International MUON Collider Collaboration

SRF System for Muon Collider Rapid Cycling Synchrotron

Muon collider collaboration – annual meeting

12/10/2022

F. Batsch, H. Damerau, I. Karpov

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

CERN

Outline

- **Introduction**
- **High-energy muon Rapid Cycling Synchrotron (RCS) beam dynamics constraints**
  - **Distributed RF system**
- **Acceleration and RF system parameters**
  - **RF voltage, power to beam, tuning**
  - **Beam loading**
- **Summary of requirements and open questions**

Introduction

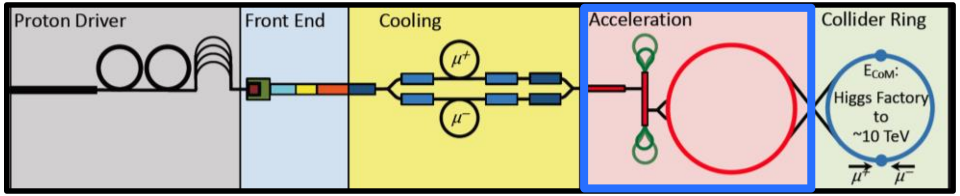
- **Fast acceleration is key** for muon survival rate

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

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

- High-gradient RF system

→ Huge **total RF voltage per turn** in circular accelerator

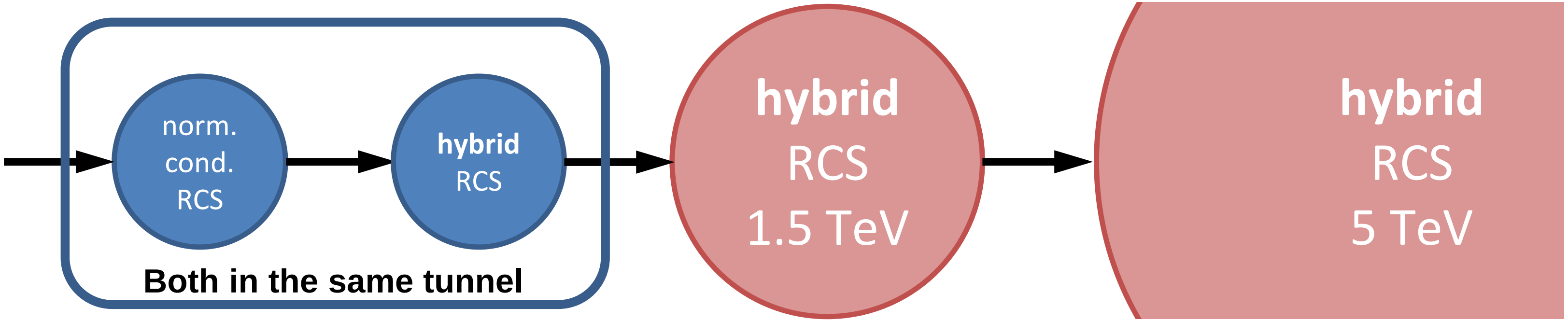


→ Few turns, **one μ^+** and **one μ^- bunch** simultaneously

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

Introduction

- **Rapid cycling synchrotrons (RCS) chain, counter-rotating μ^+/μ^- bunches**
  → 63 GeV → 0.31 TeV → 0.75 TeV → 1.5 TeV (→ 5 TeV)



- **Conventional RCS and 2…3 hybrid RCS: normal and supercon. magnets**
- **Detailed parameter table: https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz**

→ **F. Batsch, 'RF parameter choices and longitudinal stability', today 14h20**

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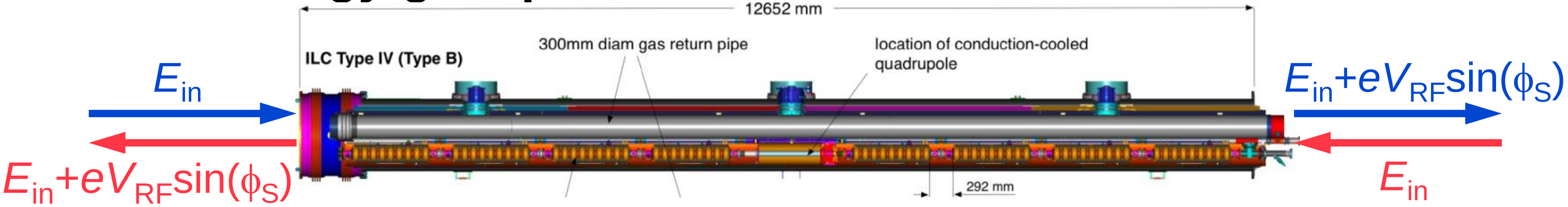
Distributed RF system along the circumference

1. Limit energy gain per RF station



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

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

→ **Transverse optics can limit the impact of beam energy differences**

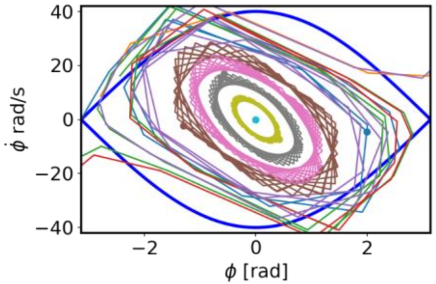
→ **A. Chancé, Parametric study for a rapid cycling synchrotron, today at 14h00**

Not the most stringent constraint

Longitudinal beam dynamics – single particle

2. Number of synchrotron oscillations per turn

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

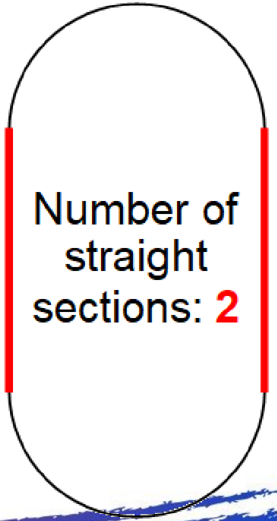


$$Q_S = \frac{\omega_S}{\omega_0} = \sqrt{-\frac{h\eta e V_{RF}\cos\phi_S}{2\pi E\beta^2}} \propto \sqrt{V_{RF}\cos\phi_S}$$

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

→ Can be easily exceeded in μ-accelerators

→ Several smaller longitudinal kicks per turn



→ Distribute RF system over several sections

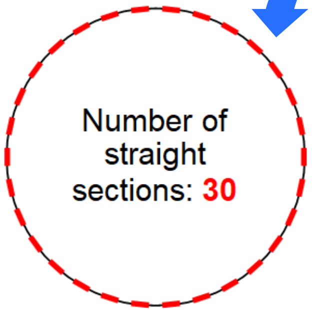
Why distributed RF system? How many stations?

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

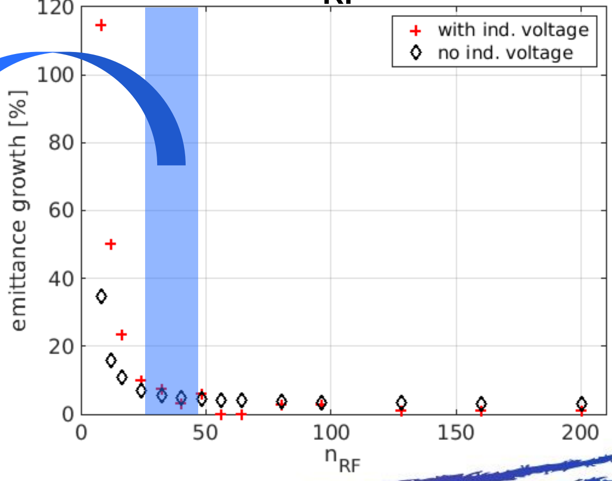
→ Favourable range of $n_{RF} \approx 30$

→ Tune Q_S as large as 1.5

→ Details see F. Batsch



Long. emittance growth versus n_{RF} in RCS1



F. Batsch

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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**

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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

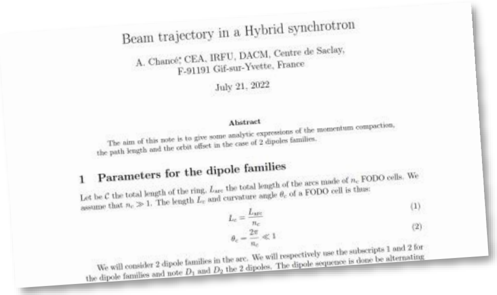
→ Even **more RF voltage** **than any other circular collider**

→ **Much fewer turns**

Rapid Cycling Synchrotron (RCS) parameters

- Principle of hybrid RCS (RCS2, 3 and 4):
  - Fast ramping of normal conducting magnets from negative to positive field: -1.8 T → + 1.8 T
  - Fixed-field super-conducting magnets in addition (max. 10 T)

→ **Beam orbit moves during acceleration → f_{rev} and f_{RF} sweep**



Beam trajectory in a Hybrid synchrotron

A. Chancé*, CEA, IRFU, DACM, Centre de Saclay, F-91191 Gif-sur-Yvette, France

July 21, 2022

Abstract

The aim of this note is to give some analytic expressions of the momentum compaction, the path length and the orbit offset in the case of 2 dipoles families.

1 Parameters for the dipole families

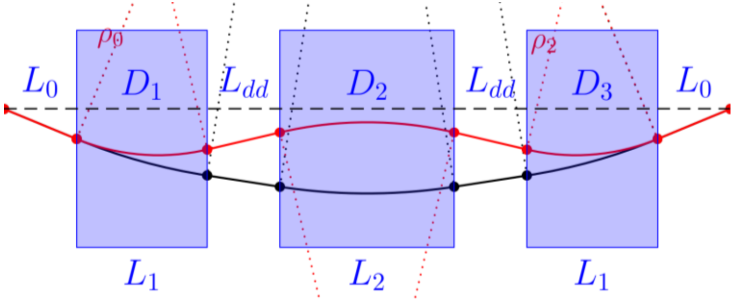
Let be $\mathcal{C}$ the total length of the ring, L_{arc} the total length of the arcs made of n_c FODO cells. We assume that $n_c \gg 1$. The length L_c and curvature angle θ_c of a FODO cell is thus:

$$L_c = \frac{L_{arc}}{n_c} \quad (1)$$

$$\theta_c = \frac{2\pi}{n_c} \ll 1 \quad (2)$$

We will consider 2 dipole families in the arc. We will respectively use the subscripts 1 and 2 for the dipole families and note D_1 and D_2 the 2 dipoles. The dipole sequence is done be alternating

A. Chancé

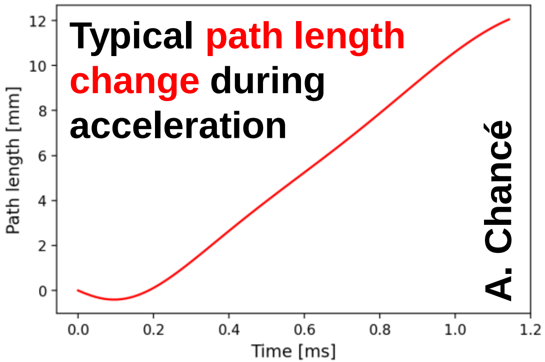


→ **Assume max. 10 cm orbit length change for RCS2**

→ Details by A. Chancé this afternoon

RF frequency sweep (example of RCS2)

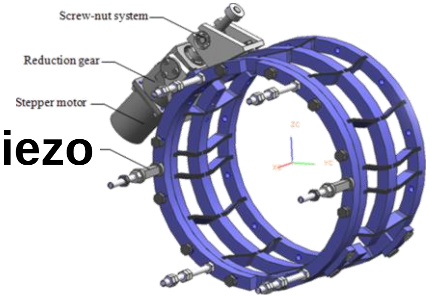
- RF frequency sweep need in ~1 ms, from injection to extraction
- $\Delta f/f = \Delta l/(2\pi R) \approx 1.7 \cdot 10^{-6} \rightarrow \Delta f \approx 2.2$ kHz



→ **Control RF frequency during 'beam pulse'**

→ **In addition to compensation of Lorentz force detuning**

- **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**



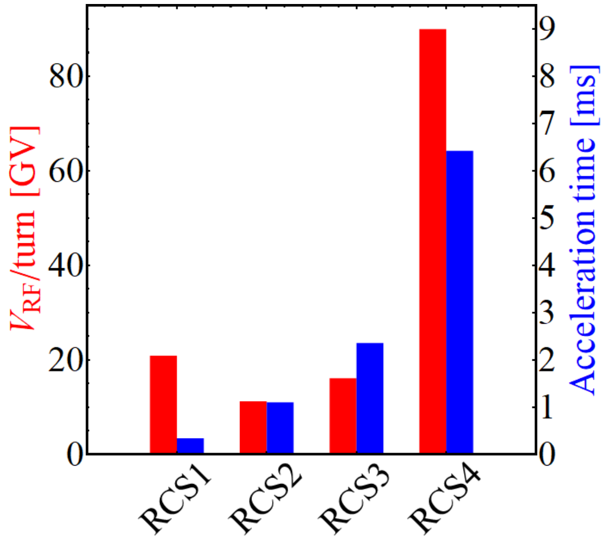
→ **Faster: Turn-by-turn transient beam-loading correction?**

→ **FerroElectric Fast Reactive Tuners (FE-FRT)**

Why super-conducting?

- **Large RF voltage** during **long pulses**
- **Energy efficient** acceleration technology
- **High accelerating gradient** per RF structure length: 30 MV/m
- **Standing wave** operation for counter-rotating bunches

RF voltage and acceleration time



RCS RF system choices

- Common frequencies for superconducting RF

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

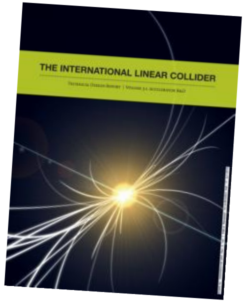
→ 1.3 GHz assumption → F. Batsch, see talk later today

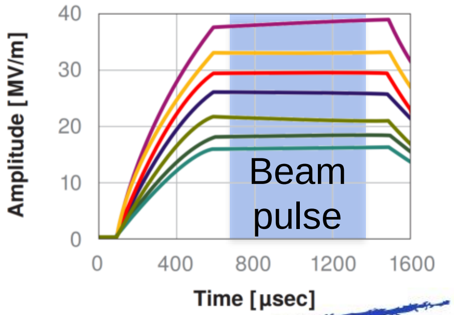
Pulsed of operation, duty cycle

- Repetition rate of RCS chain: 5 Hz (as ILC)
- Minimum beam pulse length for RF system?

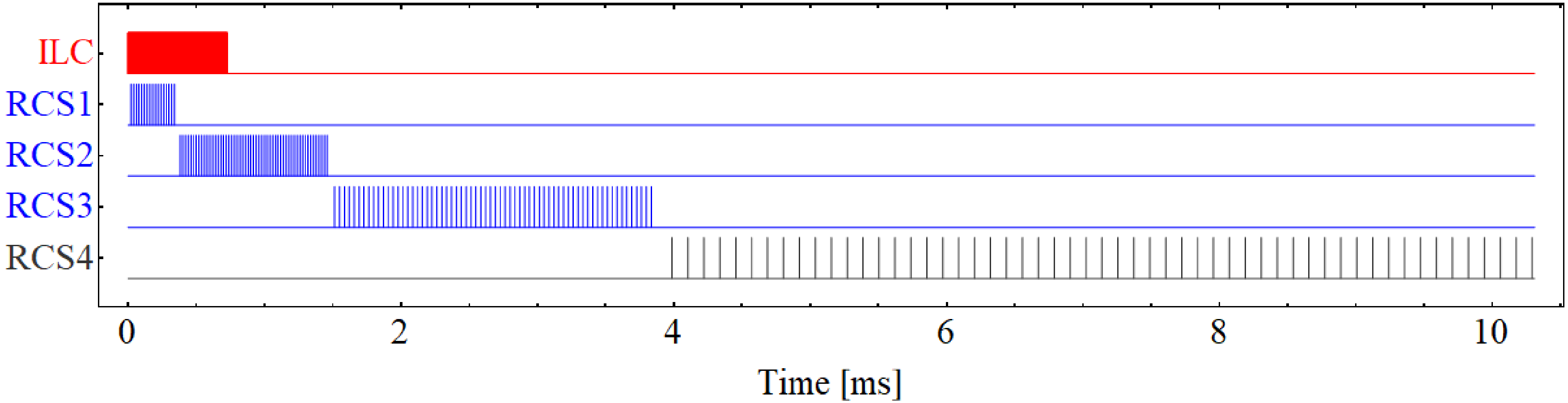
	RCS1	RCS2	RCS3	(RCS4)
Ejection energy, E_{ej} [TeV]	0.31	0.75	1.5	(5.0)
Circumference, $2\pi R$ [km]	5.99	5.99	10.7	(35)
Acceleration time, beam pulse length, τ_{acc} [ms]	0.34	1.1	2.4	(6.4)

→ Pulse length ~1.6 ms same order as for ILC (beam pulse length 0.7 ms)





Chronogram – bunch structure



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

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First 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	2.5 (2.3) $\cdot 10^{12}$ 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**

External loading and feedback requirements

- **Steady-state** detuning to minimize reflected power (reactive beam loading compensation)
  → $\Delta f_{RF}/f_{RF} \approx 5 \cdot 10^{-7} \rightarrow \Delta f_{RF} \approx \sim 2 \times 0.32$ kHz
- Optimal **external quality factor** $$Q_{\text{ext,opt}} \simeq \frac{V}{(R/Q) I_{\text{RF}} \sin \phi_{\text{S}}}$$

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

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

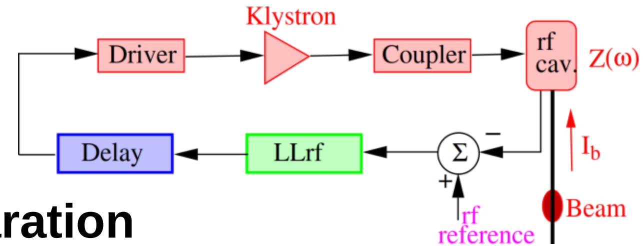
→ Assuming **constructive interference** of counter-rotating μ^+ and μ^--bunches

→ Beam-loading of counter-rotating beams subject to further studies

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 (builds up)**
- **Conventional direct feedback (e.g., loop delay, $\tau_d \approx 700$ ns in LHC) too slow**
  - **Correction would be applied after bunch**
- **Need 1-turn delay feedback with μ^+/μ^- separation**

Example: LHC RF feedback system



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

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

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

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Summary

- Challenging 1.3 GHz RF system for μRCS
- Main ‘non-conventional’ assumptions
  - **Modular, distributed** RF system: ~30 RF stations (700 9-cell cavities, RCS1) ideally equidistant → infrastructure
  - **Longer pulses** than ILC: 2.4 ms (6.4 ms) beam pulse for RCS3(4)
  - **More power**, larger beam current
  - **Cavity tuning** to compensate **orbit length sweep** during acceleration (~few kHz) → in addition to measures against Lorentz force detuning and mechanical resonances

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

Open questions for discussion

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- **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?

Thank you for your attention!