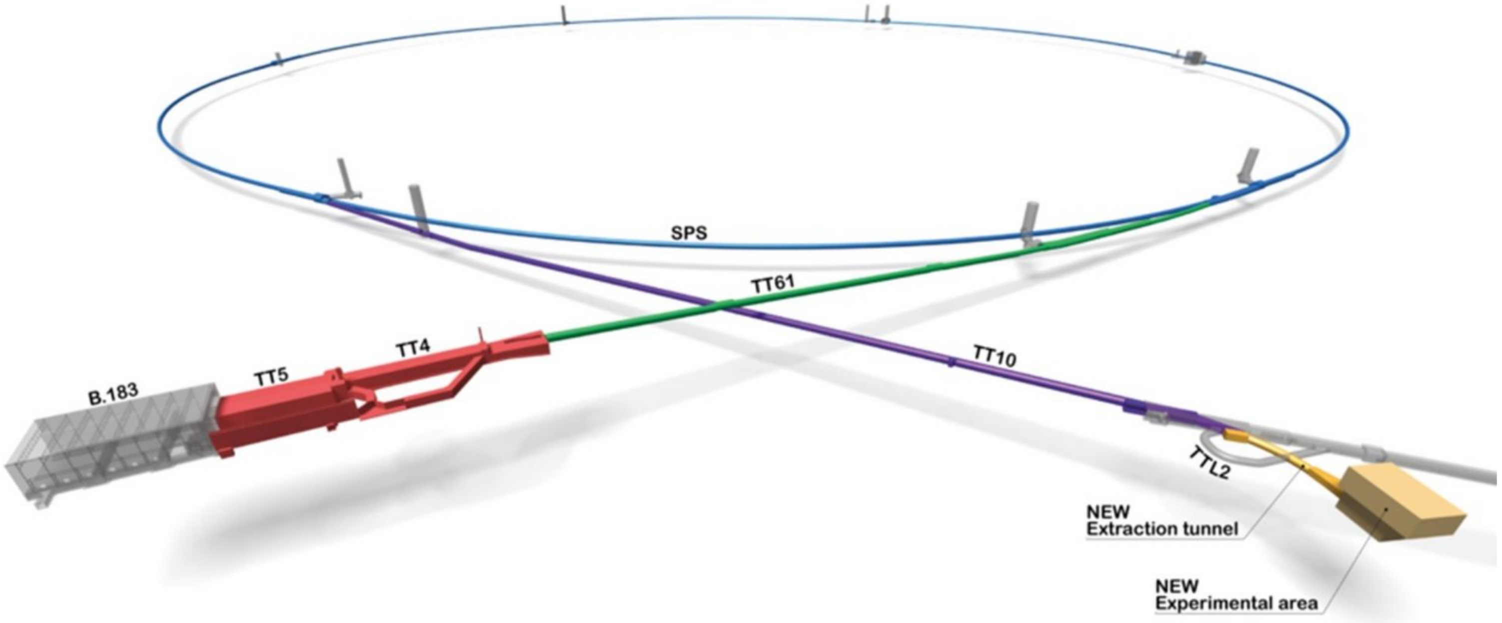
John Adams Institute for Accelerator Science

eSPS Design Study

Student Design Project 2020-2021



Majid Ali, Emily Archer, Pablo Arrutia, Joseph Bateman, Robert Murphy,
Cameron Robertson and Rebecca Taylor

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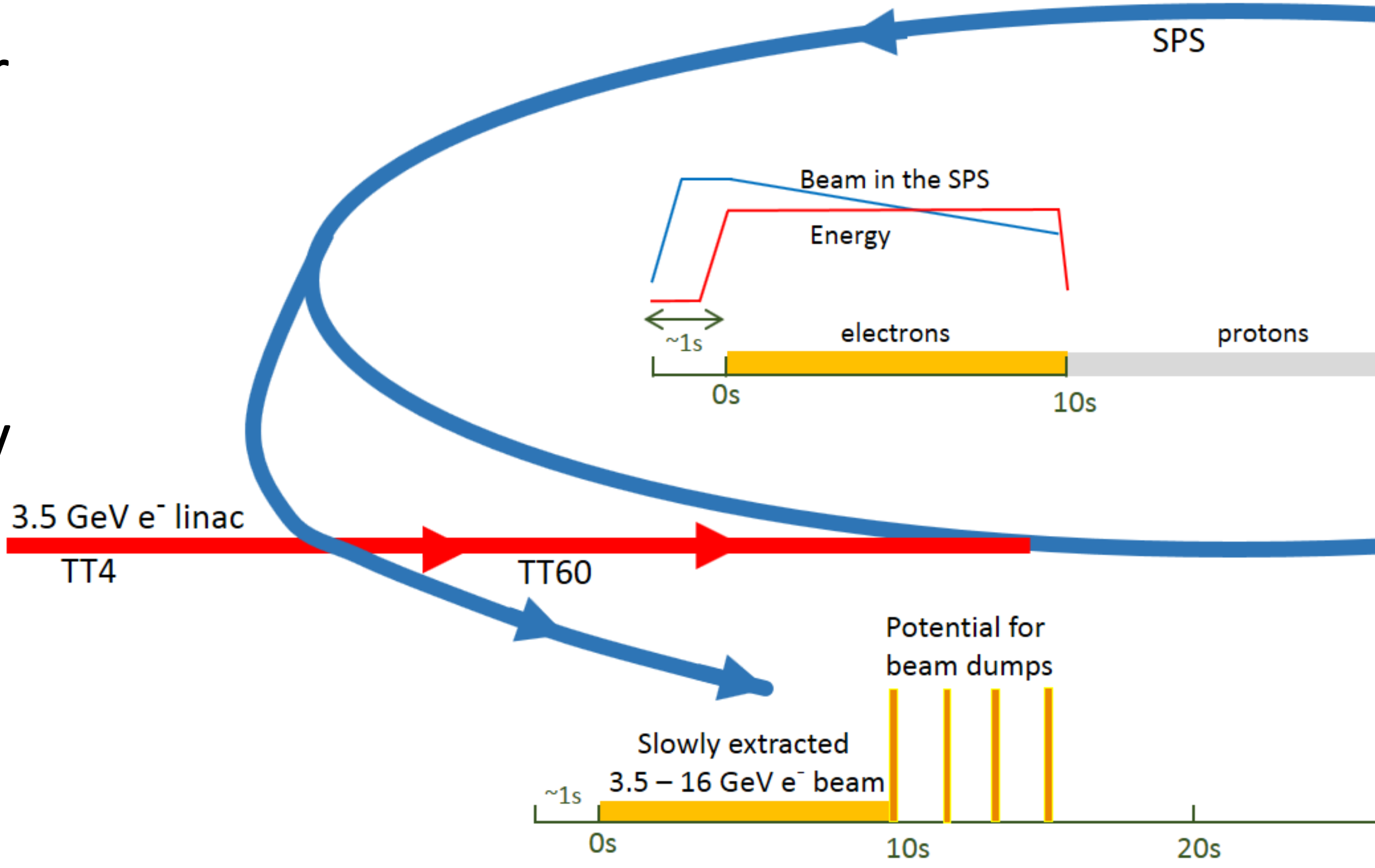
eSPS Introduction

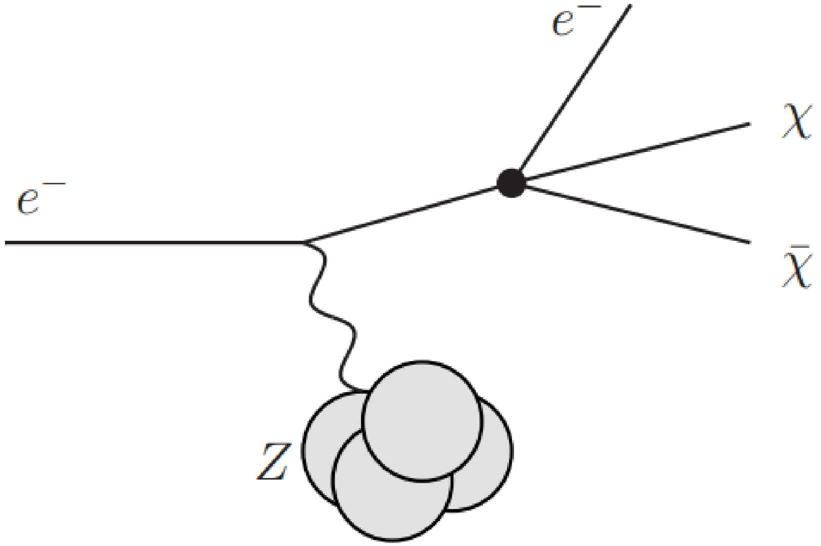
- Proposed electron accelerator using **SPS infrastructure**
- **3.5 GeV linac** with CLIC X-band technology
- Synchrotron extraction energy up to **16 GeV** (18 GeV)
- Electron target experimental area
  - Low-rate & beam dump experiments



A primary electron beam facility at CERN (2018)
https://cds.cern.ch/record/2624786

Physics Motivations: Dark Sector Physics

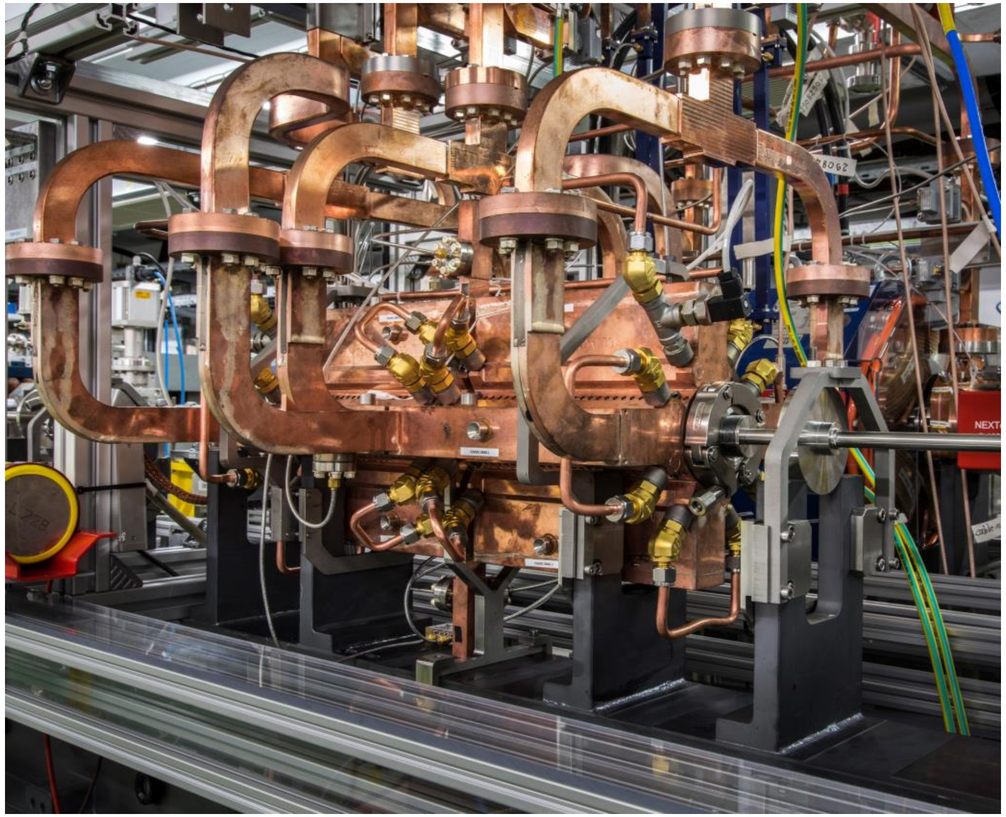
- Studying Light Dark Matter (**LDM**) candidates
  - MeV – GeV range
  - χ particle & corresponding A' boson
- Require **low-rate, high current** e^- beam
  - DM has low cross-section, so want high statistics, with low pile-up for individual measurements
- Precise electron beam gives good probe of **missing momenta** experiments
  - Axion-like particles, dark photons, etc
  - Electron-nucleus precision measurements for neutrino oscillation experiments



A primary electron beam facility at CERN - eSPS CDR (2020)
http://cds.cern.ch/record/2730589

Accelerator Motivations

- Demonstration of **CLIC X-band technology** with test site
  - 12 GHz linac from technology developed for CLIC
  - Next step in high-gradient acceleration
- Circular electron accelerator **infrastructure** & training
  - Preparation for next-generation Higgs-factories
- Wakefield accelerator **test facilities**
  - Can adapt for plasma wakefield electron bunches
- Producing **RF cavity R&D** to match FCC-ee requirements
  - 800 MHz superconducting cavities



New module installed in CLIC test facility (2015)

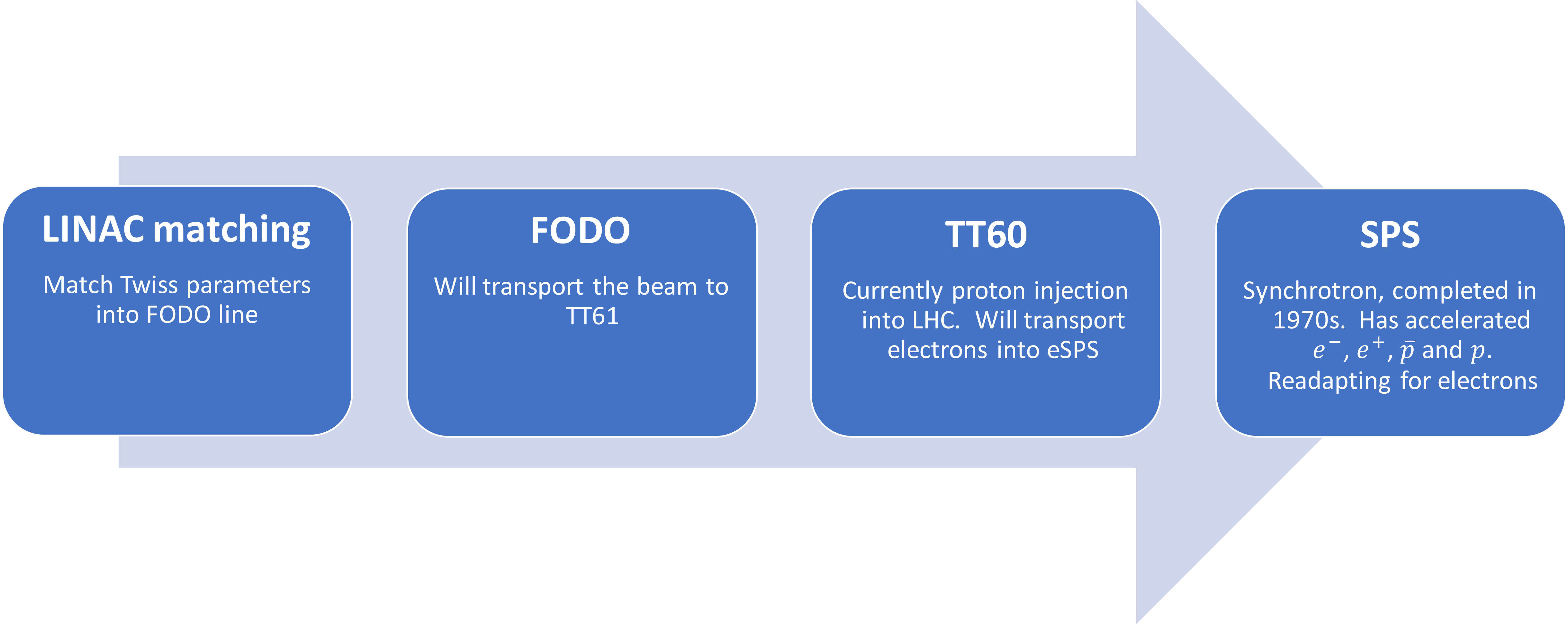
Brice, Maximilien cds.cern.ch/record/1982610

Lattice Team

Rob Murphy and Rebecca Taylor

- Injection Line
- Aperture & Acceptance
- Dispersion Effects

Injection line sections



LINAC matching

Match Twiss parameters into FODO line

FODO

Will transport the beam to TT61

TT60

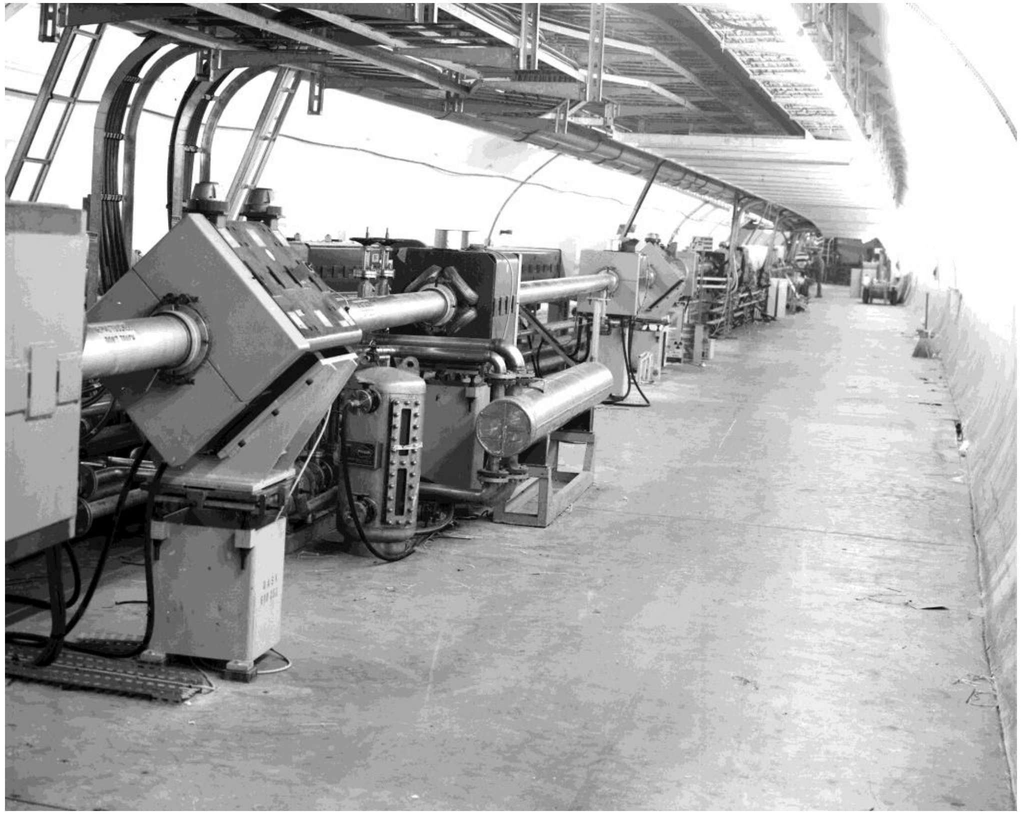
Currently proton injection into LHC. Will transport electrons into eSPS

SPS

Synchrotron, completed in 1970s. Has accelerated e^-, e^+, $\bar{p}$ and p. Readapting for electrons

Injector Line

- LINAC in TT5/TT4 provides bunch of 5->40 ns.
  - High repetition rate (200 ns at 100 Hz).
- TT60 Previously used to transfer protons to West Area.
- e^- injected in opposite direction to p.
  - 3.5 GeV kicker at 100Hz repetition rate.



View of beam traffic in TT60 tunnel, looking towards the SPS (1981)
http://cds.cern.ch/record/754068

Method

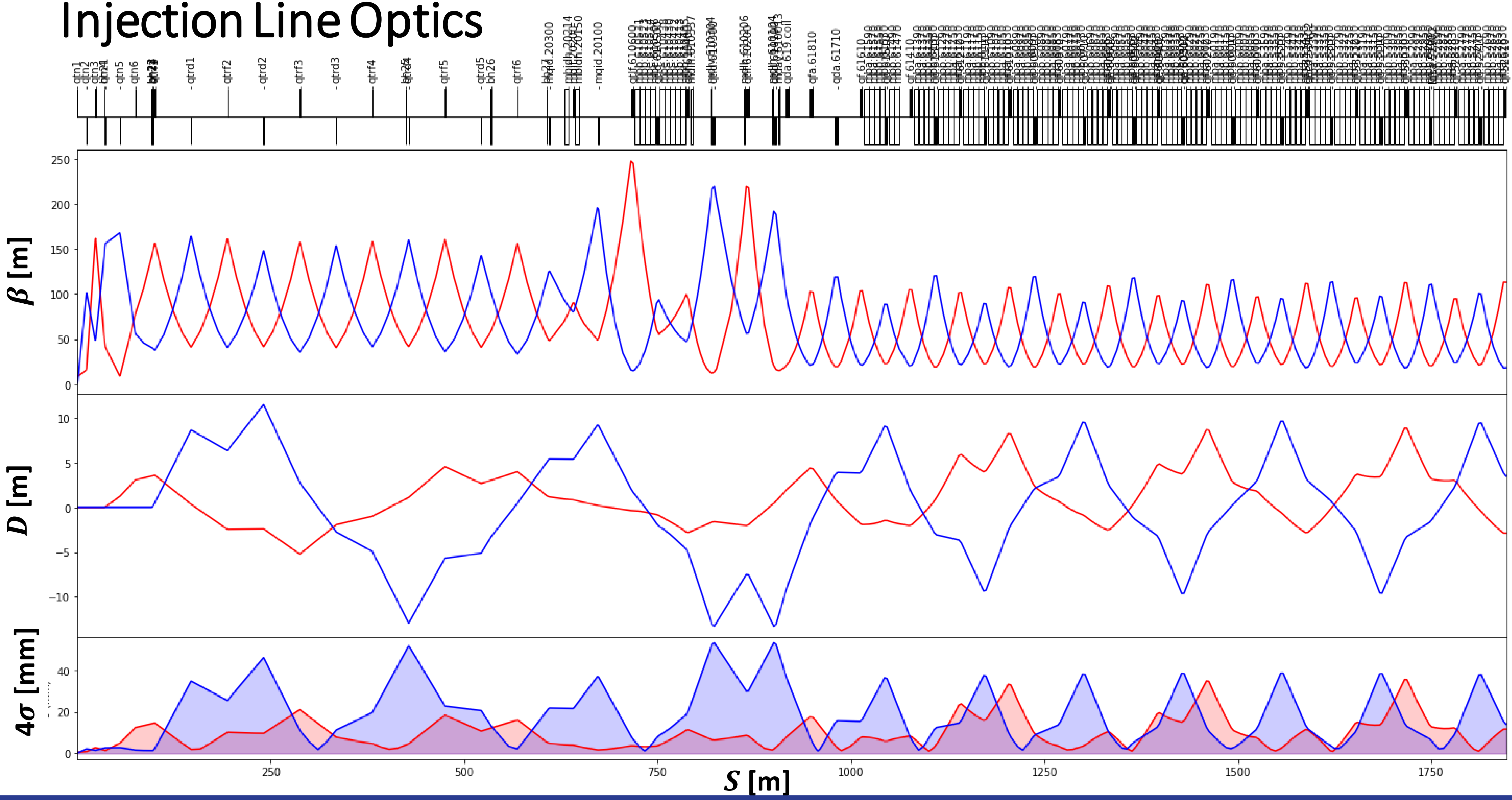
- Start with Twiss parameters (alpha, beta, dispersion) and working backwards from SPS (fixed optics).
- Use Twiss parameters, track backwards through TT61. Provides target Twiss parameters at start of TT61.
- Match parameters from LINAC into TT61 using matching routine in MADX e.g. Simplex.
- Use full Twiss parameters to calculate beam envelope.
- Compare beam envelope to physical aperture.

NAME	COMPONENT	BETX (m)	BETY (m)	ALFX	ALFY	DX
START_FODO	MARKER	295.43	19.15	-3.37	1.17	5.41
DRIFT_6	DRIFT	306.91	15.56	-3.45	0.96	5.62
QTRF1	QUAD	306.81	14.91	3.69	0.56	5.65

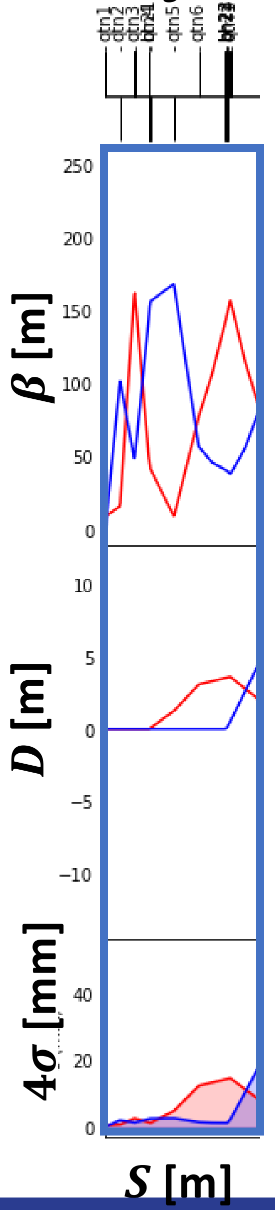
Challenges of eSPS lattice design

Pros	Cons
Existing Infrastructure	Limited Space
Development time	Constrained apertures (magnets)
Reusable components	Operational requirements
NEW PHYSICS!	Activation products/materials

Injection Line Optics



Injection Line Optics

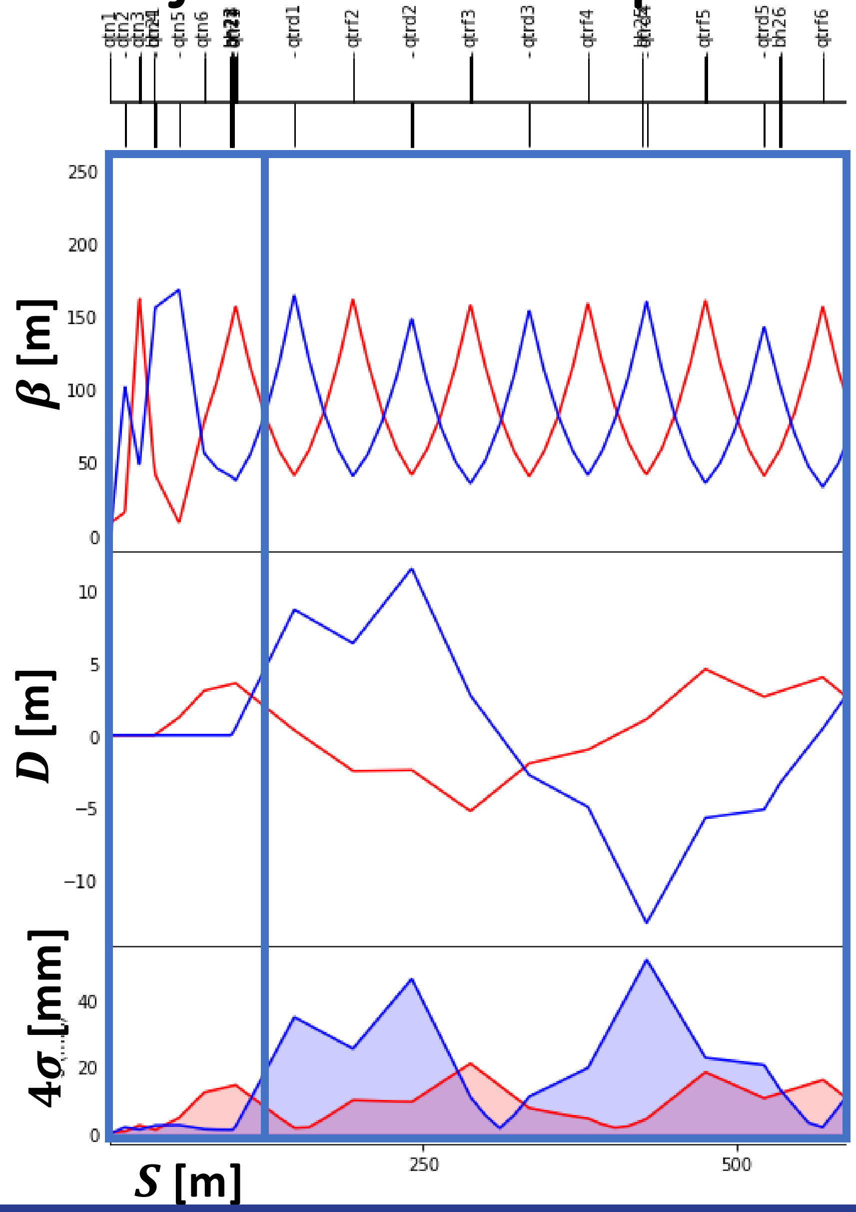


Linac Matching:

- Initial optics calculated from a FODO cell of 5.3 m length and 90° phase advance
  - βx = 9m, βy = 1.5m
- **98.5 m long** – to match small linac beam to larger beam for the FODO transport
- 6 QTN magnets & 4 BH2 magnets
- 20° slope causes large dispersion in y
  - 36.4% tunnel downwards

Credit to Pablo Arrutia for the MADX sequence

Injection Line Optics

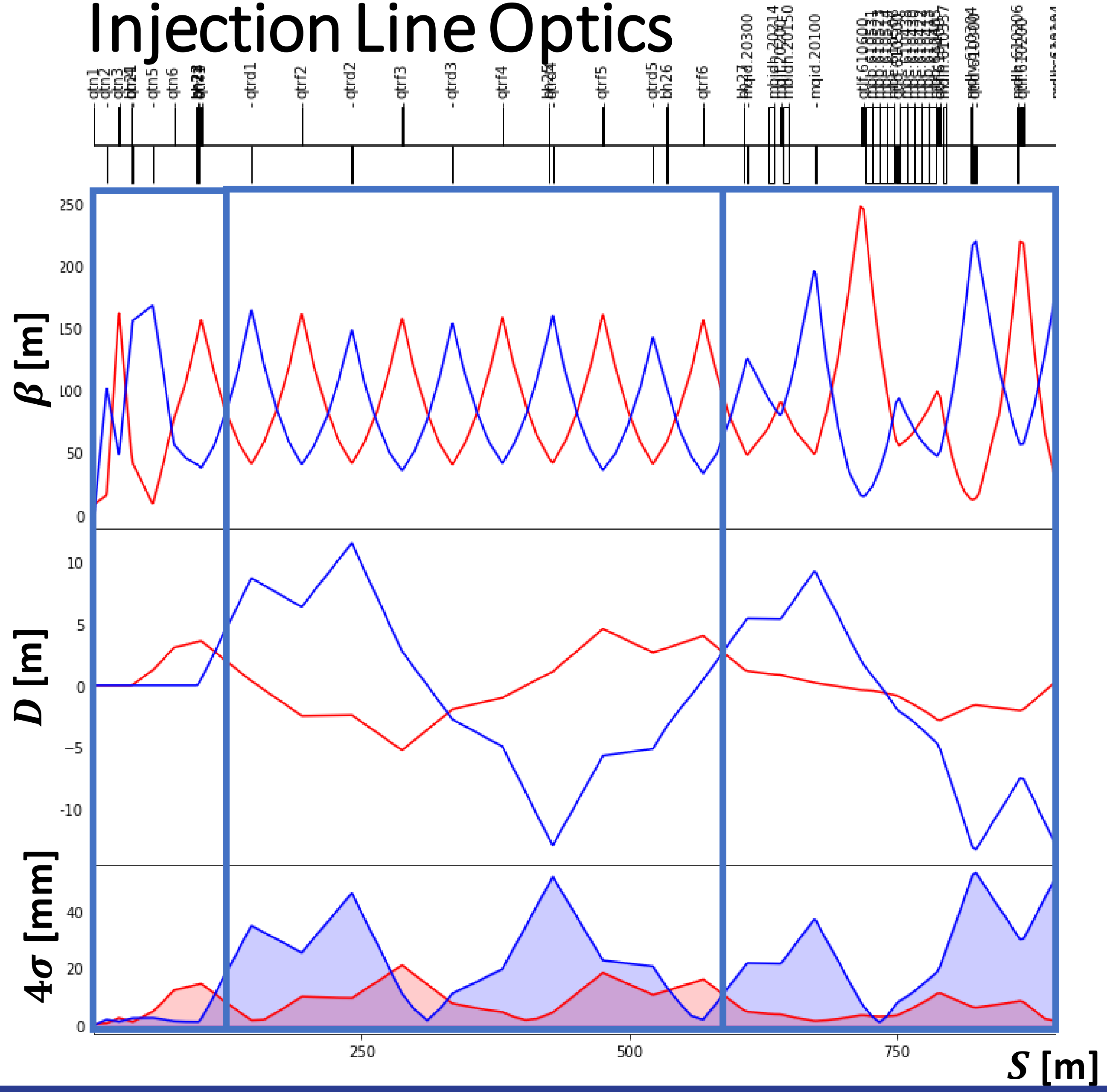


FODO line:

- Transporting beam from linac towards SPS
- **510 m long** – want quadrupoles with large focusing length
- 10 QTR magnets & 3 BH2 magnets

Credit to Pablo Arrutia for the MADX sequence

Injection Line Optics

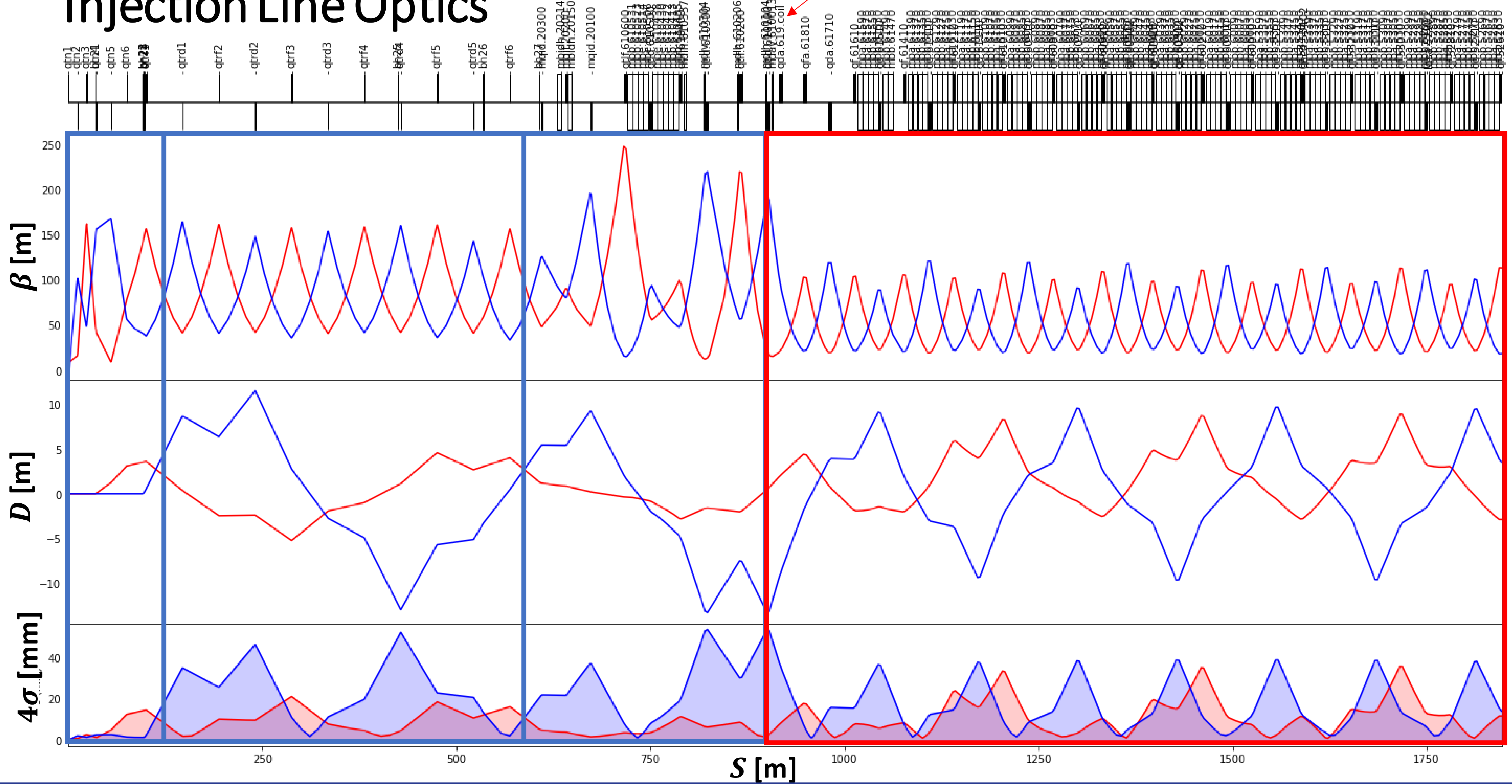


TT61 Line:

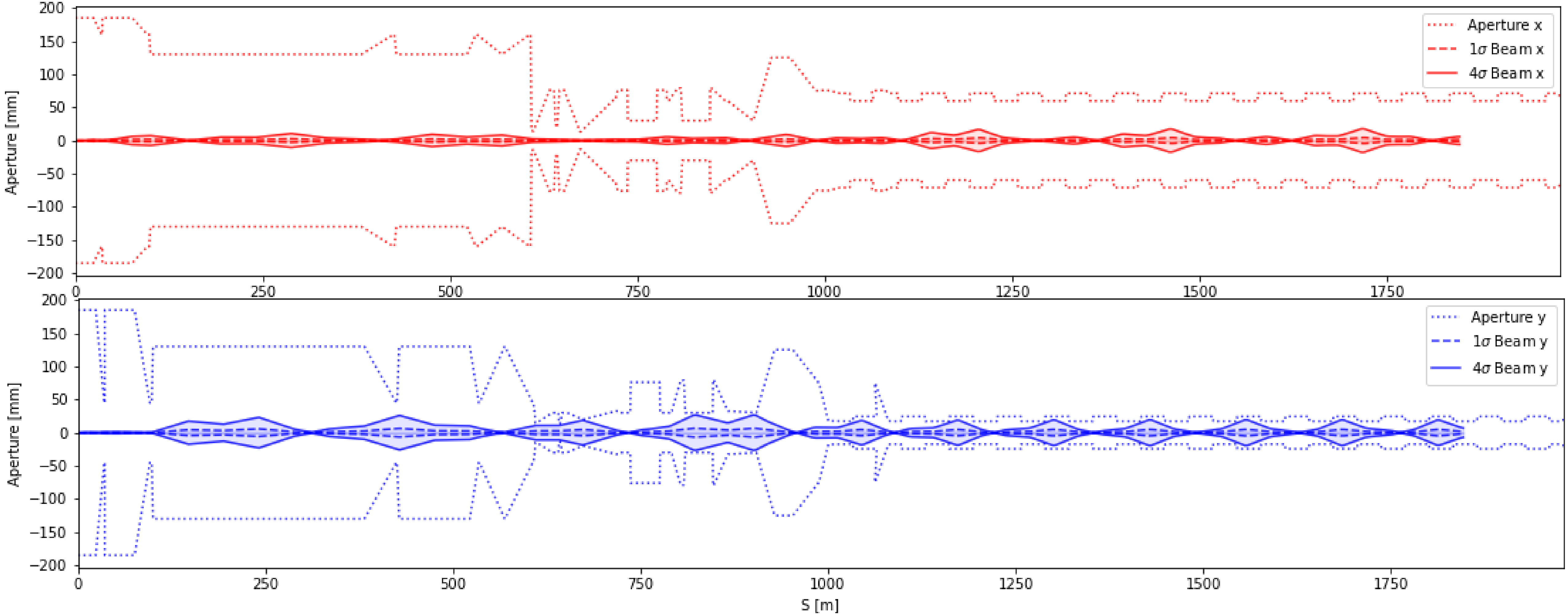
- Same as existing line
  - Reversed it and matched to SPS injection
- **307 m long**

Credit to Pablo Arrutia for the MADX sequence

Injection Line Optics

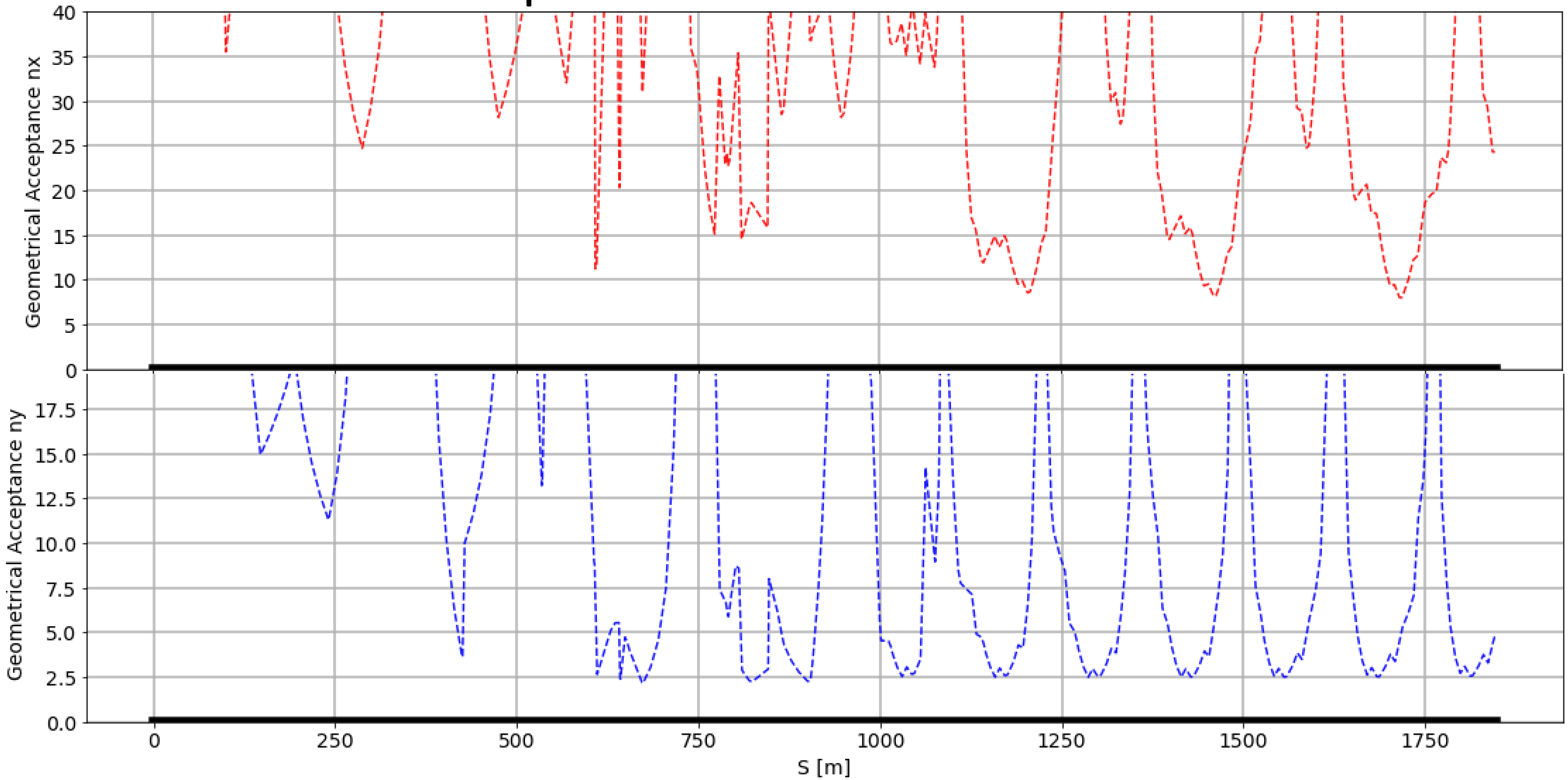

SPS start

Beam size & apertures

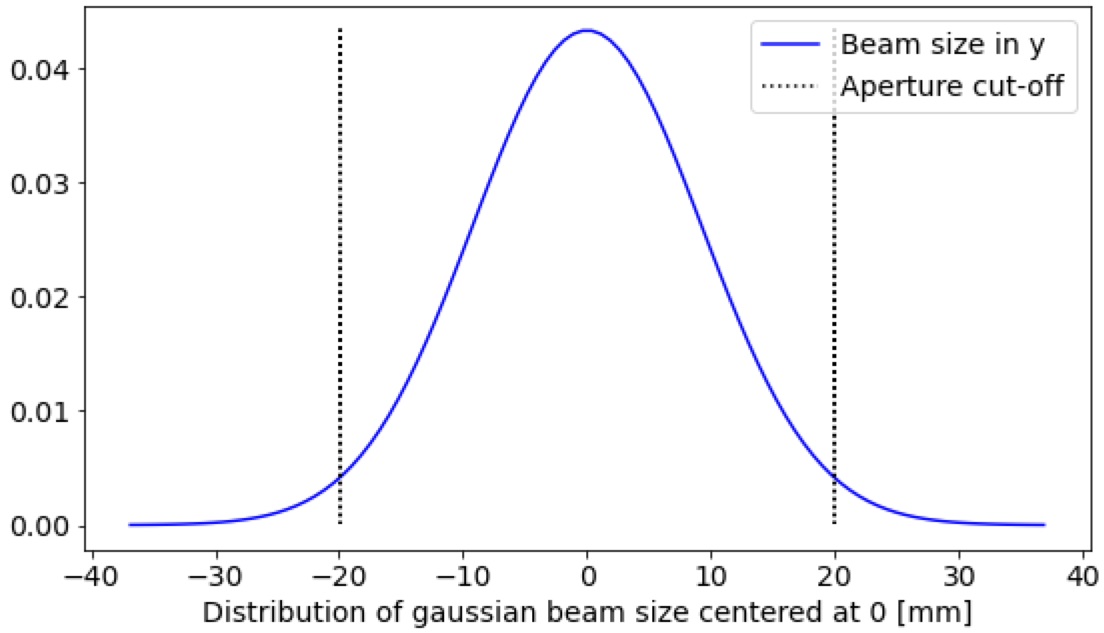


Beam size & apertures

$$n_x = \frac{A_x}{\sigma_x}, \quad n_y = \frac{A_y}{\sigma_y}$$

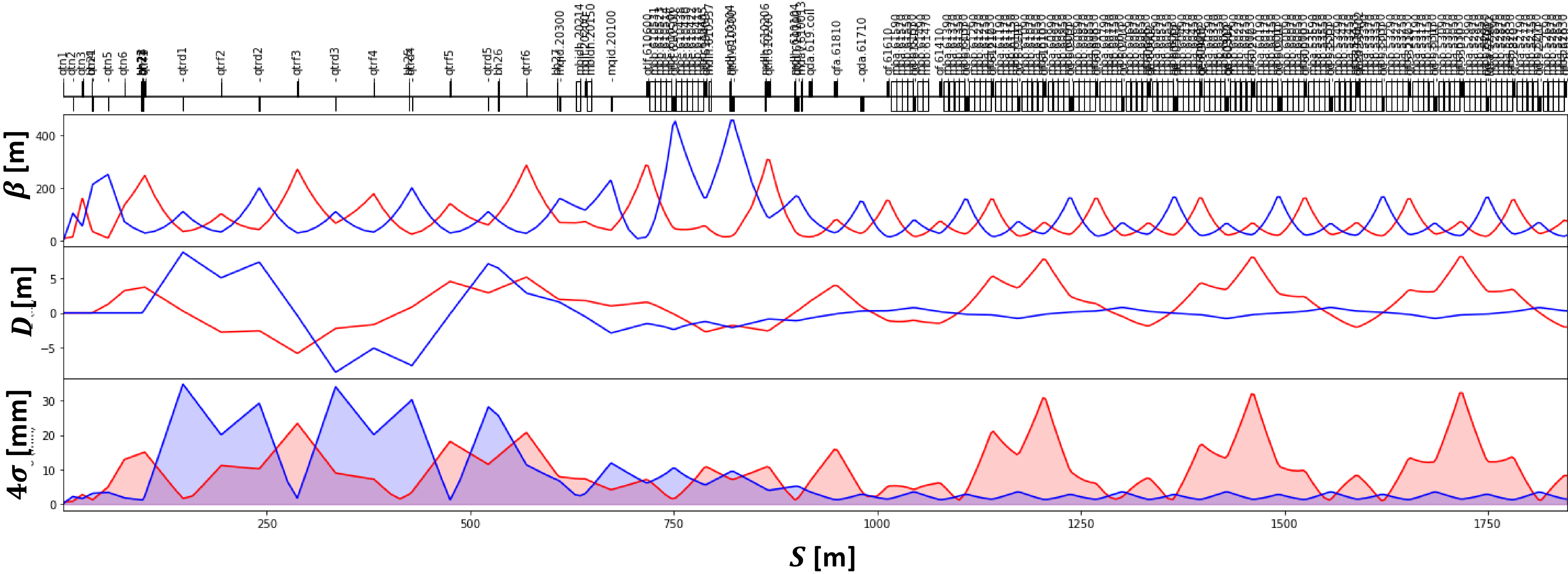


Beam size & apertures



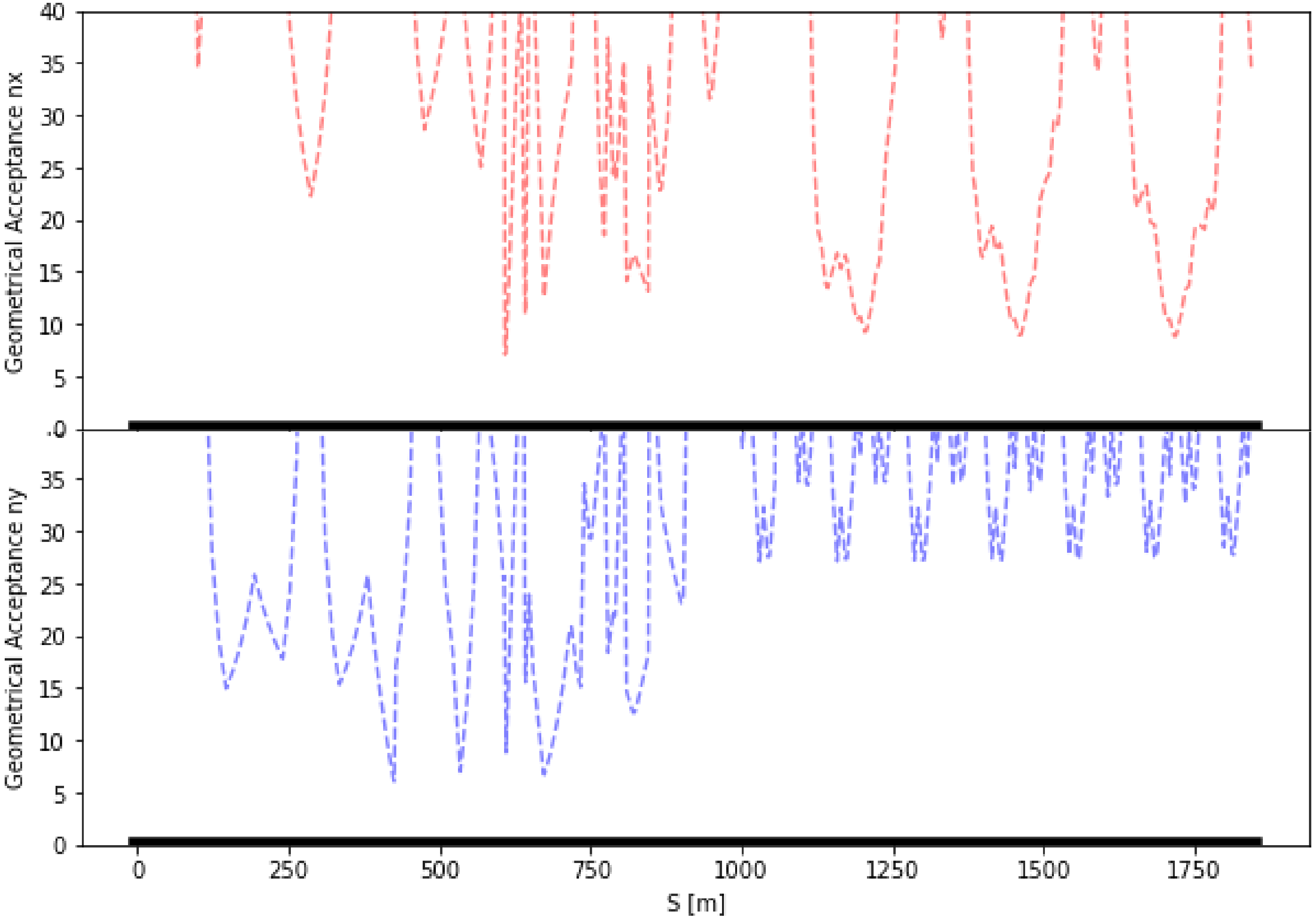
- Large y dispersion from the 20° slope
    - Large beam envelope 2.1σ away from the aperture
    - Beam transmission: **97.0%**
- To reduce y-plane dispersion:
    - Adjust phase advance
    - Dispersion cancelling techniques
- It is possible to increase beam current to replace losses
- Try matching but reduce dy and dyp

Optics solution with reduced dispersion



Optics solution with reduced dispersion

- Matching with $dy < 1$, $dpy < 0.1$
    - Less periodic solution
    - Reduces beam size
- Sigma from aperture is 7σ in x and 6σ in y
- Further investigations can find more appropriate solutions



Future Lattice Studies

To observe beam optics through many turns of the SPS

Incorporating RF cavity design and observing effects to the beam

To ensure injection phase-space matches those required for the SPS

Less requirements on e^- matching due to synchrotron radiation

To find periodic solutions with reduced x & y-dispersion

Ensure beam transmission remains good throughout turns of the SPS

Apply dispersion cancelling techniques to cancel effect of 20° slope

Apply the same techniques to design extraction line

Design new beamline with a large defocusing for the target area

Use existing TT10 line to see if beam fits after extraction

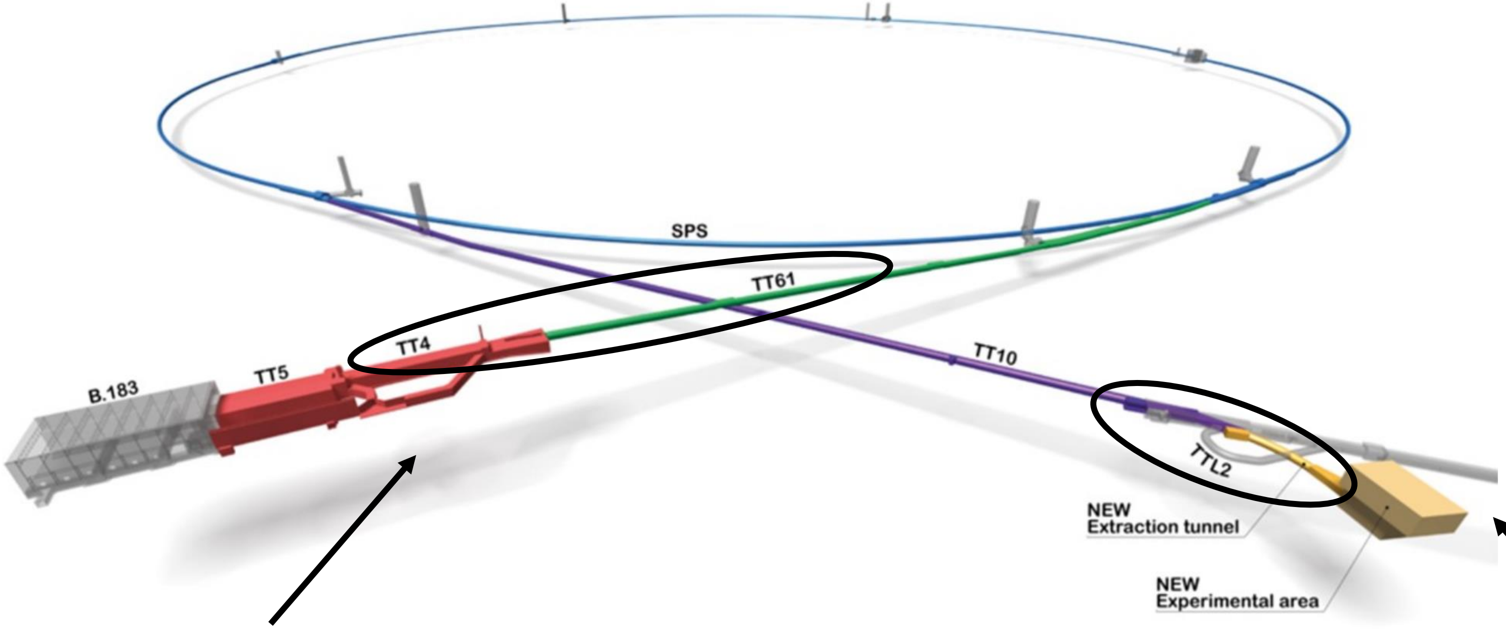
Magnets Team

Emily Archer and Joe Bateman

- Injection & Extraction
- FEMM Simulations
- B-Field Analysis

A primary electron beam facility at CERN - eSPS CDR (2020)
http://cds.cern.ch/record/2730589

eSPS Magnets



Injection

- 3.5 GeV Compact X-band Linac to existing TT61 transfer line.
- The magnets in TT61 line should be air-cooled to avoid installation of a new water supply.

Using existing magnets!

Extraction

- Existing TT10 transfer line to new experimental hall
- Electrons extracted from the SPS cross protons being injected from the PS

Dipole Bending Angle

magnet length

$$\alpha = \frac{L}{\rho},$$

bending radius

$$\rho \approx \frac{3.3356|\overline{p}|}{B} = \frac{11.6746\,\mathrm{T\,m}}{B\,\mathrm{T}}, \qquad |\overline{p}| = 3.5\,\mathrm{GeV}/c$$

injection from the linac

$$\rho \approx \frac{3.3356|\overline{p}|}{B} = \frac{53.3696\,\mathrm{T\,m}}{B\,\mathrm{T}}, \qquad |\overline{p}| = 16\,\mathrm{GeV}/c$$

extraction to the experimental hall

INJECTION

$$\alpha = \frac{L * B\,\mathrm{T\,m}}{11.6746\,\mathrm{T\,m}},$$

EXTRACTION

$$\alpha = \frac{L * B\,\mathrm{T\,m}}{53.3696\,\mathrm{T\,m}},$$

Quadrupole Focusing Strength

Normalised field gradient coefficient (K1 in MADX), often k in literature

$$K = \frac{1}{B\rho}\frac{\partial B_y}{\partial x}$$

$$B\rho \approx 3.3356|\overline{p}| = 11.6746\,\mathrm{T\,m}$$

injection from the linac

$$B\rho \approx 3.3356|\overline{p}| = 53.3696\,\mathrm{T\,m}$$

extraction to the experimental hall

use the gradient nominal field B_{nom} at peak current to estimate $\partial B_y/\partial x$

$$f = \frac{1}{KL}$$

L is the length of the magnet

https://www.femm.info/wiki/pyFEMM

FEMM + pyFEMM

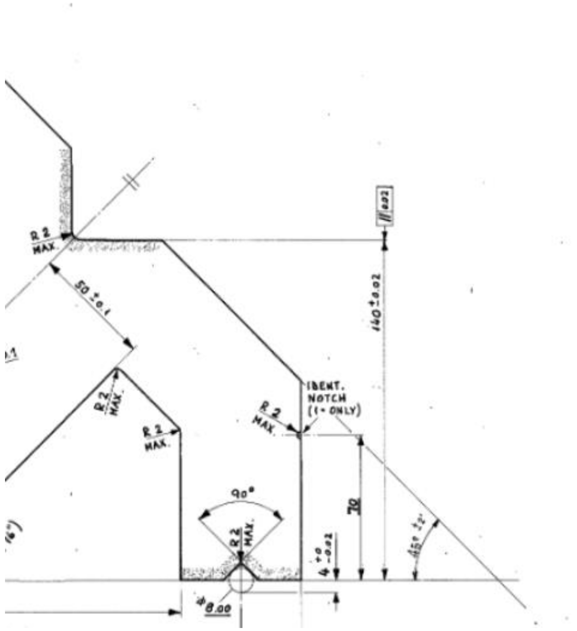
Technical Drawing

Design Problem Geometry in FEMM

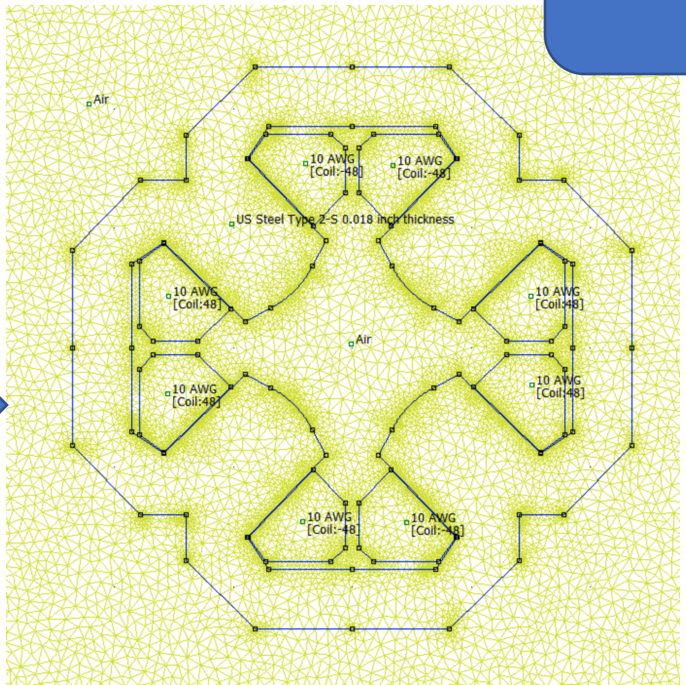
Triangular Mesh

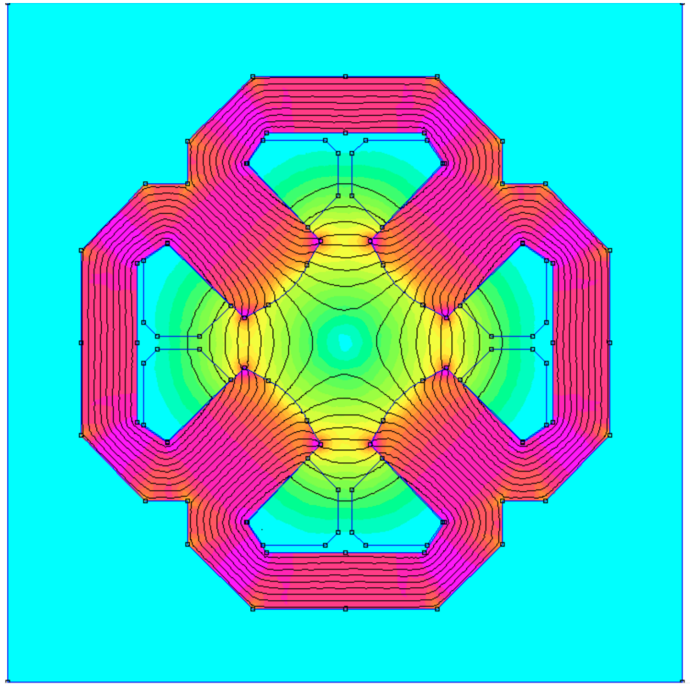
Magnetostatic field solver

Post-processing of field and analysis in pyFEMM



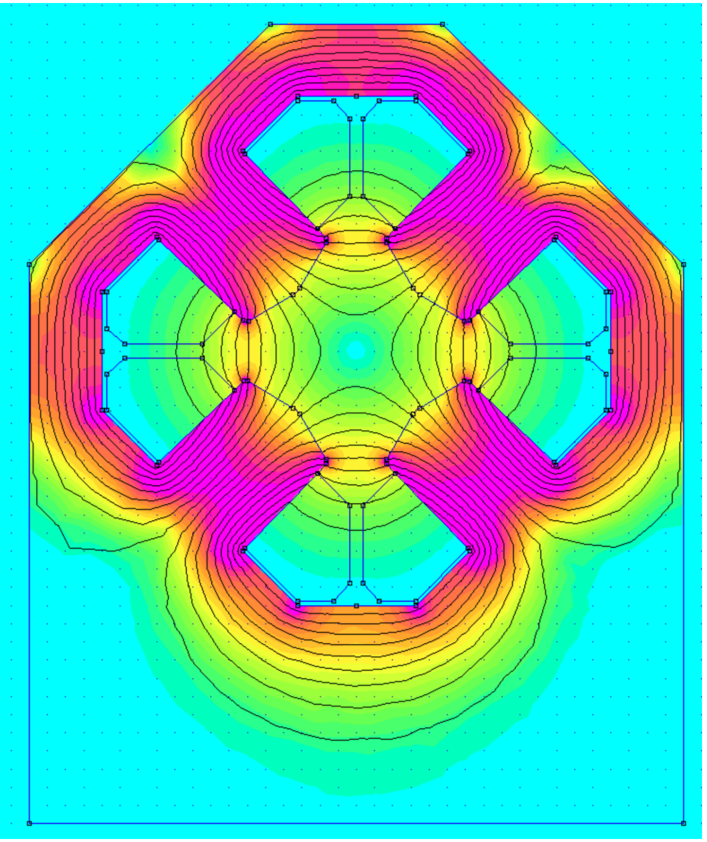
CERN Database (Accessed: 2020)

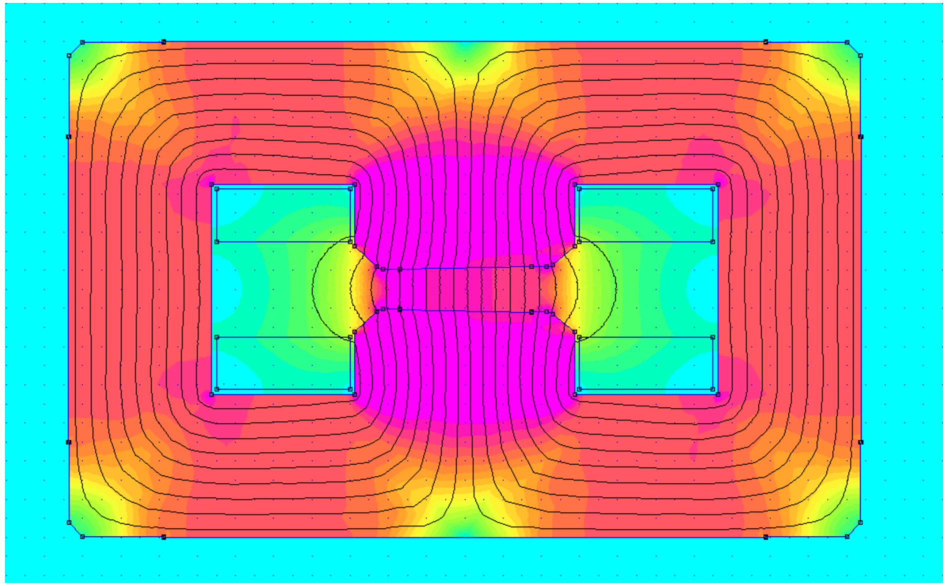




FEMM Models - Injection

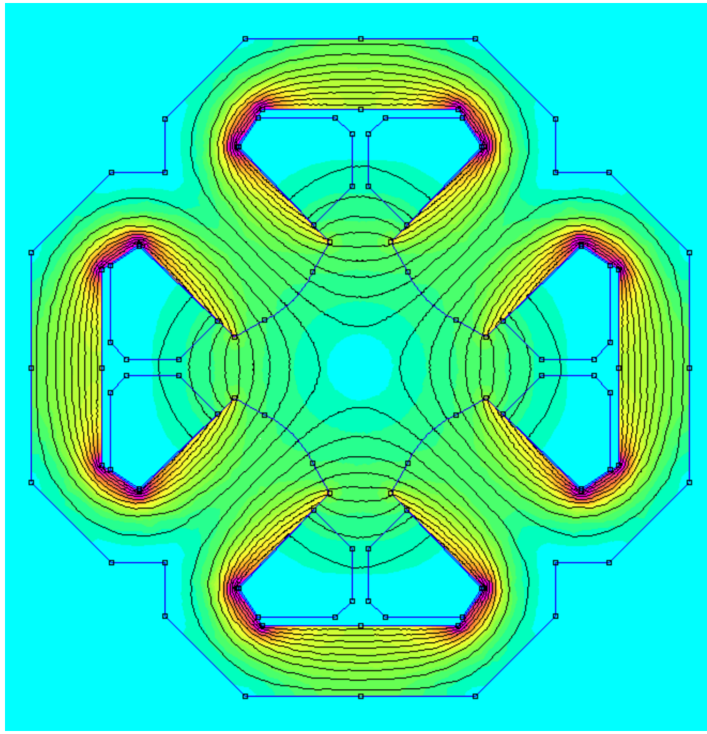
QTN Quadrupole



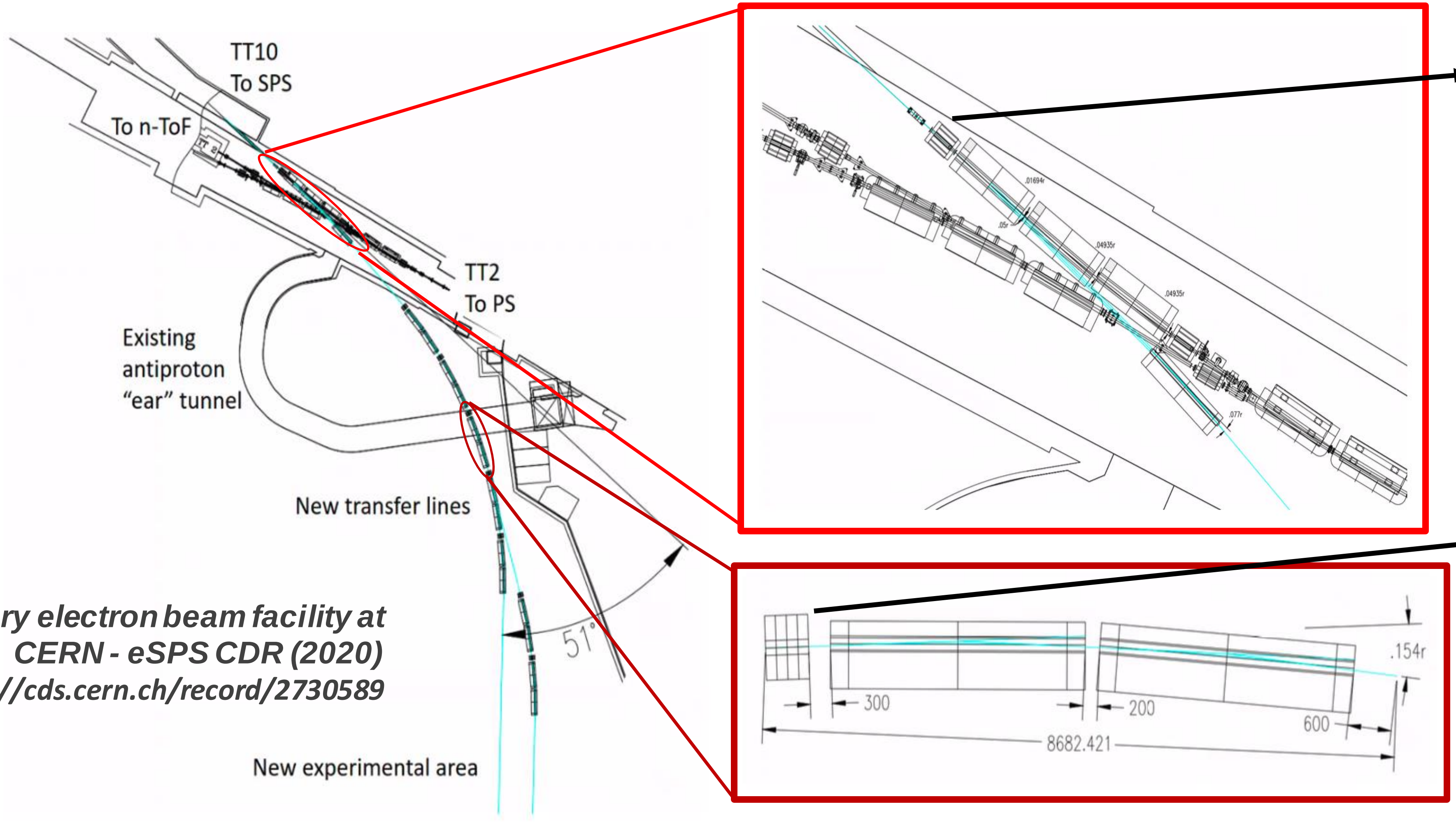


BH2 Dipole

QTR Quadrupole



Extraction Line Magnets



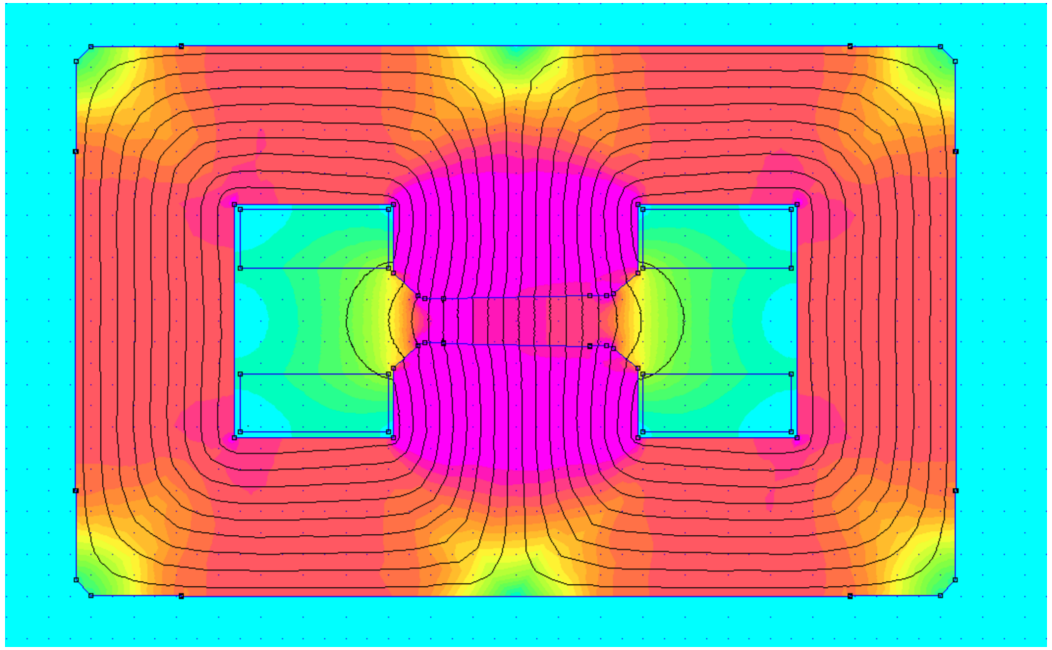
A primary electron beam facility at CERN - eSPS CDR (2020)
http://cds.cern.ch/record/2730589

CDR: BH2 – 50 mrad.
(would require 4)
Or MCW at 258.75 A.

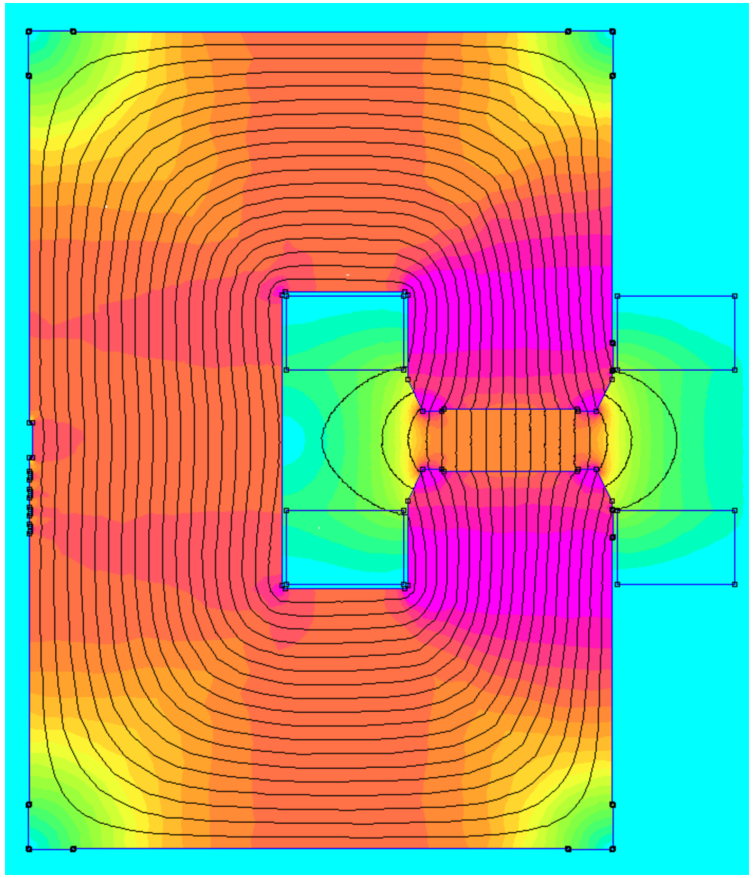
Bending Cell – 2 MCW at
414.5 A (77 mrad each)
and FODO arrangement.

FEMM Models – Extraction

BH2 Dipole

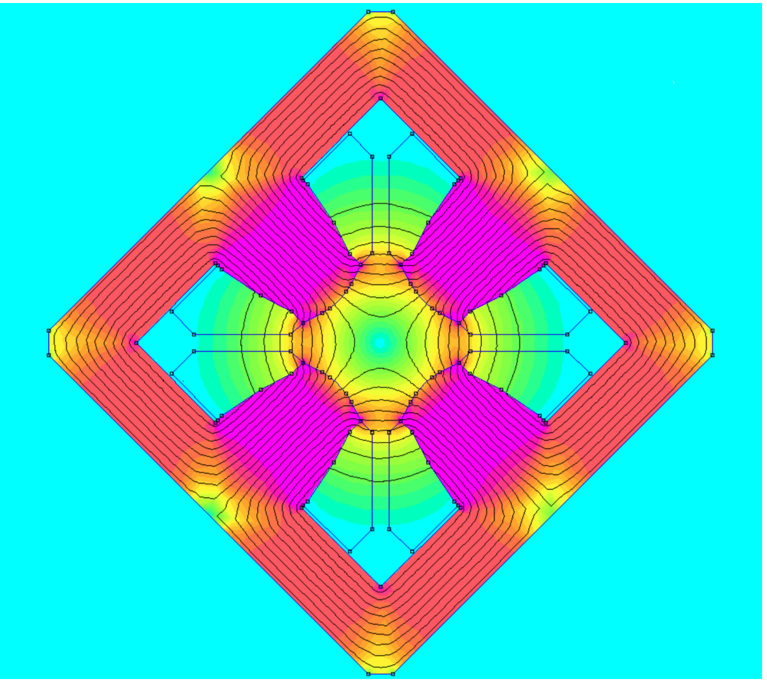


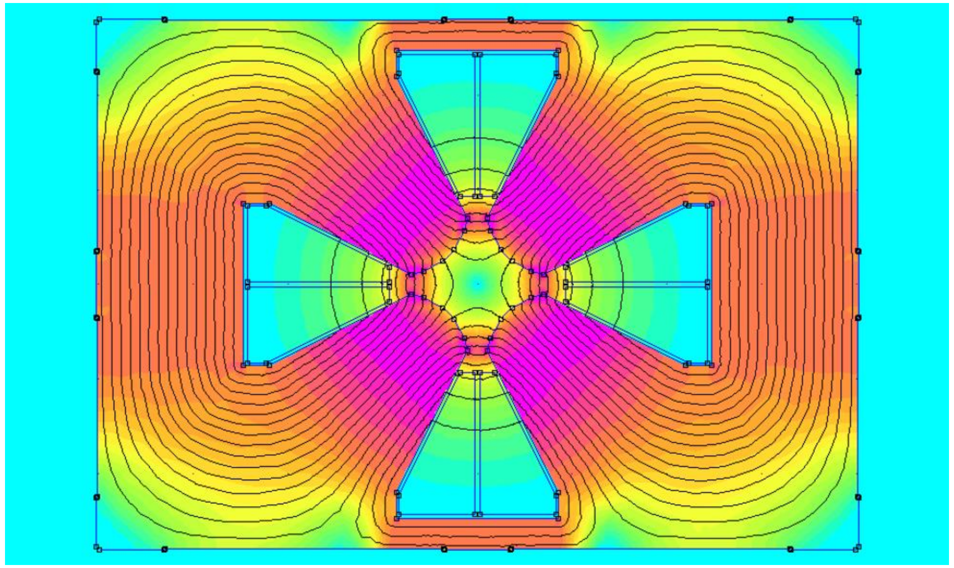
MCW Dipole



FEMM Models – Extraction

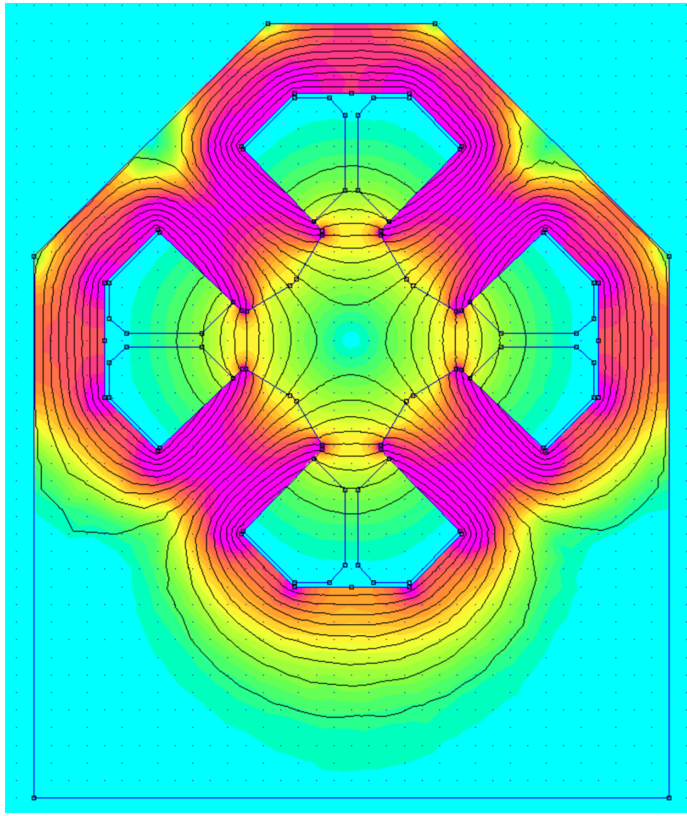
Q200 Quadrupole



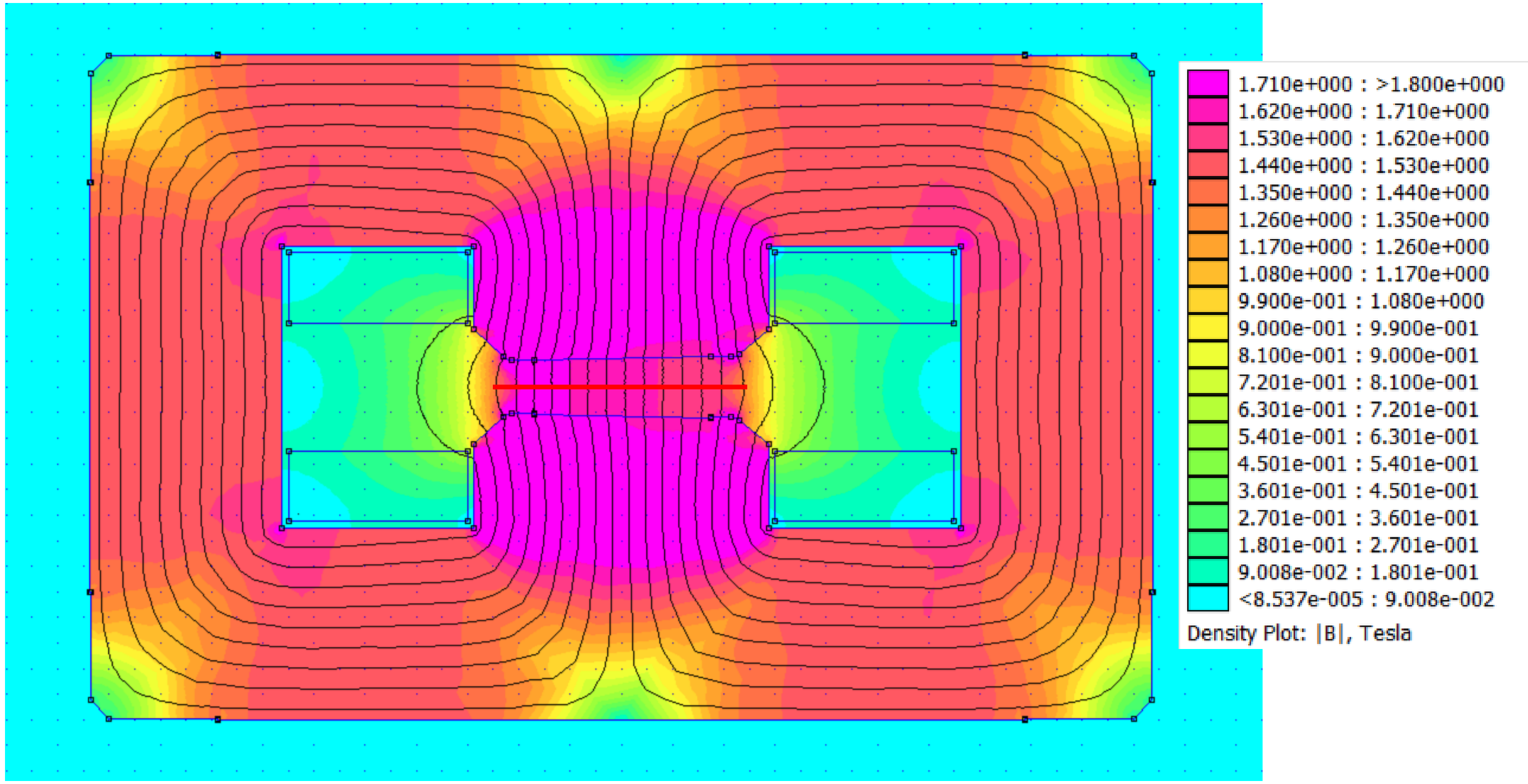


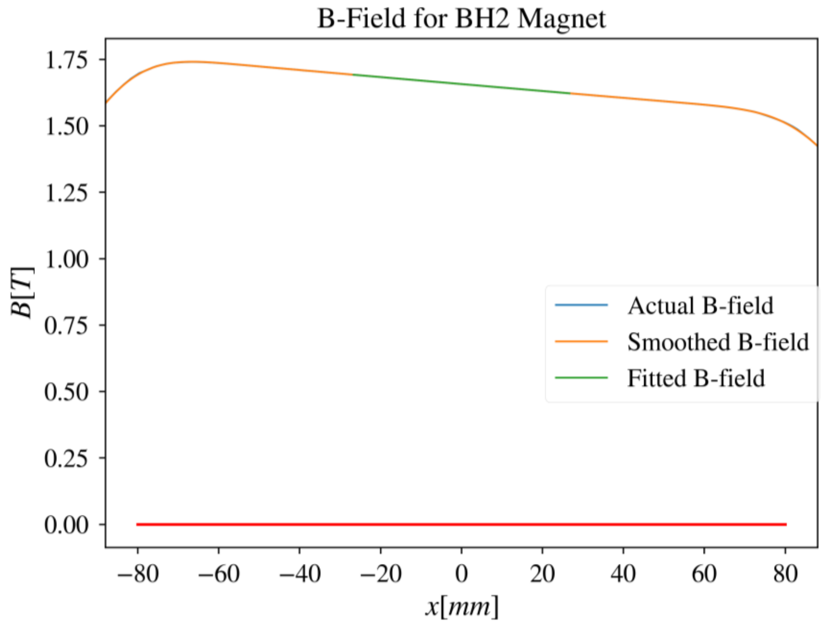
QTS Quadrupole

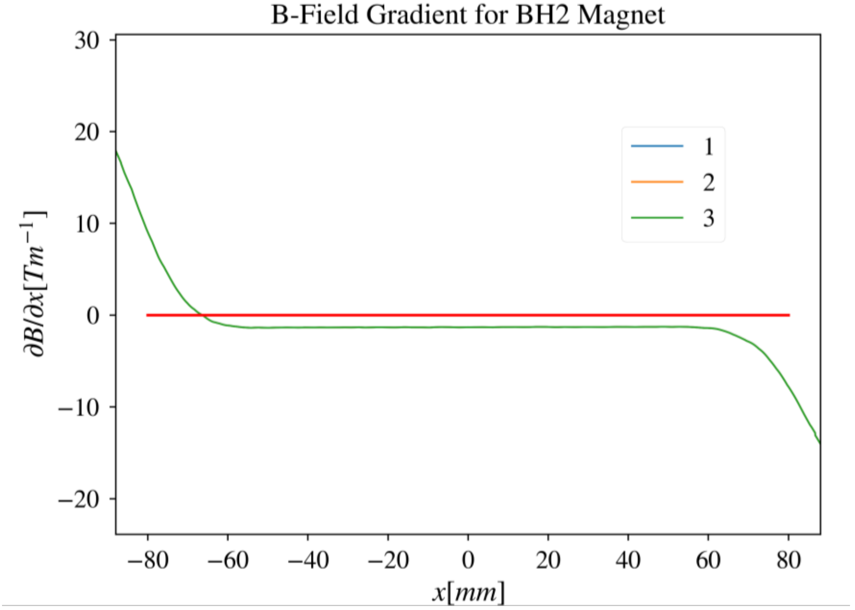
QTN Quadrupole



Field Analysis- BH2





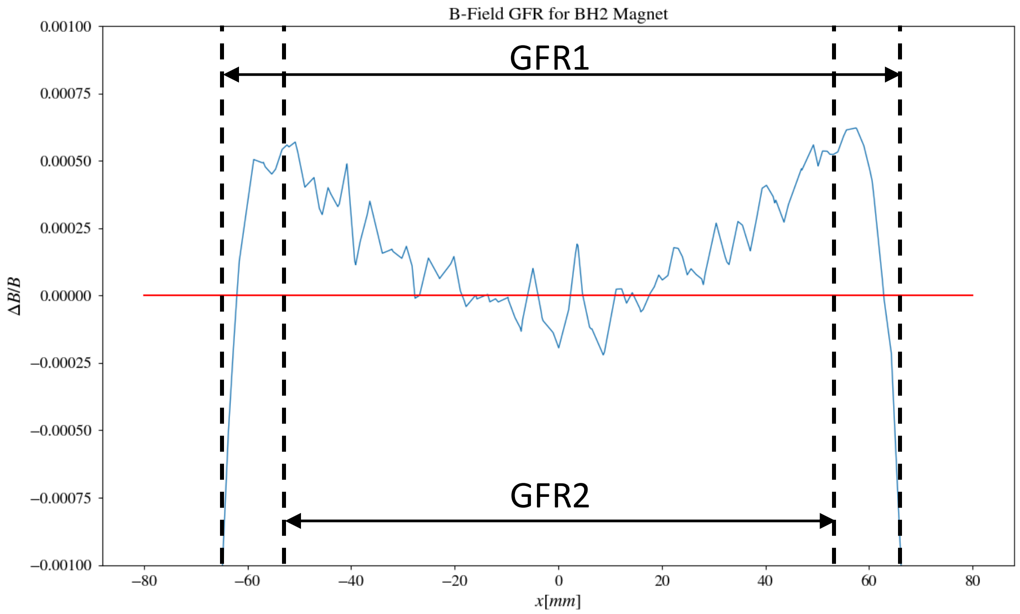


48 turns/pole, 650 A (peak)
Aperture width and height: 160 mm, 45 mm
Total width and height: 915 mm, 570 mm

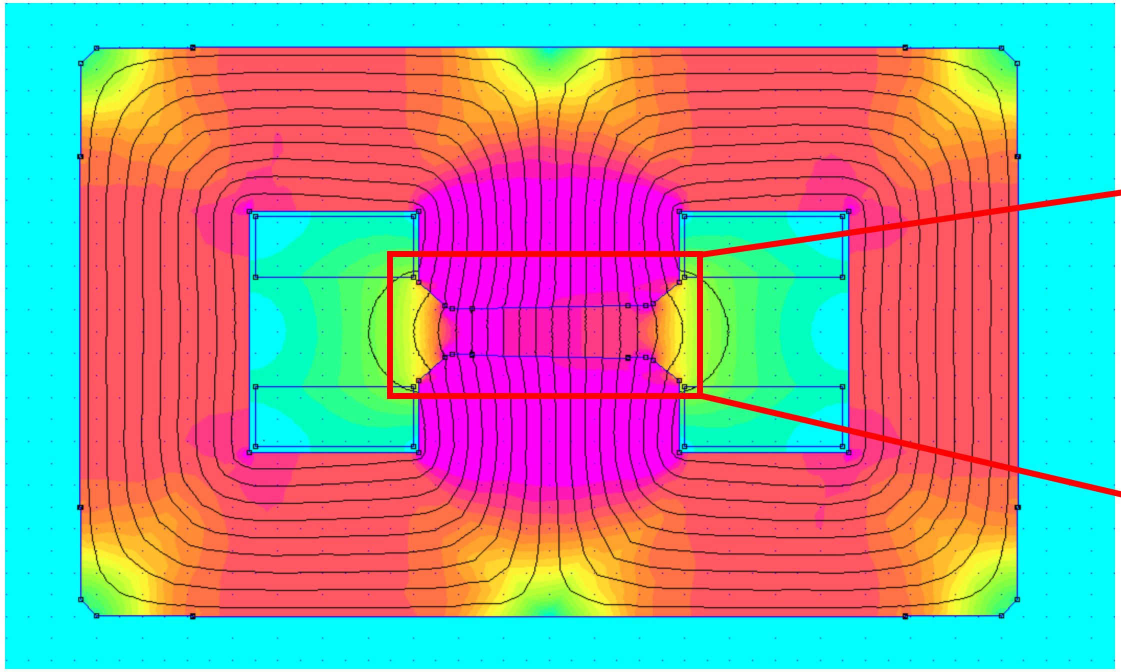
Max field strength:
1.5-1.75T
Field gradient = -1.3099 T/m

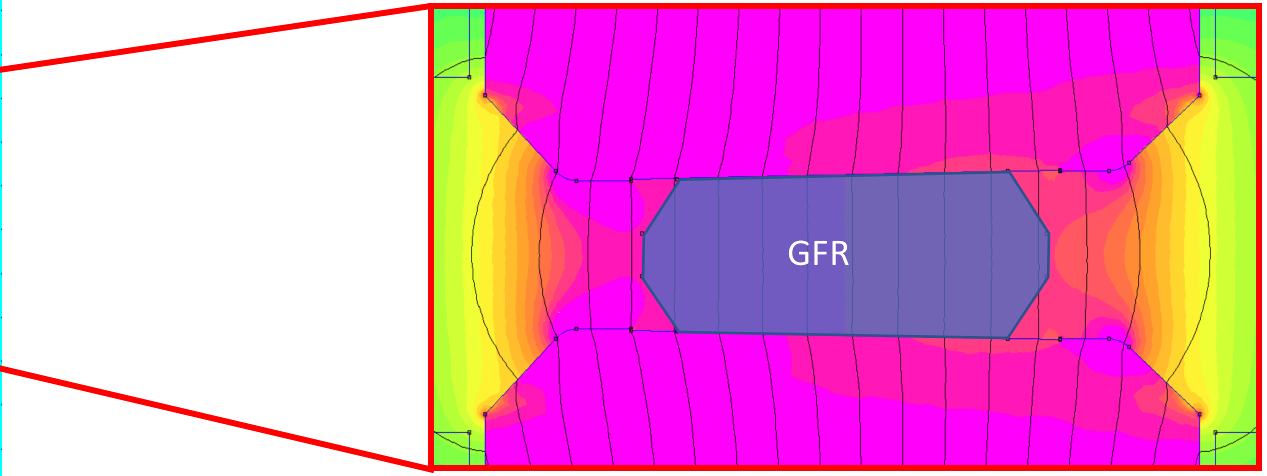
Good Field Region - BH2

$$\left(\frac{\Delta B}{B_{id}} < 1 \times 10^{-3}\right)$$

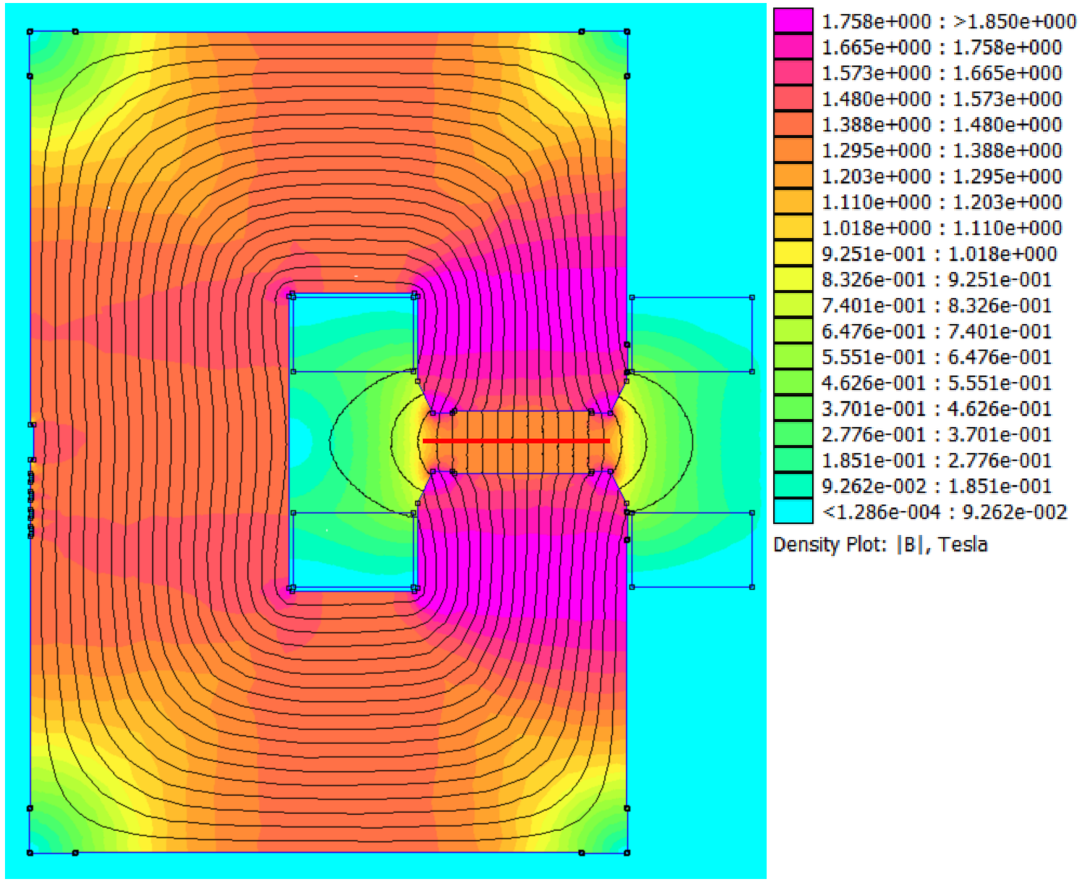


GFR1 = 130 mm x 12 mm
GFR2 = 106.6 mm x 45 mm



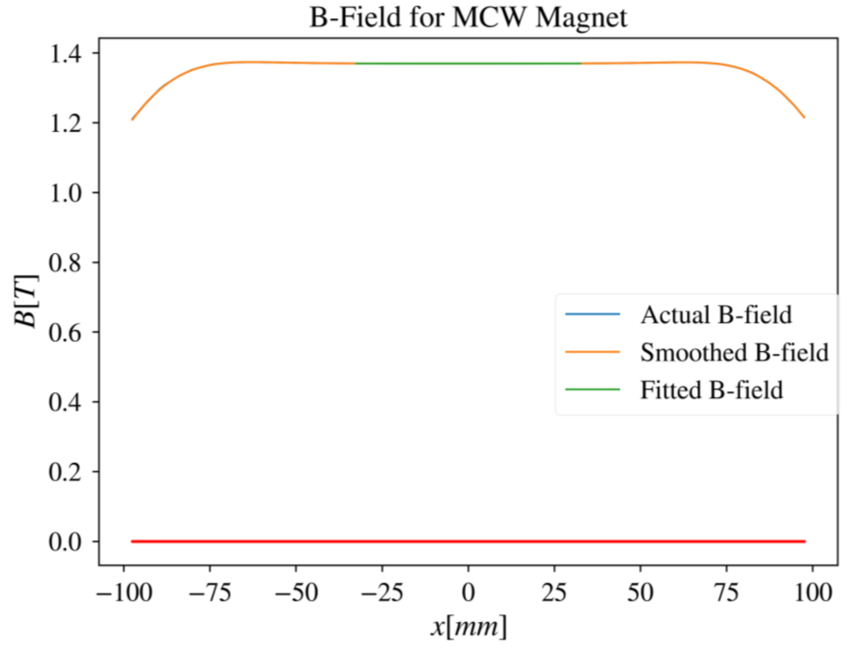


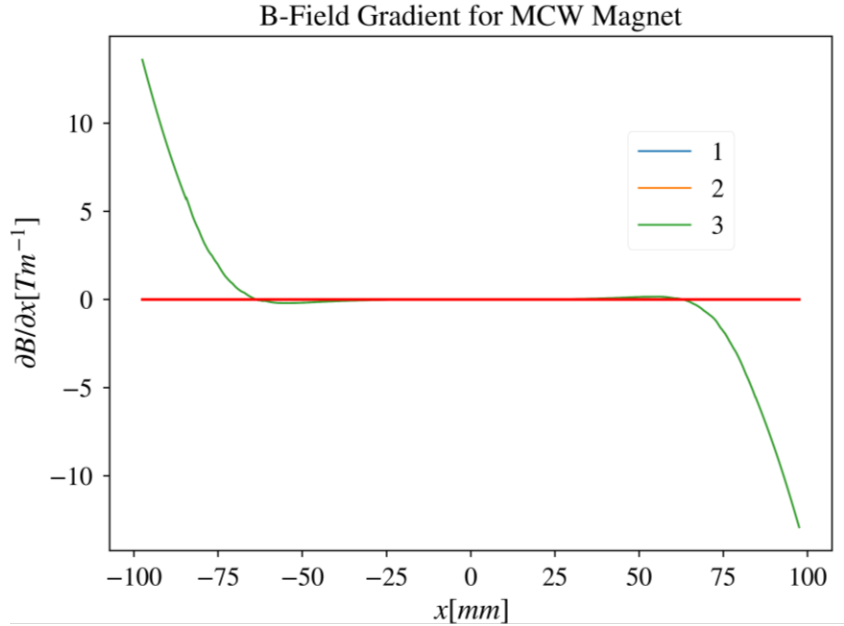
Field Analysis - MCW



96 turns, 1000 A (peak), 414.46 A
Aperture width and height: 195 mm, 70 mm
Total width and height: 850 mm, 1130 mm

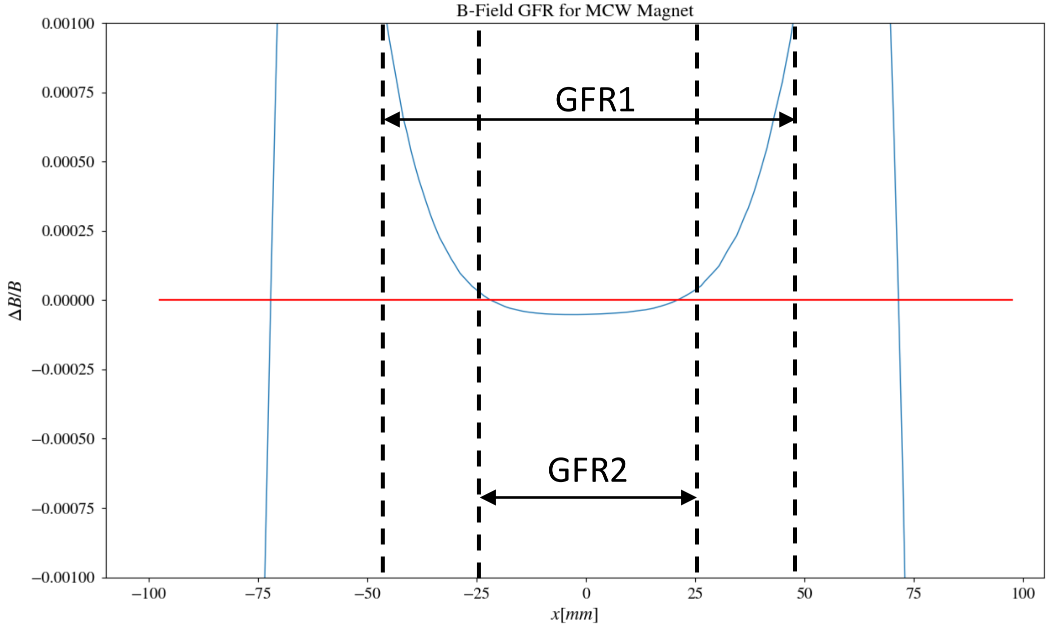
Max field strength: 1.37T (about 2T at peak current)



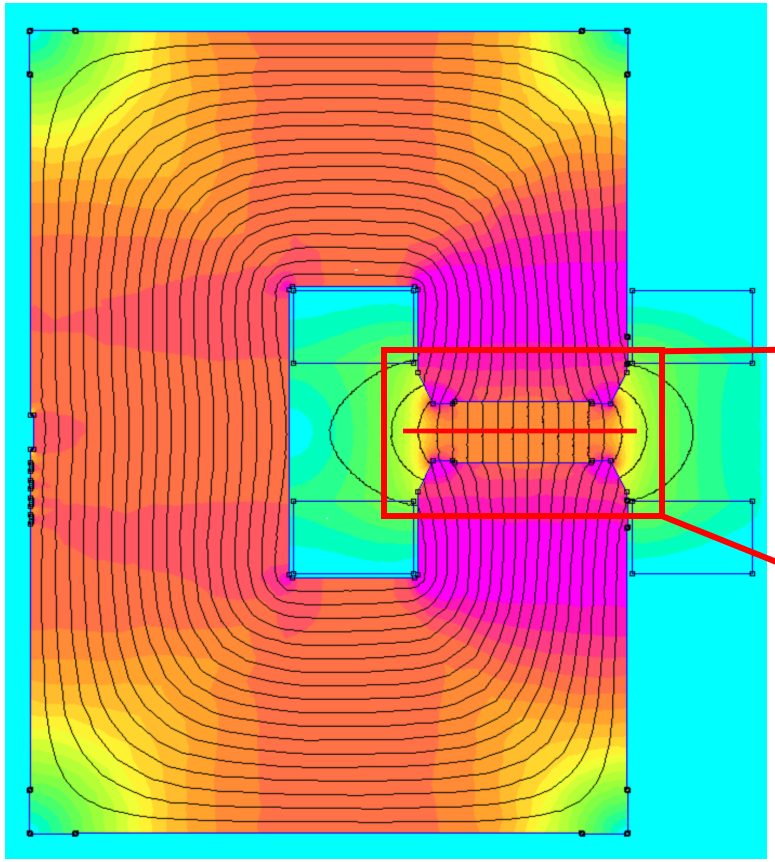


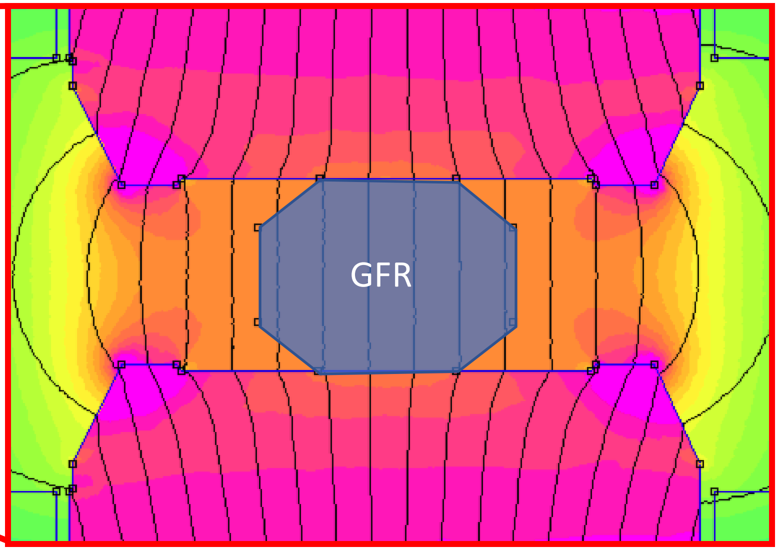
Good Field Region - MCW

$$\left(\frac{\Delta B}{B_{id}} < 1 \times 10^{-3}\right)$$



GFR1 = 93 mm x 34 mm
GFR2 = 50 mm x 70 mm

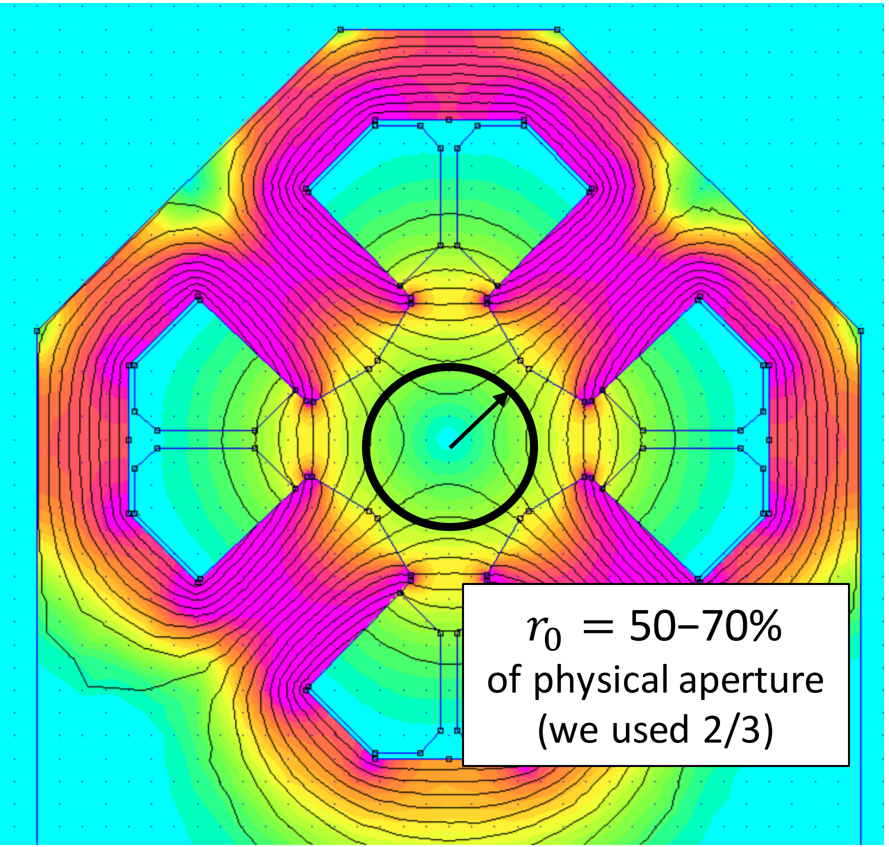




Multipole Contributions

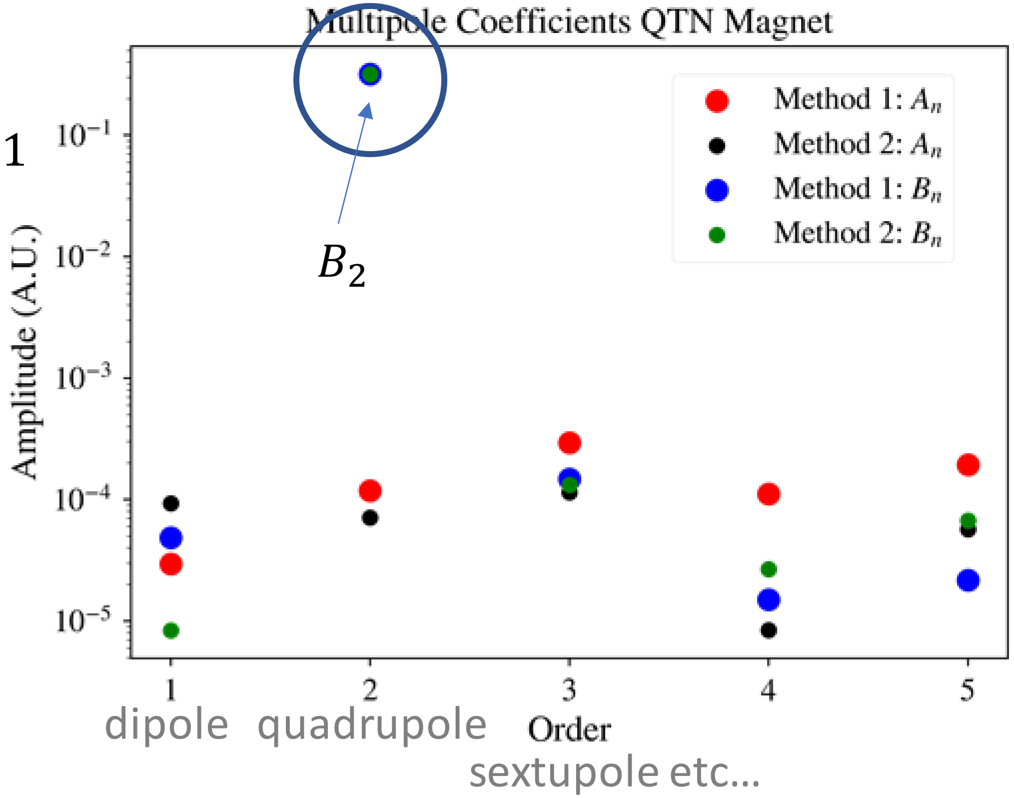
Allowed multipole contributions 'fit into' the symmetry of the device…

Sample at r_0 for $\theta_m = \frac{2\pi m}{M}, \quad m = 0,1,2, \ldots M-1$


r_0 = 50–70% of physical aperture (we used 2/3)

m: discrete angles 0,1,2…
n: multipole order 1,2,3…

Discrete Fourier transform



- ✓ Only B_2 **normal quadrupole** term contributes, as hoped
- ✓ Reasonable agreement using two slightly different methods as a sanity check

Future Magnet Studies

- Final Defocus Scheme
  - Experiment requirements for beam size
  - Determine whether existing or new quadrupole(s) required
- Benchmark FEMM
  - Compare FEMM models with equivalent OPERA-2D models
  - Model magnets in 3D and check effective lengths

RF Cavity Team

Majid Ali, Pablo Arrutia and Cameron Robertson

Infrastructure

Voltage Requirements

Cavity Design

Infrastructure

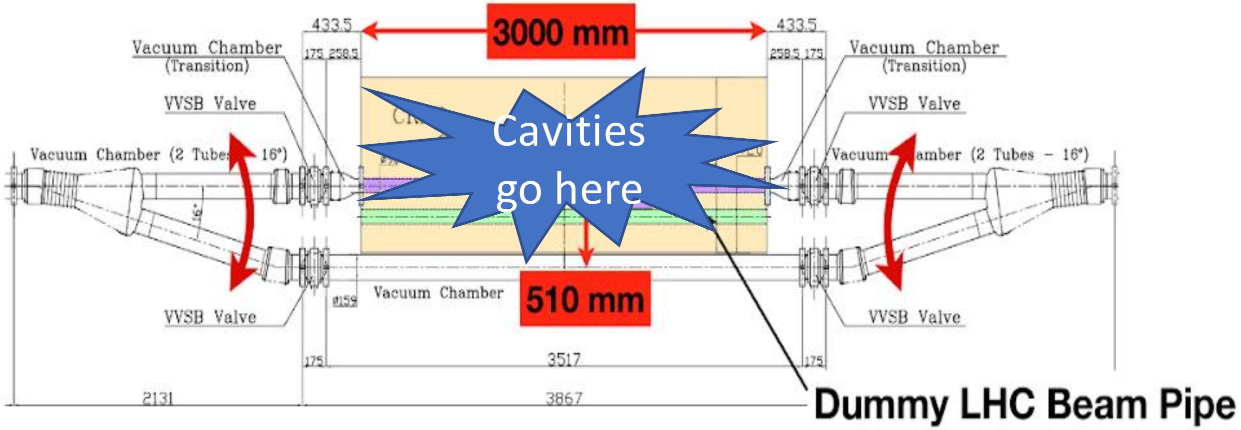
Cavity**: 800MHz 5 cell Superconducting Cavity**

- Multiple of 200MHz RF frequency -> 5 ns bunch spacing
- High acceleration gradient

Location: **LSS6 Crab Cavity Testing Zone**

- Minimise additional impedance; **HL-LHC**
- Allow rapid changeover between electron/proton modes (10 min)

802 MHz ERL Cavity Design and Development (2018)
http://cds.cern.ch/records/26538533/

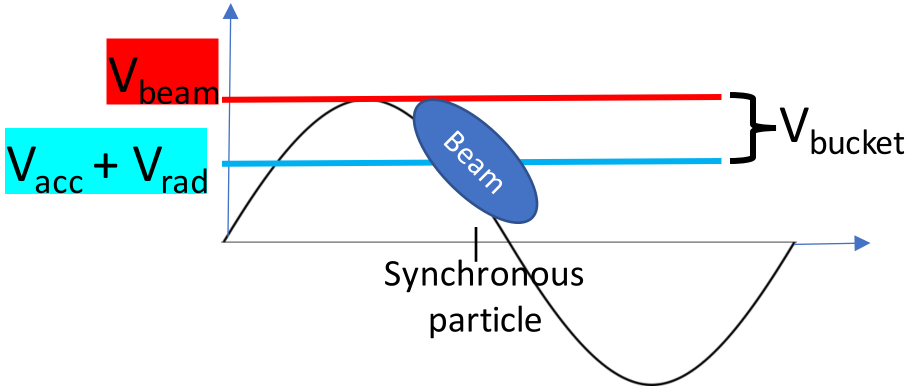


Crab Cavity Testing in the SPS (2013)
https://indico.cern.ch/event/257368/

Voltage Requirements

- Important to
  - Determine if voltage and fields achievable with the chosen technology
  - Specify the consequences of different voltage choices
- Two beam energies considered: 16 GeV and 18 GeV (for possible upgrade)

$$V_{beam} = V_{acc} + V_{rad} + V_{bucket}$$

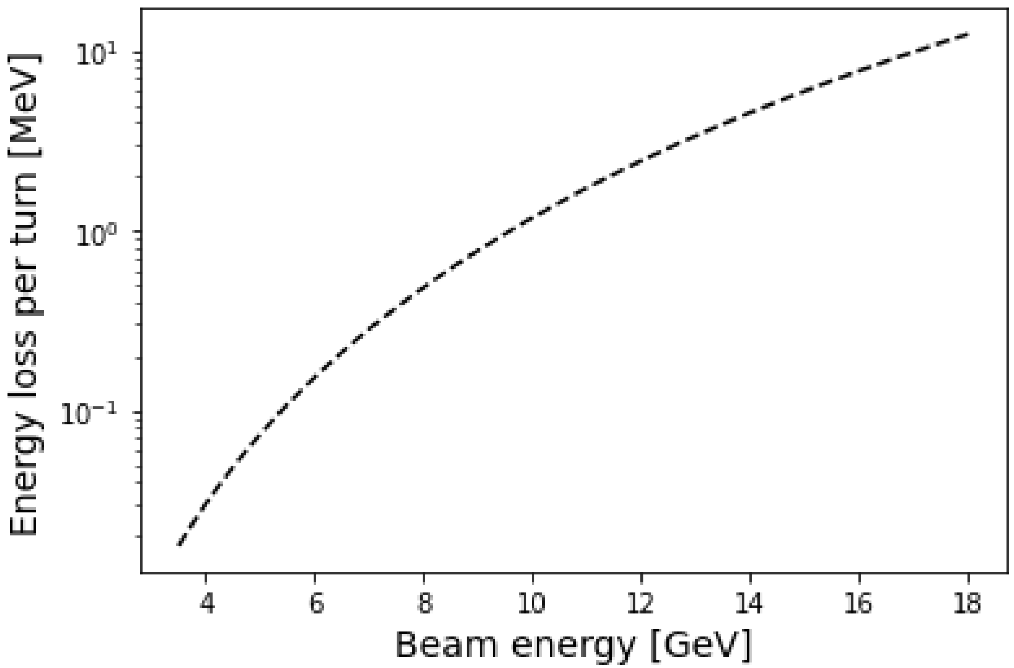


- V_{beam}: effective peak voltage visible by the beam
- V_{acc} : voltage for acceleration
- V_{rad}: voltage for synchrotron radiation
- V_{bucket}: voltage for bucket area

V_{acc} and V_{rad}

$$V_{acc} = (\underset{\substack{\downarrow \\ \text{16 or 18 GeV}}}{E_{extraction}} - \underset{\substack{\downarrow \\ \text{3.5 GeV}}}{E_{injection}}) \frac{one\ turn\ time \rightarrow \text{23 us}}{acceleration\ time \rightarrow \text{0.2 s}}$$

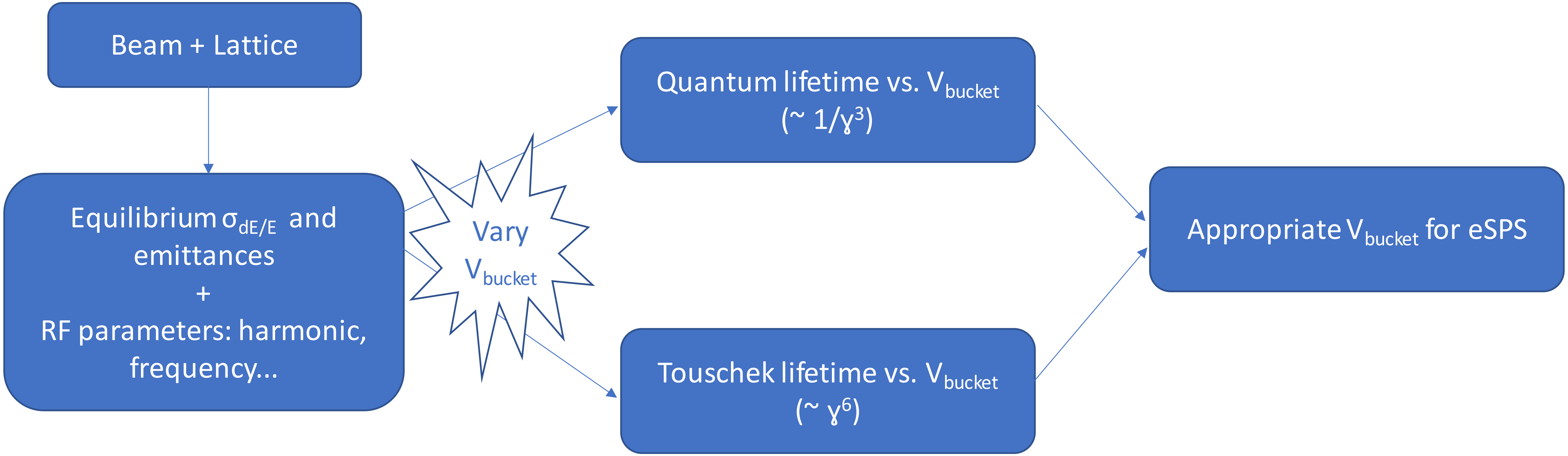
V_{rad} =



Beam Energy	**V_{acc} (~ ɣ)**	**V_{rad} (~ $ɣ^4$)**
16 GeV	1.4 MV	7.7 MV
18 GeV	1.7 MV	12.4 MV

V_{bucket}

- V_{bucket} chosen to ensure a long enough beam lifetime



Beam + Lattice

Equilibrium $\sigma_{dE/E}$ and emittances + RF parameters: harmonic, frequency…

Vary V_{bucket}

Quantum lifetime vs. V_{bucket} ($\sim 1/\gamma^3$)

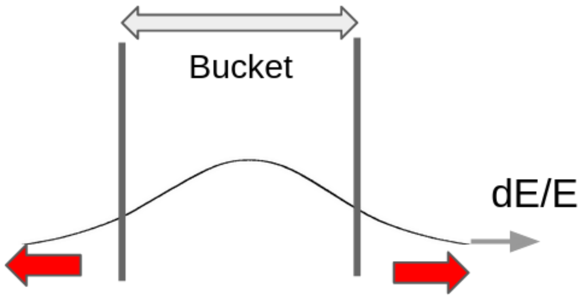
Touschek lifetime vs. V_{bucket} ($\sim \gamma^6$)

Appropriate V_{bucket} for eSPS

V_{bucket}

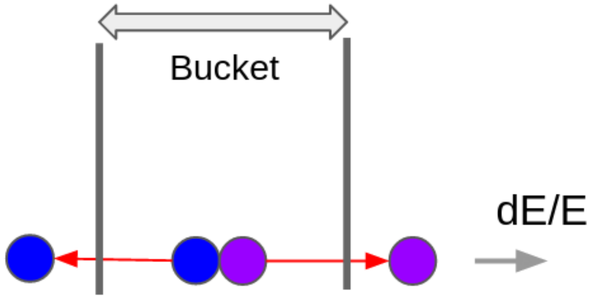
Quantum lifetime

Beam diffuses from quantum excitation



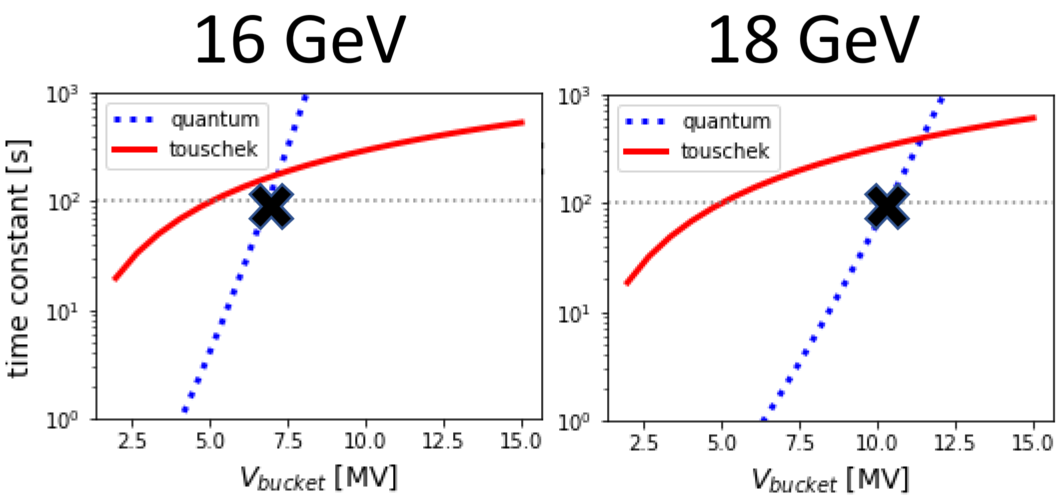
Touschek lifetime

Beam scatters from e-e- scattering



- Lifetimes characterised by their time constants

-We aim for time constants >100 s (~10x cycle)



Need V > 7 MV

Need V > 10 MV

Quantum dominates, but Touschek also relevant!

V_{beam} and E_0

The on-axis accelerating electric field E_0 is important for R&D considerations:

$$E_0 = \frac{V_{beam}}{\underset{\underset{2}{\downarrow}}{(\# \ of \ cavities)}\underset{\underset{0.7}{\downarrow}}{(transit \ time \ factor)}\underset{\underset{94\text{ cm}}{\downarrow}}{(cavity \ length)}}$$

Beam Energy	V_{acc}	V_{rad}	V_{bucket}	V_{beam}	E_0
16 Gev	1.4 MV	7.7 MV	7.0 MV	16.1 MV	**12.2 MV/m**
18 Gev	1.7 MV	12.4 MV	10.0 MV	24.1 MV	**18.3 MV/m**

Achievable

(will show comparison to other projects in upcoming slides)

Cavity Design

- Minimize the peak surface electric field (E_p/E_0)

  Field emission limit (E_0 limit)

- Ratio of the magnetic peak with respect to the accelerating gradient (H_p/E_o) . Quench limit (SC thermal breakdown)

- (Large geometrical factor (G) and R/Q, Lower power dissipation)

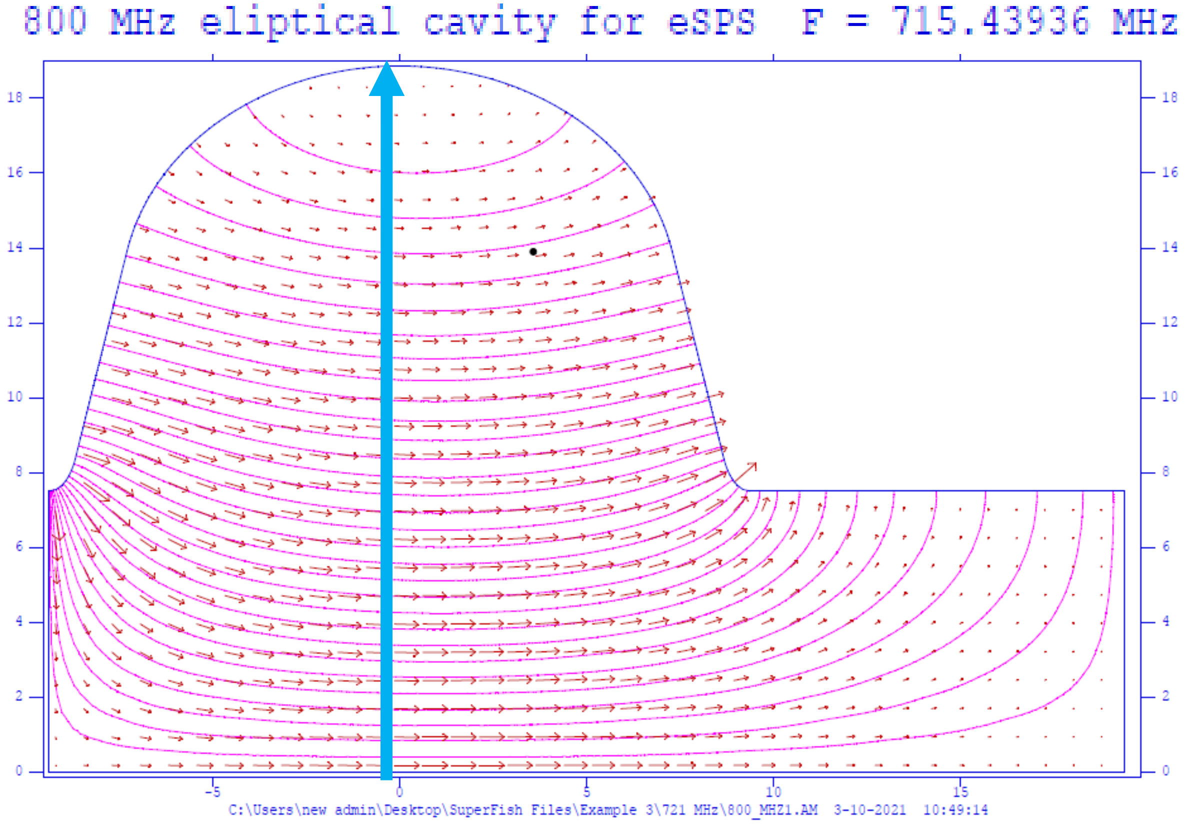
- Efficient use of RF energy (end-cell design)

  Have good field flatness

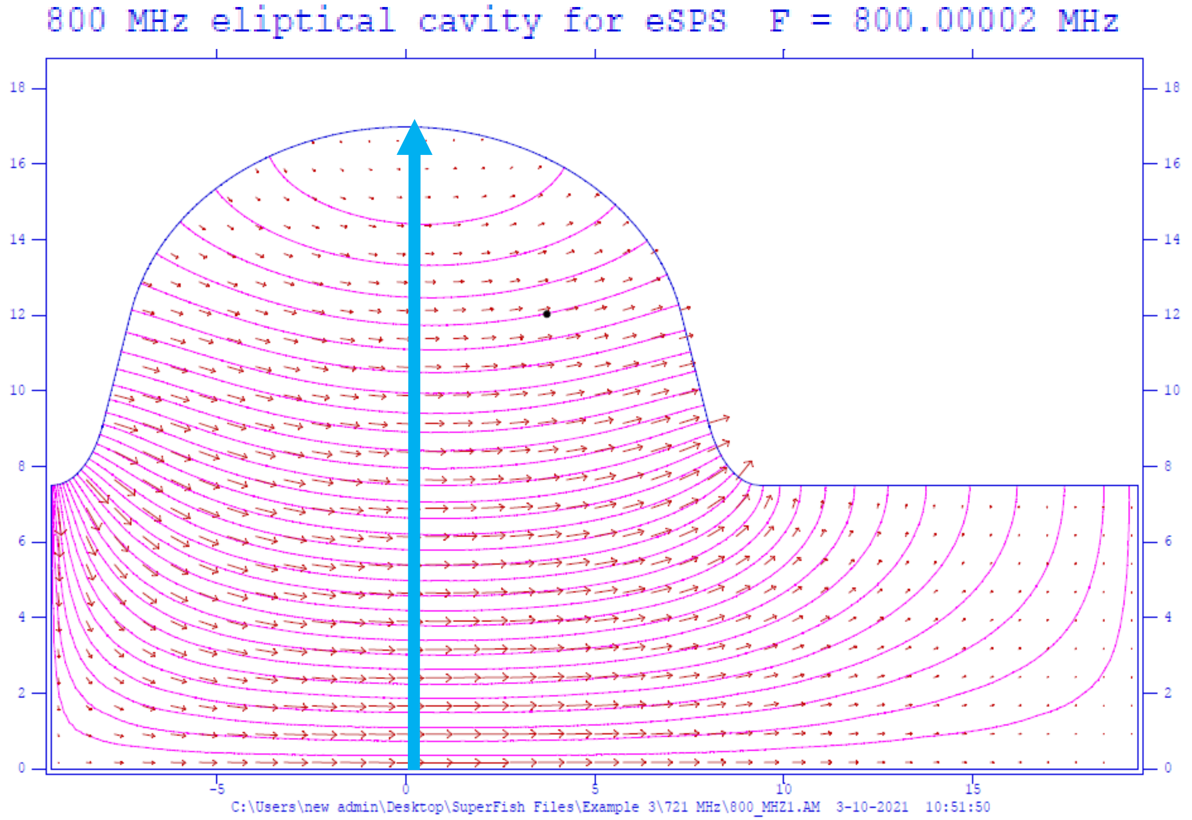
2D Model in Superfish

Equator radius used to tune cavity frequency

Before



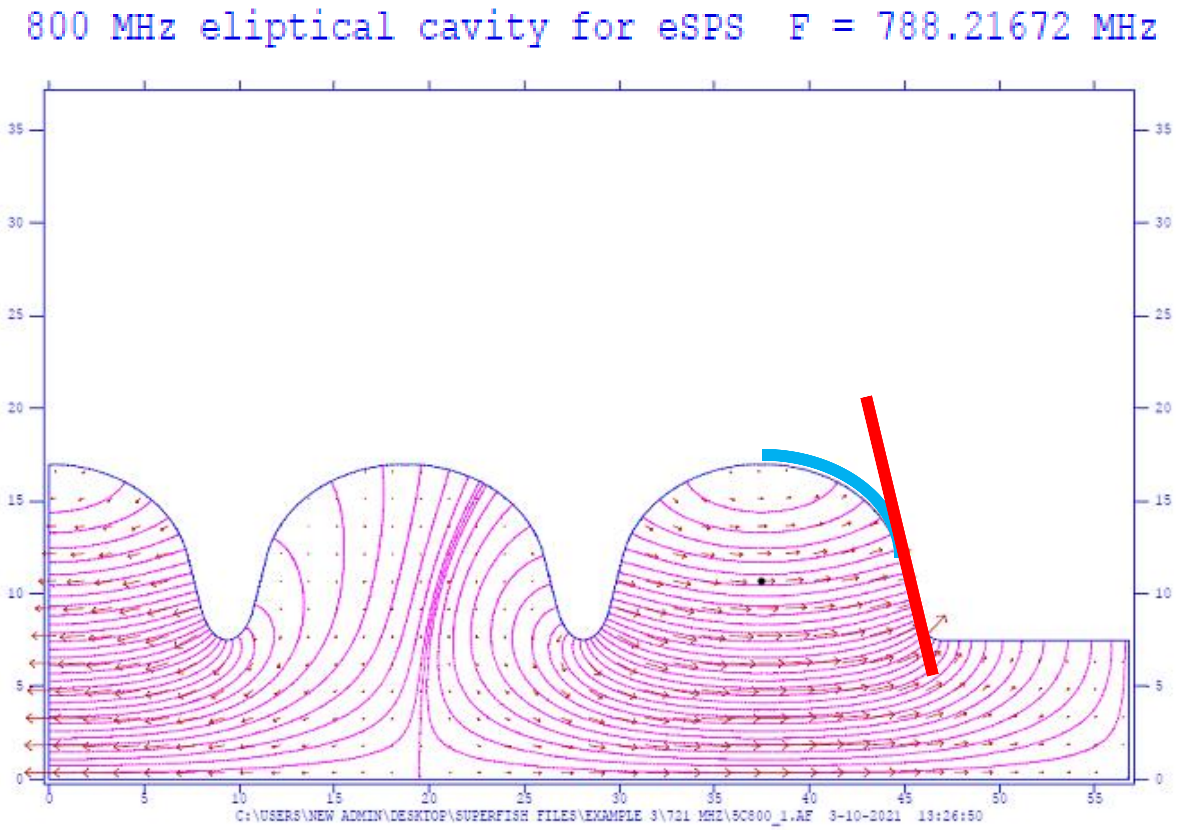
After



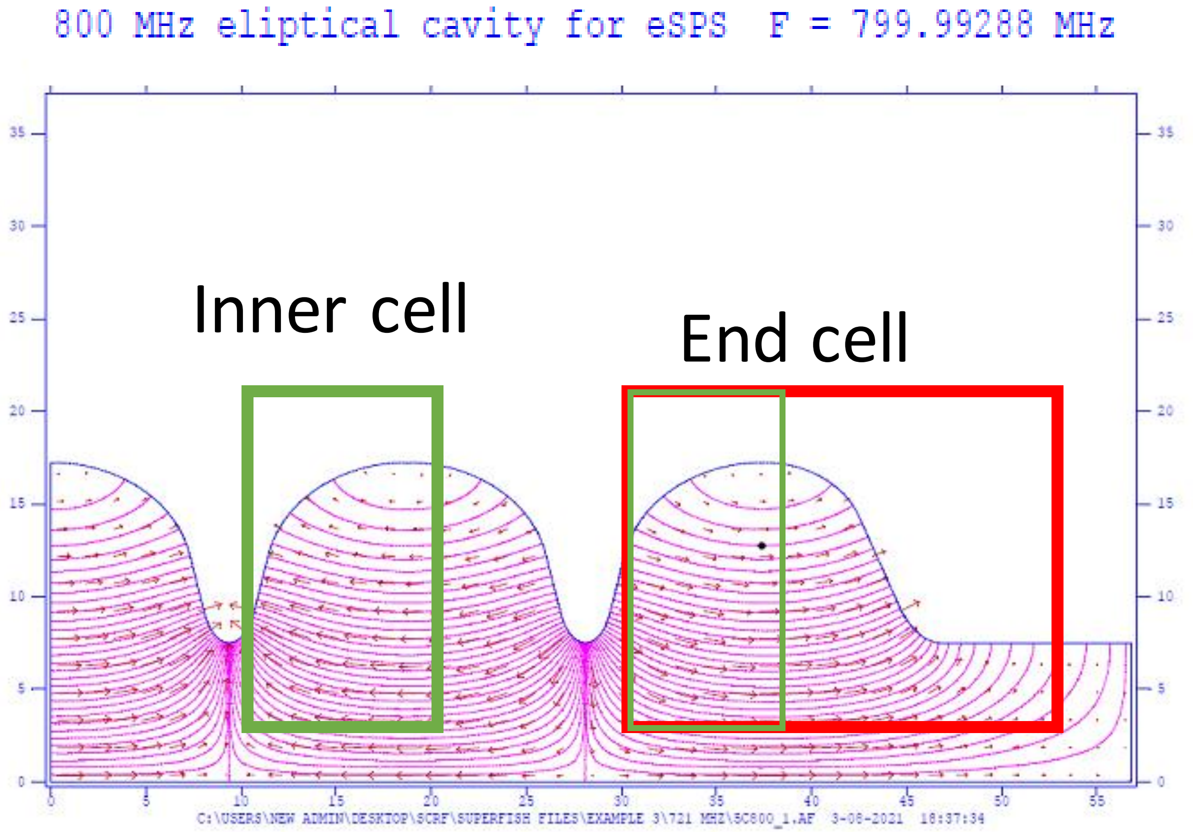
2D Model

Varied dome ellipse + wall slope to optimize end-cell

Before Tuning



After Tuning

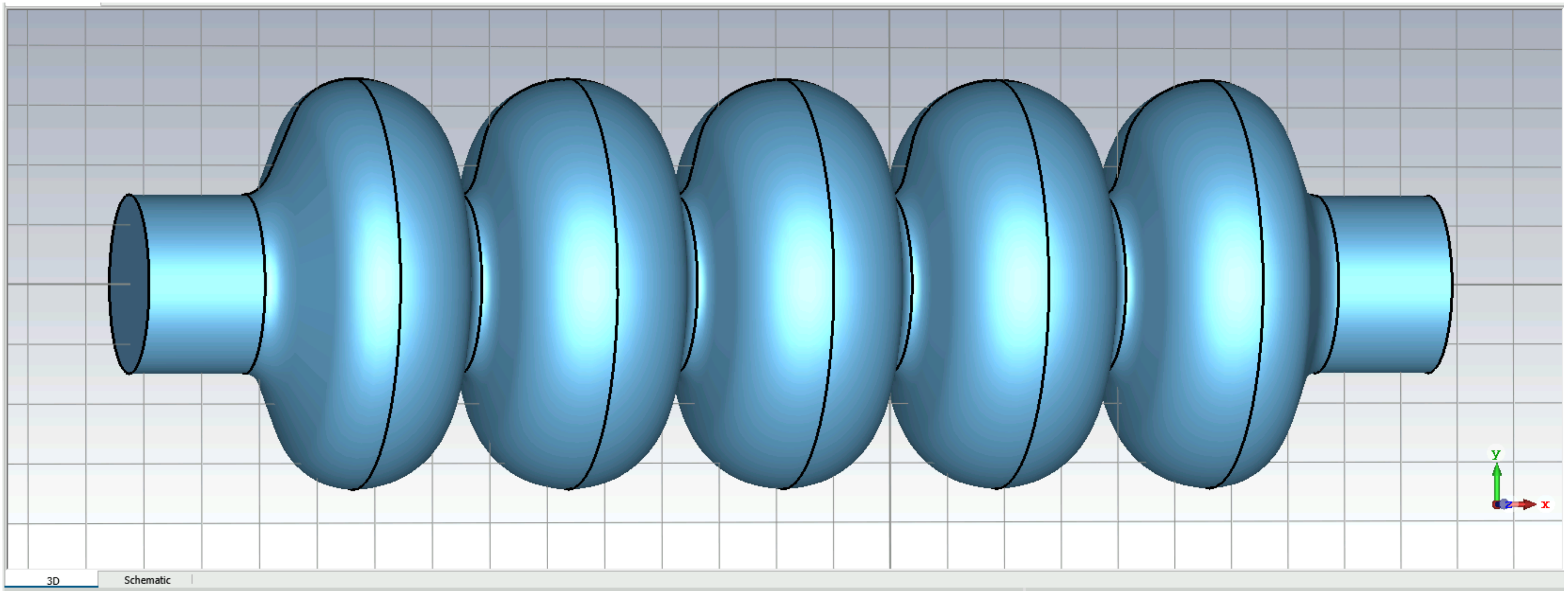


A five-cell 800 MHz cavity parameters are listed for comparison

	JLab	**ESS**	**OUR DESIGN 16 GeV (18 GeV)**
Number of cells	5	5	5
Freq (MHz)	800	704.42	800
L_{act} Length (cm)	93.5	85.5	93.68
E_o (MV/m)	11.8	19.9	12.2 (18.3)
E_p (MV/m)	30.68	43.75	29.38 (44.07)
B_p (mT)	57.82	85.57	43.63 (65.45)
R/Q (ohm)	523.9	518	427.58

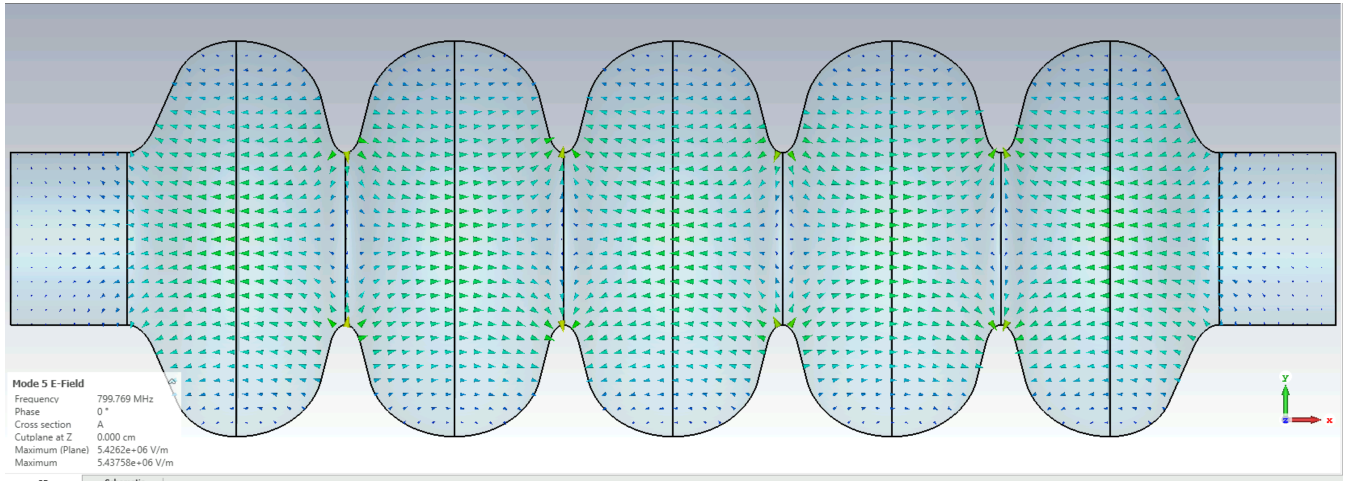
3D model

- CST Studio Suite – Electromagnetic field simulation software
- Geometry imported from Superfish input files
- Complete 3D model, eigenmode solver, mode analysis, EM visualisation

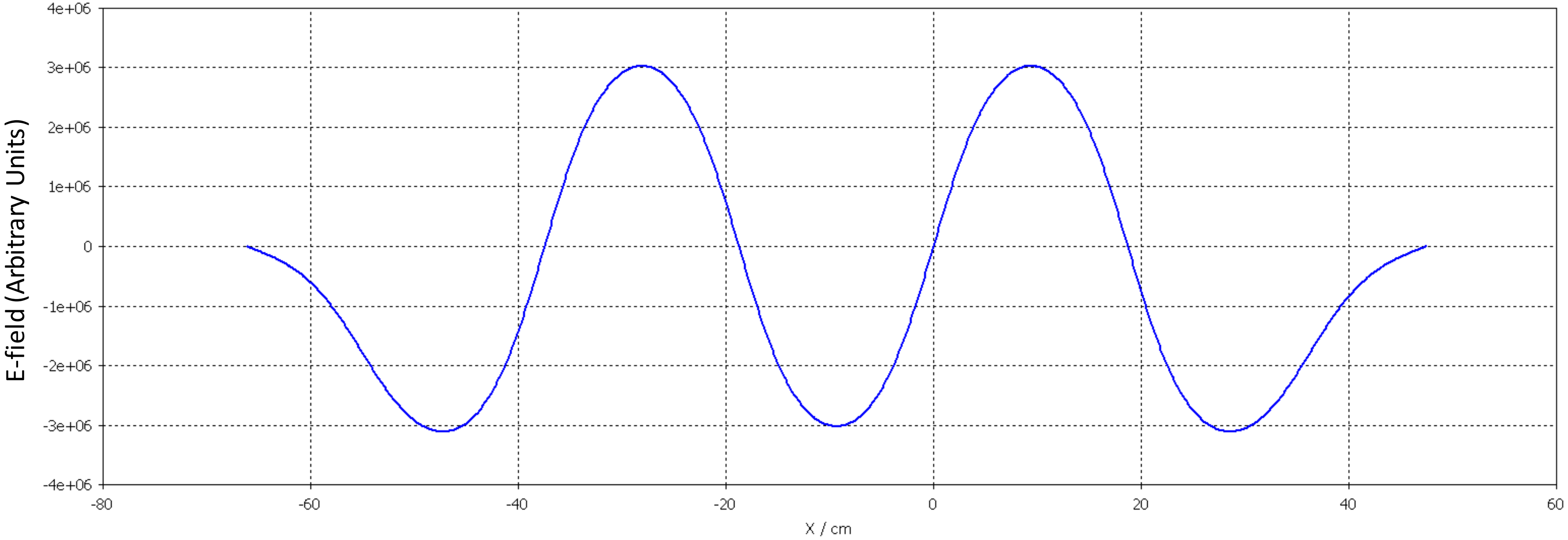


3D model

- Multiple modes
  - Mode 1 – 0 mode, 757.6815MHz
  - Mode 5 - π mode, 799.769MHz
- Asymmetric effects
  - Good field flatness
- 'Hot spots'

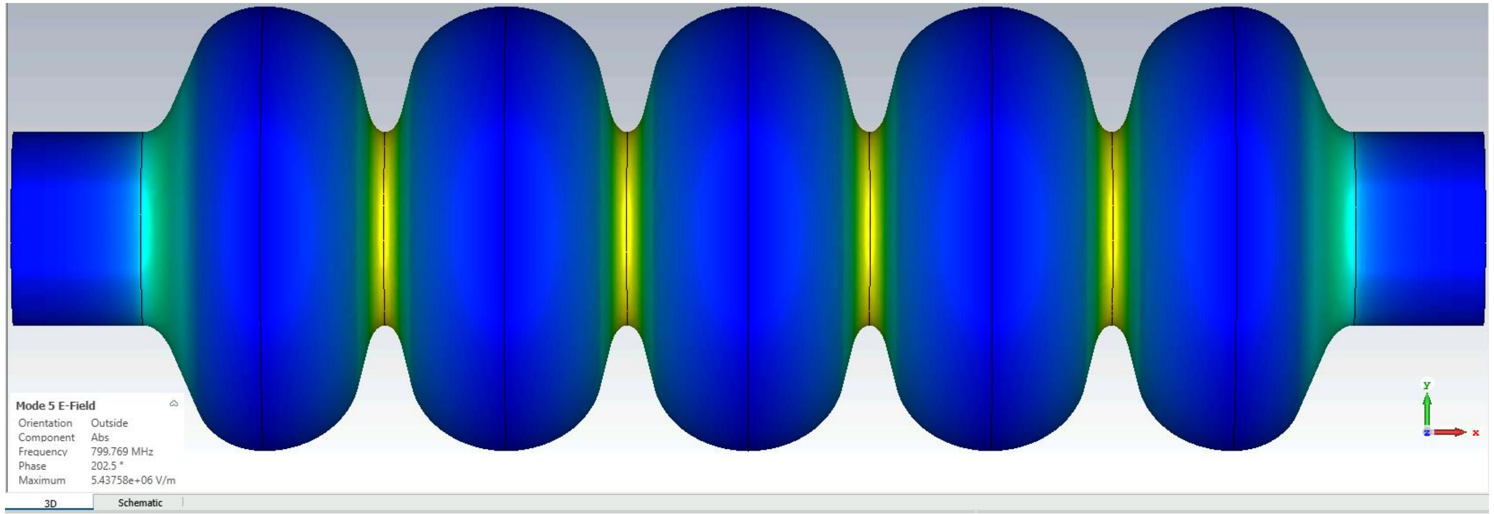


Mode 5 E-Field
Frequency 799.769 MHz
Phase 0 °
Cross section A
Cutplane at Z 0.000 cm
Maximum (Plane) 5.4262e+06 V/m
Maximum 5.43758e+06 V/m



3D model

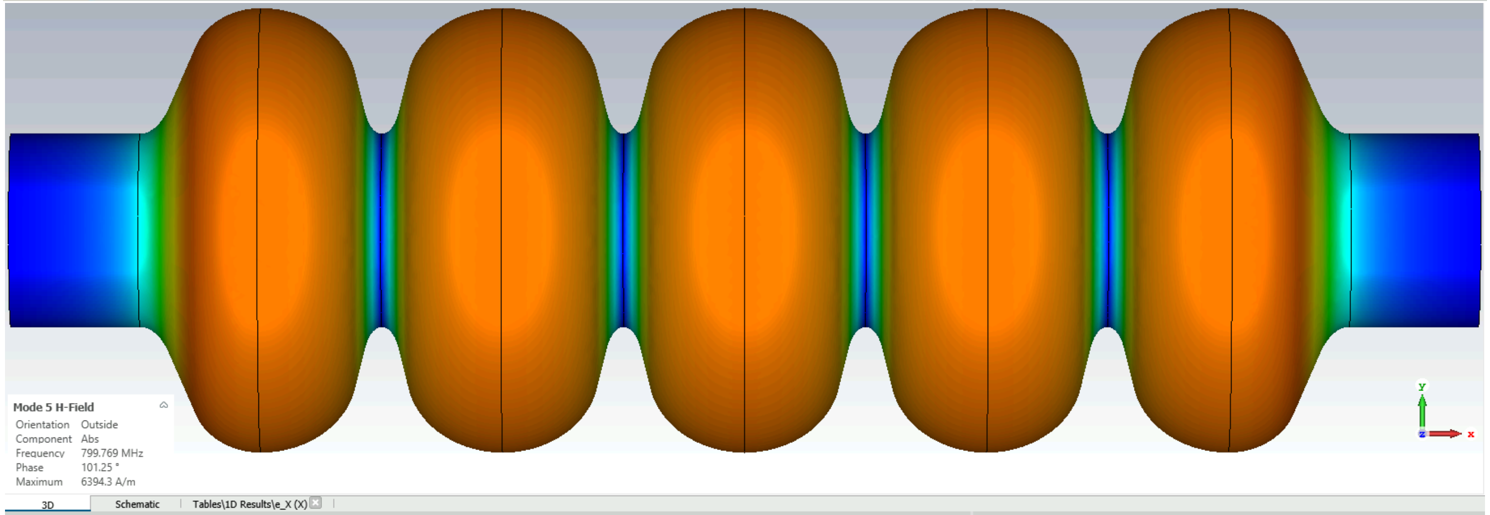
E-Field



Mode 5 E-Field

Orientation	Outside
Component	Abs
Frequency	799.769 MHz
Phase	202.5 °
Maximum	5.43758e+06 V/m

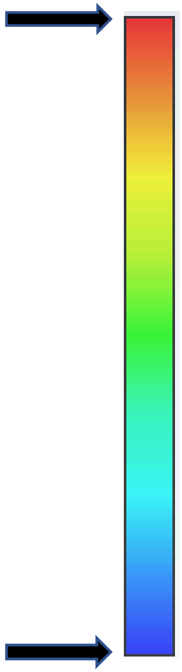
H-Field



Mode 5 H-Field

Orientation	Outside
Component	Abs
Frequency	799.769 MHz
Phase	101.25 °
Maximum	6394.3 A/m

Arbitrary field strength units



3D model

Parameter	Superfish Design	CST Design	Difference
U at E_0= 10MV/m (J)	19.90	19.86	<1%
E_{max}/E_0	2.4080	2.5419	5%
B_{max}/E_0(mT/MV)	3.796	3.755	5%
r/Q(Ω)	427.58	428.37	<1%

- Geometrical properties near-identical; necessary quality check
  - Imported directly from Superfish
- Peak field strength discrepancies
  - Limitations from mesh size
  - CST optimisation required

Future RF Studies

- Study Beam Loading
  - Wakefields
  - Power Requirements

- Improve Model
  - Fundamental Coupler
  - Higher Order Mode Couplers

Conclusions

eSPS can produce a **unique Light Dark Matter physics programme** with relatively small costs and time-scales.

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2 SuperConducting 800MHz RF cavities in LSS6 bypass **fulfil requirements** for 16 and 18 GeV operation.

Extra slides

https://www.femm.info/wiki/HomePage

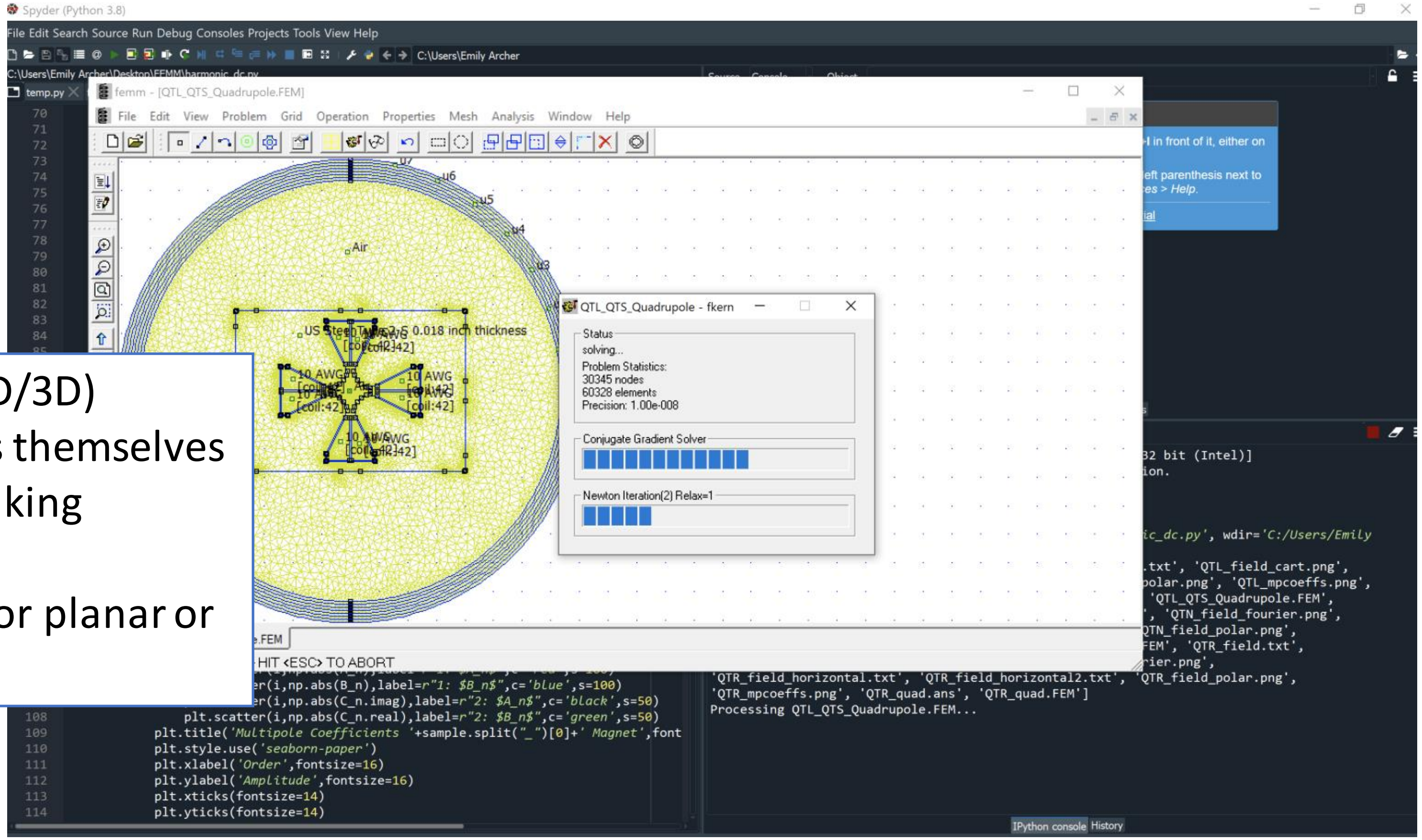
FEMM + pyFEMM

(Finite Element Method Magnetics + Python wrapper library)

- Finite element method used to solve
  - magnetostatic
  - time harmonic magnetic
  - electrostatic and
  - steady-state heat flow problems

\+ Free open-source software (unlike Opera-2D/3D)
\+ User-friendly GUI for designing the magnets themselves
\+ Controllable via pyFEMM Python library, making integrated analysis possible
\- Only for 2D problems, but with the option for planar or axisymmetric domains

Using CERN technical drawings, we modelled existing CERN magnets in FEMM



QTL_QTS_Quadrupole - fkern

Status
solving...
Problem Statistics:
30345 nodes
60328 elements
Precision: 1.00e-008

Conjugate Gradient Solver

Newton Iteration(2) Relax=1

```
er(i,np.abs(B_n),label=r"1: $B_n$",c='blue',s=100)
er(i,np.abs(C_n.imag),label=r"2: $A_n$",c='black',s=50)
    plt.scatter(i,np.abs(C_n.real),label=r"2: $B_n$",c='green',s=50)
plt.title('Multipole Coefficients '+sample.split("_")[0]+' Magnet',font
plt.style.use('seaborn-paper')
plt.xlabel('Order',fontsize=16)
plt.ylabel('Amplitude',fontsize=16)
plt.xticks(fontsize=14)
plt.yticks(fontsize=14)
```

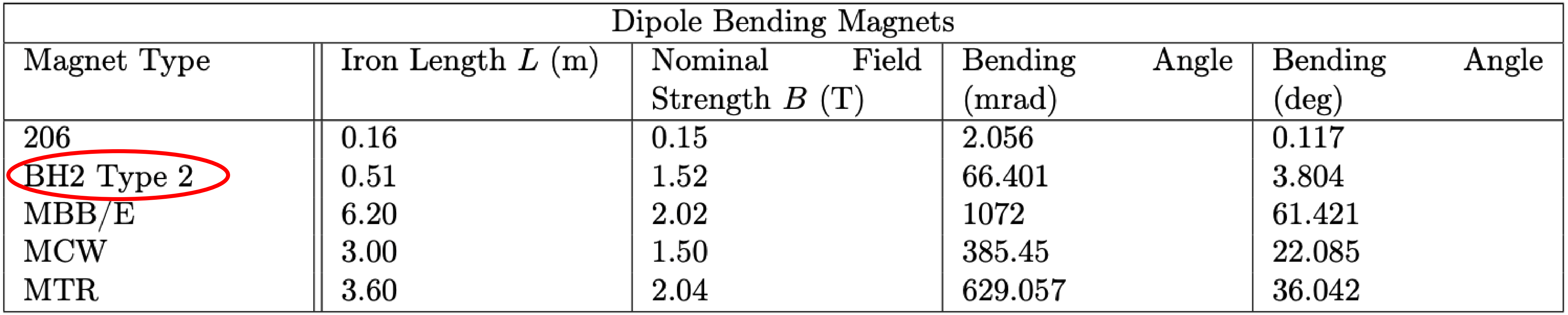
```
32 bit (Intel)]
ion.

ic_dc.py', wdir='C:/Users/Emily

.txt', 'QTL_field_cart.png',
polar.png', 'QTL_mpcoeffs.png',
 'QTL_QTS_Quadrupole.FEM',
', 'QTN_field_fourier.png',
QTN_field_polar.png',
FEM', 'QTR_field.txt',
rier.png',
'QTR_field_horizontal.txt', 'QTR_field_horizontal2.txt', 'QTR_field_polar.png',
'QTR_mpcoeffs.png', 'QTR_quad.ans', 'QTR_quad.FEM']
Processing QTL_QTS_Quadrupole.FEM...
```

Field Analysis

- Linear transect of the central field plotted
- Savinsky-Golay filter
- Numerical gradient calculated (three different methods)
- Linear fitting to determine ‘ideal field’
- **Good field region determined:**

Good Field Region → $\frac{\Delta B}{B_{id}} = \frac{B(x,y) - B_{id}(x,y)}{B_{id}(x,y)} < 1 \times 10^{-3}$

Dipole Bending Angles: Injection

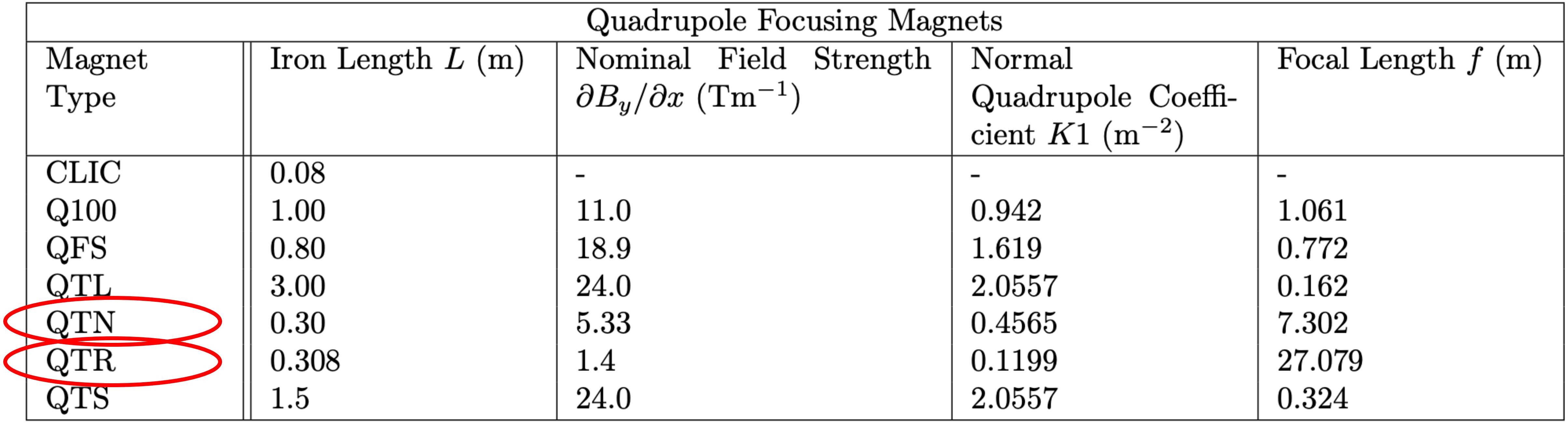


Dipole Bending Magnets

Magnet Type	Iron Length L (m)	Nominal Field Strength B (T)	Bending Angle (mrad)	Bending Angle (deg)
206	0.16	0.15	2.056	0.117
BH2 Type 2	0.51	1.52	66.401	3.804
MBB/E	6.20	2.02	1072	61.421
MCW	3.00	1.50	385.45	22.085
MTR	3.60	2.04	629.057	36.042

Note: all values assume max. operating current

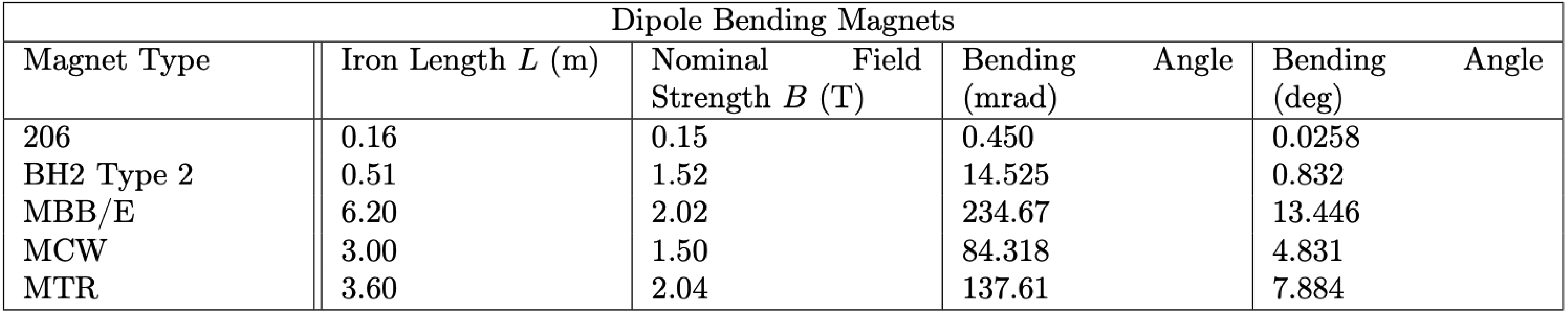
Quadrupole Focusing Strength: Injection



Quadrupole Focusing Magnets

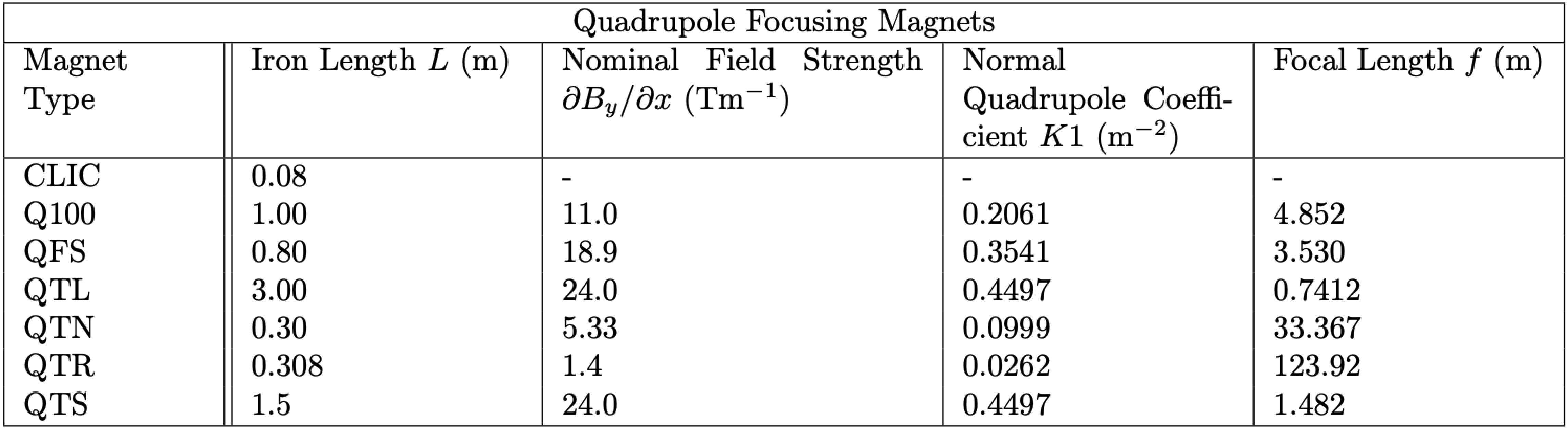
Magnet Type	Iron Length L (m)	Nominal Field Strength $\partial B_y/\partial x$ (Tm^{-1})	Normal Quadrupole Coefficient $K1$ (m^{-2})	Focal Length f (m)
CLIC	0.08	-	-	-
Q100	1.00	11.0	0.942	1.061
QFS	0.80	18.9	1.619	0.772
QTL	3.00	24.0	2.0557	0.162
QTN	0.30	5.33	0.4565	7.302
QTR	0.308	1.4	0.1199	27.079
QTS	1.5	24.0	2.0557	0.324

Note: all values assume max. operating current



Dipole Bending Magnets

Magnet Type	Iron Length L (m)	Nominal Field Strength B (T)	Bending Angle (mrad)	Bending Angle (deg)
206	0.16	0.15	0.450	0.0258
BH2 Type 2	0.51	1.52	14.525	0.832
MBB/E	6.20	2.02	234.67	13.446
MCW	3.00	1.50	84.318	4.831
MTR	3.60	2.04	137.61	7.884



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Magnet Type	Iron Length L (m)	Nominal Field Strength $\partial B_y/\partial x$ (Tm^{-1})	Normal Quadrupole Coefficient $K1$ (m^{-2})	Focal Length f (m)
CLIC	0.08	-	-	-
Q100	1.00	11.0	0.2061	4.852
QFS	0.80	18.9	0.3541	3.530
QTL	3.00	24.0	0.4497	0.7412
QTN	0.30	5.33	0.0999	33.367
QTR	0.308	1.4	0.0262	123.92
QTS	1.5	24.0	0.4497	1.482

Note: all values assume max. operating current

Multipole Decomposition

- Generally, the fields in accelerator magnets can be decomposed as a superposition of the different multipole contributions
- Radial field at any location within the aperture can be expanded in terms of the harmonics as

$$B_r(r,\theta) = \sum_{n=1}^{\infty} \left(\frac{r}{r_0}\right)^{n-1} B_n(r_0) \sin n\theta + A_n(r_0) \cos n\theta$$ (European convention)

Clearly we can find a multipole field by summing up these contributions, but what about decomposing our field simulated in FEMM to check the strength of these terms?

Sample the field and inverse Fourier transform, either normal/skew separately or complex coefficient as shown

1:

$$B_n(r_0) = \frac{2}{M} \sum_{m=0}^{M-1} B_r(r_0) \sin n\theta_m$$ NORMAL

$$A_n(r_0) = \frac{2}{M} \sum_{m=0}^{M-1} B_r(r_0) \cos n\theta_m$$ SKEW

2:

$$C_n(r_0) = \frac{1}{M} \sum_{m=0}^{M-1} B_m e^{-in\theta_m} = B_n(r_0) + iA_n(r_0)$$

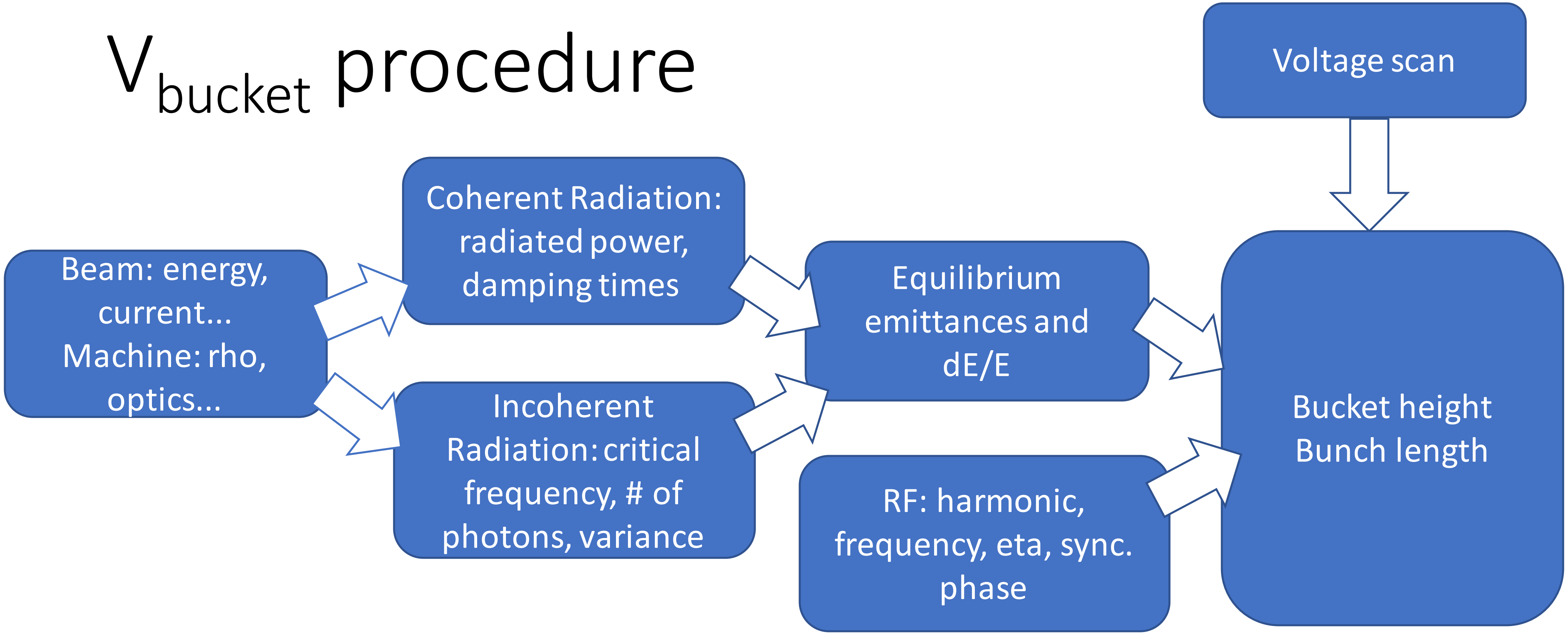
where $n = 1$ is the **dipole** contribution

$n = 2$ is the **quadrupole** contribution

$n = 3$ is the **sextupole** contribution

and so on…

V_{bucket} procedure



Voltage scan

Beam: energy, current...
Machine: rho, optics...

Coherent Radiation: radiated power, damping times

Incoherent Radiation: critical frequency, # of photons, variance

Equilibrium emittances and dE/E

RF: harmonic, frequency, eta, sync. phase

Bucket height
Bunch length

$$\tau_{quantum} = \frac{\tau_E}{(\#\sigma^2_{bucket})} \exp(\#\sigma^2_{bucket}/2)$$

$$\tau_{touschek} = \frac{48\pi\gamma^2\sigma_x\sigma_y\sigma_s}{N r_0^2 c}\left(\frac{dE}{E}\right)^3_{bucket}$$

$$\left(\frac{\Delta E}{E_s}\right)_{\max} = \sqrt{\frac{qV\beta^2}{\pi h\eta E_s}\left[2\cos\phi_s + (2\phi_s - \pi)\sin\phi_s\right]}$$

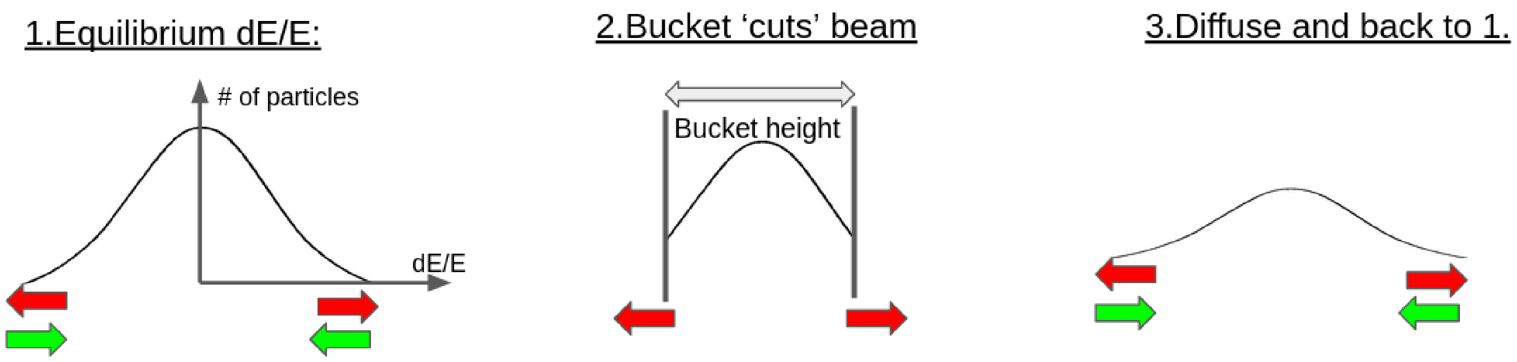
Quantum and Touschek effects

Quantum:

- Coherent synchrotron radiation vs. Incoherent quantum excitation

- RF bucket has finite area

- Particles outside bucket lose energy until lost in the aperture



1.Equilibrium dE/E:

2.Bucket 'cuts' beam

3.Diffuse and back to 1.

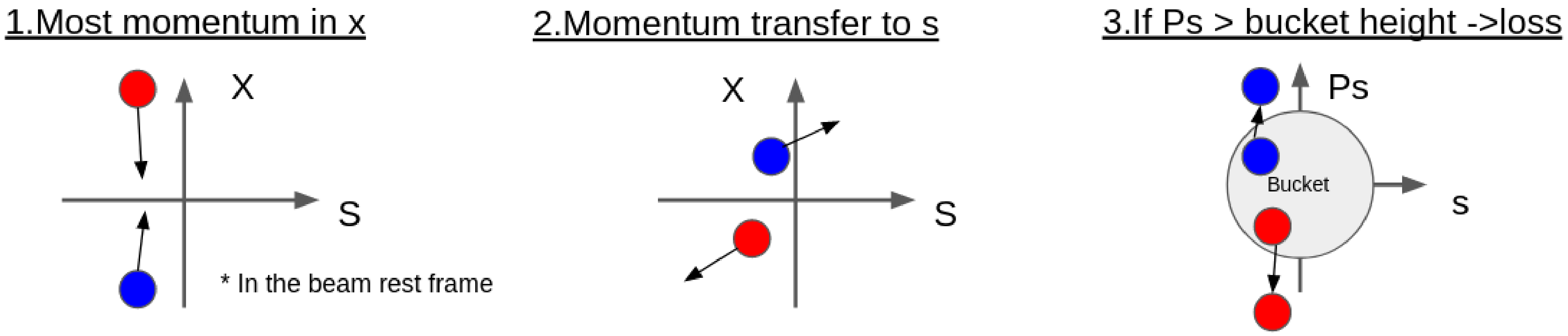
Touschek:

- Beam has most momentum spread in x

- Intra beam scattering trasfers momentum between planes

- If transfer to longitudinal plane too large, particle ends up outside bucket

- Particles outside bucket lose energy until lost in the aperture



1.Most momentum in x

2.Momentum transfer to s

3.If Ps > bucket height ->loss

* In the beam rest frame