Overview of requirements for the SRF system of RCS chain

Muon collider collaboration – annual meeting

Orsay, 21/06/2023

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Acknowledgements: David Amorim, Fulvio Boattini, Luca Bottura, Alexej Grudiev, Elias Metral, Daniel Schulte, Akira Yamamoto

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Outline

- Introduction
- Longitudinal beam dynamics requirements
    - Distributed RF system
    - Path length change
- RF system overview
    - Frequency choice and RF structure
    - Beam loading and RF feedback
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Introduction

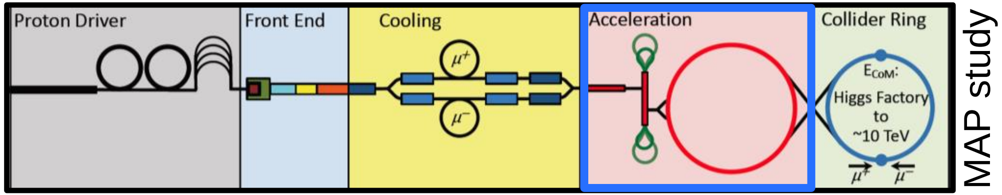
- **Fast acceleration is key** for muon survival rate

$$\frac{N}{N_0} = \exp\left(-\frac{1}{\tau_\mu}\int\frac{dt}{\gamma(t)}\right)$$

→ Needs **large RF voltage in short length**

  - High-gradient RF system

→ **Huge total RF voltage** per turn**: tens of gigavolt**

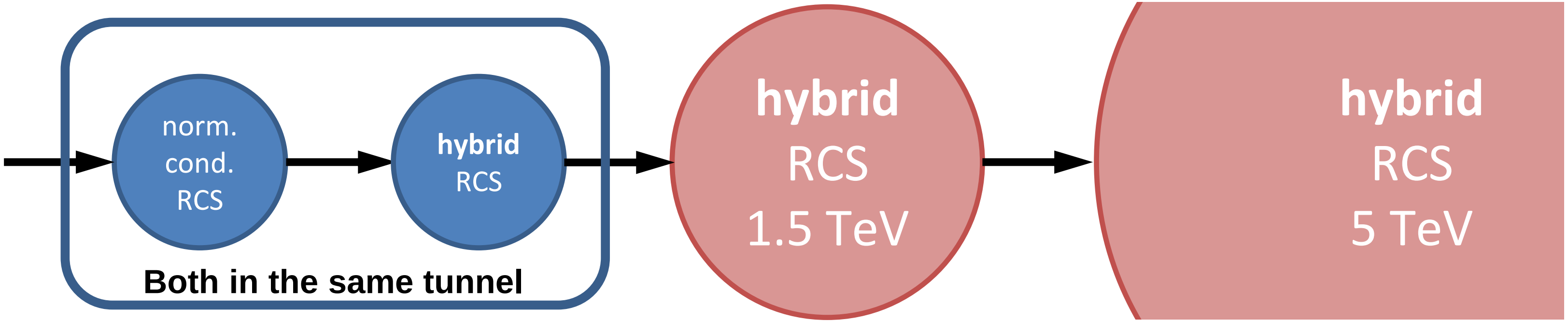


→ Few turns, **one μ^+** and **one μ^- bunch** simultaneously

- Impact longitudinal beam dynamics and **RF system design**?

The baseline RCS chain

- **Rapid cycling synchrotrons (RCS) chain, counter-rotating μ^+/μ^- bunches**
  → 60 GeV → 0.31 TeV → 0.75 TeV → 1.5 TeV → 5 TeV



- **Conventional RCS and 3 hybrid RCS**

→ **Combination of normal and superconducting magnets**

The baseline RCS chain

- **Rapid cycling synchrotrons (RCS) chain, counter-rotating μ^+/μ^- bunches**
  → 60 GeV → 0.31 TeV → 0.75 TeV → 1.5 TeV → 5 TeV

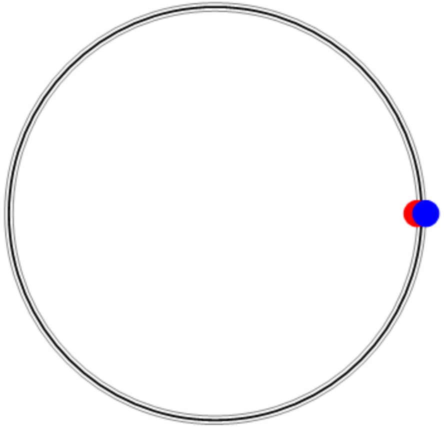
- **Challenging (preliminary) performance parameters from accelerator design meeting from 60 GeV → 5 TeV:**
  - **Total survival rate of 2/3 of muons**
  - **Only 10% longitudinal emittance blow-up (incl. 5 → 60 GeV stage!)**

- **Detailed parameter table: https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz**

→ **F. Batsch, *Updates on the rapid cycling synchrotrons studies*,**
Longitudinal tracking studies through the entire RCS chain

What makes the muon RCS special?

- Two counter-rotating bunches, intensity up to $2.7 \cdot 10^{12}$ μ/b



- Extremely fast ramping, but moderate repetition rate of 5 Hz
  - Duty cycle < 1% (RCS1-3), ~3% (RCS4)
- Hybrid magnet structure (RCS2-4)
  - Fixed super-conducting magnets (10 T)
  - Normal-conducting magnets ramping $-B_{max}…B_{max}$ (±1.8 T)
  - Orbit length and revolution frequency changes during acceleration

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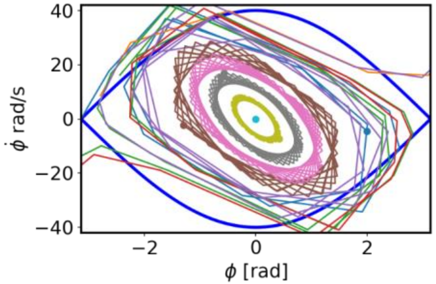
Large RF voltage in a synchrotron?

$Q_S = \omega_S / \omega_{rev} = 0.2$



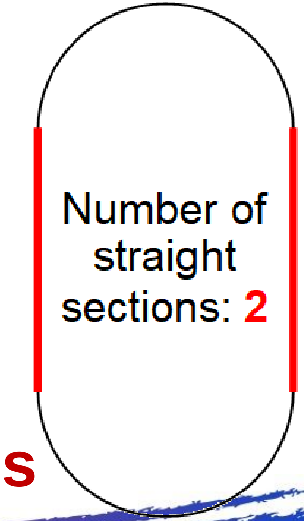
- **Large synchrotron tune due to RF voltage**
- **Number of synchrotron oscillations per turn**

$$Q_S = \frac{\omega_S}{\omega_0} = \sqrt{-\frac{h\eta e V_{RF}\cos\phi_S}{2\pi E\beta^2}} \propto \sqrt{V_{RF}\cos\phi_S}$$

  - **Stable synchrotron oscillations and phase focusing only for $Q_S \ll 1/\pi$**
    (T. Suzuki, KEK Report 96-10)

→ Can be easily exceeded in μ-accelerators

→ Several smaller longitudinal kicks per turn


Number of straight sections: 2

→ Distribute RF system over multiple sections

Why distributed RF system? How many stations?

- **Multiple longitudinal kicks per turn to smoothen synchrotron motion again**
  - **Stable synchrotron oscillations and phase focusing for $Q_S \ll n_{RF} \cdot 1/\pi$**
  - **Tracking simulations to determine longitudinal emittance growth (with BLonD code)**

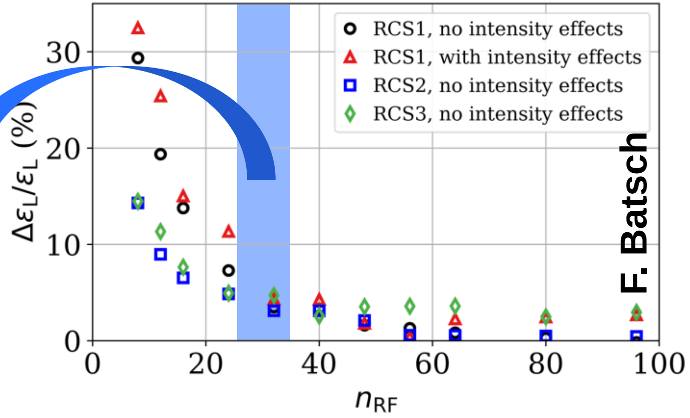
→ Favourable range of $n_{RF} \approx 30$

→ Tune Q_S as large as 1.5

→ Details see F. Batsch

Number of straight sections: **30**

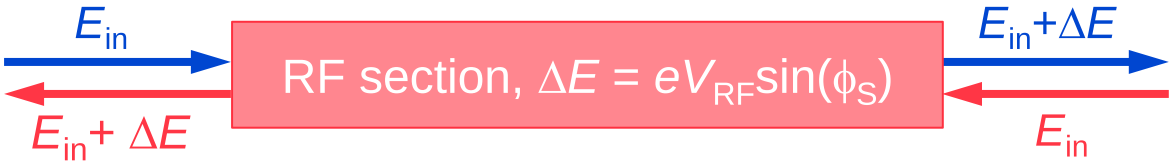
Long. emittance growth versus n_{RF} in RCS1



F. Batsch

Energy difference of counter-rotating beams

- **Limit energy gain per RF section**



E_{in}

$E_{in}+\Delta E$

RF section, $\Delta E = eV_{RF}\sin(\phi_S)$

$E_{in}+\Delta E$

E_{in}

→ **Avoid large energy difference between counter-rotating μ^+/μ^- beams**

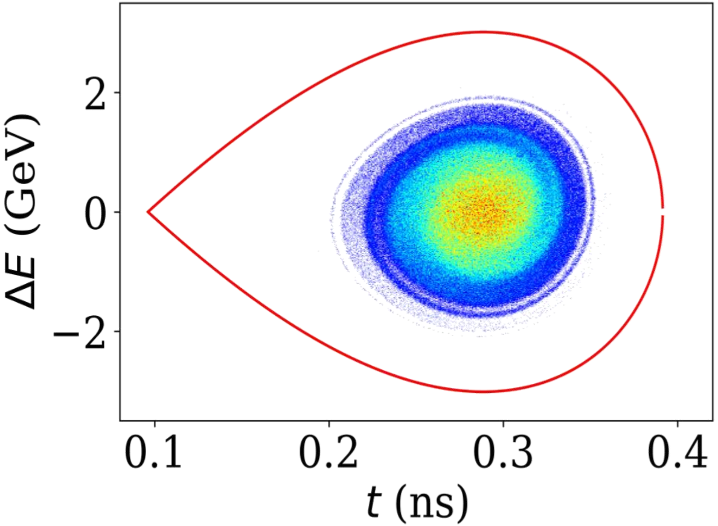
  - **During first turn in RCS1 energy gain is about 20% of beam energy!**

→ **Adapted transverse optics limits impact of beam energy differences**

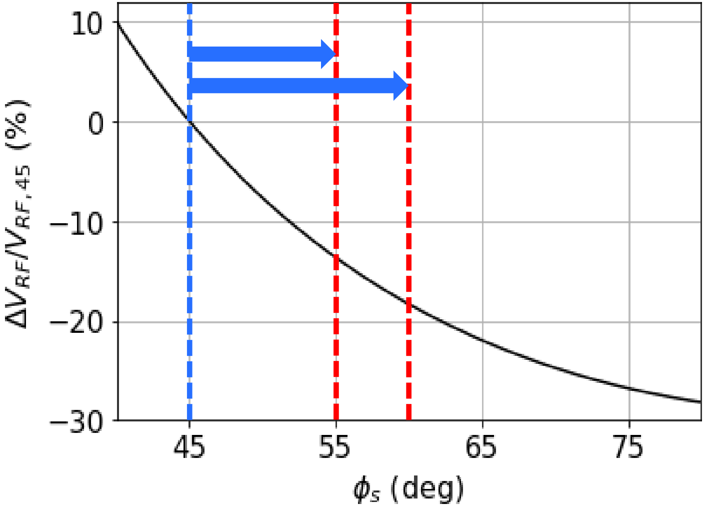
→ **A. Chancé, *RCS parameters and optimization***

Impact of synchronous phase choice

- Conservative initial choice of stable phase: $\phi_S = 45°$



F. Batsch et al.
IPAC23, TUPA040

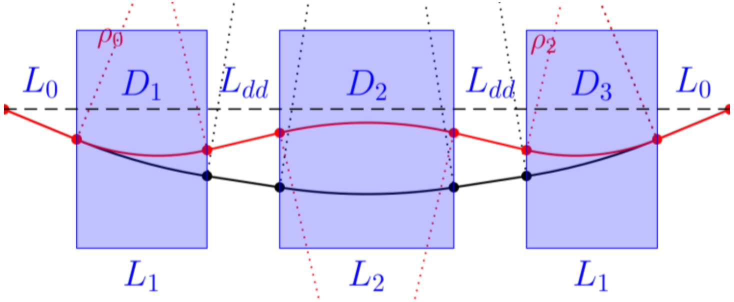


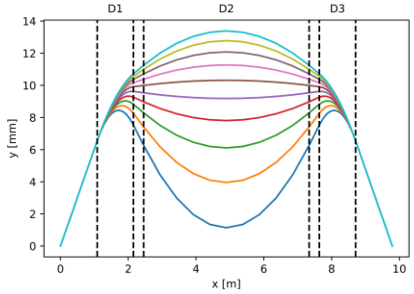
→ Increase up to 55° (RCS1) or even up to 60° (RCS2/3) under study

→ Relax RF voltage requirements → ✓increase bunch length

Consequences of RCS2/3/4 as hybrid

- **Difficult to keep orbit length constant**
  - → **Superconducting magnets act as spectrometers**





A. Chancé et al.
IPAC23, MOPL162

	RCS1	RCS2	RCS3	RCS4
Path length difference, Δl [mm]	0	9.1	2.7	9.4
Relative path length, $\Delta l/l$ [10^{-6}]	0	1.52	0.25	0.353

RF system requirements

- Maximum gradient is key
- 5 Hz repetition rate with low duty cycle
- RF stations distributed around the RCS ring
- Slight tuning during acceleration to track orbit length change

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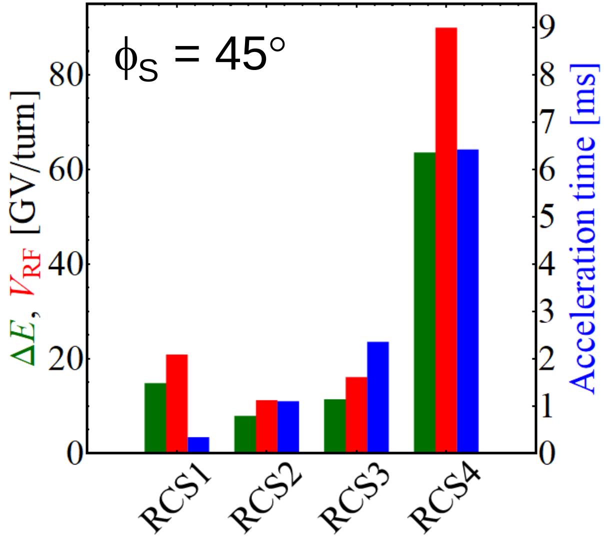
Why super-conducting?

- **Large RF voltage** during **long pulses**
- **Energy efficient** acceleration technology
- **Standing wave** for mode to accommodate counter-rotating bunches
- **High accelerating gradient** per RF structure length

RF voltage and acceleration time



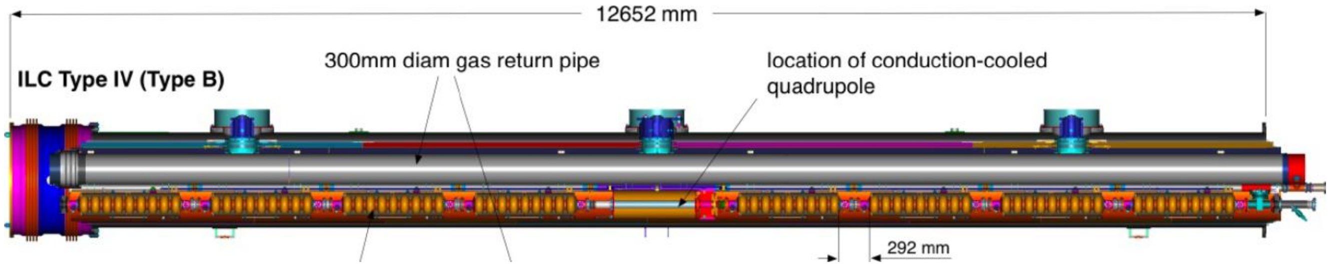
RCS RF system choices

- Large scale superconducting RF systems

Frequency	Accelerator	Remark
352 MHz	LEP	Moderate gradient, CW
400 MHz	LHC, FCC	Moderate gradient, CW
650 MHz	PIP-II	Alternative options also for μRCS
800 MHz	ERL, (FCC)	
1.3 GHz	TESLA, ILC, FELs (XFEL)	Wide-spread technology with decades of experience
1.5 GHz	JLab-CEBAF	

→ Largest gradients presently achieved at 1.3 GHz

1.3 GHz structures for muon acceleration?



- **Well studied, industrialized design (A. Yamamoto, IMCC22)**
  - → **Achieved gradient during suitable pulse length: > 30 MV/m**

→ **Gradient assumption for muon RCS:**

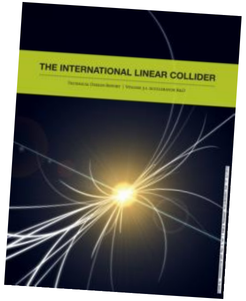
Achieved (conservative)	**30 MV/m**
Optimistic scenario	**45 MV/m**

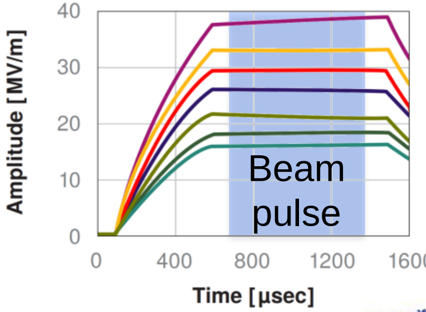
Pulsed of operation, duty cycle

- Repetition rate of RCS chain identical to ILC: 5 Hz
- Minimum beam pulse length for RF system?

	RCS1	RCS2	RCS3	RCS4
Ejection energy, E_{ej} [TeV]	0.31	0.75	1.5	5.0
Circumference, $2\pi R$ [km]	5.99	5.99	10.7	35
Acceleration time, beam pulse length, τ_{acc} [ms]	0.34	1.1	2.4	6.4

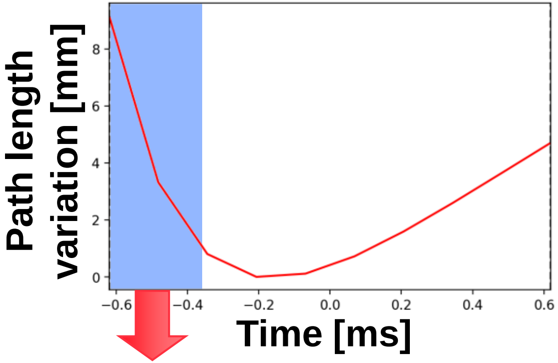
→ Similar, pulsed regime


THE INTERNATIONAL LINEAR COLLIDER



RF frequency sweep

- **RCS2 most demanding**,
  RCS3 and RCS4 more relaxed
  - Well-defined RF frequency sweep needed in ~1 ms, from injection to extraction



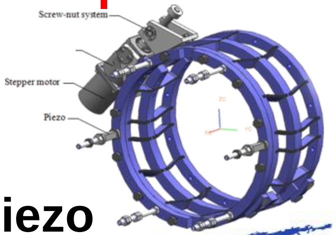
A. Chancé

- $\Delta f/f = \Delta l/(2\pi R) \approx 1.52 \cdot 10^{-6} \rightarrow \Delta f \approx 2$ kHz $\rightarrow d\Delta f/dt \approx 10$ MHz/s

→ **Controlled RF frequency sweep during ‘beam pulse’**

→ **Present tuning systems only for Lorentz force detuning compensation**

- **Reported tuning ranges for ILC-style cavities**
- **W. Cichalewski et al., ICALEPCS2015:** $\Delta f \approx 1.2$ kHz
- **Y. Pischalnikov, ILCX2021-ILC:** $\Delta f \approx 3$ kHz

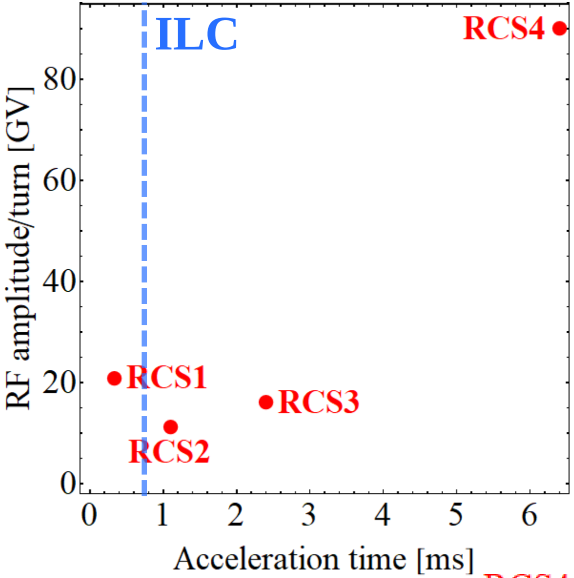


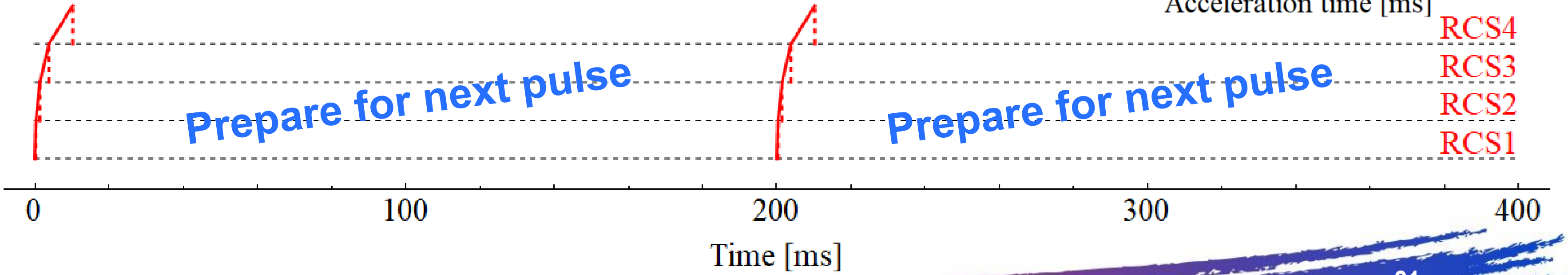
Piezo

Pulsed of operation, duty cycle

- Large RF voltage during short (0.34 ms) pulses in RCS1
  - Pulse length dependent gradient?
- Low duty cycle

	RCS1	RCS2	RCS3	RCS4
Duty cycle	0.17%	0.55%	1.2%	3.2%





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Beam loading considerations

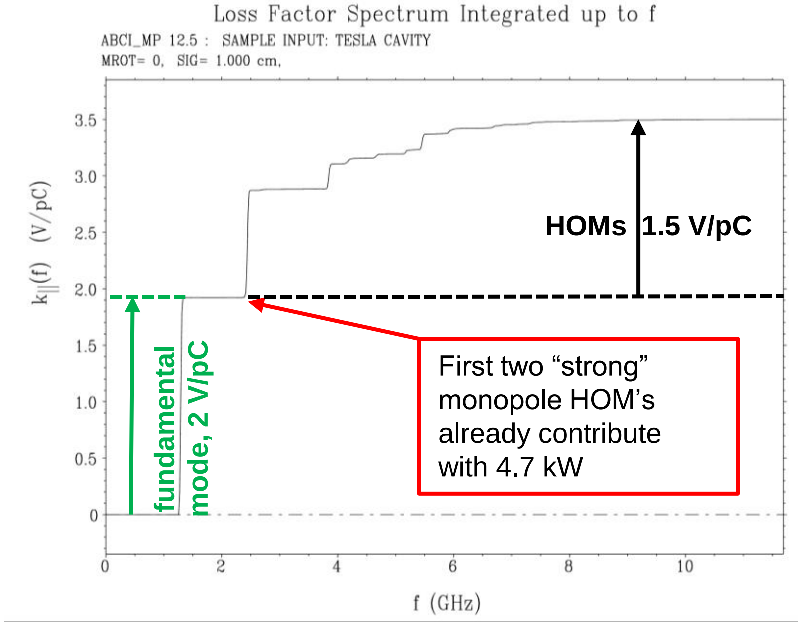
- Only one high-intensity bunch (of each type) accelerated in RCS

	ILC	RCS1 (and RCS2)
Number of bunches, n_b	1312	1 each μ^+ and μ^-
Bunch spacing, τ_{bs}	554 ns	T_{rev} = 20 µs
Bunch intensity, N_b	$2 \cdot 10^{10}$ p/b	$2.7\ (2.5) \cdot 10^{12}$ p/b
Average beam current, I_b	5.8 mA	2 × ~20 mA

- **Average beam current more than three times (2×) above ILC**
- **Very strong transient beam loading**

Higher-order mode power and damping

- HOMs loss factors from ABCI (ABCI file from S.-A. Udongwo)
- 1.3 GHz structure in **RCS1**



First two "strong" monopole HOM's already contribute with 4.7 kW

→ 1.5 V/pC corresponds to almost P_{HOM} = 8 kW during beam pulse of 0.34 ms (duty cycle: 0.17%)

→ Millisecond RF acceleration in intermediate regime between CW and pulsed RF

→ Requires more detailed (thermal) study for **10 kW HOM class couplers**

F. Batsch, *Longitudinal tracking studies through the entire RCS chain*

External loading and feedback requirements

- **Steady-state** detuning to minimize reflected power (reactive beam loading compensation)

  → $\Delta f_{\mathrm{RF}}/f_{\mathrm{RF}} \approx 5 \cdot 10^{-7} \rightarrow \Delta f_{\mathrm{RF}} \approx \sim 2 \times 0.32$ kHz

- Optimal **external quality factor** $Q_{\mathrm{ext,opt}} \simeq \dfrac{V}{(R/Q) I_{\mathrm{RF}} \sin \phi_{\mathrm{S}}}$

J. Tückmantel, CERN-ATS-Note-2011-002 TECH

→ Suggests optimal external quality factor **$Q_{\mathrm{ext,opt}} \approx 1 \ldots 2 \cdot 10^6$**
(within $1 \ldots 10 \cdot 10^6$ of tunable fundamental power coupler for ILC)

→ **Too high (5-6 turns filling time) for efficient feedback → $Q_L \approx \mathcal{O}(10^5)$**

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Beam feedback considerations

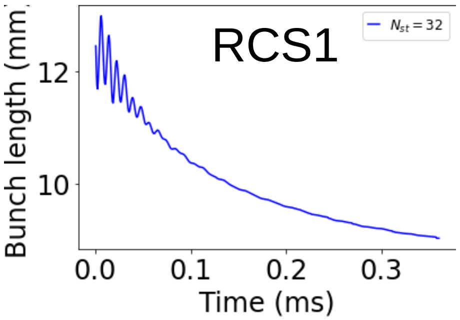
- **Only 10% budget for longitudinal emittance growth (5 GeV → 5 TeV)**

  → **Critical at injection:** **Phase/energy mismatch** → Dipole oscillations
  RF voltage → Quadrupole oscillations

- **Filamentation extremely fast**
  (few turns) due to $Q_S = f_S/f_{rev} > 1$

1. **Beam phase loop**
2. **Quadrupole damper**

} **Gated per bunch, extremely fast?**



BLonD tracking (F. Batsch)

→ **Requires turn-by-turn modulation of RF phase and voltage**

→ **Impact of counter-rotating bunches to be checked**

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Summary

- Muon RCS: single μ^+, μ^- bunches accelerated to 5 TeV
  - **Largest RF gradient** **key to muon survival**
  - Important HOM power due to high bunch intensity, strong beam-loading
  - RF frequency sweep to compensate path length change (hybrid RCS)
- Present RCS chain design based on 1.3 GHz (ILC)
  - **Modular, distributed** RF system: ~30 RF stations (700 9-cell cavities, RCS1) ideally equidistant → infrastructure
  - **Pulsed** regime: 0.34 ms (RCS1) to 6.4 ms (RCS4)
  - **Cavity tuning** with piezo tuners?
  - **Feasibility** of HOM couplers?

Summary of RF requirements

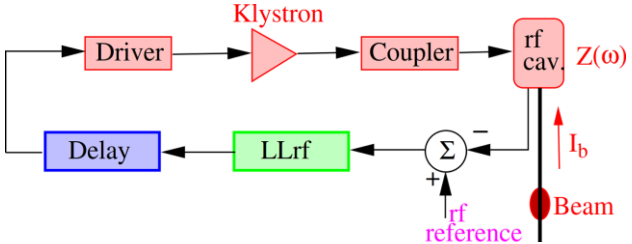
Parameter	RCS1	RCS2	RCS3	RCS4
Frequency, f_{RF}	**1.3 GHz**			
Beam pulse length, τ_{acc}	0.34	1.1	2.4	6.4
RF voltage per turn	**20.9 GV**	11.2 GV	16.1 GV	**90 GV**
Frequency sweep width, Δf	n/a	**2 kHz**	0.32 kHz	0.46 kHz
Gradient, V_{RF}/l	**30 MV/m (conservative), 45 MV/m (pushed)**			
Beam current, I_{DC}	**2 × 22 mA**	2 × 20 mA	2 × 10 mA	2 × 3 mA
Power to the beam	2×320 MW	2×160 MW	2×120 MW	2×190 MW
HOM power (beam pulse)	**~10 kW**	**~10 kW**	~5 kW	~1.5 kW

Thank you for your attention!

Transient power and feedback considerations

- **With 2 × 20 mA beam current, power to beam ~2 × 430 kW**
- **Beam induced voltage at f_{RF} about 2 x 1.7 MV during bunch passage**

Example: LHC RF feedback system



P. Baudrenghien, T. Mastoridis, PRAB 20, 011004 (2017)

- **Conventional direct feedback (e.g., loop delay, $\tau_d \approx$ 700 ns in LHC) too slow**
  - **Correction would be applied after bunch**
- **1-turn delay feedback μ^+/μ^- gating**
  - **Counter-rotating beams not to meet in cavity**

- **Muon RCS advantage: only one bunch per beam and few turns**

→ **Explore cycle-by-cycle adaptive compensation**

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Open questions for discussion

- **Frequency choice** of 1.3 GHz?
- What is the **baseline gradient** for the RCS design? 31.5 MV/m? 45 MV/m?
- Impact of **distributed RF system**? Power for **cryogenics**? Cost in terms of **AC power**?
- Impact of **μ^+/μ^--bunches in opposite directions**?
- **Beam current too large** for ILC-type cavities? Limitations of **fundamental power coupler**?
- Controlled **frequency sweep** in combination with Lorentz force detuning?

Summary of RF requirements

Parameter	Value	Remark
Frequency, f_{RF}	1.3 GHz	
Tuning range (piezo), Δf	2.2 kHz	Sweep for acceleration, hybrid RCS2/3/4
Gradient, V_{RF}/l	30 MV/m	
Beam pulse length, τ_{acc}	0.34/1.1/ 2.4/6.4 ms	RCS1/2/3/4
Beam current, I_{DC}	2 × 20 mA	
Power to the beam (max., RCS1)	2 × 250 MW	~2 × 430 kW/cavity

Different regime compared to conventional RCS

	RCS1	**FNAL**	**J-PARC**
Circumference, $2\pi R$ [m]	5990	468	348
Energy factor, E_{ej}/E_{inj}	5	20	7.5
Repetition rate, f_{rep} [Hz]	5 (asym.)	15	25
Magnetic ramp	Linearized	Sinus	Sinus
Number of turns	17	42 k	17 k
Max. RF voltage, V_{RF} [MV]	21000	0.86	0.44
Energy gain per turn, ΔE [MeV]	14800	~0.4	~0.2

→ **F. Boattini, Magnet cycling considerations, Thursday**

→ **F. Batsch, RF cycling considerations, Thursday**

Different regime compared to conventional RCS

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Max. RF voltage, V_{RF} [MV]	21000	0.86	0.44
Energy gain per turn, ΔE [MeV]	14800	~0.4	~0.2

→ Significantly **more RF voltage** **than any other RCS**

→ **Much fewer turns**

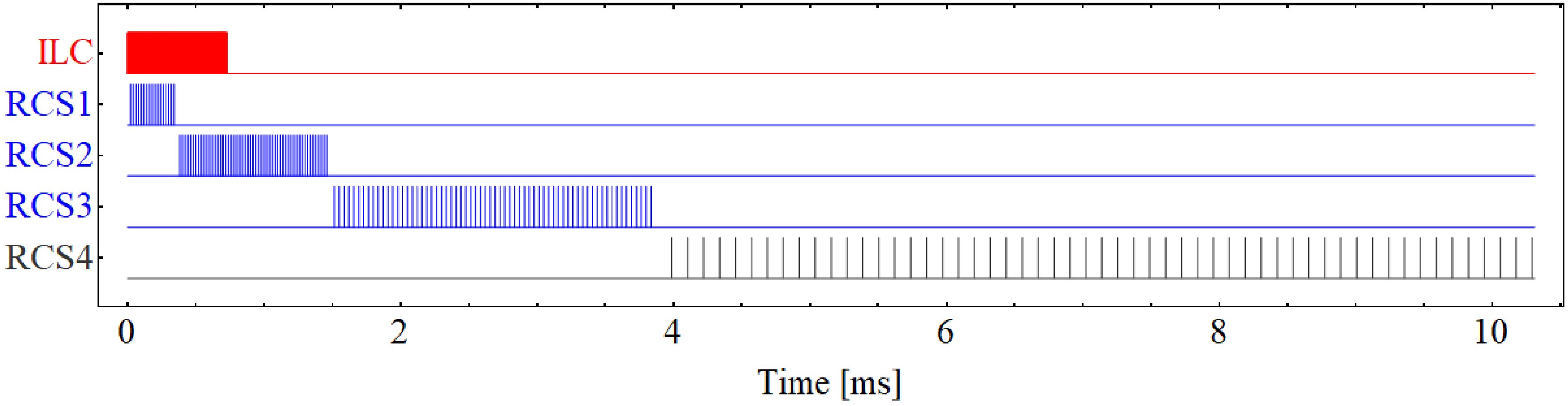
Different regime compared to colliders

	RCS1	LEP2	FCC-ee
Circumference, $2\pi R$ [m]	5990	26658	91106
Energy factor, E_{ej}/E_{inj}	5	4.8	n/a
Repetition rate, f_{rep} [Hz]	5 (asym.)	Slow (min.)	n/a
Magnetic ramp	Linearized	n/a	n/a
Number of turns	17	few 10^8	10^8
Max. RF voltage, V_{RF} [GV]	21	3.6	11.3
Energy gain per turn, ΔE [GeV]	14.8	3.49	10

→ Even **more RF voltage** **than any other circular collider**

→ **Much fewer turns**

Chronogram – bunch structure



- **ILC:** **1312 moderate intensity bunches spaced by 554 ns**
- **μRCS:** **Two very high-intensity counter-rotating bunches**