Adjusting bERLinPro optics to commissioning needs

Bettina Kuske, Michael Abo-Bakr, Meghan McAteer, HZB

Contents

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Helmholtz-Zentrum Berlin

Outline of the talk:

- ❑ Overview of different optics
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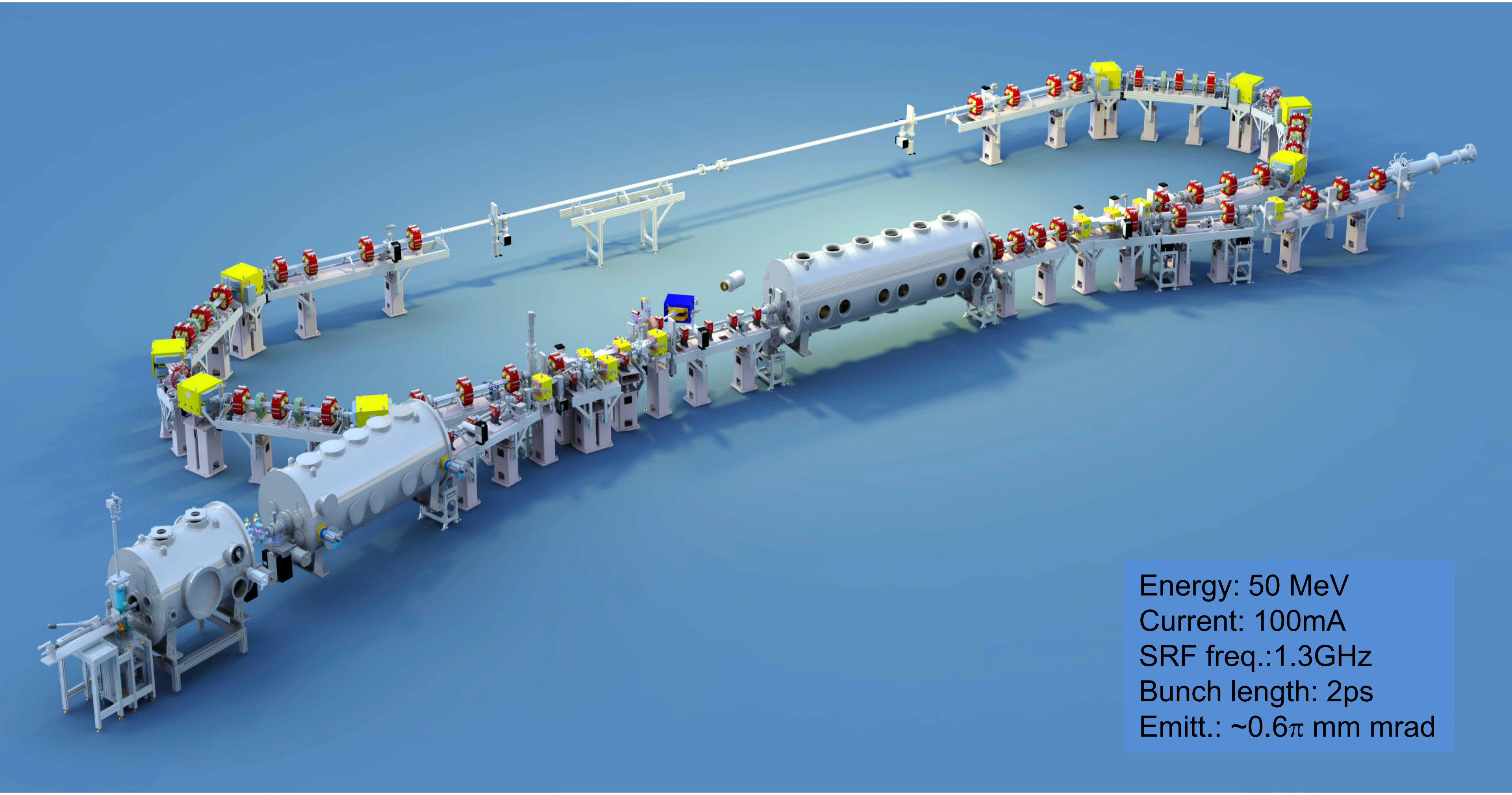
  - ❑ Low energy beams & magnetic field in bERLinPro hall
- ❑ Banana
  - ❑ Halo calculations
- ❑ Recirculator
  - ❑ MESA module ⇔ bERLinPro module
  - ❑ CSR & space charge tracking with OPAL
- ❑ Conclusion

bERLinPro: A test facility for energy recovery linac technology
Goals: show recovery of high current, low emittance beams



Energy: 50 MeV
Current: 100mA
SRF freq.:1.3GHz
Bunch length: 2ps
Emitt.: ~0.6π mm mrad

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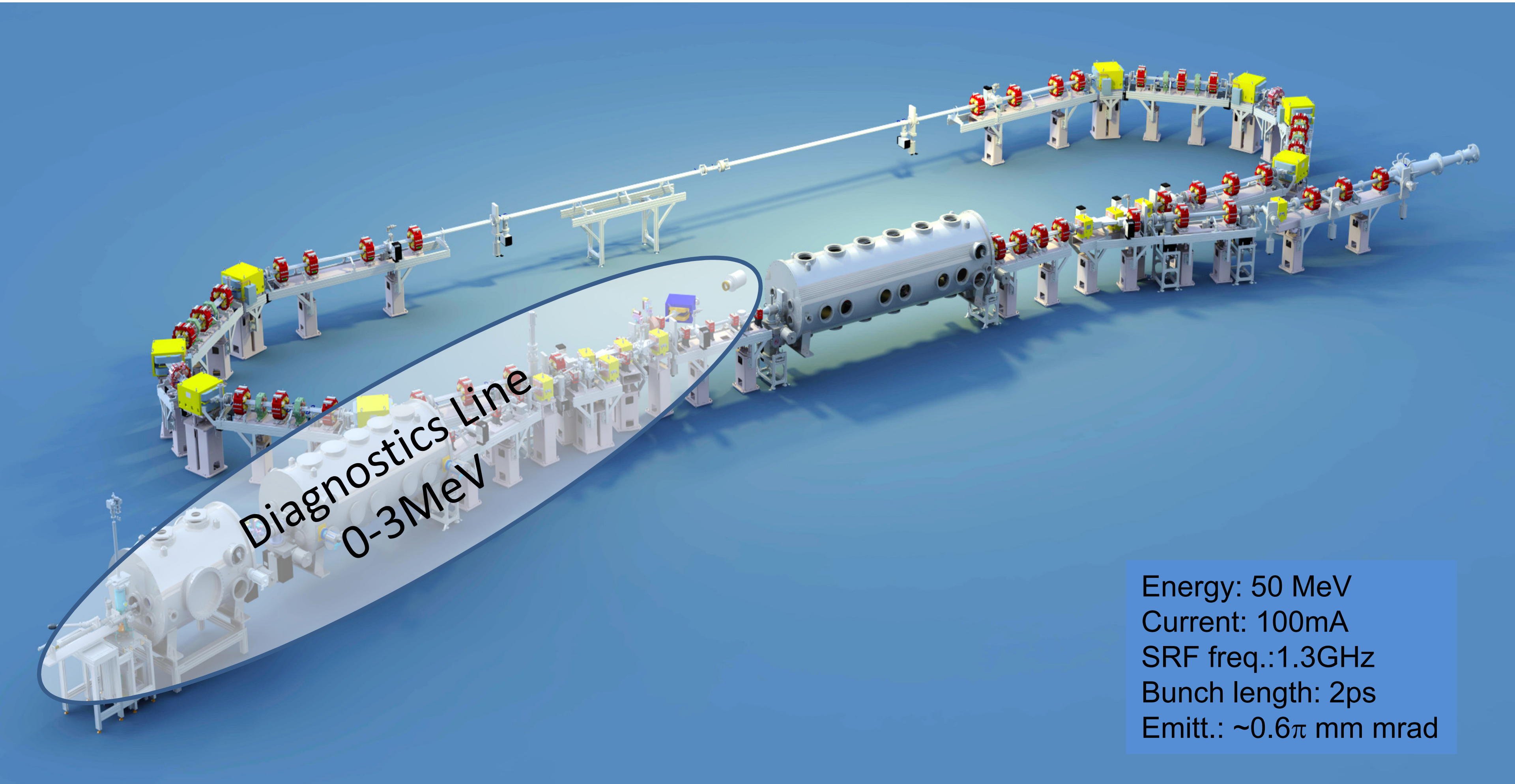

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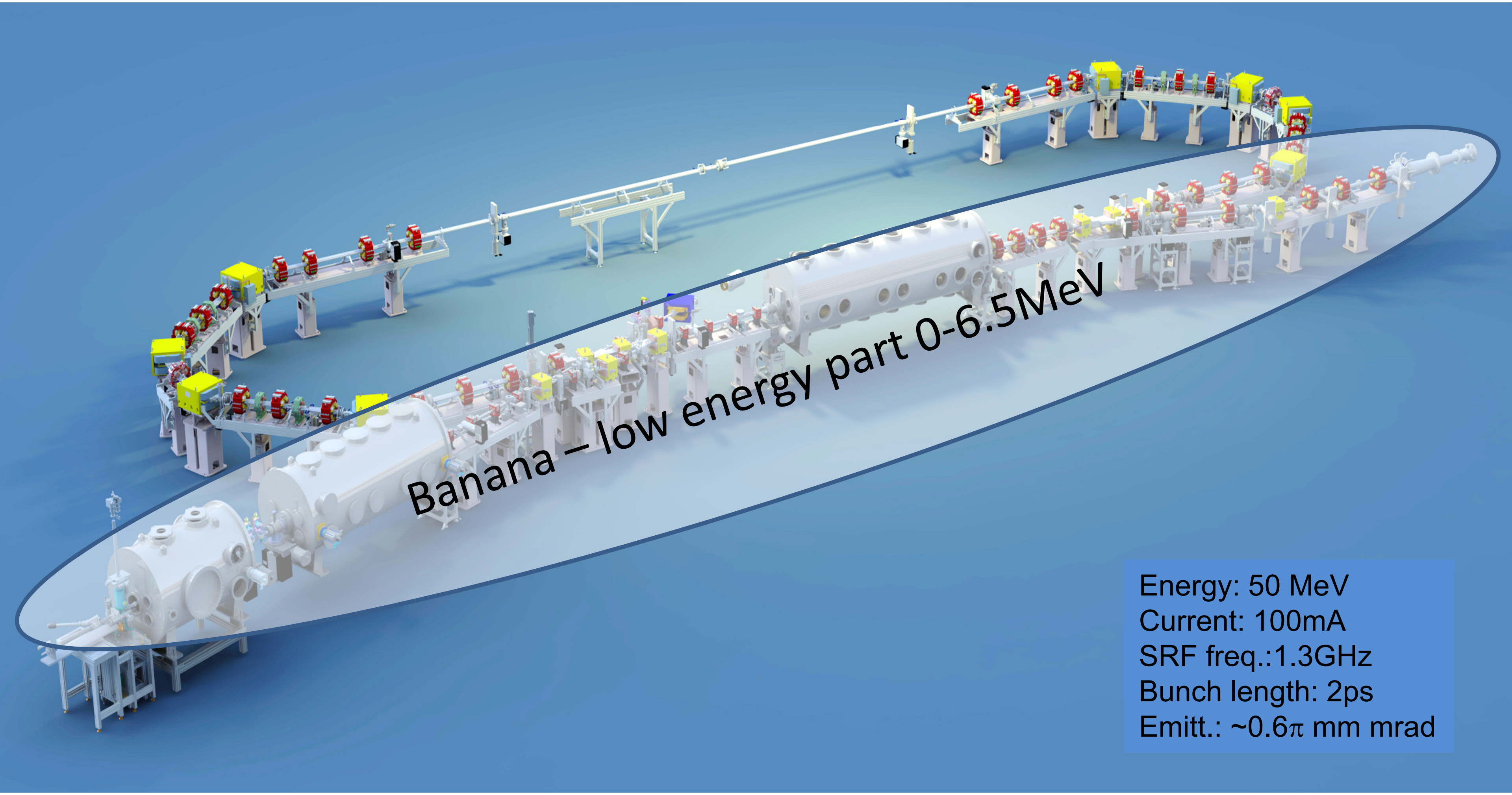

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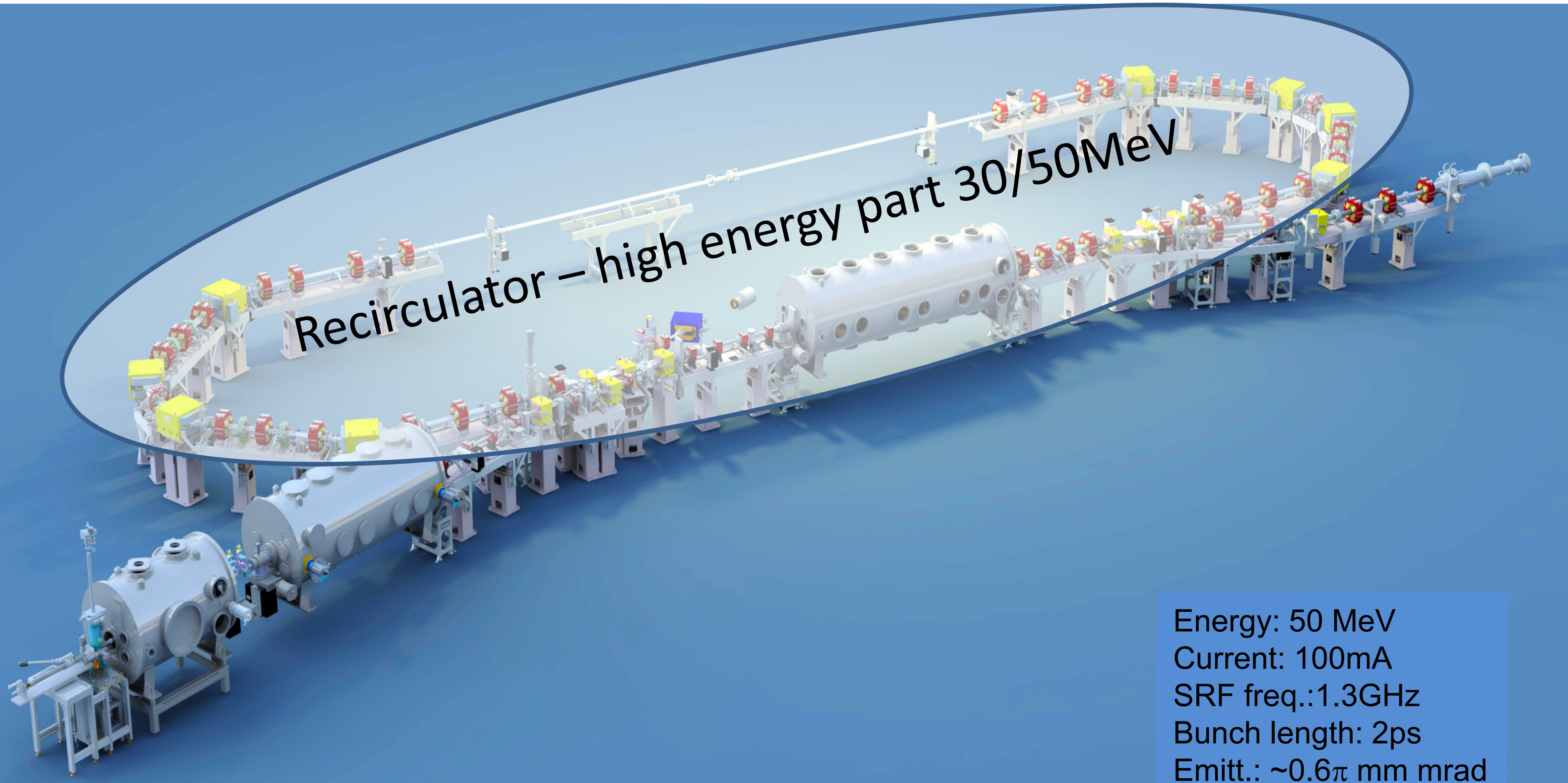

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Optics overview / staged approach

Diagnostics Line		
0-3MeV	No Booster/3 quads	Characterize gun
<6.5MeV	Booster	Characterize Booster

Banana		
<6.5MeV		Merger optics Emittance compensation Bunch length compression

Recirculator		
30MeV	MESA linac module	Recirculator optics Energy recovery path length adjustment Secure beam dumping Achieve project goal parameters
50MeV	bERLinPro linac module	

Optics overview / staged approach

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Diagnostics Line		
0-3MeV	No Booster/3 quads	Characterize gun
<6.5MeV	Booster	Characterize Booster

50MHz laser	1.3GHz laser
Single bunch: 1Hz-100kHz, 77pA-8µA CW: < 4mA	Macro pulse: 1Hz-1kHz, 6nA-20µA CW: < 100mA

Banana		
<6.5MeV		Bunch length compression

Recirculator		
30MeV	MESA linac module	Recirculator optics Energy recovery path length adjustment Secure beam dumping Achieve project goal parameters
50MeV	bERLinPro linac module	

Diagnostics line – hardware

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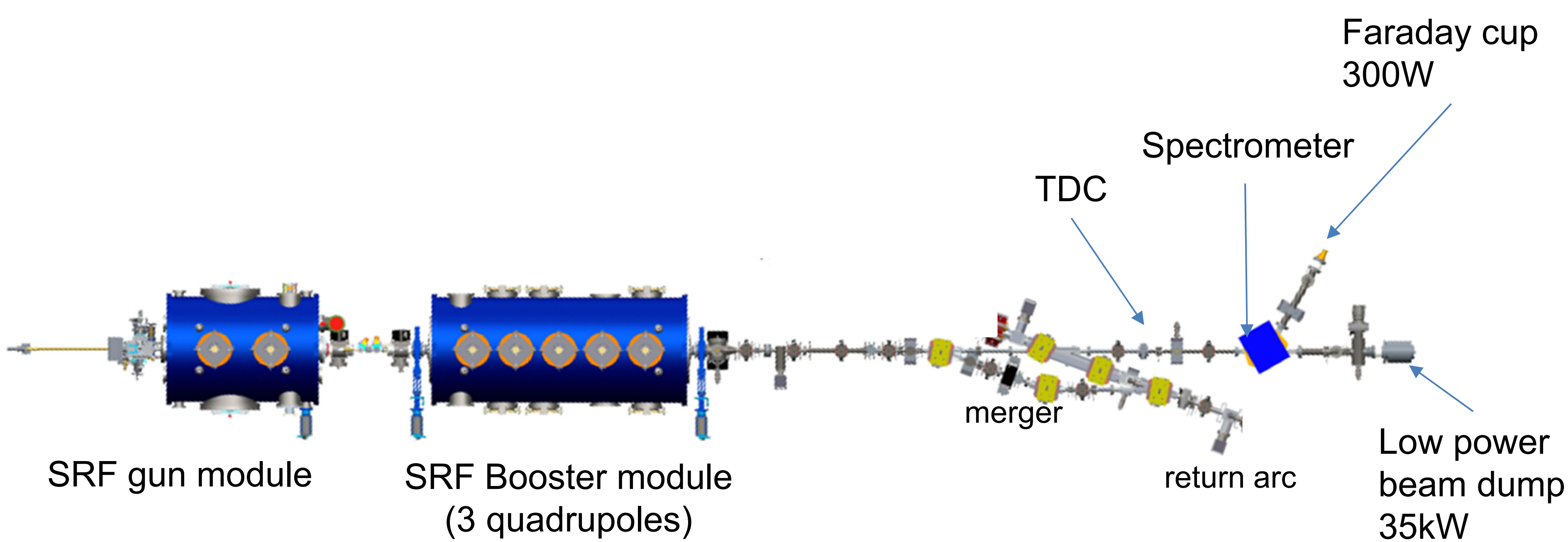
Diagnostics Line – to characterize gun gun – determines key project parameters:

- Small emittance
- Stability (laser/RF synchronization)
- Unwanted beam (stray light, ghost pulses, field emission @ 30MV/m)
- Machine up time (cathode lifetime)
- High current (100mA / 77pC per bunch)



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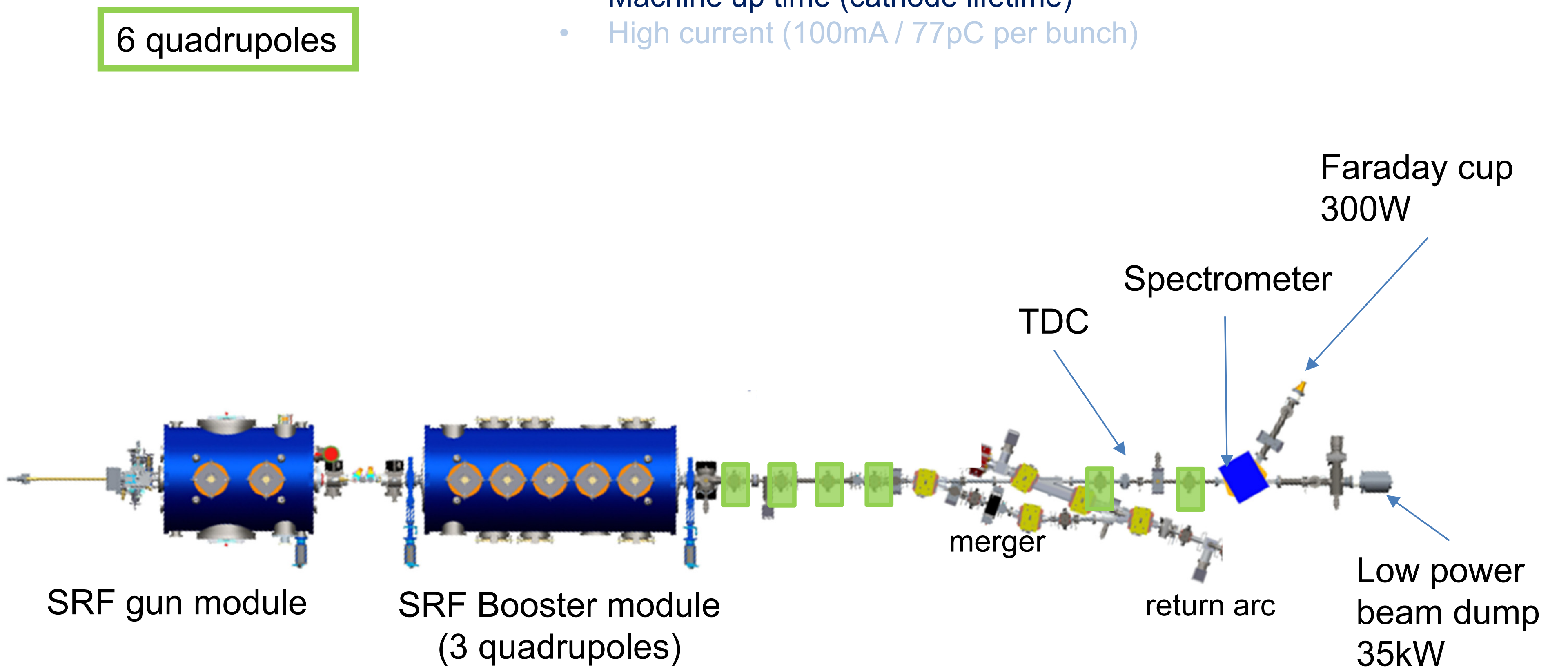

Diagnostics line – hardware

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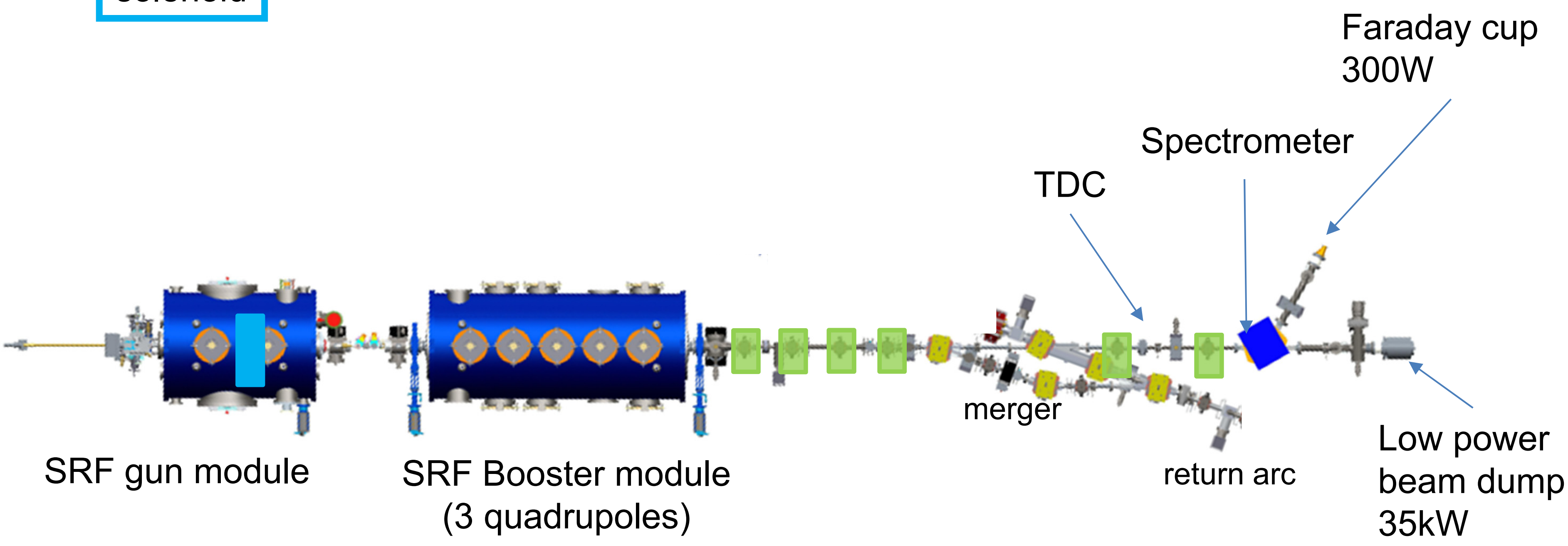
6 quadrupoles

solenoid



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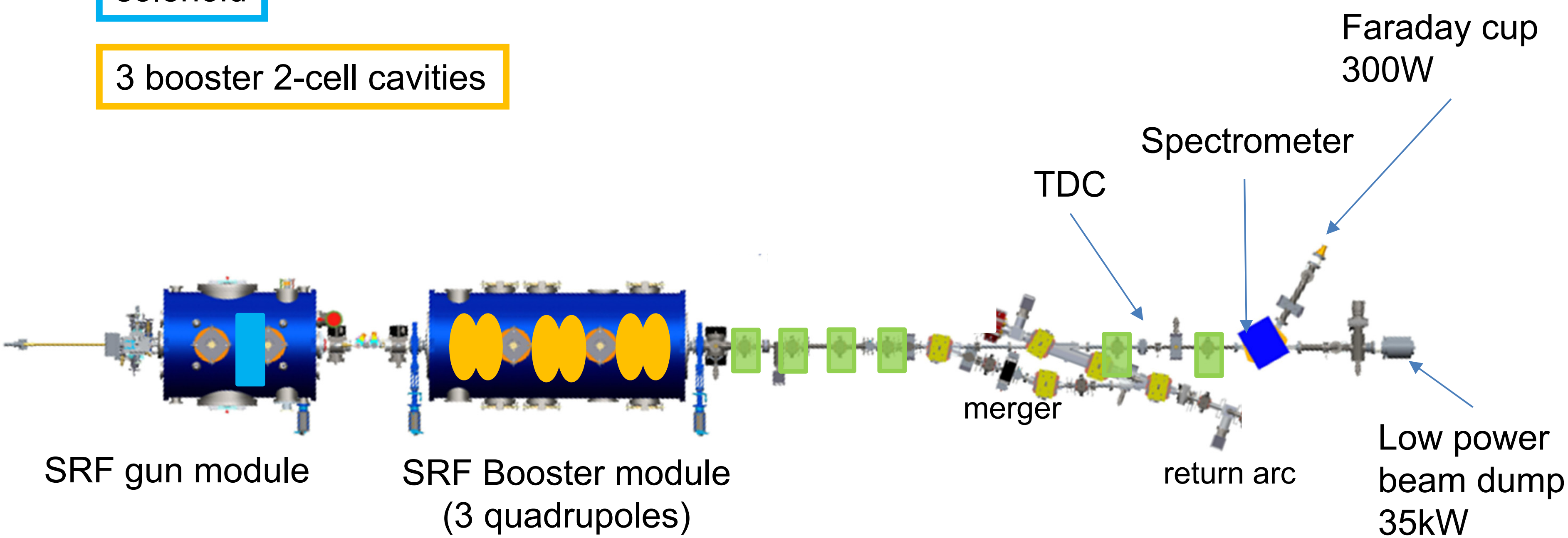

Diagnostics line – hardware

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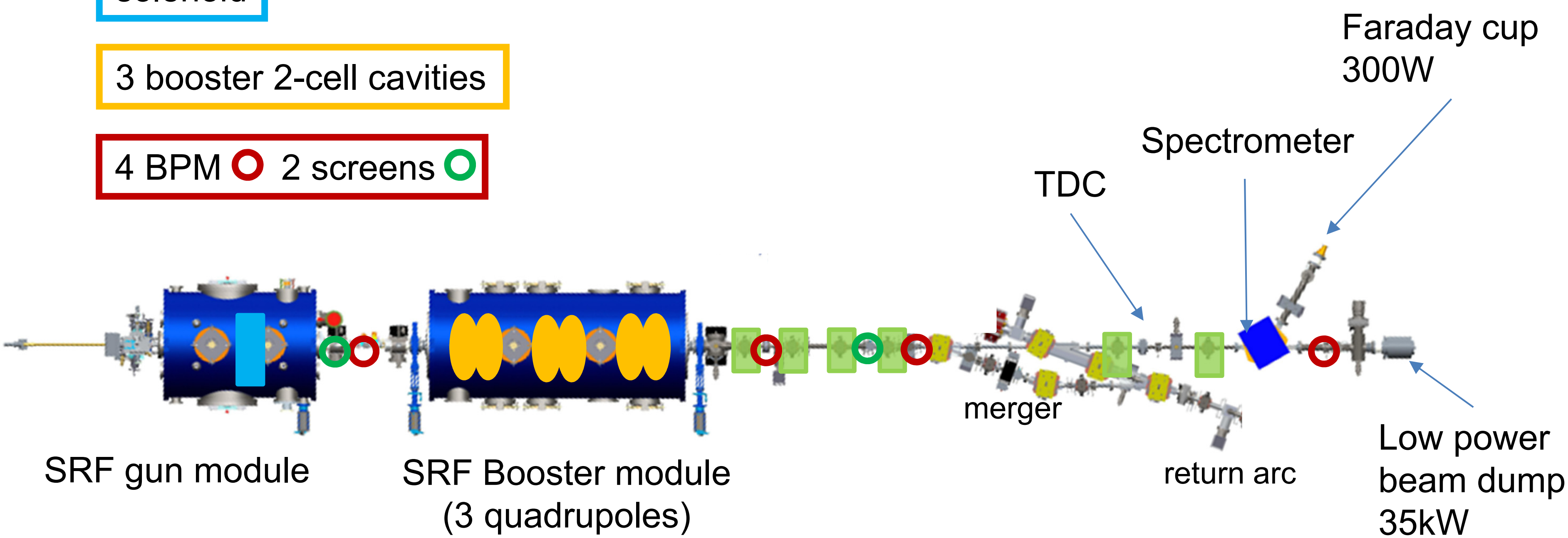
solenoid

3 booster 2-cell cavities

4 BPM ○ 2 screens ○



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Diagnostics Line – to characterize gun
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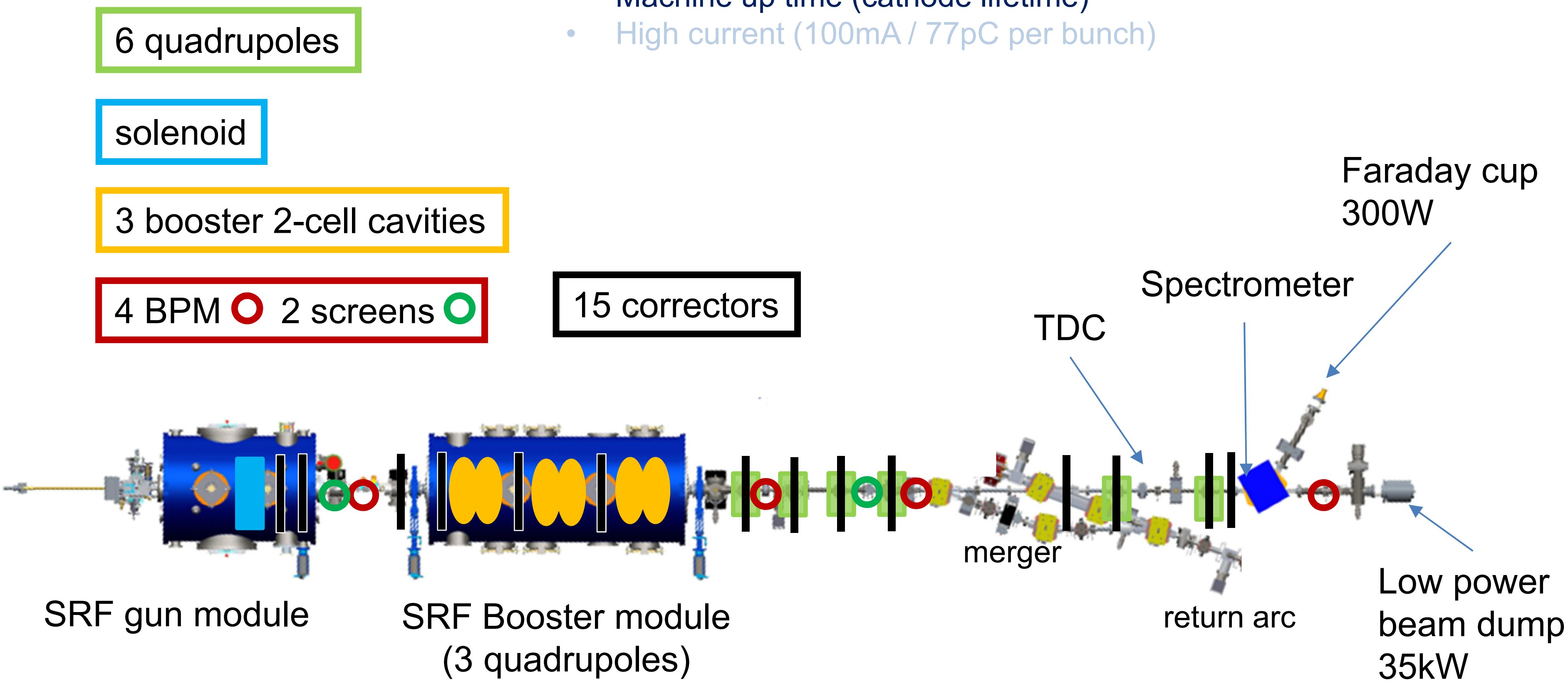
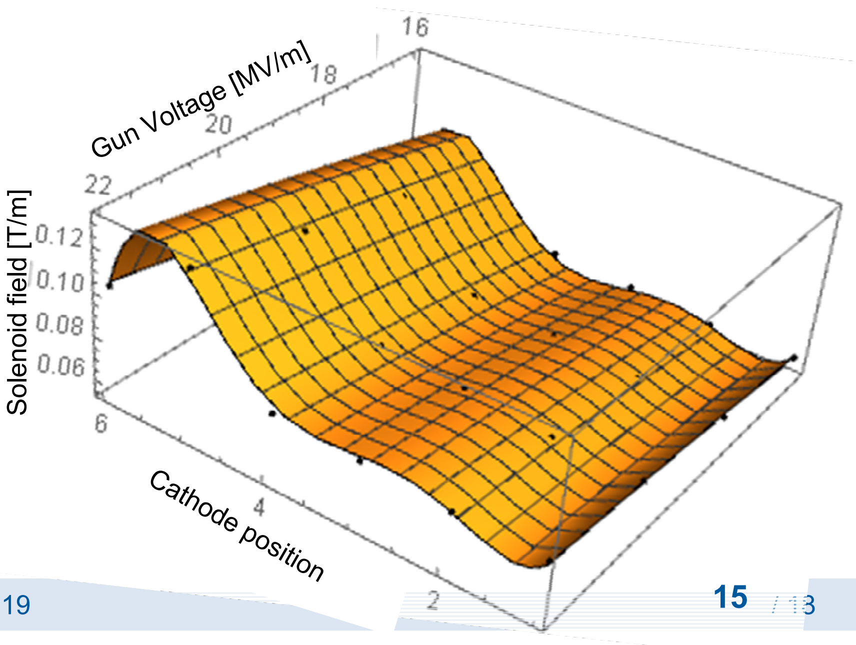


Diagnostics Line - challenges

First goal: get quick overview actual machine and create basic model

- Ambiguities in gun performance – use machine learning (see talk on Wednesday - WECOYBS04)
- Reduce number of ‚active‘ parameters for first beam
  - Set quadrupoles to produce around beam on screens
  - Develop functional dependences of parameters

    (using 5000 sample runs)



Diagnostics Line - challenges

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- Low energy < 3 MeV
  Diagnostic line (gun only): < 3MeV over 14m
  (Booster): 6.5MeV over 9m
  Banana: 6.5MeV over 12m
- Analytic estimates of Earth Magnetic
  Field showed impact on trajectory

⟹ Measure magnetic field in hall

Diagnostics Line - challenges

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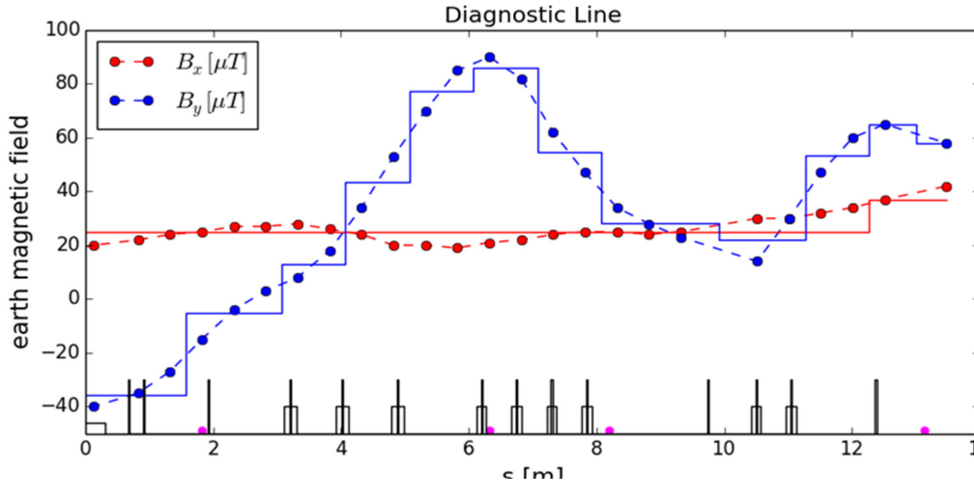
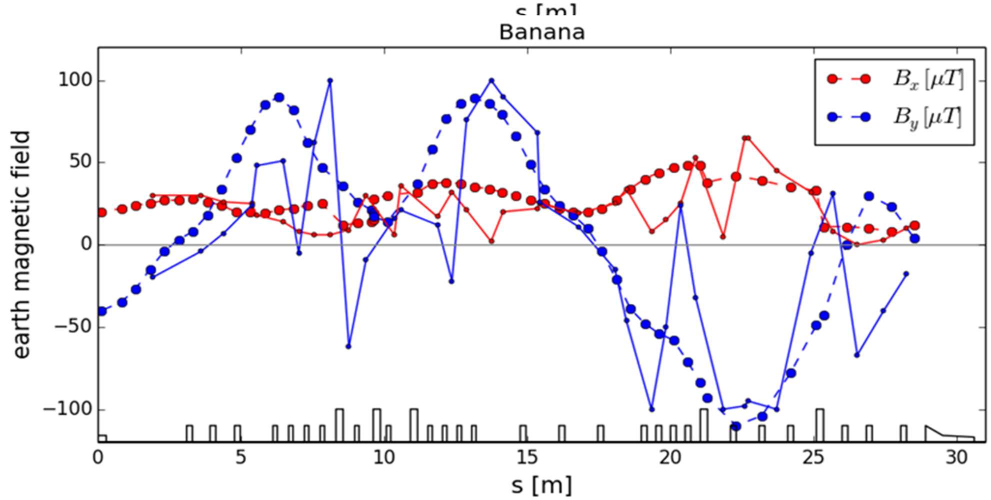
→ Measure magnetic field in hall

with 3D hall probe (<1G) along electron path, before magnet installation (red dots: Bx [μT], blue dots: By[μT])

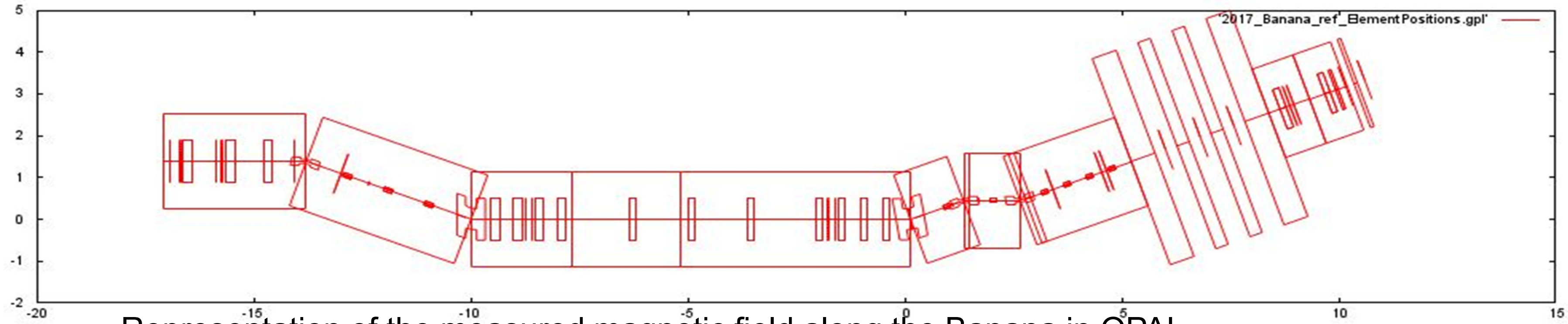




Top Solid line: Approximation with step function for OPAL simulations

Bottom Solid line: Measure after magnet installation – top part of magnets removed for installation of vacuum system

Tracking with measured magnetic field



Representation of the measured magnetic field along the Banana in OPAL

- Beam loss on aperture ~7m behind cathode
  - Error studies: stable beam throughout machine (alignment, field, timing, jitters)
  - MF MUCH stronger than commonly assumed errors
- Sufficient no. of correctors - too few BPMs
  - corrected trajectories offset up to 7mm in diag. line

Work around:

- Beam based alignment (manual offsets prior to SVD)
- Correction based on calibrate response matrix (including optics and MF)

Measurement of magnetic field in bERLinPro hall

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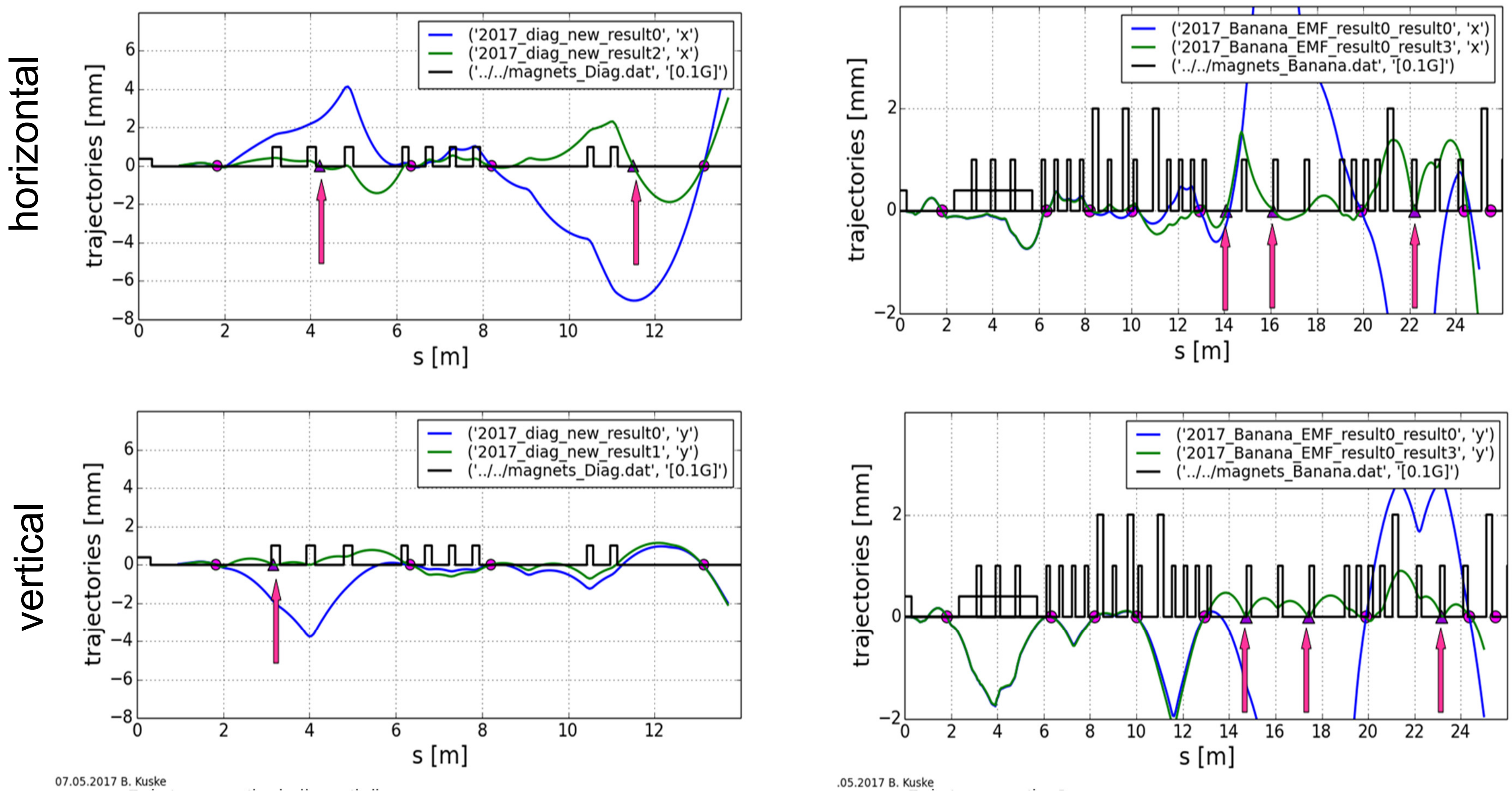
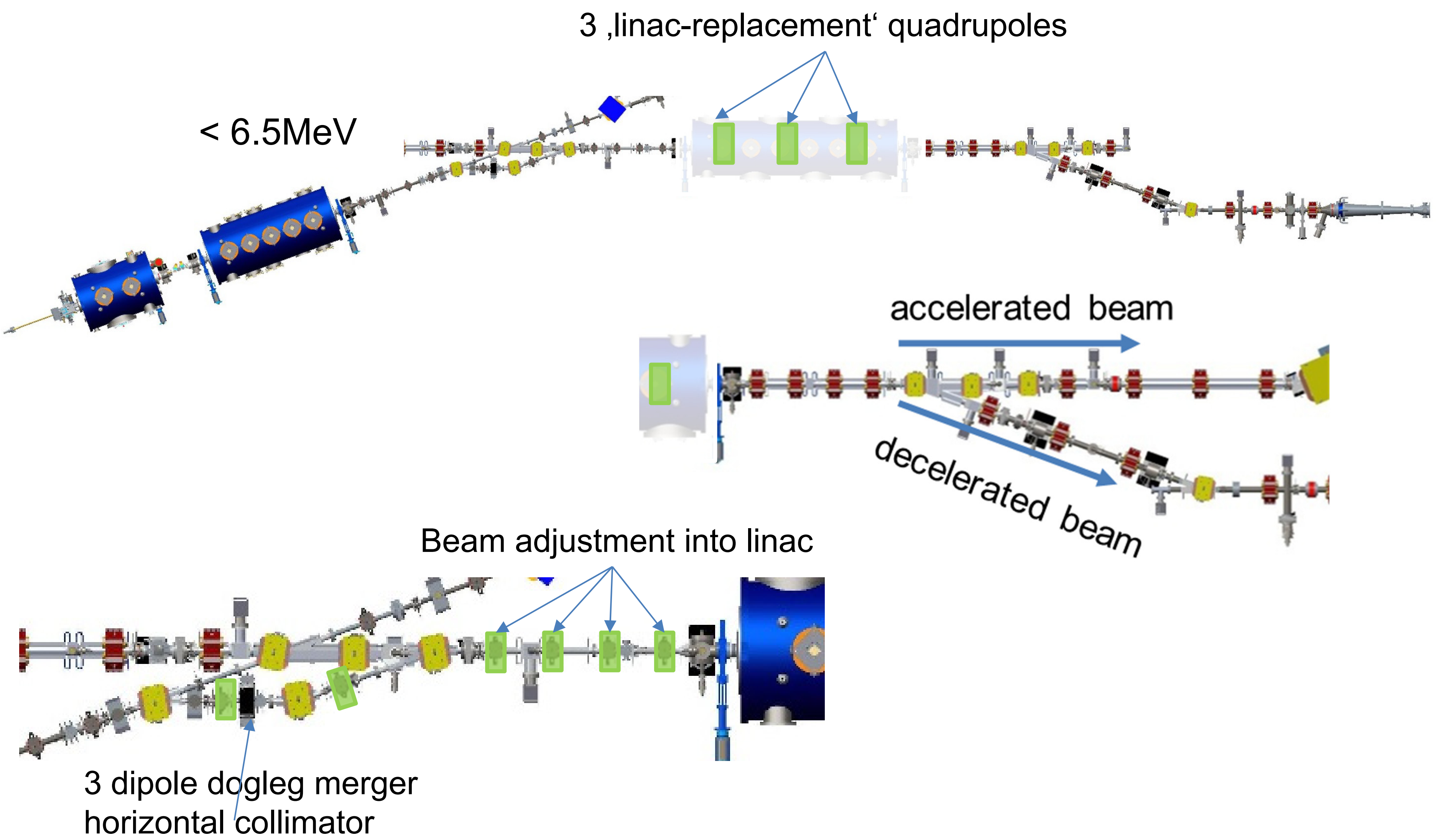
Diagnostics line 2.7MeV Banana 6.5MeV



Trajectory correction results: blue: using SVD on existing hard ware
Green: adding 'virtual' BPMs – depends on reliable model

Banana – only with ‚linac-replacement‘ quads



Banana unwanted beam studies

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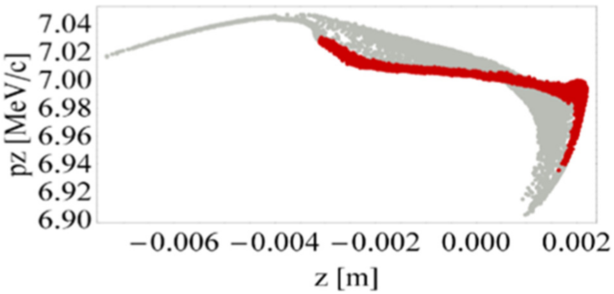
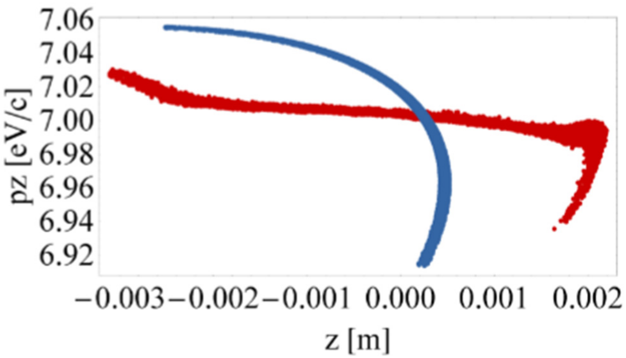
„Dark current and halo tracking in ERLs", M. McAteer, HZB, @ERL'17, CERN

- On-time halo (3D tails of laser pulse)
  - ⇒ particles stable through merger
  - ⇒ Collimator can cut lower momentum particles
- Ghost pulses
  - ⇒ Stable with different optics
- Booster field emission
  - ⇒ 75% remains in cavity
  - ⇒ 0.1% travels back to cathode
- Field emission cathode and plug
  - ⇒ 7% travels back to cathode
  - ⇒ 25% lost in gun taper/merger/ collimator (4mm half gap)
  - ⇒ 4% pass merger
- Stray light
  - ⇒ 40% travels back to cathode
  - ⇒ 40% lost in merger/ collimator (4mm half gap)
  - ⇒ 20% pass merger



Longitudinal phase space behind merger
Gray: halo, Red: main bunch



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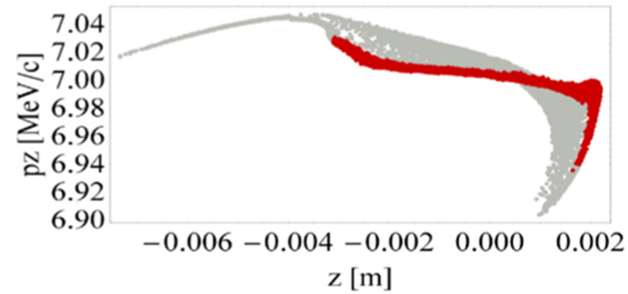

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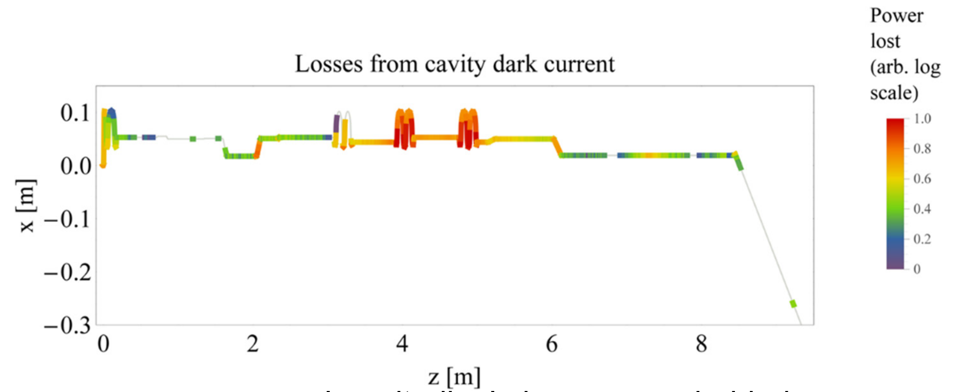

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Recirculator

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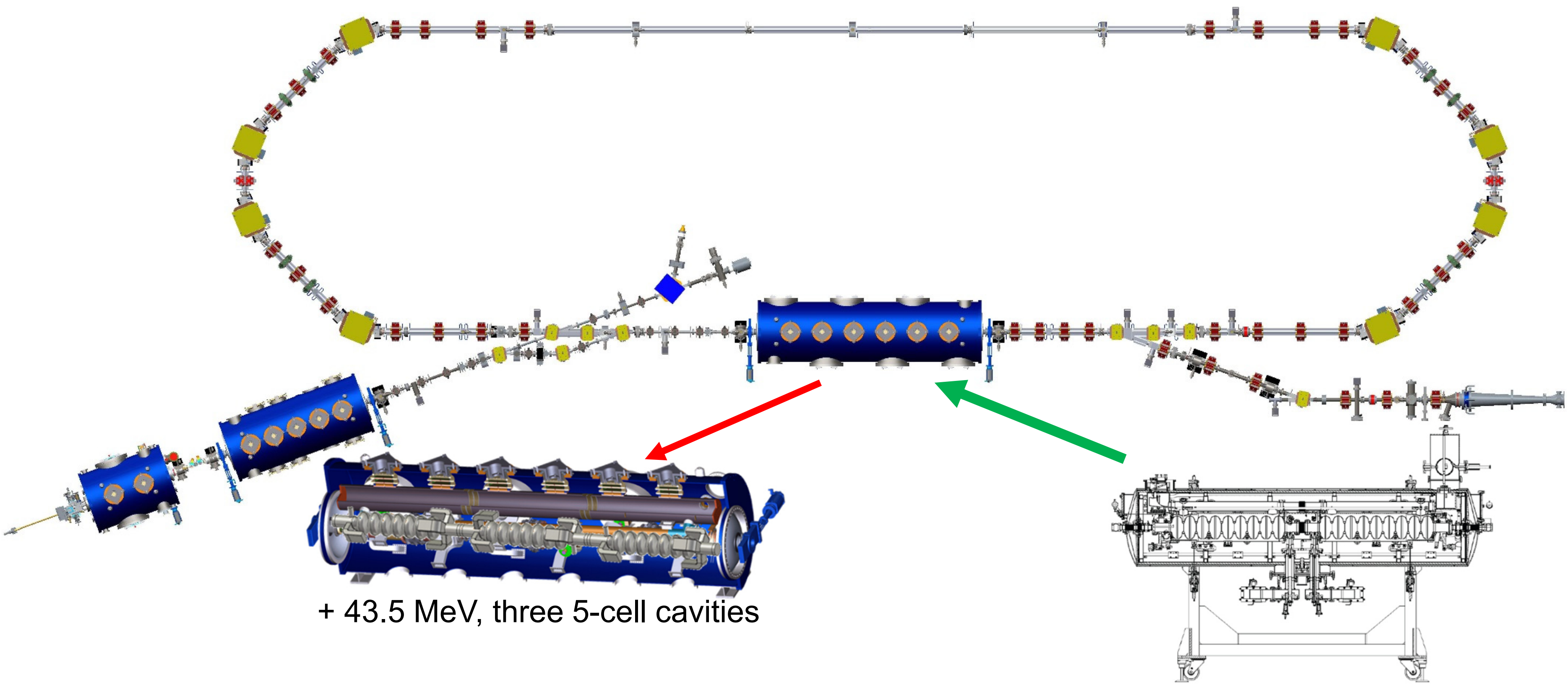
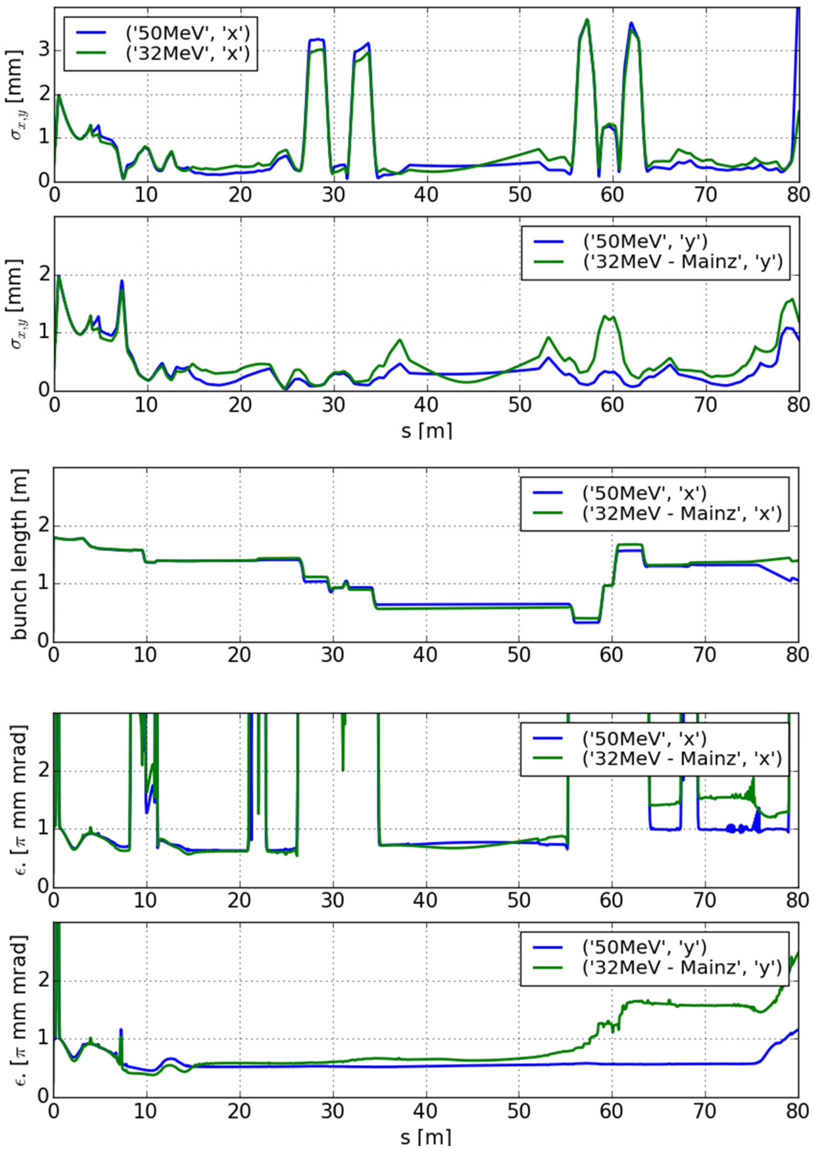


- ✓ geometry
- ✓ technical adaptations
- ✓ ΔE ⇔ Δ path length 7.7mm
- ✓ optics: chicane offset 55mm < 80mm aperture
  different RF focusing in the linac
  edge focusing splitter chicane
- ✓ only linear adjustments,
  emittance compensation scheme, SX configuration, chirp untouched

bERLinPro – MESA linac optics



Strategy: stay as close as possible settings to bERLinPro lattice

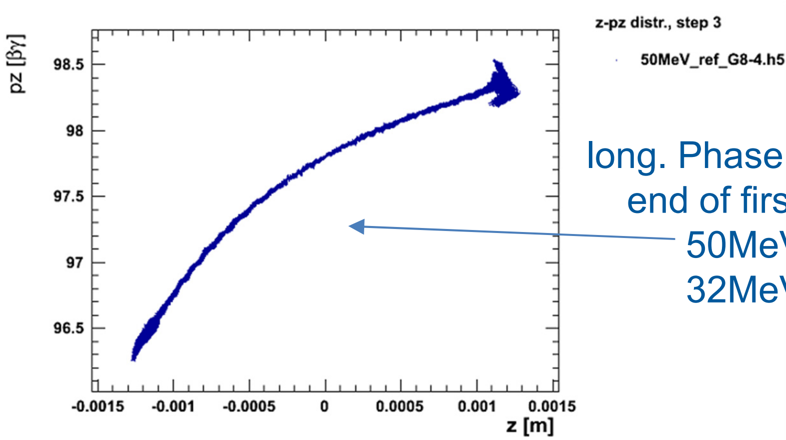
- Emittance < 1π mm mrad
- Bunch length < 2ps / 0.6mm
- Beam dimension behind 50m not relevant

But:

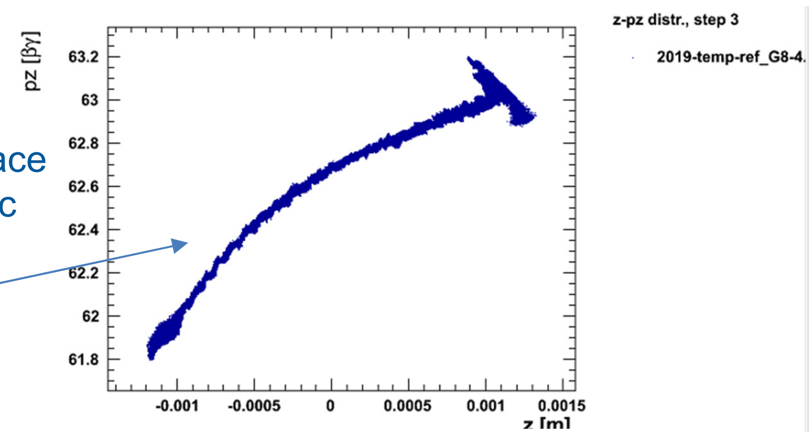
- Machine space charge effected to dump
- Micro bunching and CSR effects

Micro bunching

shot noise induced by cathode laser & space charge => energy modulations
energy modulations & R56 => micro bunching / dilution of modulation

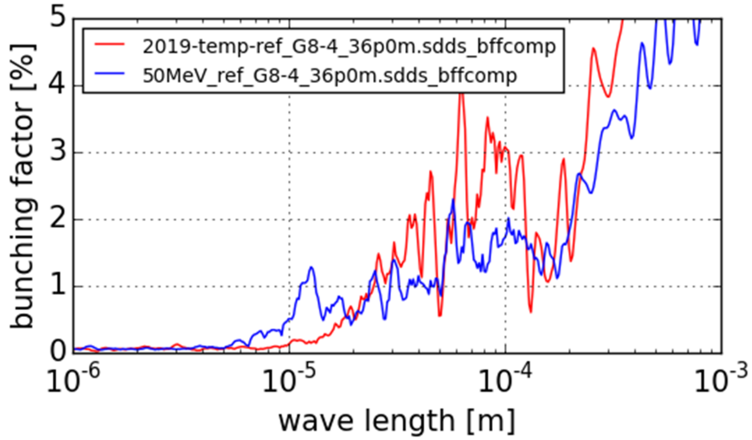


long. Phase space
end of first arc
50MeV
32MeV



Bunching factor

$$b(\lambda) = \frac{1}{Nec} \int I(z) e^{\frac{-i2\pi z}{\lambda}} dz;$$



50-100% increased bunching factors at 32MeV

bERLinPro – space charge and CSR

OPAL:

- 3D space charge from cathode
- solves the Liénard-Wiechert potentials to calculated electromagnetic field
- Saldin 1D formula [Nucl. Instrum. Methods Phys. Res. Sect. A 398, 373–394 (1997)] (transients included) for CSR

To resolve bunching at μm wave length ⇔ grid needs to resolve this

2^{21} grid cells – adapted to bunch dimensions: 128^3 (injector) to 128 x 16 x 1024 (arcs)

⇔ compared to 32^3 grid cells and 1e5 particles

Tracking studies with 2.4×10^6 particles

OPAL on HZB cluster, 64 CPU: 1/2 h/m

→ No increase of micro bunching due to CSR

	50MeV			32MeV		
	Before arc1	Behind arc1 w/o CSR	Behind arc1 w/ CSR	Before arc1	Behind arc1 w/o CSR	Behind arc1 w/ CSR
Emit-x [π mm mrad]	0.661 0.58 grid: 32^3 +15%	0.778 (+18%)	0.837 (+6%)	0.705 0.614 grid: 32^3 +15%	1.420 (+101%)	2.050 (+44%)
Energy		-10keV / 2e-4			-10keV / 3e-4	
ΔE: dominated by chirp!						

CSR impedance model

M. Venturini, "'Models of longitudinal space – charge impedance for microbunching instability"', PRST_AB 11, 304401 (2008)

LSC impedance model by Venturini:

- 3D model of shot noise
- LSCI depends on transverse beam size and energy
- Shift to shorter wave length for higher energies
- Smaller impedance for larger radii

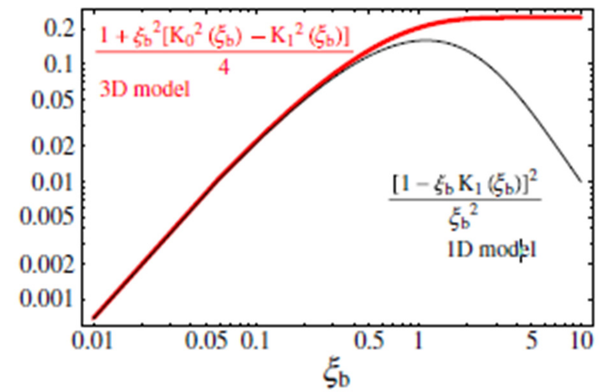


FIG. 1. (Color) The two curves are proportional to the expectation value $\langle|\tilde{E}_k|^2\rangle$ as determined from the 1D model [black curve, Eq. (9)] and 3D model [red curve, Eq. (11)]. The relative difference is less than 10% up to $\xi_b = r_b k/\gamma \simeq 0.5$.

CSR impedance model

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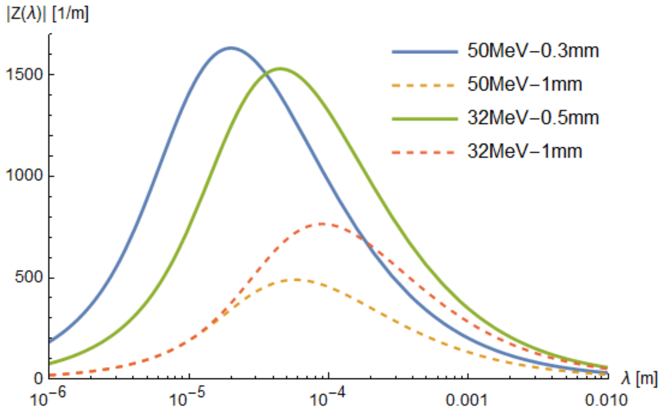

Longitudinal space charge impedance model for two energies and different radii.

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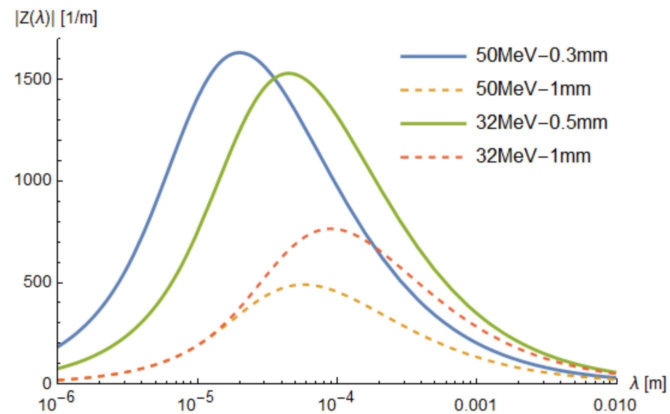
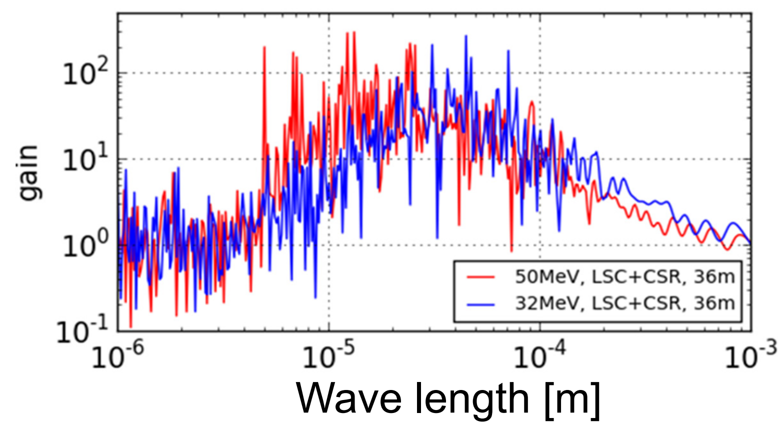


Longitudinal space charge impedance model for two energies and different radii.

$$G(s,\lambda) = \frac{|b_f(\lambda_f)|}{|b_0(\lambda_0)|}$$

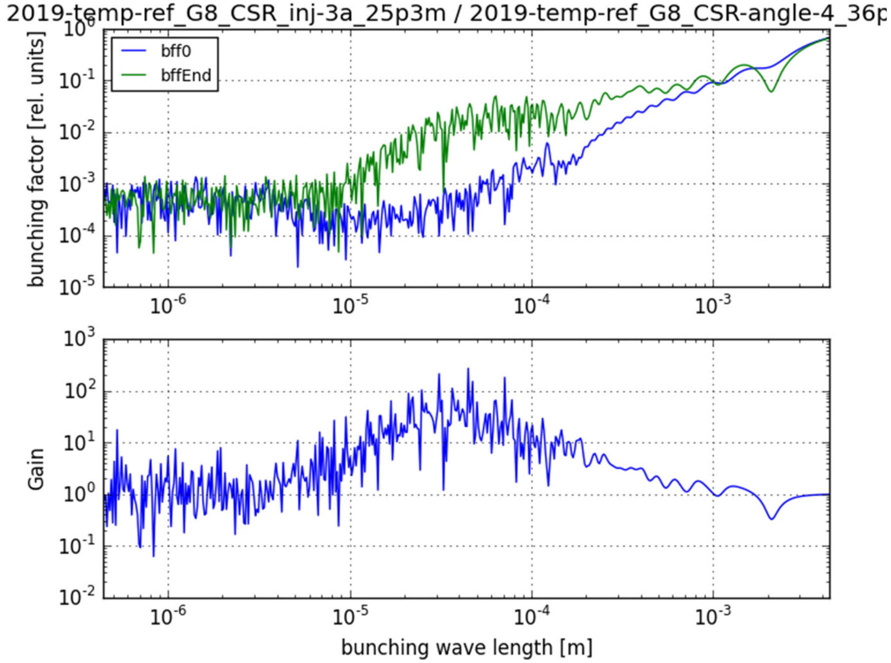
Option to boost the bunching factor
By reducting the transverse bunch parameters



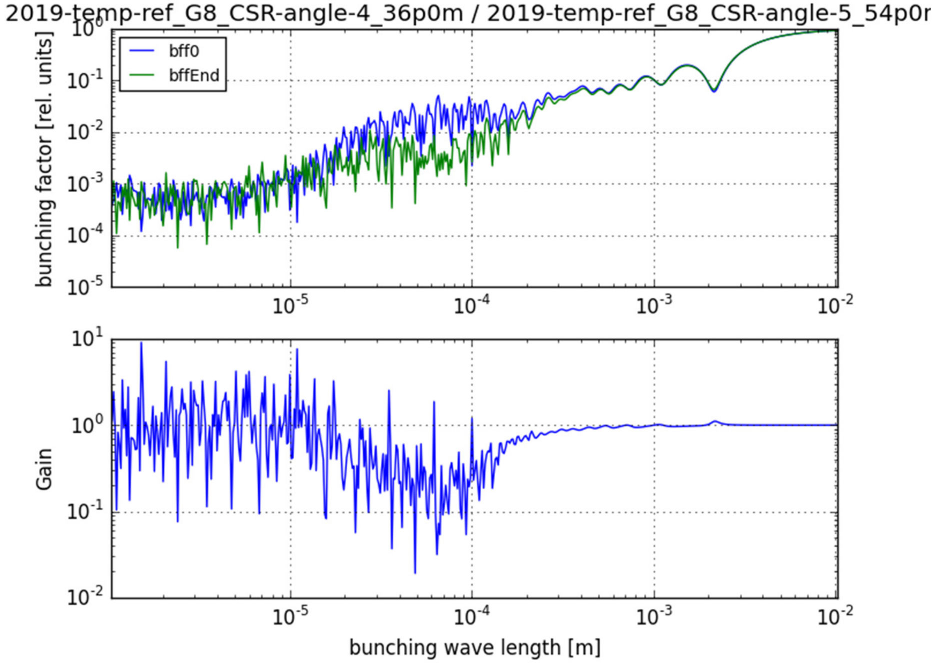
Gain in 1. arc @ 50MeV shifted to lower wave length, gain comparable as higher energy is compensated by larger beam size.

Development of bunching and gain:

Arc 1 (25.3m – 36m)



Straight section (36m – 54m)



Conclusion

Summary:

- ❖ Many different optics to be handled
- ❖ Obstacles encountered so far
  - Magnetic field in hall
  - Known halo sources
  - Micro bunching / CSR at 32MeV
    - \- seem ‘manageable’
- ❖ Inclusion of MESA linac
  - Optics work with linear adjustments
  - Strong micro bunching – usable?