A Test Bed for Intense THz Radiation at the ARIEL E-linac

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IR-FEL Workshop, TRIUMF, Mar.19

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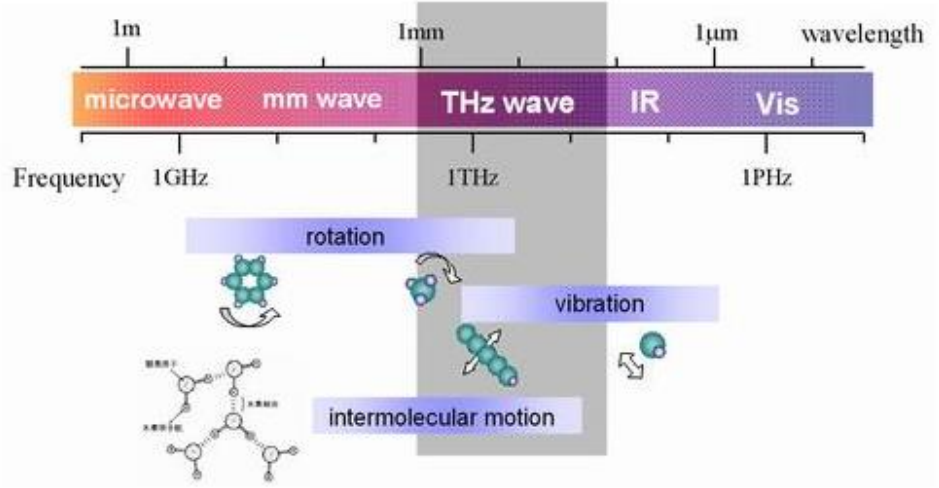
Discovery, accelerated

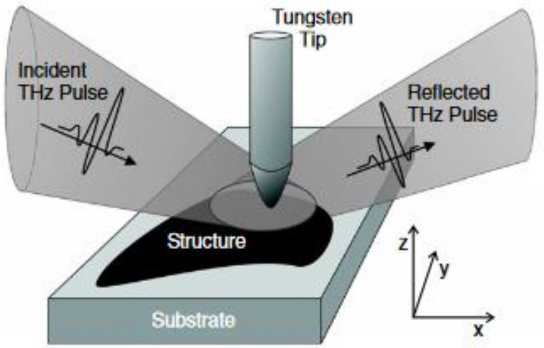
Outline

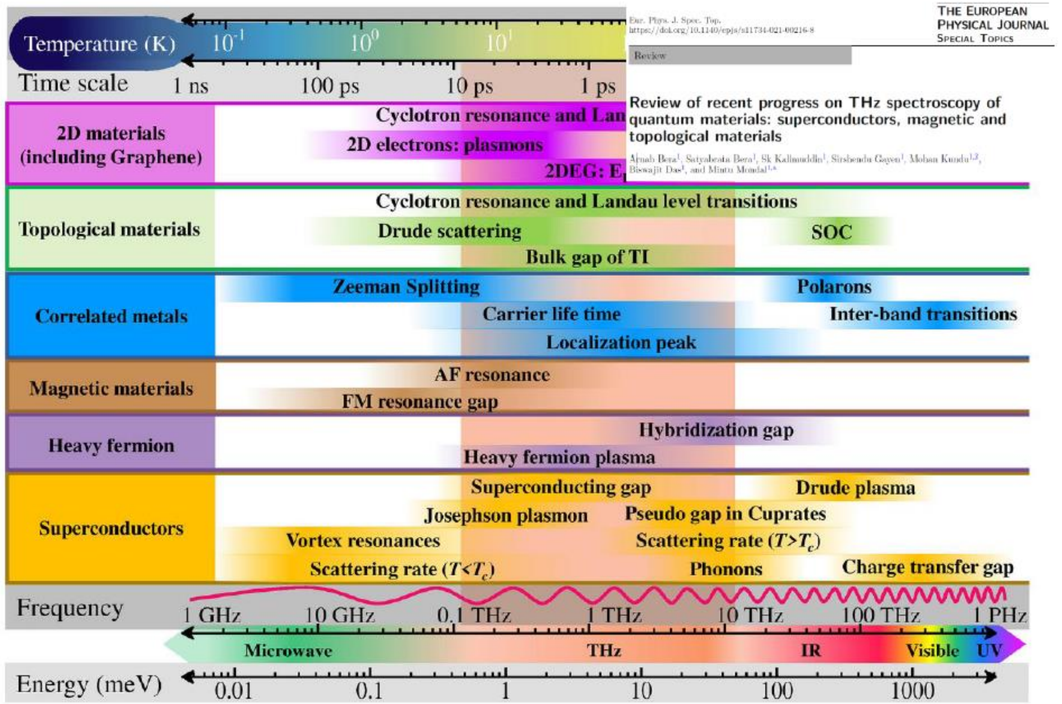
- TRIUMF project for production of intense THz radiation is a part of the National IR FEL program
- The project is gaining momentum
- The present status will be discussed in other talks
- I will focus on
  - Motivation and brief overview of the project
  - Several technical topics

THz is a popular probe across disciplines

- Linear spectroscopy
  - Many molecules have structural absorption resonances at THz frequencies
  - Many fundamental excitations in condensed matter are in the THz region
- Imaging, including microscopy
- Biological and Medical applications
- Industrial applications






Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-021-00216-8

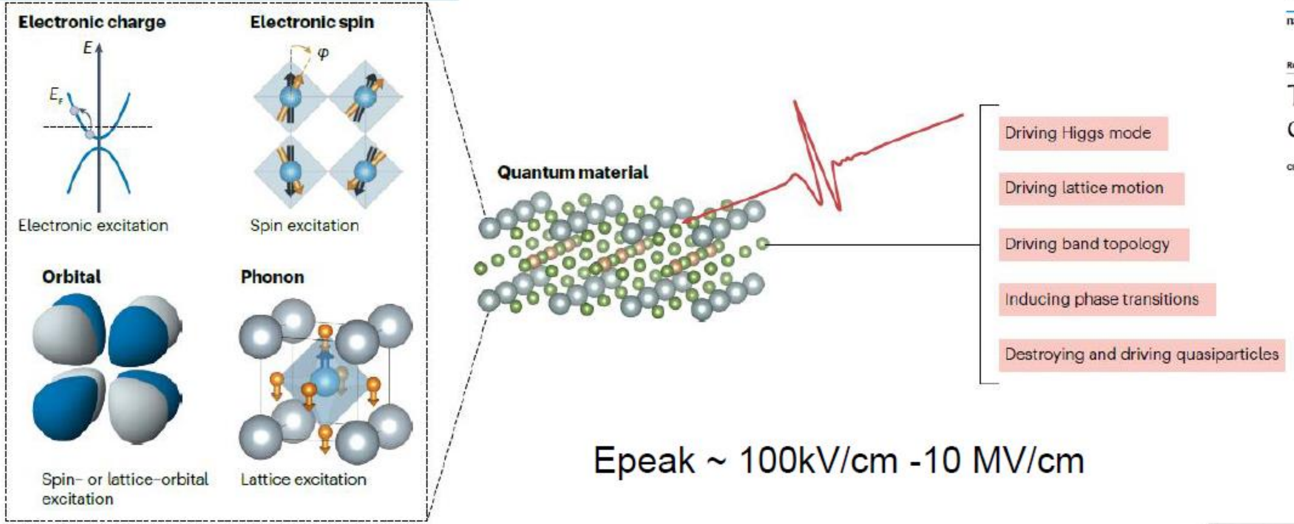
THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

Review

Review of recent progress on THz spectroscopy of quantum materials: superconductors, magnetic and topological materials

Arnab Bera[1], Satyabrata Bera[1], Sk Kalimuddin[1], Sirshendu Gayen[1], Mohan Kundu[1,2], Biswajit Das[1], and Mintu Mondal[1,a]

THz is a tool to control the matter



Epeak ~ 100kV/cm -10 MV/cm

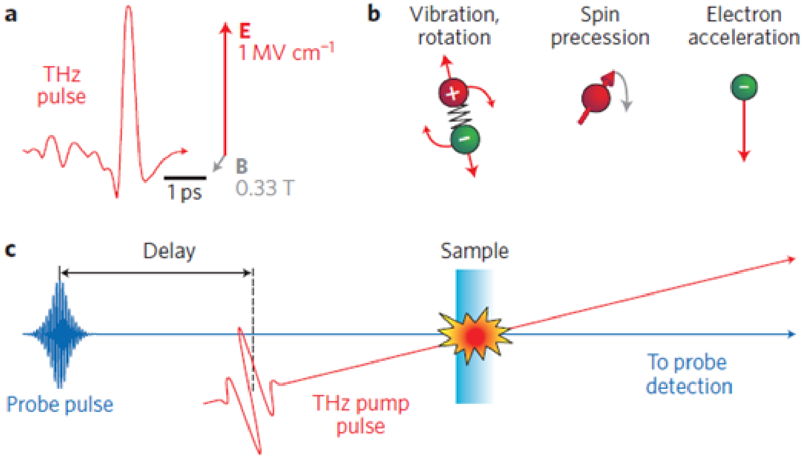

nature reviews materials https://doi.org/10.1038/s41578-023-00566-w

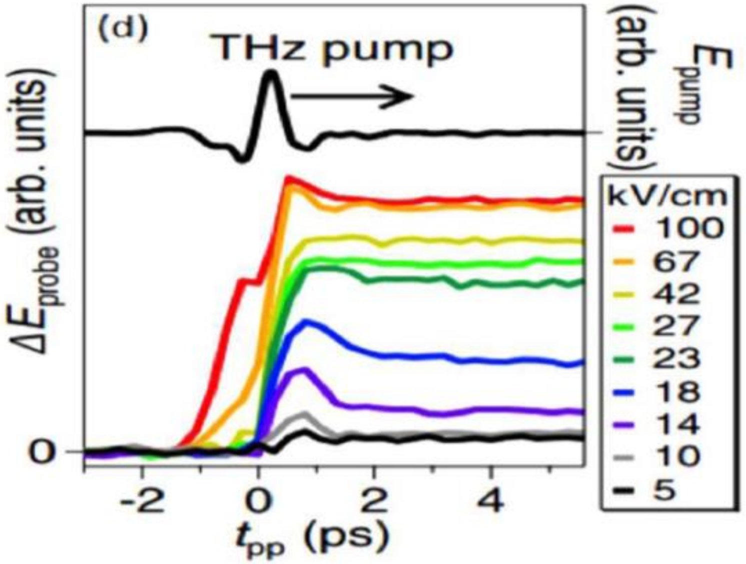
Review article Check for updates

Terahertz control of many-body dynamics in quantum materials

Chia-Jung Yang [1], Jingwen Li [1], Manfred Fiebig [1] & Shovon Pal [2]

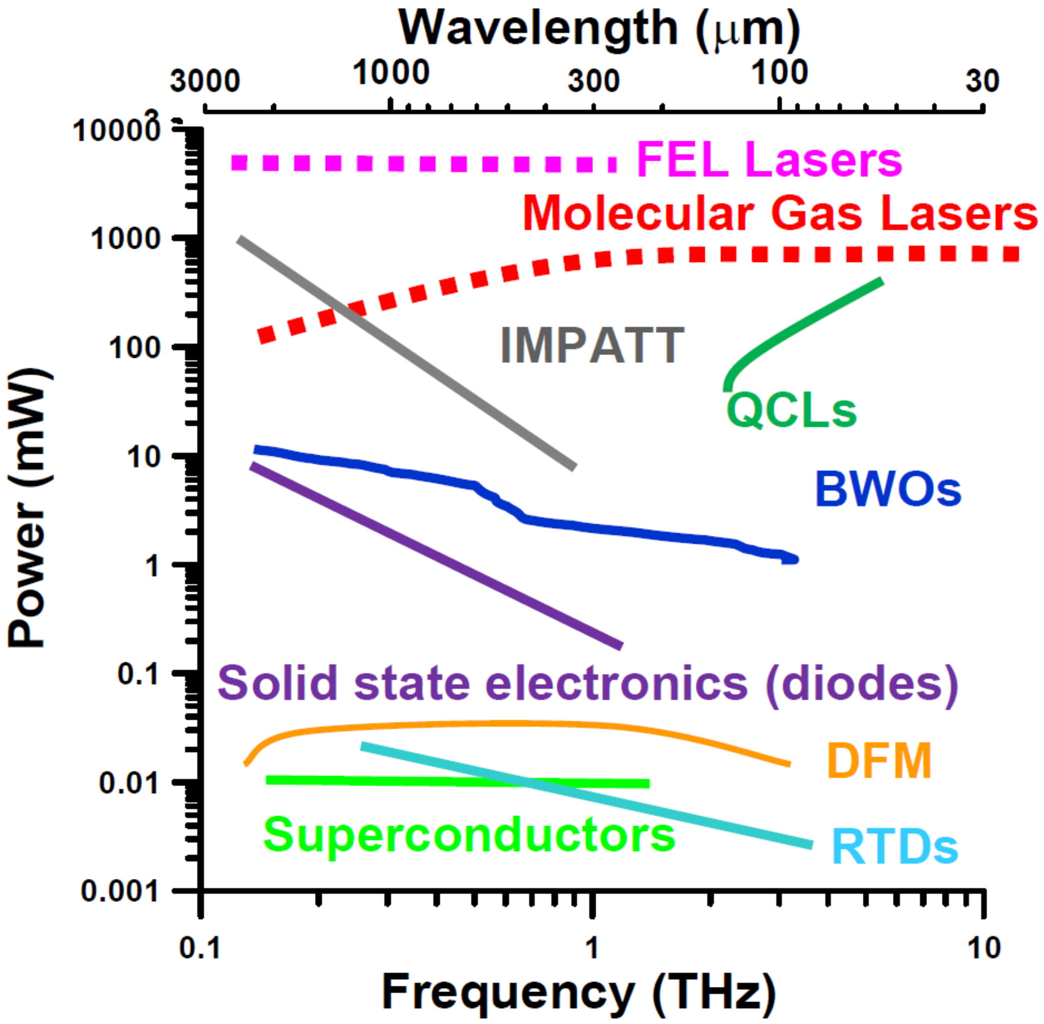
Pump and probe concept





An intense THz fields can lead to a breakup of Cooper pairs in superconductors, providing a switching from superconductor to normal metal. Ultrafast dynamics of the BCS state in a conventional NbN superconductor (with a BCS gap of 5.2 meV (1.3 THz)). Matsunaga et al., Phys. Rev. Lett. 111, 057002 (2013)

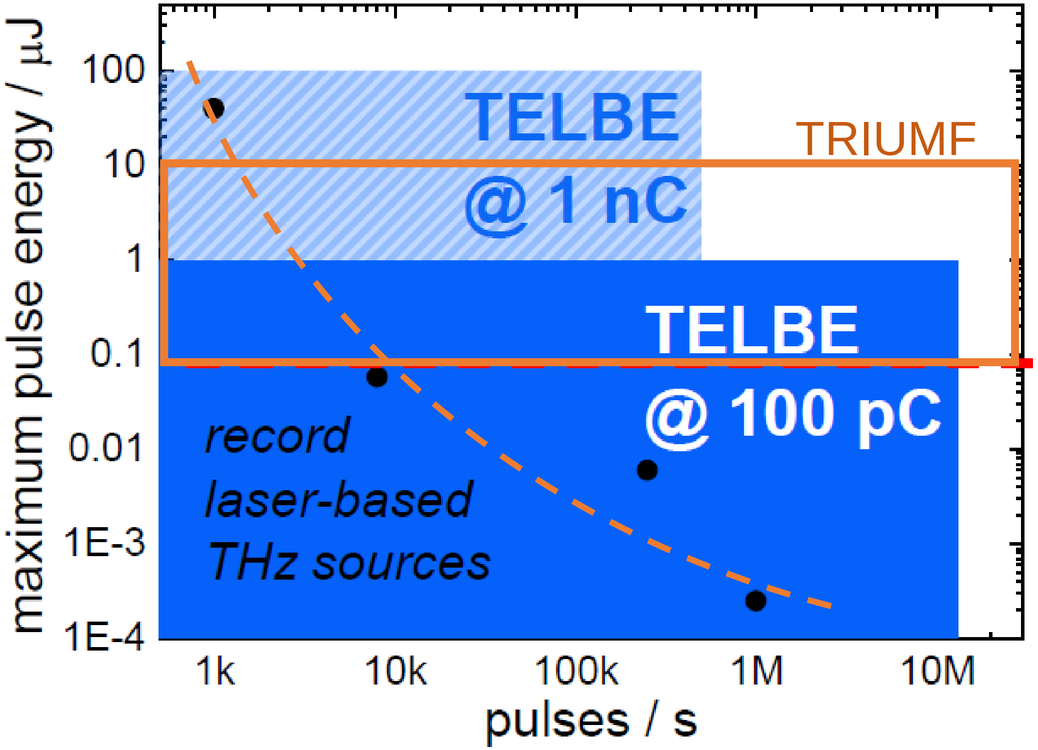
THz sources.



- It is accepted that the THz frequency band spans from 0.1 THz - 10 THz
- Available THz sources can be divided into several categories
  - Electronic devices
  - Laser based sources
  - Accelerator based sources (FEL, Synchrotrons)

TRIUMF THz project

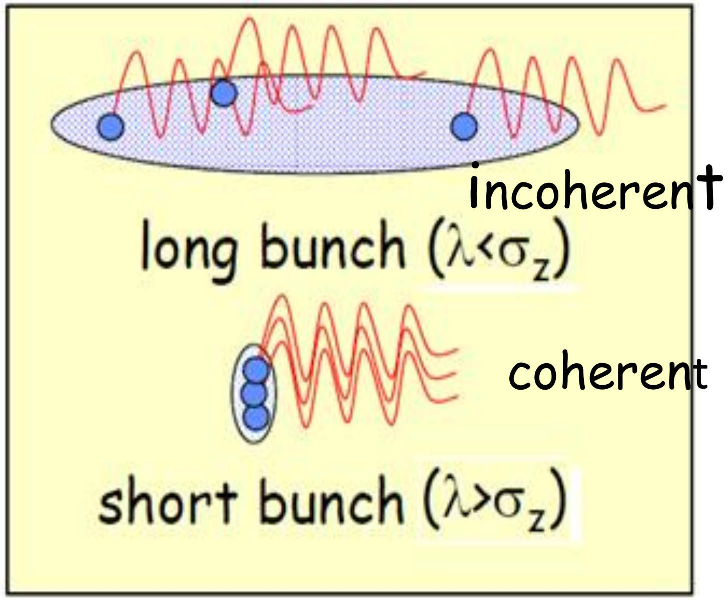
- TRIUMF THz project targets production of pulsed broadband THz radiation with a peak field strength suitable for the matter control E_z >100kV/cm
- To achieve goals the project will exploit coherent emission of electron bunches from the ARIEL electron linac
- THz pulses will be produced at a rate not accessible to laser-based sources



Coherent action what counts for intense radiation production

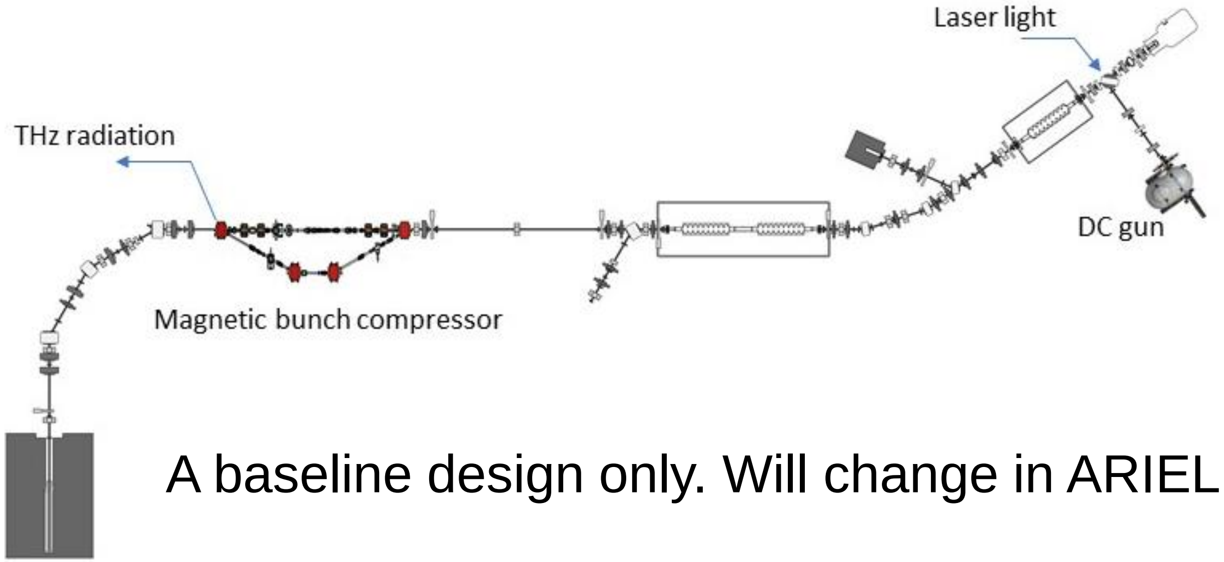
From very basic principles and valid for any electromagnetic radiation by an ensemble of charged particles !

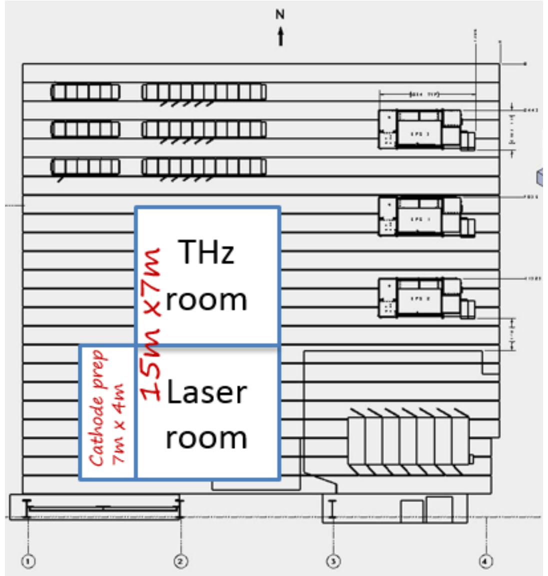
$$I_{tot}(\omega)=I_e(\omega)\left(\underbrace{N}_{\text{Incoherent}}+\underbrace{N(N-1)f(\omega)}_{\text{Coherent}}\right)$$

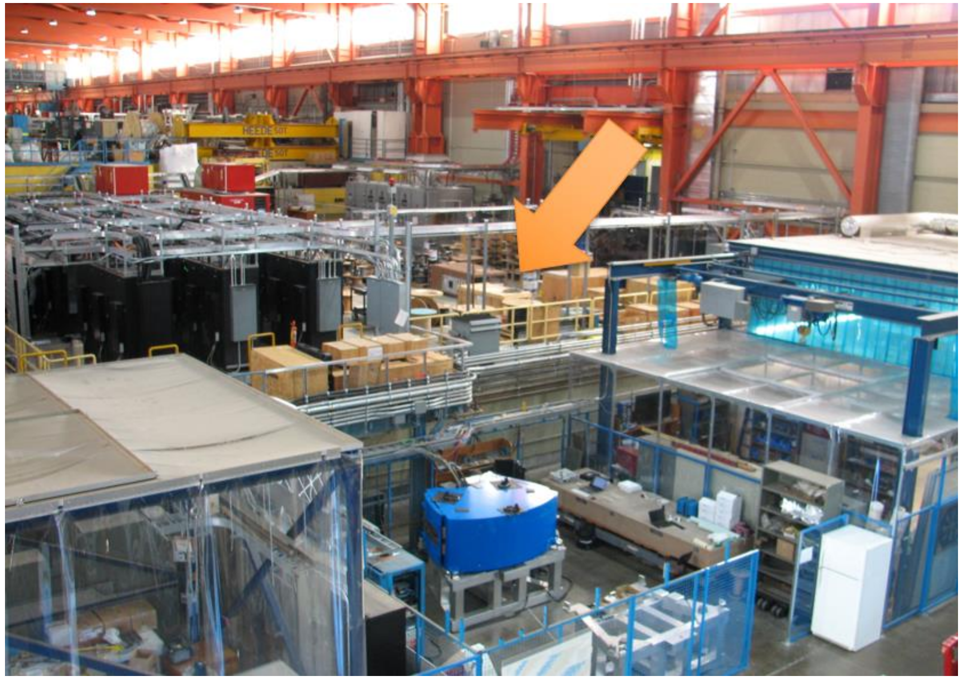


- To emit coherently the bunch length must be << λ
- Intensity of coherent radiation scales as N^2
- With a typical N ~ 10^8 -10^9 the gain is enormous
- To emit coherently in the THz region bunches must be short << 1mm
- To generate the field strength 100kV/cm and above the bunch charge in excess of 100pC is required
- Main challenge: smaller bunches and higher charges conflict with each other due to space charge (Coulomb repulsion)

Project scope







A baseline design only. Will change in ARIEL era

The scope includes
- new high-brightness photoelectron emission electron source capable of generation of short and high-charge bunches
- driver laser system
- photocathode fabrication system
- magnetic bunch compression
- THz characterization setup
- optical laboratory

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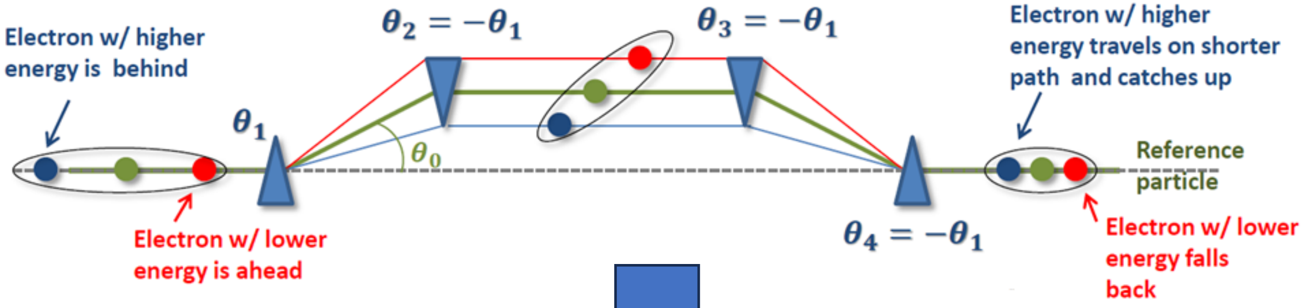
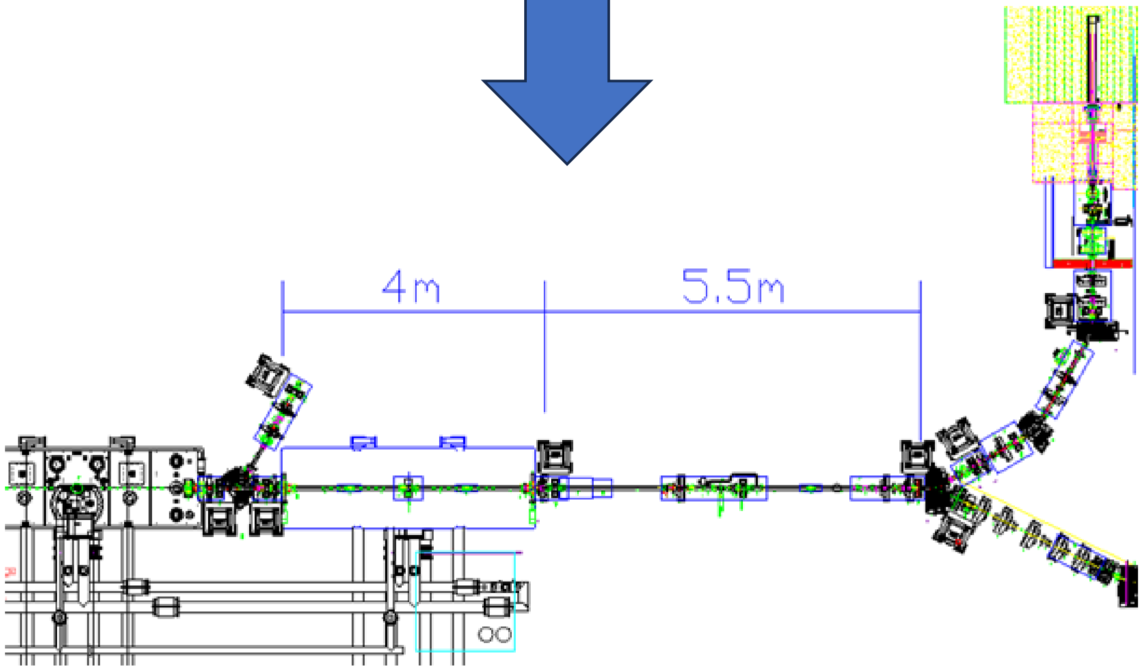
Stage 0

- It is now realized that manufacture of a high-brightness electron source can take up to 3 years
- There is still an option meantime to take a half step back and use the existing electron source for THz generation
- Bunch compressor is still required
- Stage 0 will allow us to gain experience with tuning the accelerator for bunch compression, test various schemes of THz generation, get started with THz instrumentation.

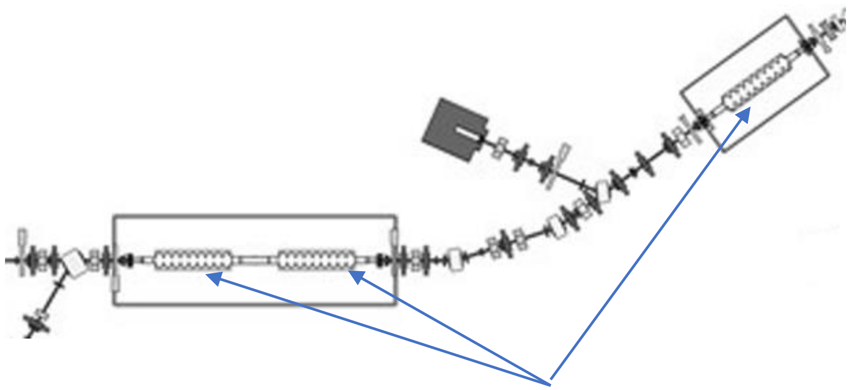




Some insight into bunch compression

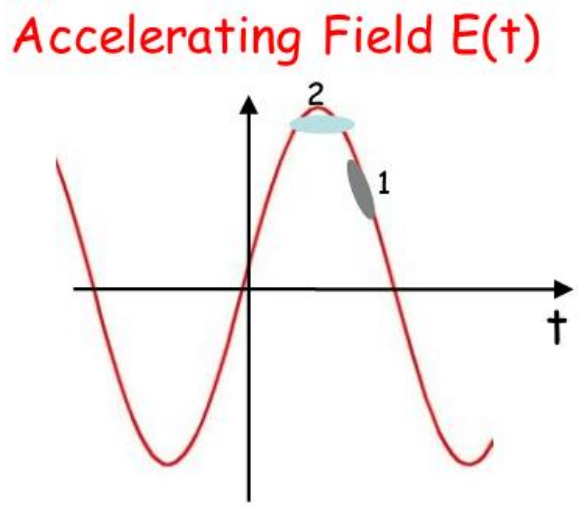
To do the bunch compression of a relativistic beam one needs

- impose a proper energy-position correlation
- an overall achromatic set of magnetic dipoles



RF cavities

The energy chirp is induced by accelerating bunches off-crest



$$h = \frac{1}{E}\frac{dE}{dz}$$ Energy chirp

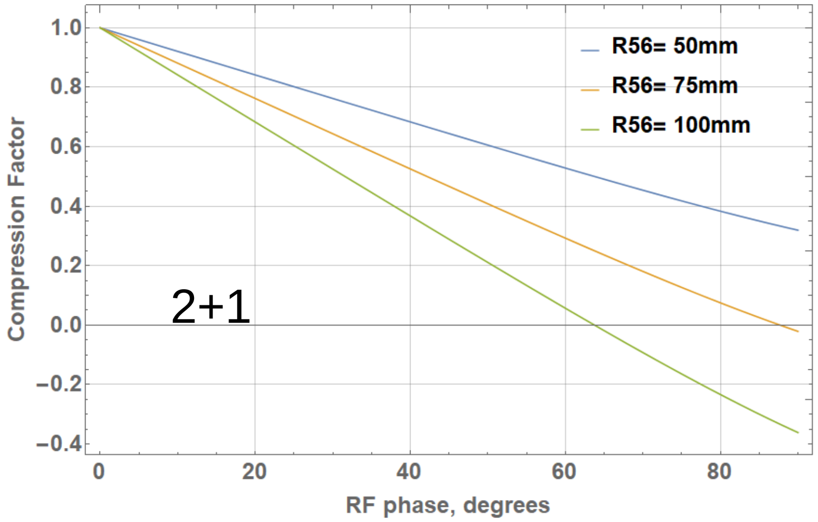
$$C = \frac{\sigma_f}{\sigma_i} = 1 + h\,|R_{56}|$$ Compression factor

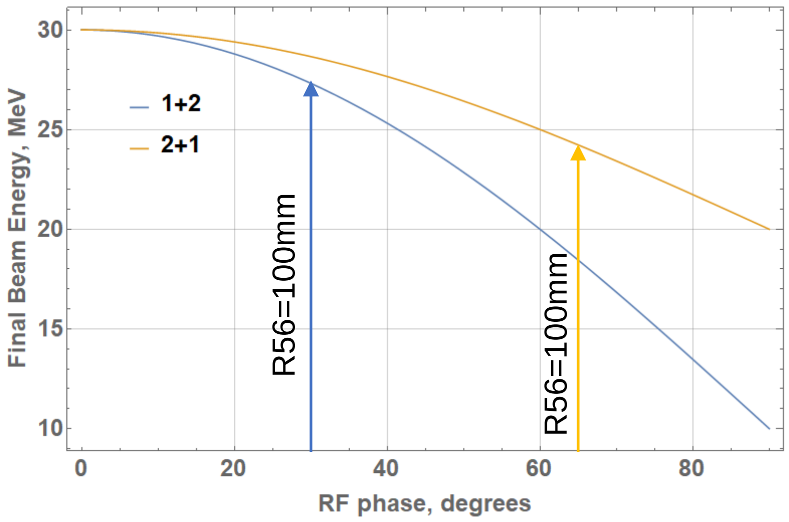
$$R_{56} = \frac{\Delta\sigma}{\Delta E/_{E}}$$

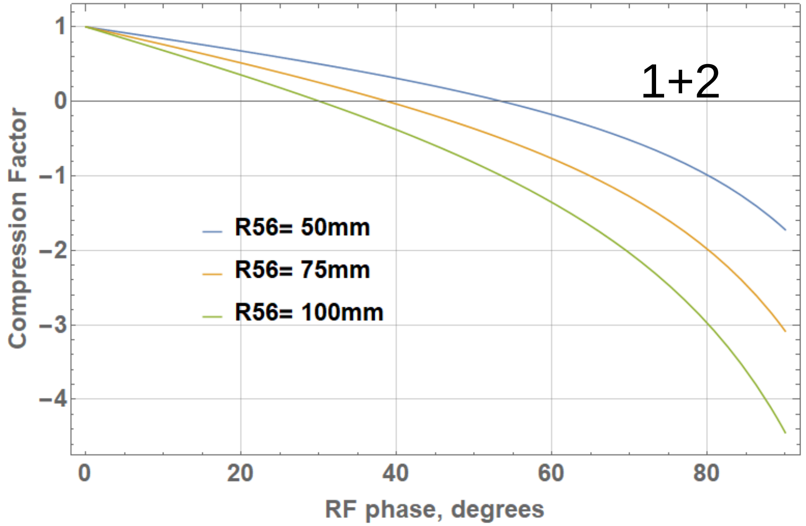
With only 3 RF cavities two options are possible

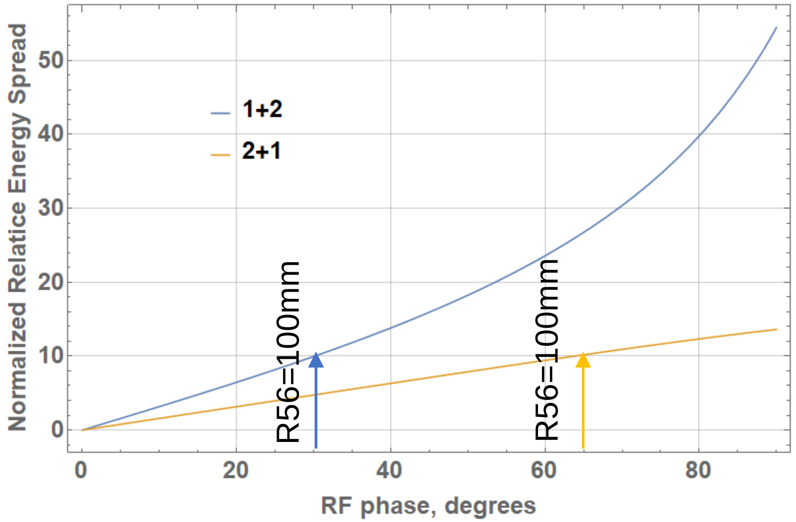
2+1 - two cavities on-crest
and one off-crest
1+2 - one cavity on-crest
and two off-crest

Some estimates







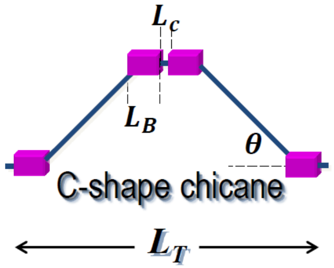


From these considerations 1+2 option seems to have some advantages : less $R_{56 ,}$ smaller the bunch compressor, higher the final beam energy

But this picture is too simplistic – nonlinear terms (curvature) and uncorrelated energy spread have to be taken into account.

Accurate simulations are required.

Chicanes

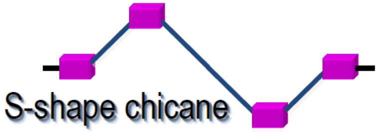


FLASH
LCLS
FERMI
X-FEL
SACLA

Bunch head < 0

$$R_{56}\approx -2\theta^2\left(\frac{L_T}{2}-\frac{4}{3}L_B-\frac{\Delta L_c}{2}\right) < 0$$

simple, achromatic



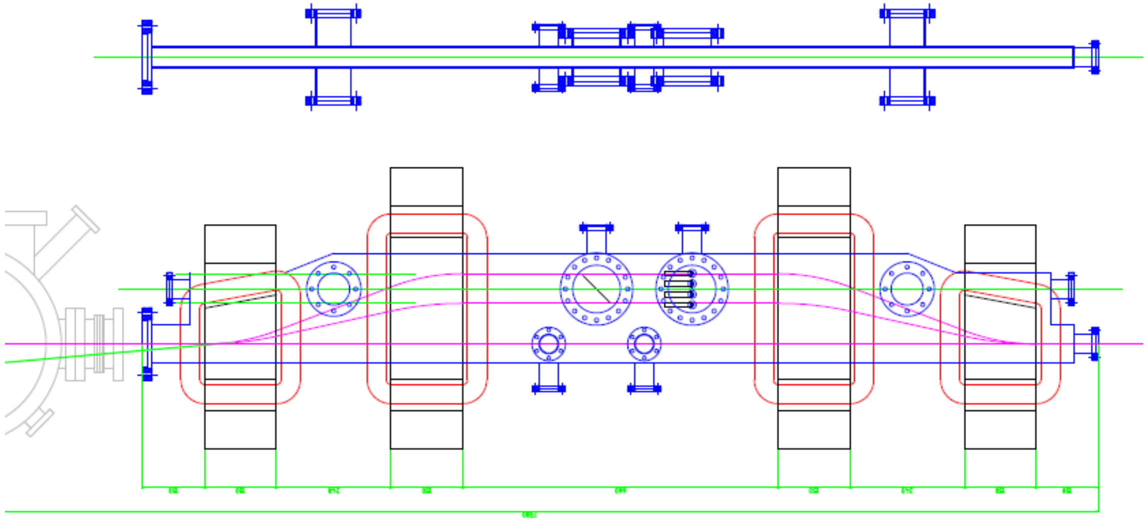
FLASH
X-FEL

$$R_{56}\approx -2\theta^2\left(\frac{L_T}{2}-\frac{4}{3}L_B\right) < 0$$

achromatic,

Both C-shape and S-shape chicanes have comparable R_{56} for similar total length

ELBE bunch compressor



Bending angle	21°
Bending radius	0.42m
Dipole length	0.15m
Drift length	0.24m
Total length	2.38m
R56	-0.094m

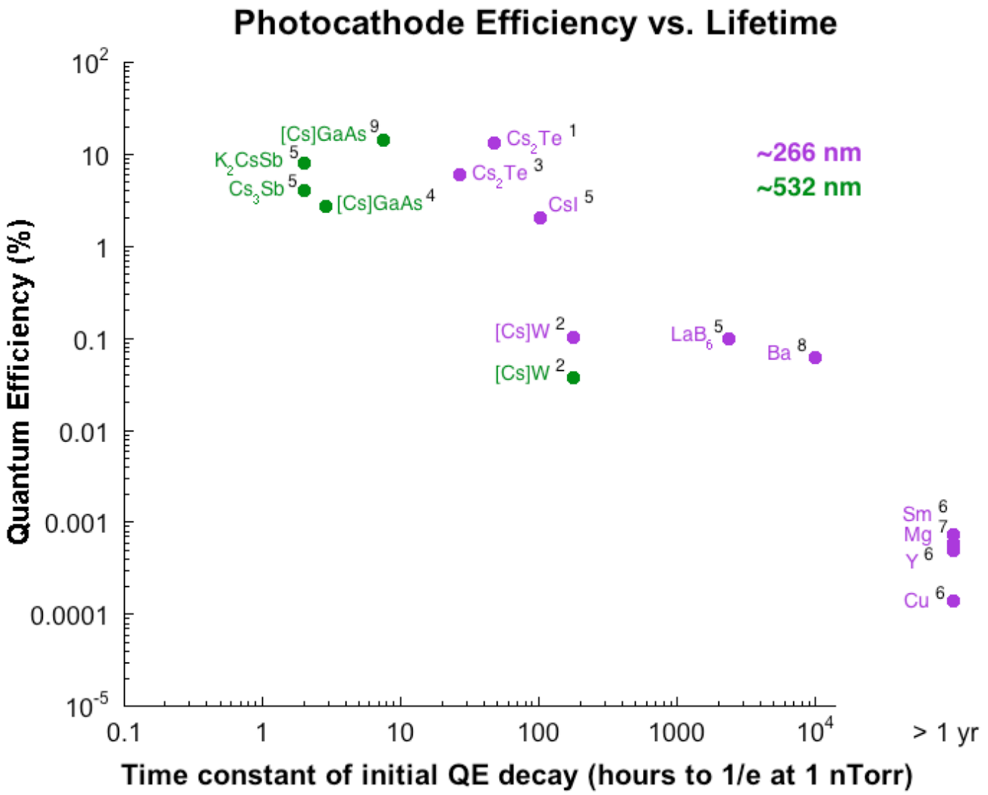
ELBE type chicane seems about right

Photocathode production

- Electron sources based on photo electron emission require a photocathode production system, unless they use low efficiency metallic photocathodes.
- For high average current accelerators semiconductor photocathodes are mostly common

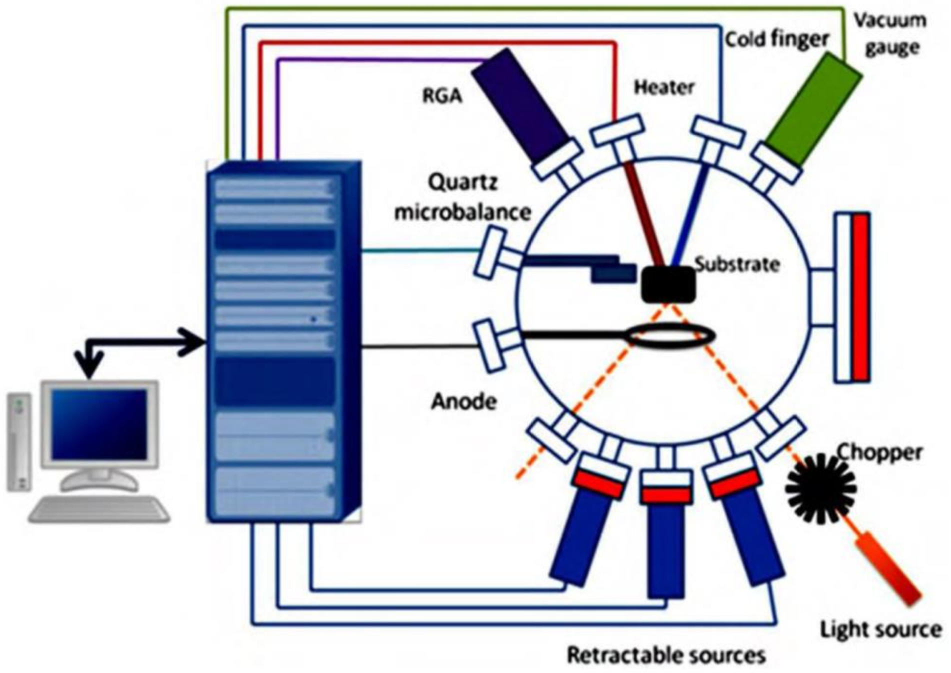
  Cs_2Te - QE ~ 7%

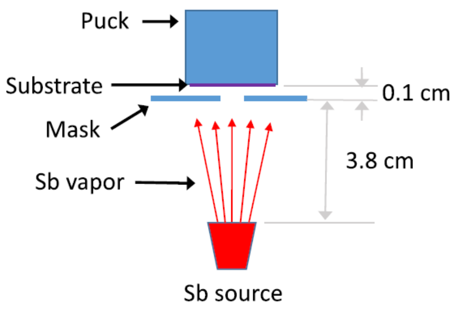
  K_2CsSb - QE >4%
- Photocathodes are consumables due to a relatively short lifetime
- But the lifetime is a bit of uncertainty and depends on operational conditions, type of the gun (RF, SRF, DC) and production technique
- Design and construction of the photocathode fabrication facility should start asap to build the required expertise in time
- Collaborators for photocathode production and characterization are welcome

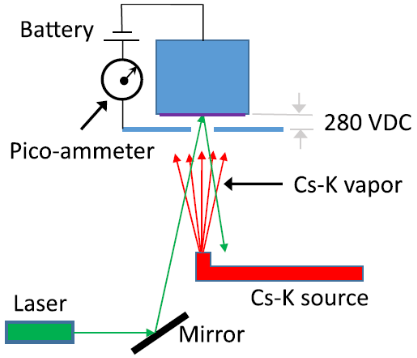


Photocathode fabrication tips

- Plenty of literature available
- Photocathode production, storage and operation require ultra high vacuum of down to 10^{-11} torr
- Substrate, typically Mo, is mirror-like polished (<100 nm)
- Substrate is cleaned under vacuum by heat/ ion beam/ plasma before deposition
- Deposition is sequential or co-deposition
- Sb or Te are deposited first
- QE is measured in situ while depositing alkali metals
- Adhesion of deposited material to substrate is important for thermal conductivity and lifetime.
- Instrumentation (thermocouples, quartz microbalance sensor, RGA) are essential for repeatability
- Load-lock manipulators for loading substrates and unloading photocathodes without venting the system

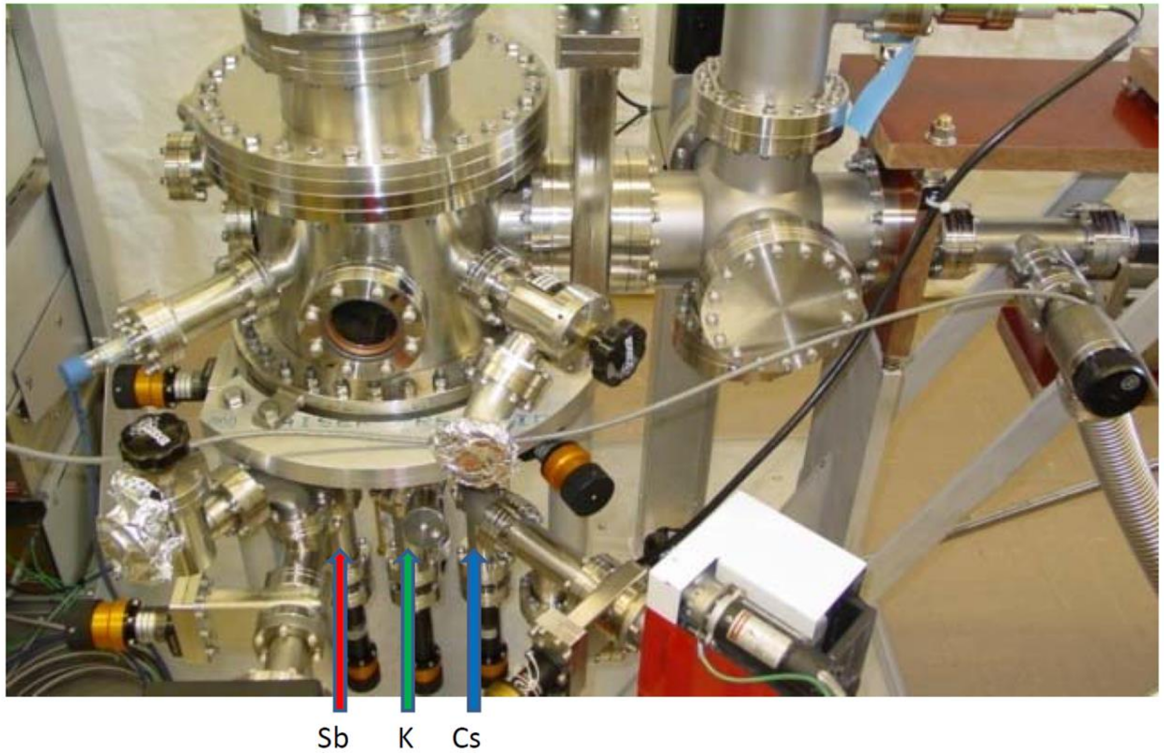




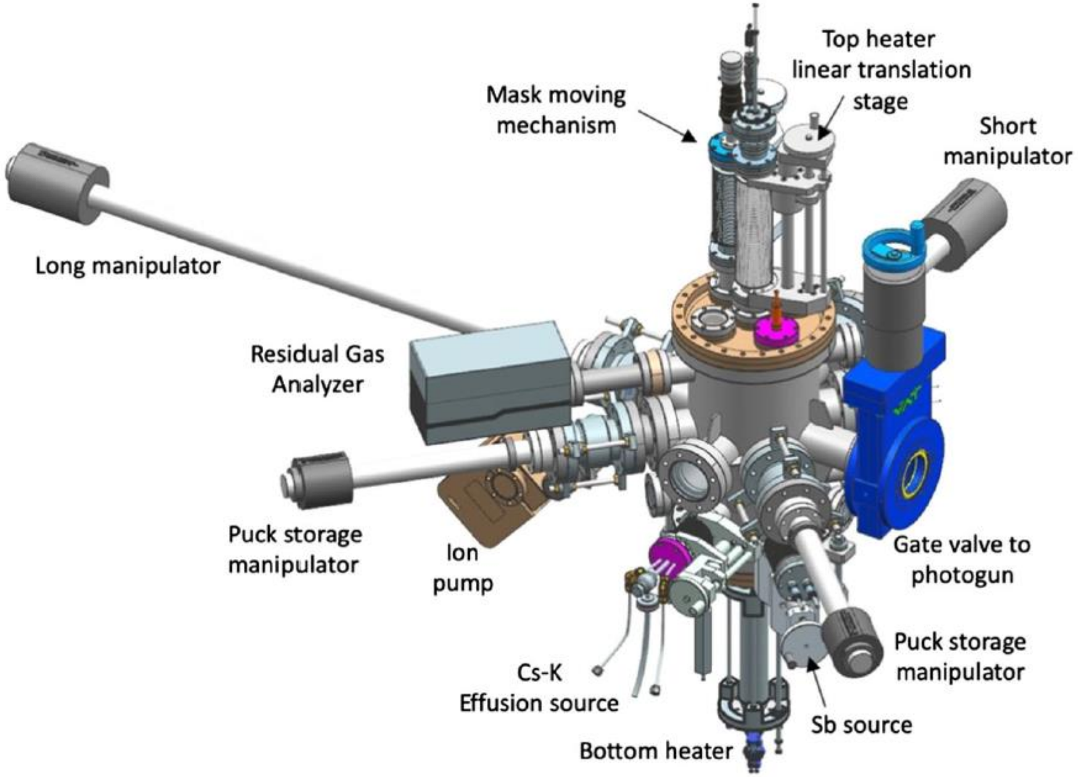


Examples

BNL



TJNAF



Summary

- TRIUMF THz project is getting momentum
- Stage 0 aiming on production of THz radiation with a present thermionic electron source is seen as a reasonable midterm step
- It includes construction and commissioning of the magnetic bunch compressor
- Photocathode fabrication system is another immediate target

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Thank you
Merci

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