RF Power Systems, CLIC Drive Beam

- Introduction to RF Power Sources
- Introduction to CLIC
- CLIC Drive Beam
- Quest for efficiency

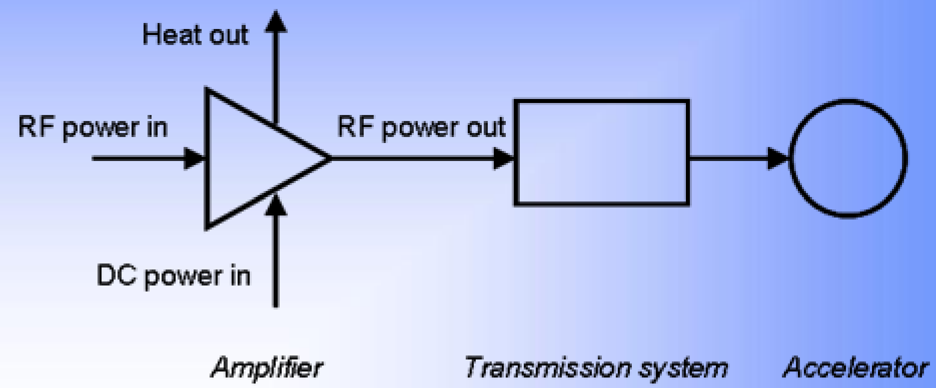
The CERN Accelerator School

Steffen Döbert, BE-RF

RF Power Sources and Example Systems

RF system, General principles

- RF systems
  - RF sources extract RF power from high charge, low energy electron Bunches (vacuum tubes)
  - RF transmission components (couplers, windows, circulators etc.) convey the RF power from the source to the accelerator
  - RF accelerating structures use the RF power to accelerate low charge bunches to high energies
  - Energy not extracted as RF must be disposed of as heat

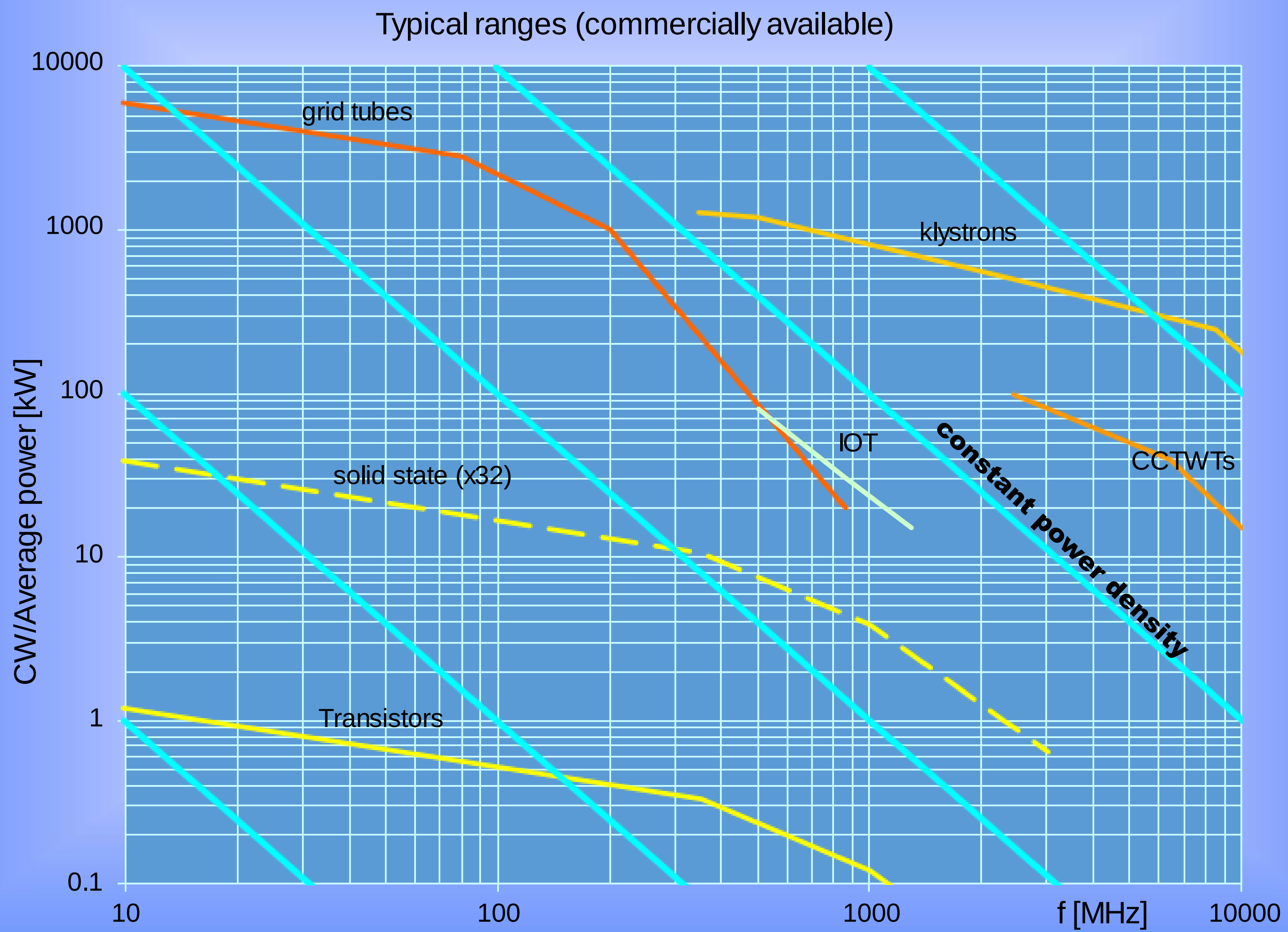


$$P_{RF\ in} + P_{DC\ in} = P_{RF\ out} + Heat$$

$$Efficiency = \frac{P_{RF\ out}}{P_{DC\ in} + P_{RF\ in}} \approx \frac{P_{RF\ out}}{P_{DC\ in}}$$

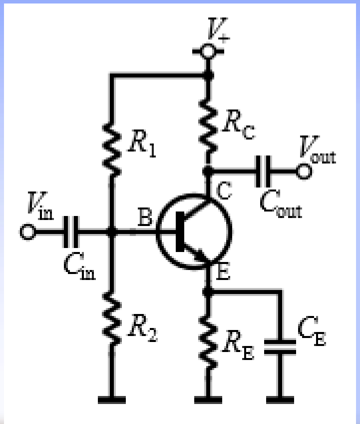
$$Gain(dB) \quad 10\log_{10} = \frac{P_{RF\ out}}{P_{RF\ in}}$$

RF power sources

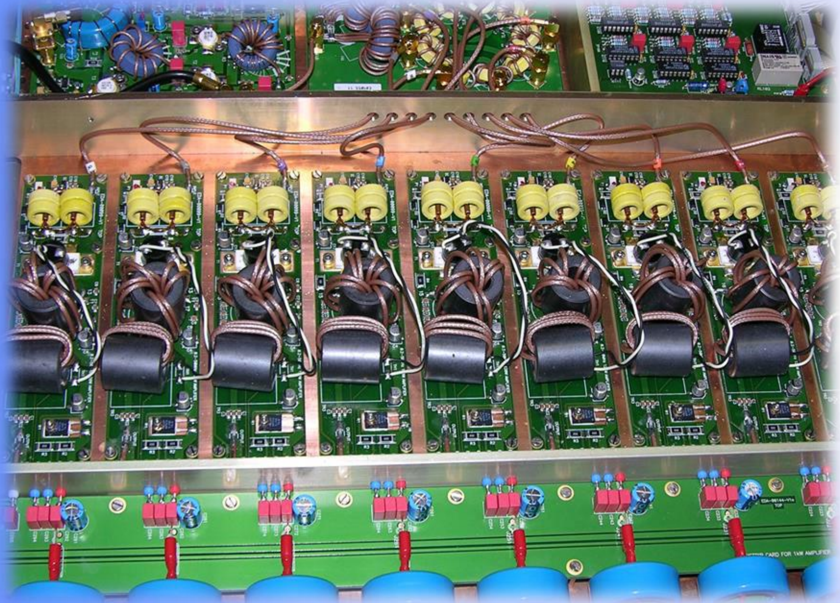


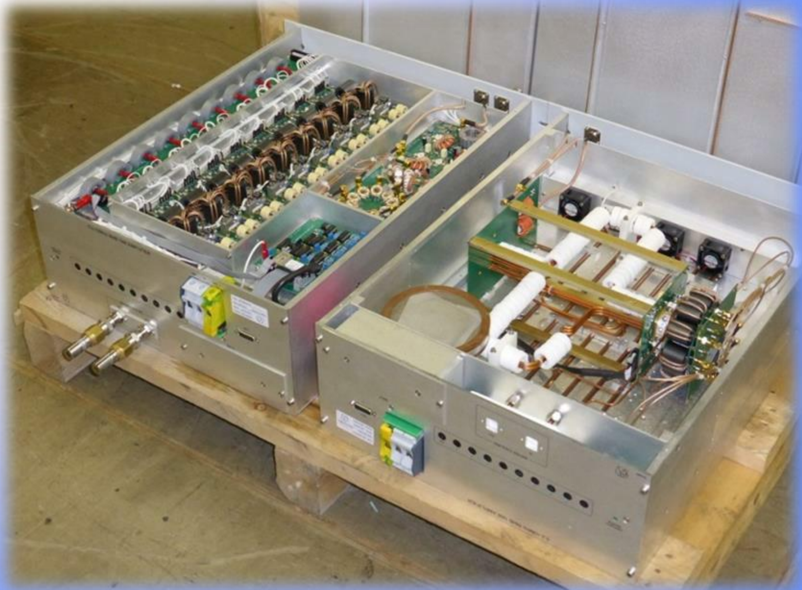
Typical limitation: power/energy density

Solid state amplifier SSPA, 1 kW



$(0.2 \div 50)$ MHz, 1 kW solid state amplifier for LEIR





$(0.2 \div 10)$ MHz, 1 kW SSPA for MedAustron

Takes advantage from 'mobility' of electrons in semi-conductor

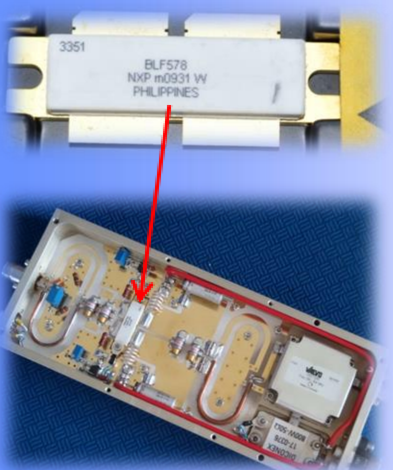
Low voltage controls high voltage or current

M. Paoluzzi

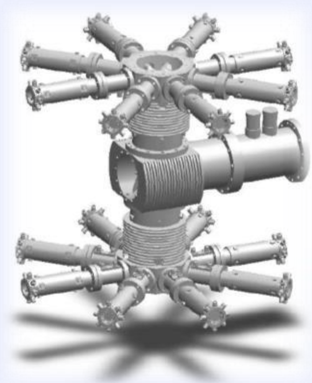
Soleil/ESRF Booster SSPA, 150 kW, 352 MHz

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA

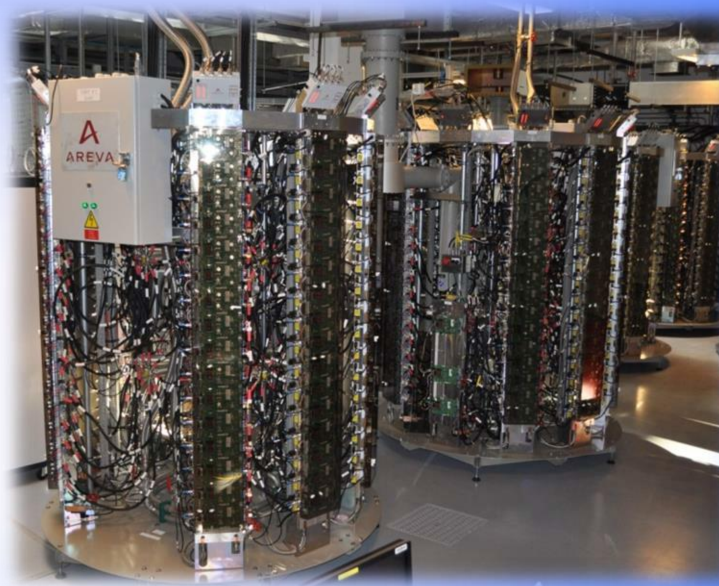
Pair of push-pull transistors



x 128



x 2



650 W RF module

- ➢ 6th generation LDMOSFET (BLF 578 / NXP), V_{ds} = 50 V
- ➢ Efficiency: 68 to 70 %

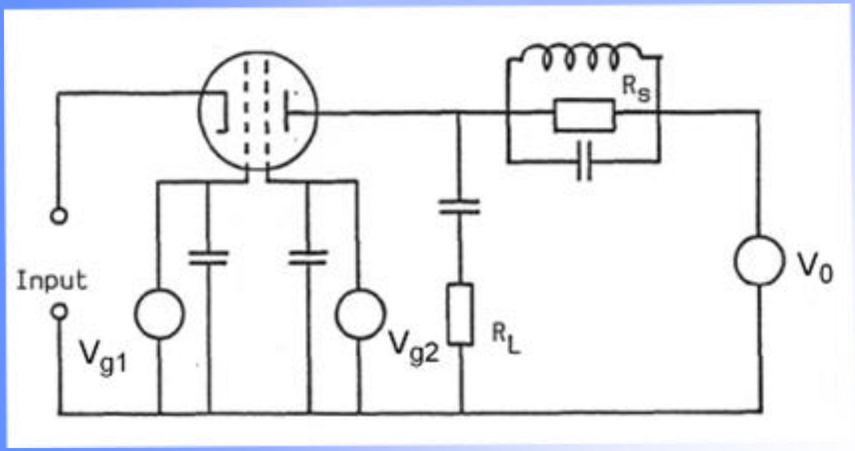
75 kW Coaxial combiner tree

with $\lambda/4$ transformers

150 kW, 352.2 MHz Solid State Amplifiers for the ESRF booster (7 in operation)

Efficiency: > 57 % at nominal power

Tetrode common grid connection



- Grids held at RF ground isolate input from output
- Input is coaxial
- Anode resonant circuit is a re-entrant coaxial cavity
- Output is capacitively or inductively coupled

RS 1084 CJ (ex Siemens, now Thales), < 30 MHz, 75 kW

Takes advantage from 'mobility' of electrons in vacuum

Classes of amplification

Class	Conduction angle	Maximum theoretical efficiency	Gain increasing	Harmonics increasing
A	360°	50%		
AB	180° – 360°	50% - 78%		
B	180°	78%		
C	< 180°	78% - 100%		

- All classes apart from A must have a resonant load and are therefore narrow band amplifiers
- Class AB or B usually used for accelerators

High power tetrode amplifier

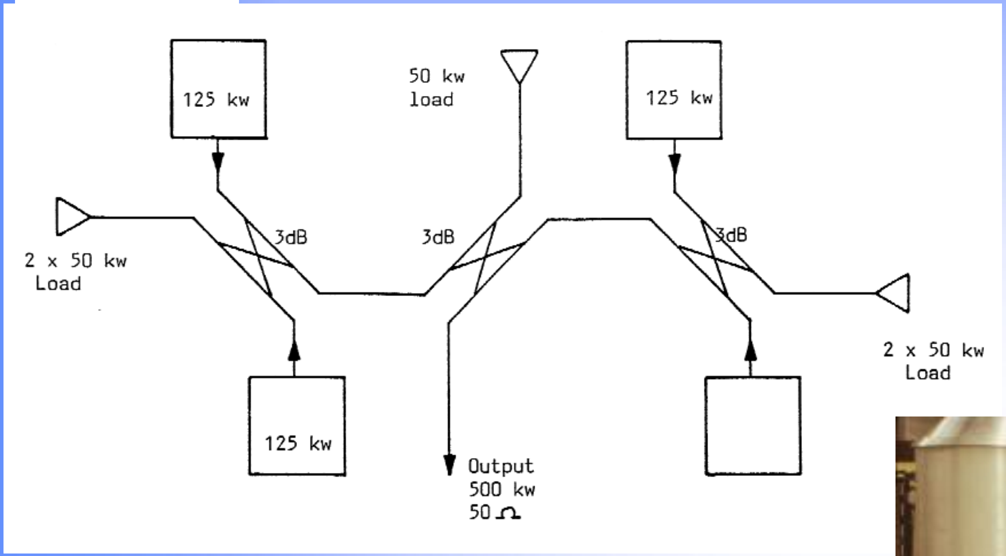
CERN Linac3: 100 MHz, 350 kW

50 kW Driver: TH345, Final: RS 2054 SK

CERN PS: 13-20 MHz, 30 kW

Driver: solid state 400 W, Final: RS 1084 CJSC

Combining tetrode amplifiers



CERN SPS 200 MHz, 500 kW, amplifiers

SPS 200 MHz RF system

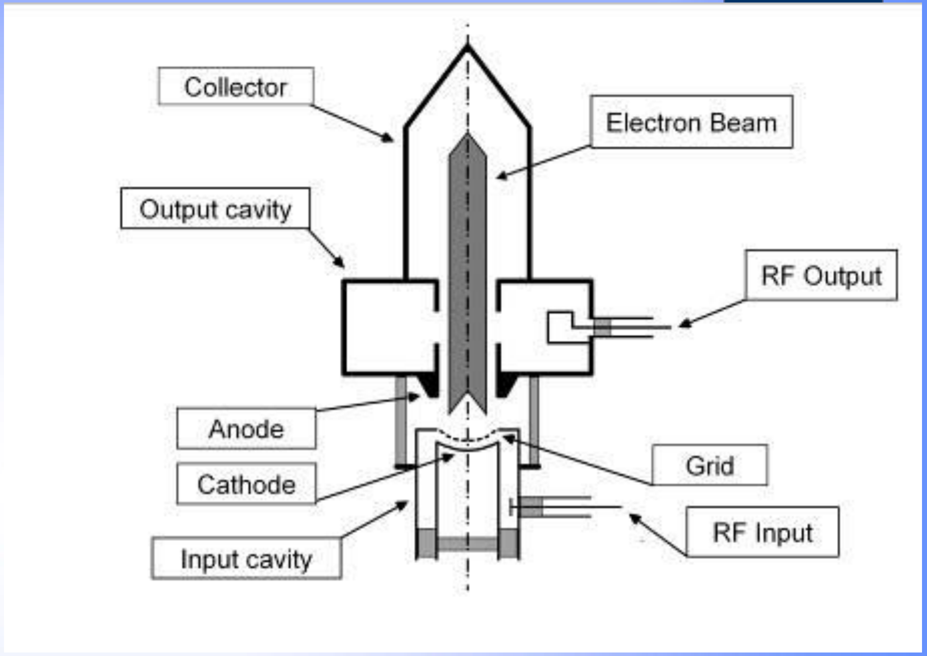
“Siemens”:
4 x 550 kW (28 tetrode amplifiers)

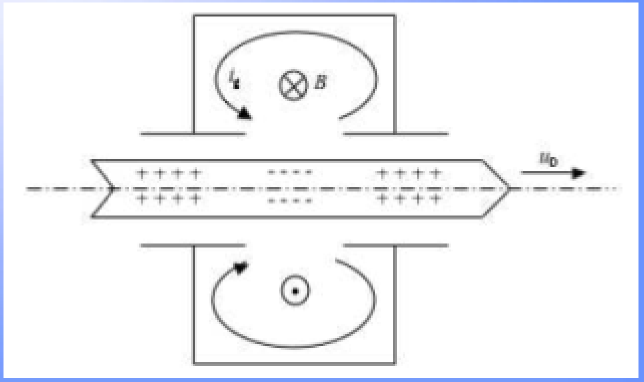
“Philips”:
4 x 550 kW (72 tetrode amplifiers)

Inductive output tube (IOT)

<u>Differences from tetrode</u>

- Electron flow axial
  - Requires axial magnetic field to prevent beam spreading
- Anode voltage is constant
  - Electron velocity is high
- Bunched beam induces current in output cavity
- Separate electron collector
  - Large collection area
- Increased isolation between input and output
- Effective gap voltage reduced by transit time effects
- Effective gap voltage less than ~$0.9V_0$ to allow electrons to pass to the collector
- Theoretical efficiency ~ 70%



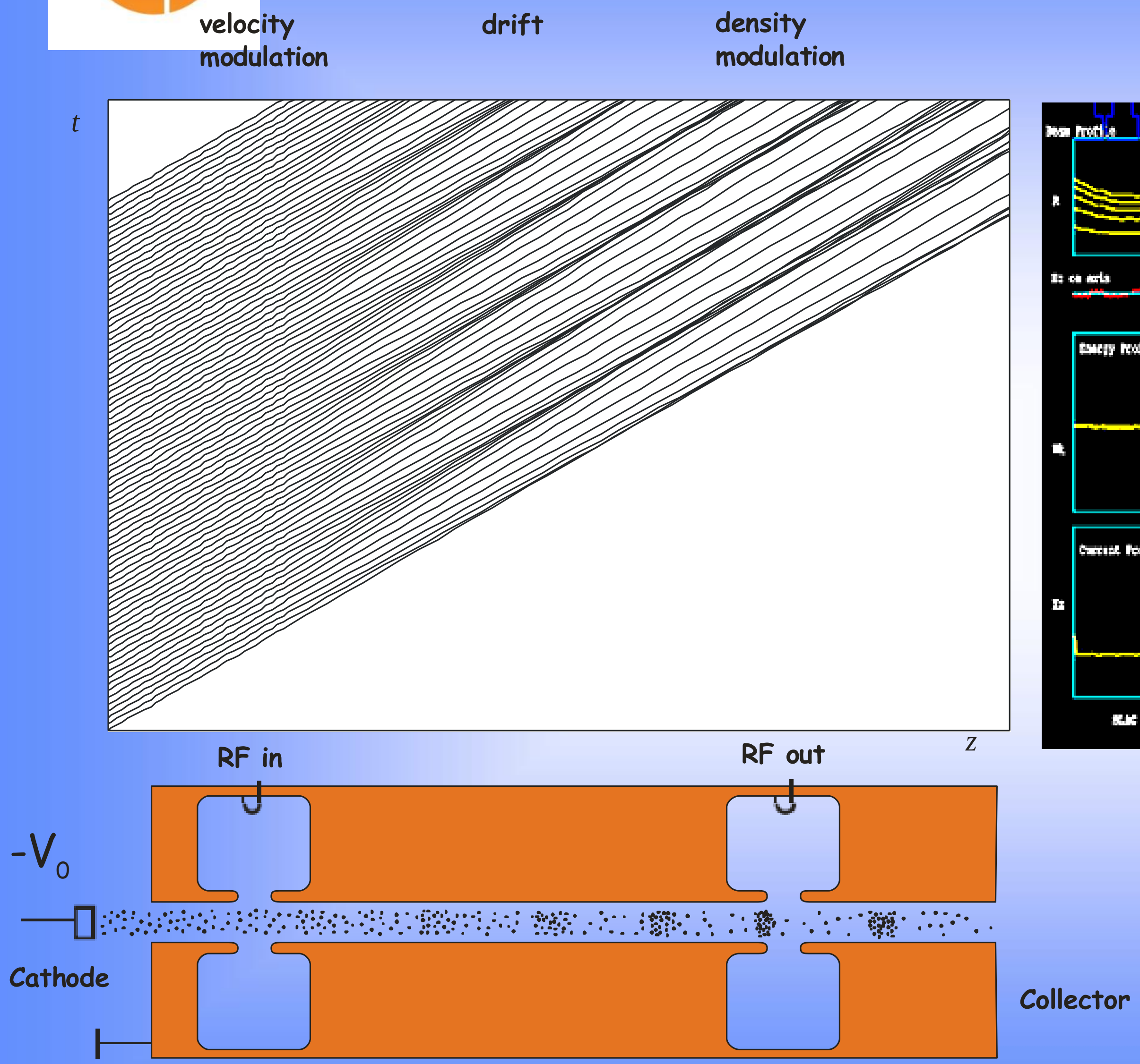


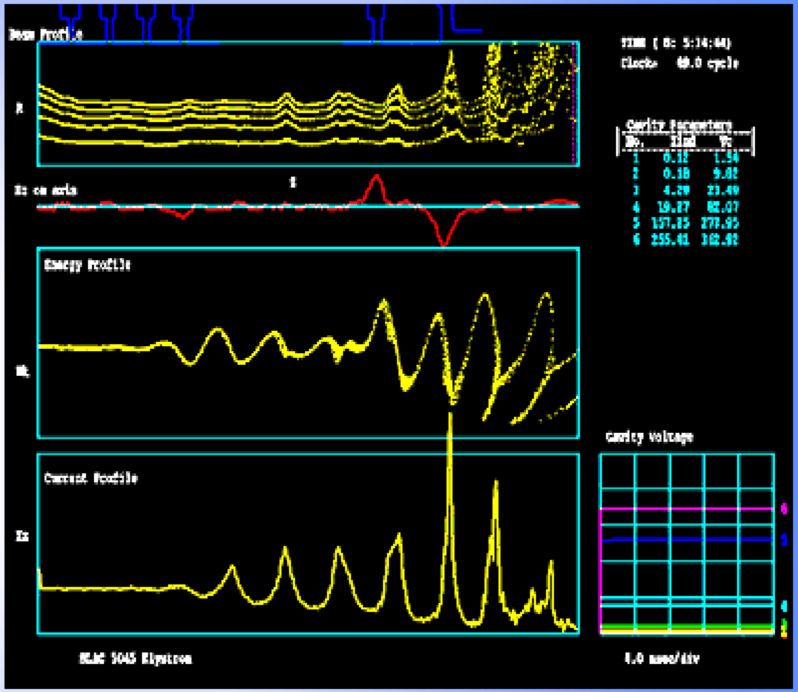
UHF IOT for TV broadcasting

Frequency	470 - 810 MHz
Power	64 kW
Beam voltage	32 kV
Beam current	3.35 A
Gain	23 dB
Efficiency	60%

Photos courtesy of e2v technologies

Klystron principle





Perveance:

$$K = I/V^{3/2}$$

DESY S-Band Tube

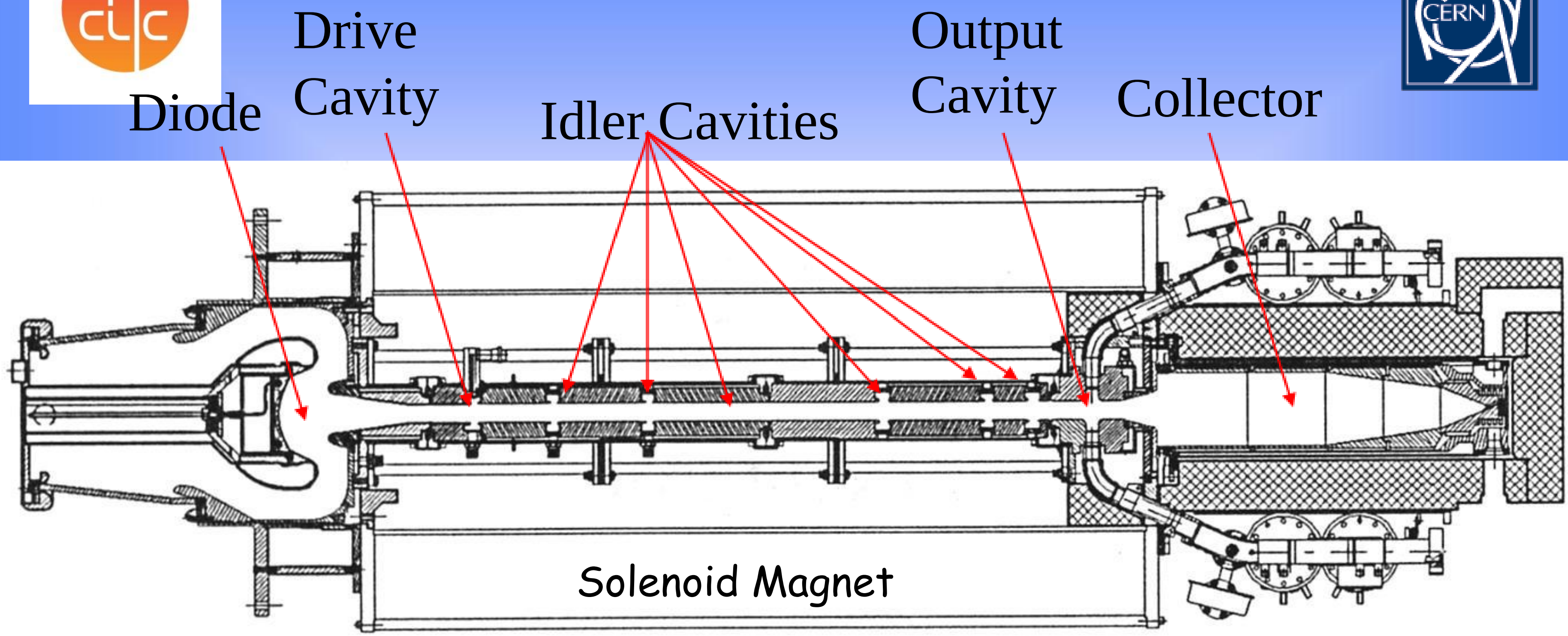


FIGURE 1. The 150-MW klystron assembly shown with magnets and lead.

f = 2996 MHz

P = 150 MW

K = 1.8 μP

V_b = 535 kV

Gain = 55 dB

B~2100 Gauss

Group Delay 150 nsec

J_{cath} = 6 A/cm^2

Efficiency: >40%

PRF: 60Hz

Pulse length: 3 μs

I_b= 700 Amps

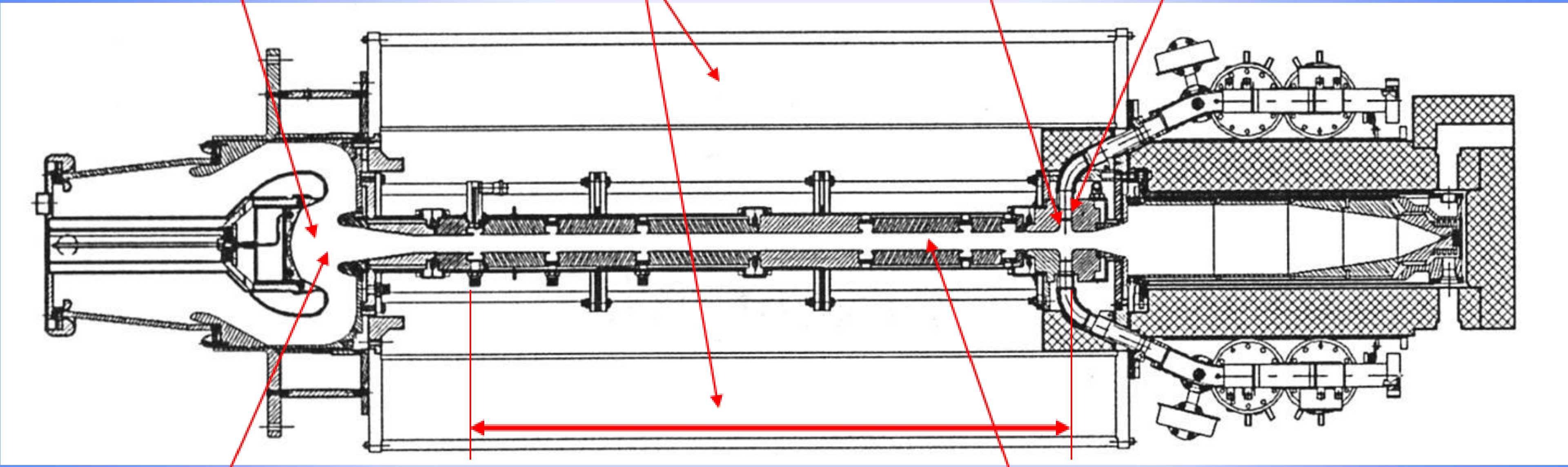
Klystron Amplifier Scalings

Cathode current density: f^{0}

Focusing field strength: $B \sim \lambda_q^{-1}$

Output Cavity Gap Fields $\sim f^{0}$

Circuit losses: $f^{1/2}$



Beam area convergence: f^{0}

Tube length: $\lambda_q \sim V^{3/2}$

Beam Power & Output Power: f^{-2}

Klystrons

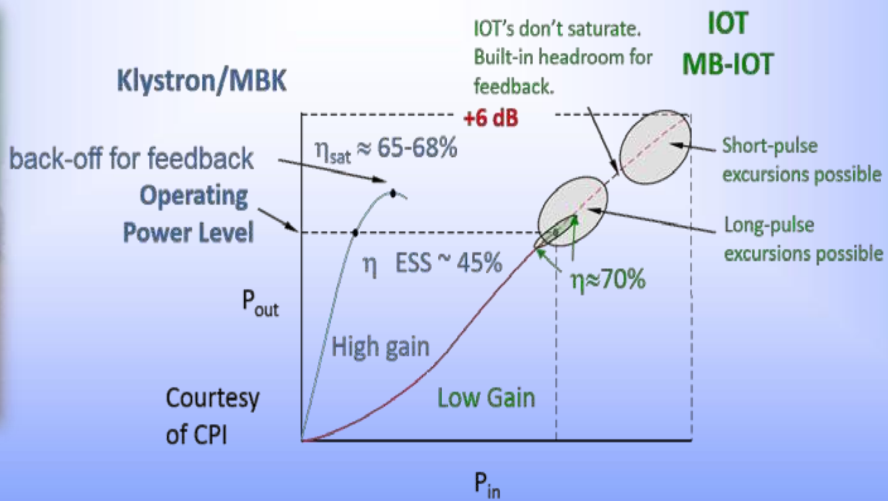
CERN CTF3 (LIL):
3 GHz, 45 MW,
4.5 μs, 50 Hz, η 45 %

CERN LHC:
400 MHz, 300 kW,
CW, η 62 %

RF power generators – efficiencies

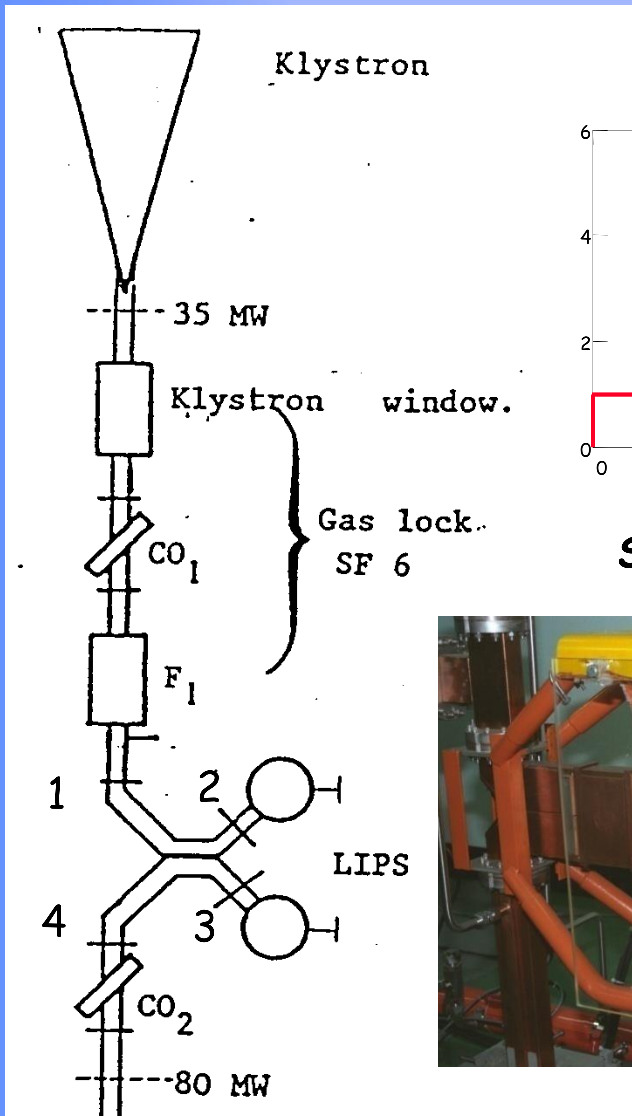
	Tetrodes	IOTs (Inductive Output Tubes)	Conventional klystrons	Solid State PA	Magnetrons
f range:	DC – 400 MHz	(200 – 1500) MHz	300 MHz – 12 GHz	DC – 20 GHz	GHz range
P class (CW):	1 MW	1.2 MW	1.5 MW	1 kW @ low f	< 1MW
typical η:	78 %	70%	50- 73 %	60%	90%
Remark	Broadcast technology, widely discontinued		new idea promises significant increase	Requires P combination of thousands!	Oscillator, not amplifier!

Thales RS 1084 CJ
< 30 MHz, 75 kW
η< 78% (class B)

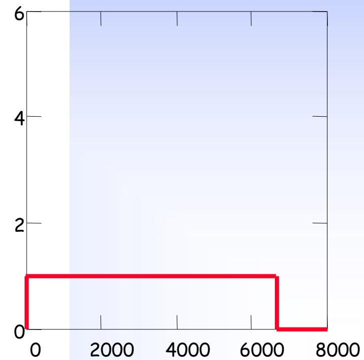


CLIC DB klystron
1 GHz, 20 MW, 15 0 μs,
50 Hz, η≈ 73%

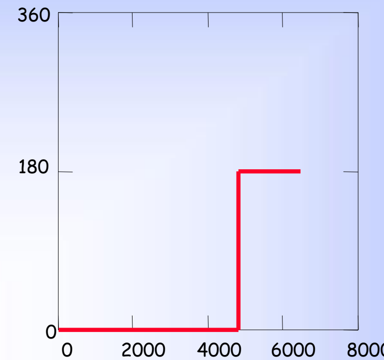
RF Pulse Compression



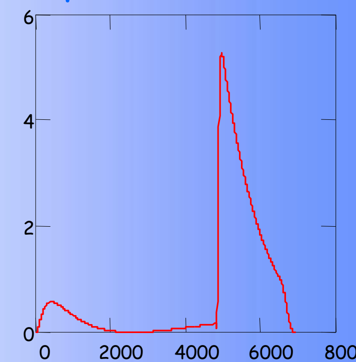
Input pulse



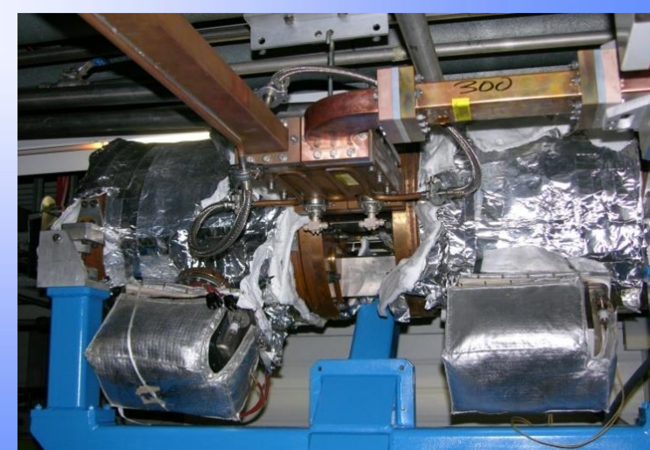
Input phase



"SLED" output pulse

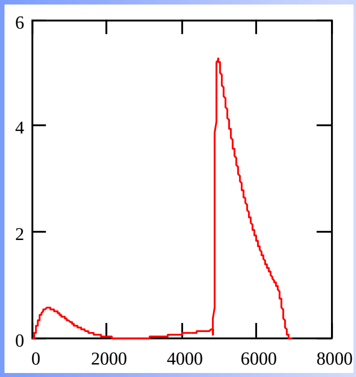


SLED: SLAC Energy Doubler **LIPS**: LEP Injector Power Saver

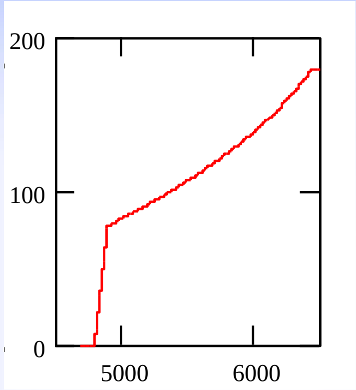


Flat output pulses

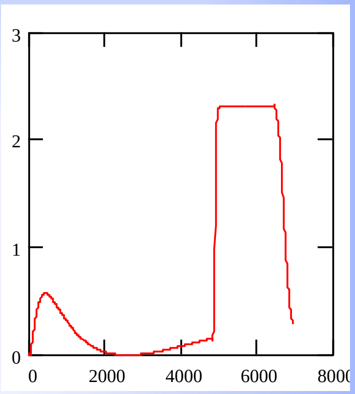
Standard "SLED" Pulse



RF phase modulation

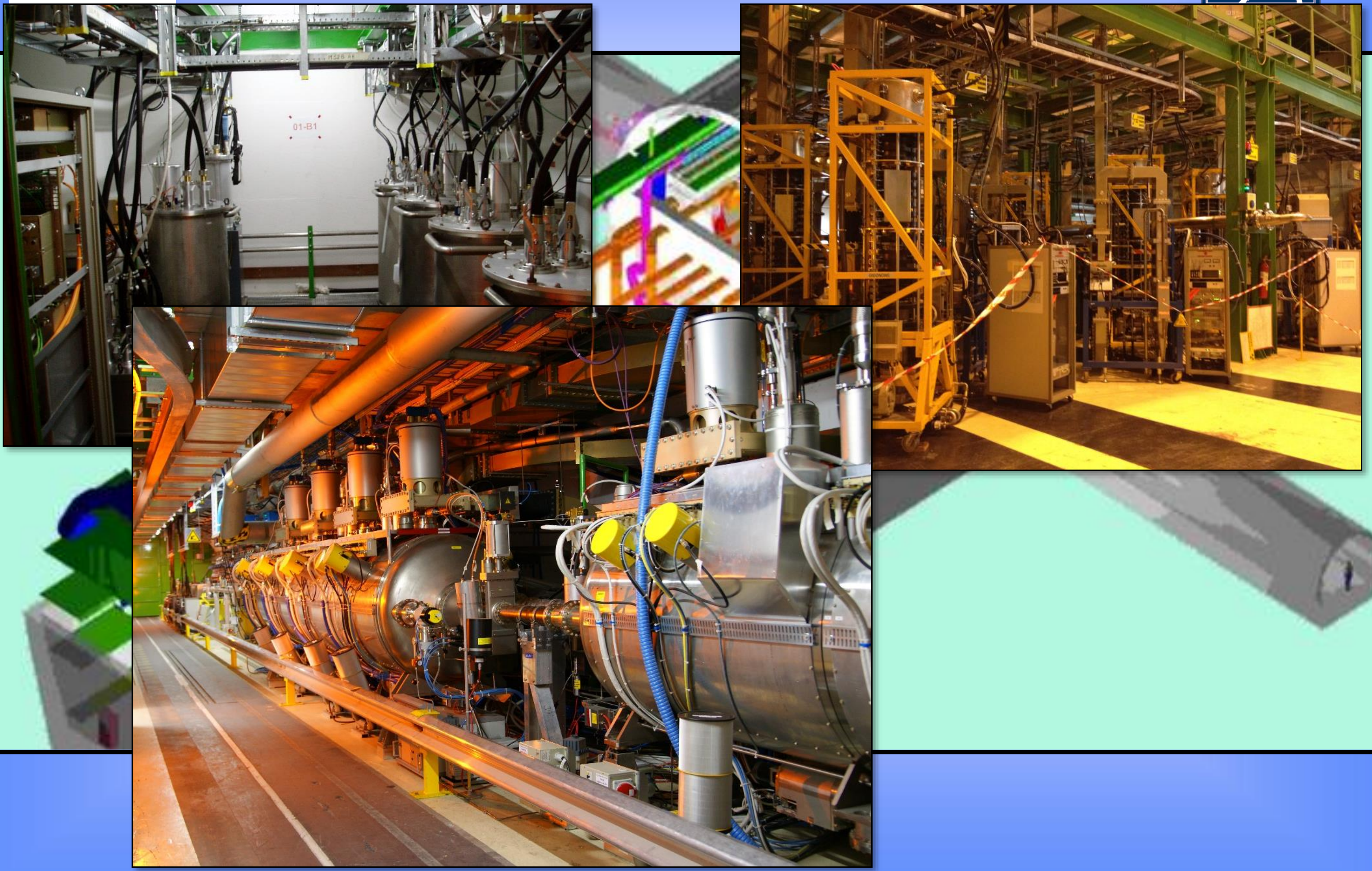


Flat pulse

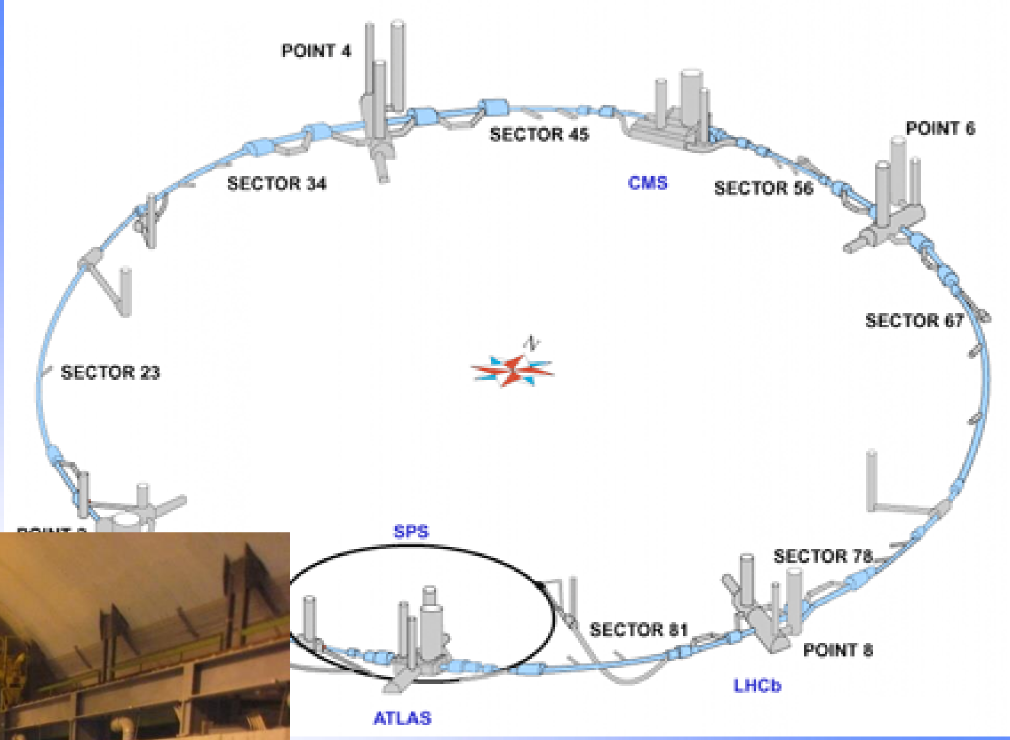


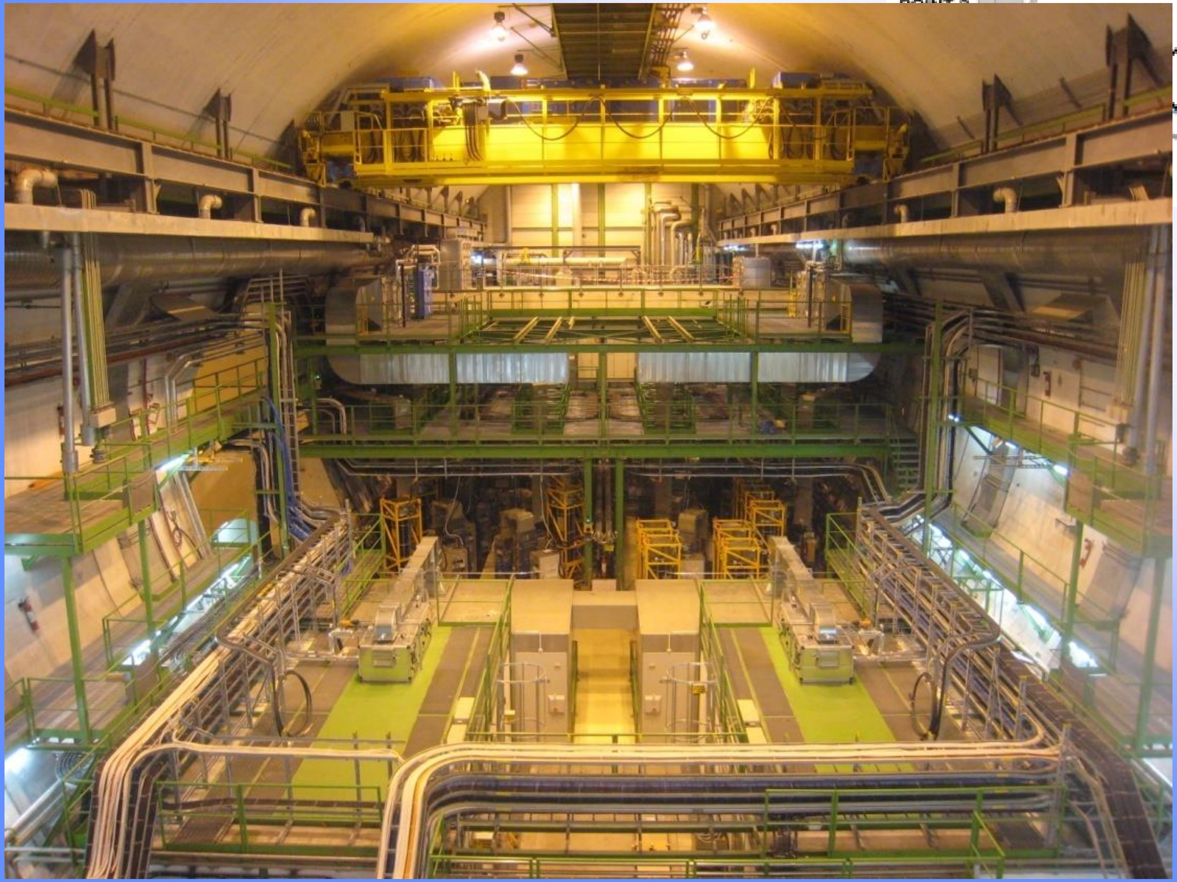
CTF3 single cavity pulse compressor using a barrel open cavity

LHC RF System



LHC





Two independent rings:

8 RF cavities per ring all installed at point 4

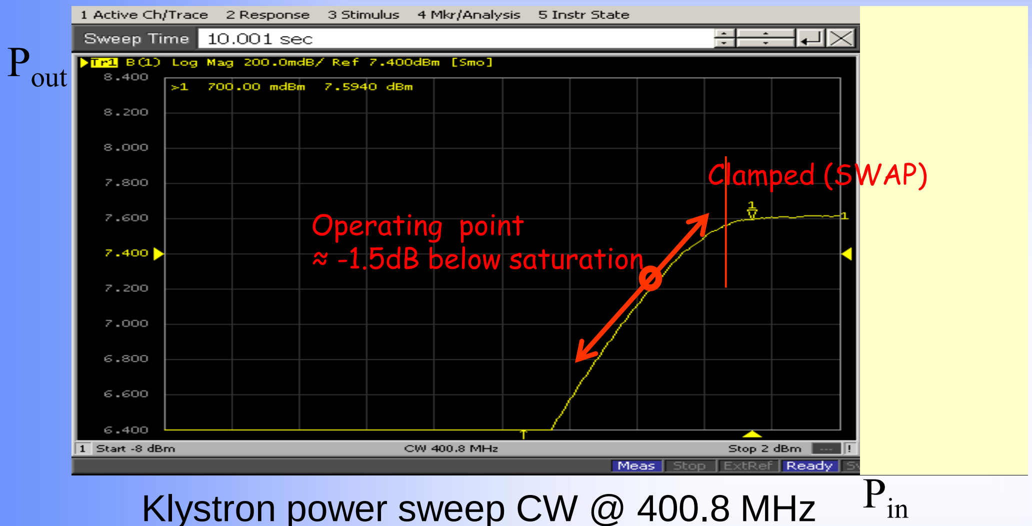
Klystrons and Cavity Controllers in a cavern ~150 m underground

LHC rf system

- 100kV, 40A (ex-LEP) power converters located at the surface
- Klystron modulators, fast protection systems in four HV bunkers
- Sixteen 330 kW klystrons + circulators + RF ferrite loads in UX45
- WR2300 HH WG distribution system to individual cavities
- LLRF for Cavity Controllers in two Faraday Cages

=> Most of RF equipment is not accessible during operation

Klystron CW



Klystron power sweep CW @ 400.8 MHz

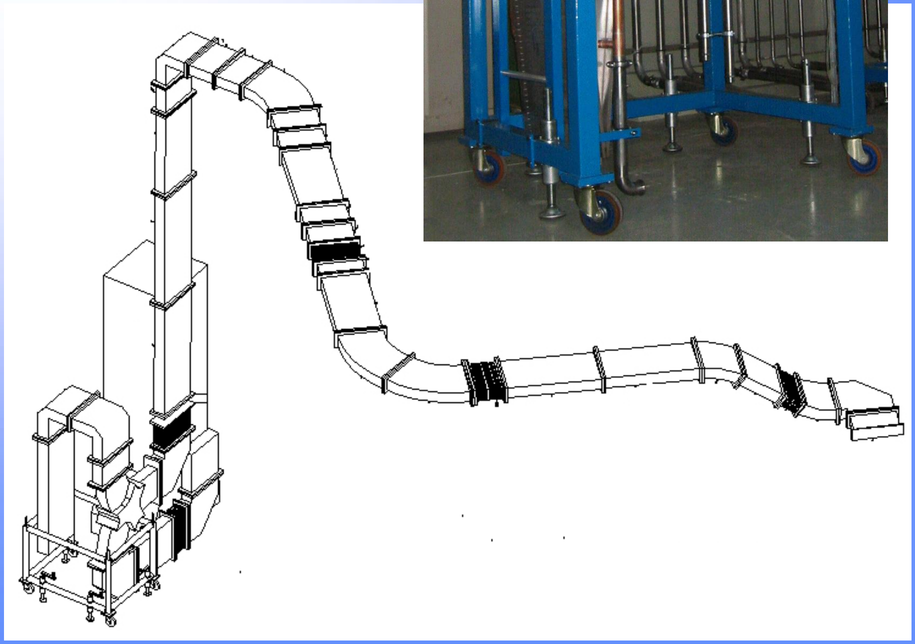
- **1 klystron per cavity**
  - **330 kW max (58 kV, 8.4 A)**
  - **130 ns group delay (~ 10 MHz BW)**
  - **CW gain 39 dB @ 200 kW, 36 dB @ 300 kW**
  - **In operation ≈ 200 kW CW**

Circulator, RF load, WG

- 1 circulator per cavity
  - 330 kW max
  - 60 ns group delay
  - Circulator equipped with temperature control system
    - ⇒Affects the Q_{ext} of the cavity

-1 RF ferrite load per circulator
  - 330 kW CW
  - RF loads reflection < -28 dB

- Wave guide system
  - WR2300 HH
  - Length: 15 to 30 meters



Cavities

8 RF cavities per ring at 400.790 MHz:

Super Conducting Standing Wave Cavities, single-cell, R/Q = 45 ohms, 6 MV/m nominal

Equipped with movable Main Coupler (20000 < Q_L < 180000)

Mechanical Tuner range = 100 kHz

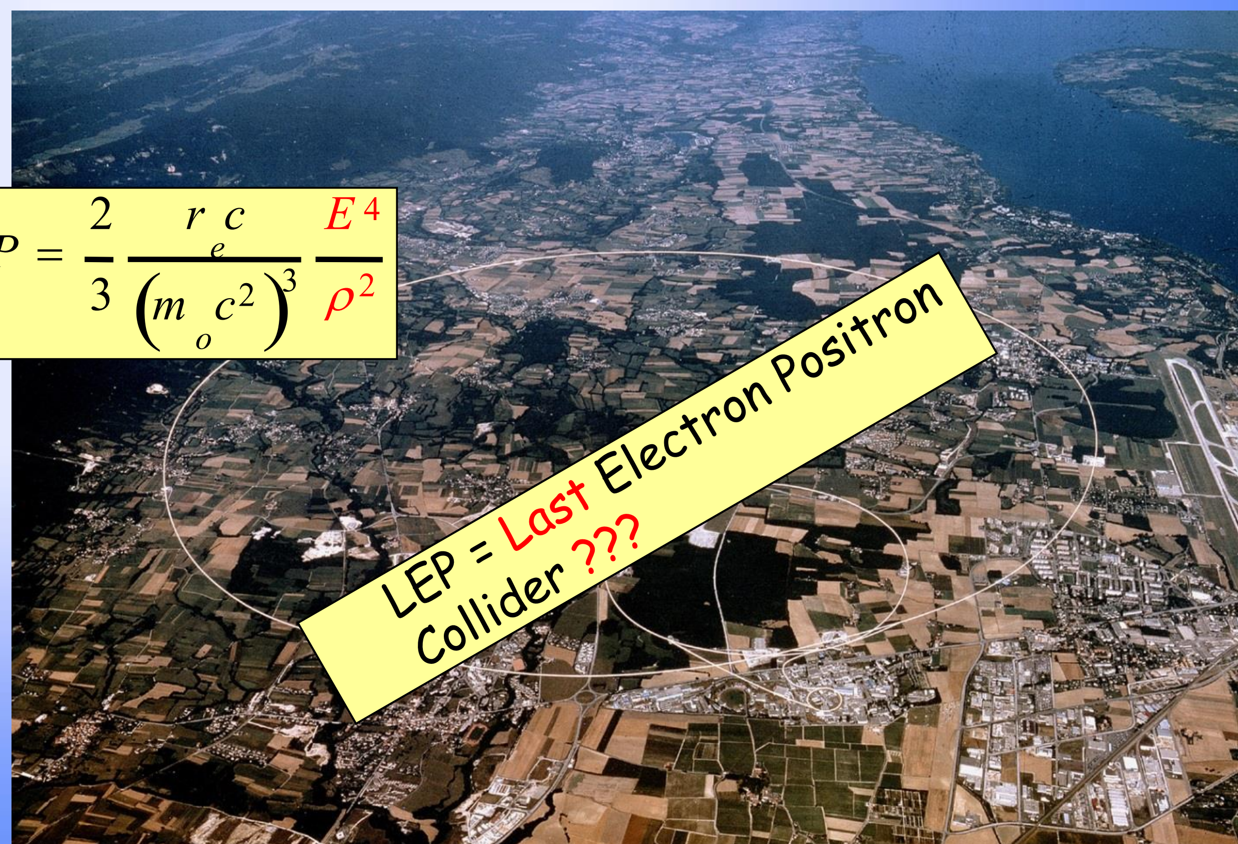
CLIC
a two beam accelerator

The LEP collider

- LEP (Large Electron Positron collider) was installed in LHC tunnel
- e+ e- circular collider (27 km) with E_{cm}=200 GeV

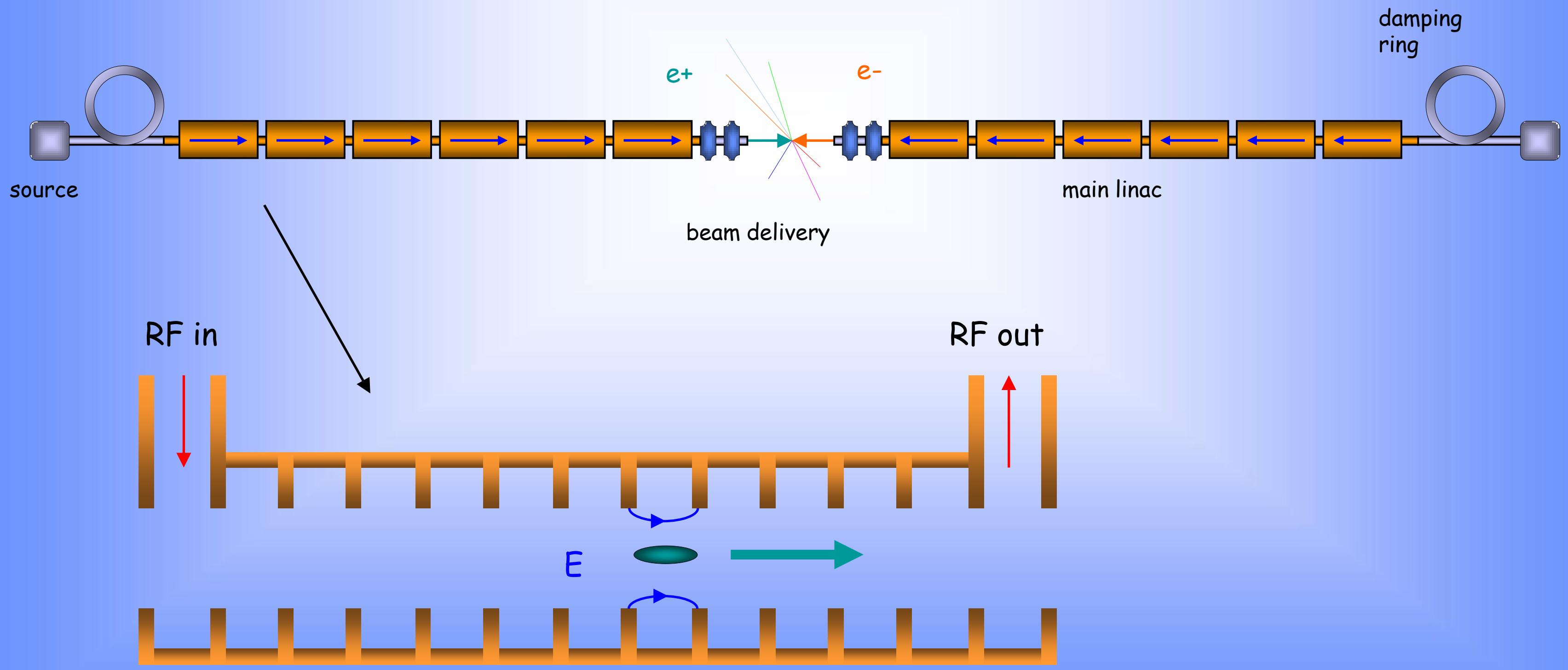
- Problem for any ring:
  Synchrotron radiation
- Emitted power:
  scales with E^4 !!
  and $1/m_0^3$ (much less for heavy particles)
- This energy loss must be replaced by the RF system !!
- particles lost 3% of their energy each turn!

$$P = \frac{2}{3} \frac{r_e c}{\left(m_o c^2\right)^3} \frac{E^4}{\rho^2}$$

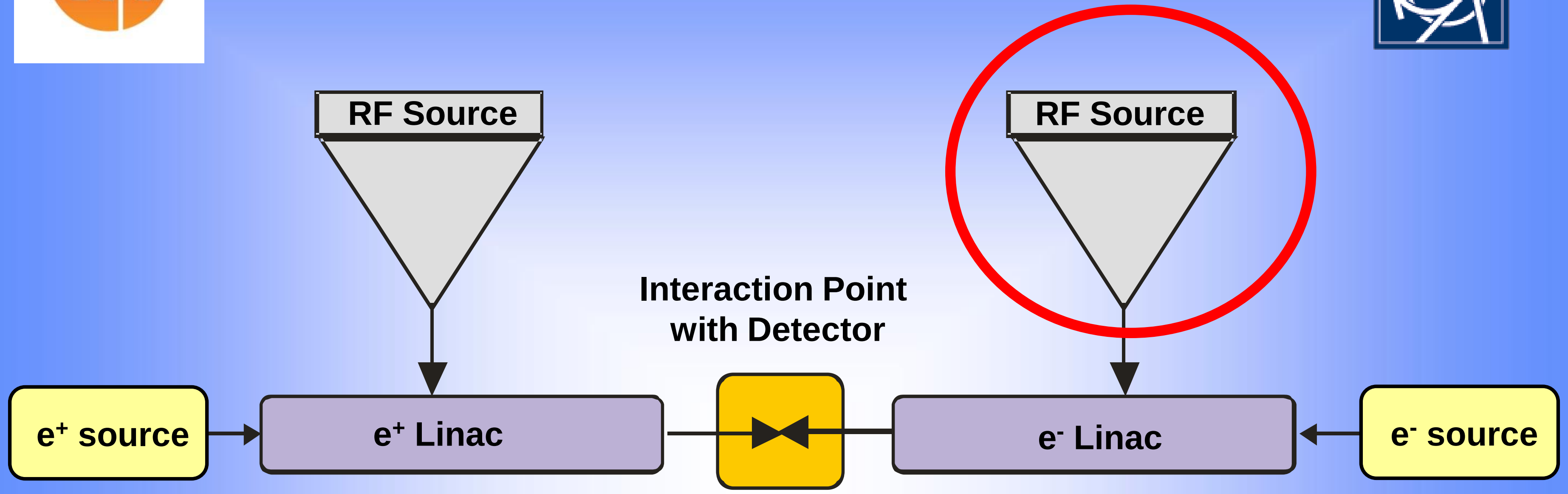


The next lepton collider

- Solution: **LINEAR COLLIDER**
- avoid synchrotron radiation
- no bending magnets, huge amount of cavities and RF

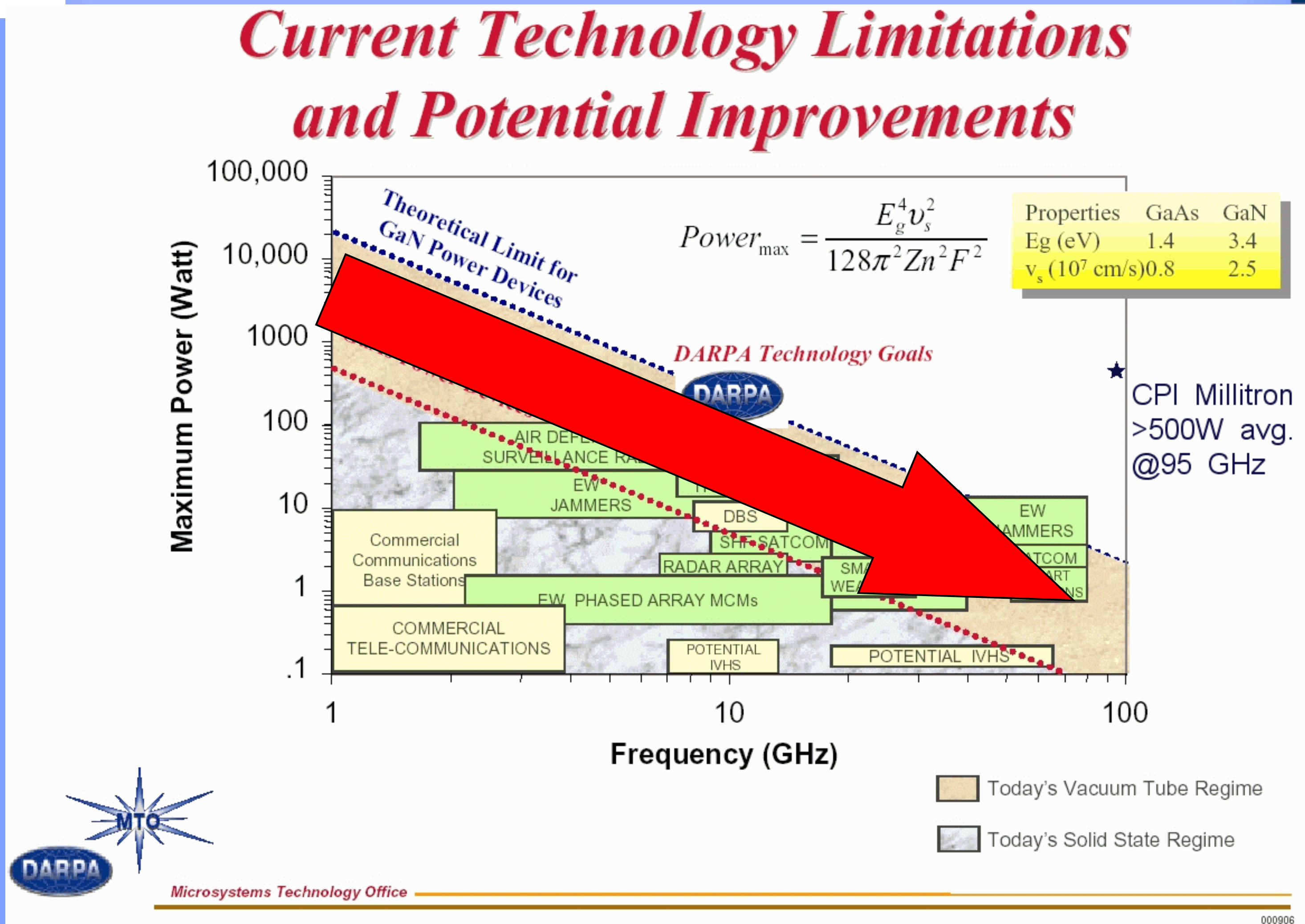


What is a Linear Collider



- High Accelerating Gradient to minimize size and cost
  in case of CLIC 100 MV/m at 12 GHz
  ~ 65 MW input peak power per accelerating structure
  rf pulse length 240 ns

Klystron, the conventional RF power source



Limited by space charge and power density

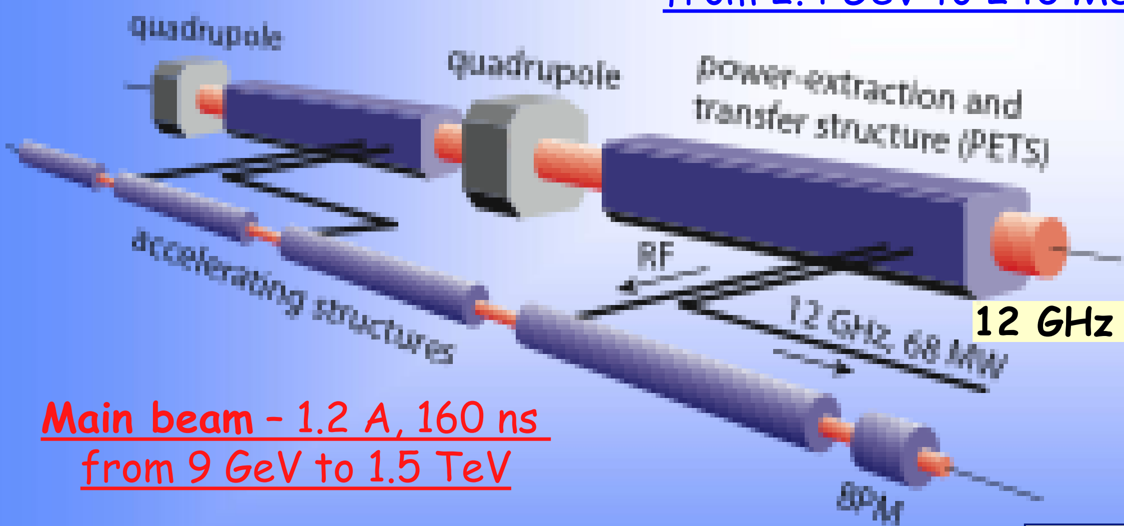
Relativistic Klystron, Two beam accelerator scheme

CLIC two beam scheme

- **Two beam acceleration scheme:**
  - High charge Drive Beam (low energy)
  - Low charge Main Beam (high collision energy)
- **High power for high gradient of >100 MV/m**

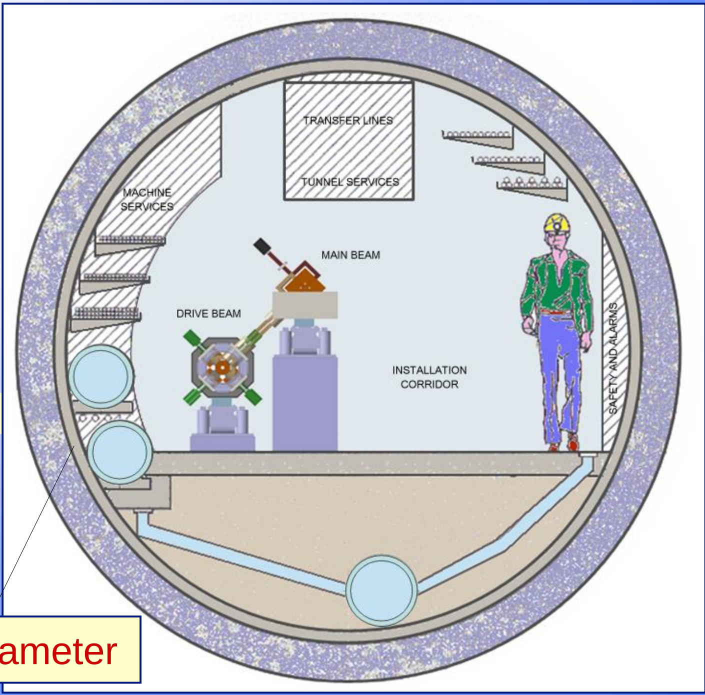
CLIC TUNNEL CROSS-SECTION

Drive beam - 100 A, 240 ns
from 2.4 GeV to 240 MeV



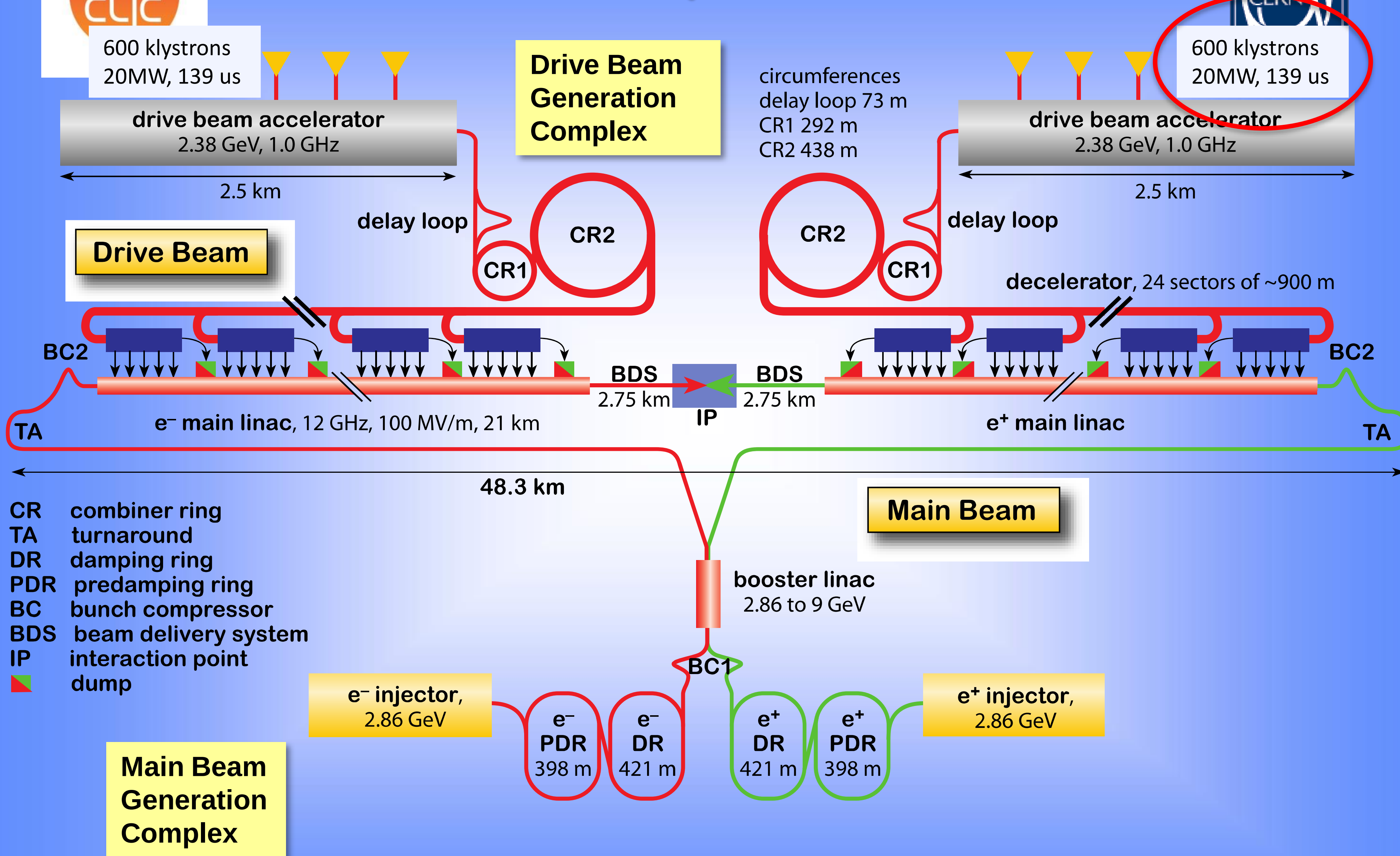
12 GHz

Main beam – 1.2 A, 160 ns
from 9 GeV to 1.5 TeV

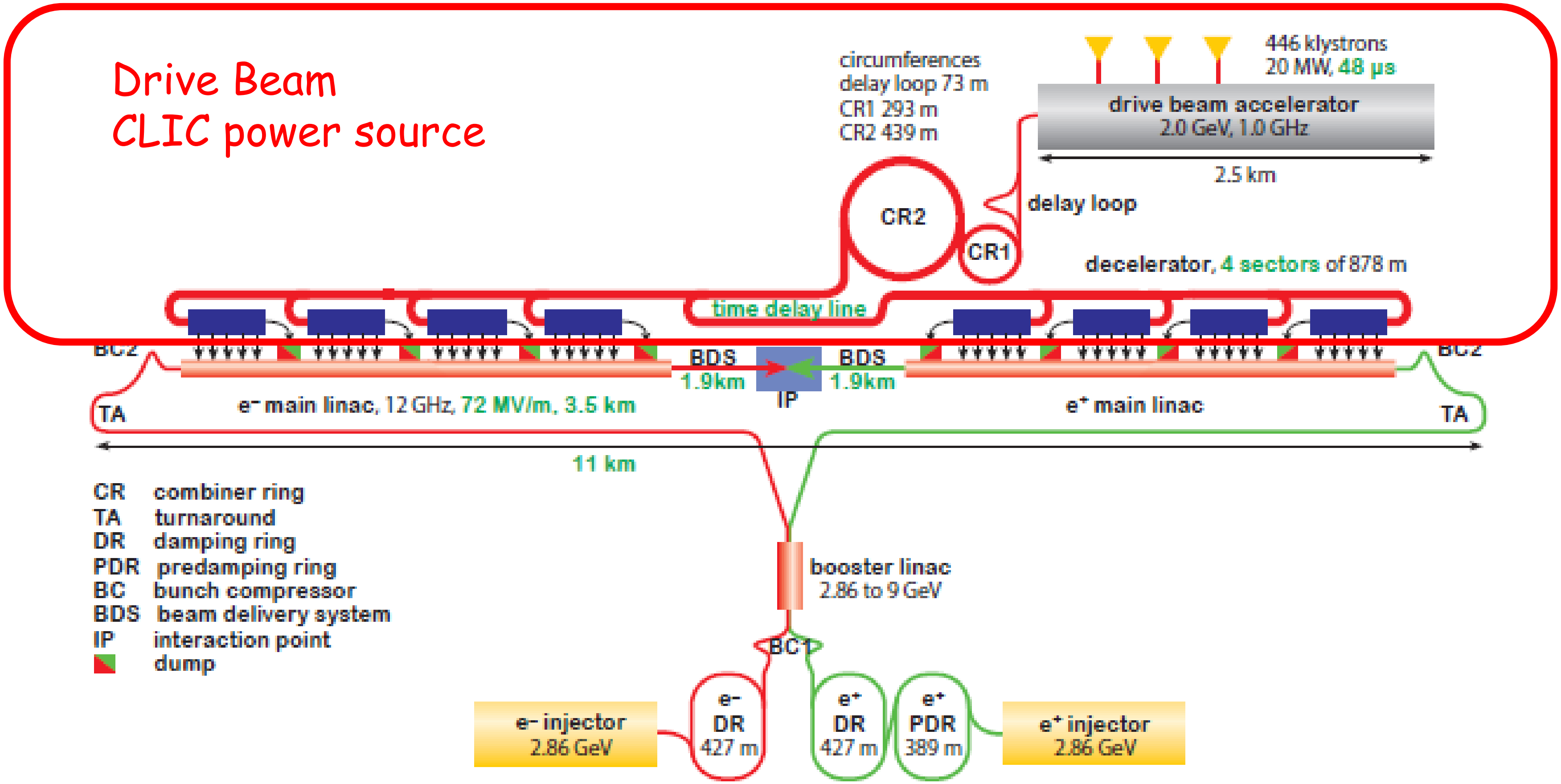


4.5 m diameter

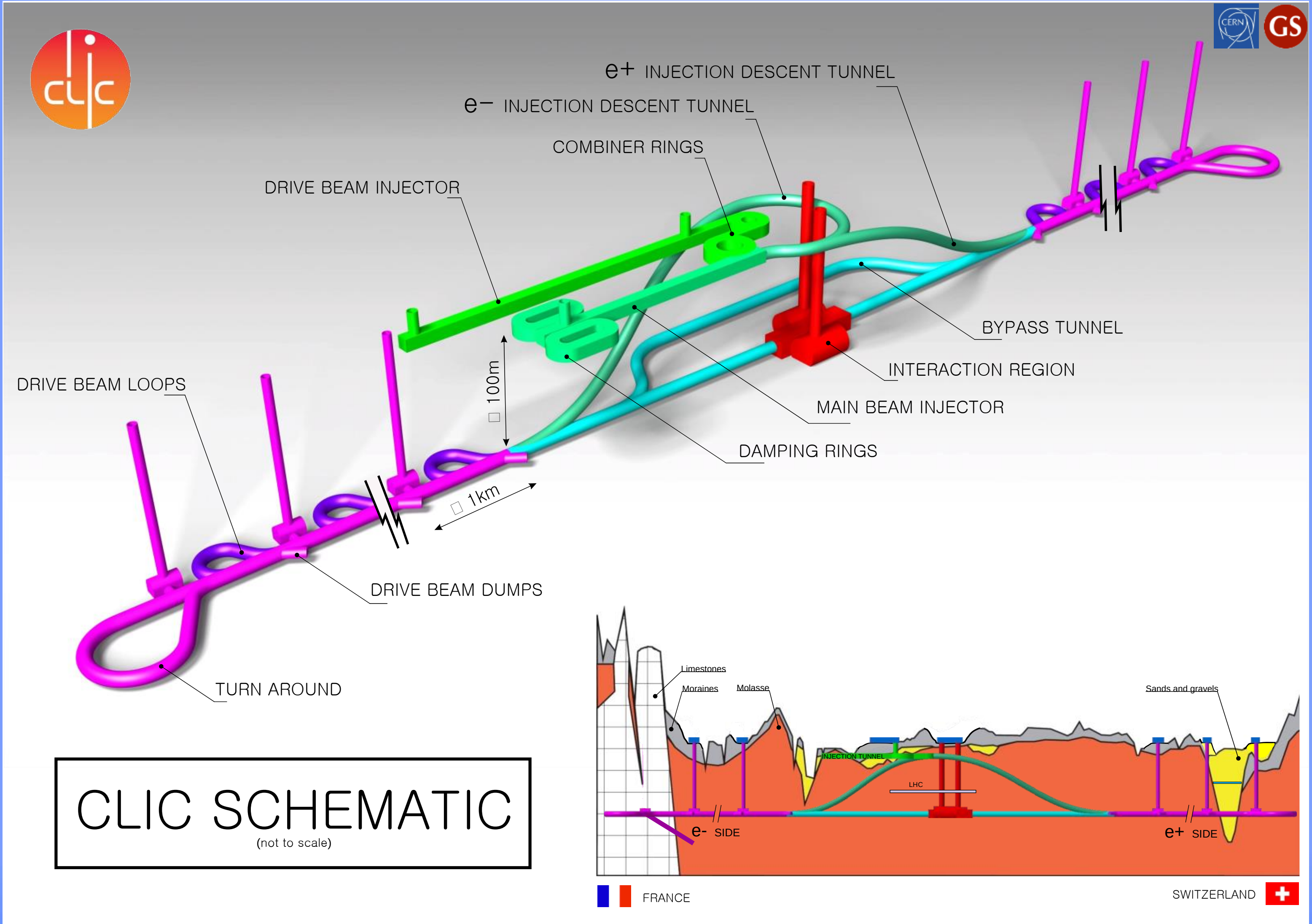
CLIC Layout at 3 TeV



New CLIC layout 380 GeV



CDR tunnel layout



CLIC Drive Beam
a relativistic klystron

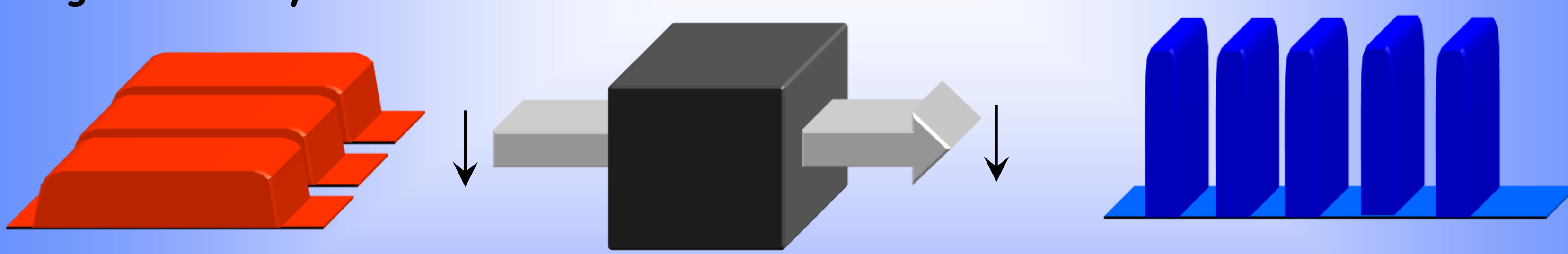
Steffen Döbert, BE-RF

CLIC Drive Beam
A 5 TW klystron ?

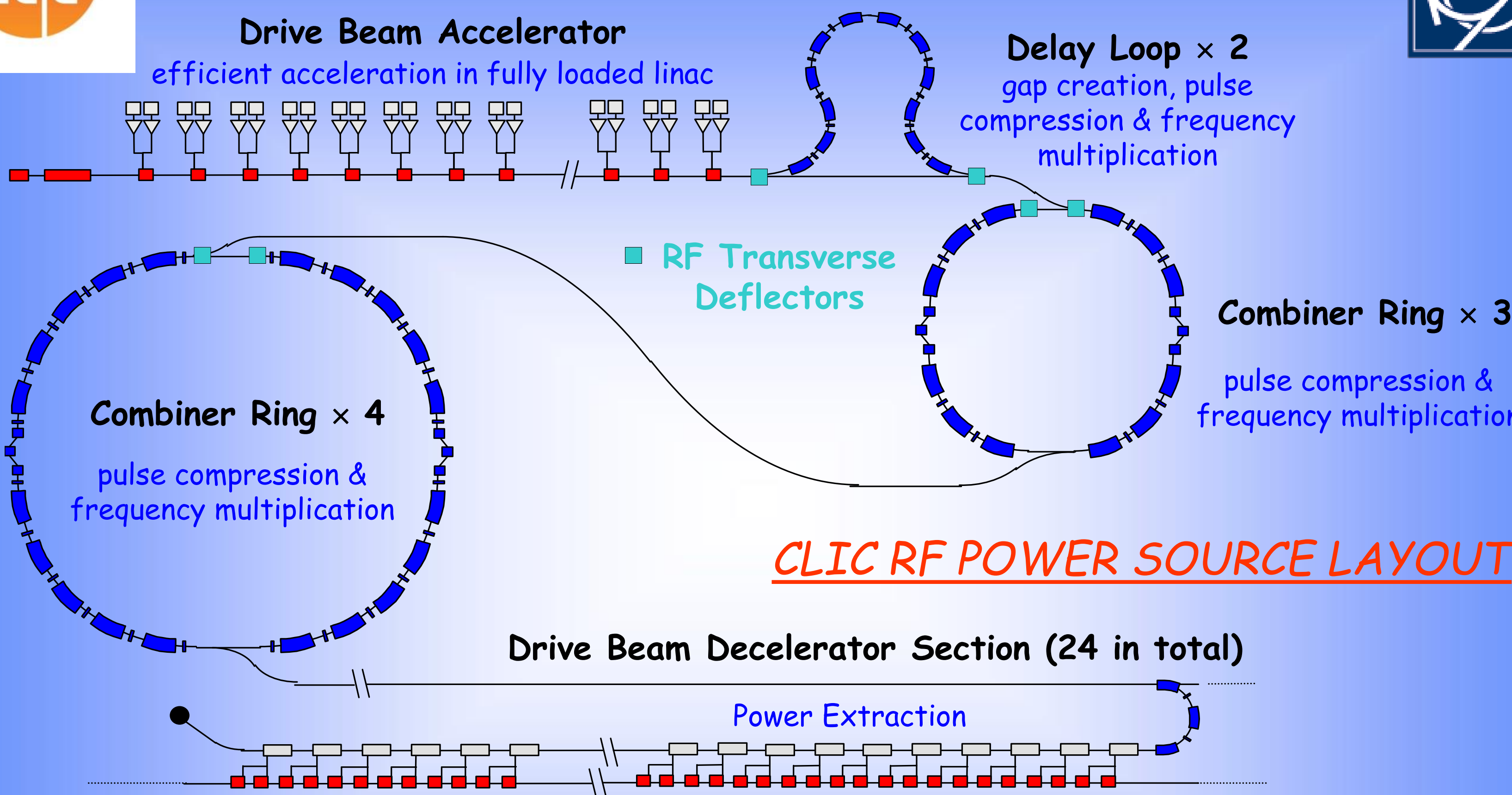
Beam current:	101 A
Beam energy:	2.4 GeV
Pulse Length:	240 ns one drive beam
Repetition Rate:	50 Hz
Average Beam Power:	3 MW / 70 MW full drive beam
Conversion efficiency:	81 % / 44% total
Peak power at 12 GHz:	202 GW / 4.8 TW
Length:	~ 30 km

Drive Beam, an efficient power source

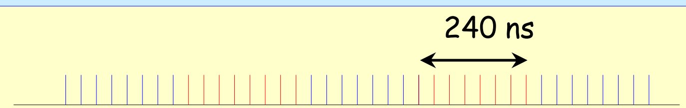
- Conventional power source (klystrons) inefficient
- Extract RF power at 12 GHz from an intense e- “drive beam”
- Generate efficiently long pulse and compress it (in power + frequency)



CLIC Drive Beam generation

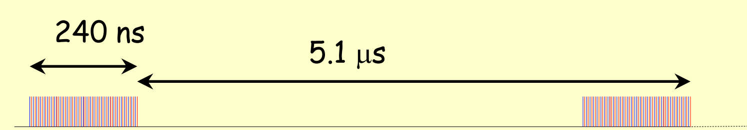


Drive beam time structure - initial



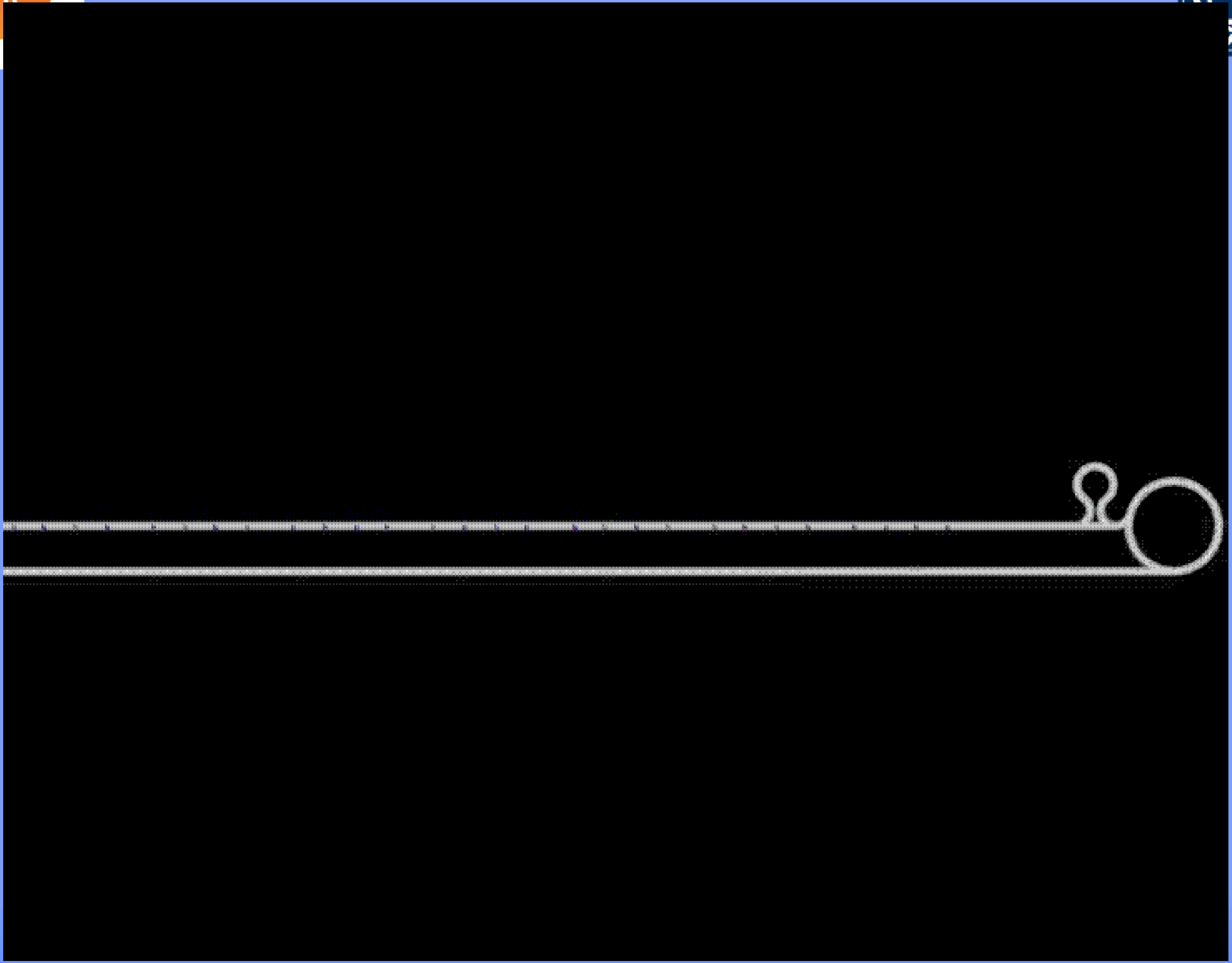
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV - 60 cm between bunches

Drive beam time structure - final

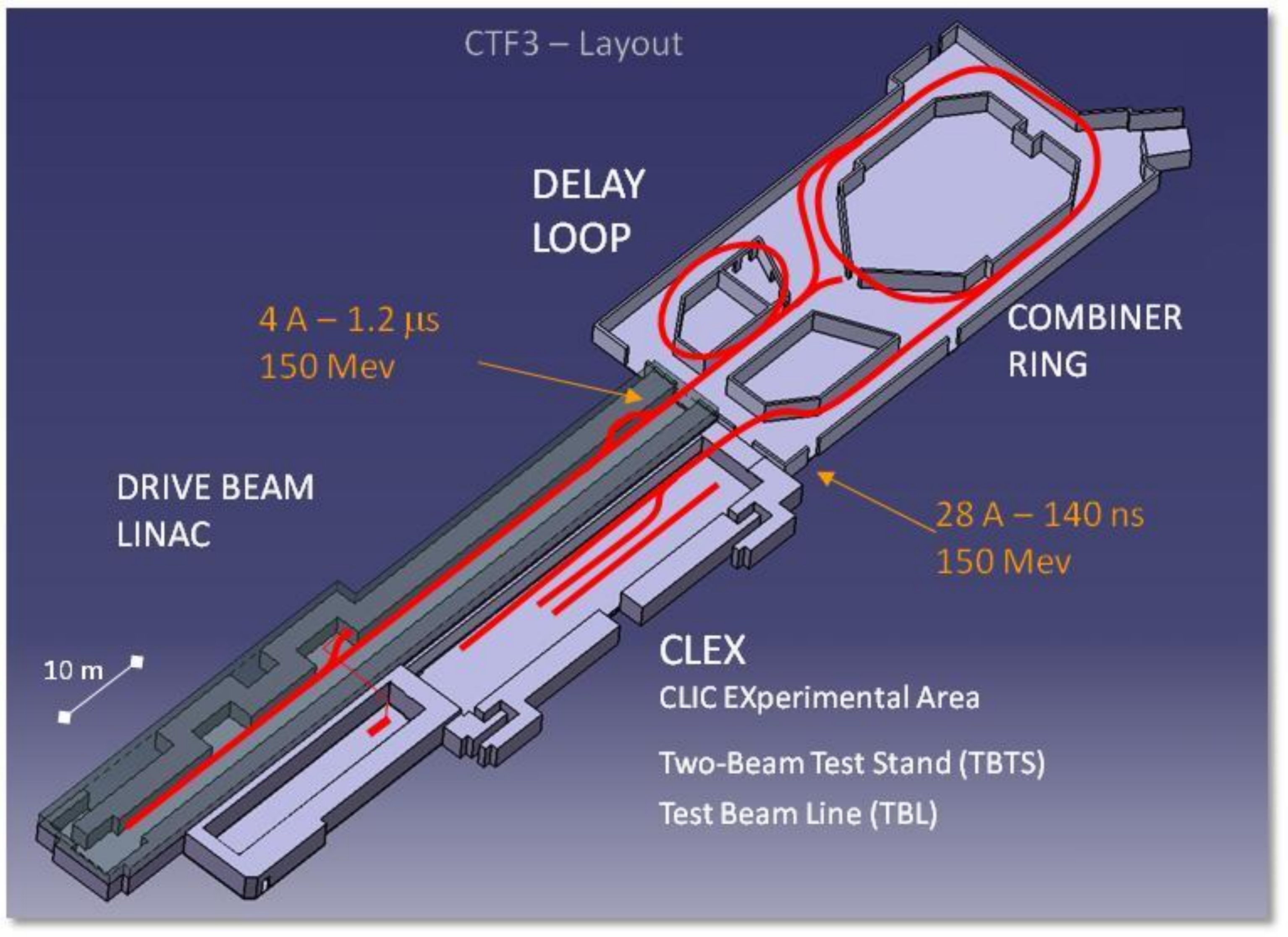


24 pulses – **100 A** – 2.5 cm between bunches

Lemmings Drive Beam



CLIC Test Facility (CTF3)

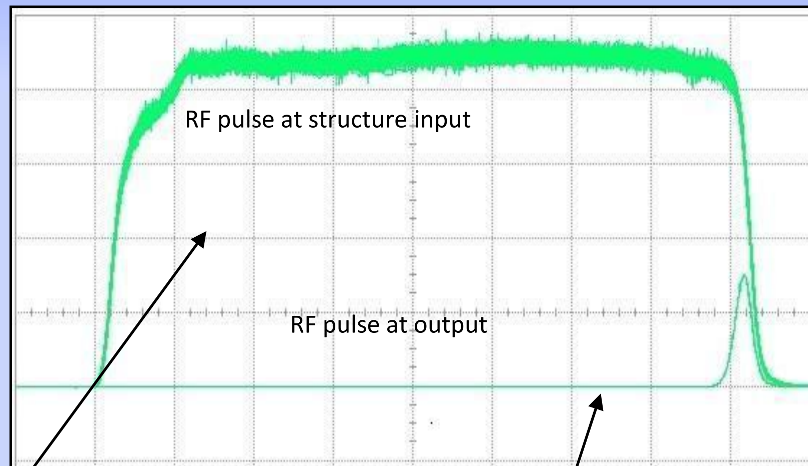


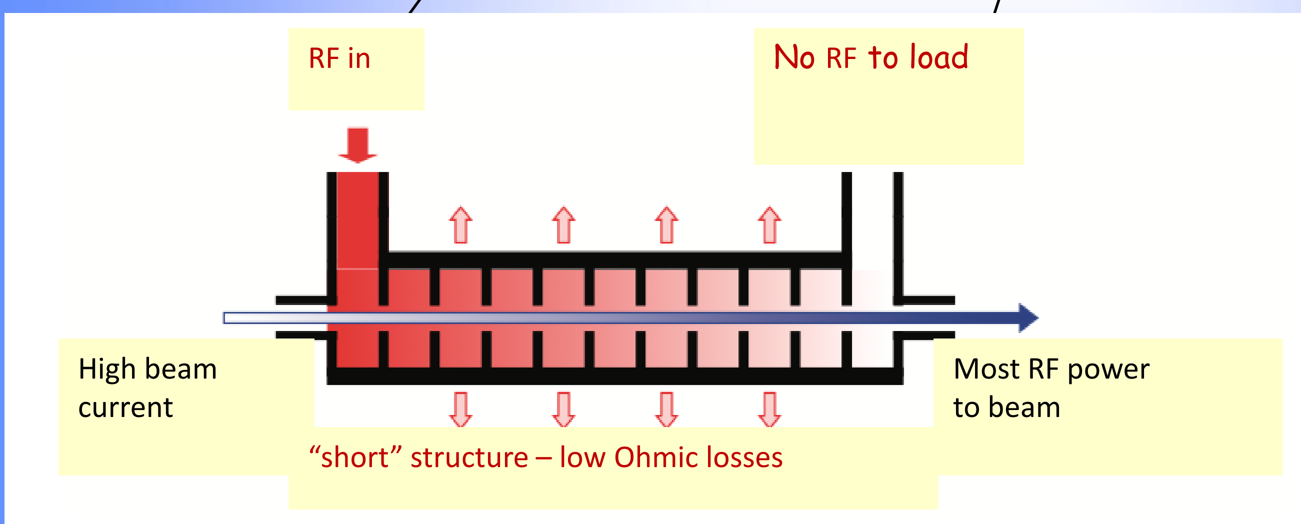
CLIC Test Facility (CTF3)

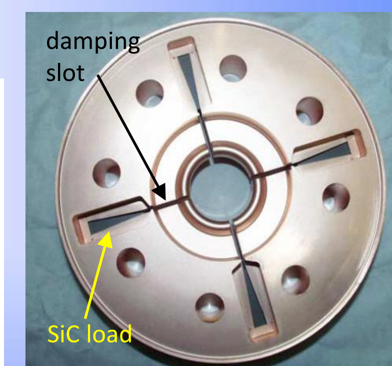
Drive Beam Generation

Full beam loading acceleration

95.3% RF to beam efficiency

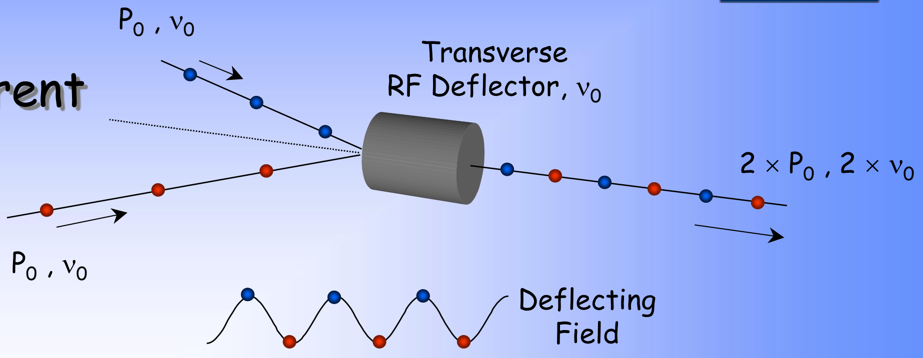


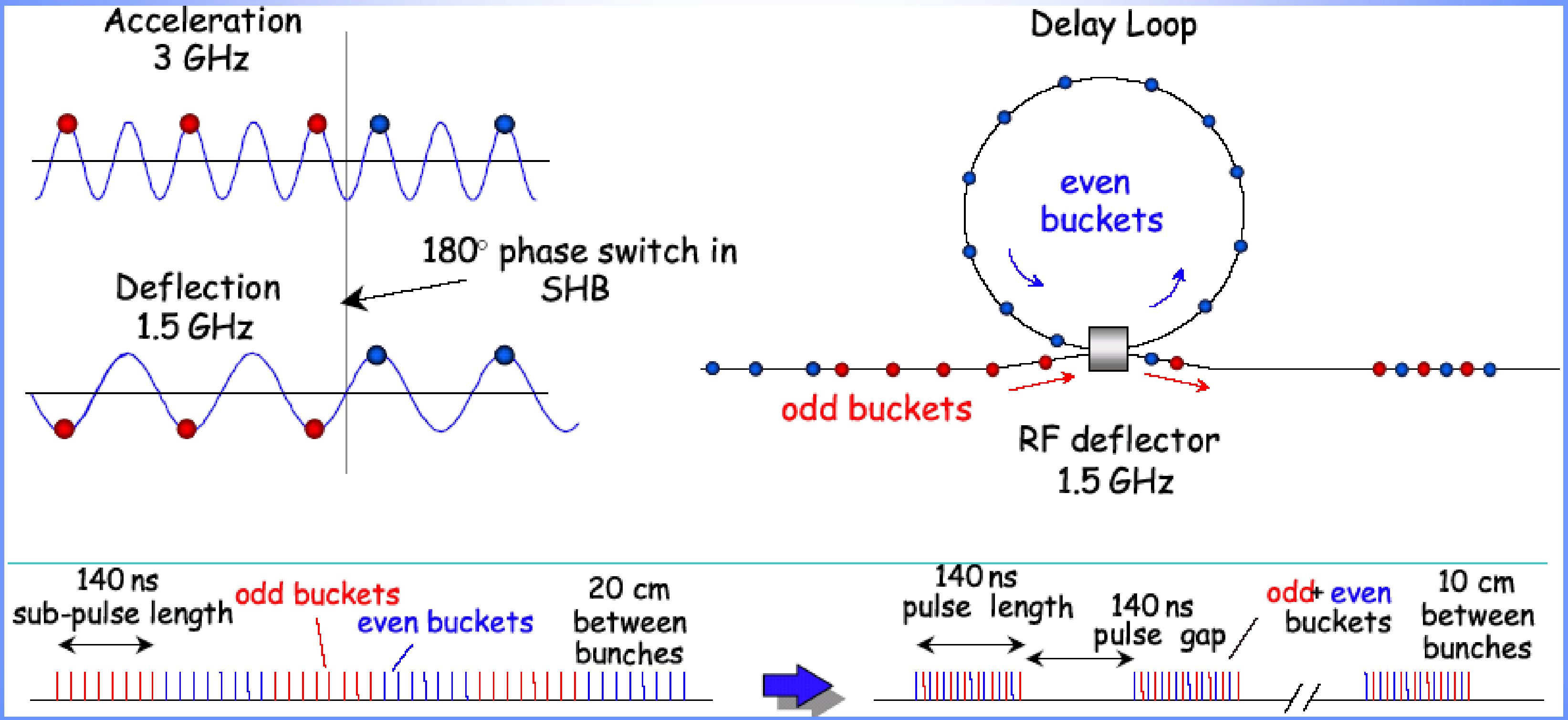




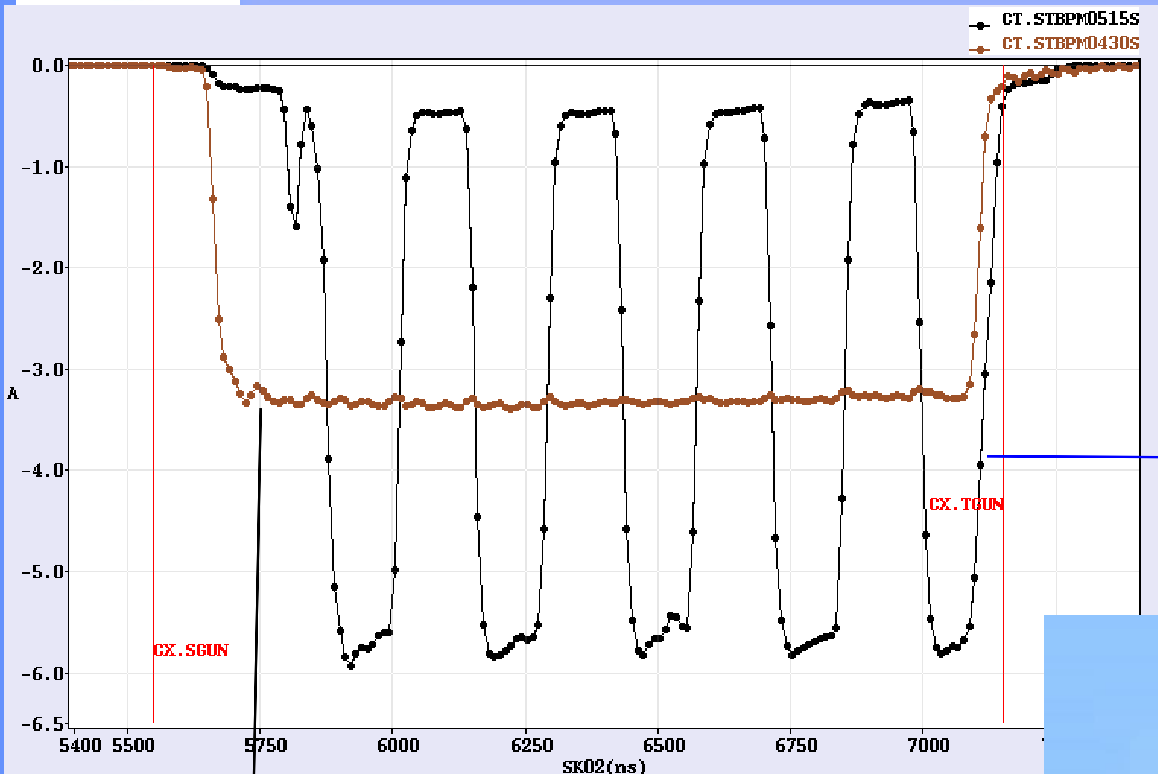
Delay Loop

- Double repetition frequency and current
- Parts of bunch train delayed in loop
- RF deflector combines the bunches

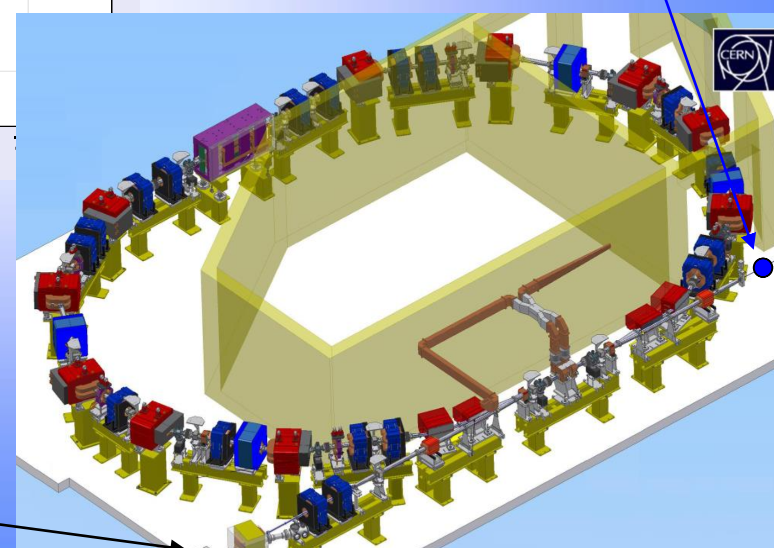




Delay Loop, with beam

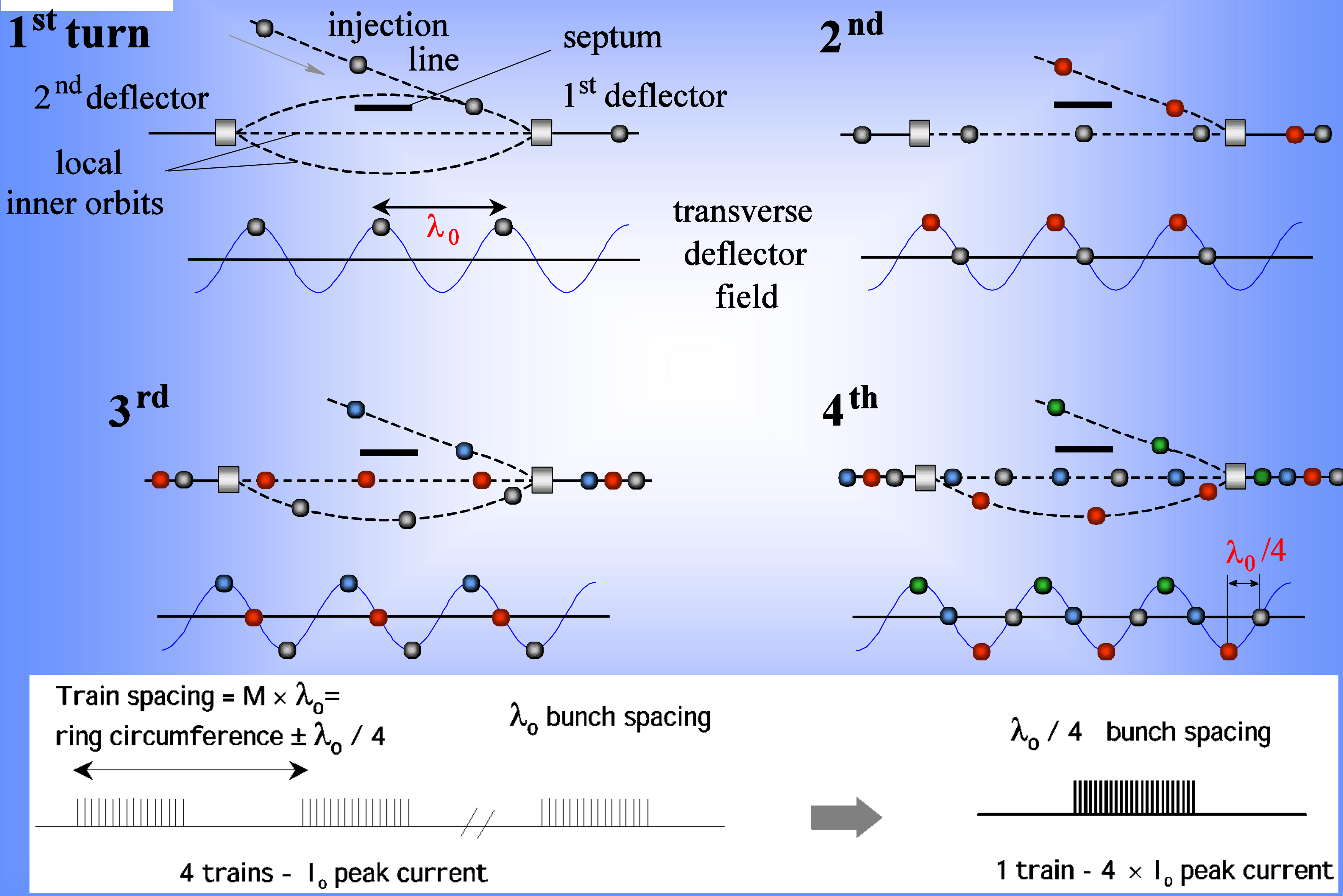


CT.BPM 515
5.8 A + 0. 5 A



CT.BPM 430
3.3 A

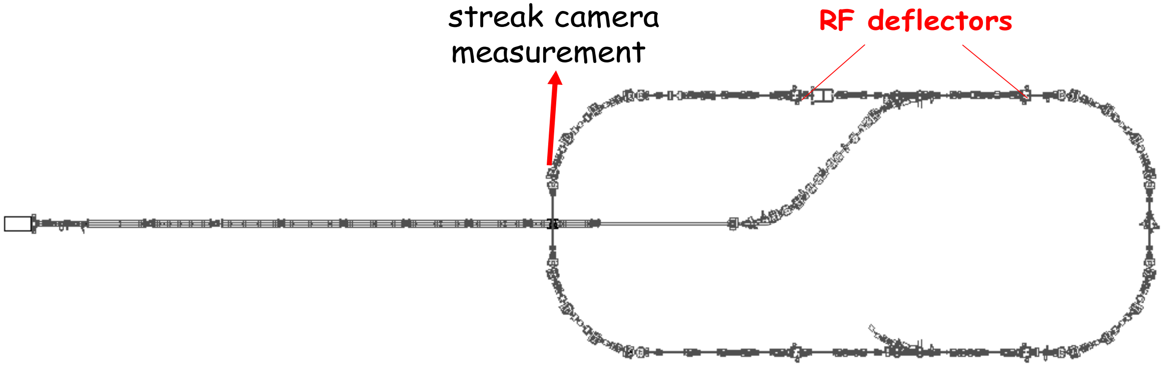
Combiner Ring

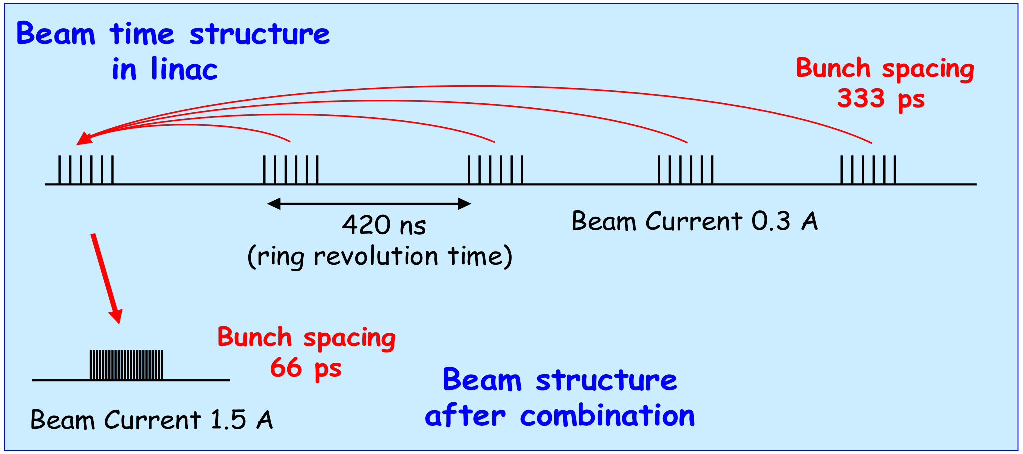


Proof of Principle

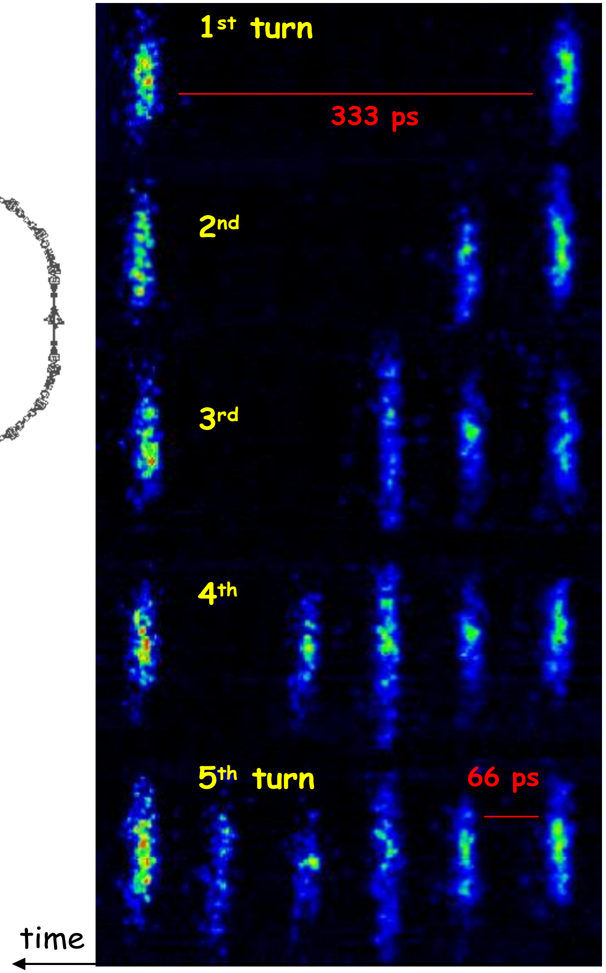
CTF3 - PRELIMINARY PHASE

Successful low-charge demonstration of electron pulse combination and bunch frequency multiplication by up to factor 5



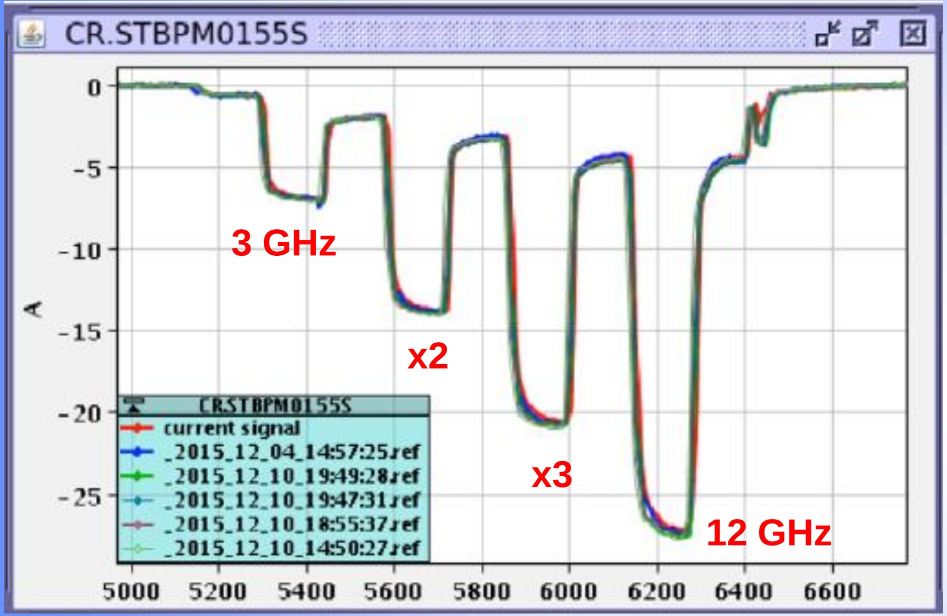


Streak camera image of beam time structure evolution



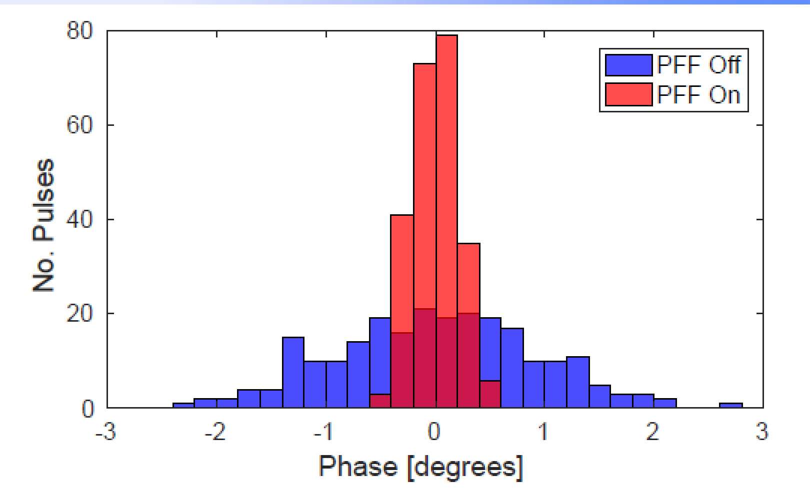
CTF3 results

- Produced high-current drive beam bunched at 12 GHz

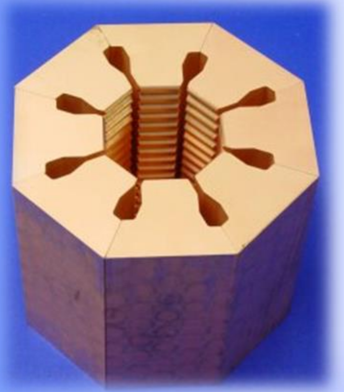


28A

Arrival time stabilised to 50 fs

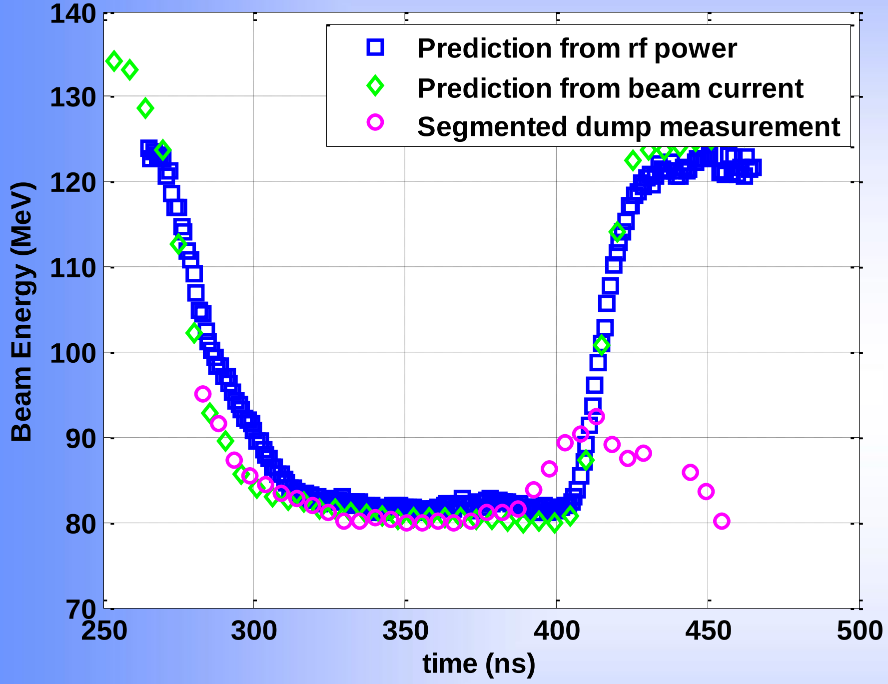


Test Beam Line in CLEX
A decelerator experiment

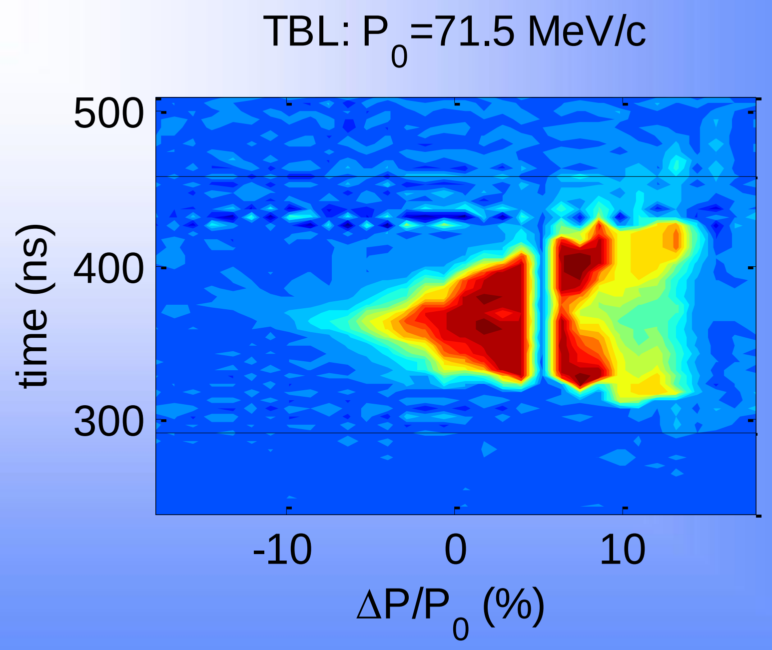


periodically corrugated structure
with low impedance (big a/λ)

Deceleration results



Minimum energy 10% threshold:
65.8 MeV
→ 51 % deceleration

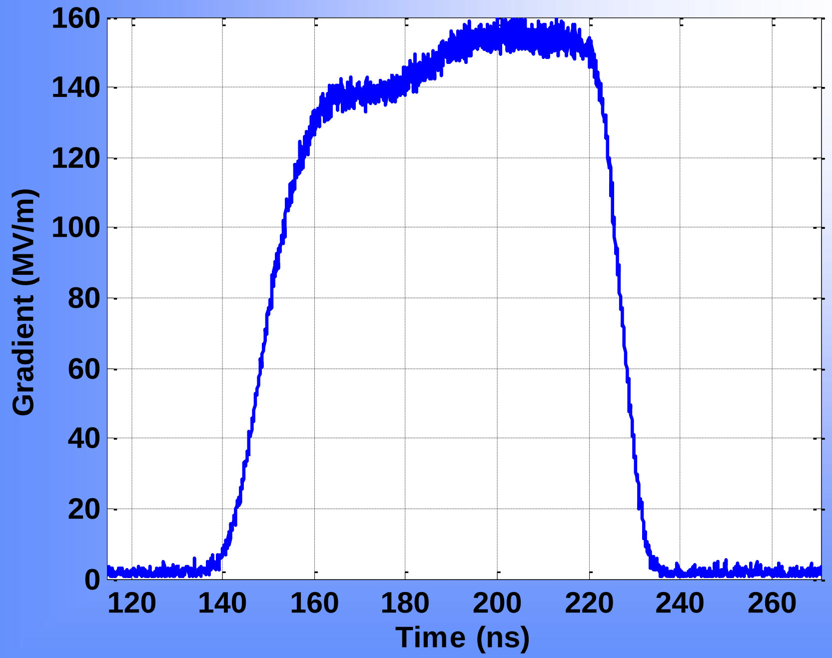


Power produced **(90 MW/PETS)** fully consistent with drive beam current (24 A) and measured deceleration

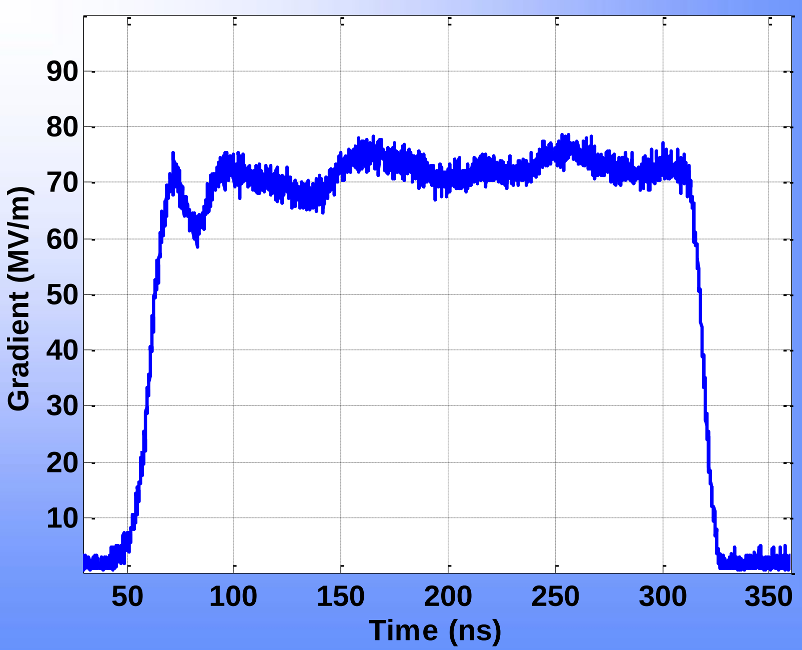
Total: 1.3 GW of 12 GHz peak power!

30 GHz Power Production in CTF3

100 MW, 70 ns

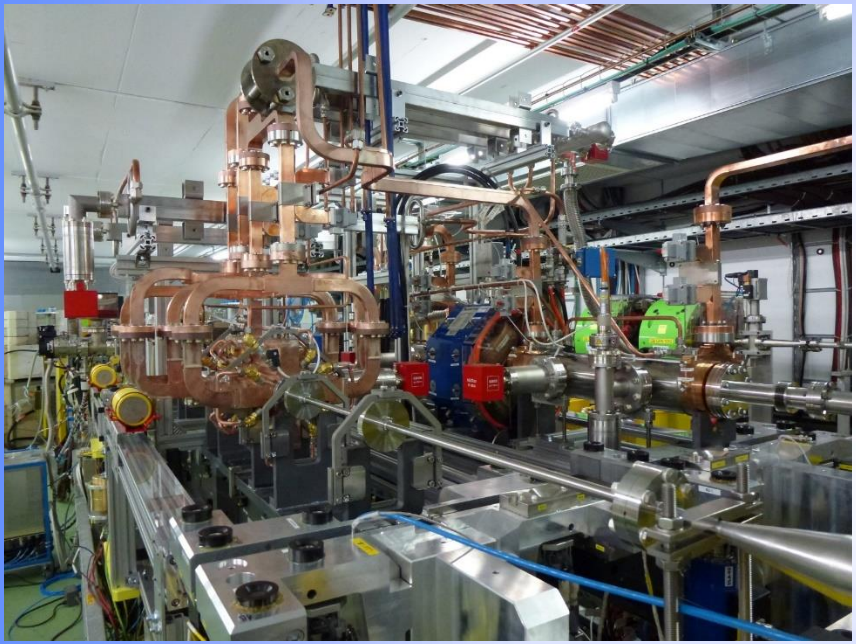


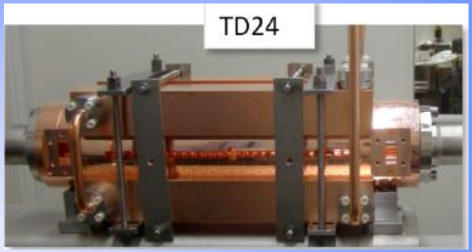
25 MW, 300 ns



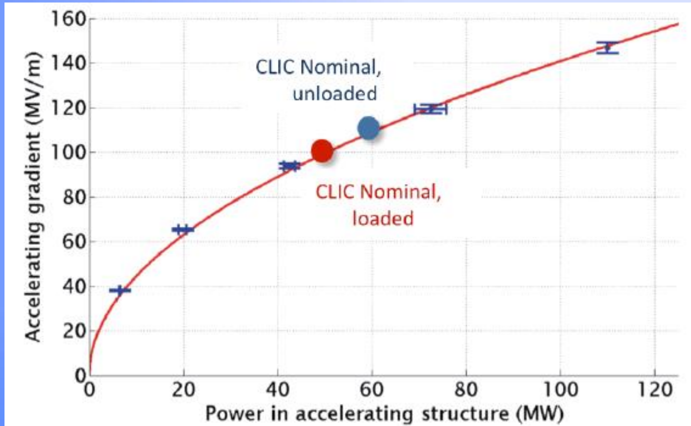
Two beam acceleration

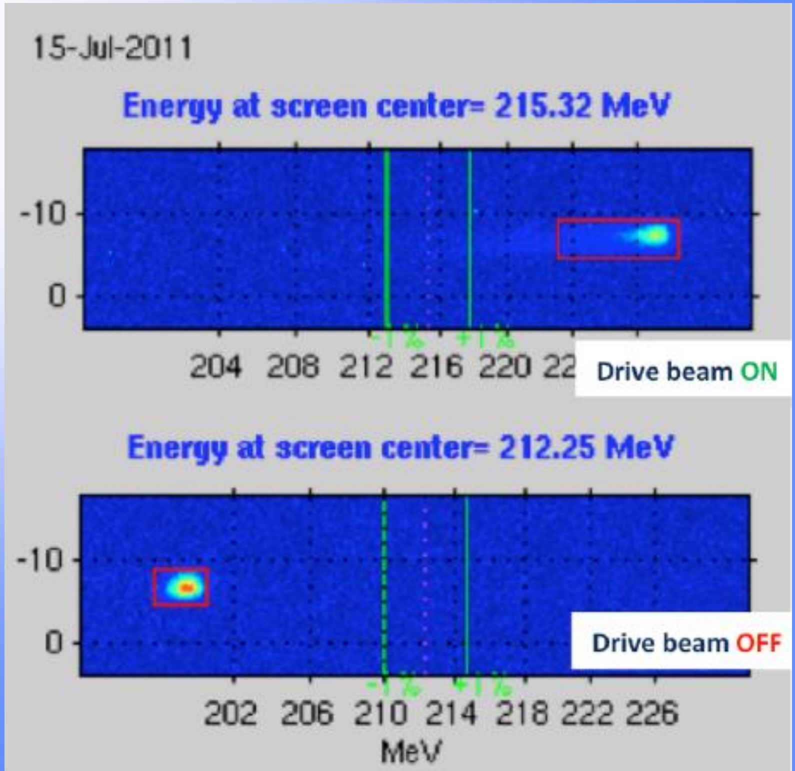
- Demonstrated two-beam acceleration





31 MeV = 145 MV/m





Quest for efficiency

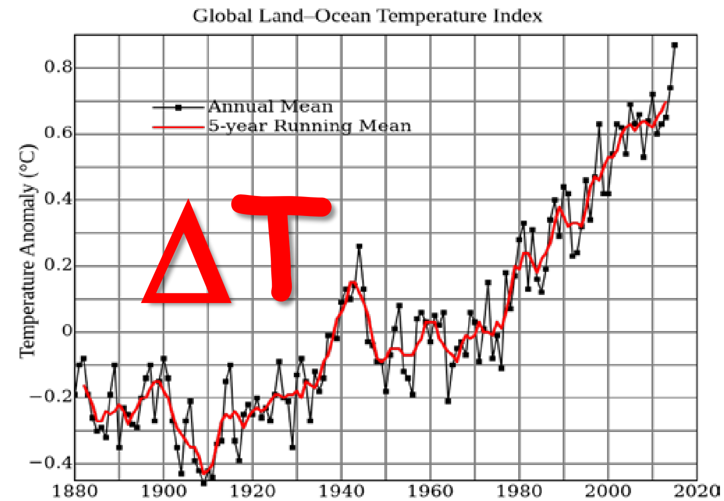
Why does energy efficiency matter?

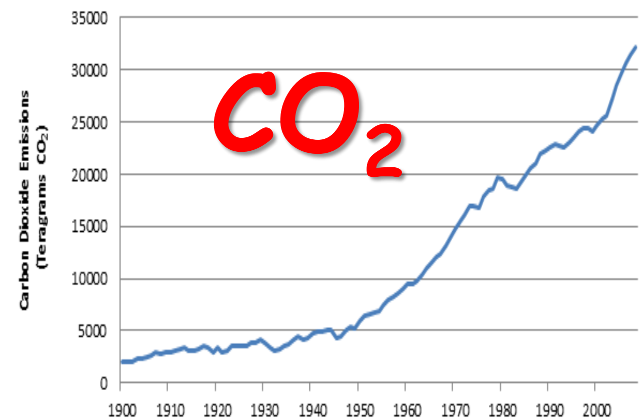
I hope no need to convince any body ☺

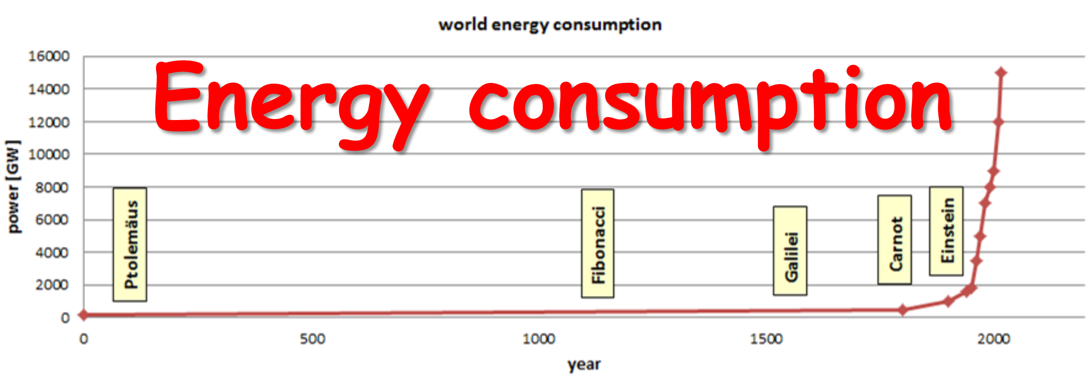
Does it matter for accelerators ?

Big interest in society,
we should set an example and show that R&D can help

We can save some money !







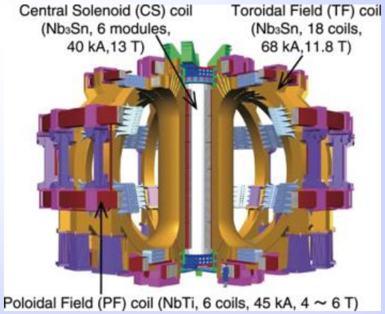
Orders of magnitude

generation	consumption	storage
1d cyclist „Tour de France“ (4h x 300W): **1.2 kWh**	1 run of cloth washing machine: **0.8…1 kWh**	Car battery (60 Ah): **0.72 kWh**
1d Wind Power Station (avg): **12 MWh**	1d SwissLightSource 2.4 GeV,0.4 A: **82 MWh**	ITER superconducting coil: **12.5 MWh**
1d nucl. Pow. Plant (e.g. Leibstadt, CH): **30 GWh**	1d CLIC Linear Collider @ 3 TeV c.m. **14 GWh**	all German storage hydropower: **40 GWh**

wind-power, 3 MW peak

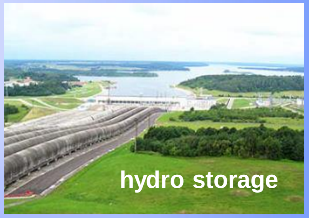
cyclist, 300 W

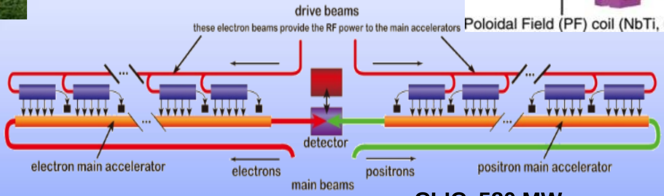
ITER



car battery

nucl. plant 1.3 GW





CLIC, 580 MW

M. Seidel/PSI

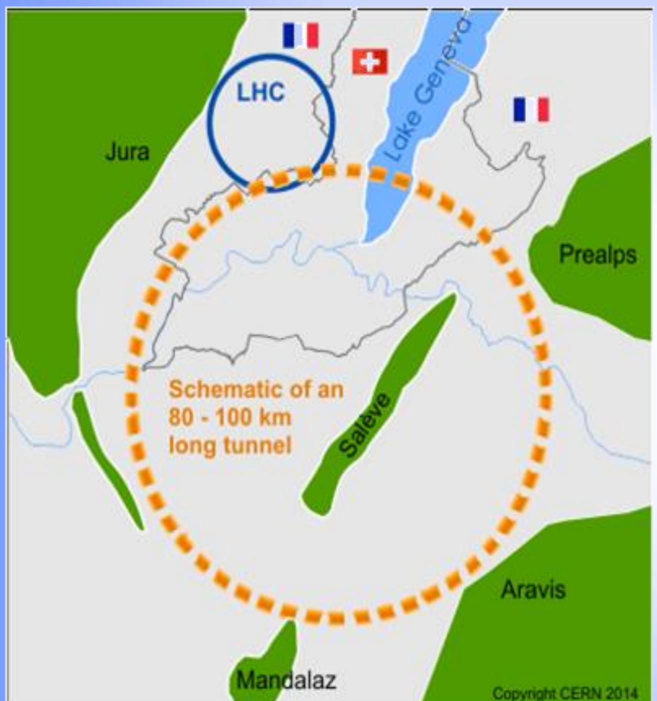
- Accelerators are in the range were they become relevant for society and public discussion.
- Desired turn to renewables is an enormous task; storage is the problem, not production!
- Fluctuations of energy availability, depending on time and weather, will be large!

Average RF power needs

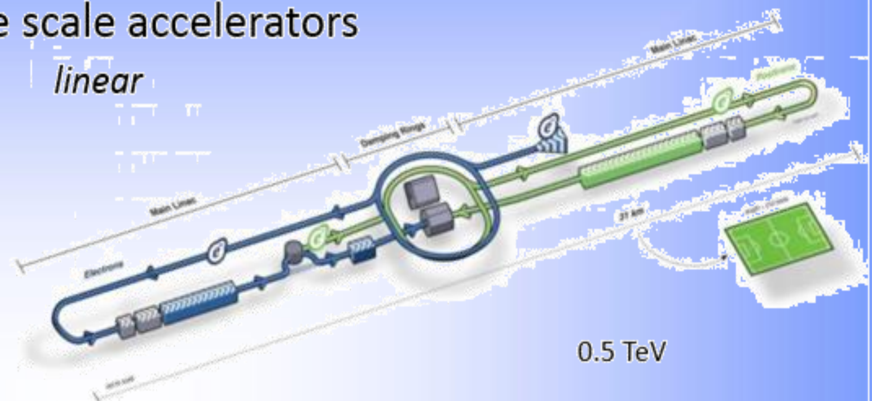
Future large scale accelerators

circular

FCC

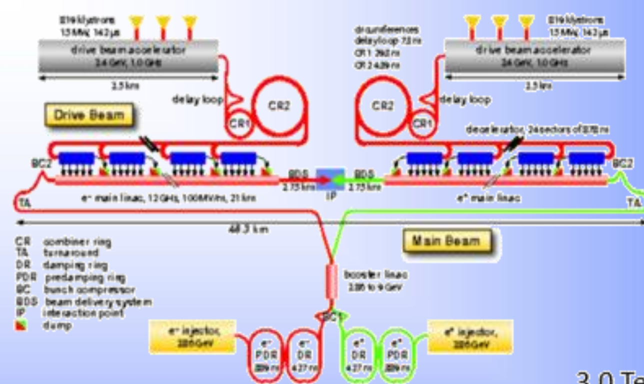


linear



0.5 TeV

ILC $^{e+e-}$: Pulsed, 1.3 GHz, P_{RF} total= 88 MW



3.0 TeV

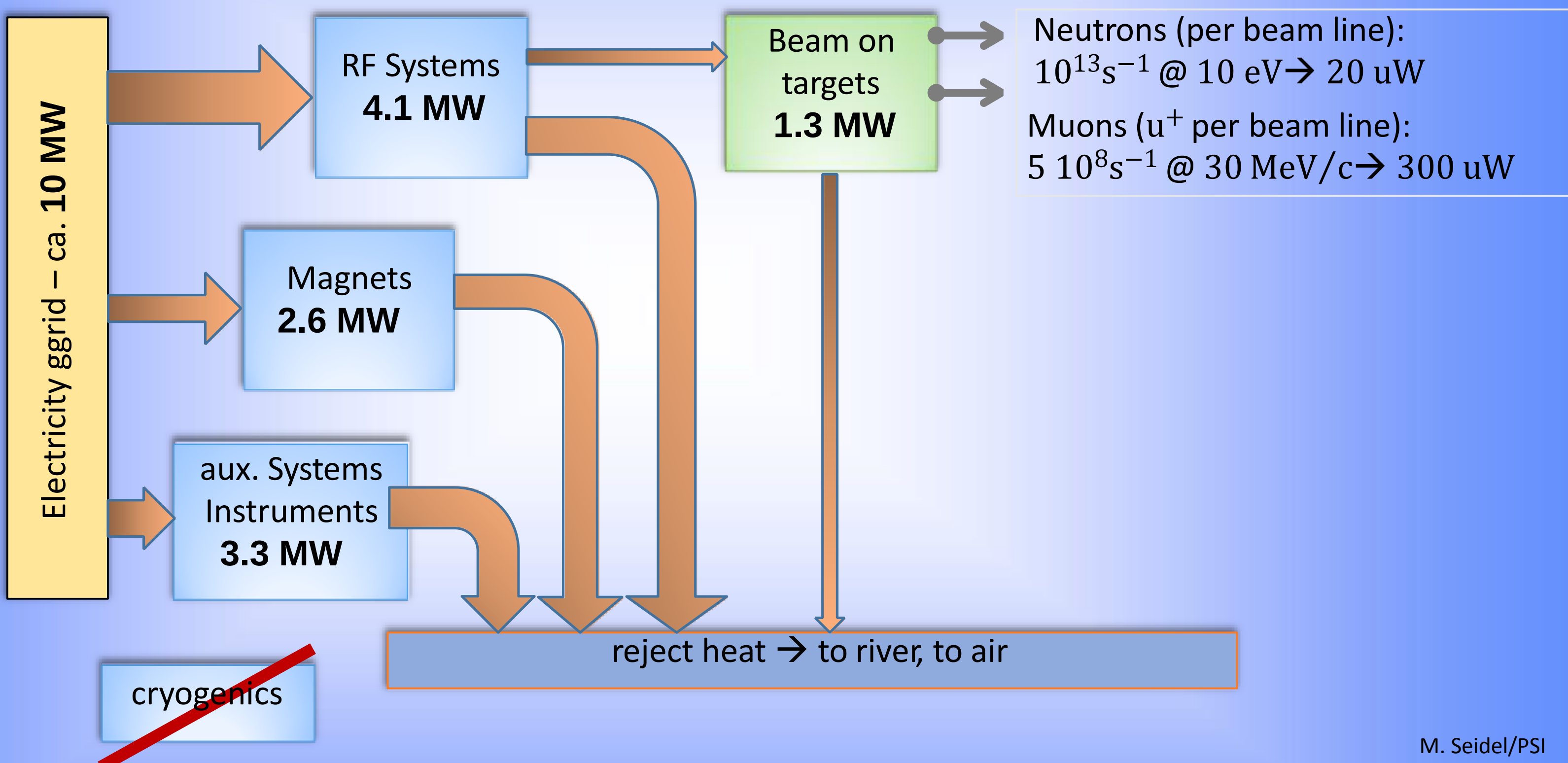
FCC-ee: CW, 400 MHz/0.8 GHz, $P_{RF,total}$ = 110 MW

CLIC: Pulsed, 1 GHz, $P_{RF,total}$ = 180 MW

EUROPEAN SPALLATION SOURCE

Pulsed, 0.7 GHz,92 MW

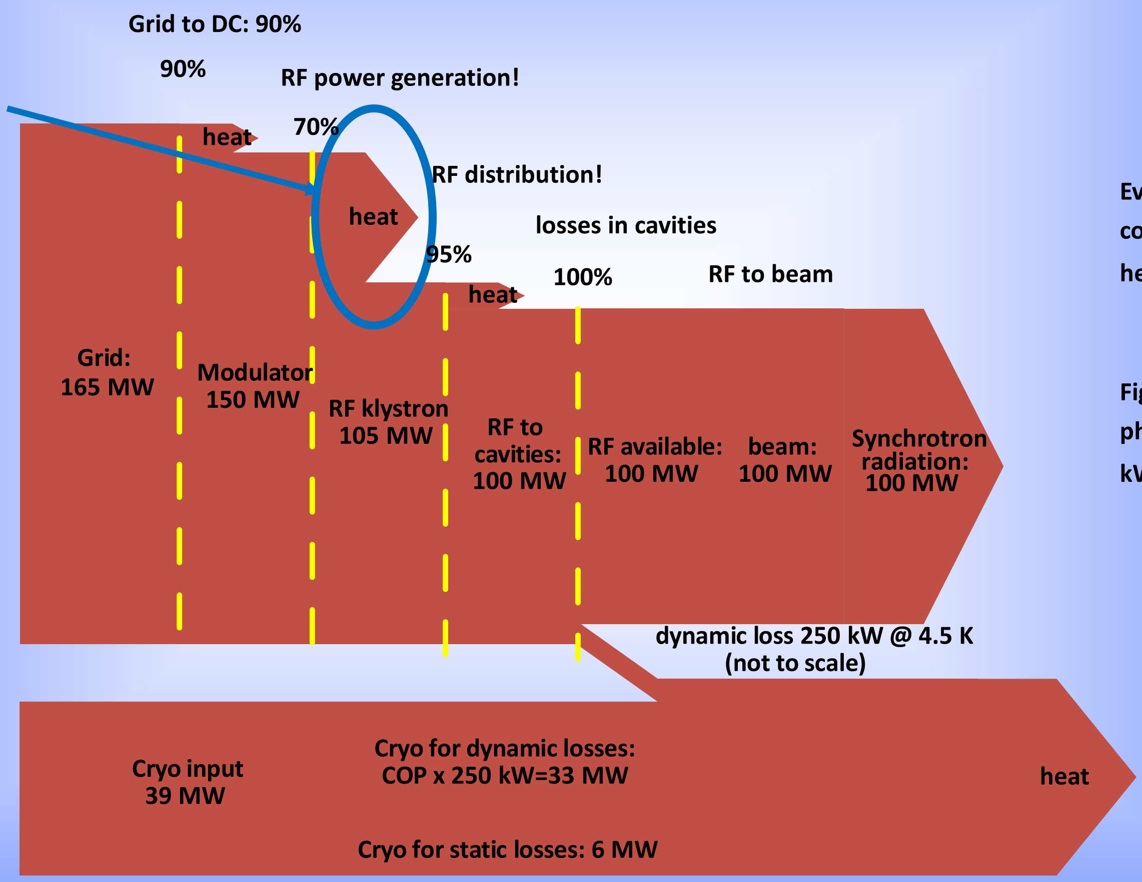
Example: PSI – 10 MW



M. Seidel/PSI

Example FCC-$t\bar{t}$: orders of magnitude

Note: largest impact by RF power generation



Eventually, all is converted to waste heat!

Figure of merit: physics results per kWh!

P. Lebrun

Example CLIC Drive Beam Klystron development

CLIC Drive Beam requirements

<u>3 TeV CLIC (CDR):</u>

1230 klystrons, 20 MW, 150 μs, 50 Hz

24.57 GW peak power, 184 MW average

0.05 ° phase jitter, 0.2% amplitude

380 GeV < 500 klystrons and factor 3 less in average power

Main energy 'consumer' in CLIC (~50 % for 3 TeV)

CLIC Drive Beam requirements

CLIC efficiency challenge

Example 3 TeV (CDR):

Total wall plug power for rf system: 255 MW

Efficiencies:
η_{mod} =0.89
η_{kly} =0.7
$\eta_{RF\text{-}DB}$ =0.89
η_{Pets} =0.98
η_{Decel} =0.81
$\eta_{RF\text{-}MB}$ =0.25

Final Main beam power: 28 MW
η_{tot} =0.11

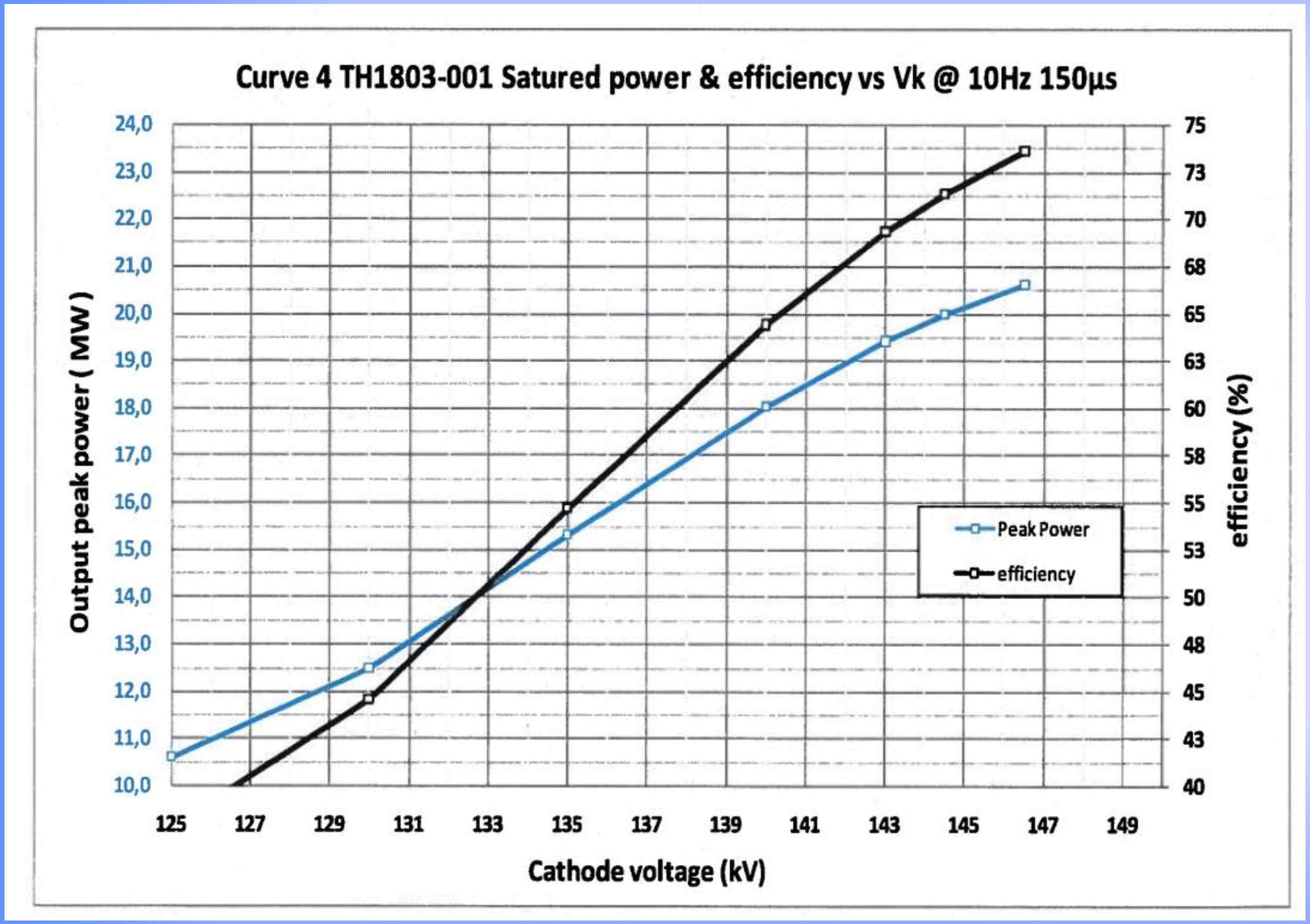
Each percentage counts !

Klystron parameters

PARAMETER	VALUE	UNITS
RF Frequency	999.516	MHz
Bandwidth at -1dB	≥ 1	MHz
RF Power:		
Peak Power	≥ 20	MW
Average Power	150	kW
RF Pulse width (at -3dB)	150	µs
HV pulse width (at full width half height)	165	µs
Repetition Rate	50	Hz
High Voltage applied to the cathode	tbd, ≤ 180	kV
Tolerable peak reverse voltage	tbd	kV
Efficiency at peak power	67 ≤ 70	%
RF gain at peak power	tbd, > 48	dB
Perveance	tbd	$\mu A/V^{1.5}$
Stability of RF output signal at nominal working point:		
RF phase ripple [*]	±1 (max)	RF deg
RF amplitude ripple	±1 (max)	%
Pulse failures (arcs etc.) during 14 hour test period	≤ 1-2	
Matching load, fundamental and 2nd harmonic	tbd	VSWR
Average radiation at 0.1m distance from klystron	≤ 1	µSv/h
Output waveguide type,	WR975	2-3 bar

Thales TH1803

10 beam multi beam klystrons, 153 kV, 76 % efficiency calculated
Design approved, delivered November 2017



Efficiency > 73% measured during test

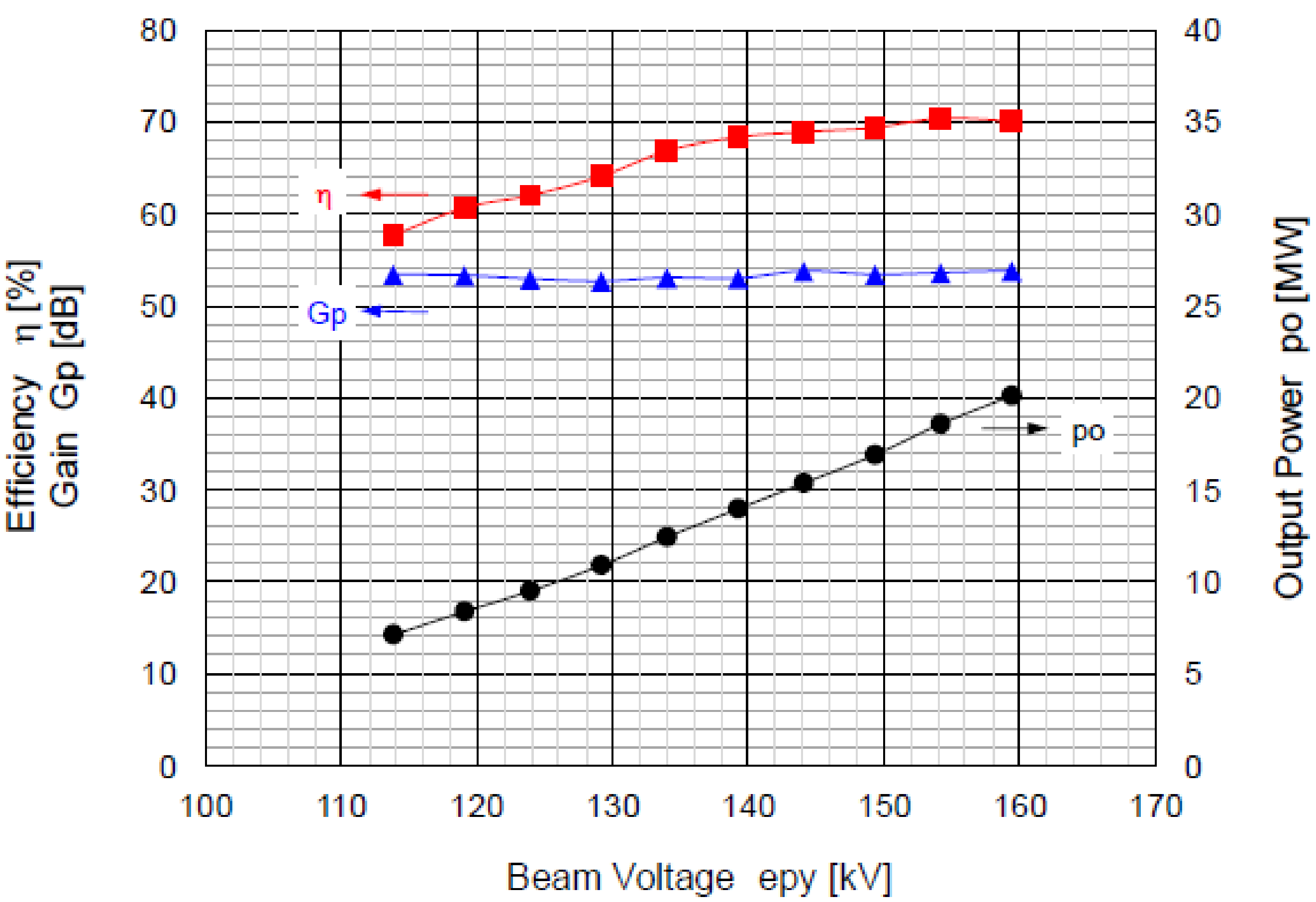
Toshiba E37503 factory test
6 beam MBK

Test results:

f= 999,5 MHz
P_{max}= 21 MW
P_L = 150 μs
V= 159.4 kV
I= 180 A
η= 71.5 %
G= 2.83 $\mu A/V^{3/2}$
Gain = 53.9 dB

Tests done at 25 Hz and double HV pulse length, nominal 50 Hz
Stable operation over a wide range of parameters

Toshiba E37503 factory test



Wide power range with high efficiency

CLIC modulators R&D

Hot R&D topics:

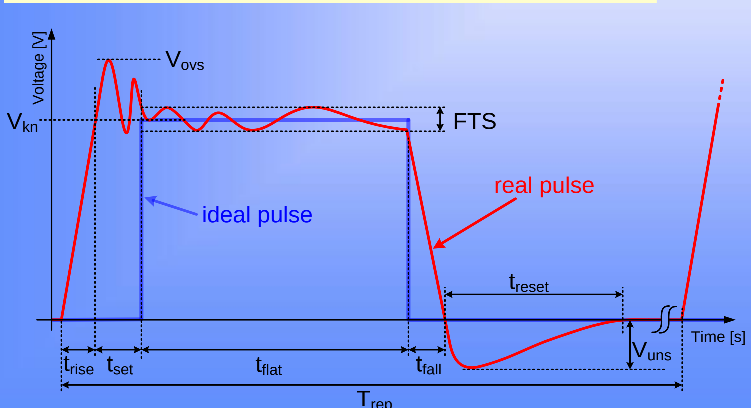
1300 modulators synchronously operated

⬇

29 MW x 1300 klystrons =

38GW of pulsed power!

CLIC Klystron modulators main specs			
Pulsed voltage	V_{kn}	180	kV
Peak nominal power	P_{out}	29	MW
Rise/fall times	t_{rise}	3	µs
Flat-top length	t_{flat}	140	µs
Rep. rate	Rep_r	50	Hz
Pulse repeatability	PPR	10-50	ppm



Distribution grid layout optimization

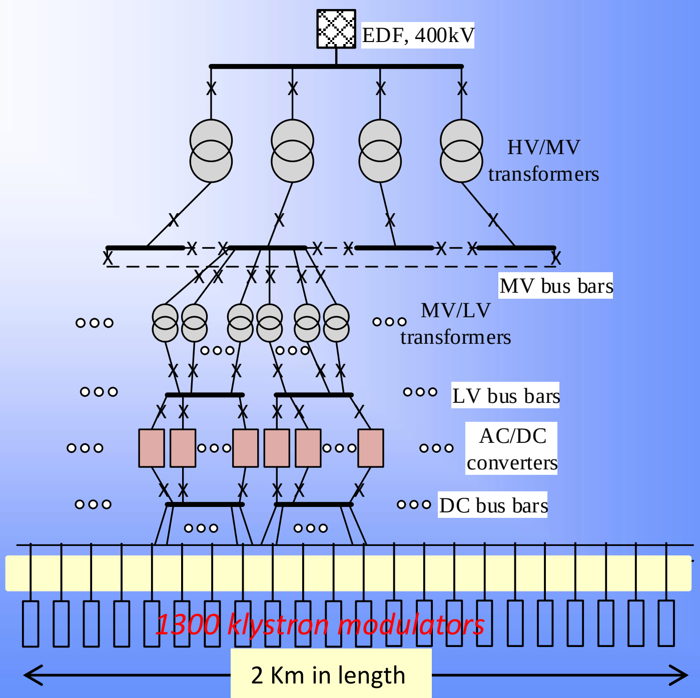
Active compensation of power fluctuation (new converters topologies)

High efficiency, high bandwidth, high repeatable power electronics

HV fast pulse transformers design

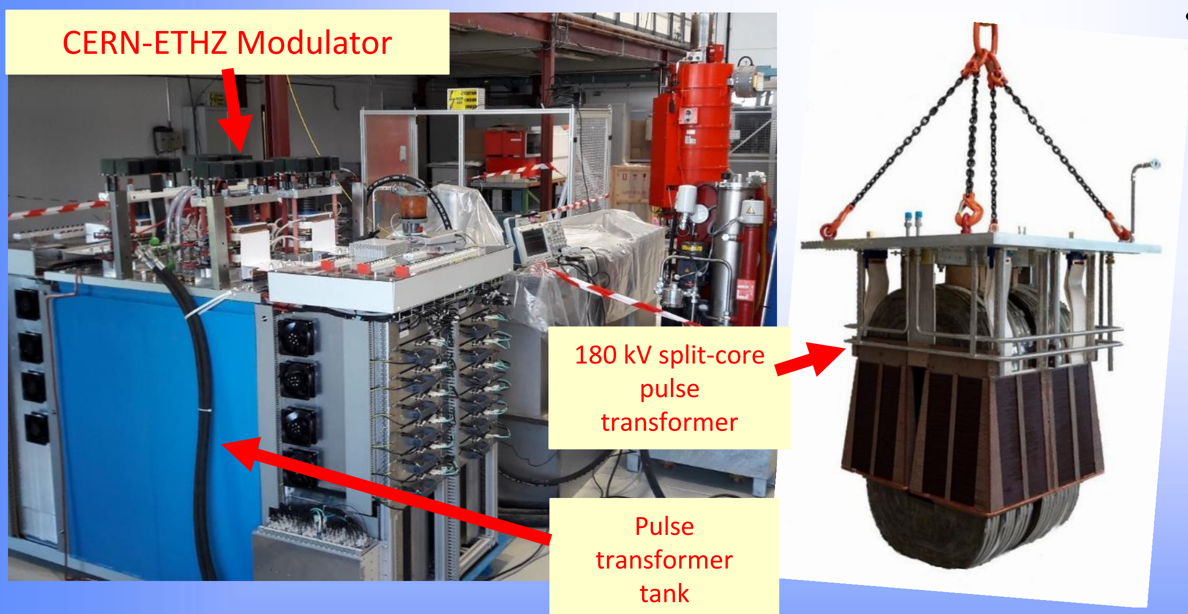
Highly repeatable HV measurements

Redundancy, modularity, availability



Klystron modulator R&D

- CERN-ETHZ collaboration for design & delivery of a CLIC's Drive Beam klystron modulator
- Modulator installed, tested and ready for commissioning with klystron in building 112
- World *première* for precise 180 kV – 30 MW pulse with 3µs rise/fall times & a "long" flat top (150µs) !
- Pulse stability better than 0.1 % !
- Collaboration with ETHZ successfully ended

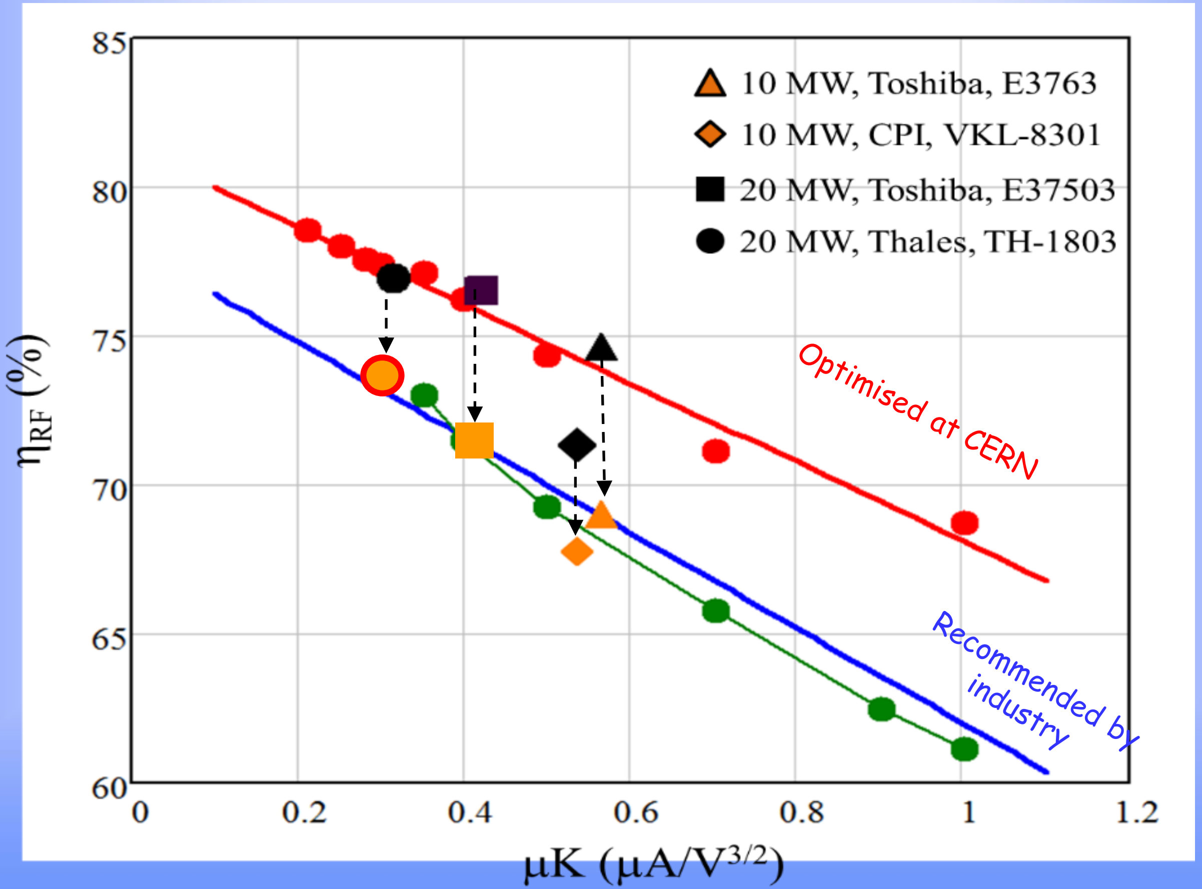


- 4 years of R&D studies achievements:
  - Feasibility to create voltage pulse verified
  - Solutions found to decouple 39 GW of pulsed power from electrical grid
  - Optimal number of powering sectors found (For civil engineering)
  - Optimal grid layout for power distribution proposed
  - Proposal of a new very high repeatable / precise measuring system for high voltage pulses
  - Discovery of excellent R&D partners in Canada, UK, Italy, & Switzerland!

State of the art

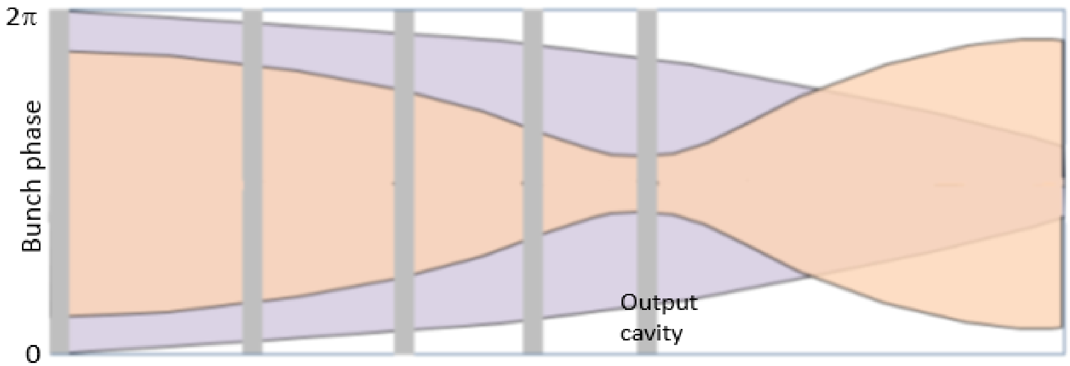
Commercial MBK (low perveance) tubes with high efficiency.

Klystron efficiency vs. perveance

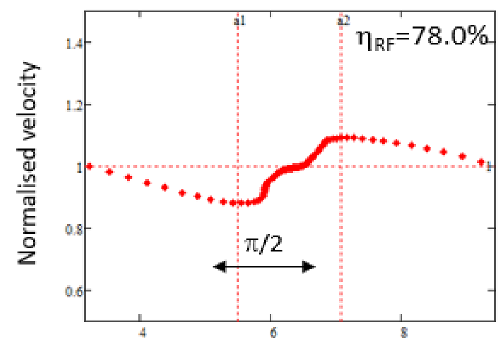


Bunch saturation issues.

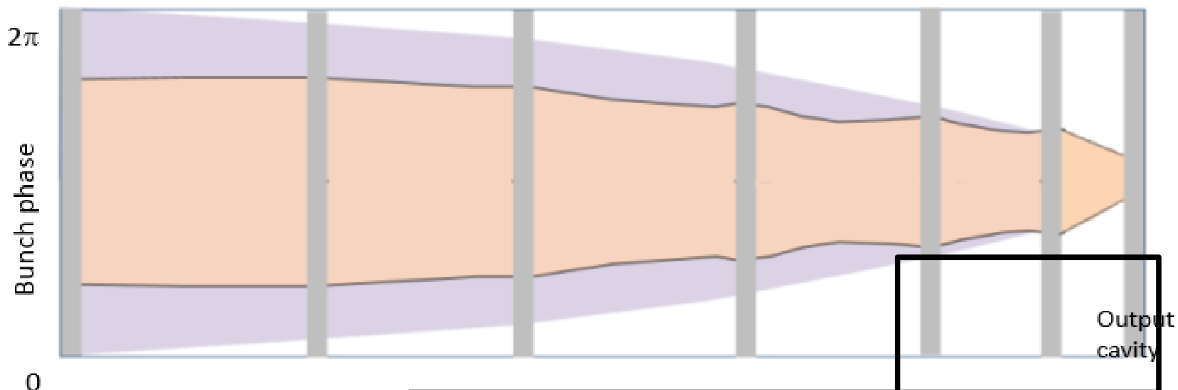
"Classical" bunching

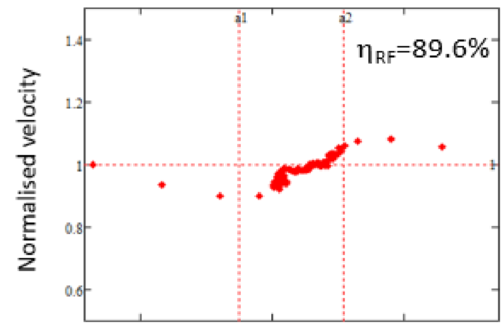


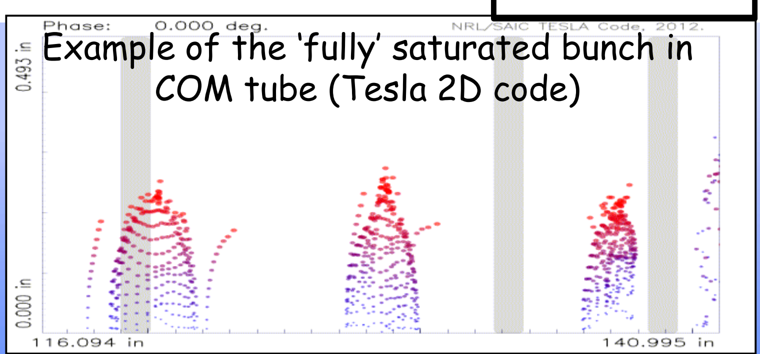
Bunch velocities distributions prior entering the output cavity



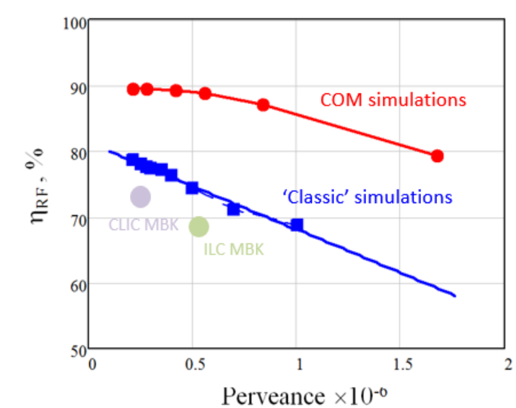
Bunching with core oscillations







Example of the 'fully' saturated bunch in COM tube (Tesla 2D code)



Igor Syratchev

End

Thanks for your interest

Stolen slides from:

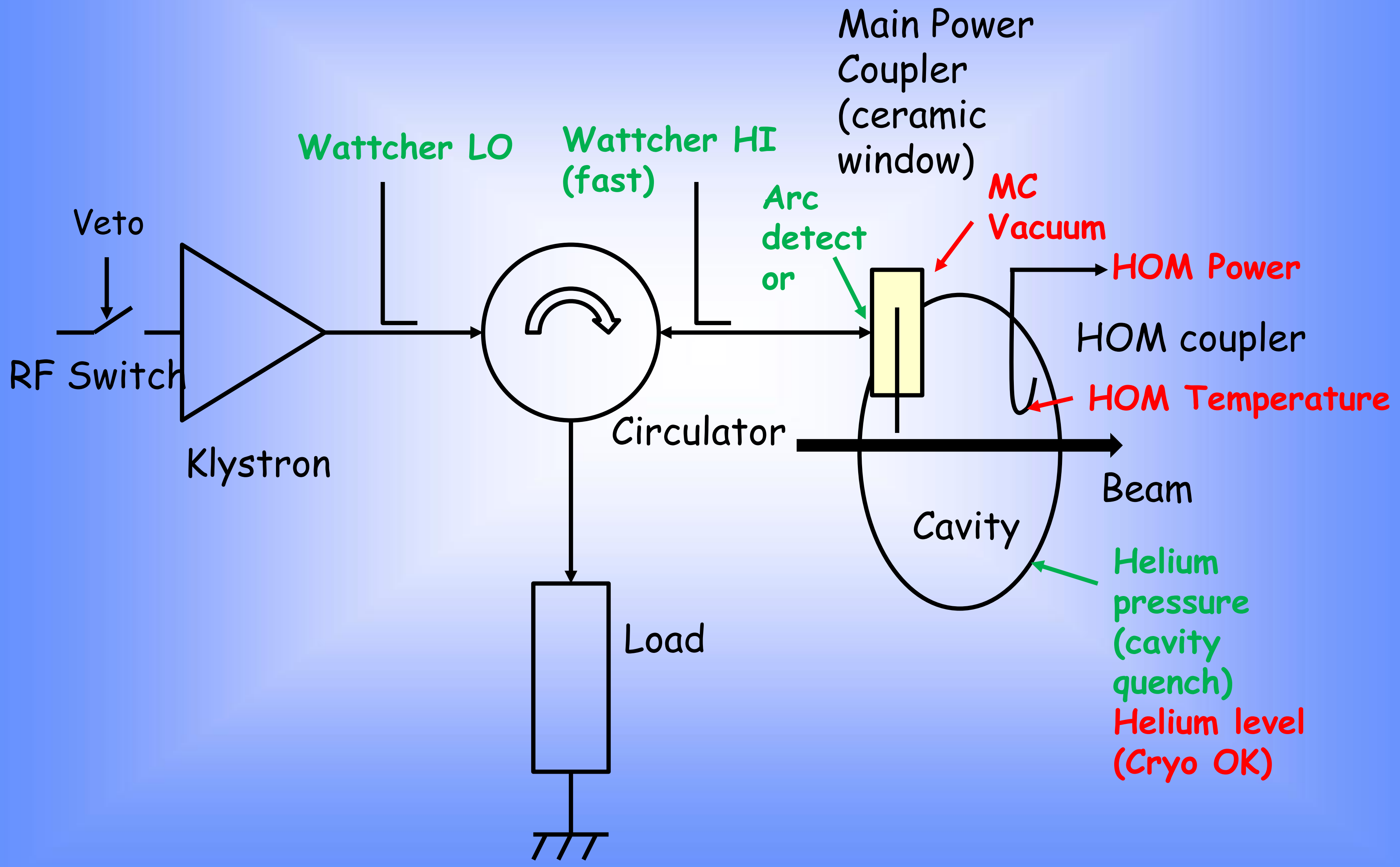
F. Tecker, E. Jensen, R. Carter, S. Stapnes, R. Corsini, I. Syratchev, M. Seidel

Future Questions: steffen.doebert@cern.ch

What else ?

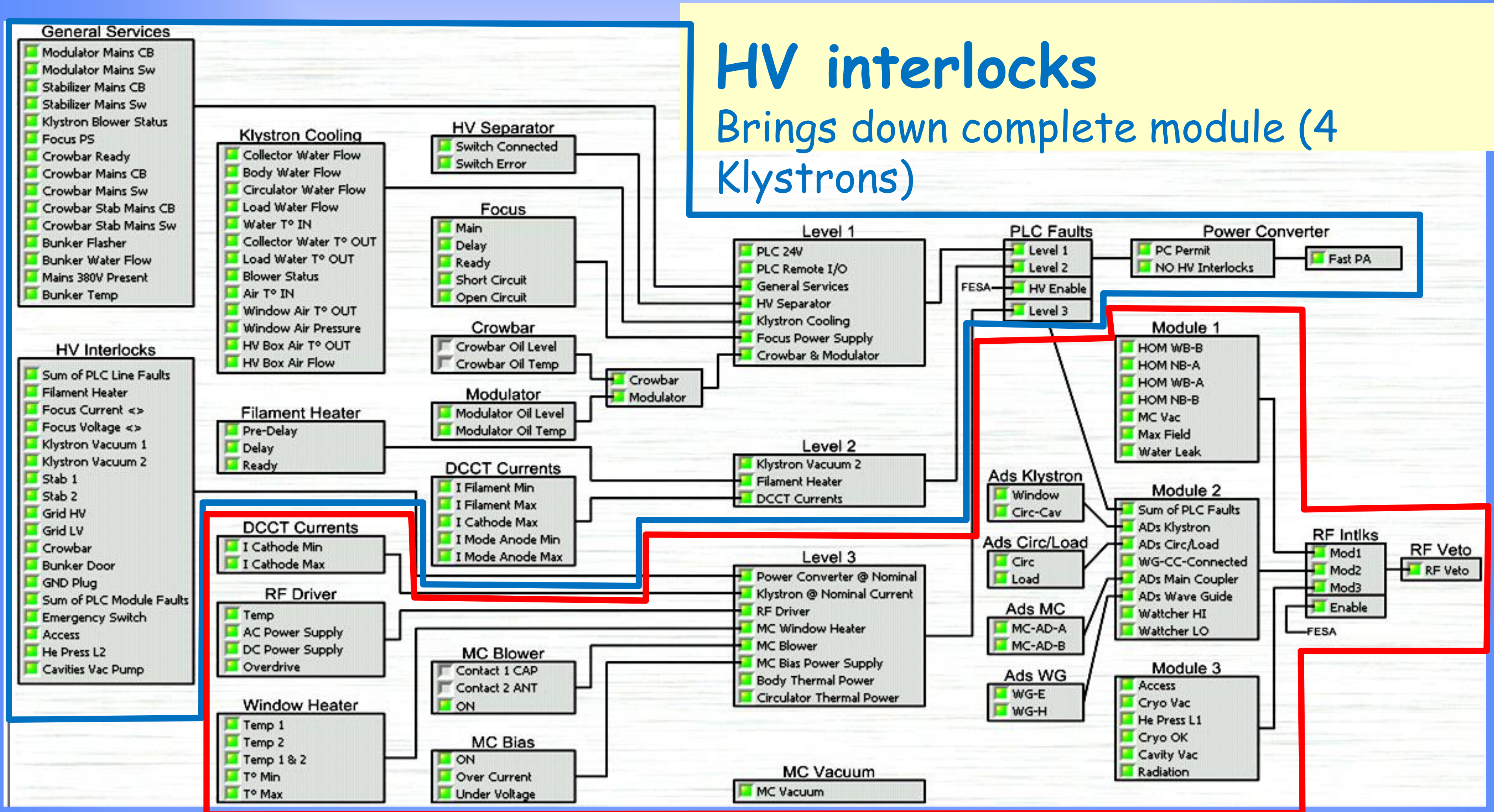
Operation, Reliability, Stability, Integration with LLRF and Acceleration Equipment

RF power distribution & critical interlocks



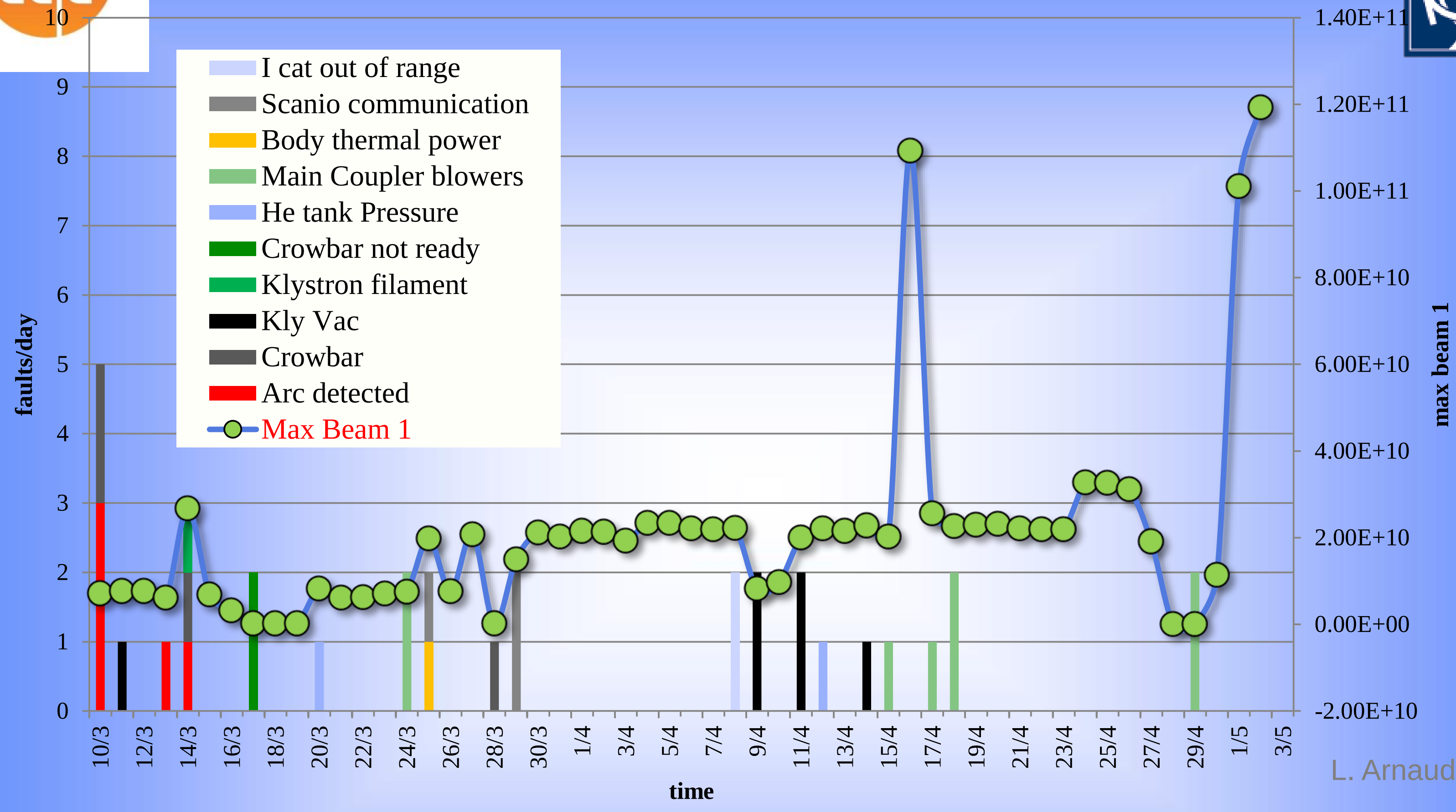
RF and HV Interlock chains

HV interlocks
Brings down complete module (4 Klystrons)



RF interlocks (Trips 1 Klystron)

Reliability and performance

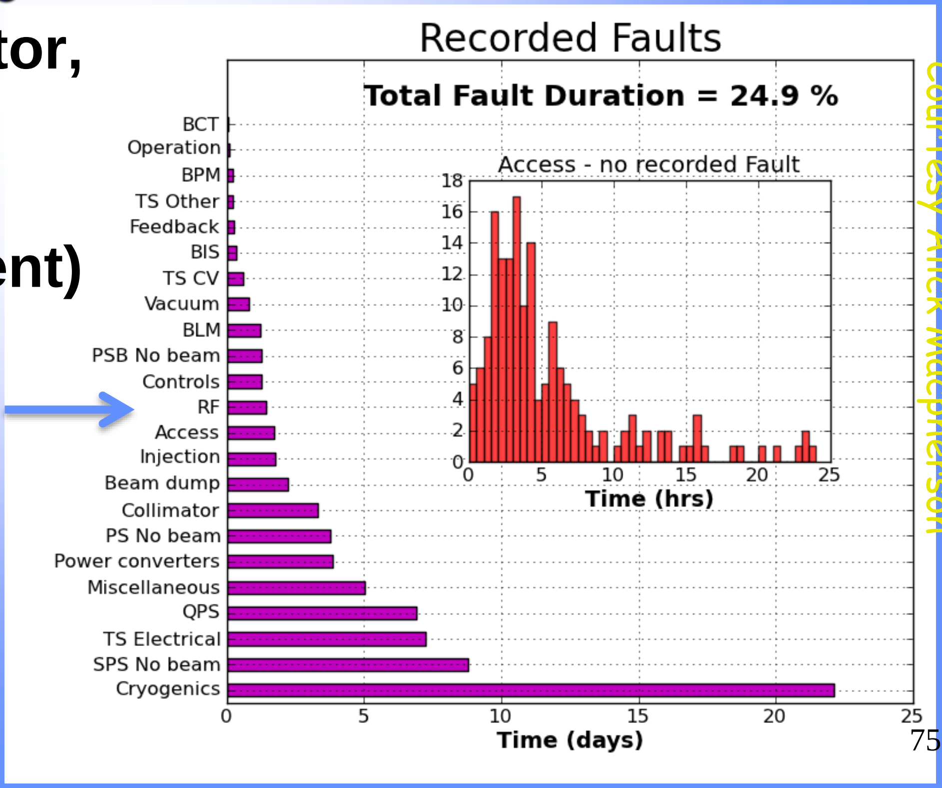


- RF system consists of about 1000 interlocks
- Long periods (>>days), without RF trips.
- The RF system is very reliable with the present beam conditions, efforts will continue to prepare for the higher intensity runs…

Operational Experience

RF System runs well -- few trips per year
(4th dump cause in numbers, 10th in downtime)
➔ still need for increase of reliability

- **Klystron Exchange for "age profile"**
  - **exchanged 1 for multipactor, 1 for gun short**
  - **1 dead due to collector design issue (ongoing collector boiler replacement)**
- **Tetrode Replacement**
  - **5 dead per year**
- **Arc Detector Deployment**
- **Oil Re-conditioning**
- **R Module replacement**



Spare slides

Accelerating gradient ?

We need higher gradient per unit length (cost)

10 MV/m

15 – 30 MV/m: Routinely achieved (LIL)

50 MV/m: Super-conducting limit

100 MV/m

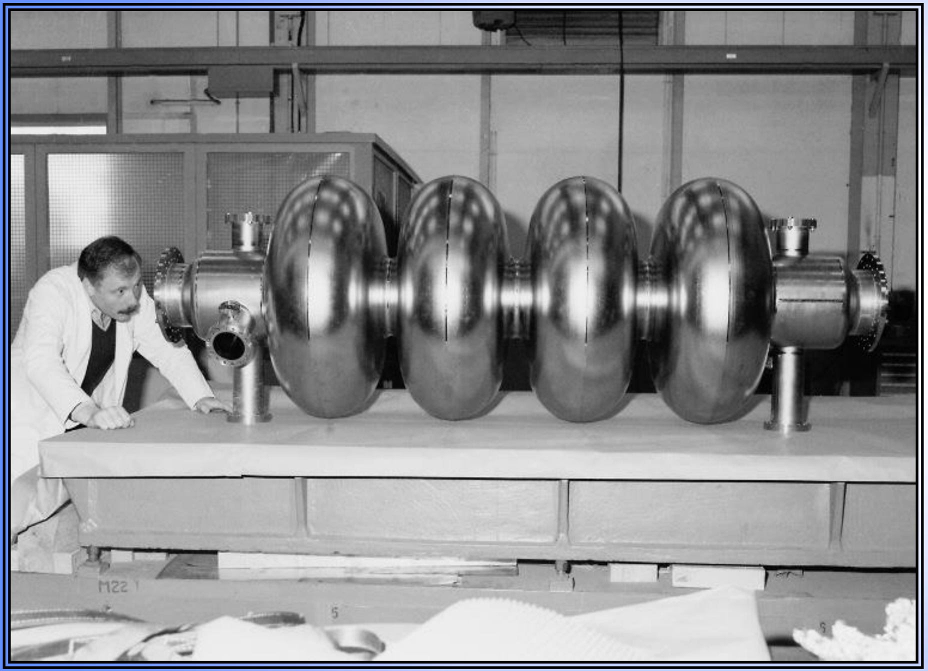
50 –150 MV/m:
Normal-conducting linear collider

Future: Plasma/Laser/Wakefield acceleration

> 1 GV/m

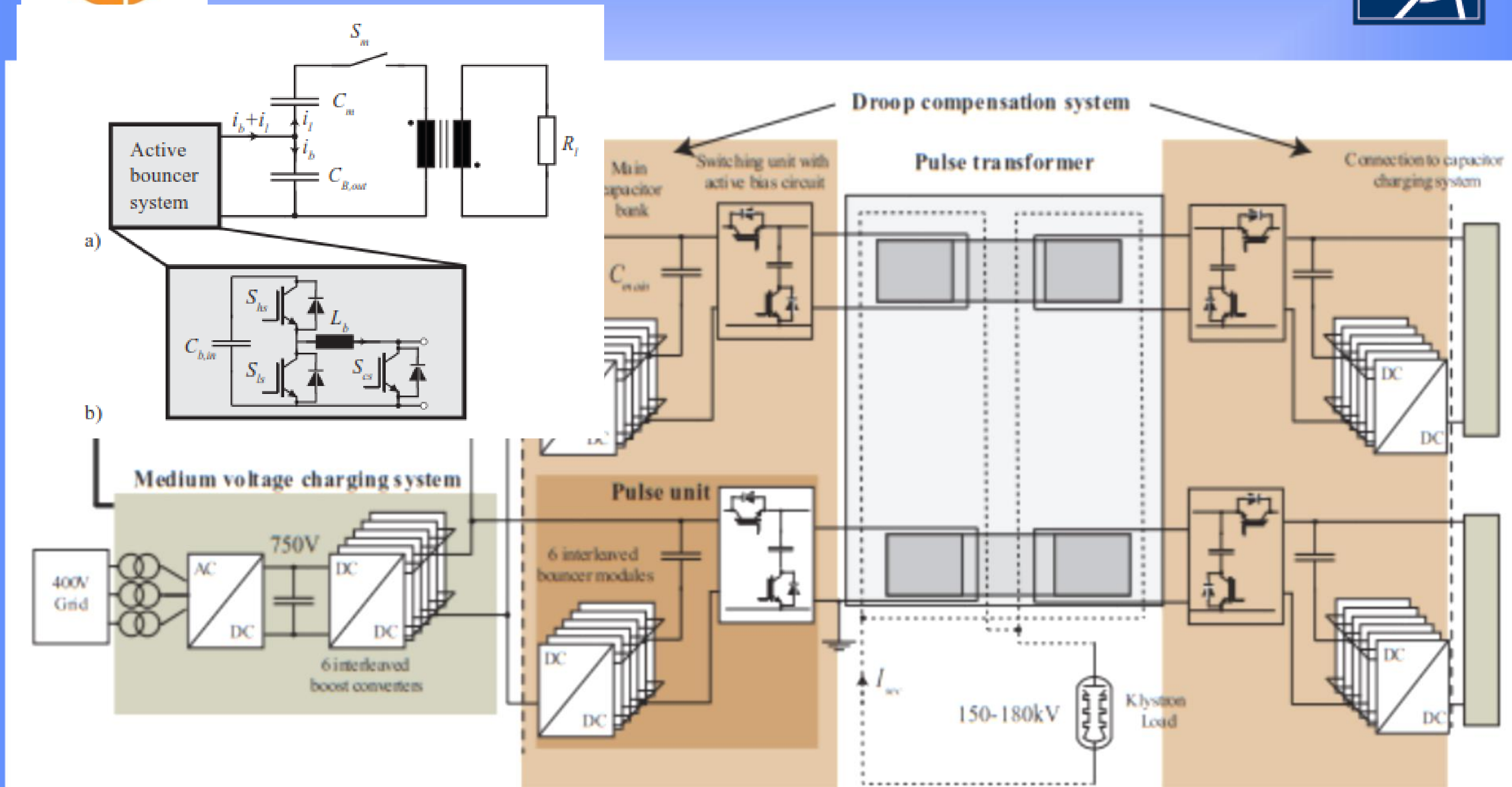
Why very high frequency ?

LEP-Cavity 350 MHz



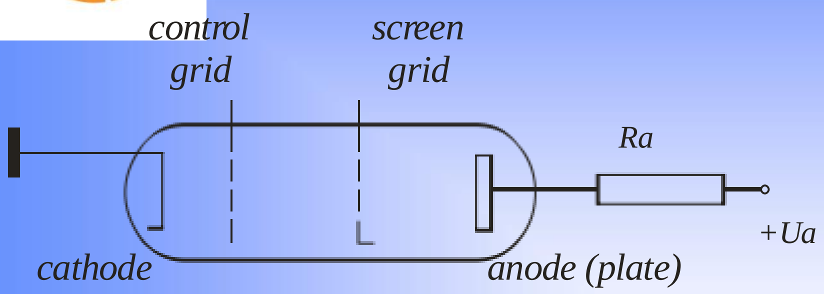
CLIC-Cavity 30 GHz

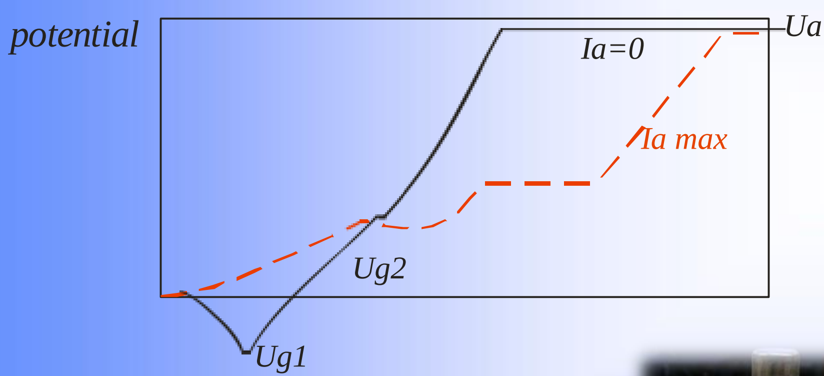
Klystron modulator R&D



Modulator schematic layout (thesis. S. Blume)

Tetrodes





RS 1084 CJ (ex Siemens, now Thales), < 30 MHz, 75 kW

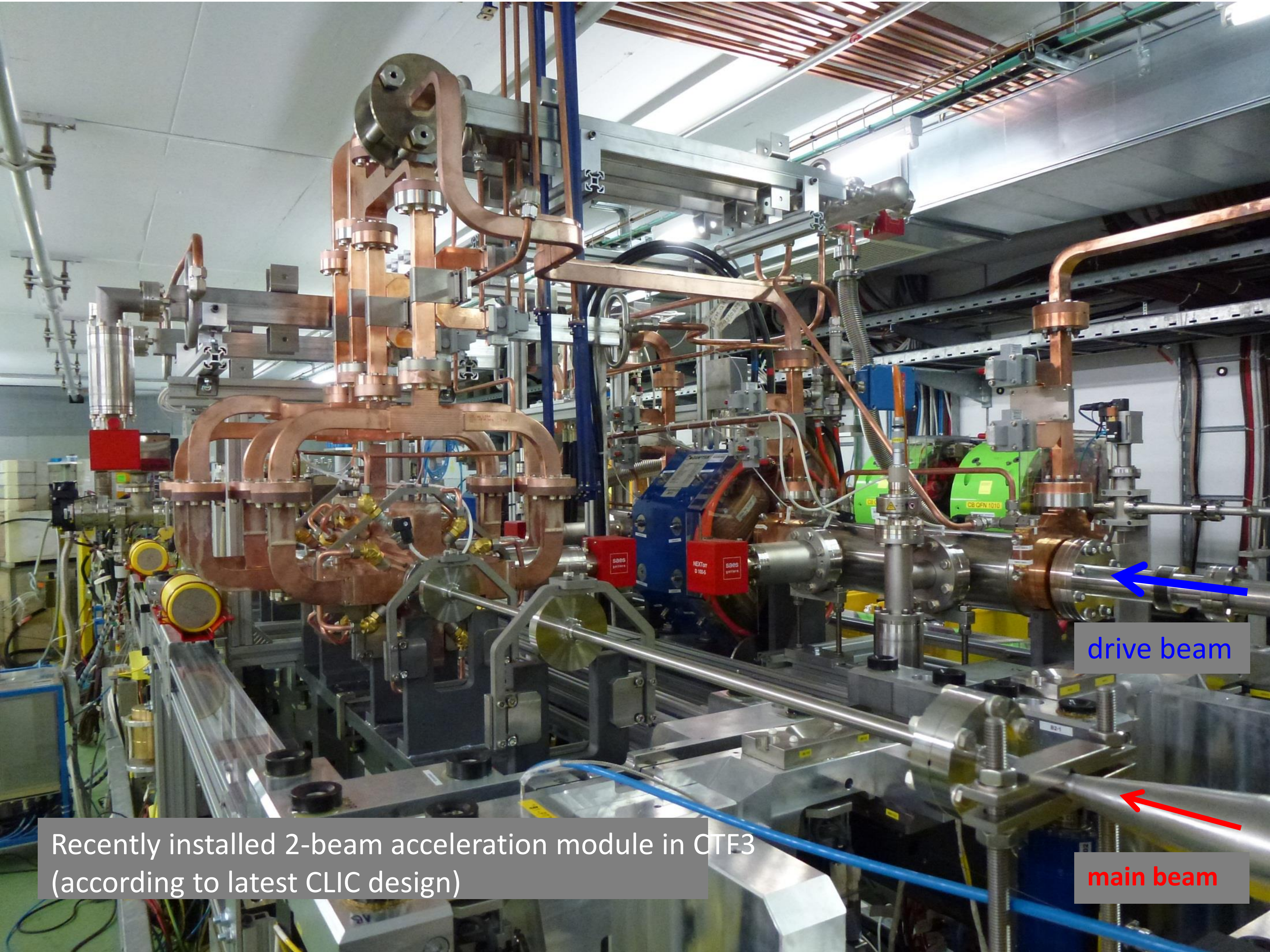
4CX250B (Eimac/CPI), < 500 MHz, 600 W (Anode removed)

YL1520 (ex Philips, now Richardson), < 260 MHz, 25 kW

Takes advantage from 'mobility' of electrons in vacuum

Klystron Test Stand

Location: CERN Bldg: 112



Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)