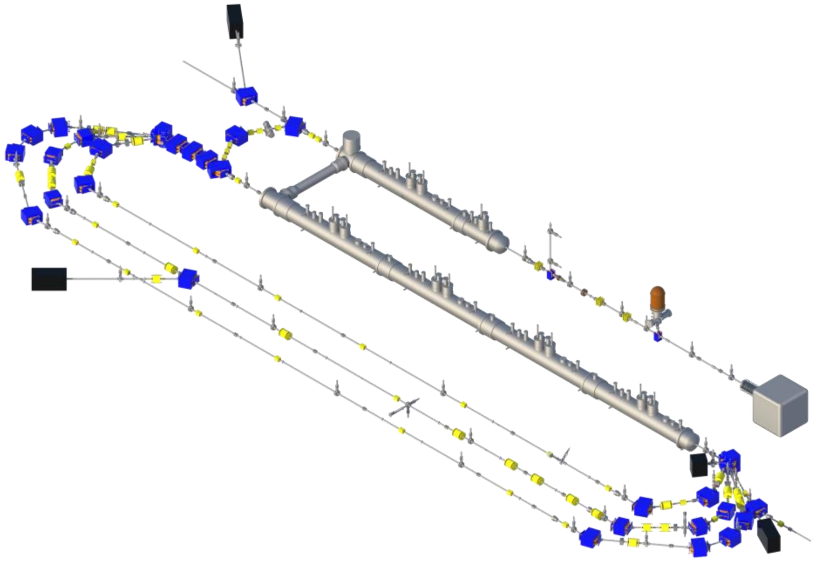
INDICATIONS OF MICRO-BUNCHING



- Measured: entrance to S2 (beginning of second pass)
- Charge dependent
- Single bunch effect
- Optics dependent

Picture: Jan-Christoph Hartung



S-DALINAC

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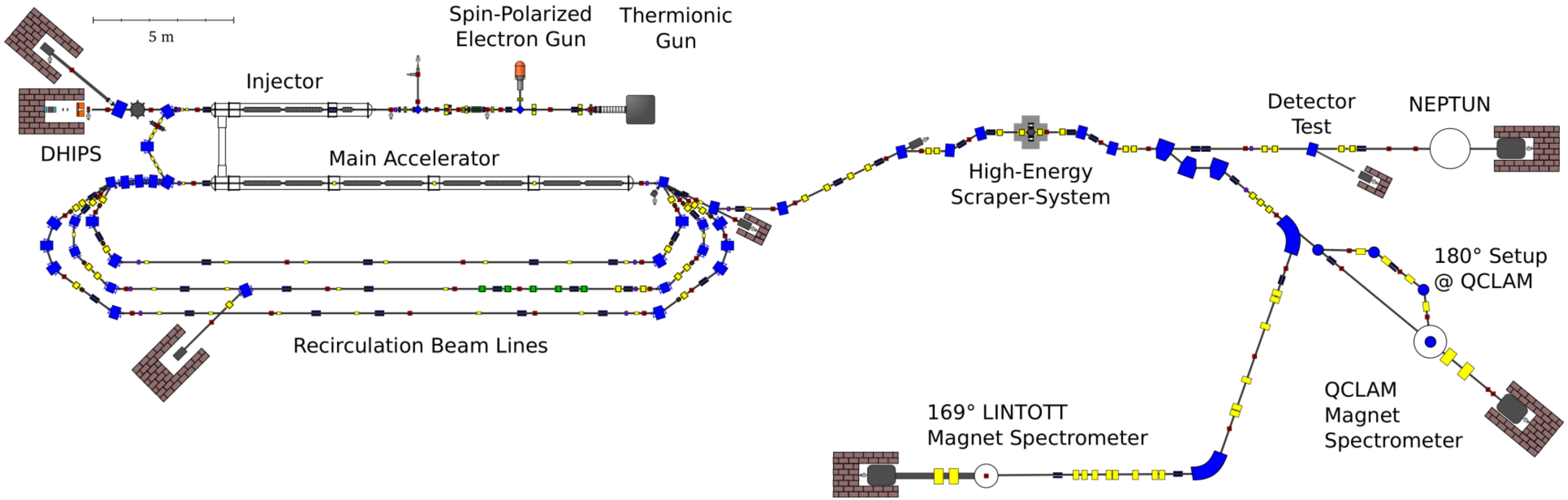
S-DALINAC

SUPERCONDUCTING DARMSTADT LINEAR ACCELERATOR



- **Design (extracted beam):** 130 MeV, 20 µA
- **Design (NRF):** 10 MeV, 60 µA
- **Particles:** electrons
- **Rep. rate:** 2.9973 GHz, cw

- In operation since 1991, modified, improved and operated mainly by students (see later)

Virtual tour (click here, bottom of page)

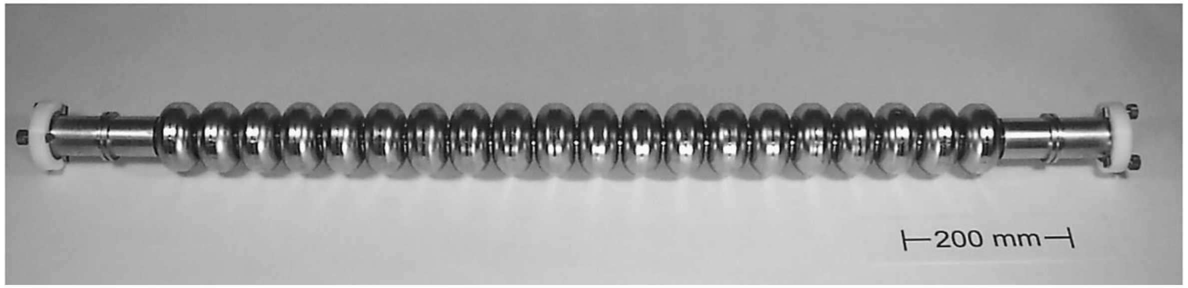
PARAMETERS SRF AND ERL

SRF injector

- 1x 6-cell (β=0.86) as capture
- 2x 20-cell (β=1)

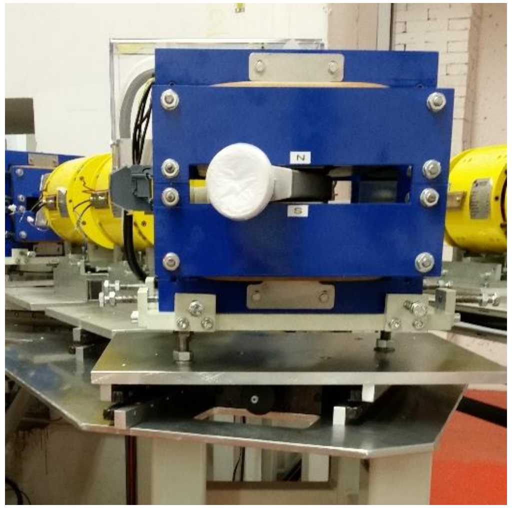
SRF main linac

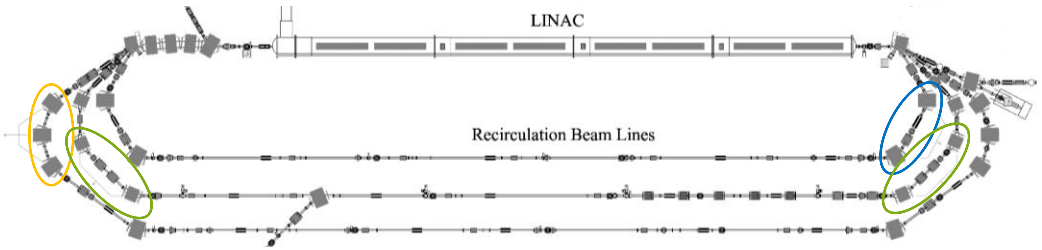
- 8x 20-cell (β=1)



f = 2.9973 GHz

- 360° path length adjustment system in second recirculation → ERL mode
- 265° for first recirculation
- 205° for third recirculation (under upgrade)
- Bunch length important for every setting

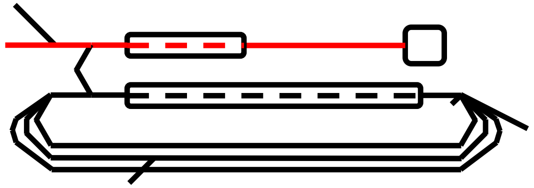




OVERVIEW OPERATION MODES/COMMISSIONING

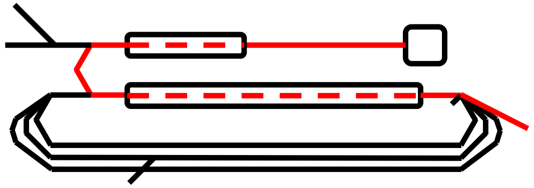
- Modification lattice 2015/2016
- Commissioning of modes followed beam time schedule

Injector



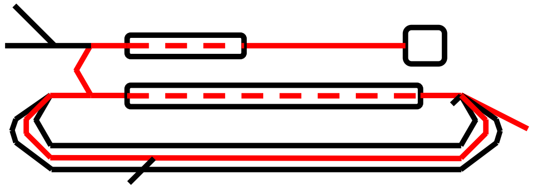
December 2016

Single pass



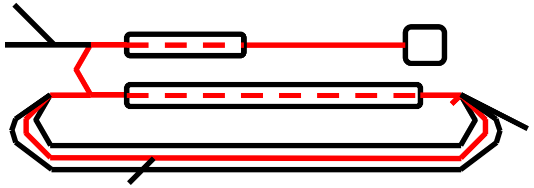
December 2016

1x rec.



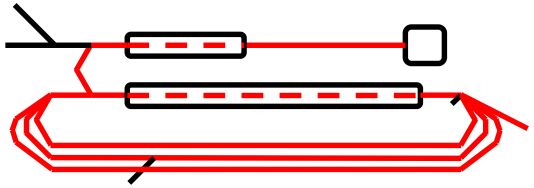
May 2017

1x ERL



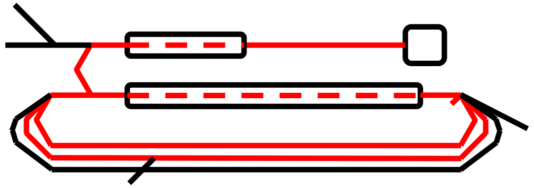
August 2017

3x rec.



November 2018

2x ERL



August 2021

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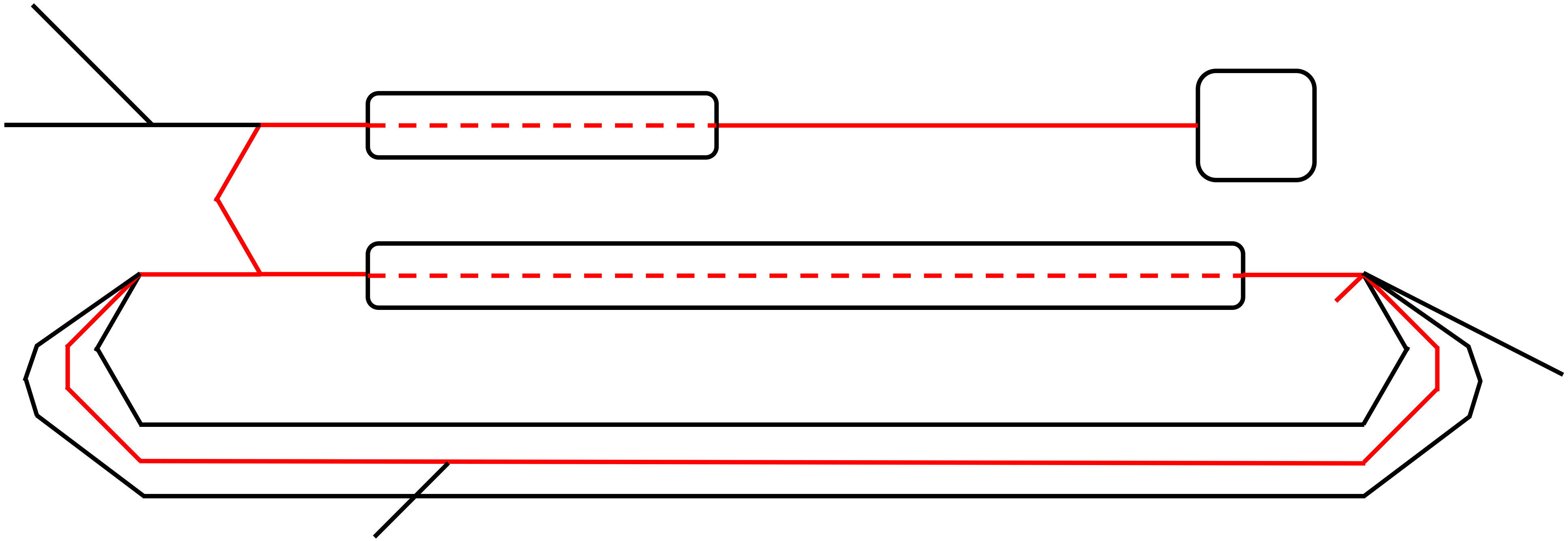
SINGLE-TURN ERL



SINGLE-TURN ERL
(AUGUST 2017)

August 2017: First ERL in Germany

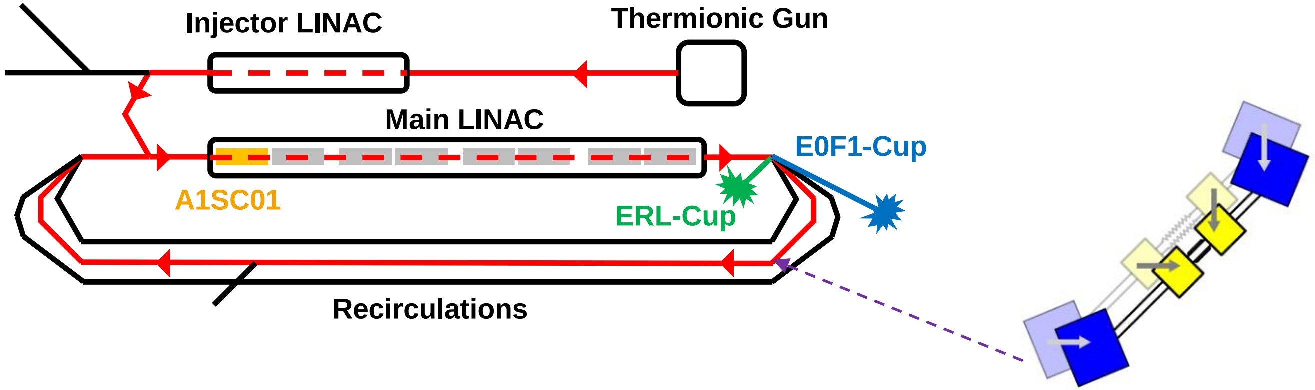
$E_{\text{kin injection}}$ = 2.5 MeV

$\Delta E_{\text{Main LINAC}}$ = 20 MeV

I_{initial} = 1.2 µA

Modes:

- No beam: RF load of cavity without beam
- 1x acc.: One accelerated beam
- 1x ERL: One accelerated and one decelerated beam
- 2x acc.: Two accelerated beams



$$t_{\text{recirculation}} = (n + 1/2) \times t_{\text{RF}} + t_{\text{offset}}$$

$$t_{\text{recirculation}} = n \times t_{\text{RF}} + t_{\text{offset}}$$

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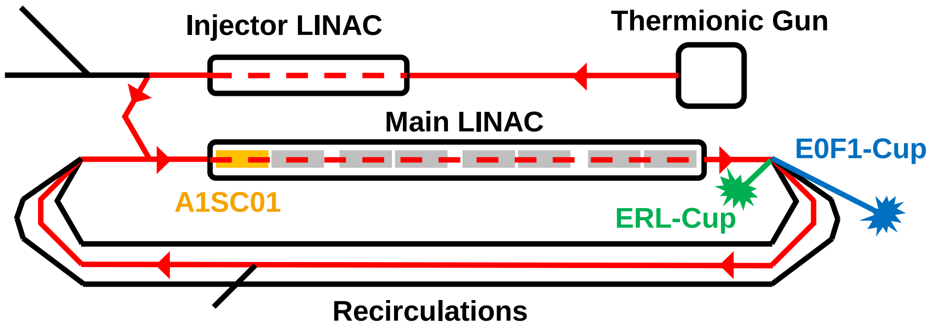
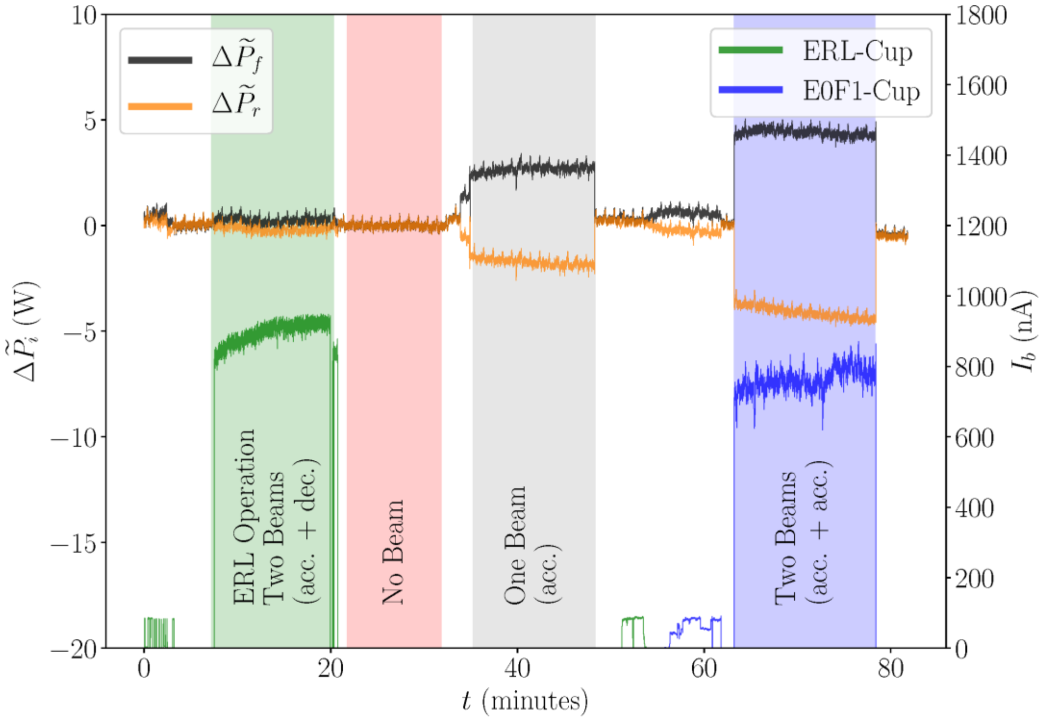
SINGLE-TURN ERL
(AUGUST 2017)

Operation mode	Load at A1SC01 (W)
No Beam	0.00 ± 0.01
One Beam (acc.)	4.51 ± 0.16
ERL (acc. + dec.)	0.45 ± 0.03
Two Beams (acc. + acc.)	8.59 ± 0.01



$$\eta_{\text{A1SC01}} = \frac{P_{\text{b,A1SC01,1x acc.}} - P_{\text{b,A1SC01,1x ERL}}}{P_{\text{b,A1SC01,1x acc.}}}$$

$$= (90.1 \pm 0.3)\ \%$$



M. Arnold et al., Phys. Rev. Accel. Beams **23**, 020101 (2020).

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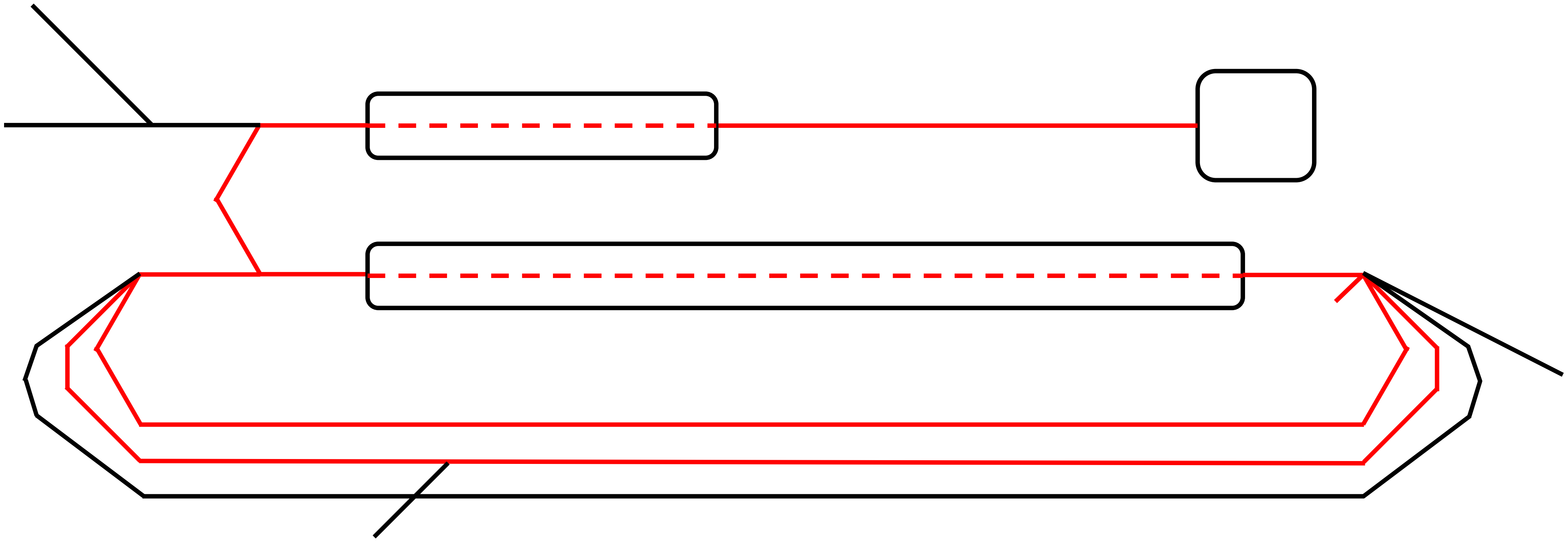
TWOFOLD ERL



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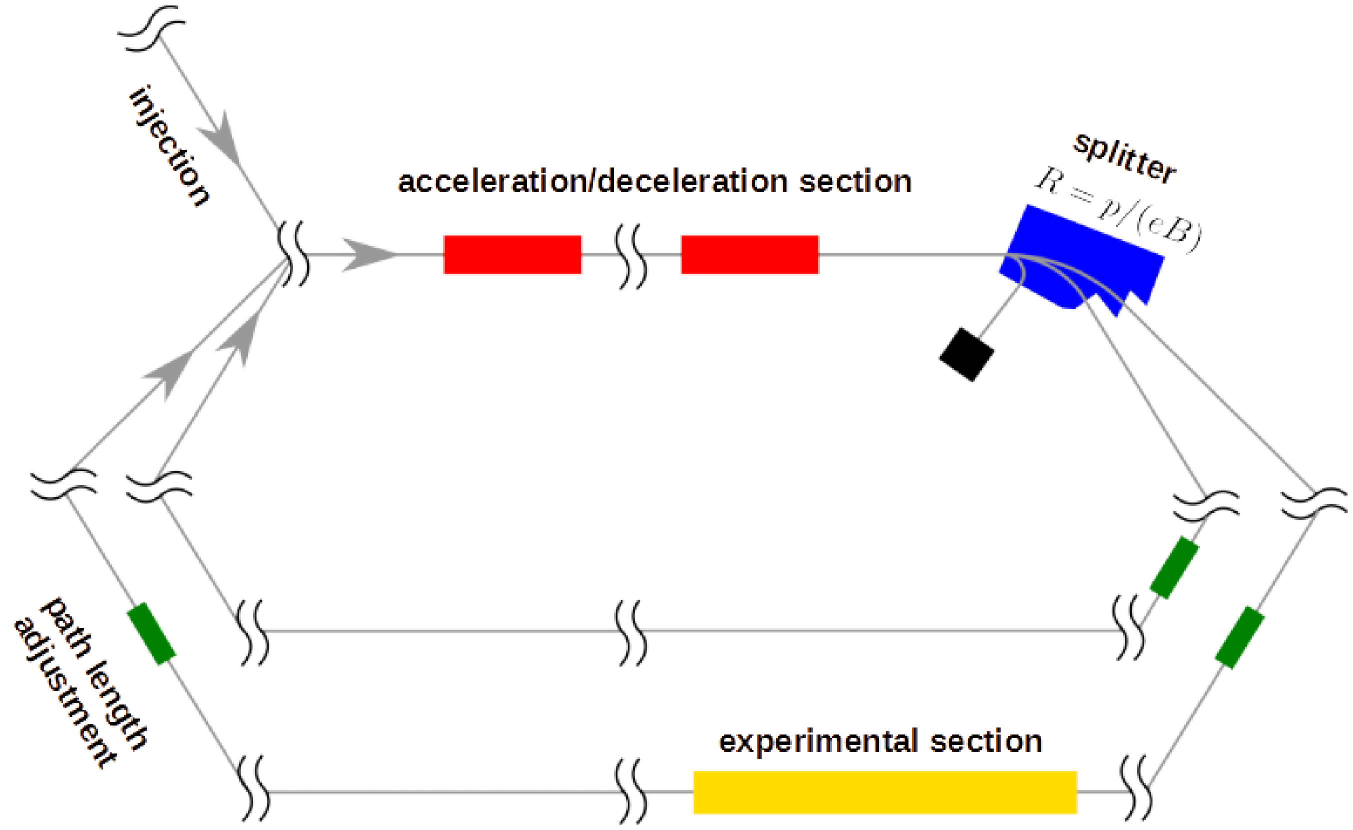
CHALLENGES

Concept based on: R. Koscica et al., Phys. Rev. Accel. Beams **22**, 091602 (2019)



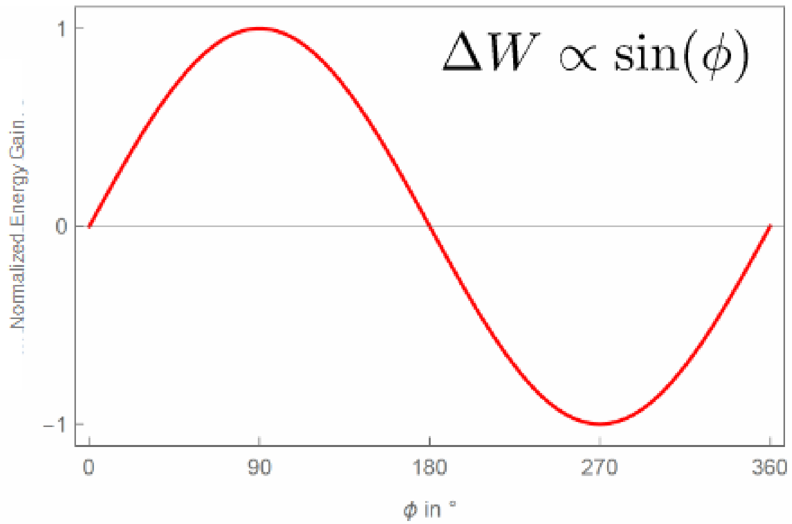
- Objective functions result from
- Splitter magnet ratio:
- $p_I : p_F : p_S = 1 : 4.73 : 8.32$

Degrees of freedom:

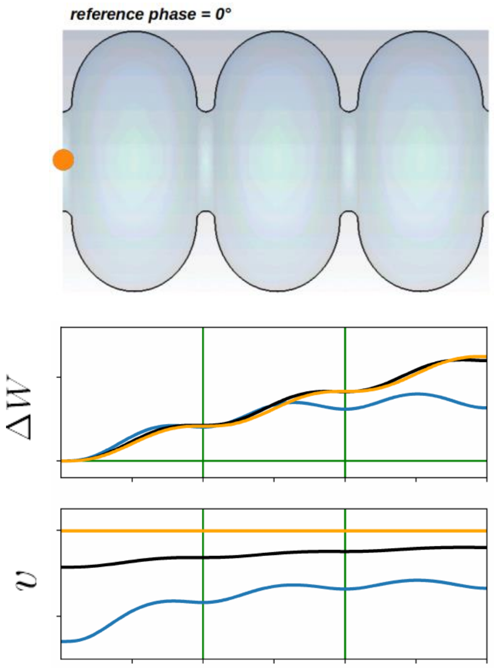
$\vec{A}, \vec{\phi}, \vec{L}, \vec{R}_{56}$

PHASE SLIPPAGE

Simplified model of energy gain



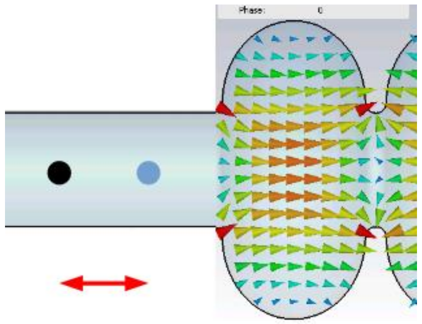
More complex model of energy gain



Speed changes along the cavity

→ Influences interaction with alternating electric field

→ Numerical simulations required



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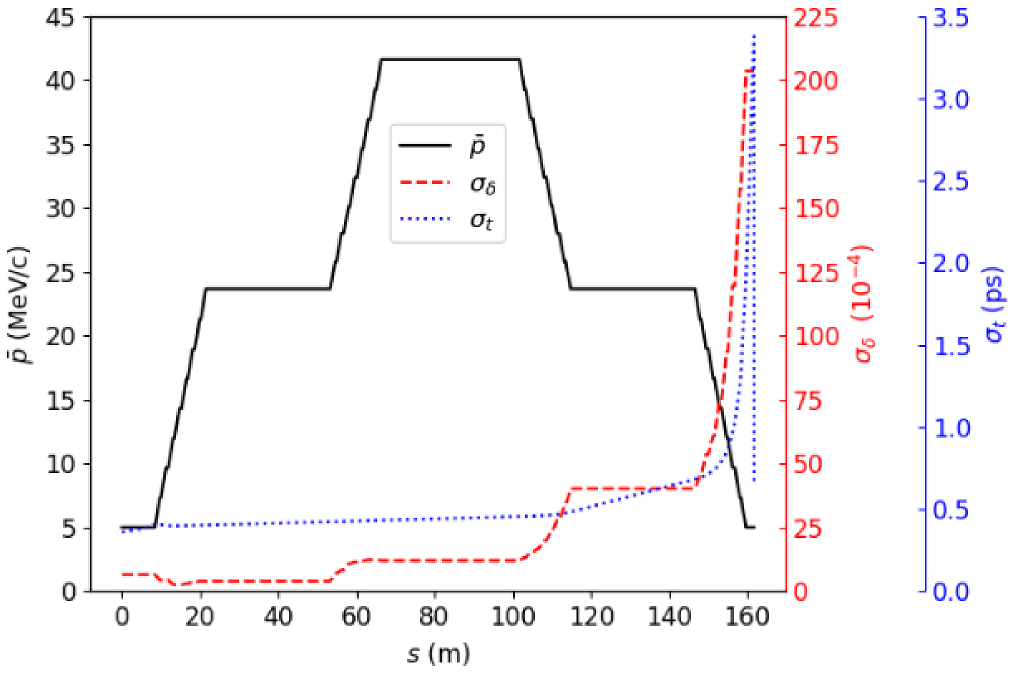
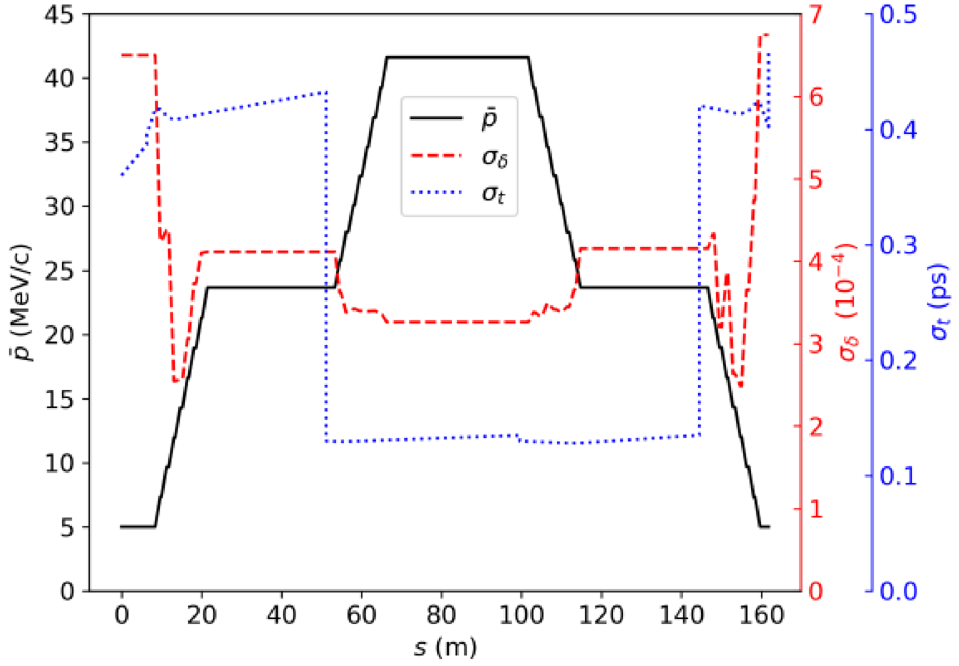
SOLUTION FOR LONGITUDINAL QUANTITIES

For min. deviation from target momenta



For min. deviation from target momenta **and** min. momentum spread



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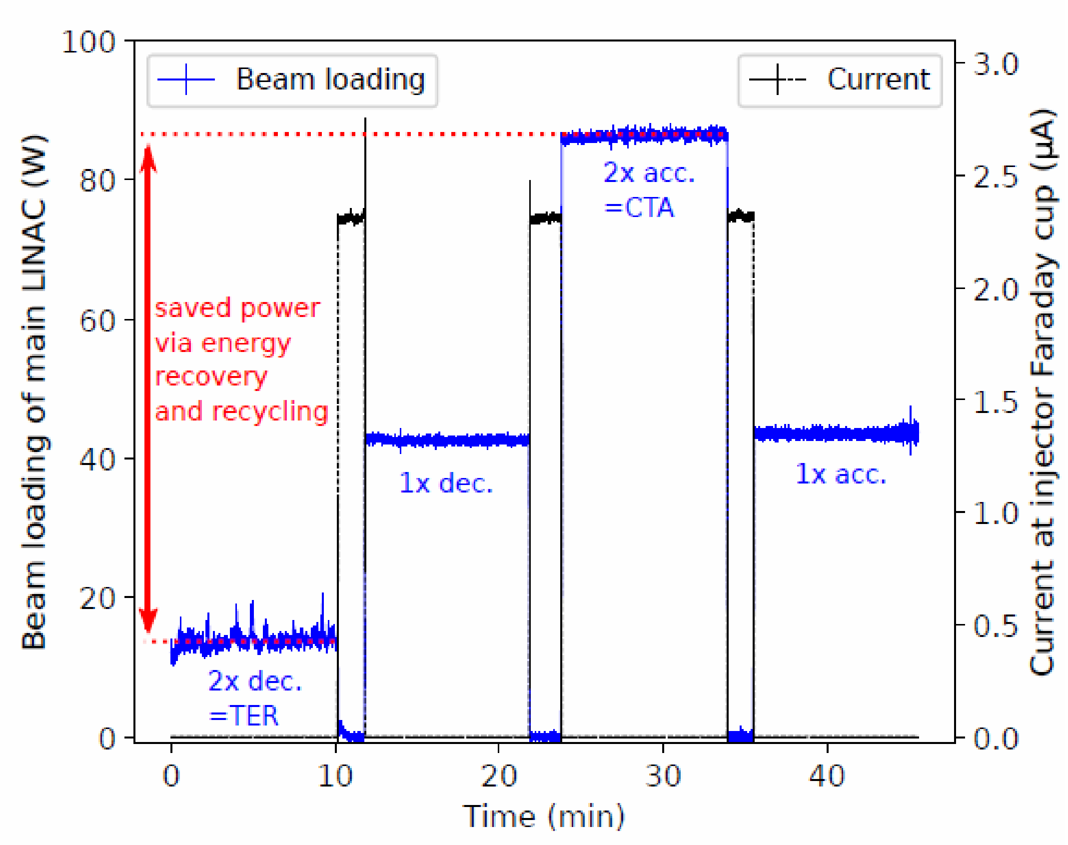
TWOFOLD ERL MODE
(AUGUST 2021)



F. Schliessmann et al., Nat. Phys. **19**, 597-602 (2023).

Operation mode	Load at main LINAC (W)
1x acc.	43.5 ± 0.2
2x acc.	86.3 ± 0.3
1x dec.	42.6 ± 0.2
2x dec.	13.8 ± 1.1

Energy-recycling efficiency:

$$\eta_{\text{main LINAC}} = \frac{P_{\text{b,main LINAC,2x acc.}} - P_{\text{b,main LINAC,2x ERL}}}{P_{\text{b,main LINAC,2x acc.}}}$$

$$= (84.0 \pm 1.2)\ \%$$

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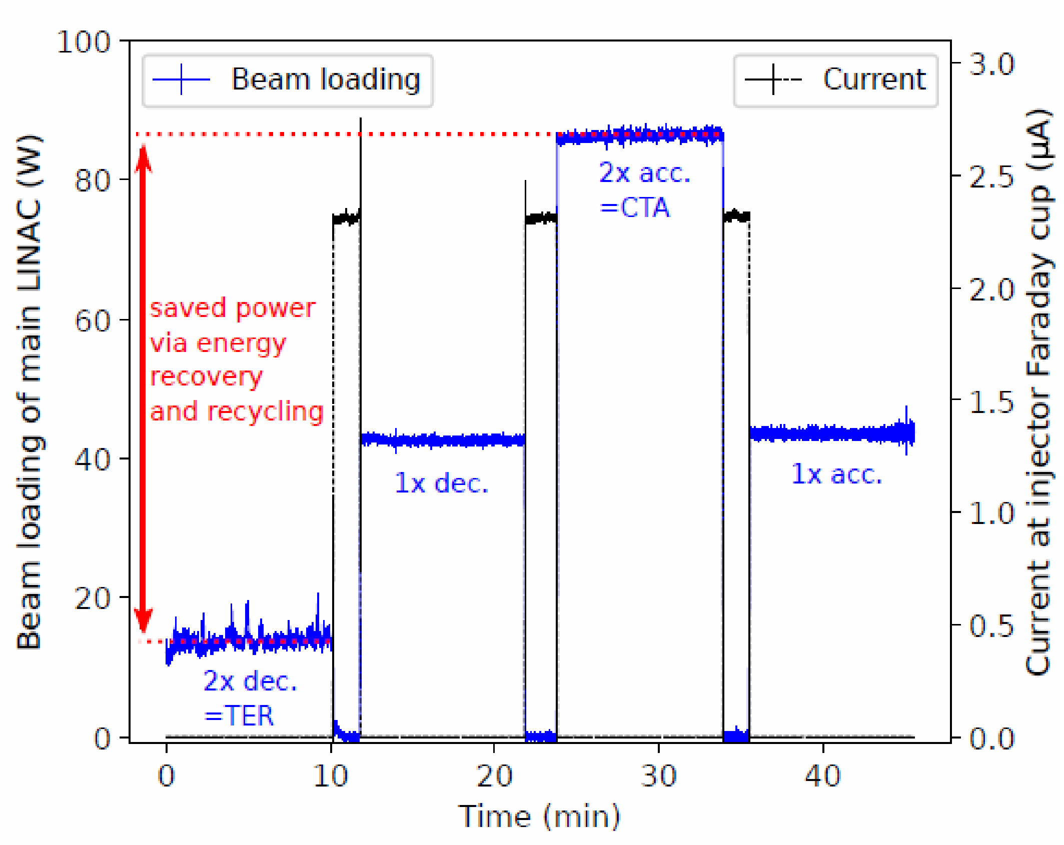
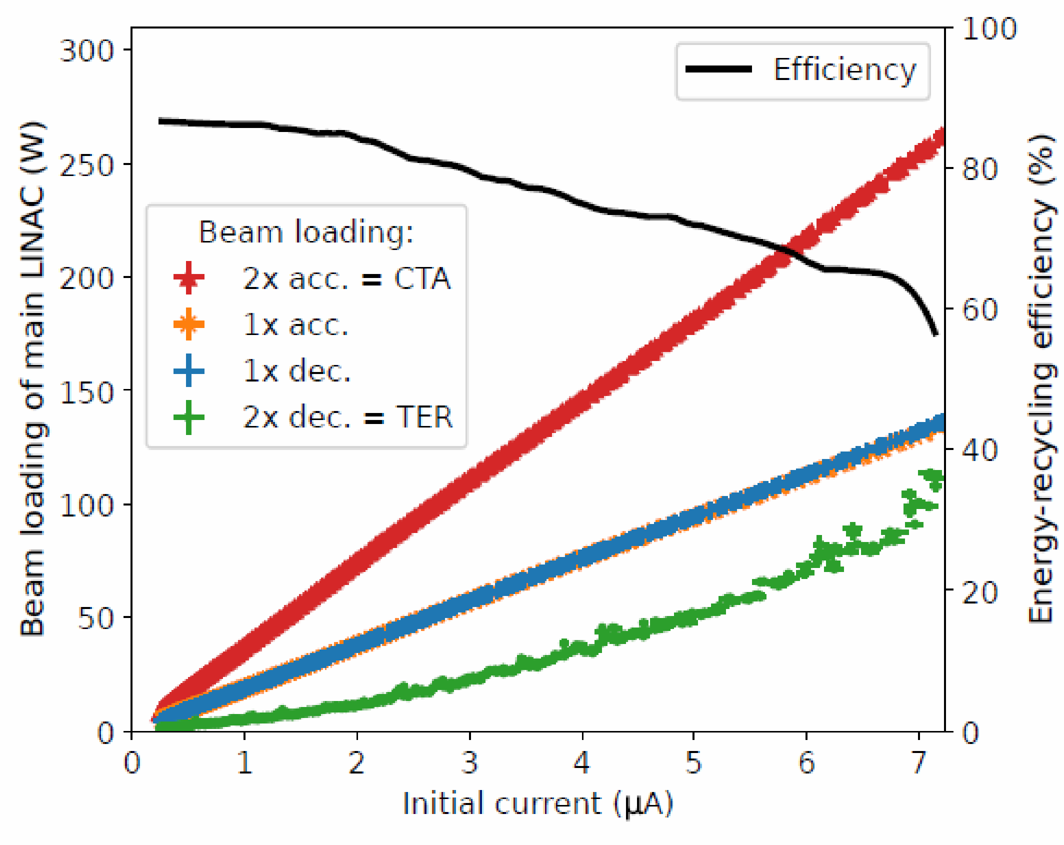
TWOFOLD ERL MODE
(AUGUST 2021)

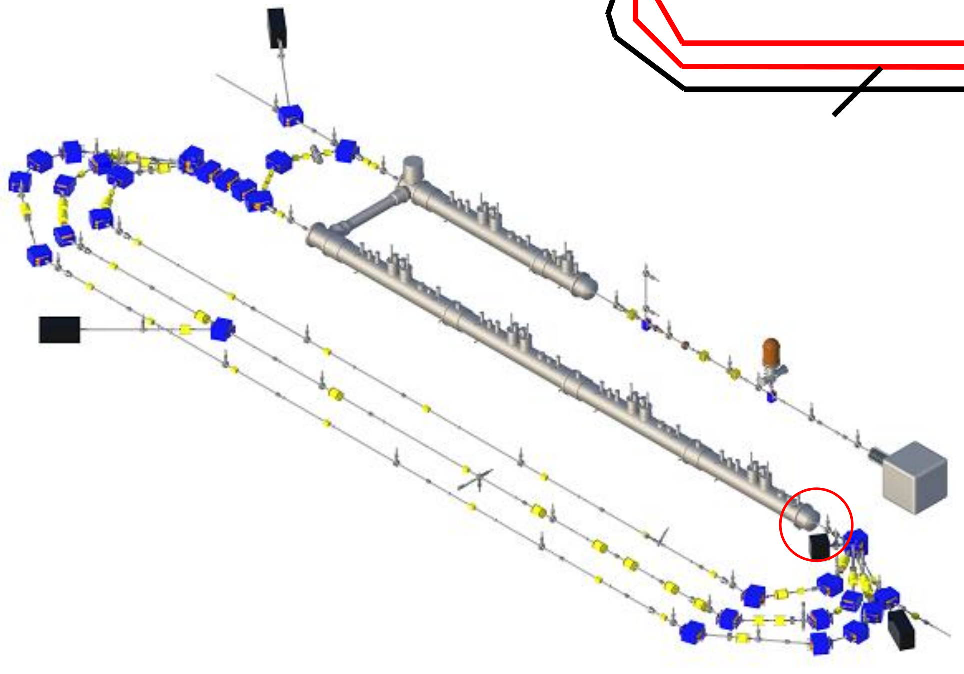


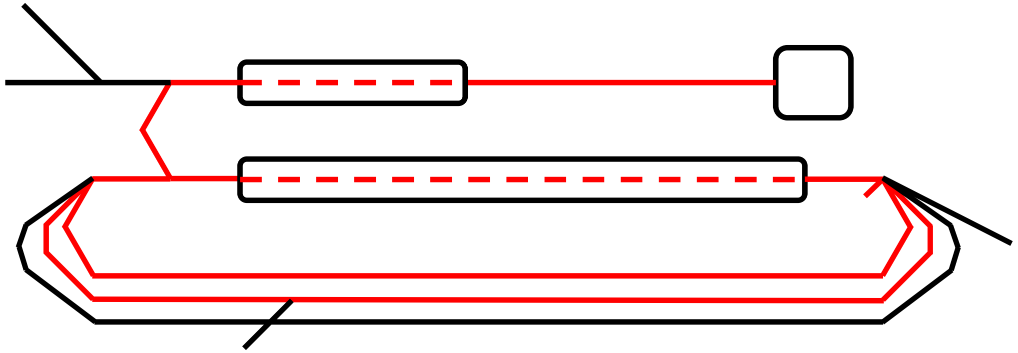
F. Schliessmann et al., Nat. Phys. **19**, 597-602 (2023).

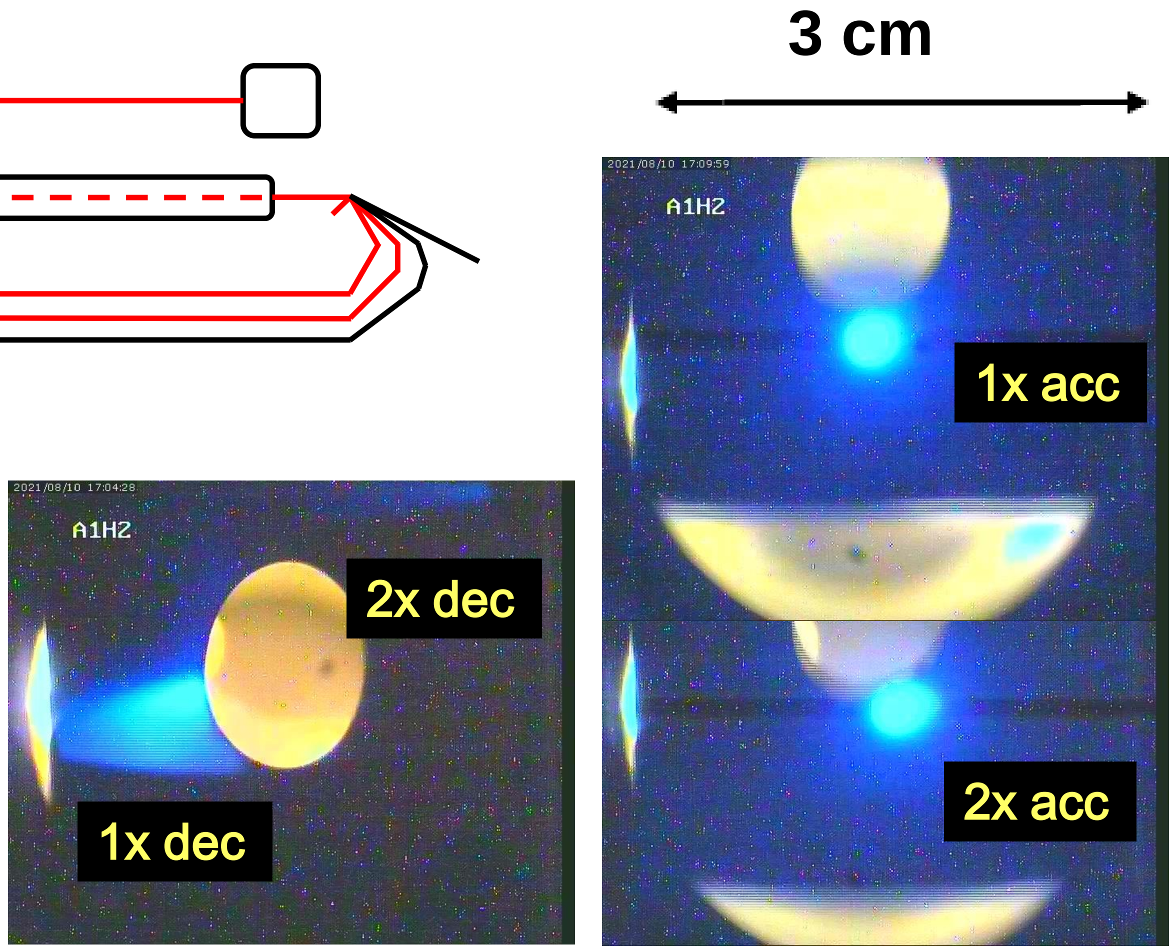


$\max(\eta_{\text{main LINAC}}) \approx 87\ \%$

LIMITS OF TRANSVERSE TUNING







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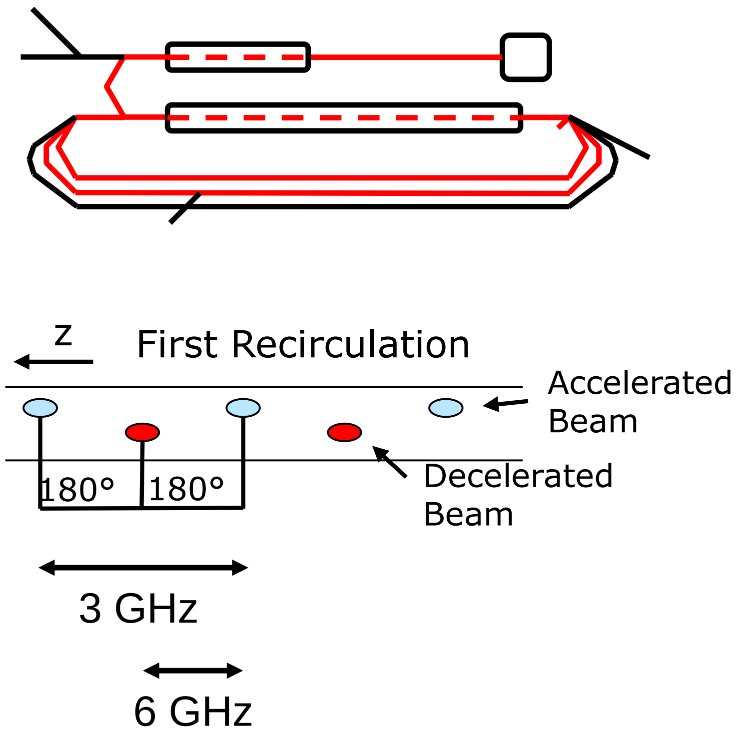
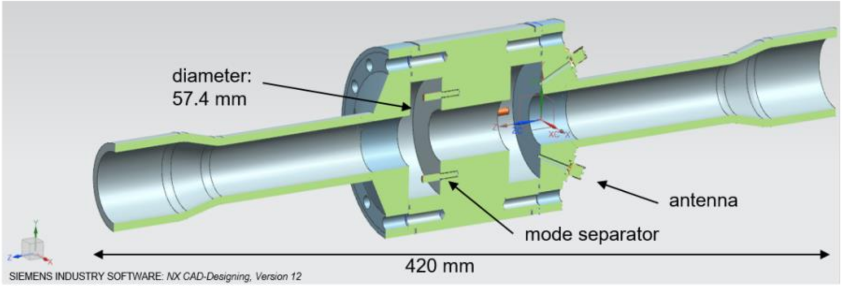
INSTRUMENTATION OF SUPERIMPOSING BEAMS



- (Non-)destructive position measurement for both beams simultaneously
- Options
  - RF beam loading
  - Screen with hole
  - Beam loss monitors
  - Wire scanner
  - 6 GHz cavity BPM (double of fundamental frequency)
  - 3 GHz cavity BPM in combination with bunch trains

M. Dutine et al., Proc. of IPAC 2022, p. 254-256 (2022).



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WIRE SCANNER

Measurement routine:

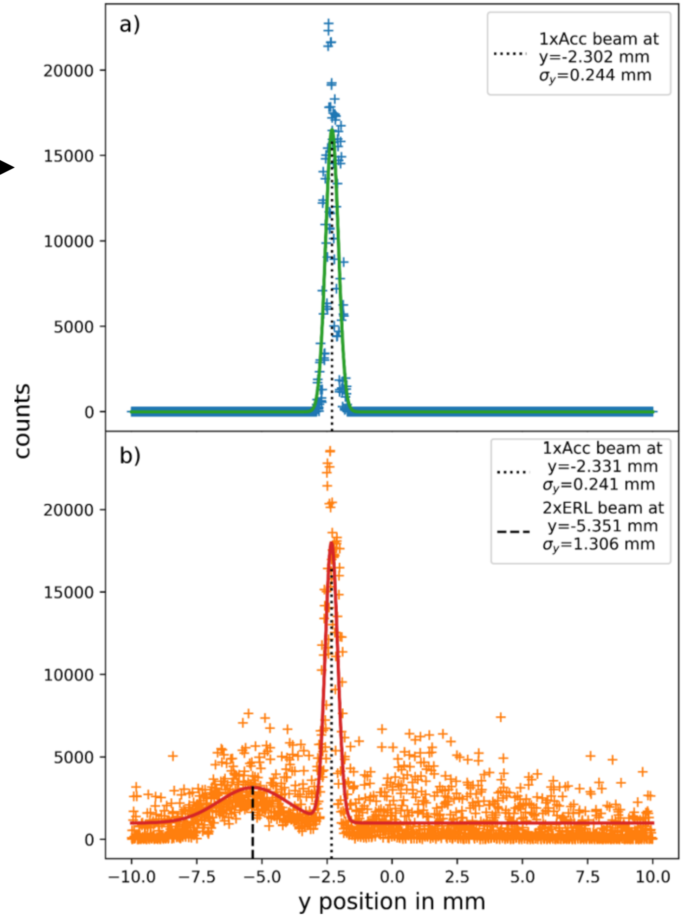
(1) Measure single-accelerated beam alone

(2) Measure both beams simultaneously

(3) Substract (1) from (2)

→ Gain position of single-decelerated beam

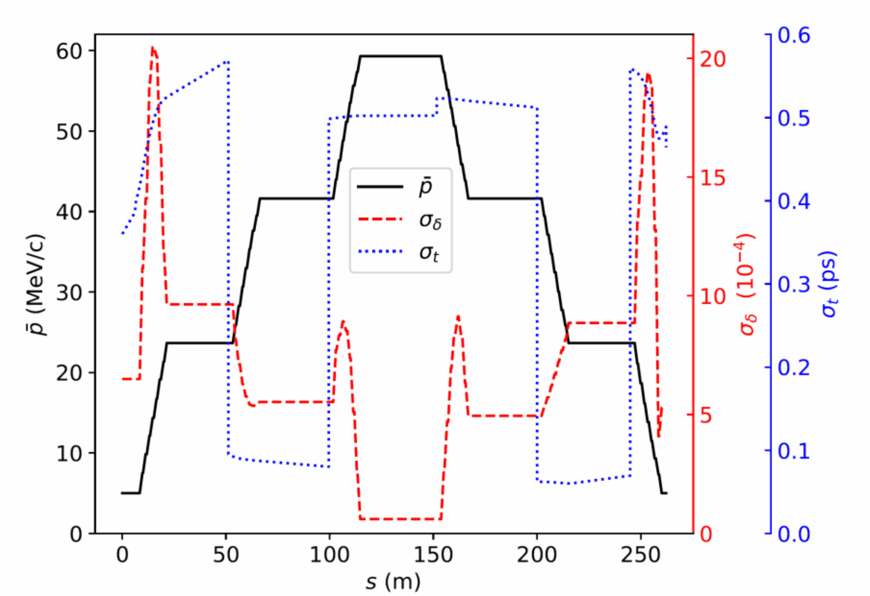
- Tuning of the first beam requires re-calibration of the system
- Measurement time: ~ 10 sec.



M. Dutine et al., Proc. of IPAC 2022, p. 254-256 (2022).

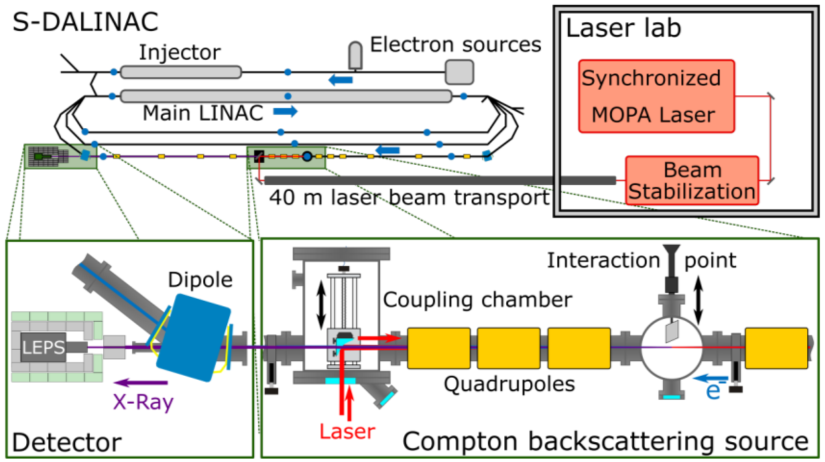
NEXT?

- Upgrade of third recirculation beamline path length system
  → 1-turn ERL using third beamline
  → 3-turn ERL – 2D simulation show, that it is in principle possible



F. Schliessmann et al., Proc. of IPAC 2023, p. 2117 – 2120 (pre print 2023).

- Laser Compton backscattering in third beamline as ERL application



M. Meier et al., Proc. of IPAC 2023, p. 2113 – 2116 (pre print 2023).

See also „Future" talk

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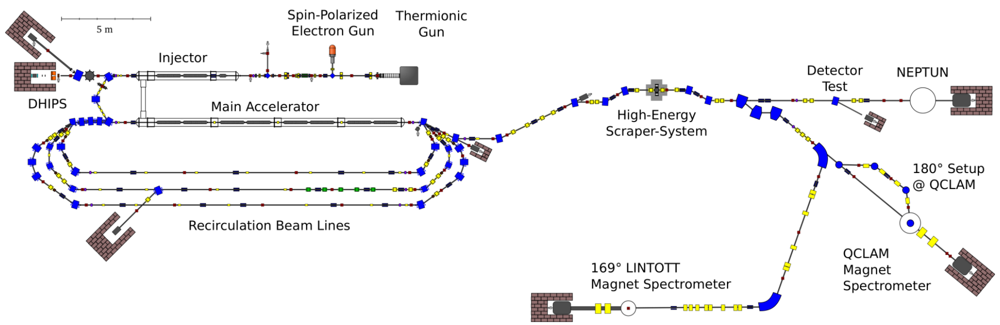
Looking for a PhD position?

YOUR CONTRIBUTION



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- BSc, MSc and PhD theses: Hands-on projects
- Broad hands-on education in accelerator science: Daily operation (beam, cryo plant, diagnostics, RF system, vacuum,…) and maintenance (alignment, work on lattice,…)
- Please contact me: marnold@ikp.tu-darmstadt.de

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- Who can apply: Female students from abroad at the end of their Bachelor studies
- Goal: Support Master studies at TU Darmstadt in the field of accelerator science, nuclear physics or nuclear astrophysics
- Scholarship of 600 €/month for 24 months + 400 €/month as student assistant
- Why you should apply: Graduates of this programme will be equipped with the perfect requirements to apply for a PhD position at TU Darmstadt

For more information: Click here

SUMMARY

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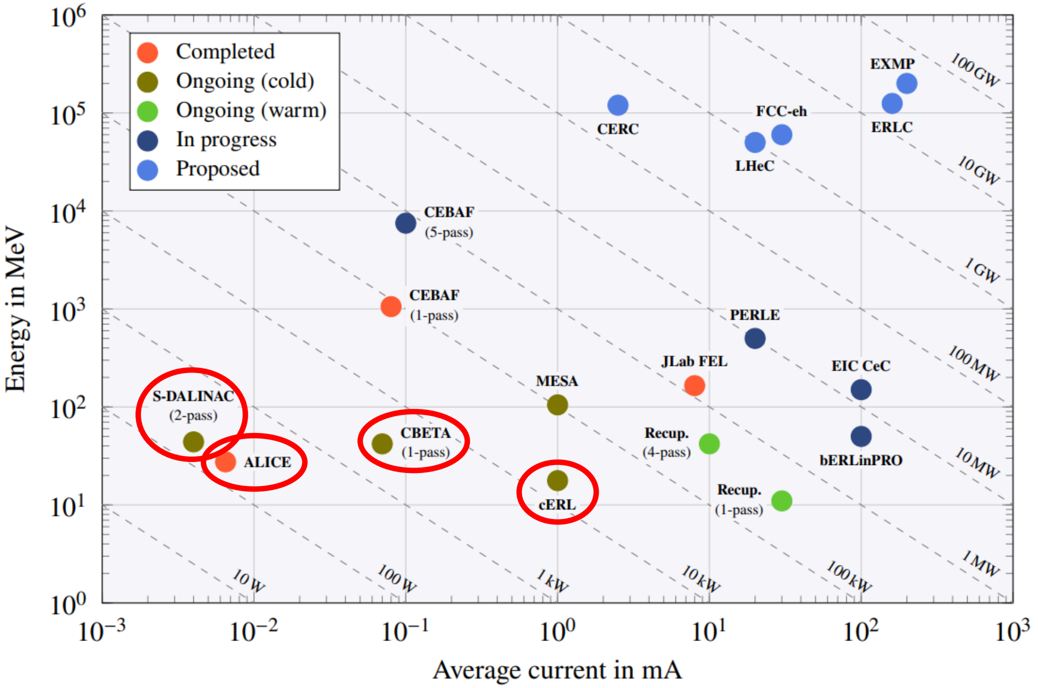
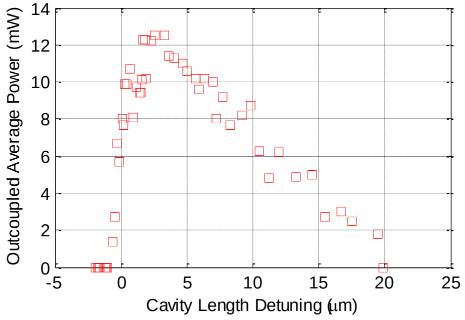
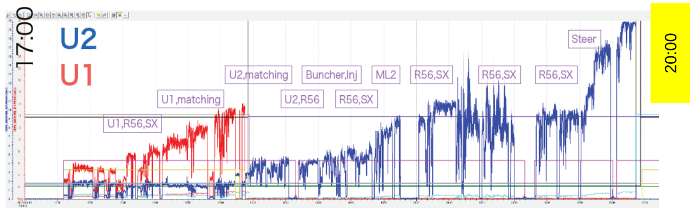
FOUR ERLS IN A NUTSHELL



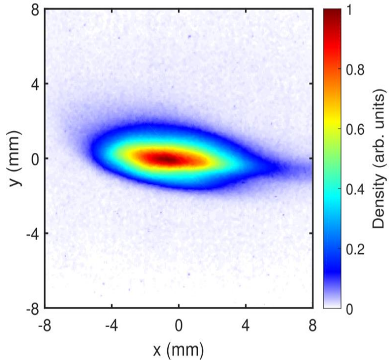
ALICE



cERL



CBETA



S-DALINAC