Acceleration

D. Amorim

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Early Career Researchers & Muon Colliders, 28th August 2024

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CHART Swiss Accelerator Research and Technology

This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).

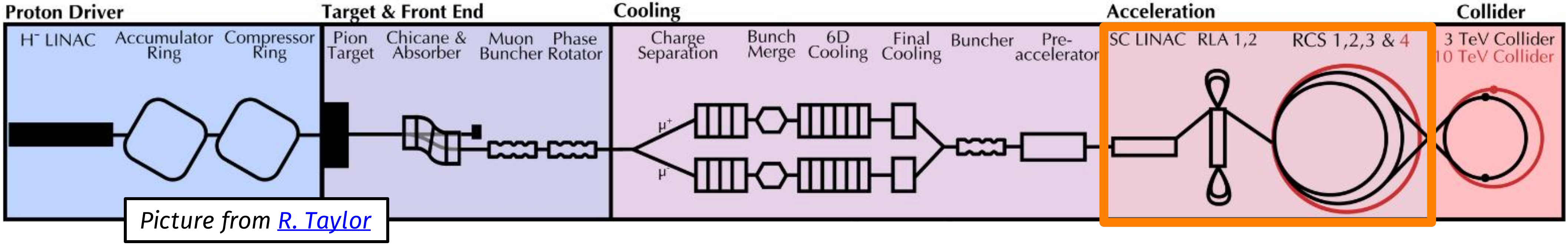
Who am I?

- **PhD in accelerator physics at CERN** obtained in **2019**, on the Transverse Mode Coupling Instability in the LHC
- **First post-doc at SOLEIL** the French synchrotron light source near Paris, working on the machine upgrade project

- **Since 2022, senior fellow at CERN** in the Accelerator and Beam Physics group, in the Coherent Effects and Impedances section
- Working on the **Muon Collider impedance models and transverse beam stability limits**

- I also like **outreach activities**: guiding visits, performing science shows…

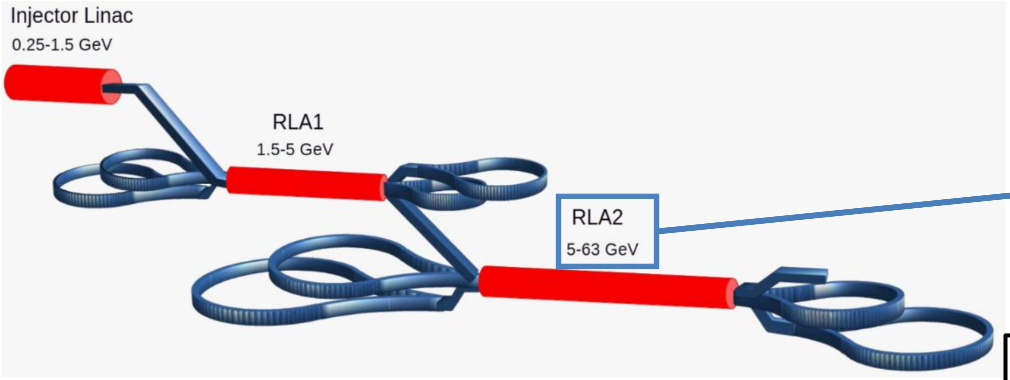
Muon acceleration challenges

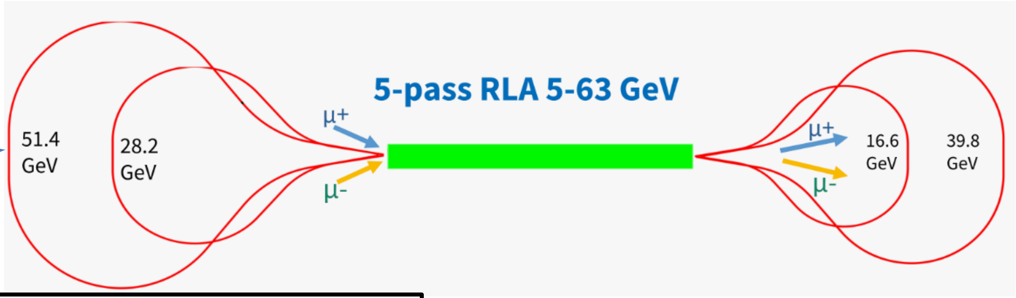


- **Fast acceleration** is required to **counter-balance the muon decay** while preserving bunch properties
- This requires a **unique accelerator chain** and **associated technologies**

Machine parameters	RLA 1	RLA 2	RCS 1	RCS 2	RCS 3	RCS 4
Circumference [km]			6	6	10.7	35
Injection energy [GeV]	1.5	5	63	313.8	750	1500
Energy increase per pass/per turn [GeV]	0.7	11.6	14.7	7.9	11.3	63.6
Bunch intensity at injection [10^{12} muons]			2.7	2.4	2.2	2.0
ε_t [μm rad] / ε_l [eV s]	25 / 0.025					

Recirculating Linacs (RLA)





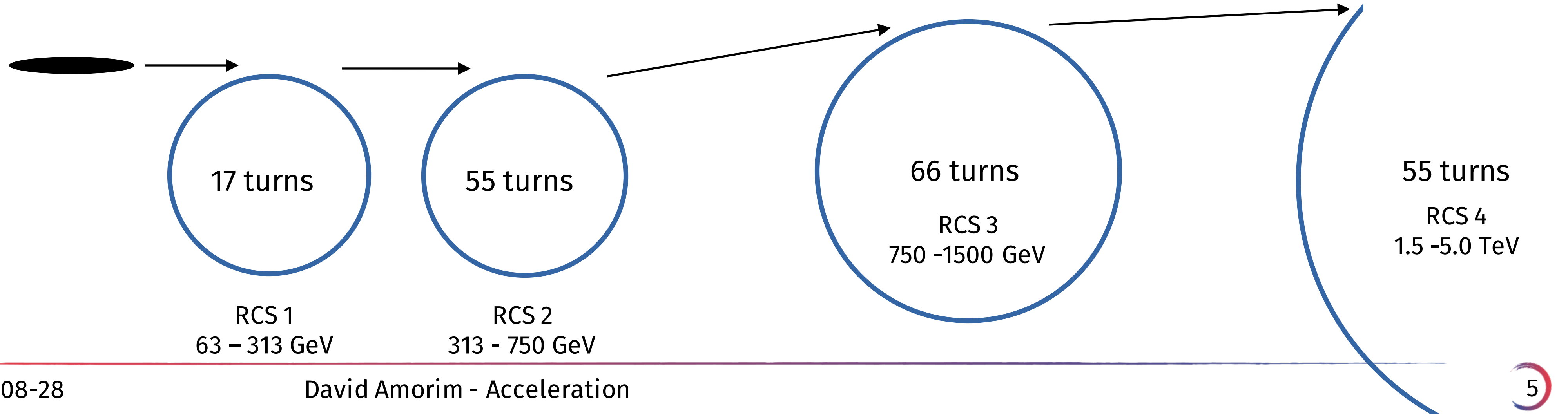
*From **Avni Aksoy** presentation*

- The muon and anti-muon bunches follow each other and are accelerated in a **Linac**, followed by two **Recirculating Linacs**

- Multiple challenges: **optics design** of the droplet arcs, choice of **RF** frequencies, **bunch crossings** in the arcs…

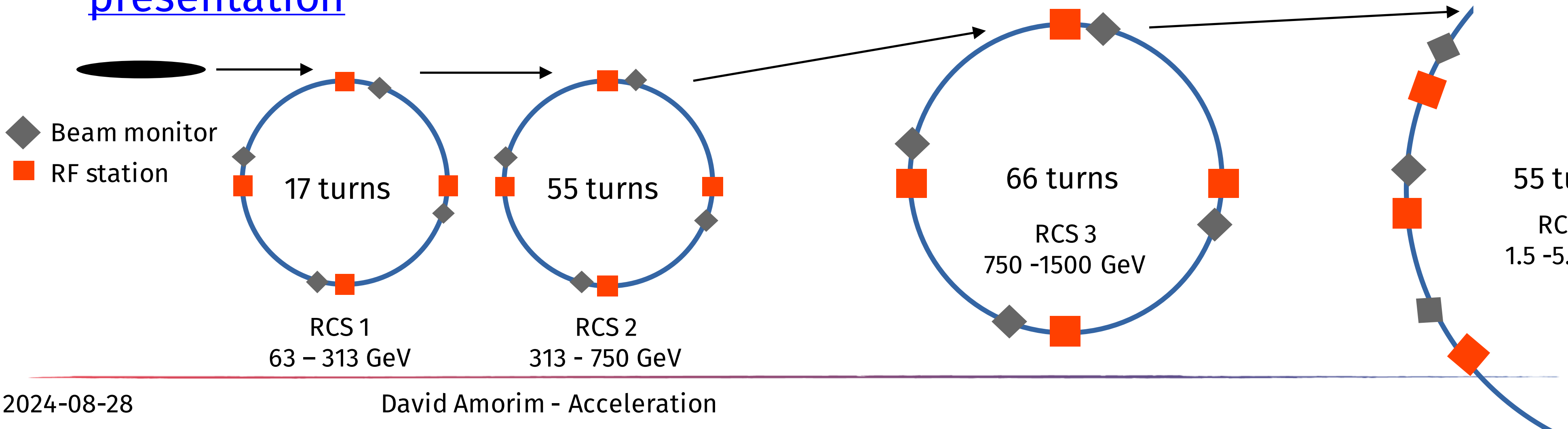
Rapid Cycling Synchrotrons (RCS)

- Chain of **four circular accelerators to reach 5 TeV** energy per bunch
- Design target: **only 10% of intensity loss** because of muon decay **per accelerator**
- Acceleration time of just **10 ms through the four RCS**



Rapid Cycling Synchrotrons challenges

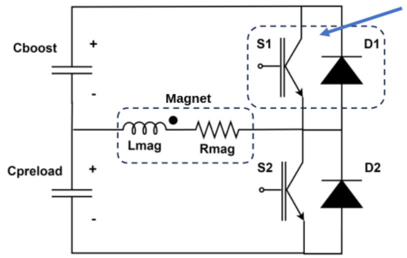
- **Large RF voltage are required** to accelerate the beams: many RF cavities in each machine. E.g., **90 GV and 3000 cavities in RCS 4 → large synchrotron tune,** and need to **distribute the RF system** in ~30 stations
- **Fast ramping magnets** are needed: e.g. **4200 T/s in RCS 1**
- RCS 2,3 and 4 are so-called **hybrid RCS**: pulsed normal conducting magnets and fixed field superconducting magnets are interleaved → see Lisa Soubirou presentation

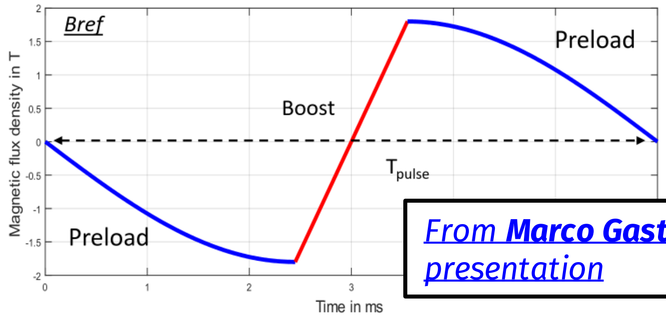


Magnets and powering for the RCS

- **Magnet design** to reach target parameters, **power loss** reduction, cooling, vacuum chamber design, **material** choice, fast ramping and fixed field **high-temperature superconductors**, magnet **power converters** design, **integration in the tunnels…**

Power converter cell

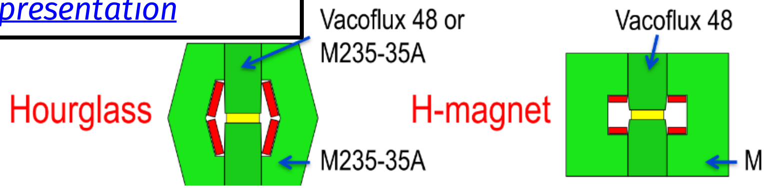




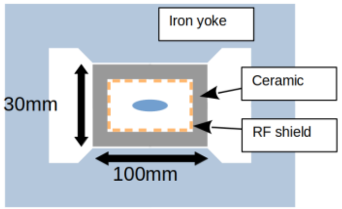
[*From **Marco Gast** presentation*]

- Magnet specifications: 1) Magnetic field in the aperture 1.8 T
  2) Good field region (30 mm * 100 mm)
  3) 1 ms ramp from –1.8 to + 1.8 T

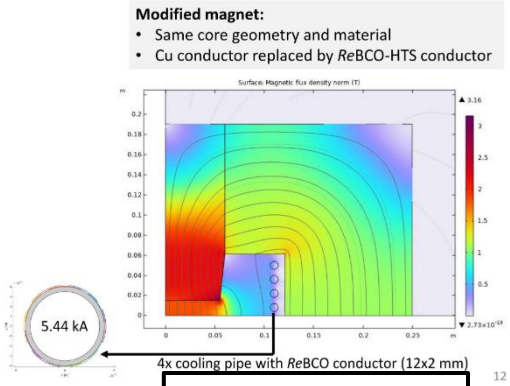
[*From **Marco Breschi** presentation*]



NC magnet and beam pipe cross section



[*From **Erik Kvikne** presentation*]

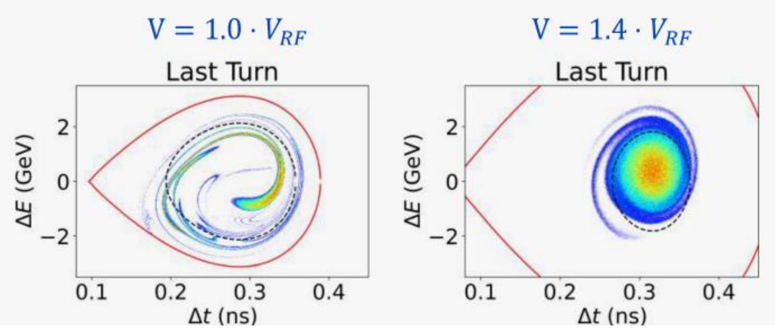


[*From **Simon Otten** presentation*]

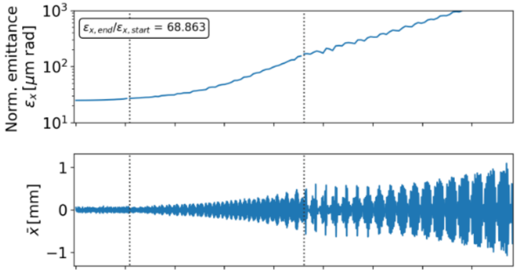
RF for the RCS

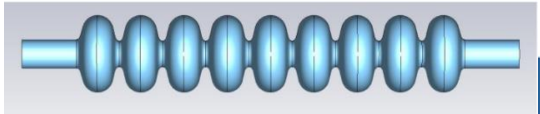
- **~ 5000 superconducting TESLA RF cavities provide the ~ 140 GV needed for the RCS acceleration chain**
- RF cavity choice, **power couplers** design, **beam loading** compensation, **high-order modes** optimization, **power distribution** optimization, **cavity integration** in the accelerator lattice, longitudinal and transverse **beam dynamics**, impedance and collective effects, **two beam effects**...

*From **Fabian Batsch** presentation*



*From **David Amorim** presentation*





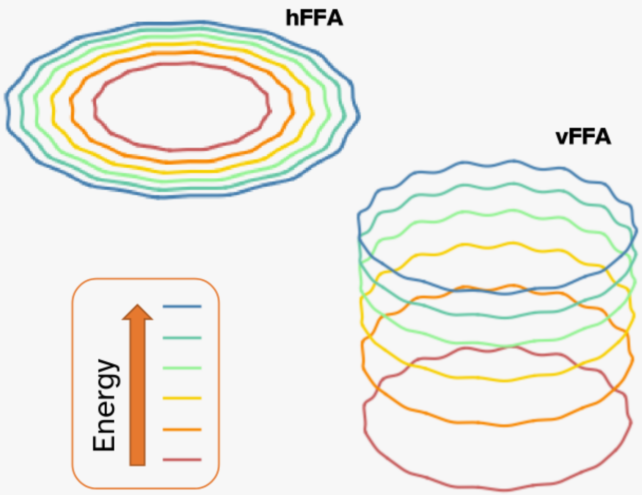
Thales TH1801 klystron

*From **Leonard Thiele** presentation*

	Unit	RCS1	RCS2	RCS3	RCS4
Total peak RF power (incl. power distribution losses)	[MW]	850	410	300	460
Average RF power (incl. power distribution losses)	[MW]	2.42	2.76	4.27	19.0
Average wall plug power (incl. klystron eff.)	[MW]	3.72	4.25	6.56	29.2
Number of klystrons	-	88	42	30	47
Cavities per klystron	-	8	9	18	64

Alternatives are also studied: Fixed Field Alternating Gradient (FFA)

- **Remove** the need for **pulsed magnets**: cost reduction for powering, higher energy reach, faster ramping possible
- Development of **analytic design tools**, lattice and insertion region design, **tracking simulations, magnet design**...



Vertical-excursion FFA (vFFA):

- Higher energy orbits are vertically translated copies of lower energy orbits
- Zero chromaticity if fields increase with vertical coordinate (Z) following scaling law

$$B = B_0 e^{mZ}$$

Zero path length difference means...

→ Zero momentum compaction factor α_c
→ Transitionless
→ Quasi-isochronous for relativistic particles

Slide from [Max Topp-Mugglestone]

Perspectives

- **Lot of ground has been covered during the past two years**
  - RF studies to determine number of RF stations and cavity type in each RCS, longitudinal and transverse beam dynamics with large synchrotron tune, tracking simulations through the RCS chain, instability mitigation measures (chromaticity, damper), normal and superconducting magnet design studies, magnet and RF powering studies, FFA alternatives…
  - The parameter set for the acceleration chain works in simulation

- **But a lot of things are ongoing and there is still a lot to do!**
  - Detailed lattice development for the RCS, beam dynamics studies with two beam effects (beam loading in RF cavities, transverse stability with beam-beam)
  - Beam transfer between machines, bunch quality preservation, full chain tracking simulations (from end of cooling to collider)…
  - Study of a RCS demonstrator facility

There are a lot of exciting topics to cover, Mio needs you to join the Muon Collider!

Gaia Fontana @qftoons

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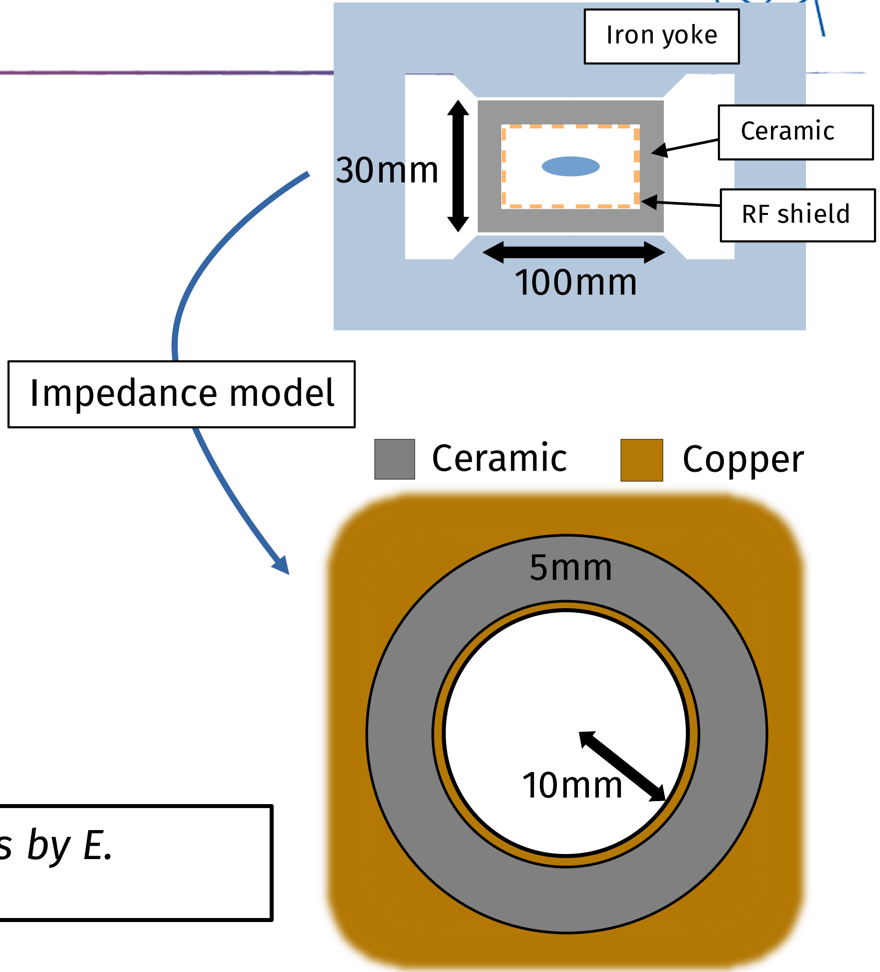
RCS vacuum chamber design

- Copper stripes modeled as a **thin cylindrical layer**.
- For simplicity, the magnet is modeled as an infinitely thick layer of copper.
- We use IW2D to compute the impedance and **scan over different copper thicknesses** to find the amount of copper needed to provide the beam with sufficient RF-shielding.
- The inner radius is kept constant at **10mm** while the ceramic thickness is set to **5mm**.

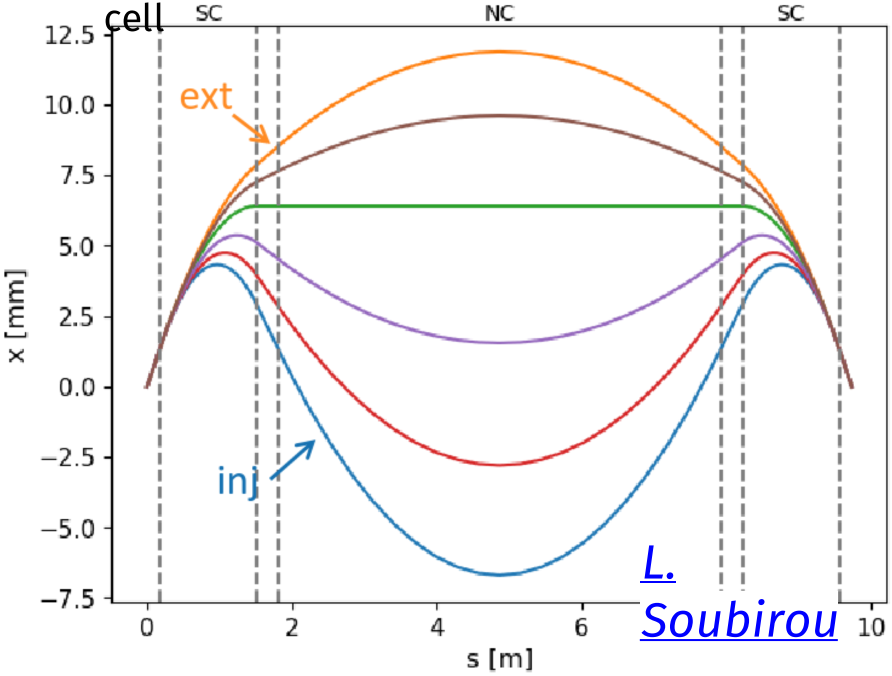


Study and slides by E. Kvikne

Optic challenge with Hybrid RCS

- Hybrid RCS alternate pulsed, normal conducting dipoles and fixed-field, superconducting dipoles
- This increases the average dipole field at injection and ejection energy
- But the bunches will perform an horizontal excursion inside the normal conducting magnets chamber
- At **injection of RCS 2**, horizontal **beam width is ~20 mm** and the **beam excursion is 20 mm in total**. **Vertical beam width is ~7 mm**.

Horizontal beam excursion in a RCS 2 half-cell



L. Soubirou

Beam and machine parameters for the RCS

Beam parameters	Unit	Value
Bunch length 1σ	**mm**	**5.7**
Bunch intensity (injection in RCS 1)	**Particles per bunch**	**2.7e12**
ε_x / ε_y	**µm rad**	**25**

Parameters from F. Batsch RCS tables

Machine parameters	Unit	RCS 1	RCS 2	RCS 3	RCS 4
Circumference	m	5990	5990	10700	35000
NC magnet length	m	3655	2539	4366	20376
Bunch intensity	10^{12}	2.7	2.4	2.2	2.0
Beam momentum	GeV/c	63	313.8	750	1500
Energy increase per turn	GeV	14.7	7.9	11.3	63.6
Rev. frequency	kHz	50	50	28	8.6
RF frequency	MHz	1300	1300	1300	1300
Harmonic number		25957	25957	46295	151433
RF voltage	GV	20.9	11.22	16.1	90.0
α_p		0.0024	0.0024	0.001	0.001
Avg. beta x/y	m	50 / 50	50 / 50	50 / 50	50 / 50
Chromaticity Q'_x/Q'_y		scan	scan	scan	scan
Detuning from octupoles x/y	m^{-1}	0 / 0	0 / 0	0 / 0	0 / 0