This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

WP16: Intense, RF Modulated E-Beams

for Application in Pulsed Electron Lenses

5th Annual Meeting / 02.05.2022

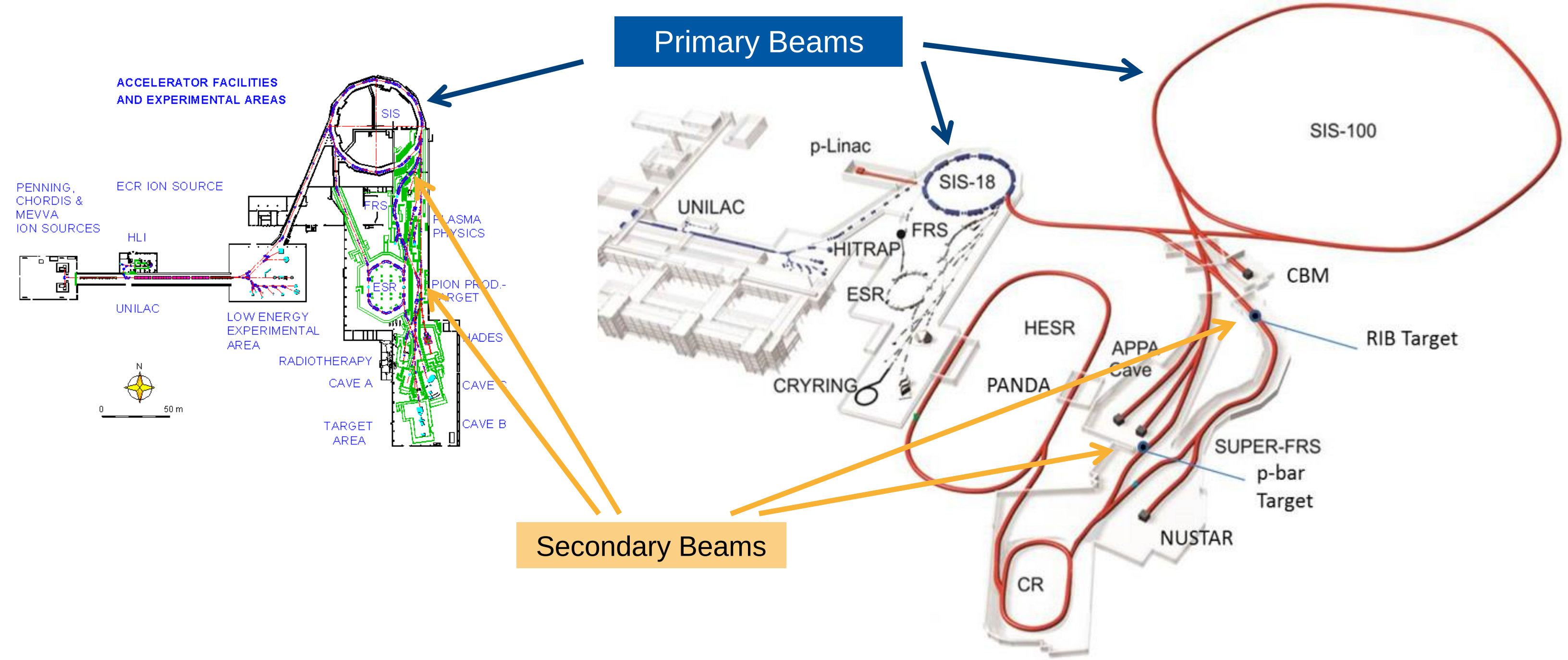
David Ondreka / GSI

Outline

- Motivation for space charge compensation
- WP16: objectives and achievements
- Beyond ARIES: SCC lens project
- Summary

FAIR Intensity Challenges

FAIR integrates existing GSI facility, using synchrotron SIS18 as main injector



FAIR designed to break intensity limits of GSI:

- Primary beam intensities: factor 10 to 100
- Lower charge states to increase **space charge limit**
- **Heavier ions** limited by injector and dynamic vacuum
- Intensity requirements expected to rise during FAIR operation
- Planned injector upgrades will make synchrotrons a bottleneck
- **Long-term efforts to push intensities for SIS18 and SIS100**

Primary Beam Intensities at GSI and FAIR

		p	Ar	Xe	U
Charge number	GSI	1	18	48	73
	FAIR	1	10	21	28
Energy [GeV/u]	GSI	4.7	1.7	1.3	1.0
	FAIR	28.8	6.6	4.0	2.7
Intensity [Ions/s]	GSI	10^{11}	**$8 \cdot 10^{10}$**	**$4 \cdot 10^{10}$**	**$4 \cdot 10^{9}$**
	FAIR	**10^{13}**	**10^{12}**	**$5 \cdot 10^{11}$**	**$3 \cdot 10^{11}$**

Space Charge as Intensity Limitation

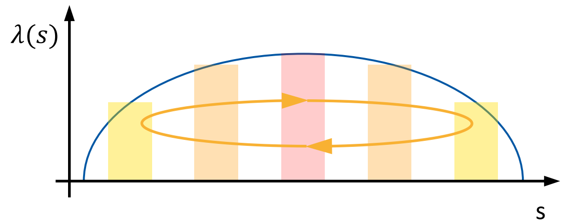
- Incoherent tune spread through SC
  - Defocusing force due to particles of same charge
  - Modifies single-particle tune in circular accelerators
  - Depends on amplitude and transverse profile

SC tune spread in bunched beam

$$\Delta Q_y^{sc} = -\frac{Z}{A} \cdot \frac{r_0}{2\pi\varepsilon_y\beta^2\gamma} \cdot \frac{ZN\lambda(s)}{\gamma^2\langle\lambda\rangle}$$

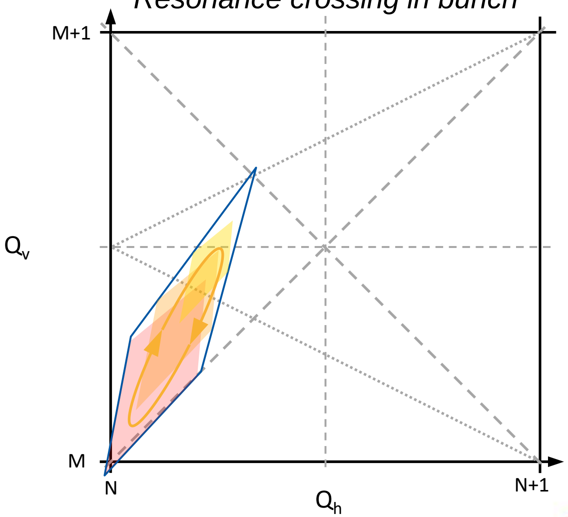
- Tune spread in bunched beams
  - Depends on local line density within bunch
  - Larger peak value due to bunching
  - Synchrotron motion slowly mixes slices

Tune spread mixing in bunch



- Beam loss due to tune spread
  - Losses driven by resonances
    - Fast beam-loss on low-order resonances
    - Slow beam-loss due to repeated crossing of resonances through synchrotron oscillations
  - Losses limit maximum intensity
  - Increasing maximum intensity requires shrinking of tune footprint

Resonance crossing in bunch

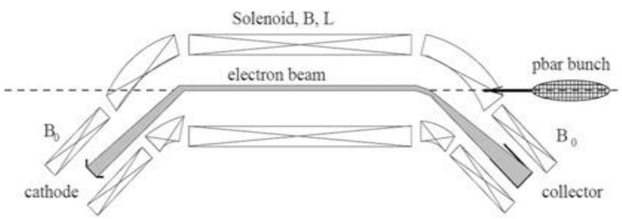


SC Compensation with e-Lenses

- Principle of electron lenses
  - Overlap ion beam with magnetized electron beam
  - Effect on ions through EM fields of electron beam
  - Existing applications
    - Beam cleaning in colliders
    - Beam-beam compensation in colliders
    - Electron cooling in low energy rings

- SC compensation in bunched beams
  - Any compensation must follow line density
  - e-lens well suited for SC compensation
    - Attractive force of e-beam to counter SC force
    - Modulate current at the source to match line density
  - Options for choosing transverse profile
    - Full compensation with matching profile
    - Linear compensation with uniform profile
    - Trade-off: non-linearities vs. footprint shrinkage
  - Active field of research
    - Demonstrator should be flexible to test concepts

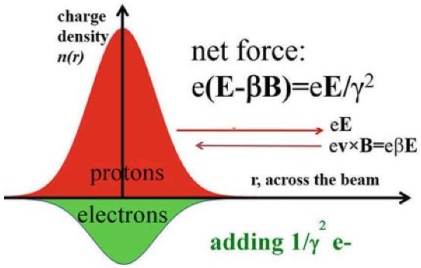
e-lens scheme (Tevatron)



V. Shiltsev, 2016

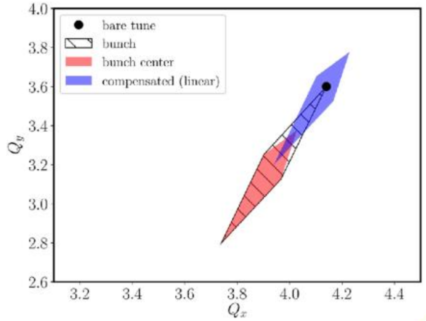
SIS18 e-cooler

Full compensation: matched profile



Shiltsev, 2016

Linear compensation: effect on tune footprint



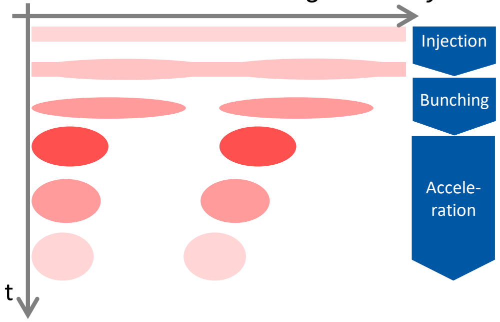
W. Stem, 2018

$$\Delta Q_y^e = \frac{Z}{A} \cdot \frac{r_0}{2\pi\varepsilon_y \beta^2 \gamma} \cdot \frac{I_e L_e}{\mathrm{ec}\,\beta_e}$$

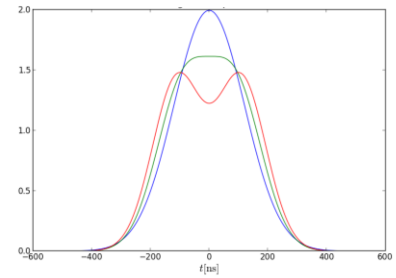
SCC Demonstrator: SIS18 as Reference Case

- SCC demonstrator lens in SIS18
  - Aiming at $\Delta Q^e \approx 0.1$ for single lens
  - Ultimately 3 lenses required for symmetry
- Constraints from SIS18 cycle
  - Parameters determining modulation
    - Tune spread peaks at start of ramp
      → time-dependent amplitude
    - Revolution frequency and bunch length variation
      → bandwidth, time-dependent center frequency
  - Parameters determining transverse profile
    - Concept of matching e-beam shall be tested
- Advantages of low energy ions
  - Large ion beam radii ($\sigma_{x/y}$ ~ 10 / 20 mm)
  - Long ion bunches ($4\sigma_t$ > 300 ns)
- RF modulated electron gun as main challenge
  - Electron currents of ~10 A at ~30 kV
  - Modulation at 0.4 – 1 MHz with 10 MHz bandwidth
  - Gaussian transverse profile, elliptic cross-section

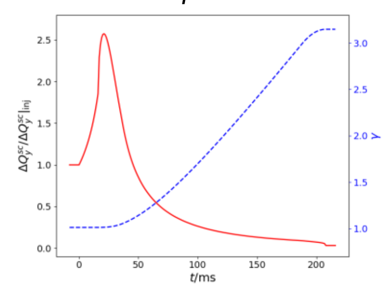
Bunches and SC during SIS18 cycle



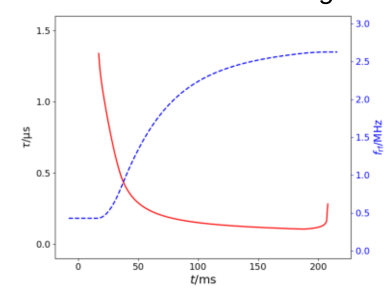
Possible bunch profiles



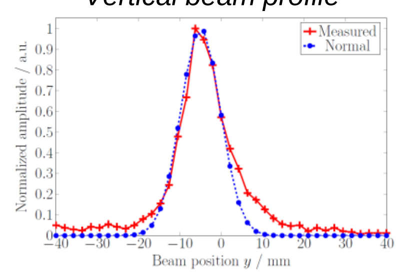
Evolution of peak tune shift



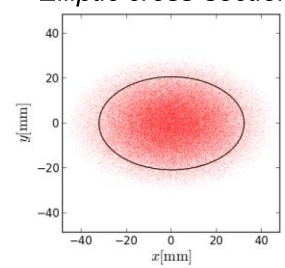
Evolution of bunch length



Vertical beam profile



Elliptic cross-section



R. Singh, PhD Thesis, 2014

WP16: Objectives

- JRA activity among four beneficiaries CERN, GSI, IAP, RTU

- Manufacturing of an RF modulated electron gun for application in electron lenses
  - High electron currents up to 10 A
  - Gaussian shaped transverse electron beam profile
  - RF modulated at 0.4 to 1 MHz with a bandwidth of up to 10 MHz
  - Grid modulation to lower power requirements on modulator

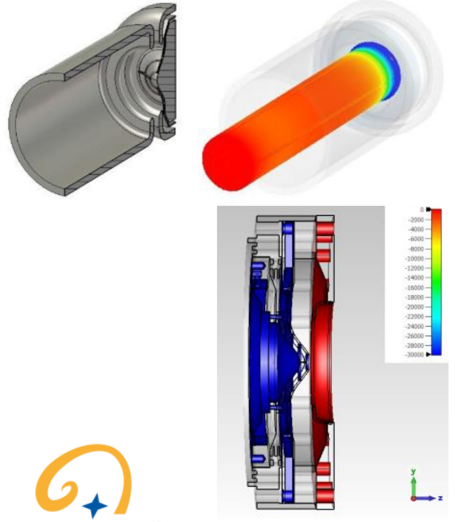
- Operation of a test stand for the RF modulated electron gun
  - Normal conducting solenoids for beam transport
  - Instrumentation for probing transverse and longitudinal electron beam profiles

WP16: RF Modulated Gun – Design

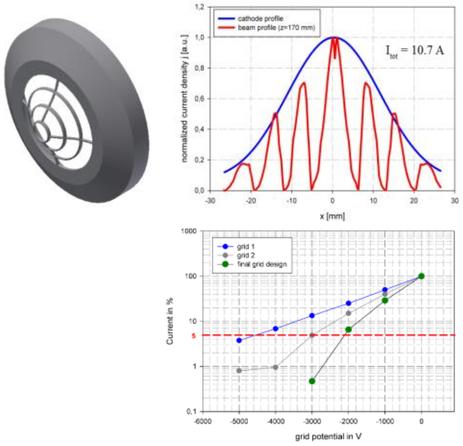
- Requirements based on SIS18 reference case
- Thermionic emission from Tungsten cathode
  - Tungsten for robustness, despite high work function
  - Design must tolerate high temperatures > 2500 K
- Modulation by grid to reduce power consumption
- Gaussian profile by shaping cathode and grid
- Elliptic cross section from round cathode
  - Achievable by integrating quadrupole coils

Gun Requirements	
Peak electron current	10 A
Anode voltage	30 kV
Cathode radius	26.5 mm
Distance cathode/anode	20 mm
Distance cathode/grid	3 mm
Grid capacitance	75 – 100 pF
Max. grid voltage	3 kV
Modulation frequency	0.4 – 1 MHz
Modulation bandwidth	10 MHz
Dissipated power	3 – 5 kW

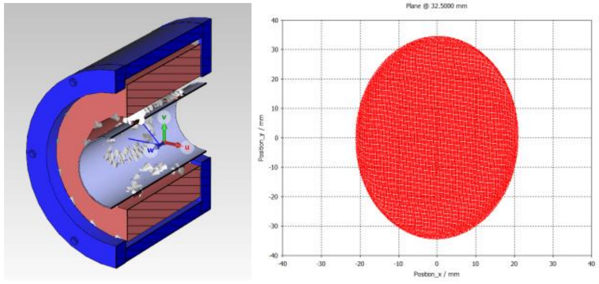
Electrode design for Gaussian profile



Grid modulation study



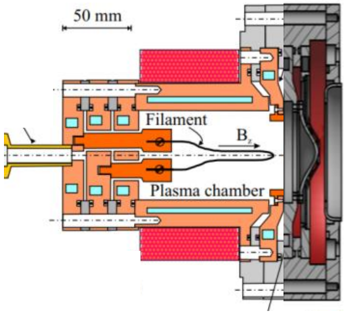
Elliptic cross-section with quadrupole

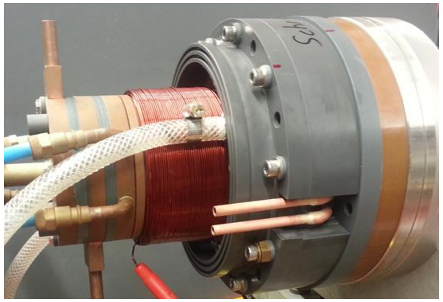


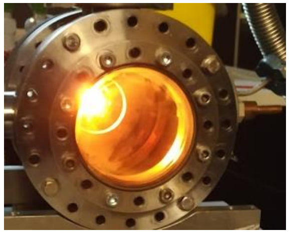
WP16: RF Modulated Gun – Realization

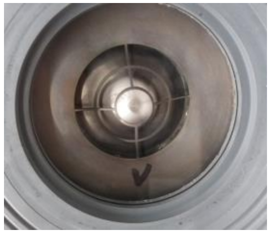
- Development of prototype (TE^2)
  - Based on volume ion source
  - Cathode heating by arc discharge from filament
  - Compact and robust design
  - Tested extensively regarding heat tolerance
- Final design by refinement of prototype
  - Optimization of grid and electrodes
  - Housing for integration into gun solenoid
  - Improved water cooling

TE^2 prototype based on volume ion source

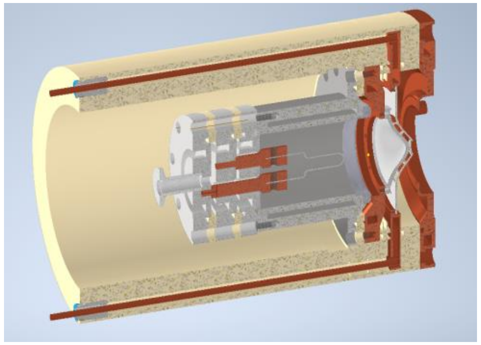


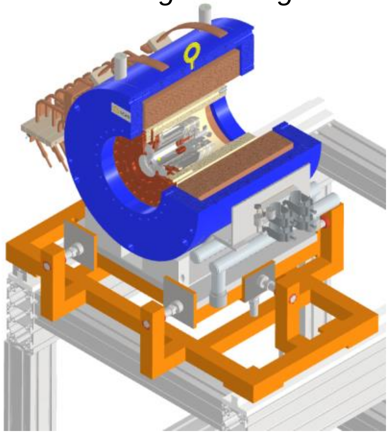


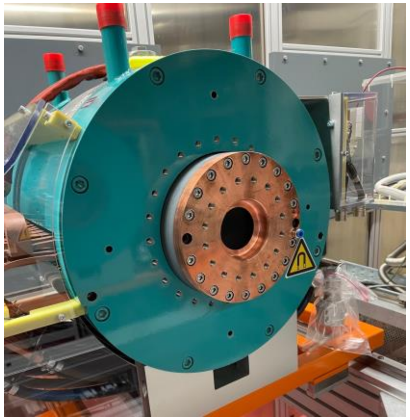




Final IRME gun: design and manufactured device



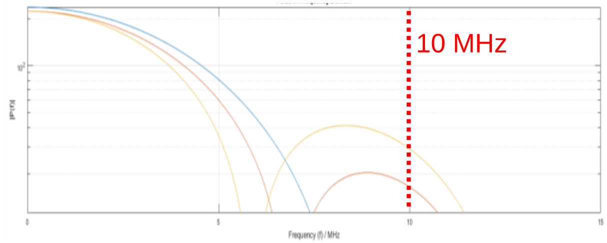




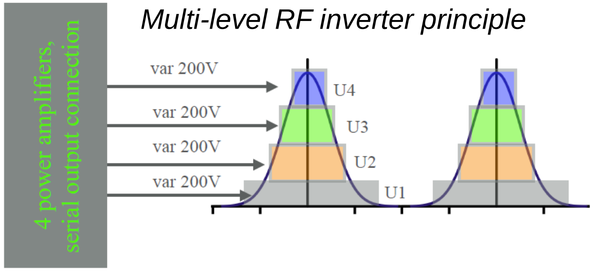
WP16: RF Modulator

- Challenging requirements
  - Sweeping central frequency (0.4 – 1 MHz)
  - Bandwidth of 10 MHz for SIS18 bunches
  - 3 kV on capacitive load (~100 pF)
  - Long cables or radiation environment
- Design iterations based on prototypes
  - Vacuum tube solution tried but discarded
  - Final design multi-level RF inverter topology
    - 26 modules supplying 150 V each
    - Bandwidth requirements satisfied
    - Allows operation outside tunnel
  - Prototypes with 4 modules built and used
  - Final device not ready due to supply problems
- Additional signal generator for testing
  - Bunch profiles input as waveforms
  - Control via optical fibers for operation on potential

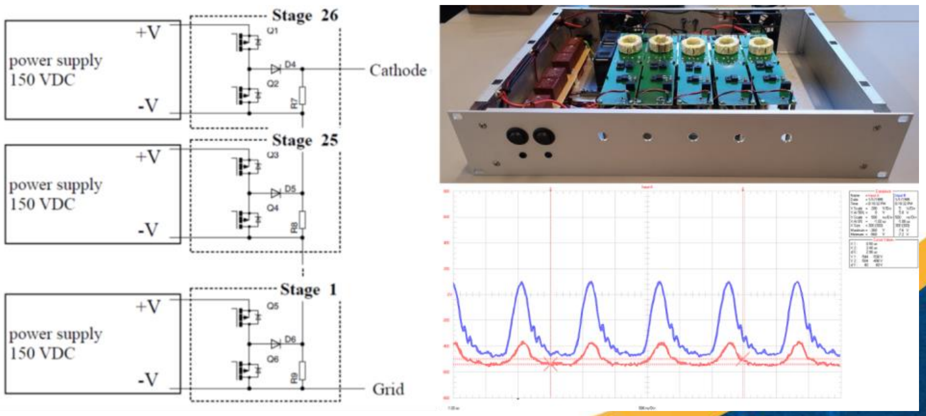
Frequency spectrum of SIS18 bunches



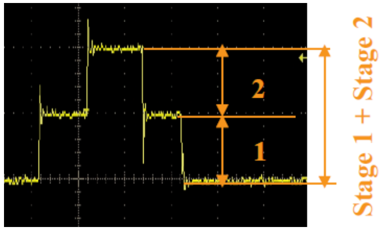
Multi-level RF inverter principle



Circuit layout and prototype of final modulator



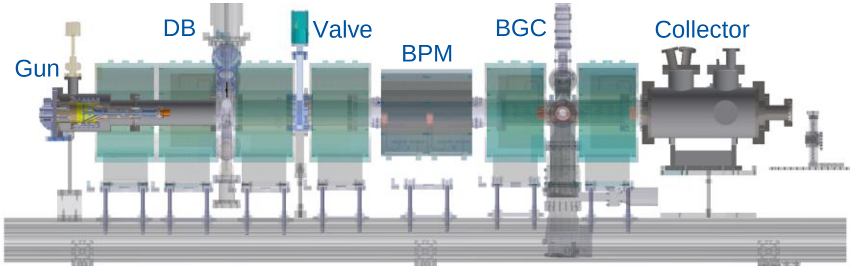
Output before filtering



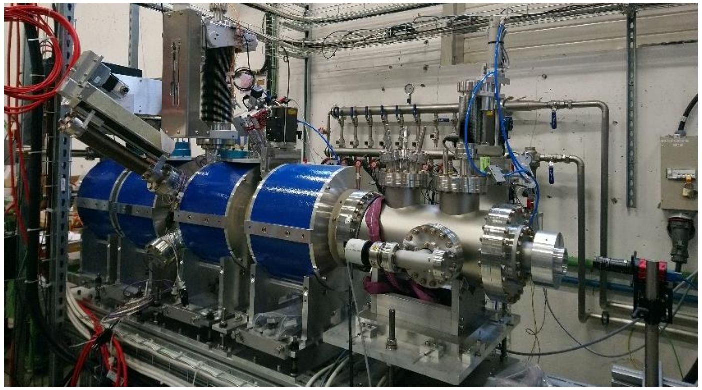
WP16: Gun Test Stand at CERN

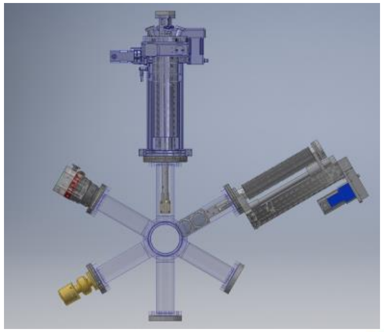
- Designed for CERN HEL gun and IRME gun
  - Co-founded by HiLumi-LHC and ARIES
- Goals
  - Operational experience with high-current e-beams
  - Testing components for HEL lens
    - Characterization of gun (yield, transverse profile)
    - Testing modulator, HV power converters, controls
    - Testing HEL diagnostics (BPM, Gas curtain monitor)
  - Testing components for SCC lens
    - Characterization of gun (yield, transverse profile)
    - Testing HV modulator
- Diagnostics equipment
  - Current transformer at cathode
  - Diagnostic box (YAG screen, movable pin-hole cup)
  - Collector measuring total current
- Test stand successfully completed
  - Inaccessible for IRME gun due to Covid-19 crisis
  - Decision to build second test stand at IAP

Layout of CERN test stand



Stage 1 of CERN test stand



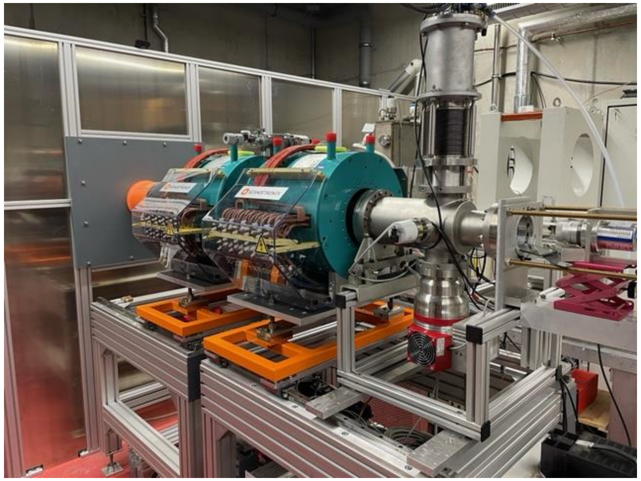


Diagnostic Box (DB)

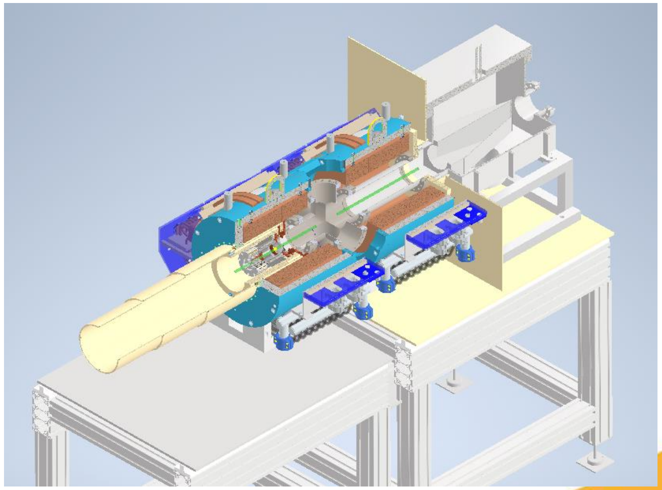
WP16: E-Lens-Lab at IAP (I)

- Lab dedicated to e-lens development at IAP
- Goals
  - Test stand for characterization of electron guns
  - Operational experience with high-current e-beams
  - Development of energy recovery system
  - R & D for electron lens components
- Test stand equipment
  - HV platform up to 50 kV / 20 kVA
  - Two separate benches
  - Two solenoids (0.6 T), Helmholtz coils (0.2 T)
  - Collector Faraday cup up to 27 kW
  - Pressure and temperature diagnostics
  - Transverse diagnostics
  - Flexible set-up for easy change of configuration

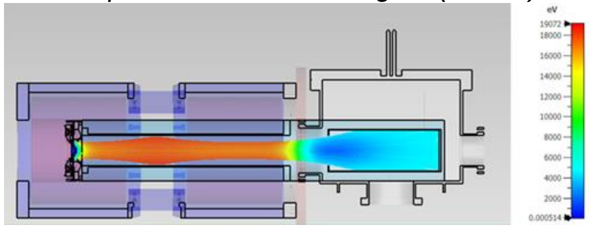
Stage 1 of test stand (present)



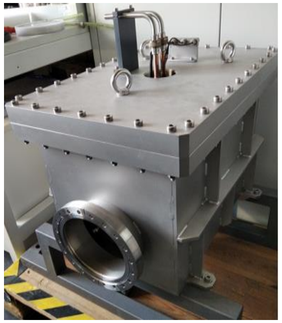
Layout of stage 2 for high intensity operation



Transport simulation for stage 2 (I = 5 A)



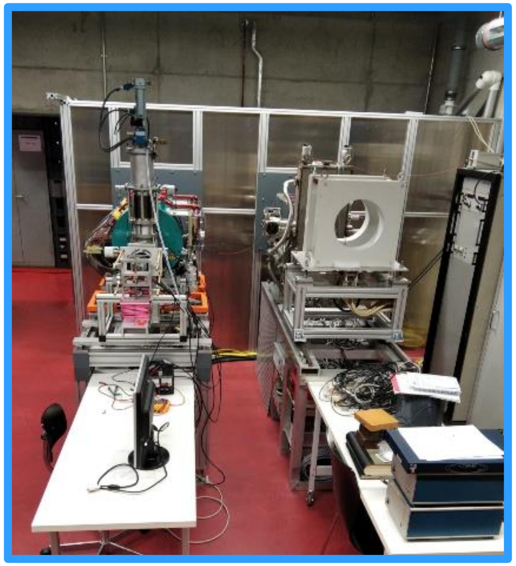
High power cup



WP16: E-Lens-Lab at IAP (II)

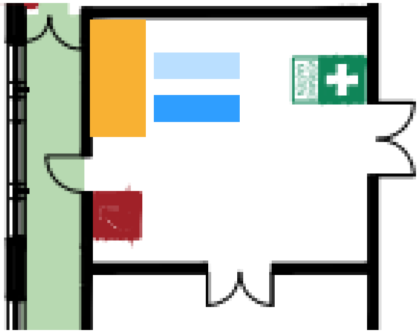
- HV terminal in Faraday cage for power supplies on cathode potential
- Remote control for safe operation
  - User interface for PC control
  - Automated measurement routines
- Floor space and infrastructure for additional installations
- Continued beyond ARIES for R&D on electron lens components

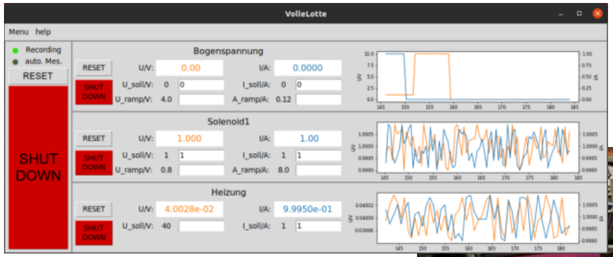
Two benches connected to HV cage



HV terminal inside cage

Floor plan of E-Lens-Lab



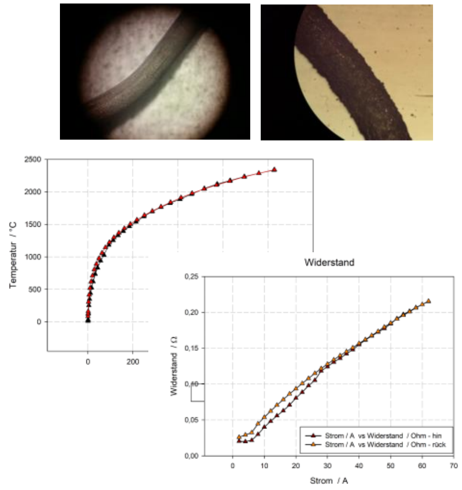


User interface for remote operation

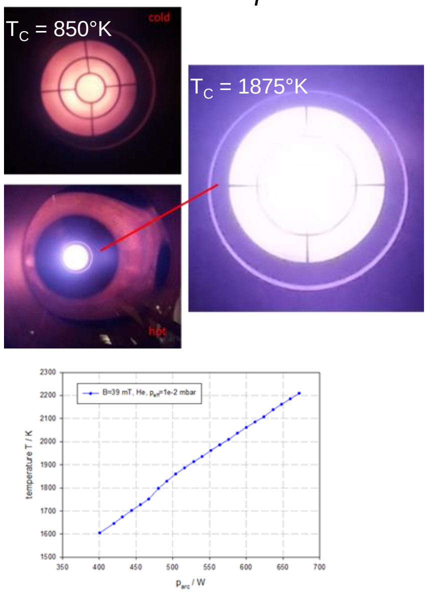
WP16: Gun Tests at IAP

- Basic tests
  - Vacuum conditioning and pressure
  - Control of cooling circuit performance
- Cathode heating
  - Novel concept using directed arc discharge
  - Uniform heating of cathode essential
  - Pyrometric measurements
  - Characterization of filament performance
- Electrical tests on grid
  - Measurements of capacitance
  - Measurements of transmission properties
  - Grid characteristics at low temperatures
- Extraction tests in preparation
  - Intensity limited with stage 1 of test stand
  - Careful intensity ramp-up to avoid damage
  - High power tests up to 5 A with stage 2

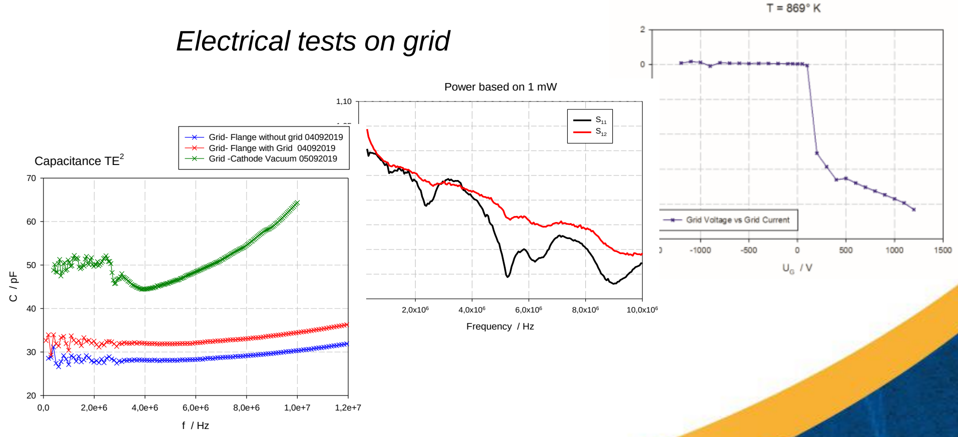
Filament characterization



Cathode heat-up tests



Electrical tests on grid

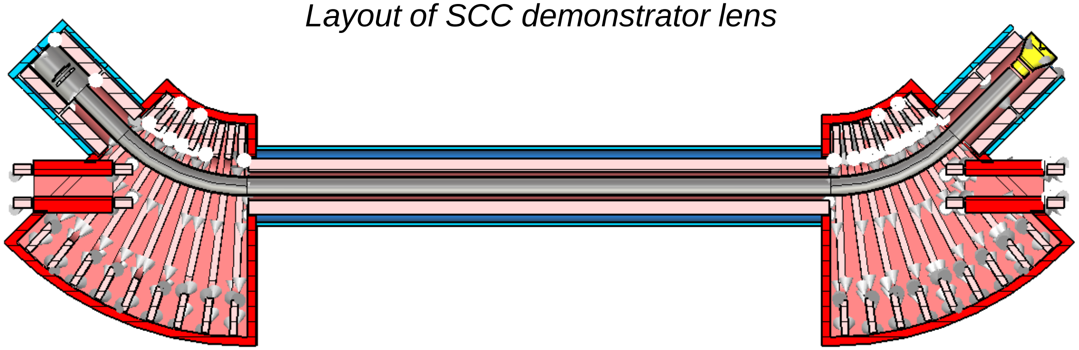


Beyond ARIES: SCC Lens Design

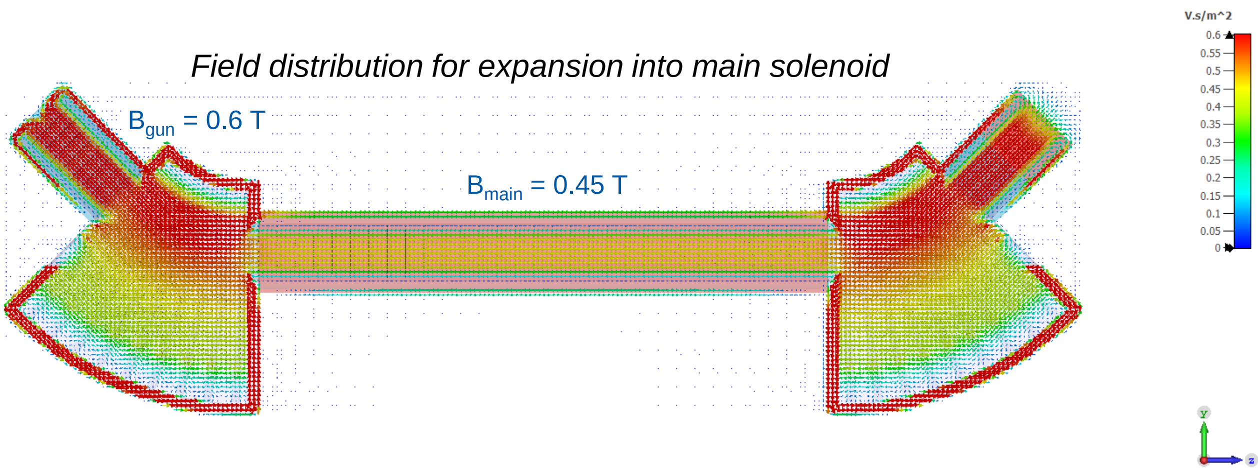
Project for SCC demonstrator lens in SIS18 among GSI, IAP, RTU

- Physical layout and mechanical design of SCC demonstrator at GSI
- Manufacturing and testing of final modulator at RTU
- Development of gun and collector as well as testing of essential components at IAP

Layout of SCC demonstrator lens



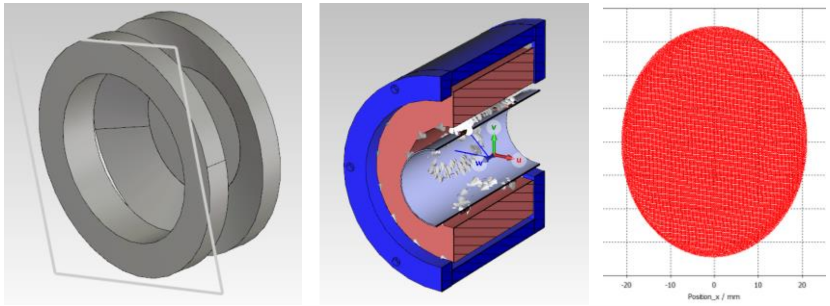
Field distribution for expansion into main solenoid



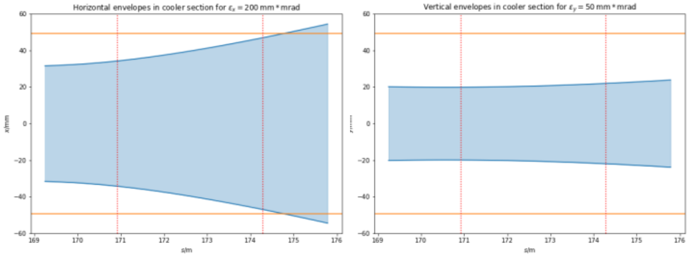
Beyond ARIES: SCC Lens Design

- Adapted requirements for demonstrator SCC lens
  - Uniform electron beam to avoid non-linearities
    → design of grid-modulated gun for uniform beam
  - Larger beam size to increase margin
    → beam expansion into interaction solenoid
  - Elliptic cross-section to lower current requirements
    → integration of quad coils around gun
- Collector design crucial component of lens
  - Optimization of bias potential and geometry
    - Minimization of power dissipation
    - Suppression of secondary electrons and reflection
  - Work in progress

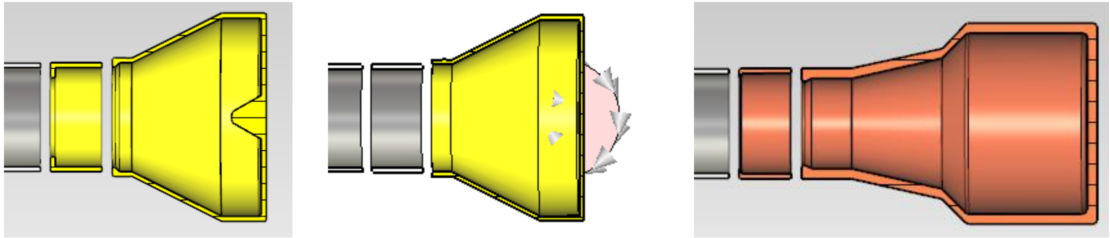
Elliptic uniform beam from round cathode using quad



Ion beam envelopes in x and y



Studies on optimal collector geometry



Summary

- Motivation for WP16 developments
  - Alleviating space charge related intensity limitations in circular hadron accelerators
  - Particular goal: increasing intensities for FAIR facility by using SCC electron lenses

- ARIES WP16: JRA for development of RF modulated electron gun
  - Requirements derived from SIS18 as reference case
  - Main objective achieved: gun manufactured, modulator prototype ready
  - Full performance not yet demonstrated due to Covid-19 related delays
  - Two test stands at CERN and IAP constructed

- Work to be continued beyond the ARIES project
  - Final modulator will be completed by RTU
  - Second gun for homogeneous transverse profile under design at IAP
  - Design of demonstrator SCC lens for SIS18 ongoing

Thank You, ARIES!

Thanks to all the collaborators who contributed to WP16 during the ARIES project:
Adriana Rossi, Sergey Sadovich (CERN)
Kathrin Schulte-Urlichs, Sayyora Artikova, Katrin Thoma (GSI)
Oliver Meusel, Martin Droba, Julian Rausch, Thomas Dönges (GUF/IAP)
Peteris Apse-Apsitis, Ingars Steiks, Johann Van De Pol (RTU)